



Estimates of aquifer geo-hydraulic and vulnerability characteristics of Imo State and environs, Southeastern Nigeria, using electrical conductivity data

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Abstract Two hundred and twenty-six vertical electrical sounding (VES) data were acquired across the study area that has six geologic formations for the purpose of evaluating the geo-hydraulic potentials and the protective capacity of the aquifers of the study area. Schlumberger array was adopted for data acquisition using the ABEM™ Terrameter SAS 4000. Results of the study revealed four to six geo-electric layers. A variety of geo-electric curve types were identified in the study area with the KK curve type being dominant. The aquifer zones lie between the third and sixth layers with their resistivity values ranging from 101 to 8900 Ωm with a mean value of 1799 Ωm . Estimates of the aquifer hydraulic characteristics using the new set of model equations based on conductivity data revealed hydraulic conductivity range of 0.925 and 13.42 m/day while transmissivity ranged between 16.0 and 887 m^2/day . These findings showed that groundwater potential is high in Benin Formation, moderate in Nsukka and Ajali Formations, and generally poor within Ogwashi and Imo Shale Formations. Aquifer vulnerability studies

revealed that the values of the integrated electrical conductivity (IEC) of the study area ranged between 28.4 and 2202 mS with a mean value of 403 mS. Results of the IEC revealed that the aquifer protective capacity of most parts of the study area were extremely poor (86.2%) with percolation period of several months while only 1.8% of the study area are fairly good. The aquifers of the study area may therefore be vulnerable to contamination from anthropogenic sources, and adequate aquifer protective strategies are therefore recommended.

Keywords Aquifer · Geo-hydraulic · Aquifer vulnerability · Integrated electrical conductivity, resistivity · Nigeria

Introduction

Groundwater is the major source of potable water in Imo State and its environs, Southeastern Nigeria, with thousands of boreholes drilled by governmental agencies, private firms, and individuals to provide the teeming population with potable water. However, in most of these cases, detailed geological and hydrogeophysical investigations were not properly carried out before the locating, drilling, and installation of these boreholes. These have led to high rate of drilling of abortive wells and borehole failures in the study area, thus making the supply of good quality water in the area grossly inadequate. For proper water resource management, there is the need for a sound knowledge of the local/regional groundwater potential and other aquifer geo-hydraulic

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characteristics. Many researchers have used several methods like GIS to delineate aquifer characteristics and aquifer potentials worldwide (Atiqur 2008; Babiker et al. 2005; Chowdhury et al. 2010; Saro et al. 2012; Nwachukwu et al. 2013; Naghibi et al. 2016). The estimation of the spatial distribution of aquifer hydraulic parameters, like porosity, conductivity, and transmissivity, using well test data and grain size analysis has also been part of the methods used by researchers over the years for studying aquifer potentials and associated characteristics (Ibeh and Njoku 1999; Ugada et al. 2013).

Hydraulic conductivity and aquifer protective capacity are two fundamental properties that describe the hydrogeology of the aquifer system of any particular area. These properties are more effectively determined using geological information extracted mainly from drilled wells. Most often pumping tests are carried out to determine aquifer hydraulic properties including the drawdown, specific yield, transmissivity, and hydraulic conductivity. However, in the case of paucity or dearth of pumping test data, few pump test information is from existing boreholes or monitoring wells within the study area together with extracted aquifer conductivity data from surficial electrical resistivity measurements. Vertical electrical sounding (VES) can be highly effective in determining these fundamental geo-hydraulic properties.

It is sufficiently known and well established that electrical conductivity data of the subsurface can be used to provide important information for detailed aquifer delineation and characterization (Metwaly et al. 2014; Madi et al. 2016; Opara et al. 2012). Surficial electrical resistivity investigation techniques have therefore been used extensively in delineating groundwater resources in various parts of the world (Niwas and Singhal 1981; Barker et al. 2001; Lashkaripour 2003; Abiola et al. 2009; George et al. 2010; Obiora et al. 2015).

Similarly, several scholars have previously established a strong relationship between aquifer hydraulic conductivity and aquifer resistivity indicating an inverse relationship (Heigold et al. 1979; Niwas and Singhal 1981; Niwas and Celik 2012; Obiora et al. 2016a, b). This relation has been applied by researchers to estimate aquifer hydraulic characteristic, geometrical potential, and vulnerability using electrical resistivity data (Obiora et al. 2016a, b; Ugada et al. 2013). It is obvious that the derived relation between aquifer resistivity and geo-hydraulic properties is highly sensitive to lithological characteristics (Heigold et al. 1979; Niwas and Singhal 1981). Uma (1989) carried out a study on the groundwater resources of the Imo River

Basin and identified both shallow and deep aquifers of the basin using few available pump test and borehole data. Similarly, some parts of the study area (Imo River Basin) have been previously explored by various researchers using Dar-Zarrouk parameters (Onuoha and Mbazi 1988; Mbonu et al. 1991; Igbokwe et al. 2006; Ekwe et al. 2006; Ekwe and Opara 2012; Opara et al. 2012; Ijeh and Onu 2012; Ugada et al. 2013, 2014; Eke et al. 2015). However, the geology of the study area is very complex and variable, with over six geological formations, several subformations and units, with some being very localized both in extent and lateral continuity. Based on this therefore, it was revealed that previously well-known equations/models used for estimating aquifer hydraulic parameters from geo-sounding data were found to be inappropriate because some of the formations/units were not similar in geology to the environments where the said equations were derived from. Therefore, a new set of geologically sensitive equations which are formation specific were proposed and used in this study.

Groundwater vulnerability is the tendency of an aquifer to receive contaminants from anthropogenic or other surficial sources. Aquifer protection capacity or vulnerability is therefore essential for a sustainable use of groundwater resources, and the protection of ground water is therefore a function of the covering layers. The degree of contamination however depends on certain intrinsic properties of aquifer systems which may include the topography, porosity/permeability, and the climatic factors amongst others. Groundwater vulnerability is a function not only of the properties of the groundwater flow system but also of its nearness to contaminant sources, the character of the contaminant, and other factors that could cause the potential contaminants to reach the groundwater resources as quickly as possible (Michael et al. 2005).

Conventionally, several geological methods that use parameters such as depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity (DRASTIC); groundwater occurrence, overlying lithology and depth to water (GOD); groundwater table (soggiacenza), effective infiltration (infiltrazione), unsaturated zone (non-saturo), overburden type (tipologia della copertura), aquifer hydrologic characteristics (caratteristiche idrogeologiche dell'aquifero), hydraulic conductivity (conducibilita idraulica) and topographical surface slope (acclivita della superficie topografica) SINTACS, have been used by several scholars to study issues related to aquifer protective capacity (Aller et al. 1987; Navulur and Engel 1996; Vrba and

Zaporozec 1994). Several classical reports and papers successfully applied DRASTIC model in evaluating aquifer vulnerability (Aller et al. 1987; Lathamani et al. 2015; Mondal et al. 2017). Generally, the DRASTIC model is the most popular and most extensively used model for aquifer vulnerability estimation. However, the GOD model presents a less cumbersome model comprising of three parameters which include ground water occurrence, overall aquifer class, and depth to groundwater table (Foster 1987). In very recent times, because of the paucity of data (generally borehole and other geological information) needed for the estimation of aquifer vulnerability, several equations based on electrical conductivity have been used with great success to predict aquifer vulnerability characteristics worldwide (Van Stempvoort et al. 1992; Rottger et al. 2005; Obiora et al. 2016a, b; Madi et al. 2016).

