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Geoelectric Investigation of Aquifer Potentials and Vulnerability at Ughelli Niger Delta Region of Nigeria

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Abstract:
The aquifer's susceptibility and protective capacity were assessed in this study using the Vertical Electrical Sounding (VES) approach. A Schlumberger design with a maximum electrode spacing of 200 m was used to conduct a 26 VES survey for the investigation. The basic geo-electric parameters were utilized to classify groundwater across the study area into different categories of vulnerability to pollution sources by utilizing the spatial distribution of Longitudinal Conductance (*S*). The longitudinal conductance (S), transverse unit resistance (TR), transverse resistance (ρt), longitudinal resistance (ρL), hydraulic conductivity (K), and transmissivity (T) were calculated using primary geo-electric characteristics, such as resistivity, thickness, and depth observed. Deduction revealed that the value for the aforementioned parameters ranges from 0.002 to 3462.3 mhos, 0.00 to 315909.6 ohm, 0.00 to 7551.4Ω/m^2, 0.18 to 40583.9, 0.058 to 31008070m/day, and 0.00 to 5.26 × 10^{-53} m^2/day respectively. Further findings obtained from VES data suggested that the layer model ranges from 2 to 7 layers. It was observed that curve HK was the dominant curve type with 39% when compared to other curve types. Findings from S revealed that aquifer protective capacity ranges from poor to excellent category and the southwest (SW), and southeast (SW) part of the study area with high S value showed the area with high aquifer protective capacity when compared to other parts of the study area. The findings of this study can be used as a guide for making decisions on groundwater abstraction and management.

Keywords: Resistivity, Dar-Zarrouk, Sounding, Layer, Thickness.

Introduction:

Geoscientists have recently expressed worry about determining the vulnerability of aquifers. Due to climate change and other causes that tend to disrupt the environment and lower the quality of water resources, a significant portion of the human population on Earth depends on groundwater for various purposes. According to Eyankware et al. (2023), contamination of groundwater reservoirs occurs readily and through a sluggish process, which is terrible. Since preventing aquifer contamination is seen as a crucial component of managing groundwater resources, aquifer vulnerability analysis becomes essential within the field of groundwater research. A variety of methods have been employed to assess groundwater risk, including the vertical electrical sounding (VES) method. A multitude of hydrological and hydrogeophysical problems have been effectively solved by researchers using the VES technique (Aleke et al. 2018; Akakuru et al. 2021a; Eyankware et al. 2020a, b, 2021; Oli et al. 2020) because, in comparison to other geophysical technologies, it is inexpensive, simple to use, and produces data quickly. In order to determine the protective capability of the overburden units, longitudinal conductance—a second-order geoelectric parameter—was used in earlier research on aquifer vulnerability (Aweto, 2011; Eyankware et al. 2020b; Akintorinwa and Olowolafe 2013). Groundwater studies have made extensive use of the VES method, which analyzes measured apparent resistivity field data to determine groundwater feature, aquifer geometry, aquifer vulnerability, and the depth to the water table (Eyankware 2015; Eyankware and Aleke 2021; Aziz et al. 2018; Akakuru et al. 2021b). Understanding the spatial distribution of aquifer geometry and aquifer protective capacity parameters was shown to be aided by the Dar Zarrouk parameters obtained from surface geoelectric soundings (Oli et al. 2020; Eyankware et al. 2020a, b; Nwosu et al. 2014). The vulnerability of Nigeria's aquifers in sedimentary and hard rock terrain has also been assessed using the VES approach (Eyankware et al. 2022; Umayah and Eyankware 2022; Eyankware and Aleke 2021; Ebong et al. 2016; Akpan et al. 2013, 2014). It is generally agreed upon that vulnerability assessment studies can provide information to regulators and enhance groundwater quality monitoring. Aquifer vulnerability is also known as aquifer sensitivity to various pressures, such as geogenic and anthropogenic activities, according to Eyankware et al. (2022a). The first method for determining whether an aquifer would be exposed to pollution was to measure its vulnerability. Aquifer vulnerability, according to Eyankware and Umayah (2022), is a relative evaluation of how susceptible a groundwater resource is to pollution as a result of specific human activities. According to Eyankware et al. (2020), vulnerability assessment is a reliable method for identifying regions where contamination from human activity is most likely to occur. As per Balal (2015), safeguarding aquifers from pollution is a crucial aspect of managing groundwater resources. In a similar vein, the scientific evaluation of aquifer vulnerability is a crucial component that provides us with groundwater resource protection options. Aquifer vulnerability approaches are developed by scientists and management to identify the most vulnerable places when they realize that an effective plan is needed to safeguard groundwater resources from contamination (Eyankware et al., 2020; Opara et al., 2022). The theory underlying the concept of groundwater vulnerability is that the physical environment may offer some degree of protection against the effects of nature, particularly with regard to the entry of toxins into the subsurface environment (Eyankware, 2019). The southeast region of Nigeria is experiencing a groundwater pollution issue. For example, the states of Imo, Ebonyi, and Enugu have already seen severe groundwater contamination as a result of both geogenic and anthropogenic activity (Akakuru et al., 2021a, 2021b; Eyankware & Akakuru, 2022; Eyankware et al., 2021). The primary sources of the pollutants are industrial wastewater, landfill leachate, and septic tank overflow. Therefore, the goal of the research is to assess the groundwater potential and susceptibility to contamination from surface sources by looking at the hydrogeophysical and aquifer vulnerability of the groundwater system in the southern part of the Niger Delta Basin.

Location, climate, and Accessibility
As seen in Fig. 1, the study location is located between latitude 5˚ 26'N to5˚ 32'N and longitude 6˚ 25'E to 6˚ 40'N , with high average annual precipitation of roughly 1900 mm and elevation of 280 m. The average yearly temperature ranges from roughly 22˚C to 34˚C, with 1,501 mm to 1850 mm of rainfall and 1117 mm of evapotranspiration (FME, 2001; Akpoborie, et al., 2011). As stated by Olabaniyi and colleagues (2006). The study region ranges in elevation from less than 6 meters above sea level (SL) in the lowlands that border the sea to more than 280 meters above SL in the plateau that delineates the state's northern border. The research area is in a tropical zone with two distinct seasons: the wet and the dry. The month of April through October is the wet season, and November through March is the dry season. Every year, there is typically more than 3000 mm of rainfall, a high of 28˚C, and 80% humidity (Iloeje, 1981). Typically, the vegetation is mangrove swamp forest, but due to substantial human alteration from farming, logging, and exploration, grassland has frequently taken the place of the original vegetation.

