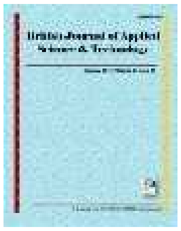

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Delineating Aquifer Systems Using Dar Zarouk Parameters Determined from Surface Geoelectric Survey: Case Study of Okigwe District, Southeastern Nigeria

Leonard I. Nwosu[1*], Cyril N. Nwankwo[1] and Anthony S. Ekine[1]

[1]Department of Physics, University of Port Harcourt, Nigeria.

Authors' contributions

This work was carried out in collaboration between all authors. Author LIN designed the study, wrote the protocol, carried out the field survey, and wrote the first draft of the manuscript and managed literature searches. Authors CNN, ASE managed the literature searches and analyses of the study data. All authors read and approved the final manuscript.

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ABSTRACT

This study is aimed at delineating the aquifer systems in the study area and hence determining the parts with higher aquifer yield. To achieve this, 120 Vertical Electrical Soundings (VES) were carried out in Okigwe District of Imo State of Nigeria, using the Schlumberger electrode array and a maximum electrode spread of 900 m. Twelve of the

**Corresponding author: E-mail: Leowos@yahoo.com, cyrilnn@yahoo.com;*

VES stations were sited near existing boreholes to enhance interpretation. The resistivity of the aquifers zones varied across the study area. The highest thickness of 104.4m for the aquifer was recorded at Amonze (VES 95). Using an average transmissivity of 1032.0848 m^2/day determined from pumping test data of the boreholes in the area, a mean conductance value of 91.222 m/day was obtained for the area. The hydraulic conductivity values obtained from the VES results varied from 9.8854 to 115.9646 m/day. The transmissivity values ranged from 992.04 to 10388m^2/day. The storativity or storage coefficient determined for the area ranged from $1.59x10^{-4}$ to $7.80x10^{-3}$ while the specific capacity was fairly uniform with magnitude of about 877 m^3/day. Using Dar Zarrouk parameters determined for the area, three aquifer systems had been identified viz: the Coastal plain sands aquifer, the Bende-Ameki sandstone/shale aquifer and the Ajali sandstone aquifer. The coastal plain sands aquifer serves the Southern part of Isiala Mbano, Ehime Mbano, Ihitte Uboma and the entire Obowo Local Government Areas (LGAs). The Bende-Ameki sandstone aquifer serves part of Ihitte Uboma, the Northern part of Ehime Mbano and Isiala Mbano. The Ajali sandstone aquifer serves the Northwestern part of the study area in Okigwe. Groundwater potential evaluation of the district based on the survey and borehole hydrogeological information revealed that the Southern part of the district is the most prolific in terms of groundwater exploitation and thus the most promising for siting productive boreholes.

Keywords: Hydraulic conductivity; aquifer systems; aquiferous zones; Dar Zarouk; VES.

1. INTRODUCTION

Okigwe District is in Imo State of Nigeria. The area lies between Latitudes 5º30′N and 5º57′N of the Equator and Longitudes 7º04′E and 7º26′E of the Greenwich Meridian (Fig. 1) covering an area of about 1824 km^2. The district is made up of six LGAs namely, Isiala Mbano, Ihitte Uboma, Ehime Mbano, Onuimo, Obowo and Okigwe. Scarcity of potable water in both the rural and urban areas of Okigwe District especially during the dry season has become a problem to the citizens of the area. Governments' intervention of siting the Okigwe regional water scheme in Onuimo LGA has not yielded the desired results of making potable water from the Imo River readily available largely due to pollution and paucity of funds for extensive project execution [1].

Many failed boreholes projects exist in many parts of the district. This borehole failures in places like Ihube, Okigwe and Anara have resulted from the nature of the geological setting of the area especially in the northern part and inadequate or lack of geophysical information to guide during the drilling phase. Hence proper geophysical investigation of the area is required as the area is fast experiencing increase in commercial and industrial activities owing to rapid urbanization. This study is aimed at mapping the aquifer systems in an environment that has high borehole failure rate. This will help in generating information that will aid borehole developers in the successful drilling of water boreholes.

Electrical resistivity of rocks is a variable property that depends on a number of factors including the resistivity of the pore electrolyte and is inversely related to the porosity and degree of saturation of the formation [2]. The resistivity of rock layers vary considerably from formation to formation as well as within a particular layer [2]. This variation can be very wide for any particular layer. (Table 1) gives approximate ranges of the electrical resistivity of rocks and soils, which was used in the interpretation of VES data in this work.

Dar Zarouk parameters derived from layer resistivity and thickness of a geoelectric layer generated from the modeling of VES data has proved to be useful in understanding the spatial distribution of aquifer hydraulic parameters [3,4] derived analytically the relationship between aquifer transmissivity and transverse resistance, and that between transmissivity and longitudinal conductance. The results of their study showed that in areas where the geologic setting and water quality do not vary greatly, the product of hydraulic conductivity K and aquifer conductivity σ, (Kσ), will remain fairly constant. Thus if the value of K is known from the existing boreholes and the σ, from the sounding interpretation around the boreholes are available, it is possible to estimate the transmissivity and its spatial variation by determining the transverse resistance longitudinal conductance for the aquifer. This is the basis of this geophysical survey.

