



Investigation of soil corrosivity, competence and comprehensive aquifer evaluation of Orlu and environs, Southeastern Nigeria

C. C. Agoha¹ · C. A. Ebekuo¹ · T. I. Mgbeojedo² · C. N. Onwubuariri³ · J. O. Njoku¹ · I. J. Ofoh¹ · C. N. Nwokeabia⁴ · S. I. Ibeneme¹ · D. N. Anuforo⁵

Received: 23 September 2023 / Accepted: 26 May 2024 / Published online: 16 June 2024
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2024

Abstract

The increasing demand for clean water for domestic and industrial purposes for the rapidly growing population of Orlu and its environs motivated this study. Vertical electrical sounding data, employing the Schlumberger array and AB/2 from 1.0 to 350.0 m, was acquired from fifteen respective locations with the aid of ABEM SAS 4000 resistivity meter. The data was processed using IP2WIN 2.0 to obtain layer resistivity curves and generate geo-electric sections. Various aquifer parameters as well as pumping test information from monitoring Wells were also obtained in addition to new model equations for obtaining aquifer transmissivity from transverse resistance and hydraulic conductivity from aquifer resistivity. 2D geospatial maps and 3D models of the aquifer parameters were obtained using Surfer 21.0. Corrosivity and competence of soils as well as aquifer protective capability of this area were also investigated. Results show that aquifer resistivity varies from 554.3 to 23500 Ω m with Orlu having the highest aquifer conductivity and transmissivity and Ntueke recording the least. The highest aquifer thickness and storativity were observed at Nwangele and the least recorded at Ntueke, while the deepest aquifer was observed at Orsu-Ihiteukwa and the shallowest seen at Ntueke. Results also indicated that the soils of most of the locations are essentially non-corrosive and competent, and the aquiferous units are poorly protected from contamination. These findings are central and critical for groundwater development and sustainability as well as structural engineering, agricultural, and industrial activities in this area.

Keywords Schlumberger array · Geo-electric sections · Pumping test · Model equation · Transmissivity · Transverse resistance

Introduction

Being crucial to all forms of life, the importance of water cannot be overemphasized. Groundwater refers to water found within pore spaces or voids that are saturated beneath

the ground. The primary source of groundwater is rainwater which percolates the topsoil and seeps downwards to the substrata until it gets to an impermeable unit where it no longer can continue its movement downward. Groundwater is essentially available when the rocks within the saturation zone are reasonably permeable to transmit a substantial quantity of water to springs, wells, or streams (Strahler 1973).

Viable and prolific aquifer prospectivity for the supply and sustainability of groundwater has been carried out over time with the assistance of several means varying from the subsurface and surface geophysical methods to physical observations (Todd and Mays 2005). In geophysical methods, the physical properties of the subsurface lithostratigraphic units are ascertained by employing different geophysical equipment. They identify differences in physical parameters like electrical resistivity in the crust of the Earth.

✉ T. I. Mgbeojedo
toomgbeojedo@gmail.com

¹ Department of Geology, Federal University of Technology, P.M.B. 1526, Owerri, Imo State, Nigeria

² Geophysical Department, Arab Center for Engineering Studies, Doha, Qatar

³ Department of Physics, Michael Okpara University of Agriculture, P.M.B. 7267, Umudike, Abia State, Nigeria

⁴ Department of Applied Geophysics, Nnamdi Azikiwe University, P.M.B. 5025, Awka, Anambra State, Nigeria

⁵ Department of Physics/Electronics, Federal Polytechnic Nekede, P.M.B. 1036, Owerri, Imo State, Nigeria

Corrosivity refers to the ability of soils to provide the conditions necessary for and also quicken the corrosion of an object buried in it. The corrosive potential of soil can be greatly determined by the nature of the background geology of the location where the soil emanates as well as the anthropogenic activities. Corrosion is induced by material-environment contact and often results in material deterioration, putting safety at risk and posing substantial problems in materials and engineering according to Mars (1987), Ekine and Emujakporue (2010), and Guma et al. (2015). Soil corrosiveness can impact in no small measure infrastructures such as clean domestic water and wastewater structures, bridges and other highway structures, transmission pipelines for liquid and gas, and facilities for storage purposes. To prevent corrosion in construction projects involving the underground laying of cables and steel pipes or other piping and tubing networks in the subsurface, it is important to understand the subsurface resistivity distribution of the area. Also, robust knowledge of the competence of soils is critical for structural and engineering constructions which may include overhead water storage facilities.

Authors including Agbodike (2019), Nwosu et al. (2020), Akakuru et al. (2023), Iheme et al. (2018), and Ibeneme et al. (2013) have carried out studies on the aquifer and water resources of this area. While Agbodike (2019), Nwosu et al. (2020), and Akakuru et al. (2023) worked on the characteristics of the aquifers of some sub-locations of the entire region of the present study, Iheme et al. (2018) and Ibeneme et al. (2013) analyzed the hydro-geochemistry and water quality of parts of this area. Being a rapidly growing and expanding region, this study, therefore, covers the entire Orlu and its bordering towns, and it involves comprehensive and integrated research of major aquifer parameters as well as soil corrosivity and competence. Aquifer protective capability of the various locations was investigated and new mathematical models for estimating the transmissivity and hydraulic conductivity of aquifers in this region were also generated.

Orlu region is one of the three major cities in Imo State of Nigeria and as such has benefited greatly from industry and commerce. The direct effects of this, including population growth and rapid urbanization, have greatly increased the water demand, both for domestic and industrial purposes (Onyekwelu et al. 2021). The Orashi, Njaba, and Okitankwo Rivers are the three rivers and drainage channels in various locations of the area of study in addition to a few streams. However, most parts of this area are very far from these surface water sources, making accessibility difficult. Also, the aquifer in this area has not been appropriately characterized, and its hydraulic parameters are still not well known. Information about aquifer storage and distribution within Orlu and its environs is not sufficient. Wells have been drilled to inadequate depths and at the wrong geological locations due to a lack of sufficient data on aquifer parameters.

In addition, steel utility pipes are reliant on drawing water from the wells and water reticulation purposes in this area. These pipes, most times, deteriorate due to corrosion leading to regular maintenance with associated cost, manpower, and operational challenges.

Therefore, detailed and comprehensive information on the aquifer geo-hydraulic parameters in addition to the corrosivity and competence of soils in this area is very essential and critical in ensuring safe and seamless drilling and reticulation operations and unhindered access to viable groundwater in this area.

Location and background geology of the study area

This area sits within Orlu Local Government Area (LGA) and its border towns of Ideato North, Nwangele, Orsu, and Oru East LGAs in Southeastern Nigeria. The area is situated within longitudes $6^{\circ} 45' E$ and $7^{\circ} 8' E$, and latitudes $5^{\circ} 39' N$ and $5^{\circ} 55' N$. This region is the fastest-growing region in the Southeastern part of Nigeria with a dense population. Figure 1 is the location/topographic map of the region.

This region is mainly situated on three geological formations, namely the Benin, Ogwashi-Asaba, and Ameki Formations. The Ameki Formation is the oldest and lies beneath the Ogwashi-Asaba, which then sit under the youngest Benin Formation (Ibeneme et al. 2013). The area is located in the Anambra sedimentary Basin. Previous authors, including Uma (1989), Reyment (1965), and Whiteman (1982), have extensively studied the geology of these formations. Some notable features of the Benin Formation include friable sandstones that are poorly consolidated. These sandstones are also relatively poorly sorted according to Onyeagocha (1980) and have varying grain sizes, including coarse and fine grains (Ibeneme et al. 2013). Clay lenses that are thin and often discontinuous separate the thick sand units.

The Ogwashi-Asaba Formation underlies the Benin Formation and consists of intercalations of sands, clays, lignites, and grits (Bassey and Eminue 2012). According to Reyment (1965), the age of this formation is Oligocene–Miocene. The formation is believed to be the lateral equivalent of the Agbada Formation in the Anambra Basin (Akpoborie et al. 2011).

The Eocene–Oligocene Ameki Formation underlies the Ogwashi-Asaba Formation. It is characterized by coarse to medium-grained sandstone which may be pebbly, silt with mottled clays, and thin limestone (Ibeneme et al. 2013). This formation consists of coarse to fine-grained sandstone lenses having shales in addition to thin, shaly limestone, particularly in the lower portion. Figure 2 shows the geological map of the area.

