Reliability of Geophysical Techniques in the Evaluation of Aquifer Vulnerability at Igbo-Imabana, Cross River Sate, Nigeria using Electrical Resistivity Method

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Abstract
An investigation has been made of the groundwater potentials of Igbo-Imabana, Abi L.G.A of Cross River State, Nigeria, using electrical resistivity survey. This study was motivated to determine the electrical resistivity parameters of the area. This work aims to use the electrical resistivity method to explore the groundwater potentials of the study area with the determination of its second-order parameters. A total of fifteen vertical electrical soundings (VES) were conducted with a maximum electrode spacing of 400 m. The data was acquired using ABEM SAS 4000 Terrameter and processed using Interpex software. The interpreted and analyzed results reveal four to six geoelectric layers. The VES curves obtained were Q, H, A, QH, KH, KQ, and KHK. From the result, the Dar Zarrouk parameters longitudinal conductance (*S*) and transverse resistance (*Tr*) were calculated. The longitudinal conductance and transverse resistance range between 0.0022 to 2.81 ohms, and 36.59 to 86102.9 Ω/m^2 respectively. Further findings revealed that the hydraulic conductivity (K_c) values range from 7.95×10^{-4} to 2.06×10^{-3} m/day while, transmissivity values vary between 8.25 x $10^{-3}$and 2.82 m^2/day. Findings from the calculated parameters suggested that the study area has moderate to good groundwater prospects at certain VES points. However anthropogenic activities that pose a threat to aquifer contamination should be closely monitored by relevant bodies.

Keywords: Dar- Zarrouk, Conductance, resistance, curve, Lithology.

INTRODUCTION:
Geoelectric surveying, a form of geophysical surveying, has been an effective and dependable method of discovering potential aquifers for long-term water supply (Eyankware and Aleke, 2021; Adeniji et al. 2013). When compared to other geophysical survey methods, this method has the advantages of being non-destructive to the environment, being cost-effective, having a short survey duration, and having less ambiguity in the interpretation of the results. The traditional Schlumberger array, which has a symmetrical architecture with electrodes scattered on either side of the array spread, is the most preferred configuration in vertical electrical sounding (VES) (Umayah and Eyankware, 2022; Obasi et al., 2020; Oladunjoye and Jekayinfa 2015; Olorunfemi et al. 2005). The earth's effective response to a flow of subsurface electrical current is the basis for geophysical resistivity approaches. The method entails transmitting electrical current into the ground via two current electrodes AB and two potential electrodes MN, which are used to record the subsequent potential difference between them, resulting in electrical impedance measurement (Eyankware, et al., 2022a; Egbai 2013). Because the gathered data are mostly governed by lithological

characteristics of the aquifer, electrical resistivity is commonly employed in hydrogeological research. The approach can also be used to compare lithological facies between borehole wells (Obianwu et al. 2015; Eyankware, 2019). When used in conjunction with other geophysical methods, geologic mapping, and accessible well data, VESs can substantially aid in the location and completion of water wells in difficult hydrogeological bedrock locations. The VES approach is typically preferred for investigating subsurface geologic environments with horizontal or nearly horizontal layers, such as those found in unconsolidated sedimentary periods (Umayah and Eyankware, 2022; Ojekunle et al. 2015; Eyankware and Umayah, 2022; Badmus and Olatinsu 2012; Alile et al. 2008). According to Laouini et al. (2017), the results of their study on the delineation of aquifers using Dar Zarrouk parameters in parts of Akwa Ibom, Nigeria's Niger Delta, revealed that the area is vulnerable to contamination due to high permeability in the aquiferous layer. The study also revealed that the area has a high groundwater yield.

Other geophysical techniques (electrical, electromagnetic, magnetic and gravity have also been used to determine the degree of fracturing in the environment (Pérez and López 2011; López, et al., 2015; Redhaounia et al. 2016; Schiller et al. 2016; Sun et al. 2017). The VES survey has been demonstrated to be quite effective in enhancing groundwater survey interpretation (Ekwe et al., 2006). Because rocks have resistivity ranges, according to Telford et al. (1976), if VES and well log data are appropriately connected, the resistivity of these rocks beneath the earth can infer the areas of groundwater potential and the yield of the well. The focus of this research is on areas having a high fracture risk.

