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Application of Geoelectric and Hydrogeological Methods in Delineation of Aquifer Potential and Protective Capacity in Parts of Asaba Metropolis, Niger Delta Region of Nigeria

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ABSTRACT

This study evaluated aquifer potential and protective capacity in parts of Asaba Metropolis, using fifteen Vertical Electrical Soundings (VES) with the Schlumberger array. The ABEM Terrameter SAS 1000 was used and the maximum current electrode spacing (AB/2) was 300 m. Geoelectrical data were interpreted using WINRESIST and integrated with Dar-Zarrouk parameters to estimate hydraulic conductivity (K) and transmissivity (T). The subsurface comprises three to six geoelectric layers. Aquifer resistivity ranges from 156.0 Ωm to 7365.2 Ωm, aquifer thickness from 3.0 m to 33.7 m, and aquifer depth from 4.9 m to 39.8 m. Longitudinal conductance (S) varies from 0.0111 ℧ to 0.1236 ℧, indicating predominantly poor overburden protective capacity and high vulnerability to surface contamination. Hydraulic conductivity ranges from 0.095 m/day to 3.477 m/day, while transmissivity varies from 0.602 m²/day to 53.353 m²/day, with the highest values occurring in the southwestern sector, indicating the most productive aquifers. High transverse resistance, anisotropy and fracture porosity further delineate favourable groundwater-bearing zones. This study concludes that the integrated geoelectrical approach effectively identified aquifer geometry, groundwater potential and vulnerability, providing a scientific basis for borehole siting, groundwater protection and sustainable water-resource management in parts of Asaba and similar Niger Delta sedimentary terrains.

INTRODUCTION

In fast urbanizing areas like Asaba, the capital of Nigeria's Delta State, access to drinkable water continues to be a major problem. Groundwater is the most dependable substitute for household, industrial, and agricultural demands as surface water supplies become more vulnerable to pollution and seasonal variations (Eyankware, et al., 2025). The distribution of groundwater is not consistent; rather, it is influenced by a complex interaction of lithology, structural factors, and secondary porosity (Ejije and Atakpo 2025; Eyankware et al., 2025). A thorough comprehension of the subsurface structure in the Niger Delta region, especially within the Ogwashi-Asaba and Benin Formations, is crucial for accurately identifying viable aquifer units. This understanding is vital to avoid the drilling of unproductive boreholes and to support the sustainable use of resources (Sunday, et al., 2025). Notably, the electrical resistivity method, with a specific emphasis on Vertical Electrical Sounding (VES), has played a significant role in conventional groundwater exploration. According to (Odunayo et al. 2024; Ojo et al. 2024) this method is preferred due to its affordability as well as its capacity to distinguish water-saturated zones and lithological boundaries using resistivity contrasts. Although VES offers high-resolution vertical data at certain locations, its capacity to offer a synoptic, spatial picture of vast or topographically diverse areas is frequently constrained (Onifade et al., 2023). The sustainability of groundwater resources in the Niger Delta is becoming an increasingly pressing issue, driven by the swift industrial expansion and rising population in urban areas such as Asaba. Serving as the administrative center of Delta State, Asaba lies within the sedimentary basin of the Niger Delta, which features a complex arrangement of Tertiary to Quaternary geological deposits. The hydrogeological characteristics of this region are predominantly influenced by the Benin Formation and the Ogwashi-Asaba Formation, both renowned for their high permeability and substantial groundwater output. Nevertheless, the unregulated drilling of boreholes, conducted without proper geophysical assessments, has resulted in elevated failure rates and the potential for cross-contamination between aquifer layers. The Ogwashi-Asaba Formation, which dates from the Eocene to Oligocene epochs, is characterized by a succession of lignite, clay, and sand deposits. In contrast, the Benin Formation, spanning the Miocene to Recent periods, primarily features substantial layers of continental sands and gravels. It is essential to comprehend the spatial arrangement of these lithological units, as the occurrence of intercalated clay lenses may serve as aquitards. These geological layers can obstruct the movement of groundwater, potentially affecting the productivity of wells. The electrical resistivity method, particularly the VES, is highly advantageous in this context as it leverages variations in the electrical properties of subsurface materials to ascertain the thickness and depth of aquifer-bearing layers. The availability of freshwater resources in the study area is significantly influenced by both temporal and spatial conditions. Consequently, accessing alternative freshwater sources such as groundwater and surface water poses considerable challenges. For groundwater exploration, methods such as boreholes and manually drilled wells can be employed (Eyankware et al., 2018). The VES technique has demonstrated its efficacy as a reliable method for groundwater exploration, providing a clear and trustworthy framework for such investigations. Central to this methodology is the electrical resistivity of rock, which is significantly affected by its lithological characteristics and the quantity of fluids it contains. Likewise, the electrical resistivity technique aids in assessing bedrock depth, characterizing surface deposits, and conducting structural mapping. Boundaries of aquifers and areas with high yield potential have been identified through this method. Recognized as the predominant geophysical technique utilized in foundation and sedimentary environments, the electrical resistivity method has been effectively applied using a multi-electrode resistivity profiling array for groundwater The vertical electrical method was similarly utilized by Opara et al., (2022) to delineate the groundwater potential in the southeastern region of Nigeria. Likewise, Omosuyi et al., (2008) applied this technique to pinpoint two shallow aquifer units within the Okitipupa area of Nigeria's southwestern coastal plain. The sedimentary sequences of the study region, as well as the Niger Delta Basin in Nigeria, are recognized to contain numerous aquiferous units. The region benefits from relatively good groundwater recharge, owing to an impressive average annual rainfall of approximately 1900 mm (Eyankware and Ephraim, 2021). Nevertheless, numerous boreholes in the study area have proven ineffective, primarily due to suboptimal design and insufficient technical geo-scientific assessments aimed at deciphering the area's complex geology. Compounding this issue is the inadequate comprehension of aquifers, particularly regarding the configuration and characteristics of their hydraulic boundaries. Although several boreholes have been drilled in the Niger Delta Basin, the systematic and comprehensive understanding of the aquifers' characteristics and distribution remains lacking (Eyankware et al., 2021; Aleke et al., 2018). It is crucial not only to quantitatively describe the geometric and hydraulic properties of these aquifers but also to assess their vulnerability to pollution from surface sources. The significance of this issue cannot be overstated, as the processes of urbanization, population growth, and associated challenges have progressively deteriorated groundwater quality in the research region, a situation worsened by insufficient waste management strategies. In a similar vein, the establishment of new constructions, including mini-factories and several medium-sized enterprises, may have contributed to an influx of migrants in the Asaba area, subsequently increasing the demand for clean water. This situation poses potential risks to the groundwater resources within the study area. Consequently, the success of groundwater management and its sustainable use relies heavily on the prevention of pollution. The challenges in effectively monitoring groundwater systems, primarily due to spatial variability and data constraints, result in costly and ineffective cleanup initiatives in developing countries, particularly in Nigeria. Research into aquifer vulnerability plays a crucial role in groundwater studies, as it is widely accepted that averting aquifer contamination is vital for the sustainable management of groundwater resources (Ma'aji, et al., 2024). Various methodologies have been employed to assess groundwater vulnerability, including the vertical electrical sounding (VES) technique, among others. A number of researchers have addressed various hydrological and hydro-geophysical challenges through the implementation of the VES method (Aleke, et al., 2018; Adegboyega, et al., 2024; Eyankware, et al., 2020a; Eyankware, et al., 2020b; Eyankware and Aleke, 2021; Bayode, et al., 2006). This approach is favored due to its user-friendly nature, cost-effectiveness, and the clear results it yields, especially when compared to alternative geophysical methodologies. In earlier investigations concerning aquifer vulnerability, researchers have utilized longitudinal conductance, a second-order geoelectric parameter, to evaluate the protective capabilities of overburden materials (Akintorinwa and Olowolafe, 2013; Aweto, 2011).

