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Scientific Research

Delineation of Shallow Aquifers of Umuahia and Environs, Imo River Basin, Nigeria, Using Geo-Sounding Data

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ABSTRACT

This work was undertaken to study the hydrogeophysical characteristics of Umuahia and environs, Imo River Basin using geophysical data. Thirty (30) vertical electrical sounding data with a maximum electrode spacing of (AB/2) of 500 meters were acquired using the Schlumberger electrode configuration. The VES data were interpreted using the conventional partial curve matching technique to obtain initial model parameters, which were used as input for computer iterative modelling using the OFFIX software. The study revealed three (3) to six (6) geo-electric layers with underlying shale beds. Aquifer apparent resistivity in the study area ranges from about 50 to 850 Ωm with the aquifer depth varying between 0.53 - 82.67 m. Similarly, the aquifer thickness in the study area ranges from 0.8 - 110 m, with very low thicknesses around Ajata Ibeku. These shallow aquifers with very small thicknesses in the western areas around Ajata Ibeku are believed to be perched or fractured shale units with very low or no yield. Finally, transverse resistances in the study area range from 200 - 3400 Ωm^2 with low values in the western part. Information extracted from iso-resistivity models, geoelectric cross sections, litho logs and electric logs revealed a sandy clay lithology at very shallow depths with a thick layer of shale/clay extending to over 300 m within the western part. These shallow aquiferous units are however perched, partially saturated and may not have sufficient yield. Finally, this study has helped to delineate the aquifers of the study into two distinct zones, thus revealing a groundwater divide.

Keywords: Geo-Sounding; Aquifer Units; Resistivity; Transverse Resistance; Longitudinal Conductance; Nigeria

1. Introduction

The Umuahia area is underlain by the sedimentary rocks of the southeastern Nigeria. The study area constitutes the middle segment of the extensive Imo River Basin [1]. Two principal geologic formations delineated in the study area are the Benin Formation at the southwestern and central parts of the area, and the Ameki Formation which underlines the northeastern part. The inhabitants are mostly subsistence farmers who rely on perennial streams for their domestic water needs. In order to have portable water, many communities, private individuals, and age grades have at different times embarked on borehole projects. The indiscriminate search for groundwater has lead to the existence of failed boreholes and dry wells which pose great concern to the inhabitants of Umuahia and adjoining towns. A lot of these projects were incorrectly sited; some function seasonally, while others have been abandoned. These failures are mainly due to the inability to carry out detailed geophysical surveys that could delineate aquifers and groundwater potentials of Umuahia in addition to the poor knowledge of the geology underlying part of the study area. High productivity of many boreholes that already drilled in the area supports the prolific nature of the Benin Formation which appears at the southeastern part of the study area within Amachara, Ossa, Nkata, Umu-Ekwule, Olokoro and Umudike. This covers about a third quarter of the entire study area while the northwestern part which lies within the Ameki Formation where most of the Ibeku towns are located is associated with acute groundwater problems as a result of thick sequence of shale formation.

Geophysical methods for determining groundwater aquifer are based on the fact that certain physical properties of the rock change considerably depending on their water contents thereby creating a physical boundary between the host rock and the water bearing strata. Such changes in physical properties interpreted by the presence of water include changes in elastic wave velocity, changes in density and increase or decrease in elastic conductivity. It has been established that groundwater is found in pore spaces of sediments such as sand, silt and clays (fractured). These rock bodies and sediments have their specific range of resistivity. The electrical resistivity of a given medium is dependent on such factors such as grain size, water content and porosity, of which porosity is the major control of the resistivity of rocks. Resistivity generally increases as porosity decreases and vice versa. Several authors have therefore delineated shallow aquifers and estimated aquifer hydraulic parameters using surface geophysical methods in different parts of the world [2-14].

This study is a detailed hydrogeophysical study of the area aimed at delineating the shallow aquiferous units in the study area. Geophysical sounding data were compared with lithological logs from boreholes and available electric logs for correlation purposes. In light of the foregoing, it is hoped that results from the present study would address the groundwater problems of part of the study area especially around Ibeku area, as well as help to reduce the cases of borehole failures within Umuahia and adjoining towns.

1.1. Location, Geomorphology and Drainage of the Study Area

The study area consists of parts of the present Umuahia North, Umuahia South and Ikwuano Local Government Areas of Abia state, Southeastern Nigeria. The area is accessible through the main roads that lead to Bende, Ikot Ekpene, Uzuakoli, Okigwe, Enugu and Aba. It lies between longitudes 7˚23' to 7'36 ', and latitudes 5˚26' to 5˚37' This is shown in the topographic and location maps of the study area below (**Figures 1(a)-(c)**).

The study area which is characterized by a lot of features has a submerged or flooded bed in the wet season, a situation that always last till the middle of the rainy season [15]. The size of the local watershed in this area is different from those found in other areas; the extension of the hydrological system depends on what section of Umuahia and Ikwuano areas that is being discussed.

Onwuchuriba [15], revealed that the drainage pattern of this watershed influences the drainage density of the study area (defined as the ratio of length of all streams (km) to the area of the watershed (km^2). In areas with dendritic and tree-like branching patterns, the valley that is associated with the study area extends in all directions while in areas with trellis drainage pattern, the valleys are oriented in lines [15].

1.2. Geology of the Study Area

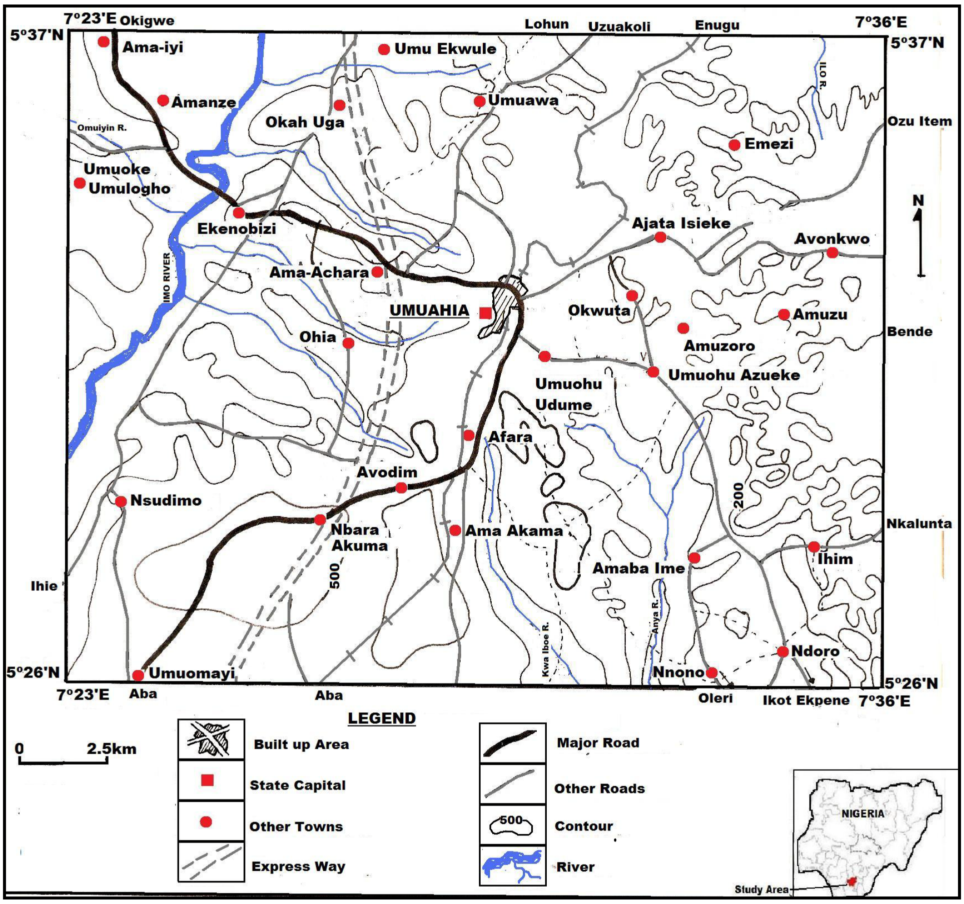
The geology of the study area is that of the Imo River Basin [1], as shown in **Figure 2**. A striking feature in the geologic map is the similarity in the trend pattern of the Formations. Almost all the formations occur along NW-SE bands that are grossly parallel to the regional strike. The rock units also get younger south westward, a direction that is parallel to the regional dip of the rock units [1,16]. There are two principal geological formations in the area namely: the Ameki Formation which appears at the western section and the Benin Formation which appears in the eastern part and covers a large part of the study area. The Ameki Formation of the Eocene to Oligocene age consists of medium to coarse grained white sandstones, bluish calcareous silt with mottled clays and thin limestone. Considerable lateral variation in lithology has been observed in many areas. The lower part of the formation consists of fine to coarse grained lenses of sandstones with abundant calcareous shales and thin shaly limestone. Lithologic units of the Ameki Formation fall into two general groups [17-19]; an upper grey-green sandstones/sandy clay and a lower unit with fine to coarse grained sandstones and intercalations of calcareous shales and thin shaly limestone.

