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Full Length Research Paper

Geoelectrical studies for estimating aquifer hydraulic properties in Enugu State, Nigeria

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Three hundred and twenty two vertical electrical soundings (VES) have been used to evaluate the hydraulic properties of aquifers in Enugu State, Southeastern Nigeria. The project domain lies within longitudes 7°6' E to 7°54'E and latitudes 5°56'N to 6°52'N, and covers an area of about 7161 km^2 over eight main geological formations. The thickness, lateral extent and resistivity of the aquiferous layers were determined by the electrical survey. Also, zones of high yield potentials were inferred from the resistivity information. Transmissivity values were inferred using the empirical relationship between hydraulic conductivity and formation factor. Results show highly variable thickness of the main aquifer in the study area. Aggregate longitudinal conductance indicates greater depth of the substratum in the central part of the area, underlain by the Ajali and Nsukka Formations. High values of transmissivity, specific yield and moderate porosity also predominate, thus suggesting thick and prolific aquiferous zone. Lower average values of these parameters were obtained in southwestern and eastern parts underlain by the Imo and Ezeaku/ AwguNdeaboh/ Nkporo Formations, with the eastern part recording the lowest values, except porosity with the highest estimated average value. Maps of various geoelectrical and hydraulic parameters have been produced and the overall results can serve as a useful guide in planning a drilling program in the study area.

Key words: Formation factor, transmissivity, porosity, specific yield.

INTRODUCTION

Knowledge of hydraulic properties of subsurface aquifers is essential for the determination of natural flow of water through an aquifer and groundwater assessment. Hydraulic conductivity (k), transmissivity (T) and storativity (S) are aquifer properties that may vary spatially because of geologic heterogeneity. Estimation of these properties allows quantitative prediction of the hydraulic response of the aquifer to recharge and pump. Transmissivity, the hydraulic conductivity multiplied by the saturated thickness of the aquifer, represents a vertical average of hydraulic conductivities that may vary with depth. Most of the analytical techniques used to estimate the hydraulic properties of aquifer were developed for porous media, such as unconsolidated sediments. Although these properties are mainly deduced from pumping test analysis, geophysical methods now provide an effective technique for aquifer evaluation and can greatly reduce the number of necessary pumping tests, which are both expensive and time consuming.

In recent years, attempts have been made by several authors to obtain hydraulic parameter estimates from resistivity soundings (Kelly, 1979; Koinski, 1981; Mazac and Kelly, 1985). Transmissivities, formation factors and specific yield have been estimated using empirical and semi-empirical relationships (Schimscal, 1981; Frohlick and Kelly, 1985; Huntly, 1986; Urish, 1987; Chen et al., 2001; Singh, 2005). Although previous attempts in relating geoelectrical and hyrogeological parameters have been made, the empirical relations obtained were mostly applicable to areas with uniform geology. There is therefore the need to make these relations more general in nature, so that they can be more widely applied in areas with diverse lithological characteristics.

In the present study, an attempt has been made to find a general functional relationship between surface resistivity depth soundings and hydraulic parameters in the study area. Hydraulic conductivity obtained from well tests is correlated with formation factor. Model calculations

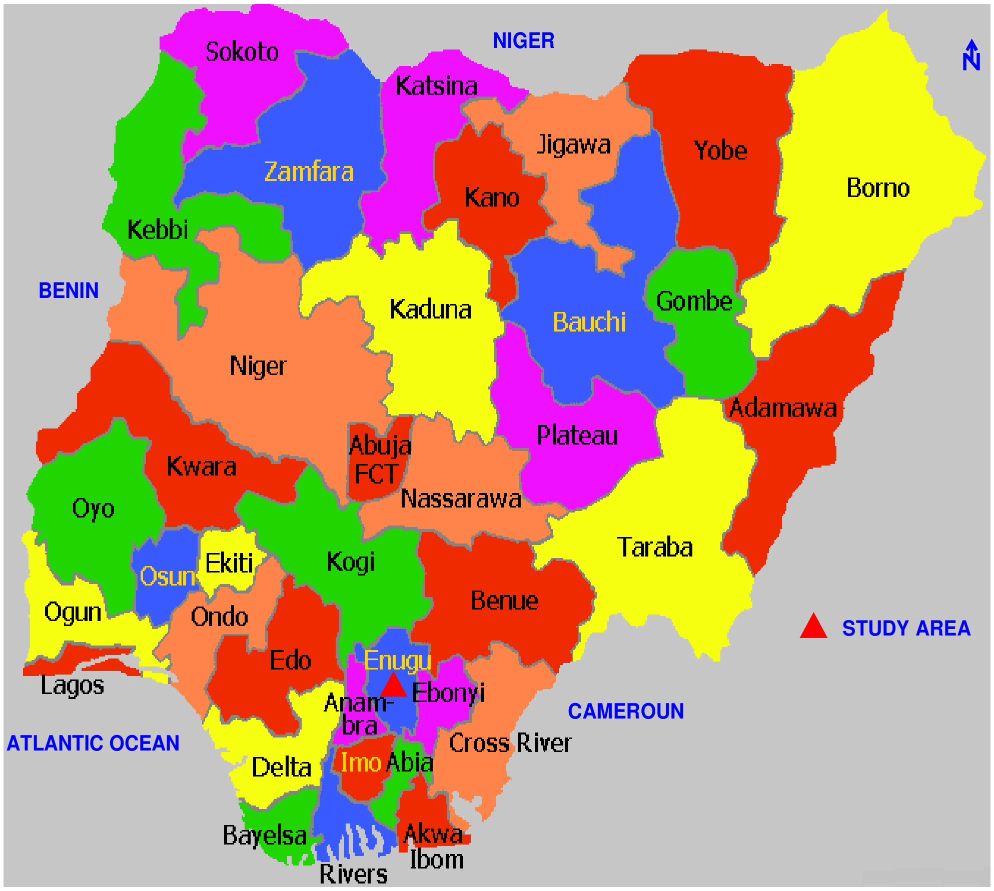

Figure 1. Map of Nigeria showing the location of the study area (World Gazette, 2011).

have been used to obtain regional patterns of transmissivity, porosity and specific yield.

Description of study area

Physiography

The study area (Figure 1) shows two major types of landforms which consists of a high relief central zone with undulating hills and ridges and the lowland area (Figure 2). Both are related to the geology of the area.

The high relief zone is geologically associated with the outcrops of Ajali Sandstone and Nsukka Formation, while the eastern lowland zone is associated with outcrops of Asu River group, Eze Aku Shale group, Awgu/Ndeabor shale group, Asata/Nkporo Shale group and parts of Mamu Formation. The western lowland zone is associated with outcrops of the Imo Formation. On the scarp face, slope failures, land slides, soil and gully erosion and slump features are common. In general terms, the Ajali Sandstone usually underlies areas of height above 300 m while the Nsukka Formation is characterized by abundant residual hills.

