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Depiction of Aquifer Potential and Vulnerability Mapping: A Case Study of Delta North, Southern Part of Nigeria, Using Geophysical Approach

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ABSTRACT

In order to identify the aquifers, characterize their geometric properties, and determine their susceptibility to contamination by surface contaminants, a detailed hydrogeophysical investigation of the aquifers of the study area was conducted. The study area was subjected to fifteen (15) vertical electrical soundings (VES) with a Schlumberger array configuration with a maximum electrode separation of 200 m. Curve matching methods and iterative computer modeling were combined to process the VES data. Parameters estimated are aquifer thickness, longitudinal conductance (S), transverse unit resistance (*Tr*), average longitudinal resistance (ϱL), aquifer conductivity (Ω^{-1}), hydraulic conductivity (K), and transmissivity (T), and their corresponding estimated values, which vary across the study area, range from 1.63 to 103.83 m, 0.02 to 0.05, 0 to 122169.9 ohms, 0 to 3406.4, 0.000037 to 0.001126, 0.0538 to1.13×10^{23}m^2/day, 0 to 1.85×10^{23}m^2/day, respectively. Deductions from *S.* revealed that the study area is prone to contamination from the study. Further findings from groundwater modeling, hydraulic conductivity, and transmissivity suggested that the southwestern part of the study area showed more groundwater prospects when compared to other parts of the study area. Within the study, it was observed that curve Q is the most dominant curve within the study area.

Keywords: Aquifer, Vertical, Schlumberger, Vulnerability, Resistance, Depth.

1. INTRODUCTION

In order to manage groundwater resources, it is necessary to evaluate their quality, particularly in relation to human health. In 2015, the UN General Assembly ratified Sustainable Development Goal 6 (i.e., ensuring availability and sustainable management of water and sanitation for everyone), which states that freshwater is essential for human health and societal development (Jialiang, et al., 2021). Within a locality, the distribution of freshwater resources varies significantly depending on time and place. As a result, it is challenging to get alternate freshwater sources, such as groundwater and surface water. It is possible to explore groundwater using hand-dug wells and boreholes (Eyankware, et al. 2018; Esi, et al., 2025). VES is a powerful method because it is a reliable and simple process for groundwater investigations. Electrical resistivity is a property of rock that is affected by lithology and fluid volume. Similarly, the electrical resistivity method is used to determine the depth of bedrock, the nature of the surface deposit, and structural mapping. The limits of the aquifer as well as zones with significant yield potential have been located. The electrical resistivity method is the most widely used geophysical technique in foundation and sedimentary terrain (Umayah and Eyankware, 2022; Eyankware and Umayah, 2022) employed a multi-electrode resistivity profiling array for groundwater. This method was also employed by Opara, et al., (2022) to picture the distribution of electrical properties in hydrogeological and dam site investigations. Omosuyi, et al., (2008) used this method to identify two shallow aquifer units in the Okitipupa region of southwest Nigeria's coastal plain. Many aquiferous units are known to be present in the sedimentary sequences of the study area and the Niger Delta Basin in Nigeria.

Groundwater recharging in the region is comparatively good due to the high annual average rainfall of about 1900 mm (Eyankware and Ephraim, 2021). However, due to poor design and a lack of technical geo-scientific investigations to understand the area's complicated geology, a number of boreholes in the research area are ineffective. The inadequate understanding of aquifers (including the geometry and nature of their hydraulic boundaries) that has been applied to the problem makes it worse. The nature and distribution of the aquifers inside the Niger Delta Basin have not been established systematically or thoroughly, despite the fact that several boreholes have been sunk there (Eyankware, et al., 2021; Aleke, et al., 2018). The evaluation of these aquifers' susceptibility to pollution from surface sources is extremely important, in addition to the requirement for quantitative descriptions of their geometric and hydraulic features. This is important because, over time, urbanization, population increase, and other related problems have led to a decline in groundwater quality in the research area, which has been exacerbated by inadequate waste management practices. Similar to this, the construction of new buildings and mini- factories, along with a few other medium-sized businesses, may have led to a rise in migration in the Asaba area and a greater demand for potable water, both of which could have a detrimental effect on the groundwater in the study area. Therefore, effective groundwater management and utilization depend on pollution prevention. The inability to effectively monitor the groundwater system due to spatial variability and data limitations makes cleanup efforts expensive and unsuccessful in developing nations, most notably Nigeria. Aquifer vulnerability research is essential in the field of groundwater study since it is believed that preventing aquifer contamination is a key component of managing groundwater resources. The determination of groundwater vulnerability has been done using several methods, one of which is the vertical electrical sounding (VES) technique. Numerous academics have solved a variety of hydrological and hydrogeophysical problems using the VES approach (Aleke, et al., 2018; Akakuru, et al., 2021; Adegboyega, et al., 2024; Eyankware, et al., 2020a; Eyankware, et al., 2020b; Eyankware and Aleke, 2021; Bayode, et al., 2016). Based on the fact that, in comparison to other geophysical approaches, it is simple to use, inexpensive, and straightforward to get the findings that it produces. Previous studies on aquifer susceptibility have employed longitudinal conductance, a second-order geoelectric parameter, to assess the protective capacity of the overburden units (Akintorinwa and Olowolafe, 2013;Aweto, 2011). The VES method has been widely used in groundwater exploration to evaluate the groundwater feature, aquifer shape, aquifer vulnerability, and depth to the water Table by analyzing measured apparent resistivity field data (Adetola and Igbedi, 2000; Aziz, et al., 2018). Several studies have shown that the Dar Zarrouk parameters, which are derived from surface geoelectric soundings, are essential for understanding the geographic distribution of protective capacity parameters and aquifer geometry (Akinseye, et al., 2023; Esi, et al., 2025; Eyankware and Aleke, 2021).

Additionally, the VES technique has been used to estimate the aquifer's susceptibility in Nigeria's hard rock and sedimentary region. In study conducted by Waramate, (2016), hydrological qualities were determined by estimating Dar Zarrouk parameters using data from the VES technique. According to the study's findings, the aquifer was thought to be extremely prolific, with resistivity values above 1000 m, and it was thought to be susceptible to pollution due to its high groundwater potential. In certain regions of Akwa Ibom, Niger Delta, the aquifer was located using the Dar Zarrouk criteria. The findings indicated that the high permeability in the aquiferous layer and the high aquifer output make the area vulnerable to contamination (Laouini, et al., 2017). In other areas of the Niger Delta Basin in Nigeria, groundwater contamination and aquifer protective capacity have been evaluated using geochemical and geophysical methods (Ibuot, et al., 2013; Egwebe, et al., 2024), but little to no research has been done within the study area and its surrounding areas to ascertain these factors. As a result, determining the research area's aquifer's capability for protection requires a careful analysis. This research is aimed at determining the aquifer protective capacity of the study area from VES data and is also used to infer the area of groundwater potential within the study area. In order to identify the aquifers, and determine their susceptibility to contamination from surface contaminants.