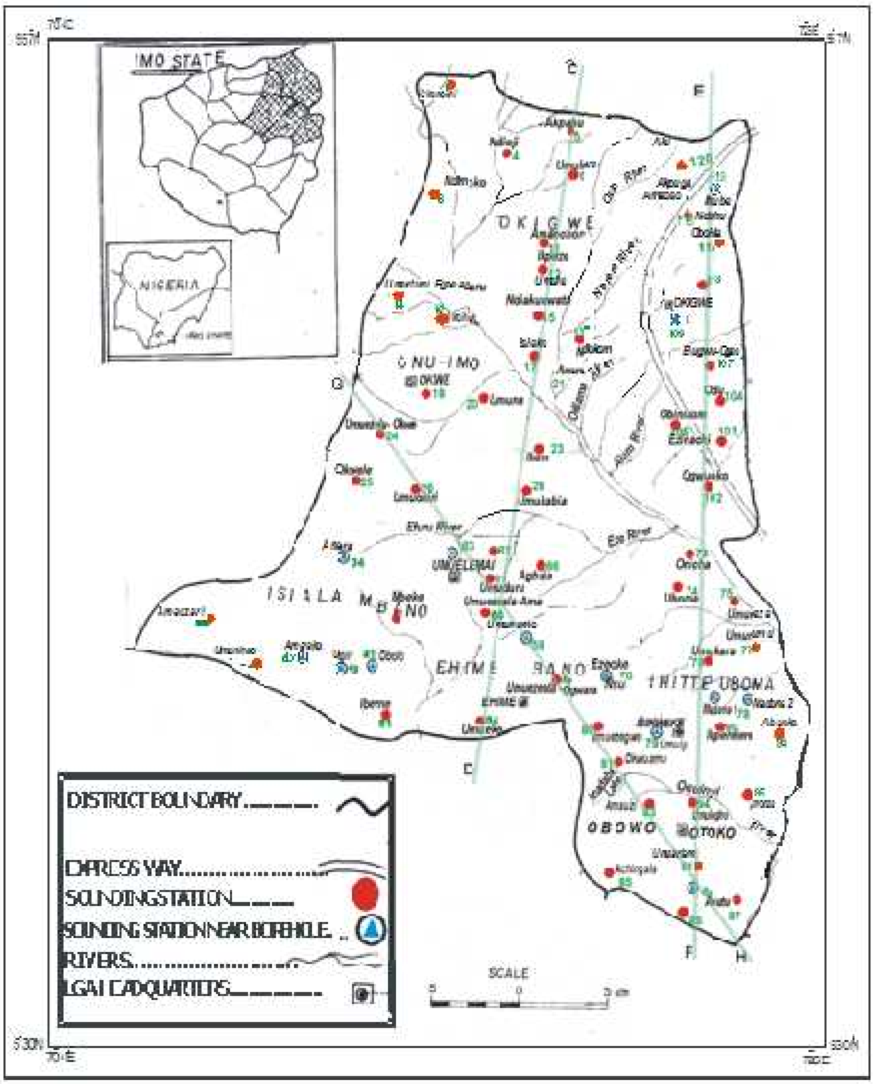
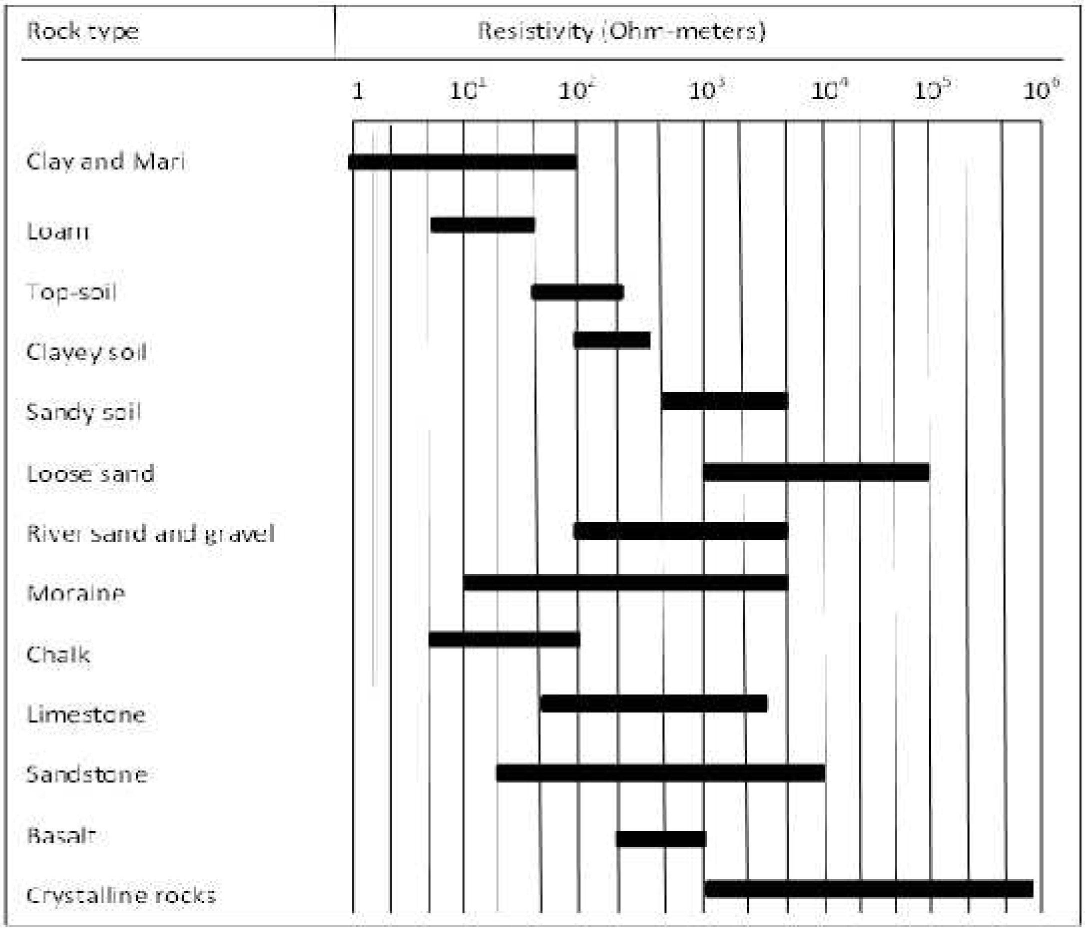


Fig. 1. Map of study area showing some of the sounding stations and interpretative geoelectric cross-section (IGCS) traverse

Table 1. Approximate ranges for the electric resistivity of rocks and soils [5]



1.1 Geology of the Study Area

A review of the geology of the district (Fig. 2) reveals the following stratigraphic units; the Benin Formation, the Ogwashi - Asaba Formation, the Bende - Ameki Formation, Imo Shale Formation, Nsukka Formation and Ajali Formation [6].

The Benin Formation is overlain by lateritic overburden and underlain by the Ogwashi - Asaba Formation, which is in turn underlain by the Ameki Formation of Eocene to Oligocene age [7]. The Benin Formation consists of coarse - grained gravelly sandstones with minor intercalations of shales and clay. The sand units are mostly coarse to fine grained, pebbly and poorly sorted [8,9]. The southern part of the study area covering Obowo, southern part of Ehime Mbano and Isiala Mbano fall within this formation. The Ogwashi - Asaba Formation is made up of variable succession of clays, sands and grits with seams of lignite. It also forms part of the study area. The Bende-Ameki Formation consists of greenish - grey clayey sandstones, shales and mudstones with interbedded limestones. This Formation in turn overlies the impervious Imo Shale Group.

The Ajali Formation consists of thick friable, poorly sorted sandstones typically white in colour but sometimes iron- stained. A marked banding of coarse and fine layer is displayed [10]. The Ajali Formation is often overlain by a considerable thickness of red earth, which consists of red, earthy sands formed by the weathering and ferruginisation of the formation [10].

