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Hydrogeophysical Delineation and Hydrogeochemical Characterization of the Aquifer Systems in Umuahia-South Area, Southern Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. All authors were actively involved in the field investigations. Author CAU designed the study and performed the statistical (graphical) estimation analysis of hydraulic parameters, and wrote the first draft of the manuscript. Authors CAU, MUI and GUC wrote the protocol. Authors CAU, GUC and KOO managed the borehole analyses of the study. Authors CAU, MUI, GUC and TKE carried out the geophysical data analysis. Authors CAU and TKE managed the literature searches. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

In Umuahia-South Local Government Area of Abia State Nigeria, some cases of boreholes failure and groundwater discolouration have been observed. An investigation in order to determine the hydrogeological conditions of the area was carried out using geoelectrical, drill-hole and hydrogeochemical data. Using the Schlumberger electrode configuration, ten vertical electrical sounding data were acquired and the computer-aided Resist software method was used for further processing and interpretation. The interpretation of the VES data obtained from the study area shows that the vicinity of VES station 1 is likely to record

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failure in bore-hole exploration. A high variation in aquifer thicknesses is observed with the least as 27m at VES Station 5, and the highest 226m at VES Station 3. A new approach was used in the estimation of aquifer hydraulic parameters such as hydraulic conductivity and transmissivity. Some geoelectric sections generated from VES stations were compared with some lithologs which gave a good geological description of the study area; thereby revealing a multi-aquifer hydrogeologic system. Water samples were taken from ten boreholes for hydrogeochemical investigation which reveals the occurrence of same geochemical process; but slightly varying water quality which is associated to the multi-aquifer status of the area. The discolouration of water observed in some boreholes owes its origin from the silty-sand aquiferous units with slightly high iron content. A further analysis of the samples when plotted on Gibb's Diagram reveals that recharge occurs through precipitation, but the local geology of the area is the source of major ion concentrations in the samples.

Keywords: Benin formation, Umuahia-South, aquifer characteristics, parameter estimation, groundwater quality, hydrogeochemical facies.

1. INTRODUCTION

In Abia State of Nigeria, there are many cases of boreholes failure especially in the northern and central parts of the state while the southern part has huge groundwater potentials. Umuahia-South Local Government Area which is in the central part of the state exhibit a different hydrogeological setting to that of the northern and central parts, this is because the area is overlain by Benin Formation which comprises of shale/sand sediments with intercalation of thin clay beds (Asseez, 1976; Murat, 1972). The high permeability of Benin Formation and the intercalation of the sands with clays/clayey shale layers, with its overlying lateritic earth and underlying Bende-Ameki Formation gave rise to a favourable multi-story aquifer system but some cases of boreholes failure and groundwater discolouration have been observed recently which gave rise to this study.

Geologically, Umuahia-South lies in the South eastern part of the Cenozoic Niger Delta Basin of Nigeria (Fig. 1). Cenozoic Niger Delta sedimentary basin was formed from the interplay between subsidence and deposition arising from a succession of sea transgressions and regressions (Hosper, 1965; Short and Stauble, 1965); which gave rise to the deposition of three lithostratigraphic units in the Niger Delta. These units are Marine Akata Formation, Paralic Agbada Formation, and the Continental Benin Formation (Table 1). The Akata and Agbada Formations are the source and reservoir rocks respectively for petroleum in the Niger Delta while the Benin Formation serves as the aquifer for all the groundwater supplies. The overall thickness of these Cenozoic sediments is about 10,000 meters.

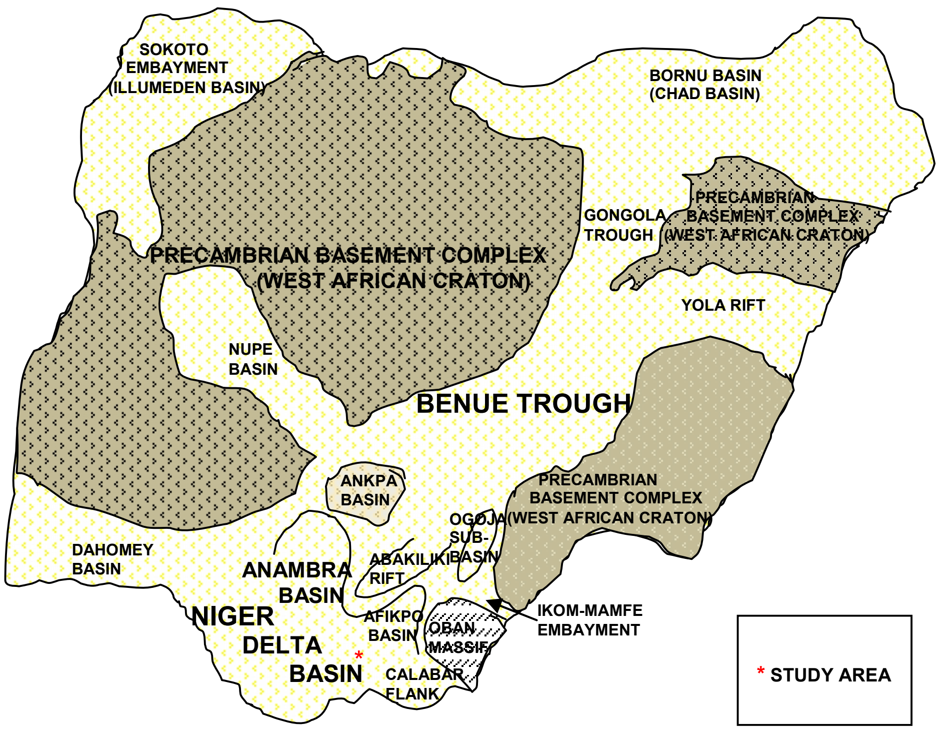

Fig. 1. Geological Outline Map of Nigeria showing Basement outcrops and Sedimentary basins.

In this present study, the Miocene to Recent Benin Formation which is the surface outcrop of Umuahia-South area serves as the aquifer for all the boreholes. The Miocene to Recent Benin Formation is made up of sands which are mostly medium to coarse grained, pebbly, moderately sorted with local lenses of poorly cemented sands and clays. But generally, Benin Formation consists of shale/sand sediments with intercalation of thin clay beds (Asseez, 1976; Murat, 1972). The high permeability and the intercalation of the sands with clays/clayey shale layers of Benin Formation, with underlying Bende-Ameki Formation of paralic delta front setting are indicative of a multi-aquifer system (Table 1). Petrographic analysis of Benin Formation indicates that the composition of the rocks is as follows: 95-99% quartz grains, 1-2.5% of Na+K-mica, 0 -1.0% of feldspar and 2-3% of dark coloured minerals (Onyeagocha, 1980).

Table 1. Stratigraphic correlation chart of Niger delta outcrops and subsurface

Age	Surface Outcrop Equivalent Formation		Subsurface formation	Mega-depositional environment
Pliocene - Recent	Coastal Plain Sands		Benin Formation	Paralic Continental
Miocene - Recent	Ogwashi-Asaba Formation	Ijebu Formation	*Afam Clay Member*	Continental Delta Plain
Eocene - Recent	Bende-Ameki Formation	Ilaro Formation Oshoshun Formation	Agbada Formation	Paralic Delta Front
Paleocene – Recent	Imo Formation	Ewekoro Formation	Akata Formation	Marine Pro-Delta
Maastrichtian - Paleocene	Nsukka Formation		Equivalents Not Known	Pro-Delta Successions
Maastrichtian - Paleocene	Nsukka Formation		Equivalents Not Known	Pro-Delta Successions
Santonian - Maastrichtian	Nkporo-Enugu Shale		Equivalents Not Known	Pro-Delta Successions
Turonian - Coniacian	Awgu Shale		Equivalents Not Known	Pro-Delta Successions
Turonian	Eze-Aku Shale		Equivalents Not Known	Pro-Delta Successions
Albian	Asu-River Group		Equivalents Not Known	Pro-Delta Successions

**Modified after Amajor (1986), and (Short and Stauble 1965).*

The present study area (Umuahia-South) lies within latitudes 5º26’ and 5º34’ N, and longitudes 7º22’ and 7º33’ E (Fig. 2). It has high relative humidity values over 70%, and is characterized by high temperatures of about 29º–31ºC. The area is part of the sub-equatorial belt with average annual rainfall of about 4000mm per annum. The wet season starts from Mid-April to October and dry season from November to Mid-April, and has double maxima rainfall peaks in July and September with a short dry season of about three weeks between the peaks locally known as the August break.

Umuahia-South Local Government Area of Abia state, Nigeria is bounded in the north and north-east by Umuahia North, in the south by Isiala Ngwa North, in the east by Ikwuano Local Government Areas respectively and the Imo River demarcates it with Imo State in the western part (Fig. 3). The area is endowed with natural springs and streams including Imo River on the western flank which flow in a southerly direction and empty into the Atlantic Ocean. On the other hand, Anya River (though small compared to the Imo River) traverses the Southeastern flank of Umuahia-South. This Anya River is a main tributary of the great Kwa Ibo river of Akwa Ibom and Cross River States of Nigeria.

