Water Supply

Water Supply Vol 22 No 5, 5044 doi: 10.2166/ws.2022.191

Geophysical investigation of transmissibility and hydrogeological properties of aquifer system: A case study of Edem, Eastern Nigeria

Emmanuel T. Omeje *, Johnson C. Ibuot, Desmond O. Ugbor and Daniel N. Obiora

Department of Physics and Astronomy, University of Nigeria, Nsukka, Nigeria

*Corresponding author. E-mail: emmanuel.omeje.pg82415@unn.edu.ng

ETO, 0000-0002-2943-3577

ABSTRACT

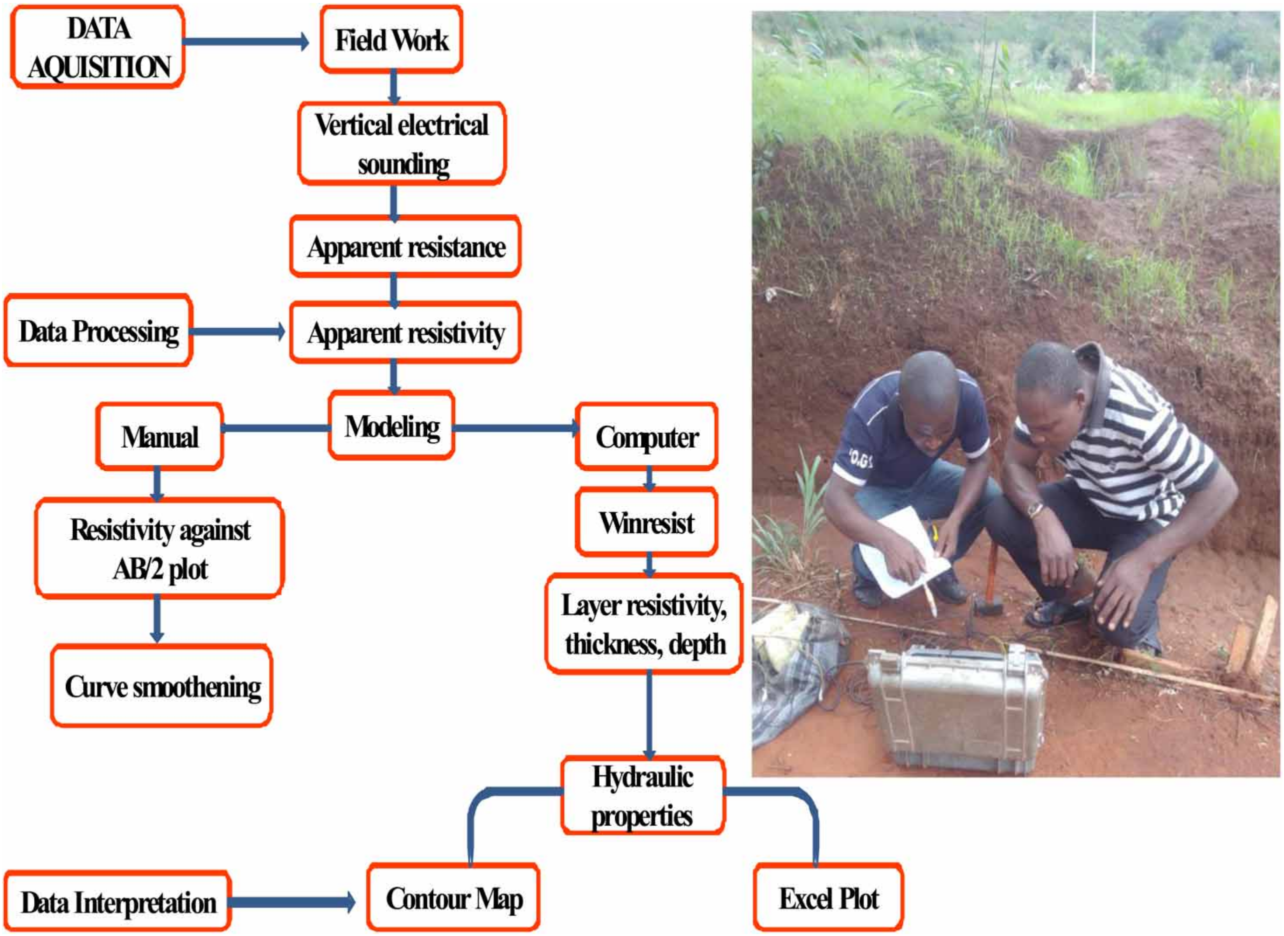
This research study aimed at investigating the transmissibility magnitude of hydrogeologic units of Edem employing a vertical electrical sounding technique. This was as a result of the rapid increase in population and failures of water scheme projects in Edem. Hydraulic properties used in characterizing the transmissibility magnitude were calculated from values of aquifer resistivity and thickness. Results from the field data showed that the aquifer resistivity ranged from 34.800 to 67,561.200 Ωm while thickness ranged from 24.800 to 147.600 m. Fractional porosity with an average value of 0.290 ranged from 0.256 to 0.326. Values of surface area per unit pore volume and permeability range from 460.250 to 13,038.710 m^{-1} and 1.680E-09 to 1.973E-06 μm^2 respectively. Hydraulic capillary radius ranges from 7.67×10^{-5} to 0.00217 m, while transmissivity values range from 0.8607 to 458.0727 m^2/day. From the contour map, hydrogeologic units across the western and eastern parts of the area were depicted as having high indices of transmissibility magnitude. The northwestern part was characterized with very low indices of transmissibility. Plots of permeability against these hydraulic properties revealed their various coefficient of determination. The results from this study will assist in characterizing the hydrogeologic units of the area for proper groundwater exploration and management.

Key words: hydraulic capillary radius, permeability, porosity, tortuosity, transmissibility, transmissivity