Through the evaluation of apparent resistivity data gathered from the field, the Vertical Electrical Sounding (VES) technique has gained considerable traction in the field of groundwater exploration. It serves to evaluate a number of factors, such as groundwater characteristics, aquifer configuration, aquifer vulnerability, and the vertical distance to the water table (Adetola and Igbedi, 2000; Aziz, et al., 2018). According to several studies (Ogholaja et al., 2025; Akinseye et al., 2023; Eyankware and Aleke, 2021), the Dar Zarrouk parameters, which are derived from surface geoelectric measurements, are essential for understanding the spatial distribution of protective capacity parameters and the geometry of aquifers. The vulnerability of the aquifer in Nigeria's hard rock and sedimentary regions has also been estimated using the VES technique. Warmate's (2016) study used data from the VES approach to estimate Dar Zarrouk parameters in order to establish hydrological qualities. The study's conclusions indicated that the aquifer was highly prolific, with resistivity values above 1000 m, and that its great groundwater potential made it vulnerable to pollution. The Dar Zarrouk criteria were used to locate the aquifer in specific areas of Akwa Ibom, Niger Delta. The results showed that the area is susceptible to contamination due to the high aquifer output and high permeability in the aquiferous layer (Laouini et al., 2017). Geochemical and geophysical techniques have been employed to evaluate groundwater pollution and the protective capabilities of aquifers in various regions of Nigeria's Niger Delta Basin (Ibuot et al., 2013; Egwebe et al., 2004). Nonetheless, there has been a significant lack of research focusing on the study area and its vicinity regarding these critical aspects. Consequently, a comprehensive analysis is essential to ascertain the aquifer's protective capacity within the research locale. This investigation utilizes Vertical Electrical Sounding (VES) data to assess the protective capacity of the aquifer in the study area and to estimate the potential for groundwater resources, while also identifying the aquifers and evaluating their susceptibility to contamination from surface sources.

Location of Study Area

The geographical scope of the study is defined by the coordinates of latitude 6˚ 10ˈN to 6˚ 14ˈN and longitude 6˚ 40ˈE to 6˚46ˈE. The area is surrounded by numerous small streams that originate from different sources, suggesting its foundation on rocky terrain. The prominent features of the Asaba region include the plateau's hills and the River Niger. Due to the gentle easterly slopes, Asaba is positioned in a valley along the western bank of the Niger River. The cities of Okpanam and Ibusa are located at the periphery of the Asaba plateau, which completely diminishes to the south of Asaba. In the study area, the only significant waterway that converges with the River Niger is the relatively broad Amilimocha River. In contrast, various streams originate from springs situated at elevated regions, weaving their way across the slopes of the plateau. The typical annual temperature fluctuates between 20°C and 34°C, with average yearly rainfall and evapotranspiration recorded at 1,501 mm and 1,850 mm, respectively (Olobaiyi, et al., 2007).

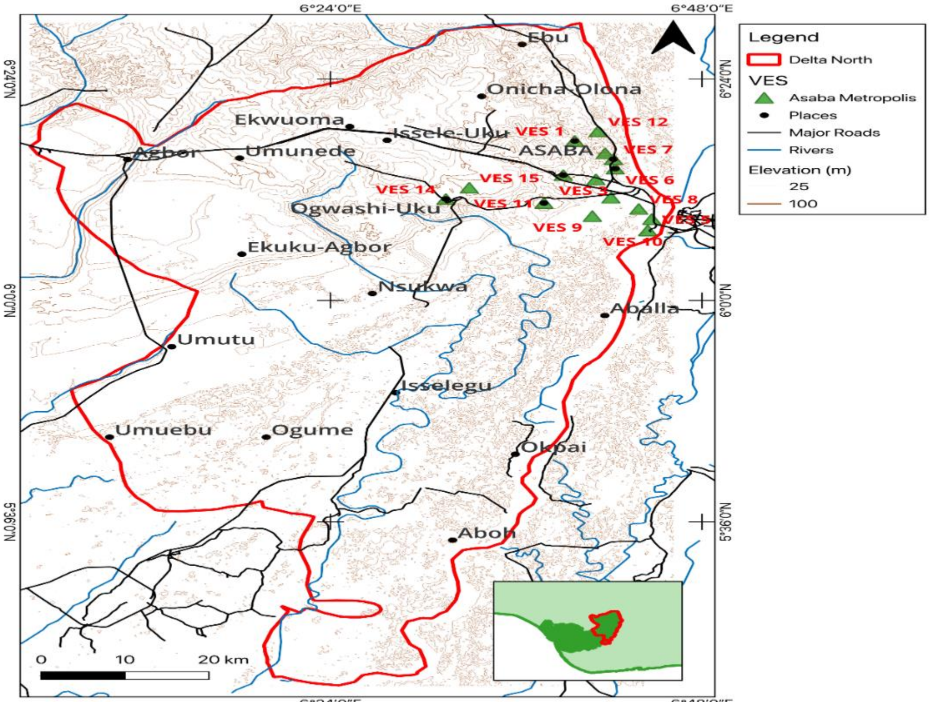

Figure 1: Location Map of the Study Area showing VES points

Geology of the study area

The Akata, Agbada, and Benin Formations are the three separate formations that make up the basin fill, arranged from oldest to youngest as seen in Figure 2. Shale makes up the majority of the Akata Formation, with sandstone making up around 10% (Short and Stauble, 1967; Murat, 1970). Both under-compaction and over-compaction are thought to be present in this shale. This formation, which dates from the Eocene to the present, was deposited in a marine environment. The Agbada Formation is at a conformable position directly above the Akata Formation. The dates of the paralic sandstone and shale in this formation range from the Pliocene/Pleistocene in the south to the Eocene in the north, with more recent deposits evident near the Delta's surface (Oteri, 1990). The surface equivalents of the Eocene-Oligocene Ameki Formation and the Ogwashi-Asaba Formation are present in the region. Within the Asaba capital territory, the predominant rock formations consist of the Ogwashi-Asaba formation. Overlying the Agbada Formation is the continental Miocene-Recent Benin Formation. This formation is characterized by a composition of approximately 10% shale and clay, with more than 90% consisting of sand. The sand grains exhibit a range of sizes from coarse to fine. Additionally, the formation contains fragments of wood and streaks of lignite, is poorly sorted, and displays shapes that vary from sub-angular to well-rounded (Oteri and Atolagbe, 2003).

