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Application of Geophysical methods in estimation of Aquifer Vulnerability and Contaminant Plume. A Case Study of Southern Delta University, Ozoro and Environs, Southern Nigeria

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ABSTRACT

The groundwater potential and aquifer vulnerability of Southern Delta University and the surrounding area in the Niger Delta region of Nigeria were investigated using the VES geophysical technique. Additionally, 2D resistivity survey and 1D (VES) soundings were obtained in the field using the Schlumberger and Wenner profiles, respectively. Sixteen (16) VESs point were selected using a Schlumberger array applied for the conduction of the VES. The ABEM Terrameter SAS 1000 was used for this study with maximum current electrode spacing (AB/2) was 150 m. The evaluation of aquifer protective capacity was based on the following Dar- Zarrouk parameters: longitudinal conductance (S), Transverse Unit Resistance (Tr), Transverse Resistivity (ρ_t) and longitudinal resistance (ϱL). The aforementioned results ranges from 0.029733 to7.327213, 0 to20135092 Ω/m^2, 0.00 to 42768.57and 60.695 to 9535.021 Ω-m respectively. Hydraulic conductivity and transmissivity, for example, range from 29.49481 to 1E+165 m/day with an average value of 6.4E+163 m/day, whereas K ranges from 0 to 3.9E+167 m^2/day with an average value of 2.4E+166 m^2/day. The contour maps help to define zones with distinct layer characteristics by revealing the distributions of these parameters. The results of the study can be used to guide decisions regarding groundwater abstraction and management.

Keywords: Aquifer, Resistivity, Depth, layer, Potential

1. INTRODUCTION

The socioeconomic advancement of any nation is fundamentally reliant on water resources. This reliance stems from its critical use in residential homes, industrial and agriculture use (Eyankware, et al., 2018; Eyankware et al., 2020a). Given this significance, water resource is considered as a crucial asset that need comprehensive study to ensure sufficient availability. Groundwater represents the most substantial reserve of freshwater across the globe (Eyankware, et al., 2020b; Okolo et al., 2025;

Venkateswaran et al., 2014). Moreover, it is the most cost-effective alternative in comparison to conventional surface water systems, which necessitate the establishment of reservoirs, piping infrastructures, and additional facilities, as extracting water from manually excavated wells and boreholes incurs significantly lower costs (Adeyeye et al., 2019; Osisanya et al., 2025; Eyankware et al., 2025a). Advanced sustainable development requires an an in-depth understanding of the groundwater system, according to Arsene et al. (2018). Groundwater is largely a result of geological processes. It is also crucial to remember that investigating groundwater availability in terms of quantity alone is insufficient. Additionally, the quality of the groundwater and the degree of contamination susceptibility of the identified aquifers should be highlighted. Vulnerability evaluation in hydrogeology usually refers to an aquifer's susceptibility to pollution that can lower groundwater quality (Eyankware, 2019; Onwe et al., 2024). The susceptibility of groundwater to contamination is known as vulnerability, and it depends on physical parameters, anthropogenic activities, and pollutant characteristics (Odesa et al., 2025). In order to reduce negative effects on groundwater and accomplish groundwater protection, vulnerability information can help choose appropriate locations for certain activities (Jamrah et al., 2008; Odesa et al., 2024). Aquifer evaluation necessitates a comprehensive geophysical strategy that incorporates procedures such as seismic research, magnetic surveying, electrical techniques, depth drilling, geophysical well logging, and the use of geographic information systems (Eyankware and Okeke, 2018).

In order to effectively use groundwater resources, a method that can evaluate the aquifer layers, groundwater vulnerability and groundwater quality must be used. On the other hand, one of the most important techniques for finding aquifers in the earth is the electrical resistivity approach (Eyankware and Aleke, 2021; Akinseye et al., 2023). This approach has been used extensively in the study and analysis of the Earth's subterranean layers. It is useful because it can distinguish between freshwater and saltwater aquifers, porous and impermeable rocks, and clayey and sandy formations. According to Opara et al. (2022), it is crucial for obtaining information about the subsurface layers and determining whether groundwater is present. The delineation of subsurface layers and the assessment of groundwater potential in the region are conducted by analyzing variations in the electrical resistivity of multiple subterranean lithological formations (Esi et al., 2025; Eyankware, et al., 2025b). This method also effectively identifies resistivity differences among diverse geological strata, making the electrical resistivity technique particularly applicable for such purposes (Eyankware, et al.,2021a). Geophysical methods have been employed to solve various exploration challenges, owing to their proficiency in swiftly covering extensive geographical areas and their ability to penetrate deeper into the subsurface (Eyankware, et al., 2026). Furthermore, the capacity to link hydrogeological characteristics, such as porosity and permeability, with electrical resistivity data enhances the value of geoelectrical methods in groundwater studies (Helaly, 2017). Determining hydrogeological zones for groundwater exploration has been accomplished with success using the electrical resistivity method (Evans et al., 2010; Eyankware et al., 2021a; George et al., 2010; Adiat et al., 2012; Ibuot et al., 2013; Akinlalu et al., 2017). The sensitivity of rock resistivity to its ionic composition makes the electrical resistivity method one of the most successful approaches in groundwater geophysics. This method makes it easier to obtain quantitative data by using a source that is controlled and has predetermined dimensions. The resistivity approach is specifically concerned with evaluating the potential differences that are seen at the surface as a result of the current flowing through the materials underneath. According to George et al. (2015), hydraulic and electrical conductivities are mutually dependent since the principles governing fluid movement and electric current conduction usually function under the same physical and geological conditions. Furthermore, the geoelectric parameters obtained by the electrical resistivity technique are useful for both the assessment of the subsurface hydrological conditions and the evaluation of the aquifer's protective capacity (Adeeko et al., 2019; Eyankware et al., 2021b; Umayah and Eyankware, 2022). The study will employ VES to develop a conceptual model to map aquifer vulnerability in a sedimentary context and evaluate groundwater potential. The specific objectives involve determining the subsurface layers and their geoelectric characteristics, identifying potential geological features that are useful for identifying an aquifer unit or units, evaluating the groundwater potential, and mapping the groundwater vulnerability of the study area.

