

# Geohydraulic Investigation of Aquifer Parameters in Abak, Southern Nigeria

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## Abstract

A geophysical investigation was carried out to characterize aquifer parameters and assess the groundwater condition in Abak, southern Nigeria. Vertical electrical sounding (VES) was carried out using Schlumberger configuration in 10 locations within the area. Both manual and computer interpretation of the resistivity data reveals three to four geoelectric units (laterite topsoil, medium-grained sand, coarse-grained sand, and sandy clay sand) which agrees with the lithologic log from existing boreholes. The aquifer layer was identified along the third formation with resistivity values ranging from 1239 - 5719  $\Omega\text{m}$  and aquifer depth ranging from 30.2 - 54.8 m. The aquifer thickness ranged from 24.2 - 43.7 m. Hydraulic conductivity ranged from 0.1206 m/day - 0.5026 m/day with an average value of 0.29403 m/day. Formation factor ranged from 14.55 - 16.64. Porosity ranged from 15.98% - 22.40%, with an average value of 19.64%. The aquiferous zone falls within the medium/coarse-grained sand. The aquifer is shallow, unconfined, and prolific with a little overburden formation of 13.5 m. The area shows good prospects for groundwater development.

## Keywords

Electrical Resistivity, Porosity, Formation Factor, Hydraulic Conductivity

## 1. Introduction

Water, next to air, is the most important need of man. Despite inevitability, a large population particularly in rural and developing areas like Abak, southern Nigeria, are yet to have unlimited access to clean and readily available water. Groundwater has proven to be a better source for sustainable and clean water supply (Akankpo et al., 2009; Ibuot et al., 2013; Joel et al., 2020; Uwa et al.,

2018). Groundwater is usually free from odor and color and has a very low dissolved solid content. To satisfy the growing need for clean water, proper studies and exploration steps should be taken. The need for improved global water evaluation cannot be over-emphasized observing the rapid urban-rural migration and increasing industrialization activities. Readily available and accurate information on water resources will ensure proper groundwater management and conservation, hence reducing exposure of individuals to waterborne diseases and eradicating drilling failed boreholes in these areas.

The electrical resistivity method of geophysical exploration happens to be the most applied in groundwater exploration (Anomohanran, 2011; Akanmu & Adewumi, 2016). The most commonly used method for electrical resistivity is vertical electrical sounding (VES). The vertical electrical sounding (VES) technique is used in electrical resistivity surveys to determine the vertical variation between the electrical resistivity below the earth's surface and the potential field generated by the current. Several studies have been carried out using the VES method and these studies have proven the efficacy of VES in groundwater exploration (Akanmu & Adewumi, 2016; Anomohanran, 2011; Akankpo & Igboekwe, 2011; Obiora et al., 2016; Uwa et al., 2018; Omeje et al., 2021). Uwa et al. (2018) carried out a Geohydrodynamic estimation of aquifer parameters in parts of Abak Local Government using VES, laboratory analysis of soil samples, and borehole information. Their findings exposed that the combination of the resistivity exploratory technique and the complementary laboratory method in association with geological/borehole lithologic information permitted the extrapolation of geoelectric and geohydrodynamic parameters.

It has been observed that there is quite little detailed resistivity data currently available for most rural areas within Abak Local Government, as such the groundwater potential, aquifer parameters, and depth to sustainable groundwater of these areas are not well known. To effectively manage and protect these aquifers, there is a pressing need for accurate and comprehensive information regarding their hydrogeological parameters, such as depth, thickness, and hydraulic conductivity. With the increase in the advancement of technology and the introduction of 2D/3D subsurface imaging, there is a need for detailed surveys in rural areas to identify aquifer zones for easy exploration.

Therefore, this study seeks to enhance our understanding of subsurface aquifers, provide the locals with vase subsurface information thereby averting drilling failed boreholes, and provide valuable insights for the exploration, management, and protection of sustainable groundwater resources. This study will investigate groundwater potential and aquifer parameters using the vertical electrical sounding technique, parameter contouring, and borehole information.

## 2. Location and Geology of the Study Area

The survey area is located between Longitudes 7°40'E and 7°50'E and Latitude 4°50'N and 4°10'N with the total area of about 50 km<sup>2</sup> (Figure 1). The area