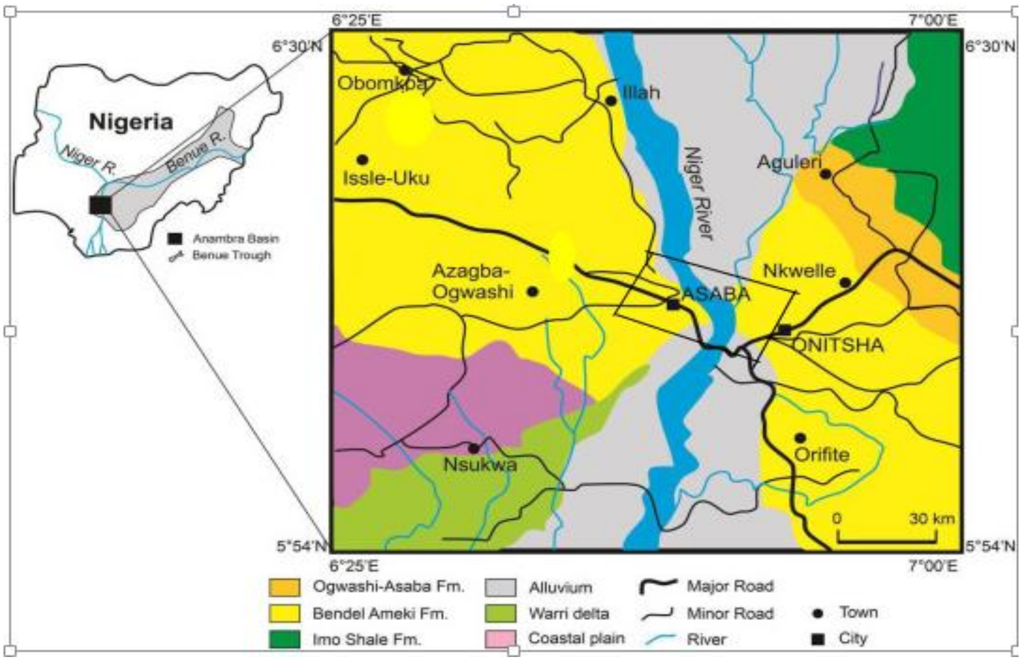

Figure 2: Geology map of the study area. (Source: Adeoye, et al., 2022)

Hydrogeology of the study area

The Niger Delta is included in the research area. Because the ground is mostly composed of sand and lacks rocks, it cannot be considered a basement complex. There, laterite makes up the majority of the terrain, which is usually stone. Due to a lack of understanding of the hydrogeologic issues, previous attempts to drill a borehole have not always been successful, but they have been made. According to Akpoborie et al. (2011), events held at fire department facilities are among the most successful.

MATERIALS AND METHODS

Geoelectric measurements

An ABEM Terrameter SAS 1000, pairs of electrodes, Global positioning system (GPS) were used to conduct fifteen (15) Vertical Electrical Soundings (VES) at the research location. A Schlumberger electrode configuration with a maximum half current (AB/2) electrode spacing of 100 m and a maximum half potential (MN/2) electrode spacing of 5 m was used for each VES profile. Surfer software was used to construct spatial distribution maps for S, Tr, L, and pt. Equation (1), which is described as follows, was used to translate the field data into apparent resistivity (a) values:

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

as proposed by Akinseye, et al., 2023.

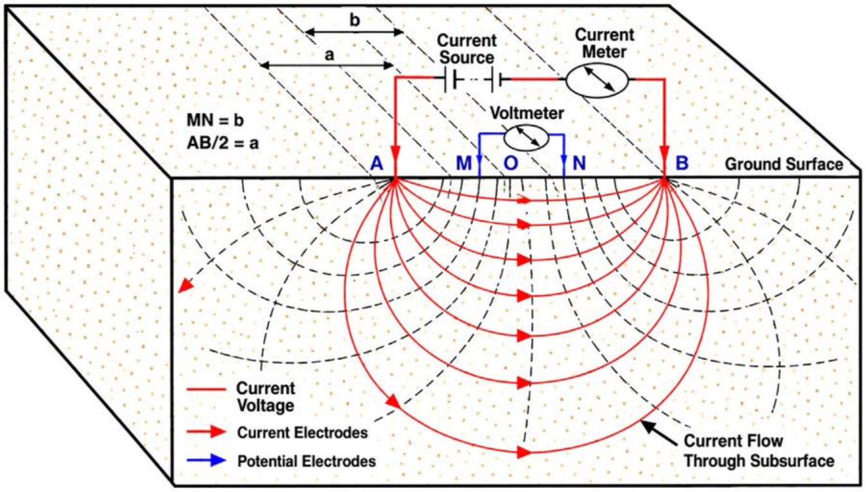

Figure 3: Drawing schematically showing the procedure in geo-electrical resistivity operation

The geoelectrical curves were constructed by graphing the apparent resistivity values in relation to the current electrode spacing (AB/2). The utilization of the IX1D programme, which facilitated the data processing, allowed for the development of accurate curves. The aquifer's thickness was determined through the use of geoelectrical sections derived from the data obtained from the sounding curves. By referencing the charts provided by (Kearey, et al., 2002) and (Loke,1999), the lithologies corresponding to the geoelectric section were identified. The investigation and understanding of the geological model depend on certain elements related to the various combinations of thickness and resistivity inside the geoelectric layer (Zohdy, et al., 1974; Maillet, 1947). Dar Zarrouk's longitudinal (S) and transverse (T) characteristics are obtained by:

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

as proposed by (Opara, et al., 2022).

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

as proposed by (Akinseye, et al., 2023).

Additionally, total longitudinal unit conductance (S) was calculated using the following formula. The number of layers (n) equals the total longitudinal conductance.

$$S = \sum_{i=1}^{n} \frac{h_i}{pi} = \frac{h_1}{p1} + \frac{h_2}{p2} + \cdots + \frac{h_n}{pn} \quad (4)$$

as suggested by Eyankware and Aleke (2021) and Opara et al. (2022). The Transverse Unit Resistance (Tr) was calculated for the following equation.

The total resistance of the transverse unit is

$$Tr = \sum_{i=1}^{n} h_i p_i = h_1 p_1 + h_2 p_2 + \cdots + h_n p_n \quad (5)$$

as proposed by (Eyankware, et al., 2020a).

Below is the average longitudinal resistance for a given VES points

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

as proposed by (Akinseye, et al., 2023)

The equation is used to calculate the Transverse Resistance for a particular VES curve.

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

as proposed by (Suneetha and Gupta, 2018).

From equation (5), p_i and h_i represent the resistivity and thickness of each layer, respectively. While H is the summation of the different layer thickness. The transmissivity of the aquifer (T) is calculated by equation (8), as the product of the hydraulic conductivity (K) and the thickness of the layer (h).

$$T = K \times h \quad (8)$$

The true resistivity (p) of the aquifer, obtained from geoelectric investigations, can serve as a proxy for aquifer hydraulic conductivity (K) in the absence of pumping test data.

$$T = K \times h = p \times h \quad (9)$$

$$D = \sum_{i=1}^{n-1} h_i \quad (10)$$

RESULTS AND DISCUSSION

The findings of the interpreted VES survey are presented in Table 1. As shown in Table 1, VES results showed geoelectric layers with different intra-facies and inter-facies modifications, ranging in number from three to six layers.