Location of Study Area

The study area lies within latitude 6˚ 8ˊ00ˊˊN - 6˚ 16ˊ00ˊˊN and longitude 6˚ 40ˊ0ˊˊE - 6˚ 48ˊ0ˊˊE (Fig. 1). Numerous small streams originating from various sources encircle the study area, indicating that it is located on a rock. The hills of the plateau and the River Niger are the dominant features of the Asaba region. Because of these gently sloping easterly slopes, Asaba can be situated in the valley and on the west bank of the Niger River. On the edge of the Asaba plateau are the cities of Okpanam and Ibusa. The plateau itself vanishes entirely to the south of Asaba. Only one, the comparatively wide Amilimocha River, meets the River Niger in Asaba town, while numerous streams that begin as springs at higher elevations crisscross the plateau slopes. The average annual temperature ranges from 220°C to 340°C, while the average annual rainfall and evapotranspiration are 1,501 mm and 1,850 mm, respectively (Olobaiyi, et al., 2007).

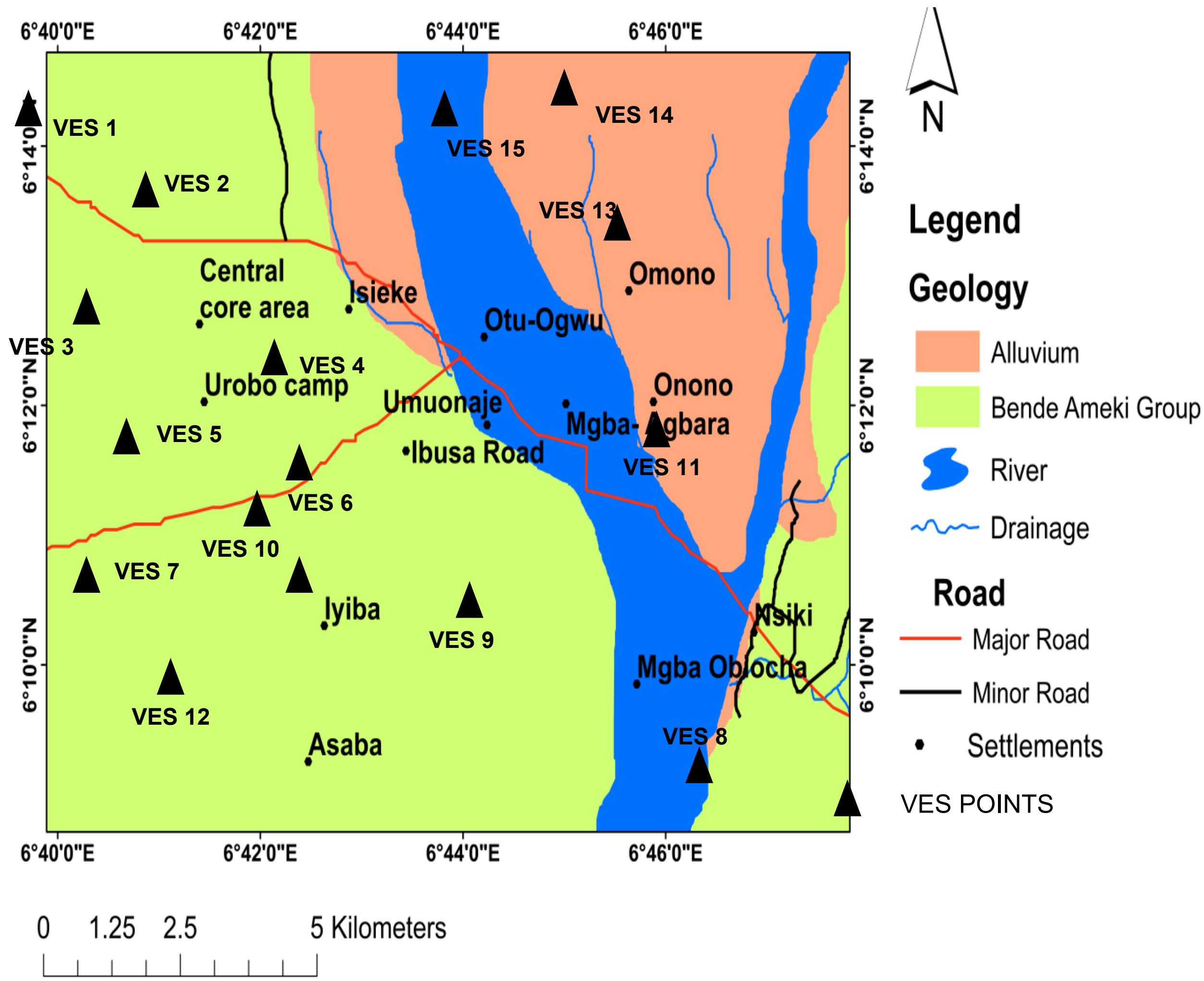

Figure 1. Geology Map of the Study Area showing VES points.

Geology of the study area

Three formations make up the basin fill: the Akata, Agbada, and Benin Formations are the oldest to youngest. Shale dominates the Akata Formation, with 10% or so sandstone (Short and Stauble, 1967; Murat, 1970). It is thought that the shale is both under- and over-compacted. The depositional environment was marine, and its age spans from the Eocene to the Recent. Underneath the Akata Formation, the Agbada Formation conformably sits above it. It is an alternating series of paralic sandstone and shale, varying in age from the Pliocene/Pleistocene in the south to the Eocene in the north and recent on the surface of the Delta (Oteri, 1990). The Eocene–

Oligocene Ameki Formation and Ogwashi–Asaba Formation are their surface counterparts. In the Asaba capital territory, the primary rock outcrops are part of the Ogwashi-Asaba formation. Comfortably sitting on the Agbada Formation is the continental Miocene-Recent Benin Formation. Its composition is roughly 10% shale/clays and over 90% sand. The sands vary in size from coarse to fine-grained sand. In addition, they have wood pieces and lignite streaks, are poorly sorted, and range in shape from sub-angular to well-rounded (Oteri and Atolagbe, 2003).

Hydrogeology of the study area

The study region includes the Niger Delta. It is not a basement complex because the majority of the ground is formed of sand and contains no rocks. There, the terrain is mainly composed of laterite and is typically stony. Although prior attempts to drill a borehole haven't always been successful due to incomplete knowledge of the hydrogeologic problems, they have been made. Among the most successful are those held at a fire department facility (Akpoborie, et al., 2011).

