



Estimating Aquifer Parameters with Geoelectric Soundings: Case Study from the Shallow Benin Formation at Orerokpe, Western Niger Delta, Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

A study of the use of geoelectric sounding employing Schlumberger configuration in delineating aquifer(s) and estimation of hydraulic parameters 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 well was combined with electrical conductivity (σ) obtained from geoelectric sounding data, the resulting diagnostic relation ($K\sigma = \text{constant}$) was combined with Dar-Zarrouk parameters to estimate the transmissivity and hydraulic conductivity values of the aquifer. The results indicated that the transmissivity values of the aquifer varied between 418.6 m²/day and 1637.3 m²/day while hydraulic conductivity values varied between 10.50 m/day and 45.71 m/day. The estimated parameters indicated that the aquifer in

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seventy five (75) percent of the study area have high aquifer potential while the remaining twenty five (25) percent have moderate aquifer potential.

Keywords: Aquifer parameters; Dar-Zarrouk parameters; resistivity; Benin formation; Niger delta.

1. INTRODUCTION

Water supply provision from public agency facilities in most parts of Nigeria is well below demand and which perennial problem is further aggravated by rapid population growth, urbanization and associated industrialization. In the Niger Delta petroleum province ground water has been always preferred over surface water sources and is thus the primary source of water supply. The reason for this is probably the existence of rich aquifers, especially in the Benin Formation that are easily exploited in many areas with shallow boreholes and dug wells. However, groundwater exploitation has not been accompanied by resource evaluation studies that are based on aquifer characteristics. These characteristics include porosity, specific yield, hydraulic conductivity, transmissivity and storativity without which it is impossible to answer questions related to resource management. Consequently, many groundwater based schemes and associated boreholes that are designed and established without appropriate and relevant information perform well below capacity and are not sustainable. Furthermore, aquifer characteristics are crucial for environmental management studies involving site characterization, fate and transport of pollutants as well as remediation of contaminated sites in this petroleum province where groundwater contamination is a prevailing problem.

The conventional method for determining aquifer parameters is the pumping test. However, this method can be time consuming and yields results relevant only to a relatively small portion of the aquifer [1]. Furthermore, in the presence of diverse field conditions, the various necessary assumptions which are seldom upheld during pump test performance easily lead to erroneous estimates [2]. However, the most important problem that discourages the regular performance of pump tests in the Niger Delta region is the paucity of resources. Thus a combination abstraction well/dedicated observation well pump test is a rarity. Most pump test records in public agency archives are thus from tests conducted on abstraction wells and which further reduces the reliability of estimated parameters.

An alternative non – invasive and less expensive approach that provides more regional information is the integration of geoelectric surveys with existing borehole data. Geoelectric surveys are an increasingly important tool in subsurface hydrogeological applications and are used to rapidly evaluate properties of an aquifer matrix [3-10]. Scerascia [11] used electrical soundings to estimate transmissivity of aquifers in Italy. Niwas and Singhal [12] estimated the aquifer transmissivity from the Dar-Zarrouk parameters in porous media by using an analytical relation between aquifer transmissivity and transverse resistance. Kelly [13] established an empirical relation between aquifer electrical resistivity and aquifer hydraulic conductivity. Onuoha and Mbazi, [14], Ekwe et al. [15] estimated aquifer characteristics in southeastern Nigeria by integrating geoelectric and pumping test data.

The present study attempts to estimate transmissivity and hydraulic conductivity values 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 [16,17]. 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 [18] 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.

Groundwater in the Niger Delta is contained in mainly very thick and extensive sand and gravel aquifer. Etu-Efeotor and Akpokodje [19] 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 semi-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 [20-22].

3. MATERIALS AND METHODS

3.1 Pumping Test

A five hour pump test was carried out in the drilled well marked BH in Fig. 1 which was pumped at a uniform rate of 2500 m³/day. Drawdown during the pumping period was measured at an observation well located approximately 60 m away from the abstraction well. Aquifer hydraulic parameters were estimated with the Cooper-Jacob's straight line method [23,24] using the following relationships:

$$T = \frac{2.30Q}{4\pi\Delta S} \quad (1)$$

$$S = \frac{2.25Tt_0}{r^2} \quad (2)$$

where T = transmissivity, Q = pumping rate and S = storativity.

