



## Quantification of groundwater reserve in a sedimentary milieu from superficial resistivity measurements

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### Abstract

Recent changes in climatic conditions and the resulting changes in demands for potable water call for a thorough understanding of groundwater resources. In this research, the usability of the electrical resistivity technique in the volumetric estimation of groundwater reserve is demonstrated. Sixteen (16) vertical electrical soundings were made at predetermined locations in Akwa Ibom State University main campus, southern Nigeria, with the primary aim of delineating the hydrostratigraphic units and estimating the groundwater reserve in the area. Three to four geoelectric layers comprising poorly sorted continental sands with minor clay intercalations have been identified in the study site. Groundwater extraction in the area takes place in the second and third layers, based on location, at depths ranging from 1.1 to 50.2 m. The aquifer system is shown to have a mean effective porosity of 0.26, a mean specific yield of 0.184, and mean specific retention of 0.075. The total aquifer volume is estimated to be  $1.8 \times 10^8 \text{ m}^3$  while the effective water volume reserve in the area is  $4.68 \times 10^7 \text{ m}^3$ . The usable groundwater volume releasable by the aquifer during pumping is shown to be 71 % of the effective volumetric groundwater reserve, while the fractional volume retainable by the aquifer is 29 %. This, by implication is an indication that the area has good groundwater potential for the sustainability of water wells. The regression equations derived in this study can be used for easy and rapid prediction of aquifer porosity and specific yield/retention from surface resistivity data in regions with similar geological characteristics. These outcomes are very auspicious, particularly in devising sustainable groundwater development and exploitable schemes to meet current and future needs of the university community.

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## 1.0 Introduction

Groundwater is a natural resource that is stored in underground rocks known as aquifers. Virtually all the groundwater reserves emanate from rainfall, which infiltrates into the subsurface from the earth's surface. Groundwater is critical for the survival of both plants and soil organisms. The importance of water for humans' continued existence and development has provoked a global upsurge in groundwater studies. The uppermost soil layer is unsaturated in nature with only a limited amount of water that varies over time and is incapable of saturating the soil (Evans *et al.*, 2015, Ibuot and Obiora, 2021). The rock unit, which can give away water in adequate quantities for a variety of applications on a dependable scale, is described as the water-bearing unit or simply the aquifer. Aquifers are large stores of groundwater on which the world population depends for their everyday lives. The term 'groundwater reserve' refers to the amount of underground water that is stored in the aquifers and constitutes part of the hydrological cycle (George *et al.*, 2014, Ajaykumar and Mondal, 2022). The volume of groundwater reserve in a given area depends on some dynamic rock properties, which include porosity, permeability, pore geometry, hydraulic conductivity, transmissivity, specific yield and retentive capacity (Rangarajan *et al.*, 2009, Okiongbo and Oborie, 2015, Mondal *et al.*, 2016).

Groundwater reserve estimation is significant for the development and efficient utilization of groundwater resources to ensure adequate clean water supply for the world's rapidly growing population (George *et al.*, 2011, Mondal and Ajaykumar, 2022, Ibim *et al.*, 2022). Since rainfall is majorly the key source of groundwater recharge, information on natural groundwater reserve is vital in groundwater development and exploitation (Mondal and Ajaykumar, 2021),

The increasing universal reliance on groundwater resources over the years has deepened concerns about their quality and continuous availability in sufficient quantities to meet human domestic, agricultural and other needs. The key aim of this research is therefore to locate, delineate the hydrostratigraphic units and estimate the groundwater reserve on the main campus of Akwa Ibom State University (AKSU) located in Ikot Akpaden, Mkpato Local Government Area (LGA), southern Nigeria, using the electrical resistivity technique. AKSU is a fast-growing state University in southern Nigeria and the University community relies massively on groundwater for drinking and other purposes. There are growing worries about the continued availability of potable water from water wells on the campus and the possibility of saltwater intrusion, since the University is located in a swampy area. Recent changes in climatic conditions and the resulting changes in demands for water call for a thorough understanding of the area's groundwater resources (Dao *et al.*, 2024). The hydraulic and dynamic properties of the water-bearing units on the university main campus are not fully understood, thus hampering the accurate design of development and management plans for optimal groundwater exploration in the area. Even though up to six boreholes have been drilled on the university main campus for groundwater abstraction, there is still a lack of a fuller understanding of the nature, geometry, and distribution of aquifers in the area, as well as groundwater reserve estimates. Aquifer thickness and distribution oftentimes do not necessarily offer useful information on groundwater reserves because some of the identified aquifers may not be porous, sufficiently saturated, or productive (Ekanem and Udosen 2023a, b). The evaluation of aquifer potentiality to sustain water wells and

groundwater reserves depends on the estimation of aquifer porosity and specific yield (Ibim *et al.*, 2022, George *et al.*, 2022). Ekanem (2020) investigated the cause of waterlogging experienced in parts of the University main campus using the electrical resistivity method and concluded that the major cause was the sand – clay intercalations in the shallow layers. Waterlogging in this case is simply a phenomenon where an area is flooded with water arising from severe rainfall or a poor drainage system. In a like manner, the results of studies by Thomas *et al.* (2020) reveal that the major lithological succession in the university main campus and its environs comprises motley topsoil/dry strata, saturated clay/saline water depository, fine-grained sand/brackish water deposit, medium-grained sand /freshwater depository, and gravelly sand. None of these studies investigated the groundwater reserve estimates in the study area. Thus, the novelty in this study is the quantitative estimation of the exploitable groundwater reserve as well as the releasable groundwater volume by the aquifers in the area to water wells during pumping. Furthermore, the regression equations derived for the first time in this study provide a simple and inexpensive means of predicting aquifer effective porosity, specific yield and retention from surface resistivity data. The findings of the study provide scientifically-backed data that will undoubtedly assist in the designing, development, and efficient utilization of groundwater resources on the university main campus.