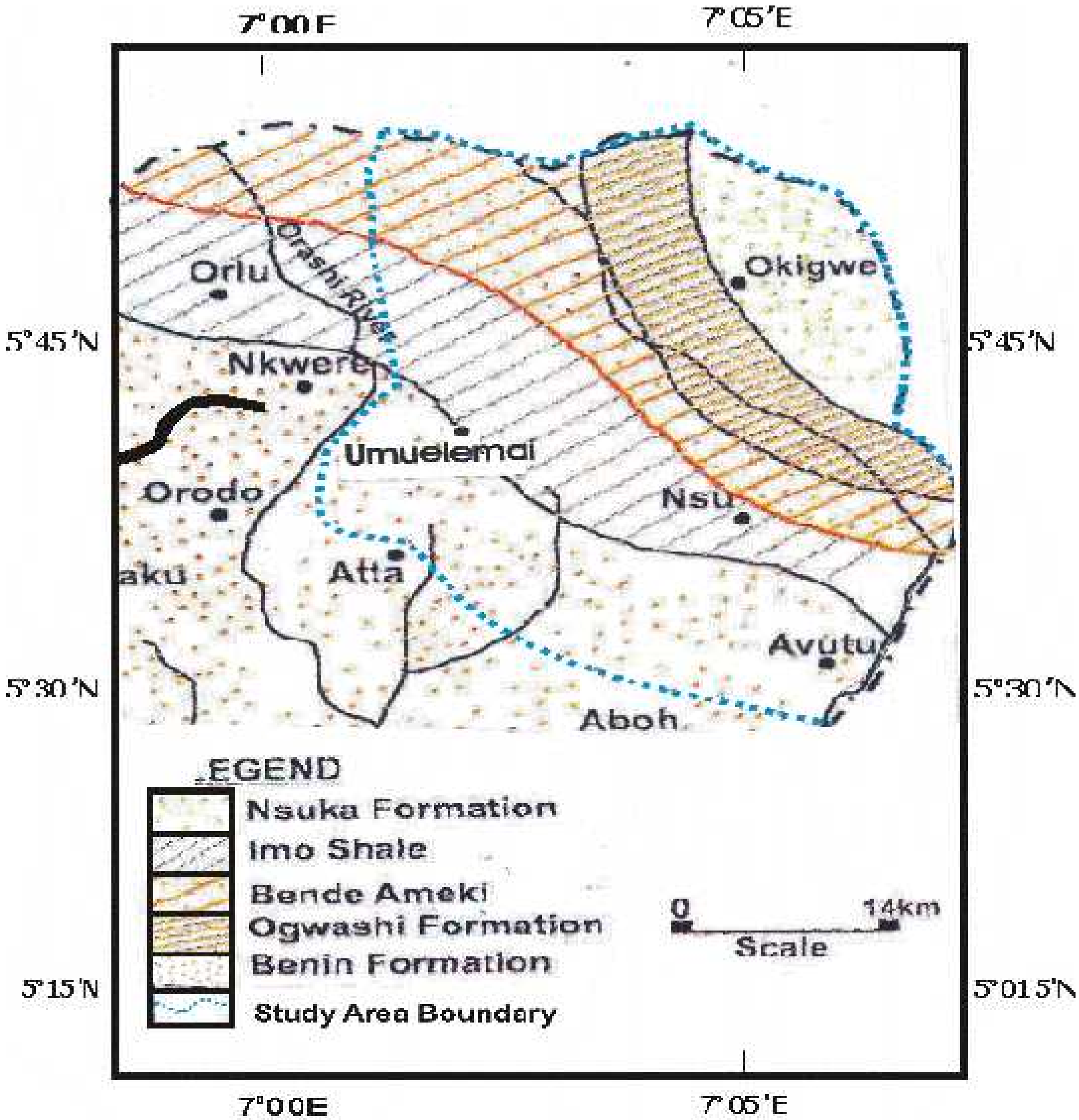


Fig. 2. Geological map of parts of Imo state showing the study area (ADAPTED from [6])

1.2 Theoretical Bases of the Study

Using the Logan's approximation of Theim's equation [11], aquifer parameters from pumping test data can be determined for steady state as follows:

$$Q=\frac{2\pi S_{mw}Kh}{2.3\log\frac{r_{max}}{r_w}} \quad (1)$$

where

Q = well discharge in m^3 / day, K = average hydraulic conductivity in m / day,
h = thickness of the aquifer in m, S_{mw} = maximum drawdown in the pumped well in m,
r_w = radius of the pumped well in m and r_{max} = radius of influence of the pumping in m

The area circumscribed by r_{max} is the area in the borehole environment that contributes water to the well. Equation (1) was modified by [11] for steady state flow in confined aquifer as

$$Kh = \frac{2.3Q\log\frac{r_{max}}{rw}}{2\pi S_{mw}} \quad (2)$$

And since the logarithm of the ratio of r_{max} to r_w is very small, assuming average condition of radii, r_{max} = 500 m, r_w= 0.3048 m, then

$$\log\frac{r_{max}}{r_w} = 3.21$$

The equation further reduces to

$$Kh = \frac{1.18Q}{S_{mw}} \quad 3$$

$$\therefore K = \frac{1.18Q}{hS_{mw}} \quad 4$$

(Table 3) shows the pumping test data obtained for some boreholes in the study area. Computation of the aquifer parameters using equations 1 to 4 gave the values displayed in (Table 2) for parameters 1 to 6.

Dar Zarouk parameters are derived by considering a column of unit square cross-sectional area cut out of group of layers of infinite extent. The total transverse unit resistance R, and total longitudinal unit conductance S, are respectively given as:

$$R = \sum_{i=1}^{n}\rho_i h_i \qquad i = 1,2,3,....n \quad (5)$$

The total longitudinal unit conductance,

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \qquad i = 1,2,3,...n. \tag{6}$$

where ρ_i and h_i are the resistivity and thickness of the *ith* layer. The parameters R and S are called the Dar Zarouk parameters.

The average longitudinal resistivity is

$$\rho_l = \frac{H}{S} \tag{7}$$

where

$$H = \sum_{i=1}^{n} h_i \quad i = 1,2,3,...n \tag{8}$$

and the average transverse resistivity

$$\rho_t = \frac{R}{H} \tag{9}$$

Transmissivity, T_{ri}, used in groundwater hydrology [7], is given by

$$T_{ri} = K_i h_i \tag{10}$$

where Ki is the hydraulic conductivity of the ith layer of thickness hi.

The relationship between aquifer transmissivity, T_r and transverse resistance, R and that between T_r and S have been derived analytically by [4] as

$$T_r = K\sigma R = KS/\sigma \tag{11}$$

Thus, it is possible to estimate the transmissivity and its spatial variation from values of R and S of the aquifer.

Parameters 7 to 15 of (Table 3) were determined using equations 4 to 11. Notice the close agreement between parameters 2 and 15 for Madonna 2 Ihitte Uboma.

Table 2. Existing borehole/pumping test data converted values

S/no	Location	Drill depth (m)	Casing diameter (m)	Screen diameter (m)	Casing depth (m)	Screen length (m)	Swl (m)	Draw down (m)	Yield (m^3/day)
1	Avutu No. 2 BH	170.7	0.34	0.20	146.3	21.3	53.0	10.7	4364.25
2	Anara 1	73.2	0.30	0.20	54.9	15.2	52.4	Abortive	218.21
3	Umunumo 1	73.2	0.30	0.20	54.9	15.2	23.8	28.7	618.99
4	Umunumo 2	79.3	0.30	0.20	67.1	9.2	21.6	27.1	392.78
5	Amaraku 1	99.4	0.20	0.15	76.2	1.5	31.1	-	-
	Amaraku 2	118.9	0.30	0.25	83.5	6.1	74.4	1.8	1091.06
6	Madonna 1 Ihitte Uboma	128.0	0.34	0.25	97.5	30.5	95.1	6.3	654.64
7	Madonna 2 Ihitte Uboma	182.9	0.34	0.25	151.8	22.0	93.3	6.4	2518.55
8	Nsu	143.3	0.20	0.15	125.6	17.7	35.3	Collapsed	781.96
9	Ugiri	121.9	0.25	0.20	103.6	15.2	71.3	6.1	1745.70
10	Mbano	91.4	0.13	0.12	73.8	6.1	46.0	20.1	78.56
11	Mbano Hospital	85.6	0.25	0.15	78.9	9.8	44.8	3.7	1854.80
12	Umuelemai	140.2	0.30	0.20	121.9	15.2	30.9	3.8	5237.10
13	Isinweke L.G.A.	155.5	0.30	0.20	121.9	12.2	87.6	2.0	8292.07
14	Okigwe	94.5	0.17	0.13	85.3	5.4	23.2	-	327.32

Source: Imo State Water Board Owerri Imo State

Table 3. Aquifer characteristics calculated for some boreholes located in the study area