Geology

The study area is underlain by the following geological formations (Figure 3), the Asu River group, Eze Aku Shale group, Awgu/Ndeabor Shale group, Nkporo Shale, Mamu Formation, Ajali Formation, Nsukka Formation and Imo Formation.

The Asu River group is the earliest recorded marine sediments consisting of bluish grey to brown shale and sandy shale, fine-grained micaceous sandstones and dense blue limestone (De-Swardt and Casey, 1963; Reyment, 1965).

The sediments of the Eze Aku formation consist of fossiliferous limestone and shale. The thickness varies, but may attain 1000 m in places. The Awgu/Ndeaboh Formation is about 400 m thick and consists of bluish grey, well-bedded shales, with subordinate calcareous sandstones and limestones (Kogbe, 1981). The Nkporo Formation comprises dark shales and mudstones, with occasional thin beds of sandy shale and sandstone and thickness of about 150 m. The Owelli sandstone, Enugu Shale and Asata shales are lateral equivalents of the Nkporo Shale. The Owelli sandstone comprises medium to coarse-grained sandstones with pebble bands while

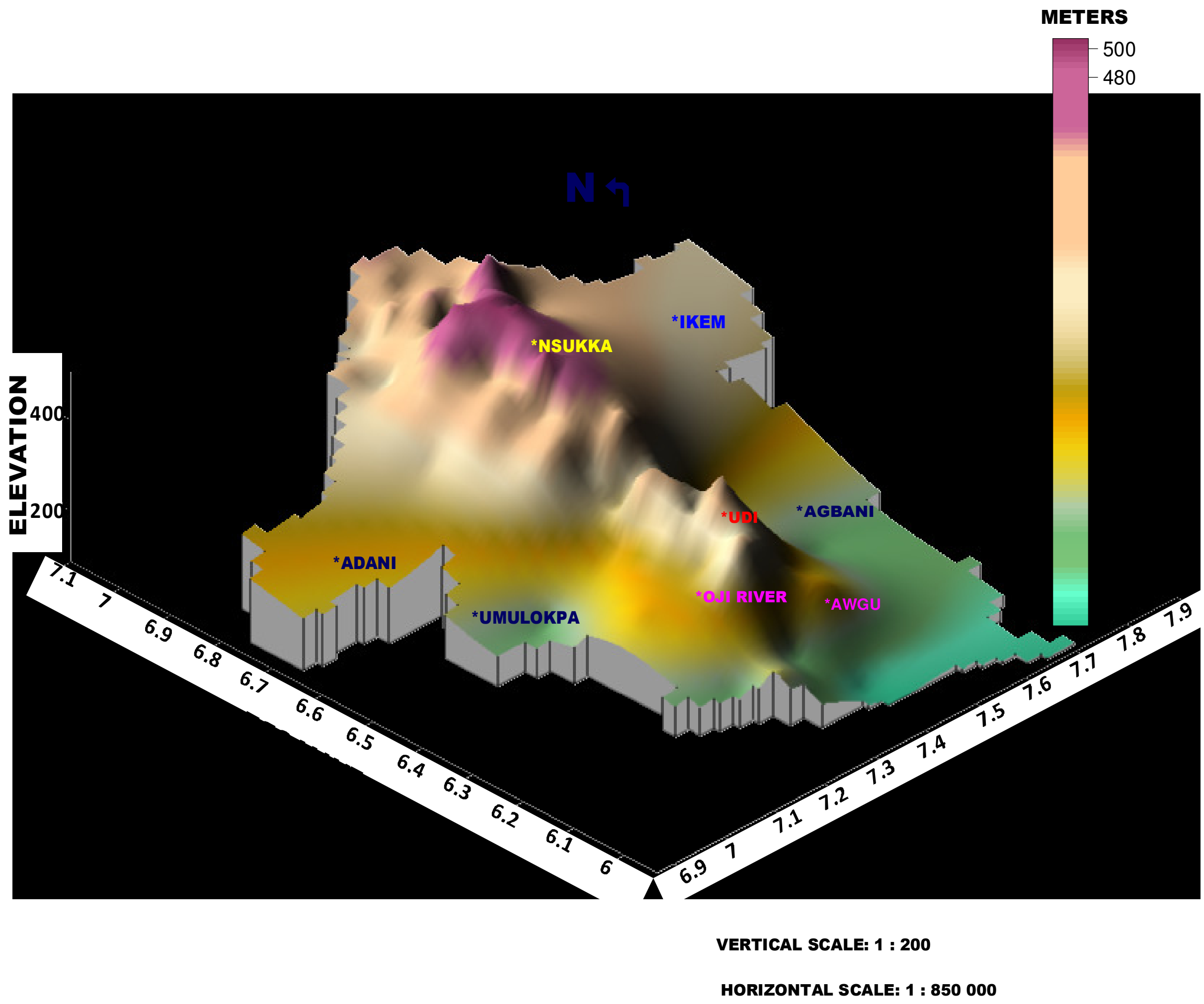

Figure 2. Surface map of the study area.

the Enugu/Asata shales consists of soft dark grey shales and mudstones with occasional thick beds of white sandstones and sandy shales.

The Mamu formation consist of fine to medium grained, white to grey sandstones, shaly sandstones, sandy shales, grey mudstones, shales and coals. The thickness is about 450 m and it conformably overlies the Enugu shale.

The Ajali Formation, also known as false bedded sandstone, consists of thick friable, poorly sorted sandstones, typically white in colour but sometimes iron-stained. The thickness averages 300 m and is often overlain by considerable thickness of red, earthy sands, formed by the weathering and ferruginization of the formation.

The Nsukka Formation lies conformably on the Ajali Sandstone. The lithology is very similar to that of Mamu Formation and consists of an alternating succession of sandstone, dark shale and sandy-shale, with thin coal seams at various horizons. Eroded remnants of this formation constitute outliers and its thickness averages 250 m.

The Imo information consists dominantly of blue to dark grey shales, with occasional bands of clay- ironstone and subordinate thin sandstones. The formation includes thick sandstone units at several horizons and rests conformably on Nsukka Formation with a thickness of about 500 m. Quaternary alluvial deposits overlie the Northwestern parts of the area. These areas are within the Anambra River flood plain and are generally less than 100 m in altitude.

Hydrogeology

The hydrologic units in the study area include confined, semi-confined, unconfined, perched and fractured shale aquifers.