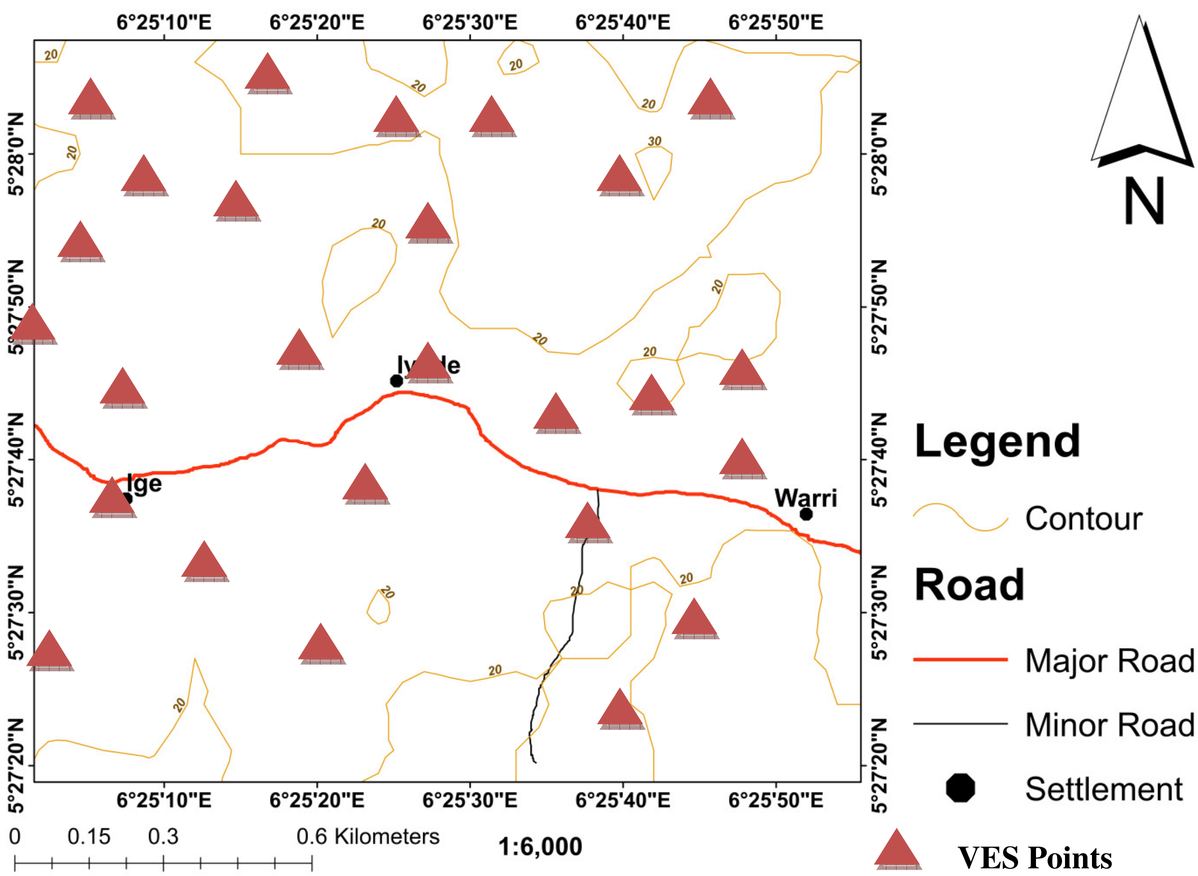

Fig. 1: Topographic map of the study area.

Geology of the area

The study area is characteristically underlain by the Niger Delta formations sequence, which comprises of the Benin, Agbada and Akata Formations. Ughelli is directly underlain by the Somebreiro-Warri Deltaic Plain sands, which is the top of the Benin Formation. The geology of the Niger Delta have been studied and well documented by several authors (Allen, 1965; Reyment, 1965; Short and Stauble, 1967; Weber and Daukuro, 1975). Studies show that the Somebreiro - Warri Deltaic Plain sand is Quaternary to Recent has and a thickness of about 120 m (Wigwe 1975). The sediments are unconsolidated in texture and vary from fine plastic clay through medium - coarse grain sand that are sometimes gravelly. Predominantly, the Benin Formation consists of unconsolidated sand, gravel and occasionally intercalation of shale. It is the main source of freshwater in the Niger Delta region and with about 2000 m thick ranging from Oligocene to Pleistocene in age.

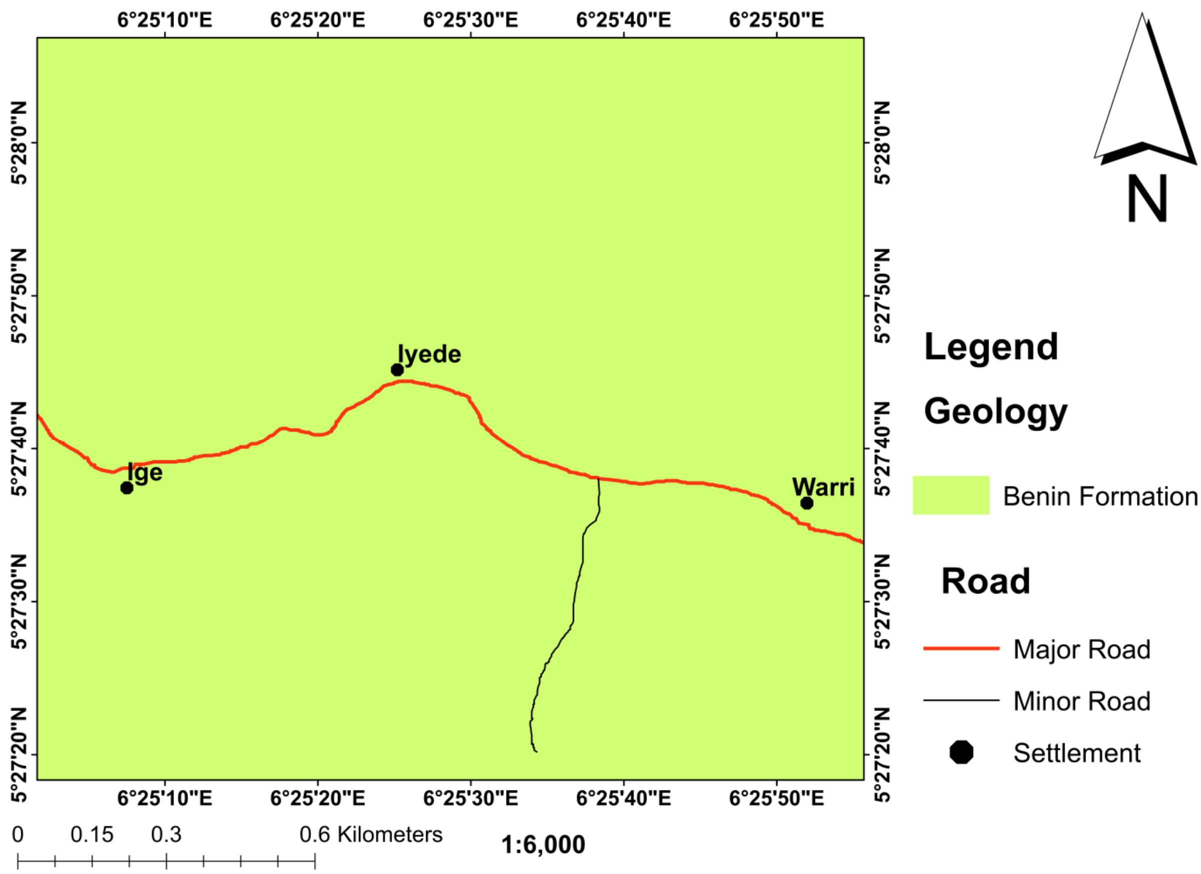

Fig. 2: Geology of the study area.

