Geophysical Investigation of Groundwater Contamination Level Within Ikot Ekpene and Obot Akara Metropolis Using Dar-Zarrouk Parameters

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Abstract- Rapid urbanization and population growth in Ikot Ekpene and Obot Akara, Akwa Ibom State, have intensified concerns over groundwater contamination due to unregulated waste disposal, poor sanitation, and indiscriminate land use. This study aims to assess the vulnerability of groundwater resources in these areas using geoelectric methods, particularly Vertical Electrical Sounding (VES) integrated with Dar-Zarrouk (DZ) parameters. Twenty-six VES soundings were acquired using the Schlumberger configuration with a maximum AB/2 spacing of 300 m. Apparent resistivity data were processed and inverted using the WINRESIST software and validated with borehole lithologic logs. Primary geoelectric parameters (resistivity, thickness, and depth) and secondary indices, longitudinal conductance (S) and transverse resistance (T) were computed to evaluate aquifer protective capacity and transmissivity. The study revealed three to four geoelectrically distinct subsurface layers. Resistivity values in the topsoil ranged from 65.3 to 1172.1 Ωm; in the aquifer zones, values ranged from <400 Ωm in polluted areas of Ikot Ekpene to >2000 Ωm in Obot Akara's clean, gravelly aquifers. Longitudinal conductance varied from <0.1 S to 0.36 S, indicating generally poor to moderate aquifer protection. Transverse resistance ranged from <5000 Ωm² in vulnerable zones to >10,000 Ωm² in transmissive aquifers, particularly in Obot Akara. The results show that Ikot Ekpene has shallow, poorly protected aquifers and a higher contamination risk, while Obot Akara's deeper and more resistive formations indicate better groundwater integrity. The integration of VES data with Dar-Zarrouk analysis proves effective in delineating vulnerable zones and supports informed groundwater management in rapidly urbanizing tropical regions.

Indexed Terms- Groundwater Vulnerability; Vertical Electrical Sounding (VES); Dar-Zarrouk Parameters; Aquifer Protective Capacity; Geoelectrical Survey

I. INTRODUCTION

The accelerated rate of urbanisation in Ikot Ekpene and Obot Akara Local Government Areas (LGAs) in northern Akwa Ibom State, Southern Nigeria, has raised significant concerns over the integrity and sustainability of local groundwater systems. As in many rapidly developing regions, population growth, housing expansion, and land-use change have placed increasing pressure on the already fragile water resources (Ekanem et al., 2022a). Groundwater, which constitutes the primary source of domestic water supply in these areas, is becoming increasingly vulnerable to contamination due to unregulated development, indiscriminate waste disposal, and intensifying agricultural practices (Ikpe et al., 2025; Ekanem et al., 2022b). This situation is especially critical in regions underlain by shallow, unconfined aquifers, where pollutants from the surface can easily infiltrate and compromise water quality (Etu-Efeotor, & Akpokodje, 1990; Thomas et al., 2025). Despite the growing recognition of these threats, geophysical investigations aimed at systematically assessing aquifer vulnerability in Ikot Ekpene and Obot Akara remain limited. Without such data-driven assessments, it is difficult to implement effective groundwater management strategies or establish scientifically sound protection zones (George et al., 2016; Ikpe et al., 2022).

To bridge this knowledge gap, the present study adopts vertical electrical sounding (VES), a cost-effective and widely used geophysical method, to characterize the subsurface lithology and evaluate aquifer properties (Ekanem, 2020; Ikpe et al., 2025; Nwozor et al., 2025). Specifically, the study integrates VES data with Dar Zarrouk (DZ) parameters, a set of secondary geoelectrical attributes derived from resistivity primary geo-electric measurements to assess the protective capacity of overlying geological layers and quantify the aquifer's susceptibility to surface-borne contaminants (George & Thomas, 2023). Twenty-six Schlumberger VES stations were strategically distributed across the Benin Formation, a coastal plain sand unit that dominates the area, within latitudinal and longitudinal bounds of 4.96°–5.10° N and 7.54°–7.77° E.

Analysis of previous resistivity data in other parts of the province revealed the presence of three to four distinct subsurface layers, including a topsoil unit, lateritic sand, a principal aquifer of coarse to medium-grained sand, and a deeper gravelly or clayey sand formation. Based on these layered profiles, the DZ parameters, longitudinal conductance (LC), transverse resistance (T), longitudinal resistivity (ρL), and transverse resistivity (ρT) were calculated to infer the aquifers' natural capacity to filter contaminants (George et al., 2022a). According to the classification of Oladapo et al. (2004), about 67% of the aquifer zones fall within the poor to weak protective capacity range (S < 0.2 S), indicating high vulnerability, particularly in locations where the overburden is thin or composed of highly permeable materials (George & Thomas, 2024 & George et al., 2024).

In addition to evaluating protective capacity, the authors used geoelectric data to estimate hydraulic conductivity using Heigold's empirical relation, yielding values from 0.8 to 18.4 $m \cdot d^{-1}$. These facts suggest a moderate aquifer yield that reinforce the need for careful protection, as higher productivity zones are often more susceptible to rapid contaminant transport (Oteri, 2014).

A notable strength of this study lies in its use of geoelectric data to generate maps that can be used for monitoring groundwater management in the area. This approach provides a quantifiable basis for decision-making, directing attention and resources to the most priority risk zones. This research introduces a scientifically grounded and scalable framework for evaluating groundwater vulnerability in densely populated and rapidly urbanizing regions (Ibanga & George, 2016). By leveraging geoelectrical data and Dar Zarrouk interpretations, the study provides a more direct and hydrologically meaningful assessment than generalized indices (Ibuot et al., 2013; Ikpe and Ekanem, 2024).

