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DELINEATION OF SUBSURFACE LITHOLOGY AND AQUIFER STRUCTURES USING ELECTRICAL RESISTIVITY SURVEYS IN PARTS OF UKWUANI LOCAL GOVERNMENT AREA OF DELTA STATE

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ABSTRACT

This study investigates aquifer structures and properties in Ukwuani Local Government Area, Nigeria, using Vertical Electrical Soundings (VES) with Schlumberger and Dipole-Dipole configurations. The Schlumberger were conducted at Obiaruku (VES 1–6), Obinomba (VES 7–12), Umutu (VES 13–15), and Umuaja (VES 16–18), employing an ABEM SAS 1000 Terrameter for data acquisition. Interpretation was done using WinResist for VES and Dipro Software to generate 2D resistivity images, vertical profiles and delineate subsurface formations and aquifer zones in the study area. Near-surface high resistivity values of 200 to 1000 ohm-m corresponding to compact topsoil, transiting to clayey sands and laterite layers with moderate resistivity, indicating varying clay content and moisture retention. Deeper layers in Umutu and Umuaja exhibit high-resistivity coarse sands, highlighting viable groundwater formations. In contrast, stations located in Obiaruku and Obinomba predominantly show medium-grain sand and clay layers. The Dipole-Dipole survey further delineated profiles showing unconsolidated, moisture-bearing topsoil transitioning to dense, low-permeability formations. The first two layers in Obiaruku with resistivity values of 116–145 ohm-m, suggest the presence of shallow aquifers, while deeper layers characterized by resistivity values of 581–930 ohm-m consist of gravels that serve as confining layers. This geophysical approach identified promising aquifer zones in upper layers and thick sand formations which are conducive to groundwater storage and flow. These findings provide valuable insights for sustainable groundwater exploration and management in Ukwuani Local Government Area.

Keywords: *Resistivity, Sand, Aquifer, Clay, Groundwater.*

INTRODUCTION

Groundwater, a vital component of Earth's freshwater reserves, is essential for sustaining ecosystems and human activities (Giordano, 2009). The growing populations, urbanization, and industrialization have led to the overexploitation and contamination of groundwater, highlighting the need for effective management strategies (Li *et al.*, 2021). Groundwater resources play a critical role in meeting diverse water needs across Nigeria, including household consumption, agricultural irrigation, industrial processes, and environmental balance (Singh, 2014).

Geophysical methods offer valuable tools for subsurface characterization, enabling researchers and geoscientists to map geological features, assess groundwater resources, and mitigate geological hazards with greater precision and efficiency (Umayah, 2022). By leveraging these techniques, we can unlock new insights into the Earth's subsurface and address critical challenges related to resource management, environmental monitoring, and infrastructure development (Umayah and Eyankware, 2022). Geophysical data give

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continuous information about subsurface properties across large areas, this helps add to the detailed measurements taken from boreholes at specific points. (Atakpo and Ofomola, 2012).

Ukwuani Local Government Area, located in the southern region of Nigeria within Delta State, is characterized by a diverse geological landscape shaped by geological processes spanning millions of years (Oseji, 2009). The sedimentary sequences in Ukwuani serve as reservoirs for hydrocarbons and groundwater aquifers. Therefore, it is pertinent to empirically delineate the geological and hydro-geological structures in Ukwuani for sustainable water management and development (Agbalagba, 2017). Aquifers within the sedimentary formations provide a vital source of freshwater for drinking, irrigation, and industrial purposes, making groundwater a precious resource for the local communities (Okolie, 2010).

LOCATION AND GEOLOGY OF THE STUDY AREA

Ukwuani Local Government Area is within Delta State, Nigeria, positioned between the latitudes of 5°30'N and 6°30'N, and longitudes of 6°15'E and 7°00'E. This region is famed as the source of the River Ethiope, a vital waterway that begins its journey here. The Ethiope River holds immense significance for the local communities, serving as a lifeline for residents, agriculture, and wildlife alike (Oseji, 2013; Enebeli *et al.*, 2021).