S/no	Parameters	Avutu Bh	Anara Bh	Umunumo 2 Bh	Amaraku 2 Bh	Madona 2 Ihitte/ Uboma Bh	Nsu Bh	Ugiri Bh	Mbano Hosp. Umuelemai Bh	Isinweke Bh	Okigwe Bh
1	Screen length (m)	21.34	15.24	15.24	5.10	21.95	17.68	15.24	9.75	0.18	5.39
2	Average filled hydraulic conductivity k (m/day)	22.70	-	1.6729	115.3321	21.9952	-	22.158	61.333	393.463	-
3	Transmissivity (m^2/day)	483.51	-	25.4950	703.5285	482.7946	-	136.272	597.997	4792.314	-
4	Storativity	0.000257	-	0.000210	0.000375	0.000226	-	0.000073	0.000319	0.02588	-
5	Specific storage	0.000012	-	0.000014	0.000061	0.000010	-	0.000005	0.000033	0.000210	-
6	Specific capacity (m^3/day)	409.8634	-	21.6707	577.997	410.3754	-	287.035	508.297	4076.867	-
7	Resisstivity of aquifer (Ωm)	5810	13400	12500	15000	16200	2430	6080	14800	4368	13950
8	Aquifer thickness h (m)	24.80	18.20	16.00	35.50	38.20	23.6	24.50	71.70	18.40	16.40
9	Conductivity σ ($\Omega^{-1}m^{-1}$)	0.000172	0.000075	0.000079	0.000067	0.000062	0.00412	0.000164	0.000068	0.000229	0.000072
10	Longitudinal conductance S	0.0043	0.0014	0.0013	0.0024	0.0024	0.0097	0.0040	0.0048	0.0042	0.0012
11	Transverse resistance R	144088	243880	201600	532500	618840	57348	148960	1061160	80371.20	228780
12	Kσ value	0.00716	0.0045	0.005095	0.001948	0.001675	0.018018	0.006909	0.000979	0.012845	0.004531
13	K/σ value	241918.6	756000	816522.8	433907.5	435,772.6	106,146.6	619,498.5	211,683.8	244,611.4	874,055.6
14	Transmissivity of aquifer zone Tr (m^2/day)	1031.67	1037.10	1027.337	1037.245	1036.625	1033.282	1029.112	1038.691	1032.366	1036.626
15	Hydraulic conductivity	41.61	56.70	64.5053	29.0728	27.0179	43.7324	42.1259	14.3945	56.0916	62.9320

2. MATERIALS AND METHODS

A total of 120 VESs were carried out in the study area using the Schlumberger electrode configuration with a maximum electrode spacing of 900 m in some occupied stations. The ABEM Terrameter (SAS) 300B was used to acquire the data. It has a liquid crystal digital read-out and an automatic signal averaging microprocessor. Four stainless steel electrodes made up of two current and two potential electrodes were used. A 12V dc source was used to power the instrument.

The current electrode spacing was increased symmetrically about the centre, keeping the potential electrode constant until it became necessary to increase the potential electrode spacing as the strength of the recorded signal diminished. The apparent resistivity values computed were plotted against half of the current electrode spacing (L/2) on a log-log graph (Fig. 3 (i)). The sounding curves obtained were subjected to conventional partial curve matching using the [12] master curves to obtain the initial model parameters (resistivities and thicknesses) for computer aided interpretation. The field measurements were inverted using the Schlumberger automatic analysis version 0.92 software package [13] to determine the true resistivities and depths of subsurface formations. The resulting model curves have three to five interpretable geoelectric layers with less than 5% RMS errors.

3. RESULTS AND DISCUSSION

The survey revealed that the study area is multi-layered exhibiting variation in resistivity with depth. The geoelectric section compares favourably with the borehole lithology and the resistivity model gave the resistivity of the probable aquifer, the depth to aquifer and the aquifer thickness. (Figs. 3, 4 and 5) show typical modelled VES curves, the geoelectric section and borehole lithology of VES 79 near Isinweke borehole in Ihitte Uboma LGA; VES 32 near Anara borehole and VES 110 near Okigwe borehole respectively.

The interpretative geoelectric cross-sections (IGCSs) constructed for the area along profiles CD, EF and GH (Fig. 1) reveal that there are variations in resistivity and thickness of the aquifers zones across the entire study area. The top layers generally show large variations in layer resistivity. These layers correspond to the brown to reddish lateritic overburden interspersed with sandy soils, sandy clay with humus. The aquifers consist of fine to medium coarse sands, sandstones and sandy shales. They are thicker in the southern part of the study area. The aquifers layer is underlain by conductive layer composed of clay-sand/lignite and shale. The geoelectric sections CD, EF and GH (Figs. 6, 7 and 8) indicate that the main aquifers are confined in some parts of the traverses. The Northeastern part and the South-South area indicate prospective area for siting water boreholes with high yield expectations. Similar observation is recorded by profile GH in the Southern and South-South zone with high aquifer thickness [14,15].

(Table 3) compares aquifer characteristics determined from pumping test data with those calculated on the basis of VES data. Parameters 1 to 6 were determined from pumping test data while parameters 7 to 15 were computed from VES results. The computation was based on the screened sections of the aquifer in the borehole. The hydraulic properties of the aquifers horizon determined for VES stations 61 to 80 are displayed in (Table 4). The (Table 4) shows variation in transmissivity and storativity values as well as other hydraulic properties of the aquifer.

The hydraulic conductivity values obtained from the VES results varied from 9.89 to 115.96 m/day. The storativity values determined for the area varied from 1.59×10^{-4} to 7.80×10^{-3} while the specific capacity is fairly uniform with a maximum value 877 m^3/day. The transmissivity value of 992.04 m^2/day was observed in the Northern part of the study area. The value increased towards the southern part with corresponding higher values of aquifer thickness and storage coefficient.