Principally, the study aims to map the subsurface architecture of Ikot Ekpene and Obot Akara using vertical electrical sounding (VES) to delineate lithological variations and identify aquifer zones (George, 2021; Okon et al., 2019). In addition, it seeks to compute and interpret Dar zzarouk parameters including longitudinal conductance and transverse resistance as a basis for classifying the protective capacity of the overburden materials. To better understand the hydraulic performance of the aquifers, the study further aims to estimate hydraulic conductivity, thereby providing insights into aquifer transmissivity and yield potential.

II. STUDY AREA

2.1 Location

The geophysical survey was conducted in Ikot Ekpene and Obot Akara local government areas in Akwa Ibom State, Nigeria (Fig. 1). These areas lie within the tropical rainforest belt and are characterized by sedimentary formations with aquifers located in the Benin Formation.

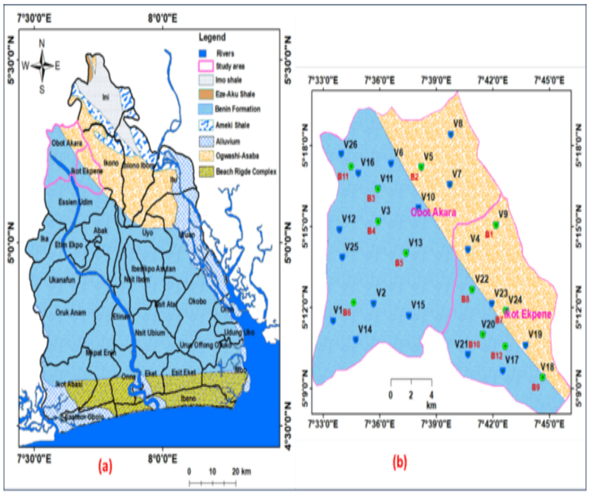

Fig.1: (a) Map of Akwa Ibom State showing the locations of Ikot Ekpene and Obot Akara in the northern part of the state; (b) Map of Ikot Ekpene and Obot Akara showing geology, VES points (e.g., V1, V2) and borehole locations (e.g., B1, B2)

2.2 Geological and Hydrogeological Setting

Ikot Ekpene and Obot Akara LGAs sit on the north eastern fringe of the Niger Delta sedimentary basin. The Benin Formation (Miocene - Recent) dominates, comprising unconsolidated coarse sands, gravel and minor clay lenses up to 200 m thick. Ground elevation ranges from 35 m asl in the south east to 140 m asl in the north west. Annual rainfall averages 2,300 mm, with a bimodal peak in June and September. The unconfined aquifer is typically encountered between 8 and 25 m depth; deeper, semi confined units occur below 50 m.

III. MATERIALS AND METHODS

3.1 Data Acquisition

Twenty-six vertical electrical soundings were recorded with maximum half current electrode spacing (AB/2) of 300 m. Instrumentation included an ABEM SAS 1000 Terrameter and GPS tagged coordinates, which allowed for georeferencing of the study area. The electrical resistivity method was employed for subsurface characterization due to its sensitivity to changes in lithology and fluid content. The Vertical Electrical Sounding (VES) technique was used, specifically the Schlumberger electrode configuration.

3.1.1 Field Equipment Used

Resistivity meter and its accessories such as steels used as current and potential electrodes, measuring tapes (100 m), GPS device (Garmin eTrex), WinResist software modeling and inversion software program were used

3.1.2 Data Acquisition

VES data were collected at multiple locations across the two study areas using the Schlumberger array. The current electrode separation (AB/2) was expanded progressively while maintaining the potential electrode spacing (MN) constant, until signal strength diminished or maximum length was reached. The method deployed Ohm's law and the field layout is detailed below:

In the study areas, the apparent resistance Ra was taken and the Resistivity was calculated from the potential electrode (MN/2) and the current electrode (AB/2) using Fig. 2 and Eqs 1-3:

$$R_a = \frac{\Delta V}{I} \qquad 1$$

$$\rho_{as} = \pi\left(\frac{(AB/2)^2 - (MN/2)^2}{\text{MN}}\right)R_a \qquad 2$$

where ΔV is potential difference and I is electric current. The apparent resistance was used generally in Eq. 2 to guestimate values of apparent resistivity , which on the whole, was considered as the mean resistivity of the geo-layer through which the injected current had passed. For MN = b and AB/2 = a in Fig. 2, the Eq. 3 was used to estimate by multiplying Schlumberger related-geometrical factor Gs by the measured or .

$$R_a \text{ or } \frac{\Delta V}{I}.$$

$$\rho_{as} = \pi\left(\frac{a^2}{b} - \frac{b}{4}\right)\frac{\Delta V}{I} \qquad 3$$

where geometric factor . Hence, where a = (AB/2) and MN = b, the and geometric factor Gs were related as Eq. 4

$$\rho_{as} = G_s R_a \qquad 4$$

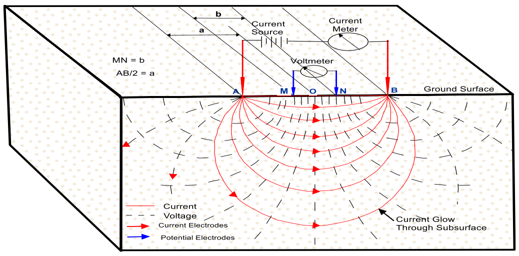

Fig.2: Diagram schematically illustrating the arrangement in geo-electrical resistivity operation

3.2 Data Processing and Inversion

After smoothing for geologic consistency, datasets were processed using WINRESIST inversion software program with iterative least-squares fitting (1 – 28 iterations). A 10% RMSE threshold ensured high accuracy (Udosen et al., 2018a, b; George et al., 2022b). Resulting inverted VES curves (Fig. 3) were integrated with borehole data to enable the estimation of primary (resistivity, thickness, depth) and secondary (hydraulic) indicial aquifer parameters as presented in Table 1.