The Benin Formation overlies the Ameki Formation and dips south westward. The Ogwashi/Asaba Formation on the other hand is overlain by the Benin Formation which is the youngest formation (Miocene to Recent) in the Imo River Basin. It occupies the middle and lower regions and directly overlies more than half of the Basin. The Benin Formation is made up of very friable sands with minor intercalations of clays. It is mostly coarse-grained, pebbly, poorly sorted and contains pods and lenses of fine grained sands, sandy clays and clays [18, 20].

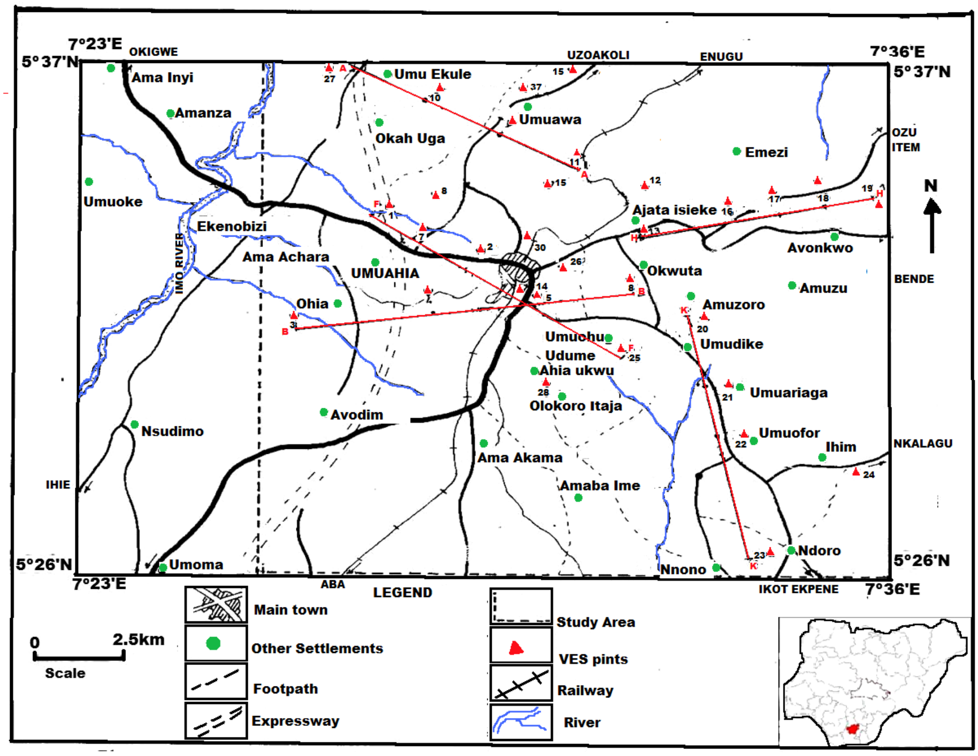
The Formation is in part cross-stratified and the foreset beds alternate between coarse and fine-grained sands. Petrographic study on several thin sections [21] revealed that quartz makes up more than 95% of all grains; but other scholars revealed the possible presence of more percentages to other skeletal materials including feldspar [22,23]. The Benin Formation and the other formations are covered (at their exposed areas) to varied depths by red acidic sandy soils and mangrove soils (lateritic soils). The formation sediments were deposited during the late Tertiary-Early Quatenary Period [24]. At Umudike, the formation is very shallow [25].

2. Data Acquisition and Processing

Most electrical techniques inject electrical current into the ground by direct coupling with the ground. The re-


7°23'E
Okigwe
5°37'N
Ama-iyi
Amanze
Umu Ekwule
Lohun
Uzuakoli
Enugu
7°36'E
5°37'N
Okah Uga
Umuawa
Omuiyin R.
Umuoke
Umulogho
Emezi
Ozu Item
Ekenobizi
Ajata Isieke
Avonkwo
IMO RIVER
Ama-Achara
UMUAHIA
Okwuta
Amuzu
Ohia
Amuzoro
Bende
Umuohu Azueke
Umuohu
Udume
Afara
Avodim
Nsudimo
200
Nkalunta
Nbara
Akuma
Ama Akama
Amaba Ime
Ihim
500
Ihie
Kwa Iboe R.
Anya R.
Ndoro
5°26'N
Umuomayi
Nnono
5°26'N
7°23'E
Aba
Aba
Oleri
Ikot Ekpene
7°36'E
LEGEND
0
2.5km
Built up Area
State Capital
Other Towns
Express Way
Major Road
Other Roads
Contour
River
NIGERIA
Study Area

(a)