HIGHLIGHTS

- The electrical resistivity method was employed.
- Hydraulic properties were calculated from aquifer resistivity and thickness.
- Groundwater transmissibility magnitude was analyzed using hydraulic properties.
- Eight VES points were delineated as having high transmissibility magnitude.
- Transmissibility magnitude distribution was revealed with the aid of contour maps.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water is a requisite demand of life and can be a great challenge when its extraction/exploitation in an area is carried out without any geophysical knowledge on the inter-transmissibility magnitude of hydrogeologic units of the area. The residents of Edem in Nsukka, local government area of Enugu State, Nigeria, has been experiencing difficulties in accessing groundwater as no functional borehole was drilled in the study area (Omeje *et al.* 2021). The only groundwater source attempted was a manual hand dug well with no established scientific data attached to it. The major source of water available is the spring water located in Akpa and the surface water located in Ozzi and Edem-ani respectively, which are very far for most residents. The growing population of the community and the increasing demand of water for their domestic use and agricultural purposes has given rise to the urgent need to address the issue of aquifer transmissibility in Edem. For this reason, it would be very helpful to explore the geological formations of the aquifer units of Edem in order to identify potential zones with high transmissibility. Zones with high transmissibility can be explored using the electrical resistivity method. The electrical resistivity method involving vertical electrical sounding has proven to be useful in groundwater study (Omeje *et al.* 2021). Several researchers have employed several methods in studying the characteristic nature of hydrogeologic units of different geologic locations. Of all the research studies carried out on groundwater by different researchers on different locations in Nigeria, only one research study conducted by Omeje *et al.* (2021) has been carried out in Edem. Edem, which is the largest and most populated community in Nsukka, is faced with failures of water scheme projects leading to a high rate of water scarcity, and with a rapid increase in population and agricultural activities requires more research studies on its hydrogeologic units. This study aims at investigating the transmissibility and hydrogeological properties of aquifer units of Edem employing the electrical resistivity method. This aim cannot be successful without the knowledge of some important geologic units' properties. Omeje *et al.* (2021) employed some geohydraulic parameters which include; porosity, tortuosity, hydraulic conductivity and formation factor in characterizing the geologic units of Edem. In their study permeability of the aquifer layer was not analysed and for an aquifer to be productive it must be permeable. The present study tends to further introduce other hydrogeologic properties needed for clearer study and investigation of the aquifer unit. Hydrogeologic properties additionally considered in this study to ascertain the geological formations of the aquifer units include; permeability, hydraulic capillary radius, surface area per unit pore volume and transmissivity. These properties were considered because they conspicuously regulate the magnitude of fluid transmissibility in geologic units. Water-bearing characteristics of hydrogeological bodies can be vividly explained using permeability (kp) knowledge, in line with transmissivity. Thus, an idea on permeability and transmissivity distribution is essential in result analysis from hydrogeological studies (George *et al.* 2010; Ibuot *et al.* 2013). Permeability is highly correlated with hydraulic conductivity of water within and across aquifer repositories. Permeability magnitude essentially influenced by geologic formation nature permits the feasibility of delineating latent water-bearing units. The degree of distribution of permeability and hydraulic conductivity assist in classifying the aquifer unit of an area as a low or high fluid transmissible unit. In order words permeability and hydraulic conductivity of a geologic unit controls pore fluid transmissibility.

Transmissibility can be defined as the rate of flow of water through a vertical strip of the aquifer (George *et al.* 2018). Its magnitude determines the productivity level of an aquifer in an area. For high transmissibility of fluid through an aquifer, permeability and hydraulic conductivity of the aquifer must be high. This range of classification (low or high) is dependent on the geohydraulic characteristics of the geologic unit of the area. An increase in transmissivity may represent an increase in hydraulic conductivity, porosity and good interconnected pore spaces. This increase thus results in a high magnitude of transmissibility which approves high permeability presupposition (George *et al.* 2017). These hydrogeologic properties which aid in defining the transmissibility of an aquifer can be estimated employing the electrical resistivity method. Electrical resistivity method Being a geophysical method, the electrical resistivity method has the widest adoption in groundwater exploration among the various geophysical methods employed in groundwater investigation (Obiora & Ibuot 2020). This is as a result of its less fatigue in field operation; its relatively high diagnostic values, portability of equipment and greater depth of penetration. This method is economical and versatile in delineating locations of apparent thickness of the weathered areas and productive aquifer sites (Ezema *et al.* 2020). Advances in geophysical techniques with geologically available information enabled accurate estimation of porosity, permeability and other hydraulic parameters through ground-based geophysical measurements, which are affordable compared to laboratory measurements (George 2020).

In this study, estimation of the additional hydraulic properties employing the electrical resistivity method will serve as a tool to the investigation of transmissibility and hydrogeologic properties of aquifer systems in the study area. The magnitude estimated will be productive in groundwater development, exploration, protection, and flow modelling in locations with identical hydrogeologic controls (George *et al.* 2015). The effectiveness of these properties as it relates to transmissibility of pore fluid in geologic units will also assist in managing and monitoring contaminants in aquifer repositories.

1.1. Location and geology of the study area

The study area as presented is examined based on location and geology.

1.1.1. Location of Edem

Edem is situated in the Nsukka area of Enugu, eastern Nigeria. It lies between latitudes 6 °50′ N to 6 °54′ N, and longitudes 7 °16′ E to 7 °23′ E (Figure 1), having an elevation variation above sea level ranging from 300 to 450 m. It covers an area of about 50.492 km^2 with an estimated total population of 309,633 (National Population Commission Census 2006). Edem is characterised with two distinct seasons (rainy and dry), and falls inside the Guinea savannah/tropical rain forest zone of Nigeria. Rainy season occurs between April to October while the dry season is between October and March (Iloeje 1995). It has a temperature range of 19–33 °C.

1.1.2. Geological setting of Edem

The study area, whose geologic formations are the upper Nsukka Formation and the underlying Ajali Sandstone (Figure 1), is within Anambra Sedimentary Basin with Upper Cretaceous rocks in age. The Nsukka formation has over 60% coverage of the entire surveyed area with its sediments serving as the geologic units. Edem is a community with elevated, flat and undulating topography. Dry valleys and residual hills characterise the study area as the prime landforms. These two major

