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ORIGINAL PAPER

Electro-geohydraulic estimation of shallow aquifer characteristics of Njaba and environs, Southeastern Nigeria

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Abstract

The study investigated the use of electro-geophysical method as an alternative to pumping test method in the estimation of geo-hydraulic characteristics of shallow aquifers in Njaba and environs, Southeastern Nigeria. This was done to ascertain the aquifer potentials of the study area. Twenty-three geo-electric resistivity soundings were acquired using ABEM Terrameter SAS-4000 and Schlumberger configuration with maximum half-current electrode spacing of 500 m. Geo-electric layers were determined using FORTRAN 2D Resistivity Software. The results indicate an undulating topography, with elevations ranging from 361 to 1336.9ft. Spread 5 m, 20 m, 50 m, 100 m, 150 m, 200 m, 250 m, 300 m, 400 m, and 500 m were probed, which gave their corresponding resistivity values at different depth slices. Results showed a fairly increasing-reducing-increasing trend of resistivity values. An averaged high resistivity value can be traced to the presence of the sand lithology of the Benin Formation in the region. Aquifer depth of 79.2 to 115 m was observed in the study area, showing a semi-deep aquifer system. Aquifer thickness of 23.4 to 48.5 m was observed in the studies, with a mean value of 37.71 m. Aquifer resistivity ranges from 28,700 to 990Ωm, indicating clean sand and sand with little clay admixtures, respectively. Average longitudinal conductance (in Ω^{-1}) of 0.00611693 and transverse resistance of 407,178.1739 was recorded in the study area. Hydraulic conductivity (in m/day), as obtained from a new model, showed a high value of 27.90068 and a low value of 0.0852, an indicator of fairly clean sand. Transmissivity (m^2/day), from a new model developed for the study area, ranges from 430.0877 to 23.552. The storativity value ranges from 0.0001515 to 0.00113139, indicating a confined aquifer, while average aquifer diffusivity of 1,398,057.749 was recorded. Altogether, aquifer vulnerability and hydro-geochemical studies of the environment are recommended, to ascertain the protective capacity of the aquifer from the surface pollutants and the quality of water in the study area, respectively.

Keywords Hydraulic conductivity · Transmissivity · Longitudinal conductance

Introduction

Geo-electric strategies are deeply grounded and generally used to settle an assortment of hydro-geophysical, land, and ecological subsurface identification issues (Opara et al. 2021; Eyankware et al. 2022a, b; Onu and Ibezim 2004; Hussein and Tarig 2014; Idornigie and Olorunfemi 2006). It is a non-disastrous testing innovation and an exceptionally helpful apparatus for portraying pressure-driven boundaries, spring weakness, dampness content, porosity, immersion, type, and mineral creations of soil and application possibilities because of the great specialized, ceaseless, quick, and monetary advantages (Guma et al. 2015; Aigbadon et al. 2023). The main role of the resistivity strategy is to

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quantify the expected contrasts on a superficial level because of the ongoing stream inside the ground. Since the component which controls the liquid stream and electric flow and conduction are for the most part administered by similar actual boundaries and lithological credits, the water-powered and electric conductivities are subject to one another (Nwachukwu et al. 2019; Urom et al. 2021).

As Breusse (1963) stated, real progress in the use of electrical strategies for groundwater surveys began during WW11. Information on the benefits of well boundaries, such as pressure-controlled conductivity and permeability in the study area, is valuable in assessing the site's groundwater capacity. The usual approach to determining the stated swelling limits was to use siphon test techniques, which proved to be costly, tedious, and boring (Agidi et al. 2022). Similarly, various equations accessible to determine spring attributes from a survey of siphon test information include spring congruence, thickness, uniformity, isotropic, well capacity, and fluid under field conditions. It is important given that various speculations about the nature of the flow are guaranteed (Freeze and Cherry 1979). Surface electrical strategies have emerged as a more convenient option than siphon test techniques for securing well boundaries (Opara et al. 2022). This strategy is costly and time-consuming and is used to predict boundaries even in areas without current wells (Freeze and Cherry 1979; Kruseman and de Ridder 1994; Sattar et al. 2016). With this in mind, the effort to drill exploratory wells in the world's hydrogeological shells has been reduced.

Various studies have been conducted on the use of geoelectric techniques in estimating desirable hydraulic parameters for aquifers (Uma 1989; Mbonu et al. 1991; Ekwe et al. 2006; Monye 2017). Uma (1989) evaluated the groundwater resources in the Imo River Basin. He concluded that the complex geological setting of the Imo River Basin provides a similarly complex water horizon setting. These aquifer systems generally have the same extent as the formation. According to him, it is almost impossible for aquifers to cross geological boundaries due to regional strata and general trends in strata. He identified three aquifers: shallow-borderless aquifers, confined aquifers, and deep-borderless aquifer systems. However, his data were so sparse that he could not make a general statement about the hydraulic properties of the Central Imo River Basin aquifer (Ekwe et al 2006; Emberga et al. 2019). Mbonu et al. (1991), while investigating the characteristics of some aquifers in the Umuahia region of Southeastern Nigeria, identified three different geo-electric layers covering conductive underground geoelectricity. The results of the survey also show two zones where hydraulic properties and water quality differ from each other. Ekwe et al. (2006) used the electrical resistivity method to estimate the shape, hydraulic conductivity, and permeability of the aquifer in the central part of the Imo River Basin. The study revealed that the sedimentary sequence in Southeastern Nigeria contains multiple aquifers. Eyankware et al. (2022c) argued that by calculating the permeability of aquifers based on the results of resistivity measurements, it is possible to depict areas with good groundwater potential. His study points out that resistivity exploration can determine the depth of the water table, the thickness of the aquifer, and the geology of the ground, thus revealing the distribution and potential of the aquifer.

An accurate assessment of groundwater resources and quantitative characterization of aquifers in and around Njaba is essential to address some hydrogeological issues associated with groundwater exploration and development. The Njaba region is experiencing enormous development and growth in population density. This population growth has increased the demand for freshwater to meet the needs of agricultural, household, and industrial water. Most residents of the study area often rely on the use of surface water that is normally contaminated or generally inaccessible, and most wells in the area are pumped from water-containing units that are vulnerable to surface pollution.

Fluid permeability, storage capacity, diffusivity, resistivity in the horizontal direction, conductivity in the vertical direction, permeability coefficient, depth, and thickness of aquifers are the basic characteristics that explain groundwater hydrology (Sheriff 1991). As a result, many research methods are often used to estimate the spatial distribution of the above hydraulic parameters. Field estimates of the above parameters are not always available. Hydraulic conductivity seems to be the most problematic to obtain due to the wide range of observed values or the unsatisfactory values observed in the laboratory measurements (Oli et al. 2022).

Therefore, the integration of the aquifer properties calculated from the borehole and the surface resistivity parameters extracted from the surface resistivity measurements is because both properties are related to pore space structure and non-uniformity. It is very effective because it allows correlation between the properties of the layer and the electrical aquifer (Eke et al. 2015; Niwas et al. 2006).

Location, physiography, and climate of the study area

The review region Njaba and its environs are in Imo State, Southeastern Nigeria, and lies between scopes 5°39′00″N and 5°45′30″N and longitude 6°58′30″E and 7°3′30″E (Fig. 1). The Njaba River advantageously outlines Umuaka and Ekwe in the western boundaries. The review region extends as an undulating land surface with an openly level surface at a rise of around 183–244 m. The review area has thick vegetation with a mean yearly precipitation of around 1800–2500 mm, which takes care of a broad hydrological framework, for which the Njaba

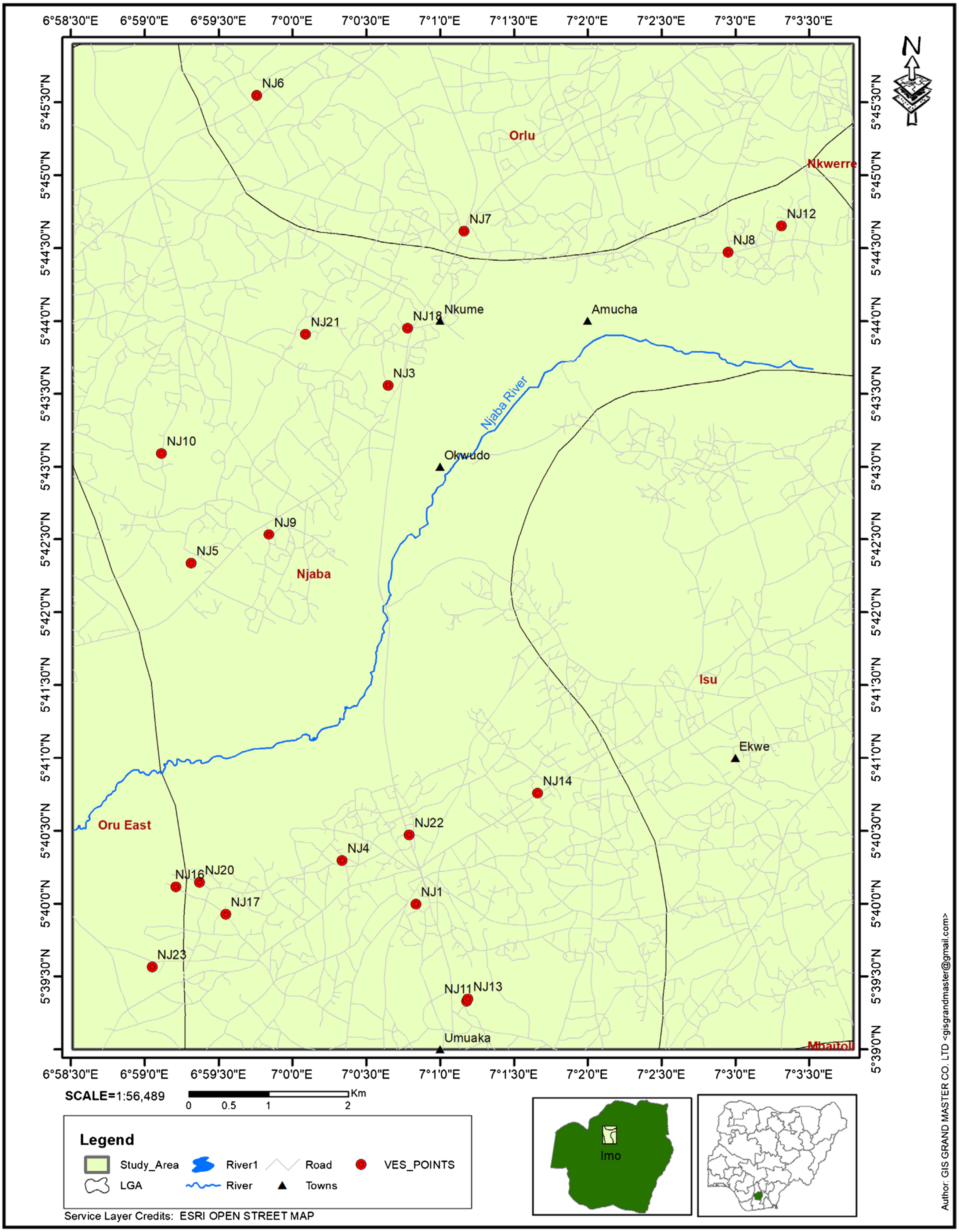


Fig. 1 Location and topographic map of the study area

waterway is important for. Temperature goes from around 27 to 32 °C with February to April being the most blazing. Relative dampness goes from 70 to 80% (Ekwe et al. 2006; Obasi et al. 2020; Onyekuru et al. 2021).