Aquifer Vulnerability Index (AVI) estimates vulnerability by hydraulic resistance to vertical flow of water through the protective layers (Van Stempvoort et al. 1992). The AVI is similar to integrated electrical conductivity (IEC) proposed by Rottger et al. (2005) which is a geo-physically based approach that estimates vulnerability using the integrated electrical conductivity of the uppermost earth layers that overlie the aquifer layer. In this study, the aquifer vulnerability of Imo State and environs was estimated using the IEC method and the result was further correlated/validated by comparing them with the estimates made using the DRASTIC method.

The sedimentary sequences of the Imo River Basin which the study area is part of are known to be made up of several aquifer units and geologic formations. High yearly average rainfall, high porosity and connectivity of the aquifer zones generally account for groundwater recharge within the study area. Despite the fact that thousands of water wells have been drilled at various parts of the study area, it is generally believed that there is a great need to carry out detailed hydrogeophysical studies to establish the nature, type, extent and hydraulic characteristics of the aquifers. This is very vital and apt in view of several unsuccessful and unproductive boreholes drilled in the study area. In addition, there is a scarcity of detailed current information on the aquifer hydraulic characteristics of the study area because of the high cost of pumping test which is very exorbitant to private individuals who have drilled water boreholes in the area.

The objective of this study therefore is to provide a cost effective technique for evaluating the groundwater geo-hydraulic and vulnerability characteristics of the study area using direct current conductivity methods. It

is strongly believed that the result of this study will be very useful for regional groundwater assessment, management and protection of the study area.

Location, physiography and geology of the study area

The study area is located within the Imo River Basin and thus lies between longitudes 6° 40'–7° 45'E and latitudes 4° 35'–6° 00' (Fig. 1). The basin is densely populated with fast growing cities and urban areas characterized by urbanization and industrialization. Before the advent of industrialization, the major occupation of the people is agriculture, fishing and trading. The drainage system of the Imo River Basin is mainly dendritic with the study area drained by so many rivers and their associated tributaries. These rivers include the Imo River, Otammiri, Oramurikwa and Orashi. The Imo River takes its course from the Okigwe/Awka upland and runs through the area underlain by Imo Shale and the coastal plain sands of the Benin Formation (Amangabara 2015). The river traverses through three states which include Imo, Abia and Rivers states. The basin has low lying to moderately high topography. The elevation of the study area ranges from about 53 to 255 m above sea level as shown in Fig. 1.

The Imo River Basin is located in the tropical, equatorial rain forest belt of West Africa. It is a 140 km north–south trending sedimentary syncline located in the upper Niger delta within the middle of Southeastern Nigeria stretching across three states. The climatic conditions of the study area are characterized by uniformly high temperatures and a seasonal distribution of precipitation with average rainfall of about 2200 mm/year (which generally increases southwards). Two main weather seasons are prominent in the area namely: dry and rainy seasons with average minimum and maximum temperatures of 25° and 34 °C respectively.

The geology of the Imo River basin is based on the sequence of alluvial deposits of Southeastern Nigeria with a thickness of about 5480 m and with ages ranging from Upper Cretaceous to Recent (Uma and Egboka 1986; Uma 1989). The generalized regional stratigraphy and detailed description of the basin is shown in Table 1. The Imo River Basin is underlain by a succession of six major geologic formations which include the Benin, Ogwashi, Ameki, Imo shale, Nsukka and Ajali Formations as shown in Fig. 2. The Benin

Fig. 1 Location and topographic map of the study area

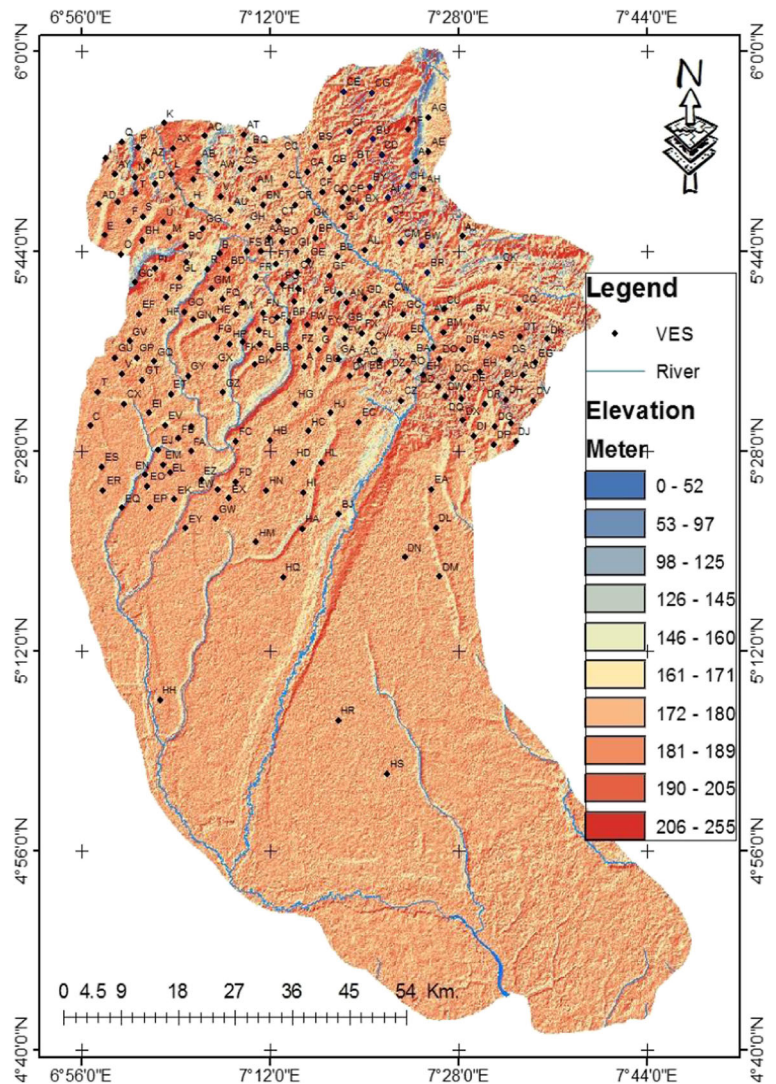
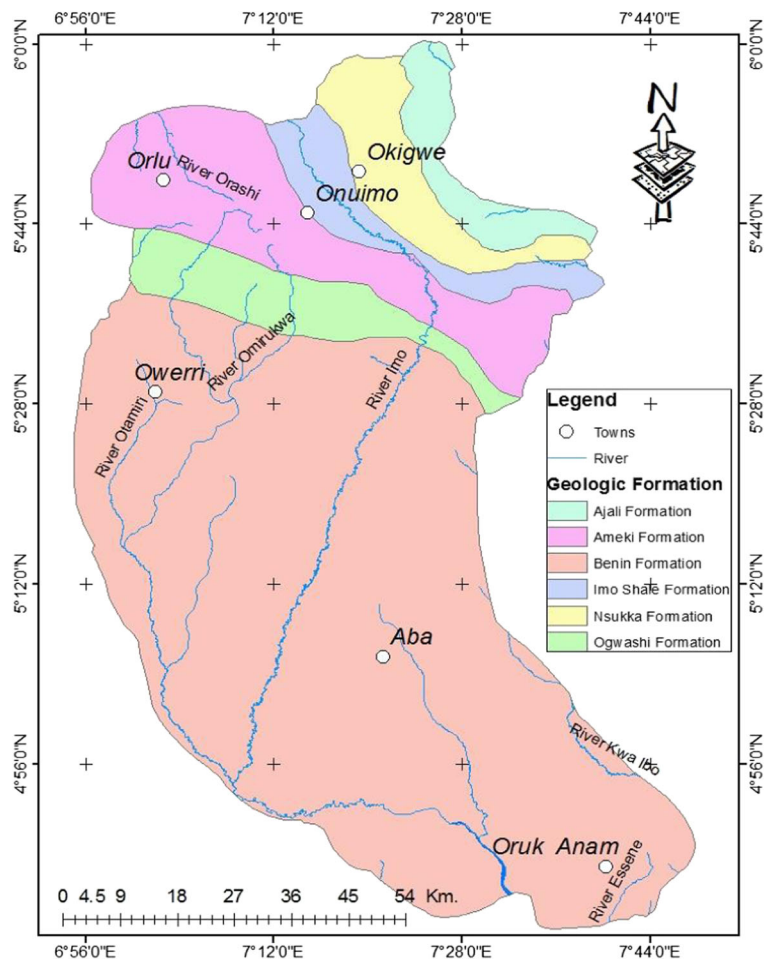


