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ORIGINAL ARTICLE

Geohydraulic study of aquifer characteristics in parts of Enugu North Local Government Area of Enugu State using electrical resistivity soundings

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Abstract

Geophysical survey employing vertical electrical sounding (VES) was achieved in Enugu State College of Education (Technical). Schlumberger electrode configuration was used in acquiring the data which were interpreted using the WinResist software. Four to five geoelectric layers were delineated from the interpreted results. The hydraulic parameters (hydraulic conductivity, porosity, formation factor, tortuosity and transmissivity) were estimated from the values of resistivity and thickness which are primary geoelectric parameters. The result shows the hydraulic conductivity varying from 2.71 to 70.45 m/day, transmissivity: 49.2288–1127.944 m^2/day, porosity: 33.71–49.44%, formation factor: 0.0014–0.0026 and tortuosity: 0.2667–0.2935. The zones with high and low values of these parameters were delineated. The potentiality of the aquifer units show moderate to high a reflection of the heterogeneity of the subsurface which is affected by the composition and geometry of the formation. The result from this study provides some important conclusions for future groundwater exploration and management.

Keywords Groundwater · VES · Hydraulic conductivity · Transmissivity · Porosity

Introduction

The subsurface characteristics are controlled by soil composition, dissolved ions, thickness and water contents. The increase in population and urbanisation has put a lot of pressure on subsurface structures as well as groundwater repositories. Potable water is a necessity and plays a major role in determining the growth and development of a settlement. Enugu has witnessed an increased in population which has signal an increase in local economy, the inhabitants being farmers, civil servants, students, business men and women. They rely mostly on boreholes as a major renewable freshwater source, thus increasing the demand for potable water supply. In subsurface formations such as sedimentary or crystalline rocks, groundwater exists within the saturated layers of sand, gravel and pore spaces (Agbasi and Etuk 2016). In order to pursue large-scale development of groundwater, it is essential to have a reliable knowledge about groundwater potential and geohydraulic parameters (Singh 1985, 2005; Ibuot et al. 2013, 2019; George et al. 2018). Groundwater yield is affected by the physical and hydrogeologic properties of the aquifer layers. The variation of pore spaces and their connectivity across the subsurface characterises a geologic/hydrogeologic units and greatly influences the movement of groundwater. The porosity and interconnectivity of rocks can change depending on the compaction and cementation factors (George et al. 2017). The deeper parts of an active aquifer (unconfined aquifer) are more saturated due to the gravity which causes the water to flow downward, and the upper level of the saturated layer being the water table.

The quality of groundwater is greatly affected by the amount of contaminants that percolate into the aquifer units through the overlying layers (Obiora et al. 2015; Ibuot et al. 2017). The movement of groundwater pollutants is controlled by the geohydraulic characteristics of the subsurface, which greatly affects the flow dynamics of the aquifer units. Also, the distribution of groundwater elevation in the

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saturated zone determines the direction in which the water will flow.

Environment can be evaluated without interfering with the hydrogeologic system through the use of geophysical studies (Yahaya et al. 2009). The results of these geophysical studies will help in solving the problems of fail boreholes as a result of wildcat drilling, since it will give useful information for characterising the heterogeneity of the subsurface lithology and delineate the aquiferous units. Electrical resistivity method utilising VES has proved to be useful in groundwater study (George et al. 2014; Ibuot et al. 2013; Niwas and Singhal 1981; Soupious et al. 2007) and has been widely used in determining the depth to water table, aquifer geometry and groundwater quality by analysing measured apparent resistivity field data. The applications of indirect and non-invasive geophysical measurement have the potential to predict the distributions of the aquifer geohydraulic parameters more effectively. This study is aimed at stratifying the subsurface and also at determining the distribution of the hydraulic parameters in aquifer repositories through the use of electrical resistivity data.

Location and the geology of the study area

The study area located within the state capital and lies between latitudes 6° 25′ 0″ N and 6° 29′ 0″ N, and longitudes 7° 28′ 0″ and 7° 32′ 0″ (Fig. 1a, b) in Enugu State and geologically located within the Anambra sedimentary basin in the Eastern part of Nigeria. The two climatic seasons that influence the study area are the dry and wet seasons; the dry season starts from November to March, while the wet season starts from April to October. Also found in the study area are the residual hills and dry valleys, which are related to the rock type or geologic formation underlying the area (Stow 2005). The escarpment of Enugu is formed by the Ajali sandstone and the sandstone units of the Mamu Formation (Egesi 2017). Underlying the study area is the Enugu shale with outcrop of Mamu Formation in some areas and is composed of shale and sandstone. The formation is said to be coaliferous and is also fractured; the fractured nature makes it a potential aquifer repository. According to Uzoije et al. (2014), the Ajali aquifer is trapped by the shaley impermeable base of the Mamu formation and the aquifer thickness varies from one location to another separated by thin bands of impermeable clay and shaley sands.