2. METHODOLOGY

Location and accessibility

The study area is situated in the tropical rainforest zone of the Niger Delta (Figure 1). The two primary distinct seasons that characterize its climate are the rainy season and the dry season (Eyankware and Ephraim, 2021). The dry season runs from November through April, whereas the rainy season lasts from May to October. Three important geological formations define the Niger Delta. The first of these is the Benin formation, which reaches a depth of around 1,800 meters and is the primary aquifer in the area. There is less shale in this formation than sand, which makes up the majority of it. An equal amount of sand and shale make up the Agbada formation, the second geological stratum. The third stratigraphic stratum, the Akata formation, is made up mostly of shale (Anomohanran, 2014).

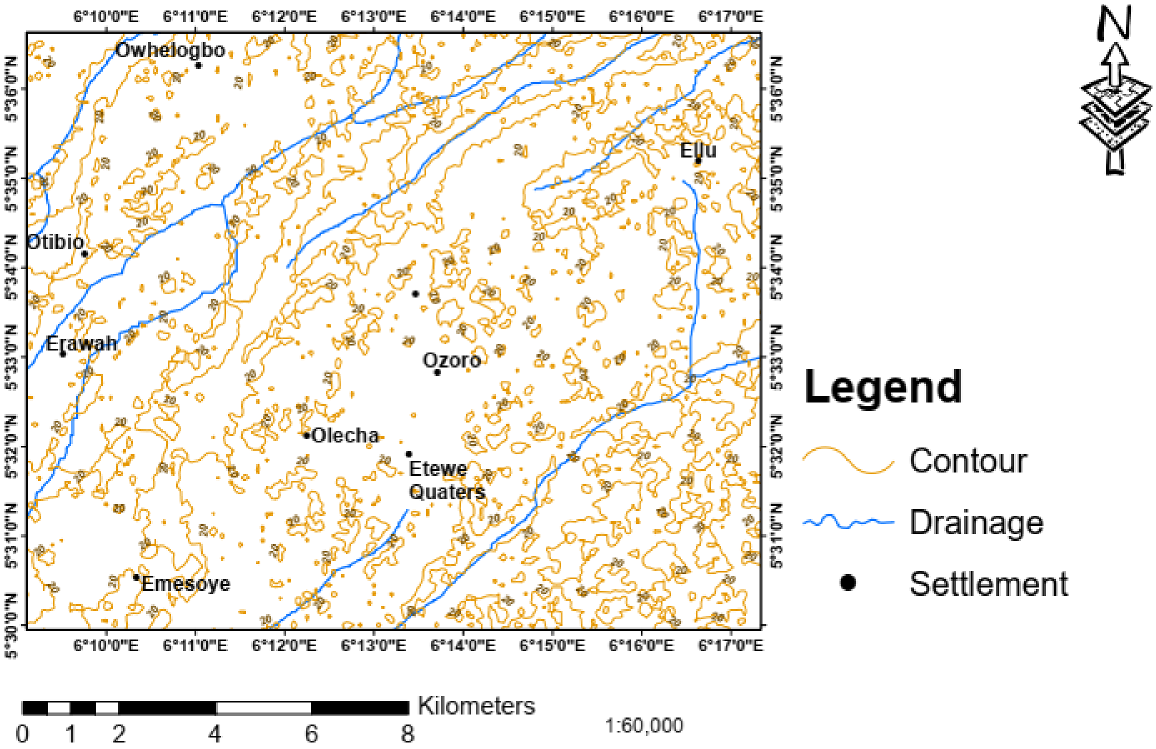
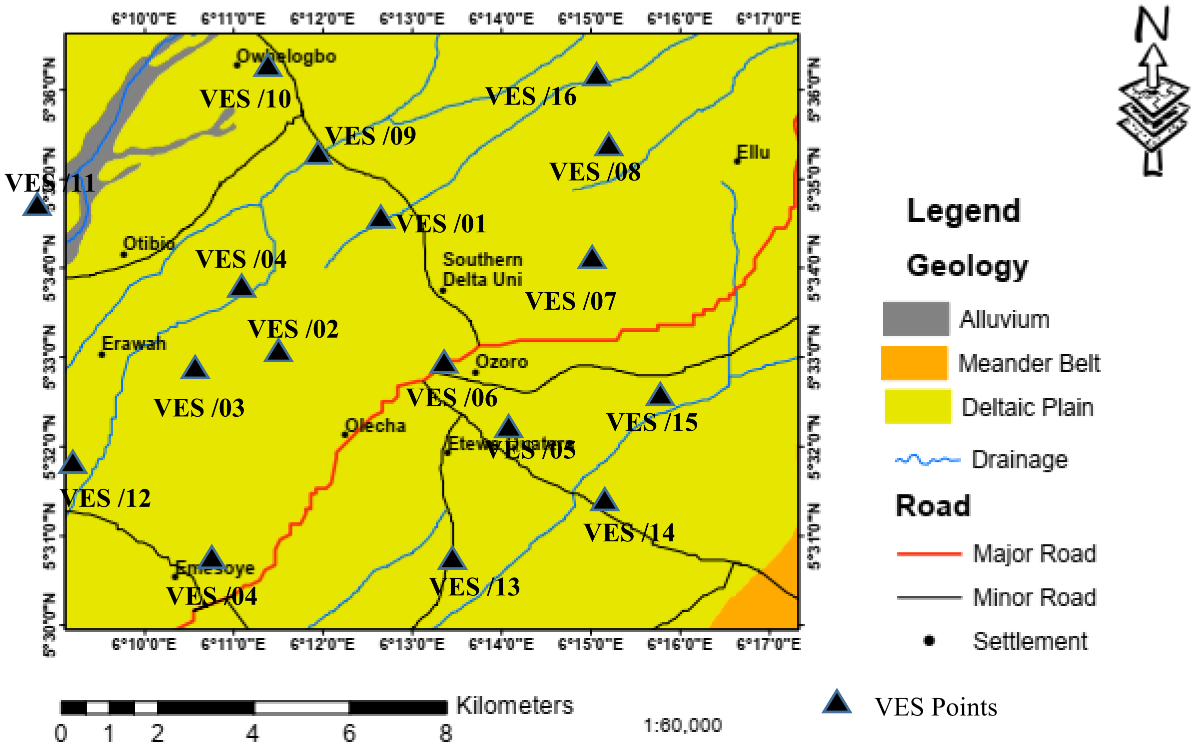


