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Appraisal of protectivity and corrosivity of surficial hydrogeological units via geo-sounding measurements

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Abstract The surface resistivity method was used to appraise the protectivity of hydrogeological units and corrosivity of the top soil in Obot Akara County, southern Nigeria. A total of 28 vertical electrical sounding (VES) was undertaken in the area using the Schlumberger electrode configuration. The results of the VES data interpretation reveal 3 to 4 geoelectric layers in the study area. The resistivity of the first layer interpreted as the Motley top soil ranges from 34.7 to 929.7 Ωm with a mean value of 381.1 Ωm. The third layer, with a resistivity range of 99.4 to 2716.7 Ωm, constitutes the aquifer unit in most communities in the area, with an average thickness of 58.3 m, while the fourth layer penetrated in most communities has a resistivity range of 216.1 to 1475.7 Ωm with a mean value of 657.5 Ωm. The longitudinal conductance and resistivity reflection coefficient of the aquifer protective layers vary from 0.04 to 0.76 mhos and −0.74 to 0.93, respectively. Analysis of these results shows that 89.3% of the hydrogeological units in the area is weakly/poorly protected, 10.7% has moderate to good protection, while 85.7% of the top soil at the sounding stations is noncorrosive and 14.3% is slightly to moderately corrosive. The implication of these results is that most of the hydrogeological units in the area are likely prone to contamination in particular by some ferrugenized materials from the overlying layers. Also, underground metal storage tanks and galvanized and steel pipes can be buried in the topmost layer in most communities in the area without any risk of failure. Although these findings are very promising especially in groundwater management and exploitation in the area, hydrogeochemical and microbiological analyses of groundwater samples from available boreholes are recommended to corroborate the results.

Introduction

Water is one of the essentials of life. Surface water bodies, for example, streams, lakes, rivers, and ponds, have been heavily relied upon for many years for both domestic and industrial usages. However, as a result of contamination of these water bodies, focus has been shifted to groundwater resource. Groundwater availability depends on the presence and hydraulic properties of the hydrogeological units (aquifers), while its potability depends on the hydrogeochemical properties and susceptibility of the aquifers to

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contamination (Mgbolu et al., 2019; Obiadi et al., 2016; Okolo et al., 2018). Unlike surface water, groundwater is usually readily available, clean, and devoid of contaminants or pollutants depending on the nature of the geomaterials that overlie the aquifer system (Bayewu et al., 2018; Umar & Igwe, 2019). The earth layers act as natural filter for percolating fluids, which could contaminate groundwater especially in areas where the aquifer unit is not overlain by sufficiently thick impermeable layers, otherwise known as protective layers. The protectivity of aquifers is mostly affected by the permeability and thickness of the protective layers. The permeability of unconsolidated sediments is largely dependent on the amount of clay present, which can be determined indirectly from surface resistivity measurements (Mogaji et al., 2011). Groundwater quality depreciates with poor waste disposal management due to the movement of leachates from dumpsites into the aquifer system, sewage from latrines, leakage from surface, and underground storage tanks, oil spillage, mining activities, and saltwater intrusion (Esu & Amah, 1999; Oseji et al., 2018; Uchegbu, 2002). As groundwater continues to be an unfailing source of potable water, a concerted effort is needed for effective management and protection of this vital georesource to forestall the outbreak of water-borne diseases such as dysentery, cholera, typhoid fever, hepatitis A, and salmonella (Nwabor et al., 2016; Nyakundi et al., 2020).

Soil is a complex environment with varying properties, which may influence materials in long-term burial. Materials such as utility pipes for transmitting water, waste, gas and hydrocarbons are usually buried in the topmost earth layer. These materials can suffer corrosion and subsequently fail if the layer is corrosive (Akintorinwa & Abiola, 2011; Umar & Igwe, 2019). Electrical resistivity or conductivity is an indicator of the degree of soil corrosivity. Soil corrosivity is a geologic hazard, which affects buried metallic pipes in direct contact with the soil. High resistivity values, greater than 180 Ωm, are associated with non-corrosive soils, while low values of less than 10 Ωm are associated with highly corrosive soils (Agunloye, 1984; Oladapo et al., 2004 and Mosuro et al., 2017). Sandy soils have relatively high resistivity or low conductivity values and are therefore considered to be non-corrosive. Clayey soils, particularly those contaminated with saline water on the other hand, are highly corrosive due to their low resistivity or high conductivity values.

The electrical resistivity method is a great tool used in investigating the electrical resistivity distribution of subsurface geomaterials. In this method, electrical current is injected into the subsurface using a pair of current electrode planted on the earth surface and the resulting potential difference is measured using a pair of potential electrodes also planted on the surface. One common technique utilized in this method is the vertical electrical sounding (VES), which investigates the vertical variation in the resistivity of geomaterials with depth. Over the years, this technique has been used with great success in many geophysical investigations of surface resistivity distribution for a variety of purposes including groundwater potential investigations, groundwater quality and aquifer protection studies, soil water retention capacity analysis, soil water corrosivity investigations, and aquifer vulnerability assessment (Ekanem et al., 2020; George et al., 2015, 2017; Hussain et al., 2017; Ibanga & George, 2016; Khalil & Santos, 2009; Naidu et al., 2020; Utom et al., 2012). Compared with classical well drillings, the VES technique is cost-effective and environmentally friendly as it does not involve actual drilling of wells or boreholes (Ekanem et al., 2020; George et al., 2017; Khalil & Santos, 2009). Thus, the VES technique provides a valuable swift, convenient and economical means of imaging subsurface aquifers without any invasion of the environment. Empirical relations exist, which link the aquifer hydraulic properties with electrical properties (Ekanem et al., 2020; George et al., 2017; Ibanga & George, 2016). These relations provide a cost-effective means of deriving aquifer hydraulic properties (hydraulic conductivity, transmissivity, etc.) from surficial resistivity measurements without the need to do any pumping test which is usually expensive.

The dwellers of Obot Akara County were solely dependent on surface water sources for their domestic and agricultural needs until the county was given a local government status in 1996. This development has led to a geometric increase in population and micro-industrial activities aside increasing the water needs of the area. Consequently, the area has witnessed deterioration in the quality of surface water, loss of aquatic life, and lands due to environmental pollution (Esu & Amah, 1999; Uchegbu, 2002). Thus, one of the major challenges of the dwellers of

Obot Akara County is that of ensuring potable water in adequate amounts to meet the needs of the growing human population. Most of the aquifers in the area are usually exploited without any assessment of the aquifer protectivity against contamination or quality of the groundwater. Equally, no information is available about the corrosivity of the shallow layers where water pipes are usually buried for water reticulation to communities in the area. This study is thus provoked by these prevalent situations to enhance the development of an effective and sustainable groundwater management scheme to circumvent any outbreak of water-borne diseases in the area. Accordingly, the study is primarily aimed at using the surface electrical resistivity method to appraise the protectivity of hydrogeological units and corrosivity of the top soil in Obot Akara County, Southern Nigeria. The results of this study are very useful in delineating the zones that are prone to corrosion as well as contamination from percolating fluids and especially hold out valuable information on groundwater resources development and waste disposal management in the area.