Fractures in the research area were determined using a variety of models. These are the secondary resistivity characteristics of fracture porosity and anisotropy. In the field of geophysics, these factors have been effective in determining fracture in sedimentary terrain (Odoh et al. 2012). If water is contaminated/polluted, it simply implies that it is unfit for various uses, regardless of the amount of groundwater potential in the area. Groundwater contamination can be caused by a variety of sources. Leachate, industrial waste, and septic tank leaks are examples of these. Various ways have been presented by various authors to protect an aquifer from surface contamination; however, the Dar-Zarrouk criteria were employed in this work. According to Ayuk (2019), the presence or lack of a protective impermeable layer, such as clay, determines the rate at which an aquifer is susceptible to pollution from the surface. Similarly, Ayuk (2019) primarily relies on the idea that subsurface rocks may provide some protection to the aquifer from geogenic and anthropogenic influences, with a focus on subsurface contamination. Subsurface rocks that filter percolating fluid to the water bearing units, according to Olorunfemi et al. (1999), can minimize the quantity and movement of contaminants into the aquifer. This, in turn, is a measure of its ability to defend. As a result, the goal of this research is to not only determine groundwater potential, fracture zones, and aquifer porosity, but also to assess the aquifer's susceptibility within the study region using longitudinal conductance (S) and transverse resistance measurements (Tr). Most publications have utilized these geoelectric characteristics to conduct similar research in different places to assess aquifer susceptibility. Eyankware et al. (2020a) found that locations underlain by shale and clay have significant aquifer protection capacity in the southern Benue Trough. According to Obiora et al. (2016), locations with high aquifer yield also have high transverse resistance.

Location, Climate, Physiography and Geology of the study area

Igbo – Imabana is a rural community in Abi Local Government Area of Cross River State, south-south Nigeria. The area is bounded by latitudes 5.50° N and 6.00° N of the Equator and longitudes 8.05° E and 8.12° E of the Greenwich Meridian. Groundwater occurrence in the area is highly variable and it is the only dependable source of water for many people in the area considering its quality especially for drinking purposes Before now, inhabitants of the area mostly illiterates rely on streams and rivers for water to meet their daily needs as it is the only source of water supply. The outbreak of water-borne diseases like dysentery, cholera, typhoid fever, and transmission of certain viral diseases has been linked to the consumption of this river water. Therefore, the villagers duly rely on groundwater for their domestic uses (Ebong et al., 2014).

Climatologically, the area is characterized by the wet and dry seasons with relative humidity of 80%, annual precipitation of 2,200 mm, with temperatures dipping to 23°C in the rainy season and up to 35°C in the dry season (Akpan, et al., 2015). When moisture-rich tropical maritime air mass from the Atlantic Ocean moves northward across the area, the wet season begins in March. Around October, as the rainy season ends, the air mass begins a gradual process of temporal termination of persistent blowing activity in the area. During the rainy season, water levels in the area's groundwater and surface water resources typically reach their highest heights above the datum (i.e. mean sea level).The beginning of the dry season is usually marked by a sudden increase in aridity, ambient temperature, and heat in November, and these harsh conditions will last until March when the arrival of the tropical continental air mass that blows southward from the Sahara Desert across the area marks the beginning of the dry season (Akpan, et al., 2015). The area is entirely drained by the river Cross which meanders through the area (see Figure 1).

Geologically, Igbo- Imabana is part of the Lower Benue Trough. Petters (1982, 1991) and Burke et al., 1972) described it as a NE–SW trending elongate intracontinental Cretaceous basin (about 1000km in length), resting uncomformably upon the Precambrian Basement rocks. The Trough spreads laterally into Western Cameroon, covering 2,016km^2 (Eseme et al., 2002). Locally, the area is underlain by the Asu River Group (ARG) and the Eze Aku Formation (EAG) (Fig.1). The Albian ARG overlies the Precambrian basement and is the oldest sedimentary strata in the area. They are mostly non-marine to marginally marine in nature, with impermeable shales, limestone with some sandstone intercalation, and ammonites as deposits (NGSA, 2006; Odigi and Amajor, 2009). The EAG is made up of thick flaky impenetrable calcareous and non-calcareous shales, calcareous sandstone, and sandy shaly limestone (NGSA, 2006; Odigi and Amajor, 2009). Sandstone, mudstone, and shale are the principal lithologic units in the EAG, which is overlain by the post-Santonian sedimentary fills (NGSA, 2006; Odigi and Amajor, 2009).