Table 1: Summary of VES Data Interpretation Results

VES NO.	Location	Long. (°)	Lat. (°)	No of layers	Bulk Resistivity (Ωm)				Thickness (m)			Depth (m)		
					ρ_1	ρ_2	ρ_3	ρ_4	h_1	h_2	h_3	d_1	d_2	d_3
1	Ubon Ukwa	7.5588	5.1918	4	1172.1	863.6	1471.2	455.7	1.7	27.7	65.7	1.7	29.4	95.1
2	Nto Eton 1	7.5949	5.2026	4	847.5	239.1	994.8	332.6	1.7	12.6	73.0	1.7	14.3	87.3
3	Ikot Idem Udo	7.5989	5.2532	3	443.1	1343.9	628.1		9.0	73.5		9.0	82.5	
4	Mbiaso	7.6780	5.2360	4	903.5	601.3	2073.6	1421.8	1.8	14.6	80.2	1.8	16.4	96.6
5	Ikwen	7.6369	5.2867	4	125.0	612.8	1904.1	401.9	2.7	25.6	60.0	2.7	28.3	88.3
6	Ikot Okim	7.6102	5.2892	3	200.5	1397.2	2065.0		19.5	30.2		19.5	49.7	
7	Nto Ndang 1	7.6620	5.2760	3	205.3	2083.6	904.0		10.5	81.7		10.8	92.2	
8	Nto Ndang 2	7.6629	5.3070	3	379.7	861.4	1834.9		22.7	75.3		22.7	98.0	
9	Ikot Atasung	7.7030	5.2510	3	65.3	1079.8	1625.6		4.5	38.6		4.5	43.1	
10	Oku Obom	7.6345	5.2618	3	231.1	716.0	1748.9		11.2	70.2		11.2	81.4	
11	Okpo Eto	7.5984	5.2733	4	724.4	190.6	1063.6	717.3	0.8	16.3	71.9	0.8	17.1	89.0
12	Ikot Essien	7.5645	5.2482	4	399.2	97.4	359.4	789.3	3.8	8.9	40.1	3.8	12.7	52.8
13	Ntong Uno	7.6235	5.2335	3	263.5	495.1	1427.9		12.5	89.0		12.5	101.5	
14	Nto Eton 2	7.5790	5.1800	3	694.6	1573.9	374.0		7.0	61.0		7.0	68.0	
15	Imama	7.6259	5.1950	3	214.1	517.8	1101.5		14.4	83.3		14.4	97.7	

16	Nto Edino 1	7.5812	5.2831	3	400.3	1738.5	524.6		6.6	86.3		6.6	92.9	
17	Abiakpo Edem Idim	7.7090	5.1610	4	865.7	327.2	2041.3	637.8	0.8	9.7	64.9	0.8	10.5	75.4
18	Utu Ikot Ekpenyong	7.7442	5.1568	3	1145.9	2005.2	762.0		2.3	82.1		2.1	84.4	
19	Uruk Uso	7.7292	5.1767	4	630.4	148.9	2472.8	690.4	1.3	11.1	68.1	1.3	12.4	80.5
20	Ifuho	7.6914	5.1832	3	213.0	970.8	1493.7		2.3	70.0		2.3	72.3	
21	Ibong Ikot Akan	7.6780	5.1710	3	228.5	2111.6	434.5		6.1	49.3		6.1	55.4	
22	Ibong	7.6820	5.2110	3	431.9	40.6	375.5		1.4	14.6	47.5	1.4	16.0	63.5
23	Ikot Abia Idem	7.6992	5.2024	4	224.4	59.1	1264.5	324.9	2.1	8.4	59.9	2.1	10.5	70.4
24	Ikot Otu	7.7117	5.1981	3	207.4	2648.1	1506.3		4.5	80.9		4.5	85.4	85.4
25	Ikot Ideh	7.5669	5.2311	4	326.2	599.1	2225.2	1273.4	0.4	24.9	71.5	0.8	25.3	96.8
26	Usaka Annang	7.5660	5.2950	4	474.9	1063.6	489.0	2658.3	0.9	29.3	55.3	0.9	30.2	85.5
	Minimum				65.3	40.6	359.4	324.9	0.4	8.4	40.1	0.8	10.5	52.8
	Maximum				1172.1	2648.1	2472.8	2658.3	22.7	89.0	82.4	22.7	101.5	107.1
	Average				457.6	920.2	1320.7	843.2	5.7	45.4	64.7	6.4	51.1	83.8