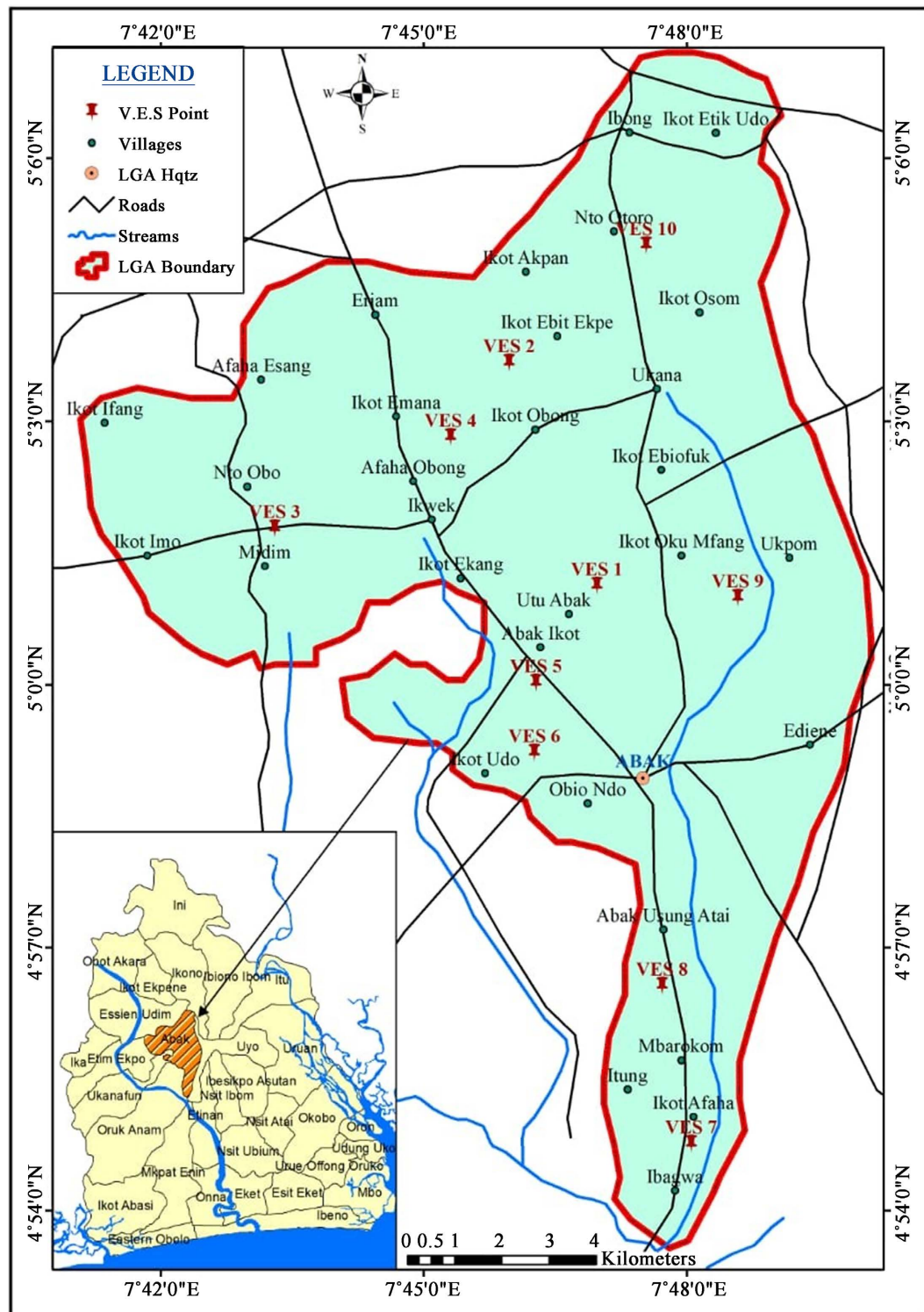


Figure 1. Map of the study area showing VES points.

generally has a land surface of very little or no significant reliefs over many kilometers. Surface water found in the area is mainly seasonal ponds and a few streams that run across some segments of the Area. The survey area is situated within a zone of climate with two noticeable seasons: the rainy season that be-

gins from March to October and the dry season that begins from November to February of every year (Uwa et al., 2018). The elevation varies between 36 - 91 m.

The geology of the study area is Recent to Tertiary sediments belonging to the Benin Formation. This formation is the youngest geologic unit in the Niger-Delta Sedimentary Basin. This formation comprises continental sand and gravel, deposited in an upper Deltaic plain environment. The grain sizes range from coarse to fine in texture and are poorly sorted. The Benin Formation which occurs at shallower horizons comprises continental deposits of sand and gravel and is important in groundwater exploration (Almeida et al., 2021).

### 3. Methodology

The electrical resistivity method was used for this survey. A total of ten VES stations were surveyed using an SSP-ATS-MRP model of an IGIS (Integrated Geo-instruments and Services) resistivity meter. The Schlumberger electrode configuration where four electrodes were placed on a straight line with  $AB \geq 5MN$  was employed, with a maximum current electrode spread of 400 m (Figure 1).

The Schlumberger electrode configuration used involved the use of four electrodes placed on a straight profile with the pair of potential electrodes having a common midpoint "O". The reference point "O" was located midway between the potential electrodes and was kept constant throughout the VES sounding. The potential electrodes (M and N), with half electrode spacing, varied from 0.25 - 10 m from the center point "O". While the current electrodes (A and B), with half electrode spacing, varied 1 - 200 m from midpoint 'O' along a profile line. The current electrode spacing was increased symmetrically along a straight line about the fixed point while the potential electrodes were kept fixed but increased only when the distance  $AB \geq 5MN$  which produced a measured signal very small.