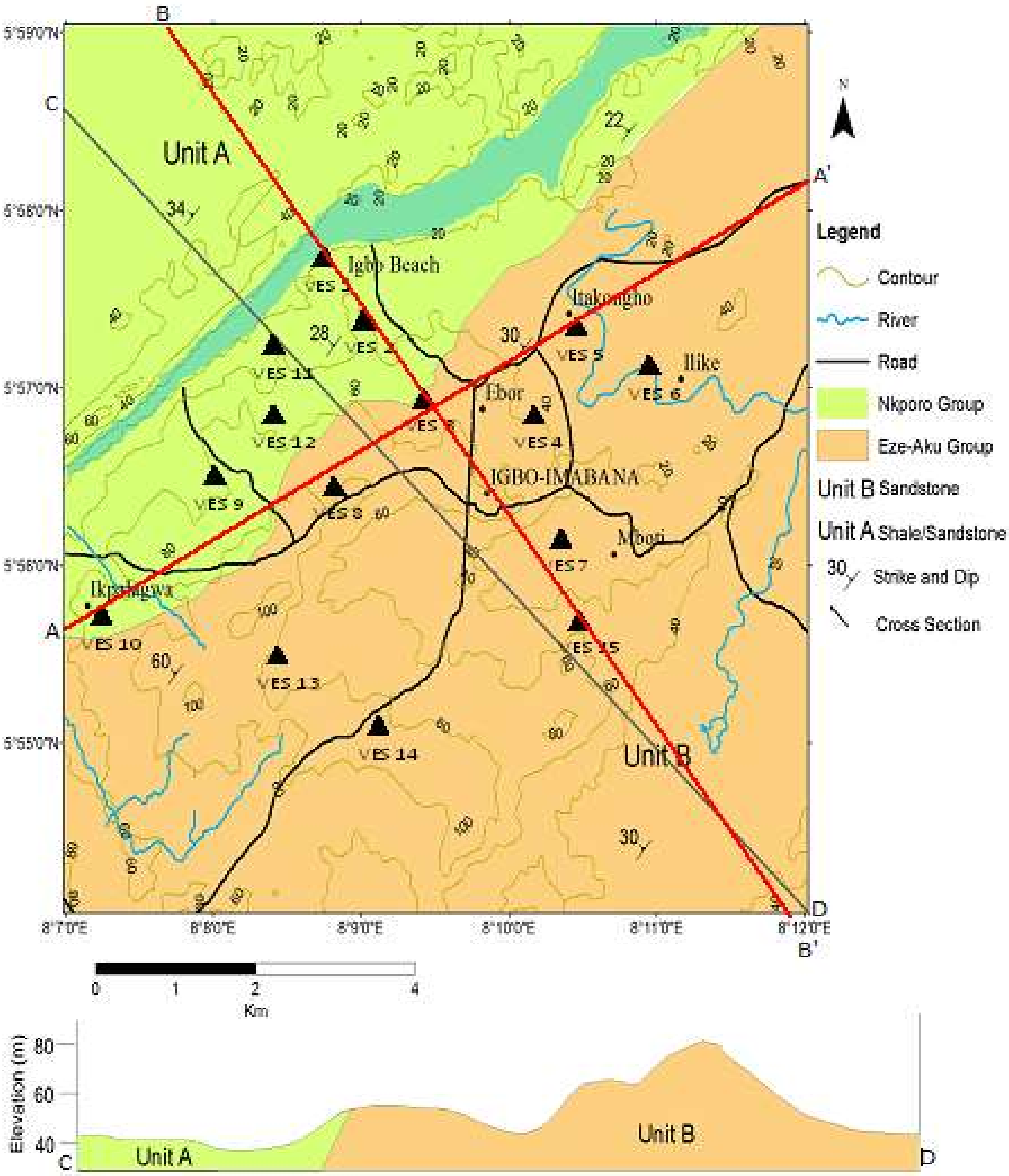

Figure 1: Geologic Map of the Study Area showing Lithostratigraphic unit of the study area VES points and transverse.

METHODOLOGY

ABEM Terrameter SAS 4000 and its attachments were used to conduct 15 VES within the study region (see Fig. 1).

Each VES profile used a Schlumberger electrode array with a maximum half current (AB/2) electrode separation of 400 m and a half potential (MN/2) electrode separation of 10 m for each VES profile. Surfer program was used to model the spatial distribution of S, Tr, L, pt, aquifer thickness, aquifer resistivity, aquifer conductivity, and Iso–resistivity contour map at AB/2 intervals from 6 to 150 m. The following equation (1) was used to convert the measured field data into apparent resistivity (a) values:

$$\rho a = \pi \left(\frac{\left(\frac{AB}{2}\right) - \left(\frac{MN}{2}\right)}{MN} \right) \Delta V / I \quad (1)$$

Geoelectrical curves were generated by plotting apparent resistivity data against current electrode spacing (AB/2).

The adoption of the IX1D software, which allows to produce sound curves, has improved the data processing. The thickness of the aquifer was calculated using the geoelectrical sections, which were produced using the information from the sounding curves. The charts supplied by Loke (1999) and Kearey, et al., (2002 were used to deduce lithologies that match to the geoelectric section. For the analysis and comprehension of the geologic model, some factors linked to the various combinations of thickness and resistivity of the geoelectric layer are crucial (Zohdy et al., 1974; Maillet, 1947). Those parameters are Dar Zarrouk: longitudinal (*S*) and transverse (*T*), respectively, given by

$$S = \frac{h}{p} \quad (2)$$

$$T = hp \quad (3)$$

Dar-Zarrouk Parameters

1. Using the formula below, the total Longitudinal Unit Conductance (S) was computed. The total longitudinal conductance for 'n' layers is