Despite the fact that the study area is endowed with perennial springs and streams which are not associated with water-borne diseases, the groundwater resources have recently come under pressure in response to man’s quest for better livelihood, urbanization, economic development and increase in population. The study covers all parts of the Local

Government Area where World Bank Housing Estate, Industrial/ Technology Village, Cattle market, Electricity Sub-station and River Basin Development Area are planned/situated. The resulting increase in population will greatly stress the groundwater resources and consequently requires special management and protection.

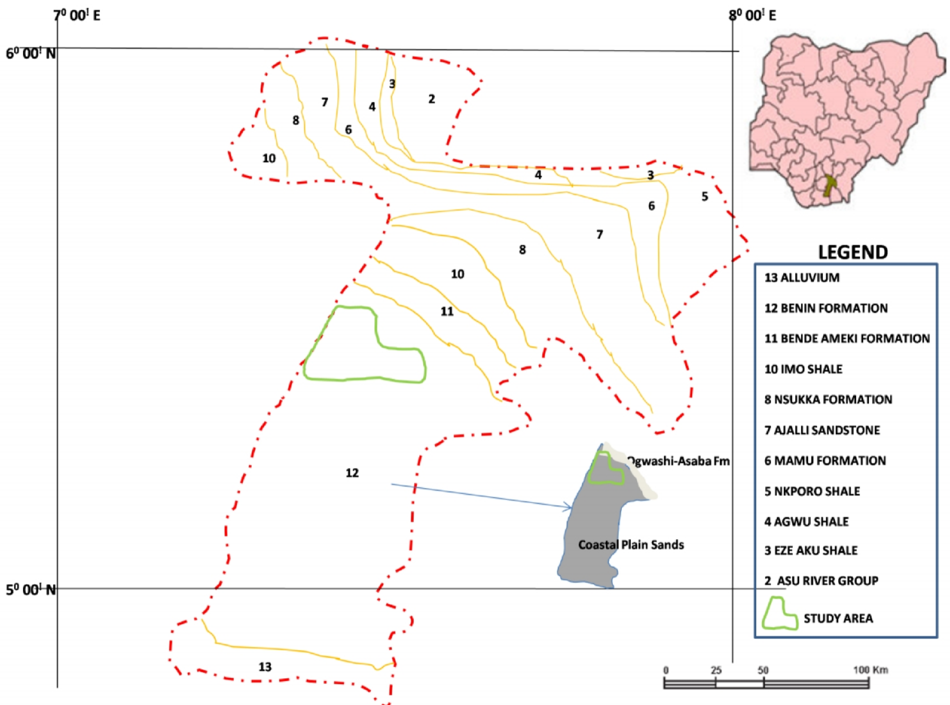

Fig. 2. Geologic Map of Abia State showing the study area

A thorough knowledge of the hydrogeological system is a precondition for any management and protection strategy. Such understanding, however, is presently lacking in the area. To meet this largely depends on the determination of aquifer characteristics and these properties are important in determining the natural flow of water through an aquifer and its response to withdrawal of fluid, but are normally done through pumping tests and permeameter tests. These tests are not normally run due to their high cost and lack of equipment or are either performed on limited areas of the experimental site, or are based on laboratory tests on a few soil samples. This is because the high monetary as well as time requirements limit the implementation of field tests over the entire experimental area.

Many alternative approaches for the estimation of aquifer characteristics have been proposed such as the use of theoretical models and also surface geoelectrical methods which quite a number of workers have done namely: Maillet (1947); (Niwas and Singhal, 1981); (Kitanidis and Vomvoris, 1983); Brown (1998); (Edet and Okereke, 2005); (Igboekwe and Amos–Uhegbu, 2011); K'Orowe et al. (2011). The alternative approaches are quick and cost effective, but accounting fully for the physical, chemical and biological interactions between soil, water, nature and society is quite complex. Therefore, the emphasis on the availability and quantity of groundwater has extended to the quality of groundwater (Edet and Okereke, 2005; Nguyet, 2006; Amos-Uhegbu et al., 2012) thus leading to an attempt in providing a thorough aquifer characteristics of the study area.

Mbonu et al. (1991) have attempted a geoelectrical determination of aquifer characteristics of parts of the area where they centred their research on the Coastal Plain Sands. While one of the authors, (Chukwu, 2008) studied the groundwater quality of some parts of the study area and attributed the high turbidity he observed in Ohiya to the presence of Kaolinite ore deposit in the vicinity. Ukandu et al. (2011) studied the hydrochemistry of some boreholes in the study area where they observed a slightly higher level of concentration of iron in two boreholes and attributed such to lower hydraulic heads.

Since a complete evaluation of a hydrogeological unit comprises the availability, productivity and quality of the groundwater. This present study therefore covers the entire Benin Formation (Ogwashi-Asaba Formation and the Coastal Plain Sands) of Umuahia-South Area (see insert Fig 2). It is the first documentation of the aquifer characteristics of the entire Umuahia-South Area using geoelectrical, drill log and hydrogeochemical data with the aim of providing a better understanding of the hydrogeological conditions of the entire area.

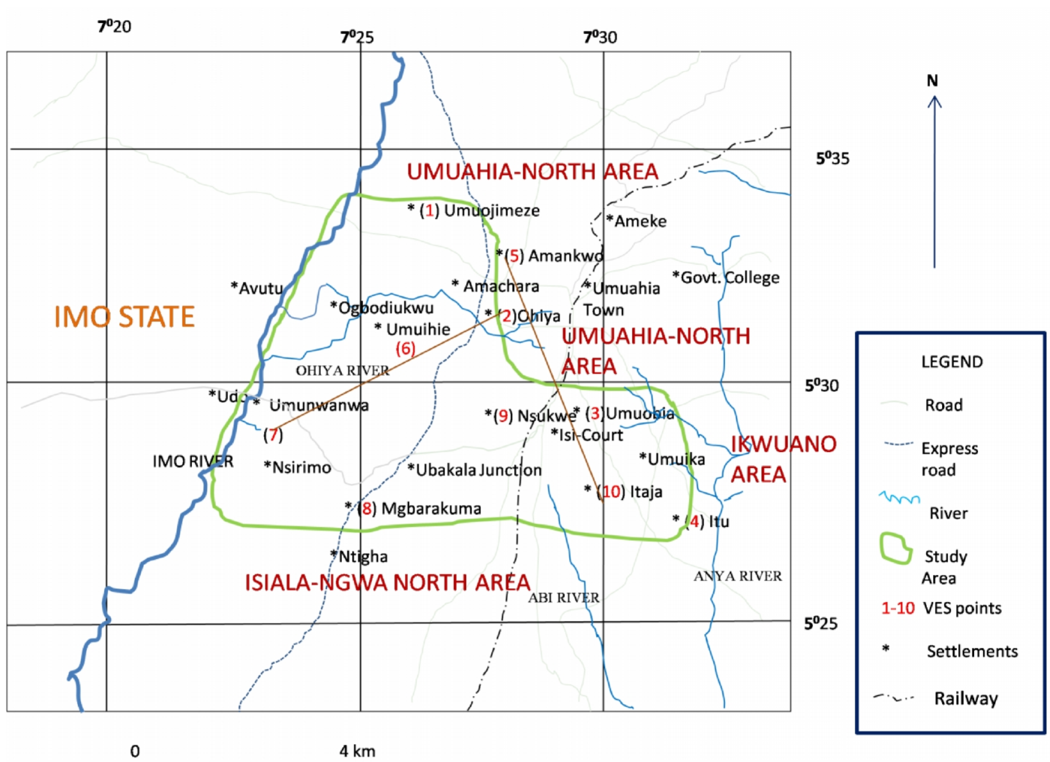

Fig. 3. Map of the Study area showing VES points, major rivers and drainage patterns.

2. MATERIALS AND METHODS

The Vertical Electrical Sounding (VES) method of electrical resistivity survey was employed using the Schlumberger electrode configuration involving four electrodes spacing with two current electrodes ‘AB/2’ widely spaced outside and two potential electrodes ‘MN/2’closely spaced within them all along the survey line as shown in Fig. 4.

A maximum half current electrode spacing 'AB/2' of 370m and a maximum half potential electrode spacing 'MN/2'of 55m was used in the study. The study area was transformed into a regular grid where ten nodal points were chosen as sounding stations at intervals of 4km. Out of the ten sounding stations, three were done at the vicinity of existing boreholes for comparative analysis.

With the location of the sounding point, the Garmin GPS 72 was used in determining the coordinates in longitude, latitude and elevation height above mean sea level. Then the ABEM Terrameter which was used in the data acquisition was deployed to the position where direct current (DC) from the terrameter was passed into the ground using two metal stakes (current electrodes 'AB/2') linked by insulated cables. The current developed a ground potential difference whose voltage was determined using two other electrodes 'MN/2', which were kept in line with the pair of current electrodes.