Methodology

Geoelectric measurement

Twenty six (26) VES were conducted within the study area, as shown in Fig. 1, with the help of an Abem Terrameter SAS 4000, and its accessories. For each VES profile, a Schlumberger electrode array was used with a maximum half current (AB/2) electrode separation of 100 m and a half potential (MN/2) electrode separation of 5 m. Surfer software was used to map the spatial distribution of S, Tr, ρL, and ρt. The following Eq. (1) was used to convert the observed feld data to apparent resistivity (a) values:

$$\pi\left(\frac{\left(\frac{AB}{2}\right)-\left(\frac{MN}{2}\right)}{MN}\right)\Delta V/I \qquad (1)$$

The geoelectrical curves were generated by plotting the apparent resistivity data against the current electrode spacing(AB/2). The data processing was aided by the use of IX1D software, which allowed for the creation of sound curves. 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 corresponded to the geoelectric section. For the analysis and comprehension of the geologic model, some factors linked to the different combinations of thickness and resistivity of the geoelectric layer are crucial (Zohdy et al. 1974; Maillet 1947). Dar Zarrouk's longitudinal (*S*) and transverse (*T*) parameters were derived via:

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

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

Using the formula below, we determined the total Longitudinal Unit Conductance (S).

The total longitudinal conductance is equal to the number of layers (n).

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

as proposed by Asfahani (2013); Oli et al. (2020)

For the equation below, the Transverse Unit Resistance (Tr) was determined.

The total resistance of the transverse unit is

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

as proposed by Oli et al. (2020); Nwachukwu et al. (2019)

Below is the average longitudinal resistance for a given VES points

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

as proposed by Suneetha and Gupta (2018).

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

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

as proposed by Suneetha and Gupta (2018).

Equation 8 can be used to define the coefficient of anisotropy, a useful characteristic of an anisotropic media that shows the degree of fracturing.

$$\lambda = \sqrt{\frac{\rho_t}{\rho_L}} = \frac{\sqrt{ST}}{H} \quad (8)$$

When interpreting sounding data, the parameters T and S—transverse resistance and longitudinal conductance, respectively—are crucial. The Dar-zarrouk parameters are those that are displayed in Equations 1 through 5.

Results and Discussion

Table 1 shows the results of the interpreted VES survey.

S/N	Number of Layers (m)	Resistivity (Ohm-m)	Thickness (m)	Depth (m)	Curve type		
VES 1	1	181.76	1.6611	1.6611	HK		
	2	47.911	2.3993	4.0604			
	3	64.83	2.676	6.7370			
	4	622.75	10.236	16.973			
	5	251.30	150.58	167.55			
	6	151.34	221.37	388.92			
	7	18.188					
VES 2	1	2560.4	1.000	1.000	HK		
	2	1226.8	3.500	4.500			
	3	1299.0	5.500	9.500			
	4	2801.7	10.500	15.000			
	5	2076.4	75.000	94.500			
	6	380.59	294.50	294.50			
	7	21.123					
VES 3	1	3307.9	0.870	0.8702	HK		
	2	1294.9	6.86	7.7323			
	3	2735.1	38.37	46.106			
	4.	888.65					
VES 4	1	907.94	1.1509	1.1509	HKQ		
	2	223.33	7.1035	8.2544			
	3	5117.0	2.2361	10.491			
	4	31.868	25.809	36.300			
	5	246.01					
VES 5	1	8.4306	2.5674	2.5674	A		
	2	35393					
VES 6	1	207.94	5.3408	5.3408	A		
	2	137.06	4.5703	9.9112			
	3	0.2584	27.662	37.573			
	4	352.99					
VES 7	1	171.70	1.967	1.96	HK		
	2	42.337	1.27	3.244			
	3	82.096	5.42	8.665			
	4	17671	0.543	9.21			
	5	164.09	34.531	43.74			
	6	237.00					
VES 8	1	121.74	0.923	0.9233	HK		
	2	1.37	0.0608	1.5323			

	3	186.12	6.717	8.2501			
	4	22.532	61.089	69.339			
	5	36.287					
VES 9	1	270.01	1.850	1.8503	HKH		
	2	46.295	6.61	8.4656			
	3	150.32	73.211	81.677			
	4	21.009	439.00	520.68			
	5	2079.9					
VES 10	1	1072.9	13.765	13.765	A		
	2	0.309					
VES 11	1	241.12	1.6263	1.6263	HKH		
	2	68.866	4.4298	6.0561			
	3	6817.8	1.0474	7.103			
	4	68.866	83.195	90.299			
	5	2622.4					
VES 12	1	274.62	1.472	1.4724	KQ		
	2	1053.5	2.2208	3.69332			
	3	421.71	9.59984	13.292			
	4	1227.6	14.844	28.136			
	5	128.60	81.037	109.17			
	6	227.98					
VES 13	1	137.45	2.6205	2.6205	HK		
	2	92.437	5.155	7.7762			
	3	152.11	36.156	43.932			
	4	44.940					
VES 14	1	137.45	2.6205	2.6205	HK		
	2	92.437	5.1557	7.7762			
	3	152.11	36.156	43.932			
	4	44.940					
VES 15	1	1263.1	3.143	3.1435	Q		
	2	41602	2.678	5.8221			
	3	1105.5					
VES 16	1	80.023	2.5665	2.5665	H		
	2	24.717	15.954	18.520			
	3	5917.7					
VES 17	1	78.383	0.2333	0.2333	HA		
	2	723.01	1.3999	1.6332			
	3	30.986	3.5975	5.2307			
	4	28021					
VES 18	1	69.17	0.2611	0.26118	HA		
	2	594.82	1.3794	1.6406			
	3	26.259	3.7714	5.4120			
	4	23015					
VES 19	1	98.181	0.13566	0.13566	Q		
	2	994.38	0.8958	1.0315			
	3	388.03					
VES 20	1	19.381	0.4903	0.4903	HA		
	2	92.522	6.773	7.264			

	3	126.30	61.750	69.014			
	4	297.41					
VES 21	1	0.9642	0.33548	0.33548	HA		
	2	3.0448	0.174	0.3528			
	3	72.377	11.632	11.985			
	4	131.21					
VES 22	1	200.07	4.4055	4.4055	Q		
	2	113.54					
VES 23	1	29414	0.7998	0.79982	QA		
	2	272.15	77.807	78.607			
	3	15675					
VES 24	1	235.22	0.96760	0.96760	AH		
	2	847.67	1.5584	2.5260			
	3	76.204	2.366	4.8926			
	4	374.13	3.2509	8.1435			
	5	15487	7.7489	15.892			
	6	0.915	715.60	731.50			
	7	30.722					
VES 25	1	76.985	0.2181	0.2181	HA		
	2	1089.4	1.4051	1.6232			
	3	37.376	1.3313	2.9544			
	4	263.68	1.7817	4.7360			
	5	0.10755	372.37	377.10			
	6	871.09	249.53	626.63			
	7	21.641					
VES 26	1	193.90	0.5416	0.5416	HA		
	2	1756.9	0.9722	1.5139			
	3	64.609	2.9833	4.4972			
	4	490.44	20.371	24.868			
	5	41274	359.62	384.49			
	6	1352.7	233.54	618.03			
	7	22.409					

Table 2: Estimated result of parameters.