Confined conditions exist over the Ajali Sandstone in areas overlain by the Nsukka Formation and/or the Imo

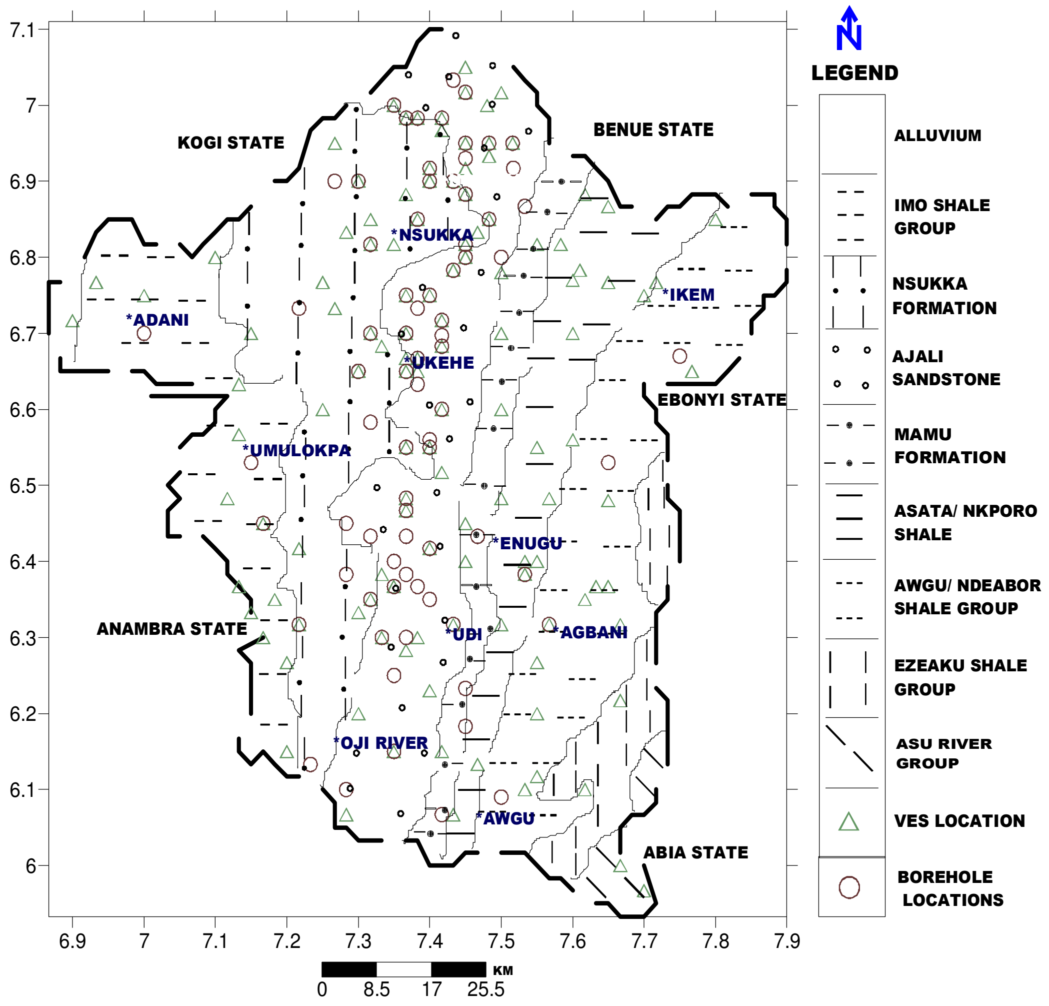

Figure 3. Geologic map of the study area showing VES and borehole locations.

Formation, and in the Mamu Formation where the overlying Ajali Sandstone and Nsukka Formation are considerably reduced in thickness or eroded. Semi-confined situation exist in places and usually comprise interbedded thick sequence of sand (aquifer) and sandy clay or clayey-sand aquicludes. Various aquifers in this group occur in the upper to middle horizons of Ajali Sandstone and in the upper section of the Mamu Formation and constitute the partial recharge zones for the deeper-seated confined aquifers (Egboka and Onyebueke, 1990; Akudinobi and Egboka, 1996). Unconfined aquifer units in the study area occur mostly in the Ajali Sandstone, and represent sections of the formation where the semi-permeable or impermeable cap beds have either been eroded or absent. The thickness of these aquifer units vary from shallow to deep in places. Perched aquifer conditions occur mostly in the lateritic/red earth cover over the Nsukka Formation and in the upper sandy units of the Nsukka Formation. The perched aquifer is generally thin and measurements in dug holes gave thickness values ranging from 3 to 8 m with an average of about 4.6 m (Uma, 2003).

Fractured and fissured shale aquifers exist mostly in the Awgu/Ndeabor and Enugu/Nkporo Shale groups where recurrence fractures and weathering result in economic water yield in the upper unites of the shales.

Basis of estimating hydraulic properties from resistivity

A clear analogy exists between mathematical descriptions of the process of groundwater flow and electrical transmission. The electrical current flow (J) in a conducting medium is governed by Ohm's law and the groundwater flow in a porous medium, by Darcy's law, both having forms of equation:

$$J = -\frac{\sigma dv}{dr} \qquad (1)$$

$$q = -\frac{kdh}{dr} \quad (2)$$

Where j, , v, r, q, k, h are respectively the current density (amps per unit area), electrical conductivity (siemens/m = reciprocal resistivity, ℓ, ohm-m or Ωm), electrical potential (volts), distance (metres) specific discharge (discharge per unit area) hydraulic conductivity (or permeability; m/s) and hydraulic head (m). The electro-hydrological analogy between these two phenomena is widely accepted (Freeze and Cherry, 1979; Fitts, 2002; Singh, 2005).

In a homogeneous and isotropic medium, both the electric current and groundwater flow satisfy the Laplace equation: for electrical flow,

$$\frac{d^2v}{dr^2} + \frac{2}{r}\frac{dv}{dr} = 0 \quad (3)$$

and for groundwater flow,

$$\frac{d^2h}{dr^2} + \frac{1}{r}\frac{dh}{dr} = 0 \quad (4)$$

For a point current source, the solution of Equation (3) in a semi-infinite, homogeneous medium for (hemispherical earth) electrical flow can be written as:

$$V = \frac{\ell I}{2\pi}\frac{1}{r} \quad (5)$$

and for hydraulic flow a similar equation can be written as

$$h = \frac{Q}{2\pi T} \ln r \quad (6)$$

Transmissivity of an aquifer of saturated thickness b, is then expressed by

$$Tr = kb \quad (7)$$

Such that equation 4 becomes

$$h = \frac{Q}{2\pi kb} \ln r \quad (8)$$

Generally, since larger connected pores make better flow characteristics for both water and electric current, it is expected that at the very least, there should be some relationship between electrical and hydraulic parameters (Singh, 2005).

