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ORIGINAL RESEARCH ARTICLE

SPATIAL ASSESSMENT OF AQUIFER VULNERABILITY USING DAR ZARROUCK PARAMETERS IN IDUNMWOWINA, EDO STATE, NIGERIA

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ABSTRACT
Rapid urbanization and unregulated sand mining in many semi-urban areas of Edo State have heightened concerns about aquifer vulnerability and groundwater contamination. This study evaluated the spatial variability of aquifer vulnerability in Idunmwowina, Ovia North-East Local Government Area, Edo State, using Dar Zarrouk parameters derived from vertical electrical sounding (VES). Five VES were conducted with the Schlumberger configuration at a maximum current electrode spacing of AB/2 = 200 m. Data interpretation was carried out using the partial curve matching technique in Surfer software, while kriging interpolation was applied for spatial mapping. The geoelectric curves identified include KHK (40%), HAA (20%), HAK (20%), and AAK (20 %), indicating predominantly semi-confined aquifers. The results of Dar Zarrouk parameters revealed hydraulic conductivity values ranging from 0.73–1.46 m/day, transmissivity between 2.72–7.67 m²/day, transverse resistance from 26,621–221,682 Ωm², and longitudinal conductance (S) values between 0.004–0.335 Ω⁻¹ (mean = 0.0752 Ω⁻¹). Additionally, the Spatial distribution maps showed higher transmissivity and hydraulic conductivity in the southwestern part of the study area, while longitudinal conductance values were generally low, suggesting weak aquifer protective capacity. Therefore, the results indicate that the aquifer system is vulnerable to contamination from leachates generated by nearby dumpsites. It It highlights the need for effective land use management and sustainable waste disposal practices to safeguard groundwater resources in the area.

1.0 Introduction

Groundwater is the largest and most accessible source of freshwater on Earth and plays a vital role in sustaining ecosystem services, supporting economic development and safeguarding human health (Wang *et al.,* 2018; Gleeson *et al.,* 2016). Groundwater is the largest and most easily available freshwater resource on Earth. It is essential to maintaining ecosystem services, economic growth, and human health (Wang *et al.*, 2018; Gleeson *et al.*, 2016). Access to clean drinkable water is crucial for maintaining good health and attaining the Sustainable Development Goals (SDGs) (Nyakno 2021; Eyankware *et al.,* 2022b). This is especially true in light of the fact that the amount of clean water that society requires for cultivation, municipal usage, and drinking is growing exponentially (Wang *et al.,* 2020; Lall *et al.,* 2020; Wang *et al.*, 2020; Lall *et al.,* 2020). However, quite a number of anthropogenic activities such as oil spills, open dumps, mine tailings, corrosion of underground tanks and other unsustainable groundwater practices have led to deterioration of groundwater quality. Water quality may degrade due to the leaching of geogenic contaminants as a result of weathering during mining operations or as water moves through the hydrologic cycle, organic and inorganic contaminants might be transferred from the soil to the infiltrating groundwater. The geology of the parent rocks plays a crucial role in the types of aquifer systems developed in a given area. Hence, aquifer vulnerability is influenced by lithologic forms that overlies beneath it (Eyankware *et al.,* 2020a, 2020b; Nyakno, 2021; Umayah and Eyankware 2022). Hence, aquifer susceptibilities will vary in locations with different geology. Several studies (Kwami *et al.,* 2013; Okiongbo and Akpofure 2012; Omali and Arogundada 2022 and Simsek *et al.,* 2006) on aquifer vulnerability have shown that aquifer protection depends on the permeability of the layers, which controls the transport of contaminants into the underlying aquifer units. Although, groundwater potential and aquifer susceptibilities studies have been conducted in basement complexes and sedimentary basins (Akinseye *et al.,* 2023; Eyankware *et al.,* 2022) and Eyankware and Aleke (2021) utilizing geophysical techniques, the appraisal of groundwater potential and the vulnerability of aquifers to contaminants in the Benin Formation has not yet taken centre stage. Therefore, this research is aimed at delineating the protective capacity of the aquiferous zones and groundwater potentials in Idunmwowina, community, Edo State utilizing the Dar Zarrouck parameters derived from vertical electrical sounding techniques. Dar Zarrouk characteristics can also be used to determine an aquifer's susceptibility the subsurface and surface contamination (Okonkwo and Ugwu, 2015). Dar-Zarrouk parameters were first introduced (Maillet, 1947), the longitudinal conductance and transverse resistance of the layers are measured using the resistivities and thicknesses of the individual layers. The second-order parameters were transverse unit resistance (Ωm^2), Longitudinal unit conductance ($\Omega{-1}$), and coefficient of anisotropy (λ).

Water resources quality is deteriorating worldwide due to a number of anthropogenic activities affecting sources of groundwater through contamination. These include septic tanks, landfills, wastewater systems, injection wells, disposal sites, cemeteries, mine tailings, deicing salts, oilfield brines, agricultural chemicals, fertilizers, and accidental spills (El-Naqa and Al-Shayeb, 2009). Groundwater contamination can occur also when water of poor quality is drawn into a well that originally has been developed in high quality water, water especially when there is saltwater intrusion in coastal areas (Akpan *et al.,* 2018). The sand mine in Idunmwowina, Oluku, Edo state has contributed significantly to the socio-economic advancement of the area. It has served as source of revenue to both local and the state governments. Small businesses continue to thrive within the area. Thus, compliments government in giving employments to our teeming youth population. However, the recent closure of the mine without adherence to international best practices regarding safe reclamation processes has led to the abandoned mine pits becoming refuse dumps for residents, breeding grounds for microbes and potential hideouts for criminals. It becomes practically more worrisome when excavation (surface mining) has already been made expose the overburden materials, thereby reducing the residence time of groundwater infiltration. Although knowledge from different fields in science has been employed to understand groundwater quality, a detailed knowledge of geology and hydrogeology is however needed for seamless and reliable interpretation of groundwater resources.

One of the inherent dangers associated with associated with open dumpsites is the production of leachates. These leachates are conveyed either as runoff or infiltrates through the soil matrix to contaminate groundwater. The rate and extent of leachate infiltration is controlled primarily by the ease with which the subsurface layers beneath the dumpsites and surroundings allow contaminants migrate. Therefore, it has become pertinent to understand the subsoil profile to assess the impact of overlying dumpsites on the underlying aquifer systems. The Dar Zarrouck parameters play vital role in assessing hydrogeological conditions in this regard.

2. Materials and methods

2.1 The Study Area

The study area Idunmwowina is located in Ovia Northeast local government area in Edo State. The area lies between Latitude N6° 26′ 5.3″ to N6° 26′51.7″ and Longitude E5° 36′ 6.1″ to E5° 36′ 57″. The area is accessible from Oluku and Uselu axis of the Benin-Lagos Road. The study area is known for hosting an active compressed natural gas station, active sand mining sites. Many of these sand mines have been turned into open dumpsites by residents due to non-adherence to international best practices by mine developers. These activities are potential sources of heavy metal enrichment in the environment.

2.2 The Geology of the Study Area

The study area lies within the Benin Formation, a major stratigraphic unit of the Southern Sedimentary Basin as depicted in Figure 2. The Benin Formation is composed predominantly of reddish to reddish-brown lateritic sands, sandy clays, silts, gravels, and ferruginized sandstones (Short and Stauble, 1967; Akujieze and Irabor, 2014). The surface layer is typically lateritized, underlain by loose sands and sandy clays, often with reticulate mud cracks. Parkinson (1907) first described this lithologic unit as "Benin Sand," representing deposits of a paleo-coastal environment dating from the Paleocene to Pleistocene. Subsequent studies (Tattam, 1943) referred to the sequence as "Coastal Plain Sands," extending across parts of Benin, Calabar, Owerri, and Onitsha. These sediments constitute the upper continental facies of the Niger Delta, reflecting ancient fluvial and coastal plain depositional systems.

