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Geo-electrical Delineation and Geochemical Characteristics of Aquifer Systems in Kwa-Ibo River Watershed, Abia State, Nigeria

C. Amos-Uhegbu[1*], M. U. Igboekwe[1], G. U. Chukwu[1], K. O. Okengwu[2] and K. T. Eke[3]

[1]Department of Physics (Geophysics group) Michael Okpara University of Agriculture, Umudike, P.M.B 7267 Umuahia, Abia State, Nigeria.
[2]Department of Geology, University of Port-Harcourt, P.M.B 5323 Port-Harcourt, Nigeria.
[3]Department of Physics/Electronics, Abia State Polytechnic, P.M.B 7166 Aba, Abia State, Nigeria.

Authors' contributions

In carrying out this work, all authors were actively involved in the field investigations. Authors CAU and MUI designed the study. Author CAU 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 KTE carried out the geophysical data analysis. Authors CAU and KTE managed the literature searches. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

Kwa-Ibo River watershed of Abia State, Nigeria cuts across four Local Government Areas in the State and lies geologically within the Benin Formation of Niger Delta Basin. Due to the prolific nature of Benin Formation aquifers, preliminary investigations for groundwater exploitation are seldom done but due to the recent borehole failures and the ever increasing population density of the area, a proper documentation of the hydro-geological conditions of the area is essential. This led to a geo-electrical investigation whereby thirteen Vertical Electrical Sounding (VES) data were acquired and the computer-aided Resist software method was used for further processing and interpretation. The interpretation of the VES data reveals the existence of three to seven geo-electric layers

**Corresponding author: E-mail: nenyemos@yahoo.com;*

in the area and a variation in aquifer thicknesses with the least as 101m at VES Station 4 and the highest as 324m at VES Station 2. A comparison of some geo-electric sections generated from VES stations with some lithologs gave a good geological description of the study area. Water samples were taken from eleven boreholes for hydro-geochemical investigation which reveals the occurrence of two major groundwater types in the area with Calcium+Magnesium chloride bicarbonate [(Ca+Mg)-HCO_3 + SO_4^{2-}Cl] dominating in the entire area except in the North-western part where Sodium+Potassium chloride bicarbonate [(Na+K)-HCO_3-Cl] dominates. Further analysis shows that the geochemical processes resulting from the major geologic controls are chloride dissolution, silicate weathering, carbonate weathering and ion exchange and by using Gibb's Diagram the recharge occurs through precipitation while the local geology is the source of major ion concentrations in the samples.

Keywords: Watershed; Kwa-Ibo River; aquifer characteristics; hydro geochemical facies.

1. INTRODUCTION

A watershed is commonly defined as an area of land where all of the water that is under it, and on it, runs off and drains into a common place. Hydro-logically, a watershed is a useful unit of operation and analysis because it facilitates a systems approach to water and land use in interconnected upstream and downstream areas.

Kwa-Ibo river watershed of Abia State, Nigeria lies within latitudes 5º19' and 5º30' N and longitudes 7º30' and 7º35' E (Fig. 1).

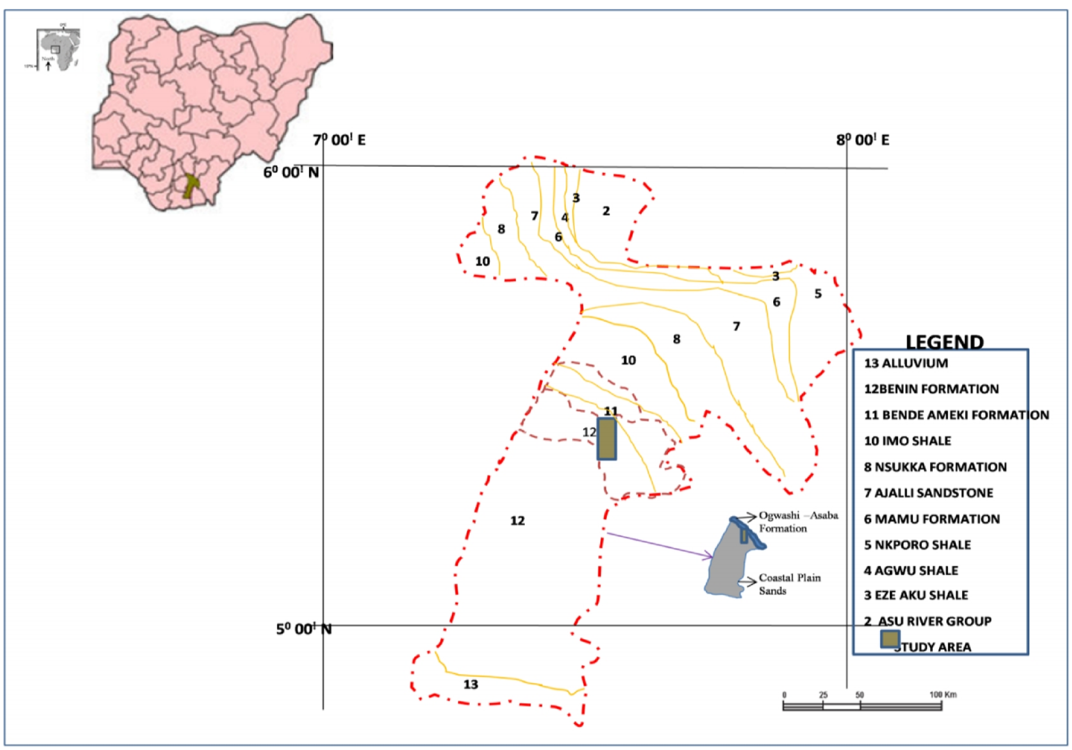

Fig. 1. Geologic Map of Abia State of Nigeria showing the study area

The area has high relative humidity values over 70% and is characterized by high temperatures of about 29º–31ºC [1]. It 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.

Kwa-Ibo River watershed of Abia State stretches across four Local Government Areas of the state. The southernmost part of Umuahia-North Local Government Area, the easternmost part of Umuahia-South Local Government Area, the westernmost part of Ikwuano Local Government Area and the North-eastern part of Isiala-Ngwa north (Fig. 2).

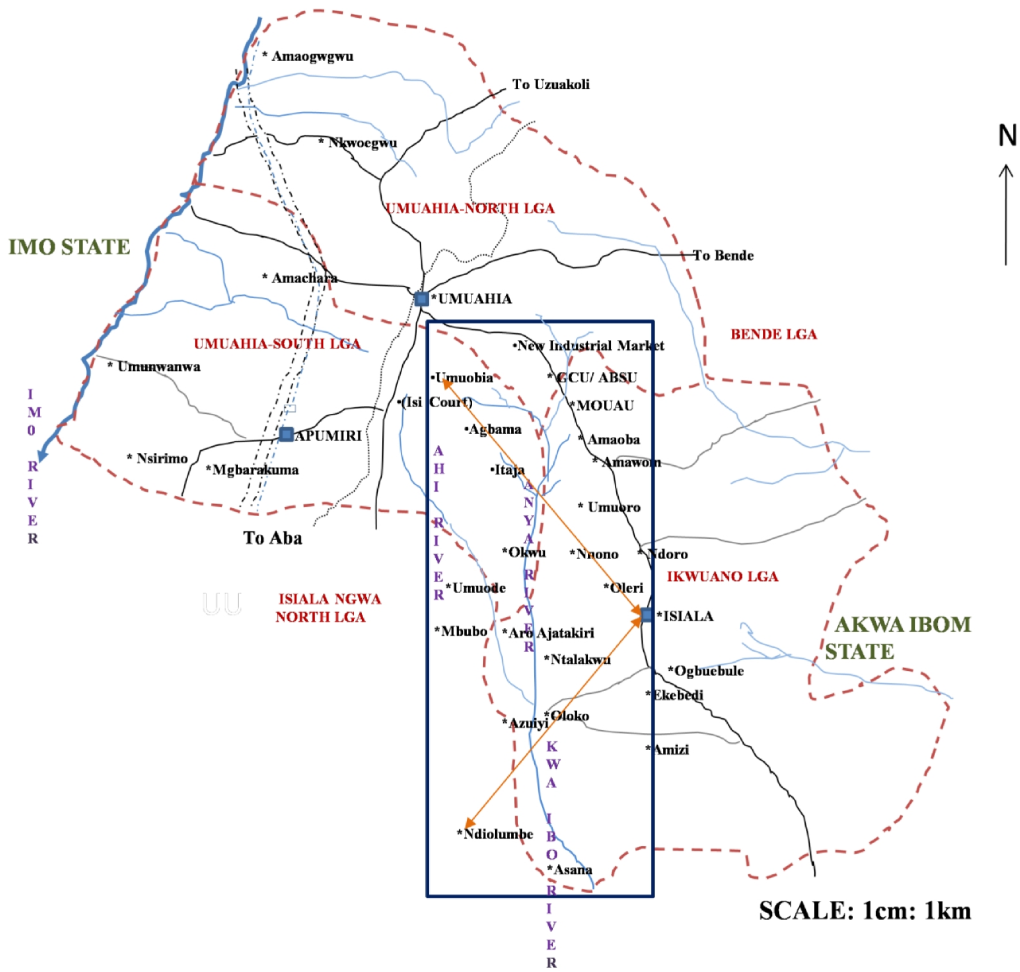

Fig. 2. Map of the Study area Kwa-Ibo River Watershed of Abia State in rectangular grid.

