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Application of geological and geo-electric methods in the assessment of corrosivity, competence, and vulnerability of soils around Southeastern Nigeria

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The study investigates the electro-geophsysical method's application to assess corrosivity, competence, and aquifer vulnerability in Njaba and its environs, in southeastern Nigeria, aiming to determine soil suitability for engineering constructions and estimate aquifer vulnerability. Urbanization in the area has led to increased man-made structures and surface pollution exposure. Twenty-three geo-electric resistivity soundings were conducted using ABEM Terameter SAS-4000 and Schlumberger configuration with a maximum half-current electrode spacing of 500 m. Results indicate undulating topography with elevations ranging from 361 to 1336.9ft. Soil resistivity assessment reveals 43.5% moderate competence, 26.1% competent, and 26.1% highly competent zones, with the remainder exhibiting incompetent clay lithology. Corrosivity assessment shows 73.9% essentially non-corrosive and 26.1% mildly corrosive topsoil. The study identifies a semi-deep aquifer system with depths ranging from 79.2 to 115 m and thickness from 23.4 to 48.5 m. Aquifer resistivity ranges from 28700 to 990 Ωm, indicating clean sand to sand with clay admixtures. Hydraulic conductivity varies from 0.0852 to 27.90068 m/day, suggesting clean sand. Aquifer vulnerability assessment indicates a high to moderately low protective capacity, making most of the area suitable for engineering construction and groundwater development. The study highlights the reliability of geological and geo-electric methods in delineating hydraulic conductivity and lithostratigraphic units. It recommends corrosion-resistant pipes in mildly corrosive areas to prevent pipe rupture within a depth of approximately 1.1 m.

Keywords: Competence, corrosivity, hydraulic conductivity, aquifer vulnerability.

INTRODUCTION

Geo-electric techniques have gained significant status as a veritable tool in providing solutions to diverse problems across several fields such as geotechnical, geological, and subsurface environmental studies (Akakuru et al., 2023a, b; Nyaberi, 2022; Opara et al., 2023; Ekwe et al, 2018). Guma et al. (2015) and Ekwe et al, (2018), among

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other numerous authors, have demonstrated the efficient applicability of this method in describing aquifer parameters, aquifer protective capacity, moisture content, etc. As highlighted by Ekwe et al, (2018), the advantage of this method over other geophysical exploration methods includes efficient techniques, continuous, fast, and economical, as well as its obvious feature of being a non-destructive testing technology. Also, recent studies have revealed that the electrical resistivity method has been applied in the study of the corrosivity and competence of earth materials before they are made to embody sub-surface structures (drink and sewer systems, gas, and liquid transmission pipelines, and storage facilities) as well as other engineering structures (road bridges and buildings) (Oki et al., 2016; Edeye and Eteh, 2021). Mohammed et al. (2012) and Rim-rukeh and Awatefe (2006) argued that it is reliable in the estimation or prediction of matrix suction of unsaturated soil and investigation of the shear strength of complicated soil quality. It is, therefore, expedient to ensure the correct protection of underground steel pipes for water distribution, in other to stop the deterioration of water quality because of pipeline corrosion (Oyinkanola et al., 2016).

One major way to protect the strength of engineering structures is to consider the corrosivity of the soil materials hosting them (Eyankware et al. 2023, 2022a, b; Agidi et al. 2022; Chizoba et al. 2023). Engineering construction such as buried pipes is susceptible to corrosion and subsequent failure if the host soil medium is corrosive or aggressive (Bayowa et al., 2015; Edeye and Eteh, 2021). Corrosion cells can lead to severe corrosion failure in civil engineering structures and are linked with low resistivity or high conductivity of earth materials (Hussein and Tarig, 2014; Bayowa and Olayiwola, 2015). The independent study of Idornigie et al. (2006) and Oli et al. (2022), has revealed that low electrical resistivity is indicative of a good electrical conducting path that stems from reduced aeration, increased electrolyte saturation, or high concentration of dissolved salts in soils, hence, the higher the resistivity of the soil, the lower the risk of corrosion. On the other hand, competence is an important concept in engineering geological practice, which takes into cognizance, the strength of the earth materials employed in construction processes (Adegoke et al., 2017; Adeyemo et al., 2020; Akintorinwa, 2017; Alhazzaa, 2007). The competence (or strength) of any geological material is influenced by several factors such as the mineralogy, the character of the particle contact, and the agent of weathering (Blyth et al., 1984; Idornigie et al., 2006). Since every civil engineering structure is seated on geological earth materials, it is imperative to conduct a pre-construction investigation of the subsurface of the proposed structures to ascertain the strength and the fitness of the host earth materials as well as the timed post-construction monitoring of such structure to ensure its integrity (Idornigie et al., 2006; Obasi et al. 2022; Usman et al 2022; Urom et al 2021; Bassey et al. 2024).

Furthermore, it is expedient to monitor the exposure of aquifer materials to surface pollutants. Usually, environmental concerns relating to groundwater generally focus on the impact of pollution and quality degradation on human uses. One of the methods to measure the exposure of groundwater resources to pollutants is vulnerability assessment. Vulnerability assessments are commonly conducted in areas where water resources are stressed due to anthropogenic activities. Many approaches have been developed to evaluate aquifer vulnerability. They include process-based methods, statistical methods, and overlay and index methods (Pouye et al., 2022; Kirlas et al., 2022; Eynakware et al 2022c and d; Kalinski et al. (1993) and Eke (2017) opined that the basis of index-based integrated electrical conductivity is that the vertical travel time of water through a set of geological layers can be related to the resistivity properties of these layers, which implies that, the method (which is based on the principle that the distribution of electrical potential in the subsurface around current-carrying electrodes) depends on the electrical resistivity. Oli et al. (2022) demonstrated that the protection degree of an aquifer or vulnerability may be considered directly proportional to the longitudinal conductance (L_C) of the overburden materials. This means that the higher the longitudinal conductance of overburden, the higher the degree of aquifer protection and vice versa. It can thus, be demonstrated that the subsurface hydrologic environment has a primary influence on groundwater movement and pollution migration to the subsurface water. Hence, groundwater vulnerability assessment has proven to be a veritable tool for delineating areas that are vulnerable to groundwater contamination (Madi et al., 2016).

Overall, there is a great demand for groundwater vulnerability assessments, especially in agricultural areas with heavy nitrate pollution and limited hydrochemical data. Barbulescu (2020) emphasized, however, that the intrinsic uncertainty and limited appropriateness of a single groundwater vulnerability approach can occasionally result in erroneous results when applied in a particular region. This work will therefore use the DRASTIC model, the GOD model, and the Integrated Electrical Conductivity (IEC) to assess the vulnerability index of aquifers in Njaba and its environs. The use and verification of these models to assess and pinpoint areas of groundwater pollution susceptibility will be the main objectives of this project. The rapid rate of industrialization and population growth in Njaba and its surroundings has led to increased discharge of household and industrial effluents, which has contaminated shallow aquifer groundwater (Akubugwo, 2013). Additionally, the area has ongoing scarcities of drinking water, which has forced people to adapt and use hand pumps and dug wells for self-supply (Anosike et al., 2019). The usage of urban groundwater is becoming increasingly compromised in the middle of these attempts due to effluents from industrial activities and non-engineered landfills. Consequently, decision-makers seeking to safeguard the Njaba aquifer system and the surrounding environment may find assistance from the integrated vulnerability assessment methodology employed in this work.

The competency and corrosivity of the soils surrounding this location have not been characterized by previous investigations using geo-electric methods. Furthermore, the previous literature for this study location has not utilized an indexed-based IEC technique in vulnerability assessment. Thus, this study will use a combination of geo-electric and geologic methodologies to estimate the aquifer vulnerability of the study region and determine if soils are suitable for engineering structures.

Location, physiography, and climate of the study area

The study area Njaba and its environs are in Imo State, Southeastern Nigeria, and lies between latitudes 54°7'N and 6°00'N and longitudes 6°15'E and 7°33'E (Figure 1). Njaba Local Government Area (LGA) is located east of Oru LGA with Awo-Omanma as the nearest border town overlooking Okwudor. It shares its common boundary with Awo on the western axis. On the north and north-east, it is bounded by Orlu Local Government; Umudioka and Umuowa communities in Orlu LGA are also surrounding the northern axis. The Local Government is bounded on the west and south-west by the Isu LGA with its towns of Amurie Omanze and Ekwe bordering Umuaka on the western side, while it shares its southern borders with Mbaitoli Local Government area with Orodo as the overlapping town still sharing borders with Umuaka. The Njaba River conveniently demarcates Umuaka and Ekwe in the western borders (Ekwe et al., 2018). The study area stretches as an undulating land surface with a free-level surface at an elevation of about 183 to 244 m. The study area has thick vegetation with a mean annual rainfall of about 1800 to 2500 mm, which feeds an extensive hydrological system, of which the Njaba River is part. The temperature ranges from about 27 to 32°C with February to April being the hottest. Sunshine hours per year are about 1400 while the mean monthly pattern is below 200 h. Relative humidity ranges from 70 to 80%. The dry seasons of December and January are always occasioned by the mild harmattan, a scourge of cold waves springing from the Northern part of Nigeria, within the Jos plateau area and dumping its wave in the east part during the season. It is mostly dominated by the rainy season from late April to the end of September. This is however normal in most of the eastern parts of Nigeria, especially in the Southern areas of Imo State. The study area is heavily reinforced with huge rainforests and valleyed topography in most places between Umuaka and Okwudor. It is predominantly a farming area, with almost 80% of its population as peasants and petty traders. They mostly trade in finished farm products (Ibeneme et al., 2013). The soils are fertile during the rainy season, which is an added advantage, and mostly dry and damp during the harvest season.

Geology of the study area

The study area, Njaba, is mostly underlain by the Benin Formation which consists predominantly of continental fluvial sands that underlie an extensive area of southern Nigeria, typified by the sands around Benin City where it is estimated to be 3050 m thick (Adegoke et al., 2017). The Benin Formation is characterized by high sand percentage (70-100%) and forms the top layer of the Niger Delta depositional sequence. These massive sands were deposited in a continental environment comprising the fluvial realms (braided and meandering systems) of the upper-delta plain (Akakuru et al 2023c, d). It is made up of friable sand and minor intercalation of clay. The sand units are majorly coarse-grained, very granular, pebbly, gravelly, fine-grained, poorly sorted, subangular to well-rounded, and consist of lignite streaks as well as wood fragments. The geologic structures associated with the Benin Formation include point bars, channel fills, natural levees, back swamp deposits, ox bow fill, and beaches, and these structures indicate variability of shallow water depositional medium. The highest dated shale underlying the sandy sequence indicated an early Miocene age, hence, the total age span is Miocene to Recent (Short and Stauble, 1967). The thickness of the Benin Formation is variable and may be more than 6,000ft, but according to Avbovbo (1978) in Ebuta (2015), the average thickness of the formation in the study area is about 800 m. At some places in the study area, the formation is overlain by a considerable thickness of earth composed of iron-stained regolith because of weathering and subsequent ferroginization of the weathered material. Benin Formation is underlain by the Ogwashi-Asaba Formation; the Ogwashi-Asaba Formation is then underlain by Amekthei Formation, which in turn is underlain by Imo Shale and Nsukka Formation successively (Figure 2).