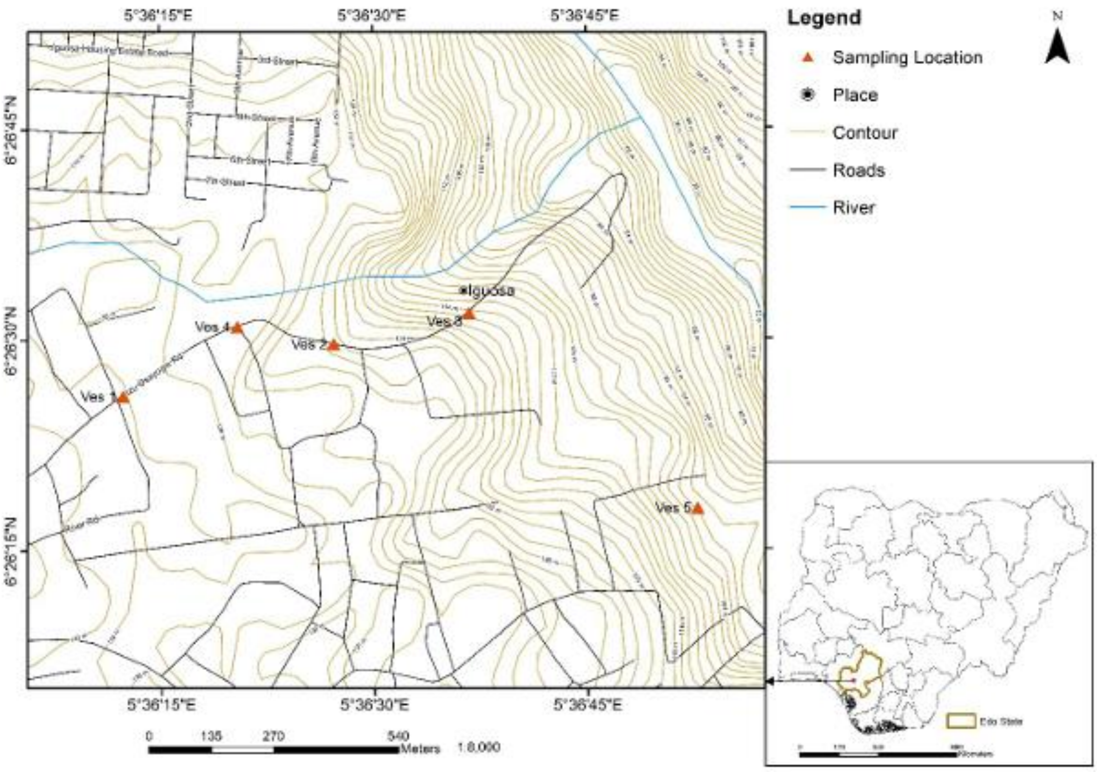

Figure 1: Sampling location map of Idunmowina

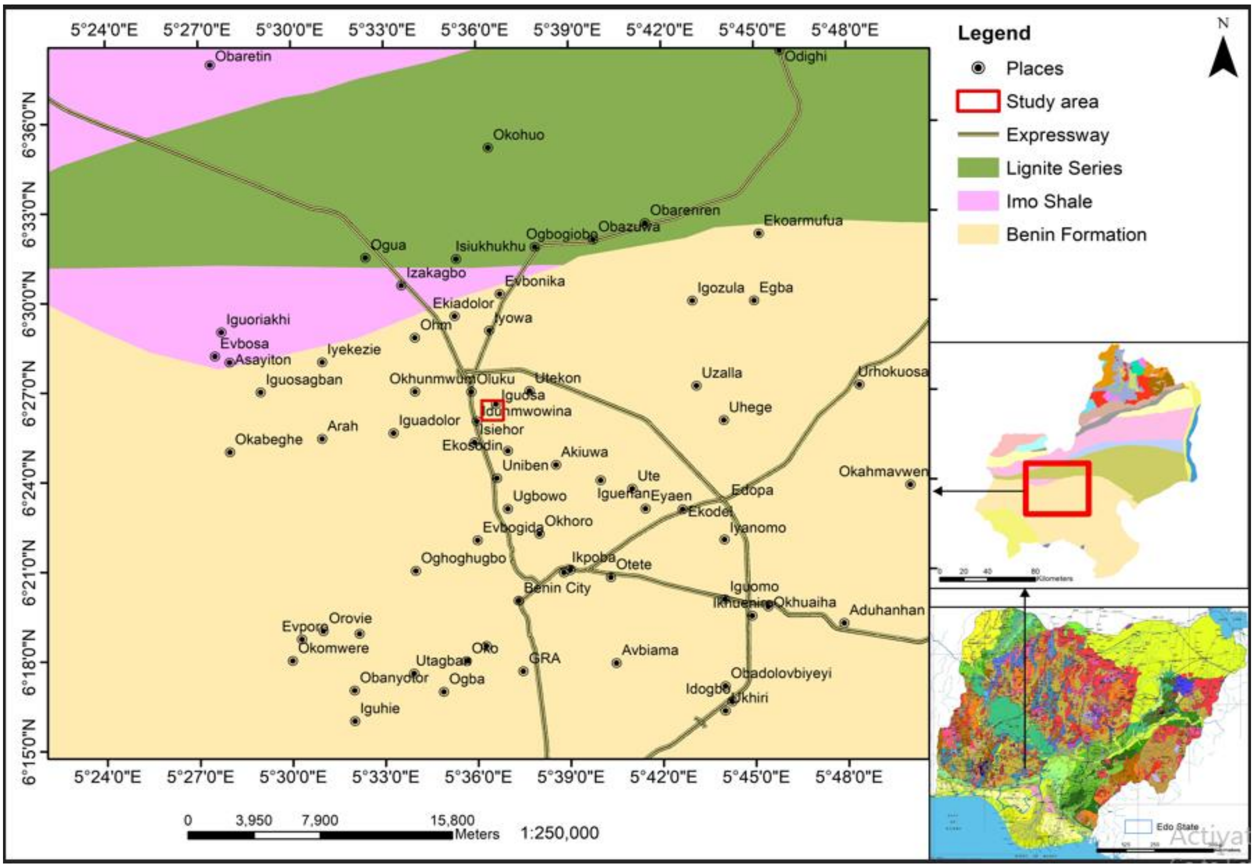

Figure 2: Geological map of the study area

2.4 Hydraulic Parameters

The longitudinal conductance (S) is a measure of the impermeability of a rock layer (Billing, 1972). Electrical anisotropy is a measure of stratified rock which is generally more conductive in the parallel plane than the perpendicular (Malick *et al.,* and Cihan *et al.,* 2014). For a sequence of horizontal, homogenous and isotropic layers of resistivity $e1$ and thickness $h1$, the Dar Zarrouk parameters (longitudinal conductance S and transverse resistance TR) is defined as follows;

$$\text{Longitudinal conductance } (S) = h1\ e1 + h2\ e2 + h3\ e3 + hn/en = \sum{}^{n}{}_{i=0} hi\ /ei \quad 1$$

$$\text{Transverse resistance } (TR) \quad = e1h1 + e2h2 + \cdots .. e3h3 = \sum{}^{n}{}_{i=0} eihi \quad 2$$

The relationship between aquifer transmissivity, and longitudinal conductance is established by the equation derived by Todd, (1980). Where Tr = Aquifer Transmissivity,

K= Hydraulic conductivity in m/day, hi= layer thickness of aquifer R = Transverse Resistance.