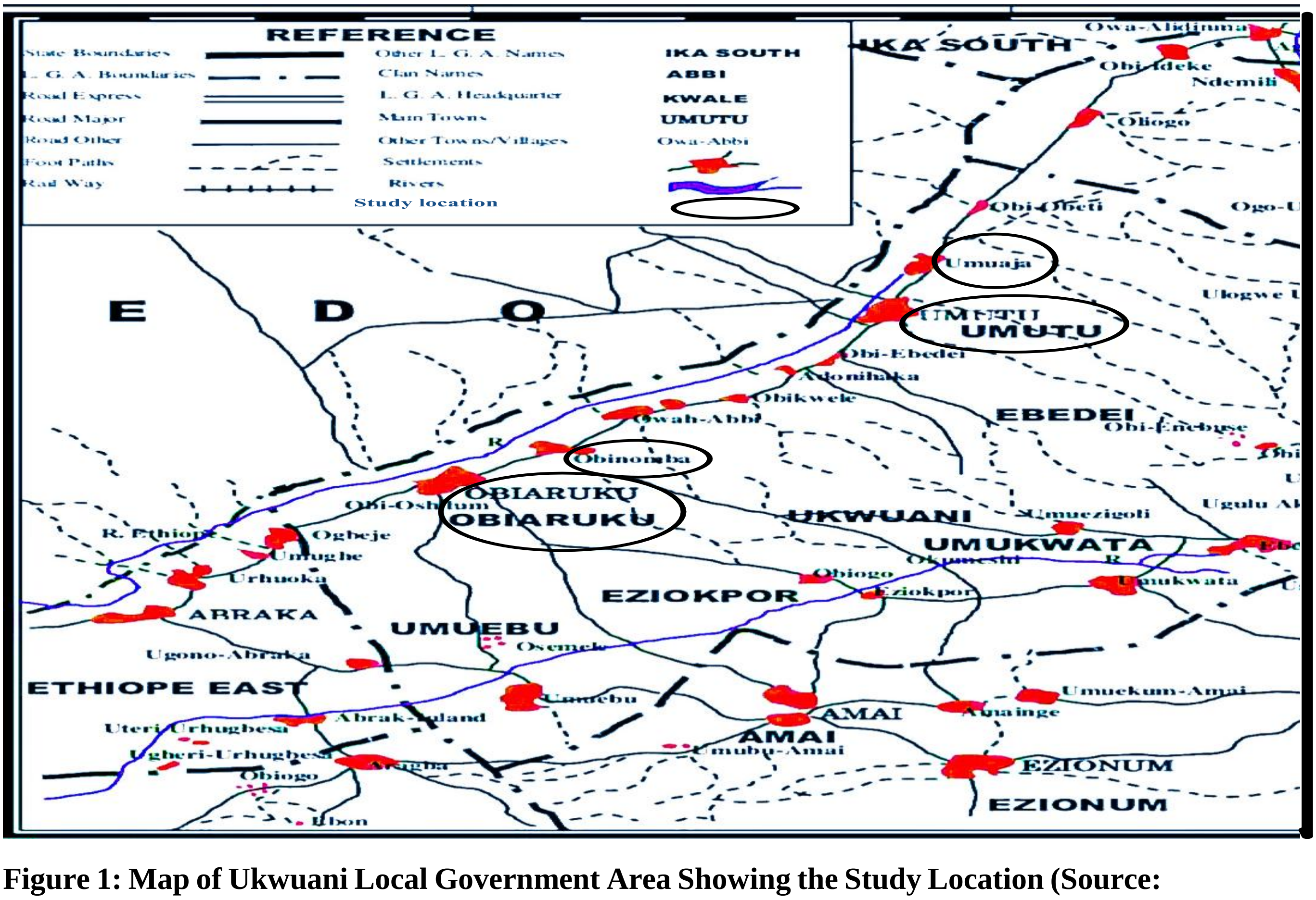

Figure 1: Map of Ukwuani Local Government Area Showing the Study Location (Source: Delta State Ministry of Housing).

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MATERIALS AND METHODS

This study employed Vertical Electrical Soundings (VES) using both Dipole-Dipole and Schlumberger configurations to delineate subsurface resistivity variations indicative of potential groundwater zones. Survey points were distributed across four key locations: VES 1 to 6 in Obiaruku, VES 7 to 12 in Obinomba, VES 13 to 15 in Umutu, and VES 16 to 18 in Umuaja. The survey utilized an SAS 1000 Terrameter, which was calibrated meticulously to ensure accurate data acquisition. Electrodes were strategically positioned, and measurements were recorded in accordance with established geophysical protocols. Data were processed using specialized software—WinResist for Schlumberger data interpretation and Dipro for 2D inversion—yielding 2D resistivity images and vertical profiles to facilitate subsurface analysis.

Theoretical Framework

The electrical resistivity method is based on Ohm's law. This law state that the resistance of a material is directly proportional to its cross sectional area, provided the material's temperature remain constant. This is mathematically represented in equation (1) below (Telford *et al.*, 1990).

$$R = \frac{\Delta V}{I} \quad (1)$$

Where R is resistance, ΔV is Potential difference and I is current.

As shown in figure 2 the current was sent into the ground using electrodes $(C_1 and C_2)$. The potential difference created by the current was then measured using the potential electrodes $(P_1 and P_2)$This process shows how potential difference happens because of the current.

$$VP_1 = \frac{I\ell}{2\pi}\left[\frac{1}{r_1} - \frac{1}{r_2}\right] \quad (2)$$

$$VP_2 = \frac{I\ell}{2\pi}\left[\frac{1}{R_1} - \frac{1}{R_2}\right] \quad (3)$$

Thus, the potential difference resulting from P_1 and P_2 can be expressed as

$$VP_1 - VP_2 = \frac{I\ell}{2\pi}\left[\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{R_1} - \frac{1}{R_2}\right] \quad (4)$$

Therefore, the apparent resistivity of the subsurface is represented by the equation

$$\ell_a = \frac{2\pi\Delta V}{I}\left[\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{R_1} + \frac{1}{R_2}\right] \quad (5)$$

The above expression in equation 5 represent the generalized apparent resistivity. The geometric factor G is given below in equation 6.

Schlumberger Array

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The Schlumberger array is widely used configuration in electrical resistivity surveys, particularly in groundwater, mineral and environmental investigations. It provides depth information about subsurface resistivity variations. This array is characterized by placing two current electrodes $(A\ and B)$far apart while the two potential electrodes $(M\ and\ N)$ remain closer to the center. Two current electrodes $(A\ and B)$inject current (I) into the ground. Two potential electrodes $(M\ and\ N)$ difference(V). The spacing between the current electrode is much larger than the spacing between the potential electrodes AB/2 > 5MN/2 (Okolie, 2013; Atakpor *et al.*, 2008). The midpoint of the array is fixed, and the measurements are taken symmetrically about the center. The Schlumberger array remains a cornerstone in geophysical investigation due to its versatility, simplicity and accuracy in characterizing subsurface resistivity variation (Okolie, 2010).

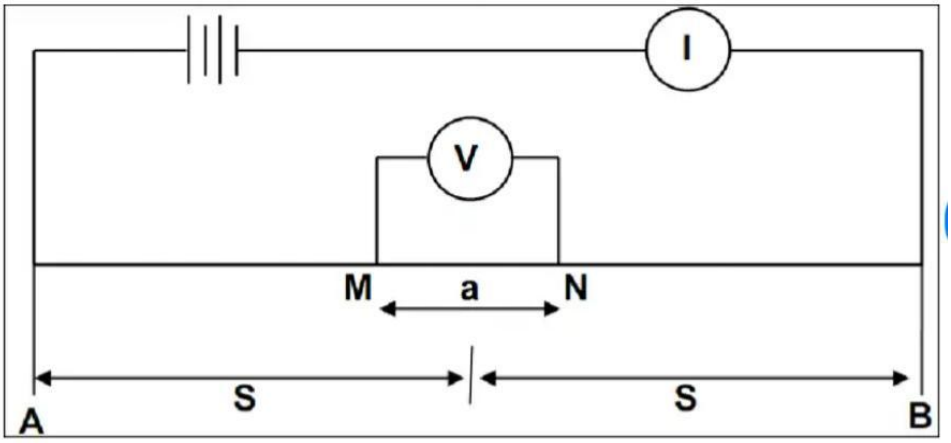

Figure 2: Schematic of Schlumberger array for data acquisition.