The area is endowed with natural springs and streams including Anya River which flows from the northern boundary through the study area in a south-westerly direction; while Ahi River the westernmost counterpart joins Anya River which with other tributaries outside the study area forms the main tributary of the great Kwa Ibo River of Akwa Ibom and Cross River States of Nigeria (Fig. 2).

Geologically, the study area lies in the eastern part of the Cenozoic Niger Delta Basin of Nigeria. Cenozoic Niger Delta sedimentary basin was formed from the interplay between subsidence and deposition arising from a succession of sea transgressions and regressions [2,3]; 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 10,000meters.

The age of Benin Formation is Oligocene to Recent in the subsurface and also as surface outcrop in the northern parts of Western Niger Delta basin and also in some parts of Umuahia area of the Eastern Niger Delta. This upper part of Benin Formation is known as Ogwashi-Asaba Formation; while the younger southern part which is Miocene to Recent in age is known as Coastal Plain Sands.

The study area comprises sediments of the Oligocene to Recent Ogwashi-Asaba Formation and Miocene to Recent Coastal Plain Sands as shown insert in Fig. 1 and Table 1 respectively.

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

Age	**Surface outcrop equivalent formation**	**Subsurface formation**	**Mega depositional environment**
Miocene - Recent	Coastal Plain sands	Benin Formation	Paralic continental
Oligocene - Recent	Ogwashi-Asaba Formation	Afam clay member	Continental delta plain
Eocene - Recent	Bende-Ameki Formation	Agbada Formation	Paralic delta front
Paleocene – Recent	Imo Formation	Akata Formation	Marine pro-delta
Maastrichtian - Paleocene	Nsukka Formation	Equivalents not known	Pro-delta successions
Maastrichtian	Ajali sandstone		,,
Campanian	Mamu Formation		,,
Santonian - Maastrichtian	Nkporo-Enugu shale		,,
Turonian - Coniacian	Awgu shale		,,
Turonian	Eze-aku shale		,,
Albian	Asu-river group		,,

**Modified after Short and Stauble [3].*

The area is made up of communities located within the south central parts of Umuahia area and few communities located within the North eastern parts of Isialangwa North area (Fig. 2).

National Cereals Research Institute, Forestry Research Institute, Abia State University Practical Agricultural Campus, National Root Crop Research Institute and Michael Okpara University of Agriculture are all located within the watershed.

Despite the fact that the study area is endowed with perennial springs and streams which are not associated with water-borne diseases, the increase in population has led to indiscriminate sinking of boreholes. This requires special management and protection and a thorough knowledge of the hydro-geological system is a precondition for any management and protection strategy.

To meet this, the development of groundwater resources and the regime of its activity largely depend on the determination of aquifer characteristics. These properties are important in determining the natural flow of water through an aquifer and its response to withdrawal of fluid but are best done through well data and pumping 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 geo-electrical methods which quite a number of workers have done [4-7]. 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 [7,8], thus leading to an attempt in providing a thorough aquifer characteristics of the study area.

Geo-electrical determination of aquifer characteristics of parts of the area have been carried out [9].

Aborted or dried-up boreholes have been reported in the area and this has been attributed to lack of prior systematic and scientific investigation because existing shallow wells reflect high drawdown during the dry season mainly November through to February each year [10].

Also, modelling of groundwater interaction with Kwa Ibo River has been carried out in parts of the study area [10], Causes of boreholes' failure in parts of the area has been investigated [1]. Unpublished PhD thesis, Michael Okpara University of Agriculture, Umudike-Nigeria), while the use of geological, drill log, geophysical and hydro-geochemical techniques was adopted in the delineation and characterization of the eastern parts of the study area [1].

As stated earlier that a thorough knowledge of the hydro-geological system of an area is a precondition for any management and protection strategy and since a complete evaluation of a hydro-geological unit comprises the availability, productivity and quality of the groundwater. This present study therefore is the first documentation of the aquifer characteristics of the entire Kwa-Ibo River Watershed of Abia-State using a combination of geo-electrical, drill log and hydro-geochemical data with the aim of providing a better understanding of the hydro-geological conditions of the entire area.

2. MATERIALS AND METHODS

The Vertical Electrical Sounding (VES) method of electrical resistivity 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.

A maximum current electrode spacing AB/2 of 500m and a maximum potential electrode spacing MN/2 of 55m was used in the study. Thirteen surveys were carried out during the study. For comparative analysis three were done at the vicinity of existing boreholes where pumping tests have been done to act as a control.

With the location of the sounding point, the Garmin GPS 72 was used in determining the co-ordinates in longitude, latitude and elevation height above mean sea level. Then the ABEM Terrameter SAS 4000 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:

$$\rho_a = \pi R \left(\frac{L^2 - l^2}{2l}\right)$$

Where

ρ_a = Apparent resistivity.

L = AB/2 = Half current electrode spacing (m).

l = MN/2 = Half potential electrode spacing (m).

R = Resistance in ohms.

$$\pi \left(\frac{L^2 - l^2}{2l}\right) = \text{Geometric factor (K).}$$

The sounding curves for each point was obtained by plotting the calculated 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 [11] and based on this, initial estimates of the resistivity's and thicknesses of the various geo-electric layers were obtained and used for computer iteration using RESIST software package.

Thereafter, geo-electric sections were generated and subsequently compared with existing lithologs.

Furthermore, eleven groundwater samples were collected from ten different boreholes for physico-chemical analyses. Collection and analysis of the water samples were done during the cold Harmattan period in the month of January, hot temperature period of the month of March, transitional season period of the month of May and the rainy season period of July. The average data of the samples were obtained, this was done in order to maintain neutrality in seasonal variation of parameters thus covering the dry season, transitional season and wet season.

Pre-washed and clean 500 ml screw cap plastic containers were used to collect water samples from the ten selected boreholes after pumping the wells for about five minutes to ensure stable laminar flow conditions.

A global positioning system (GPS), Garmin 72 model was used in recording the geographical co-ordinates and elevation of the sampling points. Due to the sensitivity of groundwater to environmental changes, the following parameters were determined *in situ;* temperature, colour, pH and electrical conductivity. Thereafter, the samples were immediately taken to the Soil and Water Laboratory Department, Federal Ministry of Agriculture and Rural Development, Umuohu Azueke, Km 5 Umuahia-Ikot-Ekpene Road, Abia State Nigeria.

3. RESULTS AND DISCUSSION

3.1 Geo-electrical Characteristics of the Study Area

In pursuit of large scale development of groundwater, it is essential to have a reliable estimate of groundwater potential [12]. 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 [1,13,14,].

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 is a powerful lithology discriminator, therefore can be best employed to estimate the thickness of overburden and also the thickness of weathered layer.

The theories of both the electrical resistivity survey and the Schlumberger electrode configuration are well documented in the standard texts like [15,16]. 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 sounding curves, aquifer thickness and other parameters were obtained as shown in Tables 2 and 3.

Table 2. Sounding curves of the study area

Curve type	Q	QQ	QQQ	HKH	KHKQ	KHKQQ	QHKH	QKQQ	AKQH	AKHKQ
Number of layers	3	4	5	5	6	7	6	6	6	7
Sounding location	VES 4,8,12	VES 2,9	VES 1	VES 6	VES 5	VES 3	VES 7	VES 10	VES 11	VES 13

3.1.1 Analysis of Sounding Curves

Sounding curves obtained over a horizontally stratified medium is a function of the resistivities and thickness of the layers as well as the electrode configuration [11]. To construct the VES curve, the calculated apparent resistivity is plotted against the corresponding half-electrode separation (AB/2) and the letters Q, A, K and H are used in combination to indicate the variation of resistivity with depth (Fig. 3). The resistivity type curves of the sounding locations in the area are as shown in Table 2 below while Figs. 3a, 3b and 3c are computer modelled curves for VES 5, 6 and 7 respectively..