MATERIALS AND METHODS

Electro-geophysical and hydrogeological methods were employed in the present study to delineate the competence, corrosivity electro-geohydrauic, and vulnerability characteristics of the study area. The Schlumberger configuration was used in the resistivity survey. The ABEM Terrameter SAS 4000 was used to obtain VES data from the field. A maximum current electrode separation of 1000 m was used in this research. A total of 23 VES data sets were obtained in the various locations. Analysis of the resulting apparent

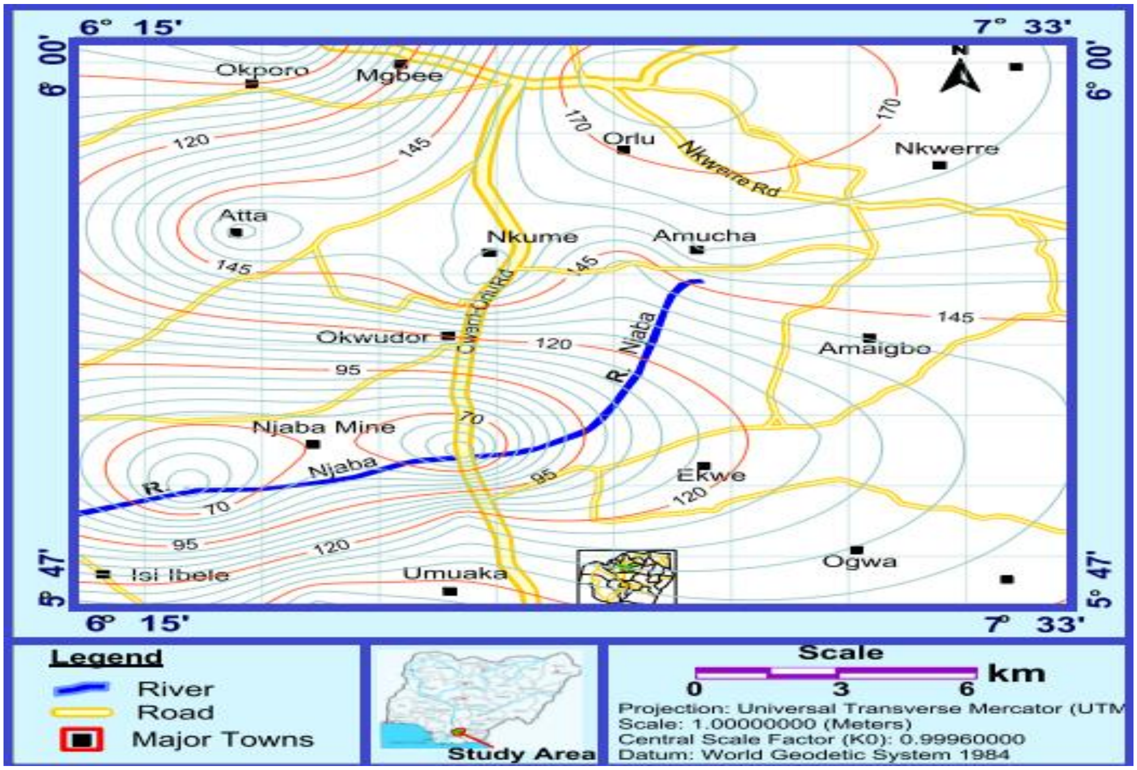

Figure 1. Location and topographic map of the study area.

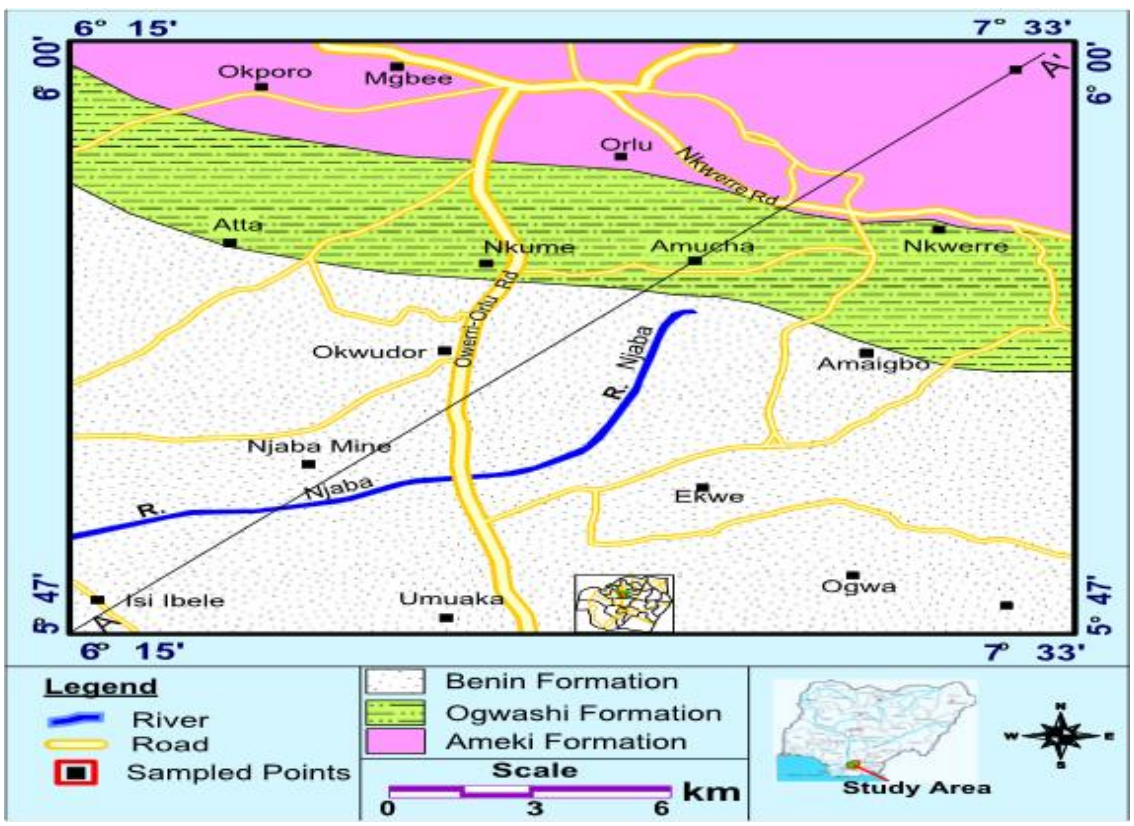

Figure 2. Geology of the study area.

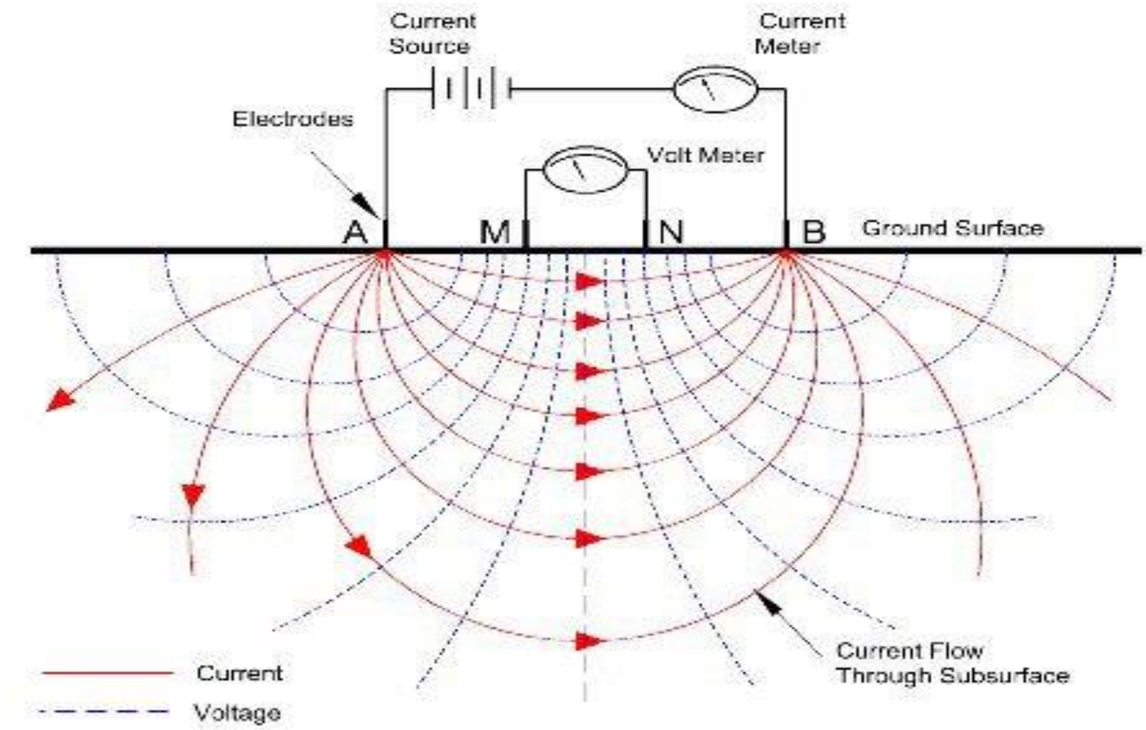

Figure 3. Schlumberger array.

resistivity versus the half-current electrode separations yielded layered earth models composed of individual layers of specified thickness and apparent resistivity. The data obtained was plotted as a graph of apparent resistivity against half-current electrode spacing (AB/2) on a log-log graph scale. Approximately, the depth of sounding at each spread is equal to two-thirds (2/3) of the electrode spacing at which an inflection occurs on the graph (Vingoe, 1972). This approximation is applied when using computer iterative modeling. Modeling of VES results was done using the FORTRAN 2D Resistivity Software, which is an iterative inversion modeling program. In the Schlumberger array (Figure 3), the current and potential pairs of electrodes have a common midpoint but the distances between adjacent electrodes differ so that a≠b. Theoretically, the resistivity (ρ) of a material is directly proportional to the potential difference (V) and inversely proportional to the induced current (I).

$$\rho \propto \frac{V}{I} \quad (1)$$

$$\rho = K\left(\frac{V}{I}\right) \quad (2)$$

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

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

Hence,

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

Recall ρ = KR

where R is the resistance.

The geometric factor K depends on the electrode separation. R responds to the resistance of the volume of ground between the potential electrodes (Akakuru et al., 2023d). The apparent resistivity data are interpreted in terms of layer resistivities and depth to the bedrock or other interfaces across which a strong electrical contrast exists. Depth-sounding curves are then interpreted on the assumption that the earth is made up of layers of approximately constant resistivity. The layers are separated based on different resistivity by a plane interface.

Geo-electric methods

Estimation of soil corrosivity and competence from first layer parameters

The corrosivity of the soil layers was determined using the first layer resistivity of the different locations. Each first layer resistivity is assigned probable lithology and the corresponding degree of corrosivity (Table 1).

As in the case of corrosivity, the first layer resistivity of different locations was used. Each first layer resistivity is assigned probable lithology and the corresponding degree of competence. The rating of subsoil competence using resistivity values is presented in Table 2.

Estimation of aquifer Dar-Zarrouk parameters

When vertical electrical sounding data are quantitatively interpreted, geoelectric layers are generated (Akakuru et al., 2023a). The information from these geoelectric layers aids in the enhancement and identification of aquifer geometric parameters which include

Table 1. Soil corrosivity rating.

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

Estimation of soil competence of the study area.
Source: Robinson (1993), Escalante (1995), Gopal (2010), Bhattarai (2013), and Oki et al. (2016).

Table 2. Rating of subsoil competence using resistivity values.

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

Source: Idornigie et al. (2006).

aquifer depth and thickness. These layer parameters thus obtained will be used to evaluate the Dar-Zarrouk parameters. The Longitudinal Conductance, (L_C), is the geo-electric parameter used to define target areas of groundwater potential. Opara et al. (2023) and Ekwe et al. (2018) have independently established that high longitudinal conductance values usually indicate relatively thick succession and should be accorded the highest priority in terms of groundwater potential.