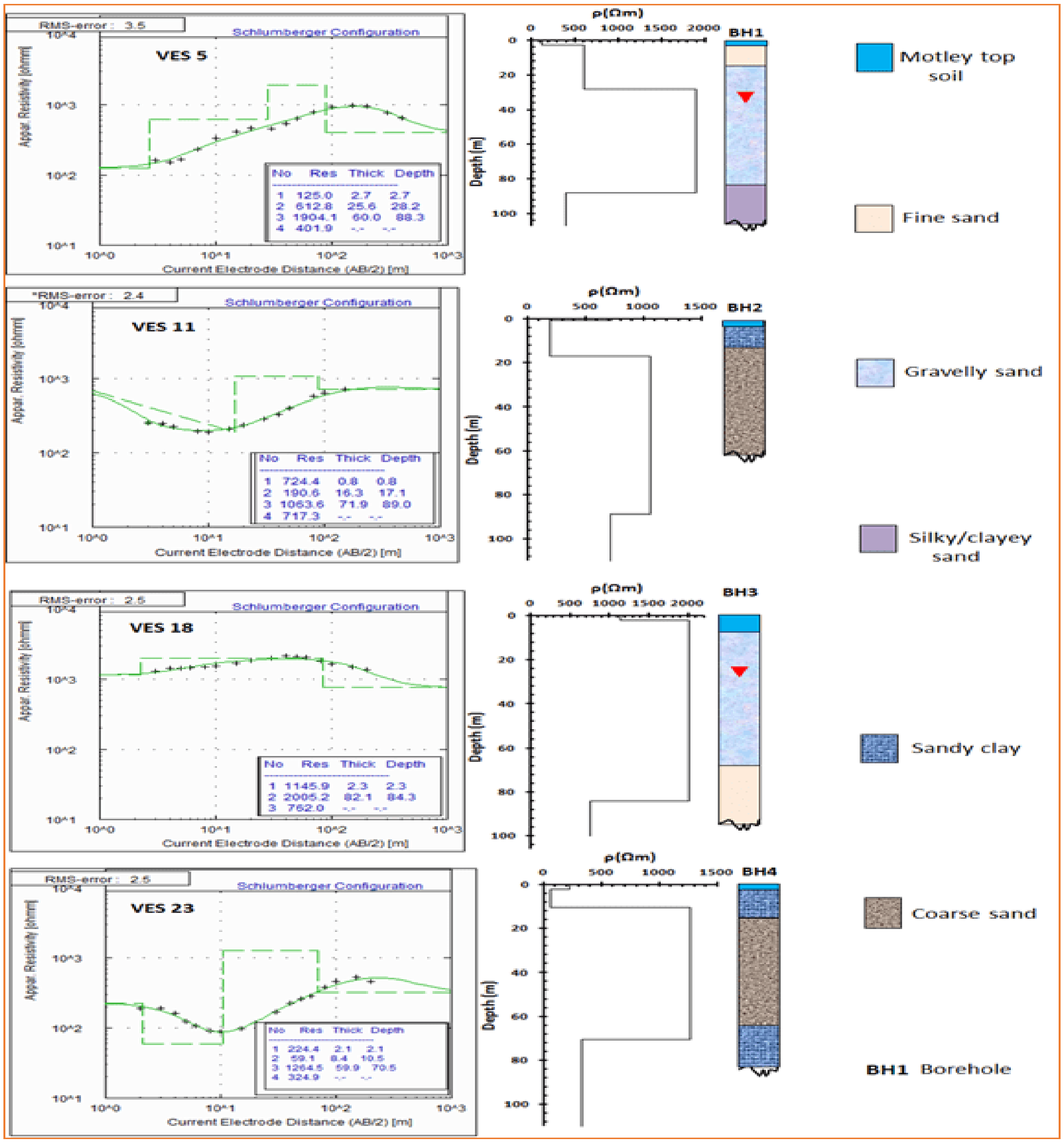

Fig. 3: Sample model VES curves at (a) Ikwen - VES 5 (b) Okpo Eto - VES 12 (c) Utu Ikot Ekpenyong - VES 19 (d) Ikot Abia Idem - VES 24. Correlations between borehole lithological logs and the VES results are displayed in the inserted legends

3.3 Computation of Dar Zarrouk Parameters

Dar-Zarrouk parameters were derived from the resistivity and thickness of subsurface layers and were useful in assessing aquifer protective capacity. The parameters were transverse resistance (T) and longitudinal conductance (LC) of the overburden layer. They were computed using Eqs. 5 and 6:

$$T = \rho h \qquad 5$$

$$LC = \frac{h}{\rho} \qquad 6$$

where T is transverse resistance (Ω·m²), LC is the longitudinal conductance of the overburden layer in Siemens (S), is the resistivity of the layer (Ωm) and h is the thickness of the layer (m). The interpretation of vulnerability rating was achieved using longitudinal conductance in Table 2.

Table 2: Longitudinal conductance and aquifer protective capacity rating (Henriet 1976; Oladapo and Akintorinwa 2007)

LC (S)	APC rating
> 10.00	Excellent
5.00 – 10.00	Very good
0.70 - 4.49	Good
0.20 - 0.69	Moderate
< 0.10 – 0.19	weak
<0.10	Poor

IV. RESULTS AND DISCUSSION

Groundwater remains a critical resource for potable water supply and agricultural use, particularly in developing regions where surface water sources are either insufficient or heavily polluted. In Nigeria, rapid population growth and ongoing urban expansion are exerting increasing pressure on subsurface hydrological systems. This pressure is especially evident in areas like Ikot Ekpene and Obot Akara, two adjoining metropolitan zones in Akwa Ibom State, characterized by a blend of urban and semi-rural land-use patterns with varying levels of groundwater vulnerability.