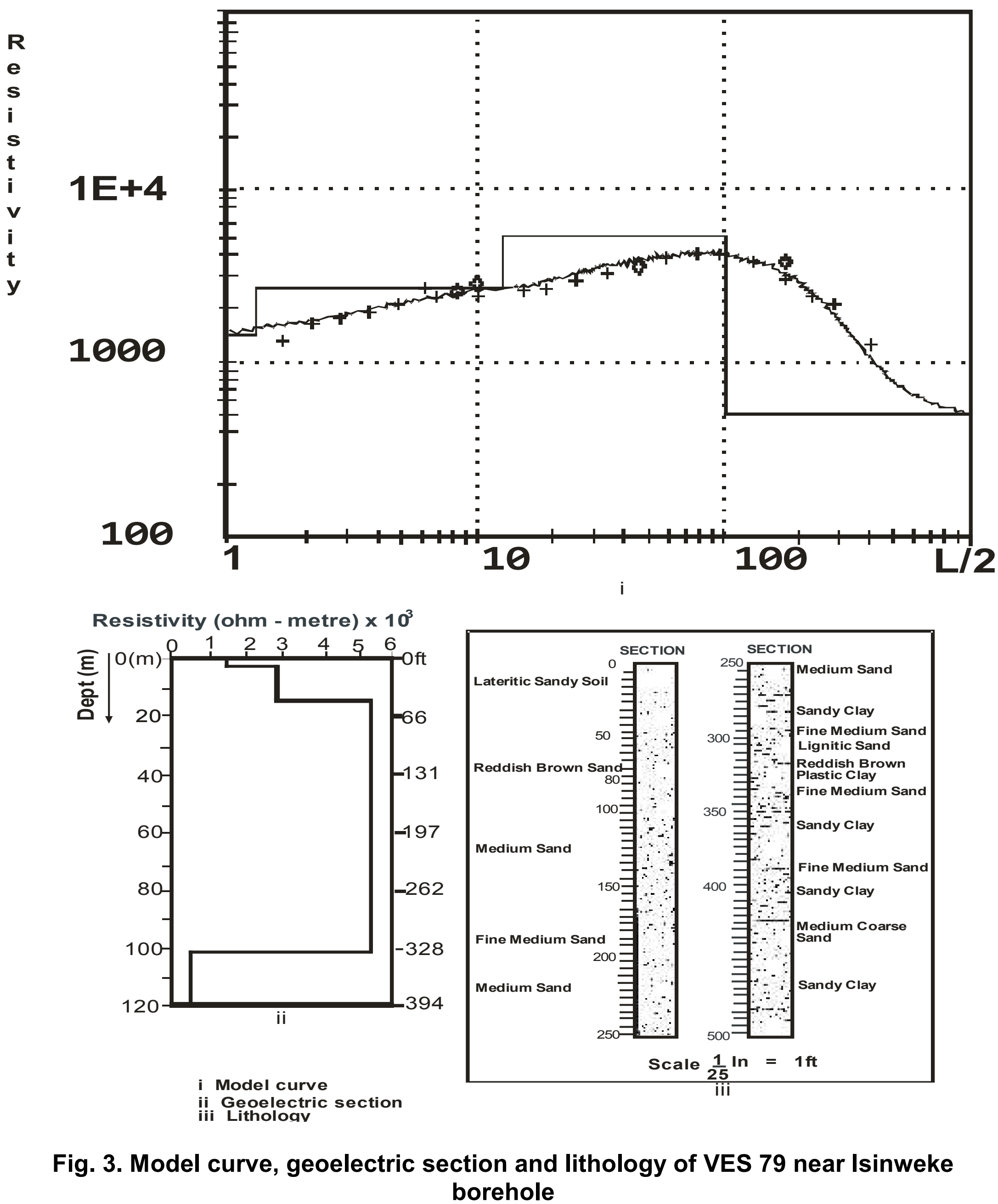


Fig. 3. Model curve, geoelectric section and lithology of VES 79 near Isinweke borehole

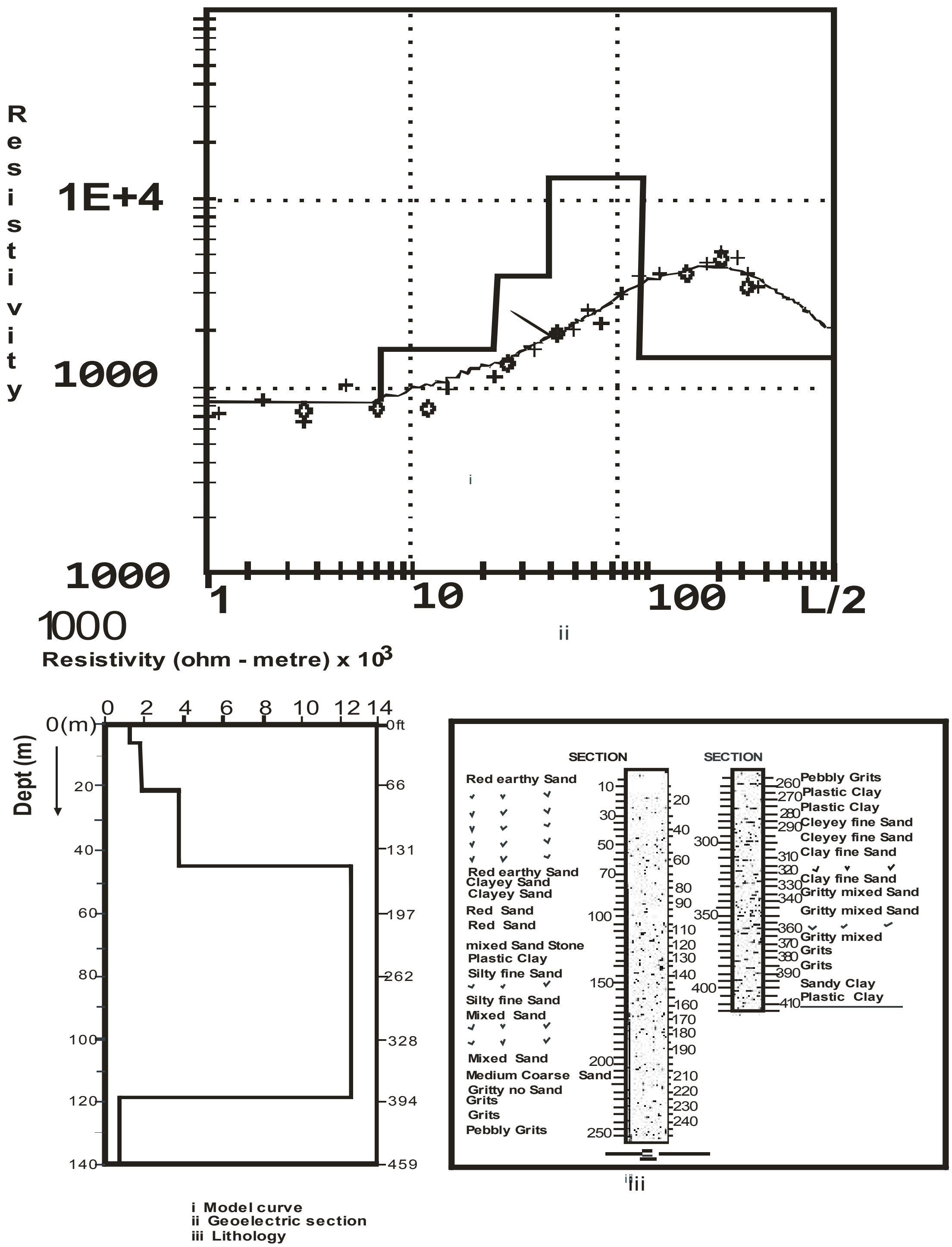


Fig. 4. Model curve, geoelectric section and lithology of VES 32 near anara borehole