Table 1: The processed VES data utilised to create curve type geoelectric layers

VES Points	Latitude	Longitude	Layer Resistivity (Ohm-m)						Layer Depth (m)						Curve Type	No of Layer	Elevation
			ρ1	ρ2	ρ3	ρ4	ρ5	ρ6	D1	D2	D3	D4	D5	D6			
1	06˚24.012'N	006˚70.262'E	1179.1	116.3	582.1	2562.5	–	–	1.0	2.1	12.5	∞	–	–	HA	4	43
2	06˚20.067'N	006˚73.618'E	985.0	1278.0	263.0	2154.0	2630.0	–	0.4	0.9	9.8	24.6	∞	-	KHA	5	50
3	06˚13.125'N	006˚41.142'E	464.5	940.8	137.4	156.0	2335.4	–	1.0	20.1	23.7	35.4	∞	–	KHA	5	54
4	06˚11.146'N	006˚42.113'E	641.0	1468.0	4571.0	6407.0	–	–	1.0	9.8	25.8	∞	–	–	AA	4	43
5	06˚16.783'N	006˚74.907'E	1063.0	450.0	898.0	1711.0	–	–	1.0	19.1	30.2	∞	–	–	HA	4	31
6	06˚42.213'N	006˚42.212'E	593.5	102.1	125.9	181.8	7644.4	–	1.0	4.8	4.8	10.8	∞	–	HAA	5	54
7	06˚15' 46.50"N	006˚42'15.50"E	224.6	1707.6	3414.5	7365.2	2735.9	–	1.0	9.3	21.8	33.1	∞	–	AAK	5	43.6
8	06˚16.759'N	006˚74.751'E	23.4	45.8	5009.1	857.3	–	–	0.3	0.5	4.9	∞	–	–	AK	4	33
9	06˚10.851'N	006˚72.412'E	55.1	1054.4	237.3	2712.7	–	–	1.3	17.4	32.7	∞	–	–	KH	4	25
10	06˚12.674'N	006˚73.814'E	47.0	43.2	329.4	3081.2	–	–	0.6	1.3	25.2	∞	–	–	HA	4	30
11	06˚16.537'N	006˚08.289'E	5147.3	552.9	138.9	291.4	7329.2	–	0.7	10.6	13.4	28.4	∞	–	QHA	5	86
12	06˚29.937'N	006˚69.694'E	605.2	571.0	286.1	485.1	6075.5	–	1.4	18.1	30.7	39.8	∞	–	QHA	5	33
13	06˚24.054'N	006˚62.517'E	7.6	12.2	24.9	2288.2	5492.6	–	0.1	0.2	0.6	22.5	∞	–	AAA	5	146
14	06˚16.052'N	006˚57.791'E	249.9	472.6	3808.2	1128.1	200.6	1294.2	0.5	0.7	2.7	2.7	22.1	∞	AQH	6	209
15	06˚12.360'N	006˚32.970'E	344.4	5732.5	2977.2	1095.5	399.7	9032.3	0.6	1.3	1.9	2.4	36.1	∞	KQH	6	208

Table 2: Results of second-order geo-electric indices

VES Points	VES Locations	Longitudinal conductance (S) (℧)	Transverse unit resistance (Tr) (Ωm²)	Longitudinal resistance (ρL) (Ωm)	Transverse resistivity (ρt) (Ωm)	Anisotropy(λa) (dimension-less	Fracture porosity (ϕf) (%)	Aquifer Resistivity (Ωm)	Aquifer Thickness (m)	Aquifer Depth (m)	Hydraulic Conductivity (m/day)	Transmissivity (m²/day)
1	Asaba I	0.0282	7,360.90	443.60	588.90	1.15	4.6	582.1	10.4	12.5	1.018	10.588
2	Asaba II	0.0416	35,380.70	591.50	1,438.20	1.56	6.24	2154.0	14.8	24.6	0.3	4.446
3	Asaba III	0.1236	20,659.50	285.70	585.30	1.43	5.72	156.0	11.7	35.4	3.477	40.683
4	Asaba IV	0.0111	86,695.40	2,334.80	3,360.30	1.20	4.80	4571.0	16.0	25.8	0.149	2.382
5	Cable Point	0.0535	19,175.80	564.30	635.00	1.06	4.24	898.0	11.1	30.2	0.679	7.541
6	Anwai	0.0792	1,904.60	136.30	176.40	1.14	4.56	181.8	3.0	10.8	3.015	9.044
7	DOU	0.0146	139,739.90	2,274.90	4,221.80	1.36	5.44	7365.2	11.2	33.1	0.095	1.069
8	Okwe	0.0181	22,056.00	270.70	4,501.30	4.08	16.32	5009.1	4.4	4.9	0.137	0.602
9	Oko-Anala	0.1034	20,784.00	317.20	633.60	1.41	5.64	237.3	15.3	32.7	2.351	35.973
10	Oko-Amakom	0.1036	7,903.00	243.20	313.60	1.14	4.56	329.4	23.8	25.2	1.732	41.21
11	Ibusa	0.0896	13,839.26	317.10	487.30	1.24	4.96	291.4	15.0	28.4	1.941	29.119
12	Ugbolu	0.0945	18,395.00	421.20	462.20	1.05	4.20	485.1	9.0	39.8	1.207	10.861
13	Okpanam	0.0512	50,122.25	439.45	2,227.66	2.25	9.00	2288.2	21.9	22.5	0.284	6.218
14	Ogwashi-Uku I	0.0997	11,728.00	221.80	530.70	1.55	6.20	200.6	19.4	22.1	2.75	53.353
15	Ogwashi-Uku II	0.0869	20,597.00	416.80	569.10	1.17	4.68	399.7	33.7	36.1	1.446	48.718
Min		0.0111	1,904.60	136.30	176.40	1.05	4.20	156.0	3.0	4.9	0.095	0.602
Max		0.1236	139,739.90	2,334.80	4,501.30	4.08	16.32	7365.2	33.7	39.8	3.477	53.353
Ave		0.0666	31,756.09	618.57	1,382.09	1.52	6.08	1676.593	14.713	25.607	1.372	20.12

Aquifer Vulnerability of the Study Area

Longitudinal Conductance (S)

The results of the VES survey interpretation are summarized in Table 1. As illustrated in Table 1, the VES findings revealed geoelectric layers that exhibit various modifications both within and between layers, with a total count varying from three to six layers. Olorunfemi et al. (1999) explain that the parameter S reflects the protective capacity of an earth medium, indicating its effectiveness in slowing or halting the movement of percolating liquids. This property is typically indicative of the aquifer's vulnerability to contamination. Furthermore, the capacity of a region to withstand damage is enhanced by the presence of a densely packed geological formation, such as compacted sandstone, shale, or clay (Henriet, 1976; Oloruntola et al., 2017). Equations (3 and 4) were used to obtain the S values for this study, which range from 0.0111 ℧ at VES 4 to 0.1236 ℧ at VES 3 as shown in Table 2. The entire research region is susceptible to surface contamination, according to a deduction from Figure 4. This is consistent with a prior study by Umayah and Eyankware (2022), who believed that the aquifer in the majority of the Niger Delta region is made of porous sandstone that readily permits water to percolate from the surface.