The need for systematic groundwater monitoring in these regions is urgent. The compounding effects of poor sanitation, unregulated solid waste disposal, and widespread agricultural runoff have introduced significant risks to groundwater quality and sustainability. In response, this study deployed 26 Vertical Electrical Sounding (VES) stations strategically across Ikot Ekpene and Obot Akara (Fig. 1). Geo-electrical data acquisition was conducted using the configuration shown in Fig. 2 and processed through the use of borehole data through the WINRESIST software suite into VES curves with samples shown in Fig. 3.

The data interpretation revealed three to four geoelectrically distinct subsurface layers, each with differing resistivity values, thicknesses, and depths - key indicators of their hydrogeological properties (Table 1). These findings were validated by correlating resistivity profiles with borehole lithologic logs (Ekanem 2022a, b; Hassan & El-Hadidy, 2023), ensuring the reliability of the subsurface characterization. Crucially, the study applied primary geo-electric indices (resistivity, layer thickness, and depth) alongside secondary parameters, notably the Dar-Zarrouk parameters - longitudinal conductance and transverse resistance. These derived indices enable a deeper assessment of aquifer protective capacity and the delineation of zones susceptible to contamination.

The integration of VES data with lithological and hydrological ground-truth information allowed for a more robust interpretation of the subsurface framework using contour and image 2D maps in Figs. 4–6, further visualized the spatial distribution of geoelectrical units, their corresponding lithologies, and the anthropogenic impacts on aquifer vulnerability. This comprehensive approach enhances the reliability of identifying safe groundwater development zones and supports evidence-based groundwater management in the region.

The resistivity contour maps in Fig. 4 highlight subsurface variations across four layers, with increasing depth corresponding to deeper hydrological zones. In the first layer (a), representing the topsoil, Ikot Ekpene displays predominantly low resistivity values (65.3 Ωm at V9 to 1145.9 Ωm at V18). The relatively low resistivities in the topsoil are especially within densely populated and commercial zones. These values likely result from organic-rich, moisture-laden clays impacted by surface runoff and percolating waste fluids. The terrain here is susceptible to infiltration, and the extensive use of septic systems and the absence of centralized waste management contribute to surface and near-surface pollution (Inim et al., 2020). Conversely, in Obot Akara, the resistivity values in the same layer range between 125.0 Ωm at V5 and 1172.1 Ωm at V1, typical of sandy or lateritic topsoil with higher permeability and less water retention. These conditions imply a relatively cleaner and well-drained surface environment, underscoring the protective advantage of its semi-rural character (Ikpe et al., 2024; Inyang et al., 2024).

