



Spatial analysis and modeling of litho-textural properties of hydrogeological units in Ofu local government area of Kogi State, North Central, Nigeria

Endurance Ojonuba Daniel¹ · Johnson Cletus Ibuot¹ · Desmond Okechukwu Ugbor¹ · Daniel Nnaemeka Obiora¹

Received: 9 September 2022 / Accepted: 25 November 2022 / Published online: 28 December 2022
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2022

Abstract

The current study used the vertical electrical sounding (VES) technique to evaluate the litho-textural properties of the sub-surface hydrogeologic units. Thirty VES were conducted across the study area employing the Schlumberger array, and the data were reduced to 1-D geological models employing both manual and computer modeling approaches. The geoelectric data were integrated with borehole lithologic information for a better description of the subsurface conditions. The result of the study revealed four geoelectric layers with varying resistivities, thicknesses, and depths, with the third layer delineated as the aquifer with resistivity and thickness ranging from 41.0 to 16,753.1 Ωm and 10.9 to 85.8 m, respectively. The primary geoelectric parameters (resistivity and thickness) were used to estimate the values of geohydraulic properties using empirical relations. The estimated parameters [resistivity gradient (RG), resistivity reflection coefficient (k_1), resistivity reflection coefficient (k_2), hydraulic conductivity (K_h), porosity (ϕ), transmissivity (Tr), storativity (S), and hydraulic diffusivity (D)] have values ranging from 27.54 to 1550.60 Ω , -0.05 to 0.98, -0.92 to 0.95, 0.04 to 12.08 m/day, 27.01 to 32.08%, 1.42 to 412.18 m^2/day , 0.033 to 0.257, and 14.75 to 4029.13, respectively. The distribution of these parameters across the study area reflects lithological discontinuities of the subsurface. The results revealed a good prospect of the aquifer for groundwater exploration and the technique as a valuable tool to characterize the litho-textural properties of aquifer repositories.

Keywords Resistivity · Groundwater · Geohydraulic properties · Lithology VES

Introduction

The demand for groundwater in the Ofu Local Government Area (L. G. A.) of Kogi state has increased in recent times, and this is attributed to an insufficient supply of public water. The water resources are useful to the indigenous of the area for their daily domestic, agricultural, and social needs and the limited boreholes cannot satisfy the inhabitants of the water. Some of these boreholes have failed, while some are productive only during the rainy season. The dynamic behavior of the hydrogeological units affects the occurrence and flow of groundwater in the subsurface. The amounts of pores and crevices in soil and rock and the way they are linked control the ease of groundwater movement

through the subsurface and the quantity of groundwater that comes from a particular layer (Akpan et al. 2006; Ekanem et al. 2019; Ibuot et al. 2019; Obiora and Ibuot 2020; George 2020), where useable volumes of groundwater can be pumped from an aquifer layer.

The occurrence of groundwater varies in size and volume through a region, it lies beneath the subsurface, and its potential for use depends on its quality and the aquifer yield (Ifediegwu et al. 2019; Anomohanran et al. 2020; Ikpe et al. 2022). The occurrence and flow of groundwater depend on the degree of weathering and the extent of fracturing of the bed rocks and the amount of groundwater in the hydrogeologic layers is controlled by factors, such as topography, permeability, lithology, geological structures, lineament density, aperture and connectivity, and also the primary and secondary porosity (Ifediegwu et al. 2019; Ekanem 2020; Omeje et al. 2021; Ekanem et al. 2022). The subsurface of the earth is made of numerous kinds of rock, such as sedimentary, igneous, and metamorphic rocks, with varying amounts of porous spaces where groundwater flows.

✉ Johnson Cletus Ibuot
johnson.ibuot@unn.edu.ng

¹ Department of Physics and Astronomy, University of Nigeria, Nsukka, Nigeria

There is need for quantitative description of aquifers to proffer solutions to some hydrological and hydrogeological problems. Aquifer transmissivity, resistivity gradient, porosity, longitudinal conductance, hydraulic conductivity, reflection coefficient, formation factor, storativity, diffusivity, and aquifer depth are some of the fundamental properties describing the geohydraulic nature of the subsurface (George et al. 2015; Ashraf et al. 2018; Ibuot and Obiora 2021; Naiyeju et al. 2021). Different investigation techniques involving surficial geoelectric sounding data are commonly employed to estimate the spatial distributions and relationships of the geohydraulic parameters, since field estimations/pumping test data are not always available (Niwas and Singhal 1981; De Lima and Niwas 2000; Niwas and Celik 2012). The hydraulic behavior of aquifer units influences the accuracy in the estimation of the hydraulic parameters (Singh 2005). Earth scientists have realized that the integration of aquifer parameters estimated from surface resistivity data obtained via surface resistivity measurements may be useful, since a correlation between hydraulic and electrical properties of aquifers can be possible, and since both properties are related to the pore space structure and heterogeneity (Rubin and Hubbard 2005; De Lima et al. 2005; Metwaly et al. 2014; George et al. 2018; George 2020). Surface resistivity techniques can widely be used to solve various problems ranging from geotechnical, geological, and environmental.

The resistivity technique measures the potential differences on the earth's surface due to the current injected into the ground. The geoelectric and geohydraulic conductivities depend on each other, because the mechanisms controlling groundwater flow, electric current flow, and conduction depend on the same physical parameters and lithological characteristics. Also, factors (lithology, size, shape, mineralogy, packing, and orientation of grains, shape, and geometry of pores and pore channels, porosity, tortuosity, permeability, and compaction,) that control the flow of current and conduction in the subsurface vary greatly across the subsurface (Hiscock et al. 2002; Saleh et al. 1999; George et al. 2018; George and Ekanem 2019; Ige et al. 2021; Ibuot et al. 2021). In the design of suitable groundwater management approaches, the nature of the subsurface materials is an important factor to consider in any hydrogeologic environment, since its properties and variations are the aims of hydrogeologic and hydrogeophysical investigations (Niwas and Celik 2012; George et al. 2014; Ekwe et al. 2020; Opara et al. 2020). The present study is aimed at estimating the geoelectric and geohydraulic properties and characterizing the litho-textural properties of the study area from the direct current electrical resistivity technique.

Site location, geology, and hydrogeology of the study area

The study area (Ofu L. G. A.) is located in Kogi State, North-central Nigeria and lies between longitudes $7^{\circ}0'$ to $7^{\circ}20'E$ and latitudes $7^{\circ}12'$ to $7^{\circ}26'N$ (Fig. 1). The area lies within the Lower Benue River Basin Development Authority in North Central Nigeria. Ofu Local Government area which is the study area is surrounded by Bassa and Dekina L. G. A., Ankpa and Olamaboro L. G. A., Ighalamela-Odolu L. G. A., and River Niger to the north, east, south, and west, respectively. The wet and dry seasons experienced in the area start from April to October and from November to March, respectively. The total annual rainfall varies from 1000 to 1500 mm with an average temperature of $26.8^{\circ}C$ and relative humidity of 30% and 70% in dry and wet seasons, respectively (Jenkwe and Iyeh 2020). Lateritic soil type is predominant in the study area and some patches of hydromorphic and rich loamy soil (Jenkwe and Iyeh 2020). The area is dominated by undulating topography with the presence of sandstone and lowlands by shale, and the area is drained by River Aji and River Ola-Ofu, thus forming a dendritic drainage pattern.

The study area lies within the Anambra Sedimentary Basin which is one of the inland basins in Nigeria (Fig. 1). The Anambra sedimentary basins contain sediment fill of Cretaceous ages, and unconformably overlie the basement complex and consist of shale, siltstone, and fine-grained sandstones (Ifediegwu et al. 2019). The study area is dominated by Nsukka and Ajali Formations (Fig. 1), and according to Kogbe (1989), the Nsukka Formation overlies the Ajali Formation. These Formations are widely characterized by varying lithologies which are composed of an alternation of clays, shales, whitish sands, reddish sands, brownish sands, sandstones, laterites, and alluvial deposits (Omali et al. 2018; Eugene-Okorie et al. 2020). The flow of groundwater depends on the rock lithology, texture, and structures, and also on hydrological and meteorological factors (Ifediegwu et al. 2019).