S = Longitudinal Conductance Transmissivity (Tr)= K.hi 3

Table 1: Rating of protective Capacity of Aquifers (Oladapo and Akintorinwa 2007)

Longitudinal Conductance	Protective Capacity Rating
>10	Excellent
5-10	Very good
0.7-4.9	Good
0.2-0.69	Moderate
0.1-0.19	Weak
0.1	Poor

Table 2: Aquifer classification based on Transmissivity values (Offodile, 1983)

Longitudinal Conductance	Protective Capacity Rating
>10	Excellent
5-10	Very good
0.7-4.9	Good
0.2-0.69	Moderate
0.1-0.19	Weak
0.1	Poor

2.5 Kriging Interpolation

Kringing interpolation is an unbiased optimal estimation method based on the analysis of semivariogram theory (Lin *et al.,* 2011). Because the mathematical expectation of the regional variables is unknown, we adopted the ordinary kriging method for local estimation:

$$\hat{Z}(x_0) = \Sigma_{i=1}{}^{n}\ \lambda_i\ Z(x_i) \quad 4$$

Where: $\hat{Z}(x_0)$ = predicted value at location x_0, λ_i = kriging weight for observation i, Z (x_i) = observed value at location x_i, n = number of observations

3. Result and Discussion

The results of Vertical electric sounding (VES) showing the thickness, apparent resistivity and depth across sampling points is presented in Table 3. Tables 4 and 5 showed the values of Dar –Zarouck parameters calculated in each VES points in the area of study. The number of layers, lithologic units and curve types is also presented in Figures (3 to 12) respectively. 3 to 10 and 12 respectively. The spatial distribution of Dar Zarrouck parameters are presented in Figures (13 to 17) (13 - 17).

Table 3: VES data used to create geo-electric layers and curve types in the study area

VES	Latitude	Longitude	Resistivity (Ωm)						Layer Thicknes						Curve type	No of Layers
			ρ1	ρ2	ρ3	ρ4	ρ5	ρ6	h1	h2	h3	h4	h5	h6		
VES 1	N6°26’ 25.98”	E5° 36' 12. 36”	259.31	970.2	137.5	2924.9	2758.6	4719	1.55	2.09	5.78	5.86	40.87	∞	KHK	6
VES 2	N6°26’29.64”	E5°36'27.18”	552.98	755.47	458.99	13656	1267.9	1314.4	0.43	3.89	3.54	18.56	42.55	∞	KHK	6
VES 3	N6°26’31.8”	E5°36'36.72”	740.04	225.08	880.62	26166	4199.9	739.19	2.23	2.04	1.95	23.48	29.24	∞	HAA	6
VES 4	N6°26’30.9”	E5°36'20.24 ”	260.52	200.89	57096	7215.6	646.84	∞	0.95	2.07	13.2	18.35	∞	∞	HAK	5
VES 5	N6°26'17.88”	E5°36'52.74"	109.97	609.17	858.57	1521.3	1823.1	73.345	0.24	3.77	11.78	18.19	73.35	∞	AAK	6

3.1 Geoelectric Curves

The geoelectric curves obtained from the geophysical sounding in the area of study as shown in Figures 3 to 7 revealed variations in curve types. The curves were KHK, HAA, HAK and AAK types. It has been asserted that the shape of VES curve depends on the thickness of each layer, the number of layers in the subsurface and the ratio of the resistivity of the layer (Kwami *et al.,* 2019). The occurrence of multiple curve types (KHK, HAA, HAK and AAK types) in the study area reflects non-uniform layering, aquifer discontinuity and lateral heterogeneity typical of the Benin formation. The variation in geoelectric curve types (KHK, HAA, HAK, and AAK) indicates a complex subsurface lithology typical of the Benin Formation, composed of alternating sand and clay sequences of fluvial–deltaic origin. These variations suggest non-uniform layering, aquifer discontinuity, and lateral heterogeneity, consistent with observations by Oseji *et al.,* (2005) and Amadi *et al.,* (2012). The KHK curve type, characterized by alternating high–low–high resistivity layers, reflects multilayer aquifer systems where sand units are interbedded with clay or lateritic horizons. Similar patterns, associated with confined to semi-confined aquifers of moderate to high yields, were reported by Okiongbo and Akpofure (2012) in the Niger Delta. This implies that groundwater occurrence in the area largely depends on the thickness and continuity of sandy horizons. The HAA and HAK curves further reveal subsurface variability. The HAA curve represents a clayey or lateritic overburden overlying sandy aquifers, consistent with findings by Ehirim and Ebeniro (2010) in Port Harcourt. The HAK curve, is indicative of perched or semi-confined aquifers, aligns with interpretations by Amadi *et al.,* (2012) and Oyeyemi *et al.,* (2017). The AAK curve type, dominated by resistive layers, suggests predominantly sandy subsurface zones with high porosity and permeability favorable for groundwater storage, similar to the findings of Aghamelu *et al.* (2020) in the Anambra Basin.