The observed field data which is the ratio of the resulting voltage to the imposed current is only a measure of resistance of the subsurface (ground resistance). This is read off directly from the terrameter and is used to compute the corresponding apparent resistivity in Ohm-meters by multiplying with the geometric factor 'values as functions of electrode spacing', which then gives the required apparent resistivity results as functions of depths of individual layers: ${}_a = \pi R\left(\frac{L^2-l^2}{2l}\right)$

Where ${}_a$ = Apparent resistivity,
R = Resistance in ohms.
L='AB/2'=Half current electrode spacing (m).
l= MN/2 = Half potential electrode spacing (m).
$\pi\left(\frac{L^2-l^2}{2l}\right)$ = Geometric factor (K).

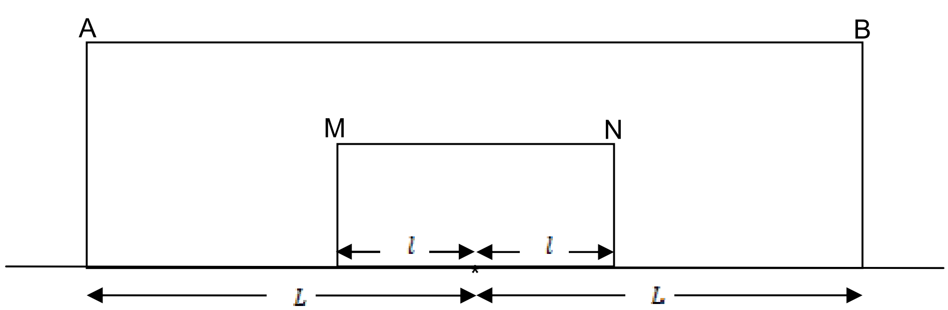

Fig. 4. Schematic diagram of the Schlumberger electrode configuration used.

The sounding curves for each point was obtained by plotting the computed apparent resistivity against the half current electrode spacing (AB/2) on a log-log graph scale paper. The sounding curves were used for the conventional partial curve matching technique and use of auxiliary point diagrams (Zohdy, 1976); and based on this, initial estimates of the resistivities and thicknesses of the various geoelectric layers were obtained and used for computer iteration using RESIT software package.

Furthermore, a borehole was drilled, two more understudied while being drilled and the lithologs outlined with other available lithologs including those sourced from Anambra Imo River Basin Development Authority.

Groundwater samples were collected from different boreholes for physico-chemical analysis. The sampling was carried out at the onset of the rainy season (Middle of April) just when a couple of rainfall had taken place in order to maintain a neutrality in seasonal variation in the data. The physical parameters such as temperature, electrical conductivity, pH, and dissolved oxygen were measured in the field. The concentration of the cations and anions was determined by the Soil and Water Laboratory Department, Federal Ministry of Agriculture and Water Resources, Umuohu-Azueke Ibeku Umuahia (Nigeria). The types of data collected at each locality are listed in Table 2.

3. RESULTS AND DISCUSSION

In pursuit of large scale development of groundwater, it is essential to have a reliable estimate of groundwater potential (Singh, 1985). This is realized by a systematic exploration program using modern scientific tools. Geophysical methods provide valuable information with respect to distribution, thickness, and depth of groundwater bearing Formation. Various surface geophysical techniques are available but the most widely used for groundwater exploration studies is the Electrical Resistivity Method (Olorunfemi, 1999; Afolayan et al., 2004).

This is because the field operation is easy, it can clarify the subsurface structure, delineate groundwater zone and is not expensive. The equipment is also portable; less field manpower is required and has greater depth of penetration. The electrical resistivity method can be best employed to estimate the thickness of overburden and also the thickness of weathered layer. Since groundwater accumulates in sedimentary rocks (sands, gravels, silt, limestone etc), and in weathered overburden, joints, fractures and faults zones in crystalline basement rocks. The electrical resistivity of subsurface materials (rocks, minerals etc.) can be determined by the subsurface resistivity distribution to the ground which is at times related to the physical conditions of interest such as lithology, porosity, degree of water saturation and presence or absence of voids in the rocks (Ako, 2002). The theories of both the electrical resistivity survey and the Schlumberger electrode configuration are well documented in the standard texts like Griffiths and King (1983); Kearey and Brooks (1991); Keller and Frischnech (1966); Telford et al. (1990). The VES method of electrical resistivity survey was chosen because it gives detailed information of vertical succession of individual thicknesses, resistivities and their different conducting zones. In each case, the VES was used to delineate the subsurface stratigraphy based on resistivity differences; from those values the aquifer thickness and other parameters were obtained as shown in Table 3.

Table 2. Data localities and type of data collected for the study

Data Number	Data Location	GPS Reading			Type Of Data
		Elevation (m) m.s.l	Latitude °N	Longitude °E	
GWBB1	Umunwanwa	118.6	5°29.799	7°23.915	PCD, SWL,DHL
GW2/VES8	Mgbarakuma	151.9	5°28.324	7°25.160	VES, PCD, SWL,DHL
GW3	Ahiaukwu	151	5°29.199	7°29.041	PCD, SWL.
GW4	Ubakala junction	164.1	5°28.395	7°25.966	PCD
GW5	Amachara	134	5°32.446	7°27.323	PCD
GW6/VES10	Itaja	150	5°28.132	7°30.526	VES, PCD, SWL,DHL
GW7	Ogbodiukwu	121.6	5°32.033	7°24.409	PCD
GW8/VES3	Umuobia (Isi court)	151	5°29.273	7°28.931	VES, PCD, SWL, DHL
GW 9	Nsukwe	146.5	5°30.079	7°26. 563	PCD, SWL.
GW10	Umuika	141.1	5°28.108	7°30.801	PCD, DHL
VES1	Umuojimeze	109	5°33.749	7°25.823	VES
VES 2	Ohiya	139	5°31.304	7°27.508	;;
VES 4	Itu	141	5°28.106	7°30.803	;;
VES 5	Amankwo (Ihu Park)	138	5°32.516	7°27.503	;;
VES 6	Umuihie	102.8	5°30.506	7°25.200	;;
VES 7	Umunwanwa	122.9	5°29.320	7°24.156	;;
VES 9	Nsukwe	146	5°29.224	7°26.960	;;

** VES = Vertical Electrical Sounding, PCD = Physico-chemical data, DHL = Drill Hole Litholog, SWL = Static Water Level measurement.*

Table 3. VES location points and data showing apparent resistivities and thicknesses of the various geoelectric layers, and aquifer parameters

VES station	Location	GPS Reading			Number of layers	Resistivity of layers (Ωm)	Thickness of layers (m)	Total thickness (m)	Longitudinal conductance S (Siemens)	Layer conductivity σ	Transverse unit resistance of layers R (Ωm^2)	Fitting error (%)
		Elevation (m) m.s.l	Latitude ºN	Longitude ºE								
1	Umuojimeze	109	5º33.749	7º25.823	7	$_1$ = 70 $_2$ = 600 $_3$ = 1300 $_4$ = 1560 $_5$ = 2000 $_6$ = 4500 $_7$ = 8050	t_1 = 0.5 t_2 = 2.5 t_3 = 12.0 t_4 = 22.8 t_5 =44.0 t_6 =79.6	161.4	S_1 = 0.0714 S_2 = 0.0042 S_3 = 0.0092 S_4 = 0.0146 S_5 = 0.022 S_6 = 0.0177 S_T = 0.1391	σ_1 = 0.0143 σ_2 = 0.0017 σ_3 = 0.0008 σ_4 = 0.0006 σ_5 = 0.0005 σ_6 = 0.0002 σ_7 = 0.0001	R_1 = 35 R_2 = 1500 R_3 = 15600 R_4 = 35568 R_5 = 88000 R_6 = 358200	11.6
2	Ohiya	139	5º31.304′	7º27.508′	4	$_1$ =2780.3 $_2$ =1239.5 $_3$ =483.5 $_4$ = 185.0	t_1 =2.5 t_2 = 24.0 t_3 = 218.5	245	S_1 = 0.0009 S_2 = 0.0194 S_3 = 0.4519 S_T = 0.4722	σ_1 = 0.0004 σ_2 = 0.0008 σ_3 = 0.0021 σ_4 = 0.0054	R_1 = 6950.75 R_2 = 29748 R_3 = 105644.75	4.4
3	Umuobia (Isi Court) *	151	5º29.273′	7º28.931′	5	$_1$ = 4080 $_2$ =3979 $_3$ =1876.5 $_4$ =811.5 $_5$ = 177.2	t_1 = 0.6 t_2 =14.0 t_3 = 18.0 t_4 = 226	258.6	S_1 = 1.4706e-4 S_2 = 0.0035 S_3 = 0.0096 S_4 = 0.2785 S_T = 0.2425	σ_1 = 0.0002 σ_2 = 0.0003 σ_3 = 0.0005 σ_4 = 0.0012 σ_5 = 0.0056	R_1 = 2448 R_2 = 55706 R_3 = 33777 R_4 = 183399	3.6
4	Itu	141	5º28.106	7º30.803′	3	$_1$ =2997.5 $_2$ =1007.2 $_3$ =132.8	t_1 =3.0 t_2 = 98.0	101.0	S_1 = 0.0010 S_2 = 0.0973 S_T = 0.0983	σ_1 = 0.0003 σ_2 = 0.0010 σ_3 = 0.0075	R_1 = 8992.5 R_2 = 98705.6	5.4
5	Amankwo (Ihu Park)	138	5º32.516′	7º27.503′	5	$_1$ = 18 $_2$ = 265 $_3$ = 3936 $_4$ = 776 $_5$ = 242	t_1 = 0.5 t_2 = 5.0 t_3 = 20.0 t_4 = 27.0	52.5	S_1 = 0.0278 S_2 = 0.0189 S_3 = 0.0051 S_4 = 0.0348 S_T = 0.0866	σ_1 = 0.0556 σ_2 = 0.0038 σ_3 = 0.0003 σ_4 = 0.0013 σ_5 = 0.0041	R_1 = 9 R_2 = 1325 R_3 = 7872 R_4 = 20952	7.2
6	Umuihe	102.8	5º30.506′	7º25.200′	3	$_1$=1535.1 $_2$ =413.3 $_3$ =118.6	t_1 =5.0 t_2 = 200.0	205.0	S_1 = 0.0033 S_2 = 0.4839 S_T = 0.4872	σ_1 = 0.0007 σ_2 = 0.0024 σ_3 = 0.0084	R_1 = 7675.5 R_2 = 82660	3.0