VES	Longitudinal Unit Conductance (S)	Transverse Unit Resistance (Tr)	Transverse Resistivity(ρ_t)	longitudinal resistance (ρ_L)	Hydraulic Conductivity (m/day)	Transmissivity (m^2/day)
1	0.116931	6374.469	375.5653	1432.894	4.765098403	0.006217603
2	0.011225	29417.85	1961.19	8418.509	31008074.25	325584779.6
3	0.019589	104945.8	2276.185	2353.614	19196493.46	736569454.2
4	0.031807	11442.12	1090.661	1141.251	5×10^{14}	1.20177E-17
5		0	0		0.0538	0
6	107.4146	0	0	0.349794	0.683209445	0
7	0.107474	9595.353	1041.841	406.9833	9.6×10^{53}	5.2649E+53
8		0	0		0.0538	0
9	21.53247	0	0	40583.91	171578.8468	0
10		0	0		0.0538	0
11	1.279294	0	0	70.58502	8527426.62	0
12	0.030232	18222.49	647.6576	930.6623	371.0134028	5507.322952
13		0	0		0.0538	0
14		0	0		0.0538	0
15	0.002552	0	0	2281.099	154.0255023	0
16	0.677539	0	0	27.33423	2×10^{17}	0
17	0.121013	0	0	43.22412	$2.\times 10^{86}$	0
18	0.149717	0	0	36.14822	5×10^{70}	0
19		0	0		0.0538	0
20	0.587417	0	0	117.4871	0.457888391	0
21		0	0		0.0538	0
22		0	0		0.0538	0
23	0.285925	0	0	274.9221	6×10^{47}	0
24	0.04569	120007.2	7551.423	347.826	1×10^{47}	1.11336E+48
25	3462.343	217363.1	346.8763	0.180984	28.484674	7107.780703
26	0.09977	315909.6	511.1557	6194.523	913.2029894	213269.4261

Dar Zarrouk parameter of the study area

Longitudinal unit conductance (*S*), transverse unit resistance (Tr), average longitudinal resistance (ρL), and transverse resistivity (ρt). The results are obtained from primary resistivity parameters such as resistivity thickness and depth using Eqs. (2–8). The calculated results are presented in Table 1.

Longitudinal unit conductance (*S*)

Longitudinal conductance can help to define the degree of groundwater protection from vertical infiltration of pollutants (Akinseye, et al., 2023). It is the conductance in the direction. It is the conductance in the direction of the bedding plane through a column of 1 m. It is denoted by *S* (Nwanko et al. 2011). Oladapo and Akintorinwa (2007) and Henriet, (1976) stated that geologic formations with longitudinal conductance greater than 10 Ω-1 can be rated to have excellent aquifer protective capacity, while formations with (5–10) Ω^{-1} are rated very good, formations with (0.7–4.9) Ω^{-1} are rated good, formations with (0.2–0.69) mhos are moderate, formations with (0.1–0.19) mhos weak and formations with less than 0.1 Ω^{-1} are poor. For this study S value ranges from 0.002552 to 3462.343 mhos see Table 2, and Fig. 3. Findings from Table 3, revealed that VES 2, 3, 4, 12, 15, 24, and 26, VES 1, 7, 11, 17, and 18 fell within the poor and weak category respectively. Hence considered to be prone to contamination from the surface. Similarly, study conducted elsewhere in Delta State by Umayah and Eyankware, (2022) stated the major source of groundwater contamination in Delta state is attributed to anthropogenic activities, most parts of Delta state is underlie by sandstone could be attributed to major cause of aquifer contamination. Further findings from Table 3, revealed that VES 16, 20, and 23 fell within the moderate, hence to be moderately prone to contamination from the surface. Lastly VES 6, 9, and 25 fell within the excellent category hence considered not to be prone to surface contamination. We assume that the aforementioned area categorize to be excellent is underlie by clayey soil.

Table 3: Based on Oladapo and Akintorinwo's (2007) longitudinal conductance scale, modified aquifer protective capacity rating of the investigated formation (Henriet 1976)

Longitudinal conductance (mhos)	Protective capacity Rating	VES Points
>10	Excellent	VES 6, 9, 25,
5-10	Very Good	
0.7-4.9	Good	
0.2-0.69	Moderate	VES 16, 20, 23
0.1-0.19	Weak	VES 1, 7, 11, 17, 18,
< 0.1	Poor	VES 2, 3, 4, 12, 15, 24, 26

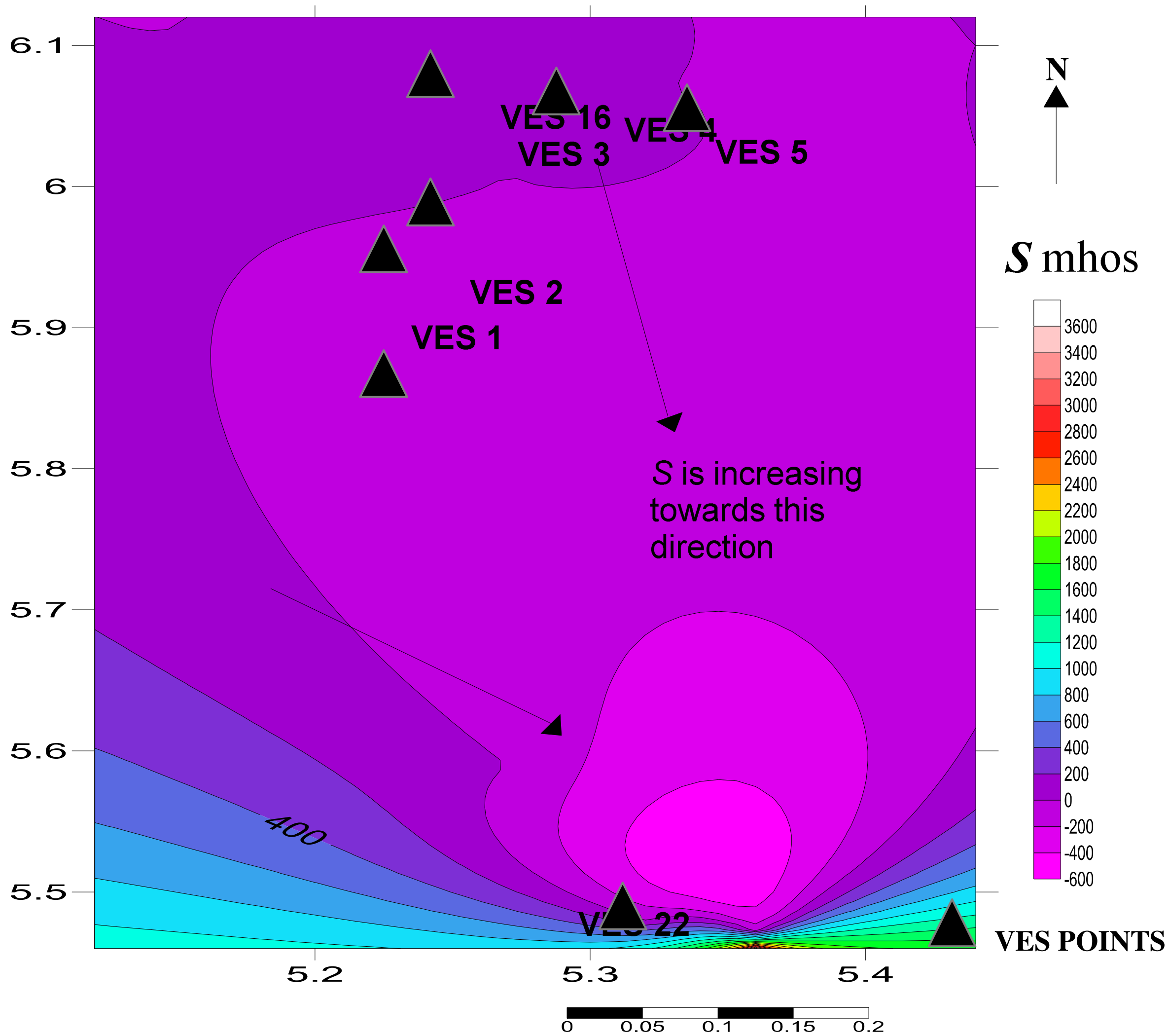

Fig. 3: Spatial distribution of *S* in 1D.