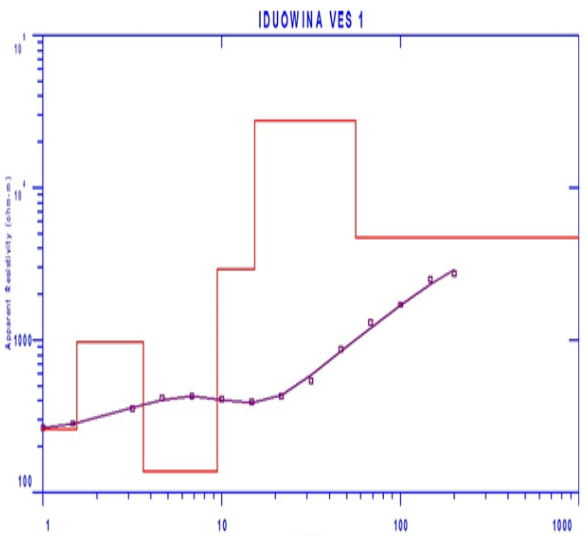

Figure 3: Hydrogeophysical Sounding Curve of VES 1

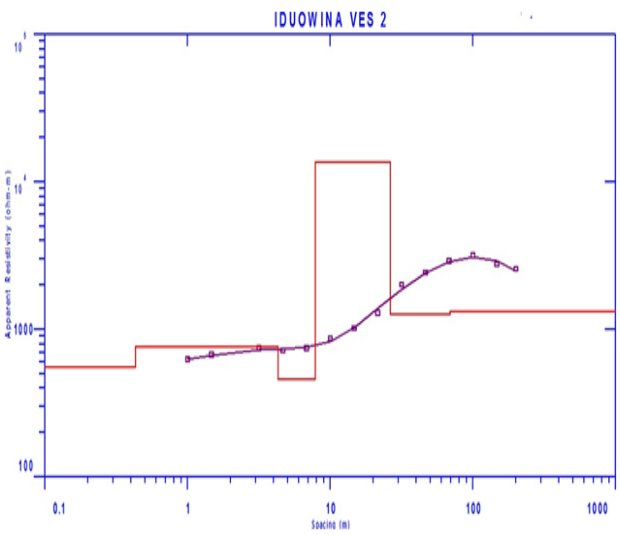

Figure 4: Hydrogeophysical Sounding Curve of VES 2

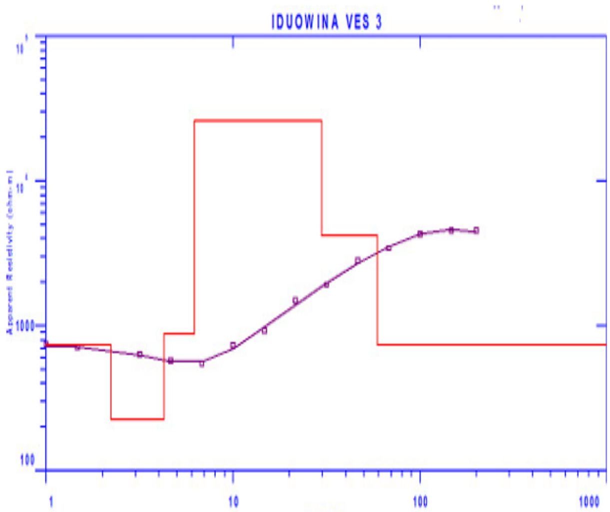

Figure 5: Hydrogeophysical Sounding Curve of VES 3

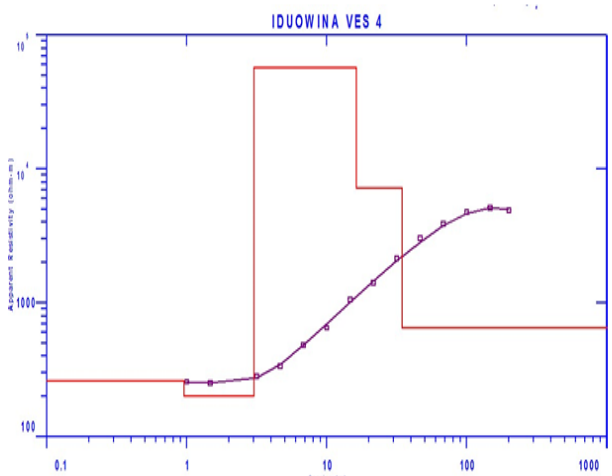

Figure 6: Hydrogeophysical Sounding Curve of VES 4

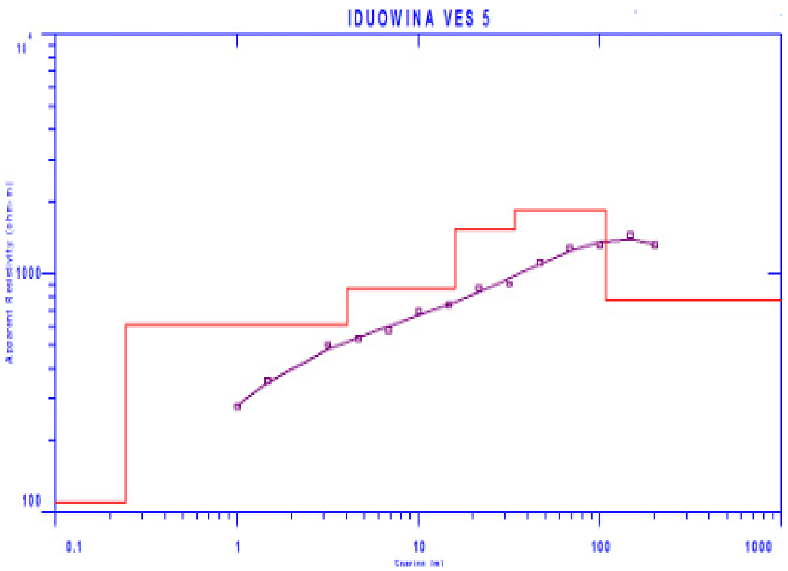

Figure 7: Hydrogeophysical Sounding Curve of VES 5

3.2 Geo-electric Sections

The geoelectric section presents a maximum of six (6) layers with varying resistivities and thicknesses in each of the VES conducted in the area of study points with the exception of VES 4 with five (5) layers as shown in Figures 8 to 12. The first layer (topsoil) which is composed of unconsolidated sand has resistivities ranging from 109.97 to 740.04 Ωm 109.97 - 40.04 Ωm, and thickness varying from 0.24 – 2.22 m. The second layer composed of lateritic soil is characterized with resistivities ranging from 200.89 – 970.20 Ωm and thickness ranging from 2.04-3.89 m. The third layer consists of lateritic clay, clay, lateritic soil, fine sand and sandstone has resistivities ranging from 137.50 – 57096 Ωm with thickness values ranging from 1.95-13.2 m. The fourth geoelectric layer consisting of medium to coarse sand, sandstone, medium sand and coarse sand has resistivities ranging from 1521.3-2924.9 Ωm and thickness varying from 5.85-23.48 m. The fifth geoelectric layer was composed mainly of medium to coarse sand with resistivities varying from 646.84- 4199.9 Ωm and thickness 29.24 – 73.34 m. The aquifer systems in the study area could, therefore, be delineated as medium to coarse grained sand which accounts for about four (4) of the VES locations. The high resistivity values of the aquiferous units give credence to its porous and permeable characteristics.

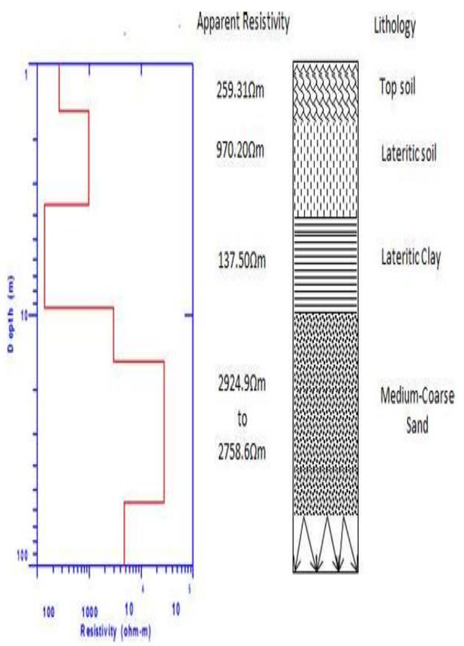

Figure 8: Layered inversion model VES 1

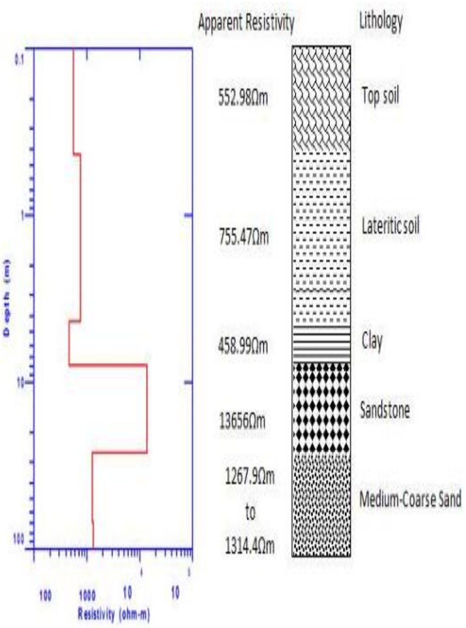

Figure 9: Layered inversion model VES 2

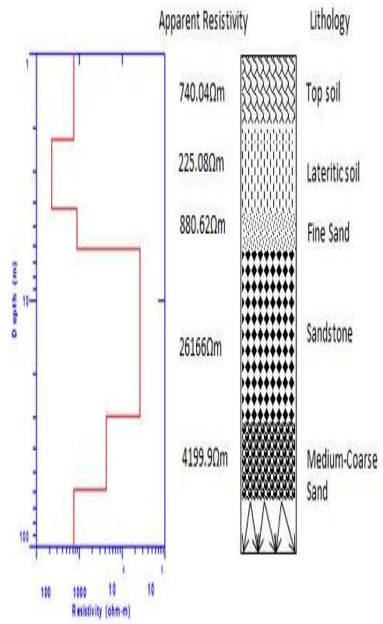

Figure 10: Layered inversion model VES 3

3.3 Dar Zarrouck Parameters

The data from VES VES conducted to estimate the Dar Zarrouck parameters (Hydraulic conductivity, longitudinal conductance, Transverse resistance and Transmissivity) as shown in Table 4. The Dar Zarrouck parameters are essential in establishing aquifer characteristics and vulnerability to contamination.

3.4 Spatial Distribution of Dar- Zarrouck Parameters

The data from VES conducted was used to estimate the Dar Zarrouck parameters (Hydraulic conductivity, longitudinal conductance, Transverse resistance and Transmissivity). The Dar Zarouck parameters are essential in establishing aquifer characteristics. These parameters are related to different combination of the thickness and resistivity of each geo-electric layers (Braga, 2006).