Fig. 1: Topographic Map of the study area



Fig, 2: Geology map of the study area showing VES Points

Geology of the study area

According to geology, the area being studied is located in Nigeria's Niger Delta, which is divided into three different formation strata: the Agbada, Akata and Benin formations, stretching over the coastal plain sands Fig. 2 (Allen, 1965; Reyment, 1965; Short and Stauble, 1967). Sand and gravel make up the majority of this formation, which ranges in thickness from 0 to 2100 m (Short and Stauble, 1967). The sands and sandstones have a coarse to fine texture and are frequently granular in form. They can also be partially unconsolidated and have the ability to hold onto water. The Agbada formation, the second layer of the Niger Delta's three-part, highly diachronous complex, is located under the Benin formation. Sands, sandstones and siltstones make up the majority of the Agbada formation (Short and Stauble 1967). The sandy portions, which range in thickness from 3,000 to 5,000 m, are the main hydrocarbon reserve in the delta oil fields. According to Olorunfemi et al. (1999), the Niger Delta complex's lowest significant time transgressive lithologic unit is the Akata formation. Shale, turbidite sandstones and siltstones make up the majority of this maritime Pro-Delta megafacies. However the formation is evident beneath the surface in the outer Delta region, it is not exposed on land. Its thickness ranges roughly from 0 to 6,000 m. Mostly dark grey homogeneous shales make up the upper part of the formation.

Geophysical survey

Two electrical configuration arrays were set up and sixteen (16) VES were completed for this inquiry. To determine the leachates' vertical and lateral variation. The Wenner and Schlumberger arrays were selected. In order to evaluate the lateral variation of the leachate or contaminants, the Wenner array was used in order to monitor the electrical conductivity anomaly. The Schlumberger array was used for evaluating the electrical property fluctuation of the subsurface and, as a result, the vertical and depth-dependent region of influence of the leachate. The two data sets created an area geoelectrical model of the subsurface in the study area. Geoelectric layers are generated by analyzing VES data, which enables the identification and study of layer properties such as aquifer depth, thickness, and frequency that indicate the possibility of aquifer pollution. These layer characteristics were then used to compute the longitudinal conductance (S) and transverse resistance (Tr) distributions using data from earlier pumping tests in dug wells.

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

Dar Zarrouk's longitudinal (S) and transverse (T) parameters were derived via

$$S=\frac{h}{p} \tag{2}$$

$$T=hp \tag{3}$$

Using the formula below, we determined the total longitudinal unit conductance (S).

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

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

as proposed by Eyankware, (2019)

The Transverse Unit Resistance (Tr) was calculated for the following equation.

The total resistance of the transverse unit is

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

as proposed by Nwachukwu et al. (2019)

Below is the average longitudinal resistance for a given VES point

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

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).

$$K = 0.0538E^{0.0072p} \qquad (8)$$

Where is the aquifer layer resistivity

Transmissivity (T) is the product of the hydraulic conductivity (k) and the aquifer layer thickness.

$$T = K \text{ x } h \qquad (9)$$

Wenner profile (RES)

For the two-dimensional imaging, the Wenner array method was applied along four profiles. A direct current was sent into the ground in the field using a pair of current electrodes, and the voltage drop was tracked using a second pair of potential electrodes. For each profile, a constant electrode spacing of 1a, 2a, 3a, 4a, and 5a was used for both the current and potential electrodes.

3. RESULTS AND DISCUSSION

Table 1 presents the findings from the VES survey that was interpreted.

Table 1. VES survey output

VES LOCATIONS	Longitudinal Unit Conductance (S)	Transverse Unit Resistance (Tr)	Transverse Resistivity (ρ_t)	longitudinal resistance (ρ_L)	Hydraulic Conductivity (m/day)	Transmissivity (m^2/day)
VES 1	0.069049	14836415	42768.57	1738.93	4×10^{147}	1.4645E+150
VES 2	0.064642	386216.3	2150.305	2778.519	2729647149	3.07931E+11
VES 3	0.055553	4400019	15994.84	4951.852	1.29687E+56	3.1095E+58
VES 4	0.042966	20135092	0	9535.021	1.0183E+165	3.856E+167
VES 5	0.044549	168120.7	2878.977	1310.814	2.18012E+15	6.90096E+16
VES 6	0.029733	120192.9	1629.867	2480.209	720022.8223	37971843.58
VES 7	0.085772	661892	2473.623	3119.682	1473812162	2.92242E+11
VES 8	0.11839	134898.4	10054.29	113.3289	1.2123E+105	4.8081E+105
VES 9	0.093275	8721504	15946.29	5863.645	2.40575E+50	1.27024E+53
VES 10	0.158566	299480.4	763.7859	2472.795	191.2991031	50449.39948
VES 11	7.327213	448398.5	1008.249	60.69565	264+.1185851	100330.7269
VES 12	0.236731	0	0	380.1958	75388319652	0
VES 13	0.233713	1374537	0	1067.487	1.48751E+19	3.12764E+21
VES 14	1.258836	1343292	2181.873	489.071	2422324.534	1329420151
VES 15	0.068035	4448.848	361.8421	180.7154	29.49480624	149.8041209
VES 16	1.237495	2882758	4919.718	473.5051	1.05509E+15	5.83747E+17
Min	0.029733	0	0	60.69565	29.49481	0
Max	7.327213	20135092	42768.57	9535.021	1E+165	3.9E+167
Aver	1.026748	4225131	8105.6	2639.603	6.4E+163	2.4E+166

Dar Zarrouk parameter of the study area

The following Dar Zarrouk parameters have been computed: transverse resistivity (ϱt), average longitudinal resistance (ϱL), longitudinal unit conductance (S), and transverse unit resistance (Tr). These results were derived from basic resistivity data, such as resistivity thickness and depth, in accordance with Eqs. (4–10). The calculated values are shown in Table 1.