Methodology and data acquisition

The VES technique with the Schlumberger electrode configuration was employed to investigate the litho-textural properties of the study area. Profiles for the study were taken along fairly straight traverses. Thirty vertical electrical soundings were taken which translated to wider coverage of the areas earmarked for this study. The choice of the sounding points was such that it allowed for electrodes to be spread along a straight traverse. The total traverse

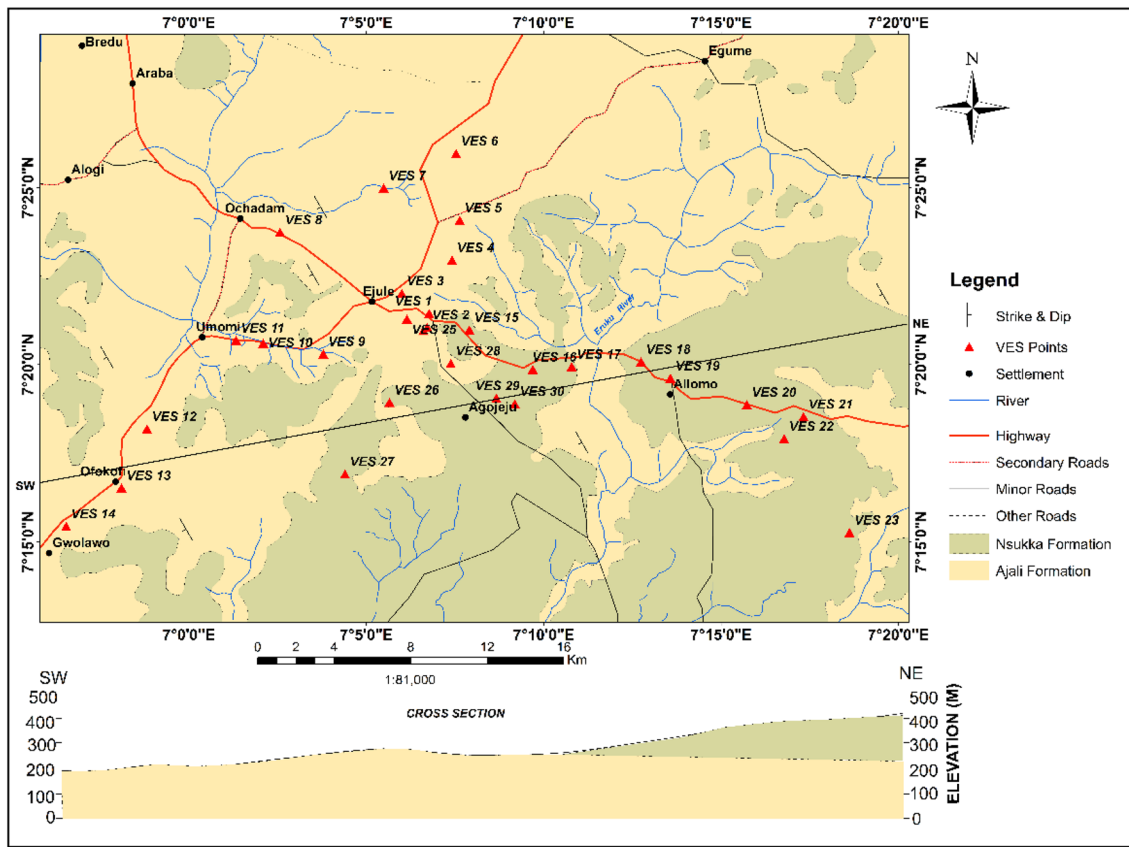


Fig. 1 Map showing the Geologic Formation of the study area

length for each sounding gives the maximum current electrode separation for that particular sounding. The potential difference was measured between the potential electrodes (M and N). The first potential electrode separation was 0.5 m, that is, 0.25 m from the center to each potential electrode. While the corresponding current electrode separation (AB) was 2.0 m, that is, 1 m from the center to each of the current electrodes. The four electrodes were connected via the copper cable to the resistivity meter at the terminals P_1 , P_2 , and C_1 , C_2 for potential and current electrodes, respectively. The extension of current electrode separation (AB) and potential electrode separation (MN) was from 2.0 to 600.0 m and 0.5 to 40.0 m, respectively. The IGIS resistivity meter measures the potential difference generated in the subsurface, and the process was repeated by increasing the spacing of the current electrodes proportionally from the midpoint point. Increase in spacing between the potential electrodes when it was observed that the potential field is weak and care was taken to make sure that the distance between the potential electrodes did not surpass one-fifth of the distance between the current electrodes. The measured resistance R was converted to apparent resistivity (ρ_a) using Eq. 1).

The reduction of the data to 1-D geological models was done employing both manual and computer modeling approaches (Zohdy 1965; Zohdy et al. 1974; George et al. 2015). The values of ρ_a obtained from Eq. (1) were plotted against $\frac{AB}{2}$ on bi-logarithmic graph sheets and the curves were smoothed. The smoothed aid in the removal of the effects of lateral heterogeneities and other unwanted signatures (Chakravarthi et al. 2007; George et al. 2015; Ekanem et al. 2022). The master curves and charts were used curve matched according to Orellana and Mooney (1966). In computer modeling, the apparent resistivity values were used as input parameters in the WinResist software program to produce geoelectric curves, as shown in Figs. 2 and 3. The values of resistivity, thickness, and depth at each geoelectric layer were obtained from the geoelectric curves which displayed wide variations in the values of the geoelectric parameters between and within the subsurface strata penetrated by the current

$$\rho_a = G.R_a, \tag{1}$$

where G is the geometric factor: $\pi \cdot \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right]$ and R_a is the apparent resistance.

Fig. 2 Geoelectric curves at VES 4

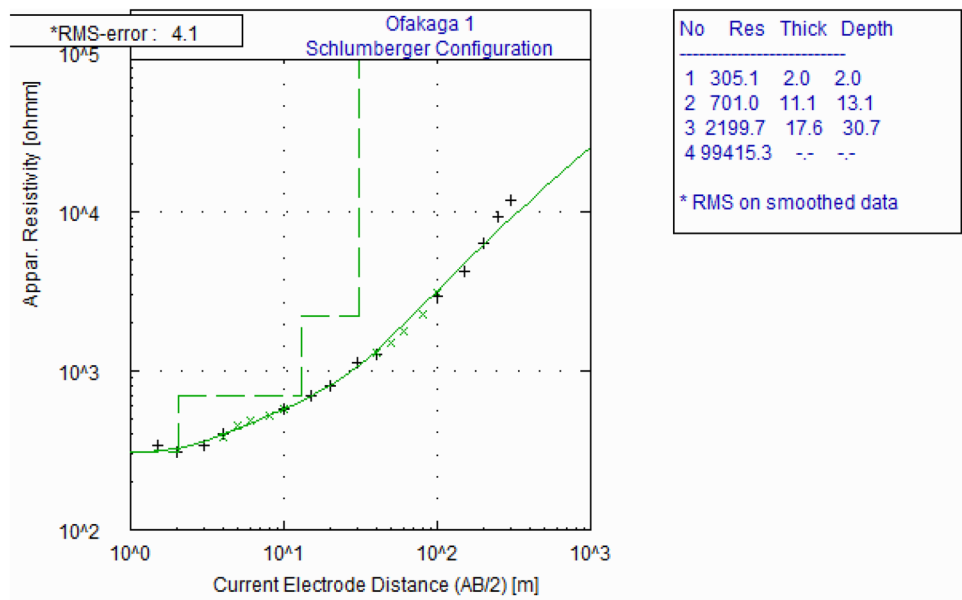
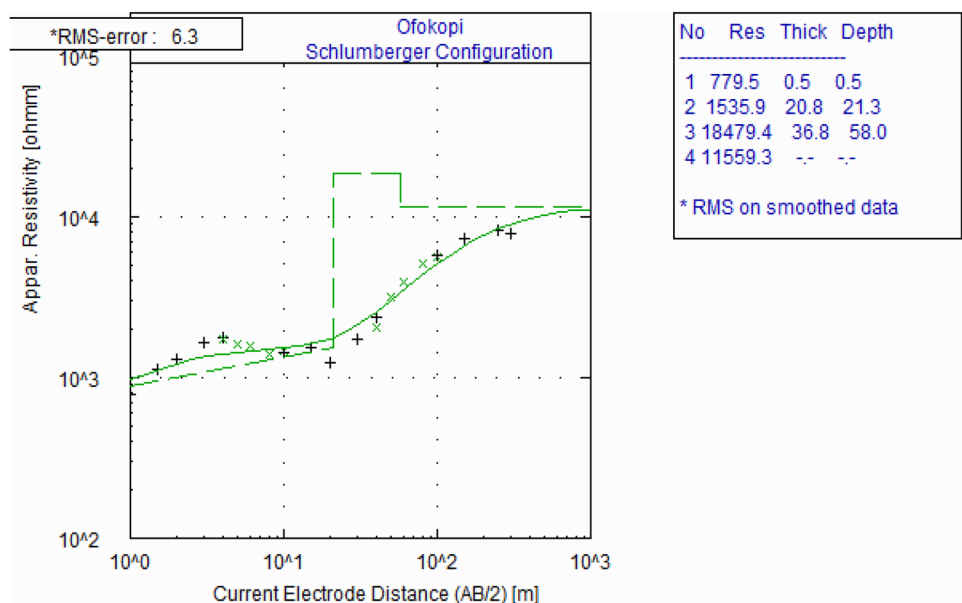


Fig. 3 Geoelectric curve at VES 13



Geoelectric and geohydraulic indices

The primary geoelectric parameters (resistivity and thickness) also known as the first-order geoelectric indices were used in estimating the geohydraulic parameters (second-order geoelectric indices). The second-order geoelectric indices estimated in this study are resistivity gradient (RG), reflection coefficient (k_1 and k_2), hydraulic conductivity (K), porosity (Φ), storativity (S), and hydraulic diffusivity (D).