Data acquisition and analysis

Data from seven vertical electrical sounding (VES) points were acquired on the study area using the IGIS resistivity meter employing the Schlumberger electrode array with the half current electrode spacing ($\frac{AB}{2}$) varying between 1.0 and 500 m and half potential electrode spacing ($\frac{MN}{2}$) varying between 0.25 and 20 m. The direction of electrodes spread was chosen to enable a more or less horizontal electrode line in order to avoid topographic effects. Using Eq. (1), the apparent resistivity (ρ_{a}) was determined.

$$\rho_{\mathrm{a}} = \pi \cdot \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right] \cdot R_{\mathrm{a}} \tag{1}$$

where AB is the distance between the two current electrodes, MN is the distance between the potential electrodes and R_{a} is the apparent electrical resistance measured from the equipment. The equation can be simplified to

$$\rho_{\mathrm{a}} = K \cdot R_{\mathrm{a}} \tag{2}$$

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

The Global Positioning System (GPS) was used in measuring the coordinates of the sounding points. In processing the data, apparent resistivity obtained was plotted against $\frac{AB}{2}$ using a bi-logarithm graph and the curves were smoothened and quantitatively interpreted in terms of true resistivity and thickness by a conventional manual curves and auxiliary charts (Orellana and Mooney 1966). The manually interpreted data were improved upon using the WinResist software package to perform automated approximation of the initial resistivity model from the observed data using inversion technique, and the modelled geological curves were obtained (Figs. 2, 3). The interpretation of the resistivity curves was based on the number of layers depicted on the observed curves and models that are geologically reasonable and produce acceptable fit. The geoelectric parameters of different layers are obtained after a number of iterations with minimal RMS error.

To avoid drilling abortive wells, geophysical investigation is imperative because it helps to delineate aquifer (or potential water bearing geological units), while on the other hand, the assessment of the aquifer repositories traditionally determined from parameters obtained from well pump tests and well log data (Singh 2005), which is time-consuming and expensive. A faster and less cost-effective means of determining these parameters involves the estimation of some geohydraulic parameters (hydraulic conductivity, transmissivity, porosity, tortuosity and formation factor) from primary electrical resistivity data (resistivity and thickness) particularly where bore wells are not sufficient or not available (Kelly 1977; Niwas and Singhal 1981; Singh 2005; Dhakate and Singh 2005; George et al. 2015; Ibuot et al. 2019).

