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ORIGINAL PAPER

Evaluation of aquifer potential, geoelectric and hydraulic parameters in Ezza North, southeastern Nigeria, using geoelectric sounding

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Abstract A geoelectric survey involving vertical electrical sounding (VES) employing Schlumberger electrode configuration was carried out with the aim of evaluating the aquifer potential, electric and hydraulic parameters in Ezza North. Schlumberger electrode configuration was used to acquire data for twelve VES stations. The interpreted and analyzed results reveal four to six geoelectric layers. The VES curves obtained were QQH, QHK, QHA, QQQ, HAK, KHK, HKH and QQ. From the result, the Dar Zarrouk parameters (longitudinal conductance and transverse resistance) were calculated. The longitudinal conductance ranges between 0.1528 and 4.6 mhos. The transverse resistance ranges between 662.4 and 38,808 Ωm^2. The range of hydraulic conductivity is 1.1645–38.0491 m/day, while the range of transmissivity is 89.66–2100.3 m^2/day from the estimated values. The contour maps were drawn using the electrical and hydraulic parameters, and the distribution of the aquifer parameters is shown. Based on the results, aquifer potential and protective capacity of the study area were determined.

Keywords Aquifer potential · Ezza North · Hydraulic conductivity · Longitudinal conductance · Transmissivity · Transverse resistance

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Introduction

A detailed knowledge of the subsurface geology and structure is provided by the geophysical surveys. Electrical resistivity method has been used successfully in delineation and exploitation of groundwater (Evans et al. 2010; George et al. 2010; Ibuot et al. 2013). It gives detailed information about hydrogeological settings and groundwater repositories. Groundwater is that water contained in the voids of the geologic materials that comprise the crust of the earth and exists at a pressure greater than or equal to atmospheric pressure (Al Sabahi et al. 2009). Comparatively, groundwater is less exposed to contamination than surface water. This reason underscores the reason, while it is more preferable to surface water. To man, groundwater has provided a great socioeconomic benefits including domestic and industrial uses, irrigation and tourism. In groundwater exploration, vertical electrical sounding (VES) employing Schlumberger electrode configuration is a common geophysical technique (Ezeh and Ugwu 2010; Olawuyi and Abolarin 2013; George et al. 2011; Ibuot et al. 2013). This is because instrumentation is simple; field logistics are easy and straightforward, while the analysis of data is less tedious and economical (Zohdy et al. 1974; Ekine and Osobonye 1996). The resistivity method is aimed at measuring the potential differences on the surface due to the current flow within the ground. Since the mechanisms that control the fluid flow and electric current and conduction are generally governed by the same physical parameters and lithological attributes, the hydraulic and electrical conductivities are dependent on each other (George et al. 2015).

The need for water in the study area has aroused interest in the use of groundwater due to lack of surface water both saline and fraught with coliform. Most of the hand-dug wells or drilled boreholes have been done without any preliminary geophysical investigations. This has resulted to failures of some boreholes and contamination of water which has resulted to various waterborne diseases. None of the surface water is as hygienic or as economical for exploitation as the groundwater (Singh 2007). Groundwater is recommended for its natural microbiological quality and its general chemical quality for most uses (McDonald et al. 2002). The guinea worm infestations in some parts of Ebonyi State are attributed to ignorance and lack of safe drinking water (Okoronkwo 2003). The people of Ezza lack functional boreholes and depend only on ponds and other existing contaminated and coliform-stricken surface sources which are open to physical, chemical and microbial contaminations. The inhabitants of the area had suffered severely from the outbreak of guinea worm, and they trek long distances in search of water, especially during dry season. The area has argillaceous minerals that seem to act as a protective cover to the underlying layers. The intrusions that gave rise to the existence of rocks and minerals during the Santonian uplift account for several fractures within the shale. These fractures contain water, serving as aquifer. Groundwater flow in fractured aquifers is very complicated, and accuracy in estimation of the hydraulic parameters depends on the hydraulic behavior in particular fractures, which is site specific (Singh 2005).

The determination of aquifer characteristics involves the analysis and interpretation of soil and water samples of drilled boreholes, but due to the fact that these tests are capital and labor intensive, a noninvasive geoelectrical method (vertical electrical sounding) is used as an alternative to pumping tests. This paper attempts to evaluate aquifer potential, geoelectric and hydraulic parameters in the study area.