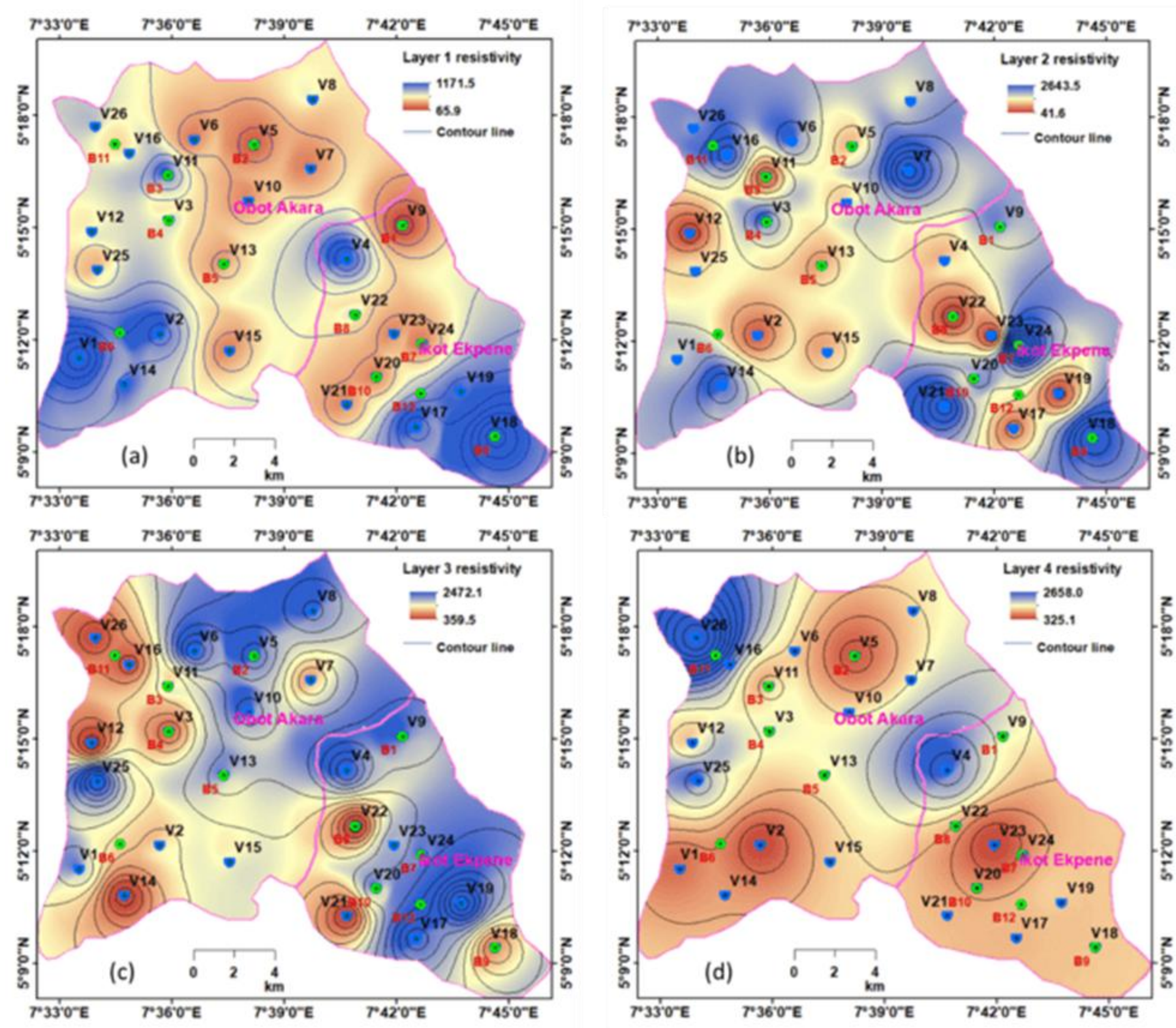

Fig. 4: Layers 1 to 4 resistivity contour maps for the Obot Akara and Ikot Ekpene study areas represented in (a)-(d), respectively

As the depth increases to the second layer (b), characteristic of weathered horizons, the contrast between the two areas remains apparent (Umoh et al., 2022). Ikot Ekpene, particularly the central belt, reveals resistivity values between 40.6 Ωm at V22 and 2648.1 Ωm at V24, a signature of water-saturated sandy formations possibly intercalated with clay zones or layers of accumulating leachates (Inyang et al., 2024). These mix-ranged resistivities suggest active contaminant transport into deeper zones, likely facilitated by porous pathways (Asfahani et al., 2023). In contrast, eastern Obot Akara continues to show moderately higher resistivity (>400 Ωm), indicative of fine-sandy substrata less prone to vertical pollutant migration. The integrity of the vadose zone in Obot Akara thus acts as a compromised buffer against surface pollutants infiltrating into the aquifer system directly (George et al., 2025). This suggests the reason for the generally vulnerable zone with weak-poor protecting layers.

The third layer (c) marks the aquifer-bearing formation (Ikpe et al., 2025). Here, the disparity becomes even more striking. The northwest quadrant of Ikot Ekpene is dominated by moderately low resistivity pockets (<400 Ωm), suggestive of fine-grained, clay-rich or saline water-bearing strata according to Ekanem and Udosen (2023a). This region, characterized by intensive farming and proximity to older residential zones, may be receiving nitrate-rich inflows from fertilizers or poorly managed greywater (Inyang et al., 2024). On the other hand, the southwestern section of Obot Akara features high resistivity zones > 2000 Ωm, aligning with sandy or gravelly aquifer units known for their high permeability and low susceptibility to contamination due to the low resistivity overlaying sandy materials characterized by poor permeability. These findings are consistent with prior studies such as Ako & Osondu (1986), who linked similar resistivity profiles to deeper productive and clean aquifers in sedimentary environments.

At the deepest interval analyzed, the fourth layer (d) representing the saturated zone, the resistivity patterns reinforce earlier observations. Southeastern Ikot Ekpene records relatively low resistivity values (< 650 Ωm), a possible indication of elevated ionic content within the sandy groundwater aquifer repository as demonstrated by the ground truth, likely from long-term contamination (Thomas et al., 2021). These findings raise concerns over the integrity of the deep aquifer system, especially under sustained urban pressure. In stark contrast, central Obot Akara registers relatively high resistivity > 650 Ωm, signifying uncontaminated, fresh groundwater in a well-protected aquifer unit. The implications are clear: while Obot Akara benefits from natural lithological barriers and lower anthropogenic stress, Ikot Ekpene's groundwater resources are under immediate threat.

Complementing the resistivity interpretations, the contour maps of longitudinal conductance and transverse resistance (Fig. 5) provide crucial insights into subsurface hydraulic behavior. Longitudinal conductance, a function of the thickness-to-resistivity ratio of overburden materials, is typically associated with protective capacity (Oladapo & Akintorinwa, 2007). Relatively Low values (0.2 0.36 S) observed in central and northern Obot Akara are often interpreted as indicative of moderate aquifer protection due to thin layer and conductive clays. However, in this case, they may also signal the presence of highly saturated, pollutant-laden layers - highlighting the limitations of relying solely on conductance without contextual geological data. Ikot Ekpene, especially its Northern sector, shows also, a moderate to low conductance values (0.2–0.36 S), which, although less protective in theory, may also reflect a relatively clean, sandy overburden with moderate contaminations. Outsides these identified layers as shown in Ikot Ekpene and Obot Akara in Fig. 5, other locations have weak to poor aquifer protective capacity and the corresponding susceptibility with longitudinal < 0.10 – 0.19 s and <0.1S, respectively.

