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DETERMINING AQUIFER TRANSMISSIVITY AND HYDRAULIC CONDUCTIVITY IN KWALE, DELTA STATE, NIGERIA, VIA INTEGRATED ELECTRICAL RESISTIVITY AND PUMP TEST DATA ANALYSIS

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ABSTRACT

The integration of Vertical Electrical Soundings (VES) and pump test analysis has successfully determined the aquifer transmissivity and hydraulic conductivity in Kwale, Delta State, Nigeria. The VES data provided a detailed view of subsurface resistivity variations, identifying potential aquifer zones and layers with reduced permeability. Complementary pump test results confirmed these findings, showcasing the aquifer's ability to sustain a stable water yield suitable for industrial and domestic purposes. Notably, data from VES 16 near the pump test site highlight localized aquifer property variations, likely influenced by lithological differences. This study delivers crucial insights for groundwater resource management, offering a valuable framework to support water supply planning and sustainable land use in the region.

Key words: *Transmissivity, Aquifer, Schlumberger, Resistivity, Water.*

INTRODUCTION

An aquifer is a geological formation, layer, or group of layers that contain and transmit groundwater. It is a critical component of the hydrological cycle, storing and conveying water underground (Alam *et al.*, 2021). Aquifers are typically composed of porous materials such as sand, gravel, or fractured rock that can hold and transmit water (Egbai and Iserhien-Emekeme 2015). They play a vital role in providing a sustainable source of water for various human activities, including drinking water supply, irrigation, and industrial use (Oseji *et al.*, 2018).

Aquifers can be classified based on their geological and hydrological characteristics. Unconfined aquifers are those in which the water table, or the upper surface of the groundwater, is not confined by overlying layers (Egbai, 2013). These aquifers are more susceptible to contamination and are often recharged by precipitation directly infiltrating the ground. Confined aquifers, on the other hand, are bounded above and below by impermeable layers, which can create pressure that causes water to rise in wells above the aquifer. Confined aquifers are typically more protected from contamination but may require deeper wells for extraction (Zhang and Kanyerere, 2020; Raji and Packialakshmi, 2022)

The properties of an aquifer, such as Its porosity, permeability, and transmissivity, govern its ability to store and transmit water. Porosity refers to the volume of pore spaces in the aquifer material and is expressed as a percentage (Moharir *et al.*, 2020). Permeability is a measure of how easily water can flow through the aquifer material and is influenced by factors such as grain size, sorting, and packing of the grains (Báez *et al.*, 2021). Transmissivity is a measure of the aquifer's ability to transmit water under a hydraulic gradient and is dependent on hydraulic conductivity and aquifer thickness (Egbai, 2013)

Aquifers can be recharged naturally through processes such as infiltration of precipitation, seepage from rivers and lakes, and lateral groundwater flow from adjacent areas (Zhang and Kanyerere, 2020). However, human activities can also significantly impact aquifer recharge rates. Excessive groundwater pumping for irrigation, industrial use, or domestic supply can lead to groundwater depletion and reduced recharge rates (Levintal *et al*., 2023). Contamination from activities such as mining, agriculture, and improper waste disposal can also affect aquifer quality and recharge rates (Grinshpan *et al.,* 2021)

Sustainable aquifer management ensure a reliable water supply. This involves monitoring groundwater levels and quality, implementing water conservation measures, and regulating groundwater extraction to prevent overexploitation. Sustainable management practices can help maintain aquifer health and ensure that groundwater resources are available for future generations (Alam *et al.,* 2021; Zhang and Kanyerere, 2020).

Aquifer transmissivity is a key parameter that characterizes the ability of an aquifer to transmit water (Egbai, 2013). It is defined as the product of hydraulic conductivity and aquifer thickness and the formation of numerous structural features, such as faults and folds, which have influenced the distribution and accumulation of hydrocarbons in the basin (Okolie, 2010).

Kwale is home to several oil and gas fields, which have been developed by various oil companies (Dami *et al.,* 2014). These fields produce both oil and gas, which are vital to Nigeria's economy. Additionally, the area hosts deposits of clay, which are used in the ceramics industry (Dami *et al.,* 2014; Oseji, 2011). These clay deposits are found within the sedimentary formations and are a valuable economic resource for the region (Ezeigbo and Ozumba, 2012).

