Journal of Spatial Hydrology
Vol.6, No.2, Fall 2006

Estimation of aquifer hydraulic characteristics from electrical sounding data: the case of middle Imo River basin aquifers, south- eastern Nigeria.

A.C. Ekwe[1], N.N. Onu[2] and K.M.Onuoha[1]

ABSTRACT

We have used the concept of Da - Zarrouk parameters (transverse unit resistance (R) and longitudinal conductance (C)) in porous media to determine aquifer hydraulic characteristics within the middle Imo river basin. The lithostratigraphic units within the study area include: Imo formation, Bende - Ameki formation, Ogwashi Asaba formation and Benin formation. The direct current electrical resistivity method was utilized for the present study. Twenty-four (24) vertical electrical soundings (VES) using the Schlumberger array was acquired for the study area. A maximum current electrode spacing (AB) of 1000 meters was used. Eight of the soundings were carried out near existing boreholes. A combination of curve matching techniques and computer iterative modelling was used in processing the data. Results show that the depth to water table varies between 12m at Ife and 153m at Aba Branch. Interpretative cross - section along two profiles show that aquifer thicknesses range between 9m and 104m. The diagnostic $K\sigma$ = constant value was used to delineate the different lithostratigraphic units within the study area. We have also used the established relationship between aquifer characteristics and geoelectric parameters to estimate hydraulic conductivity and transmissivity values of all the sounding locations including areas where boreholes were non - existent. Hydraulic conductivity varies between 1.24 m/day at Amuzukwu and 26.41 m/day at Obinze. Transmissivity values also vary between $41m^2$/day at Osuachara and 1370 m^2/day at Obinze.

Keywords: Aquifer hydraulic characteristics, Dar - Zarrouk parameters, Resistivity, Imo River Basin, Nigeria.

Introduction

The sedimentary sequence of south-eastern Nigeria especially those of the Imo river basin are known to contain several aquiferous units. However, the characteristics of these aquifers such as transmissivity, hydraulic conductivity and storage potentials are not fully known and it has not been possible to design management strategies for optimal exploitation of these aquifers. The problem is further compounded by the poor knowledge of the aquifers (their geometry and nature of their hydraulic boundaries) being tapped. Although numerous boreholes have been drilled at various parts of the Imo river basin, there have not been any systematic and comprehensive studies to establish the nature and distribution of the aquifers beneath the basin (Uma, 1989).

The stratigraphy and faunal assemblages within the Imo river basin have been determined (Reyment (1965), Short and Stauble (1967)). Uma (1989) carried out a study on the ground resources of the Imo river basin using hydro geological data from existing boreholes. He concluded that three aquifer systems (shallow, middle, and deep) exist in the area. His data were however too sparse to make any general statement on the hydraulic characteristics of the middle Imo River Basin aquifers.

The present study is aimed at the estimation of geometry, hydraulic conductivity and transmissivity of the aquifers within the middle portion of the Imo River Basin using the electrical resistivity method. Twenty four

1. Shell Chair in Geology, University of Nigeria, Nsukka, Nigeria.
2. Department of Geology, Federal University of Technology, Owerri, Nigeria.
Corresponding Author: amobiekwe@yahoo.com

vertical electrical soundings (VES) have been acquired at various sites within the study area. The Schlumberger method was adopted because the fieldwork is faster and easier and softwares are readily available for its interpretation. It is hoped that results from the present study would help to reduce the cases of borehole failures within the area.

THE STUDY AREA

The study area (Fig. 1.0) lies between latitudes 5°00'N and 5°45'N and longitudes 6°50' E and 7°45'E and covers an area of about 2256km^2. Some major communities within the study area include: Nekede, Ihiagwa, Obowu, Umuahia and Aba. A good network of motorised roads, railways and track roads made the collection of data in this area possible. Twenty-four (24) VES results using the Schlumberger configuration were collected in the area. Eight of the soundings were taken near existing boreholes.