The Schlumberger configuration equation is shown below.

$$P_{as} = \frac{2\pi R}{\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}} \qquad (6)$$

By substituting r_1, r_2, r_3, r_4 in equation (6), the apparent resistivity for the Schlumberger array is expressed as:

$$P_{as} = \frac{2\pi R}{\frac{1}{na_1} - \frac{1}{na+a} - \frac{1}{na+a} + \frac{1}{na}} \qquad (7)$$

$$P_{as} = \left[\frac{2\pi R}{\left(\frac{1}{na} - \frac{1}{na}\right)\left(\frac{1+1}{na+a+na+na}\right)}\right] \qquad (8)$$

$$P_{as} = \left[\frac{2\pi R}{\frac{2}{na} - \frac{2}{na+a}}\right] \qquad (9)$$

$$P_{as} = \frac{2\pi R}{\frac{2(na+a) - 2na}{na(na+a)}} \qquad (10)$$

$$P_{as} = \frac{2\pi R}{\frac{2na}{na(na+a)}} \qquad (11)$$

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$$P_{as} = 2\pi R \frac{na(na+a)}{2a} \tag{12}$$

$$= \pi Rn(na + a)$$

$$P_{as} = \pi Rn(na + a) \tag{13}$$

Here, P_{as} represents the apparent resistivity for Schlumberger array.

Dipole-dipole array

The dipole-dipole array is a geophysical method used to investigate subsurface features by measuring electrical resistivity and induced polarization. It involves two pairs of electrode: one pairs inject current into the ground while the other measures the resulting voltage. The spacing between this pairs (dipole) is adjusted to explore different depths and lateral variations (Wiwatthanachang and Giao, 2011). This method provides high resolution imaging of subsurface resistivity, making it ideal for applications such as groundwater exploration, environmental contamination studies and mineral exploration (Salman *et al.*, 2020).

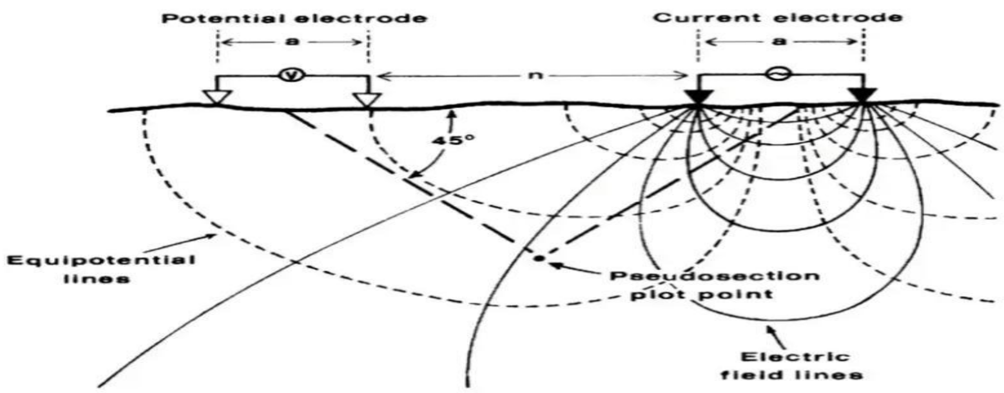


Figure 3: Dipole-dipole configuration, including electric field lines (solid) and resultant equipotential surfaces (dashed).

Recall the generalize equation, we have that

$$\rho a = 2\pi \frac{\Delta V}{l}\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right) \tag{14}$$

The apparent resistivity of the Dipole array is give as follow

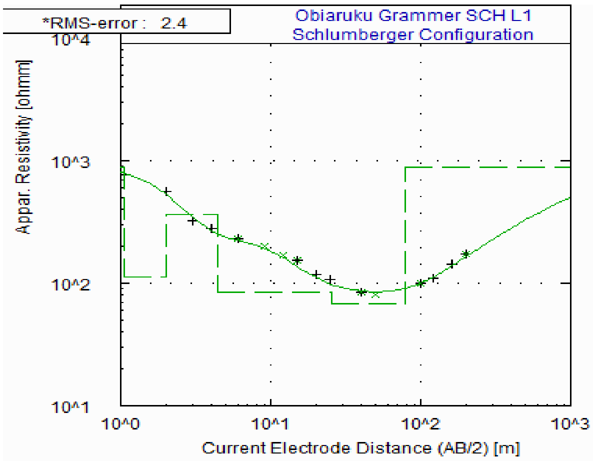
$$pa = 2\pi \frac{\Delta V}{l}\left(\frac{1}{a+na} - \frac{1}{na} - \frac{1}{2a+na} - \frac{1}{a+na}\right) \tag{15}$$

$$pa = 2\pi \frac{\Delta V}{l}\left(\frac{2}{(n+1)a} - \frac{1}{na} - \frac{1}{(n+2)a}\right) \tag{16}$$

$$pa = 2\pi \frac{\Delta V}{l} \frac{n(n+1)(n+2)a}{2n^2+4n-(n^2+3n+2)-n^2+n} \quad (17)$$

$$pa = 2\pi \frac{\Delta V}{l} n(n+1)(n+2)a \quad \text{(Telford } et\ al.\text{, 1990)} \quad (18)$$

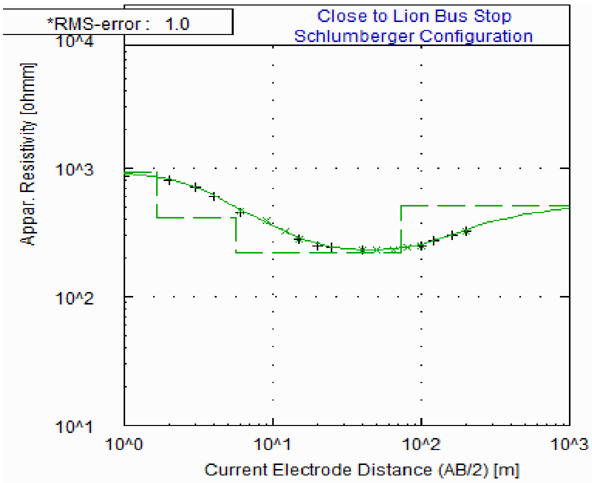
RESULTS



No	Res	Thick	Depth
1	889.0	1.1	1.1
2	113.0	0.9	2.0
3	368.0	2.5	4.5
4	84.3	21.1	25.6
5	68.3	52.5	78.1
6	892.0	-.-	-.-

* RMS on smoothed data

Figure 4: VES 1 Obiaruku



No	Res	Thick	Depth
1	923.9	1.6	1.6
2	411.7	4.0	5.6
3	218.8	67.3	72.9
4	509.9	-.-	-.-