MATERIALS AND METHODS

represents the volume of water that can flow through a unit width of the aquifer under a unit hydraulic gradient (Pozdniakov *et al.,* 2021). Estimating aquifer transmissivity is essential for assessing groundwater potential, designing effective groundwater exploitation schemes, and implementing sustainable groundwater management practices (Qi *et al.,* 2024).

Geology and Describtion of the Study Area

Kwale, located in Delta State, Nigeria, lies within the Niger Delta Basin, a prolific sedimentary basin known for its hydrocarbon resources. The geographical coordinates of Kwale are approximately 5.6324° N latitude and 6.5282° E longitude (Oseji *et al.,* 2005). The area is characterized by its sedimentary formations, including sandstones, shales, and claystones, which were primarily deposited during the Cretaceous and Tertiary periods.

The geology of Kwale Is influenced by several tectonic events, including rifting, sedimentation, and structural deformation (Oseji, 2011). These processes have led to

A total of 20 Vertical Electrical Soundings (VES) were conducted, along with a pumping test (plate 1), to determine aquifer transmissivity and hydraulic conductivity in Kwale, Delta State, Nigeria. The geophysical survey in the Kwale area of Ndokwa West Local Government Area was designed to investigate groundwater resources. Site selection was carefully planned based on geological and hydrogeological factors. The equipment, including the ABEM SAS 1000 Terrameter, was calibrated to ensure precise data collection. The survey utilized Schlumberger configurations, placing electrodes to capture subsurface resistivity variations. Collected data was processed using specialized software, such as Winresist, to ensure accuracy and

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reliability in interpreting the aquifer's characteristics.

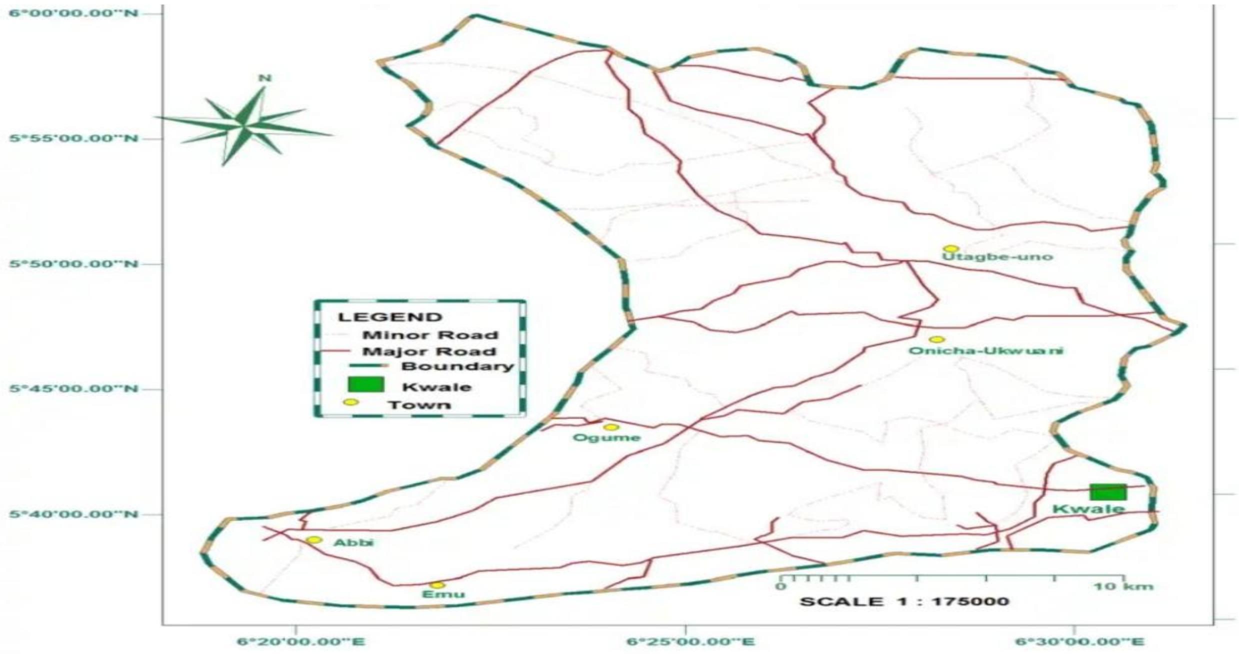

Figure 1: Map of Ndokwa West L.G.A showing Kwale. Source: Ndokwa West Local Government Council, (2015).