Table 1 Generalized stratigraphy of the Imo River Basin (after Uma, 1989)

Age	Formation	Character
Miocene to Recent Oligocene	Benin Formation (BF)	Unconsolidated, yellow and white sands, occasionally pebbly with leases of grey sandy clay
Miocene to Ogwashi	Formation (OF)	Unconsolidated sandstones with carbonaceous mudstones, sandy clays and lignite seams
Eocene	Ameki Formation (AF)	Sandstones (grey to green argillaceous sandstones), shales and thin limestone
Paleocene	Imo shale (OF)	Blue to dark grey shales and subordinate sandstones. It includes two sandstone members: the Umuna and Ebenebe sandstones
Upper Maestrichtian	Nsukka Formation (NF)	White to grey coarse-to-medium-grained sandstone, carbonaceous shales, sandy shales, subordinate coals and thin limestones
Lower Maestrichtian	Ajali Formation (AJF)	Medium-to-coarse-grained, sandstones, poorly consolidated with subordinate white and pale grey shale bands

Fig. 2 Geological map of the Imo River Basin (modified After Uma., 1989)



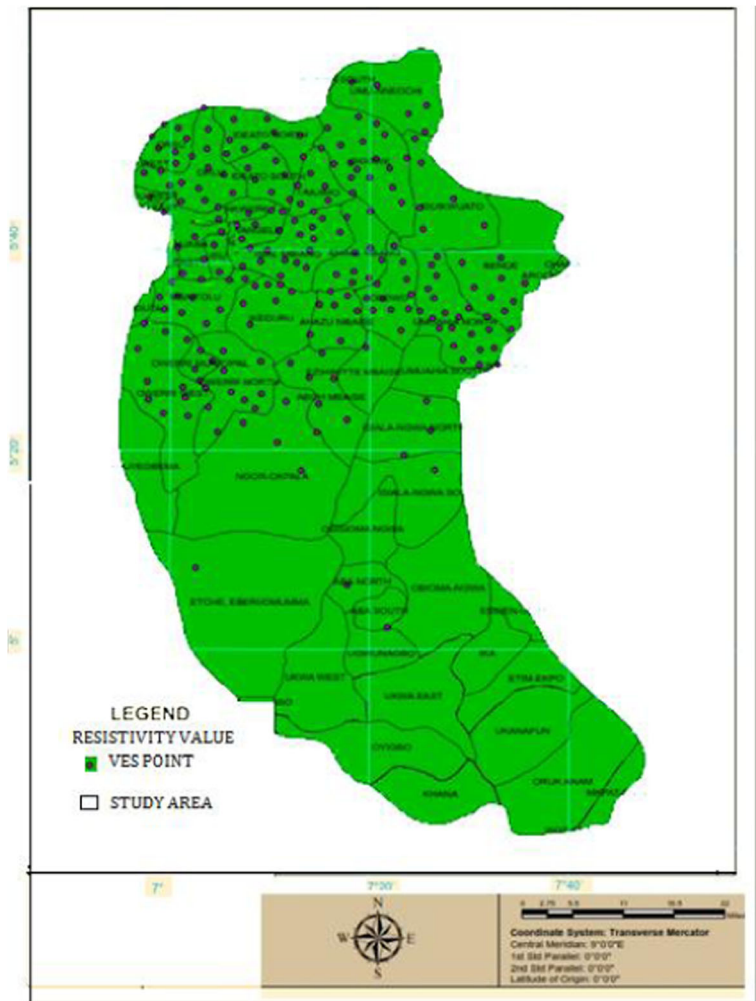
Formation consists of unconsolidated yellow and white coastal plain sands with gravel beds, occasionally pebbly with grey sandy clay lenses. It is made up of friable sands with minor intercalation of clay. A detailed description of the stratigraphy of the study area is presented in Table 1. Uma (1989) identified three aquifer units in the Imo River Basin including a shallow unconfined aquifer, a confined aquifer and a deep unconfined aquifer system. Near surface shallow unconfined aquifers are the main sources of water used by both public and private wells within the study area. These aquifers are especially prolific along the southern flank of the Imo River basin and most often occur at depths of about 70–100 m (Nwachukwu et al. 2010). Generally, the occurrence of groundwater, the extent and the distribution of aquifers and aquitards are normally determined by the lithology, stratigraphy and

structure of the geological strata present (Hiscock 2005).

Materials and methods

Two hundred and twenty-six vertical electrical soundings (VES) were carried out in the study area (Fig. 3). The data was acquired using ABEM™ Terrameter SAS 4000 with a maximum current electrode separation of 1000 m. For correlative and parametric purposes, (Igbokwe et al. 2006) parametric soundings were carried out at the sites of existing monitoring wells. This was done in addition to the correlation of the resistivity data with the litho-log, electric log and available pump test data from the monitoring wells across the study area. The objective was to constrain the predictive models formulated (based on data

Fig. 3 Location map of the study area showing the vertical electrical sounding (VES) points

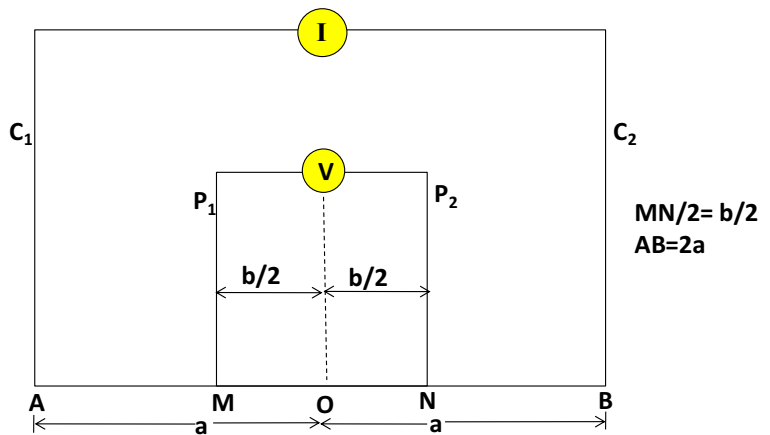


from electrical conductivity close to monitoring wells) with the local geology of the study area.

The Schlumberger electrode array (Fig. 4) was employed for the acquisition of vertical electrical sounding

with half current electrode separation ($AB/2$) of 500 m and half potential electrode separation ($MN/2$) of 55 m. The observed field data were processed to apparent resistivity using the appropriate geometrical factor (k) given by Eq. 1:

Fig. 4 Schematic diagram of the Schlumberger array used for vertical electrical sounding



$$K = \frac{\pi(a^2 - b^2)}{2b} \tag{1}$$

where K is the geometric factor, a is half current electrode separation while b is half potential electrode separation.

The field data was reduced to their equivalent geological models using computer modeling techniques (Zohdy et al. 1974). WinResist™ software which took care of the effects of lateral inhomogeneities and other forms of noisy signatures were used to generate smooth VES curves using the apparent resistivity and the electrode distance parameters as the input data. Figure 5 shows samples of some of the VES curves generated within the study area. Generally, geo-electric curves give insight into the local geology and stratigraphy by indicating the earth layers, layer resistivities (ρ) and their corresponding depths (d). The thickness of the layers is generally estimated from the depths of the layer parameters which were initially estimated from the available VES curves.