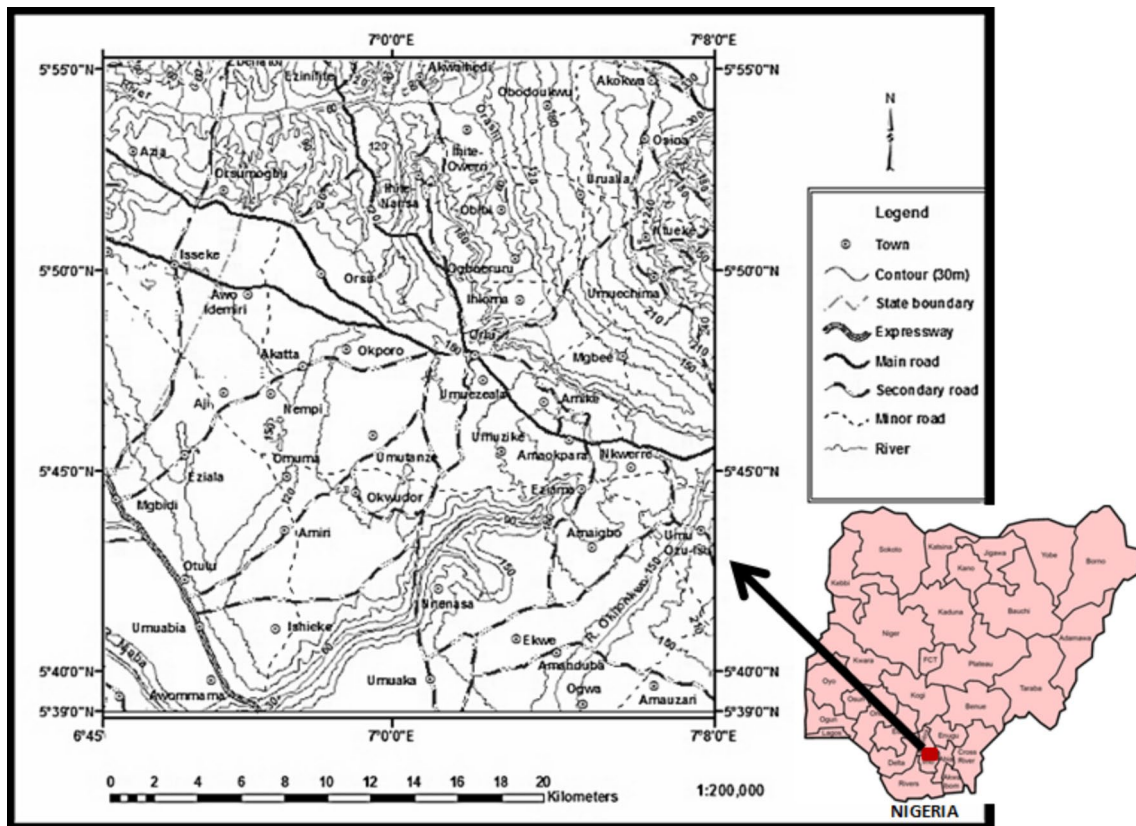


Fig. 1 Location/topographic map of the study area

Materials and methods

Materials

The materials employed in carrying out this study include ABEM Terrameter SAS 4000 resistivity meter, Geological hammer, potential and current electrodes, electrical cable rims (two each for the potential and current electrodes), Brunton compass (for direction and measurement of strike and dip), measuring tapes for linear measurements, field note, location map, topographic map, and GPS (for measurement of latitude, longitude, altitude, and directional azimuths). Other materials are the resistivity data acquired from the area, standard workstation, IP2WIN 2.0 software for data analysis, Surfer 21 for geospatial maps and generation of 3D models.

Methods

The acquisition of resistivity data was conducted in 15 different locations using the vertical electrical sounding (VES) method. These locations are situated within the Imo State Local Government Areas of Ideato North, Orlu, Nwangele, Orsu, and Oru East. At each location, direct current resistivity

surveys using the Schlumberger array and AB/2 from 1.0 to 350.0 m were carried out, and the different resistivity readings were recorded.

In resistivity data evaluation, there is a direct proportionality between material electrical resistivity (ρ) and potential difference (V) on one hand, and an inverse proportionality between ρ and current induced (I) as shown in Eq. 1.

Therefore,

$$\rho \propto \left(\frac{V}{I} \right) \tag{1}$$

Introducing the geometric factor k , we have Eq. 2 as

$$\rho = k \left(\frac{V}{I} \right) \tag{2}$$

The term k known as the geometric factor is determined using Eq. 3 given as

$$k = \pi \left\{ \frac{\left[\left(\frac{AB}{2} \right)^2 - \left(\frac{MN}{2} \right)^2 \right]}{MN} \right\} = \pi \left(\frac{a^2}{b} - \frac{b}{4} \right) \tag{3}$$

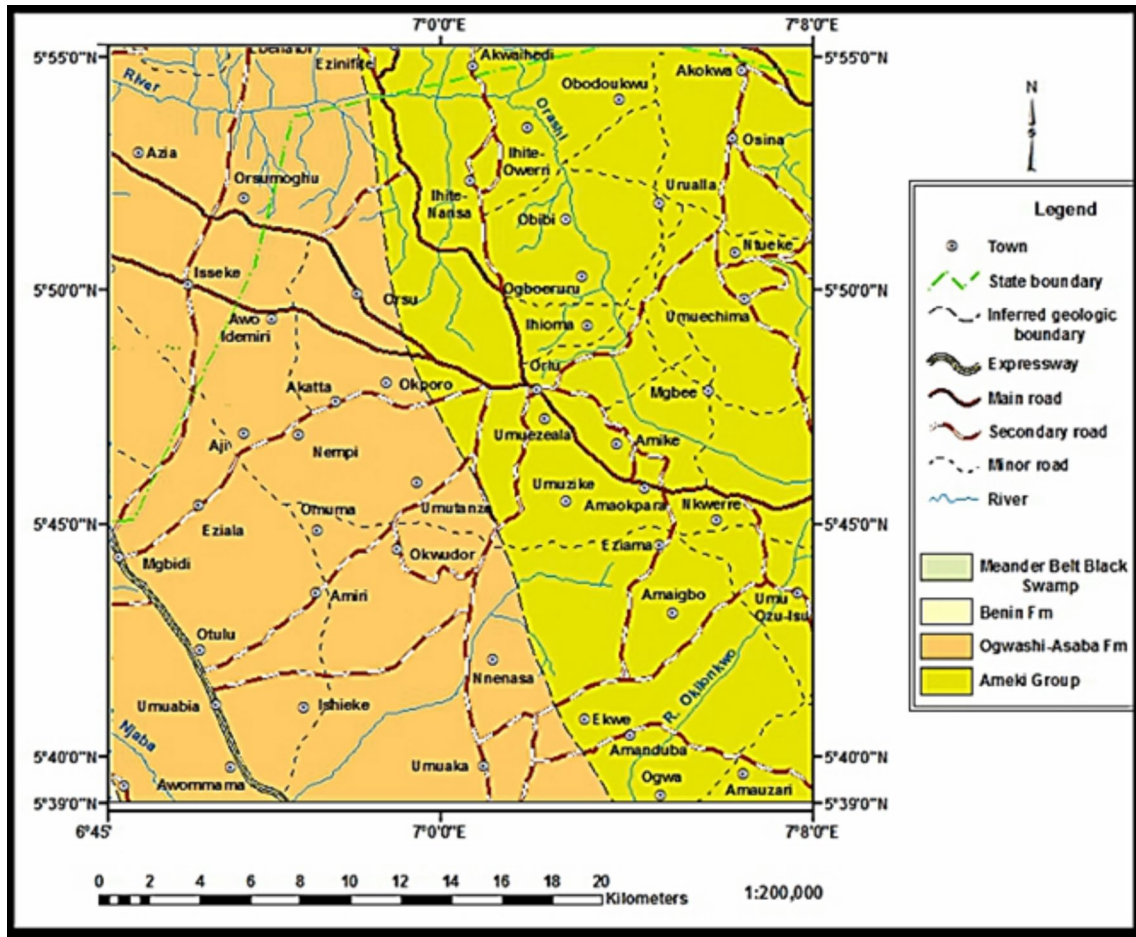


Fig. 2 Geologic map of the area of study

where AB = the linear distance separating the current electrodes and MN = the linear distance separating the potential electrodes. It then follows in Eq. 4 that

$$\rho = \pi \left(\frac{a^2}{b} - \frac{b}{4} \right) \left(\frac{V}{I} \right) = \pi \left(\frac{a^2}{b} - \frac{b}{4} \right) R \tag{4}$$

It implies that the electrode spacing controls the value of the geometric factor. The locations and coordinates of the data points are shown in Table 1. VES 1.

The acquired resistivity data was processed using IP2WIN 2.0 software to obtain layer resistivity curves and generate geo-electric sections for each data point. This software holds the advantage of seamless manual data interpretation; model parameters could be varied in diverse ways including in worksheets, on the cross-section of resistivity, and also by drag-and-drop of the part of resistivity curve. Aquifer parameters, including aquifer depth, thickness, conductivity, transverse resistance, longitudinal conductance, storativity, hydraulic conductivity (obtained using Niwas and Singhal 1981; Heigold et al. 1979) models, and transmissivity were calculated.

Table 1 Locations and coordinates of the data points

Longitude	Latitude	VES No	VES location
E7° 06.587'	N5° 54.007'	VES 1	Akokwa
E7° 05.128'	N5° 53.423'	VES 2	Osina
E7° 04.927'	N5° 51.870'	VES 3	Urualla
E7° 06.380'	N5° 50.752'	VES 4	Ntueke
E7° 03.106'	N5° 48.577'	VES 5	Mgbee
E7° 03.756'	N5° 47.280'	VES 6	Orlu
E7° 05.367'	N5° 43.002'	VES 7	Amaigbo
E7° 04.800'	N5° 46.0391'	VES 8	Nwangele
E6° 59.718'	N5° 51.256'	VES 9	Orsu-Ihiteukwa
E6° 59.248'	N5° 52.558'	VES 10	Ihittenansa
E7° 00.847'	N5° 47.572'	VES 11	Okporo
E6° 57.632'	N5° 46.892'	VES 12	Akatta
E7° 00.697'	N5° 53.054'	VES 13	Ihiteowerri
E7° 01.22	N5° 50.660'	VES 14	Obibiochasi
E7° 01.538'	N5° 50.283'	VES 15	Ogberuru

Aquifer conductivity was obtained by simply inverting the values of the aquifer resistivity. The transverse resistance

(R_T) was obtained by multiplying the resistivity of the aquifer (ρ) and the thickness of the aquifer (h). Longitudinal conductance (C_L) was calculated through the division of the aquifer thickness with the aquifer resistivity. These are shown in Eqs. 5 and 6.

$$R_T = h\rho \quad (5)$$

$$C_L = h/\rho \quad (6)$$

The confined aquifer storativity (S) and that of the unconfined aquifer system was calculated from the equation of Todd (1980) given in Eq. 7.

$$S = 3 \times 10^{-6}b \quad (7)$$

where b = aquifer saturated thickness.