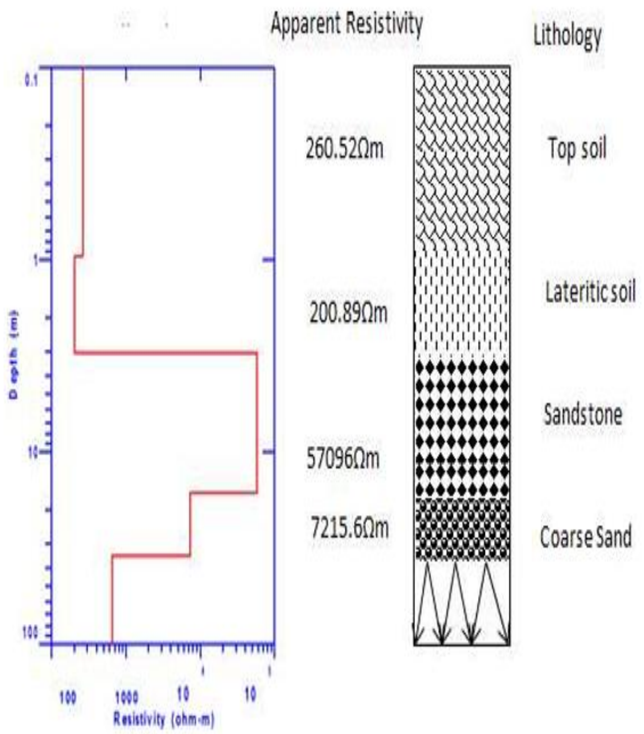

Figure 11: Layered inversion model VES4

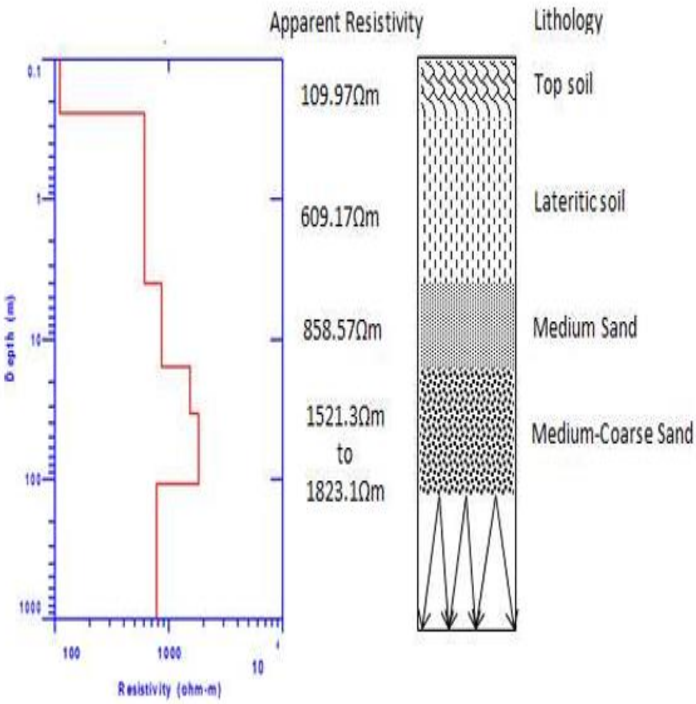

Figure 12: Layered inversion model VES 5

3.4.1 *Hydraulic conductivity*

The hydraulic conductivities of various aquiferous units in the study area are shown in Table 5. Hydraulic conductivity is the ease in which fluids in pores of geologic material will pass under specific hydraulic gradient. It is a function of fabric, texture and grain size of the aquifer system. Intrinsic permeability is a measure of a material (rock or soil) ability to allow the movement of fluids (Kwami *et al.,* 2019). In this study mean values of hydraulic conductivities for VES 1, 2 3, 4 and 5 were 1.43 m/day, 0.73 m/day, 0.83 m/day m/day, 1.25 m/day and 1.46 m/day with a mean of 1.14 m/day and the aquifer systems delineated were mainly medium to coarse grained sand. Therefore, it can be inferred that the aquifer units in the study area is of moderate to high permeability due to varying degree of grain sizes and well interconnected pore spaces. Spatial map showing variation in hydraulic conductivity is presented in (Figure 13). Hydraulic conductivity values ranged from 0.73 – 1.46 m/day. Hydraulic conductivity classes were fairly and evenly distributed with the low class (< 1.17) occupying the north central areas while the moderate (1.1701 – 1.34 m/day) and high class (>1.3401) occupy the southern and western part of the study area. These values are lower than those reported by Kwami *et al.,* (2019), Omali and Arogundade (2022), and Ojeaga and Osauzou (2024). The occurrence of high hydraulic conductivity in the southern and western part indicates better yield due to the presence of permeable materials that would allow the passage of fluids. The area also correlates with areas of high transmissivity.

Table 4: Dar Zarouck parameters obtained from VES points in the study area.

	Apparent Resistivity (Ωm)	Thickness (m)	Longitudinal Conductance S (Ω^{-1})	Transverse Resistance TR (Ωm^2)	Electrical conductivity δ (Ωm^{-1})	Hydraulic conductivity K	Transmissivity Tr (m^2 /day)
				VES 1			
	259.31	1.5457	0.005961	400.8155	0.003856	2.164483	3.345641
	970.2	2.0924	0.002157	2030.046	0.001031	0.632126	1.322659
	137.5	5.7825	0.042055	795.0938	0.007273	3.911688	22.61934
	2924.9	5.8555	0.002002	17126.75	0.000342	0.225811	1.322235
	2758.6	40.873	0.014817	112752.3	0.000363	0.238484	9.747561
Mean			**0.33496**	**26621**	**0.00951**	**1.43**	**7.67**
	VES 2						
	552.98	0.43211	0.000781	238.9482	0.001808	1.067961	0.461477
	755.47	3.8889	0.005148	2937.947	0.001324	0.79827	3.104392
	458.99	3.539	0.00771	1624.366	0.002179	1.270654	4.496844
	13656	18.559	0.001359	253441.7	0.0000732	0.053639	0.995492
	1267.9	42.554	0.033563	53954.22	0.000789	0.492477	20.95688
Mean			**0.01897**	**62439.44**	**0.0012**	**0.73**	**6.00**
				VES 3			
	740.04	2.2222	0.003003	1644.517	0.001351	0.813785	1.808394
	225.08	2.0417	0.009071	459.5458	0.004443	2.470055	5.043112
	880.62	1.9526	0.002217	1719.499	0.001136	0.691911	1.351025
	26166	23.48	0.0008974	614377	0.000038	0.029244	0.68665
	4199.9	29.241	0.006962	122809.3	0.000238	0.161128	4.711545
Mean			**0.00443**	**148201.96**	**0.00144**	**0.83**	**2.72**
				VES 4			
	260.52	0.9509	0.00365	247.7285	0.003838	2.155103	2.049288
	200.89	2.0748	0.010328	416.8066	0.004978	2.74643	5.698293
	57096	13.2	0.000231	753667.2	0.0000175	0.014123	0.186426
	7215.6	18.349	0.002543	132399	0.000139	0.097258	1.784585
Mean			**0.0124005**	**221682.68**	**0.00224**	**1.253**	**2.4296**
				VES 5			
	109.97	0.242	0.002201	26.61274	0.009093	4.818094	1.165979
	609.17	3.77	0.006189	2296.571	0.001642	0.975775	3.67867
	858.57	11.788	0.01373	10120.82	0.001165	0.708473	8.351476
	1521.3	18.192	0.011958	27675.49	0.000657	0.415501	7.558786
	1823.1	73.345	0.040231	133715.3	0.000549	0.350958	25.74102
Mean			**0.01486**	**34766.958**	**0.00262**	**1.45376**	**4.15098**

3.4.2 Electrical conductivity

Electrical conductivity values range between 0.0012 to 0.0095 Ωm^{-1} with mean of 0.0035 Ωm^{-1}. Spatial distribution map in Figure 14 shows that low electrical conductivity values (< 0.00365) is the dominant class and occupy the eastern areas, the high class (> 0.00685) is the least and occupy the southwestern corner whereas the moderate class (0.00365 – 0.00685) occupy the central western part of the study area. Overall, the spatial distribution of EC values underscores the hydrogeological heterogeneity of the study area. The predominance of low EC values in the east highlights this sector as the most promising for groundwater development, both in terms of yield and quality. Conversely, the occurrence of high EC zones in the southwest delineates areas of limited aquifer potential and possible water quality concerns.