Plate 1**:** A Pump Test at Umusam Kwale Community.

A 200-minute pumping test was conducted in the borehole (Plate 1) using 1.5HP Astral pump with a uniform discharge rate of 0.169m^3/min and the water level in the pumped well was measured at intervals using a deep meter. After the 200minute pumping, the well was allowed to recover and the water level was measured again at the same interval. The following equipment were used in conducting the pump test.

i. Deep meter (Water level indicator)
ii. Stop watch
iii. Submersible pump (Astral 1HP)

iv. Recording sheet
v. Power supply (Generator Set)
vi. Valves, Fittings and Riser Pipes
vii. Flow Meter (for measuring discharge rate)
viii. Measuring tape
ix. Vernier Caliper

Theoretical Background

Schlumberger Array

The Schlumberger array is an electrode configuration commonly used in electrical resistivity surveys for subsurface imaging. Unlike the Wenner array, which has a fixed electrode spacing, the Schlumberger array allows for variable spacing between the current and potential electrodes (Fediuk *et al.,* 2020). This flexibility makes it particularly useful for investigations where greater depth penetration or higher resolution imaging is required.

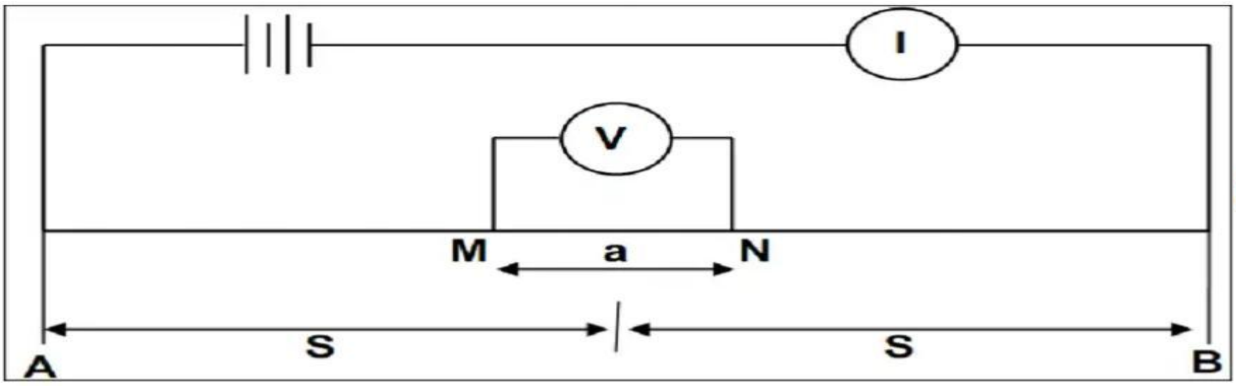

Figure 2: Schematic of Schlumberger array for data acquisition.

In a Schlumberger array, a current is injected into the ground through two outermost electrodes, while the potential difference is measured between two inner electrodes (Eluwole *et al.,* 2023). The spacing between the electrodes is gradually increased, starting from a small initial spacing and extending to a maximum separation distance. This gradual increase in spacing allows for the investigation of subsurface resistivity variations at different depths (Diya'ulhaq Abdullahi, *et al.,* 2024).

One of the main advantages of the Schlumberger array is its ability to provide detailed information about the subsurface resistivity distribution at various depths (Fediuk *et al.,* 2020). This makes it suitable for a wide range of applications, including mineral exploration, groundwater studies, and environmental assessments. However, the Schlumberger array can be more complex to set up and interpret compared to simpler arrays like the Wenner array (Mirzaei *et al.,* 2021)