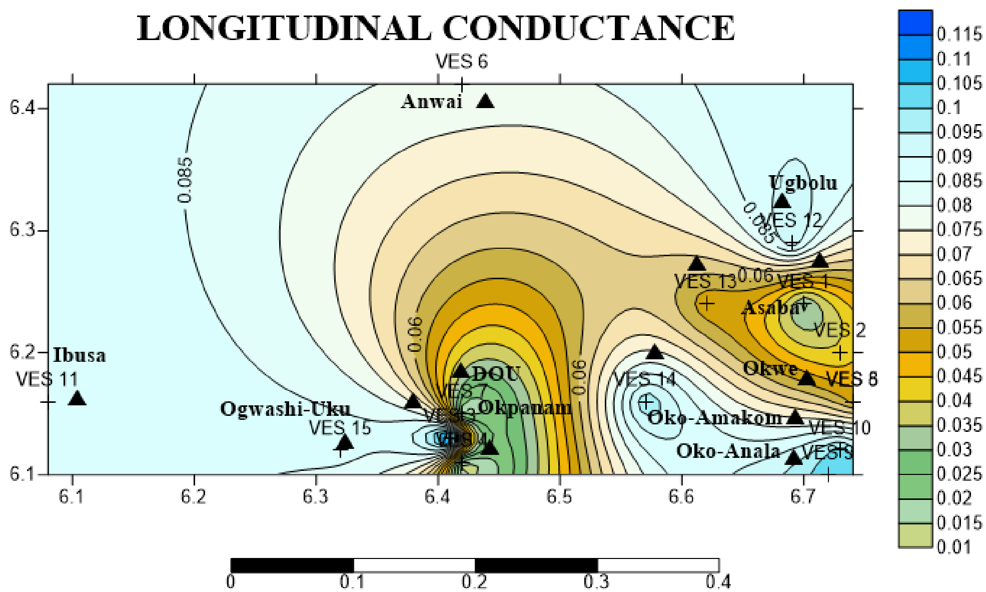

Figure 4: Spatial distribution map of Longitudinal Conductance (*S*) of the study area

Table 3: The modified rating for the aquifer's protective capability of the formation under research has been evaluated using the longitudinal conductance scale developed by Oladapo and Akintorinwa, (2007)

Longitudinal conductance (mhos)	Protective capacity Rating	VES Points	Percentage
>10	Excellent		
5-10	Very Good		
0.7-4.9	Good		
0.2-0.69	Moderate		
0.1-0.19	Weak	VES 3,9,10	
< 0.1	Poor	VES 1, 2, 4 to 8, and 11, 12, 13, 14 to VES 15	100%

Transverse Resistivity (ρt)

In contrast to other areas within the study area, Figure 5 reveals that elevated transverse resistance values are present in both the northeast and southwest quadrants. The resistance values range from 176.40 Ωm at VES 6 to 4,501.30 Ωm at VES 8 as shown in Table 2. According to Dewashish et al. (2014), these findings imply that true resistivity aligns with the stratification plane, while it is perpendicular to the stratification plane in formations like shale. Generally, increased aquifer transverse resistance is associated with enhanced aquifer transmissivity, suggesting that higher transverse resistance values are indicative of thicker and more productive aquifers (El-Gawad et al., 2017; Akinseye et al., 2023). Higher aquifer transverse resistance values are generally associated with increased aquifer transmissivity, indicating that thicker and more productive aquifers tend to exhibit elevated levels of transverse resistance (El-Gawad et al., 2017; Umayah and Eyankware, 2022). For instance, in shale formations, the true resistivity measured parallel to the stratification plane surpasses that measured perpendicular to it (Anomohanran, 2022).

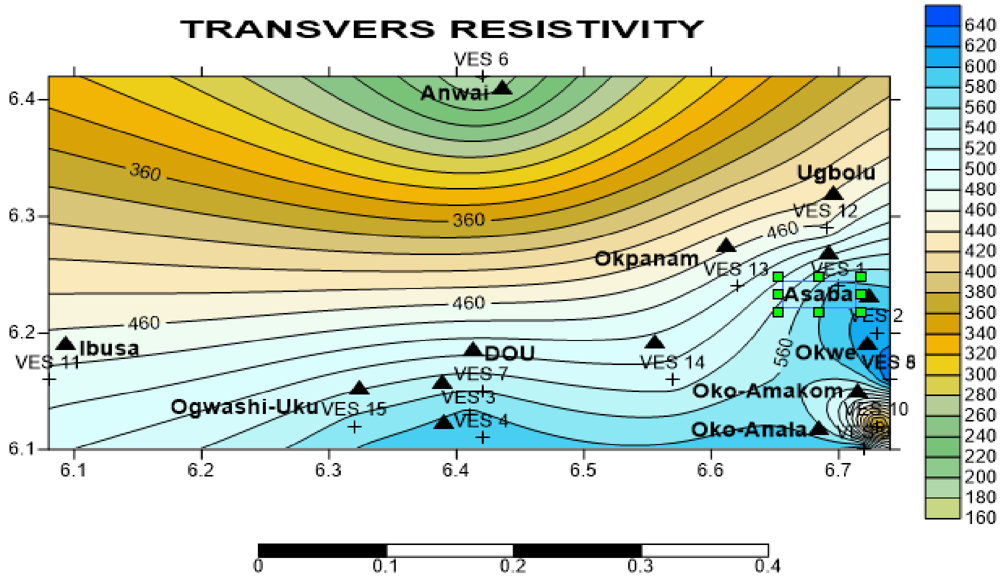

Figure 5: Spatial distribution of Transverse Resistivity (ρ_L) of the study area

Anisotropy (λa)

The anisotropy map in Figure 6 shows spatial variations in the coefficient of anisotropy, across the study area. Values range approximately from 1.05 (dimensionless) to 4.08 (dimensionless) as shown in Table 2. The highest anisotropy values occur around Okpanam–Asaba, where concentric contours indicate a structurally controlled zone. High anisotropy values suggest strong directional dependence of subsurface electrical properties, commonly associated with intense fracturing, faulting, weathering, or lithologic heterogeneity (Keller and Frischknecht, 1966; Olorunfemi and Fasuyi, 1993). The low anisotropy zones around Ibusa, Anwai and parts of Ogwashi-Uku indicate relatively homogeneous subsurface conditions with limited structural deformation. The concentration of elevated anisotropy around Okpanam and Asaba suggests enhanced secondary porosity and permeability resulting from fracture development. Such zones are generally favourable for groundwater accumulation and movement because, fractures improve hydraulic connectivity within aquifer materials.

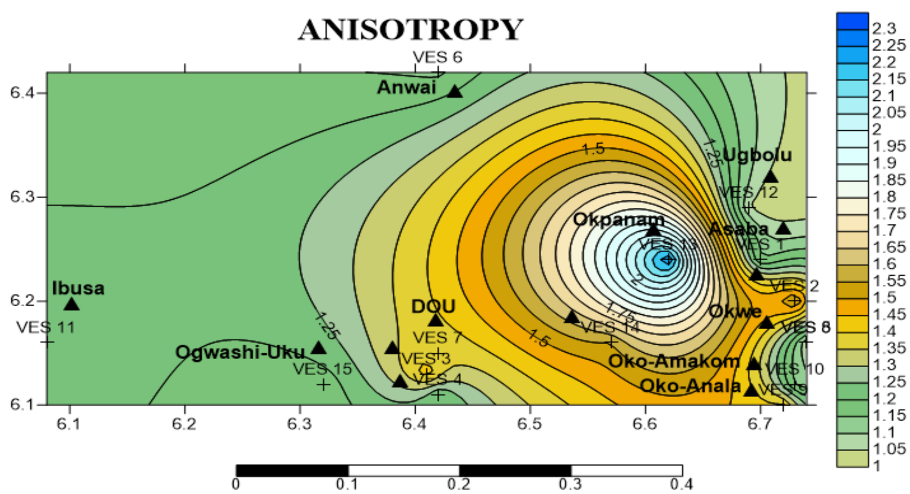

Figure 6: Spatial distribution of Anisotropy (λa) of the study area

Longitudinal Resistance (ρL)

Longitudinal resistance varies approximately from 136.30 Ωm to 2,334.80 Ωm with an average value of 618.57 Ωm as shown in table 2. The highest values occur around Asaba–Okwe, while lower values are observed around Anwai and portions of the central study area. According to the Dar-Zarrouk concept, longitudinal resistance is directly related to aquifer protective capacity and transmissive properties (Maillet, 1947; Henriet, 1976). High longitudinal resistance values indicate thick, relatively resistive subsurface layers capable of protecting groundwater from surface contamination. The high-value zones around Asaba and Okwe therefore suggest favourable aquifer conditions with good groundwater protection. Moderate values observed around DOU, Okpanam and Oko-Amakom indicate intermediate protective capacity, while the lower values around Anwai may reflect thinner overburden materials or relatively conductive formations. Consequently, groundwater in these low-resistance zones may be more vulnerable to contamination from anthropogenic activities as shown in Figure 5.