3.2 Geoelectric Investigation

Geoelectrical investigation involving resistivity sounding was undertaken within the study area to provide information on the stratification of the subsurface. Direct-current electrical resistivity method still remains the most powerful and cost-effective technique in groundwater investigation [25-27]. 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 the relationship:

$$\rho_a = K \frac{V}{I} \quad (3)$$

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

$$K = \frac{1}{2\pi} \left[\left(\frac{1}{AM} - \frac{1}{BM} \right) - \left(\frac{1}{AN} - \frac{1}{BN} \right) \right] \quad (4)$$

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 [28] 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 win Resist 1.0 by Vander Velpen [29]. 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 [30]. The RMS error between the field and calculated data is generally less than 3%. The electrical resistivity contracts existing between lithological sequences in subsurface were used in the delineation of geoelectrical layers and identification of aquiferous units [31].

3.3 Aquifer Parameter Estimation from Geoelectric Data

The intuitive relationship between aquifer hydraulic conductivity and the Dar-Zarrouk parameters [32] namely, Transverse Resistance (R), Longitudinal Conductance (C) has been derived analytically from a combination of Darcy's Law and Ohm's Law by Niwas and Singhal [12] who established the following relationships:

$$R = h \rho = h / \sigma \tag{5}$$

$$C = h / \rho = h \sigma \tag{6}$$

$$T = K \sigma R \tag{7}$$

and

$$T = \frac{KC}{\sigma} \tag{8}$$

where, h and ρ are the thickness and resistivity of individual aquifer layers in meters and ohm-meters respectively. In areas of similar geologic setting and water quality, the product $K\sigma$ remains fairly constant [12,14]. Thus as shown by Onuoha and Mbazi [14] and Ekwe et al [15] for some Imo River Basin aquifers and Ajali Sandstone respectively, if hydraulic conductivity K values are known from specific well locations, possibly from pump tests and σ values are obtained from electrical sounding interpretations, transmissivity and its area wide spatial variation may be estimated from the relationships and extrapolated into areas where K values are not available. These relationships have been employed in this study to derive area wide transmissivity and hydraulic conductivity values for the Orerokpe area.