7	Umunwanwa	122.9	5º29.320'	7º24.156'	4	$_1$ =1878.9 $_2$ =819.4 $_3$ =450.3 $_4$ = 225.1	t_1 =3.0 t_2 = 31.0 t_3 = 224.1	258.1	S_1 = 0.0016 S_2 = 0.0378 S_3 = 0.4977 S_T = 0.5371	σ_1 = 0.0005 σ_2 = 0.0012 σ_3 = 0.0022 σ_4 = 0.0044	R_1 = 5636.7 R_2 = 25401.4 R_3 = 100912.2	3.1
8	Mgbarakuma *	151	5º28.324'	7º25.160'	4	$_1$ =3735 $_2$ =1690 $_3$ =473 $_4$ = 99	t_1 =2.1 t_2 = 19.0 t_3 = 196.0	217.1	S_1 = 5.6225 e-4 S_2 = 0.0113 S_3 = 0.4144 S_T = 0.4263	σ_1 = 0.0003 σ_2 = 0.0006 σ_3 = 0.0021 σ_4 = 0.0101	R_1 = 7843.5 R_2 = 32110 R_3 = 92708	5.1
9	Nsukwe	146	5º29.224'	7º26.960'	4	$_1$ =1320.4 $_2$ =821 $_3$ =475.9 $_4$ = 86.6	t_1 =2.9 t_2 = 16.0 t_3 = 172.0	190.9	S_1 = 0.0022 S_2 = 0.0195 S_3 = 0.3614 S_T = 0.3831	σ_1 = 0.0008 σ_2 = 0.0012 σ_3 = 0.0021 σ_4 = 0.0115	R_1 = 3829.16 R_2 = 13136 R_3 = 81854.8	4.4
10	Itaja *	150	5º28.132'	7º30.526'	7	$_1$ = 225 $_2$ = 2635 $_3$ = 454 $_4$ = 4055 $_5$ = 855 $_6$ = 340 $_7$ = 122	t_1 =1.5 t_2 = 4.5 t_3 = 14.5 t_4 = 36.9 t_5 =52.0 t_6 =77.0	186.4	S_1 = 0.0067 S_2 = 0.0017 S_3 = 0.0319 S_4 = 0.0091 S_5 = 0.0608 S_6 = 0.2265 S_T = 0.3367	σ_1 = 0.0044 σ_2 = 0.0004 σ_3 = 0.0022 σ_4 = 0.0003 σ_5 = 0.0012 σ_6 = 0.0029 σ_7 = 0.0082	R_1 = 337.5 R_2 = 11857.5 R_3 = 6583 R_4 = 149629.5 R_5 = 44460 R_6 = 26180	8.8

** VES station in proximity to existing bore-holes.*

3.1 Geoelectrical Characteristics of the Study Area

3.1.1 Analysis of sounding curves

Sounding curves obtained over a horizontally stratified medium is a function of the resistivities and thicknesses of the layers as well as the electrode configuration (Zohdy, 1976). The calculated apparent resistivity is plotted against the corresponding half the electrode separation (AB/2) to construct the VES curves, and the letters Q, A, K and H are used in combination to indicate the variation of resistivity with depth (Fig. 5). The resistivity type curves of some of the area are as follows: Umuojimeze AA, Umuobia Isi-Court QQ, Mgbarakuma QQ and Itaja KQ respectively. From the sounding curve, Umuojimeze (VES 1) which is AA indicates that the area may not yield high expectations in groundwater exploration.

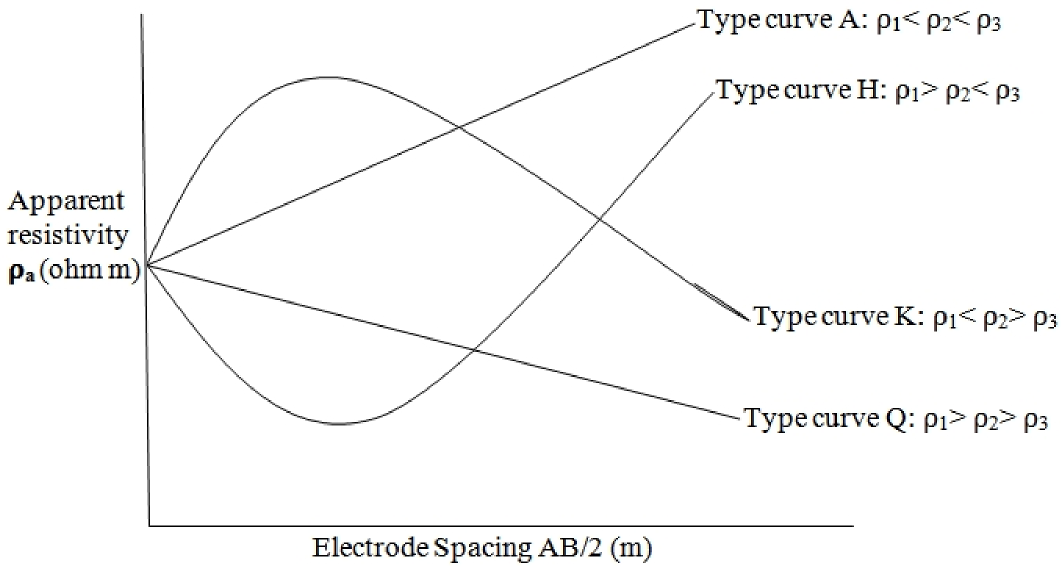

Fig. 5. Schematic diagram of resistivity type curves for layered structures

3.1.2 Geoelectric sections of the study area

Since electrical resistivity of subsurface materials are at times related to the physical conditions of interest such as lithology, porosity, degree of water saturation and presence or absence of voids in the rocks, therefore Electrical Resistivity Measurements determine sub-surface resistivity distributions thus differentiating layers based on resistivity values. So, geoelectric sections are displayed in terms of the relationship between the resistivity of the layers and their thicknesses (Fig. 6a and Fig. 6b). A geoelectric section is thus determined by respective individual layer resistivities ($_i$) and thicknesses (h_i) where the subscript 'i' indicates the position of the layer in the section. A correlation of the geoelectric sections of the study area shows that majority of the area fall under similar geologic settings (Fig. 6a and Fig. 6b).