Location and geology of the study area

The study area lies between latitudes 06°09′N and 06°18′N of the equator and longitudes 07°54′E and 08°02′E of the Greenwich Meridian (Fig. 1). The area covers about 246 square kilometers and lies in the southeastern part of Nigeria. The study area belongs to the Asu River group shales. The sediments of the Asu River group which was formed during the Albian times were folded into open northeast trend known as Abakaliki Anticlinorium (Reyment 1965). The Asu River group is overlain by succession of shales, siltstones and sandstones, with shallow marine fauna, and is estimated to have a maximum thickness of about 200 m. There are some mineral intrusions which may have contributed to its numerous fractures. The geological survey around the area reveals that the location is part of the Ebonyi Formation that overlies the Abakaliki siltstone and sandstone previously referred to in the literature as Unknown "Formation" (Reyment 1965). It is now referred to as Ebonyi Formation (Agumanu 1989). The Formation underlies a gentle undulating terrain in Ntezi–Ezamgbo area and southward to Amagu-Agba in Ebonyi State. The Ebonyi River and its tributaries (Akaduru, Nramura and Isumutu Rivers) form the major drainage system in the area. The formation is divided into three units from top to bottom. The upper siltstone–shale sequence is exposed at Amagu-Agba village. It consists essentially of rapidly alternating siltstone and silty shale with occasional thin sandstone beds. The middle limestone–siltstone sequence unit outcrops at a quarry, 2 km from Ekemoha to Agba road junction. It consists of minor sandstone, siltstone, limestone and shale. Lastly, the lower mudstone–shale sequence exposed at Umuezeoke, along drainage cut by River Akaduru. This sequence is grayish, occasionally flesh-colored and bedded with dark micaceous steaks. The study area has elevation between 57 and 89 m above sea level. Marshy conditions of lower elevation that also exist within the area are noted for rice production in the area. Most of the streams existing in the area are seasonal. The seasonal rivers which are active during the rainy seasons have the major drainage, the Ebonyi River, which flows to the Cross River, some distance to the south near Afikpo. The mudstones are highly weathered on the top. Significant groundwater is only found where the mudstone and shale are highly fractured.

Materials and methods

Twelve (12) vertical electrical soundings (VES) were carried out in the study area using OHMEGA SAS1000 Terrameter with its accessories. The Schlumberger electrode array was employed for each VES profile with half current ($\frac{AB}{2}$) electrode separation of 150 m and half potential ($\frac{MN}{2}$) electrode separation of 15 m. To reduce the field data to their equivalent geological models, both manual and computer modeling techniques were employed (Zohdy et al. 1974; Akpan et al. 2009). The observed field data were converted to apparent resistivity (ρ_a) values using Eq. (1):

$$\rho_a = \pi \cdot \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right] \cdot R_a \tag{1}$$

The manual procedure was done by plotting a graph of apparent resistivity against half-electrode spacing using a bi-logarithmic graph, and the curves generated were smoothened to remove the effects of lateral inhomogeneities and other forms of noisy signatures (Bhattacharya and Patra 1968; Chakravarthi et al. 2007).