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} = \frac{h_i}{\rho_i} + \frac{h_2}{\rho_2} + \cdots + \frac{h_n}{\rho_n} \quad (4)$$

as proposed by Asfahani (2013); Oli et al. (2020)
For the equation 5, the Transverse Unit Resistance (Tr) was determined.
The total transverse unit resistance is

$$Tr = \sum_{i=1}^{n} h_i \rho_i = h_i \rho_i + h_2 \rho_2 + \cdots + h_n \rho_n$$
(5)

as proposed by Oli et al. (2020); Nwachukwu et al. (2019)
Below is the average longitudinal resistance for each VES curve.
The longitudinal resistivity is

$$\rho_L = \frac{H}{S} = \frac{\sum_{i=1}^{n} h_i}{\sum_{i=1}^{n} \frac{h_i}{\rho_i}} \quad (6)$$

as proposed by (Suneetha and *Gupta (2018).*

Equation 6 can then be used to calculate the Transverse Resistance of a VES curve.

The transverse resistance is

$$\rho_t = \frac{T}{H} = \frac{\sum_{i=1}^{n} h_i \rho_i}{\sum_{i=1}^{n} h_I} \quad (7)$$

as proposed by Suneetha and *Gupta (2018).*

Aquifer Parameters

Transmissivity

Transmissivity is a measure of how much water can be transmitted horizontally. It is directly proportional to the hydraulic conductivity (K) and aquifer thickness (b) as illustrated in equation 8. Expressing K in m/day or cm/s and b in m, the transmissivity (T) is found in units m^2/day or cm^2/s.

T=Kb (8)

The transmissivity (T) of aquifer is related to the field hydraulic conductivity (K) by the equation 8 and 9.

According to Niwas and Singhal (1981) in a porous medium

$T_c = K_c{}^{b}$ (9)

T_c = Calculated transmissivity (m^2/day) from VES data.

K_c = Calculated hydraulic conductivity (m/day) from VES data.

^{b} = Thickness of saturated layer (m).

RESULTS AND DISCUSSION

VES survey

Table 1, 2, and 3 summarizes the results of the interpreted VES survey. As demonstrated in Table 3, VES findings revealed geoelectric layers ranging from three to six layers with variable intra-facies and inter-facies alterations. Modelling of VES data taken from the field curve yielded the following curve types.

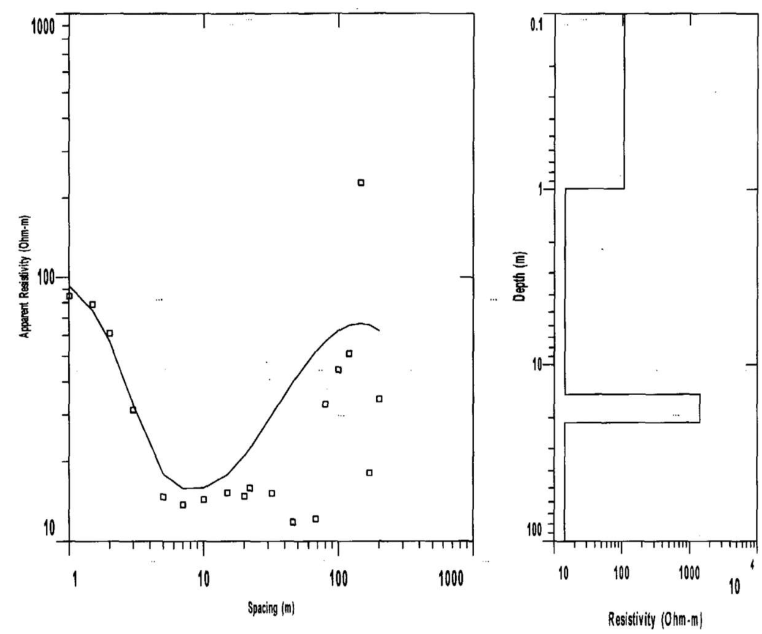

Figure 2: Sounding curve at VES location 2

Table 1: Result of interpretation for VES 2

Layer	App. Resistivity (Ω-m)	Thickness (m)	Depth (m)	Description
1	105.8	0.989	0.989	Sandstone
2	14.19	13.72	14.71	Shale
3	1405.1	6.62	21.34	Loose Sandstone
4	14.19	∞	∞	Shale