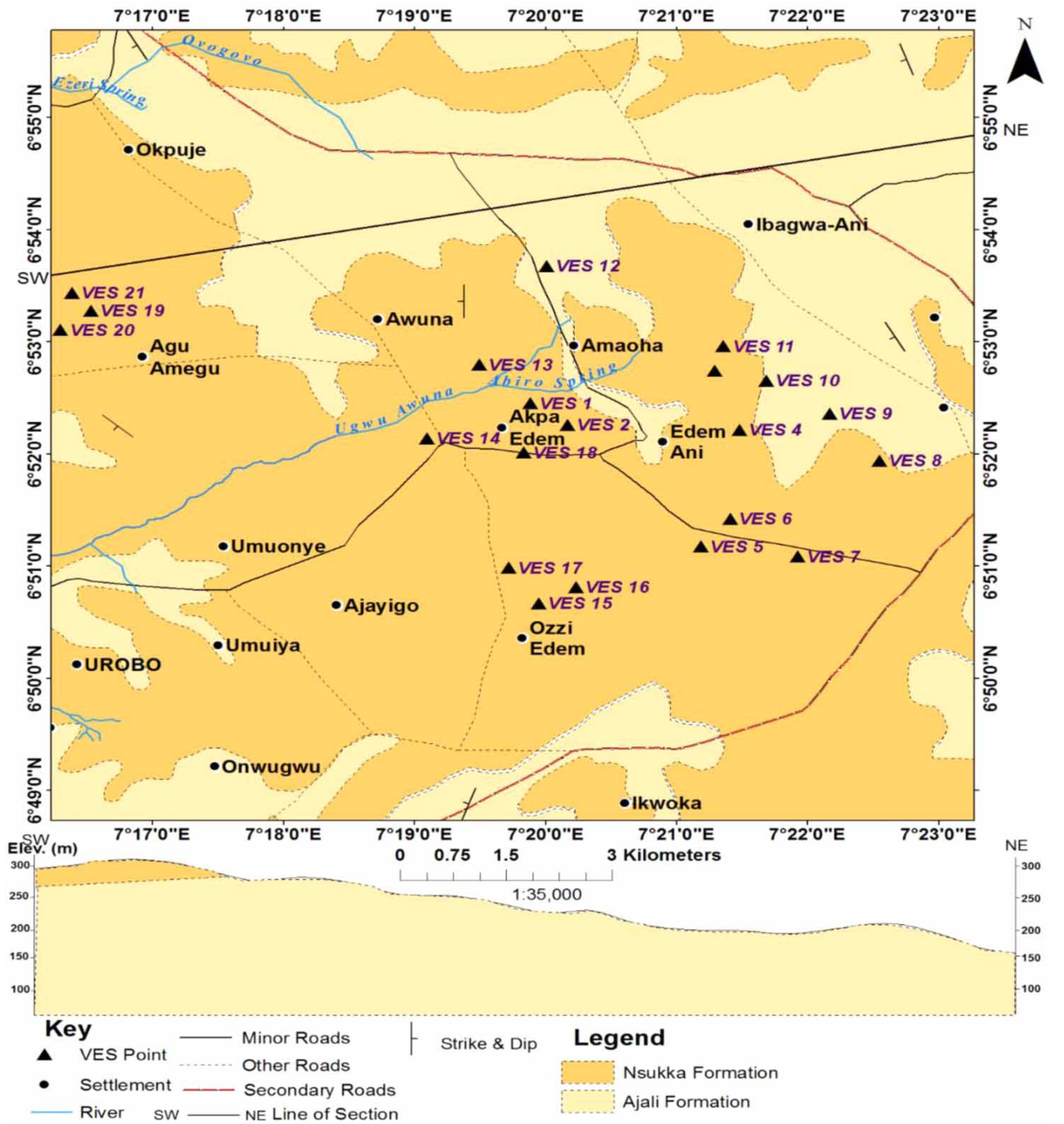


Figure 1 | Location map of the study area and its environment.

geomorphic structures are the resultant effect of weathering and differential erosion of clastic materials, which are remnants of Nsukka Formation (Ofomata 1967). The numerous conical hills and laterite capped are the outliers of Nsukka Formation. The laterite caps are aquiferous as a result of its porosity, permeability and anisotropic nature (Ugwuanyi *et al.* 2015). Water accumulation by plains in this region is from runoff of strands, the recharge of rainwater and from springs. The Ajali Formation which outcropped in some areas is a sandstone formation. The surveyed area is bounded on the east, west, south and north by Nsukka, Nrobo, Obimo,and Ibagwa-ani communities respectively.

2. MATERIALS AND METHODS

A vertical electrical sounding (VES) survey employing Schlumberger electrode configuration was conducted in 21 locations of the study area with the aid of 'SSR-MP-ATS' Resistivity Meter. The 21 locations selected were based on nearness to community settlements, areas with difficulties in groundwater exploration, areas with level or close to level ground that can accommodate a full current electrode spread of 900 m and areas not close to high tension wires. Half potential electrode ($MN/2$) and half current electrode separation ($AB/2$) of 20 and 450 m respectively, were adopted to ensure deeper current penetration, with the resistivity meter placed in between the electrodes. AB values varied with locations and were placed on the earth at a distance ranging from 2 to 900 m while potential electrode (MN) ranged from 0.5 to 40 m (Akpan *et al.* 2013). Accessible roads were considered in locating areas for VES points so as to achieve a wide extreme current electrode (AB) spread of 900 m. For standard guarantee field measurements, the potential electrode separations were one-fifth of the current electrode separations (George *et al.* 2016).

Two-thirds of the electrode length was allowed to penetrate the subsurface during planting. Field data measured and apparent resistance (R_a) were used to compute for apparent resistivity (ρ_{a}) values as shown in Equation (1):

$$\rho_a = \pi \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right] R_a \tag{1}$$

where the geometric factor $\pi\left[(AB/2)^2 - (MN/2)^2/MN\right]$ depends on the electrode configuration.

A suitable geologic model of the field data was obtained employing both computer and manual modelling techniques (Zohdy *et al.* 1974; Akpan *et al.* 2009). A plot of apparent resistivity against half current electrode spacing on a bi-logarithmic graph was carried out to achieve the manual modelling. Lateral in-homogeneities were extracted from the produced curves through smoothening by deleting any outlier at the cross over points that did not conform to the dominant trend of the curve, or by averaging the two readings at the cross over points (Akpan *et al.* 2006; Chakravarthi *et al.* 2007). The computer modelling was carried out using a computer based VES modelling software programme called WINRESIST, which refined the bi-logarithmic graph. WINRESIST software programme uses the initial layer parameters to perform some calculations, generate geoelectric sounding curves in the process and classify the curves into layers with different resistivities, depths and thicknesses (Figure 2).

Transmissivity and hydraulic conductivity are one of the important parameters used in the description of the transmissibility and permeability of the geologic unit of the area. These parameters were estimated from the aquifer thickness and resistivity values. Hydraulic conductivity (K_h) values as given in Equation (2) (Heigold *et al.* 1979) were estimated from its relation with aquifer resistivity (R_w):

$$K_h = \frac{386.40}{R_w^{0.93283}} \tag{2}$$

Hydraulic conductivity measures the opposition to the flow of water through a pore space. It helps in determining the renewal rate of groundwater, appraisal of groundwater yield and other hydraulic properties. It depends on the intrinsic permeability of the aquifer and its degree of saturation. Transmissivity (T_r) relating with hydraulic conductivity and thickness (h) was calculated using Equation (3) according to Todd (1980):

$$T_r = K_h h \tag{3}$$

It controls groundwater flow, provides a general idea on the water-producing efficiency of an aquifer and describes the capacity of the aquifer to transmit groundwater wholly in its entire saturated thickness (Omeje *et al.* 2021). Transmissivity aids in determining the safe yield of an aquifer unit and in the prediction of groundwater movement. Other parameters necessary in the description of aquifer transmissibility magnitude includes; porosity (ϕ), formation resistivity factor (F), tortuosity (τ), permeability (K_P), hydraulic capillary radius (R_c) and surface area per unit pore volume (S_{por}). Porosity is an important property that influences other aquifer hydraulic properties and the amount of water in an aquifer. Porosity can be defined