The Longitudinal Conductance (L_C) is obtained by dividing the Aquifer Thickness (h) by the Resistivity (ρ) of the aquifer (Niwas and Singhal, 1981).

$$L_C = \frac{h}{\rho} \quad (5)$$

Transverse Resistance (T_R) is one of the parameters used to define target areas of good groundwater potential. It has a direct relation with transmissivity and the highest Transverse Resistance values reflect most likely the highest transmissivity values of the aquifers (Nyaberi, 2022).

$$R_T = h\rho \quad (6)$$

Estimation of aquifer hydraulic parameters from new empirical model

Over the years, the empirical equations of Heigold et al. (1979) and Niwas and Singhal (1981) have been used to estimate aquifer geo-hydraulic characteristics from surficial resistivity data in the study area. However, the use of these empirical equations has sometimes led to the under-prediction or over-prediction of the aquifer parameters, especially in areas with different geological characteristics (Urom et al., 2021). To solve this problem, a new empirical relationship like Heigold et al. (1979) was developed using pumping test data collected from three monitoring wells in the present study area. One empirical equation was developed due to the geological homogeneity of the study area, which is generally underlain by the Benin Formation. The goal of using the new model was to constrain the predictive capacity of the empirical equation using local geology. This study, therefore, fitted a least-square line to the cross plot of the hydraulic conductivity values measured from three (3) monitoring wells and the water-saturated aquifer resistivity values acquired to develop a power-law relationship with a coefficient of determination (R^2 =0.605) (Figure 4). This resulted in an empirical equation given in Equation 7.

$$K_{NM} = 6\times10^{-7}\ \rho w^{1.720} \quad (7)$$

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

Estimation of aquifer vulnerability using the integrated electrical conductivity (IEC)

Integrated Electrical Conductivity, a modified form of Aquifer Protective Capacity (APC), is defined as the ability of the overburden unit to retard and filter penetrating ground surface polluting fluid into the aquiferous unit. It was evaluated for the study area using the longitudinal conductance measured for each VES station (Table 3). According to Abiola et al. (2009) the protective capacity of an aquifer compares directly with the sum of the longitudinal unit conductance of all the layers above the aquifer. The longitudinal conductance of a unit or layer is given by Niwas and Singhal (1981) as:

$$\mathbf{L_C} = \frac{\mathbf{b}}{\boldsymbol{\rho}} \text{ or } \mathbf{L_C} = b\sigma \quad (8)$$

where $\mathbf{L_C}$ = Longitudinal conductance; b = Layer thickness; ρ = Layer resistivity; σ= Layer conductivity.

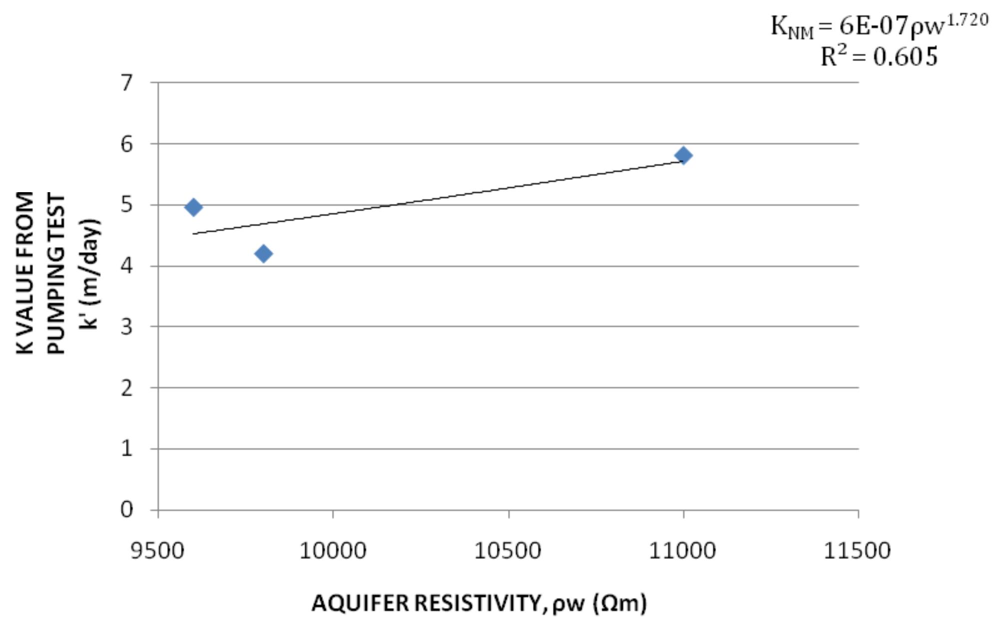

Figure 4. Plot of K_{NM}.

Table 3. Assessment of vulnerability using the IEC method.

Vulnerability index (mS)	Degree of vulnerability
<500	Extremely high
500 - 1000	High
1000 - 2000	Moderate
2000 - 4000	Low

Source: Modified from Madi et al. (2016).

IEC can be used to assess the aquifer vulnerability as:

$$\text{IEC} = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \text{ or } \sum_{i=1}^{n} \sigma_i h_i \tag{9}$$

where ρ_i = Resistivity of layer I; h_i = Thickness of each layer above the aquifer, obtained from the inversion of resistivity sounding; σ_i = Conductivity of layer i.

The estimated IEC unit is ohm^{-1} (Ω^{-1}) or Siemens (S). The vulnerability index or integrated conductivity is calculated for all layers above the groundwater table in the study area. Depth to water is one of the most important natural factors because it determines the thickness of material through which infiltrating water must travel before reaching the saturated zone (Madi et al., 2016) Table 3.

Geologic methods

Estimation of aquifer vulnerability using DRASTIC model

DRASTIC model is a geological method of evaluating aquifer vulnerability by considering the seven hydrogeological parameters: Depth to the water table, Net recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, and Hydraulic conductivity (Ibe et al., 2001). Each map is classified either into ranges (for continuous variables) or into significant media types (for thematic data) that have an impact on contamination potential. DRASTIC Vulnerability index (DVI) was calculated as the sum of the product of ratings and weights assigned to each of the parameters on a scale of 1 to 10 and 1 to 5, respectively. Every parameter in the model has a fixed weight indicating the relative influence of the parameter in transporting contaminants to the groundwater. The parameter ratings are variables that allow the user to calibrate the model to suit a given region (Vogel, 2008; Dixon, 2005). Table 4 presents the Aquifer vulnerability rating based on the final DRASTIC index. The final vulnerability map is based on the DRASTIC index (D_i) which is computed as the weighted sum overlay of the seven parameters using the following equation:

$$\text{Drastic Index } (D_i) = D_rD_w+R_rR_w+A_rA_w+S_rS_w+T_rT_w+I_rI_w+C_rC_w \tag{10}$$

where D, R, A, S, T, I, and C are the seven parameters, and the subscripts, r, and w, are the corresponding ratings and weights, respectively.

Estimation of aquifer vulnerability using GOD model

GOD model is an alternative overlay and index approach, which considers the groundwater occurrence (G) (recharge), overall

Table 4. Aquifer vulnerability rating based on the final drastic index.

Drastic index (D_i)	**1-100**	**101-140**	**141-200**	**>200**
Vulnerability category	Low	Moderate	High	Very high

Table 5. GOD values and corresponding classes of vulnerability.

Parameter	**Range**	**Description**
Step 1 (ground water occurrence rating)	0	None overflowing
	0.2	Confined
	0.3	Semi- confined
	0.5	Semi-unconfined (covered)
	1	Unconfined
	0.4	Residual soil
	0.5	Alluvial loose soil
	0.6	Aeolian sands
	0.7	Alluvial and fluvio-glacialsands+gravel
	0.8	Colloidal gravel
	0.8-1	Unconsolidated (sediments)
Step 2 (overlying lithology rating)	0.4	Residual soils
	0.5	Alluvial sands
	0.6	Aeolian sands
	0.7	Alluvial and fluvio-glacialsands+gravel
	0.8	Colluvial gravels
	0.9-1	Unconsolidates (sediments)
Step 3 (depth to Water Rating (unconfined or confined))	>100	0.4
	50-100	0.5
	20-50	0.6
	10-20	0.7
	5-20	0.8
	2-5	0.9
	<2	1

Source: Vogel (2008).

lithology of aquifer or aquitard (O), and depth to groundwater (D). The GOD method evaluates groundwater occurrence as the degree of confinement of the water table. Overall lithology of aquifer or aquitard (O) was obtained from the digitization of the geological map of the study area. Table 5 presents GOD values and corresponding classes of vulnerability while Table 6 presents GOD final rating. According to Foster et al. (2006) vulnerability indices are calculated by multiplying the rating values assigned to each of the three parameters of the method (Equation 12).

$$\text{GOD vulnerability Index} = G \times O \times D \quad (11)$$

$$\text{GOD index} = Gr^{*} Or^{*} Dr \quad (12)$$

RESULTS

Iso-resistivity from first layer parameters

The first layer parameters for the 23 processed VES results are shown in Table 7 while the iso-resistivity values across the selected depths are presented in Table 8.

Results of normal resistivity values with corresponding conductivity values are presented in Table 7. However, the iso-resistivity values are different, AB/2 (5, 20, 50, 100, 150, 200, 250, 300, 400 and 500 m) were probed, with the results giving their corresponding depth slices at various locations (Figure 5).

Generally, Umuokpurufor Amakor, recorded the highest resistivity value across the increasing depths of probe, with minimum resistivity value of 190 Ωm at AB/2 = 5 m and a maximum resistivity value of 11150 Ωm at AB/2 = 500 m; while Community Borehole, Umuodiri, recorded an averaged least resistivity value across all depths of probe, with minimum resistivity value of 97 Ωm, maximum resistivity value of 1600 Ωm and averaged resistivity value of 1282 Ωm.

Table 6. GOD final rating.

Final vulnerability rating	Class of vulnerability
0-0.1	Negligible
0.1-0.3	Low
0.3-0.5	Moderate
0.5-0.7	High
0.7-1	Extreme

Source: Vogel (2008).