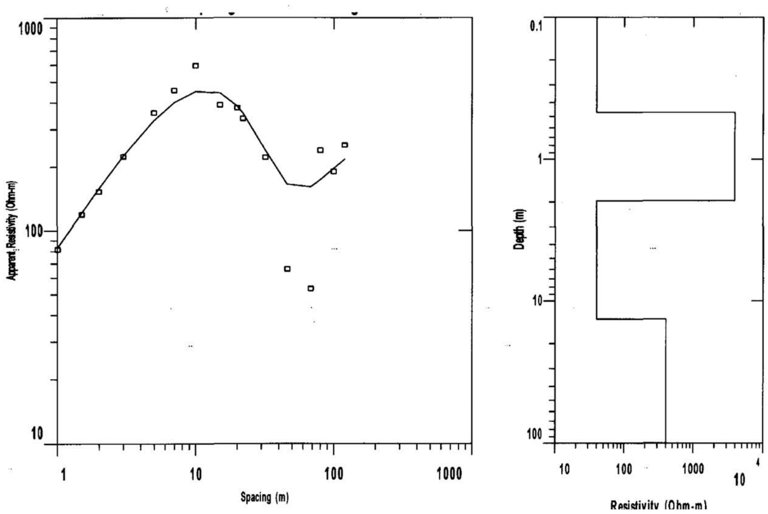

Figure 3: Sounding curve at VES location 10

Table 2: Result of interpretation for VES 10

Layer	App. Resistivity (Ω-m)	Thickness (m)	Depth (m)	Description
1	39.70	0.468	0.468	Silty Sandstone
2	3930.4	1.49	1.96	Sandy shale
3	39.70	11.49	13.45	Fractured Shaly Sand
4	396.4	∞	∞	Silty Sand

Table 3: Summary of Results of the aquifer Parameters Integrated from the Geo-electric Sections in the Study Area

VES NO	Depth to Aquifer (m)	Aquifer thickness (m)	Apparent resistivity (Ohm-m)	Transverse resistance (Ω/m^2)	Longitudinal Conductance (mhos)	Hydraulic conductivity (m/day)	Transmissivity (m^2/day)
1	Not Determined	Not Determined	Not Determined	Not Determined	Not Determined	Not Determined	Not Determined
2	14.72	6.62	1405.1	9316.0	0.00472	7.12×10^{-4}	4.71×10^{-3}
3	1.34	5.76	484.3	2790.4	0.0119	2.06×10^{-3}	1.19×10^{-2}
4	0.316	1.95	236.4	36.59	0.00273	4.23×10^{-3}	8.25×10^{-3}
5	1.39	60.04	21.31	1279.7	2.81	4.69×10^{-2}	2.82×10^{-3}
6	3.89	26.26	1573.7	41338.8	0.0166	6.35×10^{-4}	1.67×10^{-2}
7	2.12	68.41	1258.5	86102.9	0.0543	7.95×10^{-4}	5.44×10^{-2}
8	0.39	5.26	27.93	147.1	0.188	3.58×10^{-2}	1.88×10^{-1}
9	0.403	4.62	55.28	255.7	0.0836	1.81×10^{-2}	8.36×10^{-2}
10	1.96	11.49	39.7	456.3	0.289	2.52×10^{-2}	2.89×10^{-1}
11	4.77	5.69	2588.7	14738.3	0.0022	3.86×10^{-4}	3.00×10^{-3}
12	0.317	14.71	147.6	2173	0.0996	6.78×10^{-3}	9.97×10^{-2}
13	0.469	16.52	120.6	1994.7	0.136	8.29×10^{-3}	1.37×10^{-1}
14	ND	ND	ND	ND	ND	ND	ND
15	0.374	4.826	100.4	484.53	0.0481	9.96×10^{-3}	4.81×10^{-2}
Min.	0.316	1.95	21.31	36.59	0.0022	1.18×10^{-3}	2.82×10^{-3}
Max.	14.72	68.41	2588.7	86102.9	2.81	8.29×10^{-3}	9.97×10^{-3}
Ave.	3.16	20.16	711.30	16483.5	0.437	6.423×10^{-3}	2.78×10^{-1}

Aquifer vulnerability

The tendency or likelihood of an aquifer system being contaminated from the surface is termed to as aquifer vulnerability. Aquifer vulnerability is not a measurable amount, but rather a probability of contamination. As a result, some measurable quantities are required (Edwards-Jones and Gareth, 1996; Oli et al., 2020). The longitudinal conductance (S) and transverse unit resistance (Tr) values generated from the fundamental geoelectrical characteristics of the geoelectric layers were used to measure groundwater vulnerability and aquifer potential in this study (Omeje et al. 2021).

Longitudinal unit conductance (S)

A measure of an earth medium's protective capacity is its ability to delay and filter percolating fluid (Olorunfemi et al. 1999). This parameter is used to describe the aquifer's contamination vulnerability. The protective capacity of a region increases as the overburden unit of a geological formation such as clay, shale, and compact sandstone increases (Henriet 1976; Oloruntola et al.2017;

Eyankware, et al., 2020b). As indicated in Table 3, the value of S for this study spans from 0.0022 to 2.81 mhos, with an average value of 0.43 mhos. From Table 4, it was observed that VESs location VES/02, 03, 04, 06, 08, 09, 10, 11, and 15 fell within poor category, hence they are vulnerable to surface contamination. While VES locations; VES/05, VES/10, and VES/07, and 12 were classified to be good, moderate, and weak category respectively. Similar study conducted elsewhere by Eyankware and Aleke (2021); Eyankware, et al. (2022) reported that the southern Benue Trough, Nigeria. From the study, it was observed that the study falls within poor, weak, moderate, good, and very good. They also mentioned that a high S value could indicate an increase in clay content and, as a result, a strong protective capacity for the underlying aquifer, as well as a decrease in contamination.