Table 5: Summary of Second-order Geoelectric parameters of each VES conducted in the study area

VES NO	Longitudinal conductance S (Ω^{-1})	Transverse resistance TR (Ωm^2)	Hydraulic conductivity (K)	Electrical conductivity δ (Ωm^{-1})	Transmissivity Tr (m^2 /day)
1	0.335	26621	1.43	0.0095	7.67
2	0.018	62439.44	0.73	0.0012	6.00
3	0.004	160489.65	0.83	0.0014	2.72
4	0.004	221682.68	1.25	0.00224	2.43
5	0.015	34766.958	1.46	0.00262	2.42
Mean	0.0752	101199.81	1.14	0.0035	4.248

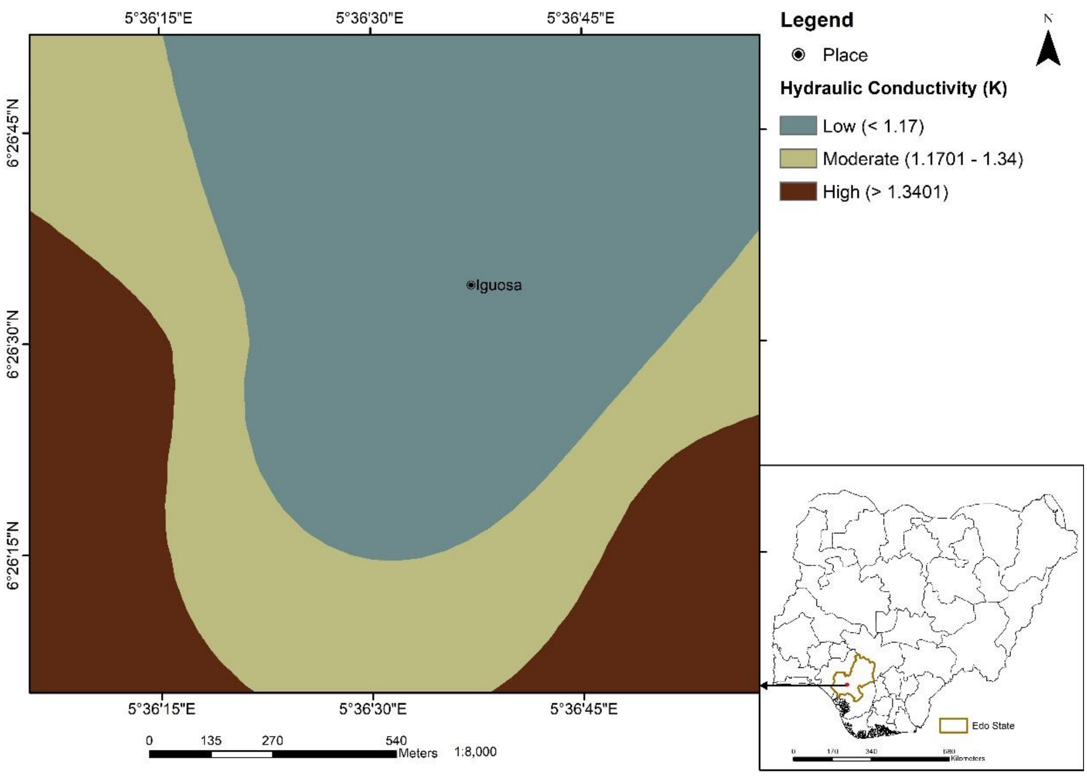

Figure 13: Spatial Distribution of Hydraulic Conductivity within the study area

3.4.3 Transverse resistance

The transverse resistance of any subsurface geological formation is a product of resistivity and thickness. It is used to delineate the most prolific area of groundwater potential for hydrological investigations. Transverse resistance determines the properties of the resistive layers (Yungul, 1996). A geologic formation reflecting a predominantly high transverse resistance values indicates that its resistivity is high, or it has thickness with presumably favorable aquifer conditions (Okiongbo and Akpofure 2012). The results of Transverse resistance as shown in Table 4 and 5 revealed that transverse resistance values for VES 1 ranged from 400.82 – 112,752.3 Ωm^2 with an average of 26621 Ωm^2; Transverse resistance for VES 2 ranged from 238.95 to 253,441.7 Ωm^2 with an average of 62439.44 Ωm^2. The transverse resistance for VES 3 ranged from 459.55 to 614377.7 Ωm^2 with an average of 148201.96 Ωm^2. VES 4 varying from 247.73 to 753,666.2 Ωm^2 with an average and that of 221682 Ωm^2 and that of VES 5 varies from 26.61 to 133,715.3 $\Omega m^2$with average of 34766.96 Ωm^2. According to (Ezeh, 2012) transverse resistance below 200,000Ωm^2 indicates inadequate aquifer thickness. The Transverse resistance of the aquiferous units were (112752.3, 53954.22 Ωm^2, 122809.3 Ωm^2, 132399 Ωm^2 and 133715.3 Ωm^2). These values of transverse resistance implies that the thickness of each aquiferous units is inadequate or represents the mixing of finer sediments with coarse materials thus, indicating low groundwater potential (Ezeh, 2012; Kwami *et al.,* 2019). These values were lower than those reported by Ojeaga and Totor (2024) in their investigation in Iyowa community but higher than 3888.06 Ωm^2 reported by Akinseye *et al.,* (2022). Thus, it is assumed that the aquifer may likely have low transmissivity with poor groundwater potentials. However, the spatial map of transverse resistance as presented in Figure 15 indicates that the southern region depicted by the blue color (>120,000) have a higher transverse resistance than the northern region depicted by pale purple color. The central area depicted by dark purple represents area of moderate transverse resistance (60,000-120,000). The hydrological implication is that higher groundwater yield is likely to occur in the southern region.

3.4.4 Transmissivity

Transmissivity is controlled by the thickness of the specific layer and the presence of fine/clay particles. It is measured in m^2/day. The values of transmissivity recorded in the study area is presented in Table 4 and 5. Transmissivity values in VES 1 ranged from 1.32 to 22.62 with mean of 7.67m^2/day, while mean values for VES 2,3,4 and VES 5 were 6, 2.72, 2.43 and 9.3 m^2/day respectively. However, the transmissivity of each aquiferous layer in geophysical sounding conducted within the study area as presented in Table 6 are in accordance with a study by Offodile, (1983) which indicates that 40% of the VES exhibited low aquifer potentials in VES 1 and VES 2, 5 while 60% of the VES show very low potentials in VES 3 and 4. This was inconsistent with the findings of Ojeaga and Totor (2024) and Ojeaga and Osauzou (2024) who reported high transmissivity in their area of study. Spatial map of the study area showing variation in transmissivity values is presented in (Figure 16). It showed a transmissivity value of < 3.5 m^2/day depicted by light blue color occurs from northwestern region to eastern zone. While transmissivity values > 5.7m^2/day depicted in pink color occupy the southwest area, values ranging from 3.501 to 5.7 m^2/day, depicted in green, extend from northwest to the west-southwestern zone. While transmissivity values > 5.7m^2/day depicted by pink color occupy the southwest area the transmissivity value from 3.501-5.7 was depicted by green color trends from northwest to west - southwestern area. The pattern of transmissivity suggests the area is controlled not only by variability in permeability of lithologic units but also by geological structures or topographic features that influence aquifer thickness and groundwater flow. Hence, it implies that the wells in the western area have potentials for high yield.

