Geoelectrohydraulic investigation of the surficial aquifer units and corrosivity in parts of Uyo L. G. A., Akwa Ibom State, Southern Nigeria

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Abstract This study was carried out employing vertical electrical sounding (VES) with Schlumberger electrode configuration. The objectives were to investigate the distribution of the geohydraulic parameters and the corrosivity of the aquifer layer within the study area. The sand-to-coarse grain sands aquifer have resistivity ranging from 8.1 to 2204 Ωm , while the thickness ranged from 7.4 to 55.3 m. These parameters were used in computing the geohydraulic parameters. Hydraulic conductivity was estimated using the Heigold equation, and its values ranged from 1.42 to 54.90 m/day. Estimated hydraulic conductivity values were employed in determining the aquifer transmissivity which ranged from 11.28 to 812.00 m^2/day , fractional porosities ranged from 0.0351 to 0.0598. The longitudinal conductance also varies from 0.01 to 1.83 Ω^{-1} . The contour plots generated from the SURFER software package show the variation of these parameters. The ranges of these estimated parameters indicate variation in grain sizes, magnitude of pore sizes and facies changes. The corrosivity rating indicates that most of the VES points were practically non-corrosive.

Keywords Aquifer · Geohydraulic properties · Transmissivity · Hydraulic conductivity · Porosity

Introduction

Groundwater is important in all aspect of life. It is the major source of drinking water and is useful in the agricultural and industrial sectors, and a good knowledge of the aquifer repositories is a concern for its sustainable and effective use (Edet and Worden 2009; Evans et al. 2010; George et al. 2015a, 2016a, 2017a; Obiora et al. 2015). Since the aquifer in the coastal regions is shallow, residents drilling for potable groundwater do not care about getting geophysical information about the area before drilling. These have led to wildcat drilling across the area, which has resulted to boreholes failure and in some cases the quality of the groundwater extracted may not be good.

Geophysical investigation of the subsurface to delineate groundwater resource have increased over the years, this is due to the advance in technology which have improved the interpretation and modeling of the parameters. The litho-textural characteristics, pore-water conductivity and fluid saturation of hydrogeological unit affect electrical conductivity of the subsurface geomaterials (Ibanga and George 2016).

Different physical parameters are distributed in the earth subsurface and the use of non-destructive and non-invasive geophysical methods can help provide information about these parameters. It is an indirect method that predicts a model of the subsurface as a result of interpreting the physical parameters. The electrical resistivity method though may be plagued with ambiguities and uncertainties in interpretation, provides an economical and reliable means to identify and delineate the subsurface characteristics/properties through the measurement of apparent resistivity (Batayneh 2009; Muchingami et al. 2012; Ebong et al. 2014; Okiongbo and Mebine 2015).

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The flow and recharge of the aquifer repositories unit is affected by the aquifer characteristics and the knowledge of these parameters such as hydraulic conductivity, transmissivity, porosity, formation factor and tortuosity is necessary to describe the hydrogeological units quantitatively. There is need for adequate information about the pore properties and the interrelationship with other aquifer parameters (George et al. 2015b). Electrical and hydraulic conductivity are functions of the pore size and have different sensitivity to the characteristic pore size (George et al. 2014). The subsurface is characterized by pores linking the formation particles and a good understanding of the pore properties gives idea about fluid movement in the subsurface (George et al. 2015a). Porosity which measures the amount of pore spaces in a formation is given by the relation:

$$\text{Porosity } (\phi) = \frac{\text{volume of pores}}{\text{total rock volume}} \quad (1)$$

Porosity is a formation property whose spatial variability depends on several factors like density, clay contents, tortuosity, hydraulic conductivity (Jackson et al. 1978). Induration or lithification of sedimentary formation leads to significant deviations in pore geometry system (George et al. 2016a). Archie's law summarized the occurrence of groundwater in rocks and soil, and gave the relationship between porosity, bulk resistivity and water resistivity in Eq. 2;

$$\rho = a\rho_w\phi^{-m} \quad (2)$$

where ρ is the bulk resistivity, ρ_w is water resistivity, a and m are the pore geometric factor and cementation factor, respectively (Keller and Frischnecht 1966). Cementation factor is fixed but varies with formation lithostratigraphy, permeability dependent factors and geologic age of geomaterials (Archie 1942; Keller 1982) according to different tabulated values. The maximum amount of information about pore structure is embedded in transport processes. Aquifer hydraulic conductivity (K) is the ease with which water can move through an aquifer. It varies in a geological unit over relatively short distances, particularly in fractured rock aquifer. The K -values are important as they help in differentiation of aquifer bodies and their yield. According to Heigold et al. (1979), the values of K for a similar formation can be estimated using the relation below;

$$K = 3.86.40R_{rw}^{-.93283} \quad (3)$$

where R_{rw} is the resistivity of the aquifer.