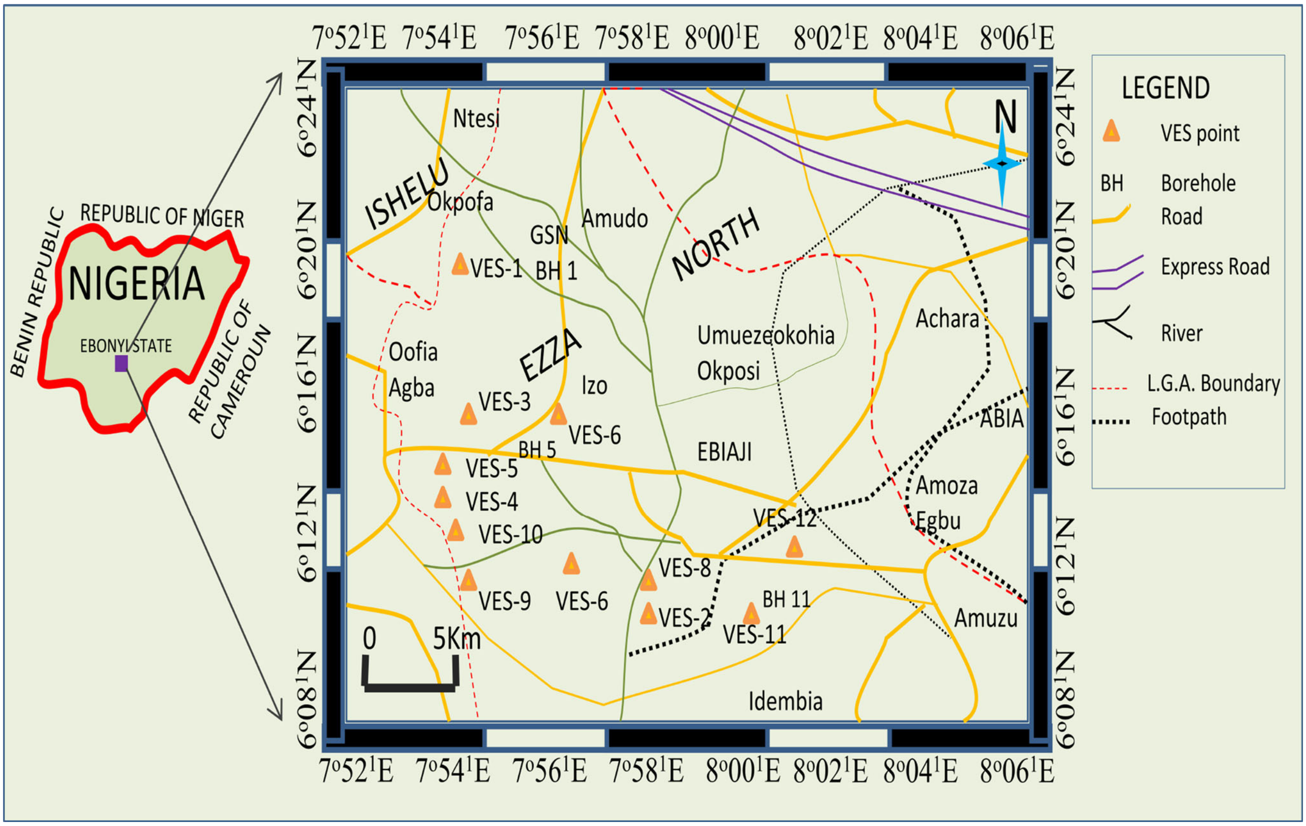


Fig. 1 Location map of the study area showing VES points

A conventional manual curve procedure using master curves and auxiliary charts (Orellana and Mooney 1966) was used to quantitatively interpret the smoothened curves in terms of true resistivity and thickness. The parameters obtained from curve matching were used by the computer software RESOUND as input data for the computer iterative modeling. Figure 2 shows typical geologic models obtained along with their correlations with nearby boreholes. For the interpretation and understanding of the geologic model, some parameters related to different combination of thickness and resistivity of geoelectrical layer are necessary (Zohdy et al. 1974; Maillet 1947). These are the Dar Zarrouk parameters: longitudinal conductance (S) and transverse resistance (T), which are, respectively, given by:

$$S = \frac{h}{\rho} \tag{2}$$

$$T = h\rho \tag{3}$$

where h is the layer thickness in meters and ρ is the electrical resistivity of the layer in ohmmeters. Since the area has the same characteristics as the one studied by (Heigold et al. 1979), the hydraulic conductivity (K) was estimated using

$$K = 386.40\, R_{\mathrm{rw}}^{-.93283} \tag{4}$$

where R_{rw} is the resistivity of the aquifer. The aquifer transmissivity (T_{r}) was estimated using the relation (Niwas and Singhal 1981):

$$T_{\mathrm{r}} = K\sigma T = \frac{KS}{\sigma} = Kh \tag{5}$$

where σ is the electrical conductivity (inverse of resistivity), S is the longitudinal conductance and T is the transverse resistance. Equations (4) and (5) were used in this study to determine the hydraulic conductivity and transmissivity of aquifers, which depends on lithology and salinity of an area.

The reflection coefficient (Rc) and fractured contrast (Fc) shown in Table 2 were calculated using Eqs. 6 and 7, respectively;

$$\mathrm{Rc} = \frac{\rho_n - \rho_{n-1}}{\rho_n + \rho_{n-1}} \tag{6}$$

$$\mathrm{Fc} = \frac{\rho_n}{\rho_{n-1}} \tag{7}$$

where ρ_n is the resistivity of the nth layer and ρ_{n-1} is the layer resistivity overlying the nth layer.

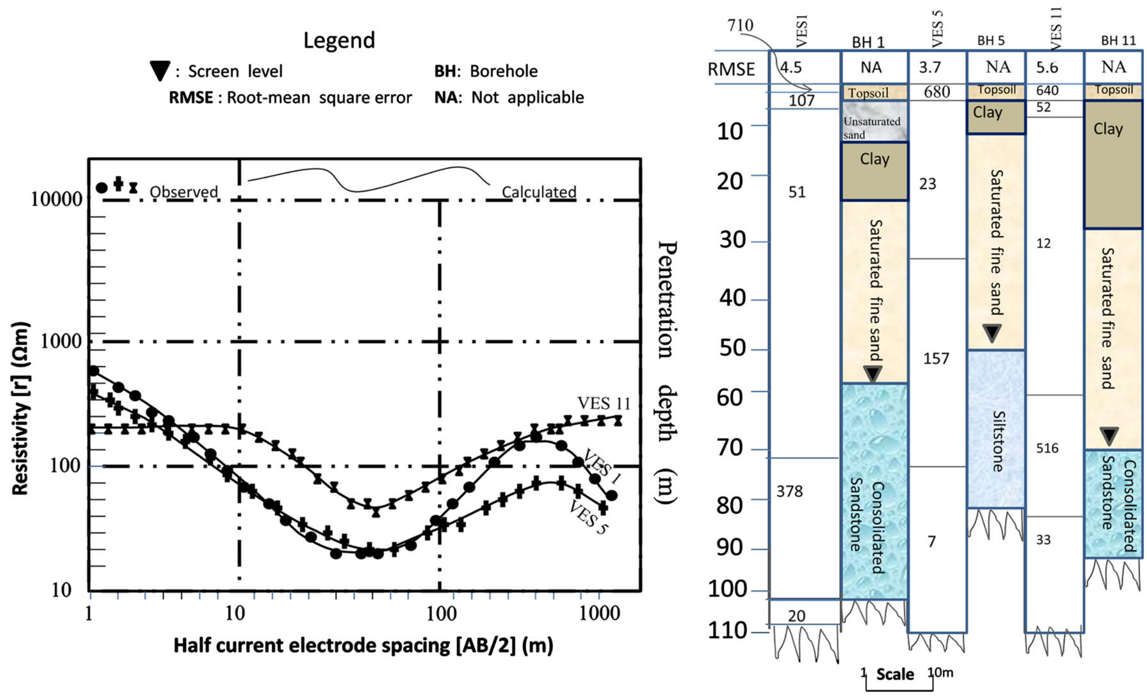


Fig. 2 Samples of 1-D derived modeled VES curves correlating with nearby borehole