## 2.0 Location and brief geology of the study area

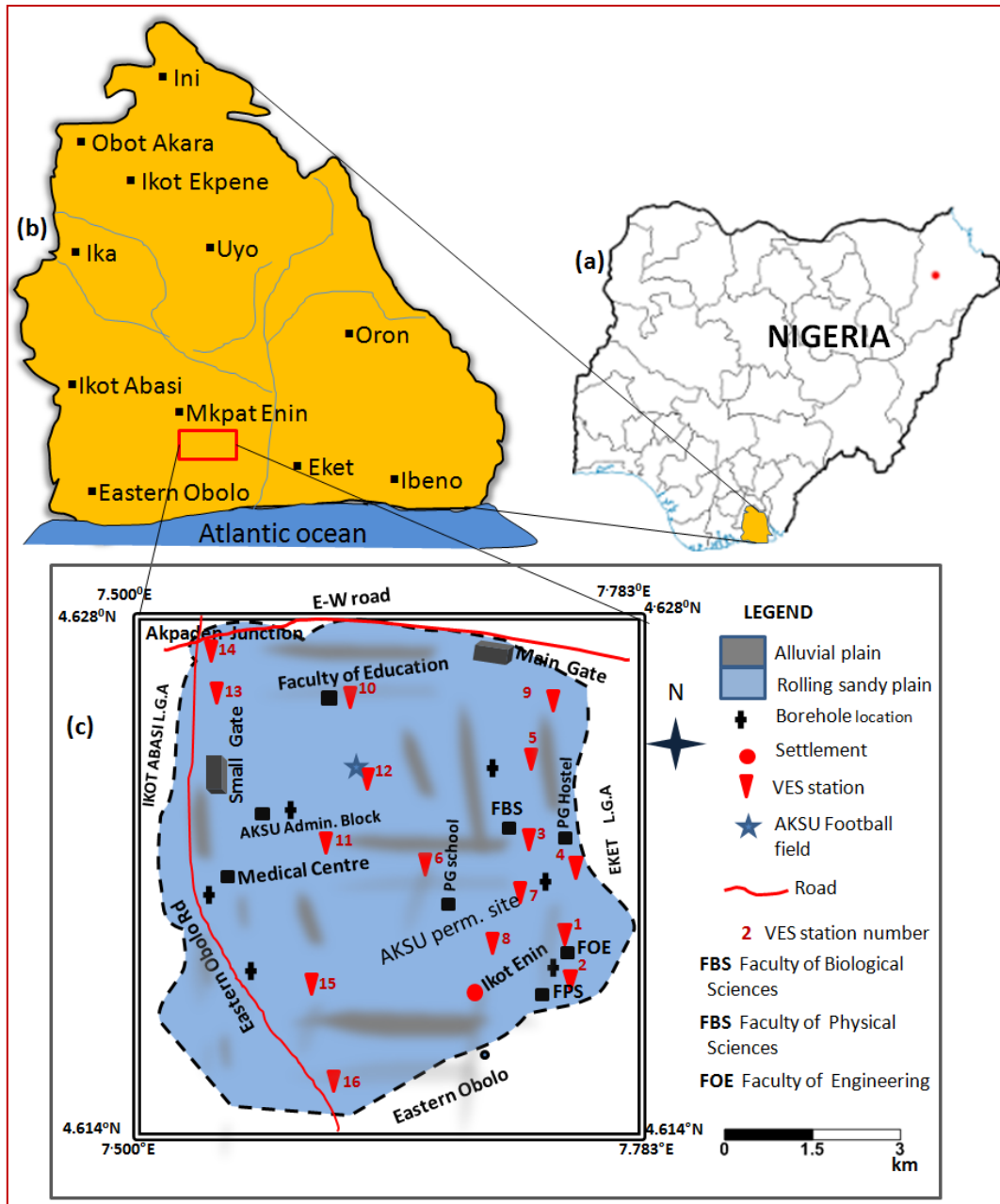
This study was carried out on the AKSU main campus located in the coastal part of Akwa Ibom State largely within Mkpat Enin Local Government Area, but also including Eastern Obolo, Onna, and Ibeno Local Government Areas. The northern highland portion of AKSU main campus is located at Ikot Akpaden,

between Eket and Ikot Abasi, along Nigeria's East-West Highway. This route goes across the Niger Delta from Calabar in the east to Eket, Ikot Abasi, Port Harcourt, Warri, and Benin to Lagos on the west coast of Nigeria. The campus stretches from the East-West highway to the Atlantic Ocean shoreline, covering around 4,600 hectares, including 180 hectares of gently rolling, sufficiently drained tableland which offers high ground suited for the University's physical expansion. The remainder of the southern portion is a deteriorated wetland, waterlogged and inundated with mangrove swamps and tidal waterways. The study area is situated in the Niger Delta region, somewhere in between latitudes 4.614 and 4.628°N and longitudes 7.500 and 7.783°E, respectively, as shown in Figure 1. The area has two distinct climatic seasons: dry and wet (monsoon or rainy). The dry season begins from around late November to early February, while the remaining months of the year constitute the wet season (Udofia and Udo, 2021, Inyang *et al.*, 2023). Nevertheless, minor variations in the top and lower boundaries of the two seasons do exist as a result of worldwide climatic shifts (Ikpe *et al.*, 2022; Allen *et al.*, 2024). The temperatures during the dry season do get up to 35°C while the average yearly rainfall in the area fluctuates between 2000 and 4000 mm with relative humidity varying between 53 and 91% (Okon *et al.*, 2020). Rainfall is the primary source of aquifer recharge in the region.

Geologically, AKSU main campus is situated in the Tertiary - Quaternary Coastal Plain Sands (CPS) commonly known as the Benin Formation (Obaje, 2009; Udo and Udofia, 2020; Udo *et al.*, 2020). Below the Benin Formation are the Agbada and Akata Formations in that order (Udo and Mode, 2013 a, b; Udo *et al.*, 2023 a, b, c) as indicated in Figure 2. The CPS, which covers over 80% segment of the University main campus comprises poorly sorted continental (fine, medium and coarse) sands and gravels

with alternating thicknesses, mixed with thin clay horizons, lenses, and lignite streaks in a few spots (Mbipom *et al.*, 1996, Udo and Mode, 2013 a, b; Allen *et al.*, 2024). Groundwater occurrence in the area is in the CPS where

groundwater extraction is done (Thomas *et al.*, 2020, Ekanem 2020). The sand-clay intercalations, where they occur create multi - aquifer systems in the study area.



**Figure 1:** Schematic map of the study location (a) Nigeria displaying Akwa Ibom State in southern part (b) Akwa Ibom State displaying the study area (c) study area displaying its geology, sounding stations and borehole locations

### 3.0 Materials and Method

Vertical electrical soundings (VES) were carried out at sixteen (16) predetermined locations in the study site distributed as shown in Figure 1 through the utilization of the Schlumberger

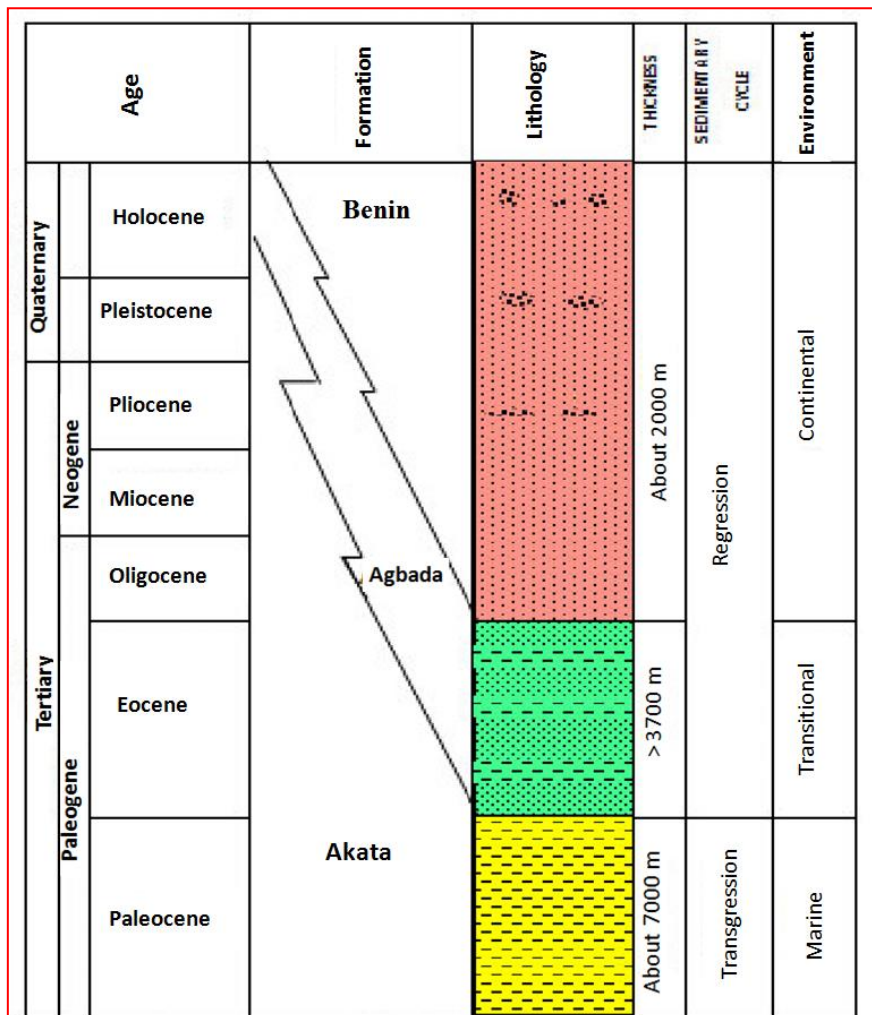
array. At each sounding point, two electrodes known as the current electrodes A and B were inserted into the earth surface to inject current into the ground. Two additional inner electrodes (Potential electrodes) M and N were also inserted into the earth surface to detect the