The layer parameters together with the subsurface geological data including litho-logs, geophysical well log and pump test data were used to estimate aquifer hydraulic parameters of the study area. Niwas and Singal (1981) combined the Ohm’s and Darcy’s laws to generate two expressions for transmissivity given as follows:

$$T = \frac{K}{\rho} R = k\sigma R \tag{2}$$

$$T = k/\sigma S \tag{3}$$

The direct and inverse relationships were further explained as being dependent on aquifer resistivity, where Eq. 2 is a case of highly resistivity basement while Eq. 3 for highly conductive basement (Niwas et al. 2011; Niwas and Celick 2012).

Similarly, Heigold et al. (1979) used an equation given in Eq. 4 to estimate the hydraulic conductivity from resistivity data.

$$H = 386.40R_w^{-0.93283} \tag{4}$$

where H is the hydraulic conductivity and R_w is the resistivity of the water saturated aquifer.

However, due the complex nature of the geology of the study area, the above models under-predicted in

most of the formations within the study area. Using the method adopted by Heigold et al. (1979), an equation of the type as shown in Eq. 5 was derived:

$$K = c\rho_w^d \tag{5}$$

where c and d are constants that depend on the geologic formations overlying the aquifer unit, ρ_w is the aquifer resistivity in ohm meter and K is the aquifer hydraulic conductivity in meters per day. These constants were evaluated from the scatter plots of aquifer hydraulic conductivity K from monitoring wells versus aquifer resistivity ρ_w from geo-electric soundings close to the monitoring wells (Fig. 6). A set of these formation specific equations were therefore generated for each of the formations as shown in Fig. 6 and Eq. 6a–f. Analysis of the bivariate regression models gave a set of power equations (each for the six different formations). From the six geologic formations, the following formation-specific model equations were therefore generated as shown in Eq. 6a–f:

$$K_{BF} = 0.010\rho_w^{0.838} \tag{6a}$$

$$K_{OF} = 6.756\rho_w^{0.02} \tag{6b}$$

$$K_{AF} = 0.065\rho_w^{0.070} \tag{6c}$$

$$K_{IF} = 305\rho_w^{-0.65} \tag{6d}$$

$$K_{NF} = 44697\rho_w^{-2.04} \tag{6e}$$

$$K_{AJF} = 3.395\rho_w^{0.110} \tag{6f}$$

Equations 6b, 6d, and 6e show inverse relationship between aquifer resistivity and hydraulic conductivity which according to Heigold et al. (1979) is paradoxical in the light of some previous studies and generally accepted ideas about relationship of resistivity of aquifer materials to its ability to produce water.

Aquifer transmissivity which is the rate at which ground water flows horizontally through an aquifer

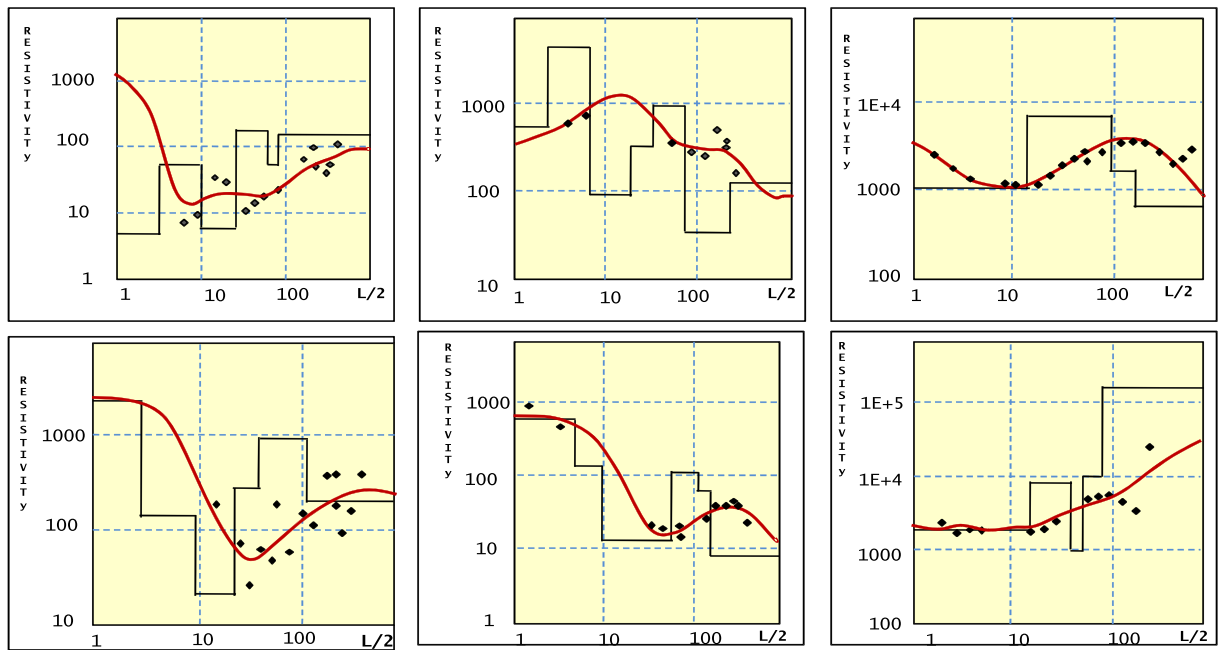


Fig. 5 Representative samples of geo-electric curves generated from the study area

was evaluated using Eq. 7. Combining Eqs. 3 and 5 gives Eq. 7 which was used to estimate the aquifer transmissivity

$$T = \left[\frac{c\rho_w^d}{\rho_w} \right] R \tag{7}$$

Diffusivity (D) and storativity (S) were estimated using Eqs. 8 and 9 respectively

$$D = \frac{T}{S} \tag{8}$$

$$S = \frac{1.3h}{R} \tag{9}$$

where h is thickness of the aquifer.

Aquifer vulnerability assessment using electrical conductivity data

Integrated electrical conductivity (IEC) technique was adopted in this work and the result was compared with estimates of groundwater vulnerability using the DRASTIC method. IEC method quantifies groundwater vulnerability by hydraulic resistance to vertical flow of

wastewater through the unsaturated layers. The (IEC) is normally estimated using Eq. 10 (Rottger et al. 2005).

$$IEC = \sum \sigma_i h_i \tag{10}$$

where σ_i and h_i are the electrical conductivities and equivalent thicknesses of each layer above the aquifer layer. The unit of IEC is given as siemens (S). A similar technique was previously used by earlier scholars in estimating aquifer vulnerability (Obiora et al. 2016a, b; Madi et al. 2016). Madi et al. (2016) established a vulnerability assessment criteria ranging from extremely high (less than 500 mS) to extremely low aquifer vulnerability (greater than 4000 mS) using the IEC method as shown in Table 2.

Similarly, Obiora et al. (2016a) used a modified form of the integrated electrical conductivity formula given in Eq. 11 below to estimate aquifer protective capacity:

$$S = \frac{\rho_i}{h_i} \tag{11}$$

where S is the longitudinal conductance, ρ_i and h_i are the resistivities and thicknesses of the layers above the aquifer zone respectively.