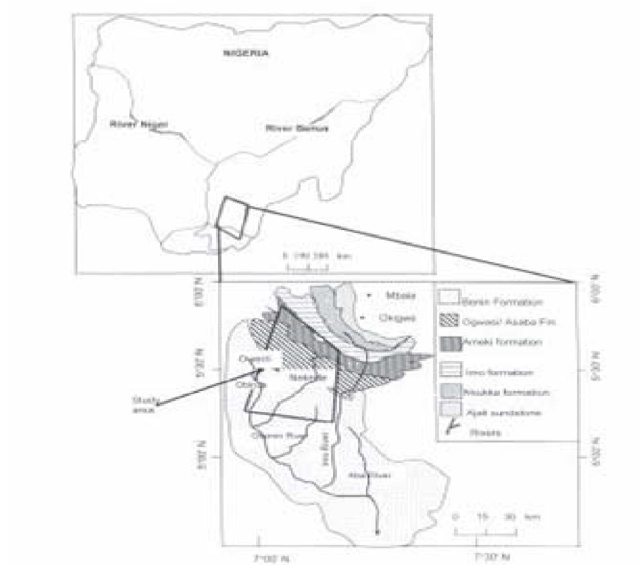

Fig.1.0. Geological map of Imo River Basin showing the stratigraphical succession of the study area (Modified from Uma, 1989)

GEOLOGY OF THE STUDY AREA

Table 1.0 summarizes the general geology of the study area (after Uma, 1989).

Age	Formation Name	Maximum Approximate Thickness	Character
Miocene - Recent	Benin	200	Unconsolidated, yellow and white sands, occasionally pebbly with lens of grey sandy clay.
Oligocene - Miocene	Ogwashi/ Asaba	500	Unconsolidated sandstones with carbonaceous mudstones, sandy clays and lignite seams
Eocene	Ameki	1460	Sandstones grey to green argillaceous sandstones, shales, and thin limestone.
Paleocene	Imo	1200	Blue to dark grey shales and subordinate sandstones. It includes two sandstone members: the Umuna and Ebenebe sandstones.

METHODOLOGY

The mode of study includes:

1. Literature review of some previous work done in the Imo River Basin and other works that were considered necessary for the present study.
2. An extensive field work involving the acquisition of 24 VES data across the study area, using the Schlumberger configuration. The Schlumberger configuration was adopted for the following reasons:
   - The method permits the acquisition of numerous data within a very short time.
   - The method allows for a clearer definition of the subsurface for a given outer electrode spacing.
   - It requires less manpower as only the current electrodes are moved.
3. Processing of the acquired data with the OFFIX software.
4. Interpretation of results.

VERTICAL ELECTRICAL SOUNDING (VES)

VES furnishes information concerning the vertical succession of different conducting zones and their individual thicknesses and resistivities. For this reason, the method is practically valuable for investigations on horizontally or near horizontal stratified earth. In the electrical sounding method, the midpoint of the electrode configuration is fixed at the observation station while the length of the configuration is gradually increased. As a result, the current penetrates deeper and deeper, the apparent resistivity being measured each time the current electrodes are moved outwards (Koefoed, 1977). For Schlumberger array, apparent resistivity is given by

$$\rho_a = \pi R\,(a^2/b - b/4) \qquad \text{(Keller and Frischnechk, 1979)} \qquad (1)$$

where a = half current electrode separation and b = potential electrode spacing

The Schlumberger configuration is preferable to the Wenner array for depth sounding because the field procedure is quicker and simpler and master curves and software are more readily available for result analysis. The data obtained is usually plotted as a graph of apparent resistivity against half electrode spacing for the Schlumberger array. The electrode spacing at which inflection occurs on the graph provides an idea of the depth to the interface. A useful approximation is that the depth of the interface is equal to two thirds (2/3) of the electrode spacing at which the point of inflection occurs (Vingoe, 1972). This approximation has found useful applications in computer iterative modelling.

AQUIFER HYDRAULIC CHARACTERISTICS FROM SURFACE ELECTRICAL RESISTIVITY DATA

Niwas and Singhal (1981) have established an analytical relationship between aquifer transmissivity and transverse resistance on one hand, and between transmissivity and longitudinal conductance on the other. From Darcy's law, the fluid discharge Q is given by

$$Q = KIA \qquad (2) \qquad \text{and from Ohm's law, } J = \sigma E \qquad (3)$$

where K = Hydraulic conductivity, I = Hydraulic gradient, A = cross- sectional area perpendicular to the direction of flow, J = current density, E= electric field intensity and σ = electrical conductivity (inverse of resistivity).

Taking into account a prism of aquifer material having a unit cross-sectional area and thickness h, Niswas and Singhal (1981) combined equations (2) and (3) to get

$$T = K\sigma R = KS/\sigma \qquad (4)$$

Where T = Aquifer transmissivity
R = Transverse resistance of the aquifer
S = Longitudinal conductance

The parameters R and S are commonly called Dar- Zarrouk parameters and are designated by
$S = h/\rho$ (5) and $R = h\rho$ (6)
where h and ρ are the thicknesses and resistivities of the individual layers.