By definition, Electric field E is the negative of potential gradient with distance r. Therefore, for a sphere, the potential is

$$U = -\int_0^r \frac{Q}{4\pi\epsilon r^2} dr \quad (1)$$

$$U = -\frac{Q}{4\pi\epsilon r} \quad (2)$$

Applying ohms' law and obtaining resistivity relation potential becomes

$$V = = -\int_r^\infty \frac{\rho l}{4\pi r^2} dr \quad (3)$$

For a hemispherical surface like earth surface the current density, I is given by

$$l = \frac{l}{2\pi r^2} \quad (4)$$

So that potential at any point, from a particular potential electrode in figure 2 is

$$v = \frac{pl}{2\pi r} \quad (5)$$

Thus, the resulting potential at electrode M due to the current electrode is,

$$v_C = \frac{lp}{2\pi r}\left[\frac{1}{r_1} - \frac{1}{r_2}\right] \quad (6)$$

Similarly, the resultant Potential at electrode N due to two current electrodes is

$$v_D = -\frac{lp}{2\pi r}\left[\frac{1}{r_3} - \frac{1}{r_4}\right] \quad (7)$$

Thus the potential difference ($(v_C - v_D)$ between the two inner electrodes measured by instrument Voltmeter connected connected between C and D

$$dV = (v_C - v_D) = \frac{pl}{2\pi r}\left\{\left[\frac{1}{r_1} - \frac{1}{r_2}\right] - \left[\frac{1}{r_3} - \frac{1}{r_4}\right]\right\} \quad (8)$$

$$p = 2\pi \frac{\Delta V}{l} \frac{1}{\left[\frac{1}{r_1} - \frac{1}{r_2}\right] - \left[\frac{1}{r_3} - \frac{1}{r_4}\right]} \quad (9)$$

$$p = 2\pi r\left[\frac{1}{\left(\frac{1}{na} - \frac{1}{na+a}\right) - \left(\frac{1}{na+a} - \frac{1}{na}\right)}\right] \quad (10)$$

With the Geometric factor G given as $G = \pi n(n+1)a$

In the field it is required that AB=2(n+1)a with $n \geq 2$ to ensure that $AB \gg MN$ at all times. Thus when $r_{1-}r_4 na, r_2 = r_3 = na + a$