7°23'E
OKIGWE
5°37'N
Ama Inyi
Amanza
Umu Ekule
UZOAKOLI
ENUGU
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Okah Uga
Emezi
OZU
ITEM
Umuoke
Ekenobizi
Ajata isieke
Avonkwo
IMO RIVER
Ama Achara
UMUAHIA
Okwuta
Amuzu
BENDE
Ohia
Amuzoro
Umuohu
Udume
Umudike
Ahia ukwu
Olokoro Itaja
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Ihim
NKALAGU
Ama Akama
Amaba Ime
IHIE
Ndoro
5°26'N
Umoma
Nnono
5°26'N
7°23'E
ABA
IKOT EKPENE
7°36'E
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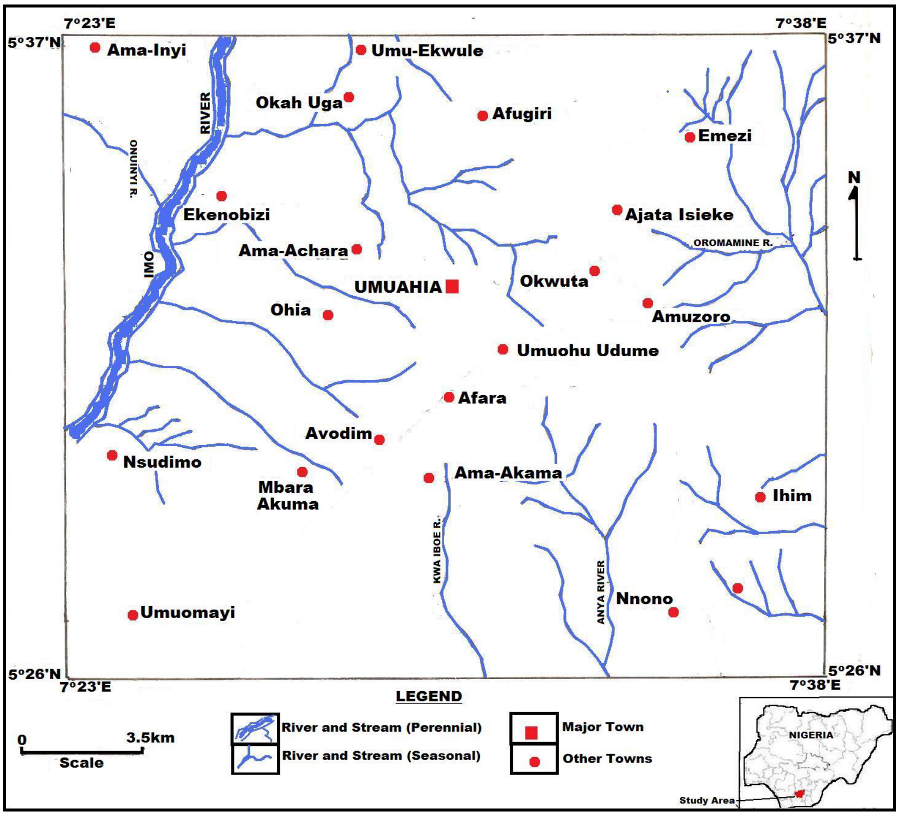
Expressway
Study Area
VES pints
Railway
River

(b)



(c)

Figure 1. (a) Topography (elevation) map of the study area; (b) Location map of the study area showing VES sounding points and interpretative cross sections; (c) Drainage map of the study area.

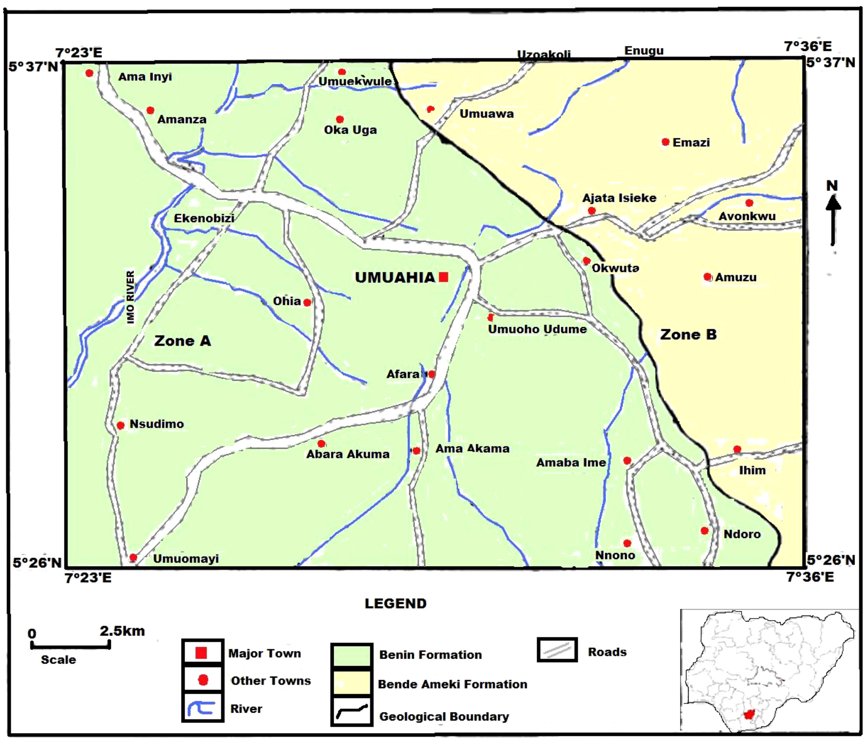


Figure 2. Geological Map of the study area showing the established geologic boundary.

sulting electrical potential is then used to measure the variation in ground conductivity, or its inverse, resistivity. Since resistivity is a fundamental electrical property of rock materials closely related to their lithology, the determination of the subsurface distribution of resistivity from measurements on the surface yields useful information on the structure and composition of buried formations.

Vertical electrical sounding using Schlumberger array measures earth resistivity by passing an electrical current into the ground and measuring the resulting potentials created in the earth. This method involves the supply of direct current or low frequency alternating current into the ground through a pair of current electrodes and the measurement of the resulting potential through another pair of electrodes called potential electrodes. Since the current is known and the potential can be measured, an apparent resistivity can be calculated. They resistivity of the subsurface material observed is a function of the magnitude of the current, the recorded potential difference and the geometry of the electrode array used. In general, the depth of penetration is small in this method and only shallow subsurface layers can be surveyed [4, 8].

The geo-sounding data was collected using Vertical electrical sounding using the Schlumberger array. Four electrode array methods are generally used at the surface, one pair for introducing current into the earth, the other pair for measurement of the potentials associated with the current. Current and potential electrodes were made of non polarisable copper electrodes. The potential drop ratio method is a variation of this procedure used for determining resistivity. Similarly, all resistivity techniques in general use require the measurement of apparent resistivity ρa, which is obtained from the four electrode array. The basic equation is given as:

$$\rho a = 2\pi G\left(\frac{\Delta v}{I}\right) \quad (1)$$

A total of thirty (30) resistivity soundings with some near existing boreholes were acquired for correlation purposes. The maximum spread used was AB = 1000 m and was carried out using the ABEM Terameter SAS 4000 which gave a direct readout of resistance (V/I). The intervals between the potentials and current electrodes were increased at appropriate steps in order to obtain potential differences large enough to be measured with satisfactory precision. The observed field data were converted to apparent resistivity values by multiplying with the Schlumberger geometric factor. The geometric factor for the Schlumberger array is given by:

$$K = \pi\left(\frac{a^2}{b} - \frac{b}{4}\right) \quad (2)$$

The data obtained was plotted as a graph of apparent resistivity against half current electrode spacing for the Schlumberger array. The electrode spacing at which inflection occurs on the graph provides an idea of the depth to the interface. A useful approximation is that the depth of the interface is equal to one third (1/3) of the electrode spacing at which the point of inflection occurs [26]. This approximation has found useful applications in computer iterative modeling. The sounding curve for each point was obtained by plotting the apparent resistivity on the ordinate against the half current electrode spacing, on a bi-logarithmic paper. Geo-electric layer parameters such as apparent resistivity and thickness obtained from both partial curve matching and the method of asymptotes were used as input data for computer iterative modeling [27,28]. Hence, the computer program allowed the reading obtained from the field to be converted to apparent resistivity values and to be stored on magnetic tapes for the detailed quantitative interpretation using the OFFIX software.