* RMS on smoothed data

Figure 5: VES 10 Obinomba

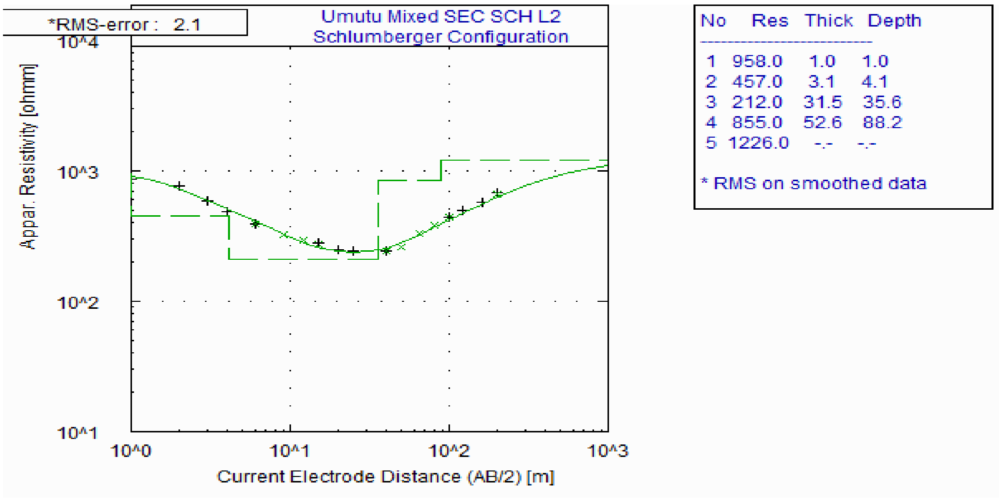


Figure 6: VES 14 Umutu

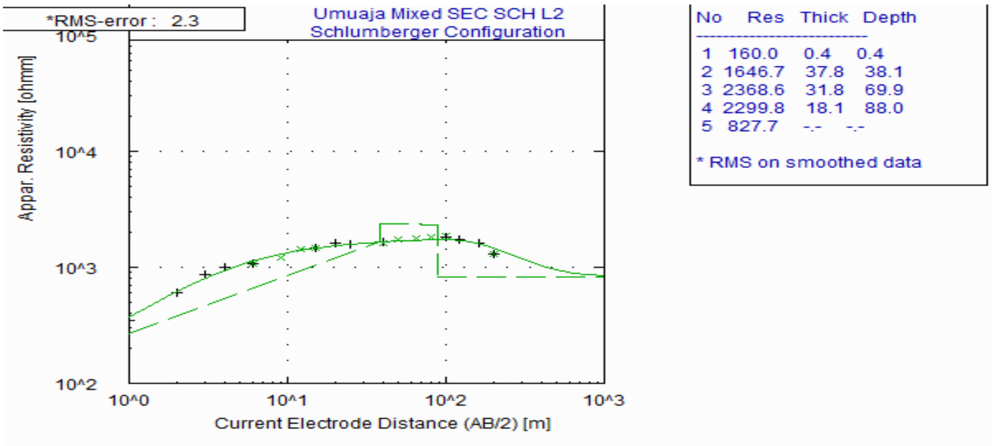


Figure 7: VES 17 Umuaja

TABLE 1a : PRESENTATION OF RESULTS FROM COMPUTER ITERATION

VES NUMBER	LAYER	RESISTIVITY (Ωm)	THICKNESS (m)	DEPTH (m)	CURVE TYPE	LITHOLOGY
VES 1	1	889.0	1.1	1.1	H	TOP SOIL
	2	113.0	0.9	2.0	$P_1>P_2<P_3$	CLAYEY SAND
	3	368.0	2.5	4.5		CLAYEY LATERITE
	4	84.3	21.1	25.6		CLAY
	5	68.3	52.5	78.1		CLAY
	6	872.0				MEDIUM GRAIN SAND
VES 2	1	1035.0	0.7	0.7	QA	TOP SOIL
	2	112.0	1.1	1.8	$P_1>P_2>P_3<P_4$	CLAYEY SAND
	3	440.0	1.1	1.8		CLAYEY LATERITE

	4	32.1	5.2	10.9		CLAY
	5	79.8	67.2	78.1		CLAY
	6	752				MEDIUM GRAIN SAND
VES 3	1	1619	0.4	0.4	QH	TOP SOIL
	2	365.0	2.4	3.4	$P_1>P_2>P_3<P_4$	CLAYEY LATERITE
	3	282.0	2.1	5.5		CLAYEY SAND
	4	75.0	70.5	76.0		CLAY
	5	750				MEDIUM GRAIN SAND
VES 4	1	1487.9	1.5	1.5	H	TOP SOIL
	2	557.7	3.3	4.7	$P_1>P_2<P_3$	CLAYEY LATERITE
	3	165.8	13.2	17.9		CLAYEY SAND
	4	41.0	70.1	88.0		CLAY
	5	455.4				MEDIUM GRAIN SAND
VES 5	1	1471.4	1.7	1.7	QA	TOP SOIL
	2	194.1	14.8	16.5	$P_1>P_2>P_3<P_4$	CLAYEY SAND
	3	371.1	12.8	29.4		CLAYEY LATERITE
	4	100.2	58.0	87.3		CLAY
	5	869.1				MEDIUM GRAIN SAND
VES 6	1	1150.0	1.1	1.1	QA	TOP SOIL
	2	468.0	1.6	2.7	$P_1>P_2>P_3<P_4$	CLAYEY LATERITE
	3	205.0	23.2	25.9		SANDY CLAY
	4	55.4	47.9	73.8		CLAY
	5	646				MEDIUM GRAIN SAND
VES 7	1	1271.0	1.3	1.3	QH	TOP SOIL
	2	44.7	1.5	2.8	$P_1>P_2>P_3<P_4$	CLAY
	3	495.0	5.8	8.6		CLAYEY LATERITE
	4	82.1	36.4	45.0		CLAY
	5	859.0				MEDIUM GRAIN SAND

TABLE 1b: PRESENTATION OF RESULTS FROM COMPUTER ITERATION

VES NUMBER	**LAYER**	**RESISTIVITY (Ωm)**	**THICKNESS (m)**	**DEPTH (m)**	**CURVE TYPE**	**LITHOLOGY**
VES 8	1	1672.0	0.2	0.2	Q	TOP SOIL
	2	754.0	1.3	1.5	$P_1>P_2>P_3$	CLAYEY LATERITE
	3	264.0	9.3	10.8		CLAYEY LATERITE
	4	128.0	28.2	39.0		CLAYEY SAND
	5	720.0				MEDIUM GRAIN SAND
VES 9	1	942.0	2.4	2.4	H	TOP SOIL
	2	160.0	5.0	7.4		CLAYEY SAND