In areas of similar geologic setting and water quality, the product, $K\sigma$ remains fairly constant (Niswas and Singhal, 1981, Onuoha and Mbazi, 1988, Onu, 1995). Thus knowing K values for existing boreholes and σ values extracted from the sounding interpretation for the aquifer at borehole locations, it has been possible to determine transmissivity and its variations from place to place, including those areas without boreholes.

We have utilised these established relationships between aquifer hydraulic parameters and electrical resistivity sounding data to determine hydraulic conductivity and transmissivity of aquifers within the middle Imo river basin.

DATA ACQUISITION

The locations of the sounding points are shown in Figure 1.1. Twenty-four (24) Schlumberger array soundings with maximum current electrode spacing (AB) of 1000m were conducted in the study area. The equipment used was ABEM SAS 300B Terrameter, a digital, averaging instrument for direct current resistivity work. Eight of the soundings were made at the sites of existing boreholes for comparative purposes to explore the interaction of subsurface materials. The existing boreholes beside which soundings were conducted are located at Owerri, Ihiagwa, Egbu, Ife, Amaraku, Aba Branch, Uboma and Obohia Ekwereazu. Their VES stations are 1,4,5,6,15,18,19 and 20.

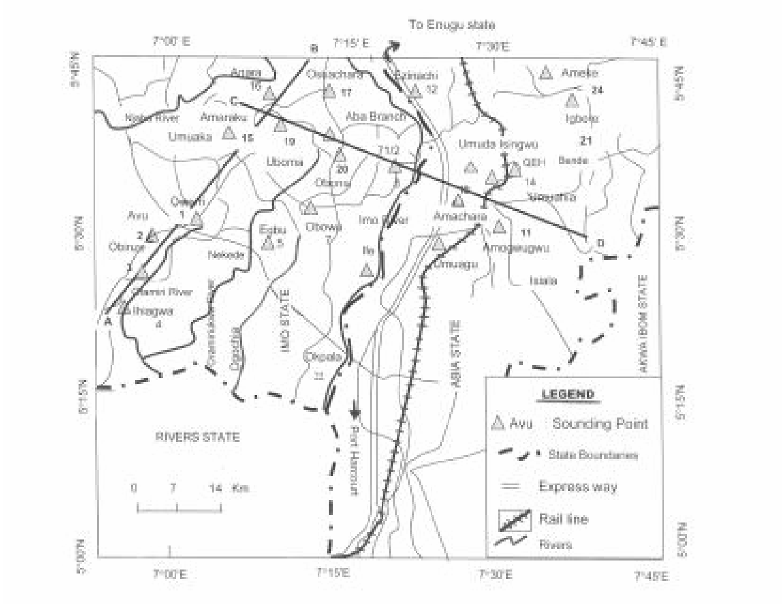

Fig.1.1. Map of the study area showing the sounding points

DATA PROCESSING

The observed field data was converted to apparent resistivity values by multiplying with the Schlumberger geometric factor. The geometric factor for the Schlumberger array is given by:

$$\mathbf{G} = \pi\ (a^2/\ b - b/4)$$

where a = half current electrode spacing and b = potential electrode spacing.

The sounding curve for each point was obtained by plotting the apparent resistivity on the ordinate against half electrode spacing on a bilogarithmic transparent paper. Parameters such as apparent resistivity and thickness obtained from both partial curve matching and the method of asymptotes were used as input data for computer iterative modelling (Zohdy, 1976; Koefoed, 1977). Detailed quantitative interpretation was done using the OFFIX software.

RESULTS AND INTERPRETATION

We have adopted the format below to present our results:

- Comparison of VES curves and lithology logs
- Depth to water and aquifer thickness along two sections.
- Map of Kσ variation across the study area
- Estimation of K and T values of areas without boreholes

COMPARISON OF VES CURVES AND LITHOLOGY LOGS

- **OWERRI:** The first geoelectric layer with apparent resistivity (ρ_a) of 3350Ωm is entirely Laterite. It is reddish brown in colour. The second layer is sand and has a light brownish colour. The third layer consists of medium to coarse grained whitish sand. The fourth layer consists entirely of gravel while the aquiferous layer consists of white sand with apparent resistivity of 1080Ωm (Fig. 1.2).
- **IHIAGWA:** The first geoelectric layer with apparent resistivity of 8900Ωm is lateritic soil. The second layer consists of another mixture of sand and clay (lower lateritic soil). The third geoelectric layer consists of white grains of sand mixed with gravel. The layer has apparent resistivity values ranging from 2500Ωm - 9700Ωm and corresponds to the water layer (Fig.1.2)

- **ABA BRANCH:** The first geoelectric layer consists of greyish red sand with apparent resistivity value of 1290Ωm. The second layer consists of clayey sand and has apparent resistivity of 478Ωm. This layer is underlain by a layer containing medium to coarse grained sandstones with some clay intercalations. The apparent resistivity of this layer ranges from 1910 - 7600 Ωm (Fig. 1.3)
- **ANARA:** The comparison shows that the geoelectric section consists of a succession of top soil, sandy grits and ferruginous sandstone, fine to medium sand and a brown clayey grit which serves as a confining material for the aquifer (Fig. 1.3).