Niwas and Singhal (1981) put together equations from Darcy's and Ohm's laws given respectively in Eqs. 8 and 9 to obtain the condition in Eq. 10.

$$Q = kIA \quad (8)$$

where Q stands for the discharge of the fluid, k represents hydraulic conductivity, I equal hydraulic gradient, while the cross-sectional area orthogonal to the flow direction is represented by A .

$$J = \delta E \quad (9)$$

where J stands for current density, δ equals electrical conductivity, and E is the intensity of electric field.

$$T = kL/\delta = k\delta R \quad (10)$$

T = aquifer transmissivity, R = transverse resistance, L = longitudinal conductance, k = hydraulic conductivity, and δ is the aquifer conductivity. Niwas and Singhal (1981) hydraulic conductivity was then computed using the relationship in Eq. 11.

$$K_{ns} = k\delta\rho \quad (11)$$

Heigold et al. (1979) model was also used to compute hydraulic conductivity of the aquifer of the area. This model is shown in Eq. 12.

$$K_{ng} = 386.40\rho_w^{-0.93283} \quad (12)$$

where ρ_w represents the resistivity of the aquifer unit that is water-saturated, and hydraulic conductivity by Heigold et al. (1979) is represented as K_{hg} .

Aquifer hydraulic conductivity as determined from the pumping test of monitoring wells in the area was also obtained. This data was used in the generation of a new hydraulic conductivity model (K_{new}) for this area. This

Table 2 Soil corrosivity classification after Bhandari et al. (2013), and Oki et al. (2016)

Soil resistivity (Ωm)	Corrosivity rating
< 10	Extremely corrosive
10–30	Highly corrosive
30–50	Corrosive
50–100	Moderately corrosive
100–200	Mildly corrosive
> 200	Essentially non-corrosive

Table 3 Subsoil competence classifications with resistivity values after Idornigie et al. (2006) and Ojo et al. (2015)

Soil resistivity (Ωm)	Lithology	Competence rating
> 750	Sand/laterite/cry-stalline rock	Highly competent
350–750	Clayey sand	Competent
100–350	Sandy clay	Moderately competent
< 100	Clay	Incompetent

was achieved by cross-plotting hydraulic conductivity obtained from the pumping test and resistivity of the aquifer. The determination of multiple aquifer hydraulic conductivities was aimed at comparing the different hydraulic conductivities to ascertain a more reliable model for this area.

Aquifer transmissivity (T) was obtained by applying the relationship according to Freeze and Cherry (1979) presented in Eq. 13.

$$k = \left(\frac{T}{B} \right) \quad (13)$$

where k is the hydraulic conductivity and B represents the thickness of the aquifer.

Investigation of soil corrosivity involved the use of the first layer (layer one) resistivity of the different locations. A probable lithology is assigned to each first layer resistivity and the corresponding degree of corrosivity using the classification after Bhandari et al. (2013) and Oki et al. (2016) as shown in Table 2.

Also, the first layer resistivities of different locations were used for soil competence investigation. Likely lithology and the degree of competence corresponding to it are assigned to each first layer resistivity using the classification after Idornigie et al. (2006) and Ojo et al. (2015) as displayed in Table 3.

Results and discussion

Layer lithology

The number of layers at each data point was identified using the obtained geo-electric curves. Figure 3 shows the VES curves obtained at Akokwa (VES 1), Orlu (VES 6), Ihittenansa (VES 10), and Ogberuru (VES 15). The different layers identified in each of the VES points and their respective lithological units are presented in Table 4.

Except for Amaigbo (VES 7) which has eight layers, and Ihittenansa (VES 10), Akatta (VES 12), and Ihitte

Owerri (VES 13) with nine layers, other locations recorded ten different layers each. The area consists of mainly sand, sandstone, clay, silt, clayey sand, silty sand, and also sandy clay. This confirms the geology of the area to be Ameki, Ogwashi-Asaba, and Benin Formations. Evidence from obtained geo-electrical sections shows that the study area is dominated by semi-confined, and confined aquifer types. Figure 4(a-d) shows the geo-electrical sections obtained at Osina (VES 2), Ntueke (VES 4), Orlu (VES 6), and Ogberuru (VES 15).

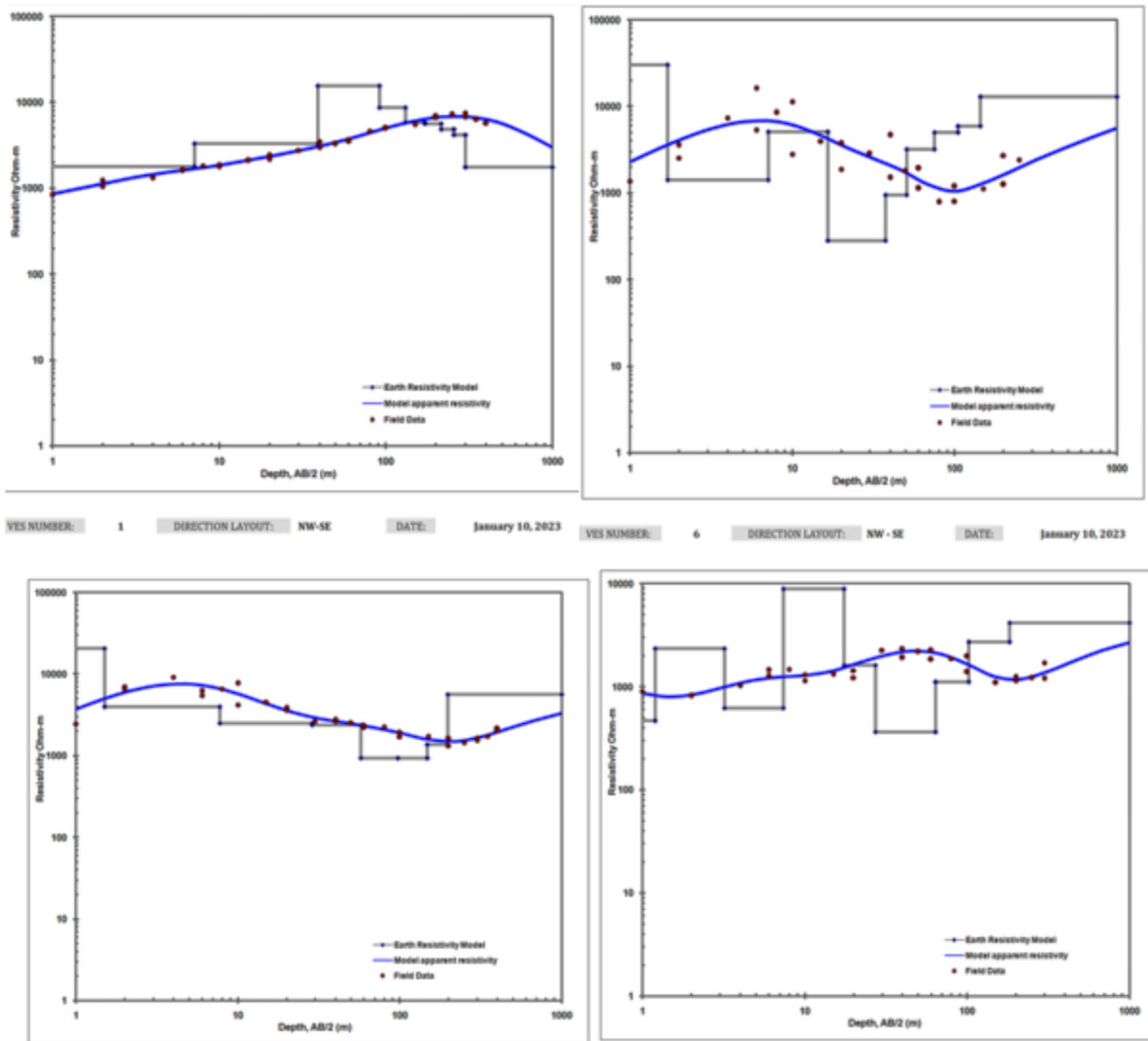


Fig. 3 VES curves of some locations

Table 4 Lithological units of the locations

VES No	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10
VES 1	Top Soil	Clayey Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand
VES 2	Top Soil	Clay	Sandy Clay	Sand	Sand	Sand	Sandstone	Sandstone	Sand	Sand
VES 3	Top Soil	Silt	Clay	Silt	Silt	Sandstone	Sand	Sand	Sand	Sand
VES 4	Top Soil	Sand	Sand	Sandstone	Sandstone	Sand	Sand	Sand	Sand	Clay
VES 5	Top Soil	Silty Sand	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Sandy Clay
VES 6	Top Soil	Sand	Sandy Clay	Sand	Clay	Sandy Clay	Sand	Sand	Sand	Sandstone
VES 7	Top Soil	Silty Sand	Clay	Sandstone	Sand	Sand	Sand	Sand		
VES 8	Top Soil	Sand	Clay	Sand	Sand	Sand	Sand	Silty Sand	Sand	Sand
VES 9	Top Soil	Sand	Sand	Sandy Clay	Sandstone	Sand	Clayey Sand	Clayey Sand	Silt	Silt
VES 10	Top Soil	Sandstone	Sand	Sand	Sand	Clay	Clay	Clayey Sand	Sand	
VES 11	Top Soil	Sand	Sand	Sand	Sand	Clayey Sand	Sand	Sand	Sand	Sand
VES 12	Top Soil	Sand	Clay	Sand	Sand	Sand	Sandstone	Sandstone	Sand	
VES 13	Top Soil	Sand	Clay	Clay	Clay	Clayey Sand	Sand	Sandstone	Clay	
VES 14	Top Soil	Clay	Sand	Silty Sand	Clay	Sandy Clay	Clayey Sand	Silty Sand	Silty Sand	Sand
VES 15	Top Soil	Clay	Silty Sand	Clay	Sand	Clayey Sand	Clay	Sandy Clay	Silty Sand	Sand

Iso-resistivity

The iso-resistivity data for various AB/2 ranging from 1.0 to 350.0 m are presented in Table 5.