Transverse unit resistance (*Tr*)

It is used to delineate the most prolific area of groundwater potential for hydrogeological investigation (Nafez et al. 2010; Eyankware et al. 2022). Longitudinal conductance determines the properties of the conducting layers, while transverse resistance determines the properties of the resistive layers (Yungul 1996). *Tr* is strongly related to transmissivity. According to Eyankware and Aleke (2021), larger *Tr* values usually represent higher aquifer transmissivity values. For this study the values of *Tr* ranges from 0 to 315909.6 as shown in Table 2, with the highest value observed that VES 26. Areas with high *Tr* tends to be a good source of groundwater potential (aquiferous). Fig. 4, suggested that SE, and NW parts of the study area has high *Tr* values that implies that the aforementioned area has high groundwater potentials.

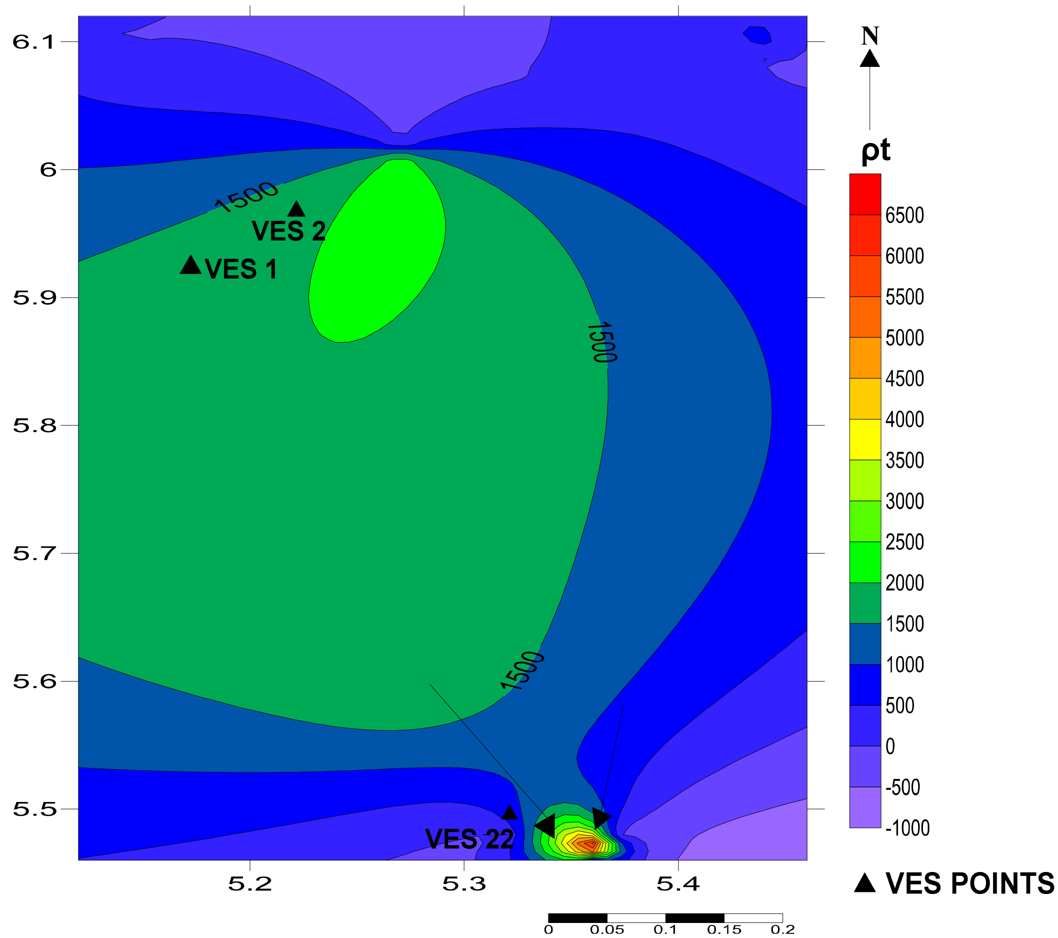

Fig. 4: Spatial distribution of *Tr* in 1D.

Average longitudinal resistance (ρL)

According to George (2021), the longitudinal resistance helps to assess the rate at which aquiferous units could be prone to infiltration. He stated further that ρL can help to determine the direction of conductivity with depth due to its sensitivity to geologic units. Deduction from Fig. 5, revealed that ρL increases towards selected parts of NE, NW, NE, and SE of the study area. The aforementioned areas could be said to be prone to contamination, deduction from Table 2, suggested that ρL ranges from 0.180984 to 40583.91Ω-m^2 as shown in Table 2. In the same vein, Fig. 5. Figure 5 showed that the spatial variation of longitudinal resistance with contour interval demarcates the saline, brackish, and freshwater aquifers into three different regions based on their varying resistivity regimes (Gupta et al, 2015; Eyankware, et al., 2020).