Resistivity gradient (RG)

The longitudinal conductance (S) and resistivity gradient (RG) are related according to the expressions in Eqs. 2 and 3. The resistivity is important in the hydrogeological study as it helps in predicting the vulnerability of aquifer units to contaminants (George 2020)

$$S = \sum \left(\frac{h_i}{\rho_i} \right) \tag{2}$$

$$RG = \sum \left(\frac{1}{S_i} \right) = \sum \left(\frac{\rho_i}{h_i} \right), \tag{3}$$

where h_i and ρ_i are the thickness and resistivity of the n th layer, respectively. The parameters S and RG are inversely related as expressed in Eq. 4. RG is also referred to as longitudinal resistance

$$S = \frac{1}{RG} = S.RG = 1. \tag{4}$$

Reflection coefficient (RC)

The resistivity reflection coefficient assesses the variability of resistivity between subsurface layers. In estimating the reflection coefficients k_1 and k_2 , in this study, we consider the resistivity values for layer 1 (ρ_1), layer 2 (ρ_2), and layer 3 (ρ_3) and are expressed in Eqs. 5 and 6 respectively

$$k_1 = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \tag{5}$$

$$k_2 = \frac{\rho_3 - \rho_2}{\rho_3 + \rho_2}, \tag{6}$$

where k_1 and k_2 are the reflection coefficients. The reflection coefficient must have values ranging from +1 to -1, for the underlain layer to be a pure insulator, then $RC = +1$, and for it to be a perfect conductor, $RC = -1$. The electrical boundary will not exist when $\rho_1 = \rho_2$, and $k = 0$ (Ibuot et al. 2019).

Hydraulic conductivity (K_h)

This property defines the ease with which groundwater flows through the hydrogeologic units and varies across the hydrogeologic units over relatively short distances mainly in fractured rock aquifers. According to Al-Khafaji and Al-Dabbagh (2016), k_h controls the rate at which groundwater flows and as such can be used in predicting groundwater flow direction. The hydraulic conductivity (K_h) can be quantitatively determined according to the expression in Eq. 7

$$K_h = 386.42\rho^{-0.933}, \tag{7}$$

where ρ is the resistivity of the aquifer unit.

Porosity (ϕ)

Porosity (ϕ) is the fraction of the volume of open space (pore space) in soils/rocks in relation to the total soil/rocks

volume. As the drainable pore space, it can be calculated using Eq. 8. According to George et al. (2018) and Oguama et al. (2020), porosity is a rock property that determines aquifer productivity and depends on the grain composition of rocks, the way the rocks are formed, and the pressure to which rocks are exposed

$$\phi = 36.51\rho_a^{-0.031}, \tag{8}$$

where ρ_a is the aquifer resistivity and ϕ in %.

Transmissivity (Tr)

Transmissivity is the property of an aquifer unit that describes its ability to transmit groundwater through its whole saturated thickness. Also, it measures the rate at which groundwater flows through a section of an aquifer unit with a unit hydraulic gradient. Transmissivity is related to Dar-Zarrouk parameters in an expression (Eq. 9) according to Niwas and Singhal (1981). The product of the hydraulic conductivity (K_h) and the aquifer thickness (h) gives the value of transmissivity in m^2/day as expressed in Eq. 9

$$Tr = K_h\sigma T = \frac{K_h S}{\sigma} = K_h h, \tag{9}$$

where T and S are the Dar-Zarrouk parameters (transverse resistance and longitudinal conductance, respectively) and σ is the aquifer conductivity.

Storativity (S)

Storativity also referred to as the storage coefficient is the amount of groundwater released from or taken into storage with respect to the change in water level (head) and surface area of the aquifer. The value of storativity depends on the aquifer type (unconfined or confined). According to Anomohanran et al. (2020), it is the groundwater bearing capacity of aquifer. The storativity of an unconfined aquifer varies from 0.01 to 0.3, while that of a confined aquifer varies from 1×10^{-5} to 1×10^{-3} . To estimate the storativity for an unconfined aquifer, we use Eq. 10 proposed by Hamil and Bell (1986) and Guideal et al. (2011)

$$S = 3 \times 10^{-3}h, \tag{10}$$

where h is the thickness of the aquifer in meters (m).

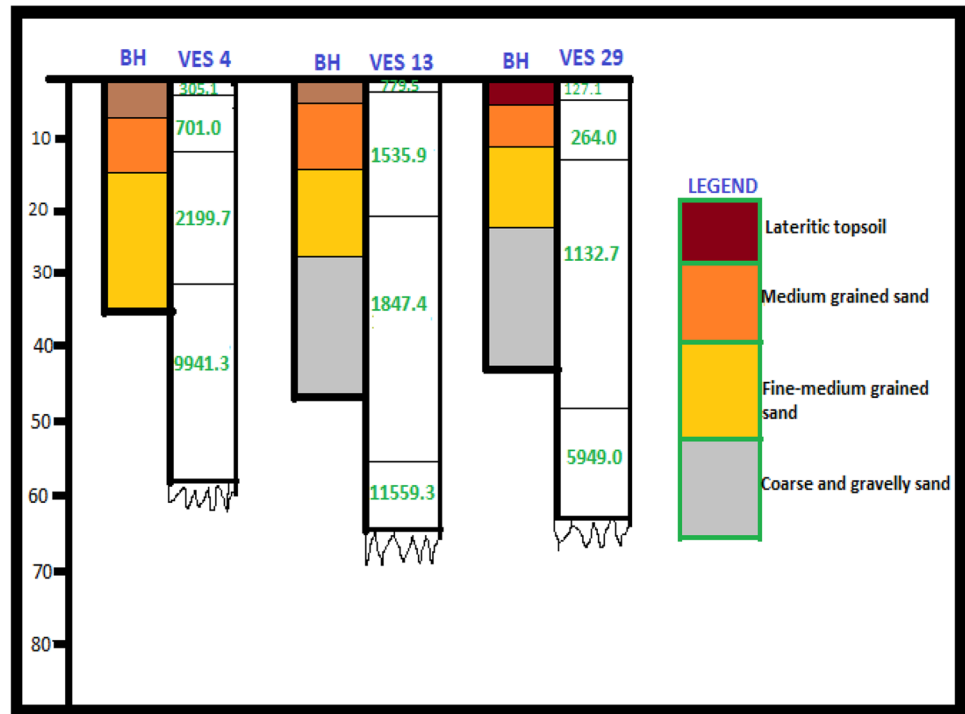
Hydraulic diffusivity (D)

This parameter describes the hydraulic properties of the aquifer unit, and it measures the diffusion speed of pressure disturbances in groundwater repositories. The combination of aquifer transmissivity and storativity gives a formation parameter called diffusivity (Hiscock 2005). It is the ratio

Table 1 Summary of VES results

VES No	Location name	Longitude (°E)	Latitude (°N)	Elevation (m)	Layer resistivity (Ωm)				Layer thickness (m)				Layer depth (m)			Curves types
					ρ_1	ρ_2	ρ_3	ρ_4	h_1	h_2	h_3	h_4	d_1	d_2	d_3	
1	St. Martins Catholic church	7.1128	7.3574	394	326.6	124.2	4634.7	903.2	1.0	6.2	47.1	1.0	7.2	54.3	HK	
2	Community Sec. Sch. Ejule	7.1119	7.3509	380	435.1	630.3	2781.6	4402.0	1.4	5.5	42.4	1.4	6.9	49.3	AA	
3	Ejule New Market	7.1001	7.3669	387	698.1	3325.9	6128.9	34,813.4	1.2	15.0	18.6	1.2	16.2	34.8	AA	
4	Ofakaga 1	7.1236	7.3825	396	305.1	701.0	2199.7	9941.3	2.0	11.1	17.6	2.0	13.1	30.7	AA	
5	Ofakaga 2	7.1272	7.4012	384	97.4	557.2	1850.6	43,855.6	1.8	7.7	19.0	1.8	9.5	28.5	AA	
6	Ogidibeje	7.1255	7.4326	418	120.8	9648.0	9577.8	39,791.0	0.8	5.5	41.9	0.8	6.3	48.2	KH	
7	Okabo	7.0915	7.4164	371	562.1	1381.4	2631.8	39,181.5	1.5	14.3	27.1	1.5	15.8	42.9	AA	
8	Ochadamu	7.0428	7.3956	265	40.0	889.1	5446.6	1228.0	0.6	6.4	51.6	0.6	6.9	58.5	AK	
9	Alome	7.0631	7.3384	247	1044.6	1726.4	1215.2	94,242.7	1.8	11.5	21.4	1.8	13.3	34.7	KH	
10	Ikpokejo	7.0349	7.3434	219	679.4	1545.0	2298.9	972.0	1.9	8.6	50.5	1.9	10.5	61.1	AK	
11	Umomi	7.0221	7.3448	205	128.2	254.5	1765.4	50,389.1	1.2	8.2	11.6	1.2	9.4	21.0	AA	
12	Akpagidigbo	6.9803	7.3031	177	2615.4	2034.5	445.5	282.2	1.2	23.9	17.5	1.2	25.1	42.7	QQ	
13	Ofokopi	6.9683	7.2754	171	779.5	1535.9	1847.4	11,559.3	0.5	20.8	36.8	0.5	21.3	58.0	AA	
14	Adikatana	6.9423	7.2573	147	1605.2	2318.1	3721.8	1067.9	3.4	17.3	85.8	3.4	20.7	106.5	AK	
15	Ojuwo	7.1317	7.3497	386	2170.3	6042.9	6093.9	23,310.9	4.1	9.0	22.3	4.1	13.1	35.4	AA	
16	Iboko	7.1615	7.3311	269	650.9	628.6	1600.9	56,875.5	4.1	18.6	11.6	4.1	22.7	34.3	HA	
17	Ogbulu	7.1798	7.3324	221	388.8	1510.9	738.5	6137.1	0.5	5.2	32.4	0.5	5.7	38.0	KH	
18	Alobi	7.2124	7.3347	238	608.5	576.0	3139.6	34,039.9	2.1	6.9	37.0	2.1	9.0	46.1	HA	
19	Alloma GSS	7.2262	7.3270	238	371.8	467.8	16,753.1	750.1	3.8	2.0	36.7	3.8	5.8	52.5	AK	
20	Omuna Ochikala	7.2621	7.3145	287	375.9	1723.9	732.8	43,765.6	2.8	9.2	22.5	2.8	12.1	34.6	KH	
21	Adupi	7.2887	7.3089	273	143.7	5234.9	1046.6	15,827.0	0.5	4.2	15.0	0.5	4.7	19.7	HH	
22	Agbaduma	7.2796	7.2985	314	1722.9	979.7	41.0	1026.4	2.8	15.3	34.1	2.8	18.0	52.1	QH	
23	Ogbonigha	7.3103	7.2544	270	1792.8	884.2	1116.6	80,154.2	1.3	7.3	21.9	1.3	8.7	30.6	HK	
24	Agojeju	7.1101	7.3494	384	387.0	1422.3	4235.7	20,396.5	2.0	13.0	50.8	2.0	15.0	65.7	AA	
25	Alla Rd	7.1024	7.3548	383	134.3	1025.7	1185.9	46,237.3	1.8	10.2	22.3	1.8	12.1	34.3	AA	
26	Egwubi	7.0942	7.3156	373	2194.6	3894.0	1737.6	79,310.3	3.7	7.3	16.4	3.7	11.0	27.4	KH	
27	Alla Ate	7.0733	7.2819	338	372.2	987.9	768.2	63,997.9	0.8	11.0	17.9	0.8	11.8	29.7	KH	
28	Ojataga	7.1230	7.3339	386	107.4	317.4	5252.2	10,050.0	1.0	1.2	10.9	1.0	8.2	19.1	AA	
29	Agojuje Rd 2	7.1444	7.3176	313	127.1	264.0	1132.7	5949.0	3.0	11.2	35.6	3.0	14.2	49.8	AA	
30	Agojuje	7.1531	7.3149	318	137.8	1292.4	148.0	3566.1	0.9	8.7	40.5	0.9	9.6	50.1	KH	
	Average				704.1	1797.5	3075.6	27,465.8	1.9	10.1	30.6	1.9	12.1	43.0		