potential difference generated (Keller and Frischknecht, 1966) as in Glas *et al.* (2019). The major sounding instrument was the the Integrated Geophysical Instrument Service (IGIS) resistivity meter (model SSR-MP-ATS) with its accessories. The field layout for the resistivity data acquisition is cartooned in Figure 3. The distance AB varied from 1 to 200 m whereas MN varied from 0.5 to 25 m. In general, in expanding the electrode spacing AB about the centre O of the sounding (Figure 3), the potential gradient assumption of  $AB \geq 5MN$  (Dobrin and Savit 1988) was ensured as in Inyang *et al.* (2024). Some soundings were conducted near existing boreholes in the area as Figure 1 shows.

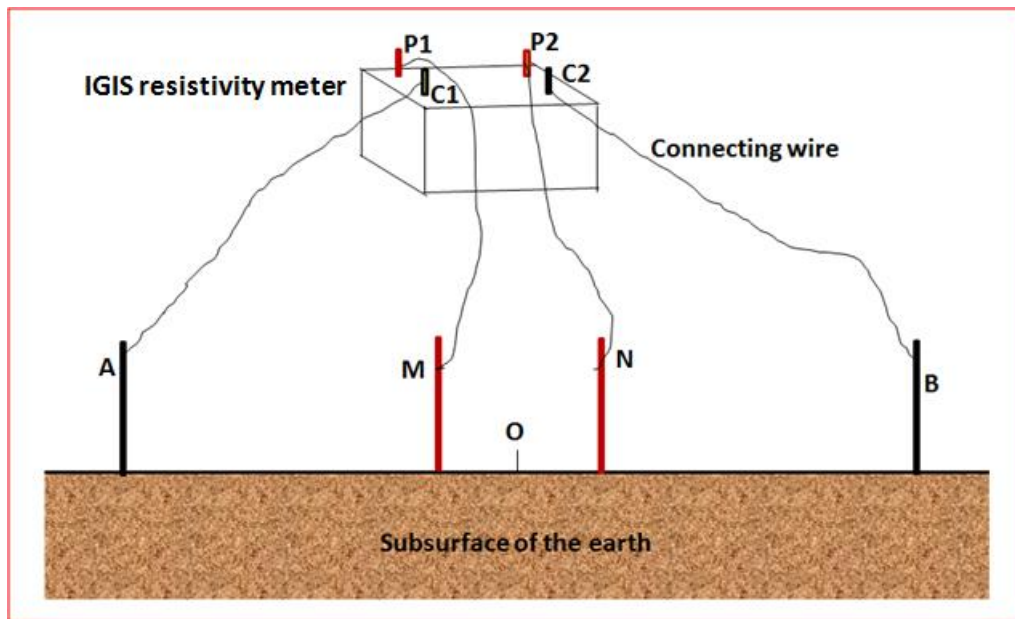
This was considered necessary for constraining the data interpretation using the lithological information from the borehole. The crude apparent resistance values gathered from the field  $R_s$  at each sounding location were transformed into apparent resistivity  $\rho_s$  via multiplication by the geometric factor  $G_s$  of the Schlumberger array as presented in equations 1 and 2.

$$\rho_s = R_s \times G_s \tag{1}$$

$$G_s = \left\{ \frac{(AM)^2 - (MN)^2}{MN} \right\} \times \frac{\pi}{4} \tag{2}$$



**Figure 2.** An illustration of the general stratigraphy of the Niger Delta region, where the study area is located (from Obaje, 2009)



**Figure 3:** Illustration of the layout of field equipment for resistivity data acquisition using the Schlumberger array. P1 and P2 are the potential terminals while C1 and C2 are the current terminals on the resistivity meter. Apparent resistance measurements are made at the centre O of the arrangement.

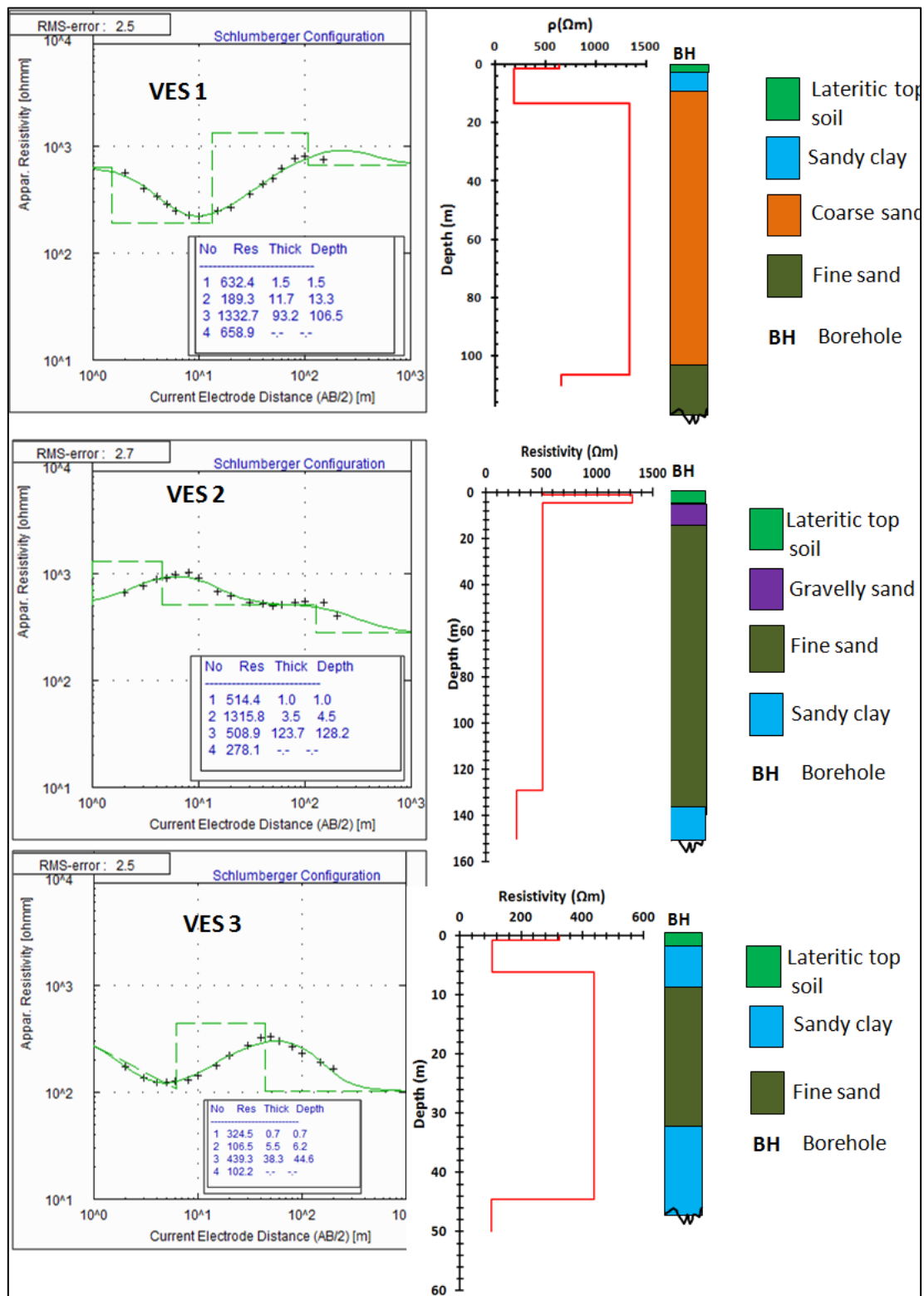
The VES curves were generated by plotting the  $\rho_s$  values determined from equation 1 against  $AB/2$  on a bilogarithmic graph. Manual smoothening of the curves was carried out to reveal the cardinal resistivity variation trend in the data. This was attainable by expunging points considered as outliers and determining the average of the  $\rho_s$  values obtained at the crossover points with the dominant trend maintained (Bhattacharya and Patra 1968; Chakravarthi et al. 2007). The curve smoothening was essential to reduce the root mean square errors (RMSE) in the later stage of computer assisted interpretation, which was accomplished in this research by using the WINRESIST computer software (Evans et al., 2015, Udosen et al., 2023). The smoothened VES curves were supplied as inputs to the software, which uses the least-squares inversion technique to compute a theoretical resistivity model (Vander Velpen and Sporry 1993). To generate the final model VES curves, the software fits the computed resistivity model with the smoothened field curves. The lithological borehole information from available water wells in the study site was used to control