2. METHODOLOGY

Geoelectric measurements

The study area was the subject of fifteen (15) VES, which were carried out using an OHMEGA Terrameter and its attachments. A Schlumberger electrode array with a maximum half current (AB/2) electrode separation of 100 m and a maximum half potential (MN/2) electrode separation of 5 m was employed for each VES profile. Maps showing the spatial distribution of *S*, Tr, L, and pt were modeled using Surfer software. The measured field measurements were transformed into apparent resistivity (a) values using equation (1), which is as follows:

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

The geoelectrical curves were made by plotting the apparent resistivity values against the present electrode spacing (AB/2). The application of the IX1D program, which supported the data processing, enabled the creation of sound curves. The thickness of the aquifer was ascertained by utilizing the geoelectrical sections that were generated from the sounding curve data. Using the charts from (Kearey, et al., 2002), and (Loke,1999) lithologies that matched the geoelectric section were identified. Some elements related to the various combinations of the thickness and resistivity of the geoelectric layer are essential for the study and understanding of the geologic model (Zohdy, et al.,1974; Maillet, 1947). The longitudinal (S) and transverse (T) characteristics of Dar Zarrouk are obtained by

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

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

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

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

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

as proposed by (Opara, et al., 2022); (Eyankware and Aleke, 2021)

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 (Eyankware, et al., 2020a; Esi, et al., 2025)

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 (Akinseye, et al., 2023)

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

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

as proposed by (Suneetha N, Gupta)

Estimation of aquifer hydraulic characteristics

The hydraulic parameters of an aquifer can be ascertained using two Dar-Zarrouk metrics: longitudinal conductivity and transverse resistance. Transmittivity and transverse resistance, as well as longitudinal conductance and transmissivity, were analytically linked by (Niwas and Singhal, 1981).

From Darcy's law, the fluid discharge Q is given by

$$Q = KIA \qquad 8$$

And from ohm's law

$$J = \delta E \qquad 9$$

$$T = K\delta R = \frac{KL}{\delta} \qquad 10$$

Where T= aquifer transmissivity, R= Transverse resistance and L= longitudinal conductance

3. 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 was utilized to create curve type geoelectric layers

VES	Latitude longitude		Layer resistivity (Ohm-m)					Layer Depth (m)					Curve type	No of layer	Elevation (m)
			ϱ1	ϱ 2	ϱ 3	ϱ 4	ϱ 5	D1	D2	D3	D4	D5			
VES 01	7°17′43″N	5°9′50″E	3075.3	374.7	26414	535.1	10.35	2.50	4.02	6.24	371.0	-	HK	5	98
VES 02	7°17′43″N	5°11′56″E	3397.5	302.79	26967	287.46	30842	1.23	2.08	3.711	15.23	-	HA	5	92
VES 03	7°16′50″N	5°10′20″E	3660.1	666.40	1840.4	945.88	1.32	3.54	19.898	83.196	-	-	HK	5	90
VES 04	7°16′05″N	5°9′56″E	5855.6	622.71	2225.7	1232.0	1038.4	0.71	2.87	3.98	87.597	-	H	5	102
VES 05	7°17′00″N	5°13′45″E	3423.7	2209.6	1176.6	670.66	-	1.30	3.437	107.27	-	-	Q	3	97
VES 06	7°16′00″N	5°12′50″E	1937.5	1849.7	39.262	-	-	2.59	17.360		-	-	Q	3	93
VES 07	7°16′55″N	5°15′40″E	898.3	334.32	2.22	-	-	1.93	23.40		-	-	Q	4	94
VES 08	7°15′10″N	5°15′05″E	3406.4	1019.7	96.25	120.52	-	0.801	12.26	85.56	-	-	Q	4	94
VES 09	7°15′05″N	5°11′20″E	1274.9	840.08	1436.2	767.56	2714.8	1.25	5.16	19.76	122.20	-	HKA	5	95
VES 10	7°14′30″N	5°12′45″E	2837.4	1725.6	1854.2	1031.7	-	0.933	2.02	24.76	-	-	Q	4	97
VES 11	7°14′20″N	5°11′00″E	3095.0	1987.4	876.01	1855.3	-	2.22	20.67	71.75	-	-	QA	4	100
VES 12	7°12′58″N	5°10′15″E	1131.6	888.34	483.37	-	-	0.52	10.04		-	-	Q	4	103
VES 13	7°12′30″N	5°11′25″E	2587.6	944.1	261.49	2057.3	197.29	1.08	11.13	21.51	59.64	-	QH	5	112
VES 14	7°11′40″N	5°15′20″E	3430.4	729.7	1498.3	20.32	1906.5	4.67	9.82	69.93	503.4	-	HK	5	93
VES 15	7°13′50″N	5°14′10″E	681.2	792.69	227.5	-	-	0.59	14.59	-	-	-	Q	3	97

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

VES Points	Aquifer thickness	Longitudinal Unit Conductance (S)	Transverse Unit Resistance (Tr)	Average longitudinal resistance (ρ_L)	aquifer conductivity (Ω^{-1})	Hydraulic Conductivity (m/day)	Transmissivity (m^2/day)
VES/1	2.22	0.00487	58639.08	825.5455134	0.000038	2.11473×10^{81}	$4.69469x10^{81}$
VES/2	1.631	0.003169	43983.177	656.3052402	0.000037	1.13355×10^{83}	$1.84882x10^{83}$
VES/3	63.298	0.025514	116493.6392	779.8853875	0.00054336	30589.0747	1936227.25
VES/4	84.727	0.00359	105486.671	799.4516257	0.000578419	13701.193	1160860.979
VES/5	103.833	0.001347	122169.9078	2551.881184	0.000849907	256.9902607	26684.06974
VES/6	15.07	0.001337	27874.979	1937.5	0.000540628	32707.45093	492901.2855
VES/7			0	0		0.0538	0
VES/8	11.459	0.000235	11684.7423	3406.4	0.000980681	83.04297029	951.5893966
VES/9	14.6	0.005635	20968.52	915.7399145	0.000696282	1665.962291	24323.04945
VES/10	22.74	0.000959	42164.508	2106.914469	0.000539316	33784.52675	768260.1383
VES/11	18.45	0.000717	36667.53	3095	0.00050317	88150.26448	1626372.38
VES/12	9.52	0.00046	8456.9968	1131.6	0.001125695	32.25155271	307.0347818
VES/13	38.13	0.050758	78444.849	423.775357	0.000486074	145812.6982	5559838.183
VES/14	60.11	0.008419	90062.813	1166.402078	0.000667423	2605.23507	156600.6801
VES/15		0.00487	58639.08	825.5455134	0.000038	$2.11473 10^{81}$	$4.69469 10^{81}$
Min	1.631	0.002	0	0	0.000037	0.0538	0
Max	103.83	0.05	122169.9	3406.4	0.001126	$1.13x10^{23}$	$1.85x10^{23}$
Aver	36.75	0.010	55523.91	1413.43	0.000549	$7.84x10^{21}$	$2.23x10^{22}$