Results and discussion

The results of the geoelectric sounding data revealed four to six geoelectric layers with varying intrafacies and interfacies changes (Table 1). The third and fourth layers constitute the aquiferous zones except VES 9 (Ohaccara-Ndiegu-Ohaccara) where the aquifer is the fifth layer. Eight geoelectric curve types were identified and grouped as: QQH (25 %), 16.7 % of QHK and QHA, while 8.3 % represents QQQ, HAK, KHK, HKH and QQ.

The first layer resistivity and thickness range between 90–5800 Ωm and 1.0–1.7 m, respectively, and consists of the top lateritic sand. The second layer has resistivity and thickness range of 30–1740 Ωm and 0.2–8.5 m, respectively. The third layer has a resistivity range of 3.0–285 Ωm and thickness range of 25–214.7 m with that of VES 10 (Ndiegu-Ekka-Onunwode Ndiegu) undefined. This layer harbors most of the aquifers in the study area. The fifth layer with resistivity range of 3–576 Ωm has infinite thickness in most of the study area.

Resistivity of the aquifer layers is shown in Table 2 with an average value of 95.42 Ωm. The variability of its resistivity values is shown in Fig. 3. It reveals that the greater part of the study area is characterized by low aquifer resistivity values <500 Ωm. Areas with resistivity values <100 Ωm indicate argillaceous formation facies which may lower the aquifer potentials, but areas with resistivity values >100 Ωm (Ogboji-Eguo-Ugwu and Ohaccara-Ndiagu-ohaccara) indicate clay–sand sequence, and this is an indication of good aquifer formation. Figure 3 shows that high resistivity is obtainable in the southeastern part of the study area.

Figure 4 is an isopach contour map showing the variation in aquifer thickness in the study area. The values of aquifer thickness range from 34.1 to 214.7 m at Adiagu-Oguji Nwudor and Ndiegu-Ogboji-Ukwu Akpara, respectively, with an average value of 71.95 m. The map shows the increase in aquifer thickness from the eastern part to the western part of the study area.

The distribution of aquifer longitudinal conductance (S) is shown in Fig. 5. The values range from 0.1528 at Ogboji-Egwu-Ugwu to 4.6 mhos at Ekka integrated primary school, Ekka, with an average value of 1.6219 mhos. From Table 2, the longitudinal conductance values aided in classification of the study area into weak, moderate and good aquifer protective capacity. VES 8 (Ogboji-Eguo-Ugwu) was classified as weak. VES 1, 7 and 9 were classified as moderate, while the rest have good aquifer protective capacity, according to Henriet (1976) classification. VES 8 is vulnerable to

Table 1 Summary of results of interpreted layer parameters

VES station	VES station name	Longitude (°)	Latitude (°)	Layer resistivity (Ωm)						Layer thickness (m)						Curve type
				ρ_1 (Ωm)	ρ_2 (Ωm)	ρ_3 (Ωm)	ρ_4 (Ωm)	ρ_5 (Ωm)	ρ_6 (Ωm)	h_1 (m)	h_2 (m)	h_3 (m)	h_4 (m)	h_5 (m)	h_6 (m)	
1	Adiagu-Oguji Nwudor	7.9183E	6.3335N	710	107	51	378	20		13	3.0	34.1	34.0	∞		QHK
2	SEkka Town Hall	7.9500E	6.1800N	750	225	48	24	3		1.2	5.4	30.1	46.4	∞		QQQ
3	Nkomoro-omuzor	7.9261E	6.2367N	545	38	19	229	720		1.7	8.5	49.6	25.0	∞		QHA
4	Ndiegu-Ogboji	7.0844E	6.2222N	100	30	33	95	9		1.4	1.8	11.5	214.7	∞		HAK
5	Umundiegu-Ohaike	7.9022E	6.2339N	680	340	162	23	156	7	1.2	1.7	3.0	71.3	35.5	∞	QQH
6	Udenyi-Azuakparata	7.9261E	6.2564N	1020	714	56	50	128		1.3	3.1	4.3	48.4	∞		QQH
7	Inyere-Ngangbo	7.9247E	6.1806N	195	117	41	93	51		1.2	4.1	8.8	63.9	∞		QHK
8	Ogboji-Eguo-Ugwu	7.9539E	6.1833N	90	360	21	504	47		1.0	1.5	7.8	77.0	∞		KHK
9	Ohaccara-andiegu-Ohaccara	7.8850E	6.1953N	480	48	104	35	120	8	1.2	0.2	7.8	35.2	52.5	∞	HKH
10	Ndiegu-Ekka-Onunwode	7.8906E	6.2072N	1000	100	64	26			1.1	2.2	84.7	∞			QQ
11	Ekka Integrated Sc	8.0161E	6.1606N	640	512	3	12	576	33	1.1	5.5	6.2	55.2	5.4	∞	QHA
12	Ohaugo Pr Sc Ekka	8.1847E	6.1739N	5800	1740	285	90	200		1.0	2.0	9.8	66.0	∞		QQH