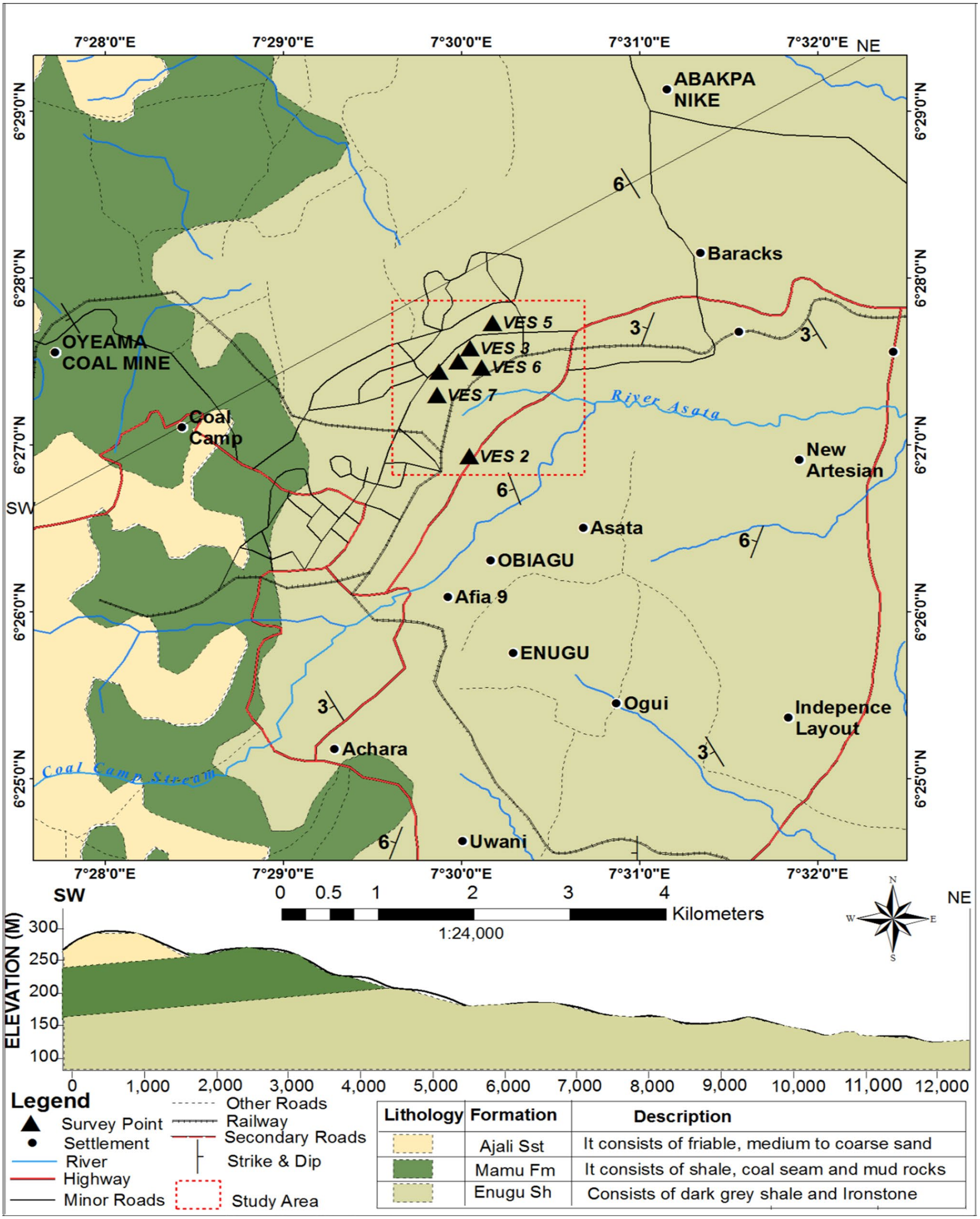
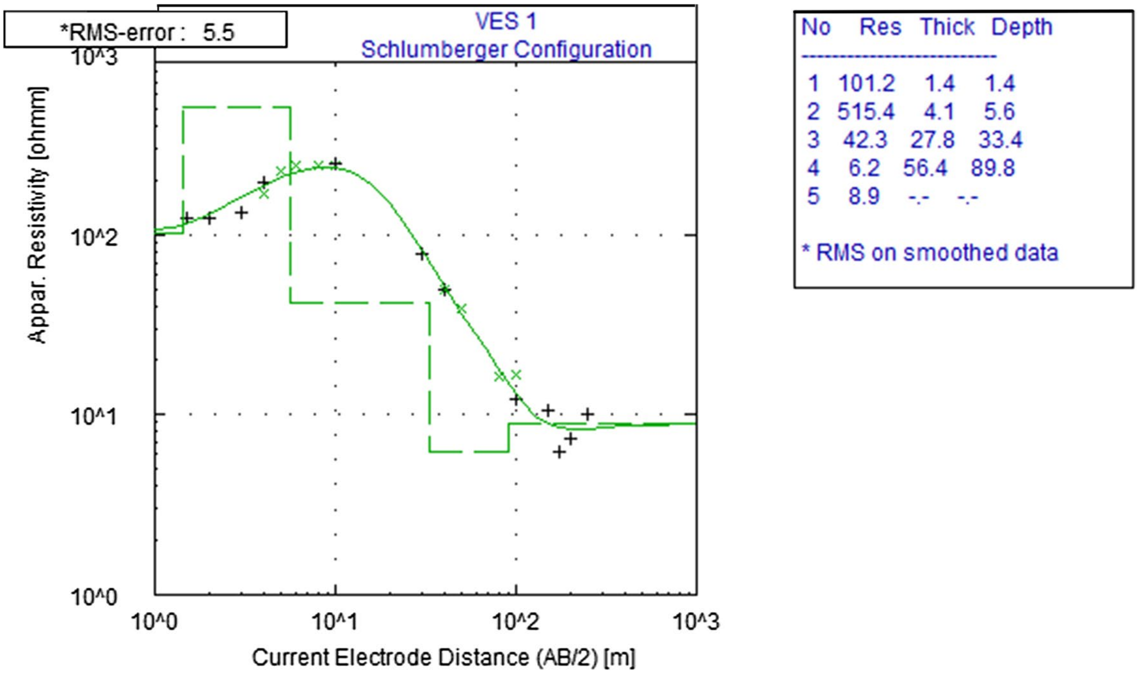


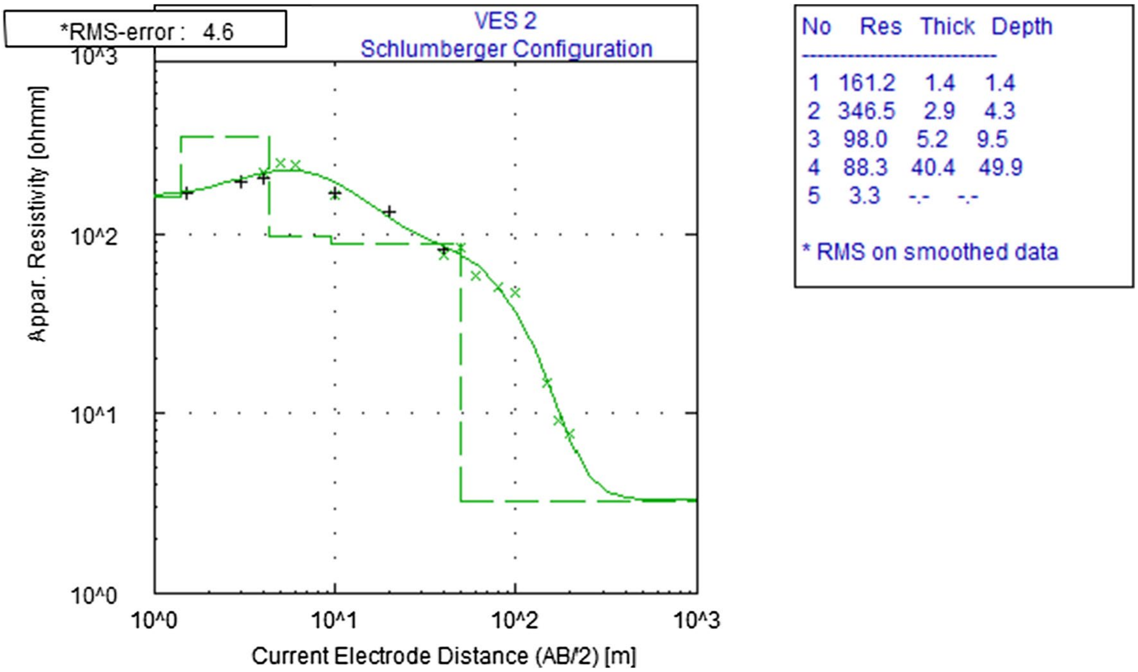
Fig. 1 Geologic map and geologic cross section of Enugu showing the VES points