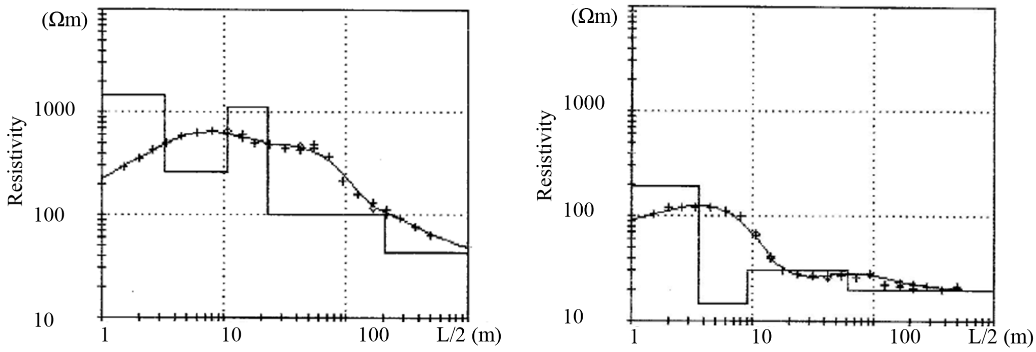
3. Result Presentation and Interpretation

Results of the curve matching were studied in details leading to qualitative and quantitative interpretations. Firstly, the shape of the curves for each sounding gave an insight into the character of the beds or layers between the surface and the maximum depth of penetration. This is because the shape of a VES curve depends on the number of layers in the subsurface, the thickness of each layer, and the ratio of the resistivity of the layers [29]. The curve types identified ranges from simple QQ to KQQ, KHK, AKQ, KQH, QHK, HKQ, to complex KHKQ, KQHK types, reflecting different facies or lithological variations in the area. The KHKQ type is the most preponderant constituting about 16.7%. This is followed by the AKQ and KQQH types which constituted about 10%. The other curve types include the KQQ, AKQQ, QHK, HKQ, HKQQ and KHAK curve types (**Table 1**). The general signature of the curves suggests alternate sequence of resistive-conductive layers. **Figure 3** shows typical curve types from the study area.

3.1. Aquifer Resistivity, Depth and Thickness

Apparent resistivity across the study area has been determined from geoelectric soundings and presented as a contour map in **Figure 4**. The minimum aquifer apparent resistivity is about 109 Ωm near Itaja Olokoro while the maximum apparent resistivity is about 850 Ωm near Ajata Ibeku. The mean aquifer apparent resistivity in the study area is in the range of 253.2 Ωm.

Depth to water table has been deduced from sounding results and the indications are that the water table is shallow in the Umuokwom Ohiya area with a depth of 18.66



(a) (b)

Figure 3. Typical curve types from the study area: (a) Umu- ofor Ikwuano (VES 22); (b) Umuire Ibeku Umuahia North LGA (VES 19).

Table 1. Interpreted layer parameters of the geophysical sounding of Umuahia and environs.

VES No	Location	Longitude	Latitude	No of layers	Layer resistivity (Ωm)						Curve Type	Depth to water (m)
					ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6		
1	Amachara	7.452	5.545	7	47.3	2610	507	900	345	108	KHKQ	47.3
2	Umuchoko Nkata	7.511	5.537	7	1010	1470	176	212	175	83	KHKQ	60.53
3	Umuokwom Ohiya	7.456	5.526	7	124	1010	302	1400	323	102	KHKQ	18.8
4	Planning Commission	7.49	5.526	6	480	1020	727	194	62		KQQ	54.73
5	Federal High Court	7.511	5.527	6	1010	1500	784	206	85		KHK	57.67
6	Umuhute Azueke Ibeku	7.54	5.519	7	202	519	477	27.7	155	39.6	KQHK	45.53
7	Atta Ibeku	7.482	5.554	7	113	1440	3210	800	448	25.6	AKQQ	43.47
8	Ezeleke Umuekwule	7.439	5.552	7	790	1600	88	122	207	26.6	KHAK	60.33
9	Umuawa Alaocha	7.459	5.564	7	566	212	900	774	459	164	HKQQ	51.73
10	Okai Ugah Nkwoegwu	7.488	5.566	7	495	160	950	735	511	167	HKQQ	50.4
11	Umuawa Alaocha	7.462	5.563	7	577	190	682	752	109	70	HAKQ	14.07
12	Ukome Ibeku	7.529	5.557	7	186	980	163	21.5	14.4	19.9	KQQH	1.4
13	Isieke Ibeku	7.55	5.557	5	2130	254	26.3	6.2			QQ	4.47
14	M. Dei Umuahia	7.528	5.477	6	122	457	1970	457	178		AKQ	82.67
15	Ubani Ibeku	7.505	5.568	6	141	202	20	13	13.3		KQH	0.7
16	Ajata Ibeku	7.554	5.542	7	509	850	8.9	28.6	13.1	23.5	KHKH	1.2
17	Ajata Ibeku	7.539	5.541	7	644	9.3	29.6	14.2	21.7	22.7	HKHA	0.67
18	Ajata Ibeku	7.567	5.54	7	408	1660	193	20.8	17.2	24.7	KQQH	0.8
19	Umuire Ibeku	7.593	5.548	6	830	191	14.5	30.6	19.9		QHK	0.53
20	Govt College Umuahia	7.538	5.499	6	3510	910	2720	390	50		HKQ	67.27
21	Umuariaga Oboro	7.548	5.479	6	57.1	800	1730	204	96		AKQ	68
22	Umuofor	7.55	5.469	6	165	1490	1110	99	42		KQQ	76.72
23	Nnono Oboro	7.547	5.434	6	250	747	2190	194	60		AKQ	80
24	Umulu Ibere	7.585	5.436	6	726	118	84	136	60.1		QHK	42.76
25	Isicourt Olokoro	7.539	5.459	7	1050	2430	890	570	283	60.1	KQQQ	34.37
26	Ministry of Agric Umuahia	7.537	5.526	7	170	1040	294	458	1710	111	KHAK	80.67
27	Okai-Uga Nkwoegu	7.454	5.557	7	186	2410	1650	900	412	141	KQQH	76.67
28	Itaja Olokoro	7.525	5.451	7	118	1500	484	3980	1220	84	KHKQ	40.73
30	Low Cost Umuahia	7.52	5.526	7	186	1640	3430	1910	870	184	AKQQ	70
31	Okaiuga Nkwoegwu	7.467	5.557	7	97	255	67	3800	417	27	KHKQ	65.4

m and much deeper in the Umuohu, Nnono Oboro area with a depth of over 80 m as shown in **Figure 5**. Mater Dei Cathederal has a depth of 82.67 m which is exceptionally deep compared to the sounding points around it. For the eastern part of the study area within Ibeku, depth to water table tends to appear at very shallow depths ranging from 0.53 m at Umuire Ibeku to 4.47 m at Okwoyi Isieke Ibeku.

Similarly, the Isopach map (**Figure 6**) revealed that the aquifers of the study area are highly variable in thickness with the thinnest in the vicinity of VES 31. The thicknesses range from 25.2 m to 126.2 m within zone A, while zone B appears at a very shallow depth ranging from 0.8 m near Umuire Ibeku to 6.7 m near Okwoyi Ishieke Ibeku. From **Figure 6**, the Blue (0 to 5) and Black (−5 to 0) colours correspond to most Ibeku towns.