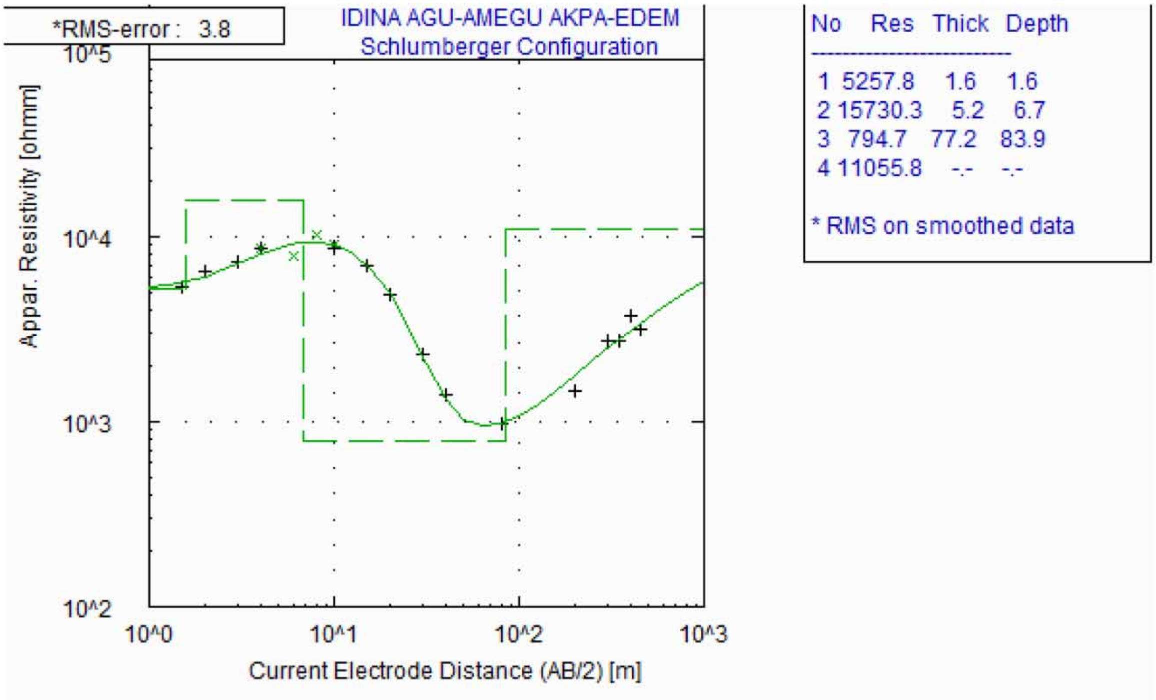


Figure 2 | Sounding curve at VES 21.

as the amount of empty space in the aquifer that is available to hold water. Porosity (ϕ) was calculated through Equation (4) following Marotz (1968):

$$\phi = 25.5 + 4.5 InK_h \tag{4}$$

It is affected by exposure pressure, formation pattern as well as grain composition of the soil. For an aquifer to be productive, it must be porous and permeable. Formation resistivity factor (F) is important in pore-nature prediction as it measures the effect of pore structure on sample resistance. It was estimated using Humbles equation in Equation (5):

$$F = \frac{0.62}{\varphi^{2.15}} \tag{5}$$

Formation resistivity factor determines the degree of compaction or cementation of the aquifer unit. Tortuosity controlled by porosity and nature of pore interconnectivity was estimated through Equation (6) TNO (1976):

$$\tau = \sqrt{F\phi} \tag{6}$$

It is an intrinsic characteristic that recounts the interconnectivity within pore space. Tortuosity is affected by the pore geometry of the aquifer unit and is important in describing groundwater flow properties like permeability. Permeability (K_P) of the hydrogeological unit is an important property that measures the efficiency of groundwater transmissibility. It is a property that quantifies the ability to transmit groundwater through an aquifer. Permeability was deduced using Equation (7) according to George *et al.* (2018):

$$K_p = \frac{\mu_d * (K_h)}{\delta_w * g} \tag{7}$$

Water dynamic viscosity (μ_d) according to Fetters (1994) was given as 0.00140 kg/m/s, water density (δ_w) given as 1000.0 kg/m^3 while gravitational acceleration (g) was given as 10 m/s^2. Permeable formations are described as formations with high transmissibility magnitude. Hydraulic capillary radius (R_c) represents the ratio of pore volume to surface area, and was estimated using Equation (8) by George *et al.* (2018):

$$R_c = \sqrt{\frac{0.52 * K_P * \tau}{\phi}} \tag{8}$$

0.52 is the geometric factor.

Hydraulic capillary radius is an important geologic property that describes the efficiency of an aquifer yield. It is an important parameter used in determining the rate of groundwater flow through the aquifer in response to pressure gradient. Surface area per unit pore volume (S_{por}) is an inverse of hydraulic capillary radius and was estimated using Equation (9):

$$S_{por} = \frac{1}{R_c} \tag{9}$$

It is an important parameter used in determining the productivity of an aquifer and the size of the cemented surface relative to the pore spaces. A high S_{por} in an area signifies more surface compaction than the pore space, thus low transmissibility in that area (George *et al.* 2018; Ibuot & Obiora 2021). The geophysical knowledge of these hydraulic parameters will be beneficial to groundwater explorationists in estimating areas of high transmissibility magnitude.

3. RESULTS AND DISCUSION

The aquifer layer resistivities having an average of 13,227.180 Ωm range from 34.8 to 67,561.2 Ωm. This range of values signifies the existence of medium to high resistive geomaterials in the aquifer layer. The aquifer thickness having an average value of 70.250 m range from 24.8 to 147.6 m. The hydraulic properties which provide an insight into the transmissibility and nature of permeability of the hydrogeologic units were estimated from the values of aquifer resistivity and thickness. Results of these properties were contoured to visualise its spatial variability. Values of these hydrogeologic properties were compared through a plot to show the dependency of permeability on these properties. Figure 3(a) is a contour map showing the variation of permeability in the study area. The map shows high values of permeability having a range $K_p > 4.7 \times 10^{-7}$ μm^2 in.the eastern and western parts of the study area. The lowest distribution having a range $K_p \leq 9 \times 10^{-8}$ μm^2 was observed in the northwestern part. Areas having $K_P > 4.7\ E \times 10^{-7}$ μm^2 reflects areas with good pore interconnectivity