Geology of the study area

The Njaba study area is largely covered by the Benin Formation, which is composed primarily of sand from continental rivers beneath vast areas of Southern Nigeria. It is typical of sand around Benin City and is estimated to be 3050 m thick (Akakuru et al. 2021). The Benin layer is characterized by a high sand content (70–100%) and forms the top layer of the Niger Delta deposition sequence. These giant sands were deposited in the continental environment, including the river regions of the Upper Delta Plains (braided and winding systems) (Obasi et al. 2020). It is composed of fragile sand and small clay deposits (Short and Stauble 1967). The thickness of the Benin Formation varies, perhaps over 6000 ft, but according to Avbovbo (1978) of Ebuta (2015), the average thickness of the formation in the study area is about 800 m.

The hydrogeological significance of the study area is attributed to the Benin Formation, which has a high degree of permeability, and has prevented the development of a stream network (Short and Stauble 1967). The highly permeable formation is prevented by impervious strata. The Njaba River which flows through the study area is a tributary of the Orashi River. The Njaba rises near Orlu and joins the Orashi River near Oguta Lake. The area has an aquifer replenishment of about 2.5 billion cubic meters per day (Ekwe et al. 2006). The aquifer is characterized by fairly high permeability, transmissivity, and storage coefficients, which makes it an excellent source of groundwater (Akakuru et al. 2021; Urom et al. 2021; Eyankware et al. 2021; Opara et al. 2021; Ekwe et al. 2006). Groundwater flow is in a south-west direction with estimated gradients of 2 to 3%. Drilling of boreholes has revealed that the upper levels of the aquifer can be estimated to be within the range of 185–190ft (Eyankware et al. 2022c; Ekwe et al. 2006) (Fig. 2).

Materials and method

In this study, we estimated the use of geo-hydrogeological characteristics of the study area using electro-geophysical and hydrogeological techniques. The Schlumberger configuration was used to measure the resistivity. VES data was obtained from the field using ABEM Terrameter SAS 4000. This study used a maximum current electrode spacing of 1000 m. A total of 23 VES datasets were collected along profiles at various locations. Analysis of the resulting resistivity and half-current electrode spacing yielded a layered earth model consisting of discrete layers of specified thickness and apparent resistivity. The data obtained were plotted as a plot of apparent resistivity against half-current electrode spacing (AB/2) on a log plot scale. Approximately, the probing depth at each spread is two-thirds (2/3) of the electrode spacing at which bending occurs on the chart (Vingoe 1972). The VES results were modeled using computer iterative inversion models. Resistivity curves were developed. The smoothened curves were qualitatively interpreted using master curves and standard charts (Opara et al. 2022; Orellana and Mooney 1966). In the Schlumberger arrangement (Fig. 3), the current–potential pairs of the electrodes share a common center, but the distances between adjacent electrodes are different, so $a \neq b$. Pumping test data were collected from monitoring wells that are close to the sampled points.

Data evaluation and modeling

Theoretically, the resistivity (ρ) of a material is directly proportional to the potential difference (V) and inversely proportional to the induced current (I).

$$\rho \propto \frac{\mathrm{V}}{\mathrm{I}} \tag{3.1}$$

$$\rho = K\left(\frac{\mathrm{V}}{\mathrm{I}}\right) \tag{3.2}$$

where K is the geometric factor and can be obtained thus:

$$K = \pi\left\{\frac{\left[\left(\frac{\mathrm{AB}}{2}\right)^2 - \left(\frac{\mathrm{MN}}{2}\right)^2\right]}{\mathrm{MN}}\right\} = \pi\left(\frac{\mathrm{a}^2}{\mathrm{b}} - \frac{\mathrm{b}}{4}\right) \tag{3.3}$$

Hence,

$$\rho = \pi\left(\frac{\mathrm{a}^2}{\mathrm{b}} - \frac{\mathrm{b}}{4}\right)\left(\frac{\mathrm{V}}{\mathrm{I}}\right)\text{Or } \rho = \pi\left(\frac{\mathrm{a}^2}{\mathrm{b}} - \frac{\mathrm{b}}{4}\right) R \tag{3.4}$$

Recall $\rho = \mathrm{KR}$
where R is the resistance.

The geometric coefficient K depends on the electrode spacing. R responds to the resistance of the bulk volume between the potential electrodes. Apparent resistivity data

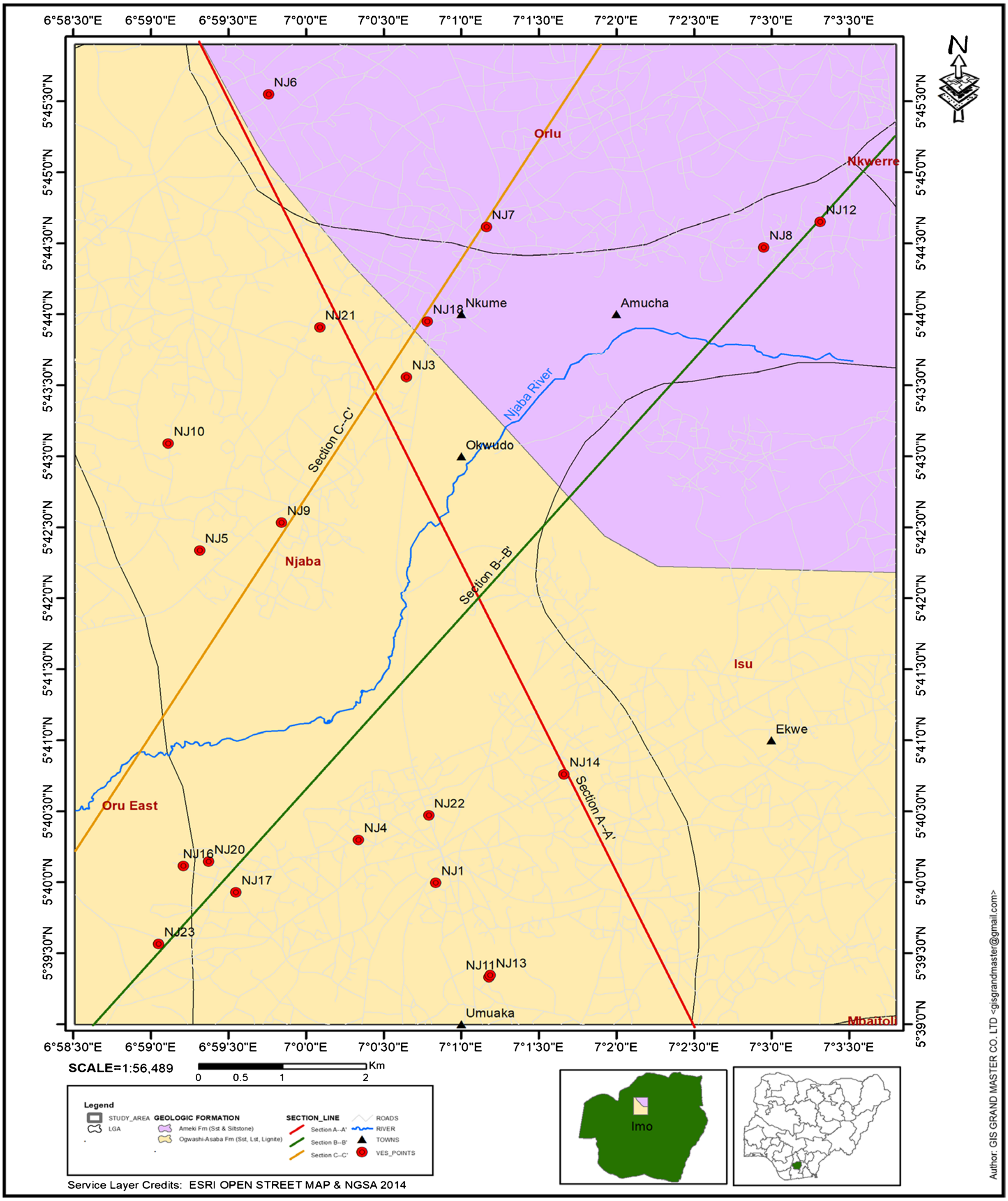


Fig. 2 Geology of the study area

is interpreted as the depth to the bedrock or bedrock, and to other interfaces where strong electrical contrast is present. Next, the vertical curve of depth is interpreted, assuming that the earth is composed of layers with almost constant resistivity. Due to the different resistances, the layers are separated by a planar interface.

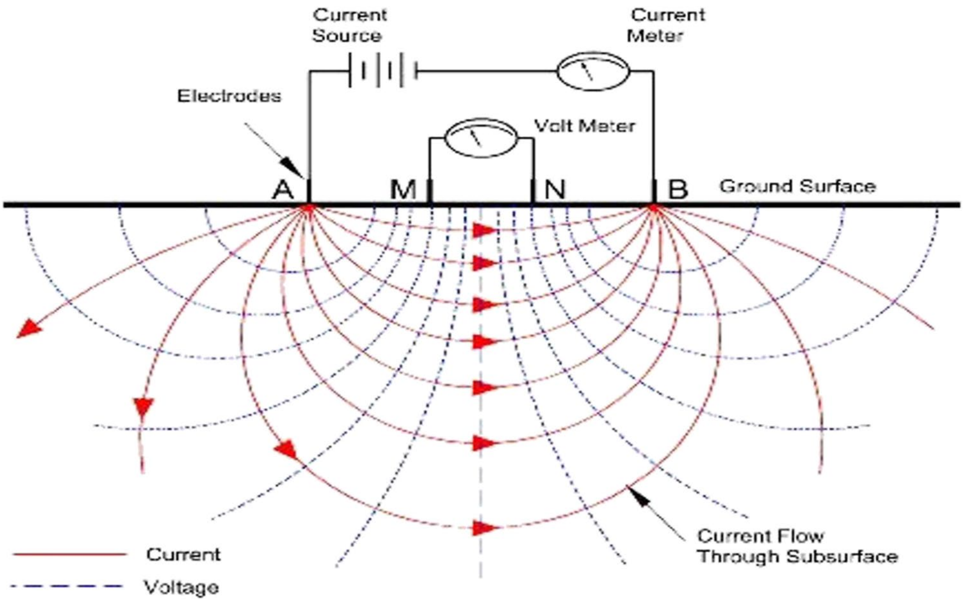


Fig. 3 Schlumberger array

Estimation of aquifer Dar-Zarrouk parameters

Quantitative interpretation of vertical electrical exploration data often leads to the formation of geoelectric layers. Information from these geoelectric layers improves the identification of layer parameters such as aquifer depth and thickness. The layer parameters thus obtained are used to evaluate the Dar-Zarrouk parameters (Opara et al. 2022; Umayah and Eyankware 2022).

Telluric conductance (LC) is a telluric parameter used to define the target area of groundwater potential. High longitudinal conductance values usually indicate a relatively thick continuum and should be given the highest priority for groundwater potential. Longitudinal conductance (LC) is obtained by dividing the aquifer thickness (h) by the resistivity of the aquifer (ρ).

$$L_C = \frac{h}{\rho} \tag{4.1}$$

Transverse resistance (TR) is one of the parameters used to define a target area with good groundwater potential. It is directly related to permeability and the highest lateral resistance values probably reflect the highest aquifer permeability values.

$$R_T = h\rho \tag{4.2}$$

Estimation of aquifer hydraulic parameters

The hydraulic properties of the aquifer can be determined using the Dar-Zarrouk parameters (lateral resistance and conductance). Niwas and Singhal (1981) established an analytical relationship between transmittance and lateral resistance on the one hand and transmittance and longitudinal conductivity on the other.

From Darcy's law, the fluid discharge Q is given by

$$Q = k'IA \tag{4.3}$$

And from Ohm's law

$$J=\sigma E \tag{4.4}$$

where K—hydraulic conductivity; I—hydraulic gradient; A—cross-sectional area perpendicular to the direction of flow; J—current density; E—electric field intensity; and σ—electrical conductivity (inverse of resistivity).

Considering a prism of aquifer material having a unit cross-sectional area and thickness, h, Niwas and Singhal (1981) combined Eqs. (4.3) and (4.4) to get:

$$T_{N\&S} = k'\delta R = \frac{k' L_C}{\delta} \tag{4.5}$$

where T—aquifer transmissivity; R—transverse resistance; L_C—longitudinal conductance; k'—hydraulic conductivity.