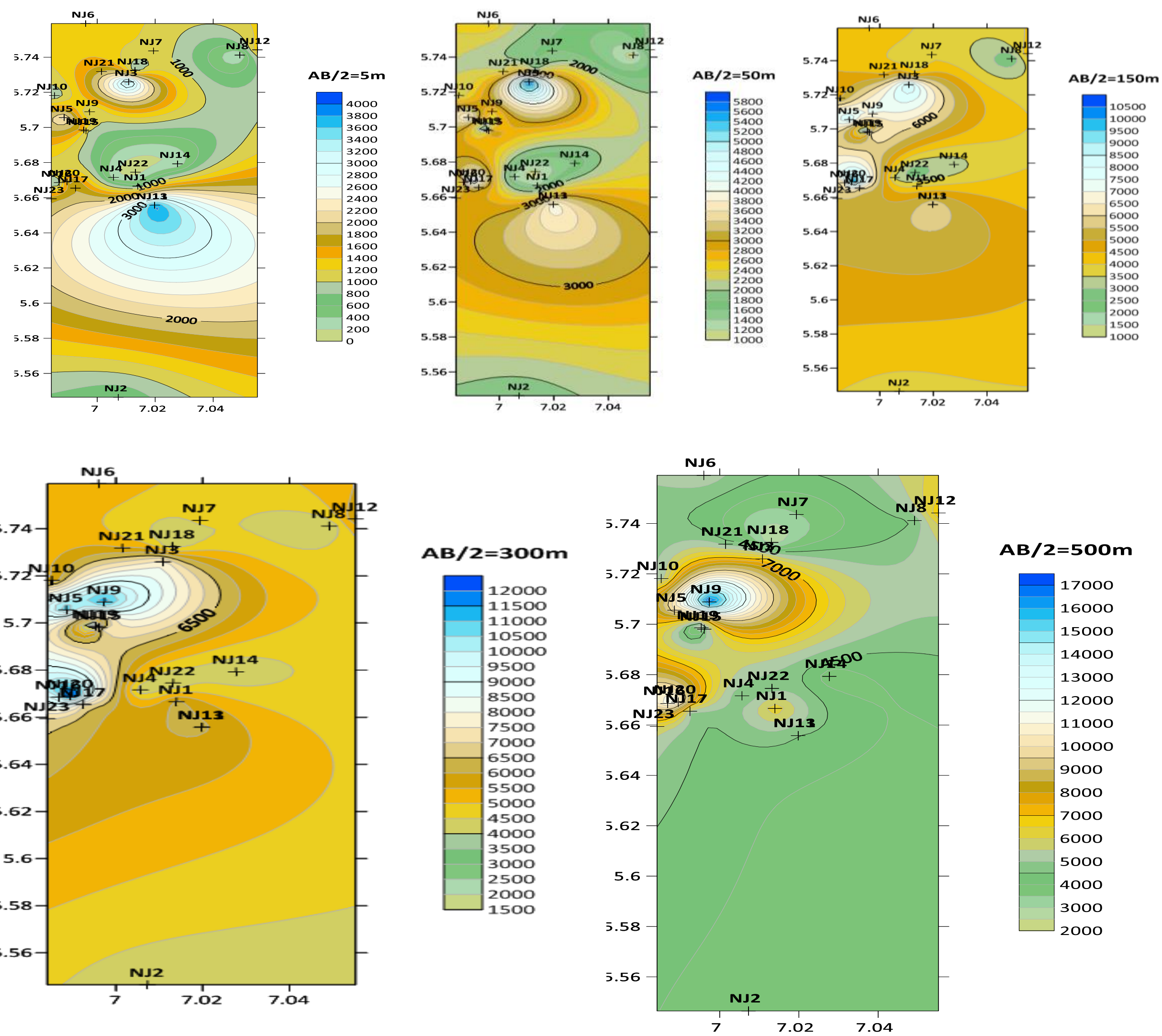

Figure 5. Iso-resistivity geospatial models at AB/2 = 5, 50, 150, 300, 500 m.

Soil corrosivity from first layer parameters

Based on the results of soil corrosivity, the corrosivity of the study area is categorized into two zones (X and Y). Zone X is essentially non-corrosive and can be deduced from the first layer resistivity of NJ1, NJ3, NJ5, NJ6, NJ7, NJ9, NJ11, NJ12, NJ13, NJ14, NJ15, NJ16, NJ17, NJ18, NJ19, NJ20, NJ21, and NJ23. The resistivity value of zone X ranges from 281 (NJ17) to 2800 Ωm (at NJ11), with a mean resistivity value of 807.58 Ωm. From Table 1,

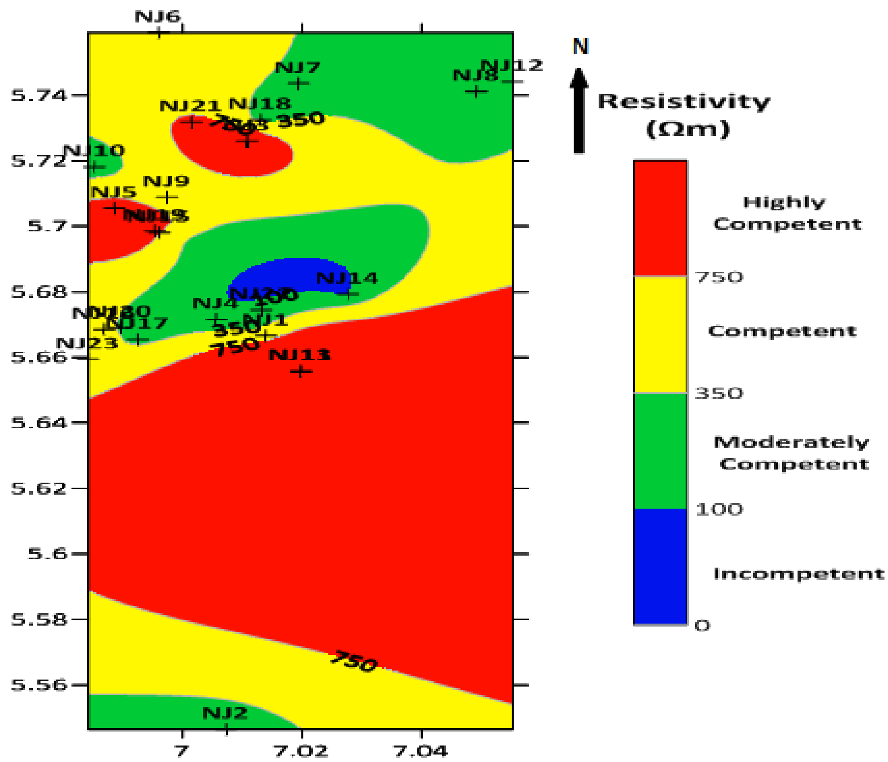

Figure 6. 2D geospatial model of soil competence.

the soil is stated to be essentially non-corrosive and has a thickness ranging from 0.4 m (at NJ6, NJ7, NJ10, and NJ18) to 30 m (at NJ19). Zone Y ranges from mildly to moderately corrosive and is represented in NJ2, NJ4, NJ8, NJ10, NJ14, and NJ22. Its resistivity ranges from 78.4 Ωm (at NJ14) to 199 Ωm (at NJ8). It is characterized by an average resistivity value of 158.08 Ωm. The thickness of the first layer lithology ranges from 0.4 m (at NJ11) to 1.8 m (at NJ4) with a mean value of 1.1 m.

Soil competence from first layer parameters

From Table 7, the first layer resistivity values across all the sounding locations range from 78.5 (at NJ14) to 2000 Ωm (at NJ11). The first layer of iso-resistivity was used to section the area into four zones of varying resistivity and competence (Figure 6) with the template developed by Idornigie et al. (2006) and Ojo et al. (2015). Zone A is incompetent and is made up of NJ14 only, with a resistivity value of 78.5 Ωm and thickness of 0.5 m. Zone B is moderately-competent and has a resistivity value ranging from 154 Ωm (at NJ10) to 321 (at NJ7), with an average resistivity value of 224.2 Ωm and a mean thickness of 0.9 m. This zone cuts across NJ2, NJ4, NJ7, NJ8, N10, NJ12, NJ17, NJ18, NJ20, and NJ22. At Zone C where the soils are classified as competent, resistivity values range from 373 (at NJ9) to 583 Ωm (at NJ21), with mean value of 479.33 Ωm and thickness, 1 m. Zone C cuts across NJ1, NJ6, NJ9, NJ15, NJ16, and NJ23. Zone D is classified as highly competent and has a first first-layer resistivity value ranging from 1000 (at NJ5) to 2800 m (at NJ11), with a mean resistivity value of 1872 Ωm and mean thickness of 6.6 m.

Aquifer electrical, geometrical and Dar-Zarrouk parameters

Aquifer electrical, geometrical, and Dar-Zarrouk parameters are presented in Table 9 with their geospatial models represented as Figure 7. High Aquifer Resistivity (Ωm) was recorded at Umuokwara Ihebinowerre, followed by Umuolu Obeapku, with values of 28700 and 27900. A drop in Aquifer Resistivity was observed at Community Borehole, Umuodiri, with a resistivity value of 990, an indication of the sand body with clay admixtures. 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. 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. The least Aquifer Thickness was observed at Umuolu Obeakpu, with a

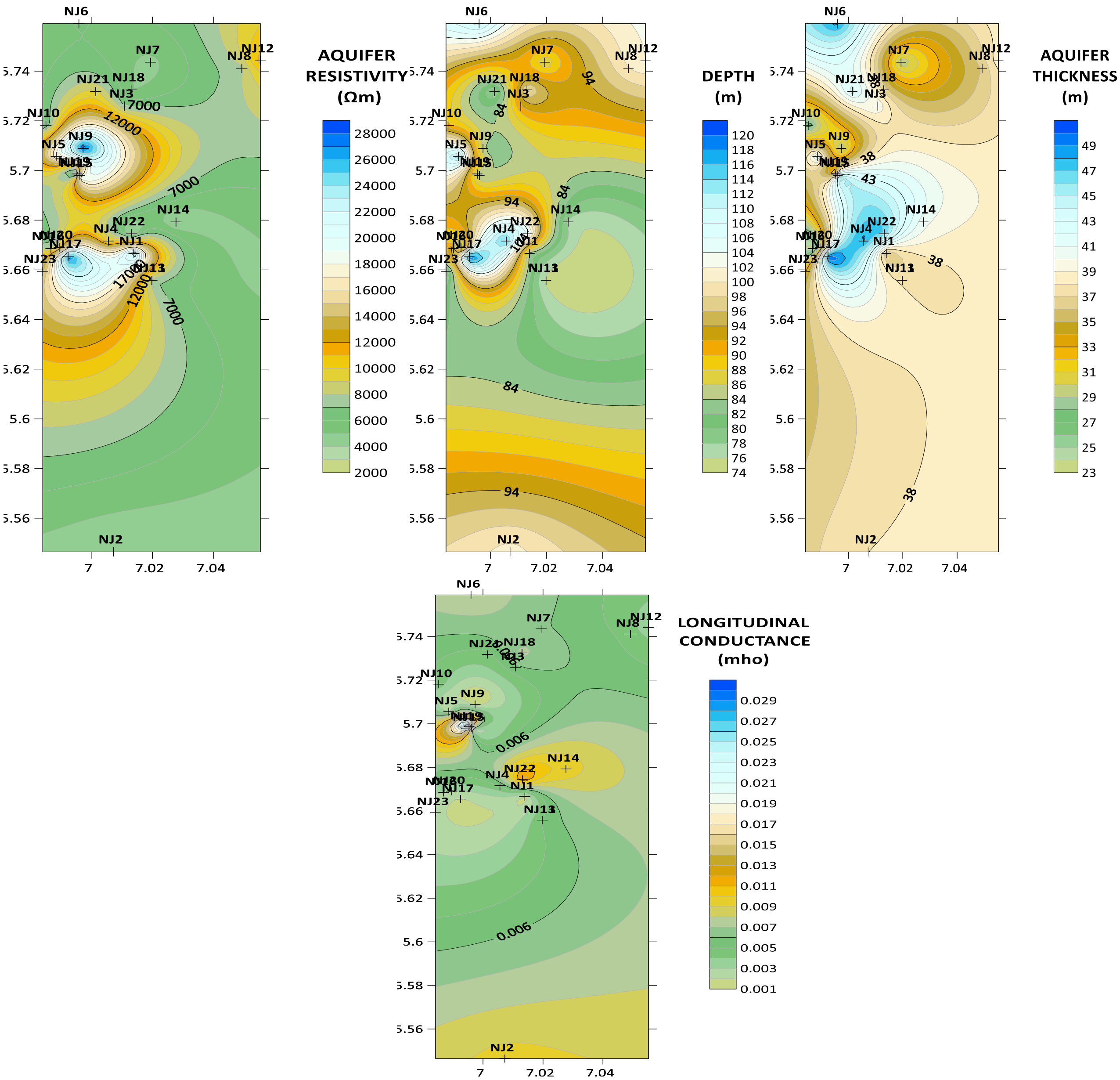

Figure 7. Geospatial model of aquifer electrical, geometrical and Dar-Zarrouk parameter.