in the refinement of the layer parameters in this final interpretation stage. The RMSE values obtained in the computer modelling stage were generally less than 5 %, which is an indication of the goodness of the automatic curve matching. Figure 4 depicts a few of the final interpreted model curves and their correlations with obtainable borehole lithological information in the study site. The thicknesses, depths, and resistivity derived from the ultimate model curves are considered to be the true layer primary geoelectric parameters in the study site.

#### 4.0 Results, Analysis and Discussion

In all, three to four geoelectric layers are identified from the outcomes of the resistivity data interpretation in the study area. A summary of the properties of these layers is presented in Table 1. The final model curves obtained are classified into seven groups as indicated in Figure 5 with the HK group dominating at 37.5 %. This, according to George et al. (2020) and Ekanem et al. (2024) may be an indication of a shift from unsaturated to saturated layers, implying a high possibility of groundwater existence in the study site. The HK resistivity

curve symbolizes a four-layered earth with a resistivity variation pattern:  $\rho_1 > \rho_2 < \rho_3 > \rho_4$ , where  $\rho_1, \rho_2, \rho_3$  and  $\rho_4$  the first, second, third and fourth layer resistivities respectively (Keller and Frischknecht, 1966).

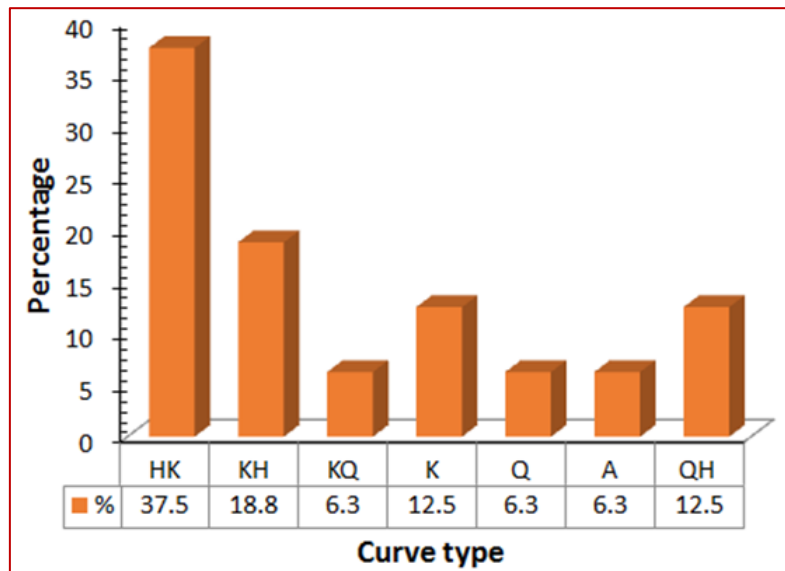


**Figure 4:** Sample final VES curves and their correlations with available borehole lithological data in the study area. The sandy clay layer constitutes the aquifer unit in VES 1 and 2 while the fine sand layer constitutes the aquifer unit in VES 3.

Table 1: VES interpretation summary

VES No.	Location	Longitude (Degrees)	Latitude (Degrees)	No. of Layers	Layer Resistivity ( $\Omega m$ )				Layer thickness (m)			Layer Depth (m)			Curve type
					$\rho_1$	$\rho_2$	$\rho_3$	$\rho_4$	h1	h2	h3	d1	d2	d3	
1	Front of Faculty of Engineering	7.77877	4.61928	4	632.4	189.3	1332.7	658.9	1.5	11.7	93.2	1.5	13.3	106.5	HK
2	Road behind Faculty of Engineering	7.77778	4.61833	4	514.4	1315.8	508.9	278.1	1.0	3.5	123.7	1.0	4.5	128.2	KQ
3	Front Faculty of Biological Sciences	7.77575	4.62097	4	324.5	106.5	439.3	102.2	0.7	5.5	38.3	0.7	6.2	44.6	HK
4	Along PG Hostel 1	7.77842	4.62047	4	403.4	110.4	574.9	258.0	6.6	6.5	78.4	6.6	13.1	91.5	HK
5	Along PG Hostel 2	7.77558	4.62339	3	494.1	1829.0	523.7		2.6	47.6		2.6	50.2		K
6	Along PG School Road	7.76983	4.62144	3	1319.8	514.2	283.8		1.4	114.6		1.4	116.0		Q
7	Along PG School Road	7.77497	4.62008	3	690.0	2481.3	826.2		1.0	26.6		1.0	27.6		K
8	Permanent site by entrance gate	7.77600	4.61880	4	395.7	1567.1	510.3	1808.6	0.6	7.9	49.3	0.6	8.5	57.8	KH
9	Permanent site by roundabout	7.77780	4.62420	4	401.6	1108.4	481.9	1195.9	1.1	27.5	50.5	1.1	28.6	79.1	KH
10	Faculty of Education	7.76200	4.62500	3	563.4	966.1	1115.9		1.1	75.1		1.1	76.2		A
11	AKSU Medical Centre	7.76400	4.62100	4	136.0	10.1	1236.3	289.1	2.0	5.9	76.8	2.0	7.9	84.7	HK
12	AKSU Football Field	7.76500	4.62300	4	95.2	8.8	746.0	217.8	1.5	7.9	58.1	1.5	9.4	67.5	HK
13	Akpaden Junction	7.75500	4.62500	4	1128.0	626.2	248.6	660.4	1.9	23.1	46.9	1.9	25.0	71.8	QH
14	Ikot Abasi Road by Obio Ndoho	7.75600	4.62600	4	334.2	992.2	357.8	876.0	1.5	15.8	45.7	1.5	17.3	63.0	KH
15	Eastern Obolo Road Near AKSU Gate	7.76200	4.61800	4	1463.7	808.8	86.5	429.0	1.3	19.9	56.5	1.3	21.2	77.7	QH
16	Eastern Obolo Road by Ikot Oyoro	7.76200	4.61600	4	858.2	1069.2	72.5	271.5	2.9	16.8	63.0	2.9	19.7	82.8	KH
	<b>Minimum</b>				95.2	8.8	72.5	102.2	0.6	3.5	38.3	0.6	4.5	44.6	
	<b>Maximum</b>				1463.7	2481.3	1332.7	1808.6	6.6	114.6	123.7	6.6	116.0	128.2	
	<b>Average</b>				609.7	856.5	584.1	587.1	1.8	26.0	65.0	1.8	27.8	79.6	