A gently increasing trend of resistivity values was observed across all probe depths for VES 1 (Akokwa), VES 2 (Osina), VES 3 (Urualla), VES 4 (Ntueke), and VES 11 (Okporo). Other data points revealed an approximate rising-falling-rising trend of resistivity values. The moderately increased resistivity values observed in the data are traceable to the sandstone units of the Ogwashi-Asaba and Ameki Formations in the area. In general, Okporo (VES 11) reported the most value of resistivity across the rising probe depths having a minimum of 812.9 Ωm at AB/2 = 1.0 m and maxima of 10,420.5 Ωm at AB/2 = 350.0 m with a mean value of 4973.51 Ωm , while Mgbee (VES 5) has the least reading across the entire probe depths with a minimum of 72.3 Ωm at AB/2 = 250.0 m and a maximum of 512.7 Ωm at AB/2 = 8.0 m with a mean value of 249.68 Ωm . Figure 5a shows the 2D Iso-resistivity geospatial map of AB/2 = 50.0 m while Fig. 5b is for AB/2 = 250.0 m.

Aquifer parameters

The major aquifer parameters obtained in this study and pumping test from nearby monitoring wells within the area are summarized in Table 6.

Nwangele (VES 8) has the thickest aquifer with a thickness of 208.9 m, with aquifer units at Amaigbo (VES 7) and Akokwa (VES 1) having substantial thicknesses of 190.3 m and 190 m respectively. These are moderately prolific aquiferous units that can essentially accommodate boreholes for large-scale water supply in these areas. The smallest aquifer thickness was

recorded at Ntueke (VES 4) having a thickness value of 35.6 m and is not suitable for siting boreholes for commercial water supply. A mean regional aquifer thickness of 115.91 m was obtained in this study area and this nearly coincides with the regionwide average of 127.9 m obtained in parts of this area by Nwosu et al. (2020). Figure 6a shows the 2D geospatial map of the aquifer thickness in the area of study and Fig. 6b shows the 2D geospatial map of the depth of the aquifer in the area.

Aquifer thickness determines the ability or otherwise of that unit to store large water volumes. Consequently, the aquifer unit of Nwangele (VES 8) has the most storage capacity with a value of 0.0006267/m while the unit at Ntueke (VES 4) has the least with a storage capacity of 0.0001068 /m. The regional average is 0.00034774 /m.

At Ntueke, shallow aquifer units of 16.7 m depth were found, while Orsu-Ihiteukwa had deep-lying aquifer units of 142 m. The mean regional aquifer depth recorded in this area was 92.7 m and this is in agreement with the regional water table depth of parts of this region as confirmed through hydrogeological studies and pumping tests. Specifically, Akakuru et al. (2023) obtained a value of 92.5 m while Nwosu et al. (2020) reported a value of 84.5 m in different subareas of this region.

Dar-Zarrouk parameters

The longitudinal conductance and transverse resistance constitute the parameters by Dar-Zarrouk. The most aquifer transverse resistance of 2,420,500 Ωm^2 was recorded at Osina (VES 2) while the least was observed at Ntueke (VES 4) with a value of 19,733.08 Ωm^2 . The mean regional transverse resistance in this area is 687,102.38 Ωm^2 . This parameter defines an area with

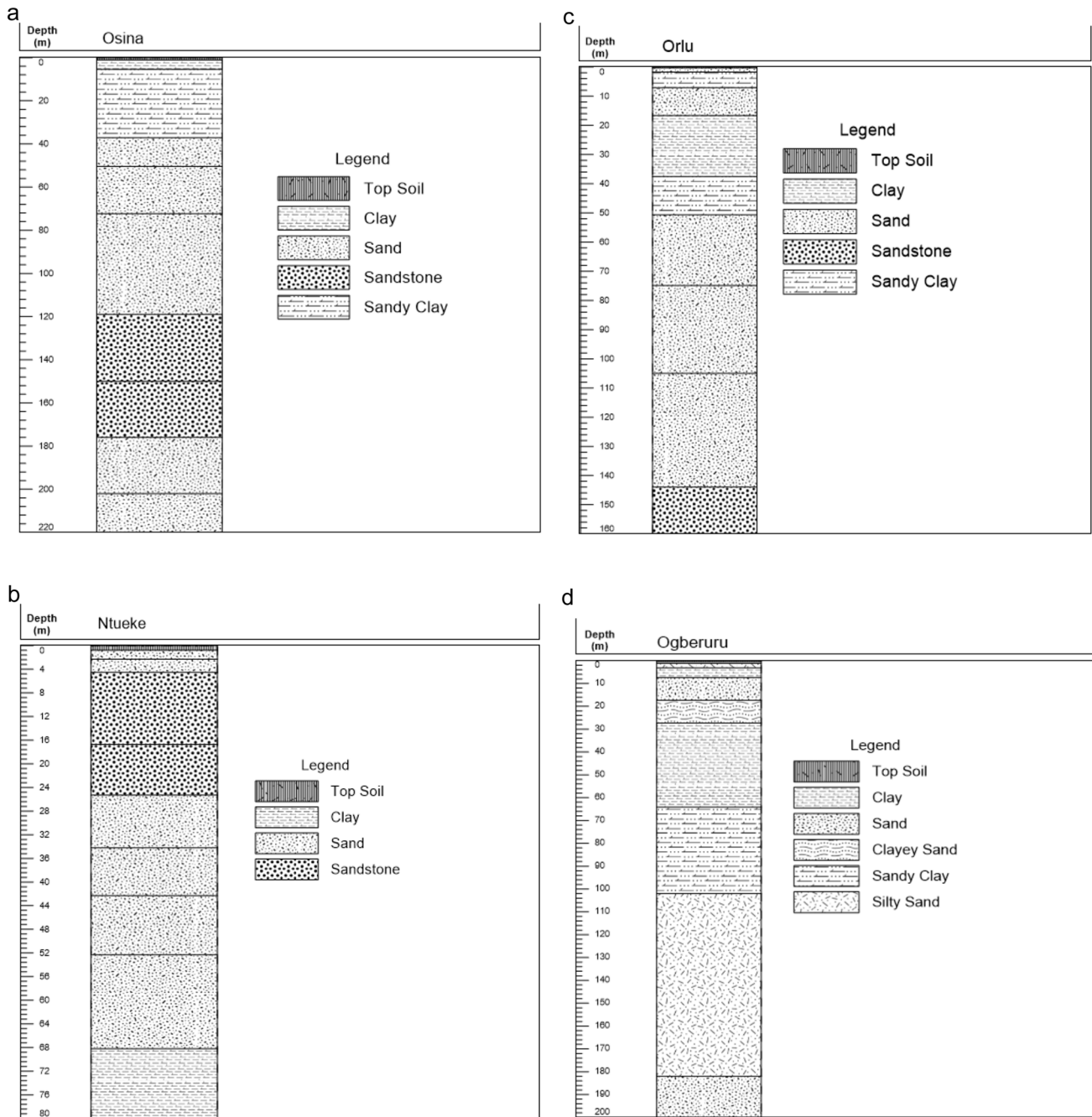


Fig. 4 **a** Geo-electrical section obtained at Osina (VES 2), **b** Geo-electrical section obtained at Ntueke (VES 4), **c** Geo-electrical section obtained at Orlu (VES 6), **d** Geo-electrical section obtained at Ogberuru (VES 15)

desirable potential for groundwater. It has a strong correlation with permeability and aquifer units exhibiting high transverse resistance most times indicate high aquifer permeability. Moreso, areas having increased transverse resistance are characterized by more electrically resistive Earth materials including sand, gravel, and sandstone which are conventional materials for aquifers in sedimentary environments (Opara et al. 2020). Figure 7a shows

a 2D geospatial map of transverse resistance in the study area.