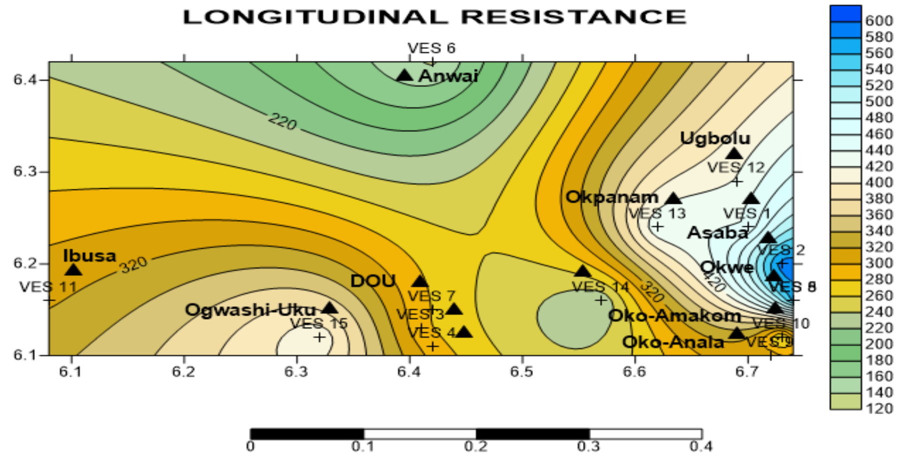

Figure 7: Spatial distribution of Longitudinal Resistance (ρL) of the study area

Fracture Porosity (ϕf)

The fracture porosity map on Figure 8 reveals values ranging approximately from 4.20% to over 16.32% with an average value of 6.08%. The highest fracture porosity occurs around Okpanam–Asaba, corresponding closely with the area of high anisotropy as shown in Table 2. This spatial relationship suggests that both parameters are responding to the same structural controls. High fracture porosity values indicate extensive development of secondary pores and fractures within the subsurface. These fractures provide storage and flow pathways for groundwater and therefore enhance aquifer productivity (Freeze and Cherry, 1979). Areas exhibiting fracture porosity above 7% to 8% can be considered promising groundwater targets because groundwater occurrence in consolidated and semi-consolidated formations is largely controlled by secondary porosity. Lower fracture porosity values around Ibusa, Anwai and Ogwashi-Uku suggest relatively compact formations with reduced groundwater storage potential.

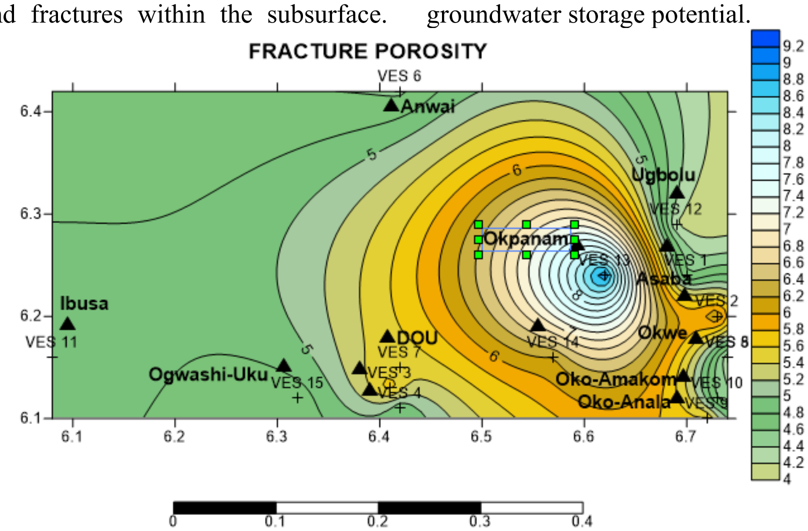

Figure 8: Spatial distribution of Fracture Porosity (ϕf) of the study area

Transmissivity (T)

Transmissivity refers to the capacity for horizontal water transmission within an aquifer. According to equation 8, it is directly related to the thickness of the aquifer (b) and its hydraulic conductivity (K). Transmissivity (T) is measured in units of m²/day or cm²/s, where K is indicated in m/day or cm/s and b is denoted in meters. The transmissivity values identified in this study vary from 0.602 to 53.353 m²/day, with an average of 20.12 m²/day, as detailed in Table 2. Analysis of Figure 9 reveals that T tends to increase towards the southwestern regions of the study area. This region, characterized by a high T-value, suggests a greater potential for groundwater resources compared to other areas within the study.

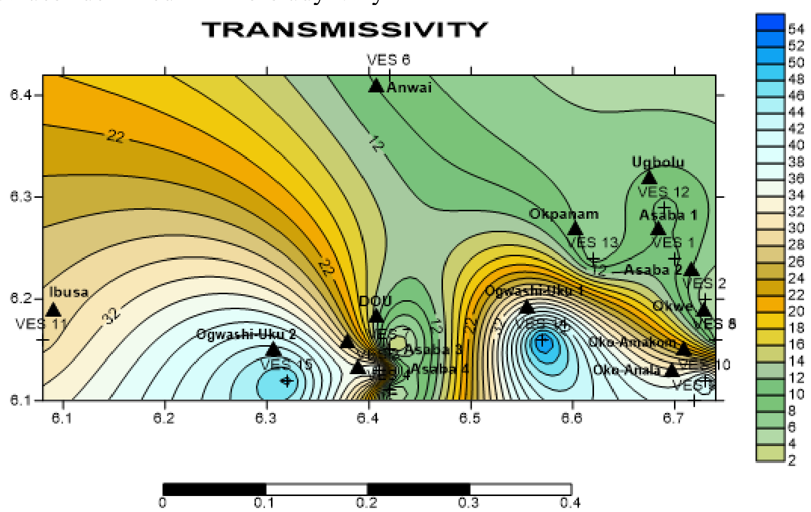

Figure 9: Spatial distribution of Transmissivity (m²/day) of the study area

Hydraulic conductivity (K)

The rate at which pore fluid can escape from compressed pore spaces is influenced by hydraulic conductivity (Obiora et al., 2016). Hydraulic conductivity refers to the capacity of a material to permit fluid movement through its pores and fractures in rock formations. As indicated in Table 2, this study has an average hydraulic conductivity (K) value of 1.372 m/day, with a range spanning from 0.095 m/day to 3.477 m/day. Additionally, the water conductivity in a given region is contingent upon the rock type present. Hydraulic conductivity plays a crucial role in governing the dynamics of groundwater movement within an aquifer. Data illustrated in Figure 8 showed elevated K values in the southwestern areas of the study. This indicates that, unlike the other areas examined, groundwater in the specified area exhibits a more consistent flow. The southwest sector of the research area shows significant promise for groundwater exploration. Based on the analysis presented in Figures 9 and 10, it can be inferred that this southwestern region has a higher likelihood of facilitating groundwater movement, rendering it more conducive to aquifer development.