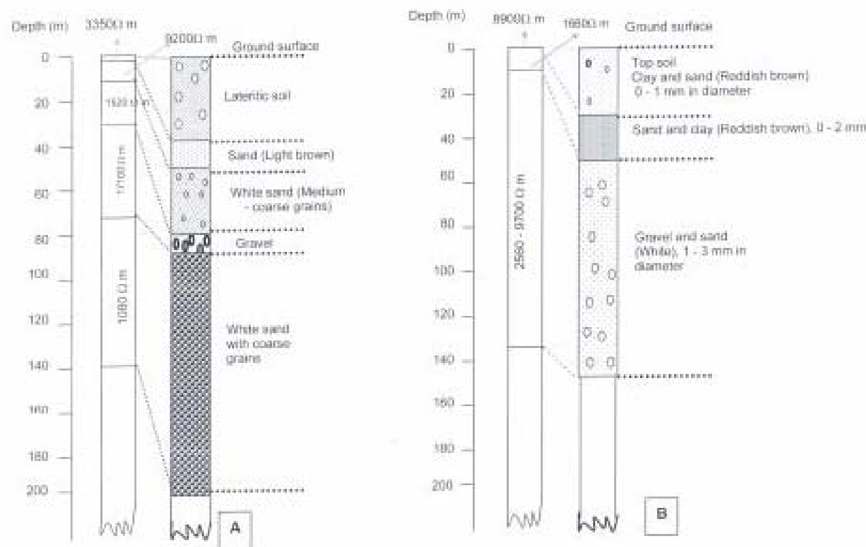

Fig. 1.2. Comparison of computer interpreted VES curves with borehole lithology logs.
A : VES 1 and lithology log of Owerri borehole; B: VES 4 and lithology log of Ihiagwa borehole.

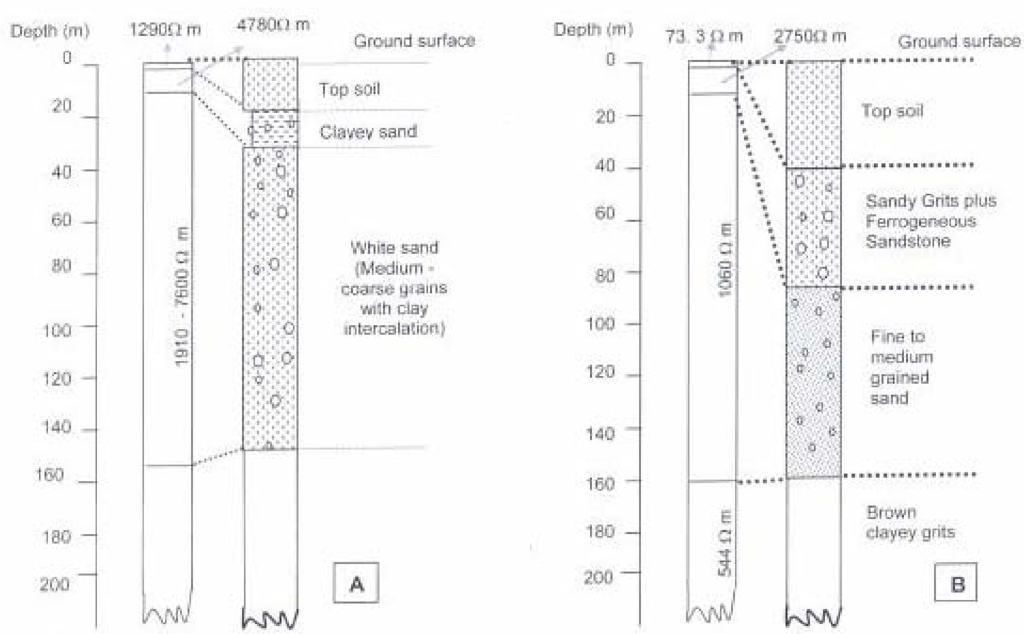

Fig. 1.3. Comparison of computer interpreted VES curves with borehole lithology logs.
A: VES 18 and lithology log of Aba Branch borehole; B: VES 16 and lithology log of Ańara borehole.