contamination from leachate. Areas that are moderate are less vulnerable, while areas with good protective capacity are not vulnerable to contamination from leachate infiltration. The average value of longitudinal conductance shows that the study area has good protective capacity. The weak protective capacity zone is associated with arenaceous material content compared to the areas with moderate and good protective capacity which the underlain aquifers are protected by the overlying argillaceous minerals.

The transverse resistance (T) of the study area varies from 662.4 to 38,808 Ωm^2 with an average value of 4375.85 Ωm^2. The distribution of the aquifer transverse resistance is shown in Fig. 6. Maximum transverse resistance is observed in the western part of the area and part of the southeastern area. This indicates that the western part of the area has high thickness as can be seen from the isopach map, and it can be assumed that these areas may likely have high transmissivity and high yield of aquifer units.

The aquifer hydraulic conductivity (K) with an average value of 12.83 m/day ranges from 1.1645 to 38.0491 m/day. The high range of hydraulic conductivity of aquifers is due to the heterogeneity of the aquifer sand repository, a condition responsible for wide range in hydraulic conductivity (George et al. 2015). Hydraulic conductivity is a measure of the ease with which a fluid will pass through a medium (Heigold et al. 1979). The distribution of hydraulic conductivity is shown in Fig. 7. It revealed that the greater part of the study area has low hydraulic conductivity values, indicating that groundwater flow in the area is not simple but complex because of the geologic controls of the confined aquifers.

The transmissivity contour map is shown in Fig. 8. The transmissivity (T_r) value range from 89.66 to 2100.31 m^2/day (Table 2). Transmissivity values increase at the extremes of the study area, leaving the middle part with low values ≤ 600 m^2/day. Areas with high transmissivity values can be identified as areas of high water-bearing potential, and aquifer materials are highly permeable to fluid movement. The average transmissivity value of 789.83 m^2/day indicates that the area has moderate-to-high aquifer potential.

The reflection coefficient (Rc) and the fracture contrast (Fc) are represented in contour maps (Figs. 9 and 10). Though the highest value is found at the N–S part of the study area, reflection coefficient (Rc) is observed to be high at the western part of the study area. The values range from −0.7514 to 0.9200 with an average value of 0.0310. The fracture contrast ranges from 0.1420 to 40.0424 with the average value of 3.337. The highest value of the fracture contrast is obtainable at the southeastern part of the study area. Lower values of fracture contrast (Fc) are

Table 2 Summary of aquifer electrical and hydraulic parameters

VES	ρ_b (Ωm)	h (m)	S (mhom)	T (Ωm^2)	K (m/day)	T_r (m^2/day)	Rc	Fc
Adiagu-Oguji Nwudor	51	34.1	0.6686	1739.1	9.8665	336.45	−0.3544	0.4766
Ekk Town Hall Azugwu	24	46.1	1.9208	1106.4	19.9313	918.83	−0.3333	0.5000
Nkomoro-Omuzor Ogbo Ojiovu	19	49.6	2.6105	942.4	24.7843	1229.30	−0.3333	0.5000
Ndiegu-Ogboji-Ukwu Akpara	95	214.7	2.2600	20,396.5	5.5228	1185.74	0.4844	2.8788
Umundiegu-Ohaike	23	71.3	3.1000	1639.9	20.7385	1478.65	−0.7514	0.1420
Udenyi-Azuakparata	50	48.4	0.9680	2420.0	10.0505	486.44	−0.0566	0.8923
Inyere-Ngangbo Nwakpa Umobi	93	63.9	0.6881	5942.7	5.6335	359.98	0.3881	2.2683
Ogboji-Eguo-Ugwu	504	77.0	0.1528	38,808.0	1.1645	89.66	0.9200	24.0000
Ohaccara-Ndiegu-Ohaccara	120	52.5	0.4375	6300.0	4.4415	233.17	0.5484	3.4286
Ndiegu-Ekka-Onunwode Ndiegu	64	84.7	1.3234	5420.8	7.9832	676.18	−0.2195	0.6400
Ekka Integrated Pri. Sch Ekka	12	55.2	4.6000	662.4	38.0491	2100.31	0.6000	4.0000
Ohaugo Pri Sch Ekka	90	66.0	0.7333	5940.0	5.8085	383.35	−0.5200	0.3158
Average	95.42	71.95	1.6219	7609.85	12.83	789.83	0.0310	3.337