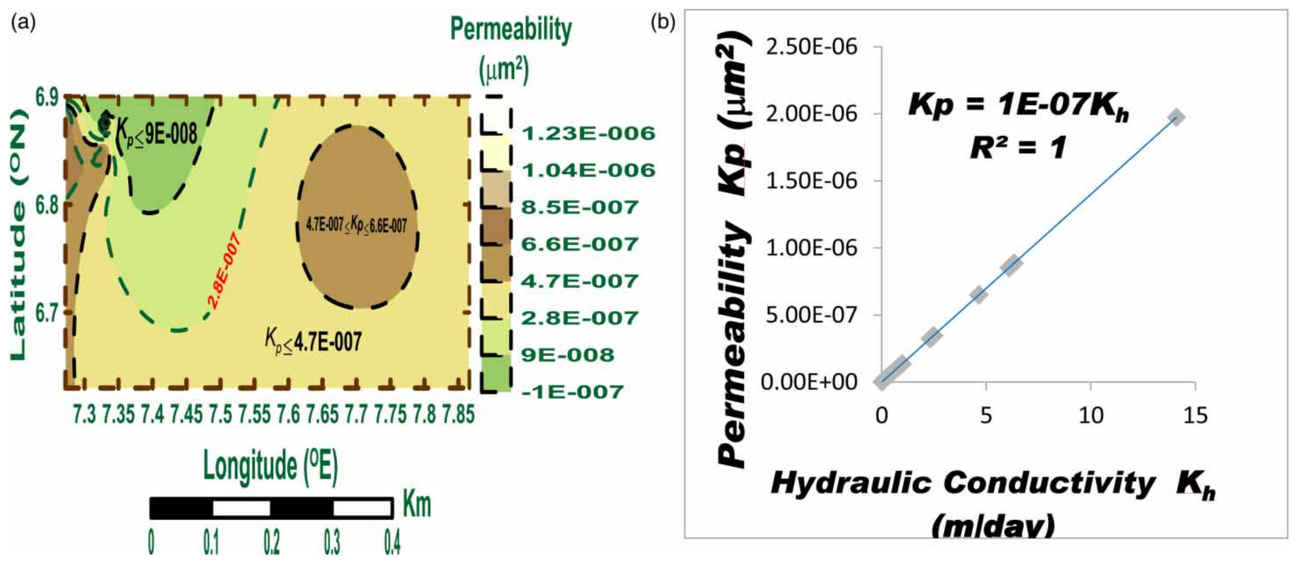


Figure 3 | (a) Contour map of aquifer permeability, (b) Plot of permeability against hydraulic conductivity.

and high rates of groundwater transmissibility in the aquifer. This also shows that these areas of high permeability can be attributed to a coarse-grained soil with an increased void ratio.

The graph of permeability against hydraulic conductivity Figure 3(b) shows a straight-line graph having a perfect coefficient of determination ($R^2 = 1$) and a good functional linear relation with hydraulic conductivity (Equation 10). The graph reveals that an increase in hydraulic conductivity increases permeability. This implies that eastern and western areas which constitute areas of high permeability are also characterised with high hydraulic conductivity. The linear relation in Equation (10) gives the translation of permeability to hydraulic conductivity for groundwater repositories in the study area (George 2020). As shown by Omeje *et al.* (2021), high hydraulic conductivity was observed along the western and eastern part of the study area, this can be attributed to the high permeability distribution along these path as observed in Figure 3(a) and supported in the plot in Figure 3(b):

$$Kp = 1E - 07K_{\boldsymbol{h}} \tag{10}$$

Areas of high permeability distribution as shown in Figure 3(a) also reflect along the line of high capillary radius in Figure 4(a). The hydraulic capillary radius contour map in Figure 4(a) ranges from 0 to 0.0004, 0.0008 to 0.0012 and ≥ 0.0012 m. These ranges of values reflect the relation between the numbers of pore spaces of the aquifer layer and the total volume in the area. High distribution of pore spaces in the aquifer unit is observed along parts of the western zone and a small proportion on the eastern zone, which may be as a result of low hydraulic pressure gradient along these areas. The northern part records the lowest distribution of pore spaces per unit area. High hydraulic radius of an aquifer in an area means high pore inter-connectivity and more efficient groundwater transmissibility in that area. These observations characterise the communicating pores in the northern part of the study area into low permeability and low groundwater transmissibility, with the communicating pores in other parts of the study area characterised with high permeability and high groundwater transmissibility. The permeability-hydraulic capillary radius relation shown in Figure 4(b) indicates that permeability increases exponentially with hydraulic capillary radius and it is as expressed in Equation (12) having a good coefficient of determination $R^2 = 0.999$:

$$K_P = 0.878R_c^{2.119} \tag{11}$$

The equation shows that with the knowledge of hydraulic capillary radius, permeability of an aquifer subsurface can be computed. Figure 5(a) shows the distribution range of surface area per unit pore volume (S_{por}). From the contour map, aquifer layer of greater parts of the study area are characterised with low S_{por} ($S_{por} < 1500$). The northern part of the area is characterised with high S_{por} ($S_{por} > 5000$). This variation may be as a result of the change in the net stress of the formations. Since S_{por} is inversely proportional to hydraulic capillary radius, it implies that areas with high S_{por} correspond to areas with low hydraulic capillary radius. From this observation, the aquifer layer located along the northern part is more compacted than

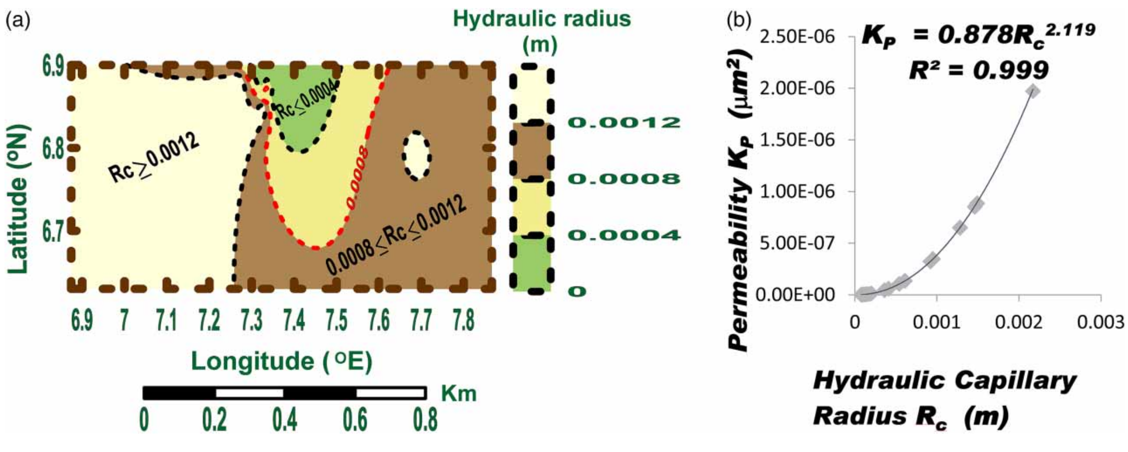


Figure 4 | (a) Contour map of aquifer hydraulic radius (b) Plot of permeability against hydraulic capillary radius.