Longitudinal unit conductance (*S*)

According to Oni et al. (2017), longitudinal conductance is a crucial parameter for evaluating the degree of groundwater protection against vertical pollutant infiltration. The symbol S denotes the conductance measured along the bedding plane inside a one-meter column (Eyankware et al. 2022). Olusegun et al. (2016); 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. According to Glain, (1979); Eyankware et al., (2020a), variations in longitudinal conductance between VES locations suggested shifts in the overall thickness of low-resistivity materials. Findings revealed that 71.9 %, of the study area was to be poor class, 27.8 % is weak class, 4 % is a moderate class and 0.3 % of the study area was to be moderate class. As indicated by the results presented in Fig. 3, certain areas within the study area, including VES 1, 5, 6, 13, and 14, exhibit low S values, suggesting that the thickness of the aquifer's overlying layer may be insufficient to prevent the infiltration of percolating fluids. Conversely, the northwest section of the research area records the highest S value, measuring 7.32 at VES-11, as illustrated in both Fig. 3 and Table 1.

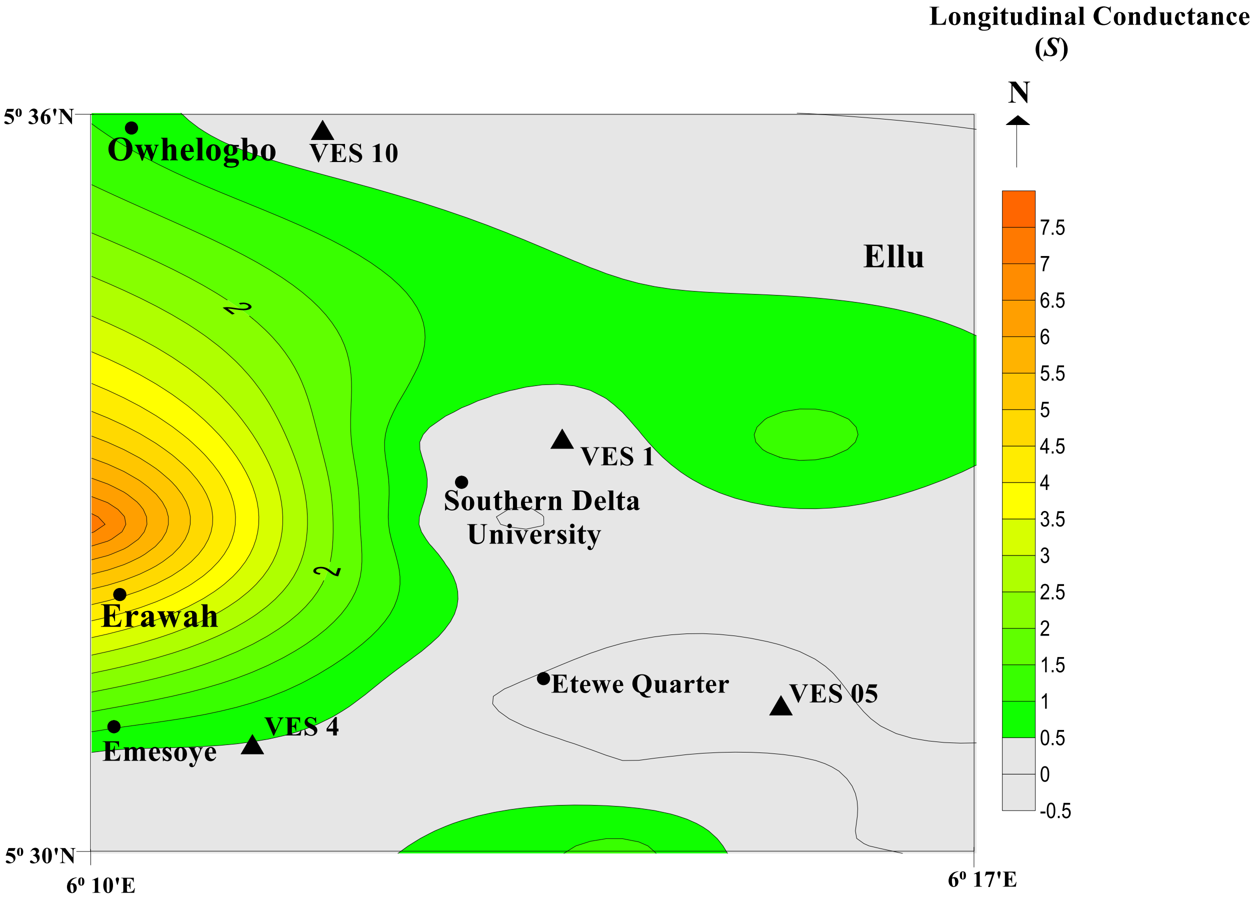


Fig. 3: Spatial distribution of *S* of the study area.

Transverse unit resistance (*Tr*)

According to Eyankware et al. (2022), it is employed to identify the most abundant region of groundwater potential for hydrogeological study. *Tr* establishes the characteristics of the resistive layers, whereas longitudinal conductance establishes the characteristics of the conducting layers (Ward, 1990; Harb et al., 2010; Yungul, 1996). Transmissivity and *Tr* are closely associated. Larger *Tr* values typically indicate higher aquifer transmissivity values, according to Eyankware and Aleke, (2021). The *Tr* value ranges from 0 Ω/m^2 at VES 12 to 20135092 Ω/m^2 at VES 4, with an average value of 4225131 Ω/m^2. It was observed that transmissivity and transverse unit resistance showed similar results. Consequently, areas of high transmissivity and that of to high *Tr* values are found in the NW parts of the study area see Fig. 4.