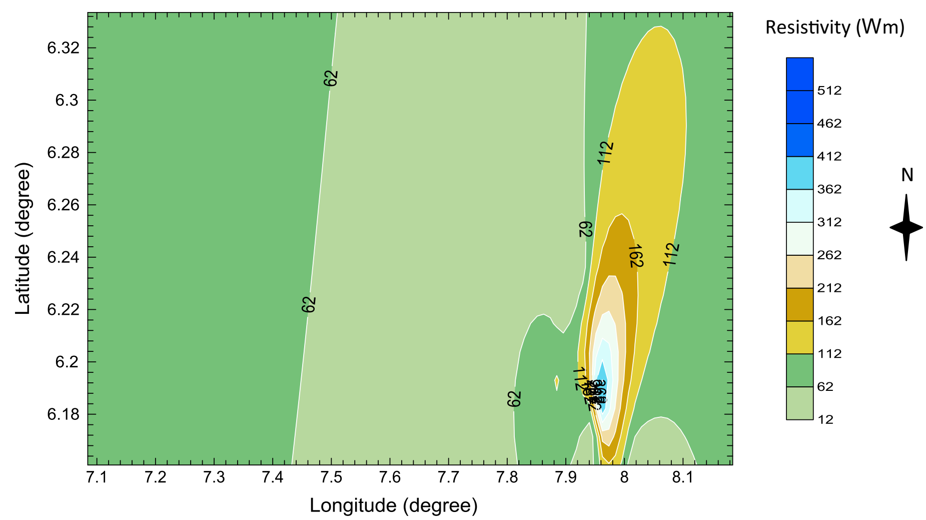


Fig. 3 Contour map of the study area showing aquifer resistivity in ohmmeters

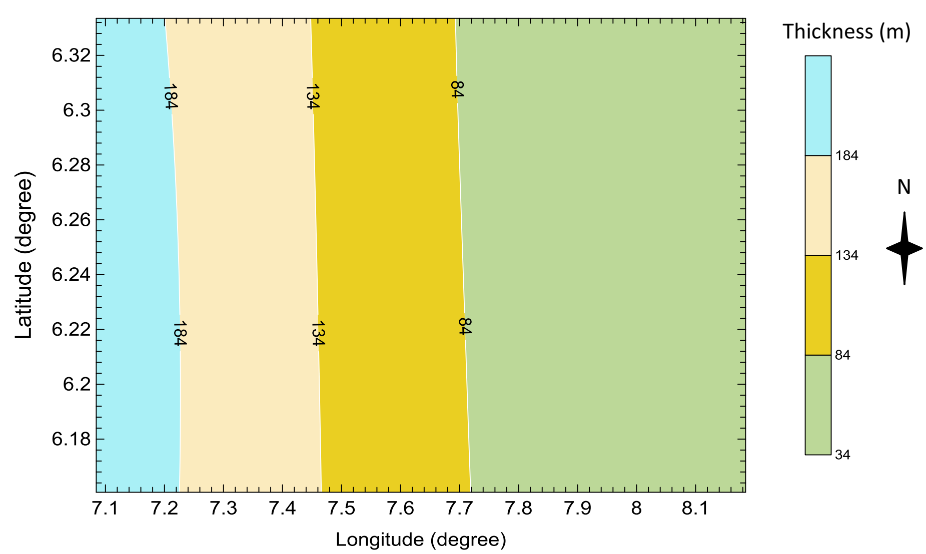


Fig. 4 Isopach contour map showing the variation of thickness in the study area

Fig. 5 Contour map showing the distribution of longitudinal conductance in the study area

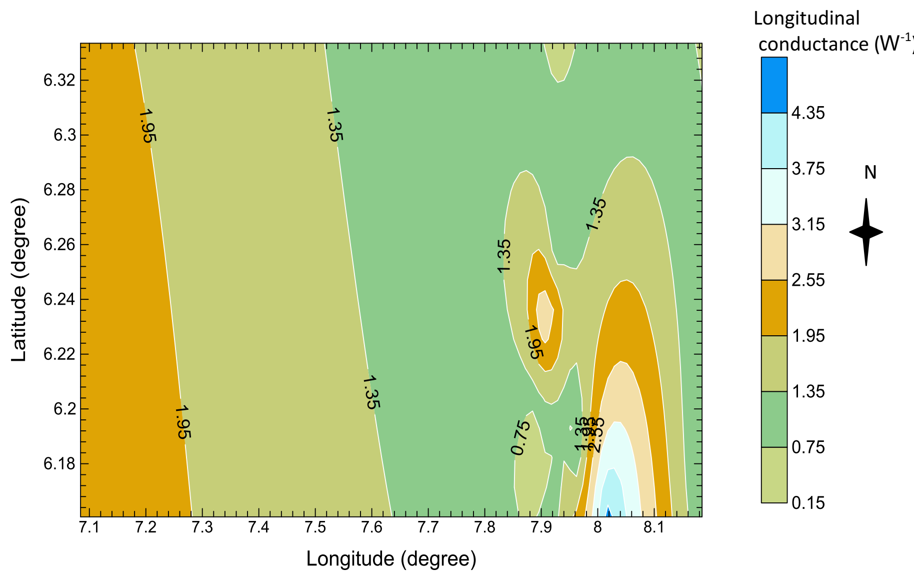


Fig. 6 Contour map showing the distribution of transverse resistance in the study area