Figure 7 shows the variation of aquifer tranverse resistance T_r across the study area. The T_r values are highest towards the seastern and central parts underlain by Benin Formation. The transverse unit resistance (T_r) map is considered a unique map for hydrological classification of an environment with a thick sedimentary sequence, as is in the case under study. This is because the transverse unit resistance (T_r) which is a product of aquifer thickness (h) and resistivity (ρ), is closely related to transmissivity (T) which is a product of aquifer thickness and hydraulic conductivity (K). Thus the eastern and central parts of the study area (**Figure 7**) where the total transverse unit resistance values are high, are expected to correlate with areas having the highest hydraulic transmissivity (T) and storage coefficients whereas the western parts of the study area with low values of total transverse unit resistance (T_r) are expected to have the least transmissivity (T) and permeability values. Transverse resistance across the study area was estimated by taking the product of aquifer apparent resistivity and aquifer thickness (m). In line with the geology of the study area (**Figure 2**), the northwestern part has the least transverse resistance of about 4107 Ωm^2 near Itaja within the light blue coloured area (4000 - 6000) while the maximum transverse resistance is about 33,580 Ωm^2 near Atta Ibeku with the red and pink colours (30,000 - 34,000). This has a mean value of 15408.39 Ωm^2. For the eastern part within Ibeku, the aquifer transverse resistance is 231 Ωm^2 near Ajata Ibeku corresponding to the region with

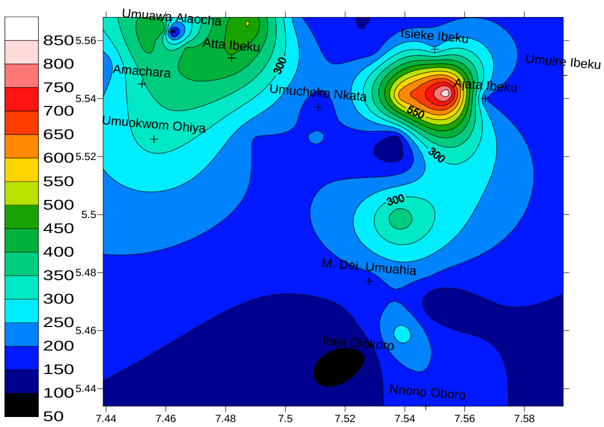


Figure 4. Plot of Aquifer apparent resistivity of Umuahia and adjoining areas.

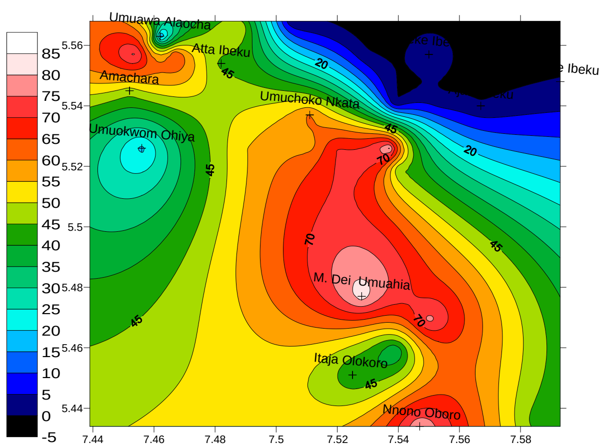


Figure 5. Depth to water table in Umuahia and adjoining areas in metres.

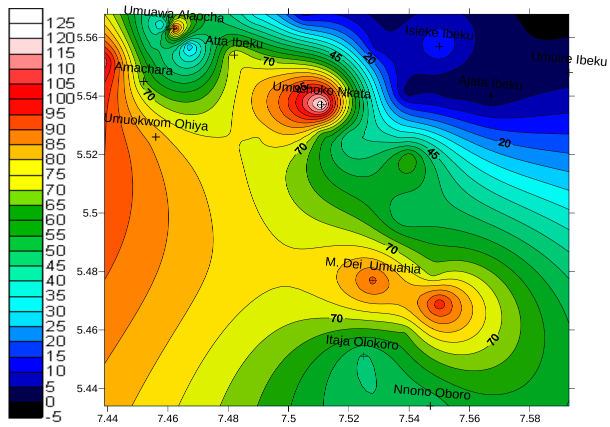


Figure 6. Contour map (Isopach) of the aquifer thickness in the study area.

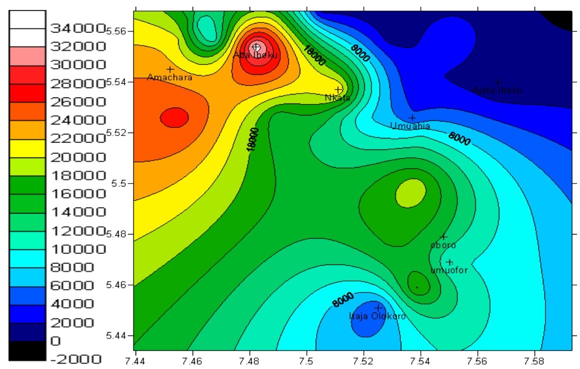


Figure 7. Plot of transverse resistance (Ohm·m^2) of Umuahia and adjoining areas.

dark blue colour (0 - 2000). The dark blue area (0 - 2000) up to the black coloured region (−2000 - 0) may not be productive since the transverse resistance value is low.

Similarly, a contour map of the aquifer longitudinal conductance S is shown in **Figure 8**. The figure revealed that around Ibeku and within the western part of the study area which lie within the Ameki Formation, the aquifer S values are low (−0.05 - 0.2 mhos) whereas the S values are high in the central and eastern part (0.8 - 1.00 mhos) which are underlain by the Benin Formation. The central and eastern part of the study area and other zones of high S values are probably underlain by thick layers of conducting sediments. These could either be fully saturated zones or areas with high percentage of conducting clays or both. Although the aquifer thickness is more in the central and eastern half of the study area, underlain by the Benin Formation, the relatively low resistivity of the aquiferous zones could account for the higher values of S in these areas. The longitudinal conductance map may also characterize the relief of the supporting horizon.

3.2. Interpretative Geo-Electric Crzoss Sections

Interpretations from electrical resistivity soundings carried out around the study area were used to generate geo-electric cross sections. Similarly, five profiles which include A-A[1], B-B[1], F-F[1], H-H[1] and K-K[1] were taken as shown in **Figure 1(a)** for the purpose of interpretation. Six distinct geo-electric layers representative of the subsurface lithology in the study area were noted with conductive (clay) layer at the base having resistivity less than 160 Ωm. Two of the cross sections covering the two distinct hydrogeologic zones are presented below and were used to infer the hydrostratigraphy of the study area.

Profile A-A[1] is 8.2 km long and is oriented northwest-southeast of the study area. It cuts across Umuewelike, Okai Ugah and Umuowa areas. The section revealed six

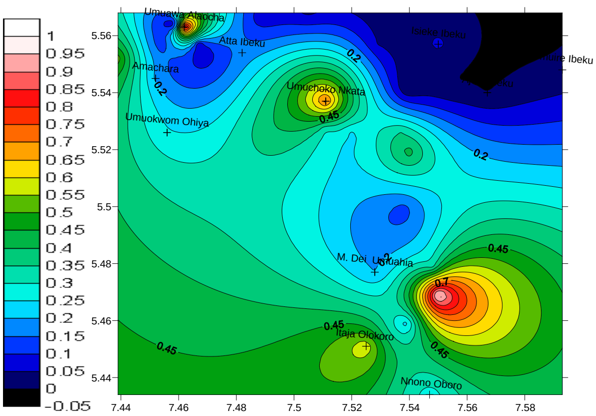


Figure 8. Plot of Longitudinal Conductance (mhos.m) of Umuahia and adjoining areas.

litho-units with the conductive (clay) layer at the base having resistivity values less than 160 Ωm; this is overlain by the clayey sand unit with resistivity ranging from 100 Ωm to 500 Ωm. Overlying this layer is the saturated sand unit with resistivity ranging from 578 Ωm to 3800 Ωm. This layer is overlain by silty sand with resistivity ranging from 200 Ωm to 1650 Ωm, the clayey-sand having the resistivity range of 160 Ωm to 2410 Ωm and the top soil with a resistivity of 186 Ωm to 515 Ωm, in that order (**Figure 9(a)**).

