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Original Research Article
**Estimating Geohydraulic Parameters With
Goelectric Soundings: Case Study From
Orerokpe, Western Niger Delta, Nigeria**

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ABSTRACT

A study of the use of goelectric sounding employing Schlumberger configuration in delineating aquifer(s) and evaluating their geohydraulic characteristics has been carried out at Orerokpe, Western Niger Delta. Twenty (20) depth soundings were carried out with a maximum current electrode spacing of 400 m. The acquired depth sounding data were interpreted by partial curve matching and computer iterative techniques. The results identified four geologic layers which include; top soil, clay/sand, sandy clay/clayey/sand and sand. The sands of the third and fourth geologic layers constitute the aquifer, the depth to the aquifer varied between 6.4 m and 28.1 m with a mean depth of 17.5 m. The thickness of the aquifer varied between 15.1 m and 67.1 m with a mean thickness of 28.24 m. The hydraulic conductivity (K) value measured in a reference borehole was combined with electrical conductivity (σ) obtained from goelectric sounding data, the resulting diagnostic relation ($K\sigma = \text{constant}$) was combined with Dar-Zarrouk parameters to evaluate the transmissivity of the aquifer. The results indicated that the transmissivity values of the aquifer varied between 418 m²/day and 1637.3 m²/day while hydraulic conductivity values varied between 10.50 m/day and 45.71 m/day. The evaluated geohydraulic characteristics indicated that the aquifer in seventy five (75) percent of the study area have high aquifer potential while the remaining twenty five (25) percent have moderate aquifer potential.

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Keywords: Aquifer, geohydraulic parameters, Dar-Zarrouk parameters, well, drawdown.

1. INTRODUCTION

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Water supply in most parts of Nigeria is insufficient. The problem of water supply has been further aggravated in recent years by the rapid population growth, urbanization and industrialization. The provision of sustainable water supply has been a major challenge to successive governments in Nigeria for decades. In the Niger Delta petroleum province the exploitation of ground water has always been preferred over surface water. The reason for this is probably the existence of rich aquifers, especially the Benin Formation which is easily exploited in many areas with shallow drilled wells and dug wells. However, groundwater exploitation has not been accompanied by resource evaluation studies that are anchored on aquifer characteristics. Such

characteristics include porosity, specific yield, hydraulic conductivity, transmissivity and storativity without which it is impossible to answer questions such as how much water would a particular aquifer release to a borehole a knowledge of which is essential for planning purposes. Consequently, many borehole schemes have been abortive or yield much below capacity. Furthermore, geohydraulic characteristics such as transmissivity and hydraulic conductivity are crucial for environmental studies involving site characterization, fate and transport of pollutants as well as remediation of contaminated sites.

The conventional method for determining geohydraulic parameters such as transmissivity and hydraulic conductivity involve pumping testing; this method is expensive and gives results relevant to only to a small area of the aquifer. Furthermore, wells may pose critical problems in the analysis of field pumping tests. In the presence of diverse field conditions, the various assumptions are seldom valid during pumping tests and thus the estimation of aquifer geohydraulic parameters may lead to erroneous values for the relevant parameters. At the same time, these procedures are time consuming and cost prohibitive if practiced indiscriminately. Also, in the Niger Delta there is paucity of observation wells to carry out pump test as these wells are expensive to drill and maintain in developing countries. The numerous wells in the region are privately owned and the owners usually will not allow the use of their wells for pump test, the reason is probable due to safety. An alternative, less expensive approach that provides more regional information is the integration of geo-electric surveys with existing borehole data. Geoelectrical surveys have become an increasingly important tool in subsurface hydrogeological applications. The spatial distribution of electrical response characteristics of the subsurface aquifer matrix can provide valuable information for characterizing the heterogeneity of the subsurface water and soil zone [1, 2].

The geoelectrical method is an effective tool for ascertaining the subsurface geologic framework of an area [3, 4, 5]. Application of the geoelectrical method has led researchers to develop surface resistivity techniques for making quantitative estimates of the water transmitting properties of aquifers [6, 7]. Ungemach et al., 1969 [8] found a relationship between transverse resistance and transmissivity. They correlated transmissivities determined from six pumping tests in the Rhine aquifers of France with transverse resistances. Scerascia, 1976 [9] used electrical soundings to estimate transmissivity in Italy. Niwas and Singhal, 1981 [10] estimated

the aquifer transmissivity from the Dar-Zarrouk parameters in porous media by using an analytical relation between aquifer transmissivity and transverse resistance. Kelly, 1977 [11] established an empirical relation between aquifer electrical resistivity and aquifer hydraulic conductivity. Onuoha and Mbazi, 1988 [12], Ekwe et al., 2006 [13] estimated aquifer hydraulic characteristics in southeastern Nigeria by integrating geoelectric and pump test data.

The present study attempts to evaluate transmissivity from geoelectric and borehole data and as much as possible use the acquired data to characterize a larger area than would have been possible with the one pump test alone. Furthermore, the areas of higher transmissivity will be delineated for location of potentially high yield water wells/boreholes.

2. LOCATION, GEOLOGY AND HYDROGEOLOGY

The study area (Fig. 1) is situated between longitudes 5°53'E, 5°58'E and latitudes 5°35'N, 5°38'N. The area is located within the Niger Delta Basin; the sedimentary sequence within the basin is over 800 m thick and consists of three distinct formations that include from bottom to top: the Akata Formation, the Agbada Formation and the Benin Formation [14, 15]. The Akata Formation consists predominantly of high-pressure marine shale while the Agbada Formation is made up of alternating sand and shale. The Benin Formation, up to 2000m thick caps the sequence and consists predominantly of fine to coarse grained, poorly sorted sand, gravel and clay lenses. In the coastal region of Delta State, the Benin Formation is overlain and masked by the Sombreiro-Warri Deltaic Plain deposits. These sediments consist of fine to medium and coarse-grained sands, gravelly sand with intercalation of clay lenses which play a considerable role as local confining beds are usually lesser than 120 m in thickness. The Sombreiro-Warri Deltaic Plain deposits are thought to be recent expression of the Benin Formation [16] and are not easily distinguished from it in borehole sections. They are both in hydraulic continuity and may be considered one and the same aquifer.