DEPTH TO WATER AND AQUIFER THICKNESS

We evaluated the variations in water depth and aquifer thickness across the study area by taking two cross-sections: AB and CD.

GEOELECTRIC CROSS- SECTION A – B

A-B was taken along the SW – NE flank of the study area and covers an area of approximately 60km. Depth to water is shallow around Avu (VES 2) – Egbu (VES 5) and Amaraku (VES 15) areas with a mean depth of 61m and deeper around Owerri (VES 1) – Obinze (VES 3) – Ihiagwa (VES 4) and Anara (VES 16) with a mean depth of 140m (Fig.1.4). Aquifer thickness ranges from 12m to 106m (Fig. 1.5).

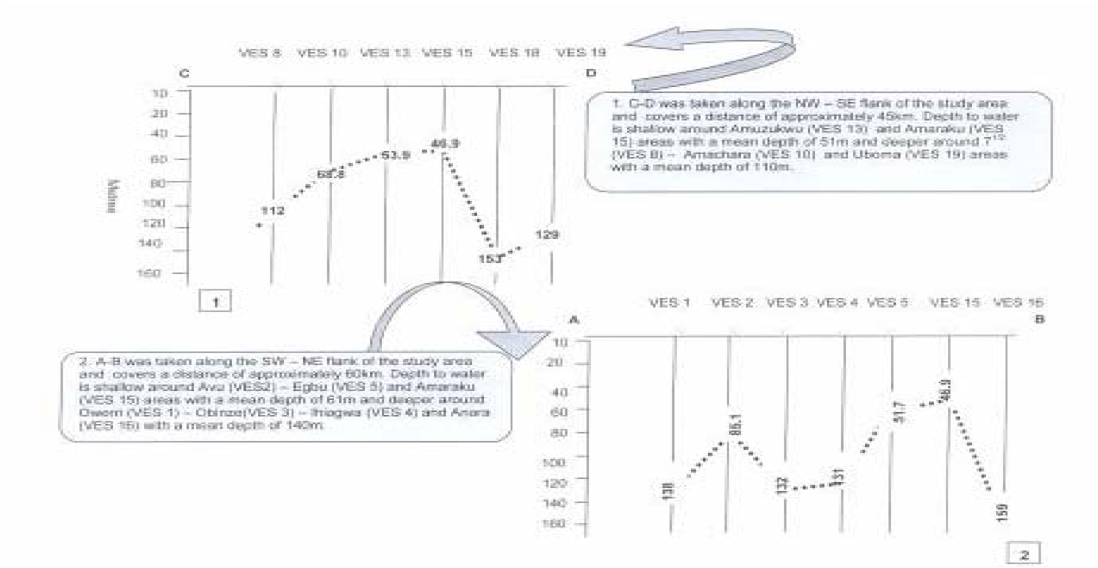

Fig. 1.4. Geoelectric cross- section A – B and C - D showing depth to the saturated Water table