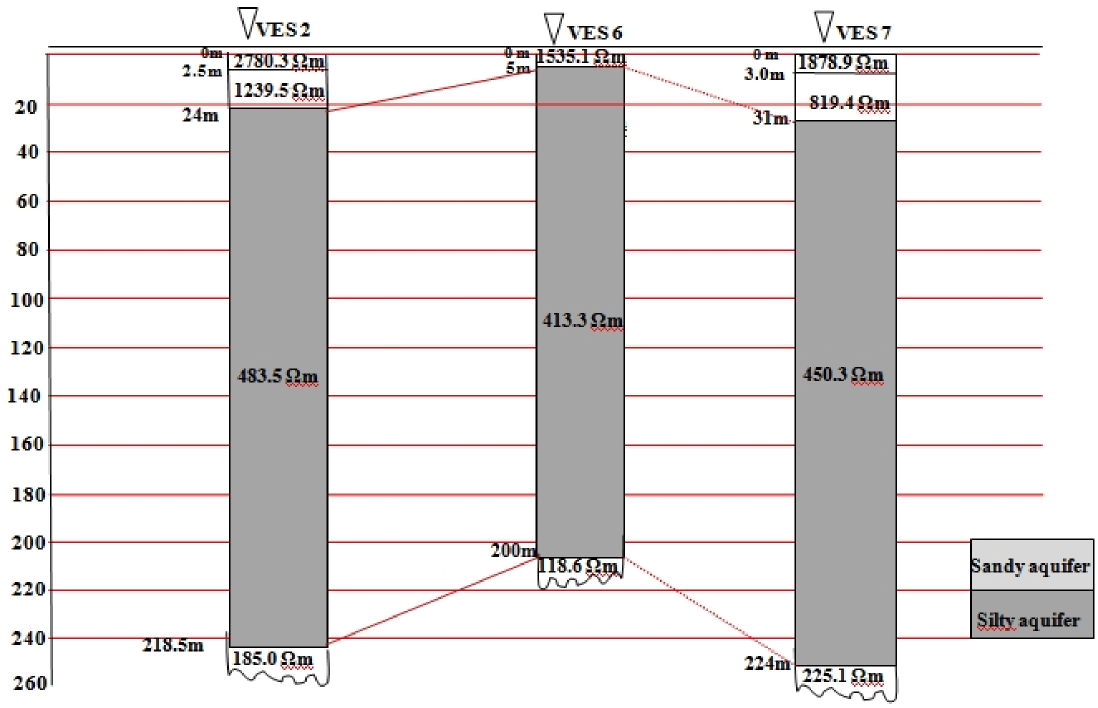

Fig. 6a. Geo-electric sections generated from VES 2, 6 and 7

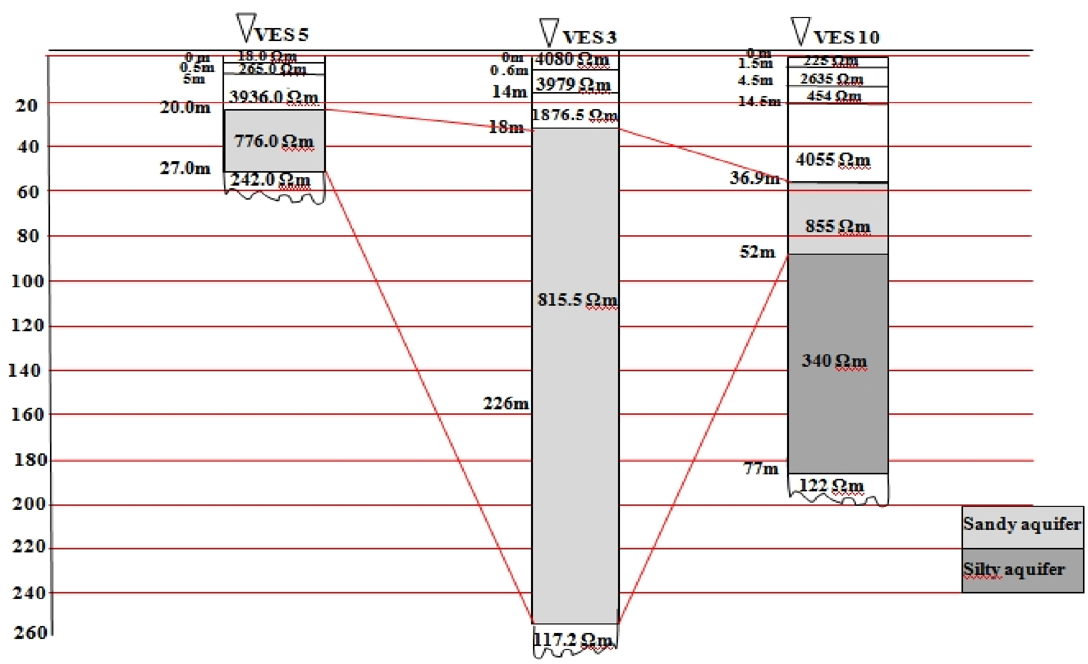

Fig. 6b. Geo-electric sections generated from VES 5,3 and 10.

3.1.3 Aquifers parameters of the study area

The resistivity and thickness of an aquiferous medium is directly related to transmissivity and hydraulic conductivity of the aquifer. The integration of these two data can give an indication of the groundwater potential of the area. Maillet (1947) shows that after obtaining the true thickness; alongside the resistivity of an aquifer from the surface resistivity measurements, the transverse unit resistance 'R' and longitudinal conductance 'S' are calculated (Table 3) using what he called the Dar-Zarrouk variable 'R' and Dar-Zarrouk function 'S'.

$$R = h \quad (1)$$

$$S = h/ \quad (2)$$

Where h and = thickness and resistivity of individual layers respectively.

The longitudinal conductance 'S' of equation (2) can also be computed as

$$S = \sigma h \quad (3)$$

Where 'σ' is layer conductivity.

Conductivity as expressed here is analogous to the layer transmissivity 'T'.

$$T = Kh \quad (4)$$

Where K and h = hydraulic conductivity and thickness of individual layers respectively.

Recall from equation (3) that $S = \sigma h$;

$$\text{Therefore, } S/\sigma = h \quad (5)$$

Recall also, from equation (4) that $T = Kh$;

$$\text{Therefore, } T/K = h \quad (6)$$

Now, substituting the value of 'h' in equation (5) into equation (6), we obtain

$$T/K = S/\sigma;$$

$$\text{Therefore, } T = KS/\sigma \quad (7)$$

Recall from equation (5) that $S/\sigma = h$; and from equation (1) that $R = h$,

$$\text{Therefore, } R/ \ = h, \quad (8)$$

Now, substituting the value of 'h' in equation (5) into equation (8), we obtain

$$R/ \ = S/\sigma;$$

$$\text{Therefore, } \sigma R = S \quad (9)$$

Recall also, from equation (2) that $S = h/$;

$$\text{Therefore, } S \ = h \quad (10)$$

By substituting the value of S in equation (10) into equation (9), we obtain

$$\sigma R = h \quad (11)$$

Now, from the above derivations, transmissivity 'T' can be expressed as:

$$T = KS/\sigma = Kh \ = K\sigma R \quad (12)$$

Dar-Zarrouk parameters have since been used in the estimation of aquifer hydraulic characteristics (Johnson, 1977; Niwas and Singhal, 1981a, b).

In areas of similar geologic setting and non varying water quality, (Niwas and Singhal, 1981a) were able to show that that the product of both conductivities 'Kσ' remains fairly constant. If values of 'K' are obtained from existing boreholes, and the values of 'σ' are obtained from VES data interpretation within the vicinity of a borehole. Then, the transmissivity can be estimated, and its variation determined from one location to the other where no borehole is located by using parameters 'R or S' and the choice of parameter is dependent upon the values of 'σ' and ' h'. Present study shows VES Stations 2,6,7,8 and 9 are within area of similar geologic setting and water quality, while VES 5 and 3 are of same geologic setting and water quality, but VES 10 have both characteristics (Table 3, Fig 6a and Fig 6b).

From Table 3, the increasing resistivity (low conductivity) values of the sediments of Umuojimeze (VES 1) with depth indicates the absence of a high conducting layer which could have been the trap (bottom seal) for a favourable aquiferous unit. This finding has corroborated with sounding curve AA of VES 1 showing that the area may not yield great expectations in bore-hole exploration but could be a good source of friable sands for construction purposes. This may be the major cause of bore-hole failures in this type locality of Ogwashi-Asaba Formation (Table 1) which is a lower member of the Benin Formation (Insert in Fig. 2). Also, borehole productivity within the vicinity of VES 4 is doubtful because of the relatively depth restricted resistivity (low conductivity) values of the sediments.

3.1.4 Estimation of aquifer hydraulic parameters of the study area

The determination of aquifer hydraulic parameters, transmissivity (*T*), and hydraulic conductivity (*K*) through analysis of pumping test has been done in some parts of the study area by the State Water Board (Table 4). The average field hydraulic conductivity (*K*) derived from the pumping test was further used to calculate the transmissivity (*T*) of the same boreholes from data (thickness) acquired through surface resistivity soundings (Table 4), and subsequently used in places where pumping test is not available for the determination (estimation) of aquifer hydraulic parameters using graphical approach (Fig. 7).