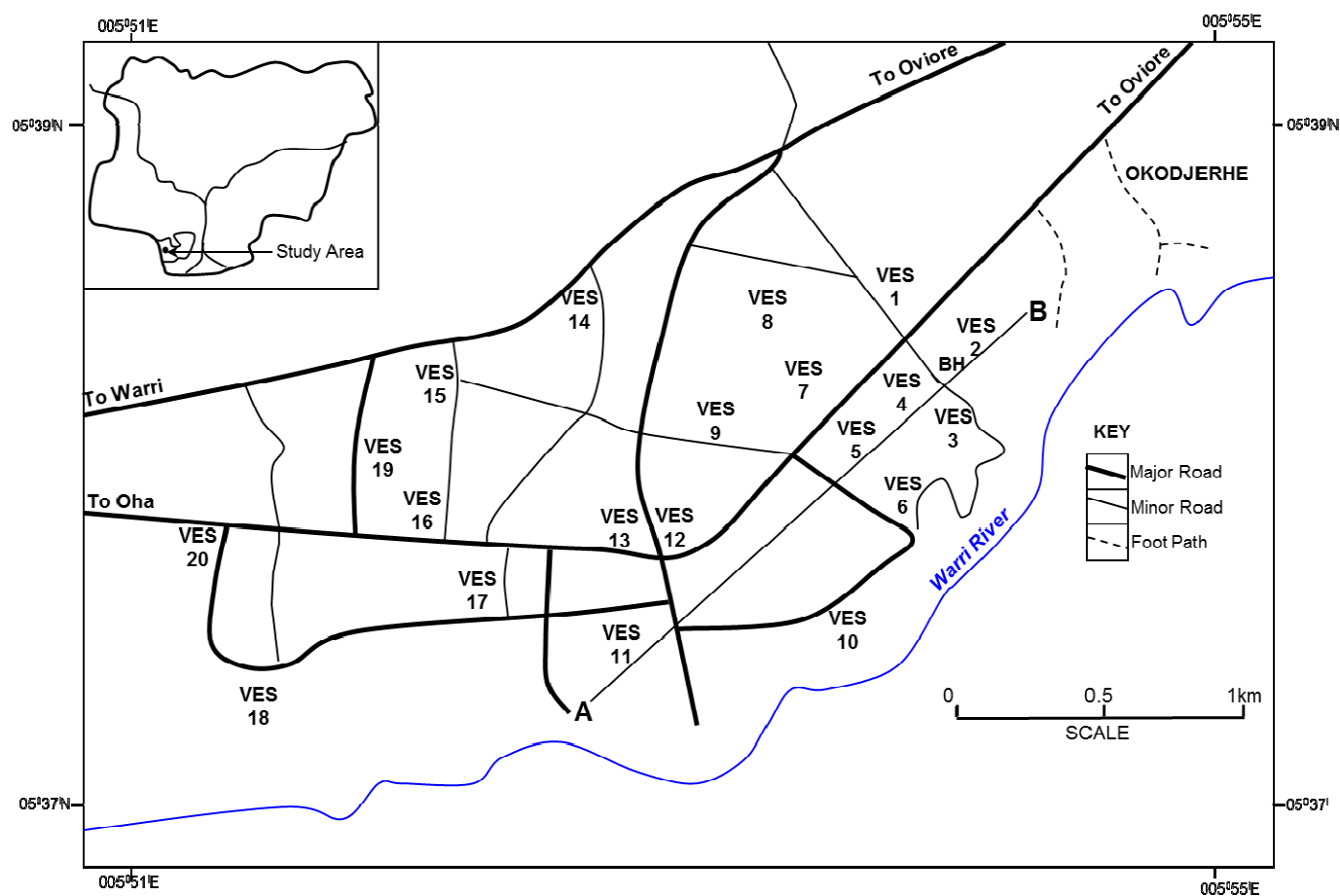


Fig. 1. Map of study Area

Groundwater in the Niger Delta is contained in mainly very thick and extensive sand and gravel aquifer. Etu-Efeotor and Akpokodje, 1990 [17] have summarized the hydrostratigraphic units of the Niger Delta as five well defined aquifers. The first aquifer occurs under phreatic conditions between depths of 0 – 45 m. It supplies water to small private and commercial boreholes and is the most extensively exploited causing water table decline, pollution and saline water intrusion. Most aquifers in this study are within these depths. The second and third aquifers (45 – 130 m and 130 – 212 m deep, respectively) are semi confined and are usually penetrated by medium sized industrial, community and municipal boreholes. The fourth aquifer is 212 – 300 m deep and is tapped by few large scale deep boreholes for municipal and industrial water schemes. The fifth aquifer is more than 300 m depth. Majority of boreholes usually penetrated only the first and second aquifers. The aquifers vary from unconfined to confined conditions at depths. They are separated by highly discontinuous layers of clays giving a picture of a complex, non-uniform, discontinuous and heterogeneous aquifer system. The hydraulic conductivity varies from 0.04 – 60 m/day, transmissivity ranges from 59 – 6050

m²/day, storage coefficient varies from 10⁻⁶ – 1.5x10⁻¹ and borehole yield is very good with production rates of about 20,010 l/h which indicates potentially productive aquifers [18,19, 20].

3. MATERIALS AND METHODS

3.1 Pumping test

A well marked BH as shown in figure 1 was pumped at a uniform rate of 2500 m³/day for six hours. Pumping tests commonly last from five to five days [21]. Drawdowns during the pumping period are measured in an observation well at a distance r = 60 m away. The pumping time t and drawdown s were observed. A time – drawdown curve was plotted and analysed for aquifer geohydraulic parameters (transmissivity and hydraulic conductivity using the Cooper-Jacob Method of solution [22]. Prior to the pumping test, the depth to the static water level in the observation well was recorded. The drawdown was obtained from the differences between depths to static water level and depths to dynamic water levels achieved during pumping test. Replacing s by Δs (drawdown difference per log cycle of t) [23], the value of transmissivity T can be evaluated from the equation the below:

$$T = \frac{2.30Q}{4\pi\Delta s} \text{ --- (1)}$$

3.2 Geoelectric Investigation

Geoelectrical investigation involving resistivity sounding was undertaken within the study area to provide information on the geoelectrical stratification of the subsurface. Direct-current electrical resistivity method still remains the most powerful and cost- effective technique in groundwater investigation [24, 25, 26]. Resistivity of the ground is measured by injecting current into the ground and measuring the resulting potential difference. The general field layout requires two pairs of electrodes are required: electrodes A and B are used for injecting current while M and N are for potential measurements. For a homogenous subsurface, the resistivity ρ_a (in ohm-meter) can be calculated from the current I and potential difference V by

$$\rho_a = K \frac{V}{I}$$

K is called geometric factor (in meter) and can be calculated from the electrode spacing by

$$K = \frac{1}{2\pi} \left[\left(\frac{1}{AM} - \frac{1}{BM} \right) - \left(\frac{1}{AN} - \frac{1}{BN} \right) \right]$$