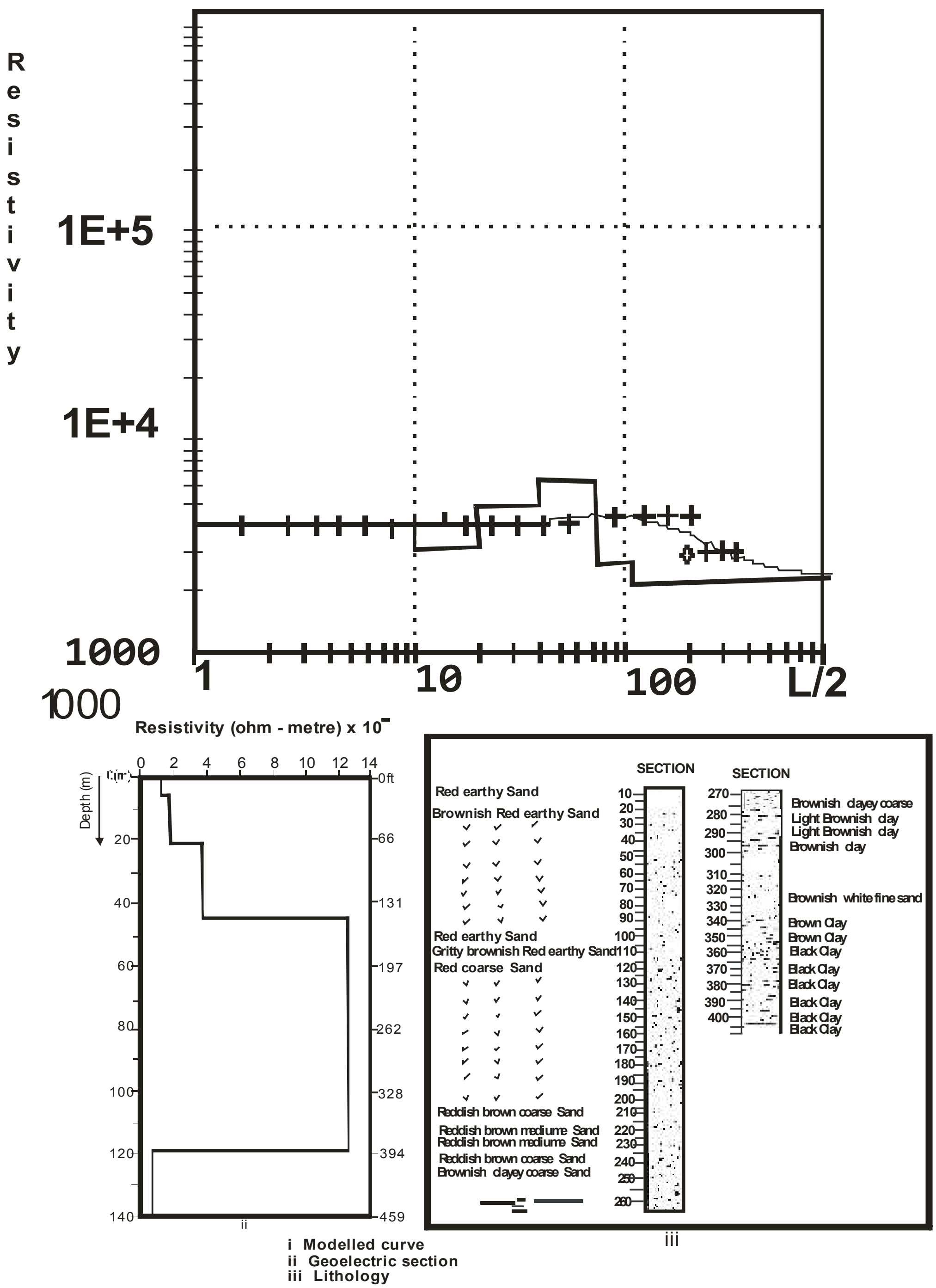


Fig. 5. Model curve, geoelectric section and lithology of VES 110 near anara okigwe borehole