The apparent resistivity values obtained considering the geometric factor were plotted against half the current electrode spacing on a bi-logarithmic graph to determine the apparent resistivities and thicknesses of various layers penetrated during the survey. The result of the field measurement was used to compute the apparent resistivity ( $\rho_a$ ) using Equation (1). The calculated apparent resistivity is measured in  $\Omega\text{m}$ .

$$\rho = \pi \left[ \frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right] \frac{\nabla V}{I} \quad (1)$$

where  $AB$  = current electrode spacing and  $MN$  = potential electrode spacing (Ibuot et al., 2021).

While the geometric factor

$$K = \pi \left[ \frac{\left( \frac{AB}{2} \right)^2 - \left( \frac{MN^2}{2} \right)}{MN} \right] \quad (2)$$

The coordinates and elevations of each location were taken using the Global Positioning System (GPS). The WINRESIST software was used for inversion models which generated the earth's primary parameters such as resistivities, thicknesses, and depths from the earth's surface to different geologic subsurface layers.

Secondary parameters such as water resistivity, porosity, hydraulic conductivity, transverse resistance, and formation factor could be computed using respective formulas.

Water resistivity is the measure of the ability of water to resist an electrical current, which is directly related to the amount of dissolved salt in the water. Water with a high concentration of dissolved salts will have a low resistivity, and vice versa. Resistivity is measured in Ohms. It is a measurement of water's opposition to the flow of a current over distance. Pores water resistivity was estimated using Equation (3) (Ibanga & George, 2016).

$$\rho_w = 0.0577\rho_a + 13.643 \quad (3)$$

A commonly used means of expressing the relationship between pore-water resistivity,  $\rho_w$ , and bulk resistivity,  $\rho_a$ , of a formation is the formation factor,  $F$  (Archie, 1942). The formation factor provides an indication of the total pore volume and how the pores are interconnected with each other. The aquifer formation factor which is the ratio of bulk resistivity of a rock filled with water ( $\rho_a$ ) to the resistivity of that water ( $\rho_w$ ) was calculated using Equation (4) (Akankpo & Igboekwe, 2011).

$$F = \frac{\rho_a}{\rho_w} \quad (4)$$

where  $\rho_a$  = aquifer resistivity, while  $\rho_w$  = water resistivity.

Hydraulic conductivity, a secondary parameter, describes the ease with which water can move through aquifer units. It varies in a geological unit over relatively short distances, particularly in fractured rock aquifers. Hydraulic conductivity depends on the permeability of the hosting rock, the viscosity of the fluid, and the specific weight of the fluid type passing through the formation (Hubbert, 1940 in Uwa et al., 2018). Hydraulic conductivity controls the rate at which groundwater flows and as such can be used in predicting groundwater flow direction. The hydraulic conductivity ( $K$ ) was estimated using Equation (5) (Heigold et al., 1979).

$$K = \frac{386.40}{\rho_a^{0.933}} \quad (5)$$

## 4. Results and Discussion

**Table 1** shows the summary of the geoelectric computer-aided model for the

study area, while **Table 2** shows the secondary geophysical and aquifer parameters estimated. The inversion models generated several curve types which reflected the subsurface conditions. The dominant curve types were AK and HK as observed from the models (**Figure 2** and **Figure 3**).

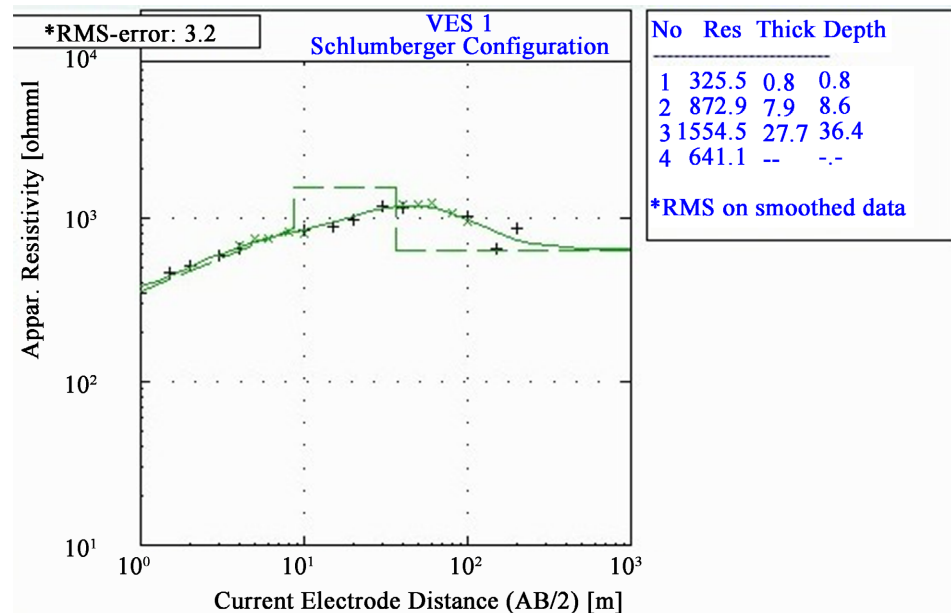
The first layer has a bulk resistivity ranging from 224.8 - 939.0  $\Omega\text{m}$ , while the second layer's resistivity ranges from 46.3 - 2040.5  $\Omega\text{m}$ . The third and fourth