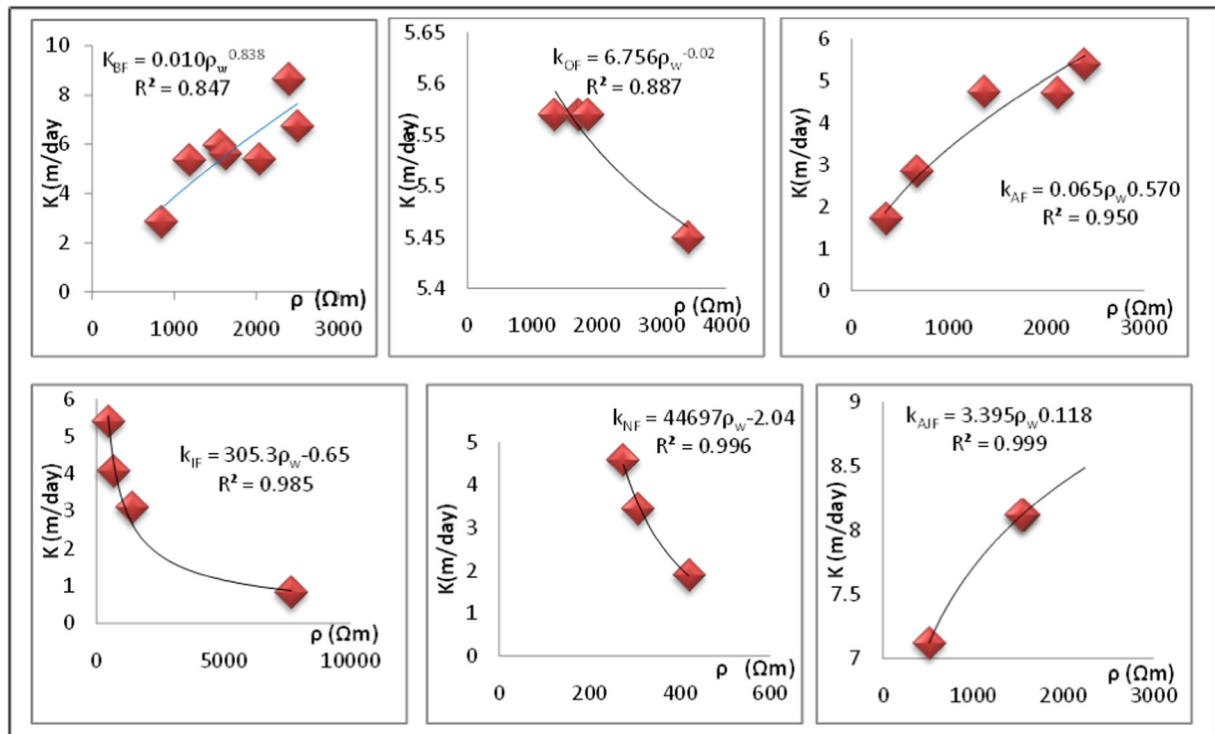


Fig. 6 Bivariate regression plots of aquifer hydraulic conductivity K , from well data versus aquifer resistivity (ρ_w)

Aquifer vulnerability estimation using the DRASTIC technique

Aquifer vulnerability of the study area was estimated using the DRASTIC method. The DRASTIC Index is usually calculated using Eq. 12:

$$DI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \tag{12}$$

where DI is the DRASTIC Index, which is the weighted sum overlay of the seven parameters, D represents depth to water table, R is the net rate of recharge, A is aquifer medium, S is soil medium, T is topography, I is impact of the vadose zone and C is hydraulic conductivity. The subscripts r and w represent the rating and weighting respectively. Depth to water level (D), soil media, aquifer media, and vadose zone characteristics were estimated in this study using information extracted from pumping test data, well logs and VES data from the study area. Similarly, the hydraulic conductivity of the various layers above the aquifer, used in calculating the DRASTIC Index, was estimated from pump test, estimates of hydraulic conductivity made from sieve

analysis of representative layer samples and those estimated from the conductivity data in this work.

The recharge capacity of the aquifer is generally defined as the capacity of water to flow from the surficial unsaturated zones to the saturated zones of the aquifers. It depends mainly on the following factors which include net recharge (R), topography (T), impact of the vadose zone (I) and hydraulic conductivity. Net recharge (R) represents the amount of water that penetrates the ground surface and percolates down to the water table per unit area and as a rule of thumb is taken as 12% of the average annual rainfall per year (USEPA 1985; Engel et al. 1996; Navulur and Engel 1996). In the study area, since the average annual rainfall is 2200 mm/year, 12% of it was calculated and converted to inches and used to rate the aquifer based on the method adopted by Engel et al. (1996). The topography (T) which refers to the slope or steepness of the land surface generally dictates whether the runoff will remain on the surface to allow contaminant percolation to the saturated zone or not. Since the area was found to be relatively flat with the slope ranging from 0 to 3%, therefore, flat areas were assigned higher rates because the run off tends to be less. The influence of the vadose zone on intrinsic aquifer

Table 2 Intrinsic aquifer vulnerability classification based on integrated electrical conductivity (IEC) showing aquifer protective capacity

S/N	Degree of vulnerability	Vulnerability index	Percolation time
1	Extremely high	< 500	Several months
2	High	500–1000	Several months–3 years
3	Moderate	1000–2000	3–10 years
4	Low	2000–4000	10–25 years
5	Extremely low	> 40,000	> 25 years

vulnerability depends on its porosity, on permeability and on the attenuation characteristics of the media. Finally, since the hydraulic conductivity is the ability of the aquifer to transmit water, it means that an area (including soil media, vadose zone and aquifer media) with high hydraulic conductivity will be more vulnerable to contamination as a contaminant plume from anthropogenic sources will easily pass through the aquifer. The basis of the classification of intrinsic aquifer vulnerability using the DRASTIC Index is presented in Table 3 below. Generally, there are four classes of aquifer vulnerability based on the DRASTIC Index (DI), ranging from low to very high vulnerability.

Results and discussion

Estimates of aquifer layer parameters

The summary of the results of the layer parameters and the estimates of the vulnerability estimates from IEC obtained from resistivity data interpretation is presented in Table 4. An analysis of the results of the 226 vertical electrical soundings (VES) revealed five to six geo-electric layers with the aquifer zones lying mainly between the third and sixth layers. Because of the complex geology of the study area, several primary curve types and their combination types were identified. The percentage of occurrence of these respective geo-electric curve types are summarized as follows: KK (22.6%); KA (8.4%); HH (8.0%); HQ (7.5%); AQ (6.6%); HK (4.8%); AK (4.4%); KH (4.0%); HKA, HKQ, and AHQ

Table 3 Aquifer vulnerability classification based on DRASTIC Index (Engel et al. 1996)

Classes of vulnerability	Low	Average	High	Very high
Drastic index	< 101	100–140	141–200	> 200

(3.1% each); AH, HHQ, and KHQ (2.7% each); KQA, KQ, and QH (2.2% each); AA and QK (1.8%); HAQ and K (1.3%); QQ and KKA (0.9%); and Q and HA (0.4% each). Generally, the KK curve type was revealed to be the most dominant curve type in the study area.

The aquifer resistivity of the study area varied from a minimum value of 101 Ωm within the Ameki Formation to a maximum value of 8900 Ωm at Amuri within the Ogwashi Formation with a mean value of 1799 Ωm (Fig. 7). Aquifer resistivity generally depends more on the saturation of the layer and not really on the thickness. The aquifer depth within the study area ranged from 12.6 to 199 m with an average value of 84.7 m. Similarly, the aquifer thickness in the study area is highly variable with values ranging from 2.3 to 99.9 m, with a mean value of and 37.1 m. The longitudinal conductance within the study area ranged from 3×10^{-3} to $4.7 \times 10^{-2} \Omega^{-1}$ with a mean value of $4.7 \times 10^{-2} \Omega^{-1}$ while the transverse resistance ranged between 1760 and 445,890 Ωm^2 with a mean value of 66,572 Ωm^2 . These results are in agreement with the findings of earlier studies carried out in various parts of the study area (Ekwe and Opara 2012; Opara et al. 2012; Ugada et al. 2014, 2013; Eke et al. 2015). Eke et al. (2015) estimated aquifer thicknesses of 1.7–108 m in parts of the Upper Imo River Basin around Umuahia and Obowo areas.