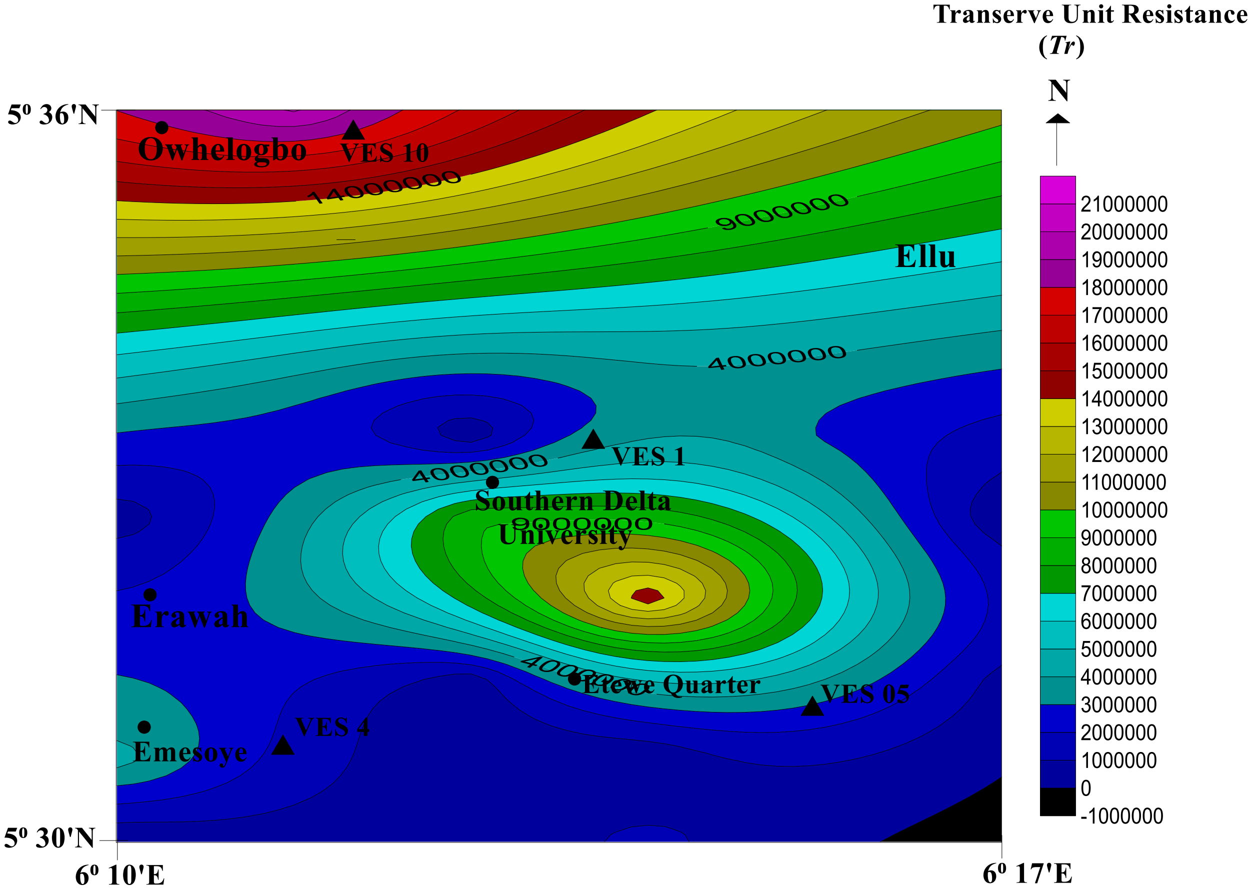


Fig. 4: Spatial distribution of *Tr* of the study area.

Transverse resistivity (ρt)

The value of ρt for this study ranges from 0 at VES 4, 12and 13 respectively to42768.57 at VES 1 with an average value of 8105.6 as shown in Table 1. High ϱt was observed around the Southern Deltas University, Ozoro part of the study area as shown in Fig. 5. Anomohanran, (2013); Eyankware et al., (2022) ascribe high ϱt to the resistivity of underlying rocks, like sandstone, in the given location, which tends to control the resistivity of rock within the area.

Longitudinal resistance (ρL)

According to Adegboyega et al. (2024) and George, (2021), longitudinal resistance plays a crucial role in assessing the likelihood of infiltration by aquiferous units. Additionally, George (2021) and Eyankware, et al., (2020b) noted that the sensitivity of ϱL to geological units allows it to be utilized for predicting the conductivity direction as depth increases. Moreover, it was observed that as depth increases and thickness grows, longitudinal resistivity tends to decrease, while ϱL indicates the degree of homogeneity relative to the adjacent layer. According to Table 1, the average value of ϱL is 2639.603Ω-m, with a range of 60.69565 at VES 11 to 9535.021 at VES 4. The longitudinal resistivity values of the 16 sounding locations collected from the research region were used to create a spatial variation map of ϱL, as shown in Fig. 6. High ϱL values were found in the northwest, northeast, and southeast regions of the research area, according to Fig. 6.