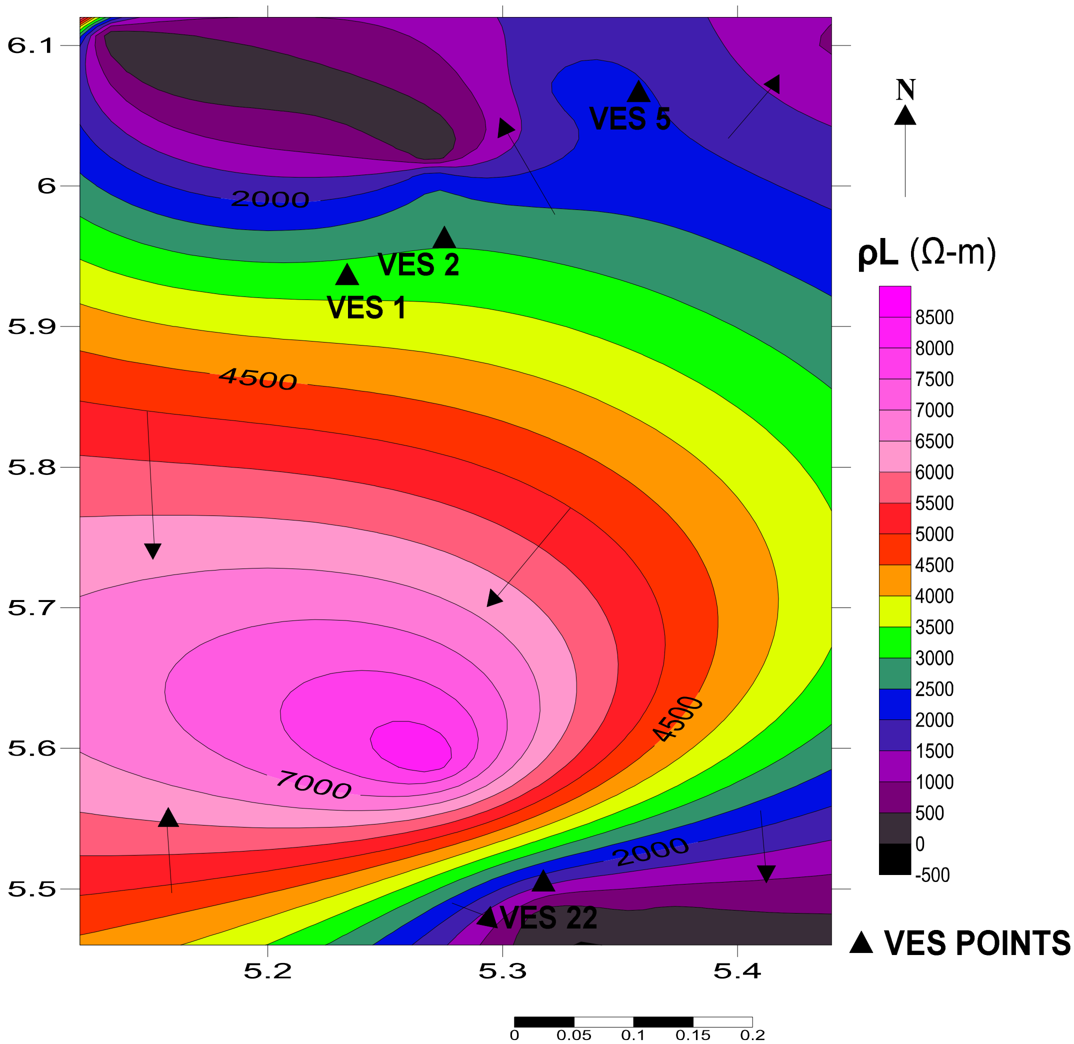

Fig. 5: Spatial distribution of ρL in 1D.

Transverse resistivity (ρt).

Fig. 6, revealed that ρt value ranges from 0 to 7551.423. From Fig. 6, it was observed that the ρt increases towards SE, and NW parts of the study area. This implies that the true resistivity is normal to the plane of stratification like shale, is greater than true resistivity is parallel to the plane of stratification (Dewashish, et al. 2014).

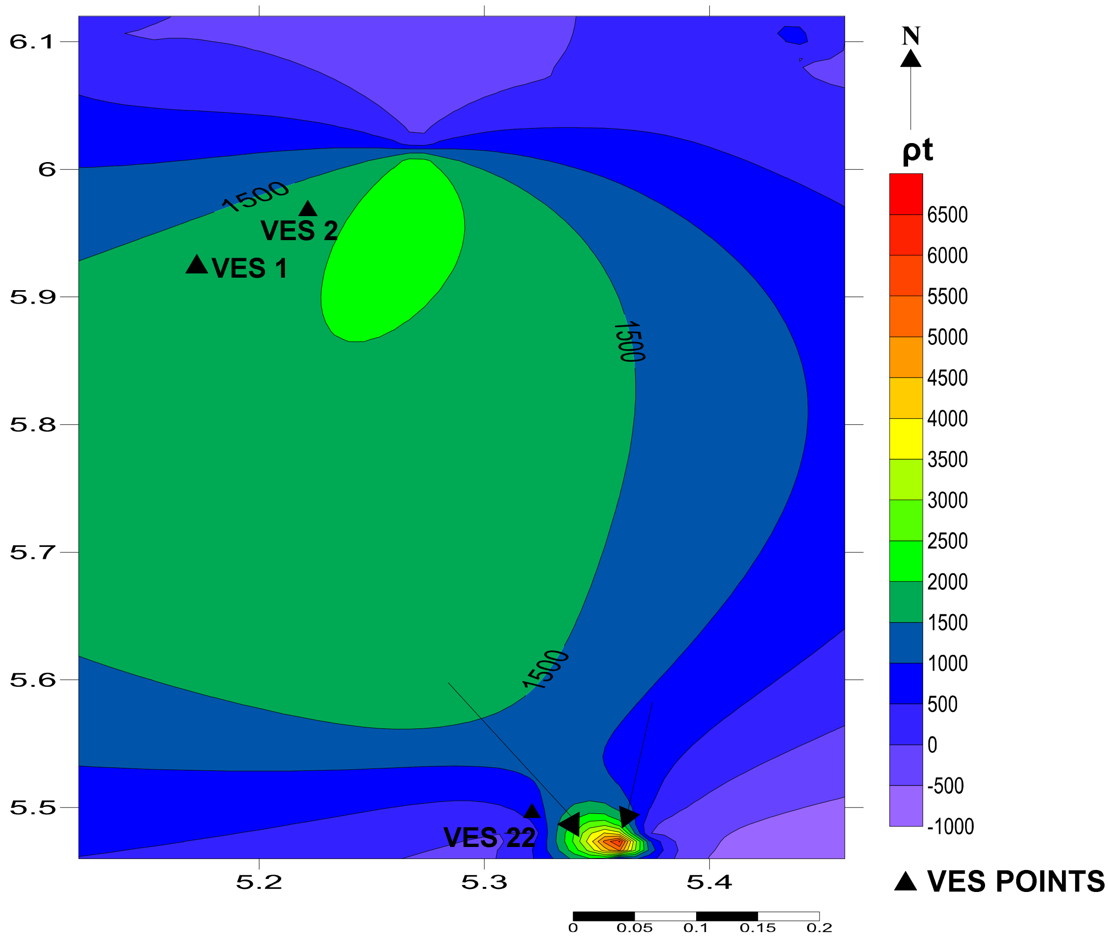

Fig. 6: Spatial distribution of ρt in 1D.

Hydraulic conductivity (K)
The hydraulic conductivity of pore fluid determines how easy it can escape the compressed pore space (Obasi, et al., 2022). 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 (Opara, et al., 2022). From Table 2, it was observed that K ranges from 0.0538 to 8527426 m/day. Findings from Fig.7, showed that the selected parts of SW of the study has high K values when compared to other parts of the study area