The results of hydraulic conductivity and aquifer conductivity estimated from borehole observations are consistent and give the term k' known as a diagnostic parameter. Symptomatic boundaries are the solid lines that connect the Dar-Zarrouk boundaries to the terrain, so boundaries that are usually indexed for areas with different land placements are determined to improve the geographic impact of the prediction cycle. However, the diagnostic parameters ($k\sigma$) are very stable in geographically homogeneous areas (Eyankware and Akakuru 2022). Hydropower conductivity (Niwas and Singhal 1981) is obtained as given in condition 4.6 in that the spring resistance ρ increases the symptomatic continuity.

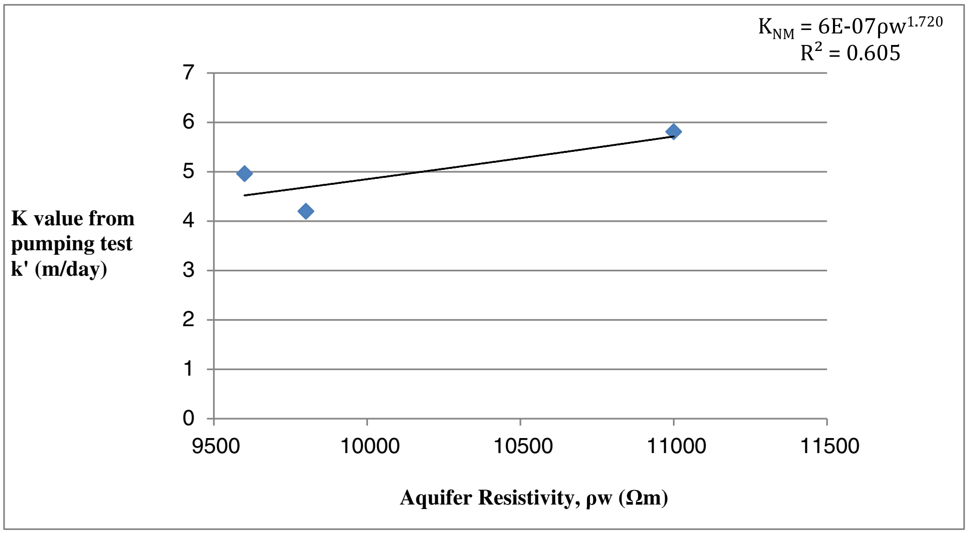


Fig. 4 Plot of hydraulic conductivity from the New Model

$$\mathbf{K_{N\&S} = k'\sigma\rho} \tag{4.6}$$

Heigold et al. (1979) carried out a cross-plot of aquifer resistivity values obtained by parametric vertical electrical exploration near the control well region with subsequent connection coefficients with the hydraulic conductivity values estimated from the three observation wells. I applied a non-rectangular line and won 0.94. This fitted least squares line provided a striking relationship between the hydraulic conductivity and resistivity of the aquifer given in condition 4.7.

$$\mathbf{K_{HG} = 386.40\rho_{rw}^{-0.93283}} \tag{4.7}$$

where K_{HG}—hydraulic conductivity was estimated using the Heigold et al. (1979) equation in cm/sec; ρ_{rw}—resistivity of the water-saturated aquifer in ohm-cm. It is this kind of expression that gives an overall idea of the water-producing strength of the aquifer from surface electrical measurements.

The empirical formulas of Heigold et al. (1979) and Niwas and Singhal (1981) were used to estimate the geological properties of the aquifer from the surface resistivity data in the study area. However, using these empirical formulas, the aquifer parameters may be underestimated or overestimated in areas that do not resemble certain geological settings. To solve this problem, new empirical relationships were developed using pump test data collected from three surveillance wells in the current study area. An empirical formula was developed for the study area because the area is geologically homogeneous and is generally covered by the Benin Formation. The purpose of the new model was to limit the predictive power of empirical formulas using local geology. Therefore, in this study, we applied the least squared line to the cross-plot of the water permeability coefficient values measured from the three monitoring wells and the water saturation resistance of the water-saturated aquifer to establish the power law relationship, with coefficient of determination of $R^2=0.605$). This led to the empirical formula given in Eq. 4.8.

$$\mathbf{K_{NM} = 6^{*}10^{-7}\rho w^{1.720}} \tag{4.8}$$

where ρ_w is the water-saturated aquifer resistivity (Ωm), K_{NM} is the hydraulic conductivity in (m/day), estimated using the New Model (Fig. 4).

The three T values obtained from the pumping test were plotted against the corresponding R_T for each of the locations. A new model was developed and was designated “Transmissivity from New Model” (T_{NM}). An empirical relationship for $T_{\text{New Model}}$, with a very strong positive correlation ($R^2=0.902$), was developed for the study area as shown in Eq. 4.9 (Fig. 5).

$$\mathbf{T_{NM} = 0.009R_T^{0.761}} \tag{4.9}$$

The storativity (S) of the confined aquifer system, and the deep and thick unconfined aquifer which may be hydraulically similar to it, may be estimated from the rule of thumb equation given by Todd (1980) as:

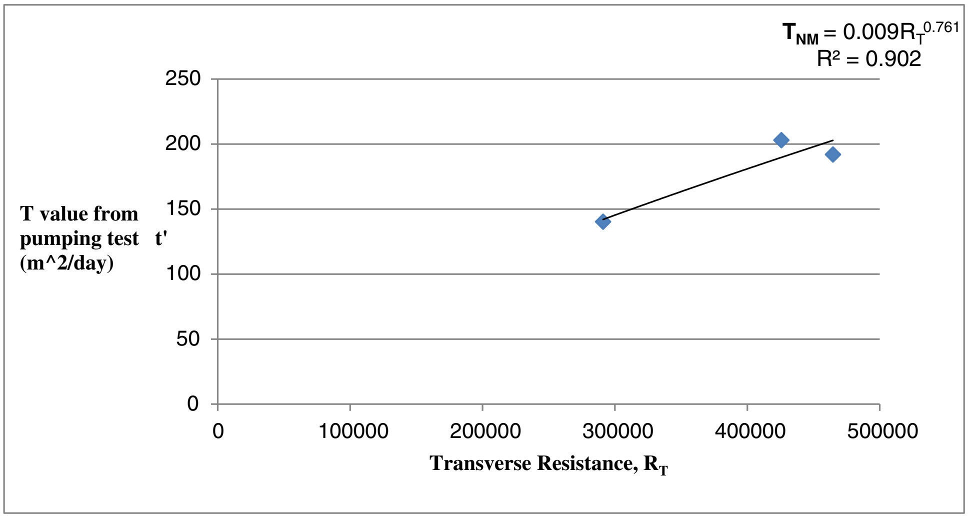
$$\mathbf{S = 3 \times 10^{-6}b} \tag{4.10}$$

where b is the saturated thickness of the aquifer.

Hiscock (2005) found that by integrating the spring properties of permeability T and conservative S, it is possible to characterize a single developmental limit called the hydraulic diffusion coefficient D, as shown in condition 4.11. Therefore, the aquifer diffusion coefficient is the ratio of the spring permeability coefficient (m^2/day) to the aquifer retention rate.

$$\mathbf{D = T/S} \tag{4.11}$$

Fig. 5 Plot of *T* values from pumping test and transverse resistance



Result and discussion

Layer parameters of the study area

The results of the layer parameters are presented in Table 1.

Modeled resistivity curves/geoelectric curve types of some locations

The results of some selected (NJ8 and NJ9) computer-modeled curve types are presented in Figs. 6–7. This was ascertained by the entering of a model represented by the apparent resistivity and thickness of each layer of the curve. The theoretical interpretation of these curves includes NJ8 (HAKHAKQ curve type) and NJ9 (KHAKQ type). About ten layers were identified from the geo-electric curve (Figs. 6 and 7). Aquifer resistivity (Ωm) of 7770 was observed for NJ8 (Fig. 6) with a corresponding aquifer depth and thickness of 100 m and 36.1 m respectively. The aquifer resistivity (Ωm) value recorded at Umuokwara Ihebinowere-1 (NJ9) showed a higher value of 28,700 when compared to the value observed at NJ8, but lesser values of aquifer depth and thickness were recorded, with values being 84 and 28.7 m respectively (Fig. 7).

Modeled curve type at Umuokwara Ihebinowere-1 (NJ9), Njaba LGA Fig. 8 Correlation of geo-electric sections across selected profiles

Three profile lines were drawn across the study area. The geo-electric sections and lithologic cross-sections of the VES points that cut across the lines were correlated as represented in the figures. Sections A-A′, B-B′, and C–C′ are presented with their interpretative lithology, as can be seen from the legend. The variations in lithology can be explained in the varying sub-surface resistivity values. The aquifer resistivity values indicate that the aquifer media is majorly sandstone and sand units of the aquiferous Benin Formation (Fig. 8). The correlation of the sandstone units along the various profiles showed that it occurred in most of the sounded points (the sandstone unit appearing and disappearing at almost equal depth at NJ2, NJ8, and NJ18), with the thickest occurrence at NJ17. The highly prolific nature of the aquifer system in NJ17 (Fig. 8c) can be attributed to the extensive nature of the sandstone unit and the favorable aquifer geometrical parameters, where aquifer depth was observed to be 122 m and aquifer thickness, 50.5 m. These aquifer materials are mostly bounded top and bottom, by low-resistivity materials of varying thickness (Fig. 8), which provide confinement to the aquifer system. These low-resistivity materials are known to occur in major parts of the Imo River Basin and have been reported by Opara et al. (2012 and 2022) to be responsible for the confined and semi-confined nature of the aquifer system in the study area.

Iso-resistivity values of the study area

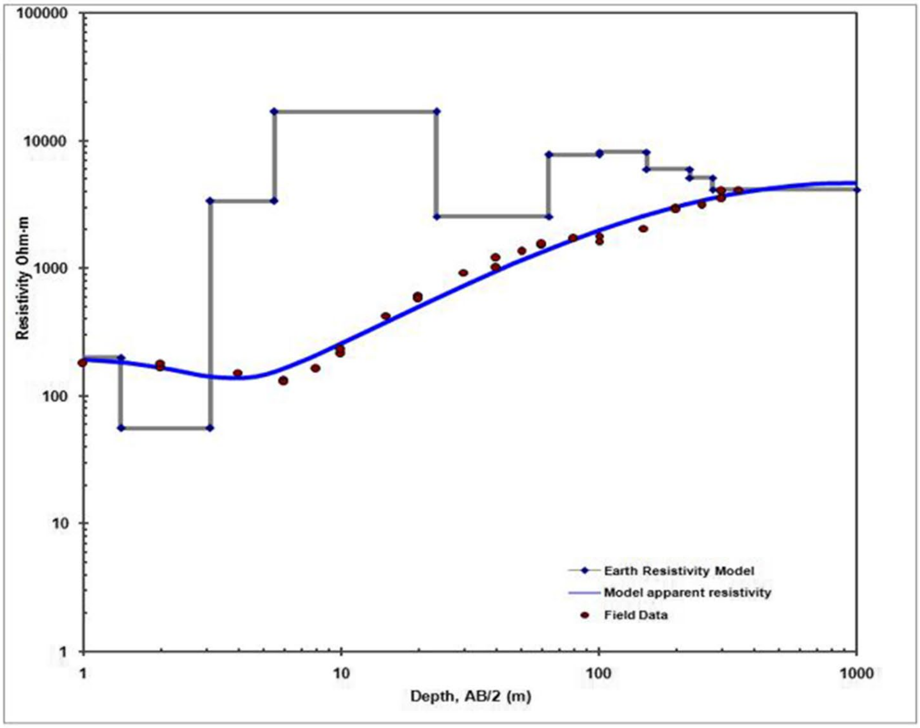
Iso-resistivity spread of 5 m, 20 m, 50 m, 100 m, 150 m, 200 m, 250 m, 300 m, 400 m, and 500 m, were probed, which gave their corresponding depth slices (Fig. 9). Results showed various resistivity values at the different AB/2. There is a fairly increasing resistivity value across all depths of probe for NJ1, NJ4, NJ8, NJ9, NJ12, NJ16, and NJ19. Other VES points showed an approximate decrease in resistivity values as the depths of the probe increased. Some locations as well showed an increasing-reducing-increasing trend of resistivity values. An averaged high resistivity value can be traced to the presence of the sand lithology of the Benin Formation in the region. Generally, Umuokpurufor Amakor recorded an average highest resistivity value across the increasing depths of the probe, with a minimum resistivity value of 190 Ωm at AB/2 = 5 m and a maximum resistivity value of 11,150 Ωm