Fig. 4 Correlations with the nearby boreholes from top to bottom



of aquifer transmissivity in (m²/day) to aquifer storativity as given in Eq. 11

$$D = \frac{Tr}{S}, \tag{11}$$

where *Tr* is aquifer transmissivity, and *S* is aquifer storativity.

Results and discussion

The VES results show that the study area comprises four subsurface geoelectric layers penetrated within the maximum current electrode separation (Table 1), and it revealed a subsurface that consists of four geoelectric layers. Figure 4 shows the correlation between VES curves and the nearby lithology formation from top to bottom in the study area. The first resistivity of the first layer ranges from 40.0 to 2615.4 Ωm and a mean value of 704.1 Ωm, indicating that the layer consists more of sand of varying contents of clay and is generally unsaturated. This layer enhances the percolation of rainwater into the underlying geologic units and interpreted as lateritic topsoil. The thickness and depth of the top layer vary between 0.5 and 4.1 m. The second layer with resistivity values ranging from 124.2 to 9648.0 Ωm with an average value of 1797.5 Ωm consists of medium-to-high resistivity materials, which may be attributed to the presence of medium-coarse brownish sand intercalation with

clay. The thickness and depth of the second layer vary from 4.2 to 23.9 and 4.7 to 25.1 m, respectively, with respective average values of 10.1 and 12.1 m. The third layer was characterized by resistivity values ranging from 41.0 to 16,753.1 Ωm with an average value of 3075.6 Ωm, while the thickness and depth ranging from 10.9 to 85.8 m and 19.1 to 106.5 m, respectively, with their respective average values of 30.6 m and 43.0 m. This layer was interpreted as fine- to medium-grained sand and was delineated as the main hydrogeologic unit. Underlain the third layer is the fourth layer which is a more resistive layer than the overlain layers with a resistivity range of 282.2 to 56,875.5 Ωm and a mean value of 27,465.8 Ωm, and the lithology of this layer suggests the presence of coarse and gravelly sand. The thickness and depth of this layer were undefined as current could not get through the layer at its maximum electrode separation. The lateral variations in resistivity can be attributed to the complex nature of the subsurface geology (George et al. 2015; Ibuot et al. 2019; Ekanem et al. 2020; Obiora and Ibuot 2020) and lateral lithological discontinuities in the study area.

The resistivity and thickness of the aquifer units (Table 2) ranged from 41.0 to 16,753.1 Ωm and 10.9 to 85.8 m, respectively, with a respective average of 3075.64 Ωm and 30.56 m. The variation of resistivity in the aquifer layer may be attributed to the density, shape, size, pore size, and porosity of the aquifer units. The distributions of these parameters are displayed in the contour maps (Figs. 5 and 6).

In Fig. 5, the highest value of aquifer resistivity is observed in the eastern part of the study area. Zones with

Table 2 Summary of VES results

VES No	Location name	Long (°E)	Lat (°N)	Ele ion (m)	Aquifer resistivity (Ωm)	Aquifer thickness (m)	RG (Ω)	Reflection coefficient		K_p (m/day)	ϕ (%)	Tr m ² /day	Storativity	Hydraulic diffusivity (m/day)
								k_1	k_2					
1	St. Martins Catholic church	7.1128	7.3574	394	4634.7	47.1	62.61	-0.45	0.95	0.15	28.10	6.91	0.141	48.93
2	Community Sec. Sch. Ejule	7.1119	7.3509	380	2781.6	42.4	154.41	0.18	0.63	0.24	28.55	10.02	0.127	78.78
3	Ejule New Market	7.1001	7.3669	387	6128.9	18.6	248.40	0.65	0.30	0.11	27.86	2.10	0.056	37.70
4	Ofakaga 1	7.1236	7.3825	396	2199.7	17.6	76.80	0.40	0.52	0.29	28.76	5.18	0.053	98.07
5	Ofakaga 2	7.1272	7.4012	384	1850.6	19.0	68.91	0.70	0.54	0.35	28.92	6.57	0.057	115.22
6	Ogidibeje	7.1255	7.4326	418	9577.8	41.9	1550.60	0.98	-0.01	0.08	27.48	3.1243	0.126	24.86
7	Okabo	7.0915	7.4164	371	2631.8	27.1	123.01	0.42	0.31	0.25	28.60	6.74	0.081	82.96
8	Ochadamu	7.0428	7.3956	265	5446.6	51.6	132.73	0.91	0.72	0.13	27.96	6.52	0.155	42.09
9	Alome	7.0631	7.3384	247	1215.2	21.4	208.35	0.25	-0.17	0.51	29.29	10.95	0.064	170.59
10	Ikpokejo	7.0349	7.3434	219	2298.9	50.5	211.85	0.39	0.20	0.28	28.72	14.26	0.152	94.11
11	Umomi	7.0221	7.3448	205	1765.4	11.6	40.71	0.33	0.75	0.36	28.96	4.19	0.035	120.40
12	Akpagidigbo	6.9803	7.3031	177	445.5	17.5	185.26	-0.13	-0.64	1.31	30.22	22.84	0.053	435.07
13	Ofokopi	6.9683	7.2754	171	1847.4	36.8	108.70	0.33	0.09	0.35	28.92	12.74	0.110	115.41
14	Adikafana	6.9423	7.2573	147	3721.8	85.8	189.53	0.18	0.23	0.18	28.30	15.45	0.257	60.04
15	Ojuwo	7.1317	7.3497	386	6093.9	22.3	626.96	0.47	0.01	0.11	27.87	2.54	0.067	37.90
16	Iboko	7.1615	7.3311	269	1600.9	11.6	56.37	-0.02	0.44	0.40	29.05	4.59	0.035	131.91
17	Ogbulu	7.1798	7.3324	221	738.5	32.4	333.28	0.59	-0.34	0.82	29.75	26.39	0.097	271.50
18	Alobi	7.2124	7.3347	238	3139.6	37.0	131.61	-0.03	0.69	0.21	28.45	7.81	0.111	70.37
19	Alloma GSS	7.2262	7.3270	238	16,753.1	36.7	144.76	0.11	0.95	0.04	27.01	1.62	0.110	14.75
20	Omuna Ochikala	7.2621	7.3145	287	732.8	22.5	174.98	0.64	-0.40	0.82	29.76	18.46	0.068	273.47
21	Adupi	7.2887	7.3089	273	1046.6	15.0	1144.38	0.95	-0.67	0.59	29.43	8.83	0.045	196.10
22	Agbaduma	7.2796	7.2985	314	41.0	34.1	149.32	-0.28	-0.92	12.08	32.54	412.18	0.102	4029.13
23	Ogbonigha	7.3103	7.2544	270	1116.6	21.9	311.28	-0.34	0.12	0.55	29.37	12.13	0.066	184.61
24	Agojeju	7.1101	7.3494	384	4235.7	50.8	120.62	0.57	0.50	0.16	28.18	8.11	0.152	53.21
25	Alla Rd	7.1024	7.3548	383	1185.9	22.3	96.67	0.77	0.07	0.52	29.32	11.68	0.067	174.52
26	Egwubi	7.0942	7.3156	373	1737.6	16.4	553.51	0.28	-0.38	0.37	28.97	6.01	0.049	122.20
27	Alla Ate	7.0733	7.2819	338	768.2	17.9	115.26	0.45	-0.13	0.79	29.71	14.05	0.054	261.69
28	Ojataga	7.1230	7.3339	386	5252.2	10.9	193.10	0.50	0.89	0.13	28.00	1.42	0.033	43.54
29	Agojuje Rd 2	7.1444	7.3176	313	1132.7	35.6	27.54	0.35	0.62	0.55	29.36	19.46	0.107	182.16
30	Agojuje	7.1531	7.3149	318	148.0	40.5	148.98	0.81	-0.80	3.65	31.27	147.80	0.122	1216.42
	Average			305	3075.6	30.5	256.35	0.37	0.17	0.88	28.96	27.69	0.092	292.92