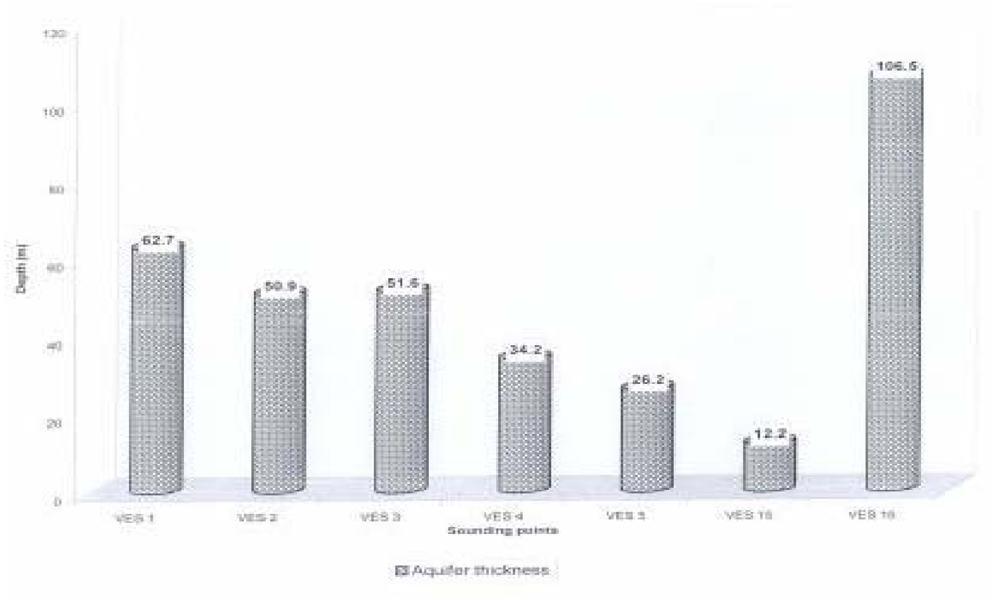

Fig. 1.5. Geoelectric cross – section A – B showing aquifer thickness

GEOELECTRIC CROSS- SECTION C – D

C-D was taken along the NW – SE flank of the study area and covers an area of approximately 45km. Depth to water is shallow around Amuzukwu (VES 13) and Amaraku (VES 15) areas with a mean depth of 51m and deeper around 71/2 (VES 8) – Amachara (VES 10) and Uboma (VES 19) areas with a mean depth of 110m (fig.1.4). Aquifer thickness ranges from 12m to 108m (Fig. 1. 6).

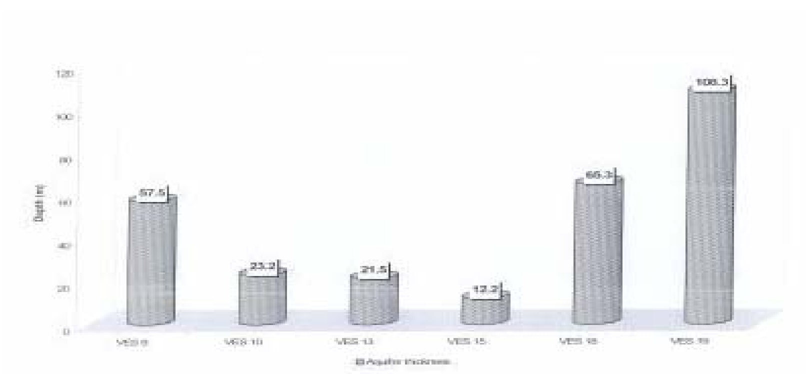

Fig. 1.6. Geoelectric cross – section C – D showing aquifer thickness

Kσ VARIATION ACROSS THE STUDY AREA

On the basis of the Kσ product (Fig.1.7), Owerri - Egbu- Ihiagwa and Ife areas (Zone A) are hydrologically homogeneous, with Kσ values varying between 0.0061 and 0.0093. Zone A has a mean Kσ value of 0.0077 and may represent the Benin formation. Uboma - Obowu - Umuagu (Zone B) are also homogeneous hydrologically with Kσ values varying between 0.0102 and 0.0316. Zone B has a mean Kσ value of 0.0209 and may represent the Ogwashi Asaba formation. Zone C (Anara - Obohia - Amogwugwu) has a mean Kσ value of 0.0047 while Zone D (Aba Branch - $7^{1/2}$) has a mean value of 0.00315. Zone C and D may represent the Bende- Ameki and Imo formations respectively.