RESULTS

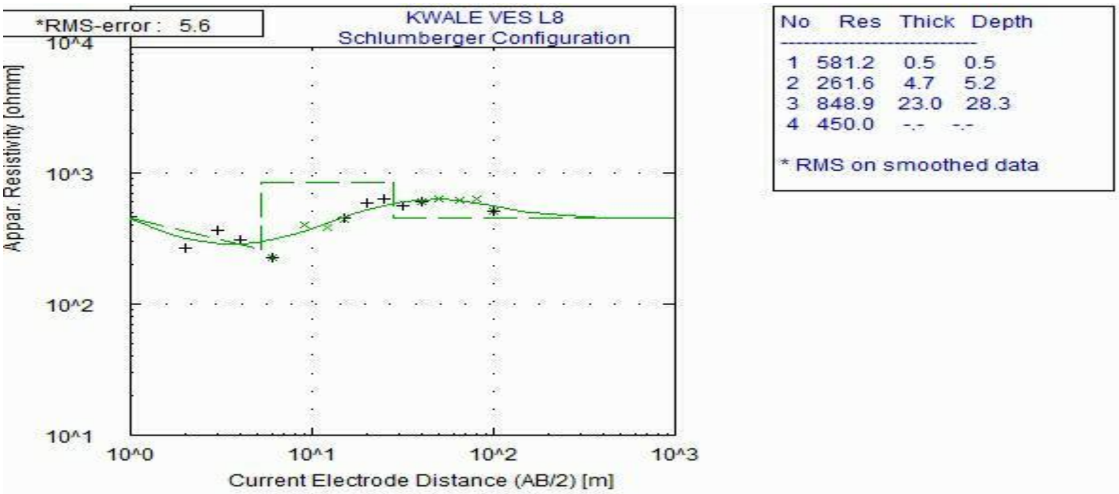

Figure 3: VES 8

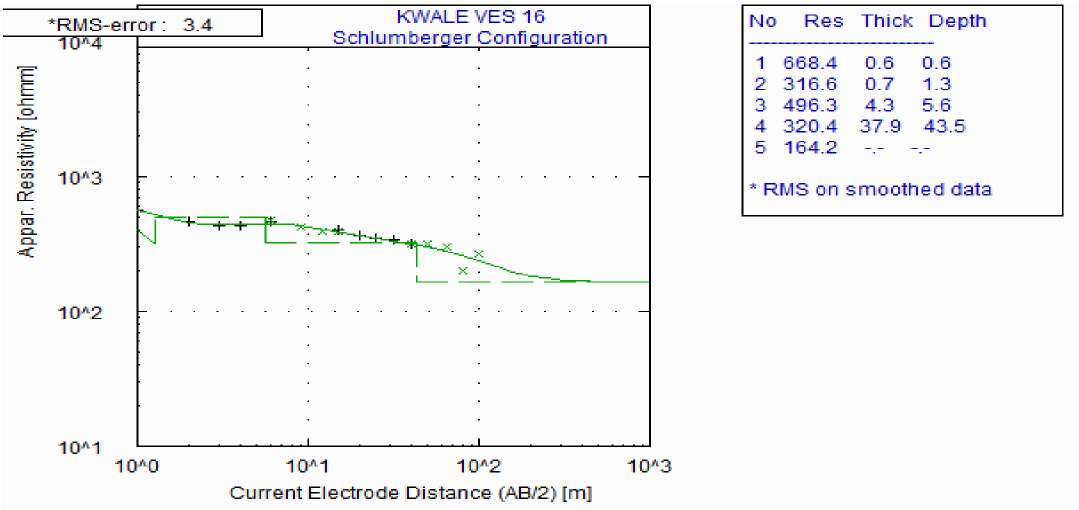

Figure 4: VES 16

Table 1: Presentation of results from computer Iteration(Kwale)

VES No.	Number Layer	Resistivity $\rho a(\Omega m)$	Thickness (m)	Depth (m)	Curve Type	Inferred Lithology
VES 1	1	267.8	0.9	0.9	KH	Topsoil
	2	717.4	2.3	3.2		Medium Grain Sand
	3	93.3	2.1	4.5		Clay
	4	559.9	9.9	14.3		Medium Grain Sand
VES 2	1	443.7	0.5	0.5	KH	Topsoil
	2	200.4	0.6	1.1		Fine Sand
	3	1019.4	2.3	3.5		Medium Grain Sand
	4	287.4	18.1	21.6		Fine Sand
	5	573.7				Medium Grain Sand
VES 3	1	419.4	1.1	1.1	H	Top Soil
	2	209.9	3.6	4.7		Fine Sand
	3	66.4	0.8	1.7		Clay
	4	785.9				Medium Grain Sand
VES 4	1	522.9	0.7	0.7	Q	Top soil
	2	210.7	1.6	2.3		Fine Sand
	3	305.1	0.2	2.6		Medium

						Grain Sand
	4	270.3	36.7	39.3		Fine Sand
	5	119.0				Sandy Clay
VES 5	1	516.4	0.8	0.8	Q	Top Soil
	2	136.9	1.0	1.8		Sandy Clay
	3	408.6	2.1	3.8		Medium Grain Sand
	4	219.2	22.8	26.6		Fine Sand
	5	163.4				Sandy Clay
VES 6	1	409.3	0.6	0.6	K	Top Soil
	2	82.6	0.4	0.9		Clay
	3	385.2	14.5	15.5		Medium Grain Sand
	4	127.2				Sandy Clay
VES 7	1	586.4	1.3	1.3	Q	Top Soil
	2	617.0	2.7	4.0		Medium grain sand
	3	298.2	0.8	4.8		Fine Sand
	4 5	237.8 136.0	16.9	21.7		Fine Sand Sandy Clay

Table 2: Presentation of results from computer Iteration(Kwale)

VES No.	Number Layer	Resistivity $\rho a(\Omega m)$	Thickness (m)	Depth (m)		Inferred Lithology
VES 8	1	581.2	0.5	0.5	HQ	Top Soil
	2	261.6	4.7	4.7		Fine Sand
	3	848.9	23.0	28.3		Medium Grain Sand
	4	450.0				Medium Grain Sand
VES 9	1	186.6	2.5	2.5	HA	Top Soil
	2	43.3	3.8	6.3		Clay
	3	148.0	32.0	38.3		Sandy Clay
	4	416				Medium Grain Sand
VES 10	1	1452.6	0.5	0.5	HQ	Top Soil
	2	321.1	3.3	3.9		Medium