The vertical electrical sounding (VES) method was adopted using the Schlumberger configuration at twenty (20) locations as shown in Fig. 1. The equipment used was the ABEM Terrameter SAS 1000 with current electrode spacing (AB) ranging from 2 m to 400 m. The data obtained was plotted on a log-log graph of apparent resistivity against half electrode spacing. The VES curves were interpreted by partial curve matching [27] and computer iteration methods. The multi-layered field curves were interpreted segment by segment using theoretically generated master curves and associated auxiliary curves. The interpretation results (layer resistivities and thicknesses) from the partial curve matching were used as initial model parameters in a forward modelling using winResist 1.0 by Vander Velpen, 2004 [28]. Computer iteration models the curve by adjusting the theoretical model and its corresponding sounding curve to the measured (field) curve which can be controlled on the computer's monitor. A best fit to stop the iteration is defined by the computer calculating a root mean square (RMS) error [29]. The RMS error between the field and calculated data is generally less than 3 %. The electrical resistivity contrasts existing between lithological sequences in subsurface were used in the delineation of geoelectrical layers and identification of aquiferous units [28].

3.3 Estimation of geohydraulic characteristics from geoelectric data

Mathematically, the flow of electric current in a conducting medium is governed by Ohm's law

$$J = \sigma E \dots\dots\dots (2)$$

where J = electric current density, σ = electrical conductivity ($\sigma = 1/\rho$, where ρ is the resistivity)

E = electric field intensity,

while groundwater flow in a porous medium is governed by Darcy's law:

$$Q = KIA \dots\dots\dots (3)$$

where Q = discharge, K = hydraulic conductivity, I = hydraulic gradient, A = Cross-sectional area.

The analogy between these two phenomena and the relationship between electric and geohydraulic parameters are universally accepted [30, 31]. Groundwater flow through an aquifer is controlled by the transmissivity (T), which is expressed by

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

where h , is the saturated thickness of the aquifer.

However, a relationship exists between transmissivity and the Dar Zarrouk parameters which were first introduced by [32] and consist of two variables: the transverse resistance (R) and the longitudinal conductance (S). They can be expressed by the following relationships.

$$R = h \rho = h / \sigma \dots\dots\dots (5)$$

$$S = h / \rho = h \sigma \dots\dots\dots (6)$$

where, h and ρ are the thickness and resistivity of individual layers in meters and ohm-meters respectively.

Taking into account a prism of aquifer material having unit cross-sectional area and thickness; Niwas and Singhal, 198 [10] combined equations (4), (5) and (6) to obtain the following relationships

$$T = K \sigma R \dots\dots\dots (7)$$

and

$$T = \frac{KS}{\sigma} \dots\dots\dots (8)$$

In areas of similar geologic setting and water quality, the product $K\sigma$ remains fairly constant [10, 12].

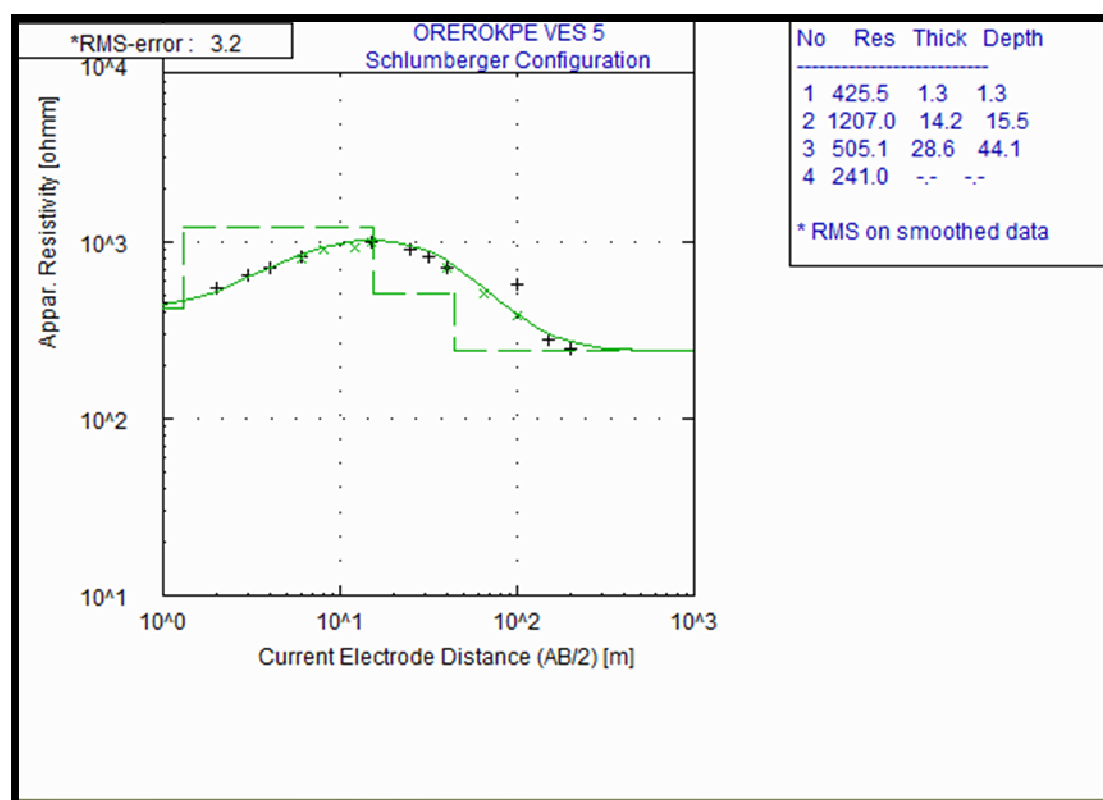
Thus, if hydraulic conductivity K values are known from a specific well location and σ values are obtained from electrical sounding interpretations, transmissivity and its variations from place to place including those places where no K values are available can be determined using the above relationships.