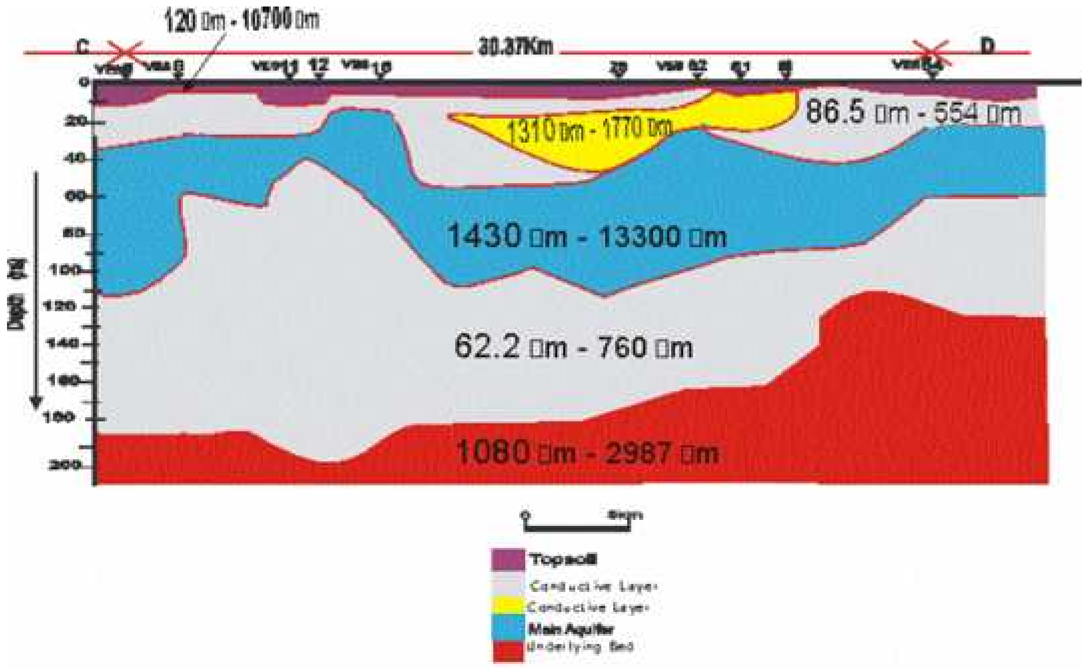


Fig. 6. Interpretative geoelectric cross-section (IGCS) along profile line CD

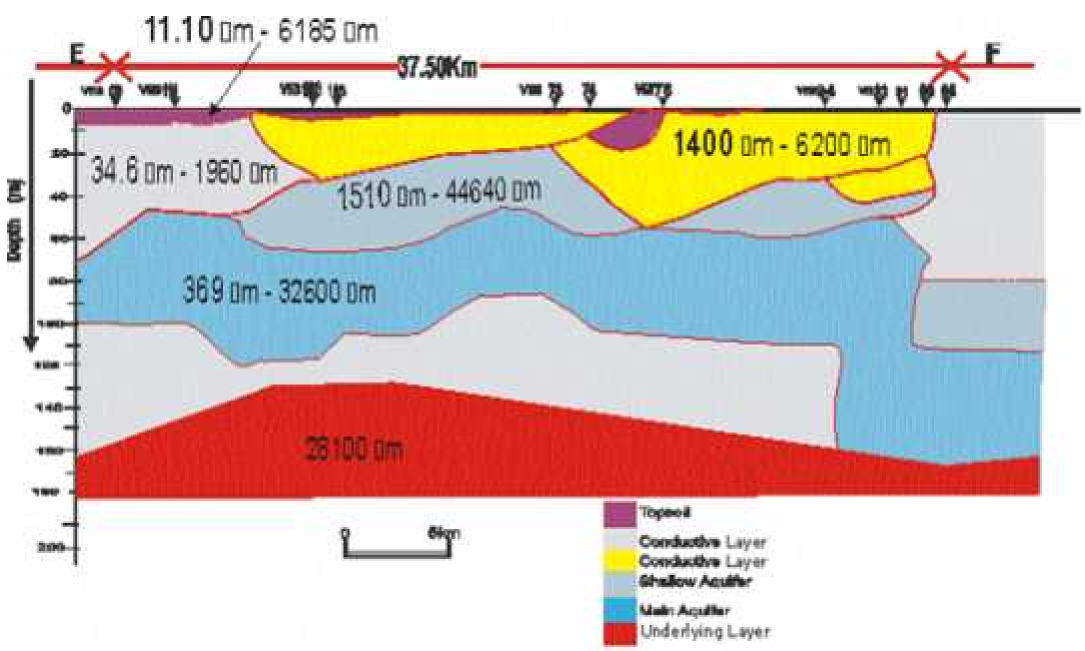


Fig. 7. Interpretative geoelectric cross-section (IGCS) along profile line EF

Table 4. Summary of aquifer characteristics for some of the sounding stations

VES station	Resistivity of aquifer (Ωm)	Thickness (m)	Conductivity σ($\Omega^{-1}m^{-1}$) X10^{-5}	Transverse resistance R (Ωm)	Longitudinal conductance (mΩ^{-1})	Hydraulic conductivity K(m/day)	Transmissivity T_r (m^2/day)	Conductivity product Kσ	Storativity x10^{-3}	Specific capacity (m^3/day)
61	1480	50.3	67.6	74444.00	0.034	20.5186	1032.086	0.014	2.48	877.27
62	1430	72.0	69.9	102860.00	0.050	14.3345	1032.084	0.010	3.55	877.27
63	14800	71.7	6.8	1357160.00	0.005	14.3945	1032.086	0.001	3.08	877.27
64	4860	64.1	20.5	311526.00	0.013	16.1012	1032.087	0.003	3.16	877.27
65	12500	34.2	8.0	427500.00	0.003	30.1779	1032.084	0.002	1.69	877.27
66	1360	25.0	73.5	34000.00	0.018	41.2834	1032.085	0.030	1.23	877.27
67	1362	42.4	73.4	57748.80	0.031	24.3410	1032.058	0.018	2.09	877.27
68	2185	34.2	47.8	74727.00	0.016	30.1779	1032.084	0.014	1.69	877.27
69	1268	47.8	78.9	60510.40	0.038	21.5913	1032.064	0.017	2.36	877.25
70	2430	23.6	41.2	64638.00	0.010	43.7324	1032.085	0.018	1.16	877.27
71	2800	62.0	35.7	173600.00	0.022	16.6485	1032.207	0.006	3.06	877.27
72	1400	50.0	71.4	70000.00	0.036	20.6417	1032.085	0.015	2.47	877.27
73	3282	35.9	42.0	85513.80	0.015	28.7489	1032.086	0.012	1.77	877.27
74	1450	62.0	69.0	89900.00	0.043	16.6455	1032.021	0.012	3.06	877.27
75	2125	58.5	47.1	124312.50	0.028	17.6425	1032.262	0.008	2.88	877.27
76	1486	54.0	67.3	80244.00	0.036	19.1127	1032.086	0.013	2.66	877.27
77	1470	68.3	68.0	100401.00	0.046	15.1111	1032.088	0.010	3.37	877.27
78	2500	8.6	10.5	81700.00	0.001	120.010	1032.085	0.012	4.24	877.27
79	5110	90.1	19.6	460411.20	0.018	11.4549	1032.087	0.002	4.44	877.27
80	24100	55.0	42.0	1325500.00	0.002	18.7652	1032.086	0.001	2.71	877.27
95	2220	104.4	45.1	231768.00	0.04703	9.8854	1032.036	0.005	5.15	877.23

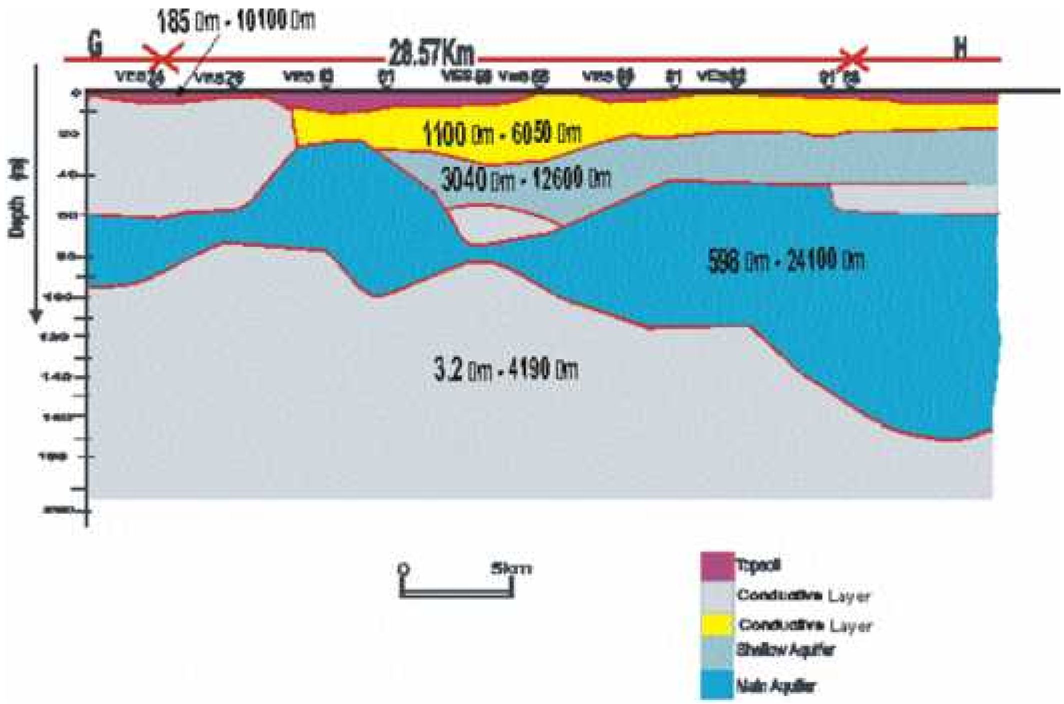


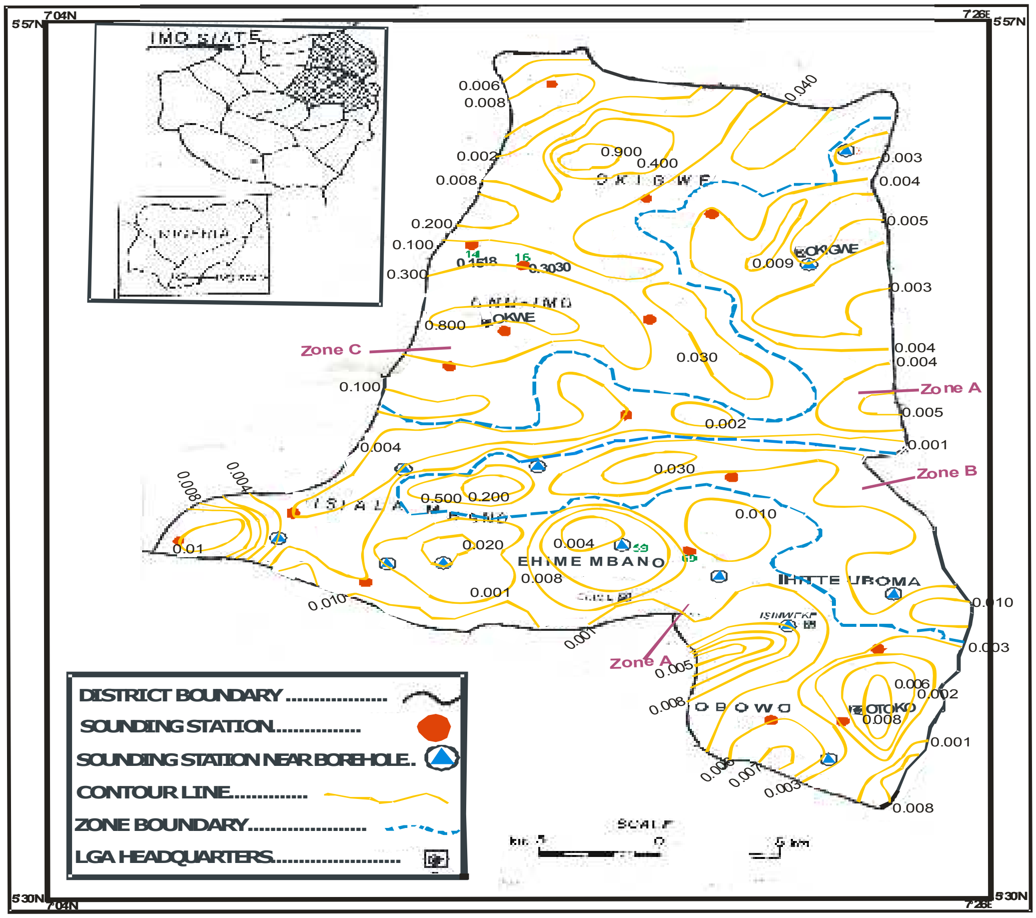
Fig. 8. Interpretative I geoelectric cross-section (IGCS) along profile line GH

3.1 Evaluation of Aquifer Systems in the Study Area

On the basis of the diagnostic Kσ values, three aquifer systems have been identified (Fig. 9). These are:

(i). The coastal plain sand aquifer (Zone A) is relatively thick and unconfined with high thickness and transmissivity values as well as storage coefficient. The aquifer materials are fine to medium coarse, unconsolidated sand and sandstone with seams of sandy clay [16]. This zone covers the southern part of Isiala Mbano, Ehime Mbano, Ihitte Uboma and the entire Obowo LGA. The Kσ values range from 0.0093 to 0.00921.This close range suggests little variation in the water quality of the aquifers. The relatively lower resistivity value recorded at Okwuoma (VES 81) could be linked to Abadaba Lake and that recorded at VES 95 to the presence of Onuinyi River. The aquifer is relatively deep in this zone. However, the lower resistivity values that VES 91 has over VES 81 could be linked to the nature of the depositional environment. The depth to the aquifer is about 53m in Obowo, 88m to 90m in Ihitte Uboma, 52 m to 70 m in Isiala Mbano and 40m to 45m in Ehime Mbano.