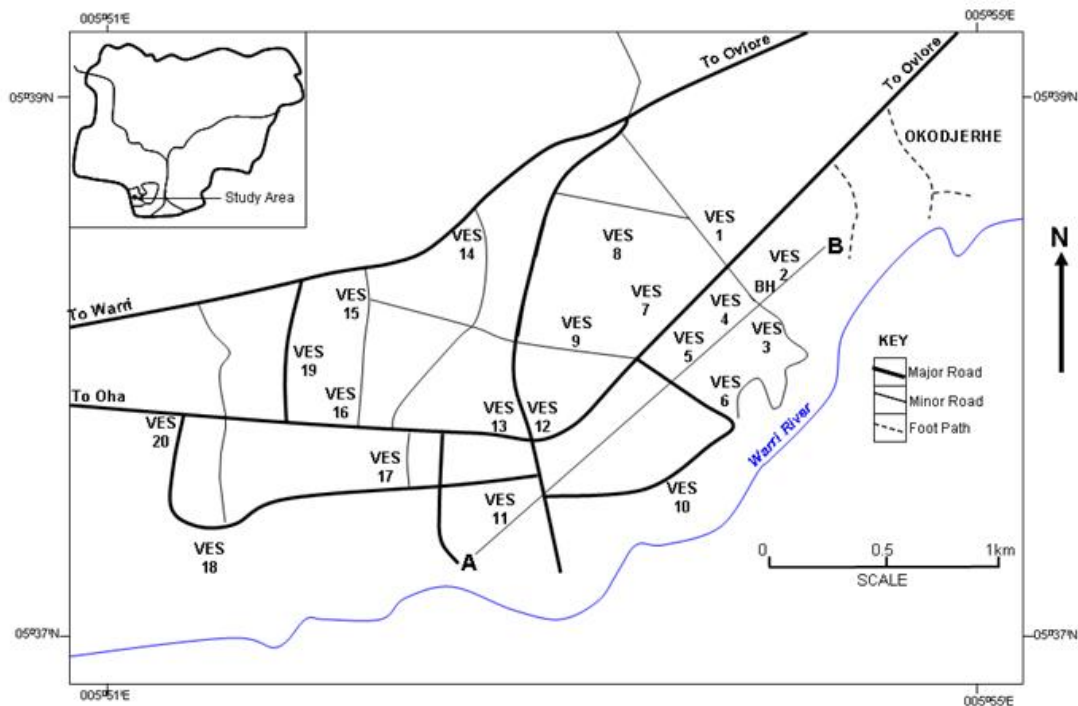


Fig. 1. Map of study Area showing VES locations and well (BH) in which pump test was performed

4. RESULTS AND DISCUSSION

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 [5]. 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.

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 diagnostic of the top soil of variable composition. The resistivity values of the second layer vary from 42.3 – 1207.0 ohm-m with thickness varying from 6.5 – 18.5 m. The low resistivity (< 100 ohm-m) is diagnostic of clay which is absent in some localities while the high resistivity (> 300 ohm-m) typifies sands. The third layer have resistivity values that vary from 108.2 – 1550.6 ohm-m, the low resistivity (>100 ohm-

m) is typical of sandy clay and clayey sand while the high resistivity (> 300 ohm-m) indicates sands. The thickness of this layer vary between 10.2 – 67.1 m and constitutes the aquifer in localities where the unit is sandy, the aquifer is confined where the overlying second geologic unit is clay and unconfined where it is sand. A fourth layer of sand which also forms part of the aquifer having resistivity values of 205.3 – 418.7 ohm-m underlie the third geologic layer. The thickness of this layer could not be ascertained as current electrode terminated within this layer. However, inference from VES 8 and 9 where there is a fifth layer comprising of sand shows that the fourth layer is over 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 values of the depth to aquifer from the geoelectric model were used with SURFER [33] terrain and surface modeling software was used to generate a map of depth to aquifer (Fig. 5).

4.2 Pump Test Results

Aquifer parameters estimated by the Cooper-Jacob's straight line method are shown in Table 1.