Table 1 Summary of layer parameters

				Layer depth (m)									Layer thickness (m)										
VES no	Longitude	Lattitude	Elevation (ft)	d1	d2	d3	d4	d5	d6	d7	d8	d9	h1	h2	h3	h4	h5	h6	h7	h8	h9	Curve type	Number of layers
NJ1	E7°00.837	N5°39.995	551.0	3	8.1	22.5	47.5	83	125	172	220	269	3	5.1	14.4	25	36	42	47	48	49	AK	10
NJ2	E7°00.437	N5°32.787	508.0	1.1	16	22.8	63	101	141	184	228	273	1.1	15.3	6.4	40.2	38	40	43	44	45	AK	10
NJ3	E7°00.649	N5°43.557	532.0	0.9	3.8	12.5	51.9	91.9	121	153	184	202	0.9	2.9	8.7	39.4	40	29	32	31	18	AK	10
NJ4	E7°00.338	N5°40.296	522.0	1.8	8.3	23.6	66.6	115	161	208	256	305	1.8	6.5	15.3	43	48	46	47	48	49	AK	10
NJ5	E6°59.315	N5°42.335	1339.0	0.5	7.1	15.4	38	72	114	157	236	281	0.5	6.6	8.3	22.6	34	42	43	79	45	AK	10
NJ6	E6°59.759	N5°45.548	610.0	0.4	1.3	5.3	27.4	62.5	111	160	210	260	0.4	0.9	4	22.1	35	48.5	49	50	50	KHA	10
NJ7	E7°01.163	N5°44.615	585.0	0.4	2	9.2	33.2	57	86	119	153	193	0.4	1.6	7.2	24	24	29	33	34	40	KHK	10
NJ8	E7°02.951	N5°44.471	646.0	1.4	3.1	5.5	23.4	63.9	100	153	225	276	1.4	1.7	2.4	17.9	41	36.1	53	72	51	HA	10
NJ9	E6°59.843	N5°42.533	499.0	1	3.8	8.9	29	55.3	84	140	191	244	1	2.8	5.1	20.1	26	28.7	56	51	53		10
NJ10	E6°59.113	N5°43.089	542.0	0.4	1.4	5.9	11.4	37.9	63.1	90	117	146	0.4	1	4.5	5.5	27	26	26.9	27	29	KHK	10
NJ11	E7°01.180	N5°39.330	505.0	0.9	2.4	6.3	37.4	75.2	138	185	236	283	0.9	1.5	3.9	31.1	38	62.8	47	51	47	KHK	10
NJ12	E7°03.314	N5°44.651	361.0	0.5	2.9	9.9	26.9	63.3	102	150	204	254	0.5	2.4	7	17	36	38.7	48	54	50	KHA	10
NJ13	E 7° 01.188	N 5°39.346	505	0.9	2.4	6.3	37.4	75.2	138.0	185.0	235.0	283.0	0.9	1.5	3.9	31.1	37.8	62.8	47.0	50.0	48.0	KHK	10
NJ14	E 7° 01.661	N 5° 40.758	567	0.5	6.7	36.8	77.2	115.0	166.0	191.0	246.0	286.0	0.5	6.2	30.1	40.4	37.8	51.0	25.0	55.0	40.0	AK	10
NJ15				0.6	2.6	8.8	37.5	83.7	120.0	161.0	202.0	245.0	0.6	2.0	6.2	28.7	46.2	36.3	41.0	41.0			9
NJ16	E 6° 59.211	N 5°40.113	502	0.8	10.1	23.0	36.6	72.6	96.0	120.0	145.0	178.0	0.8	9.3	12.9	13.6	36.0	23.4	24.0	25.0	33.0	AHK	10
NJ17	E 6°59.549	N 5°39.927	551	1.0	3.4	9.0	16.4	71.5	112.0	170.0	217.0	243.0	1.0	2.4	5.6	7.4	55.1	50.5	48.0	47.0	26.0	AHA	10
NJ18	E7°00.782	N5°43.950	403	0.4	1.8	6.0	12.3	38.5	62.0	98.5	120.0		0.4	1.4	4.2	6.3	26	23.5	36.5	21.5		KHK	9
NJ19				30.0	53.5	84.8	113.0	147.0					30.0	23.5	31.3	28.2	34.0						5
NJ20	E 6°59.373	N 5°40.145	495	0.5	2.5	7.4	11.6	17.4	48.2	74.9	111.0	150.0	0.5	2.0	4.9	4.2	5.8	30.8	29.7	32.1	40.0	AHK	10
NJ21	E 7°0.089	N 5° 43.908	479	0.5	1.6	9.2	35.0	77.6	113.0	154.0	200.0	245.0	0.5	1.1	7.6	25.8	42.6	35.4	41.0	46.0	45.0	KHK	10
NJ22	E 7°00.791	N 5°40.471	538	1.1	2.8	5.1	11.8	59.0	106.0	156.0	250.0	255.0	1.1	1.7	2.3	6.7	47.2	47.0	50.0	94.0	5.0	HAK	10
NJ23	E 6°59.051	N5°39.564	538	0.5	1.7	13.9	20.4	42.8	75.5	125.0	175.0	226.0	0.5	1.2	12.2	6.5	22.4	32.7	49.5	50.0	51.0	KHK	10

Number of Layers		10	
Layer NO	Thickness (m)	Depth (m)	ρ (Ω-m)
1	1.40	1.40	199.00
2	1.70	3.10	55.90
3	2.40	5.50	3370.00
4	17.90	23.40	17000.00
5	40.50	63.90	2550.00
6	36.10	100.00	7770.00
7	53.00	153.00	8200.00
8	72.00	225.00	6000.00
9	51.00	276.00	5130.00
10	-		4150.00

FIELD DATA	
AB/2 (m)	ρa (Ω–m)
1.0	179.40
2.0	167.00
2.0	181.90
4.0	152.80
6.0	131.90
6.0	130.50
8.0	164.20
10.0	215.20
10.0	230.20
15.0	428.00
20.0	619.80
20.0	577.60
30.0	930.20
40.0	1011.40
40.0	1205.30
50.0	1350.20
60.0	1542.90
60.0	1551.70
80.0	1719.70
100.0	1801.00
100.0	1636.20
150.0	2060.30
200.0	2945.30
200.0	2925.50
250.0	3135.00
300.0	3536.20
300.0	4009.00
350.0	4139.40
400.0	4521.90
400.0	4616.50



VES NUMBER:	7	DIRECTION LAYOUT:	NE-SW	DATE:	
LOCATION:	DURUEWURU AMUCHA, NJABA LGA, IMO STATE				
COORDINATES:	N5° 44.471'	E7° 02.951'		ELEVATION :	646ft
PROJECT:	STUDENT PROJECT WORK				

Fig. 6 Modeled curve type at Duruewuru Amucha, Njaba LGA (NJ8)

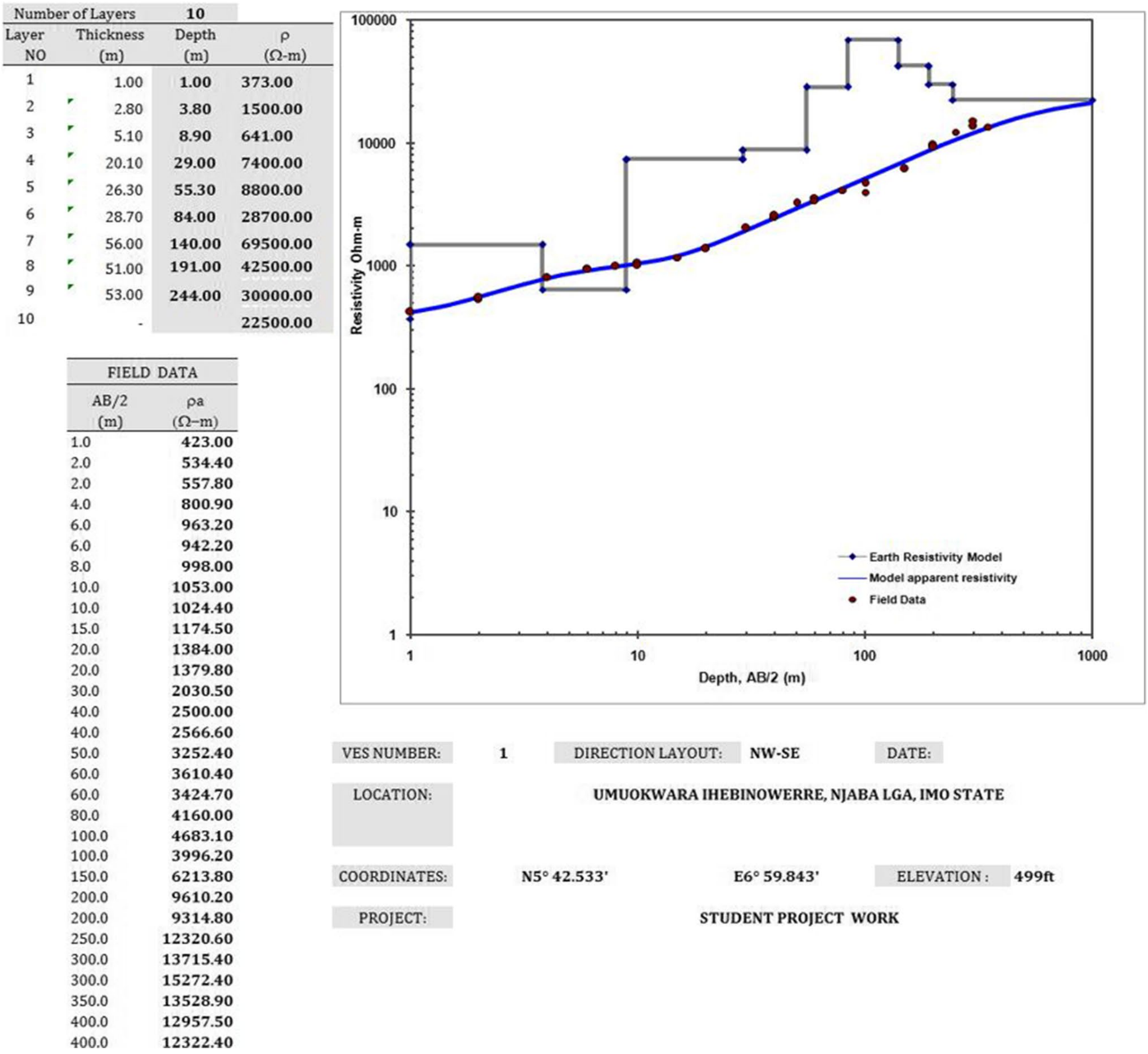
at AB/2 = 500 m; while Community Borehole, Umuodiri, recorded an averaged least resistivity value across all depths of the probe, with minimum resistivity value of 97 Ωm, maximum resistivity value of 1600 Ωm, and averaged resistivity value of 1282 Ωm. Various iso-resistivity values at different AB/2 are presented in Table 2.

Aquifer electrical, geometrical, and Dar-Zarrouk parameters

Aquifer electrical, geometrical, and Dar-Zarrouk parameters are presented in Table 3.