**Table 1.** Summary of VES results.

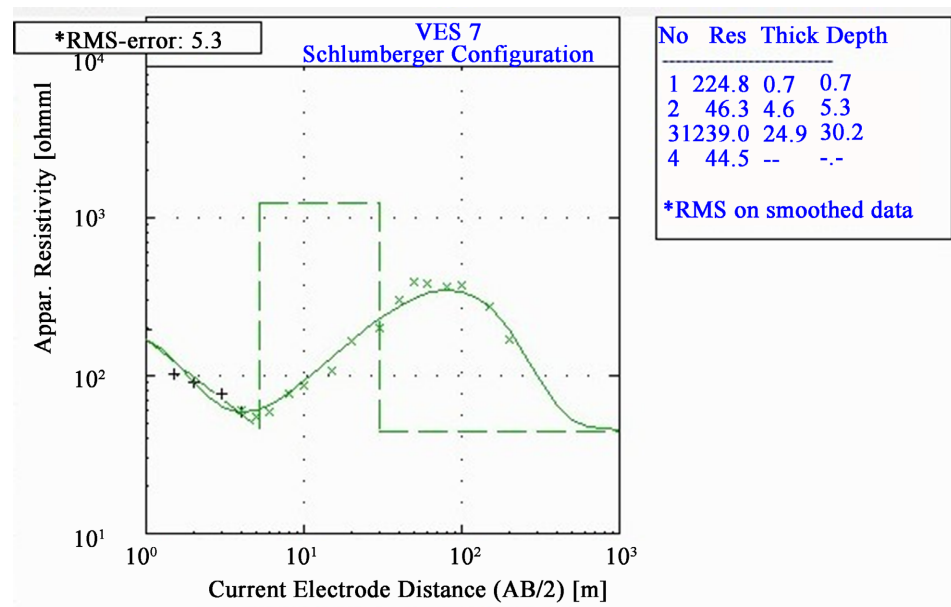
VES No.	Location Name	Longitude (°E)	Latitude (°N)	Elevation (m)	Layer Resistivity ( $\Omega\text{m}$ )				Layer thickness (m)			Layer depth (m)			Curves types
					$\rho_1$	$\rho_2$	$\rho_3$	$\rho_4$	$h_1$	$h_2$	$h_3$	$d_1$	$d_2$	$d_3$	
AB 1	Utu Abak	7.7713	5.0033	60	325.5	872.9	1554.5	641.1	0.8	7.9	27.7	0.8	8.5	36.4	AK
AB 2	Ikot Ebit Ekpe	7.7662	5.0612	91	939.0	1181.9	2078.7	602.8	1.2	12.5	39.2	1.2	13.8	52.9	AKQ
AB 3	Midim	7.7216	5.0298	71	126.5	1437.8	4028.7	1924.9	0.6	7.3	35.5	0.6	7.9	43.5	AK
AB 4	Ikot Ndue	7.7550	5.0470	83	377.6	890.1	2000.1	380.9	0.7	13.9	37.0	0.7	14.6	51.6	AK
AB5	Edem Anwa	7.7348	5.0638	80	595.6	1826.3	2271.7	485.8	1.3	10.1	33.9	1.3	11.5	45.4	AK
AB6	Ikot Etuk Udo	7.7710	4.9870	69	365.7	1582.0	1704.2	636.3	1.2	9.9	43.7	1.2	11.2	54.8	AK
AB 7	Ikot Afaha	7.8008	4.9126	36	224.8	46.3	1239.0	44.5	0.7	4.6	24.9	0.7	5.3	30.2	HK
AB 8	Abak Usung Atai	7.7953	4.9427	65	664.8	1338.7	3283.5	79.4	1.1	11.1	24.2	1.1	12.1	36.3	KQ
AB 9	Ukpom	7.8097	5.0165	78	890..5	899.5	5719.8	153.2	2.4	9.2	27.3	2.4	11.6	38.9	HKQ
AB 10	Atai Otoro Abak	7.7829	5.0188	69	796.2	2040.5	2616.6	1211.0	1.3	7.4	41.1	1.3	8.8	49.9	AK