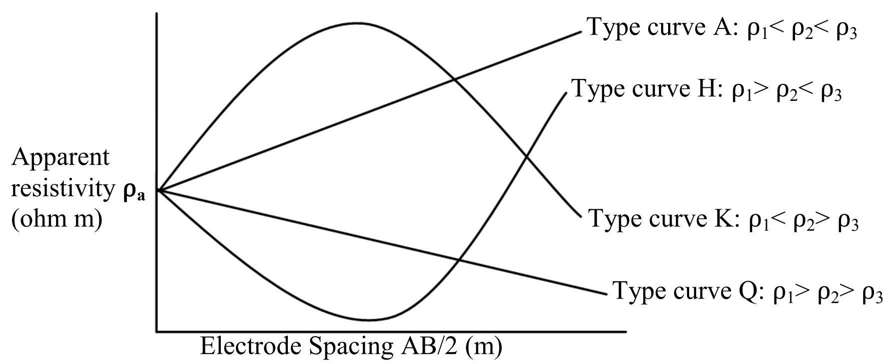

Fig. 3. Schematic diagram of resistivity type curves for layered structures.

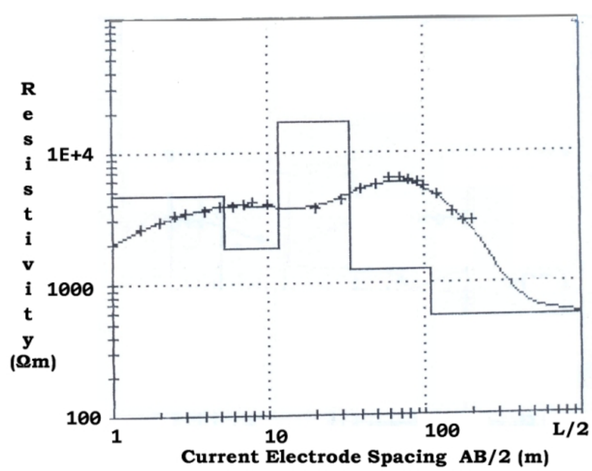

Fig. 3a. A computer modelled curve of VES 5

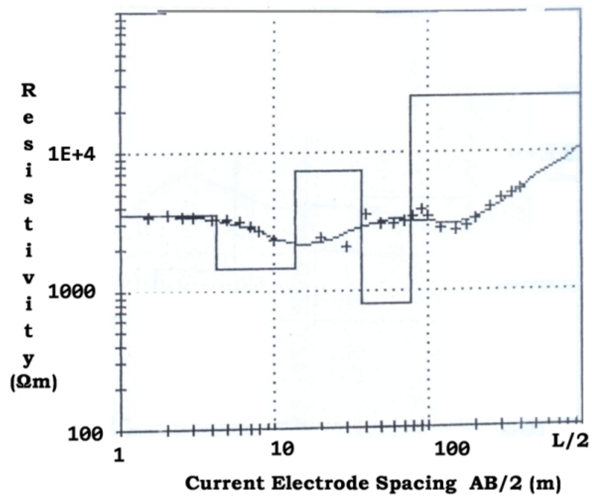

Fig. 3b. A computer modelled curve of VES 6

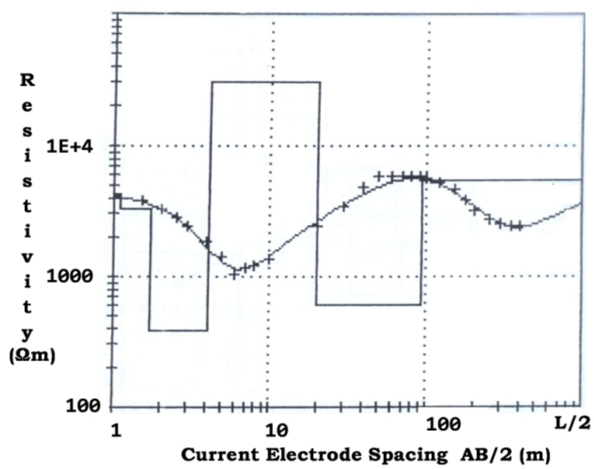

Fig. 3c. A computer modelled curve of VES 7

3.1.2 Geo-electric sections of the study area

Since groundwater accumulates in sedimentary rocks (sands, gravels, silt, limestone etc), and in weathered overburden, joints, fractures and faults zones in crystalline basement rocks. Then electrical resistivity of subsurface materials (rocks, minerals etc.) can be determined by the subsurface resistivity distribution to the ground because it 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 [1], therefore Electrical Resistivity Measurements determine sub-surface resistivity distributions thus differentiating layers based on resistivity values.

So, Geo-electric sections are displayed in terms of the relationship between the resistivity of the layers and their thicknesses (Fig. 4a and Fig. 4b).

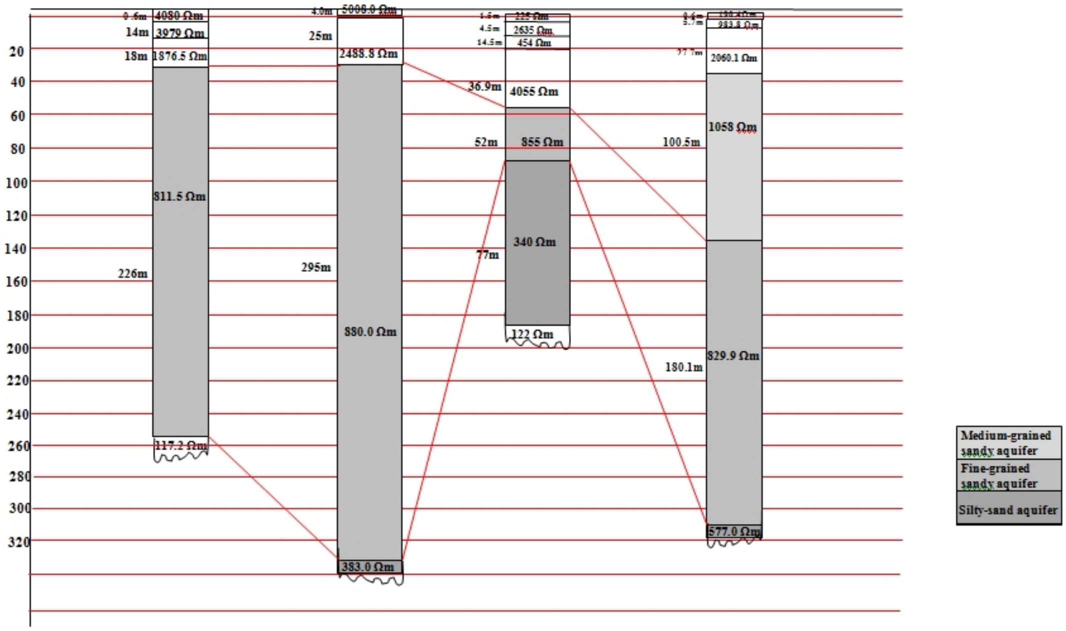

Fig. 4a. Geo-electric sections generated from VES 1, 2, 3 and 10.

A Geo-electric section is thus determined by respective individual layer resistivities (ρ_i) and thicknesses (h_i) where the subscript 'i' indicates the position of the layer in the section.A correlation of some Geo-electric sections of the study area is as shown in Figs. 4a and 4b.