No	Res	Thick	Depth
1	101.2	1.4	1.4
2	515.4	4.1	5.6
3	42.3	27.8	33.4
4	6.2	56.4	89.8
5	8.9	-.-	-.-

* RMS on smoothed data

Fig. 2 A modelled VES curve at VES 1



No	Res	Thick	Depth
1	161.2	1.4	1.4
2	346.5	2.9	4.3
3	98.0	5.2	9.5
4	88.3	40.4	49.9
5	3.3	-.-	-.-

* RMS on smoothed data

Fig. 3 A modelled VES curve at VES 2

According to Heigold et al. (1979), hydraulic conductivity (K) is related to the bulk resistivity of the aquifer through Eq. (3). This parameter characterises the dynamic behaviour of hydrogeologic unit which allows flow of groundwater and also affects the yield of wells and contaminant spread.

$$K = 386.40R_{rw}^{-.93283} \tag{3}$$

where R_{rw} is the aquifer bulk resistivity which can also be express as ρ_a in Ωm.

And in accordance with Niwas and Singhal (1981), the analytical relationship between aquifer transmissivity (T), hydraulic conductivity (K) and aquifer thickness (h) is given by Eq. (4);

$$T = Kh \tag{4}$$

The hydraulic conductivities were multiplied with the aquifer thickness of interpreted VES stations to determine aquifer transmissivity.

Porosity which describes the volume of pore space in rocks in relation to the total rock volume was estimated using Eq. (5) (Marotz 1968). Its values vary across the subsurface and are affected by grain size distribution and the geometry of the pore space

$$\phi = 25.5 + 4.5 \ln K \tag{5}$$

where K is hydraulic conductivity and ϕ is the porosity.

According to Archie (1942), the formation factor (F) which represents the microscopic property of the subsurface materials can be determined using Eq. (6). This parameter combines some properties such as porosity, pore shape and diagenetic cementation which influence electrical current flow

$$F = a\phi^{-m} \tag{6}$$

where ϕ is the porosity, m is the cementation factor and a is the geometry factor. If electric current flow follows the path of fluid flow through pore space, then the relationship between the formation factor (F) and tortuosity (τ) is given by Eq. (7). This parameter also depends on other factors such as shape of the channels connecting the pores

$$\tau = (F\phi)^{1/2} \tag{7}$$

where ϕ is porosity.

Result and discussion

The interpretation gives the values of resistivity, thickness and depth for each of the electro-stratigraphy layers within the maximum current electrode separation (Table 1). The study area is characterised by heterogeneous lithology with four to five geoelectric layers with resistivity values varying from low to high values. The primary aquifer parameters (resistivity and thickness) are determined from Table 1 and used to estimate the geohydraulic parameters (Table 2). The aquifer layer has resistivity and thickness ranging from 6.2 to 204.2 Ωm and 18.2–56.4 m, respectively. The lithology of this layer can be said to compose of sand intercalated with clay and shale. It can be inferred from the result that this layer is less conductive. Figure 4a shows a geoelectric section showing the variation of resistivities with depths; the numbers within the profile indicate the values of resistivity in Ωm at various depths. The spatial distribution of