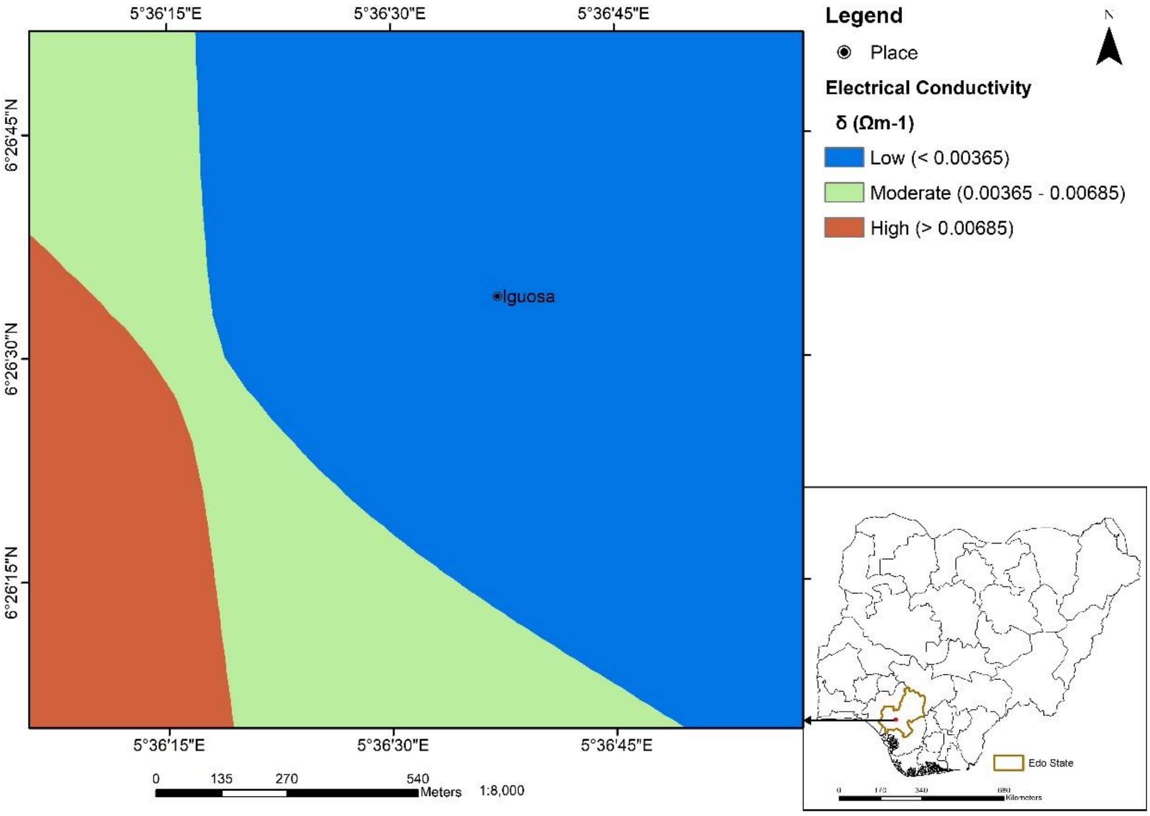

Figure 14: Spatial Distribution of Electrical Conductivity within the study area

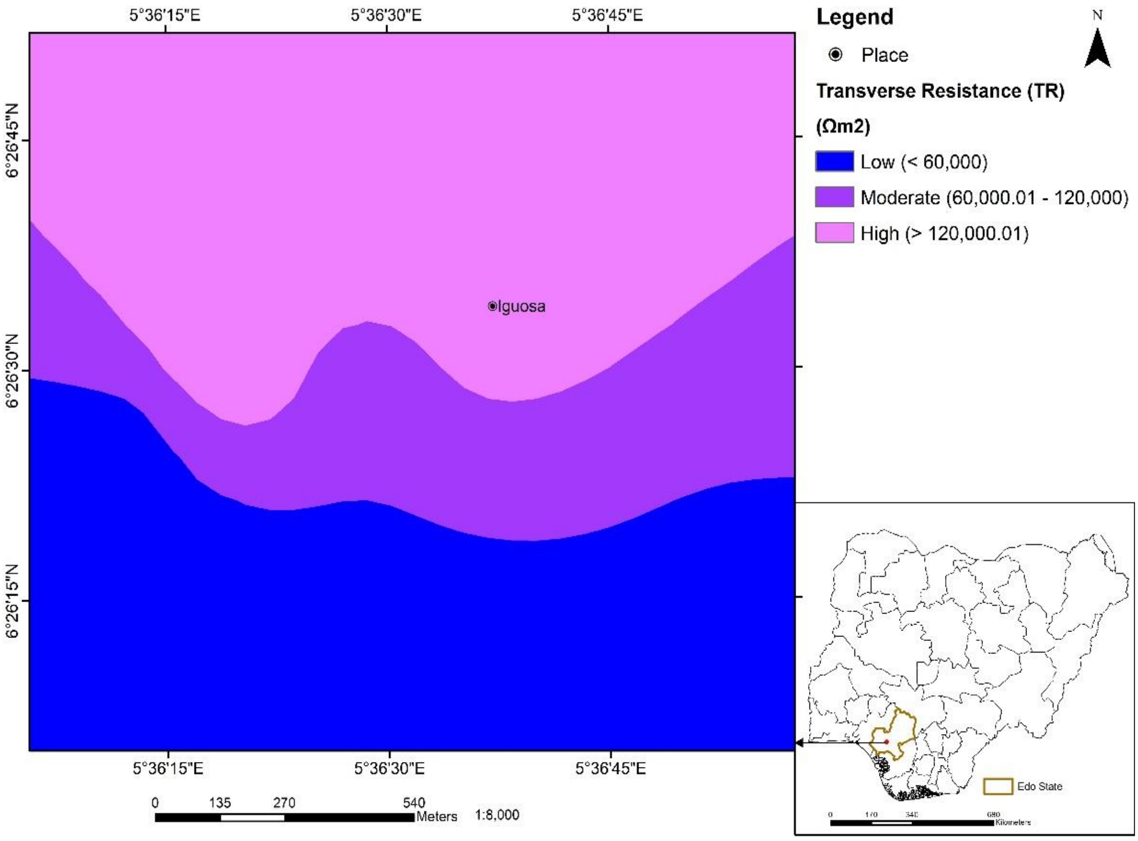

Figure 15: Spatial Distribution of Transverse Resistance within the study area

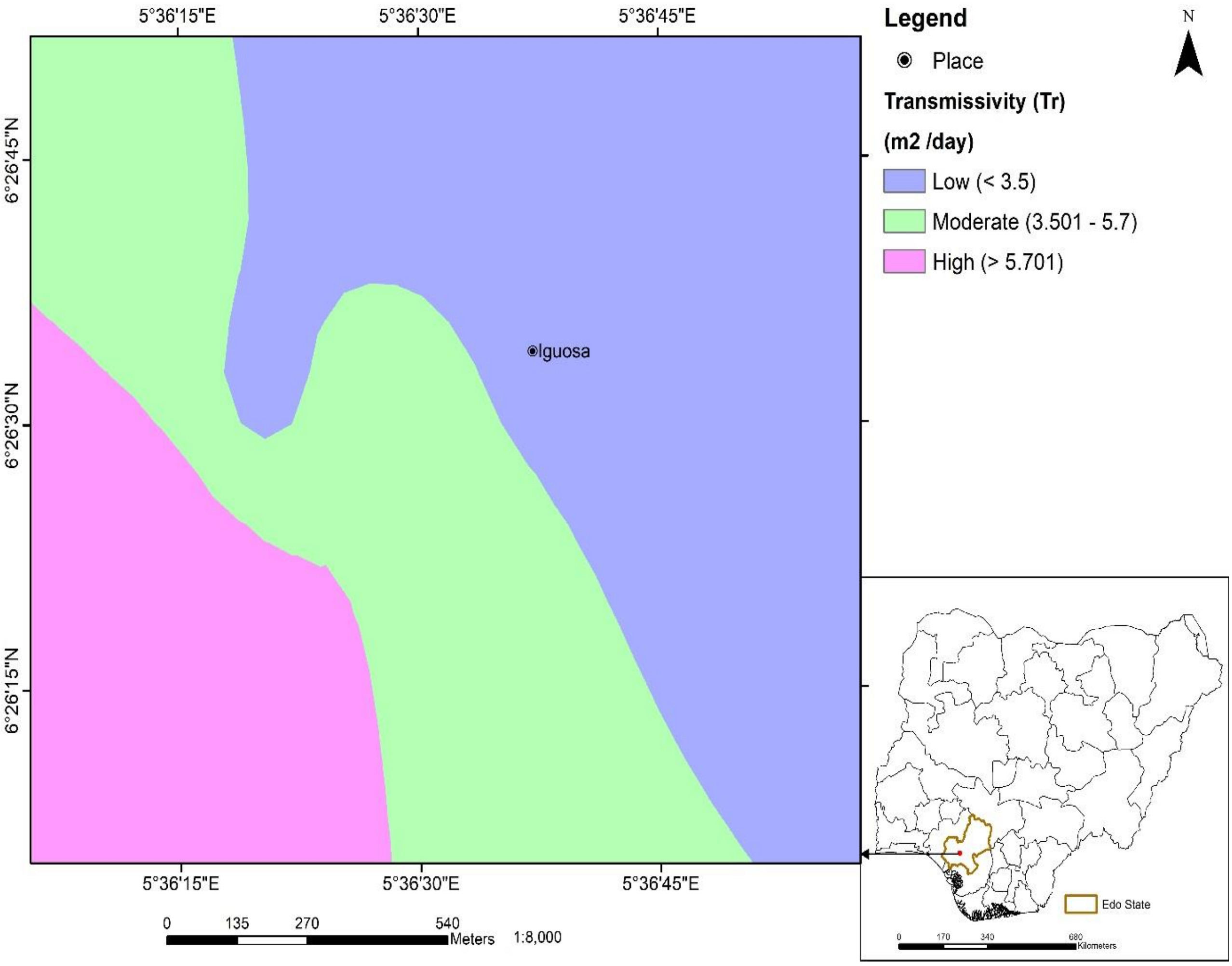

Figure 16: Spatial Distribution of Transmissivity within the study area

3.4.5 Longitudinal conductance (Aquifer protective capacity)

The protective capacity of the aquifer was evaluated using the values of longitudinal conductance and in accordance with the protective capacity rating established by Oladapo and Akintorinwa (2007) (see Table 4 and 5). The values of longitudinal conductance in the study area ranged from 0.0025 to 0.0402 Ω with an average of 0.0322 Ω as presented in Table 3. It revealed that in the study area only 20% (VES 1) exhibited moderate protective capacity, 80% (VES 2, VES3, VES 4, and VES 5) have poor protective capacity. These values shows that the protective capacity of the aquifer units/system in the entire study area was poor. Thus, the aquifers are not likely to be protected/ shielded from percolating contaminated fluids. This finding is consistent with Omali and Arogundade (2022) and Ojeaga and Osauzou (2024) who reported poor aquifer protective capacity in their investigations and in contrast with Kwami *et al.* (2019) and Ojeaga and Totor (2024) that reported that 50% of VES had good to moderate aquifer protective capacity. The spatial map (Figure 17) indicates that the longitudinal conductance in the area generally was low (< 0.0967) occupying a part of the northwest, and the entire eastern region. Moderate longitudinal conductance trends from north-central to southern region. Higher values of longitudinal conductance > (0.213) were observed in the western part of the study area. The variation in the spatial distribution pattern of longitudinal conductance suggests that the aquifer protective capacity is low, thus indicating the vulnerability or susceptibility of groundwater to contamination within the area of study which could be attributed to the absence of impermeable materials such as clay that could aid natural attenuation.

Therefore, it can also be inferred that groundwater from boreholes and wells within the study location are susceptible to contamination due to absence of natural filters/barriers to percolation of leachates derived from the overlying dumpsites. This may be attributed to the absence of sufficient thickness of fine materials that could have acted as natural filters and barriers to the infiltrating leachates (Kwami *et al.*, 2019).

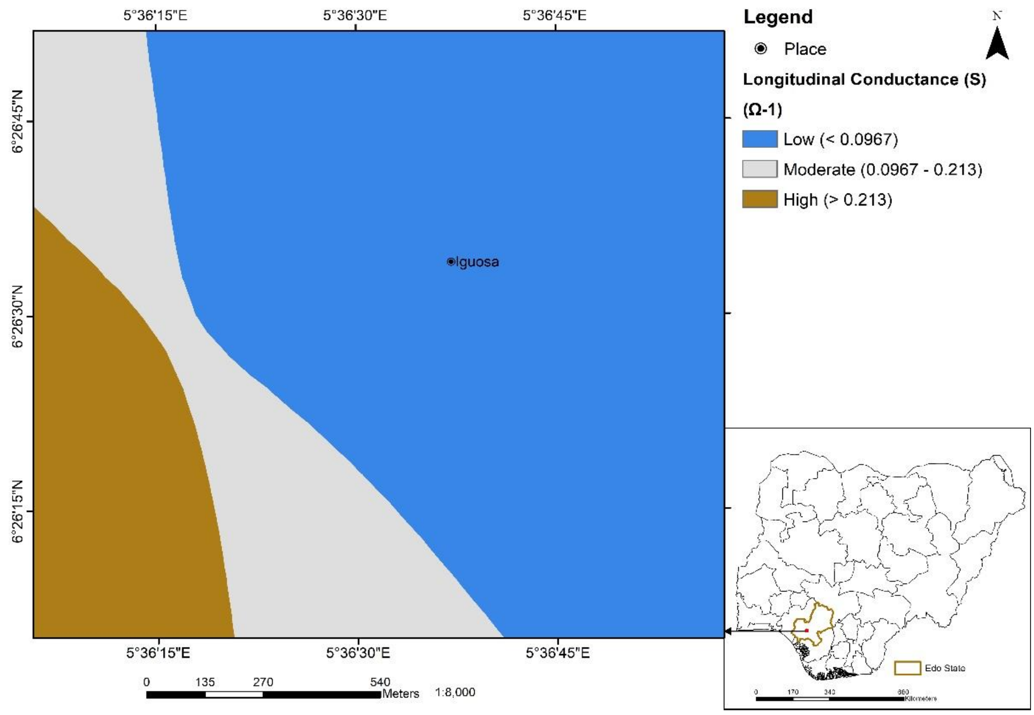

Figure 17: Spatial Distribution of Longitudinal Conductance within the study area

4. Conclusion