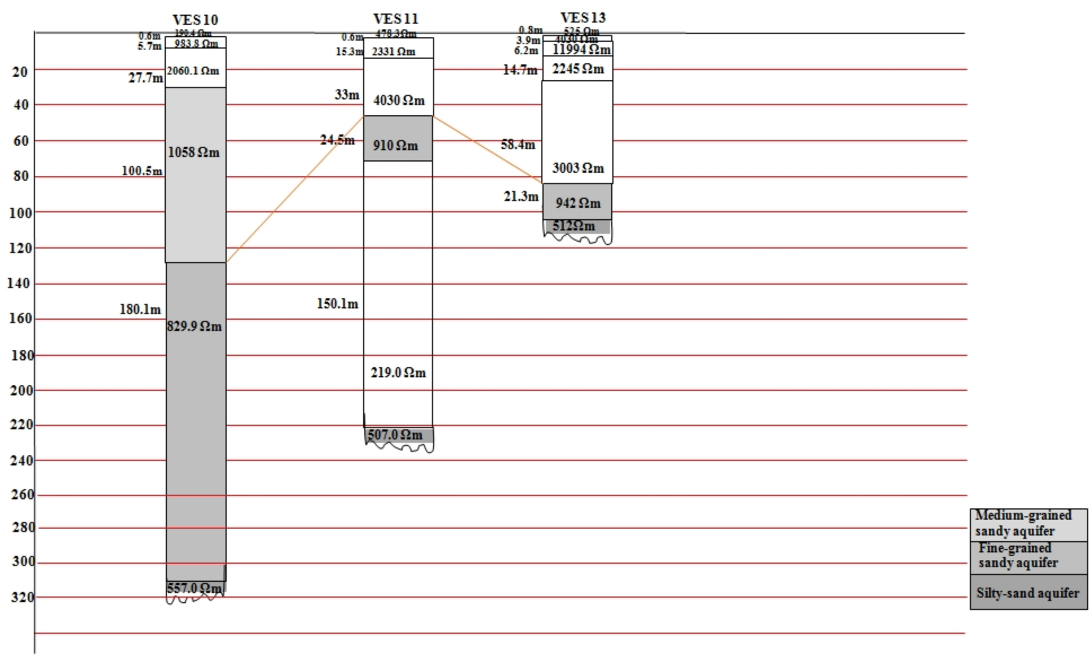

Fig. 4b. Geo-electric sections generated from VES 10, 11 and 13.

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.

After obtaining the true thickness and 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 is called the Dar-Zarrouk variable ‘R’ and Dar-Zarrouk function ‘S’ [4].

$$R = h\rho \tag{1}$$

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

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

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

$$S = \sigma h \tag{3}$$

Where ‘σ ’ is layer conductivity.

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

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

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

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

$$\text{Therefore, } S/\sigma = h \tag{5}$$

Recall also from equation (1) that $R = h\rho$,

$$\text{Therefore, } R/\rho = h, \tag{6}$$

Now, substituting the value of ‘h’ in equation (5) into equation (6), we obtain $R/\rho = S/\sigma$;

$$\text{Therefore, } \sigma R = S\rho \tag{7}$$

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

$$\text{Therefore, } S\rho = h \tag{8}$$

By substituting the value of $S\rho$ in equation (8) into equation (7), we obtain

$$\sigma R = h \tag{9}$$

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

$$T = KS/\sigma = Kh \quad = K\sigma R \tag{10}$$

Table 3. VES location points and data showing apparent resistivities and thicknesses of the various geo-electric layers and calculated geo-electrical 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(μs/cm)	Transverse unit resistance of layers R (Ωm^2)	Fitting error (%)
		Elevation (m) m.s.l	Latitude ^{0}N	Longitude ^{0}E								
1	Umuobia Isi-Court*	151	$5^0 29.273'$	$7^0 28.931'$	5	ρ_1 = 4080 ρ_2 =3979 ρ_3 =1876.5 ρ_4 =811.5 ρ_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
2	Agbama	151	$5^0 29.199'$	$7^0 29.041'$	4	ρ_1 =5008.0 ρ_2 =2488.8 ρ_3 =880.0 ρ_4 = 383.0	t_1 =4.0 t_2 = 25.0 t_3 =295.0	324	S_1 = 0.0008 S_2 = 0.0100 S_3 = 0.3352 S_T = 0.3460	σ_1 = 0.0044 σ_2 = 0.0004 **σ_3 = 0.0011** σ_4 = 0.0003	R_1 = 20032 R_2 = 62220 R_3 = 259600	6.0
3	Itaja*	150	$5^0 28.132'$	$7^0 30.526'$	**7**	ρ_1 = 225 ρ_2 = 2635 ρ_3 = 454 ρ_4 = 4055 ρ_5 = 855 ρ_6 = 340 ρ_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
4	Okwu	141	$5^0 28.106$	$7^0 30.803'$	3	ρ_1 =2997.5 ρ_2 =1007.2 ρ_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	New Industrial Market	124	$5^0 30.556'$	$7^0 32.049'$	6	ρ_1 =563 ρ_2 =4680 ρ_3 =1830 ρ_4 = 17200 ρ_5 = 1250 ρ_6 = 570	t_1 =0.2 t_2 = 5.3 t_3 = 11.7 t_4 = 33.9 t_5 = 110.0	161.1	S_1 = 0.0008 S_2 = 0.0011 S_3 = 0.0064 S_4 = 0.0091 S_5 = 0.0020 S_T = 0.088	σ_1 = 0.0018 σ_2 = 0.0002 σ_3 = 0.0005 σ_4 = 0.58e-4 **σ_5 = 0.0008** σ_6 = 0.0018	R_1 = 112.6 R_2 = 24804 R_3 = 21411 R_4 = 583080 R_5 = 137500	5.0

Continued Table 3 ……………

6	Govt College/ ABSU boundary	122.5	$5^0 29.753^!$	$7^0 32.049^!$	5	ρ_1 =3502 ρ_2 =1455 ρ_3 =7330 ρ_4 = 800 ρ_5 = 25500	t_1 =4.0 t_2 = 14.1 t_3 = 37.0 t_4 = 76.8	131.9	S_1 = 0.0011 S_2 = 0.0100 S_3 = 0.0050 S_4 = 0.0961 S_T = 0.1122	σ_1 = 0.0003 σ_2 = 0.0007 σ_3 = 0.0001 **σ_4 = 0.0013** σ_5 = 0.39e-4	R_1 = 14008 R_2 = 20370 R_3 = 271210 R_4 = 61520	4.0
7	Opposite MOUAU	125.2	$5^0 28.826^!$	$7^0 32.765^!$	6	ρ_1 =4340 ρ_2 =3250 ρ_3 =384 ρ_4 = 30200 ρ_5 = 611 ρ_6 = 5380	t_1 = 1.1 t_2 = 1.7 t_3 = 4.1 t_4 =20.3 t_5 = 94.0	121.2	S_1 = 0.0003 S_2 = 0.0005 S_3 = 0.0107 S_4 = 0.0007 S_5 = 0.1538 S_T = 0.166	σ_1 = 0.0002 σ_2 = 0.0003 σ_3 = 0.0026 σ_4 = 0.33e-4 **σ_5 = 0.0016** σ_6 = 1.86e-4	R_1 = 4774 R_2 = 5525 R_3 = 1574.4 R_4 = 613060 R_5 = 57434	3.0
8	Amaoba	135	$5^0 28.150^!$	$7^0 33.008^!$	3	ρ_1 = 5002.0 ρ_2 = 1350.0 ρ_3 = 145	t_1 =4.5 t_2 = 138.3	142.8	S_1 = 0.0009 S_2 = 0.1024 S_T = 0.1033	σ_1 = 0.0002 **σ_2 = 0.0007** σ_3 = 0.0069	R_1 = 22509 R_2 = 186705	2.0
9	Ndoro	143.5	$5^0 25.715^!$	$7^0 33.928^!$	4	ρ_1 =4930.5 ρ_2 =2603.0 ρ_3 =1120.1 ρ_4 = 688.3	t_1 =1.84 t_2 = 12.5 t_3 = 199.0	213.34	S_1 = 0.0004 S_2 = 0.0048 S_3 = 0.1777 S_T = 0.1829	σ_1 = 0.0002 σ_2 = 0.0004 **σ_3 = 0.0009** σ_4 = 0.0015	R_1 = 9072.12 R_2 = 32537.5 R_3 = 222899.9	2.4
10	Isiala *	135	$5^0 24.345^!$	$7^0 34.088^!$	6	ρ_1 =190.4 ρ_2 =983.8 ρ_3 =2060.1 ρ_4 = 1058 ρ_5 = 829.9 ρ_6 = 577.0	t_1 = 0.6 t_2 = 5.7 t_3 =27.7 t_4 =100.5 t_5 = 180.1	314.6	S_1 = 0.0032 S_2 = 0.0058 S_3 = 0.0134 S_4 = 0.0950 S_5 = 0.2170 S_T = 0.3344	σ_1 = 0.0053 σ_2 = 0.0010 σ_3 = 0.0005 **σ_4 = 0.0009** **σ_5 = 0.0012** σ_6 = 0.0017	R_1 = 114.24 R_2 = 5607.66 R_3 = 57064.77 R_4 = 106329 R_5 = 149464.99	3.0
11	Oloko	117	$5^0 22.022^!$	$7^0 34.097^!$	6	ρ_1 =478.3 ρ_2 =2331 ρ_3 =4030 ρ_4 = 910 ρ_5 = 219 ρ_6 = 507	t_1 = 0.6 t_2 = 15.3 t_3 = 33.0 t_4 =24.5 t_5 = 150.1	223.5	S_1 = 0.0013 S_2 = 0.0066 S_3 = 0.0082 S_4 = 0.0269 S_5 = 0.6854 S_T = 0.7284	σ_1 = 0.0021 σ_2 = 0.0004 σ_3 = 0.0002 **σ_4 = 0.0011** σ_5 = 0.0046 σ_6 = 0.0020	R_1 = 286.98 R_2 = 35664.3 R_3 = 132990 R_4 = 22295 R_5 = 32871.9	2.0
12	Umuode Nsulu	133.1	$5^0 24.758^!$	$7^0 28.872^!$	3	ρ_1 = 3033.0 ρ_2 = 1043.0 ρ_3 = 164	t_1 =3.4 t_2 = 108.0	111.4	S_1 = 0.0011 S_2 = 0.1035 S_T = 0.1046	σ_1 = 0.0003 **σ_2 = 0.0010** σ_3 = 0.0061	R_1 = 10312.2 R_2 = 112644	3.8

Continued Table 3 …………….