The longitudinal conductance of the aquiferous units in this area ranges from $0.004382979 \Omega^{-1}$ at Osina (VES 2) to $0.064225149 \Omega^{-1}$ at Ntueke (VES 4). Consequently, the least longitudinal conductance was recorded at Osina while the highest was observed at Ntueke, with a regional average of $0.032932574 \Omega^{-1}$. Increasing values of this

Table 5 Iso-resistivity data of the study area

VES No	AB/2 = 1.0	AB/2 = 4.0	AB/2 = 8.0	AB/2 = 15.0	AB/2 = 30.0	AB/2 = 50.0	AB/2 = 80.0	AB/2 = 150.0	AB/2 = 250.0	AB/2 = 350.0
VES 1	846.1	1316.7	1826.6	2098.4	2780.3	3285.9	4618.6	5571.6	7192.4	6304
VES 2	309.8	390.6	541.5	721.2	1093.3	1296.1	1609.1	3922.6	5476.6	7813.6
VES 3	206.5	720.2	851	965.7	1683.4	1769.7	3275.6	5207.1	7928	8276.8
VES 4	246	189.1	289.1	546.4	964.9	1324.9	1006.4	836.6	209.7	
VES 5	135.2	432.1	512.7	507.1	215.9	136.3	184.3	76.4	72.3	224.5
VES 6	1374	7370.6	8494.2	3984.6	2901.8	1822.3	787	1126.1	2415.7	
VES 7	409.5	779.6	950.4	774.3	921.5	1678.5	2350.2	4193	4841.2	
VES 8	459.1	1514.7	2358.1	3133.7	2467.9	2004.1	1883.5	2233.8	2899.5	5074.5
VES 9	1404.2	2707.7	5019.3	4471.8	2680.3	5921.4	8672.2	4321.9	4683.1	3826.1
VES 10	2454	9148	6573	4454.4	2631	2549	2276.5	1744	1430	1737
VES 11	812.9	2492.5	3555.2	3932.4	4595.6	4687.3	6510.3	5558.2	7170.2	10,420.5
VES 12	1498.6	1529.6	1596.9	967.4	1084.9	3343.3	1111	6560.9	6837.6	5800.8
VES 13	39.5	290.1	353.4	296.5	84.3	59.4	125.2	184.9	369.3	1224.7
VES 14	294.4	505.4	746.5	1211	1745.9	1501.9	1433.9	1282.7	715.3	1666.2
VES 15	903.9	1029.6	1483	1322.4	2259.6	2195.4	1883.5	1097	1222.4	

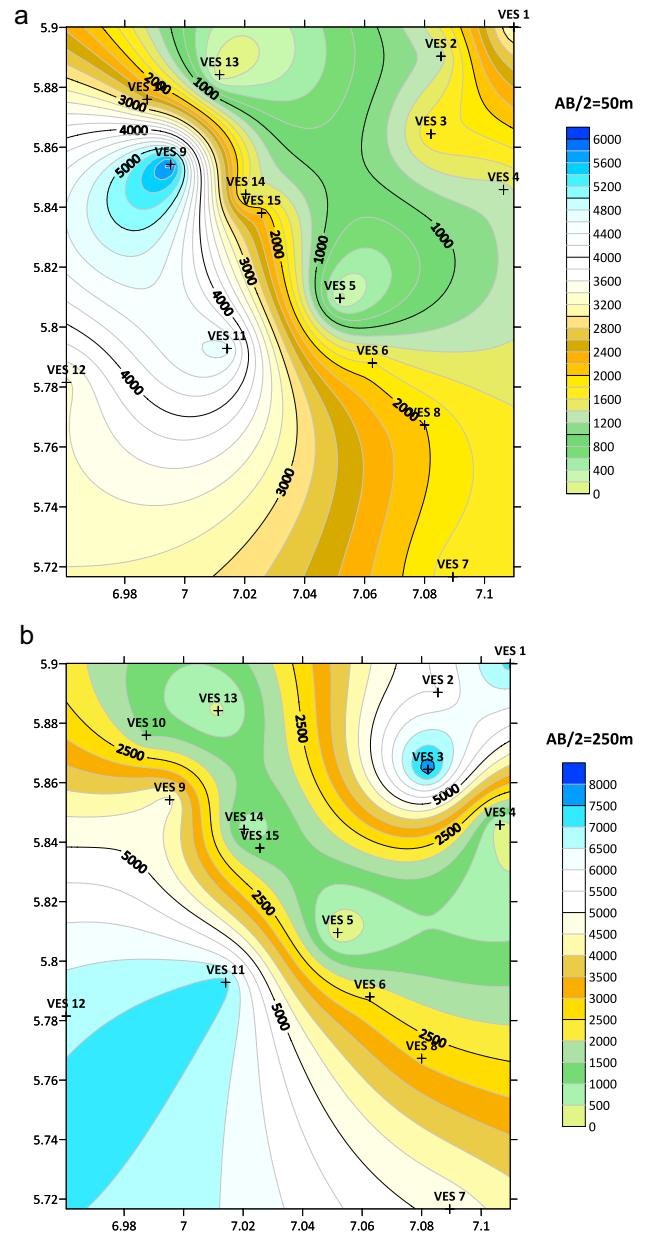


Fig. 5 a D Iso-resistivity geospatial map of AB/2 = 50.0 m, b 2D Iso-resistivity geospatial map of AB/2 = 250.0 m

parameter usually imply good aquifer protective capacity. Based on the rating by Atakpo and Ayolabi (2009), the entire study area has poor aquifer protection and might be vulnerable to contamination and pollution from point and nonpoint sources. Figure 7b shows a 2D geospatial map of longitudinal conductance in the area.

Aquifer hydraulic conductivity

Results of computation of hydraulic conductivity from Niwas and Singhal (1981) model show that aquifer units

Table 6 Summary of major parameters of the aquifer units in the area

VES No	Elevation (m)	Top of aquifer (m)	Bottom of aquifer (m)	Aquifer thickness (m)	Aquifer resistivity (Ωm)	Aquifer conductivity (Ωm^{-1})	Transverse resistance (Ωm^2)	Longitudinal conductance (Ω^{-1})	Storativity (/m)	K from pump test (m/day)	$K\delta$ (Ω^{-1} day)	Transmissivity (m^2/day)	Hydraulic conductivity (m/day)
VES 1	280.707	131	321	190	5112	0.000195618	971,280	0.037167449	0.00057	4.06	0.000794	771.19	4.06
VES 2	235.294	119	222	103	23,500	4.25532E-05	2,420,500	0.004382979	0.000309		0.000794	1921.87	18.66
VES 3	194.148	118	278	160	6877.5	0.000145402	1,100,400	0.023264268	0.00048	5.19	0.000755	830.80	5.19
VES 4	241.085	16.7	52.3	35.6	554.3	0.001804077	19,733.08	0.064225149	0.0001068		0.000755	14.89	0.42
VES 5	93.8738	134	182	48	1036	0.000965251	49,728	0.046332046	0.000144		0.008124	403.99	8.42
VES 6	192.929	74.9	164	89.1	7960	0.000125628	709,236	0.011193467	0.0002673		0.008124	5761.83	64.67
VES 7	197.806	59.7	250	190.3	7396.7	0.000135195	1,407,592.01	0.025727689	0.0005709	5.81	0.000868	1221.78	6.42
VES 8	226.76	79.1	288	208.9	4887.5	0.000204604	1,020,998.75	0.042741688	0.0006267		0.000868	886.22	4.24
VES 9	191.405	142	252	110	2370	0.000421941	260,700	0.046413502	0.00033		0.000656	171.01	1.55
VES 10	97.5312	97.1	217	119.9	3525	0.000283688	422,647.5	0.034014184	0.0003597	4.72	0.000656	277.25	2.31
VES 11	187.748	80.7	155	74.3	9125	0.000109589	677,987.5	0.008142466	0.0002229		0.000437	296.28	3.99
VES 12	150.259	107	230	123	1983	0.000504286	243,909	0.062027231	0.000369		0.000437	106.58	0.87
VES 13	41.7556	101	183	82	3400	0.000294118	278,800	0.024117647	0.000246	1.9	0.000437	121.83	1.49
VES 14	192.015	64	202	138	2667	0.000374953	368,046	0.051743532	0.000414		0.000437	160.83	1.17
VES 15	164.279	66.4	133	66.6	5330	0.000187617	354,978	0.01249531	0.0001998		0.000437	155.12	2.33

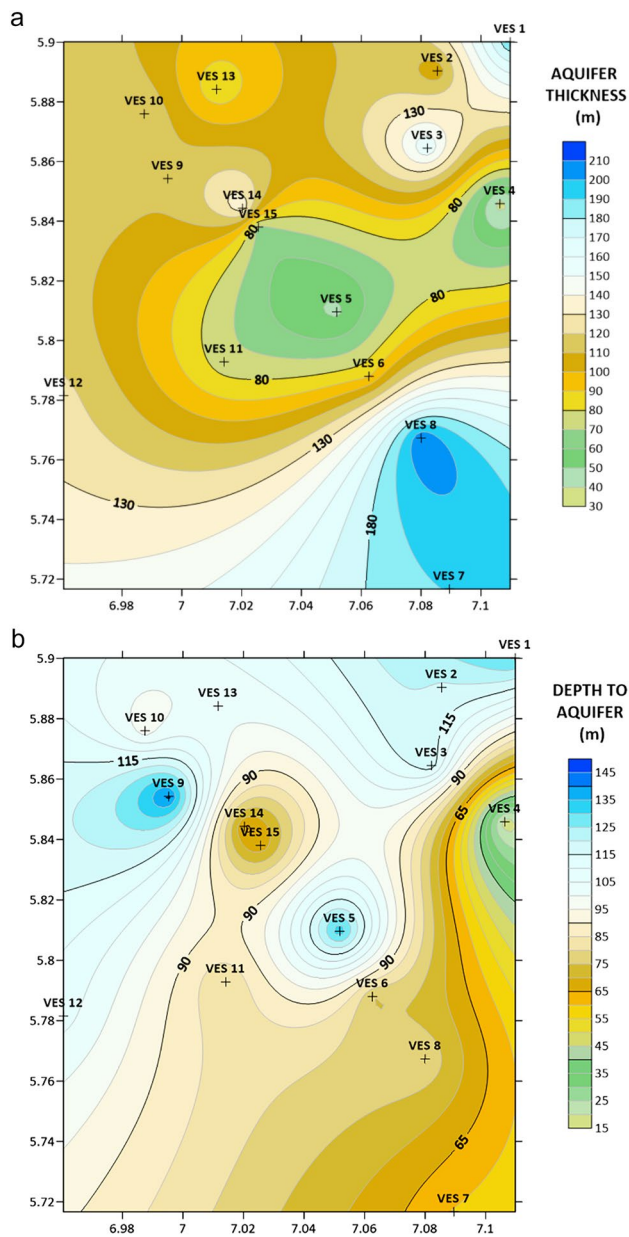


Fig. 6 Aquifer thickness map of the area, **b** Aquifer depth map of the area

within Orlu (VES 6) have the most hydraulic conductivity in the entire study area with values reaching 64.67 m/day while Ntueke (VES 4) has the least with a value as low as 0.42 m/day. The mean regional hydraulic conductivity from this model is 8.39 m/day implying that aquifer geo-materials within the Ameki and Ogwashi-Asaba Formations are sands and sandstones. It implies that aquifer units within Orlu have high hydraulic conductivity while the aquifers at Ntueke possess low hydraulic conductivity based on the classification by Yousef et al. (2011). Figure 8a shows the 2D geospatial map for hydraulic