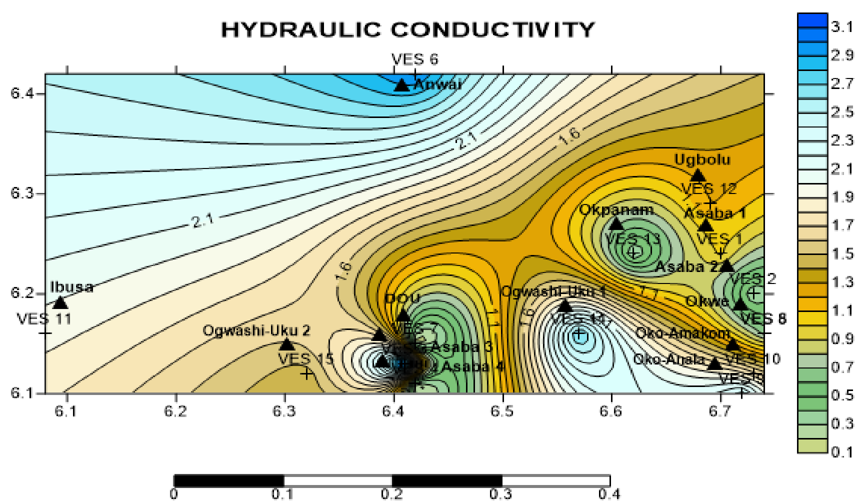

Figure 10: Spatial distribution of hydraulic conductivity (m/day) of the study area

Aquifer Resistivity

The aquifer resistivity map in Figure 11 shows spatial variations in aquifer resistivity ranging from 156.0 Ωm to 7,365.2 Ωm with an average value 1676.6 Ωm. The highest resistivity values occur around the DOU–Asaba axis, indicating highly resistive subsurface materials. High resistivity is commonly associated with clean sands, gravels and fresh groundwater conditions, whereas lower values may indicate clay-rich formations or mineralized groundwater (Todd and Mays, 2004; Yungul, 1996). The high-resistivity zones are therefore interpreted as favorable groundwater-bearing formations with good permeability and water quality potential. Lower resistivity zones around Oko-Amakom, Oko-Anala and parts of Ugbolu may contain greater clay content and lower transmissivity.

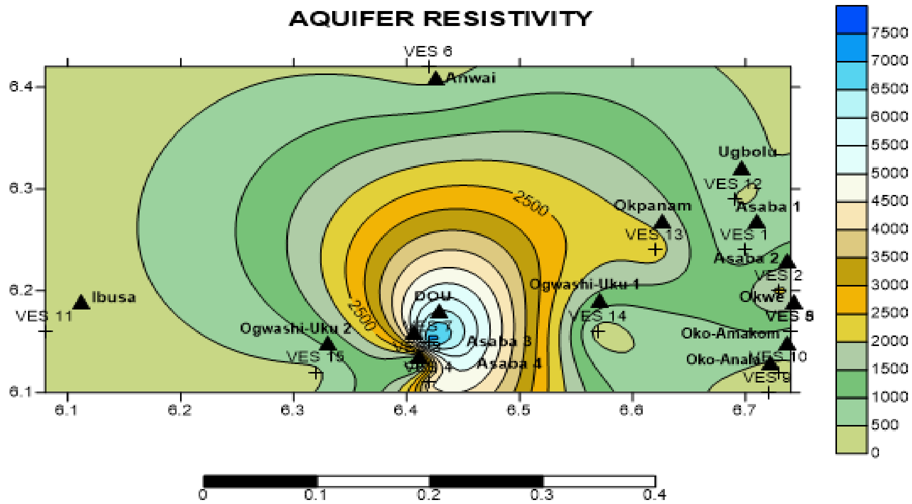

Figure 11: Spatial distribution of aquifer resistivity (Ωm) of the study area

Aquifer thickness

The aquifer thickness map in Figure 12 indicates values ranging from approximately 3m to over 33.7m with an average value of 14.713m as shown in Table 2. The thickest aquifer occurs around Ogwashi-Uku 2 (VES 15), where thickness exceeds 30m thick. Aquifers, generally possess higher groundwater storage capacity and can sustain larger abstraction rates (Freeze and Cherry, 1979). Moderate thickness values dominate the DOU, Asaba and Okpanam areas, suggesting adequate groundwater reserves. Thin aquifer sections around Anwai and parts of Ugbolu indicate lower storage capacity and potentially reduced borehole yields.

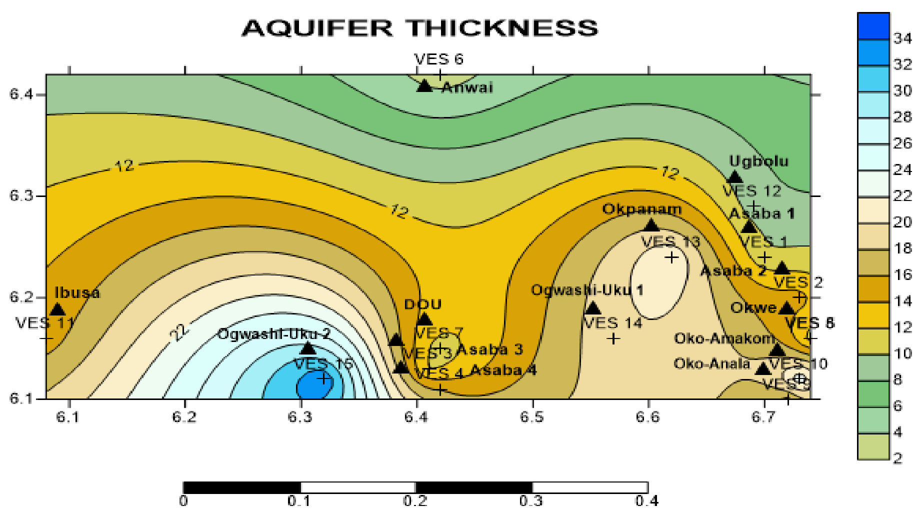

Figure 12: Spatial distribution of aquifer thickness (m) of the study area

Aquifer Depth

The aquifer depth map in Figure 13 reveals depth variations from approximately 4.9m to 39.8m with an average value of 25.607m as shown in Table 2. Deep aquifers occur around Ugbolu and Ogwashi-Uku 2, while shallower aquifers occur around Anwai and parts of Asaba. Deep aquifers are generally better protected from surface contamination because of thicker overburden cover (Yungul, 1996). However, they may require higher drilling costs. Moderately deep aquifers around DOU and Asaba provide a favorable balance between protection and economic development.