**Figure 5:** Distribution of curve types in the study area

Accordingly, the first layer is generally considered to be lateritic topsoil and has a resistivity range of 95.2 to 1463.7  $\Omega\text{m}$  (mean = 609.7  $\Omega\text{m}$ ) and thickness/depth range of 0.6 to 6.6 m (mean = 1.8 m). The second layer's resistivity ranges from 8.8 to 2481.3  $\Omega\text{m}$  (mean = 856.5  $\Omega\text{m}$ ) and thickness ranges from 3.5 to 114.6 (mean = 26.0 m). The third and fourth layers revealed in this study have respective resistivity ranges of 72.5 to 1332.7  $\Omega\text{m}$  (mean = 584.1  $\Omega\text{m}$ ) and 102.2 to 1808.6  $\Omega\text{m}$  (mean = 587.1  $\Omega\text{m}$ ). The thickness of the third layer fluctuates between 38.3 and 123.7 (mean = 65.0) while that of the fourth layer was inestimable within the bounds of the highest AB utilized in this study. The wide resistivity ranges observed could be attributed to the variations in grain sizes of the poorly sorted plain sands characterizing the Benin Formation of the Niger Delta region. The identified layers were generally taken to be composed of poorly sorted sands of varying granule sizes varying from clayey sand, sandy clay; fine and coarse sands to gravelly sands. Available borehole information in the area reveals that groundwater exploration occurs majorly in the second and third layers. These two layers were therefore considered as the main exploitable aquifers in the study area and are mostly unconfined except at VES 1, 3, 4, 11 and

12. The properties of the identified aquifer system are given in Table 2. Accordingly, the aquifer resistivity lies between 248.6 and 1332.7 Ohms-metre (mean = 696.6  $\Omega\text{m}$ ) while the thickness and depth to the top of the aquifer range from 16.8 to 123.7 m (mean = 63.4 m) and 1.1 to 50.2 m (mean = 13.6 m). The selection of the aquifer layer was based on the resistivity variation pattern in conjunction with the available borehole lithological information in the study area. Figure 6 shows the distribution of the aquifer thickness while Figure 7 shows the distribution of the depth to the top of the aquifer layer in the study area in 2D and 3D respectively. Majority of the aquifers especially in the middle portion of the study site have relatively high aquifer thickness of greater than 45 m while the remaining ones have thickness in the range of 18 to 38 m as Figure 6 reveals. Figure 7 reveals that the majority of the aquifers in the central part of the study area are shallow with depth to the top ranging from 1.1 to 17.3 m. These results are consistent with previous findings by Ekanem (2020), Thomas et al. (2020) and Inyang et al. (2024). Water electrical conductivity ( $\sigma_w$ ) was measured (in  $\mu\text{S}/\text{cm}$ ) in this study from collected water samples from five boreholes in the area by the use of a Combo EC and pH meter.

**Table 2:** Summary of aquifer properties

VES No.	Location	Longitude (Degrees)	Latitude (Degrees)	$\rho_b$ ( $\Omega m$ )	$\rho_{unsat}$ ( $\Omega m$ )	water resistivity( $\Omega m$ )		$\rho_{sat}$ ( $\Omega m$ )	h (m)	Depth to top d (m)	$\phi$	$S_y$	$S_r$	Aquifer type
						Measured	Estimated							
1	Front of Faculty of Engineering	7.77877	4.61928	1332.7	189.3	370.4		962.3	93.2	13.3	0.29	-	-	Confined
2	Road behind Faculty of Engineering	7.77778	4.61833	508.9	1315.8		120.7	388.2	123.7	4.5	0.26	0.214	0.045	Unconfined
3	Front Faculty of Biological Sciences	7.77575	4.62097	439.3	106.5		101.3	338.0	38.3	6.2	0.25	-	-	Confined
4	Along PG Hostel 1	7.77842	4.62047	574.9	110.4		139.1	435.8	78.4	13.1	0.26	-	-	Confined
5	Along PG Hostel 2	7.77558	4.62339	523.7	1829		124.8	398.9		50.2	0.26	0.251	0.009	Unconfined
6	Along PG School Road	7.76983	4.62144	514.2	1319.8		122.2	392.0	114.6	1.4	0.26	0.214	0.046	Unconfined
7	Along PG School Road	7.77497	4.62008	826.2	2481.3		209.0	617.2		27.6	0.27	0.249	0.022	Unconfined
8	Permanent site by entrance gate	7.77600	4.61880	510.3	1567.1		121.1	389.2	49.3	8.5	0.26	0.235	0.024	Unconfined
9	Permanent site by roundabout	7.77780	4.62420	481.9	1108.4		113.2	368.7	50.5	28.6	0.26	0.197	0.061	Unconfined
10	Faculty of Education	7.76200	4.62500	966.1	1115.9	212.8		753.3	75.1	1.1	0.25	0.079	0.168	Unconfined
11	AKSU Medical Centre	7.76400	4.62100	1236.3	10.1	303.0		933.3	76.8	7.9	0.26	-	-	Confined
12	AKSU Football Field	7.76500	4.62300	746	8.8	204.1		541.9	58.1	9.4	0.28	-	-	Confined
13	Akpaden Junction	7.75500	4.62500	248.6	626.2		48.2	200.4	46.9	25	0.23	0.173	0.055	Unconfined
14	Ikot Abasi Road by Obio Ndoho	7.75600	4.62600	357.8	992.2		78.6	279.2	45.7	17.3	0.25	0.207	0.040	Unconfined
15	Eastern Obolo Road Near AKSU Gate	7.76200	4.61800	808.8	1463.7		204.2	604.6	19.9	1.3	0.27	0.177	0.093	Unconfined
16	Eastern Obolo Road by Ikot Oyoro	7.76200	4.61600	1069.2	858.2	294.1		775.1	16.8	2.9	0.29	0.027	0.259	Unconfined
	Minimum			248.6	8.8	204.1	48.2	200.4	16.8	1.1	0.23	0.027	0.009	
	Maximum			1332.7	2481.3	370.4	209.0	962.3	123.7	50.2	0.29	0.251	0.259	
	Average			696.6	943.9	276.9	125.7	523.6	63.4	13.6	0.26	0.184	0.075	