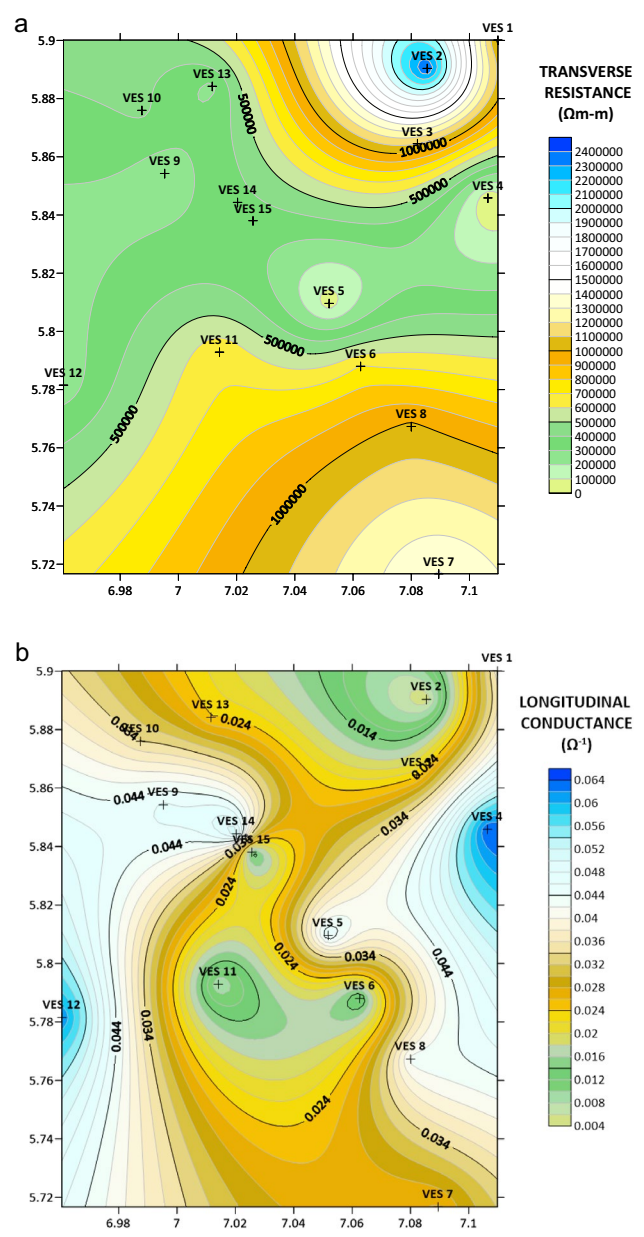


Fig. 7 a 2D geospatial map of transverse resistance, **b** 2D geospatial map of longitudinal conductance

conductivity computed from the Niwas and Singhal (1981) model.

The empirical relationship by Heigold et al. (1979) was used also to estimate the hydraulic conductivity of the aquifer of this area. Results, as shown in Table 7 revealed that Ntueke (VES 4) has moderate hydraulic conductivity with a value of 1.07 m/day while Osina (VES 2) is characterized by very low hydraulic conductivity with a value of 0.03 m/day.

Aquifer hydraulic conductivity data of this area was also obtained through pumping tests from five monitoring wells in this area as shown in Table 7. Available data shows that

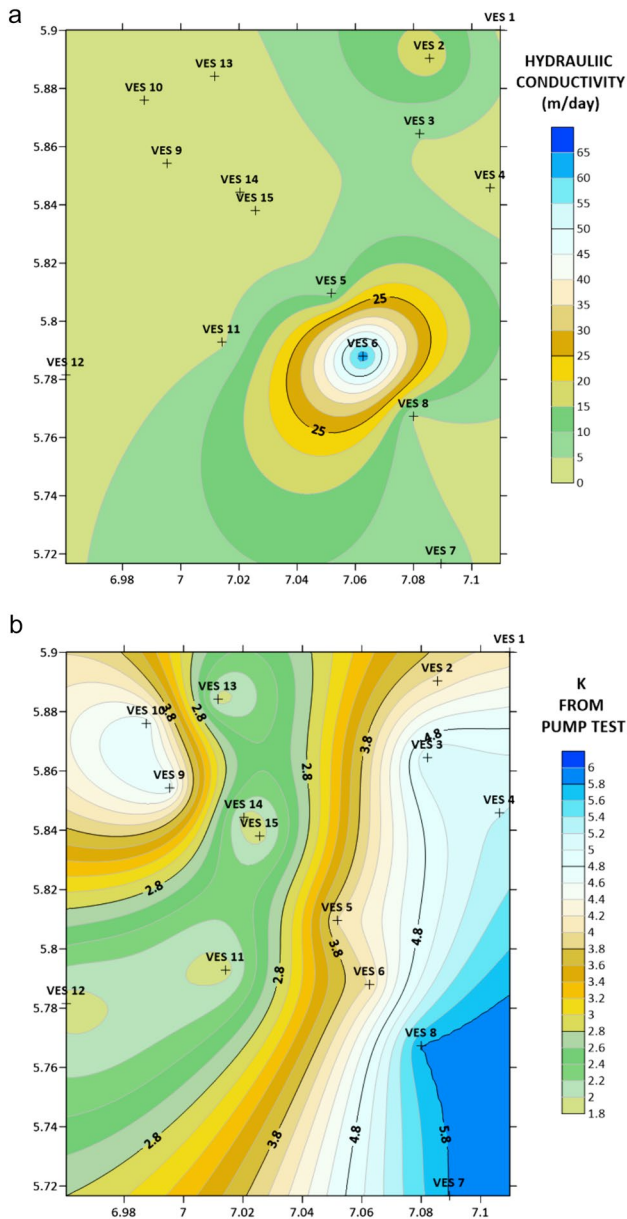


Fig. 8 a 2D geospatial map for hydraulic conductivity computed from Niwas and Singhal (1981), b 2D geospatial map of the aquifer hydraulic conductivity obtained from pumping test

all five Well locations are characterized by moderate hydraulic conductivity (Youssef et al. 2011). The 2D geospatial map of the hydraulic conductivity of the aquifer units from the pumping test is shown in Fig. 8b.

A new formation-constrained model equation which is ultimately controlled by the local geology of the area of study was generated by cross-plotting hydraulic conductivity derived from the pumping test and the resistivity of the aquifer in this area as displayed in Fig. 9. The performance

Table 7 Summary of hydraulic conductivity values as obtained from the three models and pumping test

VES no	K_{ns} (m/day)	K_{hg} (m/day)	K_{pt} (m/day)	K_{new} (m/day)
VES 1	4.06	0.13	4.06	3.40
VES 2	18.66	0.03		12.83
VES 3	5.19	0.10	5.19	4.40
VES 4	0.42	1.07		0.49
VES 5	8.42	0.59		0.85
VES 6	64.67	0.09		5.00
VES 7	6.42	0.10	5.81	4.69
VES 8	4.24	0.14		3.27
VES 9	1.55	0.27		1.74
VES 10	2.31	0.19	4.72	2.46
VES 11	3.99	0.08		5.63
VES 12	0.87	0.32		1.49
VES 13	1.49	0.20	1.9	2.38
VES 14	1.17	0.25		1.93
VES 15	2.33	0.13		3.52

prediction of this model based on the coefficient of determination (R^2) is 0.507 (50.7%) using the least squares regression approach. This performance implies that about 50% of the variation in the aquifer hydraulic conductivity is predictable from the aquifer resistivity; it is generally acceptable and the model can be relied upon for the estimation of hydraulic conductivity of the aquifer when pumping test data of the area is not available. This performance is probably due to differences in the geologic setting of the locations. The new model is given in Eq. 14.

$$K_{new} = 0.002\rho^{0.871} \tag{14}$$

where K_{new} is the new model hydraulic conductivity, and ρ is the aquifer resistivity.

Table 7 shows the different hydraulic conductivity values obtained from the area including Niwas and Singhal’s (1981) model, Heigold et al. (1979) model, pump test, and conductivity computed from the new model generated as stated in Eq. 14.

The aquifer diagnostic parameter is obtained by multiplying hydraulic conductivity obtained through pumping test and the electrical conductivity of the aquifer, i.e. $K\delta$. This parameter can be used to determine areas with almost the same geologic characteristics and water quality (Ekwe and Opara 2012). Such areas will consist of almost similar diagnostic parameters. This study revealed that Okporo (VES 11), Akatta (VES 12), Ihitte Owerri (VES 13), Obibi Ochasi (VES 14), and Ogberuru (VES 15) have the same geologic setting and water quality. Few other location pairs share similar geologic characteristics.