Table 4. Hydraulic parameters of the study area

Data Location/ Number	Average Field Hydraulic Conductivity (m/d)	Calculated hydraulic parameters based on pumping test (SWB 1988).		Calculated hydraulic parameters based on surface resistivity soundings 'VES' (Present study).	
		Screen length (m)	Transmissivity (m^2/d)	Thickness of Aquiferous zone (m)	Transmissivity (m^2/d)
Mgbarakuma GW2/VES8	10.80	12	129.6	196	2116.8
Itaja GW6/VES10	8.45	15	126.75	52	439.4
Umuobia (Isi Court) GW8/VES 3	8.65	12	103.8	226	1954.9

Statistical estimation of aquifer hydraulic parameters based on existing data has been done using linear regression analyses and correlation coefficients (Davis, 1986; Brown, 1998; Edet et al., 2005). However, we used the graphical approach by plotting the calculated values (Table 4) based on surface resistivity soundings, and determining the slope through a line of best fit in a graphical representation (y = mx, y/x = m,); where y = transmissivity, m (slope) = hydraulic conductivity and x = aquifer thickness (Fig. 7). This estimation is in line with area of similar geologic setting and water quality. Recall that VES Stations 2,6,7,8 and 9 are within area of similar geologic setting and water quality, while VES 5 and 3 are of same geologic setting and water quality, but VES 10 exhibit both characteristics (Table 3, Fig 6a and Fig 6b). Therefore line of best fit was made to pass through the resistivity-calculated value (transmissivity) of VES 10 and the resistivity-calculated upper VES values (transmissivity) of the two different geologic settings. In the graph below, the blue line is that of VES Station 8, while that of VES Station 3 is red. Since VES Stations 2,6,7,8 and 9 are within area of similar geologic setting and water quality, the intercept of the blue line (slope) is used in the estimation of aquifer hydraulic parameters of VES Stations 2, 6, 7 and 9. While, the intercept o f the red line (slope) is used in the estimation of aquifer hydraulic parameter of VES Station 5 (Fig. 7).

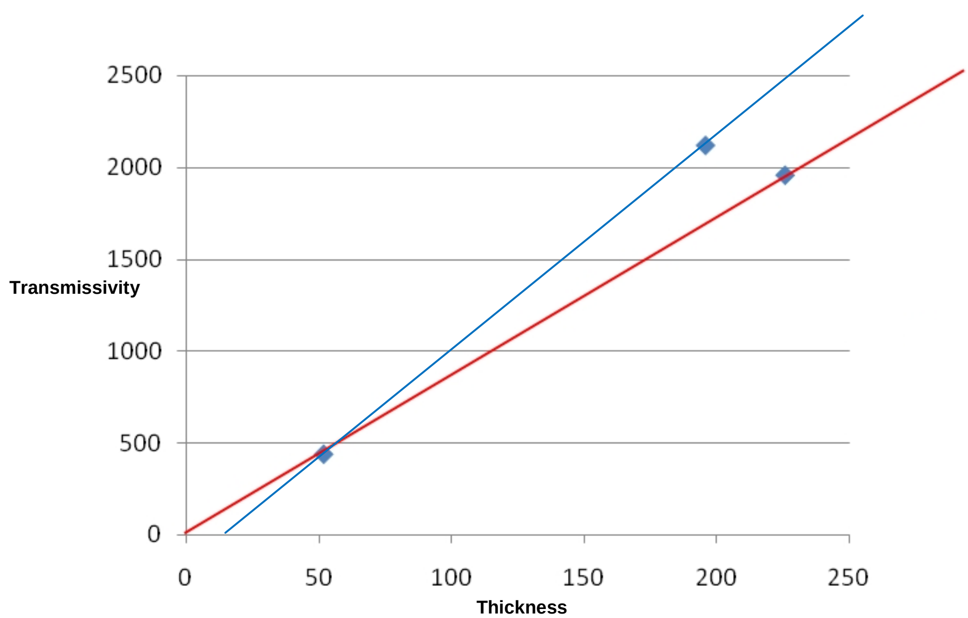

Fig. 7. A plot of Aquifer transmissivity versus thickness.

Based on the graphical illustration in Fig. 7 above, the aquifer hydraulic parameters such as hydraulic conductivity, and transmissivity are determined (estimated) once the aquifer thickness is known. This method was used in estimating the aquifer hydraulic parameters of the study area as shown in Table 5 below.

Table 5. Estimated hydraulic parameters of the study area

Data Location/ Number	Thickness of Aquiferous zone in x-axis. (m)	Calculated hydraulic parameters based on surface resistivity soundings (VES) using the graphical approach.	
		Transmissivity in y-axis (m^2/d)	Hydraulic Conductivity as slope "m" (m/d)
Ohiya (VES 2)	**218.5**	2410.06	**11.03**
Amankwo (VES 5)	**27.0**	250	**9.26**
Umuihe (VES 6)	**200.0**	2150	**10.75**
Umunwanwa (VES 7)	**224.1**	2415.80	**10.78**
Nsukwe (VES 9)	**172.0**	1900	**11.05**

This method is indeed an alternative approach since pumping tests are not normally run due to their high cost and lack of equipment. However, because the data population of the study area from which they were generated is relatively small, this might affect the accuracy. In spite of that, the estimated data presented here are representative and can be of significant value as a guide to groundwater resource development in the study area.

3.2 Hydrogeological Characteristics of the Study Area

3.2.1 Lithologs of the study area

From lithologic deductions and drill-hole data, locations of VES 2, 6, 7, 8, 9 and their environs exhibit a thickness of about 60m of silty-sand aquiferous unit occurring as second aquifer in some places (Fig. 8). This multi-aquifer status could not be detected in geo-electric sections generated from VES survey (Fig. 6a and 6b), but was indicated as a very thick aquiferous unit of slightly below or above 200m. This silty-sand aquiferous unit in some localities is sandwiched between two sandy aquifers, an upper unconfined or confined aquifer, and a lower confined aquifer. See GW1 and GW6/VES 10 (Fig. 8), though it may appear as first aquifer in some areas. See GW 2/VES 8 and GW 10 (Fig. 8).

This silty-sand aquifer is the source of discolouration being experienced in some groundwater samples in the study area due to the slightly high iron content (Table 7). The water is clear when pumped and when left exposed for some hours develops a film-like cover and subsequently a reddish-brown colour. After several days, clay-like particles settle at the bottom of the container and clean water is recovered.

3.2.2 Hydrostratigraphy of the study area

While drilling Umunwanwa (GW1), the first saturated unit encountered at a depth of about 34.2m is clean sands. The second saturated unit encountered at a depth of about 57m is silty-sands that appeared to be very clean when collected but changed to reddish-brown after about three days. This silty-sand aquifer is about 54m thick in this locality with an upper thin lignite seam and lower thin clay seal. Because of the thickness, clean appearance and highly saturated nature of this silty-sand aquifer, unprofessional drillers who are in a hurry end up tapping the aquifer which is the source of the discoloured water observed in the area. But armed with our VES 7 survey data, the Electric log profile, and the continuous hydrochemical analysis of the samples, we were determined to drill to a depth of 200m before a thin clay layer of about 0.9m ushered in a third saturated unit of clean fine-grained sandy aquifer at a depth of about 100m. The rock samples did not change colour upon exposure for days and the hydrochemical analysis indicated relatively low iron content compared to the silty-sand aquifer as shown in Table 7. This 0.9m thick clay layer plays a very significant role in Ohiya (VES 2), Umuihie (VES 6), Umunwanwa (VES 7) and neighbouring Nsirimo aquifers. This thin layer is the bottom seal of almost a 60m-thick saturated silty-sand aquifer in these localities.

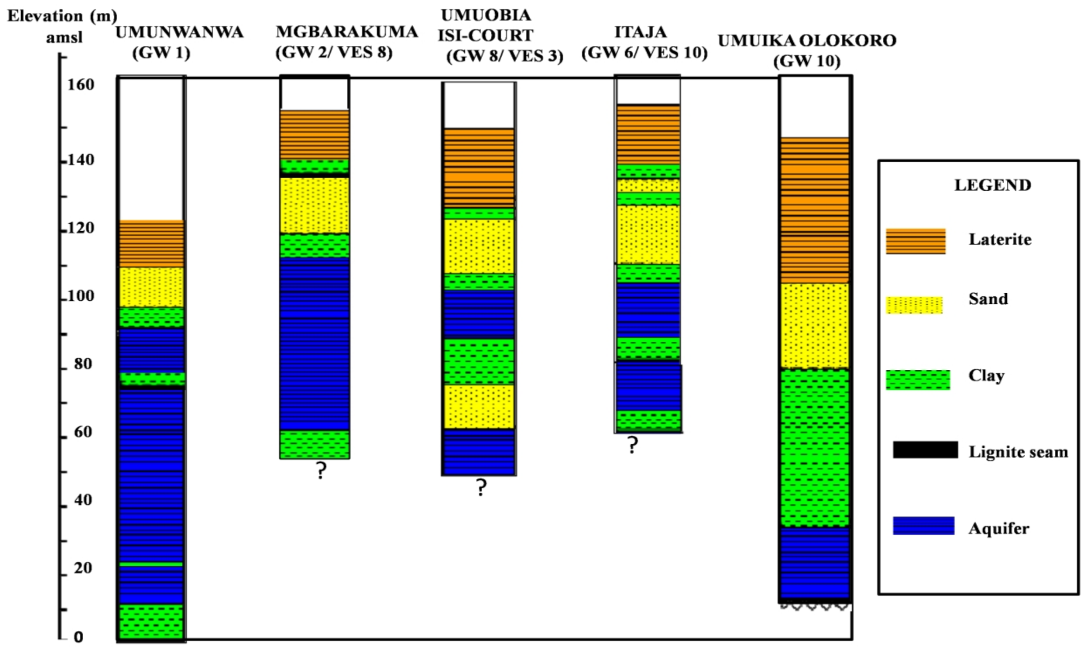

Fig. 8. Lithologs of some boreholes in the study area

In Fig. 9 below, a correlation of Geo-electric section of VES 7, the Litholog of borehole (GW1) and Electric log profile of another borehole all in Umunwanwa locality was done. A close examination of the resistivity log profile at 100m depth reveals a little kick to the left (Long Norm) and also a little kick to the right (Long Lat) thus indicating the presence of a high conducting layer but this is normally suppressed because of the thinness (0.9m) of the layer.