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	3	451.0	5.2	12.6	$P_1 > P_2 < P_3$	CLAYEY LATERITE
	4	202.0	28.1	40.7		CLAYEY SAND
	5	791.0				MEDIUM GRAIN SAND
VES 10	1	923.9	1.6	1.6	Q	TOP SOIL
	2	411.7	4.0	5.6	$P_1 > P_2 > P_3$	CLAYEY LATERITE
	3	218.8	67.3	72.9		CLAYEY SAND
	4	509.9				MEDIUM GRAIN SAND
VES 11	1	896.0	2.1	2.1	H	TOP SOIL
	2	244.0	0.8	2.9	$P_1 > P_2 < P_3$	CLAYEY SAND
	3	184.0	22.7	25.6		CLAYEY SAND
	4	397.0	34.0	59.6		CLAYEY LATERITE
	5	925				MEDIUM GRAIN SAND
VES 12	1	684.6	1.8	1.8	H	TOP SOIL
	2	179.4	16.0	17.9	$P_1 > P_2 < P_3$	CLAYEY SAND
	3	551.4	20.0	37.9		CLAYEY LATERITE
	4	101.6	9.5	47.4		CLAYEY SAND
	5	815.8				MEDIUM GRAIN SAND
VES 13	1	655.0	1.8	1.8	H	TOP SOIL
	2	1883.0	16.0	17.9	$P_1 > P_2 < P_3$	COARSE SAND
	3	252.0	53.0	70.8		CLAYEY LATERITE
	4	829.0	6.4	77.2		MEDIUM GRAIN SAND
	5	606.0				MEDIUM GRAIN SAND
VES 14	1	958.0	1.0	1.0	H	TOP SOIL
	2	457.0	3.1	4.1	$P_1 > P_2 < P_3$	CLAYEY LATERITE
	3	212.0	31.5	35.6		CLAYEY SAND
	4	855.0	52.6	88.2		MEDIUM GRAIN SAND
	5	1226.0				MEDIUM GRAIN SAND

TABLE 1c : PRESENTATION OF RESULTS FROM COMPUTER ITERATION

VES NUMBER	LAYER	RESISTIVITY (Ωm)	THICKNESS (m)	DEPTH (m)	CURVE TYPE	LITHOLOGY
VES 15	1	1622	0.4	0.4	HA	TOP SOIL
	2	498.8	1.8	2.1	$P_1 > P_2 > P_3 < P_4$	CLAYEY LATERITE
	3	98.8	2.0	4.2		CLAY
	4	376.5	71.7	75.9		CLAYEY SAND
	5	1713.0				MEDIUM GRAIN SAND
VES 16	1	405.0	0.4	0.4	A	TOP SOIL

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	2	831.0	37.8	38.1	$P_1<P_2<P_3$	MEDIUM GRAIN SAND
	3	1647.0	31.8	69.9		COARSE SAND
	4	1143.0	18.1	88.0		MEDIUM GRAIN SAND
	5	827.7				MEDIUM GRAIN SAND
VES 17	1	160	0.4	0.4	A	TOP SOIL
	2	1646.7	37.8	38.1	$P_1<P_2<P_3$	MEDIUM GRAIN SAND
	3	2368.6	31.8	69.9		COARSE SAND
	4	2299.8	18.1	88.0		COARSE SAND
	5	827.7				MEDIUM GRAIN SAND
VES 18	1	194.0	0.4	0.4	A	TOP SOIL
	2	970.0	11.9	12.3	$P_1<P_2<P_3$	MEDIUM GRAIN SAND
	3	2367.0	48.8	61.1		COARSE SAND
	4	1572.0	46.9	108		MEDIUM GRAIN SAND
	5	599.0				MEDIUM GRAIN SAND