High aquifer resistivity (Ωm) was recorded at Umuokwara Ihebinowerre (Fig. 10), followed by Umuolu Obeapku, with values of 28,700 and 27,900. A drop in aquifer resistivity was observed at Community Borehole, Umuodiri, with a resistivity value of 990, an indication of a sand body with clay admixtures.

Opara et al. (2022), Umayah and Eyankware (2022), and Eyankware et al. (2020a, b) have shown that evaluation of aquifer potential and geo-hydraulic properties is achieved using aquifer thickness and depth which are among the major parameters. From the electrical resistivity sounding done at the study area, a shallow aquifer depth of 79.2 m was recorded at Acharaji Akah, while a deep aquifer depth of 115 m was found at Comprehensive High School, Umuaka. Average aquifer depth of 92.5 m was observed (Fig. 10), and corresponds with the regional aquifer depth of the study area, as earlier established from pumping test data and other hydrogeological studies.



Number of Layers	10		
Layer NO	Thickness (m)	Depth (m)	ρ (Ω-m)
1	1.00	1.00	373.00
2	2.80	3.80	1500.00
3	5.10	8.90	641.00
4	20.10	29.00	7400.00
5	26.30	55.30	8800.00
6	28.70	84.00	28700.00
7	56.00	140.00	69500.00
8	51.00	191.00	42500.00
9	53.00	244.00	30000.00
10	-		22500.00

FIELD DATA	
AB/2 (m)	ρa (Ω–m)
1.0	423.00
2.0	534.40
2.0	557.80
4.0	800.90
6.0	963.20
6.0	942.20
8.0	998.00
10.0	1053.00
10.0	1024.40
15.0	1174.50
20.0	1384.00
20.0	1379.80
30.0	2030.50
40.0	2500.00
40.0	2566.60
50.0	3252.40
60.0	3610.40
60.0	3424.70
80.0	4160.00
100.0	4683.10
100.0	3996.20
150.0	6213.80
200.0	9610.20
200.0	9314.80
250.0	12320.60
300.0	13715.40
300.0	15272.40
350.0	13528.90
400.0	12957.50
400.0	12322.40

VES NUMBER:	1	DIRECTION LAYOUT:	NW-SE	DATE:	
LOCATION:	UMUOKWARA IHEBINOWERRE, NJABA LGA, IMO STATE				
COORDINATES:	N5° 42.533'		E6° 59.843'	ELEVATION :	499ft
PROJECT:	STUDENT PROJECT WORK				

Fig. 7 Modeled curve type at Umuokwara Ihebinowere-1 (NJ9), Njaba LGA

The thickest aquifer observed was at Umudara Ubokoro Atta, with a thickness of 48.5 m, and at Comprehensive High School, Umuaka, with a thickness of 48.4 m. These are prolific aquifer units and can accommodate a borehole for commercial water supply in the study area. The least aquifer thickness was observed at Umuolu Obeakpu, with a thickness of 23.4 m. An average aquifer thickness of 37.71 m was observed in the study area.

The aquifer longitudinal conductance, L_c, across the study area varies between $0.0009\Omega^{-1}$ at Umuokwara Ihebinowere-1 (NJ9) and $0.031613\Omega^{-1}$ at Community Borehole Umuodiri (NJ19), with an average value of $0.00611693\Omega^{-1}$. From the geospatial L_c map of the study area, it can be delineated that high L_c values were recorded in the Northwestern part of the study area. Moderate L_c was recorded in the central part, while low L_c was observed in the remaining parts (Fig. 10). Regions of high longitudinal conductance are known to have a good aquifer protective capacity.

The highest value of aquifer transverse resistance was recorded at Umuolu Obeakpu-1 (NJ17) with an R_T value of $1{,}408{,}950\Omega\text{m}^2$, while the least R_T was recorded at

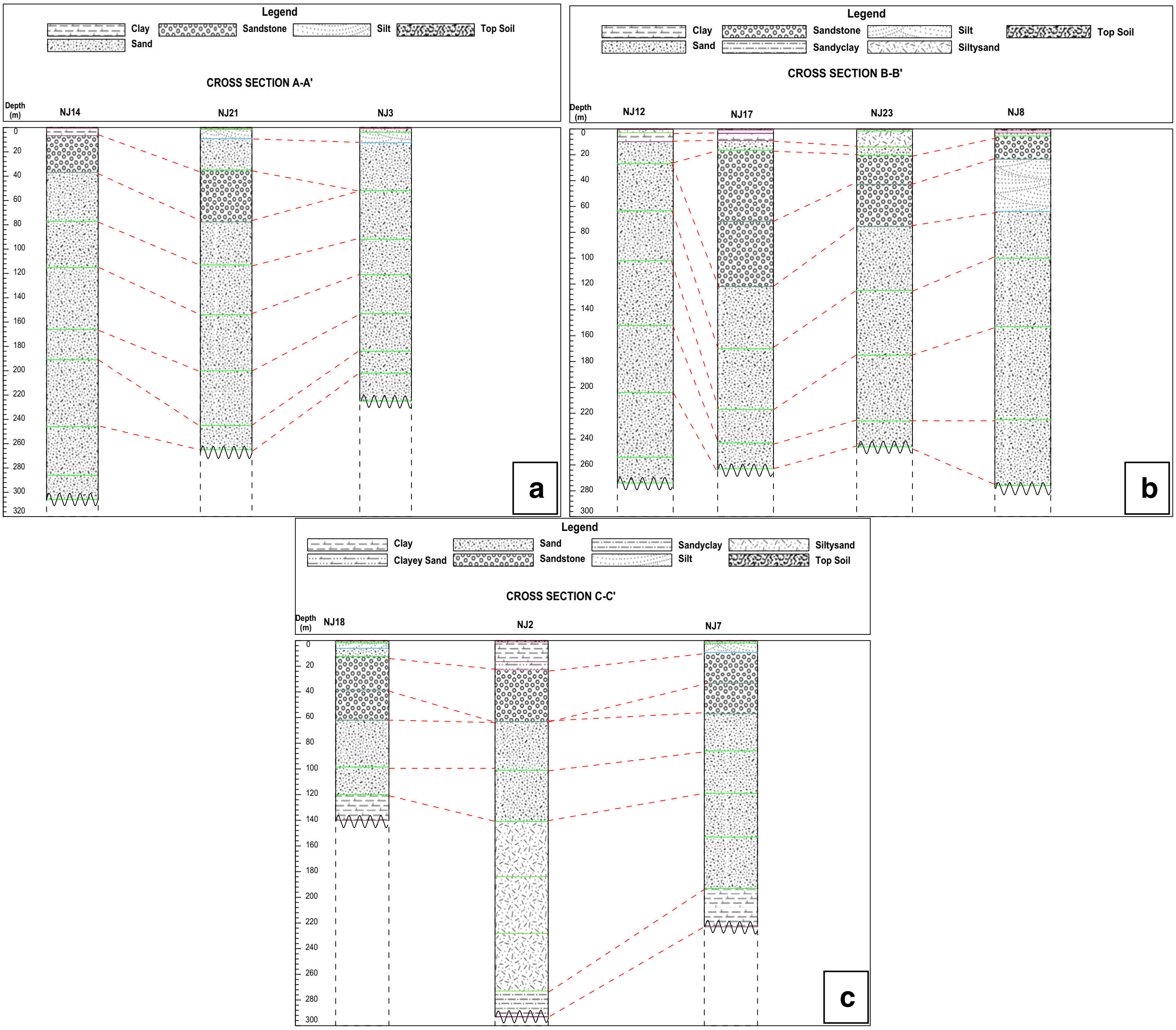


Fig. 8 Geo-electric section across profiles. a A-A′. b B-B′. c C–C′

Community Borehole Umuodiri (NJ19) with an R_T value of 30,987Ωm^2. The average R_T value in the study area is 407,178.1739Ωm^2.

Aquifer hydraulic parameters

Results of aquifer hydraulic parameters are presented in Table 4.

Aquifer hydraulic conductivity, K

An average diagnostic constant of 0.00123225 was used to estimate K from the model proposed by Niwas and Singhal (1981). It can be shown that the $\boldsymbol{K}_{\mathrm{NS}}$ value ranges from 1.2199275 m/day at Community Borehole Umuodiri (NJ19) to 35.36557 m/day at Umuokwara Ihebinowere-1 (NJ9). The average $\boldsymbol{K}_{\mathrm{NS}}$ value is 13.04738 m/day. Based on the hydraulic conductivity values, the aquifer geomaterial within the Benin Formation is thus interpreted to be sand, sandstone, and gravel (Nwachukwu et al. 2019; Ekwe et al. 2018). The K from Niwas and Singhal (1981) shows that the western and central parts of the study area are characterized by high values (Fig. 11). In summary, areas with high aquifer conductivity are usually associated with high hydropower flow values, thus indicating areas with high groundwater potential.

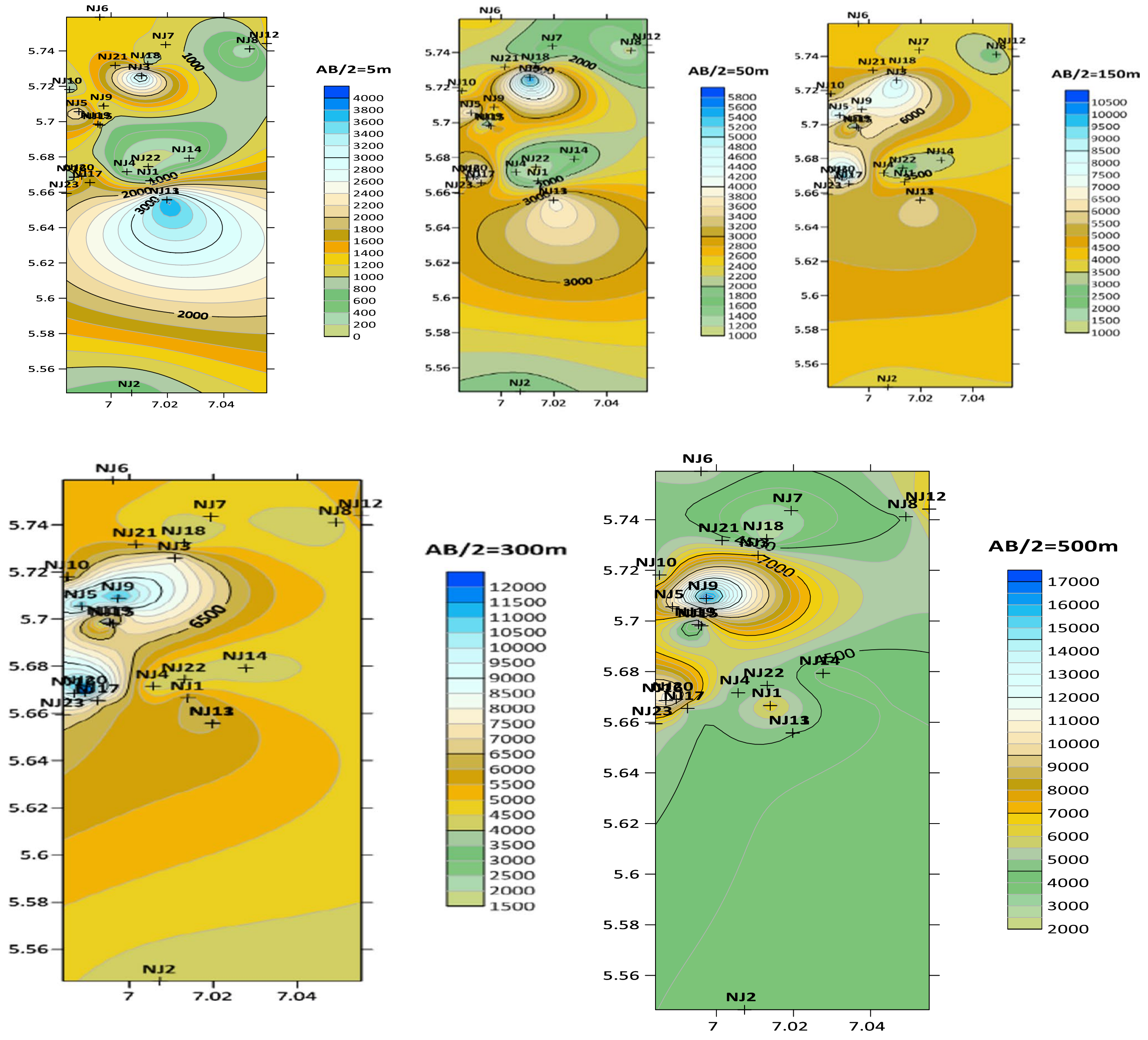


Fig. 9 Iso-resistivity geospatial models at AB/2 = 5, 50, 150, 300, 500 m

The highest K_{HG} value was recorded at NJ19 with a value of 0.620324221 m/day, while the least K_{HG} was observed at NJ9 with K_{HG} value of 0.026828176 m/day.