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 Ω^{-1} at Umuokwara Ihebinowere-1 (NJ9) to 0.031613 Ω^{-1} at Community Borehole Umuodiri (NJ19), with an average value of 0.00611693 Ω^{-1}. (Table 10). 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. 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 R_T value of 1408950 Ωm^2, while the least R_T was recorded at Community Borehole Umuodiri (NJ19) with R_T value of 30987 Ωm^2. The average R_T value in the study area is 407178.1739 Ωm^2.

Aquifer hydraulic parameters

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 lowest K_{NM} value was observed at Community Borehole Umuodiri (NJ19), with

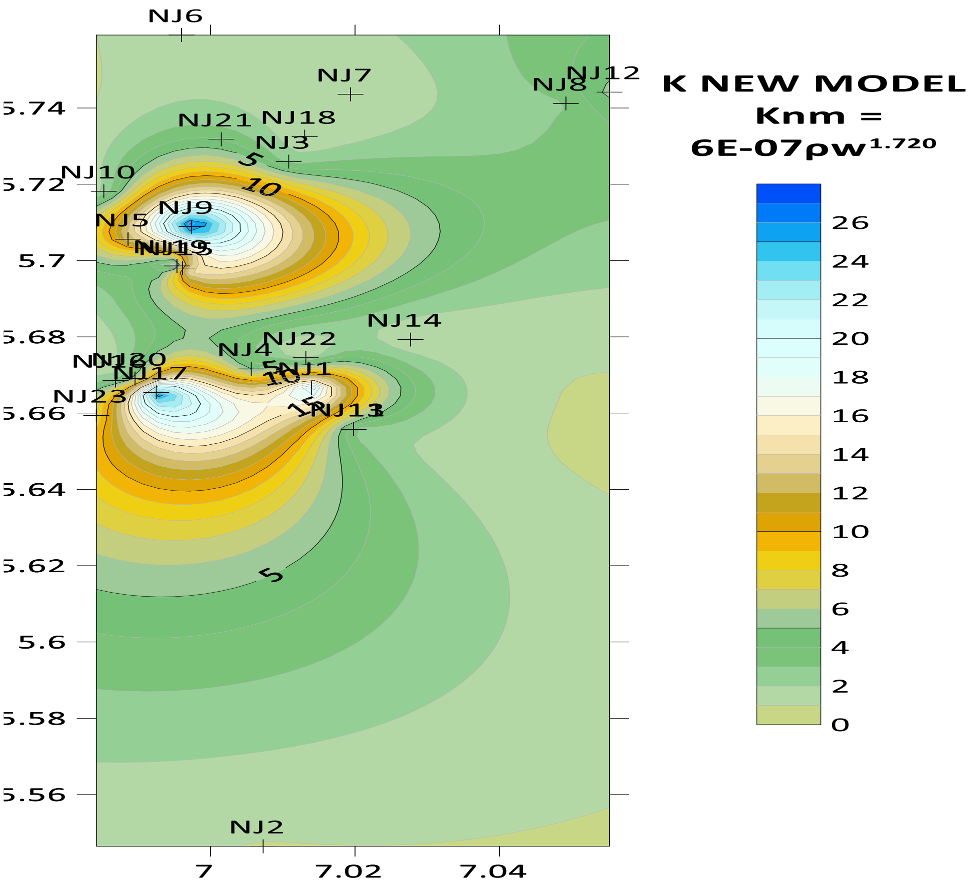

Figure 8. Geospatial model of Aquifer Hydraulic Conductivity, K.

K_{NM} value of 0.0852 m/day. From the aforementioned models, the highest and lowest hydraulic conductivity values are the same for NJ9 and NJ19, respectively (Figure 8).

Aquifer vulnerability results

Figure 9 represents the geospatial models of the various vulnerable indexes used. Results of aquifer vulnerability using the IEC model showed that the entire study area is generally vulnerable to pollution. For the DRASTIC model, 65.2% of the study area showed moderate vulnerability, while 34.75% showed low vulnerability. The vulnerability of the study area using the GOD model (Figure 9) revealed that all study areas exhibited a low vulnerability to groundwater pollution.

DISCUSSION

According to Akakuru et al. (2023a), the iso-resistivity contours are valuable in delineating the lateral variation in the sub-surface geology of the area. For this study (Table 9), resistivity probe across spreads of 5, 20, 50, 100, 150, 200, 250, 300, 400, and 500m, showed a fairly increasing value across all depths of the probe for NJ1, NJ4, NJ8, NJ9, NJ12, NJ16, and, NJ19. Umuokpurufor Amakor, recorded the 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 11150 Ωm 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. The averaged high resistivity across the study area can be traced to the presence of the sand lithology of the Benin Formation in the region while the low resistivity values at Community Borehole Umuodiri indicate clay and lenses of fine to medium sands. These values are in agreement with the findings of Emberga et al. (2019) who reported low iso-resistivity values of 0 to 1000 Ωm for AB/2 = 5 m within the Imo River Basin of southeastern Nigeria. However, it must be noted that an iso-resistivity map is a qualitative interpretation tool that shows possible variations in resistivity with depth at the given electrode spacing across a region but may not give the

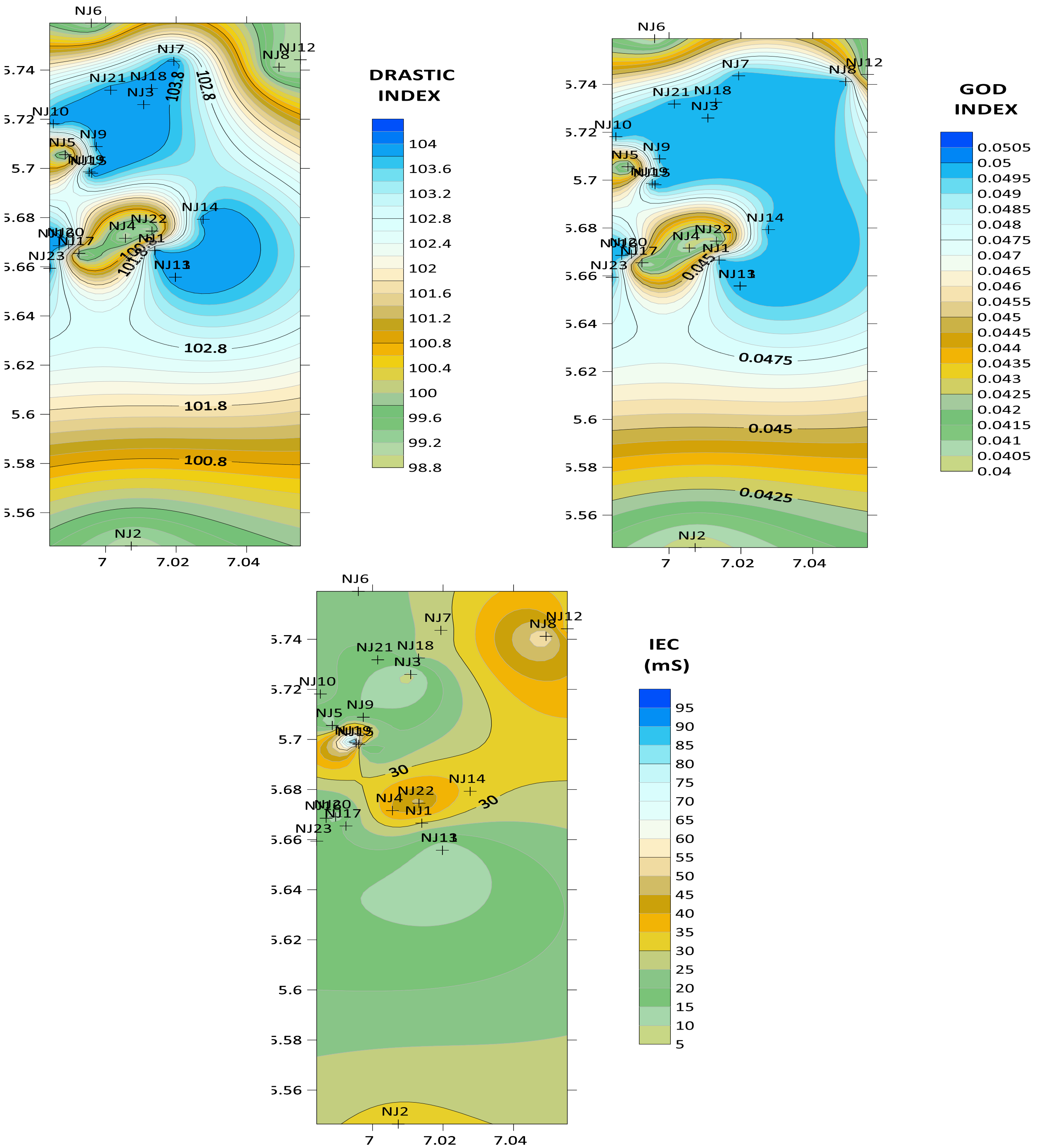

Figure 9. Geospatial model of aquifer vulnerability in the study area.

true resistivity of a definite or unit geo-electric layer.

Studies have shown that the competence of soil materials can be ascertained from first-layer resistivity (Ekwe et al., 2018; Bayowa and Olayiwola, 2015; Guma et al., 2015). The first layer resistivity of values across all the sounding locations ranges from 78.5 (at NJ14) to 2000 Ωm (at NJ11). The first layer of iso-resistivity was used to section the area into four zones of varying resistivity and competence with the template developed by Idornigie et al. (2006) and Ojo et al. (2015). Zone A is made up of NJ14 only, with a resistivity value of 78.5 Ωm. This resistivity value corresponds to a clayey overburden with a thickness of 0.5 m. This zone is incompetent; hence, geological and engineering construction works on the soil must be carried out with caution. Engineering soil stabilization or strengthening techniques can be adopted

Table 7. Summary of first layer parameters of the study area.