Table 4: Overburden protective capacity rating based on (Olorunfemi, et al., 1999), longitudinal conductance scale from (Henriet, 1976) vis-à-vis the study area.

Longitudinal conductance (mhos)	Protective capacity rating	VES Locations
>10	Excellent	
5-10	Very Good	
0.7-4.9	Good	VES/05
0.2-0.69	Moderate	VES/10
0.1-0.19	Weak	VES/07, and 12
< 0.1	Poor	VES/ 02, 03, 04, 06, 08, 09, 10, 11, and 15

Transverse resistance (*Tr*)

For this study, the *Tr* value ranged from 36.59 to 86102.9 Ω/m^2, with an average value of 16483.3Ω/m^2(see Table 3). The transmissivity of a water bearing unit has been found to be related to the resistance of its transverse unit. As a result, high Tr values equal high transmissivity, and vice versa (Henriet, 1976; Ward, 1990; Harb et al, 2010). High transmissivity values, on the other hand, indicate that the formation's water bearing units are highly permeable, porous, and freely allow fluid movement within the aquifer, potentially enhancing the migration and circulation of contaminants in the groundwater/aquifer system, whereas low transmissivity indicates a high percentage of impervious clay that slows fluid movement within the aquifer. The statement implies that the value of *Tr* at VES locations VES/03, 06, 07, 11, and 12 can be inferred to be water-bearing units.

Aquifer Parameters

Hydraulic conductivity (K_c)

The hydraulic conductivity of pore fluid determines how easy it can escape the compressed pore space. The capacity of the fluid to travel through the pores and cracked rocks is known as hydraulic conductivity of the material. Similarly, the conductivity of the water in a particular area is determined by the type of rock present. Obiora, et al. (2015) were of the believe that K controls the behaviour of groundwater flow within an aquifer. The calculated hydraulic conductivity (K_c) values from the VES results ranges from 7.95×10^{-4} to 1.81×10^{-2}m/day with the highest value at VES 3 and the lowest value at VES 7 (Table 3).

Transmissivity (T)

The ability of an aquifer to transmit groundwater throughout its entire saturated thickness is referred to as transmissivity. The rate at which groundwater can flow through an aquifer segment of unit width under a unit hydraulic gradient is known as transmissivity. Transmissivity values vary between 8.25×10^{-3} and 2.82 m^2/day (Table 3).

Geo-electric correlations within the study area

Vertical and lateral variations in layer resistivity and thickness are shown in the geo-electric correlation sections, revealing lateral and vertical lithological differences in the studied area. A-A` profile was obtained through VES locations 10, 8, 3, and 5 in the W-E direction (Fig. 4) and a B-B` profile was taken through VES locations 1, 2, 3, and 15 in the NW-SE direction (Fig.5). In the two profiles shown in Figs. 4 and 5, 3 to 5 subsurface layers were identified. The topsoil at VES 10, 8, and 3 is silty sandstone with resistivity ranging from 22.68Ωmto 764 Ωm and thickness ranging from 0.39m to 1.34m, as shown in Fig.4, The assumption of resistivity values was based on Telford, et al. (1976) classification. The topsoil of VES 5 is loamy, with a resistivity of 22.54 m and a thickness of 0.689 m. Sandy shale was found all the way through the profile, with pinchout at the ends. Sandy shale, loose sandstone, fractured shaly sand, and cracked shale are the aquifers found throughout the profile. The fractured shaly sand in VES 10 with a thickness of 11.49m might be a good groundwater potential. Findings suggested that sandy shale in VES 8 with a thickness of 5.26m can deliver water unless during extreme drought. Except during extreme droughts, the aquifer in VES 3 is loose sandstone with a thickness of 5.76m and can provide modest water. The fractured shale aquifer in VES 5 has a thickness of 60.04m, it consists of clay at the top and bottom, and can provide water all year due to its thickness, making it the most prolific aquifer in the study area.