Aquifer vulnerability study of the area

Longitudinal conductance (S)

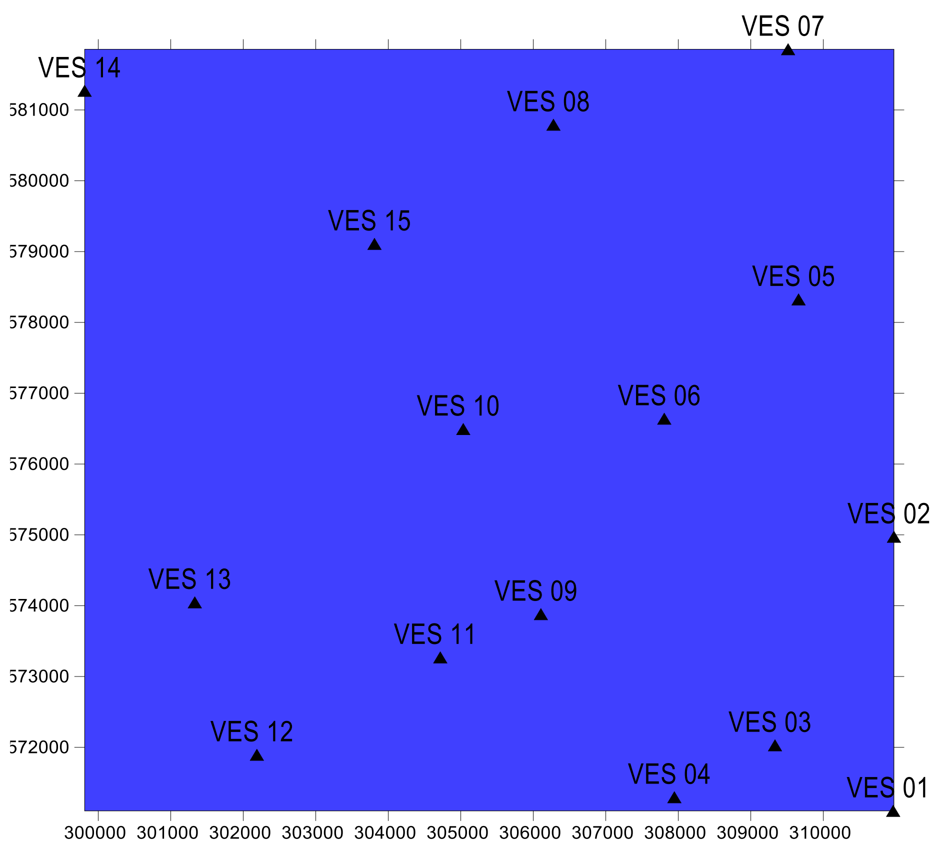

Figure 2. Spatial distribution map of the study area

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. According to Olorunfemi, et al., (1999), S is a measure of an earth medium's protective capacity that indicates how well it slows and stops percolating liquids. This characteristic usually describes the aquifer's susceptibility to pollution. A region's ability to resist damage improves with the amount of an overloaded geological formation, such as compacted sandstone, shale, or clay (Henriet, 1976; Oloruntola, et al., 2017); (Table 3). *S* values were calculated for this investigation using equations (3 and 4), and they vary from 0.00235 at VES/8 to 103.833 at VES 13. Deduction from Fig. 2 suggested that the entire study area is prone to contamination from the surface. This is in line with a previous study conducted by (Umayah and Eyankware, 2022); they were of the view that the aquifer within most parts of the Niger Delta region is considered to be sandstone that is porous and easily allows the flow of water from the surface to percolate.

Table 3: According to the longitudinal conductance scale developed by (Oladapo and Akintorinwa, 2007), the modified aquifer protective capacity rating of the studied formation (Oloruntola, et al., 2017)

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		
< 0.1	Poor	VES 1 to VES 15	100%

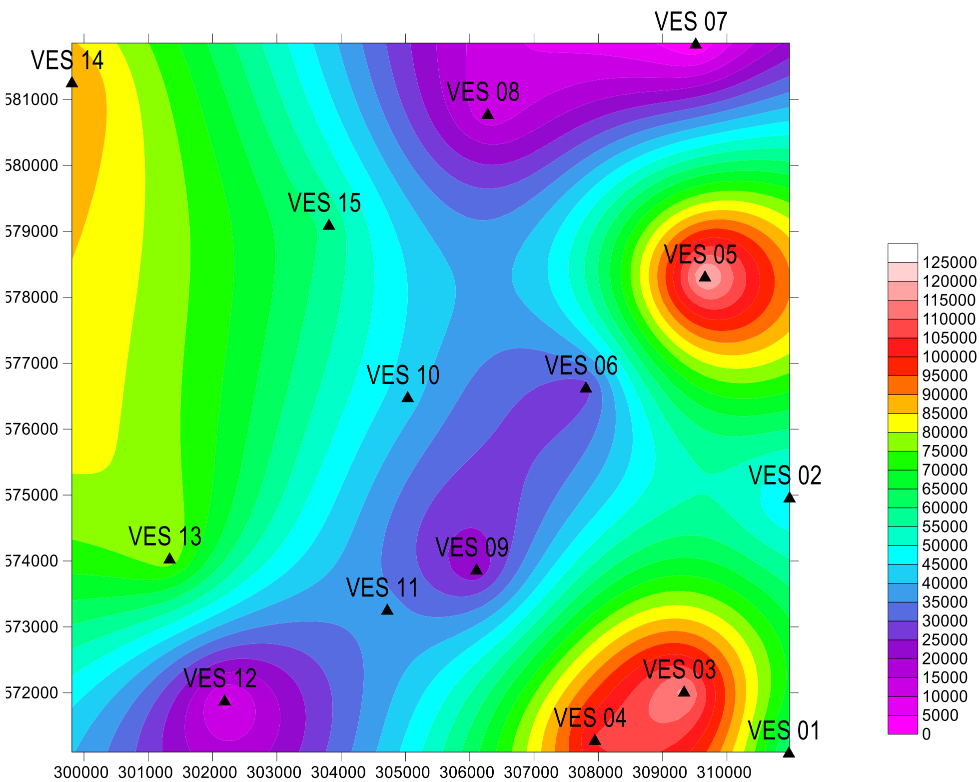

Figure 3. Spatial distribution of Transverse Unit Resistance (*Tr*) of the study area

Transverse unit resistance (*Tr*)

According to Yungul, (1996), *Tr* controls the resistive layers' characteristics. See Table 2 for the average Tr value for this investigation, which spans from 0.00 to 122169.9078 Ω/m². The transverse unit resistance of a water-bearing unit has been found to be directly related to its transmissivity (Ward, 1990; Harb, et al., 2010). As a result, high *Tr* values are associated with high transmissivity values. The study area's southeast, northeast, and a chosen portion of the northwest were found to have high *Tr* values (Fig. 3). This means that the previously specified area will be a suitable place to explore for groundwater. Similarly, a study conducted by Gulraiz and Hasan, (2016); Mbonu, et al., (1991) and Eyankware, et al., (2022), in southern Nigeria reported that areas with high *Tr* are expected to be hydrogeologically promising with thick aquifer thickness. Further observation from Fig. 3 revealed that the middle part of the study area has low *Tr* values and has low transmissivity, which implies that the area will be low in groundwater potential.