VES No.	Location	Resistivity (Ωm)	Conductivity (S/m)	Layer depth (m)	Layer thickness (m)	Lithology	Competence	Corosivity
		ρ_1	σ1	d1	h1			
NJ1	Ndiuhu Achara Umuaka Njaba, LGA	495.0	0.00202	3	3	Clayey sand	Competent	Essentially non-corrosive
NJ2	Obinwanne Umuaka, Njaba LGA	178.0	0.0056	1.1	1.1	Sandy clay	Moderately competent	Mildly corrosive
NJ3	General Hospital Okwudor Nja, Lga	1300.0	0.00077	0.9	0.9	Sand/laterite	Highly competent	Essentially non-corrosive
NJ4	Comprehensive High School Umuaka, Njaba, LGA	182.0	0.00549	1.8	1.8	Sandy clay	Moderately competent	Mildly corrosive
NJ5	Umuneke Ihiebineowere Okwudor, Njaba, LGA	1000.0	0.001	0.5	0.5	Sand/laterite	Highly competent	Essentially non-corrosive
NJ6	Umudara Ubokoro Atta,Njaba, LGA	514.0	0.001946	0.4	0.4	Clayey sand	Competent	Essentially non-corrosive
NJ7	Umuezime Nkume,Njaba, LGA	321.0	0.00312	0.4	0.4	Sandy clay	Moderately competent	Essentially non-corrosive
NJ8	Duruewuru Amucha, Njaba LGA	199.0	0.00503	1.4	1.4	Sandy clay	Moderately competent	Mildly corrosive
NJ9	Umuokwara Ihebinowerre, Njaba, LGA (1)	373.0	0.00268	1	1	Clayey sand	Competent	Essentially non-corrosive
NJ10	Umuokwara Ihebinowerre, Njaba, LGA	154.0	0.006494	0.4	0.4	Sandy clay	Moderately competent	Mildly corrosive
NJ11	Acharaji Akah, Njaba LGA	2800.0	0.000357	0.9	0.9	Sand/laterite	Highly competent	Essentially non-corrosive
NJ12	Nduhu Duruewuru Amucha, Njaba, LGA	306.0	0.003268	0.5	0.5	Sandy clay	Moderately competent	Essentially non-corrosive
NJ13	Acharaji Akah,Njaba LGA	2800	0.000357	0.9	0.9	Sand/laterite	Highly competent	Essentially non-corrosive
NJ14	Isiozi Akah, Njaba LGA	78.5	0.012739	0.5	0.5	Shale/clay	Incompetent	Moderately corrosive
NJ15	Umuele Amazano Njaba LGA	500	0.002	0.6	0.6	Clayey sand	Competent	Essentially non-corrosive
NJ16	Umuolu Obeakpu Njaba LGA (2)	583	0.001715	0.8	0.8	Clayey sand	Competent	Essentially non-corrosive
NJ17	Umuolu Obeakpu Njaba LGA (1)	281	0.003559	1.0	1.0	Sandy clay	Moderately competent	Essentially non-corrosive
NJ18	Christ The King Parish, Okwudor	218	0.004587	0.4	0.4	Sandy clay	Moderately competent	Essentially non-corrosive
NJ19	Community Borehole Umuodiri	1460	0.000685	30.0	30.0	Sand/laterite	Highly competent	Essentially non-corrosive
NJ20	Umuokpurufo Amakor, Njaba LGA	246	0.004065	0.5	0.5	Sandy clay	Moderately competent	Essentially non-corrosive
NJ21	Umuocha Umuelem Okwudor,Njaba LGA	850	0.001176	0.5	0.5	Sand/laterite	Highly competent	Essentially non-corrosive
NJ22	Ndihu Ubah Umuakah, Njaba LGA	157	0.006369	1.1	1.1	Sandy clay	Moderately competent	Mildly corrosive
NJ23	Umudim Umuele Amazano, Njaba LGA	411	0.002433	0.5	0.5	Clayey sand	Competent	Essentially non-corrosive

Table 8. Apparent resistivity values at various depths corresponding to AB/2.

VES No.	Location	Longitude	Lattitude	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	E7˚00.837	N5˚39.995	650	1200	1390	3700	4000	5750	6000	6200	6400	6500
NJ2	Obinwanne Umuaka, Njabalga	E7˚00.437	N5˚32.787	600	790	1800	2900	3800	4000	4200	4200	3700	3800
NJ3	General Hospital Okwudor Nja, Lga	E7˚00.649	N5˚43.557	3500	3900	6000	8000	8700	9000	8000	7800	7500	7000

Table 8. Cont'd

NJ4	Comprehensive High School Umuaka, Njaba,Lga	E7˚00.338	N5˚40.296	300	800	1300	2200	3400	3600	3800	4100	3600	4500
NJ5	Umuneke Ihiebineowere Okwudor, Njaba,LGA	E6˚59.315	N5˚42.335	2300	2500	4000	7000	8300	9800	10400	11100	9300	10000
NJ6	Umudara Ubokoro Atta, Njaba,LGA	E6˚59.759	N5˚45.548	1400	1500	2600	4000	4500	5000	5100	5500	5500	5400
NJ7	Umuezime Nkume,Njaba,LGA	E7˚01.163	N5˚44.615	1200	900	1800	3800	4000	4100	4500	4600	4100	3500
NJ8	Duruewuru Amucha, NjabaLGA	E7˚02.951	N5˚44.471	150	290	1050	1800	2500	3000	3300	4000	4200	4500
NJ9	Umuokwara Ihebinowerre, Njaba,LGA (1)	E6˚59.843	N5˚42.533	900	1500	2500	5000	7000	9000	10000	11500	16000	17500
NJ10	Umuokwara Ihebinowerre, Njaba,LGA	E6˚59.113	N5˚43.089	800	900	2200	3800	4900	6600	6400	5400	5100	5000
NJ11	Acharaji Akah,NjabaLGA	E7˚01.180	N5˚39.330	3900	3300	3950	5100	5900	6000	5900	6100	5800	4500
NJ12	Nduhu Duruewuru Amucha, Njaba,LGA	E7˚03.314	N5˚44.651	1400	950	2000	3500	4400	4800	5500	5950	6000	7000
NJ13	Acharaji Akah,NjabaLGA	E 7˚ 01.188	N 5˚39.346	3900	3300	3950	5100	5900	6000	5900	6100	5800	4500
NJ14	Isiozi Akah, NjabaLGA	E 7˚ 01.661'	N 5˚ 40.758	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)	E 6˚ 59.211	N 5˚40.113	700	990	2450	3900	6000	7300	8500	9900	10000	11300
NJ17	Umuolu Obeakpu NjabaLGA (1)	E 6˚59.549	N 5˚39.927	1800	2800	3100	5000	6000	6900	7000	7000	6500	5000
NJ18	Christ The King Parish, Okwudor	E7˚00.782	N5˚43.950	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, NjabaLGA	E 6˚59.373	N 5˚40.145	1900	2300	4800	9000	11100	13200	13150	13220	12500	11150
NJ21	Umuocha Umuelem Okwudor, NjabaLGA	E 7˚0.089	N 5˚ 43.908	1800	1950	2300	4000	4500	5500	5500	5500	5000	4800
NJ22	Ndihu Ubah Umuakah, NjabaLGA	E 7˚00.791	N 5˚40.471	115	480	1100	2000	2500	3200	3500	4000	5000	4800
NJ23	Umudim Umuele Amazano, NjabaLGA	E 6˚59.051	N5˚39.564	1700	1500	2800	5000	5500	6000	7000	7000	6500	6000

Table 9. Aquifer electrical, geometrical, and Dar-Zarrouk parameters.

VES No.	Location	Longitude	Lattitude	Elevation (Ft)	Aquifer resistivity (Ωm)	Aquifer conductivity (S/m)	Aquifer depth (m)	Aquifer thickness (m)	Transverse resistance = ρh (Ωm2)	Longitudunal conductance Lc = σh (Ω-1)
NJ1	Ndiuhu Achara Umuaka Njaba,LGA	E7˚00.837	N5˚39.995	551.0	24000	0.0000416	83	35.5	852000	0.0014768
NJ2	Obinwanne Umuaka, NjabaLGA	E7˚00.437	N5˚32.787	508.0	4020	0.000248	101	38	152760	0.009424
NJ3	General Hospital Okwudor Nja,LGA	E7˚00.649	N5˚43.557	532.0	6930	0.000144	91.9	40	277200	0.00576
NJ4	Comprehensive High School Umuaka, Njaba,LGA	E7˚00.338	N5˚40.296	522.0	9600	0.000104	115	48.4	464640	0.0050336
NJ5	Umuneke Ihiebineowere Okwudor, Njaba,LGA	E6˚59.315	N5˚42.335	1339.0	18200	0.0000549	114	41.7	758940	0.00228933
NJ6	Umudara Ubokoro Atta, Njaba,LGA	E6˚59.759	N5˚45.548	610.0	6060	0.000165	111	48.5	293910	0.0080025
NJ7	Umuezime Nkume, Njaba,LGA	E7˚01.163	N5˚44.615	585.0	4770	0.0002096	86	29	138330	0.0060784
NJ8	Duruewuru Amucha, NjabaLGA	E7˚02.951	N5˚44.471	646.0	7770	0.000129	100	36.1	280497	0.0046569
NJ9	Umuokwara Ihebinowerre, Njaba,LGA (1)	E6˚59.843	N5˚42.533	499.0	28700	0.0000348	84	28.7	823690	0.00099876
NJ10	Umuokwara Ihebinowerre, Njaba,LGA	E6˚59.113	N5˚43.089	542.0	5720	0.000175	90	26.9	153868	0.0047075
NJ11	Acharaji Akah,NjabaLGA	E7˚01.180	N5˚39.330	505.0	7260	0.000138	75.2	37.8	274428	0.0052164
NJ12	Nduhu Duruewuru Amucha, Njaba,LGA	E7˚03.314	N5˚44.651	361.0	11000	0.0000861	102	38.7	425700	0.00333207
NJ13	Acharaji Akah,Njaba L.G.A	E 7˚ 01.188	N 5˚39.346	505	7260	0.000134	75.2	37.8	274428	0.0050652

Table 9. Cont'd

NJ14	Isiozi Akah, Njaba L.G.A	E 7˚ 01.661	N 5˚ 40.758	567	4150	0.000241	77.2	40.4	167660	0.0097364
NJ15	Umuele Amazano Njaba L.G.A				19700	0.000051	83.7	46.2	910140	0.0023562
NJ16	Umuolu Obeakpu Njaba L.G.A (2)	E 6˚ 59.211	N 5˚40.113	502	8200	0.000122	96	23.4	191880	0.0028548
NJ17	Umuolu Obeakpu Njaba L.G.A (1)	E 6˚59.549	N 5˚39.927	551	27900	0.0000356	122	50.5	1408950	0.0017978
NJ18	Christ The King Parish, Okwudor	E7˚00.782	N5˚43.950	403	5000	0.0002	98.5	36.5	182500	0.0073
NJ19	Community Borehole Umuodiri				990	0.00101	84.8	31.3	30987	0.031613
NJ20	Umuokpurufo Amakor, Njaba L.G.A	E 6˚59.373	N 5˚40.145	495	9800	0.000107527	77.9	29.7	291060	0.003193548
NJ21	Umuocha Umuelem Okwudor,Njaba L.G.A	E 7˚0.089	N 5˚ 43.908	479	9300	0.00011	77.6	42.6	396180	0.004686
NJ22	Ndihu Ubah Umuakah, Njaba L.G.A	E 7˚00.791	N 5˚40.471	538	3700	0.00027	106	47	173900	0.01269
NJ23	Umudim Umuele Amazano, Njaba L.G.A	E 6˚59.051	N5˚39.564	538	13500	0.000074	75.5	32.7	441450	0.0024198

to enhance soil properties for construction purposes. This result is consistent with the work of Ekwe et al. (2018), who reported competent soils with first-layer resistivity values ranging from 24.3 to 88.7 Ωm at Uburu, southeastern Nigeria. Zone B has a resistivity value ranging from 154 (at NJ10) to 321 Ωm (at NJ7), with an average resistivity value of 224.2 Ωm. This range of resistivity values corresponds to a sand/clay overburden with a mean thickness of 0.9 m. The competence rating of this zone is moderately competent and is slightly suitable for most geological and engineering constructions or structures. However, where necessary, further soil improvement methods may be incorporated to enhance stability. This zone cuts across NJ2, NJ4, NJ7, NJ8, N10, NJ12, NJ17, NJ18, NJ20, and NJ22. At Zone C, resistivity values from 373 (at NJ9) to 583Ωm (at NJ21), with mean a resistivity value of 479.33 Ωm. The lithology can be interpreted from the resistivity value to be clayey overburden sand, of a mean thickness, of 1 m. The first layer of soil is competent and is observed at NJ1, NJ6, NJ9, NJ15, NJ16, and NJ23. Zone D has a first first-layer resistivity value ranging from 1000 (at NJ5) to 2800 m (at NJ11), with a mean resistivity value of 1872 Ωm. The first layer of lithology is sand/laterite and is of a mean thickness of 6.6 m. The soils are highly competent, especially those at Acharaji Akah, Njaba, with a resistivity value of about 2800 Ωm.