Location and geology of the study area

This study was undertaken in Obot Akara County, which lies between latitudes 4°55′ N and 5°00′ N and longitudes 7°30′ E and 7°40′ E in the eastern part of the Niger Delta, southern Nigeria (Fig. 1). Obot Akara County in Akwa Ibom State covers an area of 237 km^2 and is accessible through a network of roads and is bordered by Ini local government area and parts of Abia State on the northern side; Ikot Ekpene and Ikono local government area on the eastern side; Essien Udim local government area on the southern side; and also part of Abia state on the western side. Generally, the area has a land surface of very little or no significant relief over several kilometers. Surface water found in the area is mainly streams, which run across some segments of the local government area. In terms of climate, Obot Akara is characterized by two distinctive seasons, which are the rainy and dry seasons with an annual rainfall of about 2289 mm and average annual temperature of 26.2 °C, respectively, and is drained by the Kwa Ibo River and its tributaries.
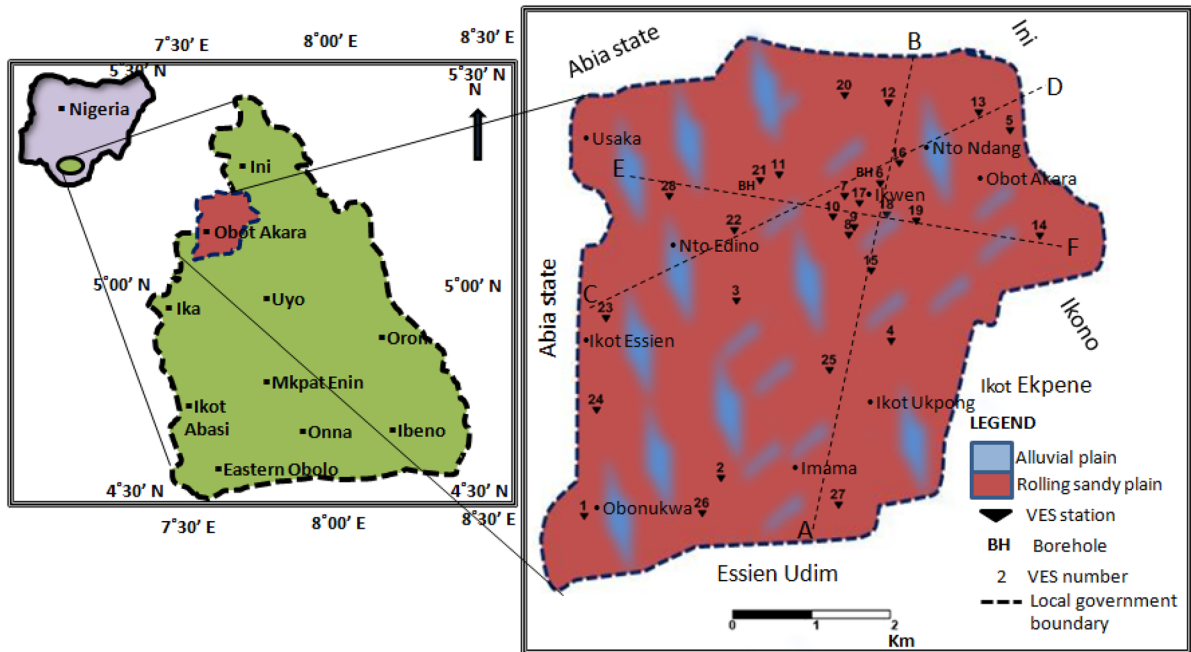

Fig. 1 Location map and geology of study area showing VES points. AB, CD, and EF are the major profiles along which data were acquired

Geologically, the major sediments covering Obot Akara County are recent-to-tertiary sands, which belong to the Benin Formation (otherwise referred to as Coastal Plain sands—CPS). The Benin Formation is the uppermost part of the Niger Delta, comprising mainly sands and gravels and constitutes the major hydrogeological units in the area. The sands are poorly sorted with grain sizes ranging from fine to coarse (Mbipom et al., 1996; Short & Stauble, 1967). In addition, slight intercalations of lignite, clays, sandstone, and silts occur at several places in the area (Reijers & Petters, 1987). A multi-aquifer system is built up at a number of places as a result of alternations of sand and clay at those places (Edet & Okereke, 2002; Esu et al., 1999; Okereke et al., 1998). The CPS is underlain by the Agbada Formation, which is the major hydrocarbon bearing unit in the Niger Delta region (Avbovbo, 1978; Short & Stauble, 1967; Stacher, 1995).

Materials and method

Protectivity of hydrogeological units

A given hydrogeological unit can be protected depending on the nature of the geomaterials of the overlying layer(s). Aquifer protection (AP) in this case is the ability of the aquifer overlying layers (protective layers) to slow down and filter percolating surface fluid (Olorunfemi et al., 1999). The factors affecting AP include permeability, soil particle size, porosity, and thickness of the protecting layers (Adeniji et al., 2014; Ekanem, 2020; Mogaji et al., 2011). Protecting layers with sufficient thickness and low hydraulic conductivity, which results in slow rate of percolating water, enhance effective aquifer protection (Adeniji et al., 2014). Aquifer protective capacity (APC) can be appraised through the use of the combination of layer thickness and resistivity (Henriet, 1976). These two first-order geoelectric parameters are often combined together to form the so-called Dar Zarrouk parameters (Maillet, 1947). The Dar Zarrouk parameters are transverse resistance (T_r) and longitudinal conductance (S_l). For a given layer of thickness h and resistivity ρ, the longitudinal conductance (in mho or Siemens) is mathematically defined as:

$$S_l = \frac{h}{\rho} \tag{1}$$

The total longitudinal conductance S for a given number of layers (n) is mathematically defined as:

$$S = \sum_i^n \frac{h_i}{\rho_i} \tag{2}$$

On the other hand, the transverse resistance (in Ωm^2) of a given layer is defined mathematically as:

$$T_r = \rho.h \tag{3}$$

As the case of the total longitudinal conductance, the total transverse resistance T for n layers is given as:

$$T = \sum_i^n \rho_i.h_i \tag{4}$$

Equations (2) and (4) allow the estimation of the second-order geoelectric parameters (Dar Zarrouk parameters) from surface resistivity data, which are consequently used to assess APC in a given region. Highly impermeable materials, for example, shale and clay, are characterized by high values of longitudinal conductance or low values of resistivity, whereas permeable materials such as gravels and sands are characterized by low values of longitudinal conductance or high values of resistivity (Adeniji et al., 2014; Ayuk, 2019). Low values of longitudinal conductance (high values of resistivity) are associated with poor/weak APC, while high values of longitudinal conductance (low values of resistivity) are associated with good/excellent APC respectively as shown in Table 1 (Abiola et al., 2009; Henriet, 1976; Oladapo & Akintorinwa, 2007).

Table 1 Longitudinal conductance and aquifer protective capacity rating (after Abiola et al., 2009; Henriet, 1976; Oladapo & Akintorinwa, 2007)

S (mhos)	APC rating
> 10.00	Excellent
5.00–10.00	Very good
0.70–4.49	Good
0.20–0.69	Moderate
< 0.10–0.19	Poor-weak

Resistivity reflection coefficient (RC)

The resistivity reflection coefficient gives information on the variation of electrical resistivity between the earth layers. For a given pair of layers with resistivity ρ_1 and ρ_2, respectively, RC is mathematically given as:

$$RC = \frac{\rho_2 - \rho_1}{\rho_1 + \rho_2} \qquad (5)$$

The value of RC can be positive or negative depending on top layer resistivity relative to the second layer. Positive values of RC imply that the top layer resistivity is lower than the underlying layer resistivity and vice versa. An impervious layer such as clay or shale with a low resistivity or high conductivity underlying a pervious sandy layer will result in a negative resistivity reflection coefficient. This arrangement will optimally result in a retarded rate of water percolation into the subsurface, allowing for adequate filtration of the fluid to protect any underlying aquifer system (Ekanem, 2020).

Soil corrosivity

Soil is a multifaceted environment with various properties, which influence materials in long-term burial and causes changes in appearance and the chemical nature of the buried materials. Materials such as utility pipes for transmission of water, hydrocarbons, waste, and gas are usually buried in the topmost layer of the earth. These materials can suffer corrosion and subsequently become damaged if the layer is highly corrosive (Akintorinwa & Abiola, 2011). The safety of these buried materials can be appraised through estimate of the burying layer resistivities. High resistivity values greater than 180 Ωm are indicative of practically non-corrosive soils, while low values less than 10 Ωm are indicative of highly corrosive soils as shown in Table 2 (Agunloye, 1984; Oladapo et al., 2004 and Mosuro et al., 2017). Sandy soils have relatively high resistivity values and are therefore considered to be non-corrosive. Clayey soils, particularly those contaminated with saline water on the other hand, are highly corrosive.

Table 2 Soil corrosivity ratings (after Agunloye, 1984; Oladapo et al., 2004 and Mosuro et al., 2017)

Soil resistivity (Ωm)	Corrosivity rating
> 10	Very strongly corrosive
10–60	Moderately corrosive
60–180	Slightly corrosive
> 180	Practically noncorrosive

Resistivity survey

One-dimensional (1D) electrical resistivity survey involving the use of the Schlumberger array was conducted in different communities in the study area using an ABEM terrameter (SAS 1000 model) and its accessories to obtain data, which were analyzed and interpreted in this study. Two current electrodes (A and B) were used on the surface to send electric current into the ground, while two other electrodes referred to as the potential electrodes (M and N) also placed on the surface were used to measure the generated potential difference. The apparent resistance (ratio of current and potential difference) of the subsurface layers penetrated by the current was measured as the output from the terrameter. In all, a total of 28 vertical electrical soundings (VES) were made at select locations of the study area shown in Fig. 1. The maximum current electrode separation (AB) varied from 600 to 1000 m depending on topography, human settlements, and general infrastructure. Two of the soundings were made near existing boreholes (VES 6 in Ikwen and VES 21 in Ikot Ukam communities, respectively, as shown in Fig. 1) for correlation with the available borehole lithological data.