The geo-electric section along profile B-B' in the W-E direction is shown in Fig. 5. The resistivity of the topsoil varies from 6.46 to 764 Ωm, while the thickness varies from 0.37 to 1.34m. With silty sandstone (VES 1 and 3), silty sand (VES 2), and loamy soil (VES 2), the topsoil changes laterally (VES 15). There is no aquiferous unit on VES 1. The aquifer in VES 2 is layer 3, which is loose sandstone and has a thickness of 6.62m. The top and bottom layer is underlain by shale. As shown in by streams that never dry up, this layer can provide water all year. Except during extreme droughts, the aquifer in VES 3 is loose sandstone with a thickness of 5.76m and can provide modest water. Layer 2 of the aquiferous unit in VES 15 is loose sandstone with a thickness of 4.826 m.

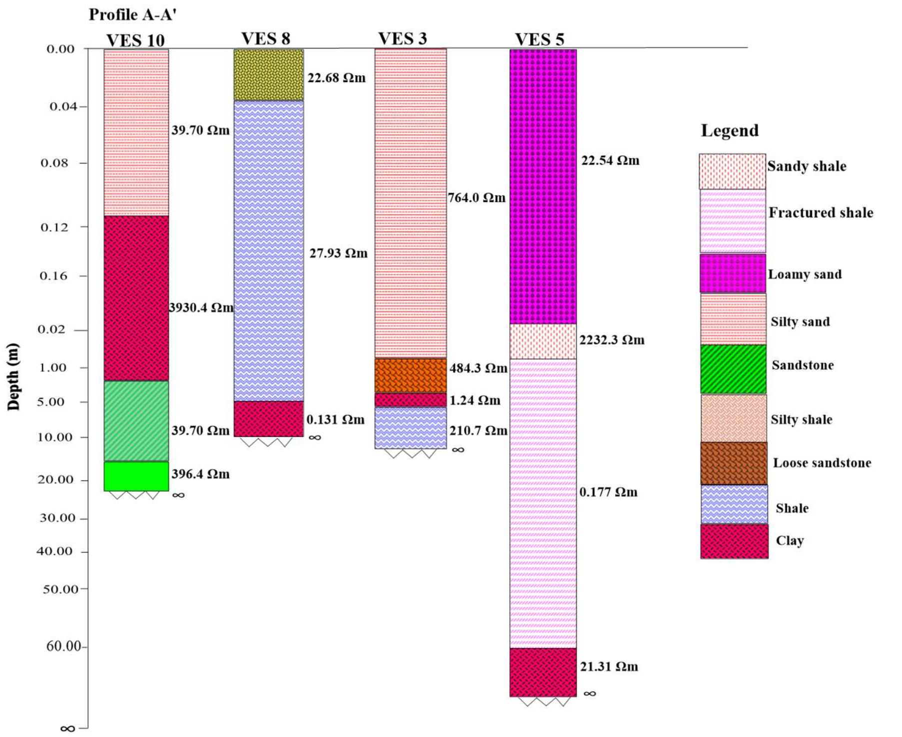

Figure 4: Geo-electric correlation along Profile A-A`

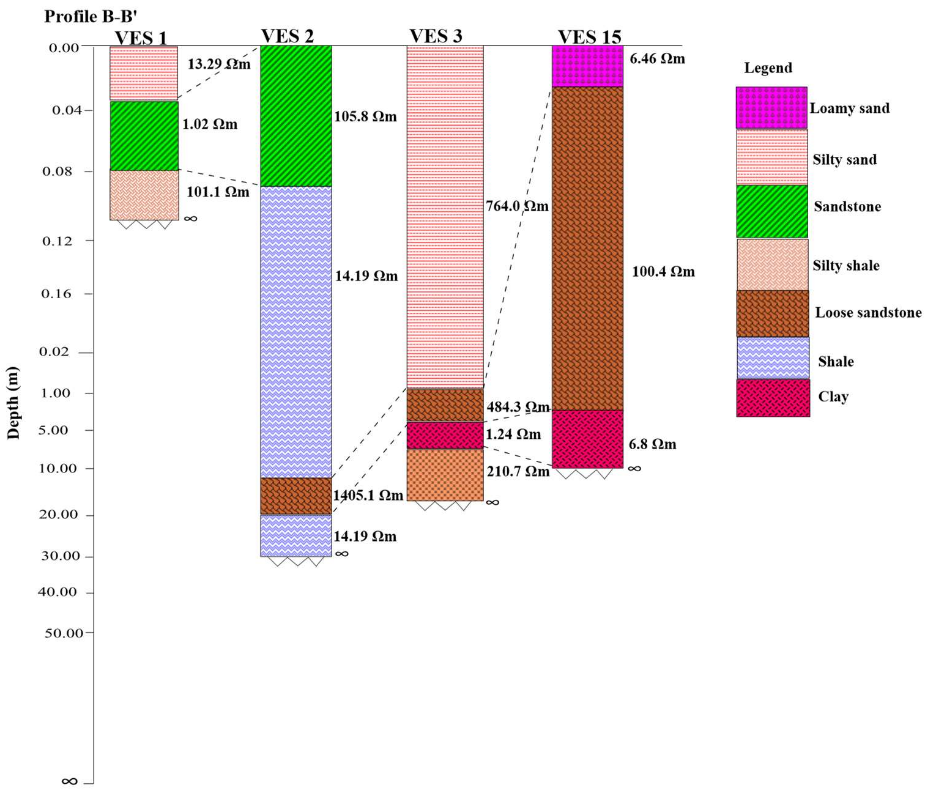

Figure 5: Geo-electric correlation along profile B-B'

The presence of loose sandstone along the DE profile in the W-E direction could have been deposited along a low plain, and subsidence has occurred in recent years, with the largest number of subsidence occurring at VES 2.