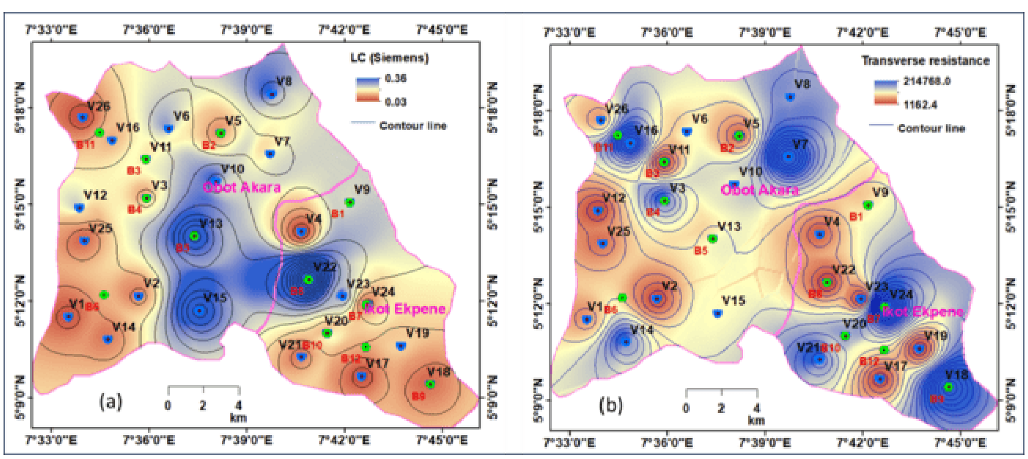

Fig. 5: Contour maps of (a) Longitudinal conductance (LC) in Siemens and (b) Transverse resistance (Ωm^2) for the layers in the Obot Akara and Ikot Ekpene study areas

Transverse resistance, derived from the product of layer thickness and resistivity, correlates with aquifer transmissivity (Fig.5) (Akpan et al., 2020; George et al., 2021, 2023). High values (>10,000 Ωm²) in northeastern, northwestern and southwestern parts of Obot Akara suggest thick, resistive, and transmissive aquifers suitable for high-yield groundwater abstraction (Ikpe et al., 2022; Ekanem & Udosen 2023b). Meanwhile, the low values (<5000 Ωm²) recorded in northern and quasi-southern regions near V17 and V19 in Ikot Ekpene are consistent with thin, and moderately low aquifer resistivity units that are both low-yielding and highly vulnerable to pollution from overly porous protective units. The interpretation aligns with the work of Singh (2005), who used transverse resistance to demarcate productive aquifers in alluvial settings. The aquifer protective capacity APC map shows that the entire area exhibits moderate to poor protectivity (Ikpe et al., 2022).

Again, Fig.6 presents a composite view of aquifer depth and aquifer protective capacity (APC). In Ikot Ekpene, aquifers are generally shallow (10.5 m at V17 to 85.4 m at V24 in Table 3), with poor APC values predominantly in the north and southern zones (Fig.6). These areas are characterized by thin sandy overburden and low conductance, offering minimal natural protection. Such conditions not only accelerate pollutant travel from the surface but also reduce the time available for natural attenuation processes. Obot Akara, in contrast, features deeper aquifer depths with range of 12.7 m at V12 and 101.5 m at V13 and overburden layer. This shows a mix-ranged protective layers, which finally results in poor protection as demonstrated in the APC map. Although the study area lacks natural protection due to its geogenic nature of the aquifer system and its seals, APC map shows that the Obot Akara is relatively more moderately quasi-protected than Ikot Ekpene. This revelation may be due to excessive anthropogenic activities occasioned by urbanization and high population density in Ikot Ekpene (George and Thomas, 2023). The two local governments are overlain by sand-clay sequence, which have APC values exceedingly less than 1.0 S. According to classification by Oladapo and Akintorinwa (2007), the results of protective rating shows that the area under study lacks excellent, good, and fair protections. The depth and protective layering ensure better groundwater quality and long-term sustainability, even under moderate anthropogenic pressure. However, the study with moderately low protective layers and depth of burial of aquifer show that the area has non-potable groundwater resource.

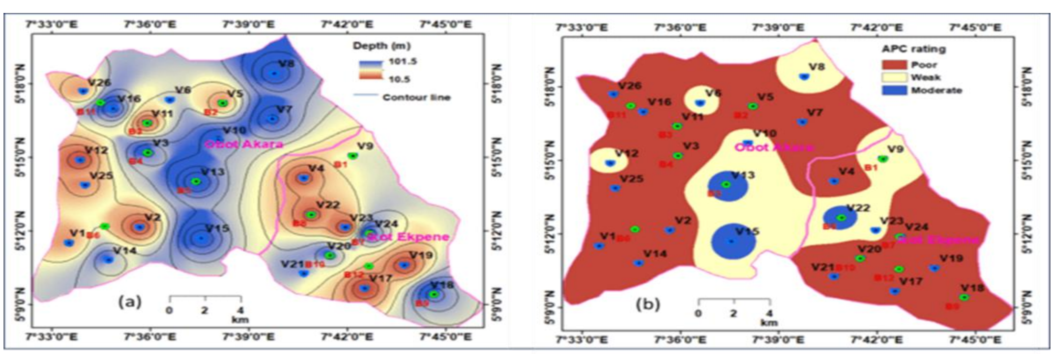

Fig. 6: Contour map of (a) Aquifer depth (m) and (b) Aquifer protective capacity (APC) image map for the Obot Akara and Ikot Ekpene study areas