						Grain Sand
	3	1093.6	8.3	12.2		Medium Grain Sand
	4	146.7				Sandy Clay
VES1 11	1	267.2	0.4	0.4	KQ	Top Soil
	2	859.6	1.5	1.9		Medium Grain Sand
	3	464.8	2.0	3.9		Medium Grain Sand
	4	195.4	23.0	26.9		Sandy Clay
	5	107.3				Sandy Clay
VES 12	1	213.3	0.6	0.6	K	Top Soil
	2	141.5	4.2	4.7		Sandy Clay
	3	408.5	19.1	23.9		Medium Grained Sand
	4	71.7				Clay
VES 13	1	41.0	0.4	0.4	K	Top Soil
	2	381.0	1.3	1.7		Medium Grained Sand
	3	44.3	0.1	1.8		Clay
	4	145.0	23.4	25.2		Sandy Clay
	5	37.4				Clay
VES 14	1	61.1	0.6	0.6	K	Top Soil
	2	540.7	0.6	1.2		Medium Grain Sand
	3	162.0	4.1	5.3		Sandy Clay
	4 5	605.7 76.8	10.6	15.9		Medium Grain Sand Clay
VES 15	1	61.0	0.3	0.3	KK	Top Soil
	2	747.7	1.4	1.8		Medium Grained Sand
	3	118.8	3.8	5.6		Sandy Clay
	4 5	410.4 85.0	12.1	17.6		Medium Grain Sand Clay
VES 16	1	668.4	0.6	0.6	K	Top Soil
	2	316.6	0.7	1.3		Medium Grain Sand
	3	496.3	4.3	5.6		Medium Grained Sand
	4	320.4	37.9	43.5		Medium Grain Sand
	5	164.2				Sandy Clay

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VES 17	1	613.0	1.7	1.7	A	Top Soil
	2	149.0	5.3	6.9		Sandy Clay
	3	829.0	29.1	36.0		Medium Grain Sand
	4	576.0				Medium Grain Sand
VES 18	1	561.0	2.3	2.3	H	Top Soil
	2	177.0	5.2	7.5		Sandy Clay
	3	812.0	28.5	36.0		Medium Grain Sand
	4	709.0				Medium Grained Sand
VES 19	1	192.6	0.6	0.6	KH	Top Soil
	2	495.5	2.0	2.6		Medium Grained Sand
	3	96.0	3.1	5.6		Clay
	4 5	784.6 526.6	32.3	37.9		Medium Grained Sand Medium Grain Sand
VES 20	1	661.5	0.4	0.4	A	Top Soil
	2	134.2	0.5	0.9		Sandy Clay
	3	722.0	0.6	1.5		Medium Grained Sand
	4	236.5	15.2	16.8		Fine Sand
	5	873.9				Medium Grain Sand