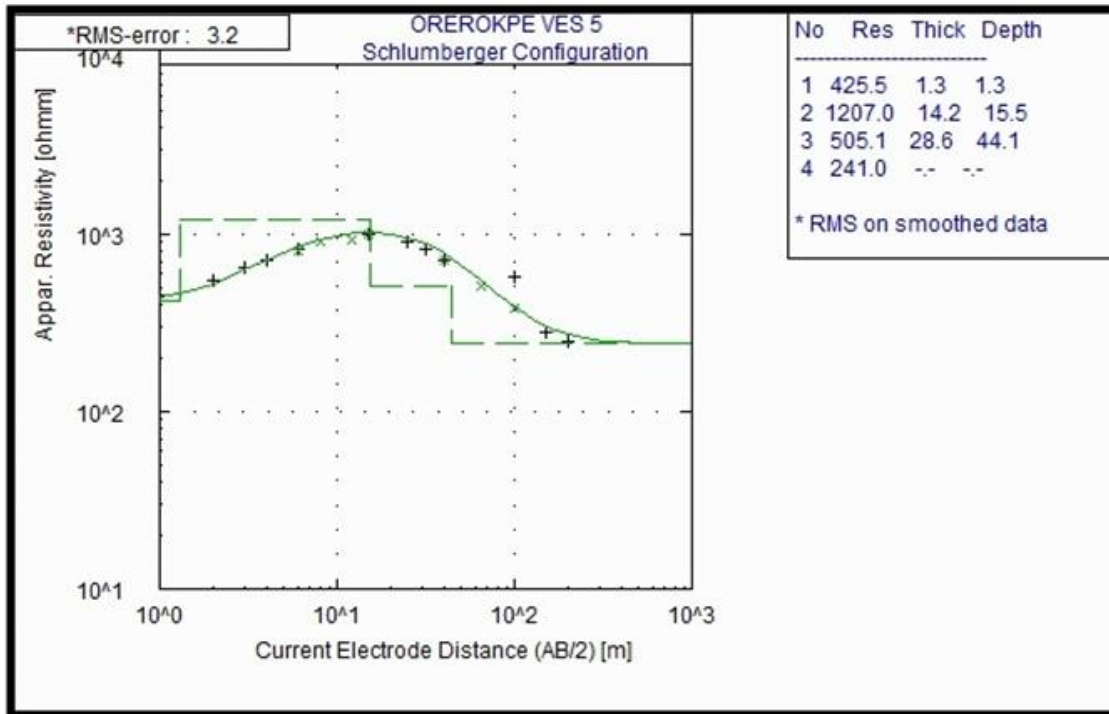


Fig. 2. Typical iterated sounding curve of the study area