13	Ndiolumbe	109.3	$5^0 15.808^!$	$7^0 28.522^!$	7	ρ_1 = 525 ρ_2 = 4030 ρ_3 = 11994 ρ_4 = 2245 ρ_5 = 3003 ρ_6 = 942 ρ_7 = 512	t_1 =0.8 t_2 = 3.9 t_3 = 6.2 t_4 = 14.7 t_5 =58.4 t_6 =21.3	105.3	S_1 = 0.0015 S_2 = 0.0010 S_3 = 0.0005 S_4 = 0.0007 S_5 = 0.0194 S_6 = 0.0226 S_T = 0.0457	σ_1 = 0.0019 σ_2 = 0.0002 σ_3 = 0.0001 σ_4 = 0.0004 σ_5 = 0.0003 **σ_6 = 0.0011** σ_7 = 0.0020	R_1 = 420 R_2 = 15717 R_3 = 74362.8 R_4 = 33001.5 R_5 = 175375.2 R_6 = 20064.6	7.1

** VES station in proximity to existing bore-holes where pumping tests were acquired. Aquifer conductivity 'σ' values in bold.*

Dar-Zarrouk parameters have since been used in the estimation of aquifer hydraulic characteristics [16,5,6].

In areas of similar geologic setting and non varying water quality the product of both conductivities ‘Kσ’ remains fairly constant [5].

If values of hydraulic conductivity ‘K’ are obtained from existing boreholes, and the values of aquifer conductivity ‘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’.

With reference to aquifer conductivity ‘σ’ (Table 3), a parameter grouping was made whereby VES Stations with range of conductivity 0.0001 to 0.0010μs/cm are grouped as Group 1. While VES Stations with range of conductivity 0.0011 to 0.0020μs/cm are grouped as Group 2.

Based on the grouping, VES Stations 1, 2, 3, 4, 6, 7, 10, 11 and 13 are within area of similar geologic setting and water quality and they fall in Group 2 while VES Stations 5, 8, 9, 10 and 12 are in Group 1.

It is noticed from the grouping that VES Station 10 falls within Group 1 and Group 2, thereby exhibiting both characteristics. But interestingly, the aquifer conductivity value of 0.0012μs/cm is found to be common in all the three stations where pumping tests were acquired (Table 3).

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). But these tests were performed on limited areas due to their high cost and 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 Geo-electrical methods [4,5,6,17,18,19,7,1] The alternative approaches are quick and cost effective.

The use of surface resistivity sounding in the estimation of aquifer hydraulic parameters by using a graphical statistical approach has been established [1]. The approach established is adopted in this work.

In the approach, the average field hydraulic conductivity (*K*) derived from the pumping test was used to calculate the transmissivity (*T*) of the same boreholes from data (thickness) acquired through surface resistivity soundings, and subsequently was used in places where pumping test is not available for the determination (estimation) of aquifer hydraulic parameters. The advantage of this approach over others is the simplicity and accuracy as shown below in Tables 4 and 5 and Fig. 5.

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)
Umuobia (Isi Court) VES 1	8.65	12	103.8	226	1954.9
Itaja VES 3	8.45	15	126.75	52	439.4
Isiala VES 10	7.76	15	116. 4	100.5	779.9

Using the graphical approach of [1] 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. 5).

Recall that by using aquifer conductivity, VES Stations 1, 2, 3, 4, 6, 7, 10, 11 and 13 (Group 2) are within area of similar geologic setting and water quality, VES Stations 5, 8, 9, 10 and 12 (Group 1) are of same geologic setting and water quality, while VES Station 10 exhibit both characteristics (Table 3).

Recall also that pumping test data have been acquired for VES Stations 1, 3 and 10; present study shows all have common aquifer conductivity value of 0.0012µscm.

From Table 4, it is observed that VES 3 has the lowest transmissivity value out of the three stations.'

So VES Stations 1, 3 and 10 were plotted on a graph and a line of best fit was made to pass through the lowest resistivity-calculated value (transmissivity) of VES 3, and the resistivity-calculated values (transmissivity) of VES Stations 1 and 10 as upper values.

In the graph below, the red line is that of VES Station 1(Group 2), while that of VES Station 10 (Group 1) is black. Both lines were made to pass through VES Station 3 since all the three VES Stations exhibit same characteristics.

For the fact that VES Stations 1, 2, 3, 4, 6, 7, 10, 11 and 13 (Group 2) are within area of similar geologic setting and water quality, the intercept of the red line (slope) is used in the estimation of aquifer hydraulic parameters of VES Stations 1, 2, 3, 4, 6, 7, 10, 11, and 13 (Group 2). While, the intercept o f the black line (slope) is used in the estimation of aquifer hydraulic parameters of VES Station 5, 8, 9, 10 and 12 (Group 1) as shown in Fig. 5.

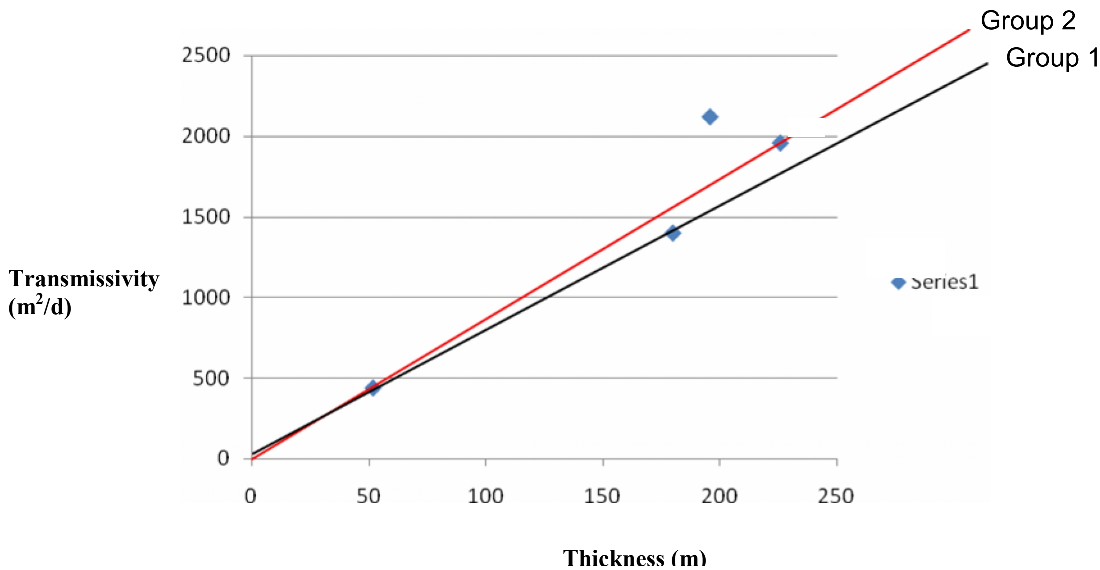

Fig. 5. A plot of Aquifer transmissivity versus thickness

Based on the graphical illustration in Fig. 5 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 values for aquifer hydraulic parameters of the study area as shown in Table 5 below.