Based on K_{NM}, the highest value was recorded at Umuokwara Ihebinowere-1 (NJ9), with K_{NM} value of 27.90068 m/day, while the least K_{NM} value was observed at Community Borehole Umuodiri (NJ19), with K_{NM} value of 0.0852 m/day.

From the above models, it can be seen that the highest and lowest hydraulic conductivity values are the same for NJ9 and NJ19 respectively. When the two models are compared, there exists a strong positive correlation as represented in Fig. 12.

Aquifer transmissivity

Aquifer transmissivity measured in m^2/day (Niwas and Singhal 1981) was estimated in the study area by taking the product of diagnostic parameters and lateral resistance. Average diagnostic constant, $k'\sigma$, of 0.00123225 was used for the study area since they are underlain by the same formation-Benin Formation. Aquifer transmissivity, T_{NS}, showed a high value at Umuolo Obeapku-1, with a T_{NS} value of 1736.178638m^2/day. The least T_{NS} value of 38.18373075m^2/day was recorded at Community Borehole Umuodiri. The average T_{NS} value in the study area is 507.745305m^2/day. The groundwater potential in this part

Table 2 Apparent resistivity values at various depths corresponding to AB/2

VES no	Location	AB/2 = 5 m	AB/2 = 20 m	AB/2 = 50 m	AB/2 = 100 m	AB/2 = 150 m	AB/2 = 200 m	AB/2 = 250 m	AB/2 = 300 m	AB/2 = 400 m	AB/2 = 500 m
NJ1	Ndiuhu Achara Umuaka, Njaba, LGA	650	1200	1390	3700	4000	5750	6000	6200	6400	6500
NJ2	Obinwanne Umuaka, Njaba LGA	600	790	1800	2900	3800	4000	4200	4200	3700	3800
NJ3	General Hospital Okwudor, NJA, LGA	3500	3900	6000	8000	8700	9000	8000	7800	7500	7000
NJ4	Comprehensive High School Umuaka, Njaba, LGA	300	800	1300	2200	3400	3600	3800	4100	3600	4500
NJ5	Umuneke Ihiebineowere Okwudor, Njaba, LGA	2300	2500	4000	7000	8300	9800	10,400	11,100	9300	10,000
NJ6	Umudara Ubokoro Atta, Njaba, LGA	1400	1500	2600	4000	4500	5000	5100	5500	5500	5400
NJ7	Umuezime Nkume, Njaba, LGA	1200	900	1800	3800	4000	4100	4500	4600	4100	3500
NJ8	Duruewuru Amucha, Njaba LGA	150	290	1050	1800	2500	3000	3300	4000	4200	4500
NJ9	Umuokwara Ihebinowerre, Njaba, LGA (1)	900	1500	2500	5000	7000	9000	10,000	11,500	16,000	17,500
NJ10	Umuokwara Ihebinowerre, Njaba, LGA	800	900	2200	3800	4900	6600	6400	5400	5100	5000
NJ11	Acharaji Akah, Njaba LGA	3900	3300	3950	5100	5900	6000	5900	6100	5800	4500
NJ12	Nduhu Duruewuru Amucha, Njaba, LGA	1400	950	2000	3500	4400	4800	5500	5950	6000	7000
NJ13	Acharaji Akah, Njaba L.G.A	3900	3300	3950	5100	5900	6000	5900	6100	5800	4500
NJ14	Isiozi Akah, Njaba L.G.A	250	640	1600	2500	3200	3400	4000	4100	3800	3700
NJ15	Umuele Amazano, Njaba L.G.A	1000	1950	3000	5000	6500	7000	7000	7000	5550	5000
NJ16	Umuolu Obeakpu, Njaba L.G.A (2)	700	990	2450	3900	6000	7300	8500	9900	10,000	11,300
NJ17	Umuolu Obeakpu, Njaba L.G.A (1)	1800	2800	3100	5000	6000	6900	7000	7000	6500	5000
NJ18	Christ the King Parish, Okwudor	800	900	2000	3500	4000	4500	4500	4000	3500	2500
NJ19	Community Borehole Umuodiri	1500	1500	1300	1000	970	1000	1250	1300	1400	1600
NJ20	Umuokpurufo Amakor, Njaba L.G.A	1900	2300	4800	9000	11,100	13,200	13,150	13,220	12,500	11,150
NJ21	Umuocha Umuelem Okwudor, Njaba L.G.A	1800	1950	2300	4000	4500	5500	5500	5500	5000	4800
NJ22	Ndihu Ubah Umuakah, Njaba L.G.A	115	480	1100	2000	2500	3200	3500	4000	5000	4800
NJ23	Umudim Umuele Amazano, Njaba L.G.A	1700	1500	2800	5000	5500	6000	7000	7000	6500	6000

of the study area can be categorized as predominantly high (100–1000 m^2/day) and very high (greater than 1000m^2/day), according to Krasny (1993).

The three T values obtained from the pumping test were plotted against the corresponding R_T for each of the locations (Fig. 13). A new model was developed and was designated "Transmissivity from New Model" (T_{NM}). An empirical relationship for $T_{\mathrm{New\ Model}}$, with a very strong positive correlation, was developed for the study area as shown in Eq. 4.9.

$$\mathbf{T_{NM} = 0.009R_T^{0.761}} \tag{4.16}$$

Just as in the case of T_{NS}, the highest T_{NM} value was recorded at NJ17, with value of 430.0877m^2/day, while the least value was recorded at NJ19, with a transmissivity value of 23.552 m^2/day. An average T_{NM} value of 159.043m^2/day was observed for the study area.

Aquifer storativity and diffusivity

To estimate aquifer storativity in the area, Eq. 4.10 was used. The highest aquifer storativity value of 0.0001515 was recorded at Umuolu Obeakpu-1 (NJ17), while the least value was recorded at Umuolu Obeakpu-2 (NJ16), with a storativity value of 0.00113139. This is consistent with the typical storativity range of 5×10^{-5} to 5×10^{-3} for a confined aquifer (Todd 1980). The hydraulic diffusivity across the study area ranges from 2,838,830.2 at Umuokwara Ihebinowere-1 (NJ9) to 695,615.1 at Obinwanne Umuaka (NJ2). The average diffusivity across the study area is 1,398,057.749 (Fig. 14).

Discussion

Aquifer resistivity value ranges from 28,700 (Ωm) to 27,900 (Ωm). A drop in aquifer resistivity was observed at Community Borehole, Umuodiri, with a resistivity value of 990(Ωm), an indication of a sand body with clay admixtures. A mean aquifer depth of 95 m was recorded for the study area, while an average thickness of 37.71 m was observed in the study area. This is in line with the regional hydrogeology of the study area (Ekwe et al. 2006; Obasi et al. 2020). The results of the aquifer Dar-Zarrouck

Table 3 Aquifer electrical, geometrical, and Dar-Zarrouk parameters

VES no	Longitude	Lattitude	Elevation (ft)	Aquifer resistivity (Ωm)	Aquifer conductivity (S/m)	Aquifer depth (m)	Aquifer thickness (m)	Transverse resistance = ρh (Ωm^2)	Longitudunal conductance Lc = σh (Ω^{-1})
NJ1	E7°00.837	N5°39.995	551.0	24,000	0.0000416	83	35.5	852,000	0.0014768
NJ2	E7°00.437	N5°32.787	508.0	4020	0.000248	101	38	152,760	0.009424
NJ3	E7°00.649	N5°43.557	532.0	6930	0.000144	91.9	40	277,200	0.00576
NJ4	E7°00.338	N5°40.296	522.0	9600	0.000104	115	48.4	464,640	0.0050336
NJ5	E6°59.315	N5°42.335	1339.0	18,200	0.0000549	114	41.7	758,940	0.0022893
NJ6	E6°59.759	N5°45.548	610.0	6060	0.000165	111	48.5	293,910	0.0080025
NJ7	E7°01.163	N5°44.615	585.0	4770	0.0002096	86	29	138,330	0.0060784
NJ8	E7°02.951	N5°44.471	646.0	7770	0.000129	100	36.1	280,497	0.0046569
NJ9	E6°59.843	N5°42.533	499.0	28,700	0.0000348	84	28.7	823,690	0.0009988
NJ10	E6°59.113	N5°43.089	542.0	5720	0.000175	90	26.9	153,868	0.0047075
NJ11	E7°01.180	N5°39.330	505.0	7260	0.000138	75.2	37.8	274,428	0.0052164
NJ12	E7°03.314	N5°44.651	361.0	11,000	0.0000861	102	38.7	425,700	0.0033321
NJ13	E 7° 01.188	N 5°39.346	505	7260	0.000134	75.2	37.8	274,428	0.0050652
NJ14	E 7° 01.661	N 5° 40.758	567	4150	0.000241	77.2	40.4	167,660	0.0097364
NJ15				19,700	0.000051	83.7	46.2	910,140	0.0023562
NJ16	E 6° 59.211	N 5°40.113	502	8200	0.000122	96	23.4	191,880	0.0028548
NJ17	E 6°59.549	N 5°39.927	551	27,900	0.0000356	122	50.5	1,408,950	0.0017978
NJ18	E7°00.782	N5°43.950	403	5000	0.0002	98.5	36.5	182,500	0.0073
NJ19				990	0.00101	84.8	31.3	30,987	0.031613
NJ20	E 6°59.373	N 5°40.145	495	9800	0.0001075	77.9	29.7	291,060	0.0031935
NJ21	E 7°0.089	N 5° 43.908	479	9300	0.00011	77.6	42.6	396,180	0.004686
NJ22	E 7°00.791	N 5°40.471	538	3700	0.00027	106	47	173,900	0.01269
NJ23	E 6°59.051	N5°39.564	538	13,500	0.000074	75.5	32.7	441,450	0.0024198