at location 5

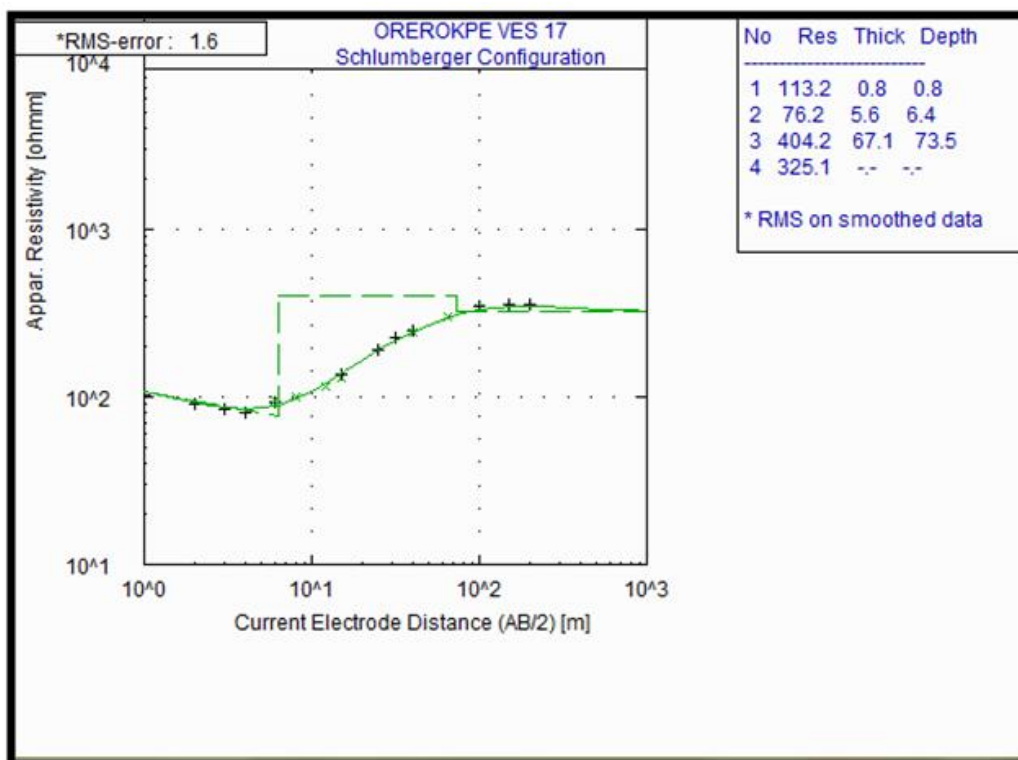
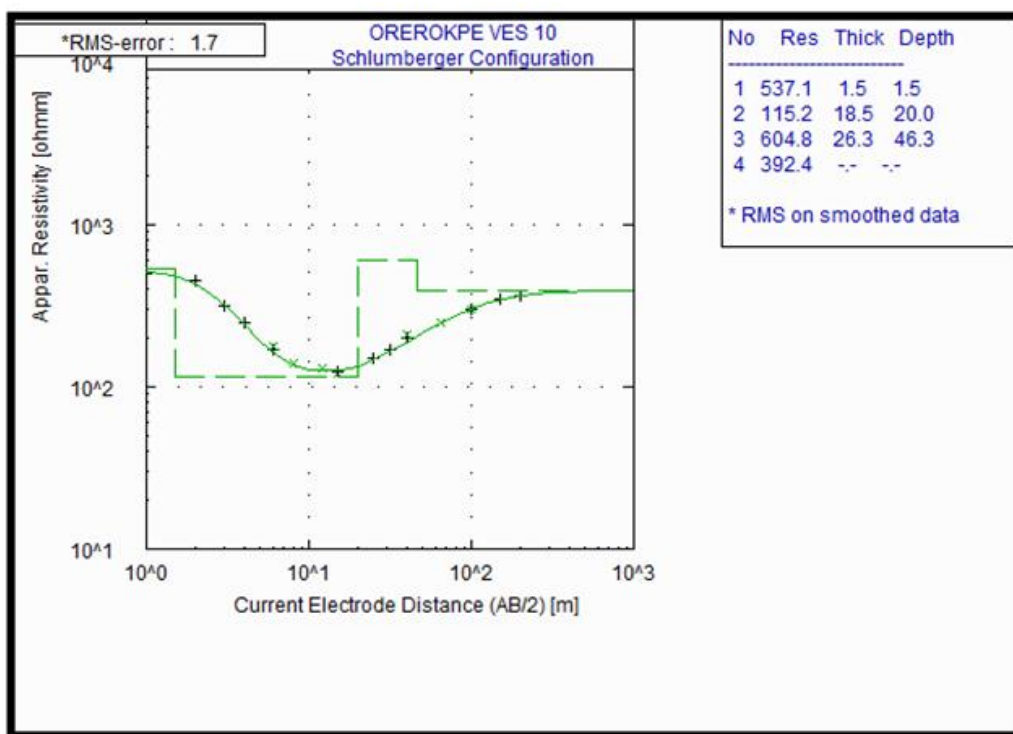