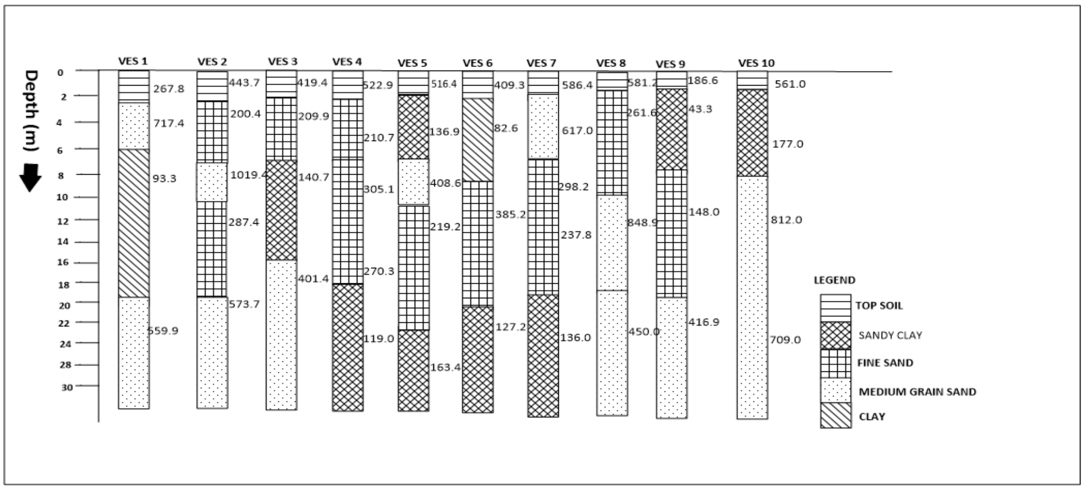

Figure 4: Geoelectric Section of VES 1-10

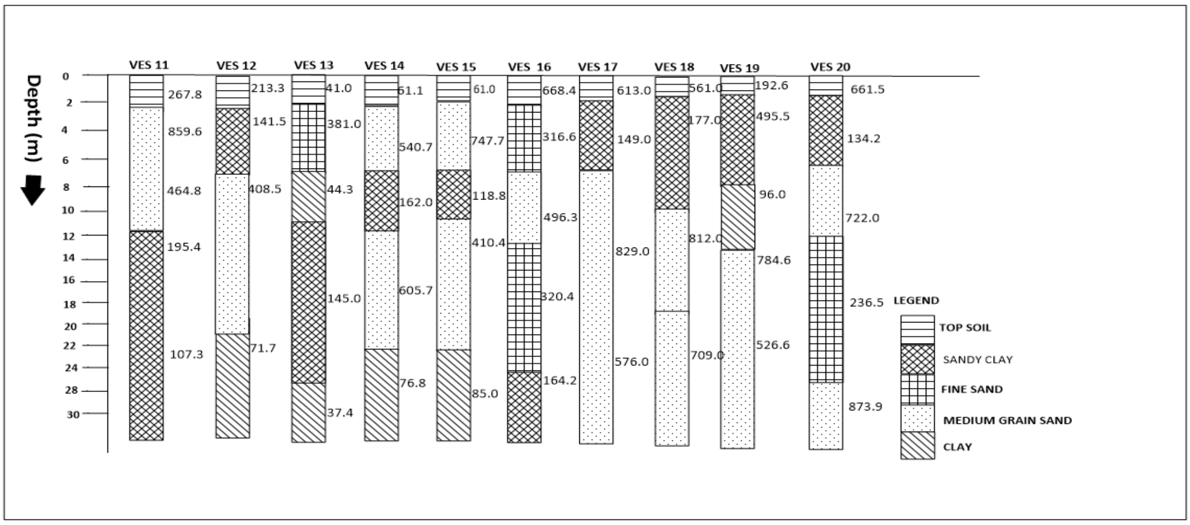

Figure 5: Geoelcetric Section of VES 15-20

Table 3 DAR-ZARROUK'S PARAMETER OF AQUIFER CHARACTERISTIC

VES NUMBER	AQUIFER RESISTIVITY (Ωm)	AQUIFER THICKNESS (m)	AQUIFER HYDRAULIC CONDUCTIVITY (m/day)	LONGITUDINAL CONDUCTANCE $(Siemens)$	AQUIFER TRANSMISSIVITY (m^2/day)
VES 1	327.1	18.7	7.18	0.0638	134.26
VES 2	287.4	18.1	7.18	0.0694	129.96
VES 3	140.7	8.4	7.18	0.0795	60.31
VES 4	270.3	36.7	7.18	0.1454	263.51
VES 5	219.2	22.8	7.18	0.1229	163.70
VES 6	385.2	14.5	7.18	0.0439	104.11
VES 7	237.8	16.9	7.18	0.0803	121.34
VES 8	261.6	4.7	7.18	0.0459	33.75
VES 9	148.0	32.0	7.18	0.3174	229.76
VES 10	321.1	3.3	7.18	0.0182	23.69
VES 11	195.4	23.0	7.18	0.1253	165.14
VES 12	141.5	4.2	7.18	0.0793	30.16
VES 13	145.0	23.4	7.18	0.1768	168.01
VES 14	162.0	4.1	7.18	0.0537	29.44
VES 15	118.8	3.8	7.18	0.0682	27.28
VES 16	320.4	37.9	7.18	0.1301	272.12
VES 17	149.0	5.3	7.18	0.0735	38.05
VES 18	177.0	5.2	7.18	0.09335	37.34
VES 19	96.0	3.1	7.18	0.0806	22.26
VES 20	236.5	15.2	7.18	0.0694	109.14

Pumping Test Results and Interpretation
Borehole Information
Location: Umusam Kwale Community

Elevation: 20.64
Co-Ordinates: 5˚41' 26'N and 6˚24'41' E
Borehole Diameter: 101.6mm
Total Drilled Depth: 40m
Static Water Level: 4.25m
Pump Installation: 18m
Discharge: 0.169m^3/min
Drawdown: 0.84
Storativity: 0.00011
Transmissivity: 222.62m^2/day
Pump Capacity: 1.5HP (Astral Pump)
Radius of Well: 50.8
Aquifer Thickness 31