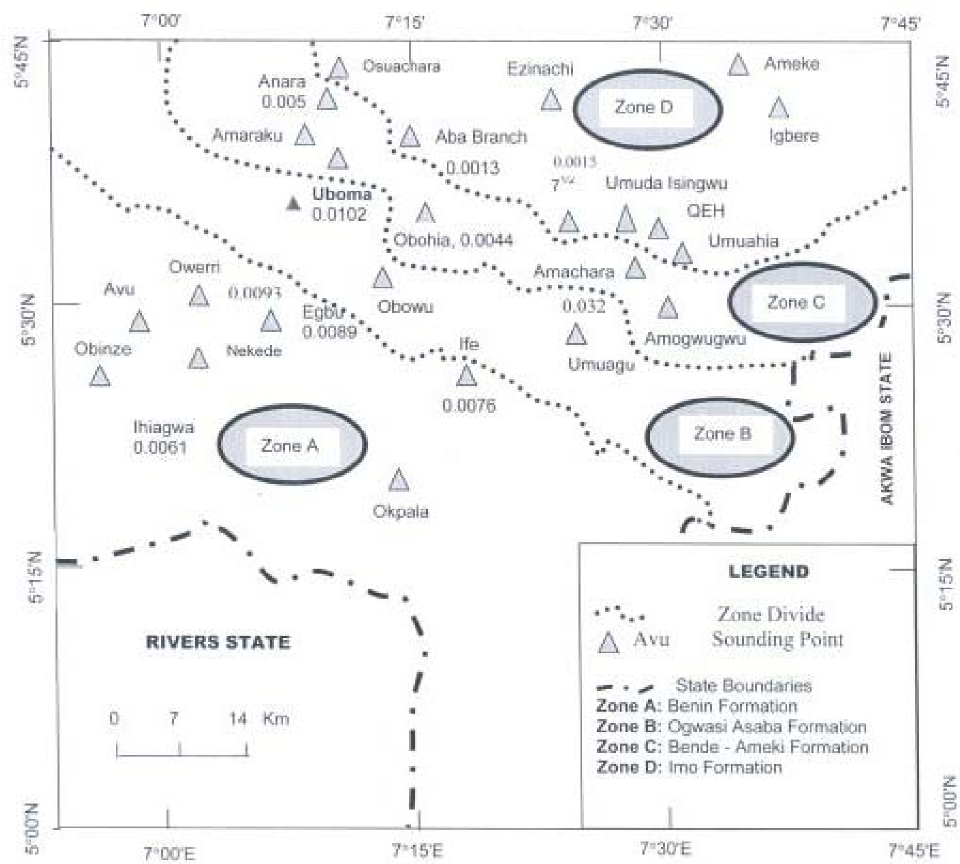

Fig. 1.7. Map of Kσ variation across the study area

AQUIFER HYDRAULIC CONDUCTIVITY

The hydraulic conductivity (K) of aquifers where no boreholes exist is obtained from the relation below:

$$K = \frac{\text{A constant}}{\sigma} \qquad \text{(Niwas and Singhal, 1981)}$$

Where K = Aquifer hydraulic conductivity in m/day

σ = Conductivity (inverse of resistivity).

The computed K values are shown in Table 1.1. The hydraulic conductivity values vary between 1.24m/day and 26.41m/day.

Table 1.1. Aquifer parameters of the sounding locations across the study area

VES no.	Location	Depth to water (m)	Aquifer Thickness (m)	Apparent Resistivity	Transverse Resistance (R) ρb (ohm - m^2)	K Value	Kσ Value	Hydraulic conductivity (m / day)	Transmissivity KσR (m^2 / day)
1	**Owerri**	138.10	62.70	1080	67716	10.02	0.0093	8.32	521.66
2	**Avu**	85.10	50.90	3120	158808			24.02	1222.62
3	**Obinze**	132.00	51.90	3430	176988			26.41	1370.68
4	**Ihiagwa**	131.00	34.20	2560	87552	15.74	0.0061	19.41	663.82
5	**Egbu**	51.70	26.20	1760	46112	15.72	0.0089	13.55	355.01
6	**Ife**	11.20	8.30	860	7138	6.57	0.0076	6.62	54.95
7	**Obowu**	27.20	26.10	1740	45414			13.40	349.74
8	**$7^{1/2}$**	112.00	57.50	3690	200675	4.98		4.98	286.35
9	**Umuda**	38.80	15.80	2510	39658			3.39	53.57
10	**Amachara**	68.80	23.20	1180	27376			5.55	128.76
11	**Amogugwu**	110.00	51.00	1230	62730			5.78	294.78
12	**Ezinachi**	66.70	41.80	960	40128			1.29	53.92
13	**Amuzukwu**	53.90	21.50	920	19780			1.24	26.66
14	**QEH**	146.00	94.00	990	93060			1.34	125.96
15	**Amaraku**	46.90	12.20	1160	25752	5.57	0.0050	5.45	120.99
16	**Anara**	159.00	106.50	544	57936			2.56	272.64
17	**Osuachara**	69.10	26.90	1140	30666			1.54	41.43
18	**Aba Branch**	153.00	65.30	1910	124723	2.52	0.0013	2.57	167.82
19	**Uboma**	129.00	108.30	510	55233	5.23	0.0102	10.66	1154.88
20	**Obohia**	111.00	55.50	1100	61050	4.82	0.0044	5.17	288.94
21	**Igbere**	144.00	35.00	3580	125300			4.83	169.05
22	**Okpalla**	97.70	62.80	1054	66191.20			8.12	509.936
23	**Umuagu**	98.20	39.60	123	4870.80			2.57	101.77
24	**Ameke Alayi**	128.00	68.20	9100	620620			12.29	838.178

TRANSMISSIVITY

Aquifer transmissivity (product of aquifer thickness and hydraulic conductivity) for all the sounding locations in the study area including those areas where there are no boreholes were computed from the relation below:

$T = K * b$ (Henriet, 1976)

where T = Transmissivity in m^2/day
b = Aquifer thickness

Transmissivity across the study area varies between 27m^2/day and 1371 m^2/day (Table 1.1.)