Average transverse resistance (ϱt)

When compared to other areas of the study area, Figure 4 demonstrated that a region of high transverse resistance value was found in the northeast and southwest sections of the study area. The value of ϱt varies from 0 at VES/7 to 3406.4 at VES-15. As per Dewashish, et al., (2014), this suggests that the true resistivity is parallel to the stratification plane, whereas the true resistivity is normal to the stratification plane, such as shale. Since higher values of aquifer transverse resistance are typically linked to higher levels of aquifer transmissivity, thicker, more prolific aquifers are indicated by higher aquifer transverse resistance (El-Gawad, et al., 2017; Akinseye, et al., 2023). Since higher values of aquifer transverse resistance are typically linked to higher levels of aquifer transmissivity, thicker, more prolific aquifers are identified by higher aquifer transverse resistance (El-Gawad, et al., 2017; Umayah and Eyankware, 2022). In shale, for example, the true resistivity parallel to the stratification plane is higher than the true resistivity normal to the stratification plane (Anomohanranm, 2015).

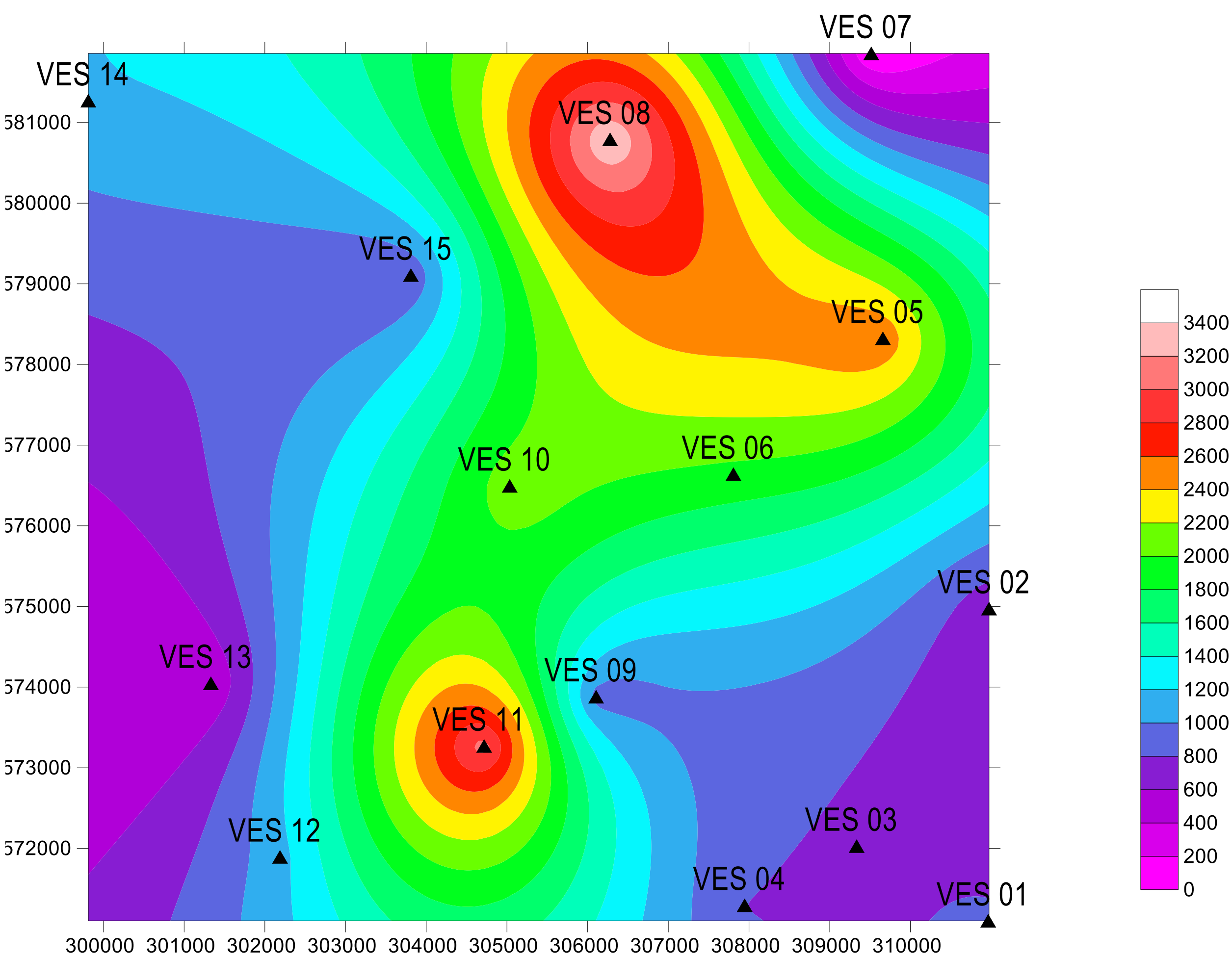

Figure 4. Spatial distribution of Average longitudinal resistance (ρ_L) of the study area.

Transmissivity (T)

The amount of horizontal water transmission is known as transmissivity. It is directly proportional to the aquifer thickness (b) and hydraulic conductivity (K), as equation 8 shows. In units of m^2/day or cm^2/s, the transmissivity (T) is expressed with K in m/day or cm/s and b in m. The value of T for this study ranges from 0 to 1.8×1023 m^2/day, with an average value of 2.23×1022 m^2/day, as shown in Table 2. From Fig. 5, it was observed that T increases towards the southwest parts of the study area.The southwest parts of the study area have a high T-value, which implies that the aforementioned area has more prospects of groundwater potential when compared to other parts of the study area.