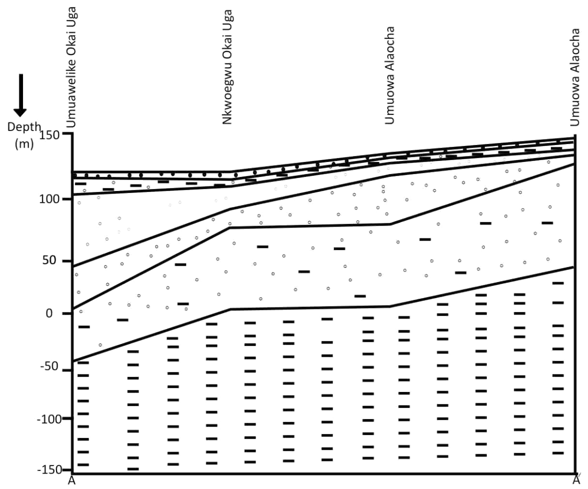
Profile F-F[1] is 10 km long and trends in the northwest-southeast of the study area cutting across Amachara, Atta, Federal High Court out post and Umuobia-Isicourt. The section revealed the presence of six litho units with the conductive (clay) layer at the base having resistivity values ranging from 25 Ωm to 108 Ωm; this is overlain by the saturated sand unit with resistivity ranging from 158 Ωm to 636 Ωm; overlying this is the sandy unit having resistivity ranging from 206 Ωm to 900 Ωm; the sandy unit is overlain by silty sand litho unit with resistivity ranging from 184 Ωm to 3210 Ωm; this is overlain by the unit modeled as laterite having resistivity ranging from 870 Ωm to 2610 Ωm, the thickness of this unit reduces and finally disappears towards Federal High Court out post; overlying this, is the topmost layer modeled as top soil with resistivity ranging from 47 Ωm to 1050 Ωm (**Figure 9(b)**).

Well to Vertical Electrical Sounding Correlations

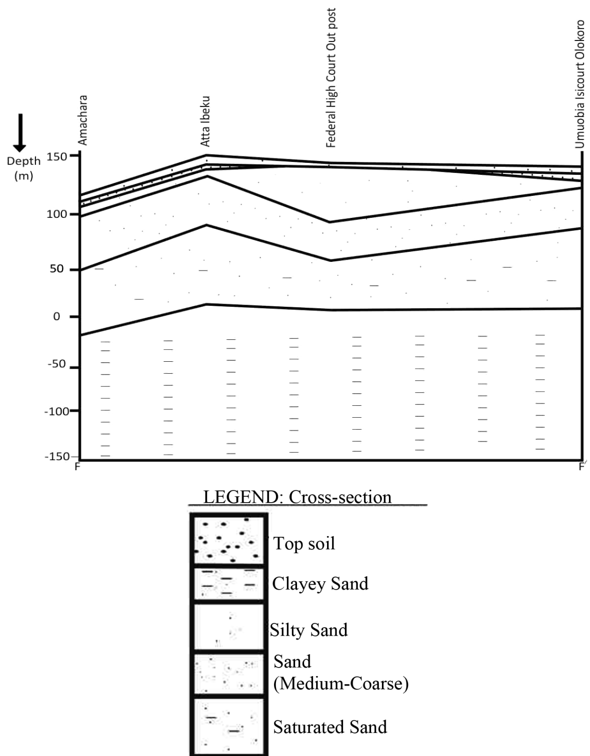
Two of the VES points from the study area with existing electric and lithology data are presented below for correlation purposes.

From the lithological log of area, the saturated zone appears between 310ft and 380ft while the geoelectric section of VES 7 revealed that the saturated zone appears between 142.61ft and 258.09ft. From the Electric log of Amangwu Olokoro, resistivity values ranges from 799 Ωm at the depth range of 70ft to 150ft, to 869 Ωm between 320ft and 380ft. For the saturated zone, the electric log of Amangwu Olokoro revealed a resistivity value of 869 Ωm, while that of the geo-electric section is given as 447.8 Ωm. A fairly good correlation therefore is established between the electric log, litho-log and geo-electric section of Amangwu Olokoro as shown in **Figure 10(a)** below.

Similarly, from the lithological log of Umuihie-Odo, the saturated zone appears between 200ft and 410ft while for the geoelectric section of VES 6 the saturated zone appears between 148.73ft and 290.9ft. From the Electric log of Umuihie-Odo, resistivity value ranges from 130 Ωm at the depth of 98ft and 107ft to 100 Ωm between 290ft and 390ft. For the saturated zone, Umuihie-Odo electric log reveals resistivity value of between 290ft and 390ft to be 100 Ωm while that of the geoelectric section



(a)



(b)

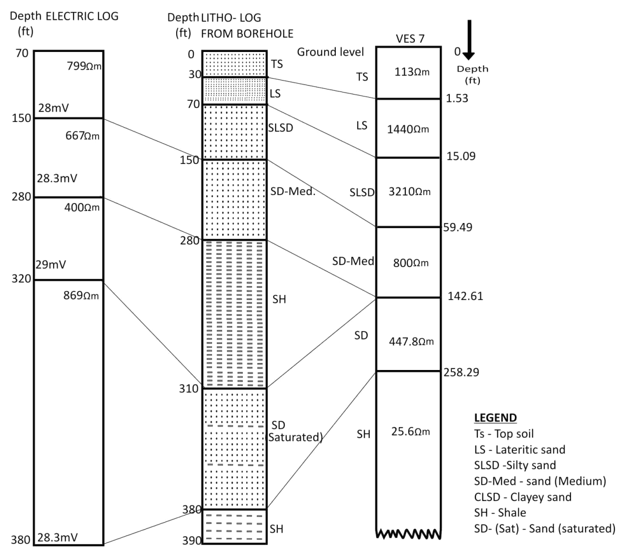
Figure 9. (a) Interpretative cross section showing A-A[1] Profile; (b) Interpretative cross section showing F-F[1] Profile.

of VES 6 is 155 Ωm. **Figure 10(b)** therefore shows a fair correlation between the electric log, litho-log and geo-electric section of VES 6.