Fig. 9 Cross plot of pumping test hydraulic conductivity vs aquifer resistivity

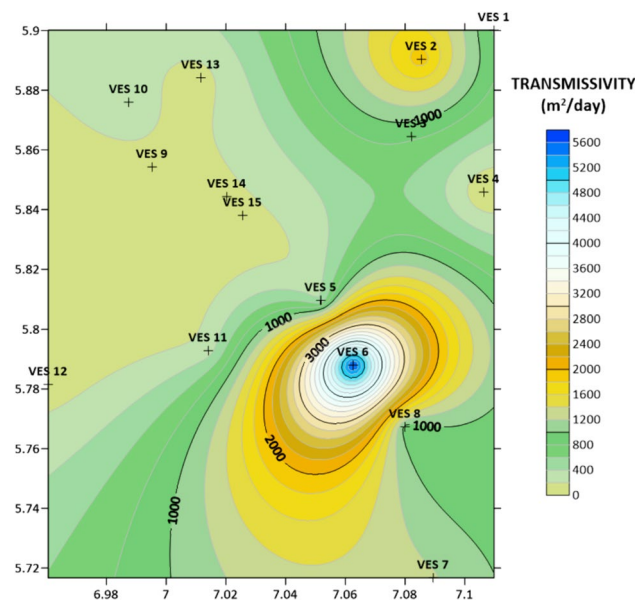
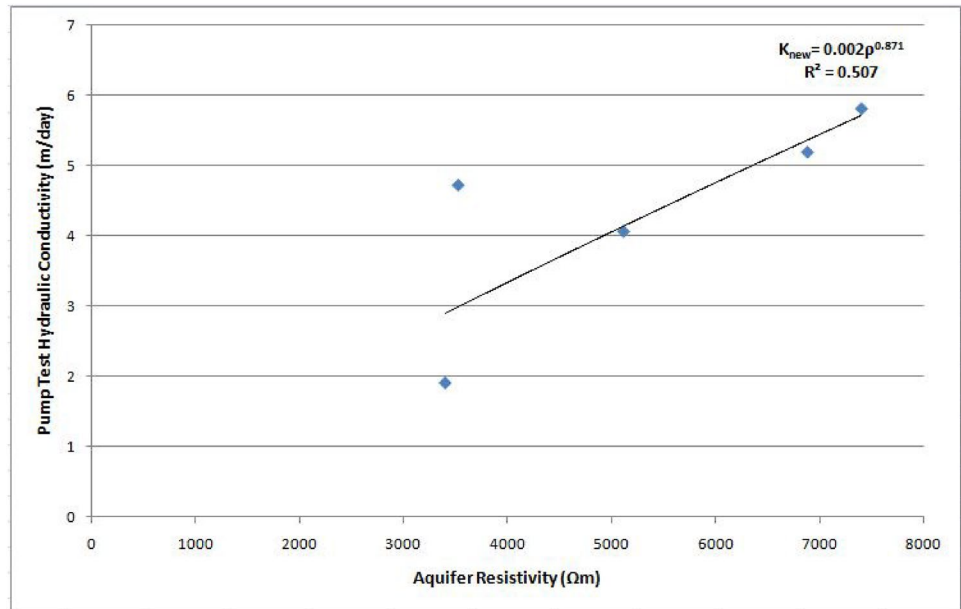


Fig. 10 2D geospatial map of aquifer transmissivity

Aquifer transmissivity

The most transmissive aquifer unit was observed at Orlu (VES 6) with a transmissivity of $5761.8333 \text{ m}^2/\text{day}$ while the least was recorded at Ntueke (VES 4) having a transmissivity of $14.898475 \text{ m}^2/\text{day}$. The direct implication of this is that Orlu has a high aquifer transmissivity and possesses the most prolific aquifer unit in the entire study area while Ntueke has a weak aquifer transmissivity based on the classification by De Wiest (1965). The mean regional

transmissivity in this area is $873.44 \text{ m}^2/\text{day}$. Figure 10 is the 2D geospatial map of the aquifer transmissivity of the area.

A cross plot of aquifer transmissivity against transverse resistance (Fig. 11) was also obtained to investigate their relationship in the study area and obtain a validated novel model equation for estimating aquifer transmissivity from transverse resistance. It was validated and its performance was predicted using statistical parameters including sum of squares regression, sum of squares error, sum of squares total, and determination coefficient (R-squared) which gave a value of 0.60 (60%). This equation is, therefore, constrained by the local geology and can be effectively applied in this area and other regions of the world with similar geological characteristics. The model is stated in Eq. 15.

$$T = 0.004R_T^{0.869} \tag{15}$$

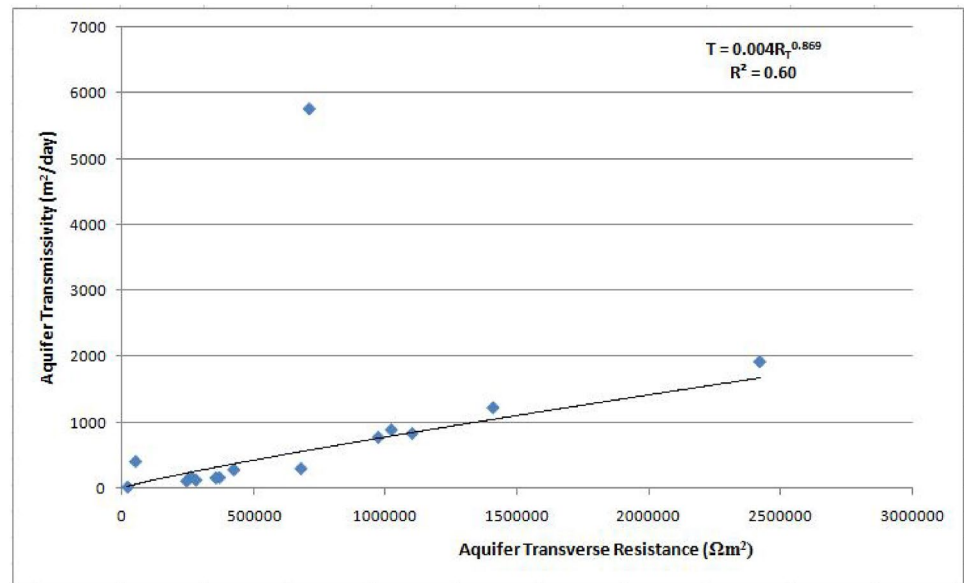
where **T** is the aquifer transmissivity in (m^2/day), and **R_T** is the transverse resistance in Ωm^2 .

The mathematical models developed in this study can be used to estimate hydraulic conductivity and aquifer transmissivity in an area with a comparable geologic setting to the study area, even when there is no pump test data available. This allows for easier and more accurate assessment of groundwater resources.

Soil corrosivity

It is general knowledge that soil that makes contact with materials employed for engineering construction can cause corrosion to steel or even concrete used for reinforcement

Fig. 11 Cross plot of aquifer transmissivity against transverse resistance



resulting in structural failure (NACE 1993). Comprehensive knowledge of the corrosivity of soils is essential, particularly in agricultural and engineering activities, and during water reticulation using steel pipes.

The soils in this area can be classified into highly corrosive, corrosive, mildly corrosive, moderately corrosive, and non-corrosive based on the classification by Bhandari et al. (2013). The corrosive nature of soils in all the locations is highlighted in Table 8. The soil at Ihitte Owerri and Mgbee are remarkable due to their respective highly corrosive and corrosive nature. Adequate care must, therefore, be taken during engineering and structural

constructions in the area, particularly subsurface metal works. The use of steel pipes for water reticulation in these areas is strongly discouraged.

Soil competence

Information about the competence of soil in any area is very central and critical for structural and engineering construction which include overhead bridges, overhead water reservoir structures, and even road construction. The soils in this area can be broadly classified into highly competent, moderately competent, competent, and incompetent

Table 8 Summary of competence and corrosivity of top soils in the area

VES No	Location	Elevation (m)	First layer resistivity (Ωm)	First layer depth (m)	Corrosivity	Competence
VES 1	Akokwa	280.707	735.00	0.70	Non-corrosive	Competent
VES 2	Osina	235.294	313.00	1.10	Non-corrosive	Moderately competent
VES 3	Urualla	194.148	96.00	0.40	Moderately corrosive	Incompetent
VES 4	Ntueke	241.085	290.00	0.80	Non-corrosive	Moderately competent
VES 5	Mgbee	93.8738	43.40	0.30	corrosive	Incompetent
VES 6	Orlu	192.929	748.00	0.30	Non-corrosive	Competent
VES 7	Amaigbo	197.806	291.00	0.90	Non-corrosive	Moderately competent
VES 8	Nwangele	226.76	154.00	0.40	Mildly corrosive	Moderately competent
VES 9	Orsu-Ihiteukwa	191.405	1230.00	1.00	Non-corrosive	Highly competent
VES 10	Ihittenansa	97.5312	1350.00	0.30	Non-corrosive	Highly competent
VES 11	Okporo	187.748	309.00	0.30	Non-corrosive	Moderately competent
VES 12	Akatta	150.259	1310.00	1.50	Non-corrosive	Highly competent
VES 13	Ihiteowerri	41.7556	24.30	0.31	Highly corrosive	Incompetent
VES 14	Obibiochasi	192.015	286.00	0.80	Non-corrosive	Moderately competent
VES 15	Ogberuru	164.279	1080.00	0.50	Non-corrosive	Highly competent

according to the classification by Idornigie et al. (2006). The competent nature of soils in all the locations is shown in Table 8. Urualla, Mgbee, and Ihitte Owerri have poor soils and require fortification and professional care before erecting large engineering structures.