4. RESULTS AND DISCUSION

4.1 Aquifer Delineation

Qualitative interpretation results of the computer modeled data curves is characterized by HQ, HK, QQ, KH and KHQ hybrid model curves [3]. Some selected examples of the 20 modelled curves are shown in Figs. 2 and 3. The results revealed four to five distinct geoelectric layers; these geoelectric layers on correlation with lithological logs (Fig. 4) are equivalent to a maximum of four geologic layers made up of top soil, clay/sand, sandy clay/clayey/ sand and sand.

178 The first layer have resistivity values that vary from 113.2 – 1221.8 ohm-m and thickness of 0.8 – 1.6 m, this is
 179 diagnostic of the top soil of variable composition. The resistivity values of the second layer vary from 42.3 –
 180 1207.0 ohm-m with thickness varying from 6.5 – 18.5 m. The low resistivity (< 100 ohm-m) is diagnostic of clay
 181 which is absent in some localities while the high resistivity (> 300 ohm-m) typifies sands. The third layer have
 182 resistivity values that vary from 108.2 – 1550.6 ohm-m, the low resistivity (>100 ohm-m) is typical of sandy clay
 183 and clayey sand while the high resistivity (> 300 ohm-m) indicates sands. The thickness of this layer vary
 184 between 10.2 – 67.1 m and constitutes the aquifer in localities where the unit is sandy, the aquifer is confined
 185 where the overlying second geologic unit is clay and unconfined where it is sand. A fourth layer of sand which
 186 also forms part of the aquifer having resistivity values of 205.3 – 418.7 ohm-m underlie the third geologic layer.
 187 The thickness of this layer could not be ascertained as current electrode terminated within this layer. However,
 188 inference from VES 8 and 9 where there is a fifth layer comprising of sand shows that the fourth layer is over
 189 17.0 m. The depth to the aquifer varied between 6.4 – 28.1 m and thickness ranged from 15.1 – 57.1 m. The
 190 values of the depth to aquifer from the geoelectric model were used with SURFER 2002 [33] terrain and
 191 surface modeling software was used to generate a map of depth to aquifer (Fig. 5).



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 193 **Fig. 2: Typical iterated sounding curve of the study area at location 5**

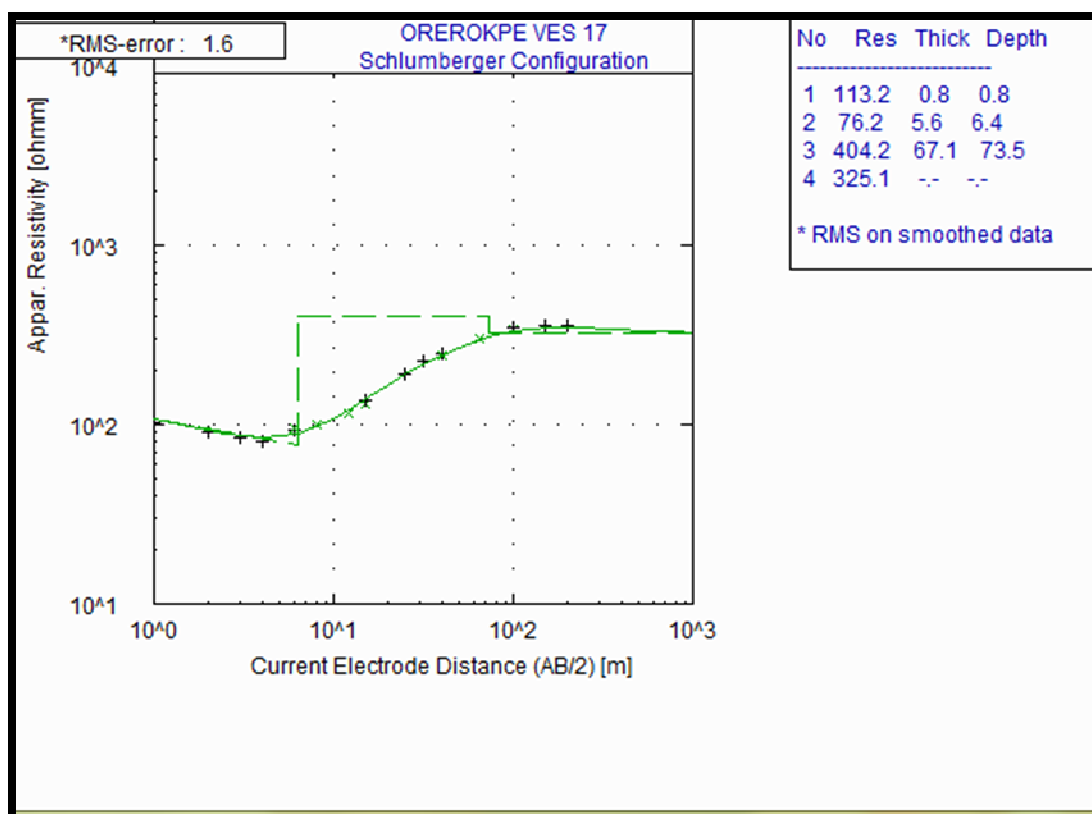
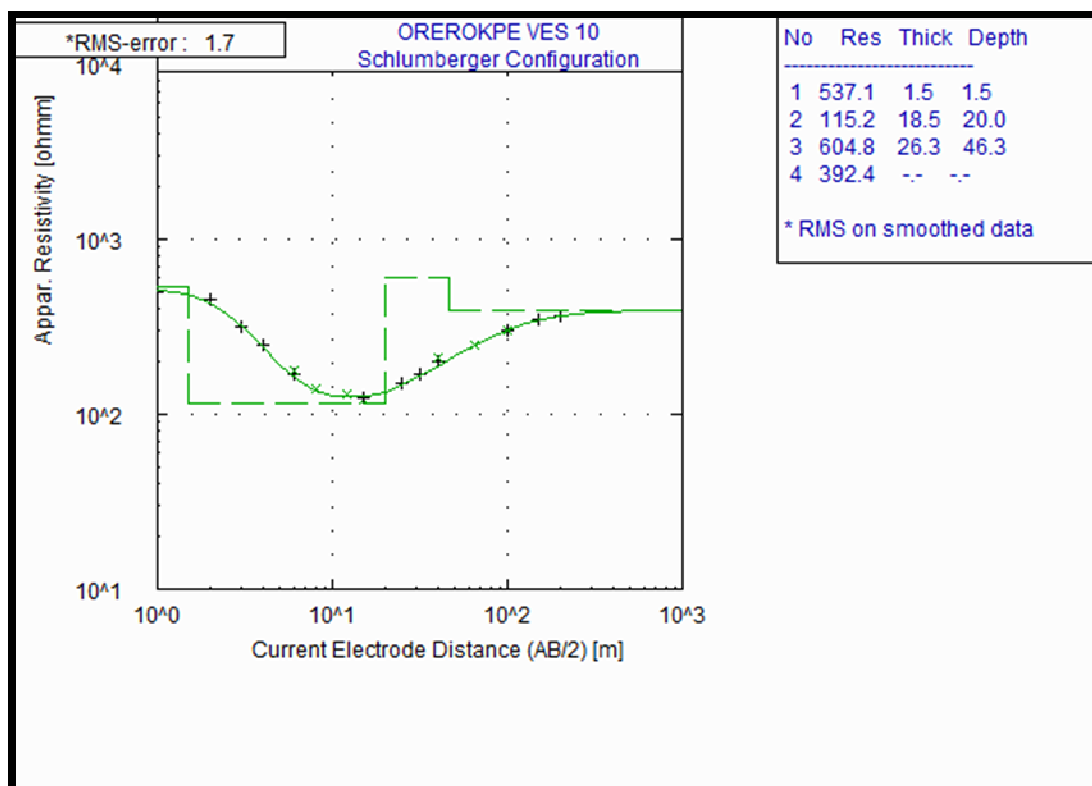