Resistivity data analysis

The raw apparent resistance measured in the field was first converted to apparent resistivity by the use of Eq. (6):

$$\rho_a = G_f {}^* R_a \qquad (6)$$

where G_f is the geometric factor, which is given by Eq. (7) for the Schlumberger array.

$$G_f = \pi * \left\{ \frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right\} \qquad (7)$$

The apparent resistivity values obtained at each sounding stations were then plotted against half of the current electrode separation (AB/2) on a bilogarithmic graph to give the VES curves. The VES curves were smoothened to remove any noisy data where necessary (Chakravarthi et al., 2007; George et al., 2015), and subsequently, any discontinuities observed in the smoothened curves were attributed to vertical variation in resistivity with depth. Each of the smoothened VES curves was interpreted using the conventional manual curve matching (Zohdy et al., 1974) to generate the preliminary layer resistivities and thicknesses, which were later used as initial inputs in the computer-aided interpretation that was

carried out using a computer software program called WINRESIST. This computer modeling software makes use of the initial layer parameters to carry out a least-squares inversion of the field data to produce 1D resistivity model curves as final outputs. In the process, the software generates a theoretical model curve and uses the iteration method to fit the model to the measured field resistivity data with the root mean square error (RMSE) indicating the goodness of the fitting (Bandani, 2011). The best fitting models to the data represent the subsurface resistivity models. Samples of the 1D-interpreted resistivity model curves are shown in Fig. 2. The green lines represent the theoretical models from the modeling software, while the dots indicate the apparent resistivity data points. On the whole, the root mean square error of the fitting ranges from 2.3 to 5.7. The borehole lithological data were used to constrain the results of the computer iteration. The distribution of the curve
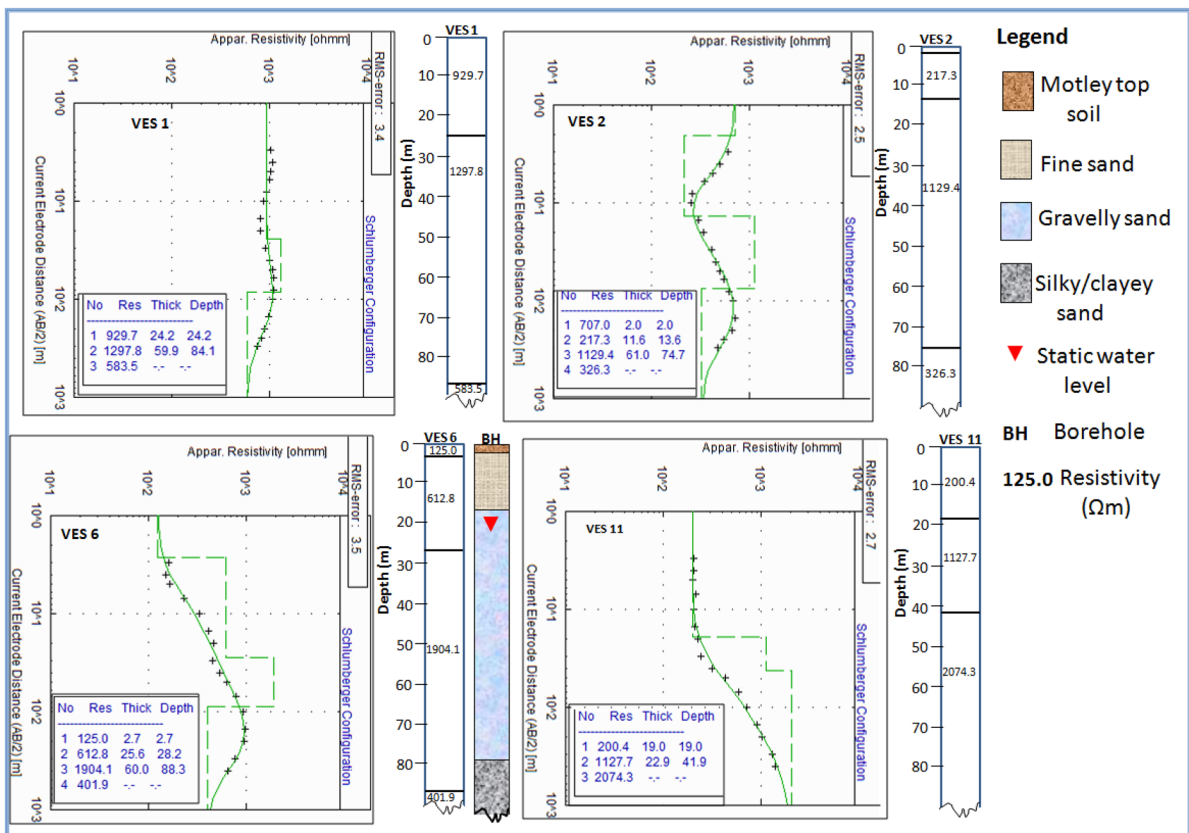

Fig. 2 1D model resistivity curves at VES 1, 2, 6, and 11. Inserted legend indicates correlation of borehole lithology log with VES results at VES 6

types are shown in Fig. 3, with the K-type curve dominating at 28.6%. The layer thicknesses and resistivities obtained from the computer-aided interpretation stage were taken to represent subsurface models of the area. Correlating the borehole information near VES 6 with the VES data shows that the third layer is the aquifer in the area, although the inferred depth is somewhat different from that indicated by the borehole. This is possible because geologic sections may not precisely coincide with geo-electrical sections (Bello et al., 2010).

Results and discussion

The 1D model curves generated show that the area under study is made up of 3 to 4 geoelectric layers with the layer parameters summarized in Table 3 and Fig. 4. Different lithologic units are shown in the geosections from top to bottom in each case (Fig. 4). The resistivity values of the prevailing materials in the topmost layer range from 34.7 to 929.7 Ωm with a mean value of 381.1 Ωm. These materials were interpreted to be lateritic materials (Motley top soil), which cut across all the communities in the area under study as shown in the geosections for the three profiles in Fig. 4. The thickness of this layer in general varies from 1.8 to 33.2 m with a mean value of 9.3 m. The distribution of the first layer resistivity is shown in Fig. 5. The observed variations in the layer resistivity may be as a result of the factitious nature of the layer coupled with continual bioturbating activities in

the layer (Ekanem, 2020; George et al., 2010). Relatively high resistivity values are observed at Obon Ukwa Community, while low values are observed in Ikwen and Nto Ekpu Nyanyaha communities and part of Nto Ndang community. The second layer has resistivity range of 31.8 to 2481.4 Ωm with a mean resistivity value of 902.9 Ωm. The thickness of this layer varies from 4.2 to 98.1 m with an average thickness of 44.8 m. The distribution of the second layer resistivity is shown in Fig. 6. The noticeable variations in the resistivity values of the second layer can be attributed to the varying grain sizes of the geomaterials encountered by the current propagating through the subsurface (Ekanem et al., 2020). This geoelectric layer was interpreted to be fine- or medium-grained sands at some communities and sandy clay or gravelly sands at other communities. The resistivity values for this layer at Ikwen and part of Ikot Ukpong communities are relatively high suggesting that the layer is made up of gravelly sand materials. The resistivity of the third geoelectric layer ranges from 99.4 to 2716.7 Ωm with a mean value of 1350.2 Ωm. The third layer thickness ranges from 37.6 to 68.9 with a mean value of 58.3m. This layer, which was interpreted to be very coarse sand (gravelly) or sandy clay at some locations, is the major aquifer in the area from where the dwellers obtain their groundwater. The last geoelectric layer penetrated by the current in many communities in the study area has resistivity values from 216.1 to 1475.7 Ωm with a mean value of 657.5 Ωm and was interpreted to be silty sand. Figure 7 shows the distribution of the aquifer bulk resistivity. The north

Fig. 3 Distribution of VES curve types. The curve is dominated by the K-type at 28.6%
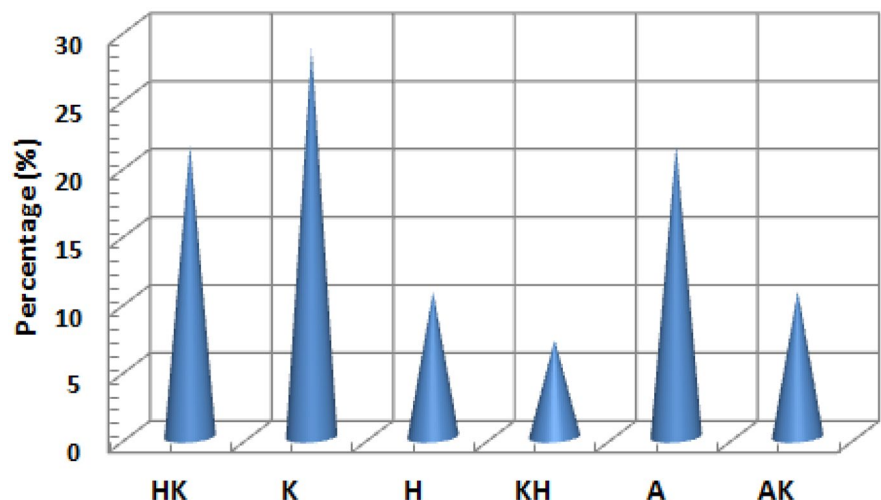
Table 3 Summary of VES interpretation