Transmissivity (T_r) is the ability of the aquifer to transmit groundwater throughout its entire saturated thickness. It is a measure of the rate at which groundwater can flow through an aquifer section of unit width under a

hydraulic gradient. Niwas and Singhal (1981) established an analytical relationship between transmissivity and transverse resistance, and also between transmissivity and longitudinal conductance. The discharge (Q) of fluid according to Darcy's law is given as

$$Q = KIA \quad (4)$$

But from Ohm's law:

$$J = \sigma E \quad (5)$$

where σ is electrical conductivity, K is the hydraulic conductivity, A is cross sectional area perpendicular to the direction of flow, J is current density, E is electric field intensity, I is the hydraulic gradient.

From Eqs. 2 and 3, Niwas and Singhal (1981) obtained relationships given as

$$T_r = K\sigma T = \frac{KS}{\sigma} = Kh \quad (6)$$

where T_r is aquifer transmissivity, T is transverse resistance and S is longitudinal conductance. The longitudinal conductance and transverse resistance (S and T) referred to as Dar-Zarrouk parameters and are given as

$$S = \frac{h}{\rho} \quad (7)$$

$$T = h\rho \quad (8)$$

where h and ρ are the values of aquifer thickness and resistivity, respectively.

The flow/percolation of fluid in subsurface may be influenced by these parameters which depends on the geometry, nature of grain size, non-uniformity of pore grain orientations and type of pore grains and pore channels and hydraulic pressure (George et al. 2017b). This work employs surface geophysical (resistivity) method to study the aquifer repositories to investigate the relationship between bulk electrical and pore properties of the aquifer repositories in the study area.

Location and geology of the study area

The study area belongs to the Niger Delta region of Nigeria which is a Cenozoic wave-dominated delta system (Fig. 1). It lies within 5.03°N and 5.09°N of latitude and 7.41°E and 8.10°E of longitude in the tropical rain forest belt of Nigeria and form part of the low lying coastal/deltaic plains of the southern Nigeria. The study area belongs to the deltaic marine environment of Cretaceous to recent age (Offodile 1992), comprising Benin formation, which is the most proximal of the three major stratigraphy megasequences of the Niger Delta. It is composed predominantly of continental fluvial deposits that do not extend offshore

Fig. 1 **a** Sketch geologic map of Akwa Ibom State showing the location of Uyo Local Government Area. **b** Map of Uyo Local Government Area

into deepwater. The Benin formation is made up of fine-coarse-grained lenses of sandstone with abundant calcareous shale. The major water sources of the area are sub-surface (boreholes) and surface (streams). The relief of the area is low having elevations of less than 10–50 m above sea level and is trending in the northward direction (Ugbaja and Edet 2004).

Materials and method

The geophysical survey was carried out employing Schlumberger electrode configuration for ten vertical electrical sounding (VES) using the IGIS Resistivity meter. The half current electrodes spacing ($\frac{AB}{2}$) ranged from 1.0 to 300.0 m, and half potential electrodes spacing ($\frac{MN}{2}$) of 0.25–20.0 m. The apparent resistivity (ρ_a) was computed from the relation;

$$\rho_a = K \frac{V}{I} = K \cdot R_a \quad (9)$$

where K is the geometric factor and it depends on the electrodes arrangements. R_a is the apparent resistance measured on the field. K is given as

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

In reduction of the VES data to 1D geological models, manual and computer modeling techniques were utilized (Zohdy 1965; Zohdy et al. 1974). Bi-logarithmic graphs were used to plot the computed apparent resistivities and

curves were smoothened to remove the effects of lateral heterogeneities and other forms of noisy signatures (Chakravarthi et al. 2007; Akpan et al. 2006). These smoothened curves were curve matched using the master curves and charts (Orellana and Mooney 1966). The computer modeling was done using the WinResist software where the calculated apparent resistivity was used as input parameter and the output was a set of geoelectric curves from where the values of resistivity, thickness and depth of each geoelectric layer were obtained.