**Table 2.** Summary of estimated aquifer hydraulic properties.

VES No.	Location Name	Long. (°E)	Lat. (°N)	Elevation (m)	Aquifer resistivity ( $\Omega\text{m}$ )	Aquifer thickness (m)	Water resistivity ( $\Omega\text{m}$ )	Formation factor	Porosity (%)	Hydraulic conductivity (m/day)
AB 1	Utu Abak	7.7713	5.0033	60	1554.5	27.7	103.34	15.04	21.45	0.4067
AB 2	Ikot Ebit Ekpe	7.7662	5.0612	91	2078.7	39.2	133.58	15.56	20.23	0.3101
AB 3	Midim	7.7216	5.0298	71	4028.7	35.5	246.10	16.37	17.45	0.1673
AB 4	Ikot Ndue	7.7550	5.0470	83	2000.1	37.0	129.05	15.50	20.39	0.3215
AB 5	Edem Anwa	7.7348	5.0638	80	2271.7	33.9	144.72	15.70	19.86	0.2855
AB 6	Ikot Etuk Udo	7.7710	4.9870	69	1704.2	43.7	111.98	15.22	21.07	0.3733
AB 7	Ikot Afaha	7.8008	4.9126	36	1239.0	24.9	85.13	14.55	22.40	0.5026
AB 8	Abak Usung Atai	7.7953	4.9427	65	3283.5	24.2	203.10	16.17	18.31	0.2025
AB 9	Ukpom	7.8097	5.0165	78	5719.8	27.3	343.68	16.64	15.98	0.1206
AB 10	Atai Otoro Abak	7.7829	5.0188	69	2616.6	41.1	164.62	15.90	19.27	0.2502

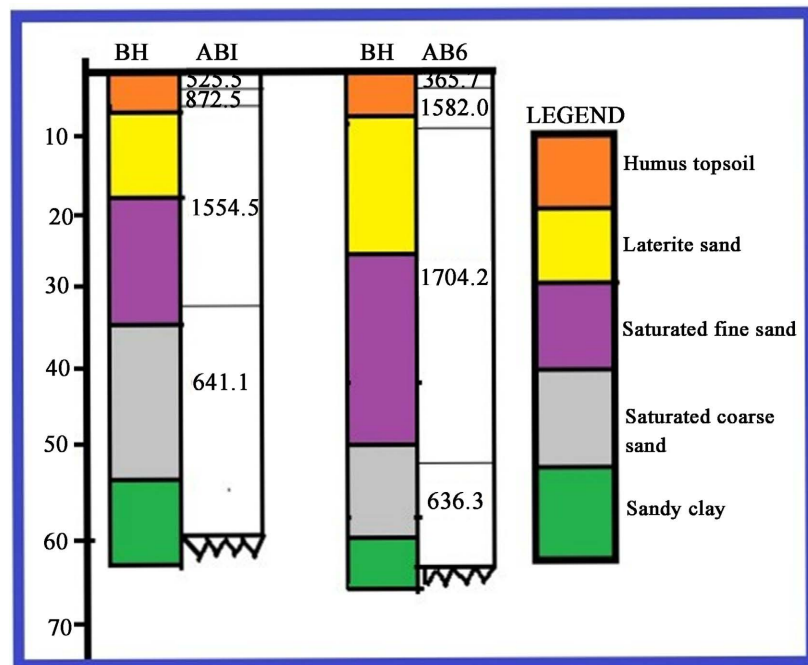


**Figure 2.** VES 1 model representing AK curve type.



**Figure 3.** VES 7 model representing HK curve type.

layer resistivity values range from 1239.0 - 5719.8  $\Omega\text{m}$  and 44.5 - 1924.9  $\Omega\text{m}$  respectively. The aquiferous layer is identified in the third layer with resistivity values ranging from 1239.0 - 5719.8  $\Omega\text{m}$ . The thickness of the aquiferous zone ranges from 24.2 - 43.7 m, with depth ranging from 30.2 - 54.8 m. The VES results were correlated with borehole data in the area (Figure 4). According to Uwa et al. (2018), to prevent the difficulties of quantitative interpretation of VES data, the results are usually correlated with borehole information from the study area. The combination of the resistivity exploratory technique and the borehole lithologic information permitted the extrapolation of geoelectric and geohydrodynamic