VES no	Location	Longitude (degrees)	Latitude (degrees)	Layers	Resistivity (Ωm)	Thickness (m)	Depth to bottom (m)	Lithology	Curve type
1	Ubon Ukwa	7.5588	5.1918	1	929.7	24.2	21.5	Motley top soil	
				2	1297.8	59.9	84.1	Medium grained sand	K
				3	583.5	-	-	Fine sand	
2	Nto Eton	7.5949	5.2026	1	707.0	2.0	2.0	Motley top soil	
				2	217.3	11.6	13.6	Sandy clay	
				3	1129.4	61.0	74.6	Medium grained sand	HK
				4	326.3	-	-	Fine sand	
3	Ikot Idem Udo	7.5989	5.2532	1	434.2	7.9	7.9	Motley top soil	
				2	1244.2	75.7	83.6	Medium grained sand	K
				3	671.9	-	-	Fine sand	
4	Mbat Esifon	7.6398	5.2417	1	705.0	21.7	21.7	Motley top soil	
				2	2355.5	66.0	87.7	Gravelly sand	K
				3	1336.2			Coarse sand	
5	Abiakpo Ibo	7.6712	5.3019	1	694.0	11.5	11.5	Motley top soil	
				2	338.8	81.3	92.8	Sandy clay	H
				3	2492.6	-	-	Gravelly sand	
6	Ikwen 1	7.6369	5.2867	1	125.0	2.7	2.7	Motley top soil	
				2	612.8	25.6	28.3	Fine sand	AK
				3	1904.1	60.0	88.3	Gravelly sand	
				4	401.9	-	-	Silty/clayey sand	
7	Ikwen 2	7.6275	5.2831	1	72.9	3.3	3.3	Motley top soil	
				2	2080.0	40.1	43.4	Gravelly sand	KH
				3	692.6	37.6	81.0	Fine sand	
				4	1139.2			Coarse sand	
8	Nto Esu 1	7.6286	5.2720	1	214.4	1.8	1.8	Motley top soil	
				2	31.8	4.2	6.0	Sandy clay	
				3	1608.9	56.2	62.2	Medium grained sand	HK
				4	458.4			Fine sand	
9	Ikot Utu	7.6300	5.2742	1	795.3	3.6	3.6	Motley top soil	
				2	444.3	20.8	24.4	Sandy clay	
				3	2436.0	61.9	86.3	Gravelly sand	HK
				4	801.5			Fine sand	

Table 3 (continued)

VES no	Location	Longitude (degrees)	Latitude (degrees)	Layers	Resistivity (Ωm)	Thickness (m)	Depth to bottom (m)	Lithology	Curve type
10	Nto Esu 2	7.6244	5.2772	1	609.5	4.4	4.4	Motley top soil	
				2	135.3	21.0	25.4	Sandy clay	
				3	1922.2	68.6	94.0	Gravelly sand	HK
				4	437.3			Fine sand	
11	Ikot Okim 1	7.6102	5.2892	1	200.4	19.0	19.0	Motley top soil	
				2	1127.7	22.9	41.9	Coarse sand	A
				3	2074.3			Gravelly sand	
12	Ikot Okim 2	7.6391	5.3097	1	34.7	5.7	5.7	Motley top soil	
				2	677.7	19.7	25.4	Fine sand	KH
				3	99.4	56.0	81.4	Sandy clay	
				4	896.2			Fine sand	
13	Nto Ndang 1	7.6629	5.3070	1	383.6	17.2	17.2	Motley top soil	
				2	577.8	39.9	57.1	Fine sand	A
				3	1509.7			Medium grained sand	
14	Nto Ekpu Nyanyanya	7.6790	5.2718	1	64.6	4.5	4.5	Motley top soil	
				2	1082.7	43.0	47.5	Medium grained sand	A
				3	1716.9			Gravelly sand	
15	Oku Obom	7.6345	5.2618	1	228.8	11.6	11.6	Motley topsoil	
				2	781.2	64.0	75.6	Fine sand	A
				3	1395.5			Medium grained sand	
16	Nto Ndang 2	7.6419	5.2925	1	196.8	7.9	7.9	Motley top soil	
				2	758.8	17.6	25.5	Fine sand	
				3	1500.4	60.0	85.5	Medium grained sand	AK
				4	670.0			Fine sand	
17	Ikwen 3	7.6314	5.2811	1	204.9	33.2	33.2	Motley top soil	
				2	2481.4	88.2	121.4	Gravelly sand	K
				3	849.8			Fine sand	
18	Nto Obio Ikang 1	7.6386	5.2778	1	332.0	12.9	12.9	Motley top soil	
				2	1980.1	70.6	83.5	Gravelly sand	K
				3	362.8			Clayey/silty sand	

Table 3 (continued)

VES no	Location	Longitude (degrees)	Latitude (degrees)	Layers	Resistivity (Ωm)	Thickness (m)	Depth to bottom (m)	Lithology	Curve type
19	Nto Obio Ikang 2	7.6464	5.2760	1	221.2	2.3	2.3	Motley top soil	
				2	841.9	46.1	48.4	Fine sand	AK
				3	2130.5	59.0	107.4	Gravelly sand	
				4	410.4			Fine sand	
20	Utu Ikot Inyang	7.6275	5.3119	1	556.6	5.4	5.4	Motley top soil	
				2	234.9	13.8	19.2	Sandy clay	HK
				3	2711.9	51.7	70.9	Gravelly sand	
				4	216.1			Clayey/silty sand	
21	Abiakpo Ikot Ukam	7.6052	5.2876	1	353.8	3.2	3.2	Motley top soil	
				2	112.6	8.6	11.8	Sandy clay	HK
				3	2716.7	68.9	80.7	Gravelly sand	
				4	1475.7			Medium grained sand	
22	Okpo Eto	7.5984	5.2733	1	244.4	3.3	3.3	Motley top soil	
				2	176.0	14.6	17.9	Sandy clay	H
				3	1350.9			Medium grained sand	
23	Ikot Essien	7.5645	5.2482	1	398.6	3.7	3.7	Motley top soil	
				2	111.0	14.2	17.9	Sandy clay	H
				3	634.1			Fine sand	
24	Ikot Amba	7.5620	5.2221	1	371.6	5.1	5.1	Motley top soil	
				2	1163.7	98.1	103.2	Coarse sand	K
				3	190.7			Clayey/silty sand	
25	Ikot Ukpong	7.6235	5.2335	1	263.9	12.6	12.6	Motley top soil	
				2	494.5	81.6	94.2	Sandy clay	A
				3	1286.3			Coarse sand	
26	Nto Eton	7.5899	5.1926	1	707.9	8.5	8.5	Motley top soil	
				2	1753.9	54.2	62.7	Gravely sand	K
				3	354.2			Sandy clay	
27	Imama	7.6259	5.1950	1	217.4	15.5	15.5	Motley top soil	
				2	410.1	67.7	83.2	Sandy clay	A
				3	1608.8			Gravelly sand	
28	Nto Edino	7.5812	5.2831	1	401.7	6.7	6.7	Lateritic sand	
				2	1758.3	83.9	90.6	Gravelly sand	K
				3	533.9			Fine sand	