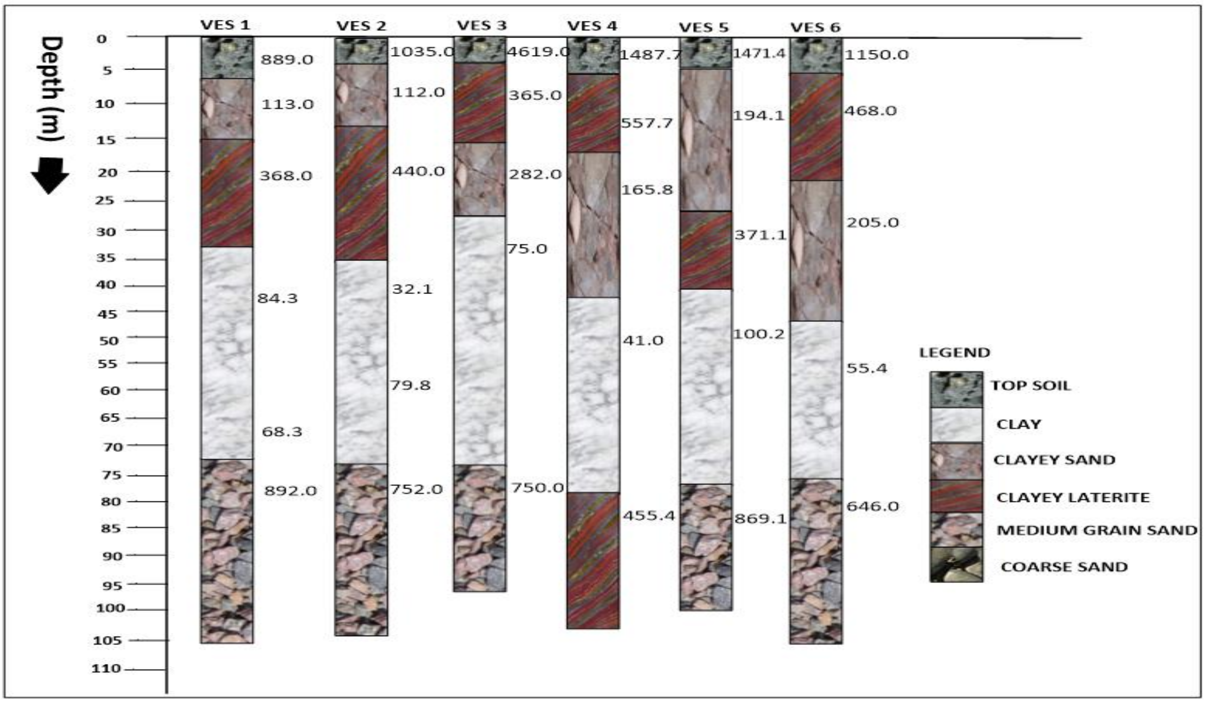

Figure 8: Geoeletric Section of VES 1-6

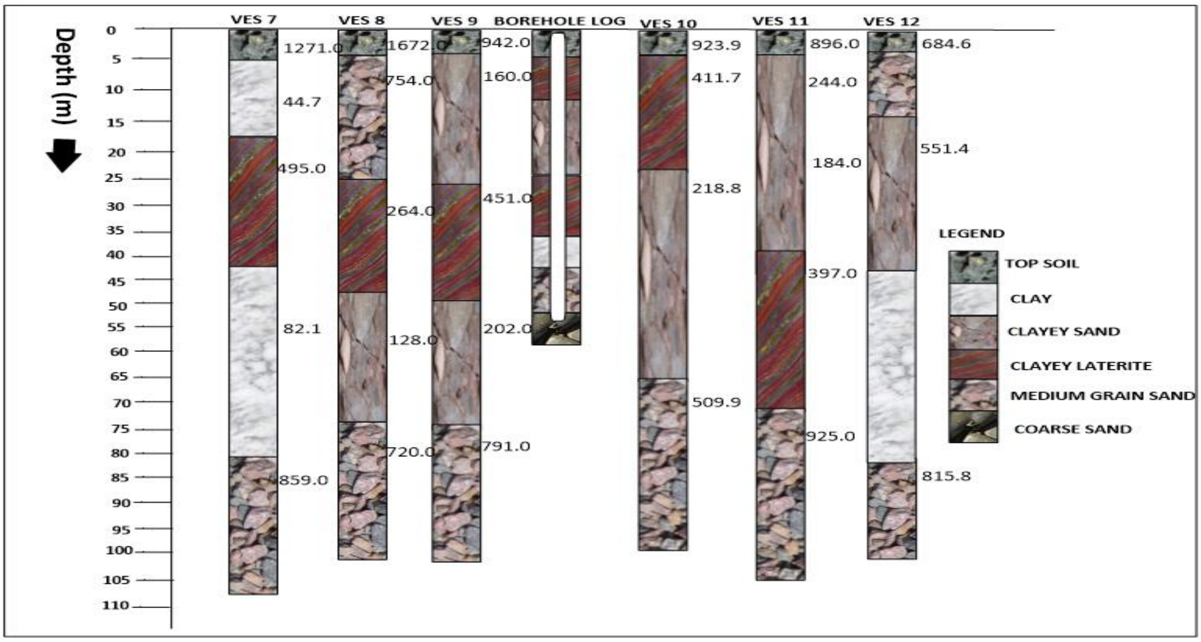

Figure 9: Geoeletric Section of VES 7-12

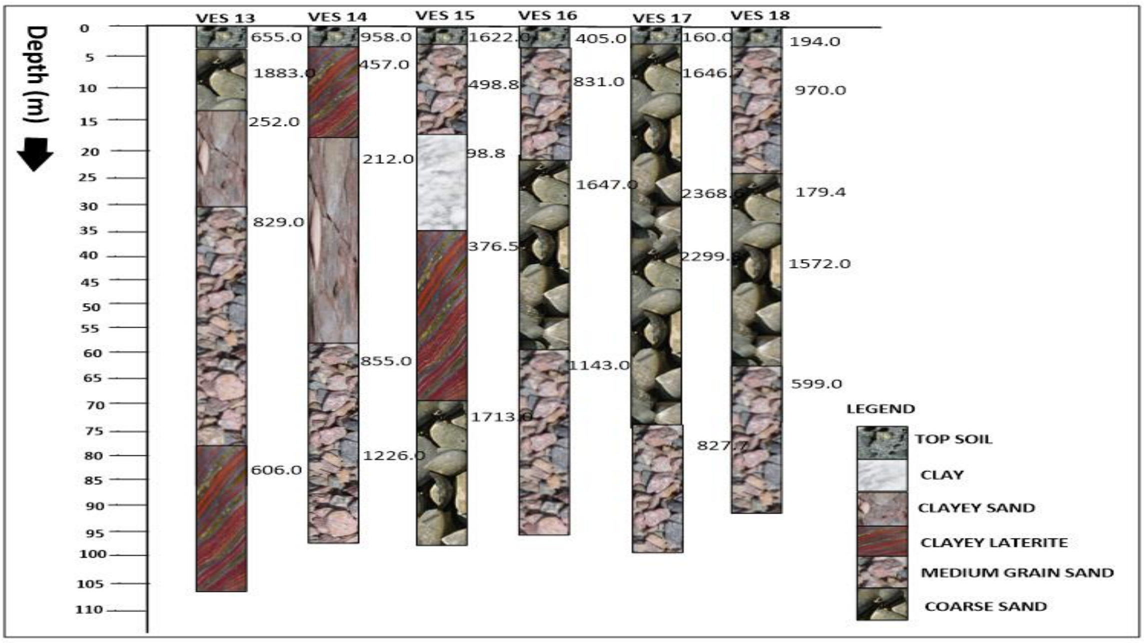

Figure 10: Geoeletric Section of VES 13-18

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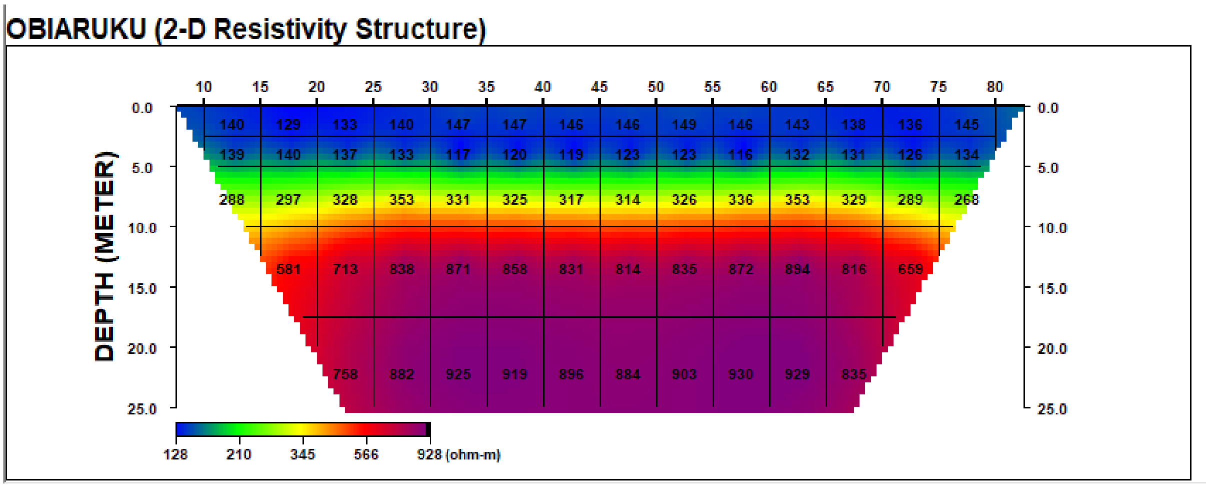