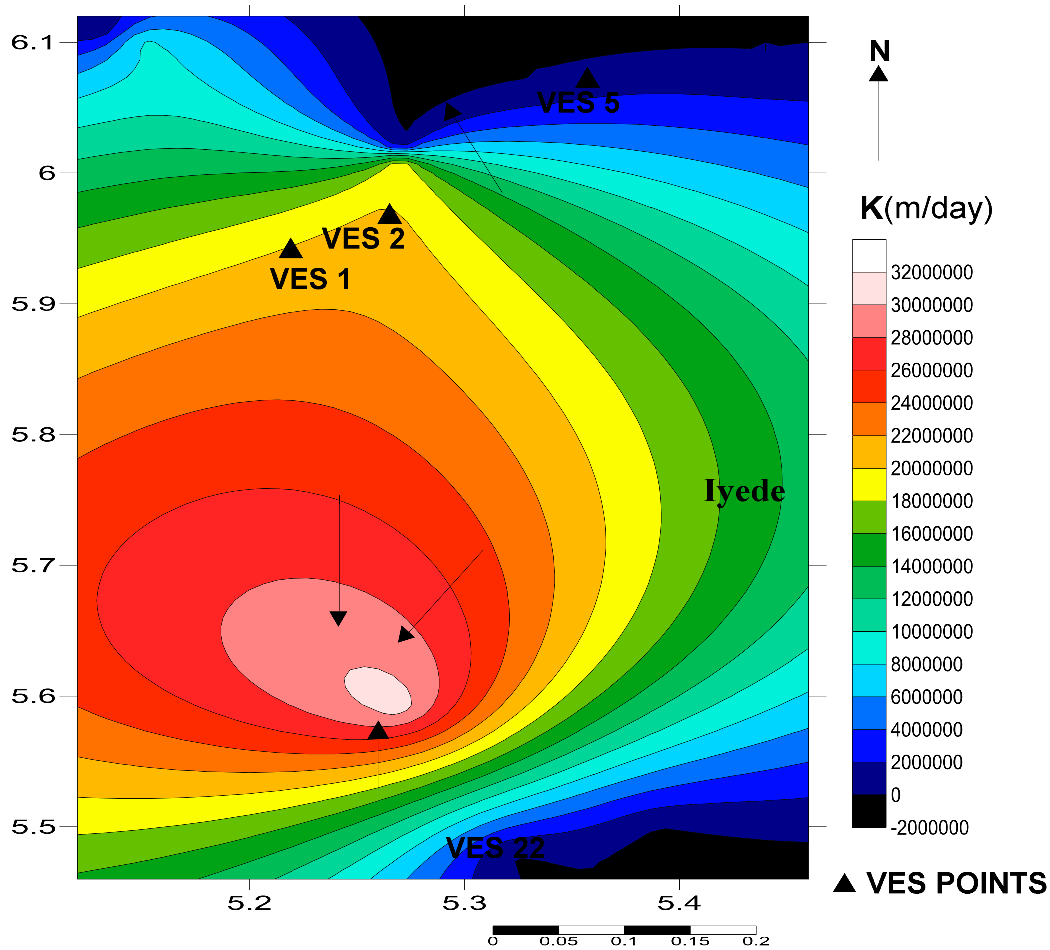

Fig. 7: Spatial distribution of K in 1D.

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 (Umayah and Eyankware, 2022). From Table 2, it deduced that T values ranges from 0.00 to 736569454.2 m^2/day.

Conclusion

For this research, sections of Ughelli and its environs Niger Delta region of Nigeria, were the subject of geophysical investigations for aquifer vulnerability. Geoelectric parameters, such as longitudinal unit conductance, transverse unit resistance, average longitudinal resistance, and transverse resistivity, hydraulic conductivity, and transmissivity were generated using the VES data from the study. From the study the following conclusion were drawn:

1. Deduction from longitudinal conductance suggest that 78.3 % fell within the weak and poor category, hence the area is said to be prone to contamination from the surface. While 10.85 % of the research area fell within the moderate category, which implies that area is moderately prone to surface contamination. Lastly, 10.85 % fell within the excellent, this area is considered to free from surface contamination, such area is believed to be underline by clay.

2. Findings from *Tr* revealed that selected parts of southeast part of the study area is considered to show high tendency of water bearing units when compared to other parts of the study area.

3. Results obtained from ρL showed that selected parts of the study area such as of NE, NW, NE, and SE of the study area. Findings from the study revealed that there is variation aquifer type.

4. Deduction from ρt suggested that highest ρt values was noticeable area around selected parts of SE axis of the study area. This implies that the true resistivity is normal to the plane of stratification like sand, is greater than true resistivity is parallel to the plane of stratification (Dewashish et al., 2014).

5. Findings from K, showed that selected portion of the SW, and NW parts of the study area has high K values when compared others parts of the study area. Further deductions from transmissivity revealed that the value of the T ranges from 0.00 to 736569454.2 m^2/day.

In conclusion, larger percentage of the study area is prone to surface contamination this could be due to the fact that the study area is underlie by sand. Based on the fact that sand is porous, permeable is allow inflow of leachate. The findings of the present study have therefore helped to delineate vulnerability of the study area.

References

Asfahani J (2013) Groundwater potential estimation using vertical electrical sounding measurements in the semi-arid Khanasser Valley region, Syria. Hydrol Sci J 58:468–482

Allen, J.R.L., 1965. Late Quaternary Niger Delta and adjacent areas: sedimentary environments and lithofacies. Bull .AAPG 49, 547–600.

Akinseye, V.O., · Osisanya, W.O., Eyankware, M.O., Korode, I.A.., Ibitoye, A.T. (2023). Application of second-order geoelectric indices in determination of groundwater vulnerability in hard rock terrain in SW. Nigeria. Sustainable Water Resources Management. 9:169, https://doi.org/10.1007/s40899-023-00936-w

Akpoborie, I. A., Nfor, B., Etobro, A. A. I., Odagwe, S. (2011). Aspects of the geology and groundwater conditions of Asaba, Nigeria. Archives of Applied Science Research, 1. 3(2):537- 550.

Akakuru OC, Akudinobi B, Opara AI, Onyekuru SO, Akakuru OU (2021a) Hydrogeochemical facies and pollution status of groundwater resources of Owerri and environs, Southeastern Nigeria. Environ Monitor Assess 193:623.
https://doi.org/10.1007/
s10661-021-09364-9

Akakuru OC, Akudinobi BE, Nwankwoala HO, Akakuru OU, Onyekuru SO (2021b) Compendious evaluation of groundwater in parts of Asaba, Nigeria for agricultural sustainability. Geosci J. https://doi.org/10.1007/s12303-021-0010-x

Akpan AE, Ugbaja AN, George NJ (2013) Integrated geophysical, geochemical and hydrogeological investigation of shallow groundwater resources in parts of the Ikom-Mamfe Embayment and the adjoining areas in Cross River State, Nigeria. J Environ Earth Sci, 70:1435–1456

Akpan AE, Ebong DE, Ekwok SE, Joseph S (2014) Geophysical and geological studies of the spread and industrial quality of Okurike Barite deposit. Am J Environ Sci 10(6):566–574

Aleke CG, Ibuo JC, Obiora DN (2018) Application of electrical resistivity method in estimating geohydraulic properties of a sandy hydrolithofacies: a case study of Ajali Sandstone in Ninth Mile, Enugu State, Nigeria. Arab J Geosci 11:322. https://doi.org/10.1007/s12517-018-3638-8

Akpoborie, I. A., Nfor, B., Etobro, A. A. I., Odagwe, S. (2011). Aspects of the geology and groundwater conditions of Asaba, Nigeria. Archives of Applied Science Research, 3(2):537- 550

Dewashishe K, Rai SN, Thiagarajan S, Kumari YR (2014) Evaluation of heterogeneous aquifers in hard rocks from resistivity sounding data in parts of Kalmeshwar Taluk of Nagpur District, India. CurrSci 107:1137–1145

Ebong DE, Akpan AE, Emeka CN, Urang JG (2016) Groundwater quality assessment using geo-electrical and geochemical approaches: case study of Abi area, south-eastern Nigeria. Appl Water Sci. https://doi.org/10.1007/s13201-016-0439-7

Etu – Efeotor, J.O., Akpokodje, E.G. (1990). Aquifer systems of the Niger Delta Jour. Min. Geol. 26 (2), 279–284.