Conclusion

High-resolution electrical resistivity data has been leveraged to carry out an integrated and comprehensive study of the aquifer characteristics as well as the corrosivity and competence of soils in Orlu area and its border towns. Among several important findings of this study, it is important to point out that Orlu has the best hydraulic conductive and transmissive aquifer units in the area. The units are appreciably thick and are suitable for siting boreholes for commercial water supply. The Orashi River and the several streams in this area serve as ready sources of groundwater recharge. Conversely, the units at Ntueke possess the least of these parameters and, therefore not suitable for groundwater development for commercial use. The aquifer protective capacity of this region is very poor and hence, the aquiferous units are highly prone to contamination that may originate from both point and non-point sources. Also, the aquifer hydraulic conductivity and transmissivity of this area can be computed seamlessly using the validated novel model equations generated in this study; these equations should be utilized for seamless and reliable estimation of hydraulic conductivity and transmissivity of aquifers in the area. The soils of this area are largely non-corrosive except for Ihitte Owerri and Mgbee which reported corrosive near surface materials. The soils are also largely competent except Urualla, Mgbee, and Ihitte Owerri which are characterized by incompetent materials; care must, therefore, be taken when erecting massive engineering structures in these localities.

Recommendations

Based on the results of this study, it is recommended that:

1. Orlu area should be considered for a commercial water supply system to help drive the rapid industrialization and agro-allied activities in addition to satisfying the domestic water needs of the growing population of this region. Large-scale water intervention programs should be built by the government for the provision of long-term water supply in areas like Ntueke which has poor groundwater potential.
2. Water reticulation using steel pipes, engineering construction works, and agricultural/industrial activities

involving subsurface metal and metal cable works within Ihitte Owerri and Mgbee should be strongly discouraged. If this must be carried out, the use of corrosion-resistant materials is strongly advised.

3. Geotechnical studies should be carried out on the soils of this area to ascertain other engineering qualities.
4. Finally, this study should also be extended to other adjoining towns that could not be covered by the present study.

Author contributions Agoha C.C. and Ebekuo C.A. conceptualized the presented work. Agoha C.C. developed the theory and performed basic computations. Ebekuo C.A., Onwubuariri C.N. Njoku J.O. and Ofoh I.J. carried out data collection, T.I. Mgbeojedo processed the resistivity data, D.N. Anuforo and Agoha C.C. generated the geospatial maps and cross plots, Ibeneme S.I., Nwokeabia C.N., and Agoha C.C. prepared the manuscript. All the authors read the work and discussed the findings for the submitted manuscript.

Funding The authors received no specific funding for this study.

Data availability The various datasets used in the course of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors have no conflict of interest to declare.

Ethical approval The paper reflects the authors' research and analysis totally and truthfully.

References

- Agbodike IIC (2019) Estimation of aquifer characteristics in parts of Oru LGA of Imo State, Nigeria using resistivity data. *Orient J Phys Sci* 4(2):70–84
- Akakuru OC, Onyeawuna UB, Opara AI, Iheme KO, Njoku AO, Amadi CC, Akaolisa CZ, Okwuosha OR (2023) Electro-geohydrological estimation of shallow aquifer characteristics of Njaba and environs Southeastern Nigeria. *Arab J Geosci* 16:318. <https://doi.org/10.1007/s12517-023-11378-1>
- Akpoborie NA, Nfor AA, Etobro I, Odagwe S (2011) Aspects of the geology and groundwater conditions of Asaba Nigeria. *Arch Appl Sci Res* 3(2):537–550
- Atakpo EA, Ayolabi EA (2009) Evaluation of aquifer vulnerability and the protective capacity in some oil producing communities of western Niger Delta. *Environmentalist* 29:310–317. <https://doi.org/10.1007/S10669-008-9191-3>
- Bassey C, Eminue O (2012) Petrographic and stratigraphic analyses of Paleogene Ogwashi-Asaba formation, Anambra Basin Nigeria. *NAFTA* 63(7–8):247–254
- Bhandari PP, Dahal KP, Bhattarai J (2013) The corrosivity of soils collected from Araniko highway and Sanothimi areas of Bhaktapur Nepal. *J Inst Sci Technol* 18(1):71–77
- De Wiest RJM (1965) *Geohydrology*. John Wiley and Sons Inc., New York, pp 366
- Ekine A, Emujakporue G (2010) Investigation of corrosion of buried oil pipeline by the electrical geophysical methods. *J Appl Sci Environ Manag* 14(1):63–65

- Ekwe AC, Opara AI (2012) Aquifer transmissivity from surface geo-electrical data: a case study of Owerri and environs, Southeastern Nigeria. *J Geol Soc India* 80(1):355–378
- Freeze RA, Cherry JA (1979) *Groundwater*. Prentice-Hall Inc., Engle Wood Cliffs, New Jersey, pp 49
- Guma TN, Mohammed SU, Tanimu AJ (2015) A field survey of soil corrosivity level of Kaduna Metropolitan area through electrical resistivity method. *Int J Sci Eng* 3(12):5–10
- Heigold PC, Gilkeson RH, Cartwright K, Reed PC (1979) Aquifer transmissivity from surficial electrical methods. *Groundwater* 17(4):338–345. <https://doi.org/10.1111/j.1745-6584.1979.tb03326.x>
- Ibeneme SI, Ukiwe LN, Selemo AO, Okereke CN, Nwagbara JO, Obioha YE, Essien AG, Ubechu BO, Chinemelu ES, Ewelike EA, Okechi RN (2013) Hydrogeochemical study of surface water resources of Orlu, Southeastern Nigeria. *Int J Water Resour Environ Eng* 5(12):670–675
- Idornigie AI, Olorunfemi MO (2006) Electrical resistivity determination of subsurface layers, subsoil competence and soil corrosivity at an engineering site location in Akungba-Akoko, Southwestern Nigeria. *Ife J Sci* 8:22–32
- Iheme KO, Akudinobi BEB, Oyeleke TA, Ibrahim KO, Abubakar HO, Usman AO (2018) An evaluation of groundwater and surface water resources in Orlu and environs, Southeastern Nigeria. *J Basic Phys Res* 8(2):31–38
- Mars GF (1987) *Corrosion engineering*, 3rd edn. McGraw Hill Book Company, New York, p 14
- NACE (1993) *Underground corrosion*. National Association of Corrosion Engineering (NACE) publications, the Corrosion 93 Symposium
- Niwas S, Singhal DC (1981) Estimation of aquifer transmissivity from Dar-Zarrouck parameters in porous media. *J Hydrol* 50:393–399
- Nwosu LI, Uzor CN, Nwosu BO (2020) Geoelectric mapping and assessment of near surface hydro-geologic units for sustainable groundwater development in Orlu area in Imo River Basin Nigeria. *Global Sci J* 8(2):3786–3814
- Ojo JS, Olorunfemi MO, Akintorinwa OJ, Bayode S, Omosuyi GO, Akinluyi FO (2015) Subsoil competence characterization of the Akure Metropolis, Southwest Nigeria. *J Geogr, Environ Earth Sci Int* 3(1):1–14
- Oki OA, Egai AO, Akana TS (2016) Soil corrosivity assessment in the pre-design of sub-surface water pipe distributary network in Yenegoa South-South Nigeria using electrical resistivity. *Geosciences* 6(1):13–20. <https://doi.org/10.5923/j.geo.20160601.02>
- Onyeagocha AC (1980) Petrography and depositional environments of the Benin formation. *J Min Geol* 17(2):147–150
- Onyekwelu CC, Onwubuariri CN, Mgbeojedo TI, Al-Naimi LS, Ijeh BI, Agoha CC (2021) Geo-electrical investigation of the groundwater potential of Ogidi and environs, Anambra State, Southeastern Nigeria. *J Petrol Explor Prod* 11:1053–1067. <https://doi.org/10.1007/s13202-021-01119-z>
- Opara AI, Eke DR, Onu NN, Ekwe AC, Akaolisa CZ, Okoli AE, Inyang GE (2020) Geo-hydraulic evaluation of aquifers of the Upper Imo River Basin, Southeastern Nigeria using Dar-Zarrouck parameters. *Int J Energ Water Res* 5:259–275. <https://doi.org/10.1007/s42108-020-00099-w>
- Reyment RA (1965) *Aspects of the geology of Nigeria-The Stratigraphy of the Cretaceous and Cenozoic Deposits*. Ibadan University Press, Nigeria, p 133
- Strahler AN (1973) *Physical Geograpy*. Wiley, New York/London/Sydney/Toronto, p 48
- Todd DK (1980) *Groundwater hydrology*, 2nd edn. John Wiley and Sons Inc., New York
- Todd DK, Mays LW (2005) *Groundwater hydrology*, 3rd edn. John Wiley and Sons Inc., New York
- Uma KO (1989) Appraisal of the groundwater resources of the Imo River Basin Nigeria. *J Min Geol* 25(1&2):305–315
- Whiteman A (1982) Nigeria, its petroleum geology, resources and potentials, 2. Graham and Trotman Publ. London, pp 234–241
- Youssef AM, Omer AA, Ibrahim MS, Ali MH, Cawlfeld JD (2011) Geotechnical investigation of sewage wastewater disposal sites and use of GIS land use maps to assess environmental hazards: Sohag, Upper Egypt. *Arab J Geosci* 4:719–733

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.