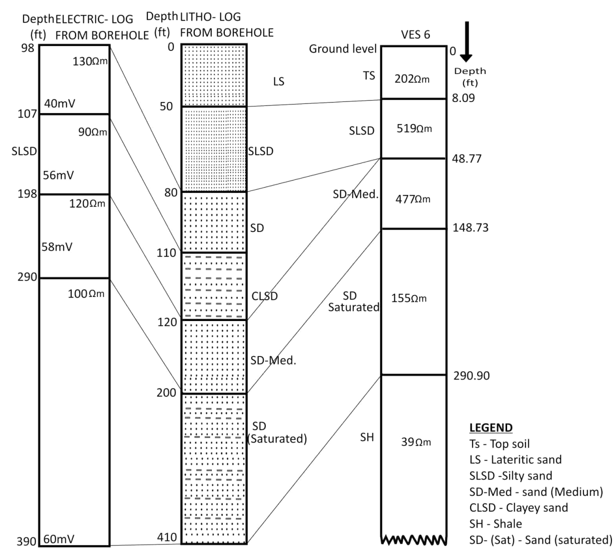
Similarly, from the lithological log of Umuihie-Odo, the saturated zone appears between 200ft and 410ft while for the geoelectric section of VES 6 the saturated zone appears between 148.73ft and 290.9ft. From the Electric log of Umuihie-Odo, resistivity value ranges from 130 Ωm at the depth of 98ft and 107ft to 100 Ωm between 290ft and 390ft. For the saturated zone, Umuihie-Odo electric log reveals resistivity value of between 290ft and 390ft to be 100 Ωm while that of the geoelectric section of VES 6 is 155 Ωm. **Figure 10(b)** therefore shows a fair correlation between the electric log, litho-log and geo-electric section of VES 6.

3.3. Iso-Resistivity Model across the Study Area

Based on the assumption that the effective depth of transmission of electric current in the ground is two third



(a)



(b)

Figure 10. (a) Correlation of the results of VES 7 with the Electric log and the litho-log from borehole at Amangwu Olokoro; (b) Correlation of the results of VES 6 with the Electric log and the litho-log from borehole at Umuihie-Odo.

Table 2. Iso-resistivity modeling (downward continuation) of resistivity across the study area.

VES NO	AB/2 (m) = 10	AB/2 (m) = 15	AB/2 (m) = 24	AB/2 (m) = 50	AB/2 (m) = 75	AB/2 (m) = 100	AB/2 (m) = 150	AB/2 (m) = 200	AB/2 (m) = 250	AB/2 (m) = 300	AB/2 (m) = 500
1	555	575.9	673	710.9	638.8	524.2	387.5	311.9	226.2	173.3	130
2	1242	1065	751	251.1	218.9	203.4	176	185.5	177.9	170.9	129.6
3	526.9	526.2	563.9	713.9	641.6	518.4	393.6	301.9	218	170.9	123.4
4	864.4	911.2	850.1	475.7	202.4	136.7	111.3	114.4	111.2	108.9	100
5	1246	1065	751.4	250.2	218.1	203.4	171.6	185.5	186.7	171.2	130
6	463	450.3	390	208.1	105.6	62.9	54.84	62.38	63.8	60.4	56.4
7	887.5	1024	1450	1909	1579	984	724.8	515.9	345.3	208.7	50
8	1390	1262	756.5	214.3	120.4	122.1	119.9	123.8	133.2	131.9	77.6
9	336.2	402.5	570.8	675.2	703.6	682	586.1	492.8	381.1	304.4	201
10	374.3	504.3	585.1	654.4	701.6	681.8	578.3	485.5	380.7	307.8	215.7
11	329.6	281.3	338.8	363.2	186.7	150.2	130.6	125.1	120.9	120	111.4
12	294.9	172.2	85	25.6	19.9	19.25	19.1	19	19.15	18.7	21.2
13	1583	930.9	460.5	87.22	28.94	8.95	7.4	7.6	7.15	6.7	6.6
14	479.8	525.6	650.2	903.5	755.8	675.8	558.6	466.5	375.6	305.5	220
15	156.8	126.2	55.4	21.7	14.2	13.9	14.1	14.13	14	12.95	13.4
16	292.2	80.52	22.8	18.12	21.7	22.2	19.3	18.65	21.2	21.85	21.1
17	137.9	23.5	22.7	20.1	24.1	20.9	18.2	19.7	21.9	20.3	21.1
18	407.3	103.8	25	23.3	18.2	17.4	17.43	18.9	20.8	19.7	22.6
19	72.96	38.7	27.8	26.78	26.8	25.2	21.4	21.7	21.85	20.75	21.2
20	965.2	974.2	1174	1454	1157	982.9	882.4	835.9	824.4	805.9	800.9
21	510.8	562.9	645.2	800	860.2	730.1	528.2	407.5	285.1	224.7	204.5
22	629.6	584.6	470	453.2	348.1	187.7	135.9	114.7	102.3	84.9	63.5
23	621.2	712.9	800	900.1	982.5	900.7	656.8	452.4	262.5	157.5	126
24	113.2	90.6	96.1	91.48	97.3	101.4	101	95.6	89.15	76.9	70.2
25	1285	1594	1467	1534	1720	1802	1669	1433	392	219.5	
26	333.6	316.5	390.7	328.7	382.5	432	534.4	603.9	591.9	489.6	
27	836.4	1163	1600	1715	1690	1469	1206	1086	789.6		
28	826.2	959.2	950.4	1144	1369	1283	1023	788.7	509.9		
29	1129	1392	1718	2163	2180	1750	1396	1056	653.9	413.6	
30	158.7	178.5	260.4	467.4	680.5	760.7	686.8	654.9	526.7	374.8	

(2/3) of half the current electrode separation (AB/2), the iso-resistivity of the sounding points across the study area were calculated. Contour maps of the iso-resistivity values at specific depth intervals of AB/2 equal to 10 m, 15 m, 24 m, 50 m, 75 m, 100 m, 150 m, 200 m, 250 m, 300 m, and 500 m (**Table 2**) were generated as shown in **Figure 11**. The contour maps revealed a continuos variation of resistivity values with depth, suggesting a high resistive overburden. However, an iso-resistivity map is a qualitative interpretative tool which shows possible variations in resistivity at the given electrode spacing and does not give the true resistivities of a definite geo-electric layer [24].

The iso-resistivity map for AB/2 = 10 m revealed that part of the study area corresponding to the Ameki Formations of Ibeku are underlain by relatively low resistive materials. The colour codes in **Figure 11** reveal that colours between 50 and 150 corresponded to conductive horizons while highly resistive areas of about 1550 Ωm are indicative of sandy units. A similar trend is maintained in all the iso-resistivity plots from AB/2 equal to 10 m, 15 m, 24 m, 50 m, 75 m, 100 m, 150 m, 200 m, 250 m, 300 m, and 500 m revealing very low resistivity values in the southwestern part around Ibeku to a depth of over 350 metres. The Iso-resistivity maps therefore indicated that the northwestern section of the study area may be unproductive of groundwater to depths less than 350 m.

4. Discussion

High S and low T_r values were obtained generally for the aquiferous zones in the Ameki Formation while relatively low S but high T_r values were obtained for the aquiferous zones in the Benin Formation. The high S values obtained in the Ameki Formation can be attributed to higher salinity of the groundwater or high clay content or both. Sufficiently high T_r coupled with good aquifer thickness is necessary for groundwater exploitation. Consequently the most prospective areas for drilling of productive boreholes in the study area have been delineated in the vicinities of Umuahia Township, Olokoro, Umudike, among others.