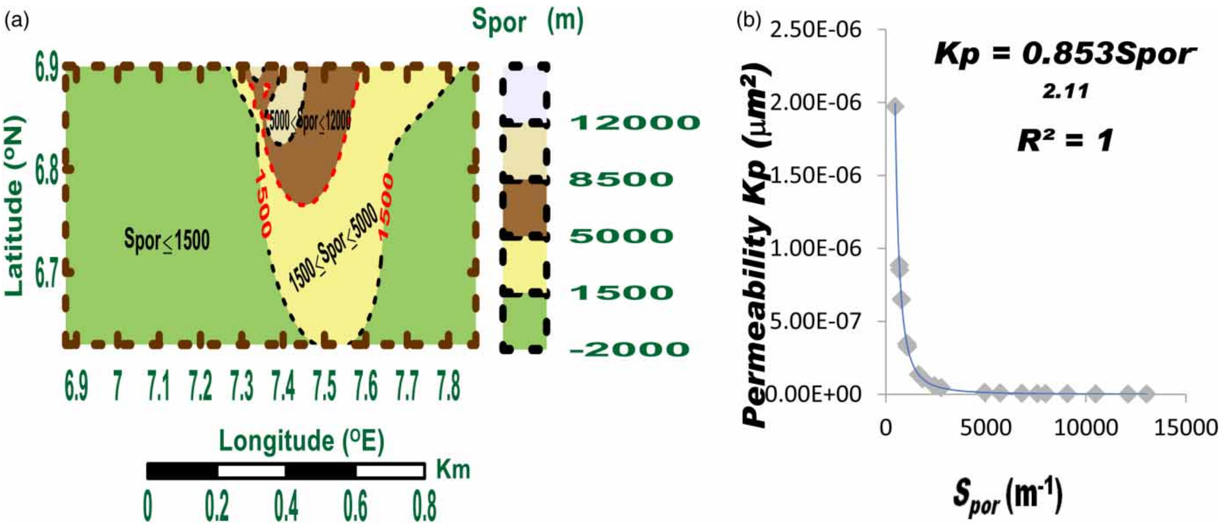


Figure 5 | (a) Contour map of surface area per unit pore volume (b) Plot of permeability against spor.

any other part of the study area. This result signifies low porosity, low permeability and low groundwater transmissibility in that zone.

The permeability-S_{por} relation shown in Figure 5(b) confirms the inverse relation between these parameters. It has an inverse square relation as shown in Equation (12) with a coefficient of determination 1:

$$Kp = 0.853Spor^{-2.11} \quad (12)$$

Transmissivity (T_r) values with average of 118.1003 m^2/day range between 0.8607 and 458.0727 m^2/day. Transmissivity distribution as shown in Figure 6(a) shows high values in areas with values ranging from 120 m^2 per day to $\leq$200 m^2 per day and areas with values $\geq$200 m^2 per day. Transmissivity considered as a hydraulic property that measures the ability of an aquifer to transmit groundwater throughout the entire thickness, shows that areas with these ranges of values are dominated with moderate groundwater potential (Offodile 1983). The distribution reveals that the western part of the study area constitute areas with high transmissivity magnitude ($T_r \geq 200m^2$/day). This conforms with the high permeability distributions observed

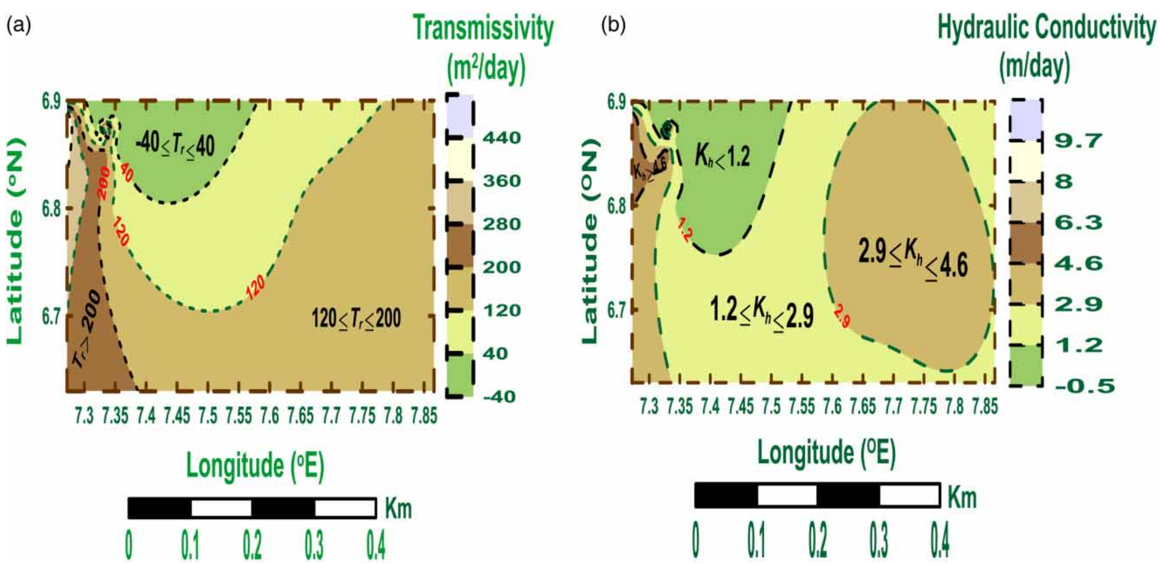


Figure 6 | (a) Contour map of aquifer transmissivity, (b) Contour map of hydraulic conductivity.

along the western part of the study area, thus suggesting high indices of transmissibility magnitude and high groundwater potential compared to other parts. Values of hydraulic conductivity (K_h) range from 0.0121 to 14.0931 m/day. The map as shown in Figure 6(b) shows areas with K values ranging from$-0.5 \leq K_h > 9/7$ m/day. These magnitudes reflect moderate to high hydraulic conductivity in major parts of the study area (Driscoll 1986; Todd 1980). Areas with values $K_h < 1.2$ m/day (northwestern part) reflect areas with low hydraulic conductivity, and this can be attributed to poor interconnectivity of the pores or low permeability (Aleke *et al.* 2018).

These variations in K_h values signify aquifer flow dynamic nature. It shows that water passes through the aquifer with ease in greater parts of the area and with much difficulty in the northwestern part. The aquifer fractional porosity as estimated from Equation (4) ranges from 0.256 to 0.326 with an average value of 0.290. The fractional porosity map as shown in Figure 7(a) ranged from 0.255 < Ø >0.315. This range may be due to the presence of sand and gravel for unconsolidated sediments and sandstone for consolidated sediments in the aquifer formation of the area (Roscoe 1990). The map reveals areas of high and low porosities with the highest porosity (Ø > 0.315) area discerned along the western part. Minimum porosity ranging from 0.255 to 0.285 is observed along the northwestern parts of the map. Comparing Figure 7(a) with 3a Figure 3(a), it is observed that the aquifer layers along the western part of the study area are both porous and permeable, suggesting a good fluid transmissibility of the aquifer. From this observation and also from the plot confirmation in Figure 7(b), it is right to say that water projects sited along the western area will be highly productive.