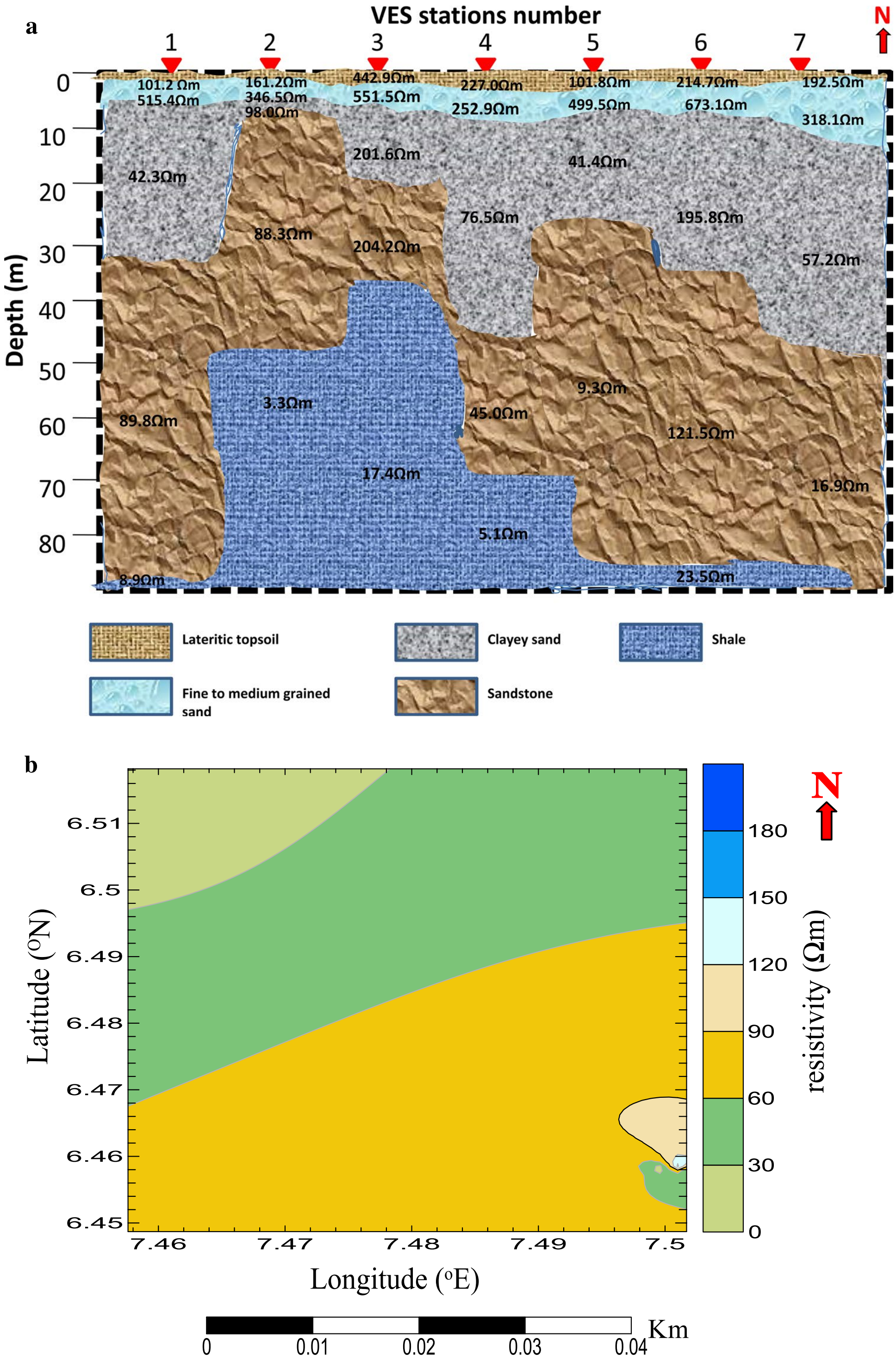
Table 1 Results of geoelectric survey of the study area

VES stations	Longitude (°E)	Latitude (°N)	Elevation (m)	Resistivity (Ωm)					Thickness(m)				Depth (m)			
				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
VES 1	7.4997	6.4583	189	101.2	515.4	42.3	6.2	8.9	1.4	4.1	27.8	56.4	1.4	5.6	33.4	89.8
VES 2	7.5008	6.4487	193	161.2	346.5	98.0	88.3	3.3	1.4	2.9	5.2	40.4	1.4	4.3	9.5	49.9
VES 3	7.5014	6.4585	194	442.9	551.5	201.6	204.2	17.7	1.3	2.9	15.7	18.2	1.3	4.2	19.9	38.1
VES 4	7.4978	6.4573	193	227.0	252.9	76.5	45.0	5.1	1.9	6.3	41.3	18.2	1.9	8.2	49.6	67.8
VES 5	7.4998	6.5182	189	101.8	499.5	41.4	9.3	–	1.5	4.4	23.2	–	1.5	5.9	29.1	–
VES 6	7.5017	6.4583	194	214.7	673.1	195.8	121.9	23.5	1.6	5.3	31.2	49.8	1.6	5.3	36.2	87.6
VES 7	7.4576	6.5076	191	192.5	318.1	57.2	16.9	–	1.5	6.4	40.8	–	1.3	12.6	48.7	–

Table 2 Computed aquifer parameters from measured resistivity and thickness

VES stations	Longitude (°E)	Latitude (°N)	ρ_a (Ωm)	h_a (m)	K (m/day)	Tr (m^2/day)	ϕ (%)	F	τ	Elevation (m)
VES 1	7.4997	6.4583	6.2	56.4	70.45	3973.283	33.71	0.0026	0.2935	189
VES 2	7.5008	6.4487	88.3	40.4	5.91	238.8735	45.66	0.0016	0.2720	193
VES 3	7.5014	6.4585	204.2	18.2	2.71	49.2288	49.44	0.0014	0.2667	194
VES 4	7.4978	6.4573	76.5	41.3	6.76	279.1588	45.02	0.0017	0.2730	193
VES 5	7.4998	6.5182	41.4	23.2	11.99	278.0601	42.26	0.0018	0.2773	189
VES 6	7.5017	6.4583	23.5	49.8	20.33	1012.263	39.71	0.0020	0.2817	194
VES 7	7.4576	6.5076	16.9	40.8	27.65	1127.944	38.22	0.0022	0.2844	191

Fig. 4 **a** Geoelectric section across the VES points, **b** Contour maps showing the variation of aquifer resistivity



the resistivity of the aquifer layer is shown in Fig. 4b; the resistivity values increases from north towards the southern part of the study area.