Fig. 3: Typical iterated sounding curves of the study area at locations 10 and 17

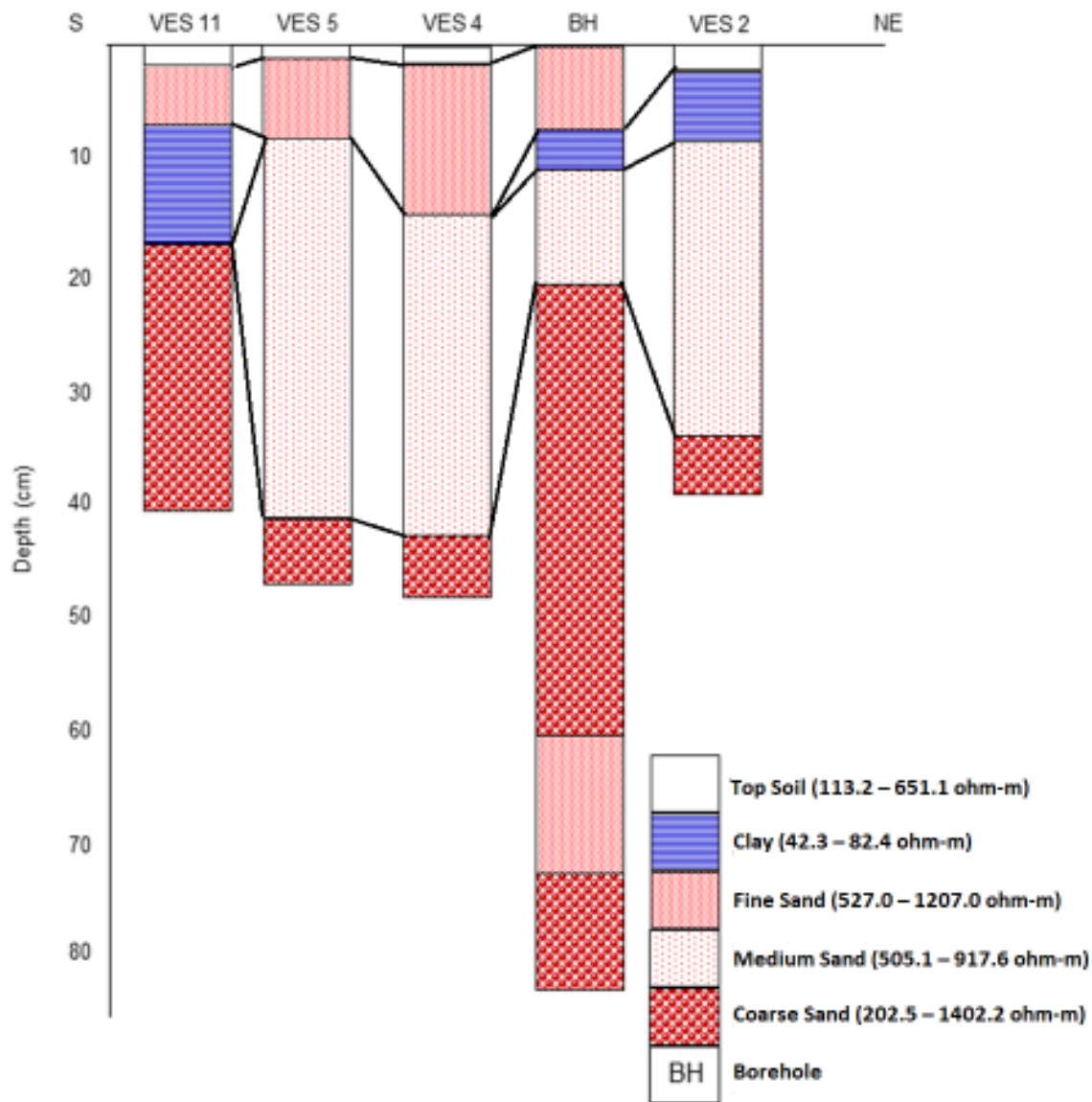


Fig. 4: Geoelectric section at Orerokpe along traverse AB correlated with a lithologic log

4.2 Estimation of Transmissivity Variation

Using $\Delta s = 0.45$ and substituting this value into equation 1, the value of T from pumping test was evaluated as shown below:

$$T = \frac{2.30(2500)}{4\pi(0.45)}$$

$$= 1016.37 \text{ m}^2/\text{day}$$

The hydraulic conductivity K of the aquifer was evaluated from equation 4:

$$K = \frac{1016.37}{38}$$

211 = 26.8 m/day

212 Where 38 m is the saturated thickness of the aquifer

213 The $K\sigma$ constant was calculated by using the K value of 26.8 m/day obtained from the pumping test of the well

214 marked BH in Fig. 1 and σ obtained from electrical sounding data at location 4 ($\sigma = 1/\rho = 1/917.6 = 0.0011$