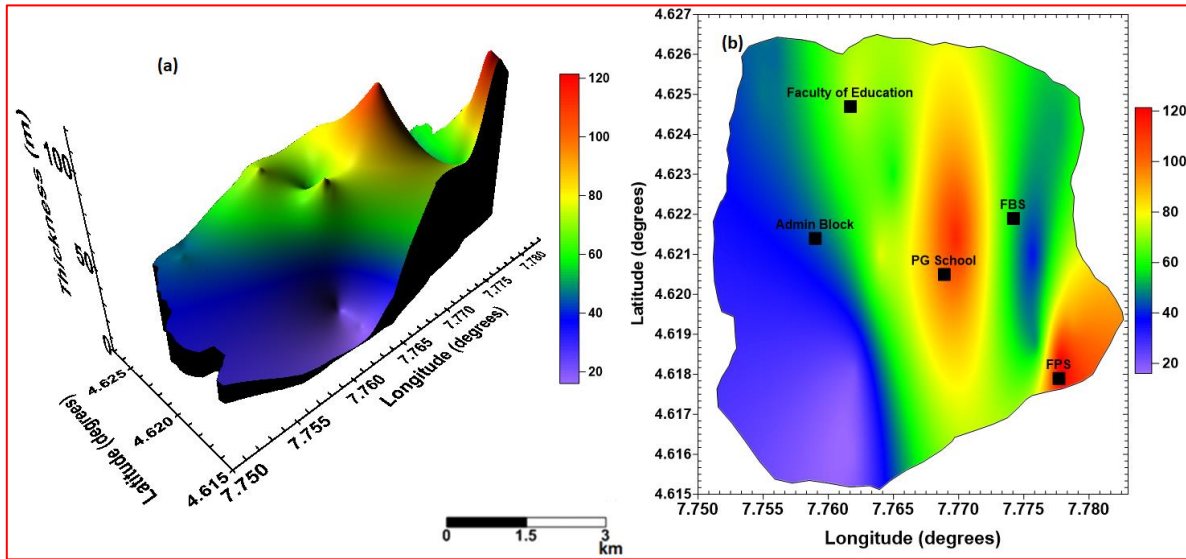


Figure 6: Distribution of aquifer thickness in the study area (a) 3D (b) 2D

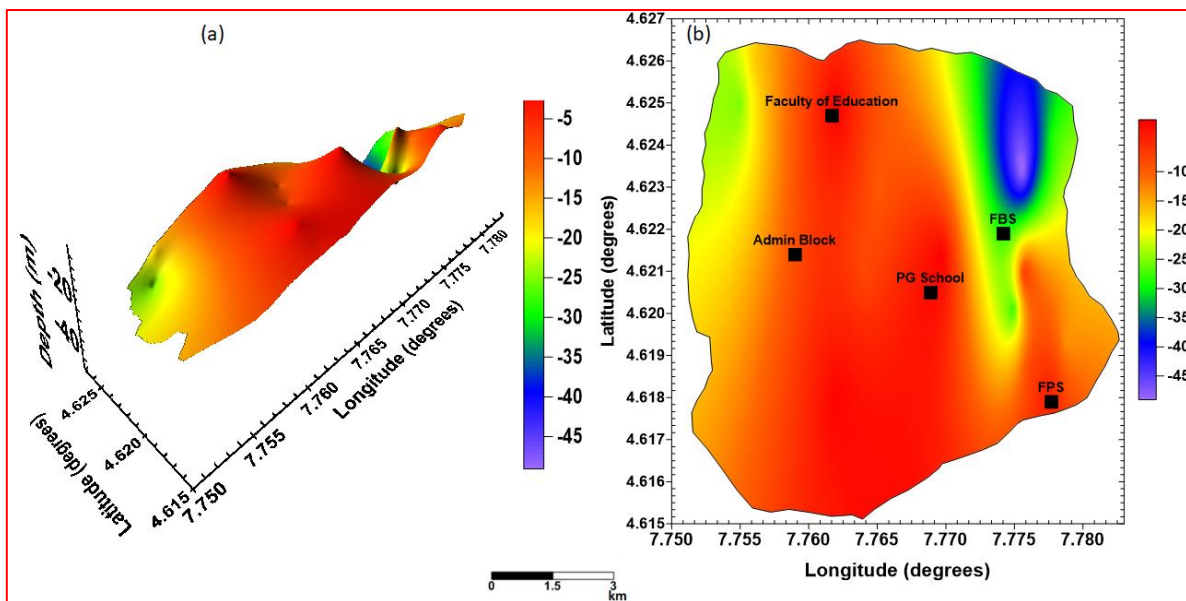


Figure 7: Water table topography showing direction of groundwater flow in the study area (a) 3D (b) 2D

From these measurements, the water resistivity  $\rho_w$  was then estimated using equation 3.

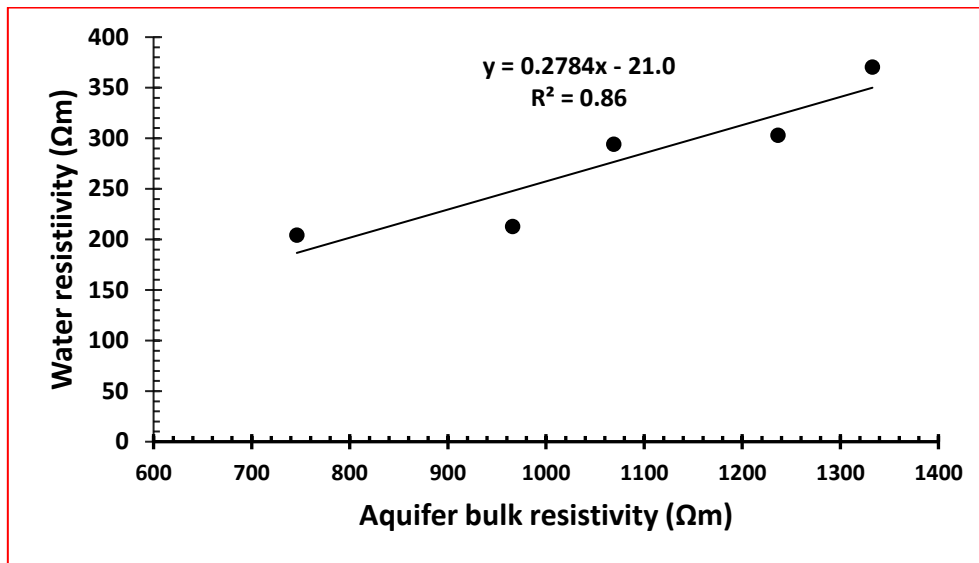
$$\rho_w = \frac{1000}{\sigma_w} \quad (3)$$

The values of the water resistivity obtained are presented in Table 2. A regression plot of the water resistivity and aquifer bulk resistivity was carried out for the five borehole locations as shown in Figure 8. The regression equation of the plot is given in equation 4 with a correlation

coefficient of 86%. Equation 4 was then utilized to predict the water resistivity for the remaining VES stations as presented in Table 2. The values of estimated water resistivity range from 48.2 to 209.0  $\Omega\text{m}$  with a mean value of 125.7  $\Omega\text{m}$ .

$$\rho_w = 0.2784\rho_b - 21.0 \quad (4)$$

The relationship expressed in equation 4 is similar to that derived by George and Thomas (2023) in a location at a distance of about 14 km to the study area still in the Niger Delta region.



**Figure 8:** Regression plot of water resistivity against aquifer bulk resistivity

Next, the aquifer effective porosity was estimated from equation 5 (Archie 1942).

$$\phi_{eff} = \left( \frac{a\rho_w}{\rho_b} \right)^{\frac{1}{m}} \quad (5)$$

Values of  $m$  (cementation exponent) and  $a$  (pore geometrical factor) in equation 4 were taken as 1.5431 and 0.5245. These values were derived by George et al. (2015) in the same geological environment in the Niger Delta region where this present study was conducted. Aquifer porosity lies between 0.23 and 0.29 with a mean value of 0.26. A plot of the aquifer effective porosity versus aquifer bulk resistivity is shown in Figure 9. The plot shows a power relation between the two aquifer parameters given in equation 6 with a correlation coefficient of 57 %. The plot provides a speedy and inexpensive means of estimating aquifer effective porosity from aquifer bulk resistivity obtained from the results of VES data interpretation.