Table 4 Pumping test data obtained from a borehole at Umusam Kwale Community

S/N	Time (min)	Water Level(m)	Drawdown(m)
1	0.2	4.26	0.1
2	0.5	4.48	0.22
3	1.3	4.78	0.3
4	2	5.13	0.35
5	10	5.57	0.44
6	20	6.11	0.54
7	30	6.73	0.62
8	40	7.41	0.68
9	50	8.11	0.7
10	60	8.85	0.74
11	70	9.63	0.78
12	80	10.42	0.79
13	90	11.26	0.84
14	100	12.1	0.84
15	120	12.94	0.84
16	130	12.94	0.84
17	150	12.94	0.84
18	180	12.94	0.84

19	200	12.94	0.84

DISCUSSION

Across the VES sites, results reveal distinct layers of topsoil, clay, and sand, with resistivity values indicating various subsurface compositions. VES 1 identifies a topsoil resistivity of 267.8 Ωm, transitioning into a clay layer with lower resistivity (93.3 Ωm) at a depth of 4.5 meters. Below this, medium grain sand layers with higher resistivities (717.4 Ωm and 559.9 Ωm) extend to 14.3 meters, indicating potential aquifer zones. Similarly, VES 2 reveals a high-resistivity topsoil (443.7 Ωm) and sand layers with resistivities from 200.4 Ωm to 573.7 Ωm, reaching depths up to 21.6 meters.

VES 3 shows moderately high topsoil resistivity (419.4 Ωm), transitioning into fine sand (209.9 Ωm), followed by a low-resistivity clay layer (66.4 Ωm) at 1.7 meters. Deeper medium grain sand layers with high resistivity (785.9 Ωm) suggest additional aquifer potential. VES 4 and subsequent VES sites (VES 5 to VES 20) also show sandy clay, medium, and fine sand layers, with resistivity and depth variations that illustrate regional stratification. These findings highlight the presence of clay zones with lower permeability, potentially acting as barriers to groundwater flow, and deeper sand layers that serve as potential aquifers.

The pump test conducted at Umusam Kwale In Ndokwa East Local Government Area further confirms these aquifer characteristics. With a transmissivity of 222.62 m^2/day and a storativity of 0.00011, the aquifer demonstrates sufficient capacity to yield water effectively to the borehole, supporting both industrial and domestic use. The pump, installed at an 18-meter depth, maintained a stable dynamic water level at 0.84 meters with a pumping rate of 0.169 m^3/min using a 1.5HP submersible pump. The aquifer displayed rapid recovery, reaching 4.25 meters within a minute of stopping the pump, indicating good well development and high aquifer responsiveness.

The combined data from VES and pump tests offer a thorough evaluation of aquifer transmissivity and hydraulic conductivity in Kwale. The VES data outline essential subsurface features such as potential aquifers and zones with reduced permeability, while the pump test data affirm the aquifer's viability for sustainable water supply. This information is crucial for managing groundwater resources in the region, supporting water supply planning, environmental assessments, and agricultural land use decisions. The integrated Vertical Electrical Sounding (VES) survey and pump test analysis provide valuable insights into the subsurface characteristics and aquifer potential in Kwale, Delta State. VES 16, conducted near the pump test site, offers particularly relevant data for estimating aquifer transmissivity. Notably, the transmissivity estimated using Dar Zarrouk parameters for VES 16 in table 3 shows a slightly higher value compared to the transmissivity determined from the pumping test. This suggests localized variations in aquifer properties around the pumping site, possibly due to differences in the lithological composition and grain size distribution.

CONCLUSION

In conclusion, the integration of Vertical Electrical Soundings (VES) and pump test analysis has successfully determined the aquifer transmissivity and hydraulic conductivity in Kwale, Delta State, Nigeria. The VES data provided a detailed view of subsurface resistivity variations, identifying potential aquifer zones and layers with reduced permeability.

Complementary pump test results confirmed these findings, showcasing the aquifer's ability to sustain a stable water yield suitable for industrial and domestic purposes. Notably, data from VES 16 near the pump test site highlight localized aquifer property variations, likely influenced by lithological differences. This study delivers crucial insights for groundwater resource management, offering a valuable framework to support water supply planning and sustainable land use in the region.

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