Fig. 3. Typical iterated sounding curves of the study area at locations 10 and 17

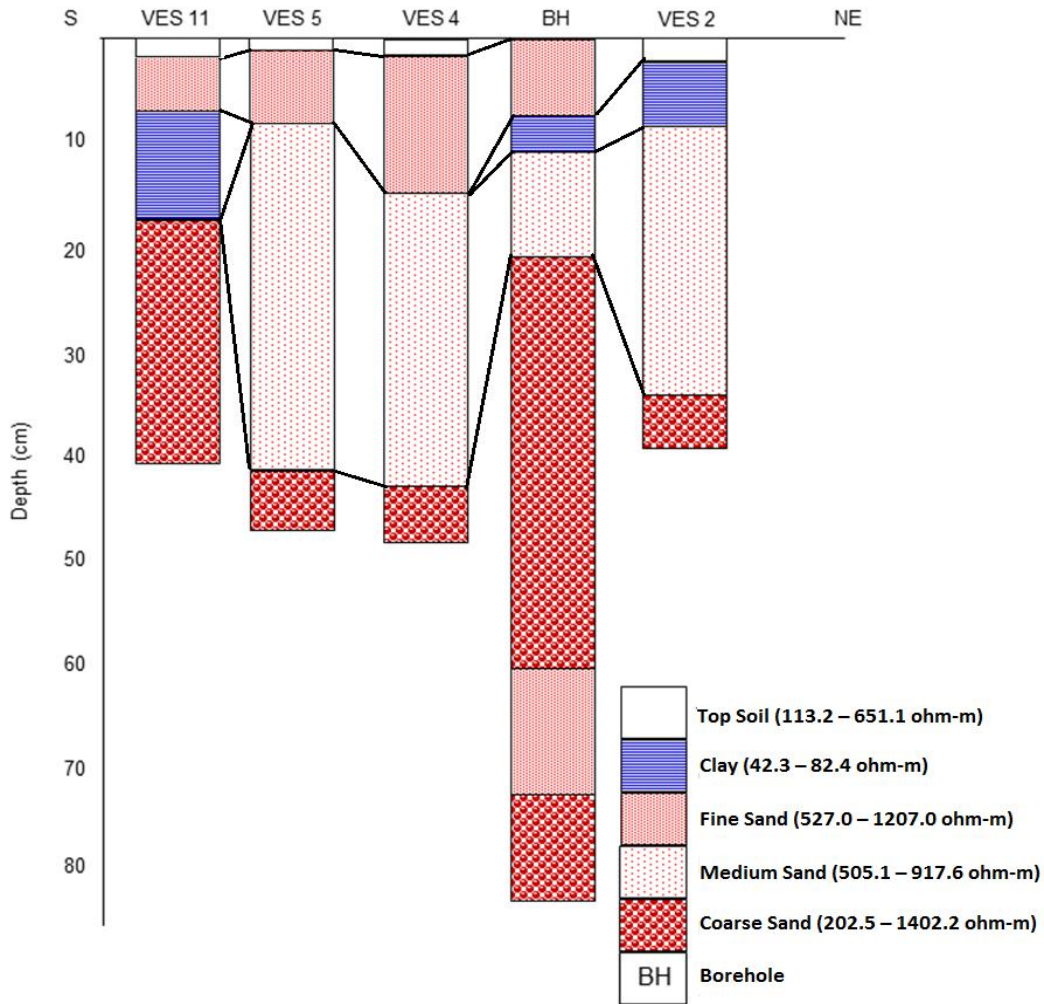


Fig. 4. Geoelectric section at Orerokpe along section AB in Fig. 1 correlated with a lithologic log

Table 1. Aquifer parameters from pumping test

Aquifer parameters	Values
Transmissivity (m ² /day) ¹	1016.37
Hydraulic conductivity (m/day) ²	26.8
Storativity ³	1.9 X 10 ⁻⁴

Notes: ¹ Δs = 0.45, Q = 2500 m³/day; ² h = 38 m and ³ t₀ = 0.44

4.3 Dar-Zarrouk Parameters and Area Wide Aquifer Characteristics

The Kσ constant from equation 7 was calculated by inserting the K value of 26.8 m/day obtained from the pumping test results, Table 1 and σ obtained from electrical sounding data at location 4 (σ = 1/ρ = 1/917.6 = 0.0011 Siemens/m).

$$\text{Hence, } K\sigma = 26.8 \times 0.0011 = 0.02948$$

The Sombreiro-Warri Deltaic Plain top sandy deposits that mask the Benin Formation exhibit similar lithological and textural characteristics at Orerokpe, Fig. 4, in addition to which Aweto and Akpoborie [34] have shown that spatial variations in groundwater chemistry in the area are negligible. Thus following from Ekwe et al. [14] and Onuoha and Mbazi [15], transmissivity values can be estimated at all locations where there are no well test data from Equation 7.

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

Where T_c is estimated transmissivity from Dar-Zarrouk parameters.

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

$$K_c = \frac{Tc}{h}$$

The estimated hydraulic parameters (transmissivity and hydraulic conductivity values) in Orokpe are presented in Table 2.

Calculated transmissivity varies from 418.6 m²/day to 1637.3 m²/day and results presented in Table 3 have been used to generate an iso-transmissivity map with the aid of SURFER [35]. The shallow aquifer underlying Orokpe may thus be considered to have a moderate to high yield potential Gheorghe [35], (Fig. 6). The calculated hydraulic conductivity values vary from 10.50 m/day to 45.71 m/day. It is also significant that the calculated hydraulic conductivity at VES 4 (27.05 m/day) closely approximates the hydraulic conductivity (26.8 m/day) obtained from pumping test of the

borehole that is proximal to the sounding location.