Fig. 4 Interpreted geo-sections along the three profiles **a** AB, **b** CD, and **c** EF shown in Fig. 1. Study area comprises three to four geoelectric layers
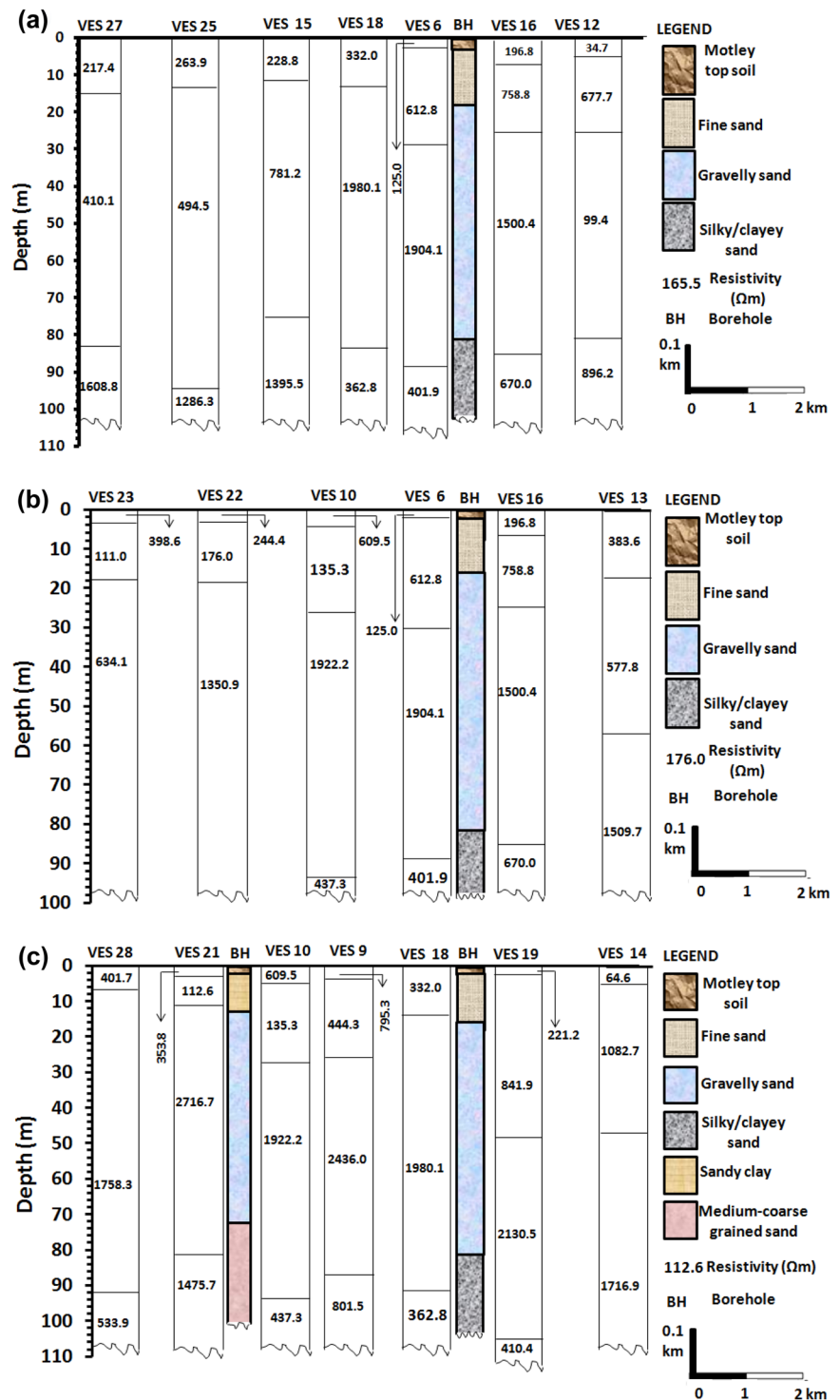
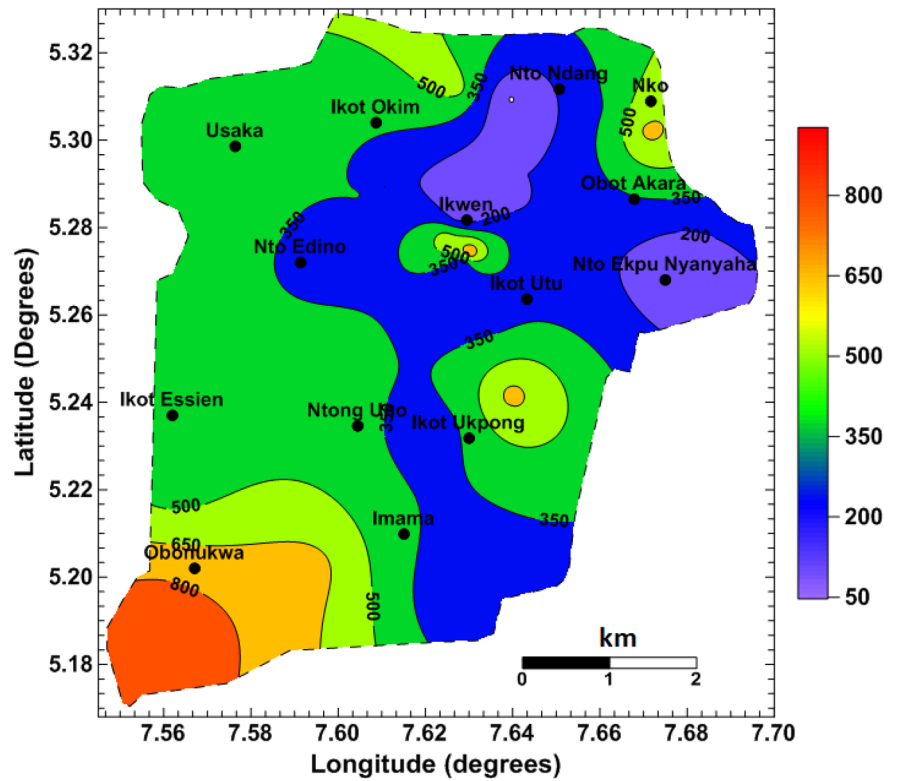**Fig. 5** Distribution of layer 1 resistivity in the survey area

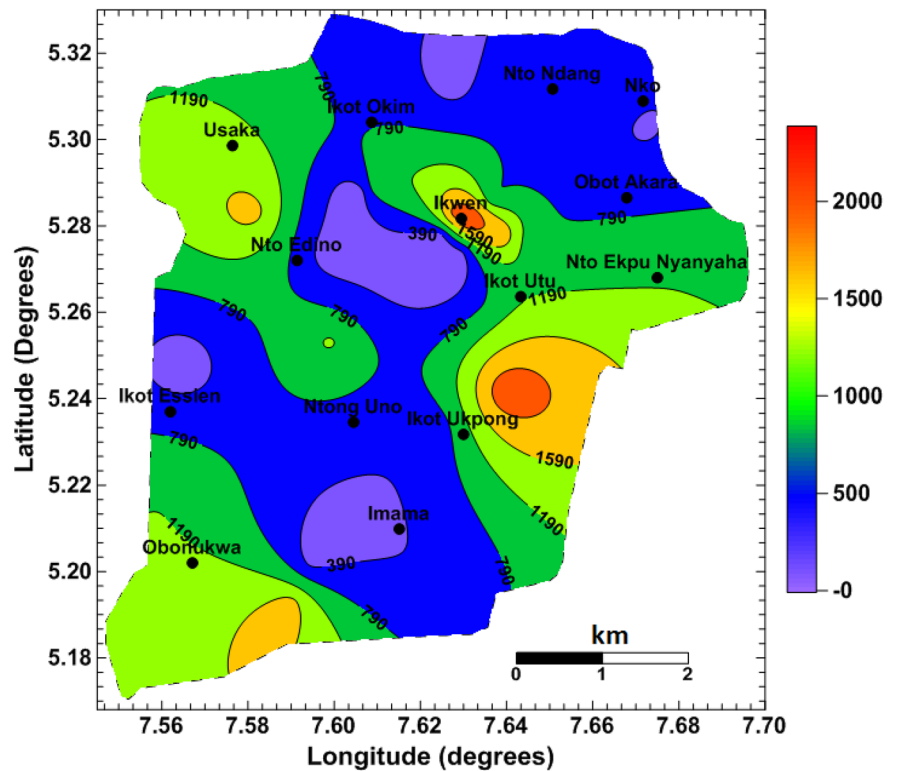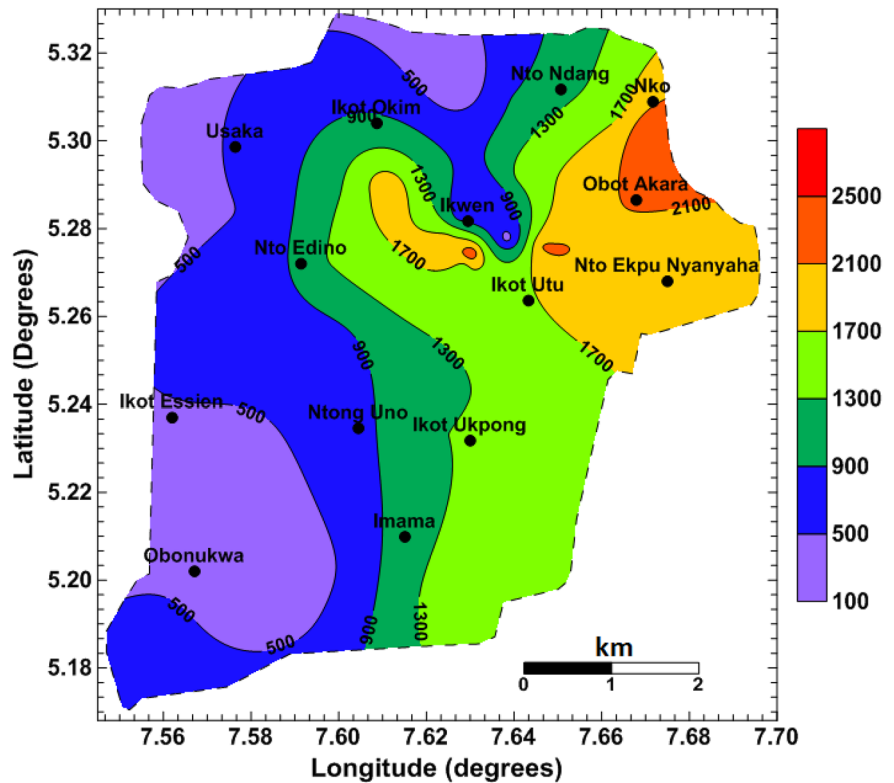**Fig. 6** Distribution of layer 2 resistivity