METHODOLOGY

Data acquisition and interpretation

Three hundred and twenty two vertical electrical soundings (VES) were carried out in one hundred and twenty six locations within the study area (Figure 3). The Schlumberger electrode spreading was used with maximum current electrode separation ranging from 400 m to 1.2 km. Most of the soundings were conducted nearby existing boreholes for correlation purposes. The locations of the boreholes are also shown in Figure 3.

The initial interpretation of the VES data was accomplished using the conventional partial curve matching technique, with two-layer master curves in conjunction with auxiliary point diagrams (Orellana and Mooney, 1966; Koefoed, 1979; Keller and Frischknecht, 1966). From this, estimates of layer resistivities and thicknesses were obtained which served as starting points for computer-assisted interpretation. The computer program OFFIX, was used to interpret all the data sets obtained. From the interpretation of the resistivity data, it was possible to compute, for every VES station, the longitudinal conductance.

$$S = hi/\ell i \quad (8)$$

and the transverse resistance,

$$R = hi\ell i \quad (9)$$

where hi and ℓi are layer thickness and resistivity respectively (Maillet, 1947).

Further quantification of geoelectrical depth sounding results was possible by relating layer resistivity to lithological, and pore water properties. The starting point was the Archie's Law (1942) which relates the layer resistivity derived from geoelectric field curve to pore water resistivity and the porosity and cementation of the porous skeleton:

$$F = \frac{\ell a}{\ell w} \quad (10)$$

where ℓ_a, is the resistivity of the saturated rock,

ℓ_w is the water resistivity and F is the resistivity formation factor which is constant for pure sands. According to Archie (1942), the formation factor is related to porosity (ϕ) by

$$F = a\,\phi^{-m} \quad (11)$$

where a and m are constants related to rock type.

After a soil with porosity Φ has been drained, its volumetric moisture content is equal to its specific retention. The unsaturated zone is assumed to represent gravity-drained aquifer material at specific retention. If the saturated zone consists of the same material at 100% saturation, then specific yield is defined by:

$$S_y = \Phi\,(1 - S_r) \quad (12)$$

where S_r is saturation at specific retention. Achie (1942), combined Equations 10 and 11 to relate the bulk resistivity to porosityϕ, the pore fluid resistivity ℓ_w and the cementation factor m, as:

$$\ell_{sat} = \ell_w\,\phi^{-m} \quad (13)$$

The resistivity of the unsaturated soil is then

$$\ell_{unsat} = \ell_{sat}\,Sr^{-n}. \quad (14)$$

From Equations 13 and 14, porosity and saturation can be expressed in terms of resistivities to give specific yield S_y as:

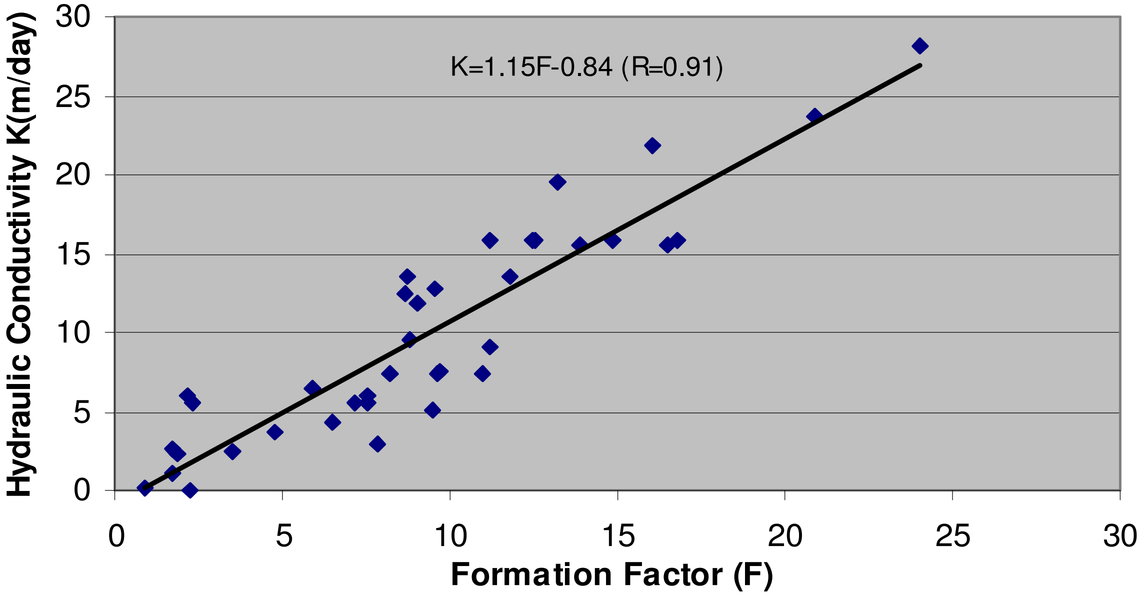

Figure 4. Plot of hydraulic conductivity versus formation factor.

$$S_y = \left(\frac{\ell_w}{\ell_{sat}}\right)^{\frac{1}{m}}\left[1-\left(\frac{\ell_{sat}}{\ell_{unsat}}\right)^{\frac{1}{n}}\right] \qquad (15)$$

ℓ_{sat} and ℓ_{unsat} are obtained from geoelectrical depth sounding, while ℓ_w is the water resistivity. In the present study, m was assigned values between 1 and 1.2 for shale and 1.5 for sand; n is assumed to be 2 (Keller and Frischknecht,1966) ℓ_a was obtained from VES sounding results while ground water resistivity ℓ_w was determined from electrical conductivity measurements at wells and boreholes well distributed in the study area. The water conductivity σ_w, measured in µmhos cm^{-1}, was converted to resistivity (Ωm) with the relation:

$$\ell_w\ (\Omega_m) = 10^4/\sigma_w\ (\mu\text{mhos cm}^{-1}) \qquad (16)$$

Estimating transmissivity

Figure 4 shows the plot of hydraulic conductivity (K) against formation factor (F) estimated from Equation 10. Through a representative average of hydraulic conductivity values obtained from pumping test analysis in parts of the study area, the following empirical relation between K and F was obtained using linear regression techniques with a correlation coefficient, R = 0.91.

$$K\ (\text{m/day}) = 1.15F - 0.84 \qquad (17)$$

The hydraulic conductivity k, obtained from Equation 17 at each sounding position and the aquifer thickness, b, resulting from multilayer resistivity models, were used to derive the transmissivity T_r, according to Equation 7:

$$T_r = Kb = (1.15F-0.84)\ b \qquad (18)$$

In order to access the reliability of the method, the estimated transmissivity values were compared with estimates of Egboka and Uma (1985), Onuoha and Mbazi (1988), Ezeigbo and Ozoko (1989) and Akudinobi and Egboka (1996). The results were considered satisfactory thus validating the applicability of the method.