Table 3. Aquifer potential (After Gheorghe [35])

T (m ² /day)	Aquifer potential
> 500	High
50 - 500	Moderate
5 - 50	Low
0.5 - 5	Very low
< 0.5	Negligible

Although the radius of influence of pump tests in a water table aquifer could be quite small, conventional pump test derived aquifer parameters are used regionally in many cases for planning purposes. The results of this study indicate that parameters derived from a combination of conventional pump tests and the Dar-Zarrouk parameters would provide more credible estimates.

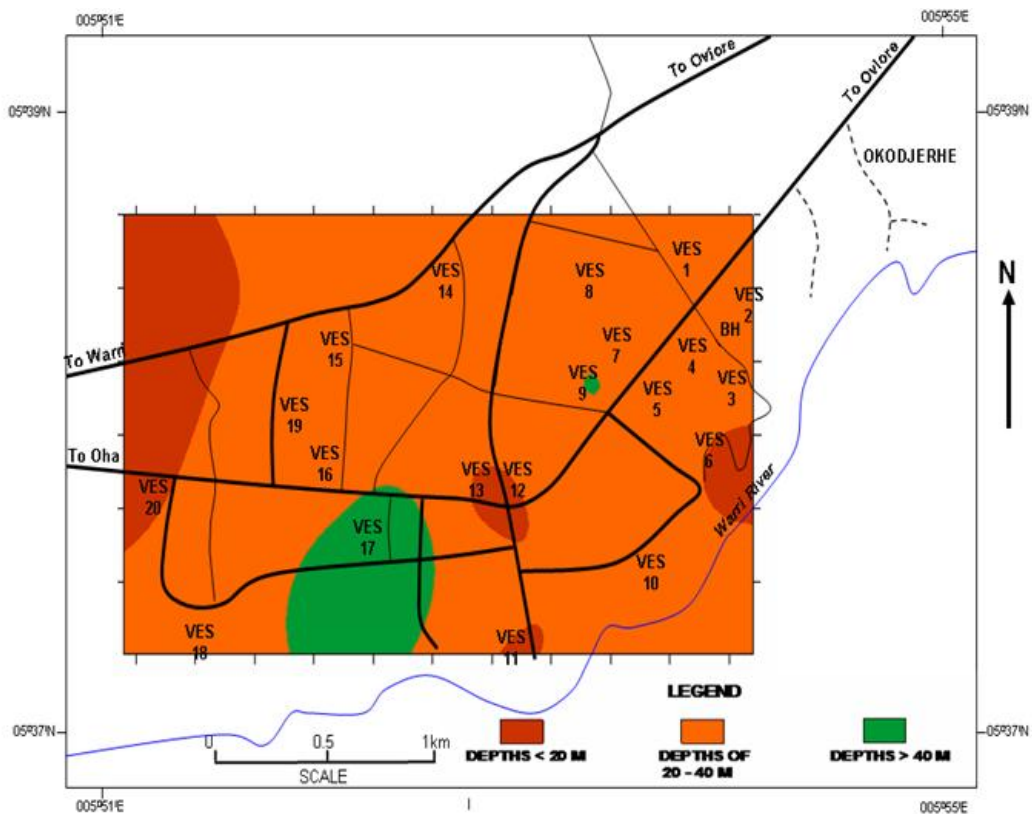


Fig. 5. Depth to aquifer in meters

Table 2. Spatial distribution of derived aquifer parameters at associated sounding locations at Orerokpe