Lithology could be correlated with resistivity; thus, the idea of engineering geophysics can give an insight into the engineering behaviors of earth materials. For instance, Sheriff (1991) and Idornigie et al. (2006) highlighted that clay characterized by low resistivity usually less than 100 Ωm are regarded as incompetent material as they tend to flow under stress, whereas sands and crystalline rocks are regarded as competent since they can withstand stress.

When soils meet construction materials, they may exhibit aggressiveness either to concrete or reinforcing steel, leading to failure of the structure or necessitating special design considerations (NACE, 1993). Soluble reaction products are formed when acidic soils react with the lime in concretes (Oyinkanola et al., 2016). They further stated that this reaction usually results in concretes with greater porosity and weaker condition, with the external surfaces of these concretes, having yellowish or rust coloration. The soil corrosivity of the study area has been categorized into two zones (X and Y). Zone X is essentially non-corrosive and can be deduced from the first layer resistivity of NJ1, NJ3, NJ5, NJ6, NJ7, NJ9, NJ11, NJ12, NJ13, NJ14, NJ15, NJ16 NJ17, NJ18, NJ19, NJ20, NJ21, and NJ23. The resistivity value, of zone X ranges from 281 (NJ17) to 2800 Ωm (at NJ11). It has a mean resistivity value of 807.58 Ωm. From Table 10, the soil is stated to be essentially non-corrosive and has a thickness ranging from 0.4 (at NJ6, NJ7, NJ10, and NJ18) to 30 m (at NJ19). The zone is underlain by sand and lateritic layers, with occasional clay and clayey-sand regions. The mean thickness of the first layer of lithology in this zone is 2.4 m. High resistivity values in this zone can be attributed to the presence of sandstone. This zone can be favorable to pipeline laying schemes since the soil is non-corrosive. Metal septic tanks and storage tanks that are stored underground will not be subjected to corrosion attack. This report is similar to the report of Ekwe et al. (2018), in which Zone F contains soils that are essentially non-corrosive with resistivity values ranging from 271 to 1,525 Ωm. However, Zone Y ranges from mildly to moderately corrosive

Table 10. Results of aquifer vulnerability using the IEC model.

VES NO	Location	σ1	σ2	σ3	σ4	σ5	σ6	h1	h2	h3	h4	h5	h6
NJ1	NDIUHU ACHARA UMUAKA NJABA, LGA	0.002020202	0.000465116	0.001364256	5.05051E-05			3	5.1	14.4	25		
NJ2	OBINWANNE UMUAKA, NJABA LGA	0.005617978	0.00131406	0.000578035	5.10204E-05			1.1	15.3	6.4	40.2		
NJ3	GENERAL HOSPITAL OKWUDOR NJA, LGA	0.000769231	0.000181159	0.000458716	6.80272E-05			0.9	2.9	8.7	39.4		
NJ4	COMPREHENSIVE HIGH SCHOOL UMUAKA, NJABA, LGA	0.005494505	0.000826446	0.001410437	8.19672E-05			1.8	6.5	15.3	43		
NJ5	UMUNEKE IHIEBINEOWERE OKWUDOR, NJABA, LGA	0.001	0.000358423	0.000793651	5.81395E-05	0.00004		0.5	6.6	8.3	22.6	34	
NJ6	UMUDARA UBOKORO ATTA,NJABA,LGA	0.001945525	0.000163132	0.001730104	0.000409836	0.000113636		0.4	0.9	4	22.1	35.1	
NJ7	UMUEZIME NKUME, NJABA, LGA	0.003115265	0.0003125	0.003164557	3.63636E-05	7.14286E-05		0.4	1.6	7.2	24	23.8	
NJ8	DURUEWURU AMUCHA, NJABA LGA	0.005025126	0.017889088	0.000296736	5.88235E-05	0.000392157		1.4	1.7	2.4	17.9	40.5	
NJ9	UMUOKWARA IHEBINOWERRE, NJABA, LGA (1)	0.002680965	0.000666667	0.001560062	0.000135135	0.000113636		1	2.8	5.1	20.1	26.3	
NJ10	UMUOKWARA IHEBINOWERRE, NJABA, LGA	0.006493506	0.000316456	0.004016064	0.000129032	1.71527E-05	9.90099E-05	0.4	1	4.5	5.5	26.5	26
NJ11	ACHARAJI AKAH, NJABA LGA	0.000357143	0.000137174	0.000729927	0.000221239			0.9	1.5	3.9	31.1		
NJ12	NDUHU DURUEWURU AMUCHA, NJABA, LGA	0.003267974	0.000429185	0.002463054	0.000331126	8.26446E-05	8.47458E-05	0.5	2.4	7	17	36.4	38.7
NJ13	ACHARAJI AKAH, NJABA LGA	0.000357143	0.000137174	0.000729927	0.000221239			0.9	1.5	3.9	31.1	37.8	
NJ14	ISIOZI AKAH, NJABA LGA	0.012738854	0.003921569	9.17431E-05				0.5	6.2	30.1			
NJ15	UMUELE AMAZANO NJABA L.G.A	0.002	0.001219512	0.000628931	0.000302115			0.6	2.0	6.2	28.7		
NJ16	UMUOLU OBEAKPU NJABA L.G.A (2)	0.001715266	0.000341297	0.000793651	8.62069E-05	2.55754E-05		0.8	9.3	12.9	13.6	36.0	
NJ17	UMUOLU OBEAKPU NJABA L.G.A (1)	0.003558719	0.000746269	0.00243309	0.000228833	2.0284E-05		1.0	2.4	5.6	7.4	55.1	
NJ18	CHRIST THE KING PARISH, OKWUDOR	0.004587156	0.0003367	0.004166667	0.000333333	5.2356E-05	9.52381E-05	0.4	1.4	4.2	6.3	26.2	23.5
NJ19	COMMUNITY BOREHOLE UMUODIRI	0.000684932	0.001560062	0.001347709				30.0	23.5	31.3			
NJ20	UMUOKPURUFO AMAKOR, NJABA L.G.A	0.004065041	0.000133333	0.001402525	0.000114943	4.85437E-05	9.80392E-06	0.5	2.0	4.9	4.2	5.8	30.8
NJ21	UMUOCHA UMUELEM OKWUDOR, NJABA L.G.A	0.001176471	0.0003003	0.000996016	0.000359712			0.5	1.1	7.6	25.8		
NJ22	NDIHU UBAH UMUAKAH, NJABA L.G.A	0.006369427	0.020661157	0.000793651	0.000125	4.80769E-05		1.1	1.7	2.3	6.7	47.2	
NJ23	UMUDIM UMUELE AMAZANO, NJABA L.G.A	0.00243309	0.000246305	0.000787402	0.000529101	4.38596E-05		0.5	1.2	12.2	6.5	22.4	

VES NO	LOCATION	Longitudunal conductance = σh (Ω-1) OR S						Sum of longitudunal conductance (Ω-1) OR S	Sum of longitudunal conductance * 1000 (Ω-1) OR mS	Degree of vulnerability	Percolation time
		σ1h1	σ2h2	σ3h3	σ4h4	σ5h5	σ6h6				
NJ1	NDIUHU ACHARA UMUAKA NJABA, LGA	0.006060606	0.002372093	0.019645293	0.001262626	0	0				Several months
NJ2	OBINWANNE UMUAKA, NJABA LGA	0.006179775	0.020105125	0.003699422	0.00205102	0	0	0.032035342	32.03534249	Etremely High	Several months
NJ3	GENERAL HOSPITAL OKWUDOR NJA, LGA	0.000692308	0.000525362	0.003990826	0.002680272	0	0	0.007888768	7.888767808	Etremely High	Several months
NJ4	COMPREHENSIVE HIGH SCHOOL UMUAKA, NJABA, LGA	0.00989011	0.005371901	0.02157969	0.00352459	0	0	0.040366291	40.36629058	Etremely High	Several months
NJ5	UMUNEKE IHIEBINEOWERE OKWUDOR, NJABA, LGA	0.0005	0.002365591	0.006587302	0.001313953	0.00136	0	0.012126846	12.12684647	Etremely High	Several months
NJ6	UMUDARA UBOKORO ATTA,NJABA,LGA	0.00077821	0.000146819	0.006920415	0.009057377	0.003988636	0	0.020891458	20.89145768	Etremely High	Several months
NJ7	UMUEZIME NKUME, NJABA, LGA	0.001246106	0.0005	0.02278481	0.000872727	0.0017	0	0.027103643	27.10364332	Etremely High	Several months
NJ8	DURUEWURU AMUCHA, NJABA LGA	0.007035176	0.030411449	0.000712166	0.001052941	0.015882353	0	0.055094085	55.09408519	Etremely High	Several months
NJ9	UMUOKWARA IHEBINOWERRE, NJABA, LGA (1)	0.002680965	0.001866667	0.007956318	0.002716216	0.002988636	0	0.018208803	18.20880265	Etremely High	Several months
NJ10	UMUOKWARA IHEBINOWERRE, NJABA, LGA	0.002597403	0.000316456	0.018072289	0.000709677	0.000454545	0.002574257	0.024724628	24.72462775	Etremely High	Several months
NJ11	ACHARAJI AKAH,NJABA LGA	0.000321429	0.000205761	0.002846715	0.006880531	0	0	0.010254436	10.25443619	Etremely High	Several months

Table 10. Cont'd

NJ12	NDUHU DURUEWURU AMUCHA, NJABA, LGA	0.001633987	0.001030043	0.017241379	0.005629139	0.003008264	0.003279661	0.031822474	31.82247371	Etremely High	Several months
NJ13	ACHARAJI AKAH,NJABA L.G.A	0.000321429	0.000205761	0.002846715	0.006880531	0	0	0.010254436	10.25443619	Etremely High	Several months
NJ14	ISIOZI AKAH, NJABA L.G.A	0.006369427	0.024313725	0.002761468	0	0	0	0.03344462	33.44462013	Etremely High	Several months
NJ15	UMUELE AMAZANO NJABA L.G.A	0.00114	0.00247561	0.003899371	0.008670695	0	0	0.016185676	16.18567569	Etremely High	Several months
NJ16	UMUOLU OBEAKPU NJABA L.G.A (2)	0.001372213	0.003174061	0.010238095	0.001172414	0.000920716	0	0.016877499	16.87749927	Etremely High	Several months
NJ17	UMUOLU OBEAKPU NJABA L.G.A (1)	0.003558719	0.001791045	0.013625304	0.001693364	0.001117647	0	0.021786079	21.78607868	Etremely High	Several months
NJ18	CHRIST THE KING PARISH, OKWUDOR	0.001834862	0.00047138	0.0175	0.0021	0.001371728	0.002238095	0.025516066	25.51606584	Etremely High	Several months
NJ19	COMMUNITY BOREHOLE UMUODIRI	0.020547945	0.036661466	0.042183288	0	0	0	0.0993927	99.39270007	Etremely High	Several months
NJ20	UMUOKPURUFO AMAKOR, NJABA L.G.A	0.00203252	0.000266667	0.00687237	0.000482759	0.000281553	0.000301961	0.01023783	10.23783006	Etremely High	Several months
NJ21	UMUOCHA UMUELEM OKWUDOR, NJABA L.G.A	0.000588235	0.00033033	0.007569721	0.009280576	0	0	0.017768862	17.76886228	Etremely High	Several months
NJ22	NDIHU UBAH UMUAKAH, NJABA L.G.A	0.007006369	0.035123967	0.001825397	0.0008375	0.002269231	0	0.047062464	47.06246396	Etremely High	Several months
NJ23	UMUDIM UMUELE AMAZANO, NJABA L.G.A	0.001216545	0.000295567	0.009606299	0.003439153	0.000982456	0	0.01554002	15.54002031	Etremely High	Several months

and is represented in NJ2, NJ4, NJ8, NJ10, NJ14, and NJ22. Its resistivity ranges from 78.4 (at NJ14) to 199 Ωm (at NJ8). It is characterized by an average resistivity value of 158.08 Ωm, corresponding to sandy clay lithology. The thickness of the first layer lithology ranges from 0.4 (at NJ11) to 1.8 m (at NJ4) with a mean value of 1.1 m.