Fig. 5 Distribution of aquifer resistivity

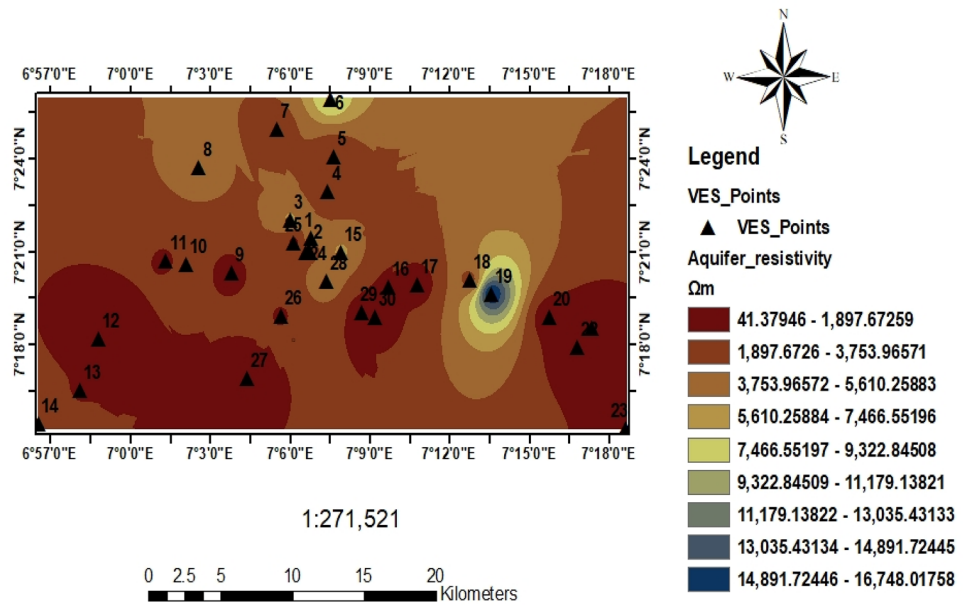
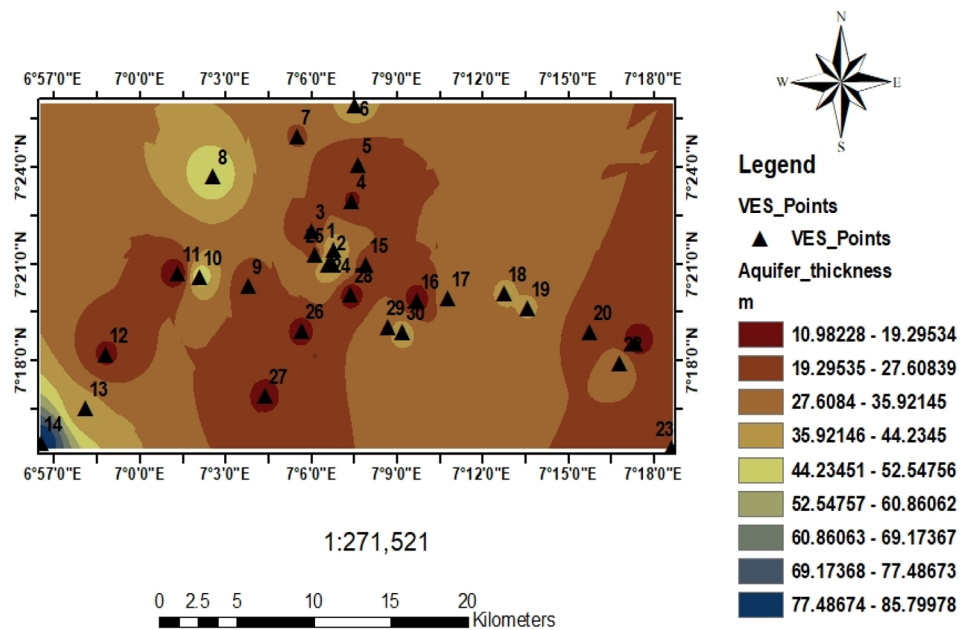


Fig. 6 Distribution of aquifer thickness



relatively high values of resistivity may have prolific aquifers where clean water can be accessed, while areas with low resistivity may be due to the presence of conductive materials such as clay. In Fig. 6, the highest aquifer thickness is observed in the southwestern part of the study area.

The Litho-textural properties (resistivity gradient, reflection coefficient, hydraulic conductivity, porosity, storativity, and hydraulic diffusivity) were estimated from the inferred

primary geoelectric parameters (layer resistivities and thicknesses). The resistivity gradient (RG) or longitudinal resistance varies from 27.54 to 1550.60 Ω with a mean of 256.35 Ω . Figure 7 shows the distribution of RG, where highest RG is observed in the eastern and northern parts of the study area. Since resistivity gradient/longitudinal resistance is the inverse of longitudinal conductance, hence, the region with high RG will have poor protective capacity. The variational

Fig. 7 Distribution of resistivity gradient

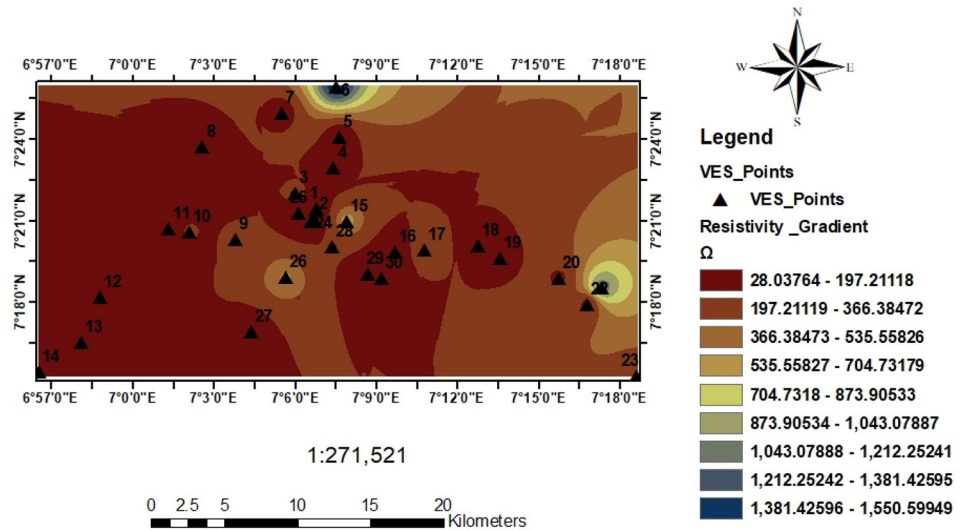
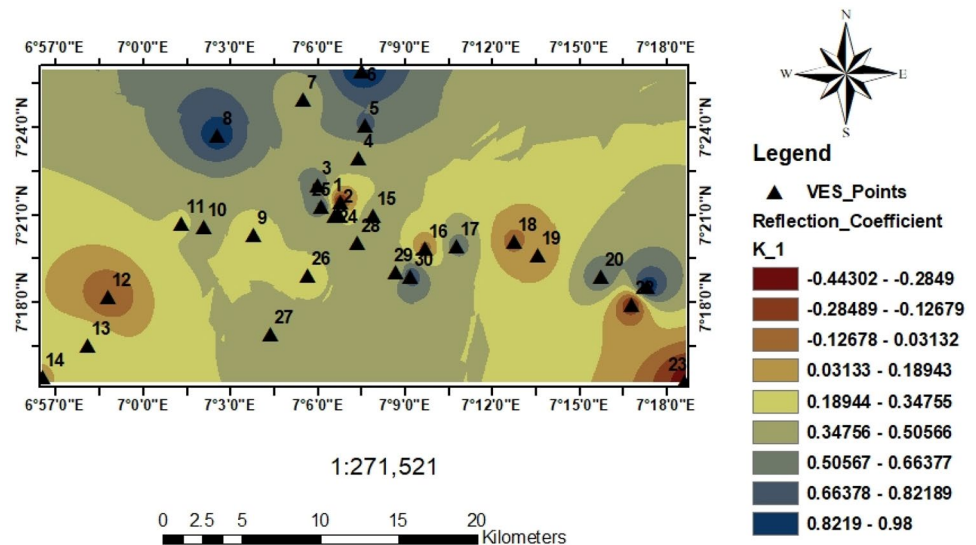


Fig. 8 Distribution of k_1



trend can be attributed to facies change in geologic units and the open aquifers are susceptible to contamination (George 2020).