Table 3: Results of assessment of aquifer protection

VES NO.	Location	Protecting Layers	Protecting Layer Resistivity (Ωm)	Thickness (m)	Aquifer Depth (m)	Transverse Resistance	Longitudinal Conductivity S (Ω^{-1})	APC rating
1	Ubon Ukwa	1	1172.1	1.7	29.4	25914.3	0.03	Poor
		2	863.6	27.7				
2	Nto Eton 1	1	847.5	1.7	14.3	4453.4	0.05	Poor
		2	239.1	12.6				
3	Ikot Idem Udo	1	443.1	9.0	82.5	102764.6	0.08	Poor
		2	1343.9	73.5				
4	Mbiaso	1	903.5	1.8	16.4	10405.3	0.03	Poor
		2	601.3	14.6				
5	Ikwen	1	125.0	2.7	28.3	16025.2	0.06	Poor
		2	612.8	25.6				
6	Ikot Okim	1	200.5	19.5	49.7	46105.2	0.12	Weak
		2	1397.2	30.2				
7	Nto Ndang 1	1	205.3	10.5	92.2	172385.8	0.09	Poor
		2	2083.6	81.7				
8	Nto Ndang 2	1	379.7	22.7	98.0	73482.6	0.15	Weak
		2	861.4	75.3				
9	Ikot Atasung	1	65.3	4.5	43.1	41974.1	0.10	Weak
		2	1079.8	38.6				
10	Oku Obom	1	231.1	11.2	81.4	52851.5	0.15	Weak
		2	716.0	70.2				
11	Okpo Eto	1	724.4	0.8	17.1	3686.3	0.09	Poor
		2	190.6	16.3				
12	Ikot Essien	1	399.2	3.8	12.7	2383.8	0.10	Weak
		2	97.4	8.9				
13	Ntong Uno	1	263.5	12.5	101.5	47357.7	0.23	Moderate
		2	495.1	89.0				
14	Nto Eton 2	1	694.6	7.0	68,0	100870.1	0.05	Poor
		2	1573.9	61.0				
15	Imama	1	214.1	14.4	97.7	46215.8	0.23	Moderate
		2	517.8	83.3				
16	Nto Edino 1	1	400.3	6.6	92.9	152674.5	0.07	Poor
		2	1738.5	86.3				
17	Abiakpo Edem Idim	1	865.7	0.8	10.5	3866.4	0.03	Poor
		2	327.2	9.7				
18	Utu Ikot Ekpenyong	1	1145.9	2.3	84.4	167262.5	0.04	Poor
		2	2005.2	82.1				
19	Uruk Uso	1	630.4	1.3	12.4	2472.3	0.08	Poor
		2	148.9	11.1				
20	Ifuho	1	213.0	2.3	72.3	68445.9	0.08	Poor
		2	970.8	70.0				
21	Ibong Ikot Akan	1	228.5	6.1	55.4	105495.7	0.05	Poor
		2	2111.6	49.3				

22	Ibong	1	431.9	1.4	16	1197.4	0.36	Moderate
		2	40.6	2.1				
23	Ikot Abia Idem	1	224.4	14.6	10.5	967.7	0.15	Weak
		2	59.1	8.4				
24	Ikot Otu	1	207.4	4.5	85.4	215164.6	0.05	Poor
		2	2648.1	80.9				
25	Ikot Ideh	1	326.2	0.4	25.3	15048.1	0.04	Poor
		2	599.1	24.9				
26	Usaka Annang	1	474.9	0.9	30.2	31590.9	0.03	Poor
		2	1063.6	29.3				

Collectively, the geophysical data reveal a clear hydrogeological divide between Ikot Ekpene and Obot Akara. The former is typified by relatively lower resistivity values, moderately elevated longitudinal conductance due to clay-rich contaminated overburden, and shallow aquifers that offer little resistance to pollutant infiltration when compared to the later averagely. Coupled with low transverse resistance and poor APC, Ikot Ekpene's groundwater system faces significant threats from ongoing urban and industrial development as 4 out of the 10 locations (40%) considered has relatively low groundwater aquifer potential as opposed to 3 out of 16 locations representing 19 % in Obot Akara. There is an urgent need for mitigation strategies such as improved wastewater management, regulated land use, aquifer sealing, and the establishment of protective buffer zones around critical recharge areas in the two metropolises.

Conversely, Obot Akara presents a more favorable scenario. Elevated resistivity across most of the layers, moderate conductance in some locations, deep aquifers, and high transverse resistance collectively suggest a well-preserved deeper aquifer system. These features render it suitable for sustainable groundwater extraction, especially in future urban development planning. However, as land-use patterns shift and agricultural intensity increases, continued monitoring is essential to prevent degradation.

CONCLUDING REMARKS

This study highlights the effectiveness of integrating geophysical methods, particularly Vertical Electrical Sounding (VES) and Dar-Zarrouk parameter analysis, in assessing groundwater contamination risks. In Ikot Ekpene, shallow, low-resistivity aquifers with minimal longitudinal conductance (<0.2 S) indicate high vulnerability to pollution, exacerbated by urban encroachment and insufficient overburden protection. Obot Akara, on the other hand, exhibits deeper, more resistive aquifer zones with high transverse resistance (>10,000 Ωm²), reflecting relatively improved groundwater conditions, though still not entirely secured.

Across both regions, sand-clay subsurface formations result in aquifer protective capacity (APC) values consistently below 1.0 S, underscoring a general deficiency in natural aquifer protection and signaling the risk of contamination if proactive measures are not implemented. These insights call for immediate interventions, including stricter land-use policies, enhanced waste management practices, and routine monitoring of recharge areas.

By leveraging geoelectric data and Dar-Zarrouk indices, this work provides a detailed understanding of the hydrogeological setting and pollution susceptibility, supporting more targeted and evidence-based water resource planning. The outcomes are consistent with previous studies (e.g., Olayinka & Olorunfemi, 1992; Ezeh, 2011; Okiongbo & Akpofure, 2012), reinforcing the critical role of resistivity surveys in groundwater management within heterogeneous tropical sedimentary environments.

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