The depth to the water table estimated from this study revealed an increasing trend as we move from Ibeku area to Umuahia Township, Olokoro and Umudike areas. Deeper depths to the water table coupled with very low transmissivity properties of the aquifer materials make the environment of the Ameki Formation low in groundwater potentials. It is therefore observed that the northeastern lowlands have low groundwater potentials while the western area has high groundwater potentials. Similarly, a good correlation is found to exist between the

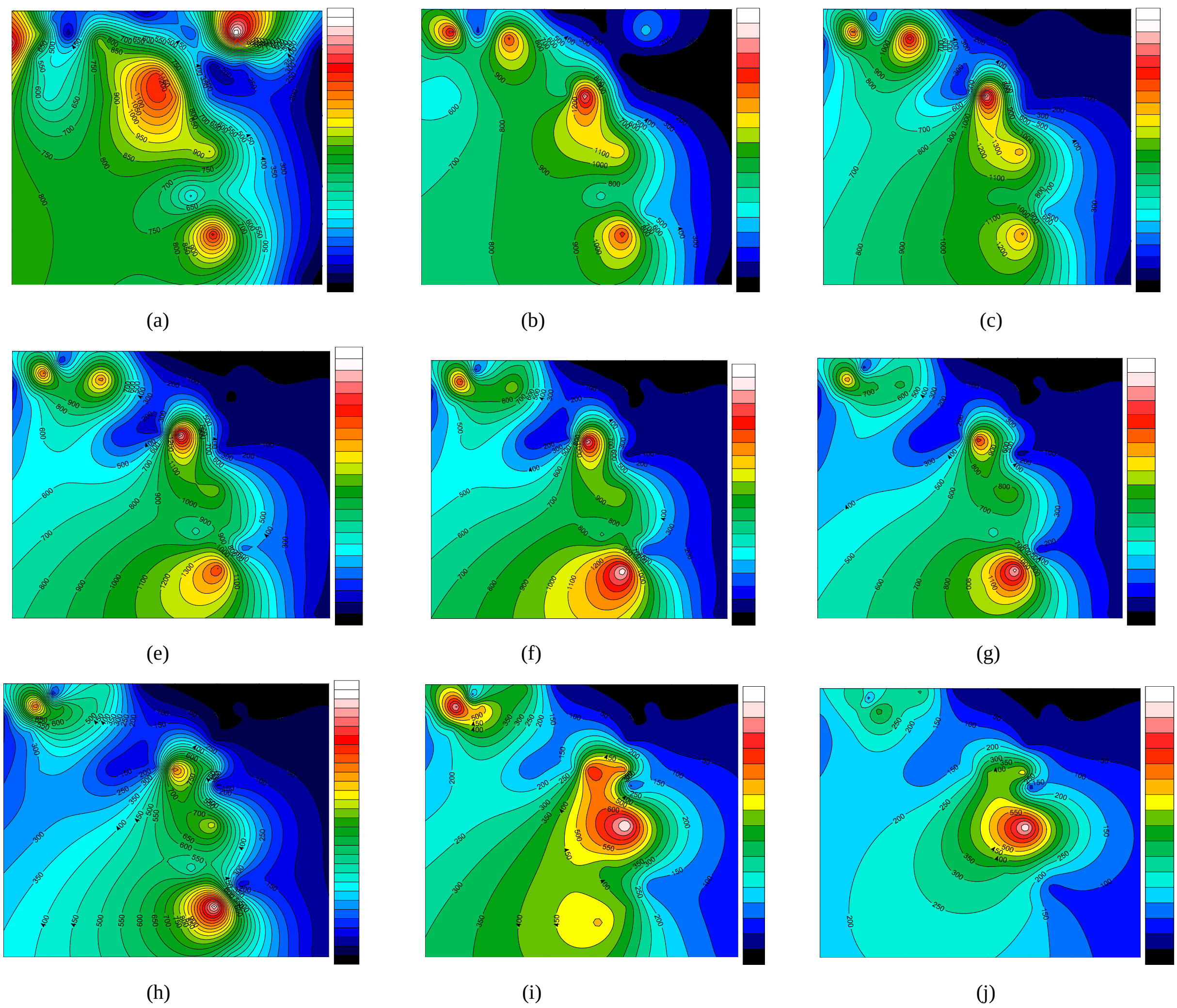


Figure 11. Iso-resistivity contour maps of the study area: (a) AB/2 = 10, (b) AB/2 = 24; (c) AB/2 = 50; (d) AB/2 = 7.5; (e) AB/2 = 100, (f) AB/2 = 150; (g) AB/2 = 200; (h) AB/2 = 250 and (i) AB/2 = 350 m.

results generated from surface geophysical data and some borehole data. The zone with the highest transverse resistance (T_r) values is expected to give the highest borehole yield. Consequently, favourable areas for future groundwater development have been suggested on the above bases.

In addition, the Iso-resistivity maps for AB/2 at 75m, 100 m and 150 m revealed that two distinct zones can be identified within the study area on the basis of resistivity values. They include the south-eastern part which covers about ¾ of the study area which is underlain by relatively high resistive materials with resistivities ranging from 202 Ωm near VES 4 to 2180 Ωm near VES 30 with a mean of 762.59 Ωm. The north-western part on the other hand is underlain by relatively conductive materials at this interval. The resistivity values in this area range from 14.2 Ωm near VES 15 to 28.94 Ωm near 13 VES with a mean of 21.98 Ωm. This variation between the two areas may possibly be traced to the variation in geology, topography or water quality and/or degree of saturation. A groundwater divide was established by previous scholars based on geo-sounding results revealing a prolific aquiferous zone within the Benin Formation and dearth of groundwater within the Ameki Formation [24, 25]. Igbokwe *et al.* [25], maintained that the two principal geological formations have comparative groundwater regime. The Ameki Formation has little groundwater potentials when compared to the Benin Formation.

Based on the generated geo-electric sections, which correlated well with strata-logs from boreholes in the study area, five to six (5 to 6) prominent geo-electric layers were identified in the south-eastern part of the study area whereas the north-western section of the study area has 2 to 3 geo-electric layers with overlying shale beds. Results revealed that aquifer apparent resistivity in the study area ranges from about 50 to 850 Ωm with the aquifer depth varying between 0.53 - 82.67 m with very low depths in the northwestern part around Ajata Ibeku. Similarly, aquifer thickness in the study area ranges from 0.8 - 110 m with very low thicknesses around Ajata Ibeku. Transverse resistance in the study area ranges from 2000 - 3400 Ωm^2 with low values in the northwestern part with the iso-resistivity maps revealing that the northwestern section of the study area may not be productive of groundwater to a probable depth of 350 m. This is because the transverse unit resistance (T_r) which is a product of aquifer thickness (h) and resistivity (Ω), is closely related to transmissivity (T) which is a product of aquifer thickness and hydraulic conductivity (K). Thus the southeastern and central parts of the study area where the total transverse unit resistance values are high, are expected to correlate with areas having high hydraulic transmissivity (T) and storage coefficient whereas the northwestern parts of the study area with low values of total transverse unit resistance (T_r) are expected to have low transmissivity (T) and permeability values. These results are in agreement with previous studies carried out earlier in the study area [1,24,25,30].

5. Summary and Conclusion

The electrical resistivity sounding method is widely used for groundwater exploration and has found serious applications worldwide. Two important limitations are however inherent in this method. These are the problems of equivalence and suppression. However, computer oriented direct interpretation methods are capable of resolving the thickness and resistivities of various subsurface layers from the surface resistivity measurements. These results are free from human bias, which is always present in the conventional curve matching techniques.

The present study has helped to map out zones for the drilling of productive boreholes in the study area. The iso-resistivity plots of the study area have proven why most boreholes drilled within the Ameki Formation, especially within Ibeku area, east of Umuahia have serious underground water problems. Boreholes drilled in these areas that are shallower than 300 m may be unproductive. It is therefore hoped that results of this study will be invaluable to planning of water supply schemes within the area.

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