RESULTS AND DISCUSSION

Regional maps of aquifer thickness, longitudinal conductance transmissivity, porosity and specific yield have been constructed using the results of the resistivity soundings interpretation.

Aquifer thickness is highly variable in the study area (Figure 5). In the central part, underlain by the Ajali and Nsukka Formations, the thickness range between 45.12 and 206.17 m with an average value of 105.20 m. Depths to the top of potential aquifers range from 12 to 40 m in these areas. In the southwestern part of the study area underlain mostly by the Imo Formation, aquifer thickness range between 31.92 and 204.18 m with an average value of 94.11 m, while the range is between 4.3 and 71.2 m with an average of 33.78 m in the eastern part underlain by the Eze Aku/Awgu Ndeaboh/Nkporo Formations. Potential aquifers occur at depths ranging from 30 to 56 m in the southwestern part and from 2 to 24 m in the eastern part of the study area.

The distribution of the aquifer raw longitudinal conductance computed from the resistivity sounding interpretation for the entire area of study is shown in Figure 6. Minimum longitudinal conductance values were observed in the central portion (Nsukka-Ukehe-Oji River axis) of the study area, underlain by the Ajali and Nsukka Formations. Maximum values were observed in the eastern part of the study area underlain by the Eze- Aku/

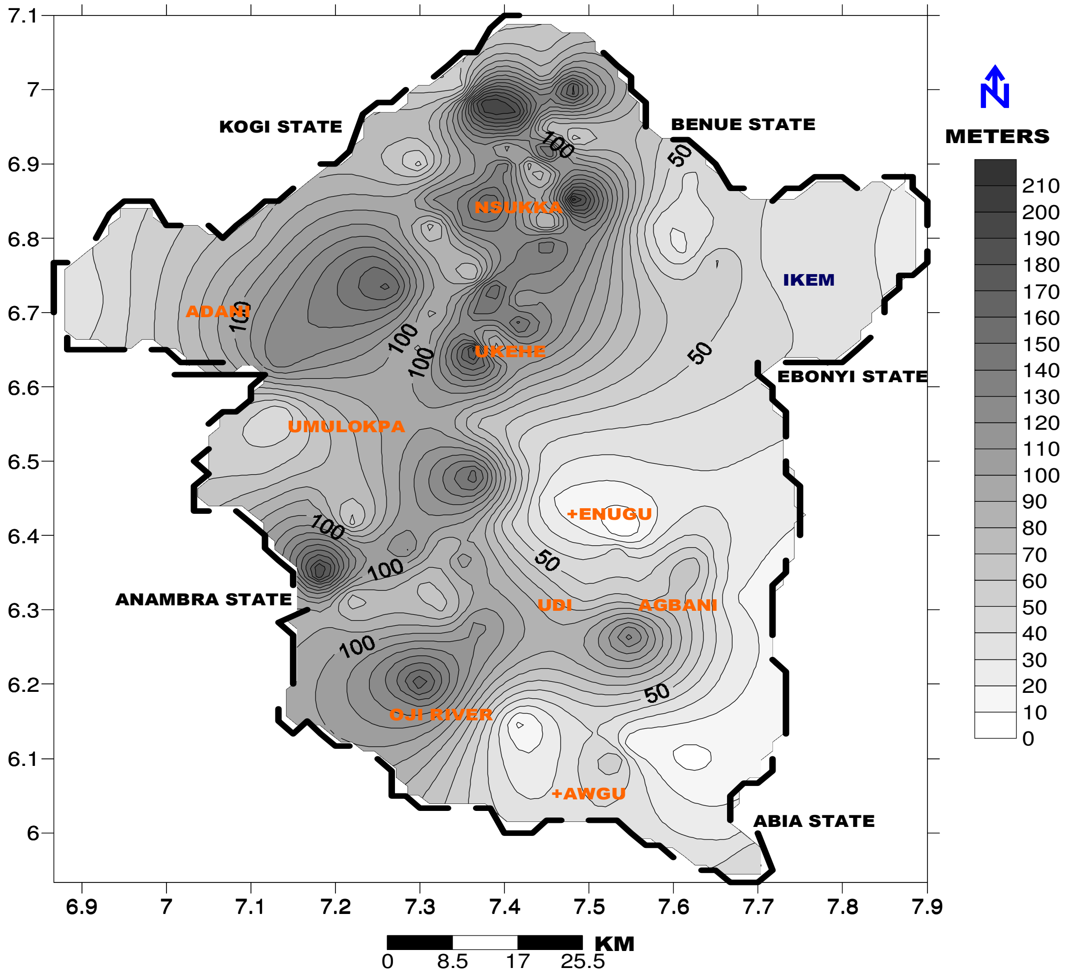

Figure 5. Isopach map of the aquiferous layer.

Awgu Ndeaboh/Nkporo Formations, thus indicating a highly conductive environment.

Transmissivity values have been estimated using the Equation 18. Zones of high transmissiviity values are concentrated on the central part of the study area, underlain by the Ajali and Nsukka Formations, where the value ranges from 317.32 to 2449.977 m^2/day, with an average value of 1163.95 m^2/day while average values of 771.38 and 120.47 m^2/day were recorded in the western and eastern parts of the study area underlain by the Imo and Eze-Aku/Awgu Ndeaboh/Nkporo Formations respectively. Generally, transmissivity of the aquifer in the study area has a wide range, from very poor to very prolific, improving from east and west to the central part of the study area. On the regional scale also, the quality deteriorates towards the discharge area. Relating the transmissivity distribution (Figure 7), and the geology (Figure 3) it is evident that T_r values are highest in the areas underlain by Ajali/Nsukka Formations, consisting lithologically of mainly sands.

The variation of porosity and specific yield in the study area are shown in Figures 8 and 9. In the central part of the study area underlain by the Ajali and Nsukka Formations, porosity values range from 13.27 to 42.5% with an average value of 25.12%, while values for specific yield range between 1.49 and 25.67% with an average value of 10.71%. In the western part underlain by the Imo Formation, porosity range between 16.56 and 57. 66% with an average value of 29.92%, while specific yield values range from 5.2 to 38.86% with an average value of 14%. Higher porosity and lower specific yield values were recorded in the eastern part, underlain by the Eze Aku/ Awgu Ndeaboh/ Nkporo formations. They ranged from 34.29 to 80.23% with an average of 59% and from 0.23 to 6.4% with an average value of 2.87% respectively.

These range of porosity and specific yield values in the different geologic formations within in the study area mostly underlain by sandy and shaly units, is consistent with the range of values for sand and shale given by Davis and DeWiest (1966), Freeze and Cherry (1979) and Pettijohn (1975).