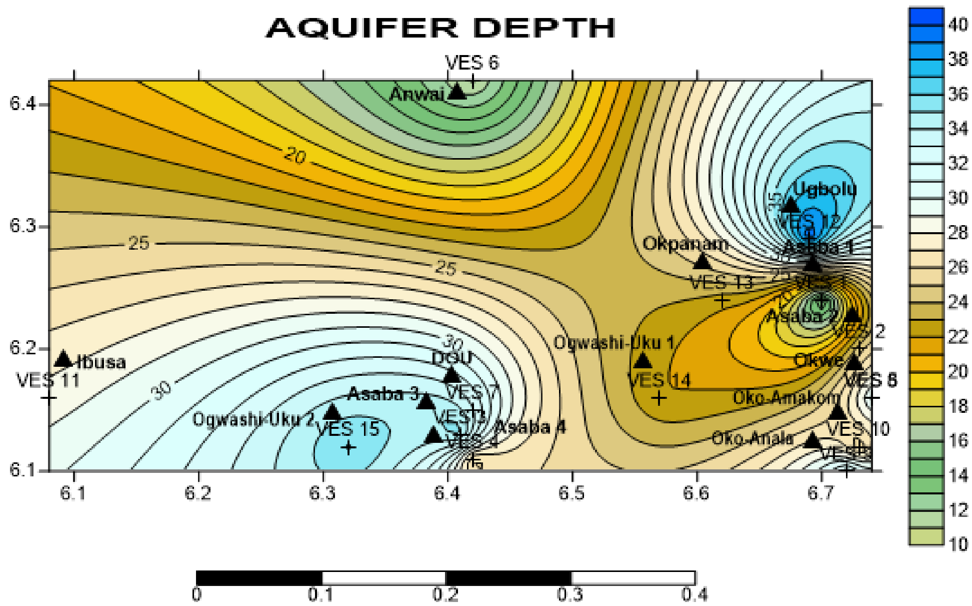

Figure 13: Spatial distribution of aquifer depth (m) of the study area

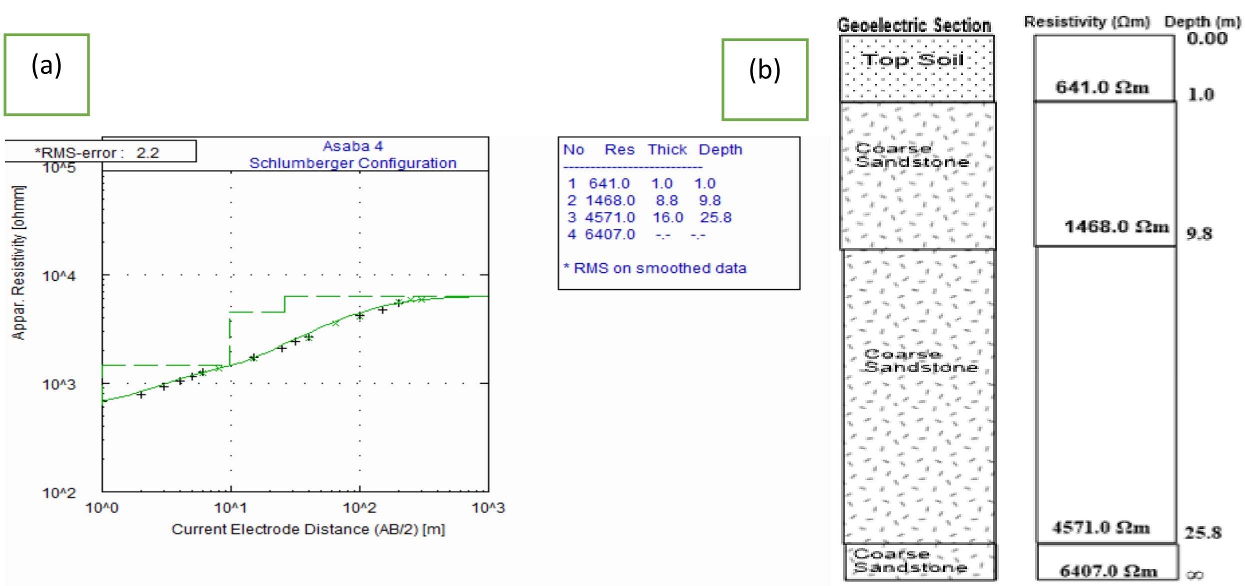

Figure 14: Curves of resistivity versus depth for (a) Plot of VES 4 (b) Geoelectric section of VES 4

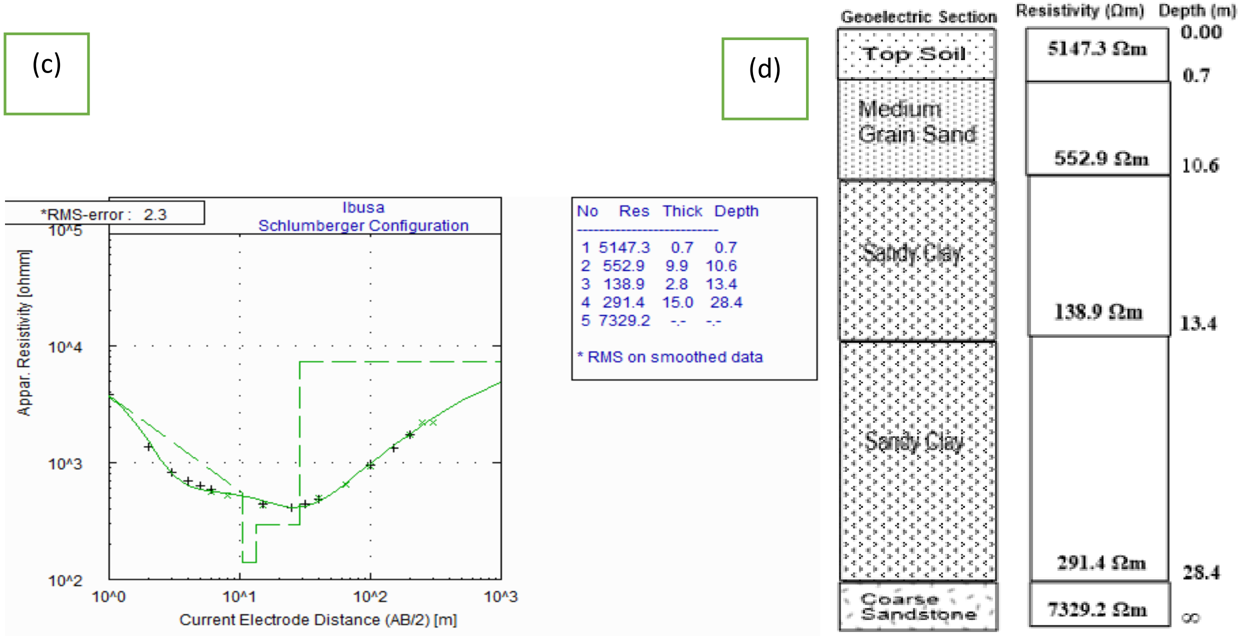

Figure 15: Curves of resistivity versus depth for (c) Plot of VES 4 (d) Geoelectric section of VES 11

CONCLUSION

The integrated VES and hydrogeological assessment successfully characterized aquifer potential and vulnerability in the study area. Aquifer resistivity (156.0 Ωm to7365.2 Ωm), thickness (3.0 m to 33.7 m) and depth (4.9 m to 39.8 m) demonstrate considerable spatial variability. Longitudinal conductance values of 0.0111℧ to 0.1236 ℧ indicate generally poor protective capacity, implying widespread susceptibility to surface-derived contaminants. Hydraulic conductivity (0.095 m/day to 3.477 m/day) and transmissivity (0.602 m²/day to 53.353 m²/day) identify the southwestern part of the area as the most productive groundwater zone, while elevated transverse resistivity (176.4 Ωm to 4501.3 Ωm), anisotropy (1.05 to 4.08) and fracture porosity (4.20% to 16.32%) confirm enhanced permeability and groundwater storage in structurally favourable locations. Overall, the area possesses good groundwater development potential but requires stringent groundwater protection, controlled land-use practices and routine water-quality monitoring because the natural overburden offers limited protection against contaminant migration.

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