The aquifer system in the study area is a multi-storey system with an unconfined to confined upper aquifer, followed by a confined second aquifer and a third aquifer. It is imperative to state here that the upper unconfined layer may be missing in some locations thus giving rise to the confined second aquifer being the first aquifer to meet in some locations (GW1, GW2 and GW10 in Fig. 8).

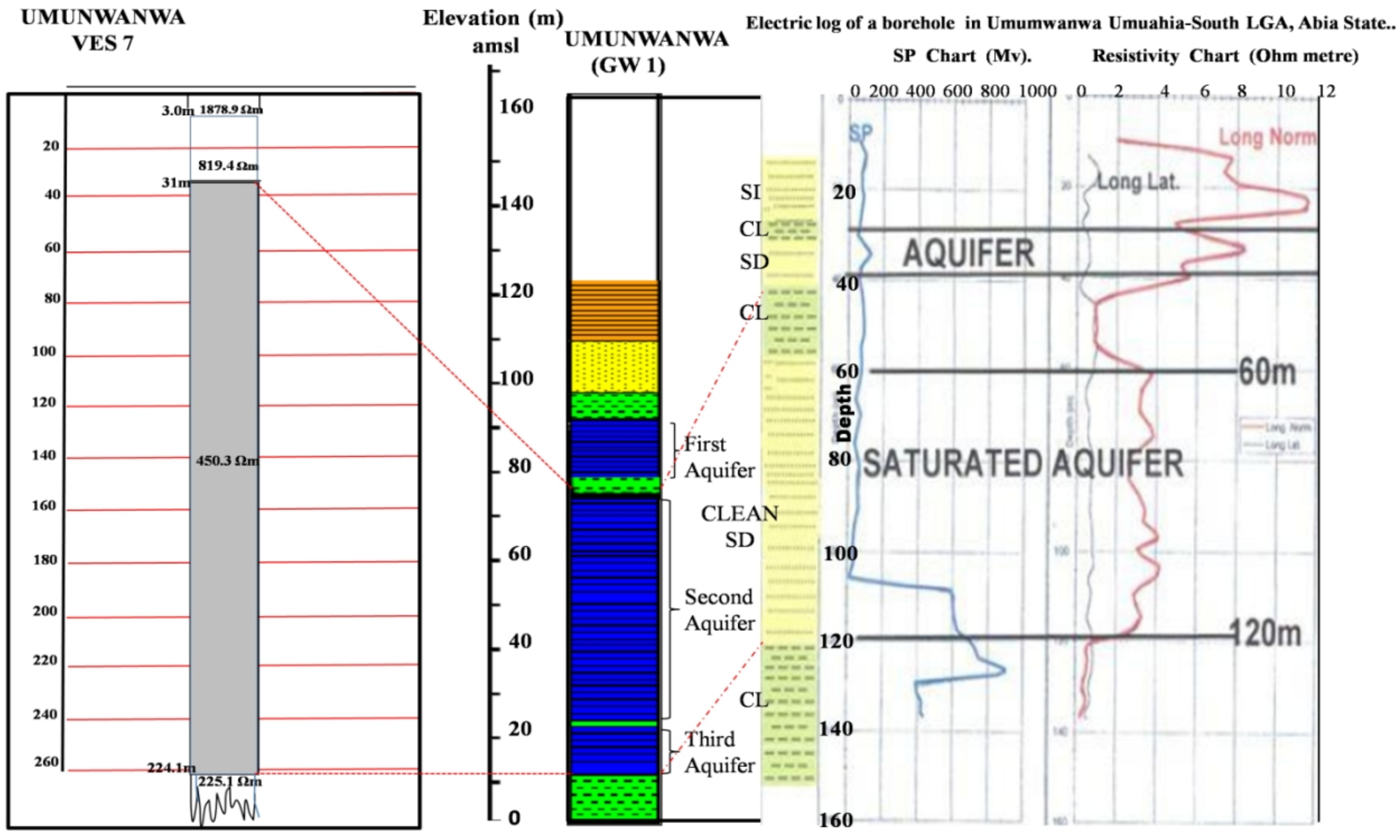

Fig. 9. A correlation of Geo-electric section of VES 7, the litholog of borehole (GW1) and Electric log profile of another borehole in Umunwanwa

** Source of Electric log profile: Anambra Imo River Basin Development Authority Owerri (Ukandu et al., 2011).*

3.2.3 Borehole characteristics of the study area

The groundwater of the study area recharges mainly through infiltration of surface runoff water (Fig. 10), while it discharges towards the Imo River in the western part, the Anya River in the eastern part and through artificial pumping for different purposes. The depth to groundwater is shallowest in the western parts and shows an increasing trend down south. Compare depth to groundwater at Umunwanwa GW1 (34.2m) in the west and 113.0m at Umuika GW10 in the east (Fig. 8). Other values of **borehole** characteristics generated from the present study are shown in Table 6.

Table 6. Borehole Characteristics of the study area

Data Locality	Surface elevation (amsl)	Top of well elevation (amsl)	Well depth (m)	Static water level (m)	Pressure head (m)	Elevation head (m)	Hydraulic head (m)
Umunwanwa (GW1)	118.6	118.9	97.5	34.2	63.3	21.4	84.7
Ahiaukwu (GW3)	155.1	155.4	94.5	39	55.5	60.9	116.4
Itaja (GW6/VES 10)	151	151.3	94.5	41	53.5	56.8	110.3
Mgbarakuma (GW 2 / VES 8)	151.9	152.2	98.5	46	52.5	53.7	106.2
Umuobia (Isi-Court) GW 8 / VES 3	150	150.3	100.6	39	61.6	49.7	111.3
Nsukwe (GW 9)	146.5	146.8	91.4	38.2	53.2	55.4	108.3

**All values are measured in metres.*

3.3 Hydrogeochemical Characteristics of the Study Area

3.3.1 Water type and quality of the study area

The groundwater analyses (Table 7) show that physical and chemical parameters are within acceptable limits for either drinking water or general domestic use. However, all samples did not meet the pH standard of 6.5–8.5 stipulated for drinking water.

The dominant chemical ion in the groundwater of the study area is Sodium bicarbonate as shown in Table 7 except at Umuika where Calcium chloride dominated. The low salinity as indicated by the low electrical conductivity and low total dissolved solids and the enrichment of the groundwater by more bicarbonate than chloride is attributed to fresh-water recharge to the overburden by rainfall.

Table 7. Physico-Chemical Parameters of Groundwater samples in the study area

Data Location / Number	Well Depth (m)	Temp (oC)	Cond. (μs/cm)	pH	TDS (mg/l)	TSS (mg/l)	Fe2+ (mg/l)	Ca2+ (mg/l)	Mg2+ (mg/l)	Na2+ (mg/l)	K+ (mg/l)	HCO3 (mg/l)	Cl- (mg/l)	SO4 2- (mg/l)	NO3 - (mg/l)
Umunwanwa	40.0	29.5	41.3	4.50	20.50	ND	0.01	0.40	0.05	2.15	0.09	30.00	5.30	ND	ND
(GW1)	***97.3***	***28.5***	***30.6***	***4.50***	***15.20***	***1.5***	***0.12***	***0.60***	***0.12***	***2.40***	***0.54***	***30.50***	***5.86***	***ND***	***ND***
5º29.799´N	110.0	29.0	28.8	4.96	14.30	ND	0.07	0.60	0.16	2.56	0.17	38.00	5.67	ND	ND
7º23.915´E															
Umuika-Ukwu Olokoro 05º28.108´N 07º30.801´E	150.0	28.0	4.6	6.48	2.28	25.50	0.10	7.70	1.40	3.55	2.54	185.00	0.01	ND	ND
Umuobia (Isi-Court) 05º29.273´N 07º28.931´E	100.6	30.5	14.7	4.87	7.30	1.02	0.02	0.50	0.08	2.40	0.15	30.00	5.30	ND	ND
Mgbarakuma 05º28.324´N 07º25.160´E	98.5	29.0	23.2	5.57	11.60	ND	0.01	0.45	0.06	2.12	0.15	45.00	4.65	ND	ND
Ubakala Junction 5º28.395´N 7º25.966´ E	82.0	30.5	13.9	4.97	7.00	1.02	0.02	0.40	0.05	2.10	0.12	30.00	5.50	ND	ND
Amachara 05º32.446´N 07º27.323´E	73.1	27.5	20.6	4.59	10.30	ND	0.06	0.45	0.06	2.00	0.15	30.50	6.00	ND	ND