The hydraulic conductivity (k) estimated from Eq. (3) ranges from 2.71 to 70.45 m/day, and the contour map (Fig. 5) shows the variation across the study area. The low values of *K* observed in some regions may be due to the poor communication channels and geometry of the pore spaces which can affect groundwater flow in the study area (Aleke et al. 2018; George et al. 2018).

The contour map (Fig. 6) shows the variation of aquifer transmissivity with high transmissivity observed at the north-western and south-eastern parts of the study area. The values of this parameter range from 49.2288 to

Fig. 5 Contour map showing the distribution of hydraulic conductivity

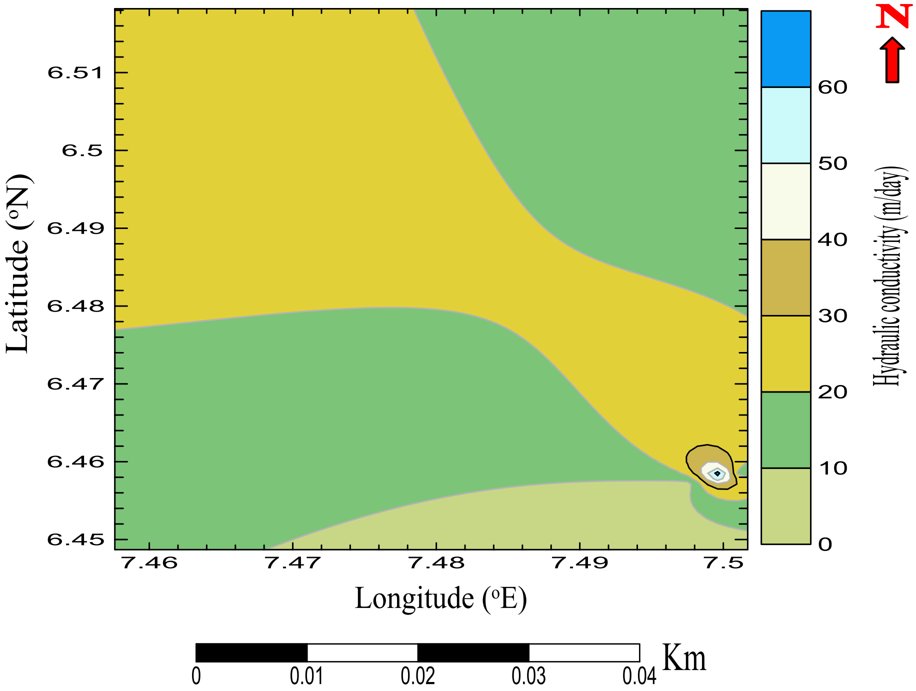
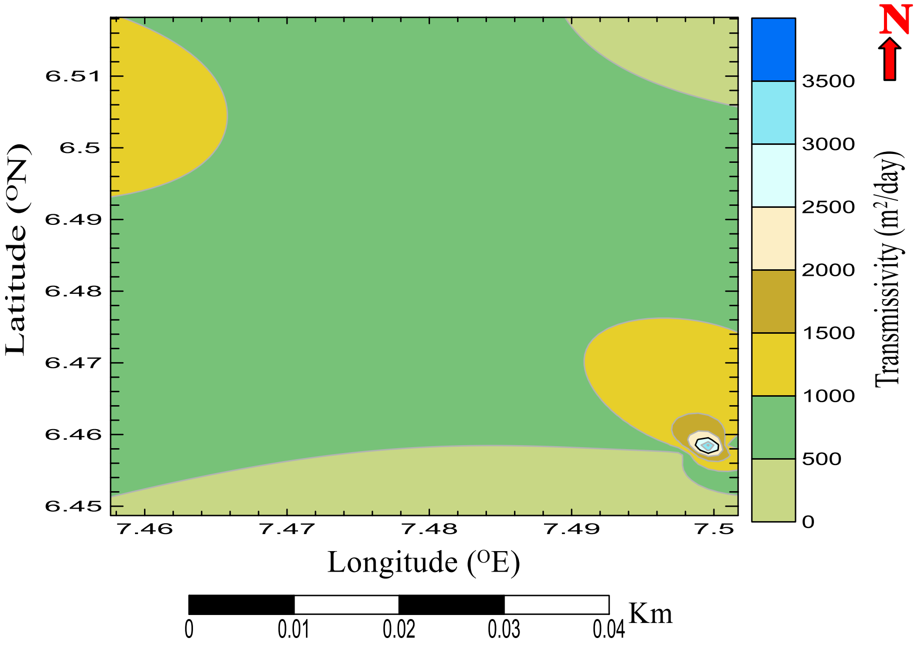