Table 5. Calculated (Estimated) Transmissivity from Vertical Electrical Sounding (VES)

Data Location / Number	Thickness of Aquiferous zone in x-axis. (m)	Calculated (estimated) 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)
1 Umuobia (Isi Court) *	226	1955	8.65
2 Agbama	295	2550	8.64
3 Itaja *	52	440	8.46
4 Okwu	98	840	8.57
5 New Industrial Market	110	870	7.90
6 Govt College	76.8	655	8.53
7 Opposite MOUAU	94.0	810	8.62
8 Amaoba	138.3	1075	7.80
9 Ndoro	199	1565	7.86
10 Isiala *	100.5	800	7.96
11 Oloko	24.5	220	8.98
12 Umuode	108.0	915	8.47
13 Ndiolumbe	21.3	170	7.98

Recall that in areas of similar geologic setting and non varying water quality, the product of both conductivities 'Kσ' remains fairly constant when values of hydraulic conductivity 'K' are obtained from existing boreholes; and the values of aquifer conductivity 'σ' are obtained from VES data interpretation within the vicinity of a borehole.

But since pumping tests are not normally run due to their high cost and lack of equipment, this alternative approach used in determining hydraulic conductivity 'K', also aided in determining whether the area is similar in geologic setting and water quality (Table 6).

Table 6. Hydraulic, Aquifer and Hydro-geo-electrical Conductivities of the study area

Data Location / Number	Hydraulic Conductivity 'K'	Aquifer (layer) Conductivity 'σ'	Hydro-geo-electrical Conductivity (K σ)
1 Umuobia (Isi Court) *	8.65	0.0012	0.01038
2 Agbama	8.64	0.0011	0.009504
3 Itaja *	8.46	0.0012	0.010152
4 Okwu	8.57	0.0010	0.00857
5 New Industrial Market	7.90	0.0008	0.00632
6 Govt College	8.53	0.0013	0.011089
7 Opposite MOUAU	8.62	0.0016	0.013792
8 Amaoba	7.80	0.0007	0.00546
9 Ndoro	7.86	0.0009	0.007074
10 Isiala *	7.96	0.0009	0.007164
		0.0012	0.009552
11 Oloko	8.98	0.0011	0.009878
12 Umuode	8.47	0.0010	0.00847
13 Ndiolumbe	7.98	0.0011	0.008778

3.1.5 Borehole characteristics from geo-electrical and lithological deductions

From lithologic deductions and drill-hole data, locations of VES 1,2,3,6, and their environs exhibit multi-storey aquifer structure with aquifer thickness range of about 15 to 60m of medium-grained to fine-grained sand to silty-sand unit (Fig. 6a). This multi-aquifer status could not be detected in some geo-electric sections generated from VES survey (Fig. 4a), but was indicated as a very thick aquiferous unit of slightly below or above 200m.

A correlation of VES 4 and drill-hole data of a nearby borehole gave a good understanding of the subsurface hydrological conditions of the area (Fig. 6b).

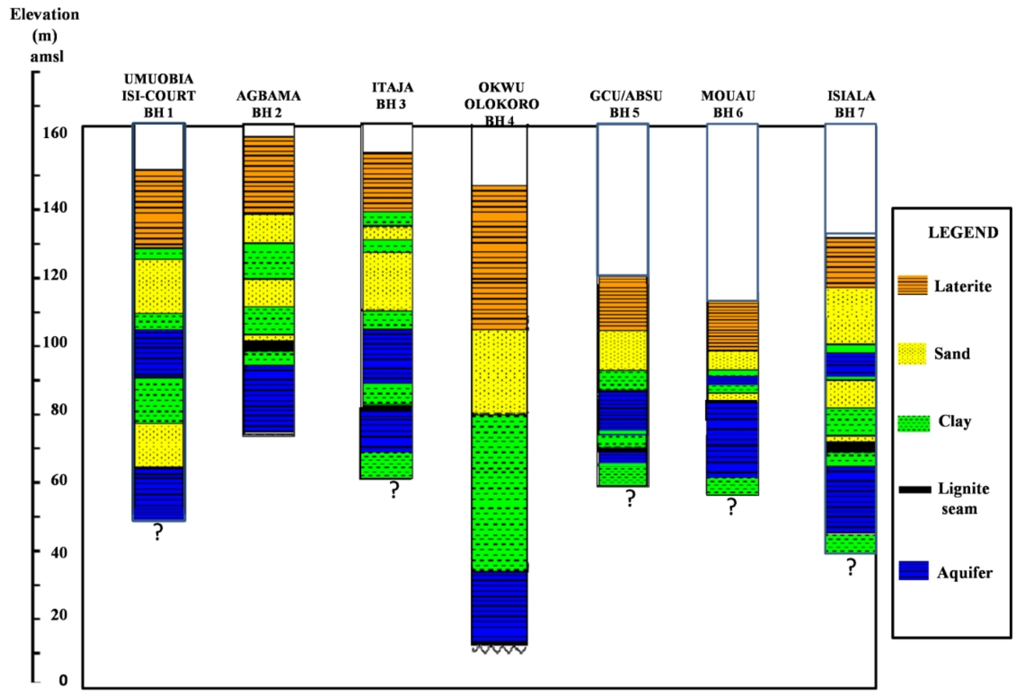

Fig. 6a. Lithologs of some boreholes in the study area

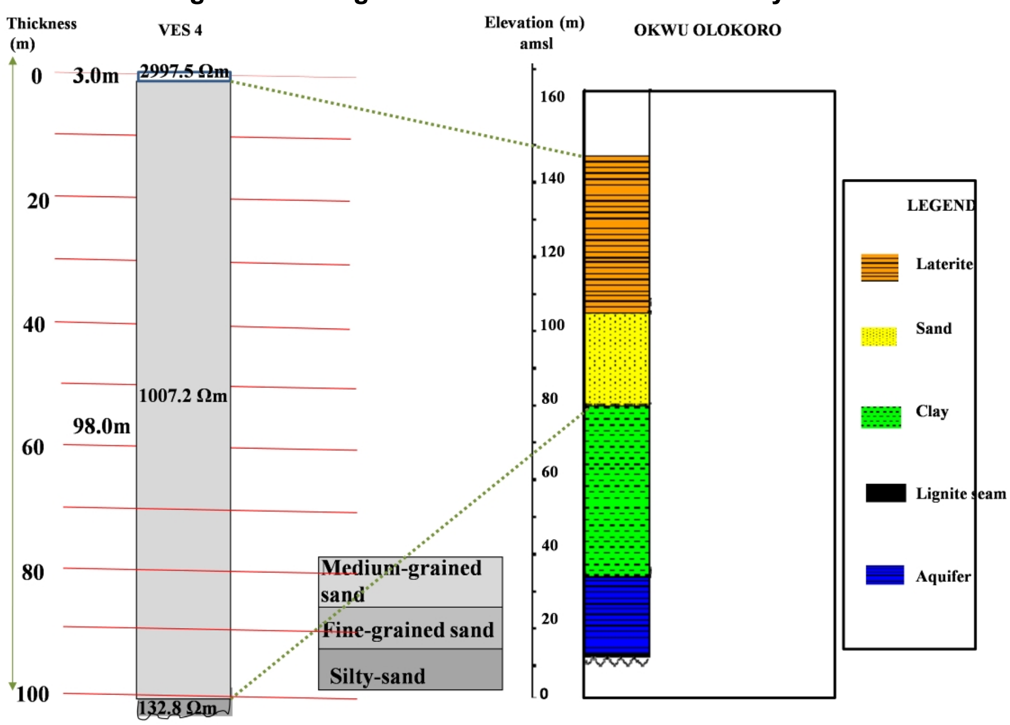

Fig. 6b. A Correlation of VES 4 and litholog of a nearby borehole

This multi-storey aquifer system exhibits an unconfined to confined upper aquifer, followed by a confined second 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 (Fig. 6a). Other values of borehole characteristics generated from the present study are shown in Table 7 below.

Table 7. 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)
Umuobia (Isi-Court) BH1	150	150.3	100.6	39	61.6	49.7	111.3
Agbama	155.1	155.4	94.5	39	55.5	60.9	116.4
Itaja(BH3)	151	151.3	94.5	41	53.5	56.8	110.3
MOUAU	125.2	125.5	120	30	90	5.2	95.2
Oloko	117	117.3	80.2	27	53.2	37.1	90.3
Isiala(BH7)	135	135.3	90.5	38	52.5	44.5	97

**All values are measured in metres.*

3.2 Hydro-geochemical Characteristics of the Study Area

The physico-chemical parameters of groundwater samples in the study area are as shown in Table 8.

3.2.1 Water type of the study area

The North-western part of the study area is characterized as follows: cation concentration $Na^+ > Ca^{2+} > K^+ > Mg^{2+}$ while that of anion $HCO_{3-} > Cl^-$ as shown in Table 8. While in the rest of the study area; the cation concentration indicates $Ca^{2+} > Na^+ > K^+ > Mg^{2+}$ and the anion $HCO_{3-} > SO4^{2-} > Cl^-$.