Ogbodiukwu Umuorinoku 5º32.033´N 7º24.409´E	73.1	28.5	35.4	5.30	16.70	ND	0.03	0.75	0.20	3.02	0.20	45.00	5.65	ND	ND
Ahiaukwu, Olokoro-2 05º29.199´N 07º29.041´E	61.0	29.5	31.2	4.97	14.70	ND	0.01	0.40	0.05	2.30	0.10	30.00	5.65	ND	ND
Nsukwe 5º30.079´N 7º26.563´E	72.0 ***91.4***	30.5 ***30.0***	21.0 ***19.0***	4.56 ***5.40***	10.70 ***9.50***	ND ***1.0***	0.01 ***0.11***	0.54 ***0.30***	0.08 ***0.07***	3.10 ***2.30***	0.14 ***0.12***	45.50 ***30.50***	5.65 ***5.67***	ND ***ND***	ND ***ND***
Itaja 5º28.132´N 7º30.526´E	90.0 ***94.5***	30.0 ***30.0***	33.0 ***42.0***	4.80 ***5.10***	16.40 ***21.00***	1.0 ***3.0***	0.02 ***0.40***	0.50 ***1.70***	0.08 ***0.60***	3.00 ***3.10***	0.14 ***0.60***	30.50 ***45.00***	5.30 ***5.30***	ND ***ND***	ND ***ND***
WHO LIMITS		25	< 500	6.5-8.5	50-750	10-25	< 2.5 < 0.3	<500	< 50	< 5	<75	<250	< 50	NS	NS

**ND = Not Detected. NS = Not Stated. Parameters of silty-sands unit are displayed in bold red italics.*

By using the concept of hydrogeochemical facies (Morgan and Winner, 1962; Back, 1966) two types of hydrochemical facies are identified: The dominant sodium and potassium bicarbonate chloride (Na+ K-HCO_3-Cl) and the subordinate calcium and magnessium bicarbonate chloride facies (Ca+Mg-HCO_3-Cl).

Hydrogeochemical facies are used to denote the diagnostic chemical character of water solutions in hydrogeologic systems whereby the facies reflect the effect of chemical processes occurring between the minerals of the lithologic framework and groundwater.

3.3.2 Origin and evolution of major chemical constituents

The study has revealed that the area is characterized by sand and silty-sand aquiferous units. Silt is sediment that falls between clay and sand in the Grain Size Scale and ranges from 0.002mm to 0.0625mm, and therefore could be defined as sediment composed of very fine sand, clay particles and other materials. Siltstones differ from sandstone due to their smaller pores and propensity for containing significant clay fractions.

A plot of TDS values versus the ratio Na/(Na+Ca) of the groundwater of the study area on a Gibbs (1970) diagram as shown in Fig.10 indicates that the water originates as direct rainfall.

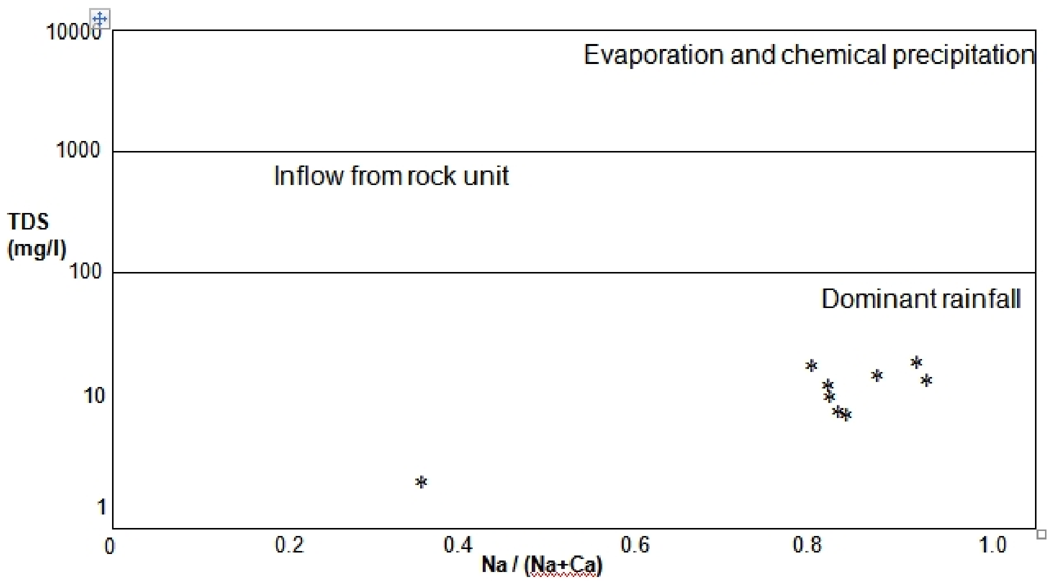

Fig. 10. Gibbs diagram of ratio of Na/ (Na+Ca) versus the Total Dissolved Solids (TDS) of water samples in the study area. (After Gibbs, 1970)

The huge presence of kaolin deposits in Ohiya, and some other clay deposits in parts of Umuahia-South Area may give a clue to the evolution of the groundwater chemistry. The knowledge of the mechanisms controlling the distribution of trace elements in clays is scarce and contradictory, in spite of the many investigations carried out on the geochemical behaviour of some trace elements used in geological reconstruction as “geochemical indicators” (Fiore et al., 2003).

It is well known that clays contain trace elements whose concentrations are widely variable depending on their geological history, and these trace elements may be in the clay (or accessory) mineral structure as well as adsorbed on clay particles. This plays the most important role in controlling their distribution and abundance because chemical elements in crystalline positions are usually “locked,” whereas those adsorbed may be mobilized and transferred to leaching solutions. The type of clay mineral formed during the decay of rocks containing Aluminium silicates and Feldspars is influenced by the climate, the Aluminium/Silicon ratio, and pH. The deposits of the study area being of continental origin may owe its provenance to Oban massif and the weathering of Albite in the crystalline rocks may have released Na+ HCO_{3-} and Kaolinite (Gascoyne and Kamineni, 1994). Thus, the dominance of sodium bicarbonate (Na+ HCO_{3-}) in the groundwater samples of the study area is understood.

The conditions conducive for Kaolinite formation are strong dissolution of $Ca^{2+,}$ $Mg^{2+,}$ Na^+ and K^+ ions and the presence of H^+ ions (pH 4–5) (Parker, 1988), and all these chemical ions and pH range are present in the groundwater of the study area (Table 4). Kaolinite can also be categorized according to whether it remained at the place of formation or was transported. Owing to the different ways in which kaolin can form, several kinds of minerals may occur in natural kaolins such as quartz, mica, muscovite, and feldspar (Patterson and Murray, 1975). This corroborates Petrographic analysis of Onyeagocha (1980): 95-99% quartz grains, 1-2.5% of Na+K-mica, 0 -1.0% of Feldspar and 2-3% of dark coloured minerals.

4. CONCLUSION

Since a complete evaluation of a hydrogeological unit comprises the availability, productivity and quality of the groundwater. This research has provided thorough information on the hydrogeological conditions of the study area. Geoelectrical and hydrogeological studies were useful for delineating the aquifer systems and the hydrogeochemical facies also aided in the characterization. The geoelectrical data guided the estimation of aquifer hydraulic characteristics such as hydraulic conductivity and transmissivity. Based on all the findings made in the interpretation of the VES data, VES stations 1 and 4 are likely to record borehole failures. Other VES Stations are indicative of good potential for groundwater. The study area is characterized by medium-grained, fine-grained and silty-sand saturated units. The locations of silty-sand saturated units are prone to water discolouration due to the relative high iron content. Thus, for exploration and development of the aquifer systems in the study area; shallow boreholes less than 55m are best developed in such areas where these conditions prevail, whereas deep boreholes greater than 94.5m are best developed where shallow saturated unit is not encountered. Despite the above recommendation, a complete hydrogeological analysis should be done prior to, and during development of borehole. The study has revealed that evolution of the major ions in the groundwater results from the local geology, and the aquifer systems in the area are recharged naturally through precipitation. Also, the physical and chemical parameter values are within the accepted national and international standards for drinking, domestic and agricultural purposes. Physico-chemical and microbiological analysis of rainwater, groundwater, spring and river water in the wet season and dry season respectively will be carried out in our future research. For better management of the resources, PVC materials are recommended for borehole construction and pipelines; and these facilities should not be located near pit latrines and waste-disposal sites. We hereby conclude that the data presented here are representative and can be of significant value as a guide to groundwater resource development in the study area.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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