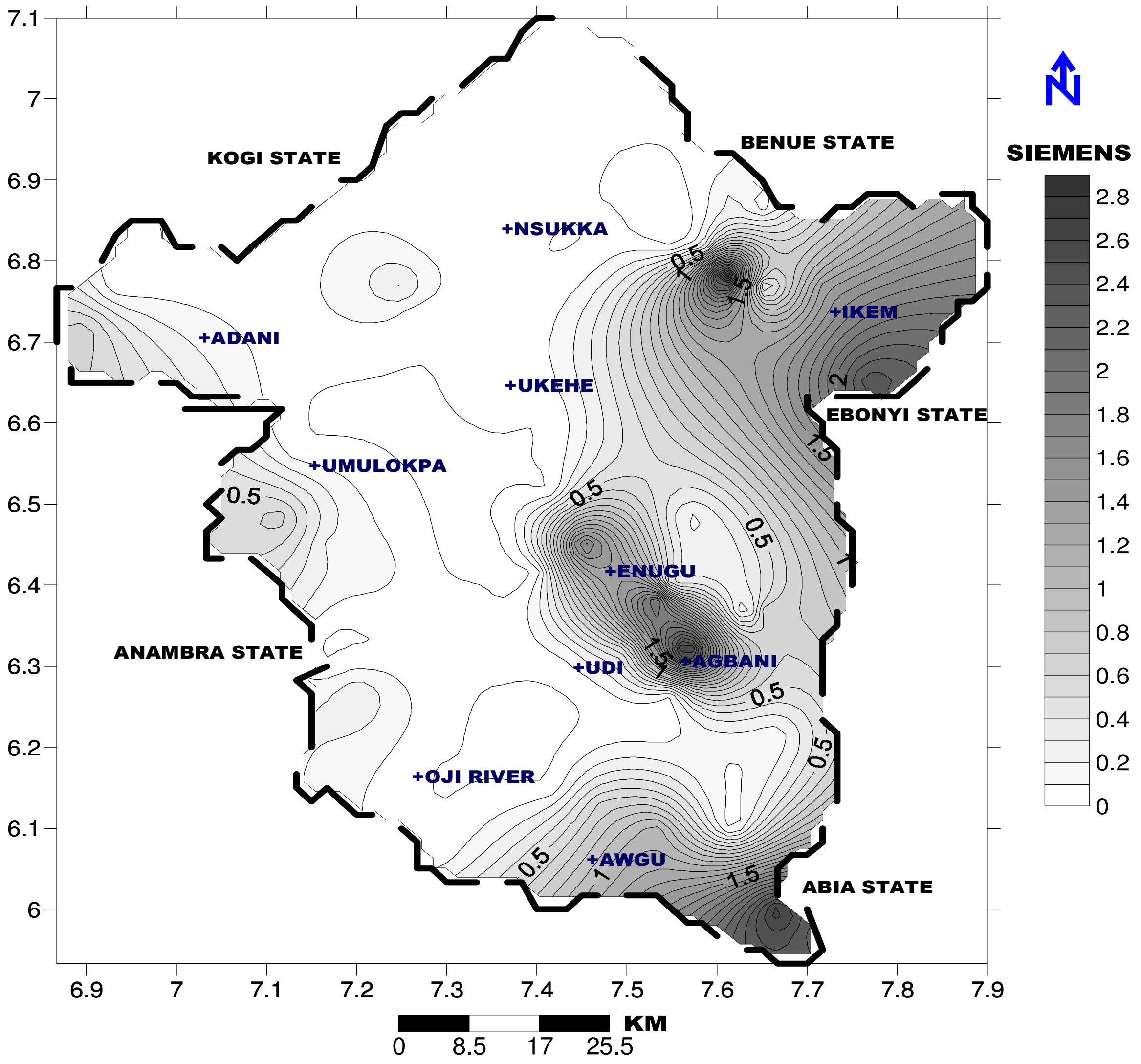

Figure 6. Longitudinal conductance map of the study area.

Relation between groundwater resistivity and earth resistivity

The relationship between water quality and earth resistivity was determined by plotting the water resistivity as a function of apparent resistivity, using results of vertical electrical soundings (VES) conducted nearby productive boreholes well distributed in the area where electrical conductivity (EC) values were available.

The fitted line between water resistivity and earth resistivity (Figure 10) indicates the following empirical relationship with correlation coefficient of 0.89:

$$\ell_w = 0.074\ell_a + 90.93 \qquad (19)$$

where ℓ_w is the water resistivity in ohm–m, and ℓ_a is the apparent resistivity in ohm-m.

This empirical relationship between apparent resistivity and water resistivity reveals that the earth resistivity is strongly affected by groundwater electrical conductivity and provides a basis for applying resistivity methods in groundwater quality evaluation especially in the coal mining areas of the state.

Conclusions

An attempt has been made to find a more general functional relationship between hydraulic conductivity and resistivity in the study area. The established analytical relationship between formation factor and hydraulic conductivity has been used to estimate and construct regional map of transmissivity. Also, geoelectrical depth soundings in combination with water tests have been