High Aquifer Resistivity (Ωm) was recorded at UmuokwaraIhebinowerre, followed by Umuolu Obeapku, with values of 28700 and 27900. A drop in Aquifer Resistivity was observed at Community Borehole, Umuodiri, with a resistivity value of 990, an indication of the sand body with clay admixtures. Within the Upper Imo River Basin, Opara et al. (2020) least aquifer resistivity 136 Ωm and also attributed it to clay lithology intercalated in a sand body. However, their maximum aquifer resistivity value was 4640 Ωm as compared to the value of 28700 Ωm observed in this study.

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. An Average Aquifer Depth of 92.5 m was observed and corresponds with the regional aquifer depth of the study area, as earlier established from pumping test data and other hydrogeological studies. 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 Ω^{-1} at Umuokwara Ihebinowere-1 (NJ9) to 0.031613 Ω^{-1} at Community Borehole Umuodiri (NJ19), with an average value of 0.00611693 Ω^{-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 which signifies low aquifer susceptibility to surficial pollutants (Alao et al., 2023). Moderate L_C was recorded in the central part, while low L_C was observed in the remaining parts. Regions of high Longitudinal Conductance are known to have a good aquifer protective capacity (Kwami et al., 2023). The highest value of Aquifer Transverse Resistance was recorded at Umuolu Obeakpu-1 (NJ17) with R_T value of 1408950 Ωm^2, while the least R_T was recorded at Community Borehole Umuodiri (NJ19) with R_T value of 30987 Ωm^2. The average R_T value in the study area is 407178.1739 Ωm^2.

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 lowest K_{NM} value was observed at Community Borehole Umuodiri (NJ19), with K_{NM} value of 0.0852 m/day. From the aforementioned models, the highest and lowest hydraulic conductivity values are the same for NJ9 and NJ19, respectively. The ability of a formation to transmit water is known as hydraulic conductivity (Emberga et al., 2022). As a result, an area with high hydraulic conductivity, including soil media, the vadose zone, and aquifer media, will be more vulnerable to contamination because a contaminant plume from anthropogenic sources will easily pass through the aquifer.

Table 11. Results of aquifer vulnerability using DRASTIC model.

VES NO	Location	Aquifer depth (m)	D		R		A		S		T		I		C		Drastic index	Vulnerability
			Dr	Dw	Rr	Rw	Ar	Aw	Sr	Sw	Tr	Tw	Ir	Iw	Cr	Cw		
NJ1	NDIUHU ACHARA UMUAKA NJABA, LGA	83	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate
NJ2	OBINWANNE UMUAKA, NJABA LGA	101	1	5	9	4	8	3	9	2	8	1	1	5	1	3	99	Low
NJ3	GENERAL HOSPITAL OKWUDOR NJA, LGA	91.9	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate
NJ4	COMPREHENSIVE HIGH SCHOOL UMUAKA, NJABA, LGA	115	1	5	9	4	8	3	9	2	8	1	1	5	1	3	99	Low
NJ5	UMUNEKE IHIEBINEOWERE OKWUDOR, NJABA, LGA	114	1	5	9	4	8	3	9	2	8	1	1	5	1	3	99	Low
NJ6	UMUDARA UBOKORO ATTA, NJABA, LGA	111	1	5	9	4	8	3	9	2	8	1	1	5	1	3	99	Low
NJ7	UMUEZIME NKUME, NJABA, LGA	86	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate
NJ8	DURUEWURU AMUCHA, NJABA LGA	100	1	5	9	4	8	3	9	2	8	1	1	5	1	3	99	Low
NJ9	UMUOKWARA IHEBINOWERRE, NJABA, LGA (1)	84	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate
NJ10	UMUOKWARA IHEBINOWERRE, NJABA, LGA	90	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate
NJ11	ACHARAJI AKAH, NJABA LGA	75.2	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate
NJ12	NDUHU DURUEWURU AMUCHA, NJABA, LGA	102	1	5	9	4	8	3	9	2	8	1	1	5	1	3	99	Low
NJ13	ACHARAJI AKAH, NJABA LGA	75.2	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate
NJ14	ISIOZI AKAH, NJABA LGA	77.2	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate
NJ15	UMUELE AMAZANO NJABA LGA	83.7	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate
NJ16	UMUOLU OBEAKPU NJABA LGA (2)	96	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate
NJ17	UMUOLU OBEAKPU NJABA LGA (1)	122	1	5	9	4	8	3	9	2	8	1	1	5	1	3	99	Low
NJ18	CHRIST THE KING PARISH, OKWUDOR	98.5	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate
NJ19	COMMUNITY BOREHOLE UMUODIRI	84.8	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate
NJ20	UMUOKPURUFO AMAKOR, NJABA LGA	77.9	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate
NJ21	UMUOCHA UMUELEM OKWUDOR, NJABA LGA	77.6	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate
NJ22	NDIHU UBAH UMUAKAH, NJABA LGA	106	1	5	9	4	8	3	9	2	8	1	1	5	1	3	99	Low
NJ23	UMUDIM UMUELE AMAZANO, NJABA LGA	75.5	2	5	9	4	8	3	9	2	8	1	1	5	1	3	104	Moderate

One of the models used in the estimation of vulnerability in the study area is the DRASTIC model (Table 11). 65.2% of the study area showed moderate vulnerability, while 34.75% showed low vulnerability. The geospatial map of vulnerability in the study area showed that the northwest and the central part of the area have a moderate vulnerability to groundwater pollution from surface pollutants (vulnerable to some pollutants but only when continuously discharged or leached), while the rest of the area showed a low value in the vulnerability index. The vulnerability of the study area using the GOD model revealed that all study areas exhibited a low vulnerability to groundwater pollution (Table 12). This implies that the aquifer is only vulnerable to conservative pollutants in the long term when continuously and widely discharged or leached. Results of aquifer vulnerability using the IEC model showed that the entire study area is generally vulnerable to pollution. This can be the geology of the study area, which is characterized by the presence of the Benin Formation coastal plain sand (Adegoke et al., 2017).

Table 12. Results of aquifer vulnerability using GOD model.

VES NO	Location	Parameter			Rating			GOD index	Vulnerability
		G	O	D	G	O	D		
NJ1	NDIUHU ACHARA UMUAKA NJABA, LGA	Confined	Alluvial soil	83	0.2	0.5	0.5	0.05	Moderate
NJ2	OBINWANNE UMUAKA, NJABA LGA	Confined	Alluvial soil	101	0.2	0.5	0.4	0.04	Low
NJ3	GENERAL HOSPITAL OKWUDOR NJA, LGA	Confined	Alluvial soil	91.9	0.2	0.5	0.5	0.05	Moderate
NJ4	COMPREHENSIVE HIGH SCHOOL UMUAKA, NJABA, LGA	Confined	Alluvial soil	115	0.2	0.5	0.4	0.04	Low
NJ5	UMUNEKE IHIEBINEOWERE OKWUDOR, NJABA, LGA	Confined	Alluvial soil	114	0.2	0.5	0.4	0.04	Low
NJ6	UMUDARA UBOKORO ATTA, NJABA, LGA	Confined	Alluvial soil	111	0.2	0.5	0.4	0.04	Low
NJ7	UMUEZIME NKUME, NJABA, LGA	Confined	Alluvial soil	86	0.2	0.5	0.5	0.05	Moderate
NJ8	DURUEWURU AMUCHA, NJABA LGA	Confined	Alluvial soil	100	0.2	0.5	0.5	0.05	Moderate
NJ9	UMUOKWARA IHEBINOWERRE, NJABA, LGA (1)	Confined	Alluvial soil	84	0.2	0.5	0.5	0.05	Moderate
NJ10	UMUOKWARA IHEBINOWERRE, NJABA, LGA	Confined	Alluvial soil	90	0.2	0.5	0.5	0.05	Moderate
NJ11	ACHARAJI AKAH, NJABA LGA	Confined	Alluvial soil	75.2	0.2	0.5	0.5	0.05	Moderate
NJ12	NDUHU DURUEWURU AMUCHA, NJABA, LGA	Confined	Alluvial soil	102	0.2	0.5	0.4	0.04	Low
NJ13	ACHARAJI AKAH,NJABA LGA	Confined	Alluvial soil	75.2	0.2	0.5	0.4	0.04	Low
NJ14	ISIOZI AKAH, NJABA LGA	Confined	Alluvial soil	77.2	0.2	0.5	0.5	0.05	Moderate
NJ15	UMUELE AMAZANO NJABA LGA	Confined	Alluvial soil	83.7	0.2	0.5	0.5	0.05	Moderate
NJ16	UMUOLU OBEAKPU NJABA LGA (2)	Confined	Alluvial soil	96	0.2	0.5	0.5	0.05	Moderate
NJ17	UMUOLU OBEAKPU NJABA LGA (1)	Confined	Alluvial soil	122	0.2	0.5	0.4	0.04	Low
NJ18	CHRIST THE KING PARISH, OKWUDOR	Confined	Alluvial soil	98.5	0.2	0.5	0.5	0.05	Moderate
NJ19	COMMUNITY BOREHOLE UMUODIRI	Confined	Alluvial soil	84.8	0.2	0.5	0.5	0.05	Moderate
NJ20	UMUOKPURUFO AMAKOR, NJABA LGA	Confined	Alluvial soil	77.9	0.2	0.5	0.5	0.05	Moderate
NJ21	UMUOCHA UMUELEM OKWUDOR,NJABA LGA	Confined	Alluvial soil	77.6	0.2	0.5	0.5	0.05	Moderate
NJ22	NDIHU UBAH UMUAKAH, NJABA LGA	Confined	Alluvial soil	106	0.2	0.5	0.4	0.04	Low
NJ23	UMUDIM UMUELE AMAZANO, NJABA LGA	Confined	Alluvial soil	75.5	0.2	0.5	0.5	0.05	Moderate

Conclusion

Estimation of soil corrosivity and competence in the study area using the electro-geophysical method gave as output a very reliable outcome, as can be evidenced from the first layer resistivity values. In terms of soil corrosivity, two zones (X and Y) have been identified. Zone X is essentially non-corrosive as can be deduced from the first layer resistivity, while Zone Y ranges from mildly to moderately corrosive. On the other hand, the study area was sectioned into four zones in terms of competence as follows; Zone A (incompetent); Zone B (moderately competent); Zone C (competent); and Zone D (highly competent). The diagnostic constant Kσ has proven to be very useful in this study. It was useful to delineate one distinct lithostratigraphic unit within the area which agrees with the geology of the area. The Kσ value was also used to estimate the hydraulic conductivity for all sounding points across 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. The vulnerability of the study area using geological models revealed that all study areas exhibited a low to moderate vulnerability to groundwater pollution, while the IEC model showed that the entire study area is generally vulnerable to pollution. It is hence, recommended that engineering soil stabilization or strengthening techniques be adopted to enhance soil properties for construction purposes within the Zone A region of the study area's competency geospatial map. Also, further soil improvement methods may be incorporated to enhance stability at Zone B of the same region. Corrosion-resistant materials should be used for depth value within 1.1 m of the study area. A thorough hydrogeochemical evaluation should be carried out to ascertain the water quality of the aquifer systems of the study area.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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