Curve type distribution of the study area

The vertical electrical sounding curve types observed within the study area include Q, H, A, QH, KH, KQ, and KHK (Fig. 6 and Table 5). Curved H was revealed to be the most common curve in the study area. According to Eyankware, et al., (2022), the variance in curve type can be attributed to the variability of the geology of the research region (2020). The H curve, according to Eyankware, (2019), who worked in the Benue Trough, is the dominant curve type within the trough. The dominant curve type within the Benue Trough, is A, K, and Q (Oli, et al., 2020; Obiora, et al., 2016; Eyankware, et al., 2022).

Table 5: Classification of VES curve types in the study area

S/N	VES Curve type	VES N0	VES curve characteristic	Frequency
1	Q	8,12	$\rho_1>\rho_2>\rho_3$	2
2	H	2, 3,4,11,13	$\rho_1>\rho_2<\rho_3$	5
3	A	1,9,14	$\rho_1<\rho_2<\rho_3$	3
4	QH	6	$\rho_1>\rho_2>\rho_3<\rho_4$	1
5	KH	10	$\rho_1<\rho_2>\rho_3<\rho_4$	1
6	KQ	15	$\rho_1<\rho_2>\rho_3>\rho_4$	1
7	KHK	5, 7	$\rho_1<\rho_2>\rho_3<\rho_4>\rho_5$	2

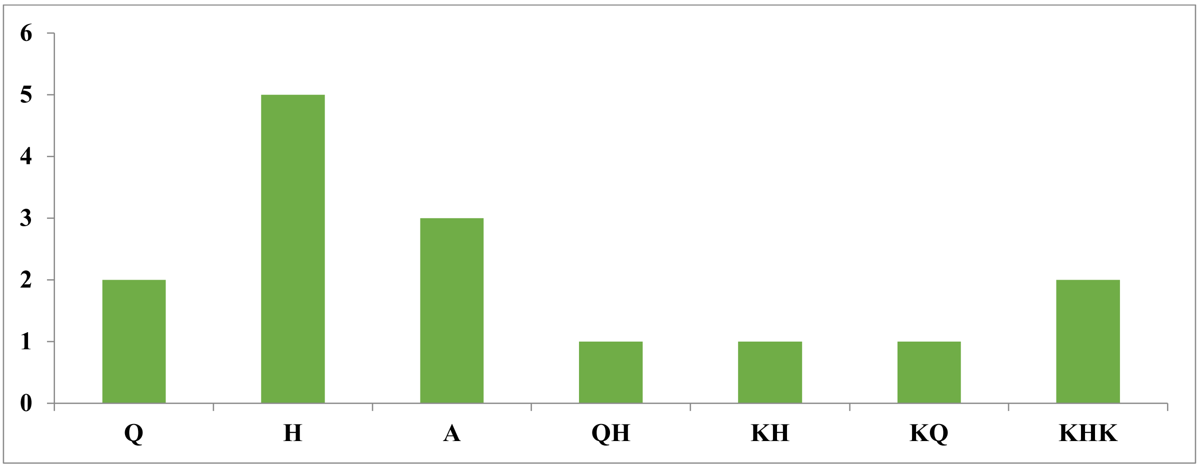

Figure 6. Graph presentation of curve type within the study

CONCLUSION

A total of 15 VES was used in assessing the aquifer vulnerability and groundwater potential of Igbo-Imabana, Cross River state, Nigeria. Primary parameters such as (resistivity and thickness) was used to S, Tr, T. Kc. Findings from S revealed the aquifer vulnerability falls within poor, weak, moderate, good, and very good. Further deductions from Tr suggested that VES locations VES/03, 06, 07, 11, and 12 can be inferred to be water-bearing units. Findings from Kc and T showed that at certain VES points, the T of aquifers are generally higher at locations with high transverse resistance especially at VESs/01, 07, 11, 12, and 13, while findings from Kc revealed that VES results range from 7.95×10^{-4} to 1.81×10^{-2}m/day with the highest value at VES 3 and the lowest value at VES 7. The transmissivity of aquifers is generally higher at locations with high transverse resistance especially at VESs/01, 07, 11, 12, and 13. This is an indication that the VES points are good water bearing units.

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