Fig. 7 Distribution of
aquifer resistivity

eastern part of the study area has relatively higher values of resistivity, which may be indicative of good groundwater quality. The distribution of the aquifer overburden thickness (i.e., sum of thickness of the layers above the aquifer) is shown in Fig. 8. The overburden thickness ranges from 6.0 to 121.4 mwith an average value of 65.4 m. Lower overburden thickness are observed in the north central part of the study area.

The major factor affecting the results of the resistivity in this study is the nature of the subsurface geomaterials in the study area. The area, according to its geology, comprises sands and gravels that are poorly sorted, ranging from fine, medium, coarse, to gravelly sands with some clay intercalation at some locations. Electrical resistivity of soils depends on a variety of factors, which include density, shape, size, pore size, and porosity of the constituent geomaterials, lithology, water content, clay content, and salinity (Choudhury & Saha, 2004; Ekanem et al., 2020; Mc-Neill, 2003). The results of the VES interpretation in

this study were validated from the correlation of the layer interpretations with information from nearby boreholes in the study area.

The water tables (depths to the top of the saturated layer) estimated from the VES interpretation were used to predict the groundwater flow directions as shown in Fig. 9. Groundwater flows from topographically high region to topographically low region (Mc-Neill, 2003). Figure 9 shows that the North-central and Southern parts of the study area are topographically low, and hence, groundwater flows from communities in the Northern region (Ikot Okim, Nto Ndang, Nko, Usaka) to communities in the North central region (Ikwen, Ikot Utu, Nto Ekpu Nyanyaya) and some communities in the Southern part, respectively. The implication of this is that the Northern part is the recharge zone while the North-central and Southern parts are the sink. Knowledge of groundwater flow direction is especially important in predicting the direction of flow of contamination plume in the subsurface.
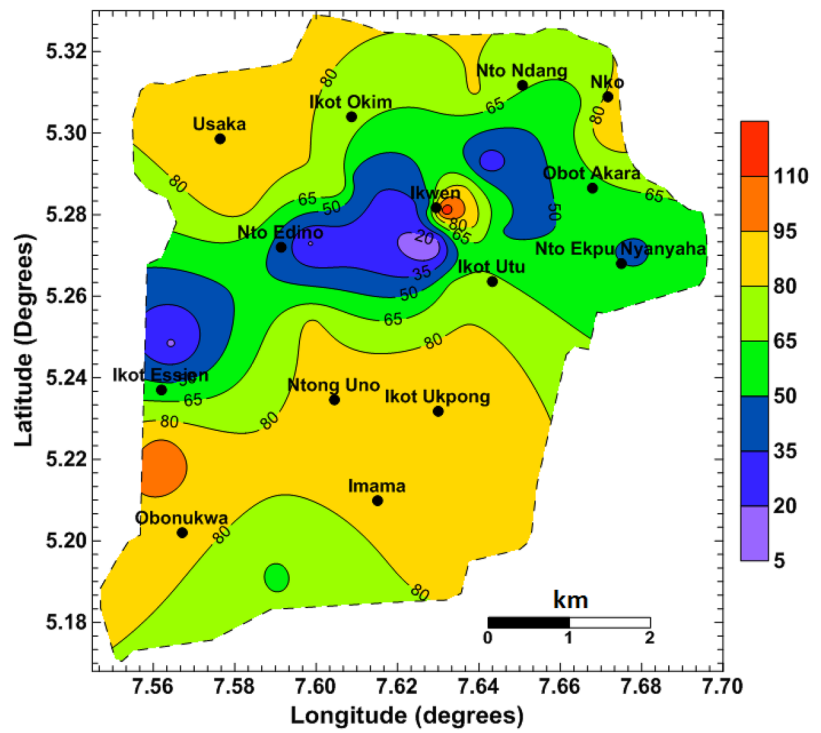
Fig. 8 Aquifer overburden thickness

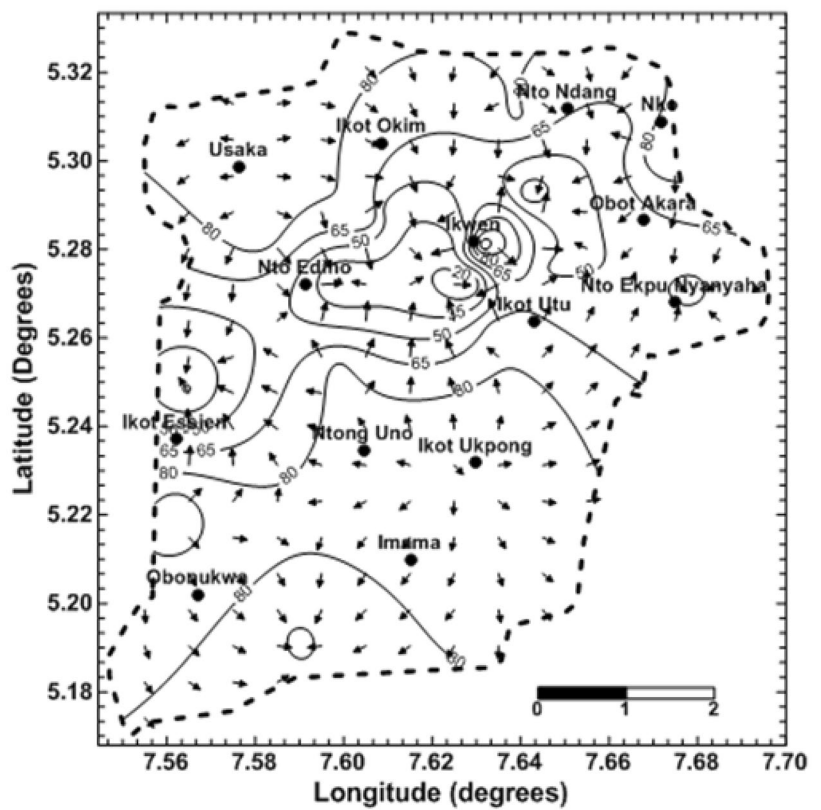**Fig. 9** Map showing direction of groundwater flow in the study area