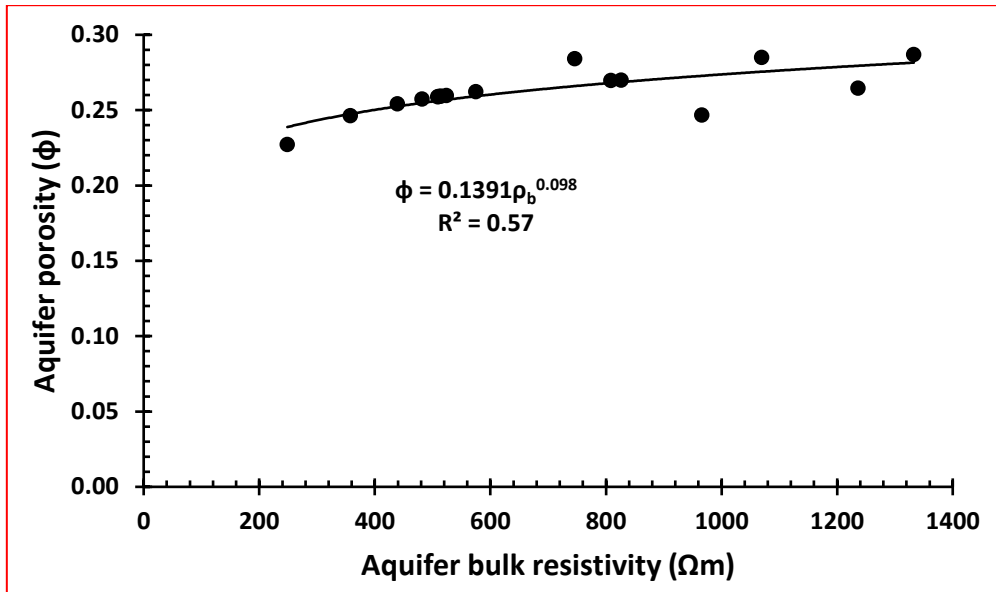
$$\phi = 0.1391 \times \rho_b^{0.098} \quad (6)$$

The volumetric estimation of groundwater reserve in the study site was made using the SURFER software by multiplying the aquifer area by the thickness represented in Figure 6a to get the total volume  $V_t$  of the unconfined aquifer as in George et al. (2011, 2022) and Ibim et al.

(2022). The volume calculation was achieved by defining the upper and lower surfaces of the aquifer layer from the results of the VES data interpretation. The difference between these two surfaces constitutes the aquifer thickness. The surfer software program makes use of three interpolation techniques for the determination of volume (Fawzy 2015). These techniques are Trapezoidal rule, Simpson's 1/3 rule and Simpson's 3/8 rule. These rules are integral approximation techniques used for estimating volume as a function  $w(x, y)$ , as described by equation 7.

$$Volume = \int_{x_{min}}^{x_{max}} \int_{y_{min}}^{y_{max}} w(x, y) dx dy \quad (7)$$

Surfer software performs the computation of the volume by first integrating over the rows,  $x$  to give the areas  $A$  under each row, and then integrating over the columns,  $y$  to find the final volume  $V_t$ . Simpson's rule, when compared with the Trapezoidal rule is more accurate because it estimates the areas using quadratic equations instead of linear equations as in the Trapezoidal rule. In this study, the Simpson's 3/8 rule was utilized for the estimation of the aquifer volume due to its accuracy, which is double that of the Simpson's 1/3 rule (George et al., 2022).



**Figure 9:** A plot of the aquifer effective porosity versus aquifer bulk resistivity in the study area

The total volume was thus calculated to be  $1.8 \times 10^8 \text{ m}^3$ . Aquifer effective porosity is a vital parameter that controls the total volume of water in storage in the aquifer (Umoh *et al.*, 2022a, b). The effective groundwater reserve volume  $V_e$  was determined by multiplying by the mean aquifer effective porosity by the aquifer total volume according to equation 8 (George *et al.*, 2011, 2022, Ibim *et al.* 2022).

$$V_e = V_t \times \phi_{\text{eff},m} \quad (8)$$

where  $\phi_{\text{eff},m}$  is the aquifer mean effective porosity, which is equal to 0.26 in this study. The computation in equation 8 gave the effective groundwater volume reserve as  $4.68 \times 10^7 \text{ m}^3$ . The uncertainty in the estimated groundwater volume was computed by using the formula expressed in equation 9.

$$\frac{\Delta V}{V} = \frac{\Delta L}{L} + \frac{\Delta W}{W} + \frac{\Delta h}{h} + \frac{\Delta \phi}{\phi} \quad (9)$$

where  $\Delta V$  is error in volume  $V$ ,  $\Delta L$  is error in length  $L$ ,  $\Delta W$  is error in breadth  $W$ ,  $\Delta D$  is error in thickness  $h$  taken as 0.1 m (George *et al.*, 2011) and  $\Delta \phi$  is error in porosity  $\phi$  taken as 0.01 (George *et al.*, 2011). The errors in length and breadth were assumed to be negligibly small (approximately zero) (George *et al.*, 2011, Ibim *et al.*, 2022).  $\Delta V$  was estimated from equation 9

as  $2.2 \times 10^6 \text{ m}^3$ . Thus, the estimated effective groundwater volume reserve is  $4.68 \times 10^7 \pm 2.2 \times 10^6 \text{ m}^3$ . However, only a fraction of this stored groundwater volume is released into the boreholes during pumping. For unconfined aquifers, the relative fraction of the total water volume that the aquifer releases by gravity is called the aquifer specific yield  $S_y$  (Lohman, 1972; Fetter, 1994, Schwartz and Zhang, 2003). On the other hand, the relative fraction of the total water volume that the aquifer retains is called the aquifer specific retention  $S_r$  (Healy and Cook, 2002). These three parameters (aquifer effective porosity, specific yield and retention) are mathematically related by equation 10.

$$\theta_{\text{eff}} = S_y + S_r \quad (10)$$

The aquifer specific yield is given by equation 11 under the assumption of 100 % water saturation of the pores in the aquifer (Frohlich and Kelly, 1988):

$$S_y = \theta_{\text{eff}} (1 - S) \quad (11)$$

where  $S$  is saturation at specific retention. From Archie's law, the resistivity of the saturated portion of the aquifer  $\rho_{\text{sat}}$  (differences between aquifer bulk resistivity and water resistivity) and

that of the unsaturated geological unit  $\rho_{\text{unsat}}$  overlying the uppermost aquifer in the unconfined aquifer system are respectively given by equations 12 and 13.