(ii). The Bende-Ameki Sandstone/Shale aquifer (Zone B) which covers the least area in the district is located around parts of Ihitte Uboma and the northern part of Ehime Mbano and Isiala Mbano LGAs. The formation is a productive aquifer though not to the extent of the coastal plain sands with transmissivity being lower due to the higher percentage of shales. Groundwater exploitation is sometimes difficult in this zone [1]. The Kσ values range from 0.00831 to 0.23787. This range suggests variation in the water quality in of the aquifers. The depth to aquifer is about 40 m to 45 m.



C

Fig. 9. Distribution of electrical conductivity and hydraulic conductivity product (Kσ) of the aquiferous zone

(iii). The Ajali Sandstone/Shale aquifer (Zone D) covers the northwestern part of the study area in Okigwe LGA. This area falls within the Ajali Formation which consists of thick friable, poorly sorted sandstones. The clay and shale members of this formation are thick which makes ground water exploitation difficult (IWADA, 2002).

Each zone is fairly homogenous in terms of geologic setting, hydraulic properties and possibly water quality. This is because Niwas and Singhal (1981) showed that in areas of similar geologic setting and water quality, the product, Kσ, remain fairly constant. This assumption has also been adopted by Ekine and Iheonunekwu (2007) and Nwosu et al. (2011) in identifying the aquifer systems in Mbaitoli and Isiala Mbano LGAs of Imo State respectively.

On the bases of longitudinal conductance and possible groundwater divides, four zones are identified using the corresponding locations of Kσ product values (Fig. 10). The areas covered by Zone D are underlain by relatively high resistive (low longitudinal conductance aquifer materials). These areas may not be good prospects for drilling boreholes with high yield expectation [7]. The dividing line between Zones A and C runs almost parallel to the channels of Nterere and Odioma Rivers that join to drain southwards into the Imo River. Similarly, the dividing line between Zones A and B runs along the channels of Efuru and Eze Rivers which are tributaries of Imo River that terminate at Abadaba Lake. These lines indicate possible groundwater divide.

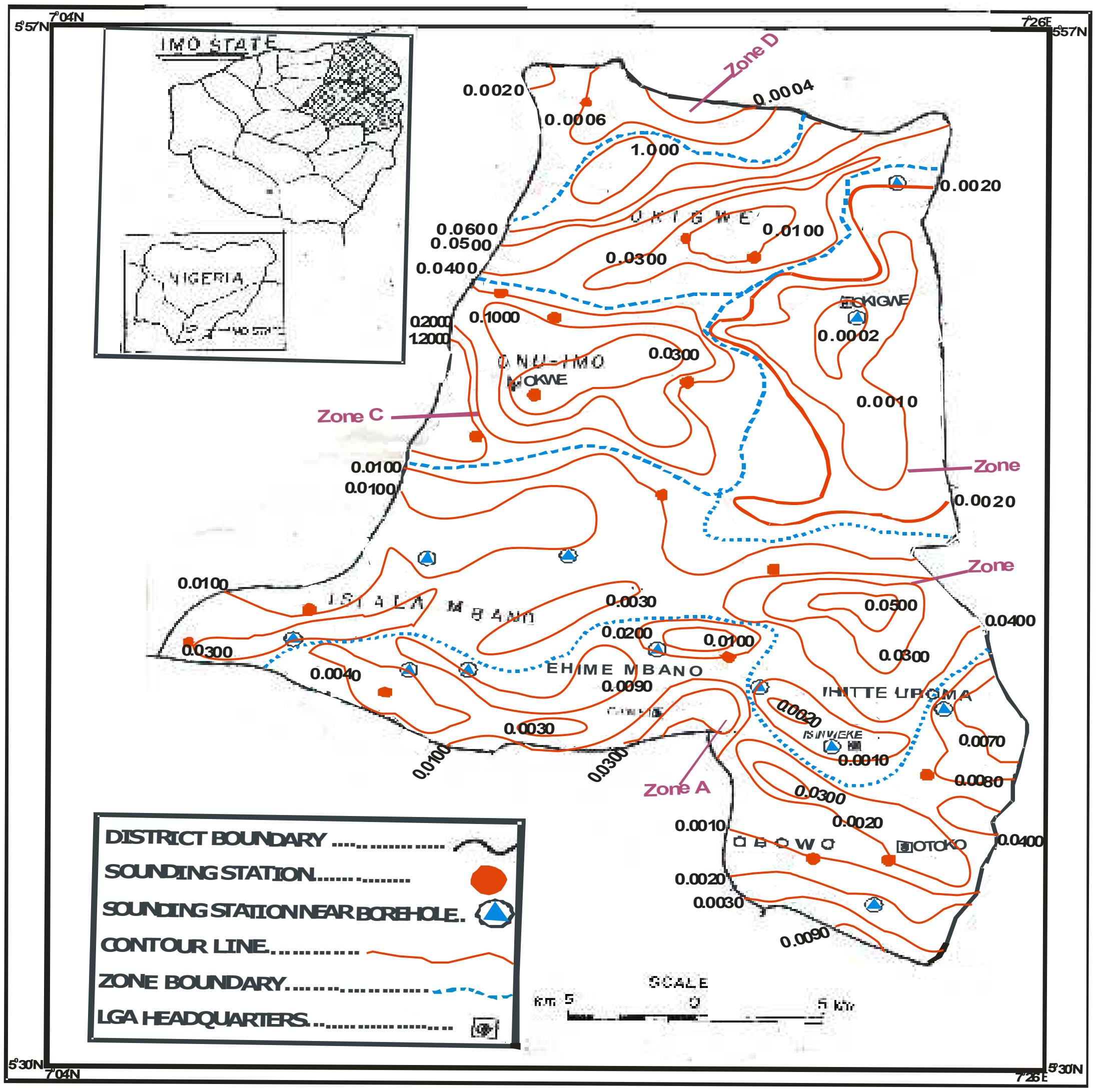


Fig. 10. Distribution og longitudinal conductance values of the aquifer zones

4. CONCLUSION

On the basis of of the diagnostic conductivity product (Kσ) and longitudinal conductance values distribution, three main aquifer systems have been identified for the study area. The resistivity of the aquifer zones varies across the area with an average value of about 3,133 Ωm. The highest thickness of 104.4 m of aquifer was recorded in the southern part of area.This work has successfully delineated the aquifer systems in Okigwe District. Based on the VES results, the southern and northeastern parts of the district are more promising for siting borehole with high yield expectations than the northwestern part as there is no well defined sand body that constitute aquifer there. The occurrence of aquifer in this area is linked to the presence of fracture in the shale members.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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