Resistivity reflection coefficients were computed for layers 1 and 2 (k_1), and layers 2 and 3 (k_2). The values of k_1 and k_2 range from -0.05 to 0.98 and -0.92 to 0.95 , respectively, with their respective mean values of 0.37 and 0.17 . The negative values of the resistivity reflection coefficient show that the top layer resistivity is higher than the underlying layer resistivity, while positive values of the resistivity reflection coefficient show increase in resistivity as current passes between two consecutive layers from overlying to its underlying layer (Ibuot et al. 2019; George 2020). The distributions of k_1 and k_2 are shown in the contour maps (Figs. 8 and 9) with a similar trend, areas having low reflection coefficient values may display weathered or fractured of

its basement rock, and this indicates a prolific groundwater repository.

The hydraulic conductivity (k_h) which is a quantitative measure of a saturated soil's ability to transmit groundwater when subjected to a hydraulic gradient, has values ranging from 0.04 to 12.08 m/day with an average value 0.88 m/day. The distribution of hydraulic conductivity is displayed in Fig. 10, and high values of hydraulic conductivity are observed in the southeastern part of the study area and decrease toward other parts of the study area. It may be inferred that high hydraulic conductivity values show areas with permeable subsurface materials through which water can easily pass, and these areas may be lithologically classified as fine-coarse-grained sand, sandstone, or gravel-dominated areas (Laouini et al. 2017; Nwachukwu et al. 2019; Opara et al. 2020). The low values of hydraulic conductivity

Fig. 9 Distribution of k_2

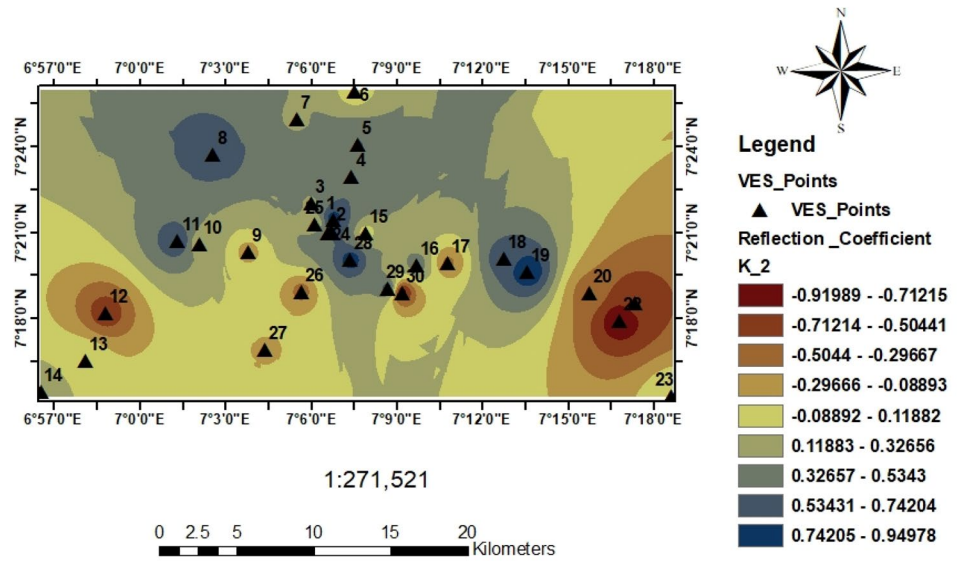
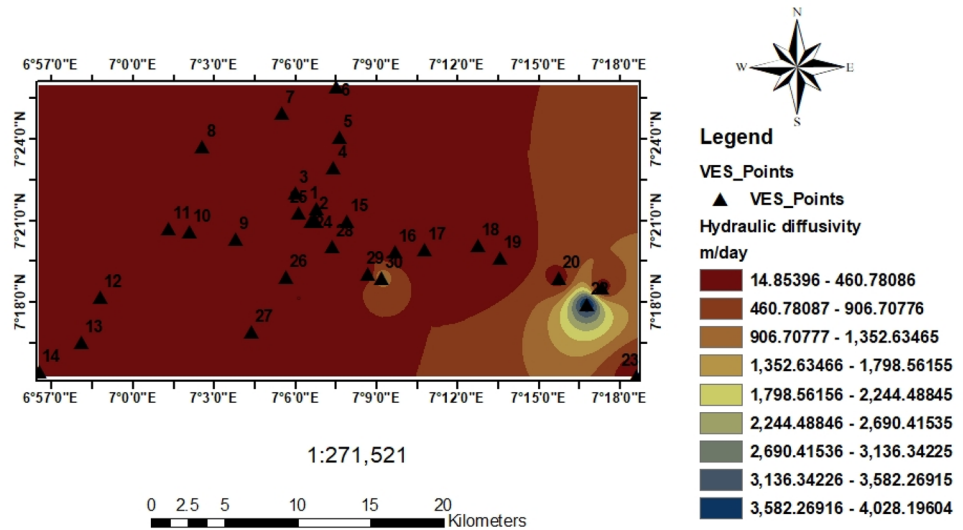


Fig. 10 Distribution of hydraulic conductivity



indicate less permeable materials, and areas with low hydraulic conductivity may be attributed to soil texture, particle size distribution, roughness, tortuosity, shape, and degree of interconnection of water-conducting pores. The effective porosity of the aquifer units which describes the volume of interconnected void space to the total volume ranged from 27.01 to 32.08% with a mean of 28.96%. Based on the porosity values, the lithology of the aquifer layer may be interpreted as sand, sandstone, and gravel according to the classification of Roscoe (1990). The distribution of porosity is shown in Fig. 11 where high porosity is in the southeastern part. The variation of this parameter is in the same trend as hydraulic conductivity, and this indicates that an increase in porosity leads to a corresponding increase in hydraulic conductivity. Areas with high porosity may have prolific aquifers, since a prolific aquifer must be porous and

permeable. The variation of porosity is influenced by the grain size, sorting, compaction, and degree of cementation of the rocks (Uwa et al. 2018).

The values of transmissivity estimated ranged from 1.42 to 412.18 m²/day and a mean value of 27.69 m²/day; this according to Offodile (1983) shows that the study area is dominated by low–moderate groundwater potential. The distribution of transmissivity in Fig. 12 reveals a similar variation trend with hydraulic conductivity and porosity where high transmissivity is observed in the southeastern part of the study area. This indicates that an increase in hydraulic conductivity and porosity translates to a corresponding increase in transmissivity.

Storativity describes the amount of water that an aquifer unit will release from or take into storage per unit surface area of the aquifer per unit change in head. The values of

Fig. 11 Distribution of porosity

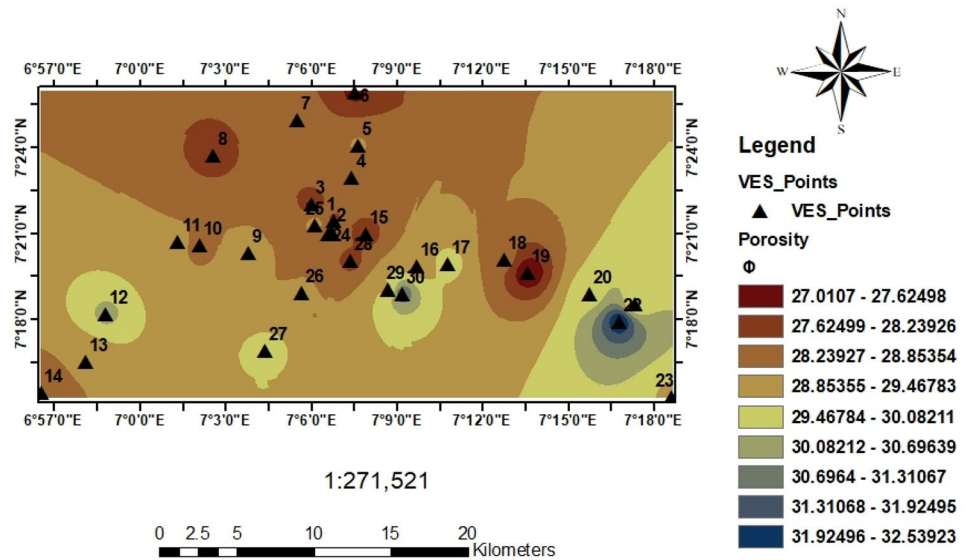
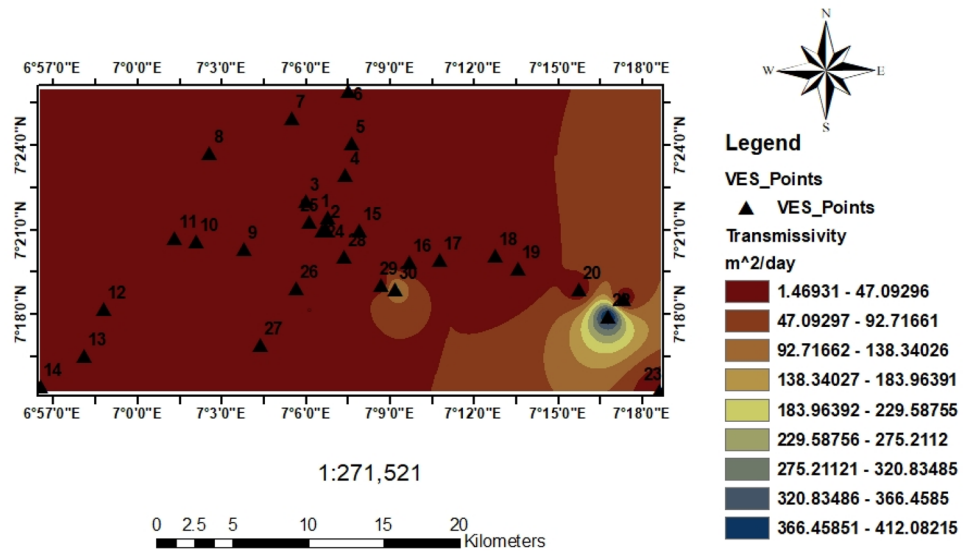