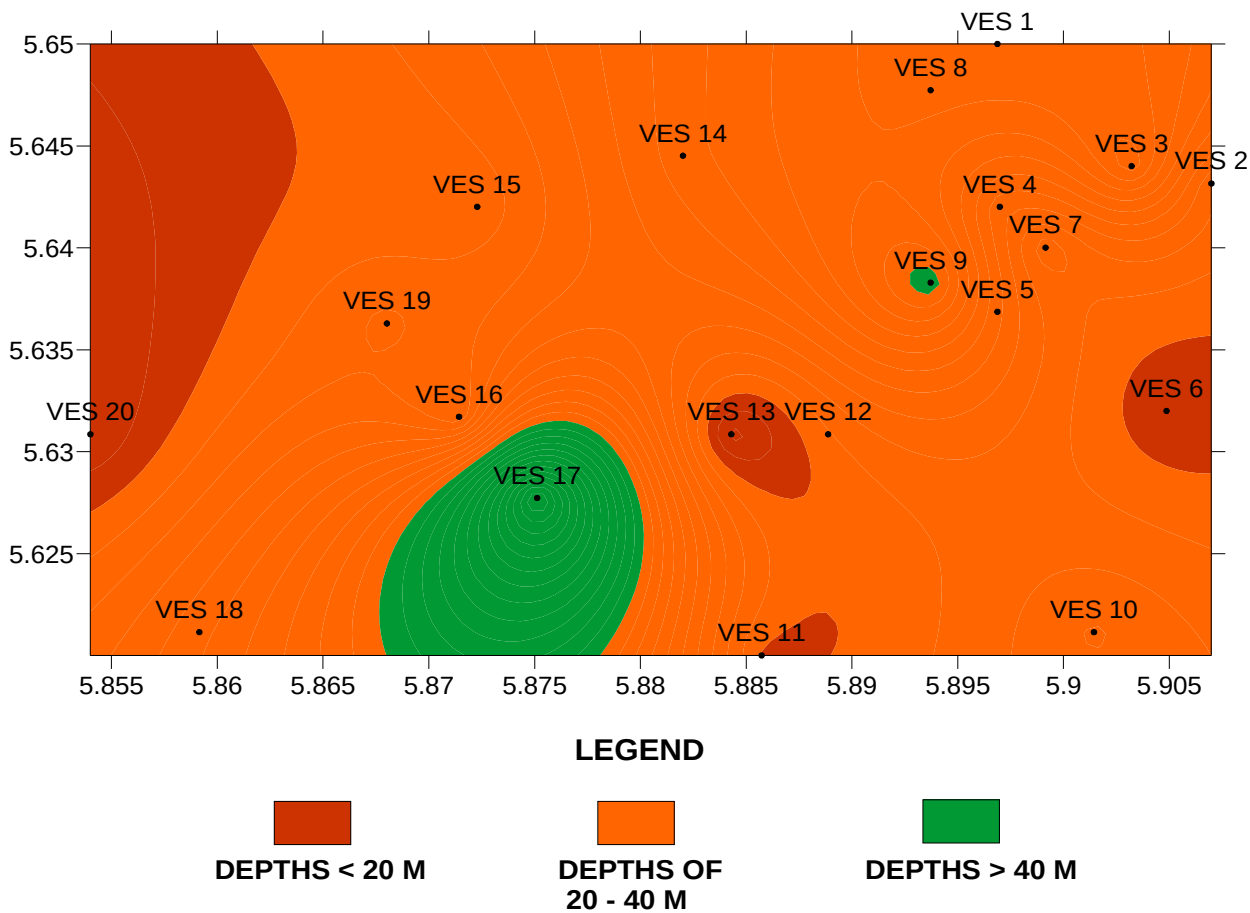
215 Siemens/m).

216 Hence, $K\sigma = 26.8 \times 0.0011 = 0.02948$

217 Transmissivity values can be estimated at all locations where there are no well test data from the relation:

218 $T_c = K\sigma R = 0.02948R$

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220

221 **Fig. 5: Depth to aquifer in meters**

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223 Hydraulic Conductivity values were calculated at all sounding locations from the relation:

224 $K_c = \frac{T_c}{h}$

225 The evaluated hydraulic characteristics (transmissivity and hydraulic conductivity values) in Orerokpe are
 226 presented in Table 1

227

228 **Table 1. Geohydraulic parameters of aquifer at sounding locations across the study area**

VES Location	ρ (Ω m)	h(m)	Z(m)	R(Ω m ²)	K _p (m/day)	K σ	T _c (m ² /day)	K _c (m/day)
1	429.9	37.9	13.8	16293.2	26.8	0.02948	480.32	12.67
2	928.7	24.3	8.3	22567.41	26.8	0.02948	665.30	27.40
3	1084.2	39.4	18.7	42717.48	26.8	0.02948	1259.30	31.96
4	917.6	26.5	14.0	24316.40	26.8	0.02948	716.80	27.05
5	505.1	28.6	15.5	14445.86	26.8	0.02948	425.86	14.89
6	1047.9	18.3	13.5	19176.57	26.8	0.02948	565.30	30.90
7	771.0	20.7	12.0	15959.7	26.8	0.02948	470.50	22.73
8	1530.0	36.8	27.4	55539.0	26.8	0.02948	1637.30	45.10
9	355.9	42	28.1	14947.8	26.8	0.02948	440.7	10.50
10	604.0	26.3	20.0	15885.2	26.8	0.02948	468.3	17.81
11	1402.2	19.6	16.4	27483.12	26.8	0.02948	810.2	41.34
12	938.7	21.8	18.2	20463.66	26.8	0.02948	603.3	27.67
13	1384.2	15.1	10.1	20901.42	26.8	0.02948	616.17	40.81
14	968.0	31.2	14.5	30201.6	26.8	0.02948	890.3	28.53
15	1621.8	20.6	18.7	33409.08	26.8	0.02948	984.9	47.81
16	1550.6	21.9	22.6	33958.14	26.8	0.02948	1001.1	45.71
17	404.2	67.1	6.4	27121.82	26.8	0.02948	799.6	11.92
18	483.0	29.4	14.0	14200.2	26.8	0.02948	418.6	14.24
19	1165.0	24.7	16.1	28775.5	26.8	0.02948	848.3	34.34
20	1225.0	16.1	18.5	19722.5	26.8	0.02948	581.4	36.11

229 Z is depth to aquifer and K_p is hydraulic conductivity from pump test

230 The results obtained indicate that the calculated transmissivity values of the aquifer in the study area varied
 231 from 418.6 to 1637.3 m²/day (Table 1). Using SURFER 2002 [33] terrain and surface modeling software, the
 232 transmissivity values in Table 1 were used to generate an isotransmissivity map. Comparing the transmissivity

values obtained above with aquifer potential estimate by Gheorghe, 1978 [34] based on transmissivity values (Table 2) indicated that the aquifer have moderate to high aquifer potential (Fig. 6). The calculated hydraulic conductivity values vary from 10.50 to 45.71 m/day.