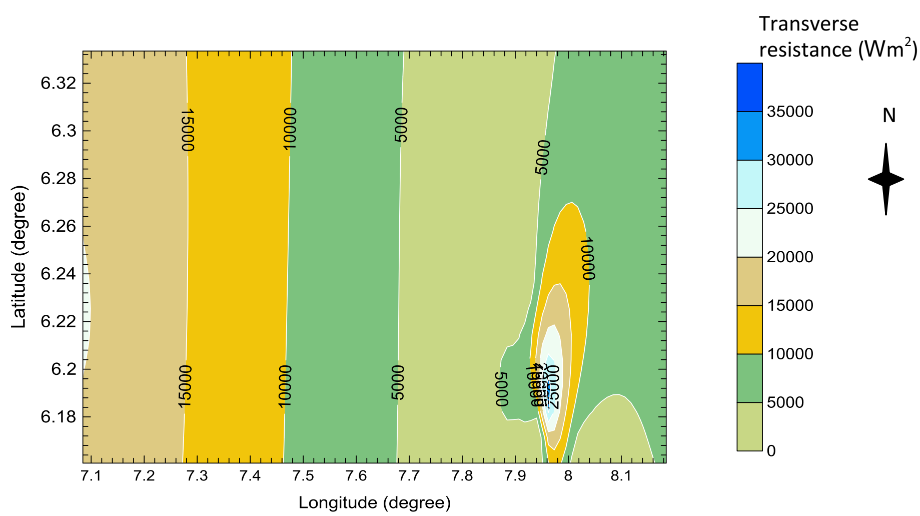
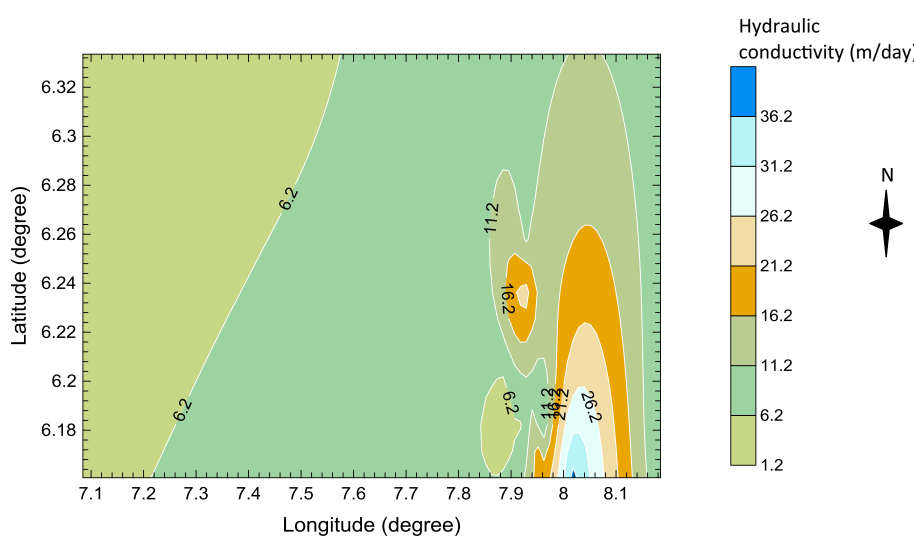


Fig. 7 Map showing the distribution of aquifer hydraulic conductivity



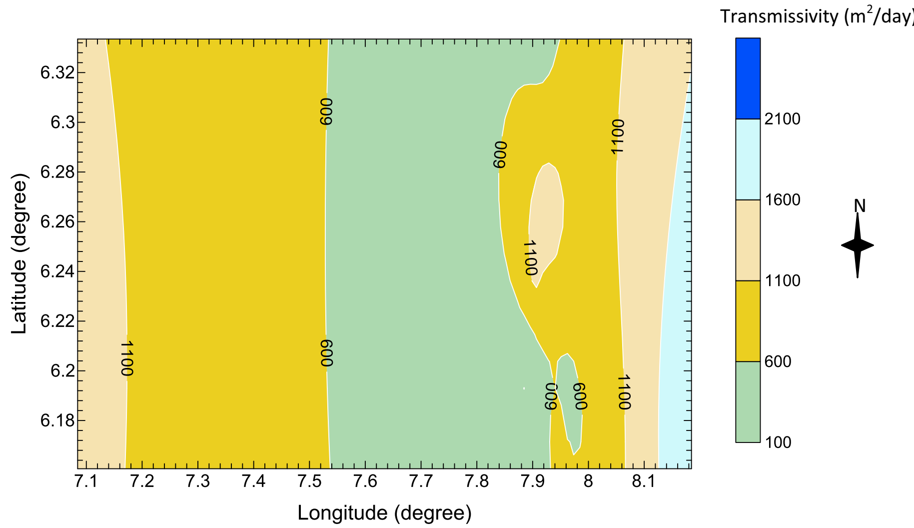


Fig. 8 Contour map showing the distribution of aquifer transmissivity in the study area