Table 4 Results of appraisal of aquifer protection capacity (APC)

| VES no	Location	Protecting layers	Protecting layer resistivity (Ωm)	Thickness (m)	Longitudinal conductance (smhos)	Reflection coefficient	Aquifer protection rating
1	Ubon Ukwa	1	929.7	24.2	0.07	0.17	Poor
		2	1297.8	59.9			
2	Nto Eton	1	707.0	2.0	0.11	0.68	Weak
		2	217.3	11.6			
		3	1129.4	61.0			
3	Ikot Idem Udo	1	434.2	7.9	0.08	0.48	Poor
		2	1244.2	75.7			
4	Mbat Esifon	1	705.0	21.7	0.06	0.54	Poor
		2	2355.5	66.0			
5	Abiakpo Ibo	1	694.0	11.5	0.26	− 0.34	Moderate
		2	338.8	81.3			
6	Ikwen 1	1	132.2	3.4	0.09	0.80	Poor
		2	1178.4	77.2			
7	Ikwen 2	1	72.9	3.3	0.06	0.93	Poor
		2	2080.0	40.1			
8	Nto Esu 1	1	214.4	1.8	0.14	− 0.74	Weak
		2	31.8	4.2			
9	Ikot Utu	1	795.3	3.6	0.05	− 0.28	Poor
		2	444.3	20.8			
10	Nto Esu 2	1	609.5	4.4	0.16	− 0.64	Weak
		2	135.3	21.0			
11	Ikot Okim 1	1	200.4	19.0	0.12	0.70	Weak
		2	1127.7	22.9			
12	Ikot Okim 2	1	34.7	5.7	0.76	− 0.74	Good
		2	677.7	19.7			
		3	99.4	56.0			
13	Nto Ndang 1	1	383.6	17.2	0.11	0.20	Weak
		2	577.8	39.9			
14	Nto Ekpu Nyanyanya	1	64.6	4.5	0.11	0.89	Weak
		2	1082.7	43.0			
15	Oku Obom	1	228.8	11.6	0.13	0.55	Weak
		2	781.2	64.0			
16	Nto Ndang 2	1	196.8	7.9	0.06	0.59	Weak
		2	758.8	17.6			
		3	1500.4	60.0			
17	Ikwen 3	1	204.9	33.2	0.20	0.85	Weak
		2	2481.4	88.2			
18	Nto Obio Ikang 1	1	332.0	12.9	0.07	0.71	Weak
		2	1980.1	70.6			
19	Nto Obio Ikang 2	1	221.2	2.3	0.07	0.58	Poor
		2	841.9	46.1			
		3	2130.5	59.0			

Table 4 (continued)

VES no	Location	Protecting layers	Protecting layer resistivity (Ωm)	Thickness (m)	Longitudinal conductance (smhos)	Reflection coefficient	Aquifer protection rating
20	Utu Ikot Inyang	1	556.6	5.4	0.09	0.84	Poor
		2	234.9	13.8			
		3	2711.9	51.7			
21	Abiakpo Ikot Ukam	1	353.8	3.2	0.11	0.92	Weak
		2	112.6	8.6			
		3	2716.7	68.9			
22	Okpo Eto	1	244.4	3.3	0.10	− 0.16	poor
		2	176.0	14.6			
23	Ikot Essien	1	398.6	3.7	0.14	− 0.56	Weak
		2	111.0	14.2			
24	Ikot Amba	1	371.6	5.1	0.10	0.52	Poor
		2	1163.7	98.1			
25	Ikot Ukpong	1	263.9	12.6	0.21	0.30	Moderate
		2	494.5	81.6			
26	Nto Eton	1	707.9	8.5	0.04	0.42	Poor
		2	1753.9	54.2			
27	Imama	1	217.4	15.5	0.24	0.31	Moderate
		2	410.1	67.7			
28	Nto Edino	1	401.7	6.7	0.06	0.63	Poor
		2	1758.3	83.9			

Appraisal of aquifer protective capacity and soil corrosivity

Two parameters were used to assess the aquifer protective capacity in this study. These parameters are the total longitudinal conductance and electrical resistivity coefficient of the overburden layers. These parameters were computed by the use of Eqs. (2) and (5), respectively. The values obtained from the computation are summarized in Table 4. The total longitudinal conductance ranges from 0.04 mhos at VES 12 (Ikot Okim 2) to 0.76 mhos at VES 26 (Nto Eton), while the resistivity reflection coefficient ranges from − 0.74 at VES 8 (Nto Esu 1) to 0.93 at VES 7 (Ikwen 1), respectively. The contour map of Fig. 10 shows the distribution of the total longitudinal conductance, while the distribution of the resistivity reflection coefficient is shown in the contour map of Fig. 11. The maps of Figs. 5-11 were generated using the SURFER software, which makes use of kriging interpolation and the gridding method. The classification of Henriet (1976), Oladapo and Akintorinwa (2007) and Abiola et al. (2009) for total longitudinal conductance given in Table 1 was used to rate the aquifer protective capacity. The ratings in Table 1 are suitable for the study area since the area is in the same geological province with similar subsurface characteristics. Total longitudinal values of 0.04–0.10 mhos were rated as poor protection capacity, 0.11–0.20 as weak protection capacity, 0.21–0.26 mhos as moderate protection capacity, while values greater than 0.26 were rated as good protection capacity. Negative resistivity reflection coefficient values correspond to moderate to good protection capacity as the second layer is made up of impervious materials with low resistivity or high conductivity values as observed in some communities in the area. Positive values of reflection coefficient on the other hand correspond to weak to poor protection capacity as the materials of the second layer are permeable with higher resistivity values and allow fluids to percolate easily to contaminate the aquifer system. The aquifer protection capacity rating based on these two parameters is summarized in Table 4. It should

Fig. 10 Distribution of longitudinal conductance
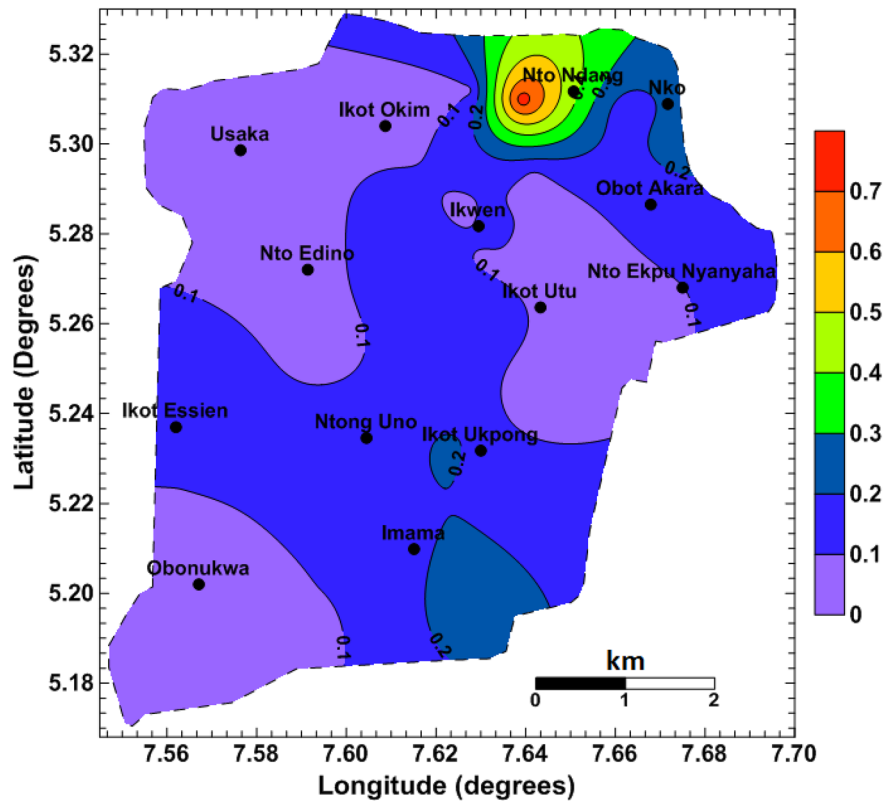
be noted that aquifer protection in this case depends on the thickness of the overburden materials, even if an impervious material is the overburden due to sand intercalation. This explains why negative values are obtained for reflection coefficient at some locations, but the aquifer is rated as weakly to poorly protected. Figure 12 shows the distribution of the aquifer protection rating in percentages. The figure shows that 89.3% of the aquifer unit in the area is weakly to poorly protected, while 10.7% have moderate to good protection.

The topsoil corrosivity was appraised using the classification of Agunloye (1984), Oladapo et al. (2004), and Mosuro et al. (2017) shown in Table 2 for resistivity values. This classification or guideline is also applicable to the study area since the area is equally located in the same region with similar geological characteristics. The topsoil in the study area is practically noncorrosive except at VES 6 and 7 (Ikwen community), VES 12 (Ikot Okim community) and VES 14 (Nto Ekpu Nyanyanya community) as summarized in Table 5. The bar chart of Fig. 13 shows that 85.7% of the top soil at the sounding stations is noncorrosive while 14.3% is slightly to moderately corrosive. The topsoil in Ikwen and Nto Ekpu Nyanyanya communities is slightly corrosive, while that in Ikot Okim village is moderately corrosive. A possible reason for this slight to moderate corrosivity in these communities is the presence of ferruginous substances in the lateritic materials of the topsoil. The implication therefore is that underground metal storage tanks, galvanized pipes, steel, and other utility pipes can be buried in most parts of the study area without any risk of failure or being damaged.