Fig. 6 Contour map showing the distribution of aquifer transmissivity



1127.944 m/day, which according to Offodile 1983 can be classified as having a moderate to high aquifer transmissivity potentiality. It may be delineated that the aquifer units are fractured which may likely contribute to groundwater occurrence. This corresponds to region with high hydraulic conductivity, hence a productive aquifer. The estimated values of porosity range from 33.71 to 49.44%; this indicates that the study area is dominated by consolidated materials like sand, gravel and clay (Roscoe 1990). The contour map (Fig. 7) shows the variation of porosity across the study area.

The formation factor estimated according from Archie's law has values ranging from 0.0014 to 0.0026 and is spatially distributed in the study area (Fig. 8). The low values were observed in the southern part of the study area which is a reverse when compared to the trend of porosity. This reflects the heterogeneity of the subsurface and also the subsurface dynamics which control the storage and transmissibility of

Fig. 7 Contour map showing the distribution of porosity

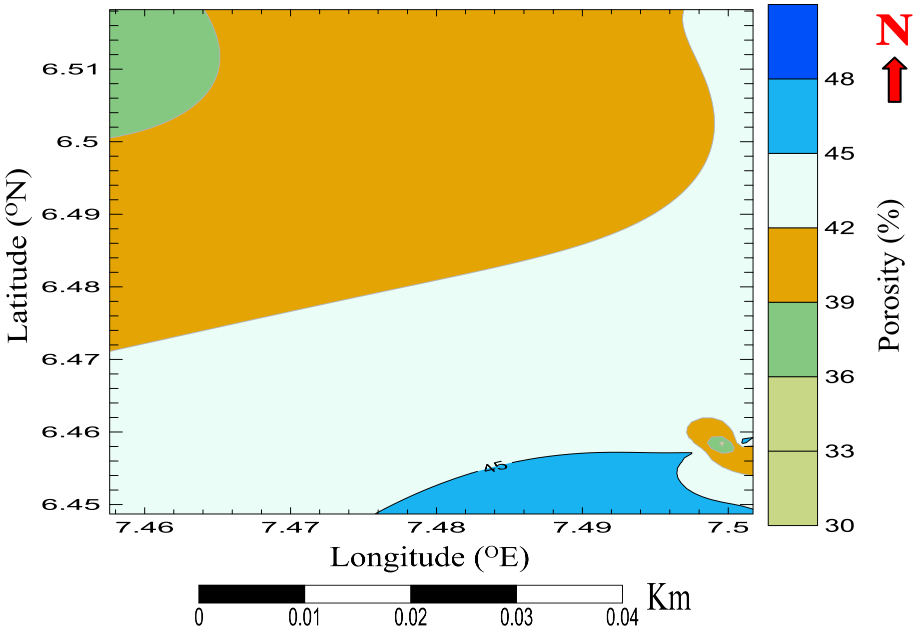
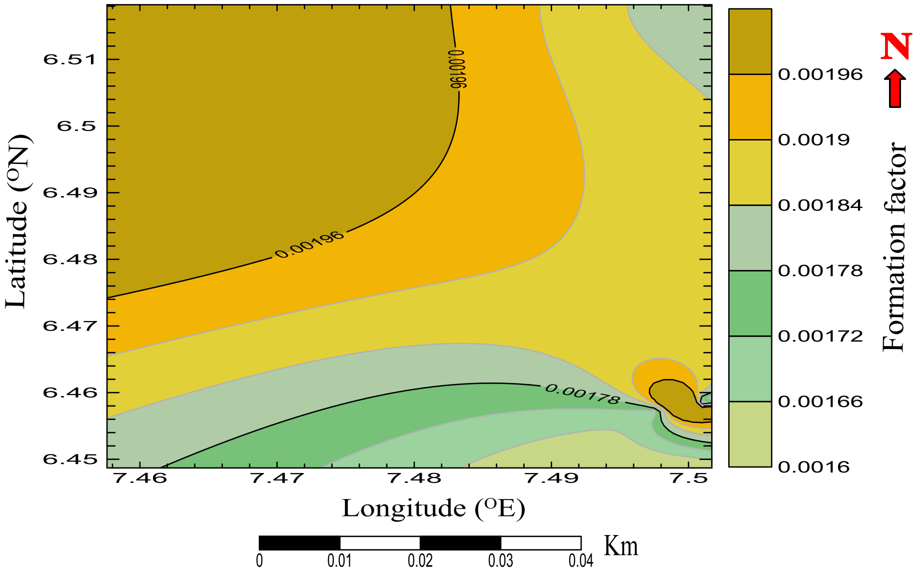


Fig. 8 Contour map showing the distribution of formation factor



the aquifer units. The parameter (tortuosity) which describes the crook path of groundwater flow is estimated from Eq. (7) and ranged from 0.2667 to 0.2935. The contour map (Fig. 9) shows the variation of this parameter across the subsurface with low values observed in the southern part of the study area. This trend shows that an increase in formation factor leads to an increase in tortuosity, and their variations are proportional to each other.