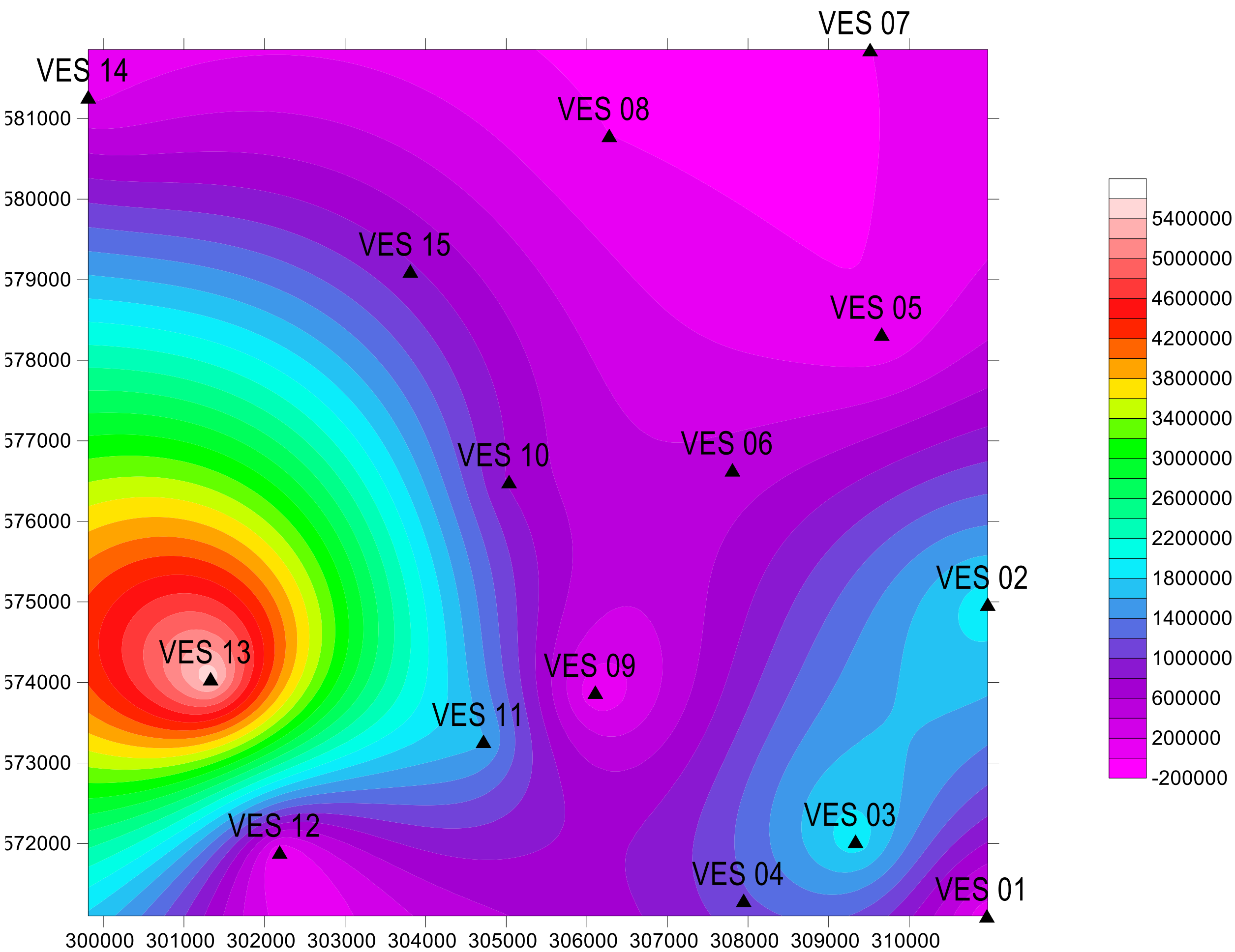

Figure 5. Spatial distribution of Transmissivity (m^2/day) of the study area.

Hydraulic conductivity (K)

The ease of pore fluid's exit from the compressed pore space is determined by its hydraulic conductivity (Obiora, et al., 2016). Hydraulic conductivity is the material's ability to allow fluid to pass through pores and fractures in rocks. According to Table 2, the average value of K for this study is 7.84×10^{21}, with a range of 0.0536 to 1.13×10^{33} m/day. Similarly, the conductivity of the water in a particular area is determined by the type of rock present. The hydraulic conductivity controls the behavior of groundwater flow within an aquifer. Findings from Fig. 6 revealed that the southwest parts of the study have high K. This suggests that, in contrast to other studied areas, groundwater flows smoothly in the aforementioned area. There was good potential for groundwater exploration in the southwest portion of the research region. The southwest portion of the research has a greater propensity to permit groundwater flow, making it more aquiferous, according to the deductions made from Figures 5 and 6.