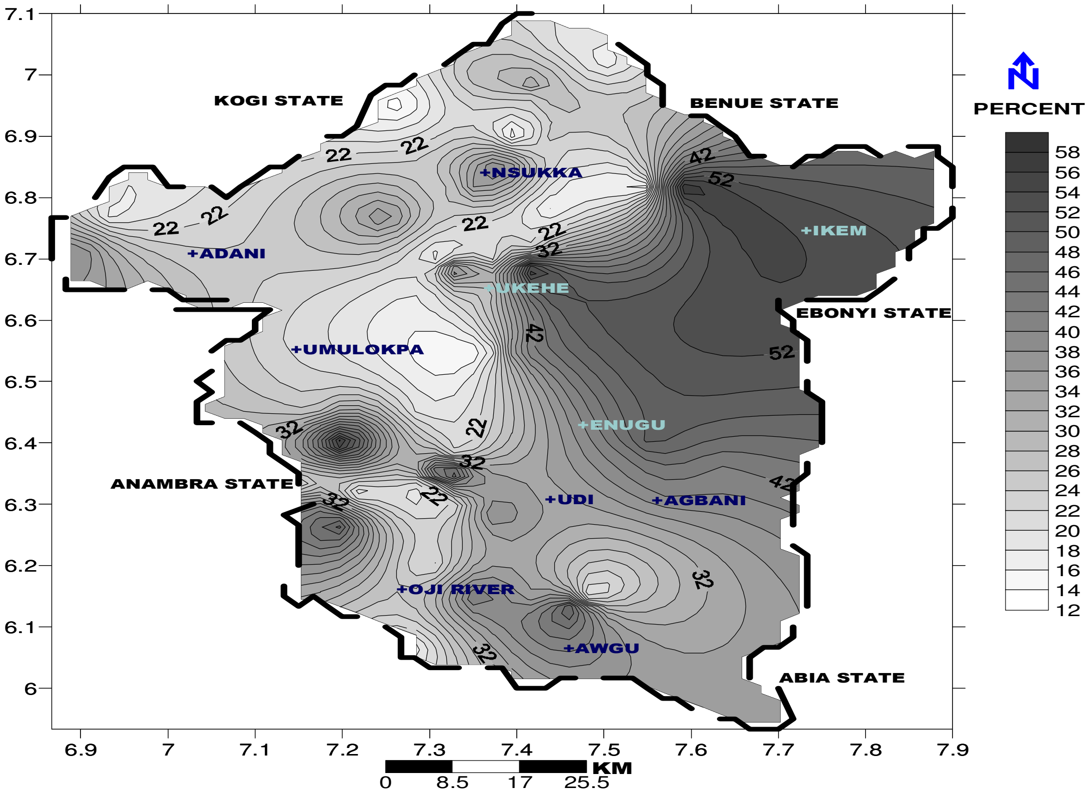

Figure 7. Transmissivity map of the study area.

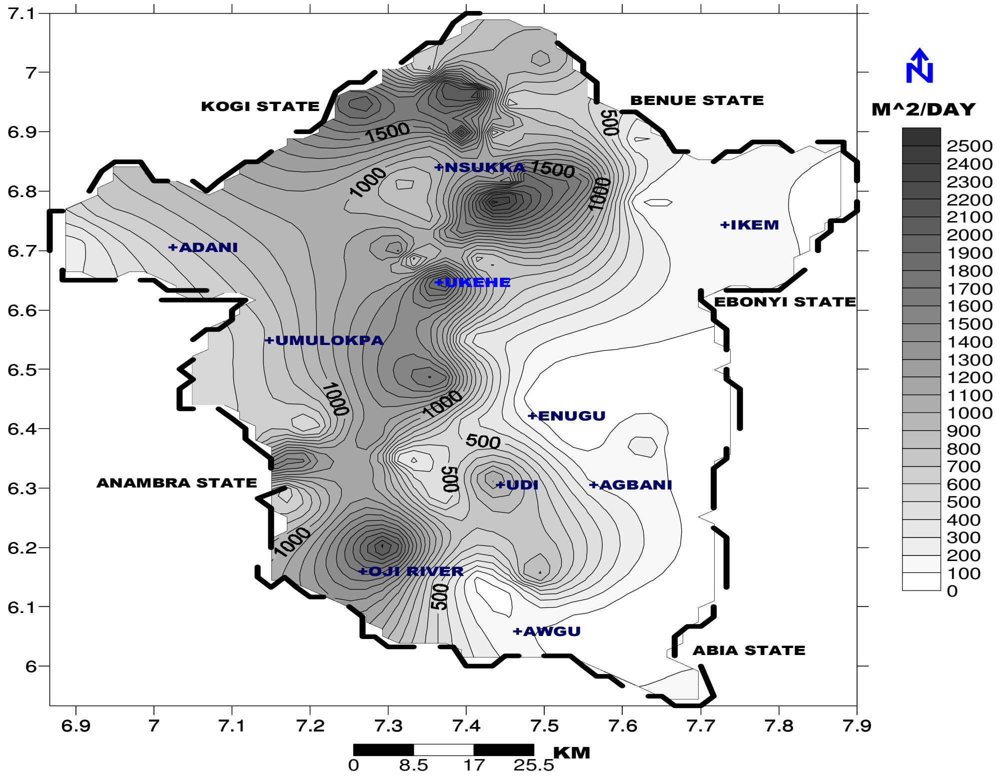

Figure 8. Map of porosity in percent.

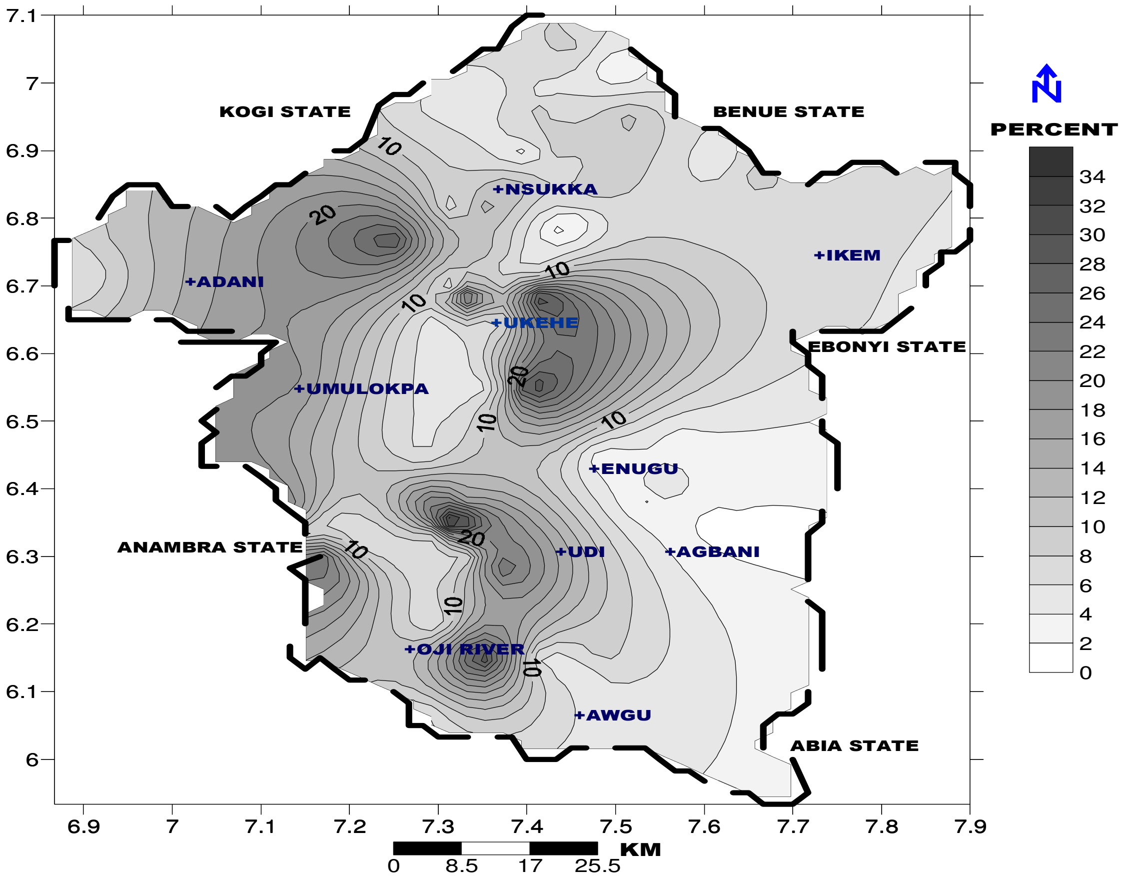

Figure 9. Map of specific yield in percent.