The study area elevation ranges from 189 to 194 m and increases from north to south and corresponds to zone with high resistivity values. This can be used to determine the direction of groundwater flow within the study area (Fig. 10).

Conclusion

The study revealed the subsurface lithology of the study area characterised by four to five geoelectric layers. The subsurface resistivity, thickness and depth values were obtained from the computer modelling software program. The hydraulic parameters were estimated from the primary aquifer geoelectric parameters and evaluated based on the results. The spatial variations of these parameters are displayed from the contour maps generated from the surfer software package. The aquifer layers shows moderate to high groundwater potential and also the influence of grain

Fig. 9 Contour map showing the distribution of tortuosity

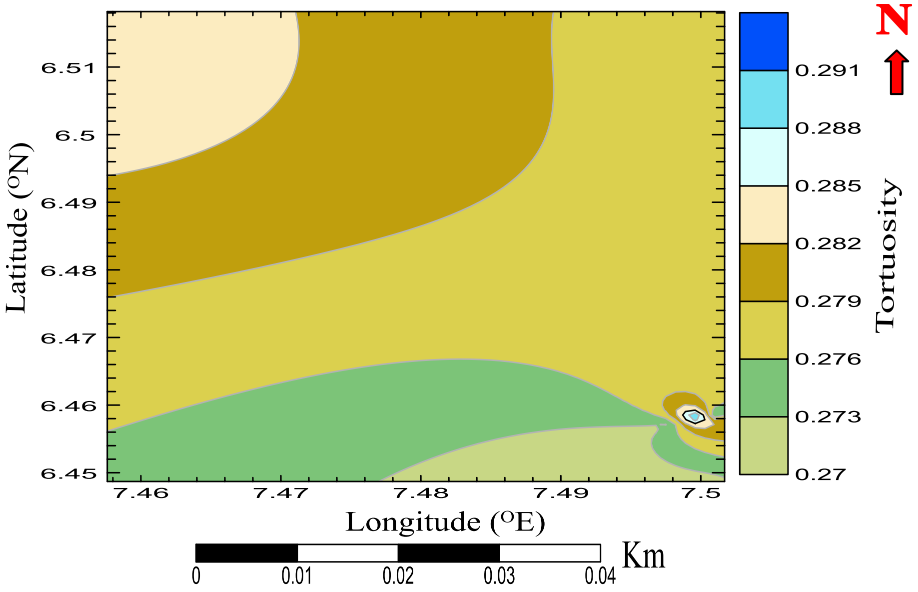
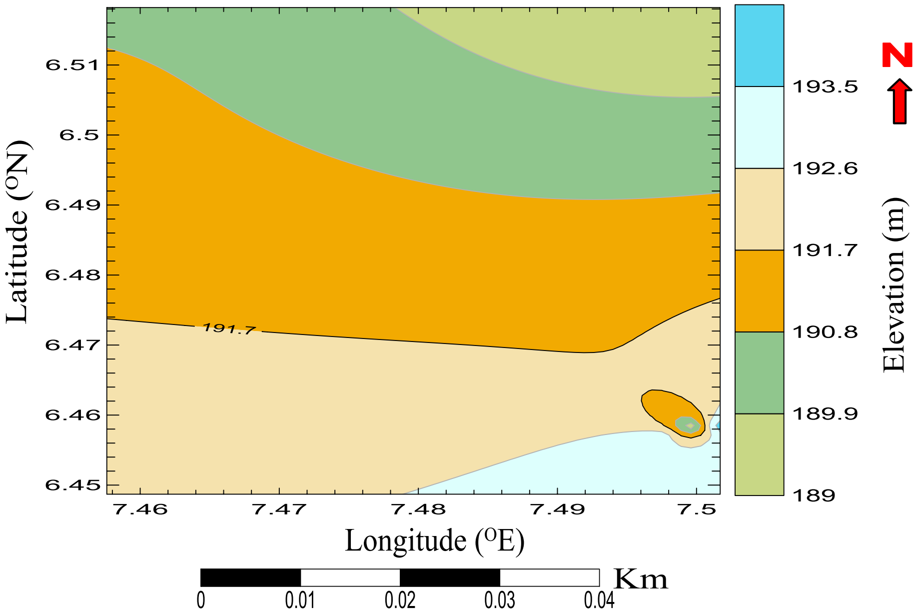


Fig. 10 Contour map showing the distribution of elevation



size distribution and the geometry of pore space. Understanding the dynamics and interactions of groundwater flow in a formation is necessary as it contributes to the solution of groundwater abstraction/exploration. It is very important to know how the different hydraulic parameters influence the aquifer behaviour, characteristics and quality of groundwater. This study emphasises the contribution of geophysical methods in the determination and distribution of hydraulic parameters in aquifer repositories.

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Compliance with ethical standards

Conflict of interest The authors have declared no conflict of interest.

Human or animal rights This article does not contain studies with human or animal subjects.

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