By using the concept of hydro-geochemical facies [20]; [21]: The Sodium and Potassium bicarbonate chloride (Na+ K-HCO_3-Cl) facies and the Calcium and Magnesium bicarbonate chloride facies (Ca+Mg-HCO_3 $SO4^2$-Cl) were identified (Fig. 7). The Sodium and Potassium bicarbonate chloride (Na+ K-HCO_3-Cl) facies dominate the Northern and Eastern part of the study area while, the Calcium and Magnesium bicarbonate chloride facies (Ca+Mg-HCO_3 $SO4^2$-Cl) dominate the rest of the study area (Fig. 8).

Hydro-geochemical facies are used to denote the diagnostic chemical character of water solutions in hydro-geologic systems whereby the facies reflect the effect of chemical processes occurring between the minerals of the lithologic framework and groundwater.

Table 8. Physico-Chemical Parameters of Groundwater samples in the study area

Data Location	Temp (ºC)	Cond. (µs/cm)	PH	TDS (mg/l)	TSS (mg/l)	Fe^{2+} (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^{2+} (mg/l)	K+ (mg/l)	HCO_3 (mg/l)	Cl-(mg/l)	SO_4^{2}- (mg/l)	NO_3- (mg/l)
UMUOBIA (ISI-COURT)	30.5	14.7	4.87	7.30	1.02	0.0 2	0.50	0.08	2.40	0.15	30.00	5.30	ND	ND
AGBAMA	30.0	19.06	4.79	9.08	ND	0.24	2.21	0.17	3.10	3.75	26.87	7.81	ND	NS
ITAJA	30.0	37.5	4.95	5.00	2.0	0.21	1.10	0.34	3.05	0.37	38.00	5.30	ND	ND
OKWU OLOKORO	28.0	85.0	6.48	2.28	25.50	0.10	7.70	1.40	3.55	2.54	185.00	0.01	ND	ND
GCU	29.7	35.50	5.35	29.6	9.70	0.19	2.19	0.31	2.33	0.66	45.35	7.15	NS	0.02
MOUAU	29.6	66.7	6.32	68.0	0.42	0.17	6.75	0.24	5.00	3.15	28.00	1.30	3.51	0.10
AMAWOM	30.0	100.2	6.22	2.60	0.20	0.16	6.05	1.40	4.70	2.30	11.50	4.20	4.20	NS
ISIALA	29.7	29.4	6.30	3.21	0.25	0.18	8.21	5.10	4.00	2.15	13.50	1.50	4.35	0.11
NNONO	29.4	36.6	6.15	3.00	3.50	NS	7.91	4.88	4.08	2.33	18.50	1.31	4.80	0.13
NDORO	29.8	36.5	6.22	2.98	3.50	NS	8.50	5.25	4.27	2.85	16.00	0.70	4.60	0.05
UMUODE	30.5	27.7	4.63	20.8	3.05	ND	14.05	0.05	18.3	0.02	10.6	4.50	12.8	0.01
WHO LIMITS	25	< 500	6.5-8.5	50-750	10-25	< 0.3	<500	< 50	< 5	<75	<250	< 50	NS	< 10
METHOD	Thermo-meter	Conduct-ometry	pH meter	Gravi-metry	Gravi-metry	AAS)	(AAS)	(AAS)	(AAS)	(AAS)	Argent-ometry	Turbid-ometry	(AAS)	Colori-metry

**ND = Not Detected. NS = Not Stated. AAS = Atomic Adsorption Spectrometry*

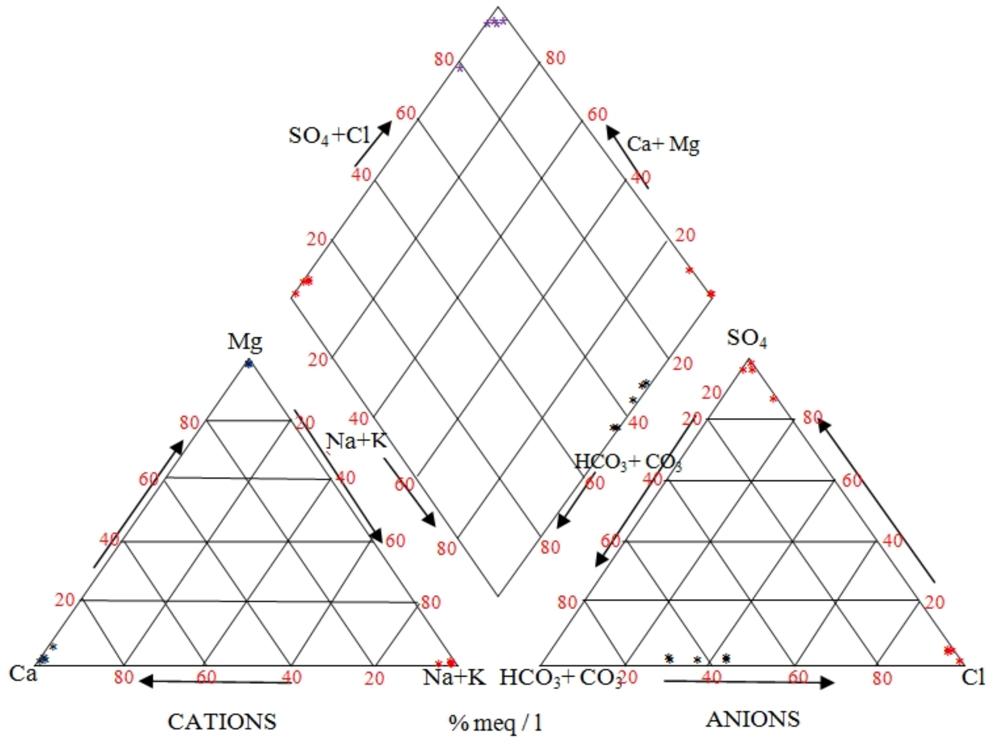

Fig. 7. Piper-Trilinear plot diagram of Groundwater samples in the study area

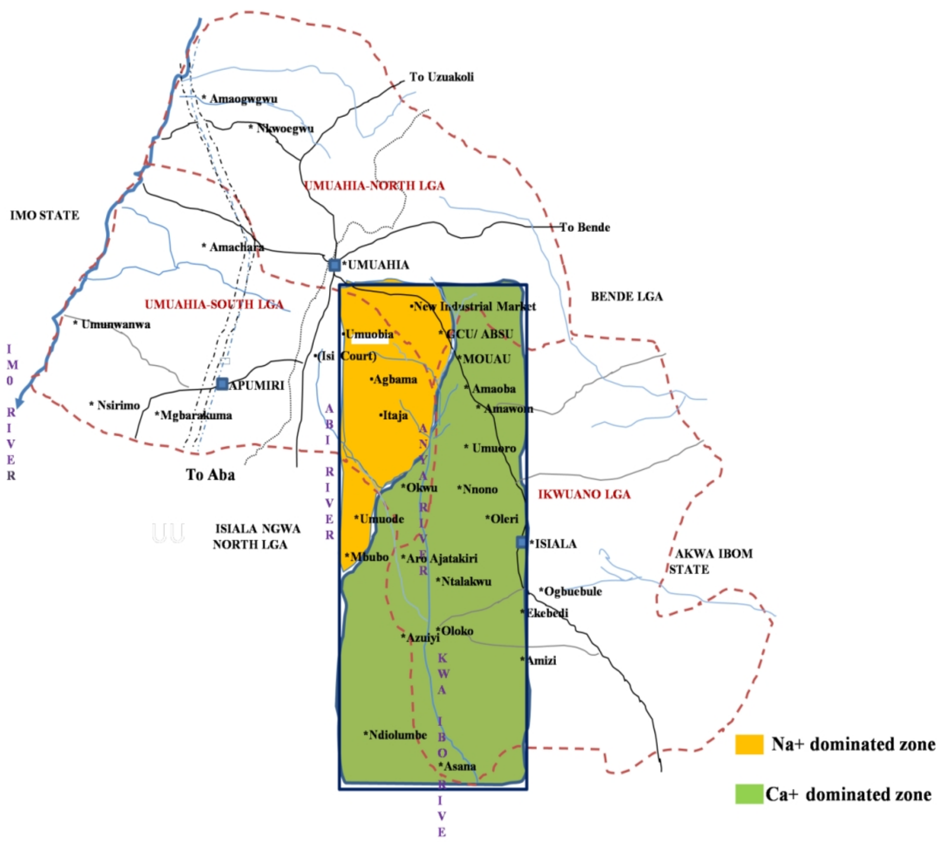

Fig. 8. Hydro-geochemical map of the study area

3.2.2 Water Quality of the Study Area

The groundwater analyses (Table 8) 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.