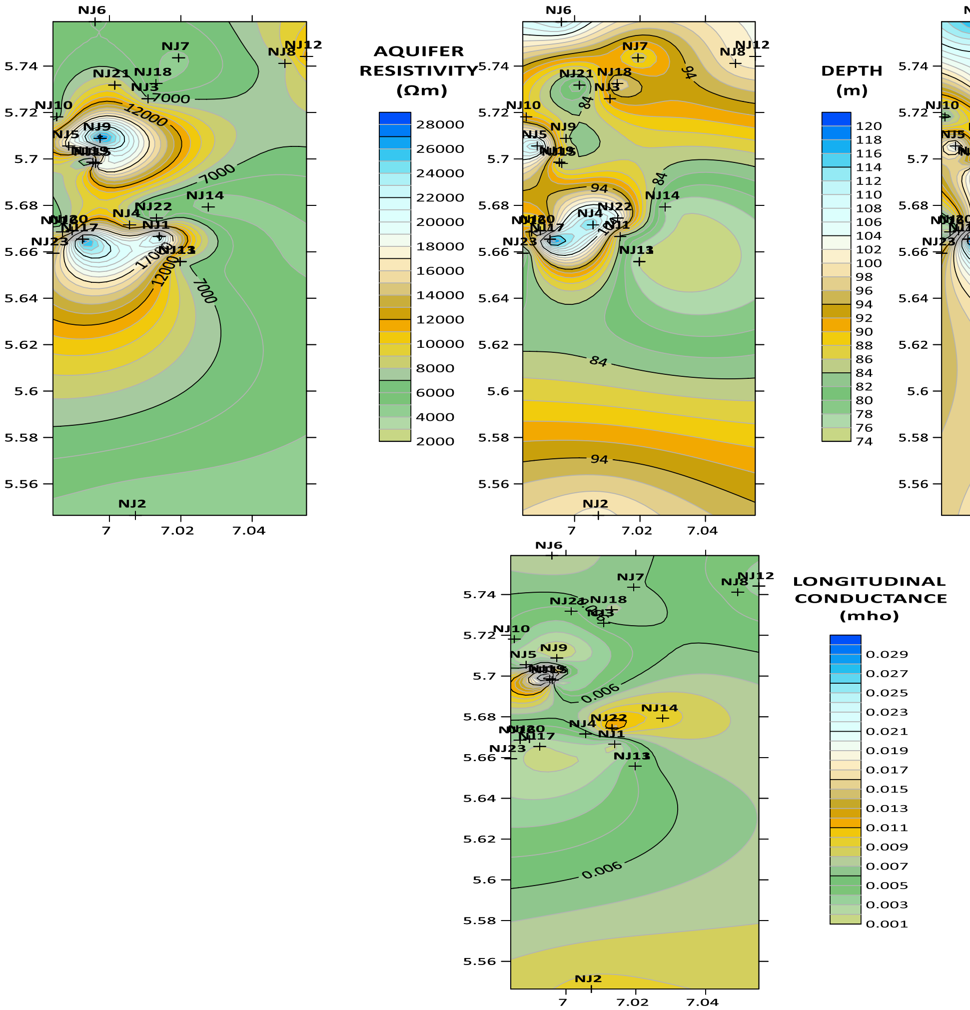


Fig. 10 Geospatial model of aquifer electrical, geometrical, and Dar-Zarrouk parameter

parameters showed that the study area has a characteristic high transverse resistance. Where high transmissivity values are recorded, a good aquifer potential is expected. This range of values agrees with previous studies within the Imo River Basin (Akakuru et al. 2021; Urom et al. 2021; Eyankware et al. 2021; Opara et al. 2012; Ekwe et al. 2006). Based on the findings of this study, several aquiferous zones with their corresponding geo-hydraulic parameters have been evaluated. The iso-resistivity values have confirmed the presence of low-resistivity materials as depth increases. This is in agreement with the geology of the study area (Short and Stauble 1967). The study area has a homogeneous geology and an average diagnostic constant of 0.00123225 was used to estimate hydraulic conductivity from the new proposed model. Hydraulic conductivity from the new model showed that the values obtained are closely related to the values from monitoring wells and pumping test data. The highest hydraulic conductivity value of 27.90068 m/day was recorded in the study area, with the least value of 0.0852 m/day. Aquifer transmissivity value for the study area ranges from 430.0877 to 23.552 m^2/day. An average transmissivity value of 159.043m^2/day was observed for the study area. These findings agree with the previous studies done in the Imo River Basin (Akakuru et al. 2021; Urom et al. 2021; Eyankware et al. 2021; Opara et al. 2012; Ekwe et al. 2006). Urom et al. (2021) stated that the average hydraulic conductivity for Owerri Metropolis is 15.5 m/day, while the average transmissivity value is 1007.18m^2/day. Although the results of aquifer transmissivity, as

Table 4 Summary of aquifer geo-hydraulic parameters

VES no	Aquifer depth (m)	Aquifer thick-ness (m)	Transverse resistance Rt = ρh (Ωm^2)	Longitudunal conduct-ance = σh (Ω^{-1})	*K* value from pumping test *k*′ (m/day)	*T* value from pumping test *t*′ (m^2/day)	Diagnostic constant *k*′*σ*	Diagnostic constant *t*′σ	Average diagnostic constant *k*′*σ* (ave)	Transmissivity from *N* and *S* *T* = *k*′*σRt* (m^2/day)	Stortivity *S* = 3*10^ − 6 *h	Diffusivity *D* = *T*/*S* (m^2/day)	*K* Newas and Singal model = *k*′*σρ*	*K* Heigold = 386.4* *ρw*^(− 0.93283)	K New Model, *K*nm = 6E − 07 *ρw*^1.720	*T* New Model, *T*nm = 0.009 *Rt*^0.761
NJ1	83	35.5	852,000	0.0014768				0.0012323	0.0012323	1049.877	0.0001065	2,753,958.8	29.574	0.0316989	20.517034	293.29661
NJ2	101	38	152,760	0.009424				0.0012323	0.0012323	188.23851	0.000114	695,615.1	4.953645	0.1678444	0.9493362	79.300122
NJ3	91.9	40	277,200	0.00576				0.0012323	0.0012323	341.5797	0.00012	1,039,984.6	8.5394925	0.1009918	2.4222135	124.79815
NJ4	115	48.4	464,640	0.0050336	4.96	192	0.00206336	0.0012323	0.0012323	572.55264	0.0001452	1,273,361.2	11.8296	0.0745169	4.2428509	184.89205
NJ5	114	41.7	758,940	0.0022893				0.0012323	0.0012323	935.20382	0.0001251	2,146,955.6	22.42695	0.0410312	12.748939	268.58415
NJ6	111	48.5	293,910	0.0080025				0.0012323	0.0012323	362.1706	0.0001455	896,789.77	7.467435	0.1144546	1.9231102	130.48291
NJ7	86	29	138,330	0.0060784				0.0012323	0.0012323	170.45714	0.000087	845,202.2	5.8778325	0.1430885	1.2740981	73.532592
NJ8	100	36.1	280,497	0.0046569				0.0012323	0.0012323	345.64243	0.0001083	1,162,752.9	9.5745825	0.0907686	2.9490043	125.92614
NJ9	84	28.7	823,690	0.0009988				0.0012323	0.0012323	1014.992	0.0000861	3,319,981	35.365575	0.0268282	27.906676	285.85037
NJ10	90	26.9	153,868	0.0047075				0.0012323	0.0012323	189.60384	0.0000807	988,072.56	7.04847	0.1207884	1.7412953	79.737455
NJ11	75.2	37.8	274,428	0.0052164				0.0012323	0.0012323	338.1639	0.0001134	1,092,127.9	8.946135	0.0967029	2.6239904	123.8473
NJ12	102	38.7	425,700	0.0033321	5.81	203	0.00049938	0.0012323	0.0012323	524.56883	0.0001161	1,489,903.6	13.55475	0.0656304	5.3622452	172.97781
NJ13	75.2	37.8	274,428	0.0050652				0.0012323	0.0012323	338.1639	0.0001134	1,092,127.9	8.946135	0.0967029	2.6239904	123.8473
NJ14	77.2	40.4	167,660	0.0097364				0.0012323	0.0012323	206.59904	0.0001212	702,313	5.1138375	0.1629346	1.002753	85.120336
NJ15	83.7	46.2	910,140	0.0023562				0.0012323	0.0012323	1121.52	0.0001386	2,225,156.8	24.275325	0.0381092	14.609426	308.40673
NJ16	96	23.4	191,880	0.0028548				0.0012323	0.0012323	236.44413	0.0000702	1,343,665	10.10445	0.0863205	3.2352741	94.325283
NJ17	122	50.5	140,8950	0.0017978				0.0012323	0.0012323	1736.1786	0.0001515	2,838,830.2	34.379775	0.0275451	26.582173	430.08277
NJ18	98.5	36.5	182,500	0.0073				0.0012323	0.0012323	224.88563	0.0001095	829,181.17	6.16125	0.1369389	1.3815915	90.795339
NJ19	84.8	31.3	30,987	0.031613				0.0012323	0.0012323	38.183731	0.0000939	250,821.37	1.2199275	0.6203242	0.0852401	23.552127
NJ20	77.9	29.7	291,060	0.0031935	4.2	140.25	0.00113400	0.0012323	0.0012323	358.65869	0.0000891	1,453,635.5	12.07605	0.0730974	4.3960245	129.51892
NJ21	77.6	42.6	396,180	0.004686				0.0012323	0.0012323	488.19281	0.0001278	1,281,468.4	11.459925	0.0767569	4.0173708	163.77166
NJ22	106	47	173,900	0.01269				0.0012323	0.0012323	214.28828	0.000141	620,713.77	4.559325	0.1813475	0.8231106	87.520641

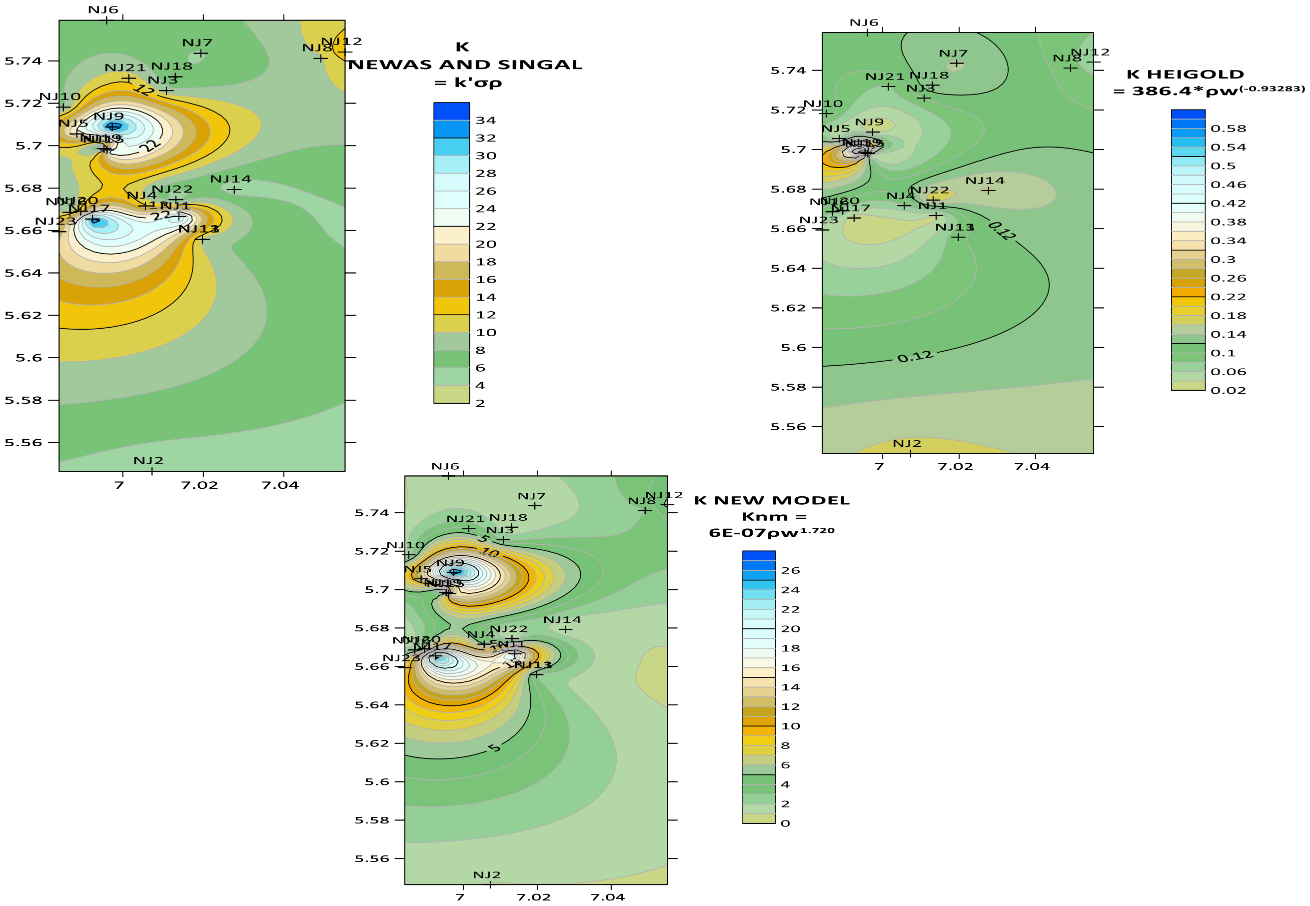
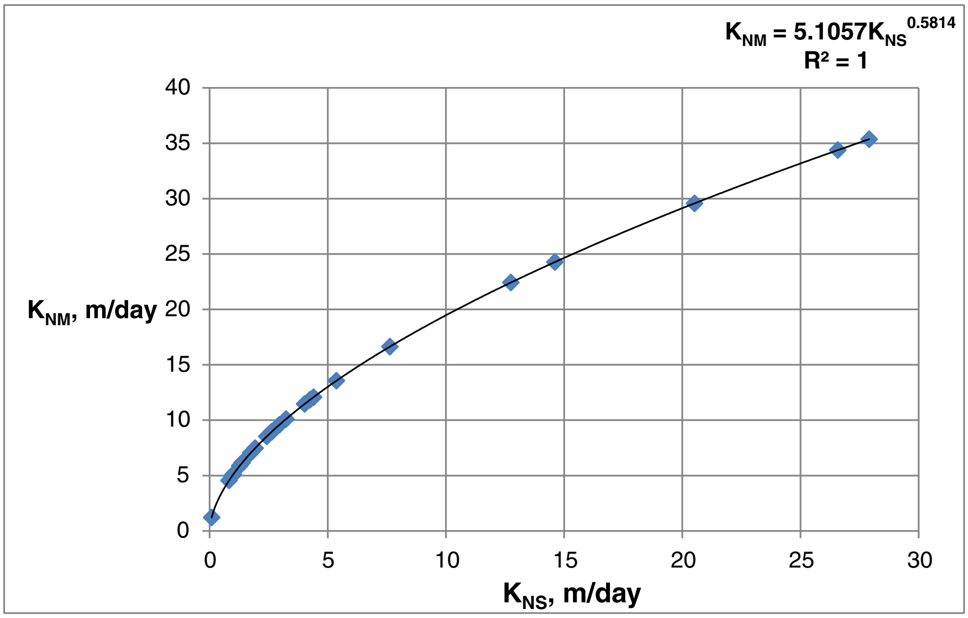