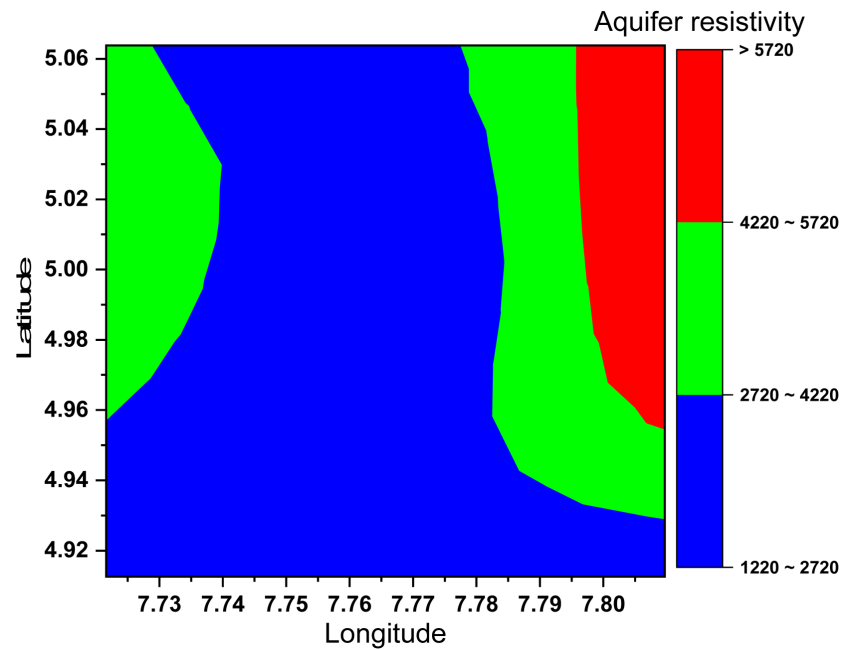


**Figure 4.** Borehole lithologic log of AB<sub>1</sub> and AB<sub>6</sub> showing depth and corresponding resistivity.

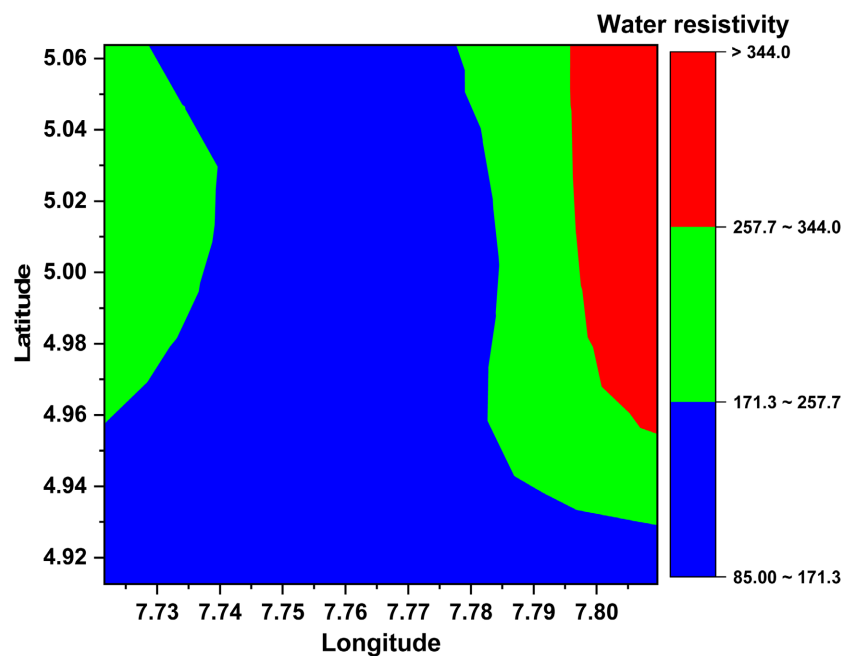
parameters. Akpabio and Ekpo (2018) in Geoelectric Investigation for Groundwater Development in parts of Uyo discovered an aquifer between fine sand and medium coarse sand with thicknesses of 3.5 m and 13.8 m. Another aquifer was found between fine sand and coarse sand with thicknesses of 28.8 m and 110.9 m. The subsurface geoelectric layers in this region are topsoil, clay soil, fine sand, medium-coarse sand, fine sand, and coarse sand. Igboekwe et al. (2012) identified three to four geoelectric layers in Eket, Akwa Ibom State. Akankpo and Igboekwe (2012) identified four distinctive layers defined as top loamy, lateritic sand, medium-grained sand, and conducting layer in Umudike, using the VES method.

The aquifer hydrodynamic parameters were obtained using already defined equations (Equations (3)-(5)). These parameters were derived from primary parameters and are referred to as secondary parameters, which include aquifer water resistivity ( $\rho_w$ ), aquifer formation factor ( $F$ ), porosity ( $u$ ), and hydraulic conductivity ( $K$ ) (Ibuot et al., 2021). The aquifer water resistivity ( $\rho_w$ ) ranges from 85.13  $\Omega m$  to 343.68  $\Omega m$  with an average value of 166.53  $\Omega m$ . The aquifer formation factor ( $F$ ) ranges from 14.55 to 16.64 with an average value of 15.67. The aquifer porosity ranged from 15.98 to 22.40%, with an average value of 19.64%. The area generally shows seemingly high porosity with a high coefficient of permeability.