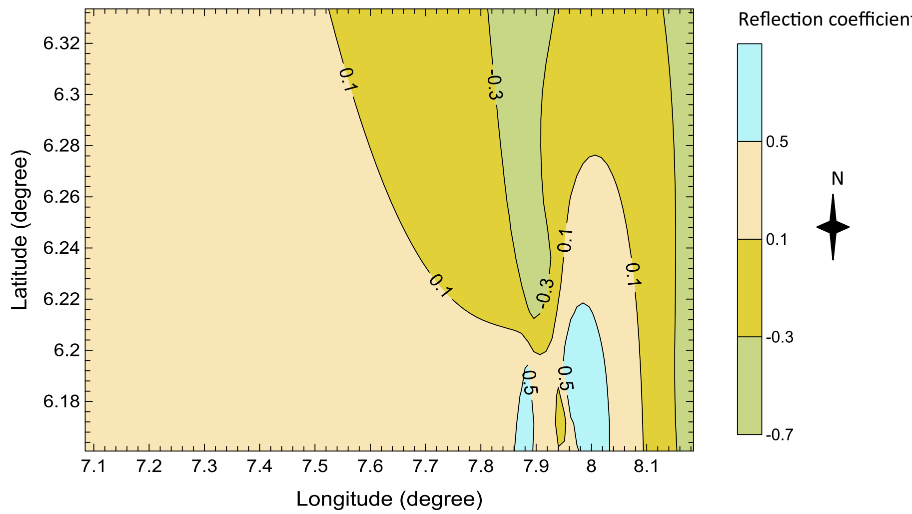


Fig. 9 Map showing the variation in reflection coefficient map

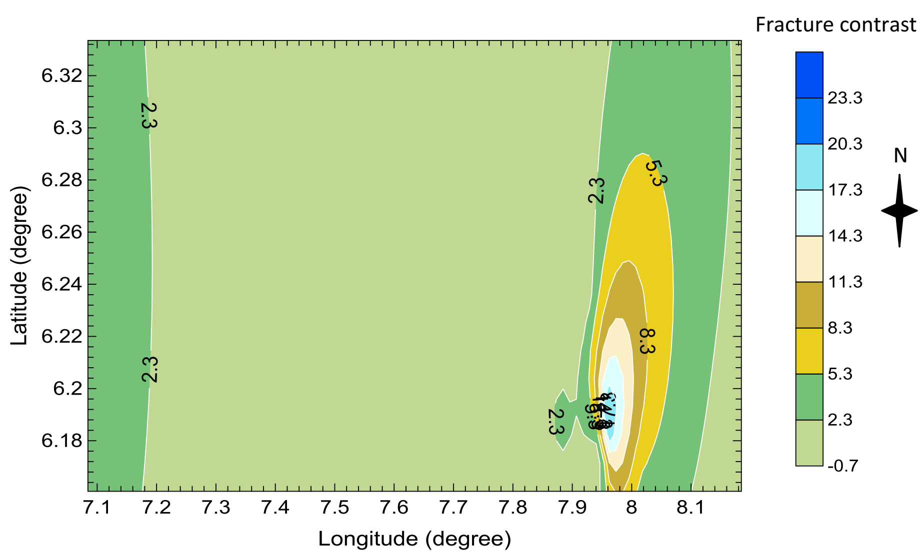


Fig. 10 Map showing the distribution of fracture contrast in the study area

found in between the east and south part of the study area. It can be said that the reflection coefficient value <0.9 and resistivity contrast value <19 may indicate high-density water-filled fractures (Olayinka et al. 2000). Based on the spread of Rc and Fc in Figs. 9 and 10, respectively, the part of the mapped area in between the eastern and western parts of the study area is characterized with high-density water-filled fractures.

Conclusion

In this paper, the electrical resistivity sounding method was used to explore the study area and to evaluate the geo-electrohydraulic parameters. The results provide data on aquifer electrical and hydraulic parameters which included the longitudinal conductance, transverse resistance, hydraulic conductivity, transmissivity, reflection coefficient and fracture contrast. These parameters were used to generate different contour maps. The frequency of curve types indicates that the area is dominated by QQH curve type with 25 and 16.7 % of QHK and QHA, respectively, while the rest have 8.3 % each. The result revealed that areas with high transverse resistance values may give high aquifer yield; the study area has good aquifer protective capacity due to the argillaceous overlying clay materials and also moderate-to-high aquifer potential. The results also show that the shallow aquifers characterized with wide ranges of hydraulic conductivity caused by heterogeneous facies change in the area can be located in the fine-sand facies underlying the clayey formation.

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