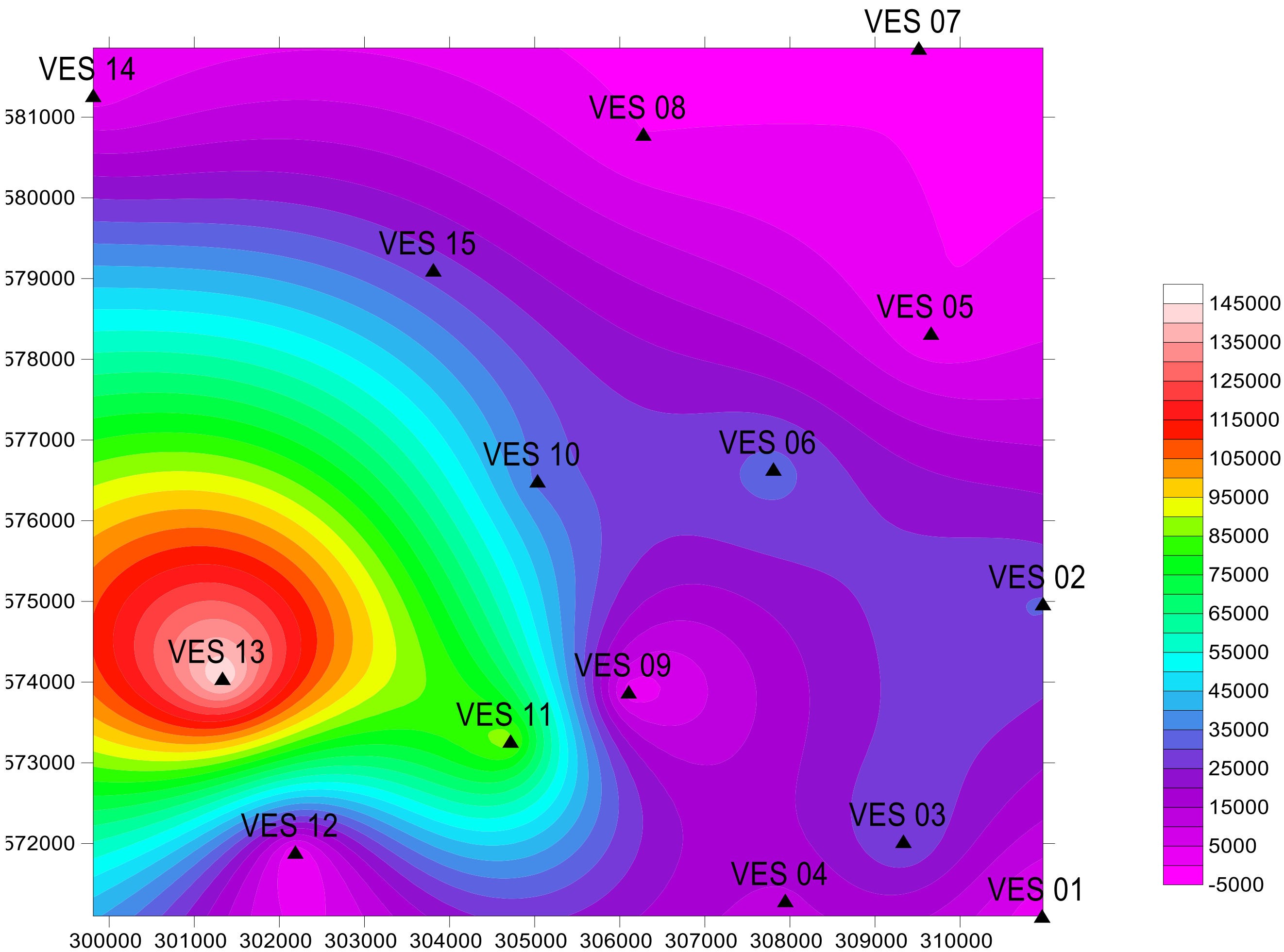

Figure 6. Spatial distribution of Hydraulic Conductivity (m/day) of the study area.

Aquifer thickness

According to El-Gawad, et al., (2017), regions with dense aquifers are known to be extremely productive and capable of supplying water to regional systems. It is often known that aquifer hydraulic properties include transmissivity, hydraulic conductivity, specific yield, and storativity (El-Gawad, et al., 2017). According to regional variation map of aquifer conductivity, a relatively high level of conductivity was noted.

Groundwater flow direction

The groundwater modeling system software (GMS) was used to calculate the direction of groundwater flow. This software takes into account the study area's elevation and geographic coordinates, as well as other pertinent information like the hydraulic conductivity of the geologic formation, well, river, recharge, lake, stream, and so forth, if available. This tool aids in managing water resources, protecting the environment, and tackling other issues pertaining to groundwater.

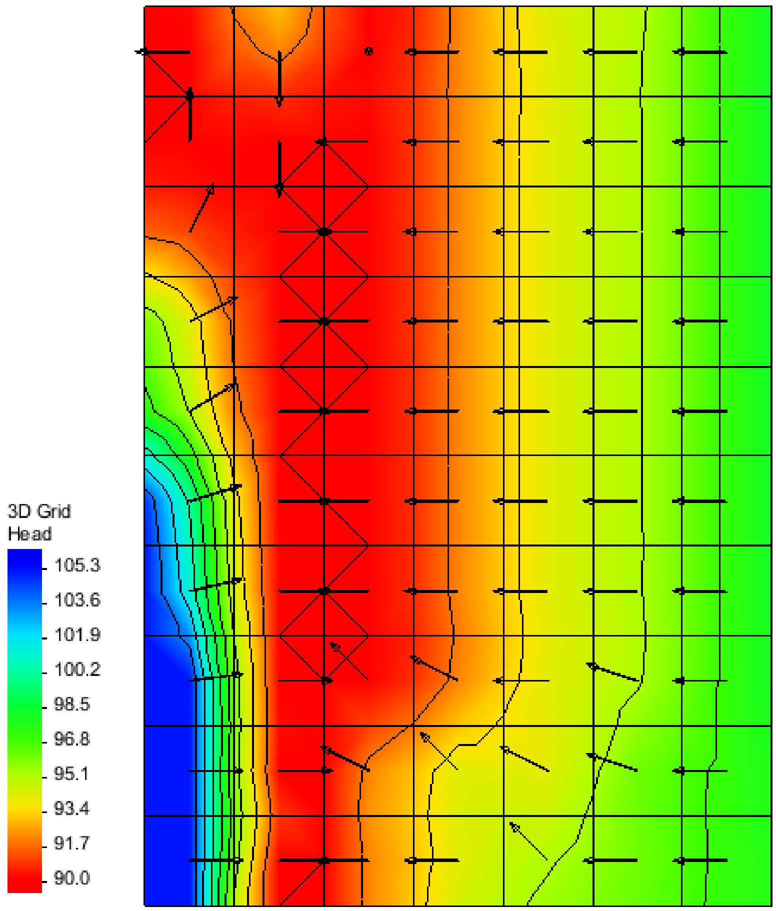

Figure 7. Groundwater flow direction in 1D

The groundwater flow model movement of the study area produced by GMS is shown in Fig. 7. This demonstrates that the research area's hydraulic heads range from 90 to 105.3 m. It may be inferred that the groundwater flow tends to flow toward the southwestern flank of the study area from the southeast, northeast, and northwest. a result, it is anticipated that the southwest portion of the research area will have a significant groundwater potential. This is consistent with the interpreted findings of the examined area's average longitudinal resistance (Fig. 4), transitivity (Fig. 5), and hydraulic conductivity (Fig. 6), which indicated that the southwestern portion of the research area is anticipated to have a significant groundwater potential. FiFig. 8epresents the 3D model of the groundwater flow model in five layers. It shows that the movement of groundwater flow in all the layers is in a uniform direction, as represented by the above-interpreted layer of Fig. 7.

Deductions from Figs. 5nd 6 are in line with findings obtained from Fig. 7, which states that the southwest of the study tends to be more aquiferous. Similarly, studies conducted elsewhere in Nigeria by Akinseye, et al., (2023), suggested that areas with high groundwater flow tend to be high in groundwater potential.

Curve type

The curve types found in the study area include HK, HQ, Q, HKA, H, QH, and QA, as shown in Fig. 9. When compared to other curve types, curve Q was the most common, occurring seven times, according to additional deductions from Fig. 9. The variety of the geology of the study area is responsible for the variance in curve type, according to Yungul, (1996). Curve H is the most denominate curve in Delta State, according to earlier research by Zohdy (1974).