Fig. 11 Geospatial models of aquifer hydraulic conductivity, *K*

Fig. 12 Plot of K_{NM} against K_{NS}



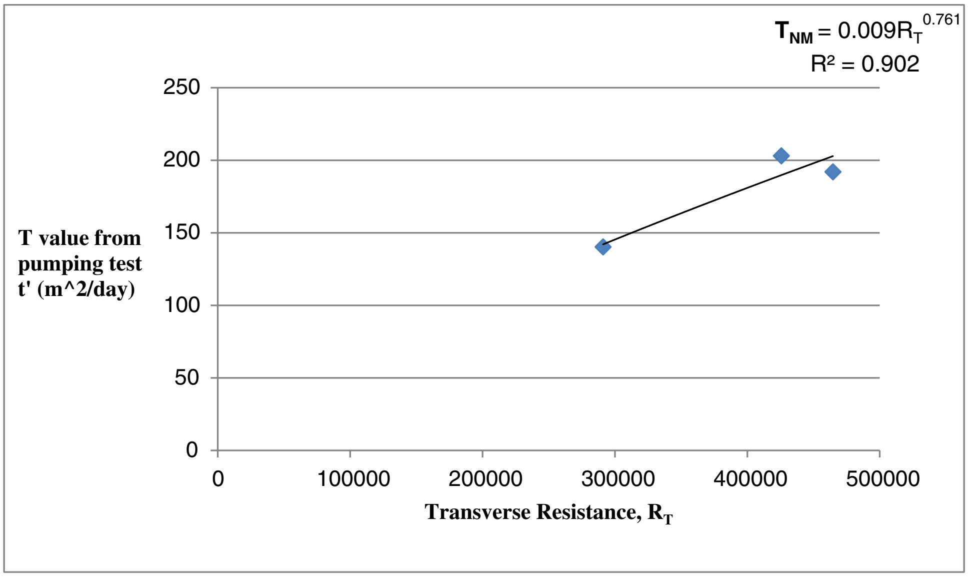


Fig. 13 Plot of Transmissivity New Model

described by Urom et al. (2021), differed from the values obtained in this study, there are similarities in the values of aquifer hydraulic conductivity as obtained at the different sampling points. The highest aquifer storativity value of 0.0001515 was recorded in the study area, with the least value of 0.00113139. This is consistent with the typical storativity range of 5×10^{-5} to 5×10^{-3} for a confined aquifer (Todd 1980). The hydraulic diffusivity across the study area ranges from 2,838,830.2 to 1,398,057.749. This agrees with the study of Opara et al. (2012) and Urom et al. (2021). Uma (1989) appraised the groundwater resources of the Imo River Basin. He concluded that the complex geologic setting of the Imo River Basin provides the environment for equally complex aquiferous horizons which are co-extensive with the geologic formation. Based on the storativity and diffusivity values, he identified three aquiferous units—a shallow unconfined aquifer, a confined aquifer, and a deep unconfined aquifer system. Based on the results of this study, the use of the empirical formula for the determination of aquifer geohydraulic parameters has proved effective. It has shown that these parameters can be acquired easily without the usual difficulties and high cost of obtaining pumping test data. The results have also revealed that the aquifer potential of the study area is fair. The parts of the study areas with good and prolific aquifer systems can serve as points for a regional water supply scheme (Akakuru et al. 2021; Urom et al. 2021; Opara et al. 2012).

Conclusion

Aquifer geohydraulic parameters' estimation in Njaba and environs using electrical resistivity method and the integrated Dar-Zarrouck parameters has proven to be a cost-effective alternative. Also, the use of the proposed New Model for the estimation of aquifer hydraulic conductivity and transmissivity has not been previously carried out in the study area. The very similar survey results and pumping test results demonstrate the importance of electrical resistivity surveys for the quantitative estimation of aquifer parameters. Computer-modeled interpretation techniques helped solve the true width, resistivity, and depth of the aquifer. The diagnostic constant $K\sigma$ proved to be very useful in this study. It was useful to depict specific lithological stratigraphic units within the area that are consistent with the geology of the area. The $K\sigma$ value was also used to estimate the permeability and permeability coefficients for all sounding points in the study area. Hydraulic conductivity, as obtained from a new model, showed a high value of 27.90068 m/day and a low value of 0.0852 m/day, an indicator of fairly clean sand. Transmissivity from a new model developed for the study area ranges from 430.0877 to 23.552 m^2/day. The storativity value ranges from 0.0001515 to 0.00113139, indicating a confined aquifer, while average aquifer diffusivity of 1398057.749 was recorded. This result indicates that most of the study area holds more potential for groundwater than other areas. The low transmissivity and

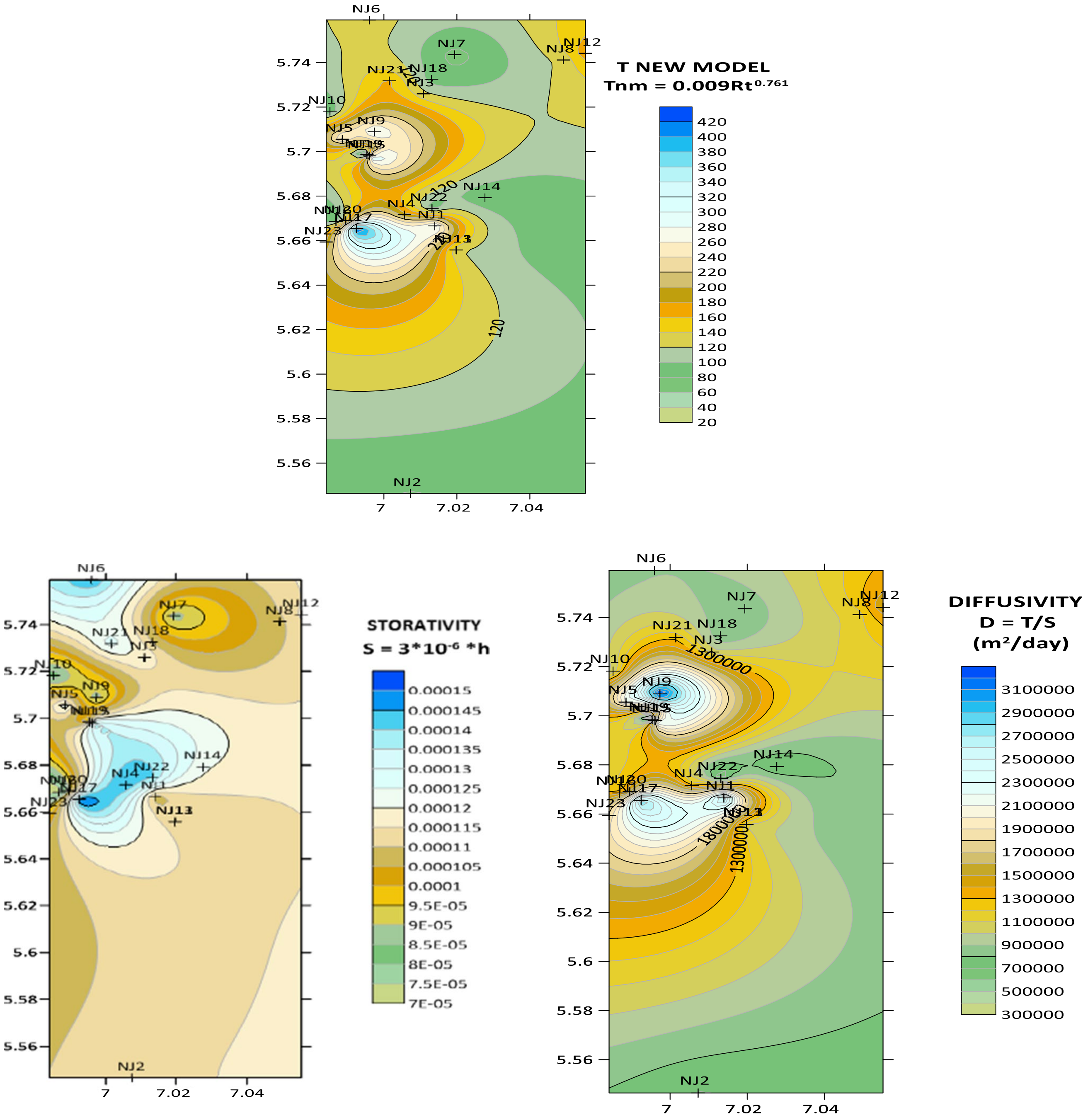


Fig. 14 Geospatial models for aquifer transmissivity, storativity, and diffusivity

hydraulic conductivity values around Umuodiri suggest poor groundwater potentials. This is opposed to the values found at Umuolu Obeakpu, which rather suggest high productivity. A thorough aquifer vulnerability and hydrochemical evaluation should be carried out to ascertain the aquifer protective capacity and the water quality of the aquifer systems of the study area. The establishment of regional water schemes to facilitate a sustainable water supply to areas with low groundwater potentials (such as Umuodiri) is highly recommended.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

This research work is carried out in compliance with transparency, moral values, honesty, and hard work. No human participation or animals are involved in this research work.

Ethical approval As per the literature review, this is neither a repetition of any work nor copied key data from another's work. The methodology, findings, and conclusions made here belong to original research work as per our knowledge and belief.

Informed consent Every step of processing for publication is informed to all co-authors of this paper at the earliest, and everything is carried out with collective decision and consent.

Conflict of interest The authors declare no competing interests.

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