Fig. 12 Distribution of aquifer transmissivity



this parameter range from 0.033 to 0.257 with a mean value 0.092. The values of storativity of an unconfined aquifer according to Lohman (1972) range from 0.01 to 0.3, and the result of this study falls within the Lohman (1972) range; this reveals that the aquifer in the study area is unconfined, and can yield significant and sustainable quantity of groundwater for the people living in the area. The distribution of storativity (Fig. 13) reveals that the southwestern part has high storativity values which are similar to that of thickness. The similarity observed in Figs. 6 and 13 shows a direct relationship between the two parameters; an increase in thickness leads to a corresponding increase in storativity. The values of the estimated hydraulic diffusivity range from 14.75 to 4029.13 with an average value of 292.92. The distribution of hydraulic diffusivity in Fig. 14 shows high values

in the southeastern part of the study area. It is observed that hydraulic diffusivity and transmissivity have a similar trend as revealed in the contour maps; an increase in transmissivity leads to an increase in hydraulic diffusivity.

Conclusion

The results of the present study revealed spatial variations of the litho-textural properties of the subsurface layers estimated from the first-order geoelectric indices. The subsurface was found to consist of four geoelectric layers with varying resistivities, thicknesses, and depths. The geohydraulic parameters used in appraising the subsurface layers were estimated from already established equations.

Fig. 13 Distribution of storativity

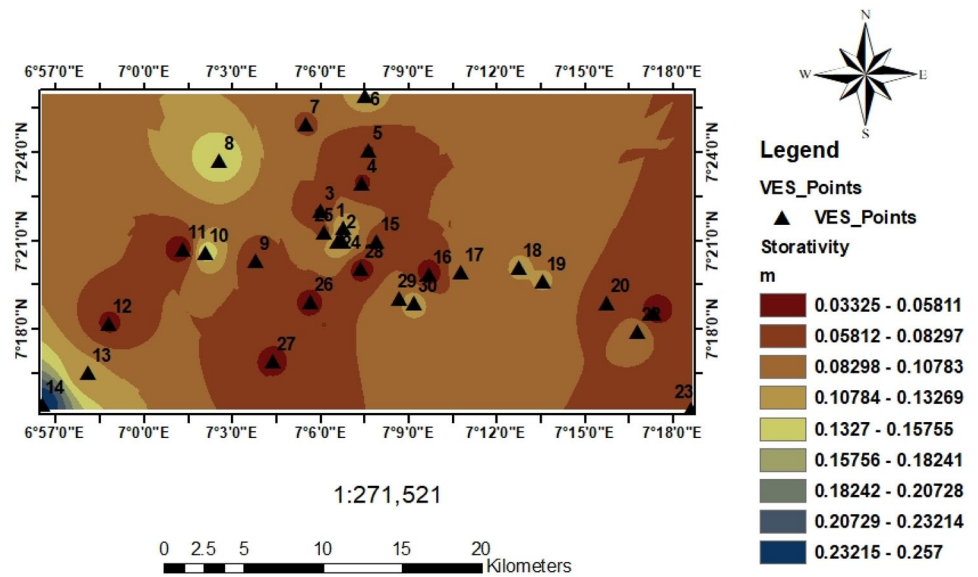
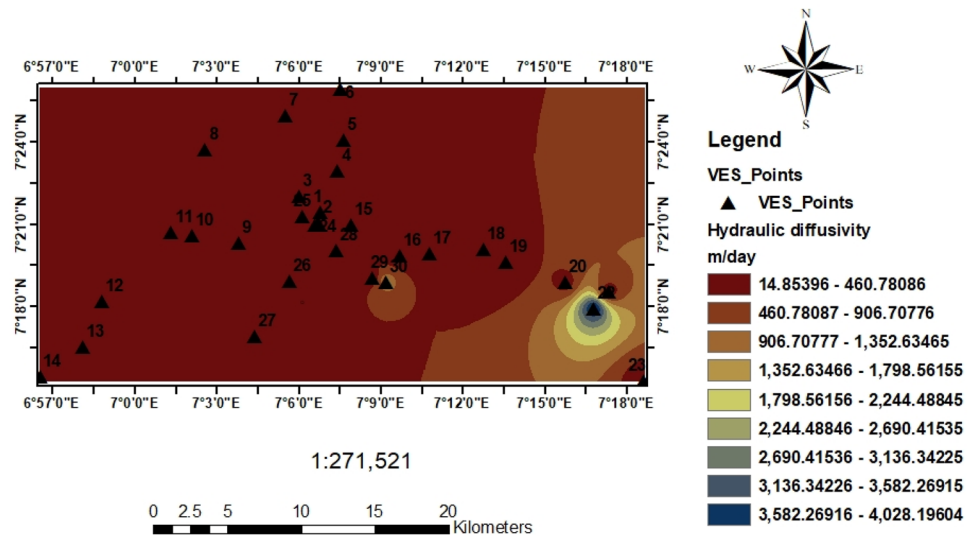


Fig. 14 Distribution of hydraulic diffusivity



The results reveal that the subsurface lithological sequence is characterized by alternating units of argillites and arenites and the variations of the electric and geohydraulic properties across the study area. The aquifer units are relatively thick and show high heterogeneity with increasing depth and are delineated as fine–medium-grained sand. The resistivity gradient shows that the aquifer protectiv-ity transits from poor–moderate protective capacity. The reflection coefficients reveal the presence of high-density water-filled fractures. The contour maps show the spread of the geoelectric and geohydraulic parameters across the study area which is controlled by the lithological characteristics of the subsurface. The results reveal that the

aquifer is capable of yielding substantial groundwater capable of sustaining the people in the study area. This information from this study will be useful as a guide in the exploitation for groundwater resources and management.

Acknowledgements The authors are grateful to members of the Atmospheric and Geophysics Research Group, University of Nigeria, Nsukka for their useful suggestions and advices. The authors are very grateful to the Editor and Reviewers for their useful contributions.

Data availability All relevant data are included in the paper or its supplementary information.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