Figure 11: 2D dipole-dipole in Obiaruku

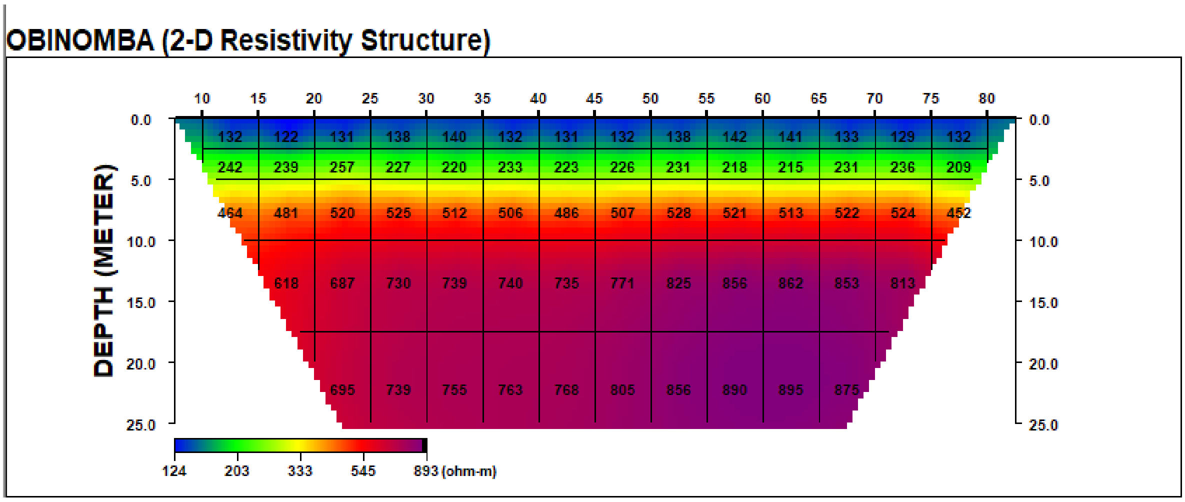

Figure 12: 2D dipole-dipole in Obinomba

UMUTU

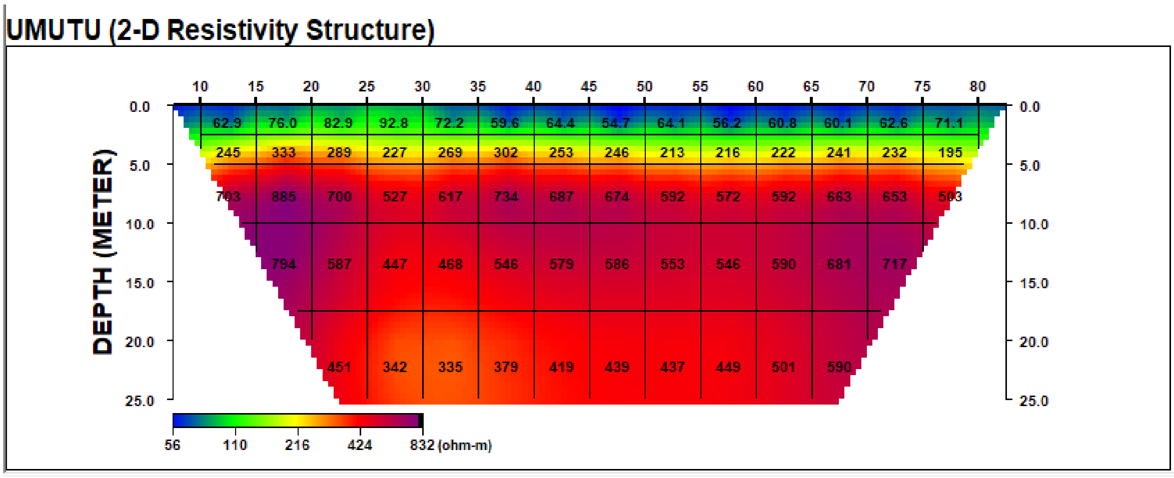

Figure 13: 2D dipole-dipole in Umutu

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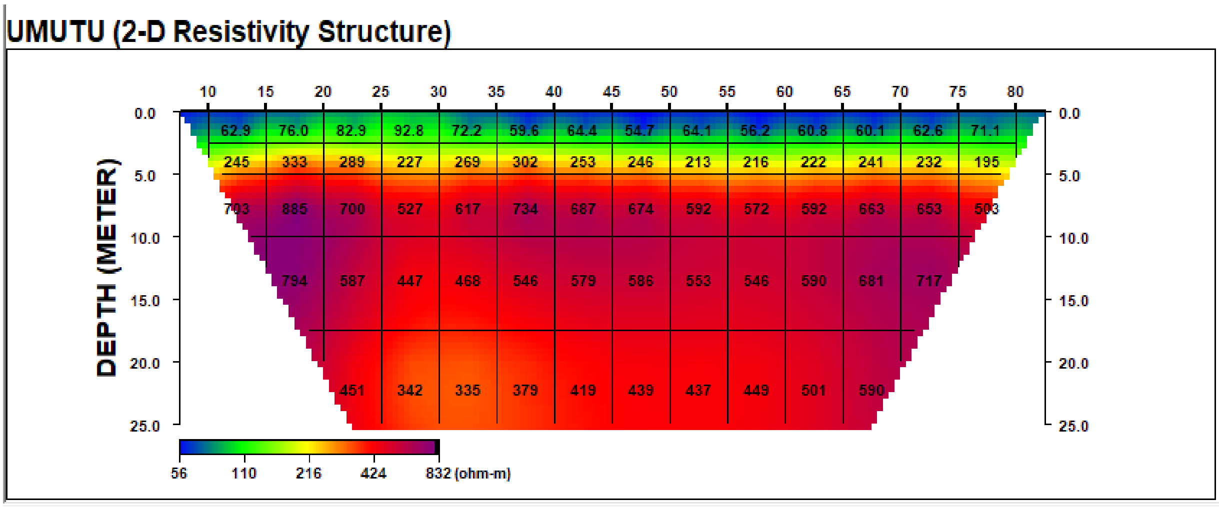