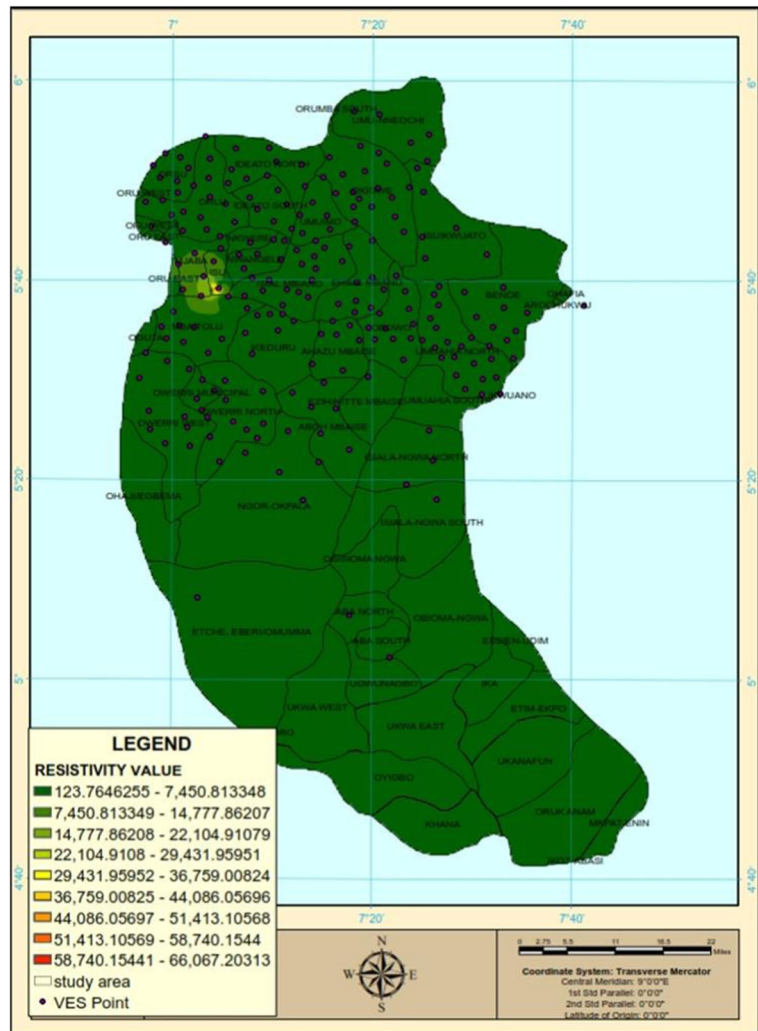
Aquifer vulnerability estimation in the study area

The intrinsic aquifer vulnerability of the study area was estimated from surficial conductivity data using the integrated electrical conductivity technique (Table 4) and is given in siemens (S) and milli-siemens (mS). For the purpose of comparison, aquifer vulnerability was also estimated at the same locations using the DRASTIC technique as shown in Tables 5 and 6. The contour maps of the spatial variation of IEC and

Table 4 Summary of aquifer layer parameters and integrated electrical conductivity estimates of the study area

VES NO	VES	Location	Longitude	Latitude	σ_1	σ_2	σ_3	σ_4	σ_5	σ_6	h_1	h_2	h_3	h_4	h_5	h_6	$\sum \sigma_i h_i$	IEC(mS)	GF
A		Umuaka	7.011	5.663	0.00028	5.99E-05	6.25E-06	0.000112	1.77E-05	2.9E-05	0.6	24.1	33.2	50.1	47		0.08	80	OF
AE		Uturu 2	7.4	5.8167	0.00171	0.00133	0.008403	0.002237	0.00102	0.00065	0.6	1.7	7	43.9	63	55	0.26	260	AJF
AF		ABSU 1	7.3833	5.8167	0.00111	0.007752	0.001351	0.004386	0.000641		0.4	3.5	11.5	15.6	68		0.155	155	AJF
AJ		Uturu 1	7.7809	5.8314	0.00272	0.003155	0.001153	0.004975			0.8	2.7	168				0.204	203.8	AJF
AN		Orie Agu	7.3092	5.6658	0.00122	0.030303	0.000476	0.004739	0.004219	0.00055	4.4	47.3	29.1	25.2	29		1.694	1694	AJF
AP		Umunumo	7.2974	5.6485	0.00364	0.000166	0.001099	0.000301	0.000833	0.00294	0.6	2.6	15.8	20.1	11	14	0.075	75	OF
BA		Nsu	7.4048	5.637	0.00613	0.004292	6.06E-05	0.000191	0.000156	0.00038	1.7	10.3	28	11.7	46	47	0.084	84	OF
BL		Agbobu	7.3122	5.804	0.00337	0.03125	0.166667	0.083333	0.015152	0.00369	1.9	0.5	59.9	40.7	44	13	2.201	2201	IF
C		Amigo	7.0613	5.77558	0.00637	0.002732	0.001292	0.001883	0.002404	0.0024	1.1	1.2	4.9	7.7	24		0.089	89	BF
CA		Ndi Ndubuisi	7.3135	5.8091	5E-05	0.000344	0.002353	0.001558	0.000747	0.00578	2	1.3	10.3	16.6	43	37	0.297	297	IF
CB		Umunwizuzu	7.3051	5.8245	0.0027	0.000645	0.009901	0.041667	0.04	0.00082	0.6	1.8	2	14.4	7.9	22	0.957	957	IF
CF		Umunneochi	7.3122	5.8229	0.00148	0.009524	0.001305				4.8	15.2	175				0.38	380	NF
CG		Umuloto	7.3214	5.9467	0.00333	0.000415	0.002262	0.009259			2.3	18.6	72.2				0.179	179	NF
CI		ABSU 2	7.4259	5.824	0.0051	0.003058	0.002667	0.000481	0.0001957		5.4	47.6	44.9	11.1			0.298	298	NF
CJ		Uturu Rd	7.4259	5.824	0.07937	0.086957	0.006579	0.001931	0.000481	0.00952	1.4	5.3	3.5	37.5	36		0.685	685	AJF
CL		FGC OKIGWE	7.1818	5.7456	0.00236	0.001031	0.000877	0.002695	0.000365	0.01111	2	3.4	7.6	49	61		0.169	169	IF
D		Amaifeke	7.0609	5.809	0.00039	0.000575	0.000518	0.000339	0.000148	0.0002	6.6	37.6	27.7	19.2	36		0.05	50	AF
E		Okporo	6.984	5.8002	0.00032	0.000338	0.000313	0.00049	0.00019		8.2	42.8	49	22			0.043	43	AF
E		Umuuduru	6.984	5.8002	0.00032	0.000338	0.000313	0.00049	0.000192		8.2	42.8	49	22			0.043	43	AF
F		Orlu	6.984	5.8001	0.00028	0.00012	0.000847	0.00119	0.000281	0.00011	11	8.7	14.3	24	26		0.052	52	AF
G		Okwudor	7.01108	5.72066	0.00034	0.004032	0.000333	5.24E-05	9.52E-05	0.0002	1.8	4.2	6	26.5	24	36	0.03	30	OF
GS		OGWA	7.07142	5.65201	0.00096	0.000358	0.002075	0.000625	0.000142	0.00025	1.9	16.2	27	46	74	35	0.111	111	BF
HL		Aboh Mbaise	7.25541	5.53372	0.00719	0.000625	0.002604	0.000649	0.000259	8.5E-05	3.3	6.5	13.9	43.5	39	41	0.106	106	BF
HM		Nisshi Ogbe	7.29176	7.29176	0.00342	0.001416	0.002008	4.24E-05	0.000386		0.4	2.9	6.6	8.3	2.3		0.02	20	BF

Fig. 7 Contour map of aquifer resistivity of the study area



DRASTIC Index values across the study area are shown in Fig. 8a, b respectively.