Figure 7(b) shows a curvilinear graph from permeability-porosity plot with an exponential Equation (13) and a relational coefficient of determination $R^2 = 1$. Figure 7(b) indicates that areas of high porosity constitute areas of high permeability while low porosity is characterised with low permeability:

$$Kp = 2E + 08\phi^{28.91} \tag{13}$$

Figure 8(a) shows the variation of tortuosity (τ) values ranging from 1.500< τ >1.698. Tortuosity range (τ > 1.698) shows areas with the highest aquifer geometric complexity. The distribution shows that northwestern parts constitute areas of high tortuosity with least distribution discerned along the western part and a small portion of the eastern part. Comparing Figure 8(a) with Figure 3(a), it is observed that due to the high permeability distribution along the western part and small fraction along the eastern part, there is a great reduction in the tortuosity distribution along these parts. The map reveals an inverse variation of permeability with tortuosity which is confirmed in Figure 8(b). This relation may be attributed to high geometric complexity of the aquifer, resulting from net overburden stress on the aquifer layer. Permeability and tortuosity relation Figure 8(b) attests to the fact that permeability decreases with a high tortuous path and increases with low tortuosity areas.

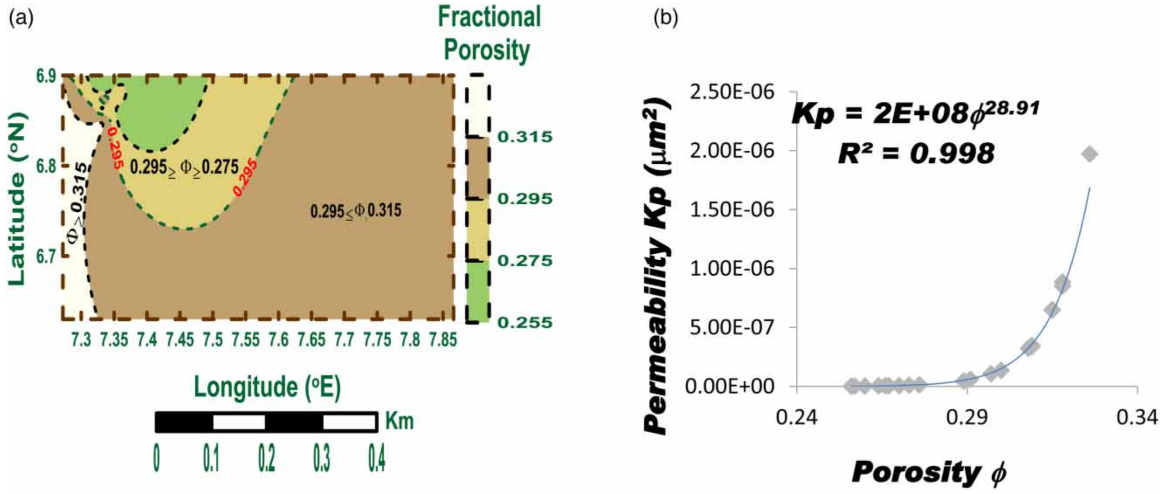


Figure 7 | (a) Contour map of aquifer porosity, (b) Plot of permeability against porosity.

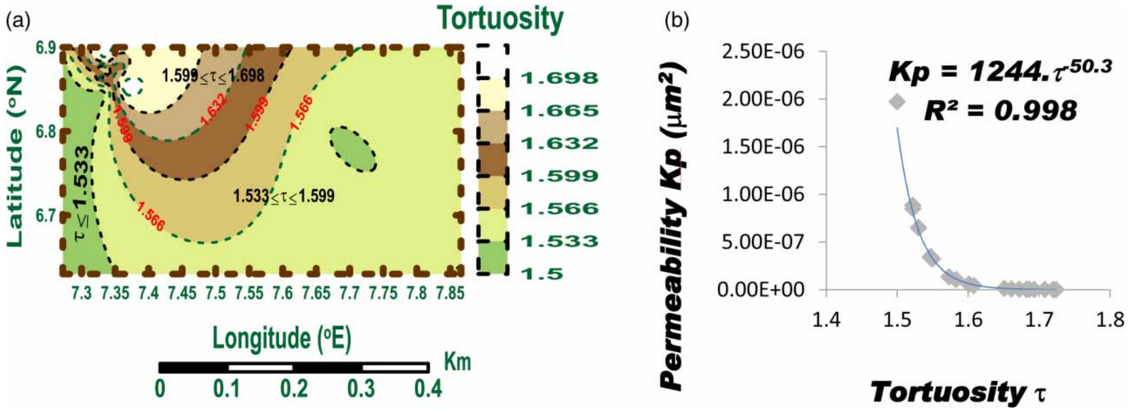


Figure 8 | (a) Contour map of aquifer tortuosity, (b) Plot of Permeability against Tortuosity.

4. CONCLUSION

The inter-transmissibility magnitude of aquifer units in Edem were evaluated from hydraulic properties estimated using aquifer resistivity and thickness. Estimation of hydraulic properties was achieved employing some empirical relations of petrophysics. Clear comprehensions of the distribution of hydraulic properties in Edem were provided with the aid of the contour maps generated. VES 1, 2, 3, 4, 16, 17, 19 and 20 were delineated as areas with high groundwater transmissibility magnitude compared to other VES stations in the study area, following the high permeability and hydraulic conductivity values observed in the aquifer layers. From the contour map, high distribution of permeability, hydraulic capillary radius, transmissivity, hydraulic conductivity and porosity with low distribution of surface area per unit volume and tortuosity was observed along the western and some eastern parts of the study area. The seemingly high values of these properties along the western parts and some at the eastern parts suggest high indices of groundwater transmissibility magnitude along these parts. VES stations found along northwestern areas are dominated with low permeability distribution and both high tortuosity and surface area per unit volume along the northwestern area. The low permeability distribution along the northwesten parts of the study area signifies a low magnitude in groundwater transmissibility. From the above, it is observed that the western and some eastern parts of the study area constitute areas with high transmissibility (high productive aquifer) and as such encourages establishment of water scheme in these areas. The results obtained from this study will serve as a guide to explorationists in areas with high productive aquifer thus limiting the rate of water scheme project failures in Edem. The established functional mathematical relations between permeability and other hydraulic properties can be utilised in characterizing the hydrogeologic units of the area for proper groundwater exploration, exploitation and management.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no competing interests

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Akpan, F. S., Etim, O. N. & Akpan, A. E. 2006 Geoelctrical investigation of groundwater potential in parts of Etim Ekpo local government area, Akwa Ibom State. *Nigerian Journal of Physics* **18**, 39–44. doi: 10.4314/njphy.v18i1.38080.

Akpan, A. E., George, N. J. & George, A. M. 2009 Geophysical investigation of some prominent gully erosion sites in Calabar, south-eastern Nigeria and its implications to hazard prevention. *Disaster Advances* **2** (3), 46–50.

Akpan, A. E., Ugbaja, A. N. & George, N. J. 2013 Integrated geophysical, geochemical and hydrogeological investigation of shallow groundwater resources in parts of the Ikom-Mamfe embayment and the adjoining areas in Cross River State, Nigeria. *Environmental Earth Sciences* **70** (3), 1435–1456. https://doi.org/10.1007/s12665-0132232-3.