Figure 14: 2D dipole-dipole in Umuaja

DISCUSSION OF RESULTS

The findings from the Vertical Electrical Sounding (VES) surveys conducted at 18 locations within Ukwuani Local Government Area offer comprehensive insights into the subsurface lithology and aquifer characteristics, revealing considerable spatial variations. The topsoil is characterized by high resistivity values ranging from 160 to 1,646 Ωm, with thicknesses between 0.4 and 1.8 m, indicative of dry or compact surface conditions. Beneath the topsoil, layers of clayey sand and clayey laterite with moderate resistivity values (44–551 Ωm) and thicknesses of 0.8–22.7 m were identified, reflecting variations in clay content and moisture levels. These layers serve as transitional units between the surface and deeper formations.

VES 1 and VES 2 exhibit similar subsurface sequences, with clayey sand resistivity values of 112–113 Ωm and clayey laterite resistivity values of 368–440 Ωm at depths of 4.5 m and 1.8 m, respectively. VES 3 through VES 8 also reveal intermediate clayey layers, with VES 8 showing a notably higher topsoil resistivity of 1,672 Ωm and a thickness of 0.2 m, suggesting drier or more compact conditions. Conversely, VES 4 and VES 5 demonstrate thick clay layers with low resistivity values of 41 Ωm and 100.2 Ωm with thicknesses of 70.1 m and 58 m, respectively, indicating significant moisture retention. Similar trends of low-resistivity clay layers are observed from VES 6 through VES 12, which likely act as barriers to groundwater flow, creating zones of limited hydraulic conductivity.

The most promising aquifer zones are identified in the deeper subsurface layers, particularly in areas such as Umutu Mixed Secondary School, Opposite the Source of River Ethiope in Umuaja, and Umuaja Mixed Secondary School. These locations feature medium to coarse-grained sand layers with high resistivity values, indicating significant groundwater potential. At Umutu, medium-grained sand layers with resistivity values ranging from 855 to 1,713 Ωm are found between depths of 77.2 m and 88.2 m, forming productive aquifers with excellent groundwater storage and flow capacity. Similarly, at the site opposite the Source of River Ethiope in Umuaja, medium-grained sand with a resistivity of 831 Ωm extends to a depth of 38.1 m and is underlain by coarse-grained sand with a resistivity of 1,647 Ωm and a thickness of 31.8 m, reaching depths of 69.9 m. These confined aquifers exhibit substantial potential for sustainable groundwater development. The shallow subsurface in the surveyed areas is predominantly composed of clay and clayey sands, which may restrict groundwater yield. However, the deeper subsurface layers, particularly those consisting of medium- to coarse-grained sands in the identified locations, present significant aquifer potential, making them suitable for groundwater exploration and development.

Profile 1: Obiaruku

In Obiaruku, five subsurface layers were identified through resistivity analysis. The first two layers displayed resistivity values from 116 to 145 ohm-m, characteristic of near-surface materials like topsoil, and sandy or loamy soils, possibly with moisture content. These moderately low resistivity values indicate unconsolidated formations that could serve as pirched aquifers suitable for groundwater extraction. The third layer, with resistivity values between 268 and 353 ohm-m, suggests more consolidated materials, such as compacted sands with reduced moisture content. The deeper fourth and fifth layers, with resistivity values ranging from 581 to 930 ohm-m, likely consist of gravels, which are highly resistive and may act as barriers to groundwater flow.

Profile 2: Obinomba

The resistivity survey in Obinomba also revealed five layers, each offering insights into subsurface conditions. The first layer, with resistivity values from 129 to 145 ohm-m, indicates the presence of near-surface materials like sandy or loamy soils that are moderately unconsolidated. The second layer, with resistivity values between 209 and 257 ohm-m, suggests a transition to slightly more compact materials, such as compacted sands, which may still hold groundwater, making it a potential aquifer zone. Higher resistivity values in the third, fourth, and fifth layers (up to 890 ohm-m) indicate dense sands, gravels, and low-permeability formations, which act as confining layers restricting groundwater flow.

Profile 3: Umutu

The Umutu survey produced five distinct layers with varying resistivity values. The first layer, ranging from 54.7 to 92.8 ohm-m, is characterized by moisture-rich near-surface materials, potentially forming a shallow aquifer. The second layer shows a resistivity increase to values between 194 and 333 ohm-m, suggesting more consolidated materials that might still hold groundwater. The third and fourth layers exhibit high resistivity values up to 885 ohm-m, indicative of gravelly sands and possibly weathered bedrock, which have lower moisture content. The fifth layer, with resistivity values between 342 and 490 ohm-m, suggests partially dense materials with limited groundwater potential. These findings highlight the first two layers as viable groundwater zones, while the deeper layers serve as confining formations.

Profile 4: Umuaja

In Umuaja, the survey results revealed five distinct layers with notable resistivity variations. The first layer, with resistivity values between 236 and 274 ohm-m, indicates near-surface materials that could contain moisture, such as sandy or loamy soils. The second layer, with resistivity values from 331 to 436 ohm-m, reflects a transition to more compact materials, such as compacted sands, potentially forming an aquifer. Higher resistivity values in deeper layers indicate dense, low-permeability materials, likely acting as barriers to groundwater flow and impacting the region’s groundwater distribution.

CONCLUSION

This research provided a comprehensive geophysical investigation of aquifer structures within Ukwuani Local Government Area, offering critical insights into subsurface properties and groundwater potential. The findings highlight significant lithological and resistivity variations across surveyed points, with deeper coarse sand formations at VES 14, VES 16, VES 17, and VES 18 identified as promising aquifer zones with substantial groundwater potential, while shallower clayey and clayey-laterite layers act as barriers to groundwater flow and deeper resistive formations serve as confining layers, limiting vertical groundwater migration. The use of vertical electrical sounding (VES) and dipole-dipole resistivity profiling further refines the understanding of groundwater dynamics, profiling provides adequate understanding of subsurface lithology, groundwater dynamics and favourable aquifer zones in Ukwuani Local Government Area, which are essential for planning sustainable groundwater exploration and resource management.

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