Hydraulic conductivity ( $K$ ) ranges from 0.1206 to 0.5026 m/day with an average value of 0.29403 m/day. These secondary parameters were contoured as shown in Figures 5-9. The aquifer hydraulic conductivity ( $K$ ) describes the ease with which water can move through aquifer units. Hydraulic conductivity of a



**Figure 5.** Contour map showing the variation of aquifer resistivity.



**Figure 6.** Contour map showing the variation of water resistivity.

soil or rock or geological formation depends on various physical and geological variables including porosity, the structure of the soil matrix, grain size distribution, type of soil fluid, particle arrangement, water contents, void ratio, and other factors (Obiora et al., 2016; Almeida et al., 2021; Ibuot et al., 2022).

The northeastern sector shows lower values of formation factor while the northwestern and the southern regions have higher values of formation factor. This implies that high bulk resistivity increases the water resistivity thereby

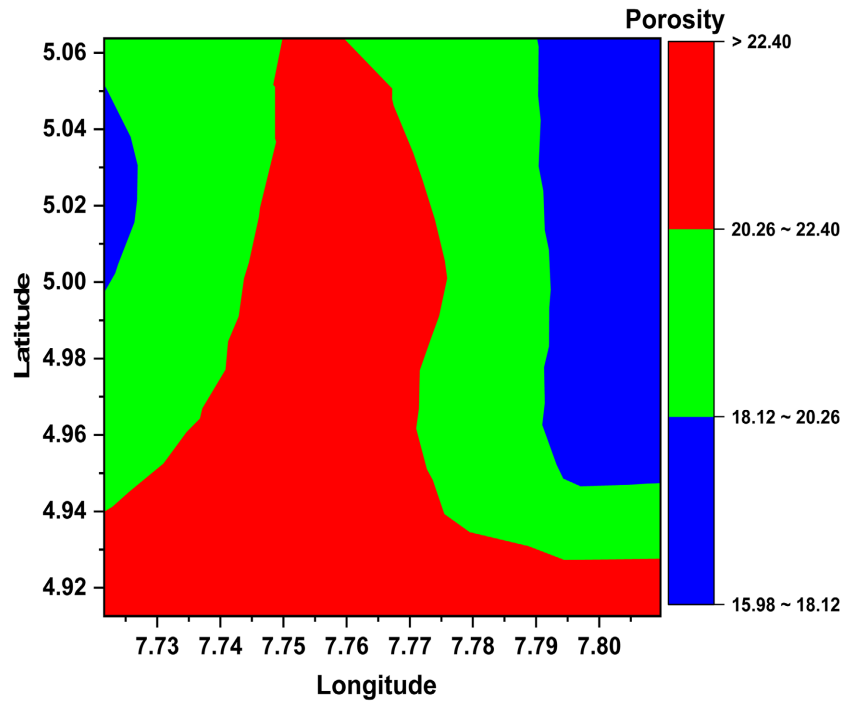


Figure 7. Contour map showing the variation of aquifer porosity.

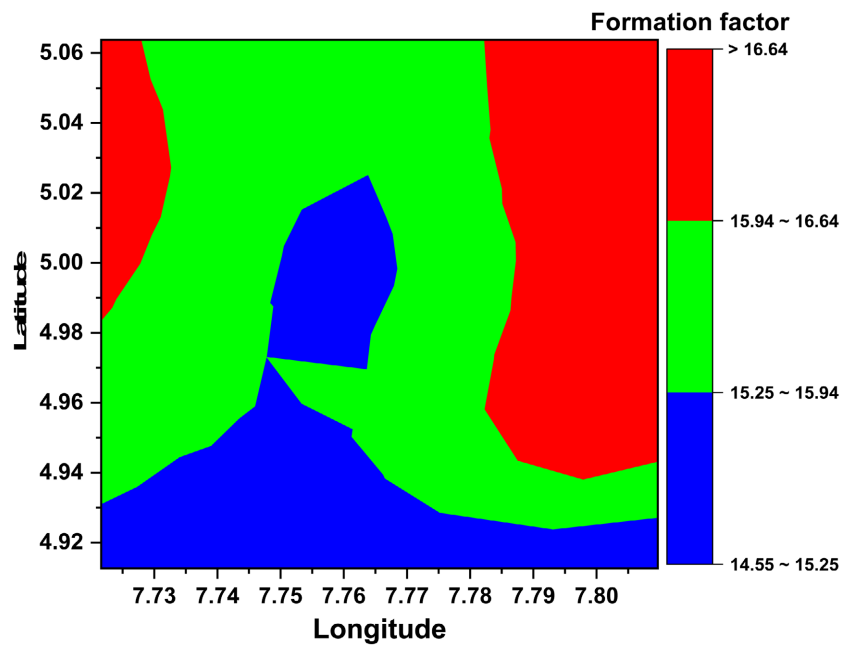
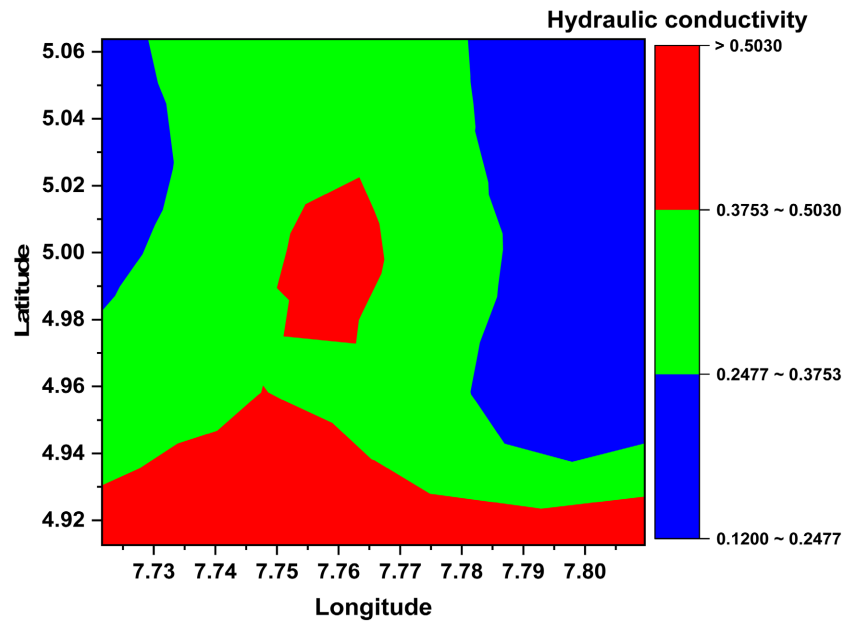