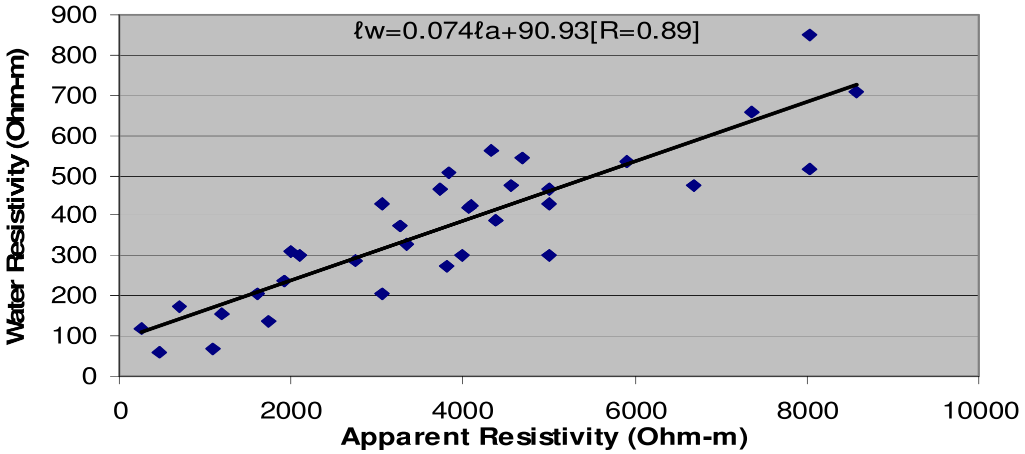

Figure 10. Plot of water resistivity versus apparent resistivity.

utilized to construct regional maps porosity and specific yield. The apparent resistivity/ water resistivity correlation relationship approximated to a linear function with significant correlation coefficient within the range of values used. Using this relationship, preliminary estimates of electrical conductivity values can be made in areas where wells have not been drilled.

The various geophysical and hydraulic parameters estimated and presented here will no doubt aid in borehole programs and provide additional database for groundwater development and utilization in the study area. The results have therefore shown that it is possible to obtain quantitative results from VES that are useful for the determination of hydraulic properties of aquifers.

REFERENCES

Akudinobi BEB, Egboka BCE (1996). Aspects of hydrogeological studies of the escarpment regions of southeastern Nigeria. Water Resour. J. NAH. 7 (1 & 2): 12 - 25.

Archie GE (1942). The electrical resistivity log as an aid in determining some reservoir characteristics. Trans. Am. Inst. Metal Petr. Eng. 146: 54 – 62.

Chen J, Hubbard S, Rubin Y (2001). Estimating the hydraulic conductivity at the south Oyster site from geophysical tomographic data using Bayesian techniques based on the normal linear regression model. Water Resour. Res., 37 (6): 1603 - 1613.

Davis SN, DeWiest RJM (1966). Hyrogeology. John Wiley and Sons, Inc.

De-Swardt AM, Casey OP (1963). The Coal resources of Nigeria. Bull. Geol. Survey of Nigeria, p. 28.

Egboka BCE, Onyebueke FO (1990). Acute hydrogeological problems Vis-à-Vis- planning and management of a developing economy: A case study of Enugu area, Nigeria. Water Res. J. NAH 2(1): 43 – 55.

Egboka BCE, Uma KO (1985). Acid mine drainage problems of Enugu Coal mines of Anambra State Nigeria. Proc. Int. Mine Water Congress Granada, Spain. I: 1 – 11.

Ezeigbo HI, Ozoko DC (1989). An evaluation of the water resources of Nsukka and environs, Anambra State, Nigeria. Water Resources J. NAH, 1[1&2]: 111-116.

Fitts CR (2002). Groundwater Science. Elsevier Sci. Publi., the Netherlands.

Freeze RA, Cherry JA (1979). Groundwater. Englewood Cliffs, New Jersey, Prentice-Hall, Inc.

Frohlick RK, Kelly WE (1985). Estimates of specific yield with the geoelectric resistivity method in glacial aquifers. J. Hydrol., 97: 33-44.

Huntly D (1986). Relations between permeability and electrical resistivity in granular aquifers. Ground Water. 24: 466-474.

Keller GV, Frischknecht FC (1966). Electrical methods in Geophysical Prospecting. Pergamon Press.

Kelly WE (1979). Geoelectric sounding for estimating aquifer hydraulic conductivity. Ground Water. 50(6): 420 – 425.

Koefoed O (1979). Geosounding principles, I. Elsevier, Amsterdam. 276p.

Kogbe CA (1981). Attempt to correlate the statigraphic sequence in the middle Benue basin with those of the Anambra and upper Benue basins. Earth Evolution Sci., 1(2): 139-148.

Koinski WK, Kelly WE (1981). Geoelectric soundings for predicting aquifer properties. Ground Water. 19 (2): 163-171.

Maillet R (1947). The fundamental equations of electrical prospecting. Geophysics. 12: 529-556.

Mazac O, Kelly WE (1985). A hydrogeophysical model for relations between electrical and hydraulic properties of aquifers. J. Hydrol., 79: 1-19.

Onuoha KM, Mbazi FCC (1988). Aquifer transmissivity from electrical sounding data: the case of Ajali sandstone aquifers southwest of Enugu, Nigeria. In: Ofoegbu CO Ed. Groundwater and mineral resources of Nigeria. Vieweg – Verlag. pp. 17 – 30.

Orellana E, Mooney HM (1966). Master tables and curves for vertical electrical sounding over layered structures. Interscience Madrid.

Pettijohn FI (1975). Sedimentary rocks 3rd Ed. Harper & Row Publ. New York.

Reyment RA (1965). Aspects of the geology of Nigeria. Ibadan University Press.

Schimschal U (1981). The relationship of geophysical measurements to hydraulic conductivity at the Brantley dam site, New Mexico. Geoexploration. 19: 115 – 125.

Singh KP (2005). Nonlinear estimation of aquifer parameters from surficial resistivity measurements. Hydrol. Earth Sys. Sci. Discuss., 2: 917 – 938.

Uma KO (2003). Hydrogeology of the perched aquifer systems in the hilly terrains of Nsukka town, Enugu State, Nigeria.Water Resour. J. NAH. 14: 85 - 92.

Urish DW (1987). Electrical resistivity-hydraulic conductivity relationships in glacial outwash aquifers. Water Resour. Res., 17(5): 1401 – 1408.

World Gazette (2011). Colourful map of Nigeria with 36 states. www.world–gazette.com.