Table 2. Aquifer Potential Estimate. (After Gheorghe, 1978 [34])

T (m/day)	Aquifer Potential
> 500	High
50 - 500	Moderate
5 - 50	Low
0.5 - 5	Very low
< 0.5	Negligible

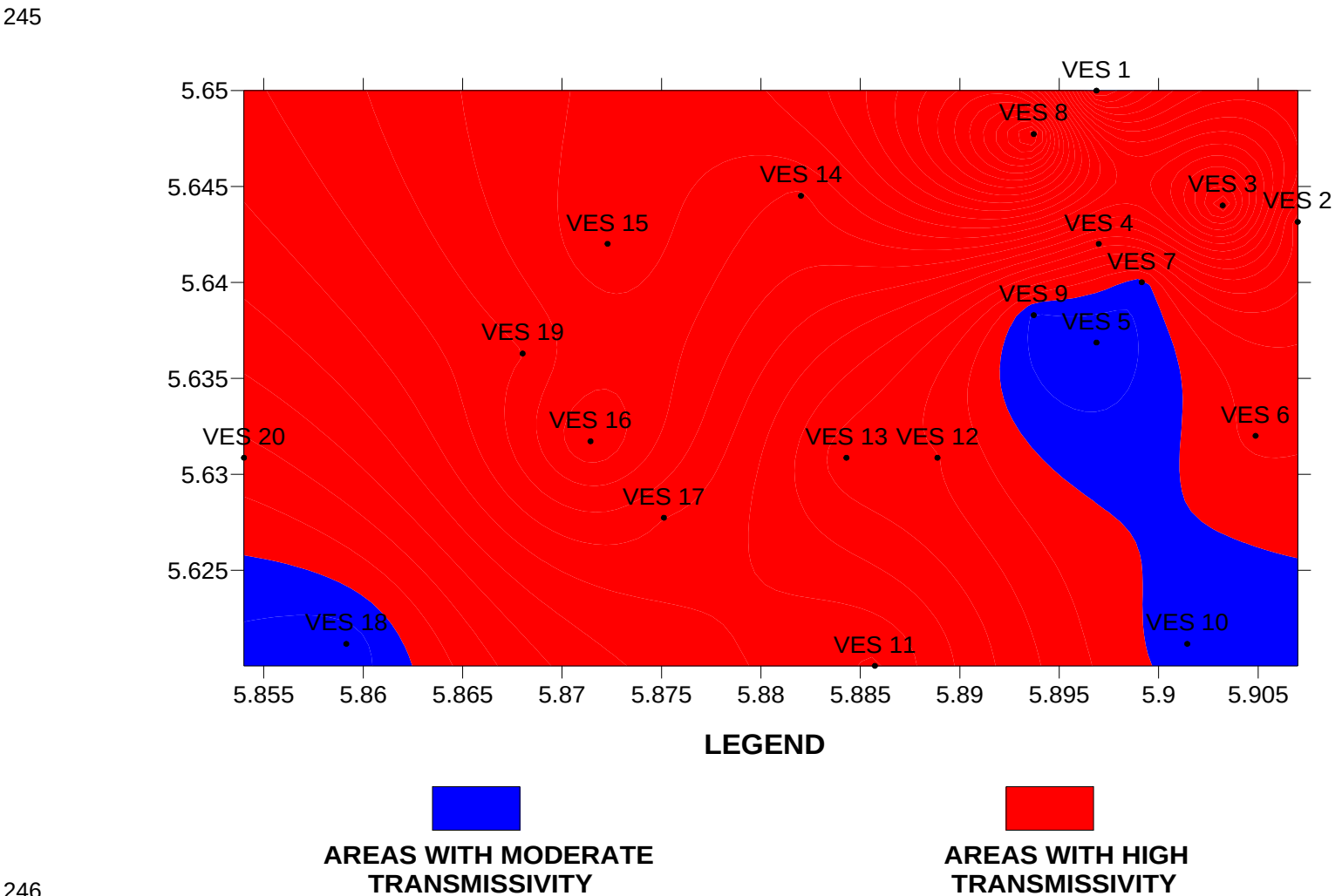


Fig. 6: Transmissivity variation across the study area

It is important to note that the calculated hydraulic conductivity (K) value at VES 4 (27.05 m/day) is close to the value (26.8 m/day) obtained from pumping test of the borehole close to the sounding location.

5. Conclusion

Optimum yield of aquifers requires studies of the aquifers in order to develop reliable information on the hydrologic properties of aquifers. This can be achieved by pump test to determine the geohydraulic characteristics and geoelectric survey to ascertain the geometry of the aquifers. Because pump test are seldom done in the Niger Delta results from one location cannot be used for even the nearest location. This is due to the fact that geohydraulic characteristics may vary in different directions within the same aquifer. A way of overcoming this shortcoming in this region is the integration of geoelectric surveys with existing well data.

The geoelectrical investigation of Orerokpe, Western Niger Delta has revealed four major geologic units and these include the top soil, clay/sand, sandy clay/clayey sand/sand and sand. The third and fourth layers constitute the aquifer units. The depth to the aquifer is relatively shallow ranging from 6.4 to 28.1 m with a mean depth of 17.5 m. Groundwater basically occurs under unconfined to mostly confined conditions in the aquifer. The geoelectric parameters were used in the Dar Zarrouk parameters to estimate transmissivity from which the hydraulic conductivity was calculated at other locations where there were no pump test data. The estimated transmissivity values vary between 418 m²/day and 1637.3 m²/day while hydraulic conductivity values vary between 10.50 m/day and 45.71 m/day. Based on these results, the aquifer in the study area have moderate to high aquifer potential. Areas with sufficiently high transmissivities coupled with good aquifer thicknesses are good prospects for drilling productive boreholes (Onuoha and Mbazi, 1988 [12]). The closeness of the value of 27.05 m/day obtained from the sounding result and the value of 26.8 m/day from the pumping tests is indicative of the reliability of the Dar-Zarrouk approach in estimation of geohydraulic characteristics of aquifers. This study has successfully shown that geoelectric method is a very useful tool for understanding the aquifer systems and their hydraulic characteristics.