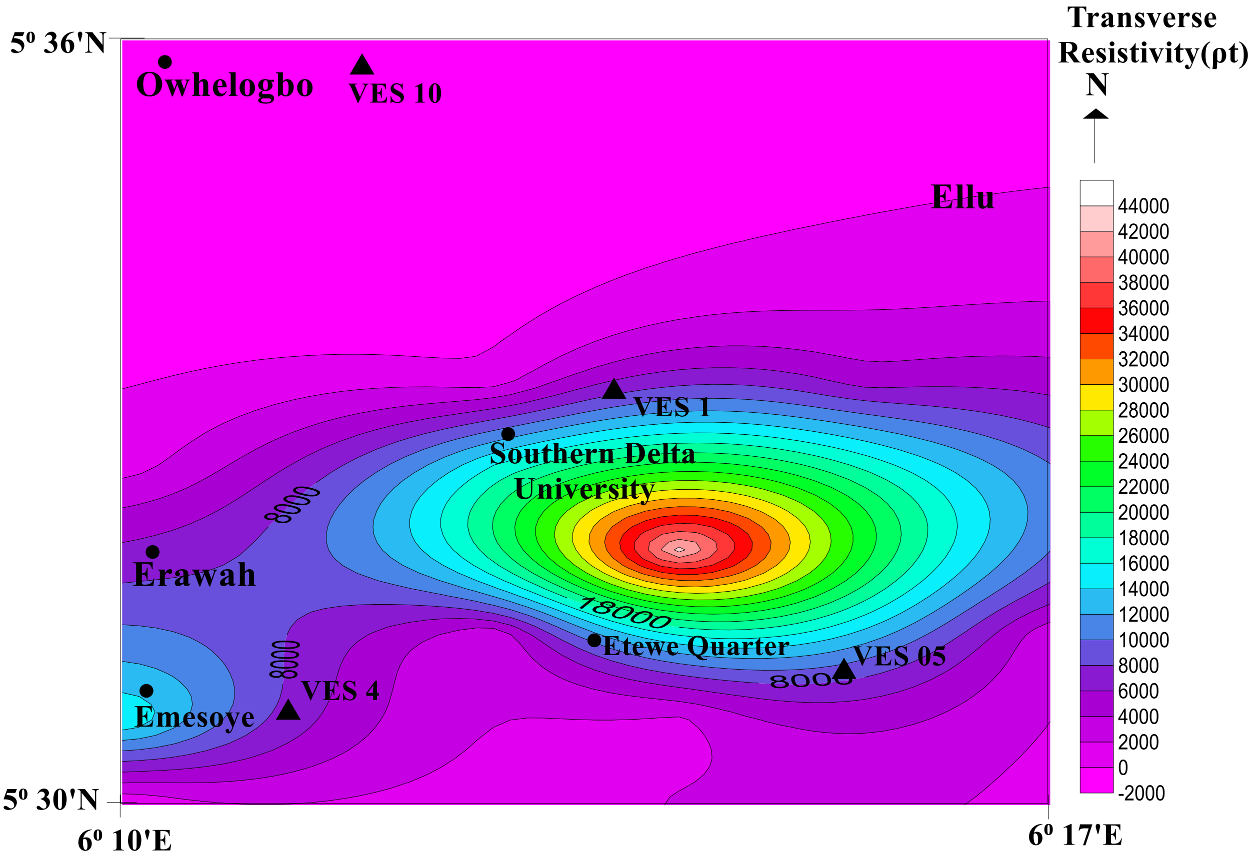


Fig. 5: Spatial distribution of ρt of the study area.

Aquifer Parameters

Hydraulic conductivity K (m/day)

The hydraulic conductivity of the pore fluid determines how easily it can exit the compressed pore space (Obasi et al., 2022). The fluid's capacity to flow through the pores and cracked rocks is known as the material's hydraulic conductivity. Similarly, the conductivity of water is influenced by the type of rock that is present in a particular location. According to Table 1, K ranges from 29.49481 to 1E+165 m/day with an average value of 6.4E+163 m/day based on hydraulic conductivity deduction. The high range of hydraulic conductivity may be due to the aquifer's heterogeneity, which results in a wide range of hydraulic conductivity (George et al., 2015). Low hydraulic conductivity (<0.0195 m/s) is the region's primary characteristic, indicating that groundwater flow in the area is complex rather than simple due to the geologic management of the limited aquifer.

Transmissivity (m^2/day)

According to Opara et al., (2022), transmissivity is the capacity of an aquifer to transfer groundwater over its whole saturated thickness. Transmissivity is the speed at which groundwater can move through a unit-wide aquifer section under a unit hydraulic gradient. From Table 1, it was observed that T ranges from 0 to 3.9E+167 m^2/day, with an average value of 2.4E+166 m^2/day. Aquifer materials are known to be comparatively permeable to fluid flow and areas with high transmissivity values can be recognized as having high water-bearing potential. The research area has an average transmissivity value of 0.0643 m^2/day. This suggests that there is little groundwater potential in the area.