Eyankware MO, Selemo AOI, Obasi PN, Nweke OM (2020a) Evaluation of groundwater vulnerability in fractured aquifer using geoelectric layer susceptibility index at Oju Southern Benue Trough Nigeria. Geol Behav 4(2):51–55. https://doi.org/10. 26480/gbr.02.2020.51.55

Eyankware MO, Ogwah C, Selemo AOI (2020b) Geoelectrical parameters for the estimation of groundwater potential in fracture aquifer at Sub-Urban Area of Abakaliki, SE Nigeria. Int J Earth Sci Geophys 6:031. https://doi.org/10.35840/2631-5033/1831

Eyankware MO, Ogwah C, Umayah OS (2021) Integrated geophysical and hydrogeochemical characterization and assessment of groundwater vulnerability in Adum West Area of Benue State, Nigeria. J Geol Res 65:6588128. https://doi.org/10.30564/jgr.v3i3.3197

Eyankware MO (2015) Estimation of Aquifer Parameters Using Geoelectrical sounding in Ochudo City, Abakaliki Ebonyi State Southeastern Nigeria. 27th Annual Nigerian Association of Hydrogeologists Conference.

Eyankware MO (2019) Integrated Landsat Imagery and Resistivity Methods in Evaluation of Groundwater Potential of Fractured Shale at Ejekwe Area, Southeastern Nigeria, Unpublished PhD Thesis

Eyankware MO, Aleke G (2021) Geoelectric investigation to determine fracture zones and aquifer vulnerability in southern Benue Trough southeastern Nigeria. Arab J Geosci. https://doi.org/10.1007/s12517-021-08542-w

Eyankware, M.O., Akakuru, O. C., Osisanya, W. O., Umayah, S. O., Ukor, K. P. (2023). Assessment of heavy metal pollution on groundwater quality in the Niger Delta Region of Nigeria. Sustainable Water Resources Management (2023) 9:189. https://doi.org/10.1007/s40899-023-00955-7

Eyankware, M.O., Akakuru, C. O., Eyankware, E.O. (2022a). Hydrogeophysical delineation of aquifer vulnerability in parts of Nkalagu areas of Abakaliki, SE. Nigeria. Sustainable Water Resources Management, https://doi.org/10.1007/s40899-022-00603-6.

Federal Ministry of Environment .FME. (2001). Guidelines and standards for water quality in Nigerian Publication, 2001. 1-114). Abuja: FME.

George NJ (2021) Modelling the trends of resistivity gradient in hydrogeological units: a case study of alluvial environment. Model Earth Syst Environ. https://doi.org/10.1007/s40808-020-01021-3

Gupta G, Patil SN, Padmane ST, Erram VC, Mahajan SH (2015) Geoelectric investigation to delineate groundwater potential and recharge zones in Suki River basin, north Maharashtra. J Earth Syst Sci 124(7):1487–1501

Henriet JP (1976) Direct application of Dar Zarrouk parameters in groundwater survey. Geophys Prospect 24:344–353

Kearey P, Brooks M, Hill I (2002) An introduction to geophysical exploration, 3rd edn. Blackwell Science Ltd Editorial Ofces, Oxford

Loke MH (1999) A practical guide to 2D and 3D surveys. In: Electrical imaging surveys for environmental and engineering studies. Course note, vol 1, pp 8–10

Maillet R (1947) The fundamental equations of electrical prospecting. Geophysics 12(4):529–556. https://doi.org/10.1190/1.14373

Nafez H, Kaita H, Samer F (2010) Calculation of transverse resistance to correct aquifers resistivity of groundwater saturated zones: Implication for estimated its hydrogeological properties. Leban Sci J 11(1):105–115

Nwachukwu SR, Bello R, Ayomide O, Balogun AO (2019) Evaluation of groundwater potentials of Orogun, South-South part of Nigeria using electrical resistivity method. Appl Water Sci 9:184. https://doi.org/10.1007/s13201-019-1072-z

Nwanko C, Nwasu L, Emujakporue G (2011) Determination of Dar Zarrouk parameters for assessment of groundwater potential: case study of Imo State, southeastern Nigeria. J Econ Sustain Dev 2:57–71

Nwosu L, Nwankwo C, Ekine A (2014) Delineating aquifer systems using Dar Zarouk parameters determined from surface geoelectric survey: case study of Okigwe District, Southeastern Nigeria. Br J Appl Sci Tech 4(34):4751–4770

Obasi PN, Ekinya EA, Eyankware MO (2022) Reliability of geophysical techniques in the evaluation of aquifer at Igbo-Imabana, Cross River Sate, Nigeria using electrical resistivity method. Water Resour J 32(1):105–121

Oladapo MI, Akintorinwa OJ (2007) Hydrogeophysical study of Ogbese, southwestern. Niger Glob J Pure Appl Sci 13(1):55–56

Olobaniyi, S. B., Ogban, F.E., Ejechi, B.O., Ugbe, F.C.(2007). Quality of groundwater In Delta State, Nigeria. Journal of Environment and Hydrology, 2007a. 15(1);1-10

Oli IC, Ahairakwem CA, Opara AI (2021) Hydrogeophysical assessment and protective capacity of groundwater resources in parts of Ezza and Ikwo areas, southeastern Nigeria. Int J Energ Water Res 5:57–72. https://doi.org/10.1007/s42108-020-00084-3

Opara, A. I. , Edward, O.O. I. , Eyankware, M. O., Akakuru, O. C., Oli, I. C., Udeh, H. M. (2022). Use of geo-electric data in the determination of groundwater potentials and vulnerability mapping in the southern Benue Trough Nigeria. International Journal of Environmental Science and Technology https://doi.org/10.1007/s13762-022-04485-1.

Opara, A. I., Ireaja, A. N., Eyankware, M. O., Urom, O. O., Ikoro, D. O., Akakuru, O. C., Dioha, E., Omoko, N. E. (2023). A critical analysis of the comparative techniques of aquifer protective capacity studies in part of Southeastern Nigeria. International Journal of Energy and Water Resources. https://doi.org/10.1007/s42108-023-00251-2

Iloeje, N.P. (1981). A New Geography of Nigeria. Longman, Nigeria.

Short, K. C., & Stauble, J. (1967). Outline of Geology of Niger Delta, the America Association of petroleum. *Geologist Bulletin, 51*(5), 761–779.

Suneetha N, Gupta G (2018) Evaluation of groundwater potential and saline water intrusion using secondary geophysical parameters: A case study from western Maharashtra India. E3S Web Conf 54:00033. https://doi.org/10.1051/e3sconf/20185400033

Umayah OS, Eyankware MO (2022) Aquifer evaluation in southern parts of Nigeria from geo-electrical derived parameters. World News Nat Sci 42:28–43

Wigwe, G.A. (1975). The Niger Delta: physical. In: Ofomata, G.E.K. (Ed.), Nigeria in Maps: Eastern States. Pp380 - 400. Ethiope Publ. House, Benin City.

Weber, K. Daukoru, J., E. (1975). Petroleum geology of the Niger Delta: 9th World Petroleum Congress Proceedings 2, 209-221.
Yungul SH (1996) Electrical methods in geophysical exploration of sedimentary basins. Chapman & Hill, London

Zohdy AAR, Eaton GP, Mabey DR (1974) Application of surface geophysics to groundwater investigations. United State Geophysical Survey, Washington