Aleke, C. G., Ibuot, J. C. & Obiora, D. N. 2018 Application of electrical resistivity method in Estimating geohydraulic properties of a sandy hydrolithofacies: a case study of Ajali Sandstone in Ninth Mile, Enugu State, Nigeria. *Arabian Journal of Geosciences* **11**, 322. doi:10.1007/s12517-018-3638-8.

Chakravarthi, V., Shankar, G. B. K., Muralidharan, D., Harinarayana, T. & Sundararajan, N. 2007 An integrated geophysical approach for imaging sub-basalt sedimentary basins: case study of Jam river basin, India. *Geophysics* **72** (6), 141–147. https://doi.org/10.1190/1.2777004.

Driscoll, F. D. 1986 *Groundwater and Wells*. Johnson Screens. U.S Geological Survey, St. Paul, MN.

Ezema, O. K., Ibout, J. C. & Daniel, N. O. 2020 Geophysical investigation of aquifer repositories in Ibagwa Aka, Enugu State, Nigeria, using electrical resistivity method. *Groundwater for Sustainable Development* **11**. https://doi.org/10.1016/j.gsd.2020.100458.

Fetters, C. W. 1994 *Applied Hydrogeology*, 3rd edn. Prentice Hall Inc, New Jersey, pp. 600

George, N. J. 2020 Appraisal of hydraulic flow units and factors of the dynamics and contamination of hydrogeological units in the littoral zones: a case study of Akwa Ibom State University and its environs, MkpatEnin L.G.A, Nigeria. *Journal of the International Association for Mathematical Geosciences*. doi:10.1007/s11053-020-09673-9.

George, N. J., Akpan, A. E. & Obot, I. B. 2010 Resistivity study of shallow aquifer in parts of Southern Ukanafun Local government area, AkwaIbom State. *Journal of Chemistry* **7** (3), 693–700. doi: 10.1155/2010/323969.

George, N. J., Ibuot, J. C. & Obiora, D. N. 2015 Geoelectrohydraulic of shallow sandyinItu, AkwaIbom State (Nigeria) using geoelectric and hydrogeological measurements. *Journal of African Earth Sciences* **110**, 52–63. https://doi.org/10.1016/j.jafrearsci.2015.06.006.

George, N. J., Akpan, A. E. & Ekanem, A. M. 2016 Assessment of textural Variational pattern and electrical conduction of economic and accessible quaternary Hydrolithofacies via Geoelectric and laboratory methods in SE Nigeria: a case study of select locations in AkwaIbom state. *Journal of the Geological Society of India* **88** (4), 517–528.

George, N. J., Ekanem, A. M., Ibanga, J. I. & Udosen, N. I. 2017 Hydrodynamic implications of Aquifer Quality Index (AQI) and Flow Zone Indicator (FZI) in groundwater abstraction: a case study of coastal hydrolithofacies in South-eastern Nigeria. *Journal of Coastal Conservation* **21** (4), 759–776. https://doi.org/10.1007/s11852-017-0535-3.

George, N. J., Ibuot, J. C., Ekanem, A. M. & George, A. M. 2018 Estimating the indices of inter- transmissibility magnitude of active surficial hydrogeologic units in Itu, AkwaIbom State, Southern Nigeria. *Arabian Journal of Geosciences* **11** (6), 1–16. doi: 10.1007/s12517-018-3475-9.

Heigold, P. C., Gilkeson, R. H., Cartwright, K. & Reed, P. C. 1979 Aquifer transmissivity from Surficial Electrical Methods. *Ground Water* **17** (4), 338–345. https://doi.org/10.1111/j.1745-6584.1979.tb03326.x.

Ibuot, J. C. & Obiora, D. N. 2021 Estimating geohydrodynamic parameters and their implications on aquifer repositories: a case study of University of Nigeria, Nsukka, Enugu State. *Water Practice and Technology* **I6** (1), 162–181.

Ibuot, J., Akpabio, G. & George, N. 2013 A survey of the repository of groundwater potential and distribution using geoelectrical resistivity method in Itu local government area (LGA), AkwaIbom State, Southern Nigeria. *Central European Journal of Geosciences* **5** (4), 538–547. https://doi.org/10.2478/s13533-012-0152-5.

Iloeje, N. P. 1995 *A New Geography of Nigeria Revised Ed*. Longman Nig. Ltd, pp. 45–50.doi: 10.4236/am.2018.912088.

Marotz, G. 1968 *TechischeGrundlageneinerWasswerspeicherungImmnaturlichen UtergrundHabilitationsschrift*. Universitat Stuttgart, Germany.

National Population Commission Census 2006 *Population and Development Review* **33** (1), 206–210. https://www.jstor.org/stable/25434601.

Obiora, D. N. & Ibuot, J. C. 2020 Geophysical assessment of aquifer vulnerability and management: a case study of University of Nigeria, Nsukka, Enugu State. *Applied Water Science* **10**, 29. https://doi.org/10.1007/s13201-019-1113-7.

Offodile, M. E. 1983 The occurrence and exploitation of groundwater in Nigeria basement complex. *Journal of Mining and Geology* **20**, 131–146.

Ofomata, G. E. K. 1967 *Some Observations on Relief and Erosion in Eastern Nigeria*. Revue deGeomorph, Dynamise. XVU, pp. 21–29.

Omeje, E. T., Ugbor, D. O., Ibuot, J. C. & Obiora, D. N. 2021 Assessment of groundwater repositories in Edem, Southeastern Nigeria, using vertical electrical sounding. *Arabian Journal of Geosciences* **14**, 421. https://doi.org/10.1007/s12517-021-06769-1.

Roscoe, M. C. 1990 *Handbook of Ground Water Development*. John Wiley and Sons, New-York. ISBN 10: 0471856118/ ISBN 13: 9780471856115

The Netherland Organisation 1976 *Geophysical Well Logging for Geohydrological Purposes in Unconsolidated Formations: Groundwater Survey TNO*. The Netherlands Organisation for Applied Scientific Research, Delft. OCLC no: 68104428

Todd, D. K. 1980 *Groundwater Hydrology* 2nd edn. John Wiley and Sons, New York.

Ugwuanyi, M. C., Ibuot, J. C. & Obiora, D. N. 2015 Hydrogeophyical study of aquifer characteristics in some parts of Nsukka and Igbo Eze south local government areas of Enugu State, Nigeria. *International Journal of Physical Sciences* **10** (15), 425–435.

Zohdy, A. A. R., Eaton, G. P. & Mabey, D. R. 1974 *Application of Surface Geophysics to Groundwater Investigation*. USGS Techniques of water resources investigations, Book 2, Chapter D1, Washington, DC, USA.

First received 3 February 2022; accepted in revised form 25 April 2022. Available online 6 May 2022