DISCUSSION AND CONCLUSION

The results have shown a very close semblance with those obtained from pumping tests and other statistical analysis methods. This shows that electrical resistivity survey is a useful method for understanding the aquifer systems within the study area. Computer modelled interpretation techniques have also helped to resolve the true thicknesses, resistivities and the depth to the aquiferous zones. The depth to water is shallow around Ife, Obowu, Umuda and Amaraku areas with an average depth of 31m. The aquifer is relatively deep around Avu, Egbu, Amachara, Amogwugwu, Ezinachi,Amuzukwu and Osuachara areas with a mean depth of 65m. Very deep aquifers with a mean depth of 130m were sensed at Owerri, Obinze, Ihiagwa, $7^{1/2}$, Queen Elizabeth Hospital, Anara, Aba Branch, Uboma, Obohia and Ameke Alayi.

The above result agrees closely with how Uma (1989) delineated the aquifer systems within the Imo River Basin. He found out that three aquifer systems exist within the Imo River basin: a shallow discontinuous aquifer system, a thick regional unconfined aquifer system, and a confined aquifer system. The diagnostic features of the $K\sigma$ product have proved very useful in this study. It was used effectively to delineate four distinct lithostratigraphic units within the study area. The same $K\sigma$ = constant parameter was used to estimate the hydraulic conductivity and transmissivity for all the sounding locations across the study area. Hydraulic conductivity varies between 1.24 m/day and 26.41m/day. The closeness of hydraulic conductivity values obtained from grain size analysis and pumping tests and those estimated from sounding interpretations is a good indication of the reliability of this study. Transmissivity values vary between $41m^2$/day and $1370m^2$/day. Sufficiently high transmissivities coupled with good aquifer thicknesses are most prospective for drilling productive boreholes (Onuoha and Mbazi, 1988). This study has helped to map out probable zones for drilling productive boreholes in the study area. Avu - Obinze areas appear most productive for Zone A. Uboma - Obowu areas appear most productive for Zone B. Anara - Obohia - Amogwugwu areas appear most productive for Zone C while Aba Branch - QEH - Ameke Alayi appear most productive for Zone D. The major aquifers within zones C and D are the Ebenebe and Umuna sandstone units. The Ebenebe sandstone unit occurs as a lens in the North-western extremity of the Imo river basin and attains a thickness of over 120m in some places (Uma, 1989).

It is however recommended that other advanced imaging techniques like cross-hole electrical tomography be used in the area to validate the results. We also recommend that a hydro chemical study be carried out to determine the portability of the water for both industrial and domestic uses.

Acknowledgements

Special thanks to our field mates: Yibo Ayebanoah, Opara Alex and Ugo Francis. We recall with nostalgia the time we spent together during the field work.

REFERENCES

Henriet, J.P., 1977. Direct applications of Da- Zarrouk parameters in groundwater surveys. *Geophysical Prospecting, vol. 24, pp. 344 - 353.*

Keller, G. V., and Frischnechk, F.C., 1979. Electrical methods in geophysical prospecting. *Pergamon Press, New York, pp 91 - 135.*

Koefoed, O., 1977. Geosounding principles 1.Resistivity sounding measurements, Elsevier, Amsterdam, 277pp.

Niwas, S., and Singhal, D.C., 1981. Estimation of aquifer transmissivity from Da – Zarrouk parameters in porous media. *Journal of Hydrology, vol. 50, pp. 393 - 399.*

Onuoha, K.M., and Mbazi, F.C.C., 1988. Aquifer transmissivity from electrical sounding data: the case of Ajalli sandstone aquifers, South East of Enugu, Nigeria. *In C.O. Ofoegbu (editors), Groundwater and Mineral resources of Nigeria, Friedr. Vieweg & Sohn Publishers, pp. 17 - 29.*

Rayment, R.A., 1965. Aspects of the geology of Nigeria. *University of Ibadan press, Nigeria, pp. 45 - 80.*

Short, K.C., and Stauble, A.J., 1967. Outline of the geology of the Niger Delta. *American Association of Petroleum Geologists Bulletin, vol.51, pp.761 - 779.*

Uma, K.O., 1989. An appraisal of the groundwater resources of the Imo River Basin. *Nigerian Journal of Mining and Geology, vol.25, nos. 1 and 2, pp. 305 - 315.*

Vingoe, P., 1972. Electrical resistivity surveying. *ABEM geophysical memorandum 5/72, pp. 1-13.*

Zohdy, A.A.R., 1976. Application of surface geophysics (Electrical methods to groundwater investigations) in: Techniques for water resources investigations in the United States. *Section D, book 2, pp. 5 - 55.*