Results and discussion

The analysis of the resistivity survey reveals three to five geoelectric layers with characteristic curves of various types. Table 1 shows the resistivity values of the layers within the maximum current separation, together with their depths and thicknesses. The depths were constrained by borehole lithologic information near VES 3 and VES 9 (Fig. 2). The topmost layer resistivity ranged from 10.2 Ω m at VES 1–2157.0 Ω m at VES 12, with thickness and depth ranging from 0.5 to 5.8 m. The resistivity of this layer is observed to be relatively lower than that of the underlying layers. The resistivity of the second layer ranges from 8.1–5820.0 Ω m and the thickness and depth varies from 1.2 to 14.8 and 1.7 to 15.8 m, respectively. The third layer resistivity varies from 23.4 to 2204.0 Ω m, while the thickness ranges from 3.0 to 56.3 m and the depth ranges from 4.7 to 60.9 m. The fourth layer gives resistivity ranging from 75.0 to 2705.50 Ω m with thickness and

Table 1 Summary of results of resistivity survey from computer modeling

VES stations	Longitude (°E)	Latitude (°N)	Resistivity (Ωm)					Thickness (m)				Depth (m)				Curve types
			ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	h_1	h_2	h_3	h_4	d_1	d_2	d_3	d_4	
1	7.9336	5.0419	10.2	18.9	23.4	82.3	–	3.0	3.5	23.5	–	3.0	6.5	30.0	–	AA
2	7.9341	5.0421	11.1	65.7	31.6	198.5	–	0.9	5.7	27.7	–	0.9	6.6	34.3	–	KH
3	7.9348	5.0416	156.4	800.8	407.8	1350.1	–	1.3	9.1	47.9	–	1.3	10.4	58.3	–	KH
4	7.9361	5.0435	298.2	683.1	377.2	1638.2	–	0.7	7.2	17.4	–	0.7	7.9	25.3	–	KH
5	7.9343	5.0426	26.0	17.0	107.3	75.0	–	1.6	2.9	56.3	–	1.6	4.4	60.7	–	HK
6	7.9355	5.0418	68.2	263.0	219.0	554.6	–	1.3	7.6	37.0	–	1.3	8.8	45.8	–	KH
7	7.9363	5.0438	377.0	217.0	1125.8	2705.5	–	1.7	9.5	30.6	–	1.7	11.2	41.8	–	HA
8	7.9359	5.0433	28.6	38.2	190.1	102.5	–	1.0	11.4	40.9	–	1.0	12.5	53.4	–	AA
9	7.9356	5.0441	12.8	8.1	101.3	–	–	1.1	14.8	–	–	1.1	15.8	–	–	H
10	7.9353	5.0436	63.0	29.6	64.7	176.5	–	2.3	10.3	42.5	–	2.3	12.6	55.1	–	HA
11	7.9217	5.0677	261	1483	1970	804	332	0.5	1.2	3.0	27.9	0.5	1.7	4.7	32.6	KHQ
12	7.9035	5.0566	2157.0	524.0	1682	507.0	–	2.0	3.3	55.3	–	2.0	5.3	60.9	–	HK
13	7.9331	5.1058	692.0	1056	5442.0	1006.0	4747.0	0.6	4.1	14.1	33.7	0.6	4.7	18.8	91.2	AKH
14	7.9293	5.0858	112.0	5820.0	2204.0	1200.0	–	5.8	9.5	30.0	–	5.8	15.3	45.3	–	KA

Fig. 2 Borehole lithologic log near VES 3 and VES 9

depth undefined in most of the VES points. The aquifer resistivity ranged from 8.1 to 2204 Ωm , while the thickness ranged from 7.4 to 55.3 m. These parameters were used in estimating the geohydraulic parameters (Table 2). The

contour maps were generated using Surfer software package. Figure 3 shows low aquifer resistivity in the south-eastern part of the study area, with high values distributed on the other parts of the study area. This may be influenced by the geological materials present in the subsurface (George et al. 2016a, b). In Fig. 4, high aquifer thickness is seen in the western part of the study area.

The distribution of hydraulic conductivity (K) is shown in Fig. 5, where high K is seen in the southeastern part and it varies inversely with the porosity distribution map (Fig. 6). The porosity estimated from Eq. 1 increases from southeast to northwest and is in a reverse direction to the variation of transmissivity. Though some geological materials may be porous but not permeable due to the presence of dead-end pores by the residual argillaceous materials in the tortuous path (George et al. 2015b). Figure 7 is a contour map showing the distribution of aquifer transmissivity, highest value is seen in the southeastern part and decreases towards the northern part of the study area. The map (Fig. 7) closely relates to the hydraulic conductivity map (Fig. 5), the sensitivity of K to facies change affects the distribution of aquifer transmissivity, which depends on K and h . The high transmissivity observed in the southern part is an indication of high groundwater reserve in that zone.