Figure 8. Contour map showing the variation of formation factor.

reducing the formation factor. Samuel et al. (2015) opined that the aquifer resistivity and the thickness distributions suggest that the study area is highly endowed with prolific aquifers. The major aquifer geomaterials are gravelly sand, fine sand, fine to coarse-grained sand, and medium-grained sand.

The aquifer resistivity shows high values in the northeastern area, while the central and southwestern zones show low resistivity values (Figure 5). This area



**Figure 9.** Contour map showing the variation of hydraulic conductivity.

is likely to have economical water repositories as they are saturated with pore water. If the water is not exposed to surface contamination, clean groundwater could be accessed in these zones of higher resistivity. The distribution of water resistivity (**Figure 6**) is similar to bulk aquifer resistivity (**Figure 5**) as shown in the contour. Water resistivity shows high values in the northeastern area, while the central and southwestern zones show low resistivity values. High values of bulk and water resistivities indicate both low conductivity and salinity of water in the area. Comparing **Figure 5** and **Figure 6** shows aquifer resistivity increases as water resistivity increases, and decreases vice versa. Hence, high aquifer resistivity and water resistivity are linearly related.

The contoured parameters are seen to have overlapping influences, aquifer resistivity, and water resistivity which look very similar. This suggests there is a direct relationship between these two parameters.

The contour map of porosity (**Figure 9**), shows that the central part of the location from North to South has a high porosity level. The map mostly indicates high-moderate porosity levels in the North, South, West, North-West, and South-West locations, with low porosity levels at the East and North-East regions of the contour map. As observed from **Figure 5** and **Figure 6**, the porosity contour shows that areas of low aquifer resistivity and water resistivity have very high porosity values.

The contour of hydraulic conductivity (**Figure 9**) and formation factor (**Figure 8**), oppositely correspond since their contours are similar but the values are opposite. Areas of high formation factor are areas of low hydraulic conductivity while areas of low formation factor correspond similarly to areas of high hydraulic conductivity. Only areas of moderate formation factor and areas of moderate hydraulic conductivity occur in same locations.

## 5. Conclusion

A prolific unconfined aquifer consisting mainly of medium-coarse grain sand was identified with little overburden soil found between depths 30 - 50 m. The aquiferous zone falls within the medium/coarse-grained sand which is the third (3<sup>rd</sup>) formation. There exists a direct relationship between aquifer resistivity and water resistivity. There is an indirect relationship between hydraulic conductivity and formation factor. Areas with high hydraulic conductivity correspond to areas of low formation factor, while areas of low hydraulic conductivity correspond to areas with high formation factor.

The most prolific aquifer was found at location Ikot Afaha (AB<sub>7</sub>), having the lowest observed resistivity, lowest water resistivity, lowest formation factor, and lowest transverse resistance. It was also observed that the location had the highest porosity percentage, highest hydraulic conductivity, and the highest longitudinal conductance. The least productive aquifer zone was found at Ukpom Abak (AB<sub>9</sub>), having the highest aquifer resistivity, highest water resistivity, highest formation factor, and highest transverse resistance with the lowest transmissivity and lowest hydraulic conductivity.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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