The IEC values ranged from 28.4 to 2202 mS with a mean value of 403 mS. Extremely high/high vulnerability areas with IEC values ranging between 28.4 and 1000 mS were interpreted in parts of the study area. Similarly, moderate vulnerability areas with IEC values between 1000 and 2000 mS and low vulnerability areas with IEC values greater than 2000 mS were also delineated within various parts of the study area. The degrees of vulnerability and percolation time of the contaminants from anthropogenic sources were estimated from the IEC method based on the method adopted by Madi et al. (2016).

The results of this study are similar to IEC values estimated in other parts of Nigeria (Obiora et al. 2016a, b; Terhemba et al. 2016). The present results of aquifer

vulnerability are similar to the findings of George et al. (2017) in the surficial aquifer units of the coastal regions of Akwa Ibom State, Southeastern Nigeria. Extremely high vulnerability index values less than 500 mS, having a percolation time of several months were revealed in most parts of the study area as shown in Table 4 and Fig. 8a. Most parts of the study area (86.2%) are within this class of extreme high vulnerability. This indicates that it will take surficial effluents or any other liquid waste in the study area some months to get into the groundwater; this is really worrisome in view of the huge and active sources of pollution like e-wastes, auto-mobile and motor scrap workshops, unprotected shallow municipal dumpsites and the general poor waste management in the study area (Ejiogun et al. 2017). The high aquifer vulnerability of the study area especially within the Benin Formation (which is prone

Table 5 Summary of estimates of DRASTIC Index, of the study area showing the evaluation of the seven parameters

VES no.	Depth to water			Rate of recharge			Aquifer media			Soil media			Topography			Impact of			Hydraulic			DRASTIC	
	D			R			A			S			T			I			Cr			Index	
	Dr	Dw	DrDw	Rr	Rw	RrRw	Ar	Aw	ArAw	Sr	Sw	SrSw	Tr	Tw	TrTw	Ir	Iw	IrIw	Cr	Cw	CrCw	DI	DI
A	1	5	5	8	4	32	10	3	30	10	2	20	4	1	4	8	5	40	2	3	6	187	H
AE	1	5	5	6	4	24	8	3	24	8	2	16	4	1	4	3	5	15	1	3	3	91	L
AF	1	5	5	6	4	24	8	3	24	9	2	18	2	1	2	3	5	15	1	3	3	91	L
Al	9	5	45	6	4	24	8	3	24	8	2	16	7	1	7	3	5	15	1	3	3	134	M
AN	1	5	5	6	4	24	8	3	24	9	2	18	4	1	4	3	5	15	1	3	3	93	L
BA	1	5	5	6	4	24	8	3	24	7	2	14	5	1	5	6	5	30	2	3	6	108	M
BL	1	5	5	6	4	24	2	3	6	8	2	16	4	1	4	3	5	15	1	3	3	73	L
C	1	5	5	8	4	32	6	3	18	7	2	14	4	1	4	3	5	15	2	3	6	94	L
CA	1	5	5	6	4	24	8	3	24	10	2	20	4	1	4	6	5	30	1	3	3	110	M
CB	1	5	5	6	4	24	8	3	24	8	2	16	5	1	5	3	5	15	1	3	3	92	L
CF	1	5	5	6	4	24	6	3	18	8	2	16	4	1	4	3	5	15	1	3	3	85	L
CG	1	5	5	6	4	24	2	3	6	7	2	14	4	1	4	6	5	30	1	3	3	86	L
CI	1	5	5	6	4	24	8	3	24	7	2	14	6	1	6	3	5	15	1	3	3	91	L
Cl	1	5	5	6	4	24	8	3	24	1	2	2	6	1	6	3	5	15	1	3	3	79	L
D	1	5	5	8	4	32	8	3	24	10	2	20	6	1	6	6	5	30	2	3	6	123	M
E	1	5	5	8	4	32	8	3	24	10	2	20	2	1	2	6	5	30	2	3	6	119	M
E	1	5	5	8	4	32	8	3	24	10	2	20	2	1	2	6	5	30	2	3	6	119	M
F	1	5	5	8	4	32	8	3	24	10	2	20	4	1	4	3	5	15	2	3	6	106	M
G	1	5	5	8	4	32	8	3	24	10	2	20	6	1	6	8	5	40	2	3	6	133	M
GS	1	5	5	9	4	36	8	3	24	10	2	20	4	1	4	3	5	15	2	3	6	110	M
BL	1	5	5	9	4	36	8	3	24	7	2	14	5	1	5	3	5	15	2	3	6	105	M
HM	3	5	15	9	4	36	8	3	24	7	2	14	4	1	4	8	5	40	2	3	6	139	M

to leachate infiltration into the groundwater) has been previously established by Akankpo and Igbokwe (2011).

Similarly, intrinsic aquifer vulnerability study using the DRASTIC technique revealed that the DRASTIC Index ranged between low and moderate vulnerability. The DRASTIC Index estimated within the study area ranged from a minimum value of 59 to a maximum value of 193 with a mean value of 110. A large portion of the study area estimated at about 72% was classified as moderate vulnerability areas while about 27.2% of the study area was identified as low aquifer vulnerability areas using the DRASTIC Index. However, high vulnerability areas are restricted only to a very small area. These results estimated from DRASTIC Index are in agreement with similar results from other parts of the Imo River Basin (Ugada et al. 2013; Eke et al. 2015). Eke et al. (2015) estimated a

DRASTIC Index of 85–99 (low vulnerability), 102–140 (moderate vulnerability) and DI values > 140 (high vulnerability). In addition, results using DRASTIC Index worldwide have been previously established by several authors (Babiker et al. 2005; Atiqur 2008; Lathamani et al. 2015; Jang et al. 2017; Mondal et al. 2017; Oni and Akinlatu 2017; Falowo et al. 2017; Aweto and Ohwoghre-Asuma 2018; Oroji 2018). Generally, the intrinsic aquifer vulnerability of the study area estimated from the DRASTIC method agreed reasonably well with the results of the IEC method.

Estimates of aquifer geo-hydraulic parameters

The aquifer hydraulic characteristics estimated from geo-sounding data revealed that the hydraulic

Table 6 Descriptive statistics of aquifer geometric and hydraulic characteristics of the study area