REFERENCES

1. Mazac O, Kelly WE, Landa I. A hydrogeophysical model for relations between electrical and hydraulic properties aquifers. Journal of Hydrology. 1985; 79:1 – 19.

2. Borner F. Complex conductivity measurement. In: Kirsch R, editor. Groundwater geophysics a tool for hydrogeology, Springer-Verlag Berlin Heidelberg, Germany 2006; 119-153.
3. Keller GV, Frischknecht FC. Electrical method in geophysical prospecting. Pergamon, Oxford. 1966; 517 pp
4. Zohdy AAR. A new method for automatic interpretation of Schlumberger and Wenner sounding curves. Geophysics. 1989; 42:245 – 253.
5. Zohdy AAR, Eaton GP, Mabey DR. Application of surface geophysics to groundwater investigations. US Geol Surv Tech Water Resour Invest. 1974, book 2, chapter D1, 116 pp.
6. Griffith DH. Application of electrical resistivity measurements for the determination of porosity and permeability in sandstones. Geoexploration. 1976; 14(3&4):207 – 213.
7. Louis I, Karantonis G, Voulgaris N, Louis F. Geophysical methods in the determination of aquifer parameters: the case of Mornos river delta, Greece. Research Journal of Chemistry and Environment. 2004, 18(4):41 – 49.
8. Ungemach P, Mostaghimi F, Duprat A. Essais de determination du coefficient d'emmagasinement en nappe libre et application a la nappe alluvial du Rhin [Tests for determination of storage coefficient in unconfined aquifer and application in alluvial aquifer of Rhin]. Bulletin of International Association of Science and Hydrology. 1969; 14:169 – 190.
9. Scerascia S. Contribution of geophysical methods to management of water resources. Geoexploration. 1976 ; 14:265 – 266.
10. Niwas S, Singhal DC. Estimation of aquifer transmissivity from Dar-Zarrouk parameters in porous media. Journal of Hydrology. 1981; 50:393 – 399.
11. Kelly WE. Geoelectric sounding for estimation aquifer hydraulic conductivity. Ground Water. 1977; 15(6):420 – 425.
12. Onuoha, KM, Mbazi FCC. Aquifer transmissivity from electrical sounding data: The case of Ajali sandstone aquifers, south east of Enugu, Nigeria. In: Ofoegbu CO, editor. Groundwater and mineral resources of Nigeria. Vieweg, Braunschweig, Germany. 1988; 17 – 29.
13. Ekwe AC, Onu NN, Onuoha KM. Estimation of aquifer hydraulic characteristics from electrical sounding data: the case of middle Imo River basin aquifers, south-eastern Nigeria. Journal of Spatial Hydrology 2006; 6(2):121 – 132.
14. Reyment RA. Aspect of the Geology of Nigeria. Ibadan University Press, Nigeria. 1965; 135pp.
15. Short KC, Stauble AJ. Outline of geology of Niger Delta. AAPG Bull. 1967; 51:761 – 779.
16. Oomkens E. Lithofacies relations in the late quaternary Niger Delta Complex. Sedimentology. 1974; 21:195 – 222.
17. Etu-Efeotor JO, Akpokodje EG.. Aquifer systems of the Niger Delta. Journal of Mining and Geology. 1990; 26 (2): 279 – 285.
18. Etu-Efeotor JO, Odigi MI. Water supply problems in the Eastern Niger Delta. Journal of Mining and Geology. 198; 3 20(1): 182 – 192.
- 19 Odigi MI. Evaluating groundwater supply in Eastern Niger Delta, Nigeria. Journal of Mining and Geology. 1989, 25:159 – 164.

- 331 20. Amadi UMP, Amadi PA. Saltwater migration in the coastal aquifers of Southern Nigeria. *Journal of Mining*
332 *and Geology* 1990, 26(1): 35 – 44.
- 333
- 334 21. Walton WC. Selected analytical methods for well and aquifer evaluation. Illinois State Water Survey, 1962;
335 Bulletin No. 49
- 336
- 337 22. Cooper HH Jr., Jacob CE. A generalized graphical method for evaluating formation constants and
338 summarizing well-field history. *Trans. American Geophysical Union*. 1946; 27:526 – 534.
- 339
- 340 23. Kruseman G, De Ridder N. Analysis and evaluation of pumping test data. International Institute for Land
341 Reclamation and improvement, Wageningen, Netherlands, 1983; 194 pp
- 342
- 343 24. Jupp DLB, Vozoff K. Joint inversion of geophysical data. *Geophys. J. Roy Astron. Soc.* 1975; 42: 977 –
344 991.
- 345
- 346 25. Koefoed O. *Geosounding Principles I*. Elsevier Scientific Publishing Comp. Amsterdam. 1979; 170 – 181.
- 347
- 348 26. Rubin Y, Hubbard S. *Hydrogeophysics*. Springer, Pordrecht. The Netherlands, 2005; 523pp.
- 349
- 350 27. Zhody AAR. The auxiliary point method of electrical sounding interpretation and its application to the Dar
351 Zarrouk parameters. *Geophys.* 1965; 30:644 – 660.
- 352
- 353 28. Vander Velpen BPA. winResist version 1.0. M.Sc. Research Project, ITC Delft, The Netherlands. 2004.
- 354
- 355 29. Deming D. *Introduction to hydrogeology*. McGraw Hill Company. 2002; 468pp.
- 356
- 357 30. Freeze RA, Cherry JA. *Groundwater*. Practice - Hall, Englewood Cliffs, NJ. 1979
- 358
- 359 31. Fitts CR. *Groundwater Science*. Elsevier, Amsterdam, The Netherlands. 2002; 167 – 175.
- 360
- 361 32. Maillet R. The fundamental equations of electrical prospecting. *Geophysics*, 1947;12:527 – 556.
- 362
- 363 33. Surfer (2002). *Contouring and 3D surface mapping for scientists and engineers*. Golden Software
364 Incorporation, Colorado, USA., 619pp.
- 365
- 366 34. Gheorghe A. *Processing and synthesis of hydrological data*. Abacus Press Junebridge Wells, Kent. 1978;
122 – 136.