The VES conducted in the study area revealed five (5) to six (6) geoelectric layers. The geoelectric curves were AHA, AHK, HAK and AAK types. The variation of the geoelectric curve confirms the heterogeneity of the Benin Formation. This studies further underscores the importance of integrating VES data with borehole lithologic logs and pumping tests to adequately delineate productive groundwater zones and reduce borehole failure in the area. This study has shown that creation of unauthorized dumpsites is an anathema to clean portable water which is crucial for the overall health of the people. The findings from transmissivity and transverse resistance in this study revealed low groundwater potential and attributed same to inadequate thickness of the aquiferous units. The aquifer systems (medium to coarse grained sand) delineated in the area of study might allow movement of fluids (groundwater) through its matrix due to their fairly large grains and interconnectivity. The longitudinal conductance shows that the aquifer protective capacity is poor and may likely contribute to groundwater contamination. The spatial distribution of Dar-Zarrouck parameters indicates that transmissivity and hydraulic conductivity is high in the southwestern region reflecting the heterogeneity of the subsurface lithologies. The spatial distribution trend of longitudinal conductance showed that the aquifer in the area have poor aquifer protective capacity. The continuous presence of the clusters of dumpsites in the area, pose serious existential threat to groundwater quality in the locality. Residents are advised to consult a team of environmental and hydro-geologist for well development. However, in order to validate some of the claims stated above; It is important that the hydro chemical composition of groundwater in the area be characterized in order to make informed decisions about its pollution status. The vertical and lateral extent of contaminant plumes using dipole- dipole techniques also need to be investigated in order to identify or established potential zones of pollution in the area of study. It is also important to investigate the direction of groundwater flow in order to understand/ decipher areas fit for proper siting of landfills and groundwater development. Therefore, it can also be inferred that groundwater from boreholes and wells within the study location are susceptible to contamination due to absence of natural filters/barriers to percolation of leachates derived from the overlying dumpsites. This may be attributed to the absence of sufficient thickness of fine materials that could have acted as natural filters and barriers to the infiltrating leachates (Kwami *et al.,* 2019).

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