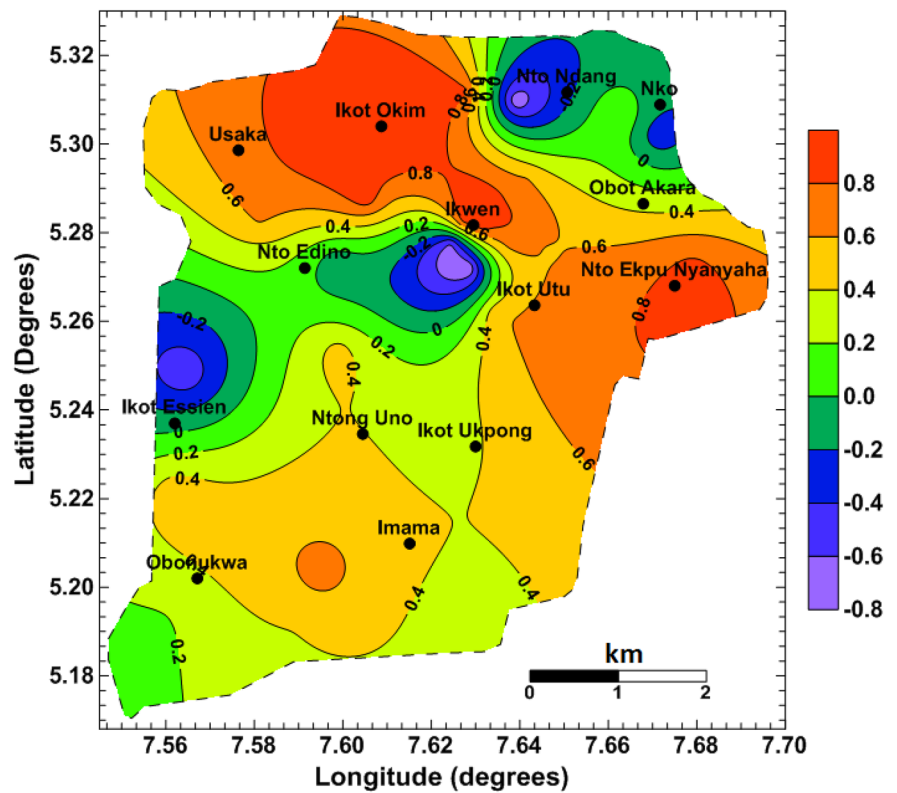**Fig. 11** Distribution of resistivity reflection coefficient
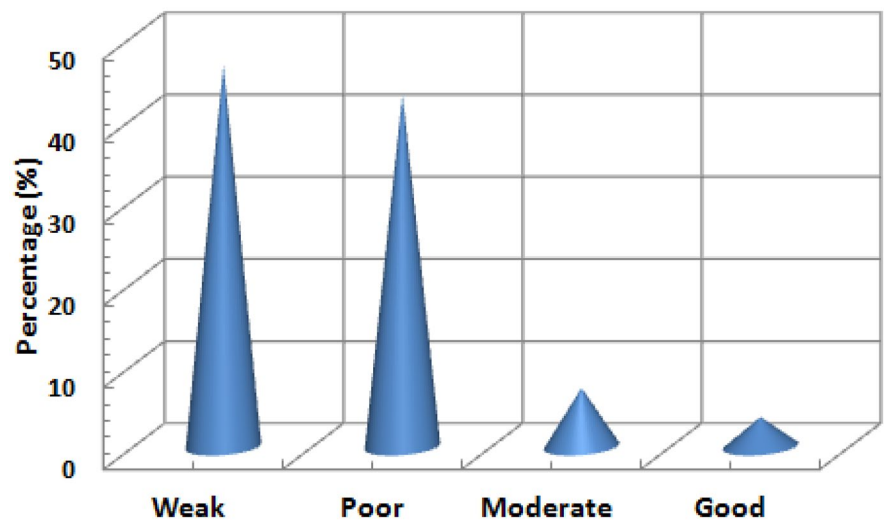

Fig. 12 Aquifer protection rating

Table 5 Results of appraisal of soil corrosivity

VES no	Location	Top soil resistivity (Ωm)	Soil corrosivity rating
1	Ubon Ukwa	929.7	Practically non-corrosive
2	Nto Eton	707.0	Practically non-corrosive
3	Ikot Idem Udo	434.2	Practically non-corrosive
4	Mbat Esifon	705.0	Practically non-corrosive
5	Abiakpo Ibo	694.0	Practically non-corrosive
6	Ikwen 1	122.3	Slightly corrosive
7	Ikwen 2	72.9	Slightly corrosive
8	Nto Esu 1	214.4	Practically non-corrosive
9	Ikot Utu	795.3	Practically non-corrosive
10	Nto Esu 2	609.5	Practically non-corrosive
11	Ikot Okim 1	200.4	Practically non-corrosive
12	Ikot Okim 2	34.7	Moderately corrosive
13	Nto Ndang 1	383.6	Practically non-corrosive
14	Nto Ekpu Nyanyanya	64.6	Slightly corrosive
15	Oku Obom	228.8	Practically non-corrosive
16	Nto Ndang 2	196.8	Practically non-corrosive
17	Ikwen 3	204.9	Practically non-corrosive
18	Nto Obio Ikang 1	332.0	Practically non-corrosive
19	Nto Obio Ikang 2	221.2	Practically non-corrosive
20	Utu Ikot Inyang	556.6	Practically non-corrosive
21	Abiakpo Ikot Ukam	353.8	Practically non-corrosive
22	Okpo Eto	244.4	Practically non-corrosive
23	Ikot Essien	398.6	Practically non-corrosive
24	Ikot Amba	371.6	Practically non-corrosive
25	Ikot Ukpong	263.9	Practically non-corrosive
26	Nto Eton	707.9	Practically non-corrosive
27	Imama	217.4	Practically non-corrosive
28	Nto Edino	401.7	Practically non-corrosive

Fig. 13 Corrosivity rating frequency
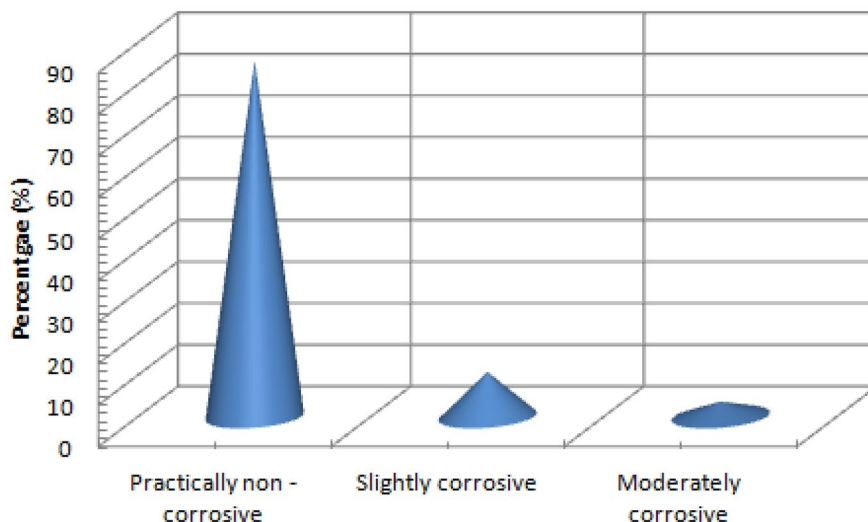
Conclusion

In this study, the surface resistivity method has been used to appraise the protectivity of hydrogeological units and soil corrosivity in Obot Akara County, southern Nigeria. The following conclusions are made from the results of this study:

1. The study area is made up of 3 to 4 geoelectric layers within the limit of the maximum electrode spacing used.
2. The third layer, with a resistivity range of 99.4 to 2716.7 Ωm, constitutes the aquifer unit in most communities in the area, with an average thickness of 58.3 m. The inhabitants of the area acquire their water for drinking and other purposes from this layer.
3. The thickness of the aquifer overburden or protecting layers ranges from 6.0 to 121.4 with an average value of 65.4 m.
4. Of the aquifer unit in the area, 89.3% is weakly to poorly protected, while 10.7% have moderate to good protection. The implication of this is that groundwater in most communities in the area is likely contaminated especially by some ferrugenized materials from the overlying layers.
5. Of the top soil at the sounding stations, 85.7% is noncorrosive, while 14.3% is slightly to moderately corrosive. This implies that underground metal storage tanks, galvanized pipes, and steel pipes and other utility pipes can be buried in most communities in the study area without any risk of failure or being rusted.

Although the results of this study are very promising in providing useful information to aid groundwater development and waste disposal management in the area, a follow-up study involving hydrogeochemical and microbiological analyses of groundwater samples from available boreholes in the area is necessary to corroborate the results.

Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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

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