VES location	ρ (Ωm)	h(m)	Z(m)	R(Ωm^2)	K_p (m/day)	$K\sigma$	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	42.0	28.1	14947.8	26.8	0.02948	440.70	10.50
10	604.0	26.3	20.0	15885.2	26.8	0.02948	468.30	17.81
11	1402.2	19.6	16.4	27483.12	26.8	0.02948	810.20	41.34
12	938.7	21.8	18.2	20463.66	26.8	0.02948	603.30	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	890.30	28.53
15	1621.8	20.6	18.7	33409.08	26.8	0.02948	984.90	47.81
16	1550.6	21.9	22.6	33958.14	26.8	0.02948	1001.10	45.71
17	404.2	67.1	6.4	27121.82	26.8	0.02948	799.60	11.92
18	483.0	29.4	14.0	14200.2	26.8	0.02948	418.60	14.24
19	1165.0	24.7	16.1	28775.5	26.8	0.02948	848.30	34.34
20	1225.0	16.1	18.5	19722.5	26.8	0.02948	581.40	36.11

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

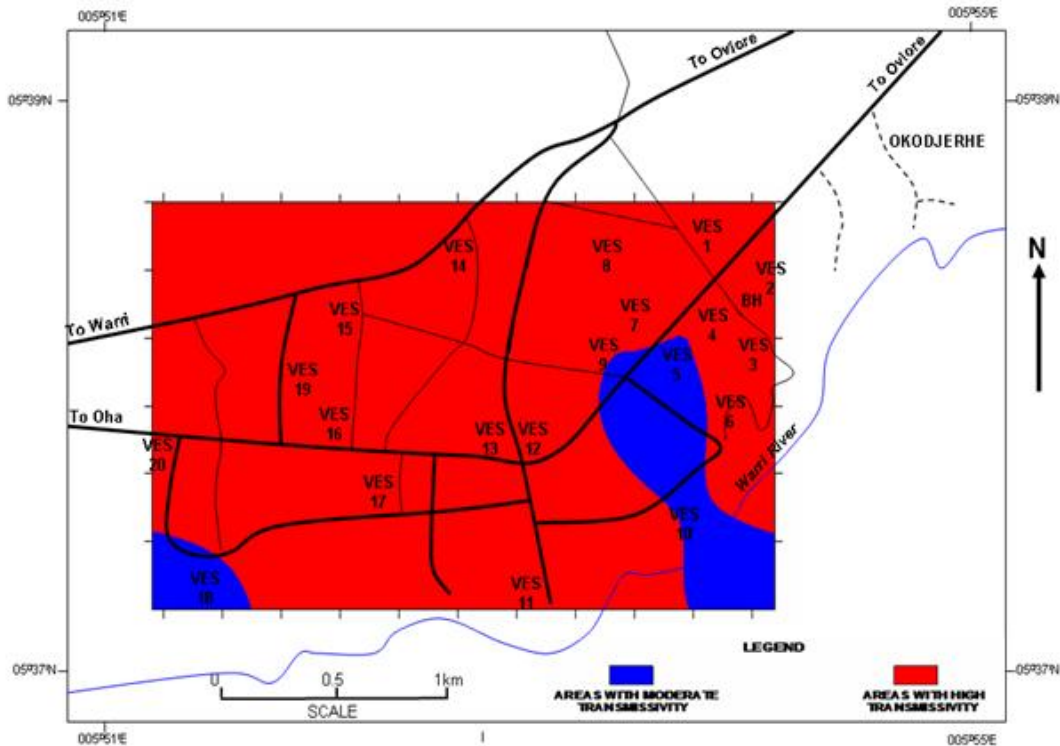


Fig. 6. Transmissivity variation across the study area

5. CONCLUSION

Transverse resistance and Longitudinal conductance obtained from geoelectric surveys have been combined with pump test derived aquifer properties to estimate area wide hydraulic conductivity for the shallow Benin Formation in the vicinity of Orokpe.

The estimated transmissivity values vary between 418.6 m²/day and 1637.3 m²/day while hydraulic conductivity values vary between 10.50 m/day and 45.71 m/day. The calculated hydraulic conductivity at VES 4 (27.05 m/day) closely approximates the hydraulic conductivity (26.8 m/day) obtained from the pumping test of the borehole that is proximal to the sounding location and suggests the potential reliability of electrical resistivity survey data in aquifer parameter estimation.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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