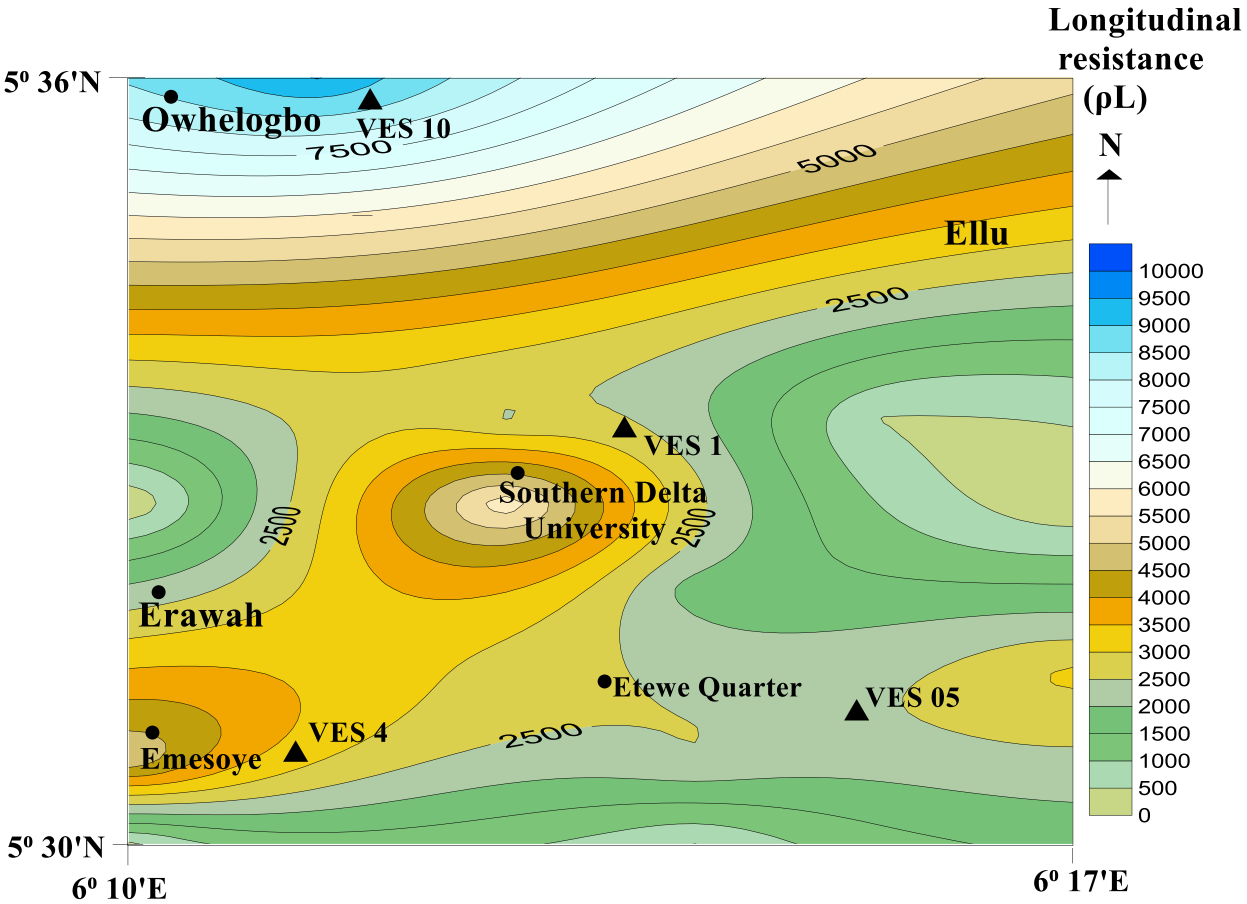
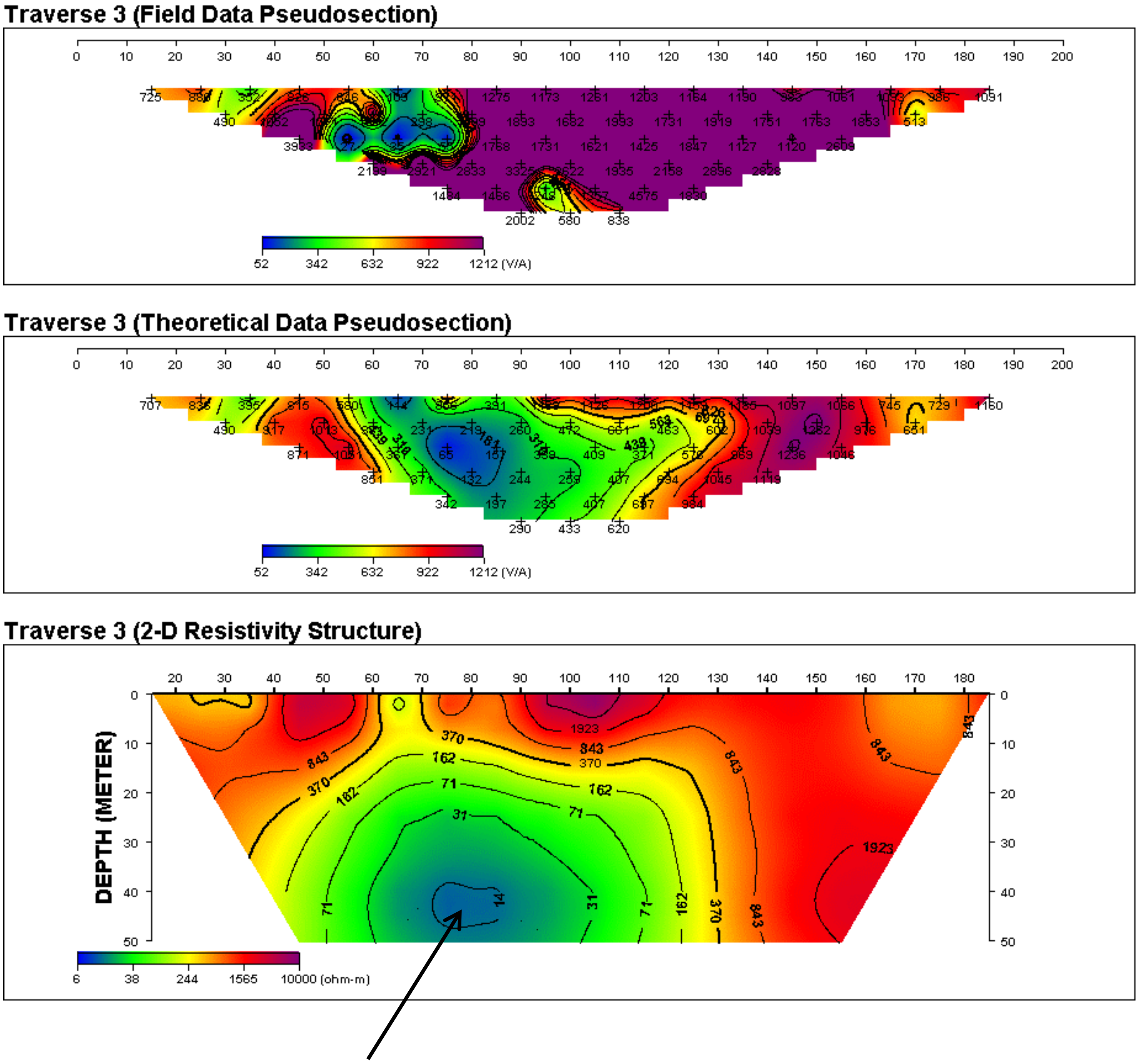


Fig. 6: Spatial distribution of ρL of the study area.

Interpretation of 2D resistivity survey

Fig. 7, showed traverse 3 with a length of 200 m in the North-South direction of the study area. The 2D section revealed an anomalously low resistivity range of (25– 47 Ωm) structure within electrode position of 20-70m at depths of 5-25 m. The low low resistivity indicate the presence of contaminat plume. Traverse 4, which was 200 meters long and ran east-west over the research area, was depicted in Figure 8. Within the electrode position of 110-120 m at depths of 0-50 m, the 2D section showed an abnormally low resistivity range of (28–57 Ωm). The presence of a contaminated plume is indicated by the low resistivity. In the midst of the trip, it was found to have seeped from the surface point to depths between 0 and 50 meters.