In computing the Dar-Zarrouk parameters (longitudinal conductance and transverse resistance), the aquifer resistivity and thickness were used and the variational trends of these parameters are shown in Figs. 8 and 9, respectively. The longitudinal conductance increases in the southeastern

Table 2 Results of aquifer hydraulic parameters from measured resistivity and thickness of the aquifer layers

VES stations	Long.	Lat.	ρ_a (Ωm)	h_a (m)	K (m/day)	ϕ (%)	Fractional Porosity	Tr (m^2/day)	S (Ω^{-1})	T (Ωm^2)	Corrosivity rating
VES 1	7.9336	5.0419	23.4	23.5	20.21	28.52	0.0351	479.58	1.00	549.90	MC
VES 2	7.9341	5.0421	31.6	27.7	15.42	28.24	0.0354	427.13	0.88	875.32	MC
VES 3	7.9348	5.0416	407.8	47.9	1.42	25.85	0.0387	67.96	0.12	19,533.62	NC
VES 4	7.9361	5.0435	377.8	7.4	1.52	25.92	0.0386	11.28	0.02	2795.72	NC
VES 5	7.9343	5.0426	107.3	56.3	4.93	27.10	0.0369	277.55	0.52	6040.99	SC
VES 6	7.9355	5.0418	219.0	37.0	2.53	26.43	0.0378	93.76	0.17	8103.00	NC
VES 7	7.9363	5.0438	1125.8	30.6	0.55	24.90	0.0402	16.84	0.03	34,449.48	NC
VES 8	7.9359	5.0433	190.1	40.9	2.89	26.56	0.0376	118.27	0.22	7775.09	NC
VES 9	7.9356	5.0441	8.1	14.8	54.90	29.51	0.0339	812.53	1.83	119.88	VSC
VES 10	7.9353	5.0436	64.7	42.5	7.90	27.57	0.0363	335.86	0.66	2749.75	NC
VES 11	7.9217	5.0677	804	27.9	2.60	16.72	0.0598	72.54	0.04	22,431.60	NC
VES 12	7.9035	5.0566	1682	55.3	3.70	18.53	0.0540	204.61	0.03	93,014.60	NC
VES 13	7.9331	5.1058	1006	33.7	3.10	17.53	0.0570	104.47	0.03	33,902.20	NC
VES 14	7.9293	5.0858	2204	30	4.70	19.86	0.0504	141	0.01	66,120.00	NC

Fig. 3 Contour map showing the distribution of aquifer resistivity

direction while the transverse resistance increases in the north–southeastern direction. The inverse behavior of the Dar-Zarrouk parameters can be seen. The changes in the contour maps may be attributed to the influence of the electric–hydraulic anisotropies, also variations in lithology, grain size, pore shape and pore channels. The corrosivity of the hydrogeological units is determined using Table 3, VES 3, 6, 7, 10, 11, 12, 13 and 14 suggests the hydrogeological unit to be non-corrosive, it is observed that these VES points have poor protective capacity rating. This non-corrosivity may be attributed to the absence of corrosive

substances in the subsurface but the aquifer may be polluted by other contaminants such as leachate. VES 1 and 2 were moderately corrosive, VES 5 is slightly corrosive with a moderate protective capacity rating.

Conclusion

The VES result from the resistivity survey was used to investigate the aquifer layer in the study area. From the result, the resistivity, thickness, depth and lateral extension

Fig. 4 Contour map showing the variation of thickness

Fig. 5 Contour map showing the variation of hydraulic conductivity

Fig. 6 Contour map showing variation of porosity in the study area

Fig. 7 Contour map showing the distribution of aquifer transmissivity

of the aquifers show that the entire subsurface studied is naturally endowed with groundwater. When wells are drilled to cut across reasonable section of the aquifer, the groundwater can be exploited and utilized. The closeness of the top of the aquifer such as VES 2, 4, 8, 11 and 13 and others with such thin overburden to the aquifer suggests that borehole within these locations are more susceptible to surface contamination. The uneven distribution of the

geohydraulic parameters may due to uneven facies changes in geological formations. This study demonstrates the relevant of electrical resistivity survey in the investigation of the subsurface characteristics which have influence on groundwater repositories and the findings are valuable tools for groundwater management.

Fig. 8 Contour map showing the distribution of longitudinal conductance

Fig. 9 Contour showing the variation of transverse resistance

Table 3 Classification of soil resistivity in terms of corrosivity (Baeckmann and Schwenk 1975; Agunloye 1984; Oladapo et al. 2004)

Soil resistivity (Ωm)	Soil corrosivity
< 10	Very strongly corrosive (VSC)
10–60	Moderately corrosive (MC)
60–180	Slightly corrosive (SC)
180 $\geq$	Non-corrosive (NC)

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