References

- Akpan FS, Etim ON, Akpan AE (2006) Geoelectrical investigation of groundwater potential in parts of Etim Ekpo local government area. *Akwa Ibom State Nigerian J Phys* 18:39–44
- Anomohanran O, Oseme JI, Iserhien-Emekeme R, Ofomala MO (2020) Determination of groundwater potential and aquifer hydraulic characteristics in Agbor, Nigeria using geoelectric, geophysical well logging and pumping test techniques. *Model Earth Syst Environ*. <https://doi.org/10.1007/s40808-020-00888-6>
- Ashraf MAM, Yosoh R, Sazalil MA, Abidin MHZ (2018) Aquifer characterization and groundwater potential evaluation in sedimentary rock formation. *J Phys Conf Ser* 995:012106
- Chakravarthi V, Shankar GBK, Muralidharan D, Harinarayana T, Sundararajan N (2007) An integrated geophysical approach for imaging sub-basalt sedimentary basins: a case study of Jam River basin, India. *Geophysics* 72(6):B141–B147
- De Lima OAL, Niwas S (2000) Estimation of hydraulic parameters of shaly sandstone aquifers from geological measurements. *J Hydrol* 235:12–26
- Ekanem AM (2020) Georesistivity modeling and appraisal of soil water retention capacity in Akwa Ibom State University main campus and its environs, Southern Nigeria. *Model Earth Syst Environ*. <https://doi.org/10.1007/s40808-020-00850-6>
- Ekanem AM, George NJ, Thomas JE, Nathaniel EU (2020) Empirical relations between aquifer geohydrologic-geoelectric properties derived from surficial resistivity measurements in parts of Akwa Ibom State, Southern Nigeria. *Nat Resour Res* 29(4):2635–2646
- Ekanem AM, George NJ, Thomas JE, Nathaniel EU (2019) Empirical relations between aquifer geohydrologic-geoelectric properties derived from surficial resistivity measurements in parts of Akwa Ibom State, Southern Nigeria. *Nat Resour Res*. <https://doi.org/10.1007/s11053-019-09606-1>
- Ekanem KR, George NJ, Ekanem AM (2022) Parametric characterization, protectivity, and potentiality of shallow hydrogeological units of a medium-sized housing estate, Shelter Afrique, Akwa Ibom State, Southern Nigeria. *Acta Geophys*. <https://doi.org/10.1007/s11600-022-00737-3>
- Ekwe AC, Opara AI, Okeugo CG et al (2020) Determination of aquifer parameters from geo-sounding data in parts of Afikpo Sub-basin Southeastern Nigeria. *Arab J Geosci* 13:189. <https://doi.org/10.1007/s12517-020-5137-y>
- Eugene-Okorie JO, Obiora DN, Ugbor IJC, DO, (2020) Geoelectrical investigation of groundwater potential and vulnerability of Oraifite, Anambra State, Nigeria. *Appl Water Sci* 10(10):1–14
- George NJ, Ekanem AM (2019) Indices of energy and appraisal for electrical current signal at polarising frequency using electrical drilling: a novel approach. In: Sundararajan N, Eshagh M, Saibi H, Meghraoui M, Al-Garni M, Giroux B (eds) *On significant applications of geophysical methods. Advances in science, technology & innovation (IEREK Interdisciplinary Series for Sustainable Development)*. Springer, Cham
- George JN, Ibuot JC, Obiora DN (2015) Geoelectrohydraulic of shallow sandy in Itu, Akwa Ibom State (Nigeria) using geoelectric and hydrogeological measurements. *J Afr Earth Sc* 110:52–63
- George NJ (2020) Appraisal of hydraulic flow units and factors of the dynamics and contamination of hydrogeological units in the littoral zones: a case study of Akwa Ibom State University and its Environs, Mkpato Enin LGA, Nigeria. *Nat Resour Res*. <https://doi.org/10.1007/s11053-020-09673-9>
- George NJ, Ibuot JC, Ekanem A, George AM (2018) Estimating the indices of inter-transmissibility magnitude of active surficial hydrogeologic units in Itu, Akwa Ibom State, Southern Nigeria. *Arab J Geosci* 11(6):1–16
- George NJ, Ubom AI, Ibanga JI (2014) Integrated approach to investigate the effect of leachate on groundwater around the Ikot Ekpenne Dumpsite in Akwa Ibom, State Southeastern Nigeria. *Int J Geophys*. <https://doi.org/10.1155/2014/174589>
- Guideal R, Bala AE, Ikponte AE (2011) Preliminary estimates of the hydraulic properties of the quaternary aquifer in N'Djamena Area Chad Republic. *J Appl Sci*. <https://doi.org/10.3923/jas.2011>
- Hamil L, Bell FG (1986) *Groundwater resource development*. Fredric Publications, New York, p 21
- Hiscock KM, Rivett MO, Davison RM (2002) Sustainable groundwater development. *Geol Soc Spec Pub*. <https://doi.org/10.1144/GSL.SP.2002.193.01.01>
- Ibuot JC, Obiora DN (2021) Estimating geohydrodynamic parameters and their implications on aquifer repositories: a case study of University of Nigeria, Nsukka, Enugu State. *Water Pract Technol* 16(1):162–181
- Ibuot JC, George NJ, Okwesili AN, Obiora DN (2019) Investigation of litho-textural characteristics of aquifer in Nkanu West Local Government Area of Enugu state, southeastern Nigeria. *J Afr Earth Sc* 157(2019):197–207
- Ibuot JC, Omeje ET, Obiora DN (2021) Geophysical evaluation of geohydrokinetic properties of aquifer units in parts of Enugu state, Nigeria. *Water Pract Technol* 16(4):1397–1409
- Ifediegwu SI, Nnebedum DO, Nwatarali AN (2019) Identification of groundwater potential zones in the hard and soft rock terrains of Kogi State, North Central Nigeria: an integrated GIS and remote sensing techniques. *SN Appl Sci* 1:1151
- Ige OO, Ameh HO, Olaleye IM (2021) Borehole inventory, groundwater potential and water quality studies in Ayede Ekiti, Southwestern Nigeria. *Discov Water* 1:2. <https://doi.org/10.1007/s43832-020-00001-z>
- Ikpe EO, Ekanem AM, George NJ (2022) Modelling and assessing the protectivity of hydrogeological units using primary and secondary geoelectric indices: a case study of Ikot Ekpenne Urban and its environs, southern Nigeria. *Model Earth Syst Environ*. <https://doi.org/10.1007/s40808-022-01366-x>
- Jenkwe ED, Iyeh OP (2020) Assessment of fuelwood harvesting and its implication on vegetation loss in Ofu Local Government Area, Kogi State, Nigeria. *FUDMA J Sci* 4(2):308–316
- Kogbe CA (1989) *The cretaceous and paleogene sediments of Southern Nigeria*. Geology of Nigeria, 2nd edn. Rock View (Nig) Ltd, Abuja, pp 325–334
- Laouini G, Sunday EE, Okechukwu EA (2017) Delineation of aquifers using Dar Zarrouk parameters in parts of Akwa Ibom, Niger Delta Nigeria. *J Hydrogeol Hydrol Eng* 6(1):18. <https://doi.org/10.4172/2325-9647.1000151>
- Lohman SW (1972) *Well Hydraulics*. United State Geological Survey Professional Paper 708
- Metwaly M, El-Alfy M, Eawaad E, Ismail A, El-Qady G (2014) Estimating aquifer hydraulic parameters from electrical resistivity measurements: a case study at Khuf Formation Aquifer, Al Quwy'ya Area, Central of Saudi Arabia. <https://doi.org/10.1190/iceg2015-060.ICEG:217-225>
- Naiyeju JO, Oladunjoye MA, Adeniran MA (2021) Aquifer evaluation in parts of north-central Nigeria from geo-electrical derived parameters. *Appl Water Sci* 11:178. <https://doi.org/10.1007/s13201-021-01520-3>
- Niwas S, Singhal DC (1981) Estimation of aquifer transmissivity from Dar Zarrouk parameters in porous media. *Hydrology* 50:393–399
- Niwas S, Celik M (2012) Equation estimation of porosity and hydraulic conductivity of Ruhrtal aquifer in Germany using near-surface geophysics. *J Appl Geophys* 84:77–85
- Nwachukwu S, Bello R, Balogun AO (2019) Evaluation of groundwater potentials of Orogun, South-South part of Nigeria using the electrical resistivity method. *Appl Water Sci* 9:184. <https://doi.org/10.1007/s13201-019-1072-z>

- Obiora DN, Ibuot JC (2020) Geophysical assessment of aquifer vulnerability and management: a case study of University of Nigeria, Nsukka, Enugu State. *Appl Water Sci* 10:29. <https://doi.org/10.1007/s13201-019-1113-7>
- Offodile ME (1983) The occurrence and exploitation of groundwater in Nigeria basement complex. *J Min Geol* 20:131–146
- Oguama BE, Ibuot JC, Obiora DN (2020) Geohydraulic study of aquifer characteristics in parts of Enugu North Local Government Area of Enugu State using electrical resistivity soundings. *Appl Water Sci* 10(5):1–10
- Omali AO, Usman AO, Oguche II (2018) Hydrogeophysical evaluation of groundwater resources within some parts of Northern Anambra Basin, Nigeria. *J Earth Sci Geotechn Eng* 8(4):17–33
- Omeje ET, Ugbor DO, Ibuot JC, Obiora DN (2021) Assessment of groundwater repositories in Edem, Southern Nigeria, using vertical electrical sounding. *Arab J Geosci* 14:421
- Opara AI, Eke DR, Onu NN, Ekwe AC, Akaolisa AC, Okoli AE, Inyang GE (2020) Geo-hydraulic evaluation of aquifers of the Upper Imo River Basin, Southeastern Nigeria using Dar-Zarrouk parameters. *International Journal of Energy and Water Resources*. Doi: <https://doi.org/10.1007/s42108-020-00099-w>
- Orellana E, Mooney AM (1966) Master curve and tables for vertical electrical sounding over layered structures. *Interciencia, Escuela*
- Roscoe MC (1990) *Handbook of ground water development*. Wiley, New York
- Rubin Y, Hubbard SS (2005) *Hydrogeophysics water science and technology* Library, vol 50. Springer, Dordrecht, p 521
- Saleh A, Al-Ruwaih F, Shehata M (1999) Hydrogeochemical processes operating within the main aquifers of Kuwait. *J Arid Environ* 42:195–209
- Singh KP (2005) Nonlinear estimation of aquifer parameters from surficial resistivity measurements. *Hydrol Earth Syst Sci* 2:917–930
- Uwa UE, Akpabio GT, George NJ (2018) Geohydrodynamic parameters and their implications on the coastal conservation: a case study of Abak Local Government Area (LGA), Akwa Ibom State, Southern Nigeria. *Nat Resour Res*. <https://doi.org/10.1007/s11053-018-9391-6>
- Zohdy AAR (1965) The auxiliary point method of electrical sounding interpretation and its relationship to the Dar-Zarrouk parameters. *Geophysics* 30:644–660
- Zohdy AAR, Eaton GP, Mabey DR (1974) Application of surface geophysics to groundwater investigation. *USGS techniques of water resources investigations*, 02-D1. <https://doi.org/10.3133/twri02D1>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.