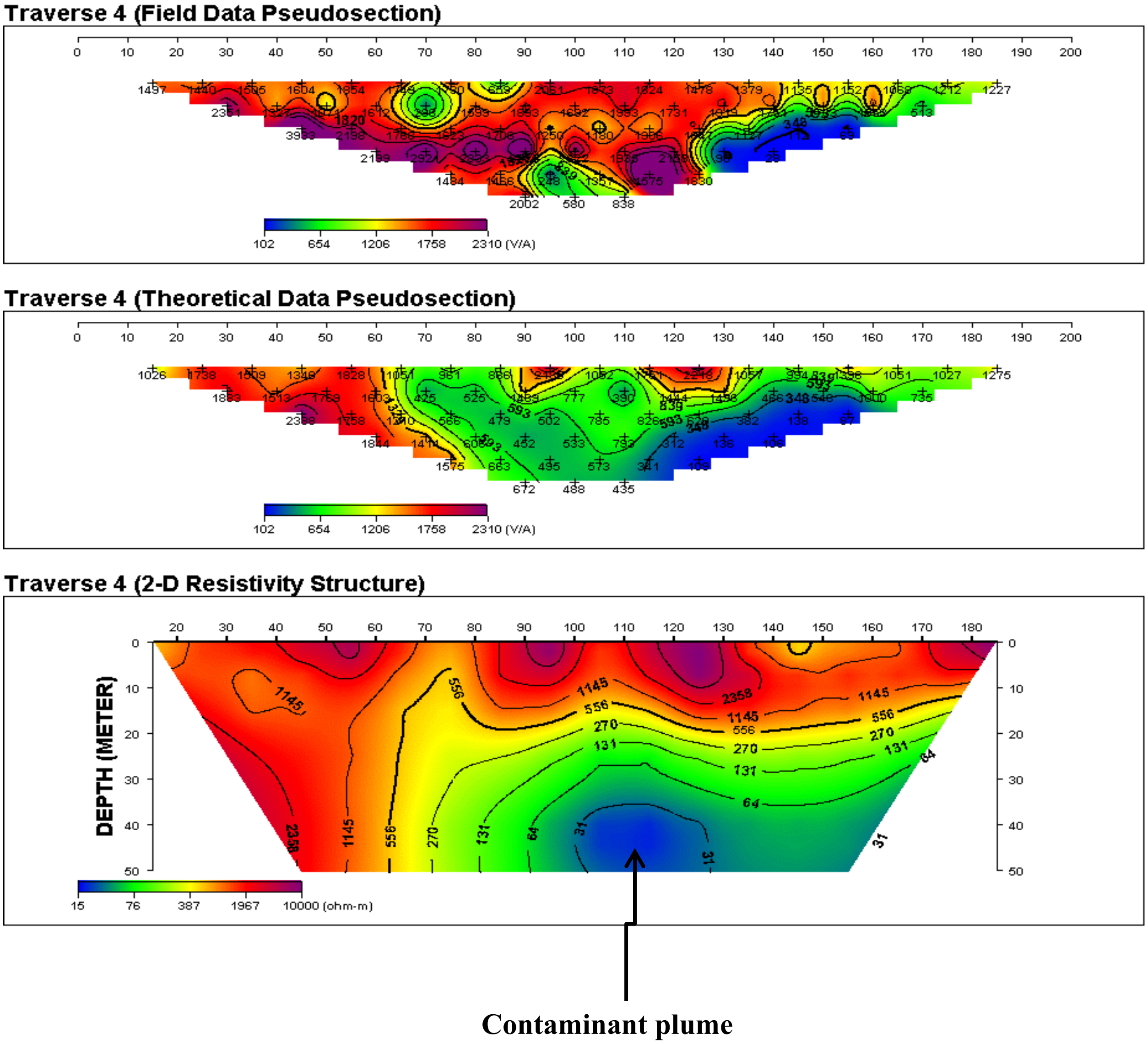
Traverse 3 (Field Data Pseudosection)

Traverse 3 (Theoretical Data Pseudosection)

Traverse 3 (2-D Resistivity Structure)

Contaminant plume

Fig. 7: Transverse 3 of dipole-dipole results of the study area


Traverse 4 (Field Data Pseudosection)

Traverse 4 (Theoretical Data Pseudosection)

Traverse 4 (2-D Resistivity Structure)

Contaminant plume

Fig. 8: Transverse 4 of dipole-dipole results of the stu area

4. CONCLUSION

The subsurface layer parameters (resistivity, depths and thicknesses) that were used to assess the groundwater potential and aquifer vulnerability of the research area were identified through sixteen (16) VES. The survey was conducted using a Schlumberger electrode design, with a maximum half potential electrode separation of 10 m and a maximum half current electrode spacing of 100 m. The Dar-Zarrouk and aquifer characteristics varied, according to the interpreted geoelectric data. The research revealed that, in terms of aquifer protective capacity, 71.9% of the study area was classified as poor class, 27.8% as weak class, 4% as intermediate class and 0.3% as moderate class. The overall groundwater potential within the study area is typically low; however, most of the generated maps suggest that the Southern Delta University, Ozoro, and the northwestern regions exhibit a higher groundwater potential compared to other areas. It is recommended to employ artificial recharge methods such as trenches, check dams, and percolation to enhance the existing groundwater supplies in the study area. Analysis of dipole-dipole data suggests that low resistivity levels are indicative of a contamination plume, with leachate migrating in the direction of the groundwater flow towards the southwest of the study area. However, the overall groundwater potential in the region is relatively low, various maps indicate that the southwest and certain areas in the northwest of the research site tend to exhibit higher groundwater potentials compared to other regions. Therefore, the implementation of artificial recharge techniques, including check dams, percolation, and trenches, is recommended to bolster the current groundwater resources in the study area.

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Informed consent
Not applicable.

Ethical approval
Not applicable. This article does not contain any studies with human participants or animals performed by any of the authors.

Conflicts of interests
The authors declare that they have no conflicts of interest, competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Data and materials availability
All data associated with this study will be available based on the reasonable request to corresponding author.

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