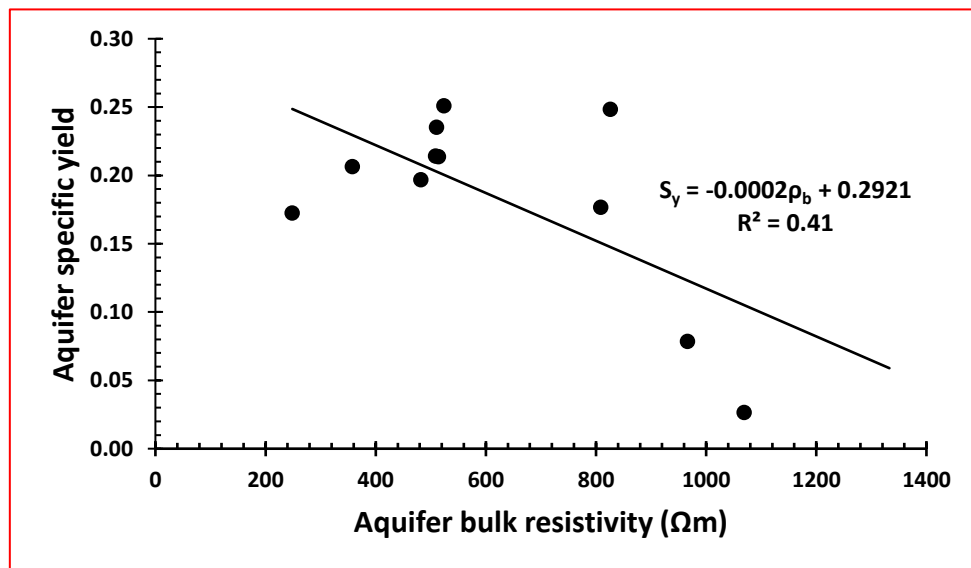
$$\rho_{\text{sat}} = \rho_w \phi_{\text{eff}}^{-m} \quad (12)$$

$$\rho_{\text{unsat}} = \rho_{\text{sat}} S^{-m} \quad (13)$$

Equations 12 and 13 can be combined in equation 11 to give the aquifer specific yield as given in equation 14.

$$s_y = \left( \frac{\rho_w}{\rho_{\text{sat}}} \right)^{\frac{1}{m}} \times \left[ 1 - \left( \frac{\rho_{\text{sat}}}{\rho_{\text{unsat}}} \right)^{\frac{1}{n}} \right] \quad (14)$$

where  $n$  is approximately equal to 2 for unconsolidated sands. The values of  $S_y$  and  $S_r$  computed from equations 10 and 14 respectively vary between 0.027 and 0.251 and 0.009 and 0.259 with corresponding average values of 0.184 and 0.075 as presented in Table 2. Figure 10 shows a plot of aquifer specific yield values against aquifer bulk resistivity. The plot showcases a linear relation between the two parameters given in equation 15 with a correlation coefficient of 41 %. Aquifer specific yield decreases with aquifer bulk resistivity as Figure 10 reveals.



**Figure 10:** A plot of the aquifer specific yield versus aquifer bulk resistivity in the study area

Equation 15 allows for easy estimation of aquifer specific yield from surface resistivity data.

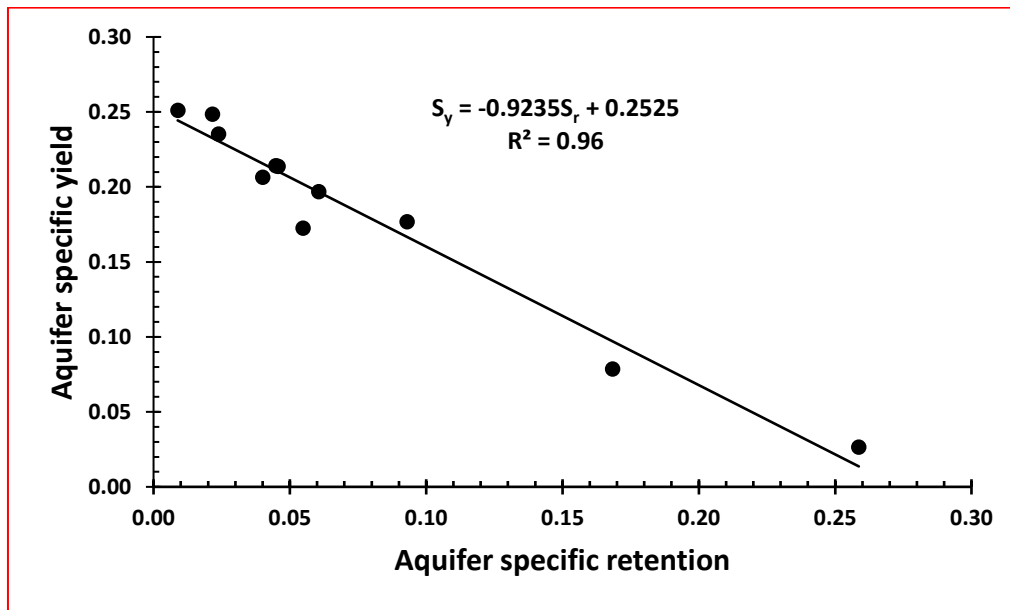
$$S_y = -0.0002\rho_b + 0.2921 \quad (15)$$

Figure 11 shows a plot of the aquifer specific yield versus aquifer specific retention in the study area. The plot reveals a linear decrease in the aquifer specific yield with aquifer specific retention according to equation 16 with a correlation coefficient of 96 %.

$$S_y = 0.9235S_r + 0.2525 \quad (16)$$

With the aquifer mean specific yield of 0.184, the groundwater volume that the aquifer could

readily release during pumping is 71 % of the effective groundwater reserve volume  $V_e$ , which is  $3.33 \times 10^7 \text{ m}^3$ . This reserve is the static groundwater reserve in the area for the unconfined aquifers. The retainable volume of water by the aquifer on the other hand given an average aquifer specific retention of 0.075 is 29 % of the effective groundwater reserve volume  $V_e$ , which amounts to  $1.35 \times 10^7 \text{ m}^3$ . By comparison, the groundwater volume released is greater than that retained during pumping. This is an indication that the study site has high groundwater potential for the sustainability of water wells



**Figure 11:** A plot of the aquifer specific yield versus aquifer specific retention in the study area

## 5.0 Conclusion

The usability of the electrical resistivity technique in the volumetric estimation of groundwater reserve is demonstrated in this study. Sixteen (16) VES were made at predetermined locations in Akwa Ibom State University main campus, Ikot Akpaden, Mkpato Enin LGA, southern Nigeria. Three to four geoelectric layers made up of poorly sorted continental sands (i.e. fine, coarse, gravelly) with minor clay intercalations have been identified in the study site from the VES data interpretation. The main aquifer in the area is found in the second layer at some spots and the third layer at others, with resistivity ranging from 248.6 to 1332.7  $\Omega\text{m}$  and thickness ranging from 16.8 to 123.7 m. The depth to the top of the aquifer layer varies from 1.1 to 50.2 m. The aquifer system is shown to have a mean porosity of 0.26, mean specific yield of 0.184 and mean specific retention of 0.075. The total aquifer volume is estimated to be  $1.8 \times 10^8 \text{ m}^3$  while the usable water volume reserve in the area is  $4.68 \times 10^7 \pm 2.2 \times 10^6 \text{ m}^3$ . The groundwater volume that the aquifer can release readily to a borehole during pumping is shown to be 71% of the effective groundwater reserve volume, which

is  $3.33 \times 10^7 \text{ m}^3$ . The retainable volume of water by the aquifer on the other hand is 29 % of the effective groundwater reserve volume, which amounts to  $1.35 \times 10^7 \text{ m}^3$ . The aquifer specific yield volume is by far greater than the aquifer specific retention volume, implying the area has good groundwater potential to sustain water wells. The regression equations derived in this study can be used for easy and rapid prediction of aquifer drainable porosity as well as aquifer specific retention from surface resistivity data in locations with similar geological characteristics. Even though these findings are very auspicious particularly in devising sustainable groundwater development and exploitable schemes in the region, geochemical and microbial analyses of water samples were recommended to ascertain the groundwater quality in the region.

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### Conflict of Interest

The authors declare that there are no known conflicts of interest.

### Data Availability

The datasets used in this study are available from the corresponding author on reasonable demand

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