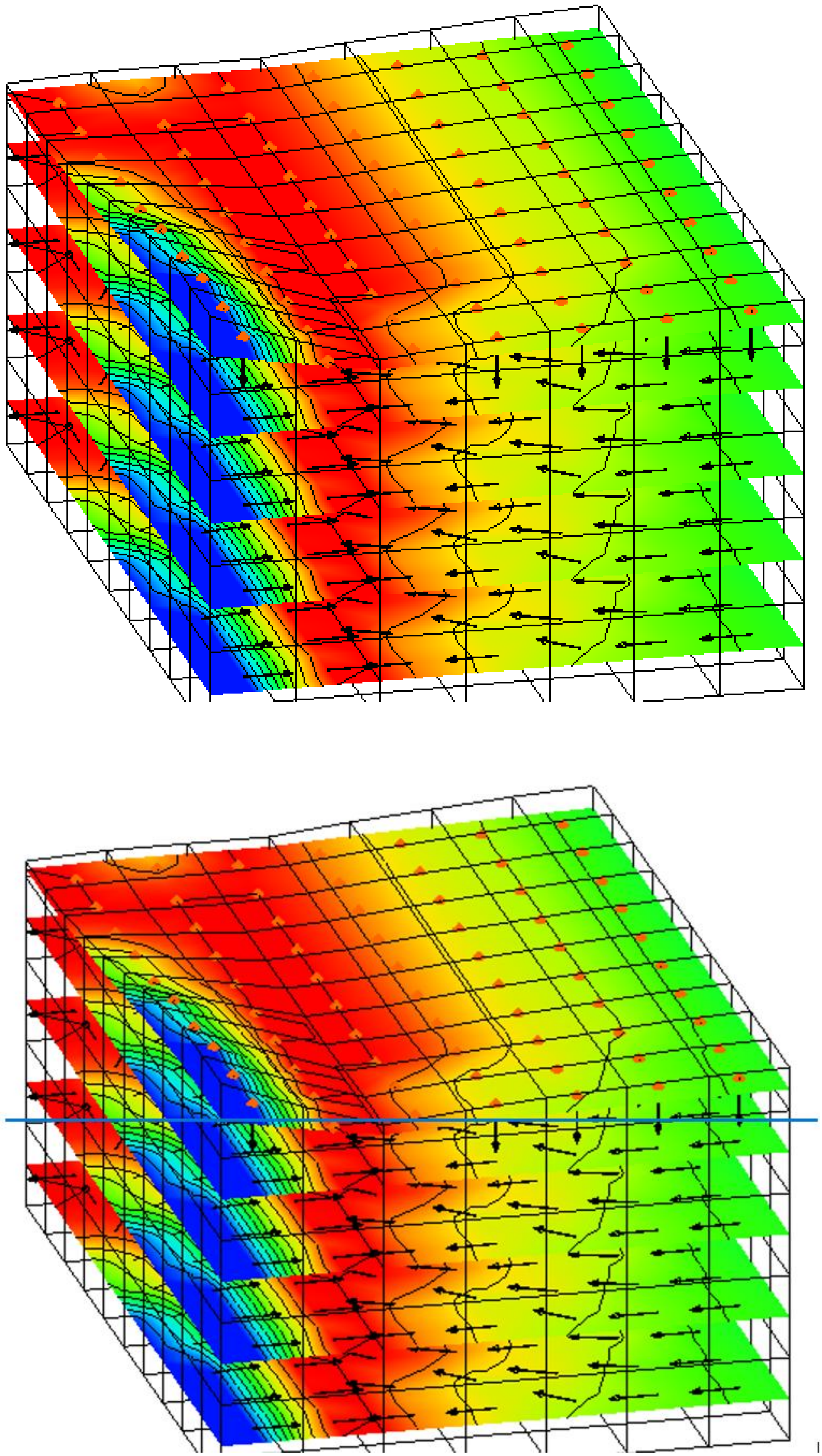

Figure 8. Groundwater flow direction of the study area

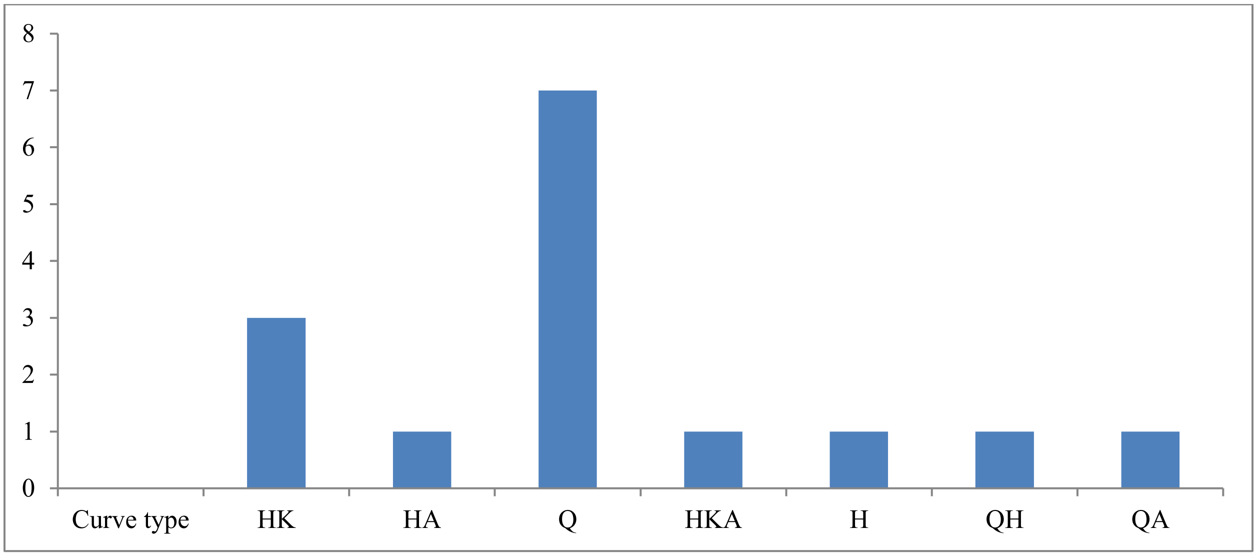

Figure 9. Plot of curve type against number of occurrence

4. CONCLUSION

To evaluate aquifer vulnerability and potential, geophysical studies were conducted in a number of locations across the study area. The study's VES data were used to determine the second geoelectric parameters, which included longitudinal conductance, transverse unit resistance, longitudinal resistance, and average transverse resistivity. The determination of aquifer potentials was done using hydraulic conductivity and transmissivity. The aquifer in the studied area is vulnerable to surface contamination since the results of S showed that the values of S were in the poor range. The results from *Tr* suggested that SE, NE, and selected parts of NW parts of the study area have high *Tr* values, which implies that they are considered to be good prospects for groundwater exploration. Results showed that certain parts of the NE and SW of the study area have high ϱt, which indicates that the aforementioned areas are considered to be aquiferous. The results indicated that SW regions of the research area with high T-values have good groundwater potential prospects. It was determined from the estimated values of K that the SW sections of the research area have a higher rate of groundwater flow than the other sections. The GMS model's results indicated that the research area's southwest regions have better opportunities for groundwater exploration. Curve Q is the most common form of curve in the studied region.

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Author's contributions
All the authors jointly conceptualized and designed the study; MOE, OOW, PNO, KPU, EEO, FOC carried out material preparation, data collection and analysis; manuscript draft preparations were performed by OCA, GEO, OSU, and MOE. All the authors read and authorized the final manuscript for submission and publication.

Informed consent
Not applicable.

Ethical approval
Not applicable.

Conflicts of interests
The authors declare that there are no conflicts of interests.

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Data and materials availability
All data associated with this study are present in the paper.

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