In two boreholes in the western part, Iron (Fe) is found to be relatively high far above others and also exhibiting a close similarity to those of the eastern counterparts. This may be associated with their host rock which is silty-sand (very fine-grained sands and clays) aquifer units; and it is well known that clays contain trace elements whose concentrations are widely variable depending on their geological history.

3.2.3 Origin and evolution of major chemical constituents

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 [22,23].

A plot of TDS values versus the ratio Na/(Na+Ca) of the groundwater of the study area on Gibbs diagram indicates that the water originates as direct rainfall (Fig. 9).

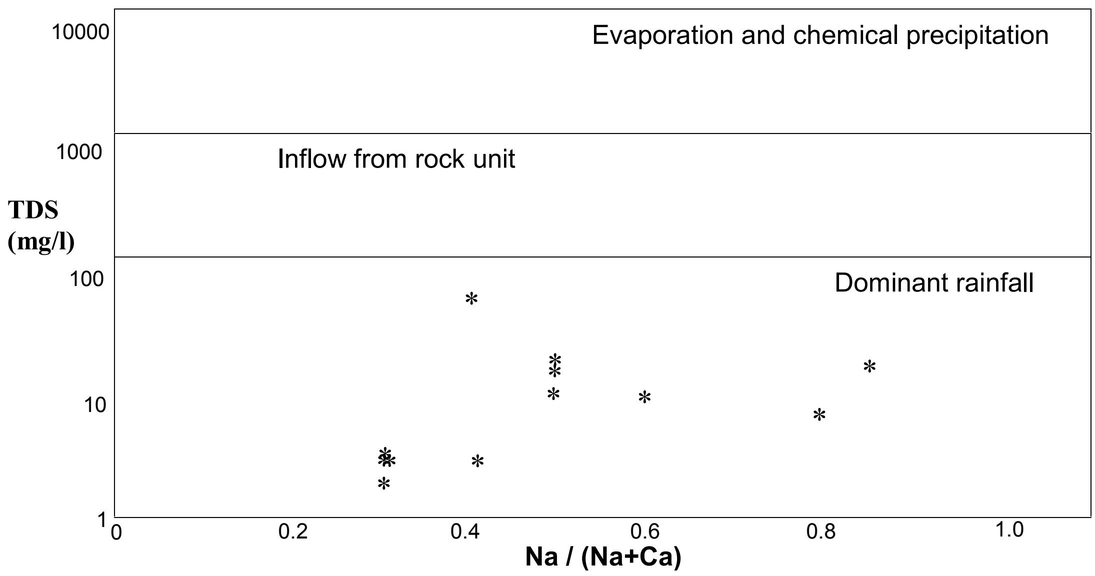

Fig. 9. Gibbs diagram of ratio of Na/(Na+Ca) versus the Total Dissolved Solids (TDS) of water samples in the study area. (After Gibbs 1970)

The study has revealed that the area is characterized by sand and silty-sand aquiferous units. Silt falls between clay and sand in the Grain Size Scale and ranges from 0.002mm to 0.0625mm, therefore could be defined as sediment composed of very fine sand, clay particles and other materials.

The huge presence of kaolin deposits in Umuahia-South Area and some other clay deposits in parts of the study area may give a clue to the evolution of the groundwater chemistry.

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 deposits of the study area being of continental origin may owe its provenance to Oban massif (Fig. 10).

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.

Also, the weathering of Albite in the crystalline rocks may have released Na+ HCO_{3-} and Kaolinite [24]. Thus, the dominance of sodium bicarbonate (Na+ HCO_{3-}) in the groundwater samples of the eastern part 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) [25], and all these chemical ions and pH range are present in the groundwater of the eastern part of the study area (Table 8).

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 [26]. This corroborates Petrographic analysis of [27]: 95-99% quartz grains, 1-2.5% of Na+K-mica, 0 -1.0% of Feldspar and 2-3% of dark coloured minerals.

From the above indications, the groundwater chemistry of the study area is likely to be from dissolution of silicate and carbonate minerals. Therefore, the concentrations of major elements are controlled by the congruent weathering of carbonate and incongruent weathering of silicates [28,29,30,31]. It is also known that ion exchange process is characterized by an excess of $(HCO_{-3}+ SO_4^{2-})$ over $(Ca^{2+}+Mg^2)$, while the reverse ion exchange is marked by an excess of $(Ca^{2+}+Mg^2)$ over $(HCO_{3-}+SO_4^{2-})$ [32,33]; thus indicating an ion exchange process in the study area.

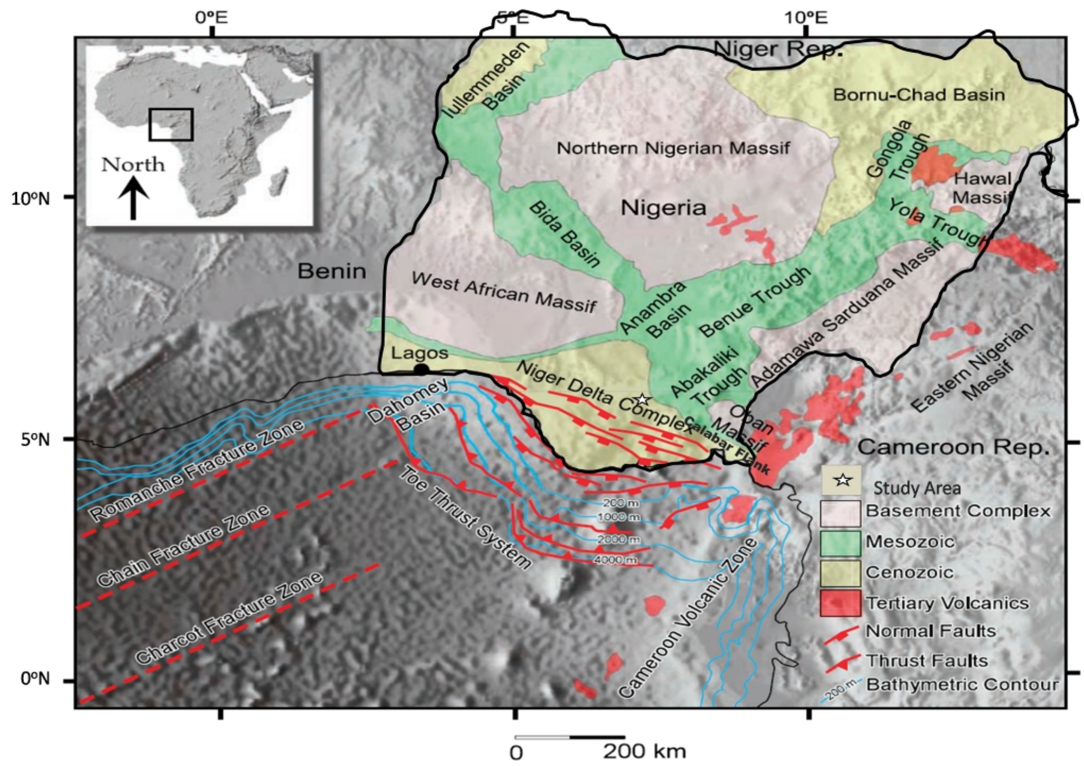

Fig. 10. Geological Outline Map of Nigeria showing Basement outcrops, main sedimentary basins and tectonic features

4. CONCLUSION

This research has provided useful information on the hydrogeological conditions of the study area. Geo-electrical and borehole studies were useful in delineating the aquifer systems and the hydro-geochemical facies also aided in the characterization. The Geo-electrical data guided the estimation of aquifer hydraulic characteristics such as hydraulic conductivity, transmissivity and helped in determining areas of similar geologic setting and water quality.

The groundwater chemistry of the study area is from dissolution of silicate and carbonate minerals mainly through congruent weathering of carbonate and incongruent weathering of silicates. There is ion exchange process characterized by an excess of $(HCO_{-3}+ SO_4^{2-})$ over $(Ca^{2+}+Mg^2)$ in the study area.

Based on all the findings made in the interpretation of the VES data and lithological deductions, the study area have good potentials for groundwater but VES stations 4, 8 and 12 may not yield expected results likely obtainable from other stations. 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 hydro-geological analysis should be done prior to and during development of borehole. 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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