Aquifer parameters	Central Tendency	Geologic formations					
		BF	OF	AF	IF	NF	AJF
Aquifer resistivity, ρ	Max	6589	8900	6173	3660	7660	2240
	Min	180	119	101	766	160	511
	Mean	1833	1968	1998	1625	1908	1490
Aquifer depth, d (m)	Max	199	160	173	160	140	171
	Min	12.6	32.2	10.5	22.6	35.6	31
	Mean	66.7	89	97.8	79.9	98.7	96.4
Aquifer thickness, T (m)	Max	79.3	74.9	99.9	75.8	72.2	68
	Min	2.3	10.6	12.5	5.5	11.1	15.6
	Mean	32	39	43.7	33	55.75	42.87
Hydraulic conductivity (m/day)	Max	13.42	6.14	7.65	3.64	4.65	82.87
	Min	1.34	5.63	0.93	1.33	1.7	2.41
	Mean	5.2	5.58	4.05	3.02	2.95	2.71
	SD	0.34	0.122	0.123	0.58	0.86	0.15
Transmissivity (m^2/day)	Max	887	813	628	506	261	192
	Min	29.9	38	16	16	26	42
	Mean	223	187	171	102	117	138
Diffusivity	Max	616,119	127,323	47,195	6478	13,028	35,839
	Min	995	236	31	4004	3.06	4.98
	Mean	22,167	12,203	10,403	5102	4104	9669
Storativity	Max	1.59E-04	1.90E-04	1.70E-04	3.10E-05	2.47E-04	8.80E-05
	Min	6.00E-06	1.40E-05	1.50E-05	7.20E-06	1.40E-05	2.03E-05
	Mean	4.40E-05	5.80E-05	5.30E-05	5.10E-05	6.90E-05	5.60E-05

conductivity in the study area varies between 0.925 and as high as 13.42 m/day with a mean value of 4.64 m/day. The maximum hydraulic conductivity value was recorded within the Benin Formation while the least aquifer hydraulic conductivity was recorded within the Ameki Formation (Tables 5 and 6). Figure 9a shows the spatial variation of the aquifer hydraulic conductivity of the study area. A detailed analysis of the results of the hydraulic conductivity of the study area revealed three major group: low hydraulic conductivity range of 0.925 and 2.00 m/day, representing 36% of the study area, moderate values ranging between 2.10 and 5.90 m/day representing 22% and high aquifer hydraulic conductivity values ranging from 6.00 to 13.42 m/day covering about 41% of the study area (Fig. 9a). Opara et al. (2012) reported that the Benin Formation is characterized by high aquifer potentials with an estimated high aquifer hydraulic conductivity value that ranged between 5.49 and 6.63 m/day. Estimated hydraulic

conductivity values in the study area are similar to the results of earlier studies carried out close to the study area (Fatoba et al. 2014; Ebong et al. 2014; Ibout et al. 2017).

Similarly, the aquifer transmissivity values estimated across the study area revealed that the values range from 16.0 to 887 m^2/day with a mean value of 589 m^2/day (Fig. 9b; Tables 5 and 6). The highest transmissivity value was recorded within the Benin Formation while the lowest value was estimated within the Imo Shale Formation. Thus, the estimated transmissivity values in the study area indicates that the ground water potentials of the study area ranges from high, medium to low potentials with the southern and north-western parts of the study area situated within the zone of high ground-water potential (Fig. 9). The results of this study are similar to the findings in other studies carried out worldwide (Fatoba et al. 2014; Ebong et al. 2014; Kazakis et al. 2016; Joel et al. 2016; Hasan et al. 2018; Ibout

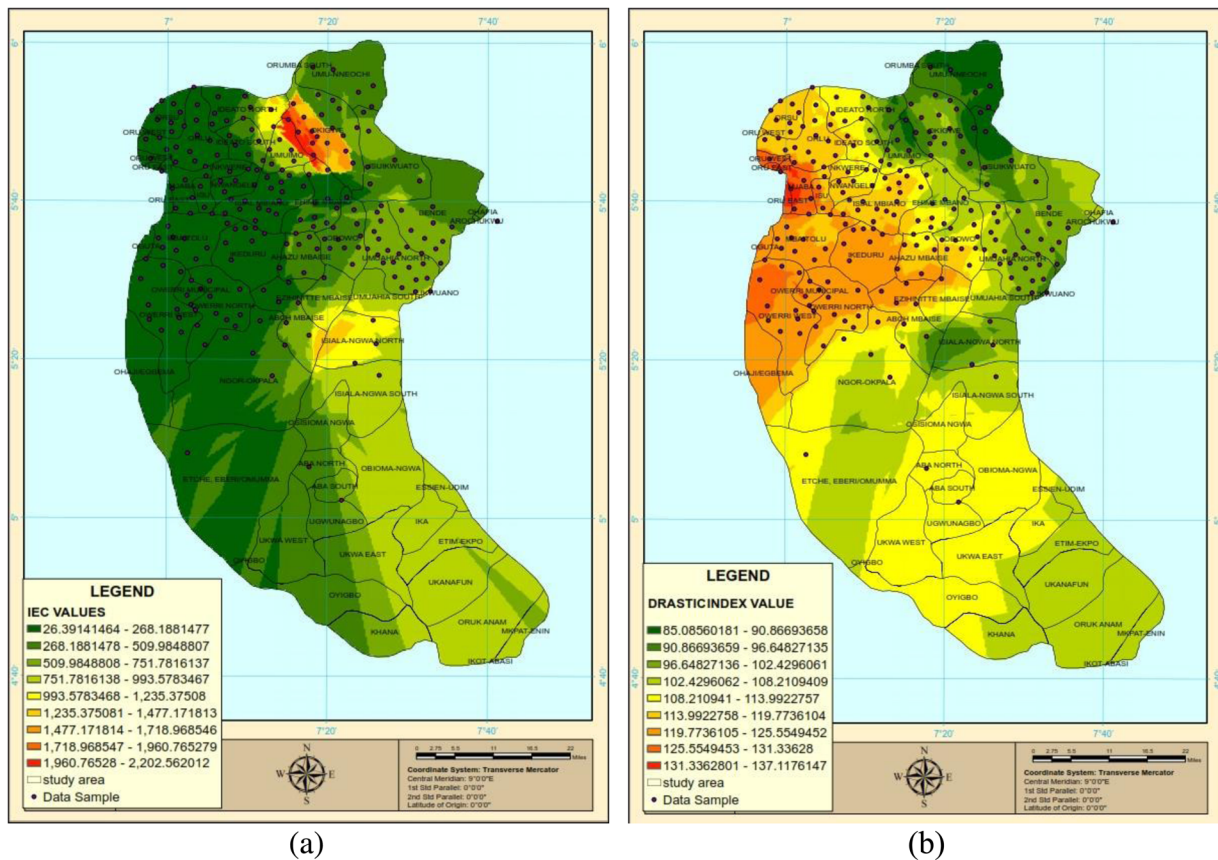


Fig. 8 Spatial variation map of aquifer vulnerability of the study area. **a** Integrated electrical conductivity (IEC). **b** DRASTIC Index

et al. 2017; Oyeyemi et al. 2018; Rabeh et al. 2019). A detailed summary of the aquifer geometrical and hydraulic characteristics on the basis of the six different formations is presented in Tables 5 and 6. Akhter and Hassan (2016) revealed that low values of hydraulic conductivity and transmissivity values are generally indicative of clay/shale aquifer materials while high values are generally due to the presence of sand/gravel aquifer materials. According to Ijeh and Onu (2012), the groundwater potential in the Imo Shale Formation is low and this agrees to the low aquifer hydraulic conductivity and transmissivity values revealed by the result of the present study.

Finally, the storativity or storage coefficient which is the volume of water released from storage per unit surface area of the aquifer or aquitard in the study area ranged from 6.0×10^{-6} to 3.1×10^{-5} with a mean value of 5.5×10^{-5} . Similarly, the diffusivity of the aquifers of the study area varies from as low as 3.06 within the Nsukka Formation to as high as 616,119 within the

Benin Formation. The typical storativity of a confined aquifer, which most often generally varies with specific storage and aquifer thickness ranges from 5×10^{-5} to 5×10^{-3} (Todd 1980). The results of the present study are in agreement with the findings of Ugada et al. (2013) carried out in the upper part of the Imo River Basin.

Summary, conclusion and recommendation

Hydrogeophysical studies of Imo State and environs were electrically studied using VES to evaluate the aquifer hydraulic characteristics and the protective capacity of the area. The aquifer resistivity of the study area varied from 101 to 8900 Ω m with a mean value of 1799 Ω m. The aquifer depth within the study area ranged from 12.6 to 199 m with an average value of 84.7 m while the thickness varies from 2.3 to 99.9 m with a mean value of 37.1 m. In addition, the

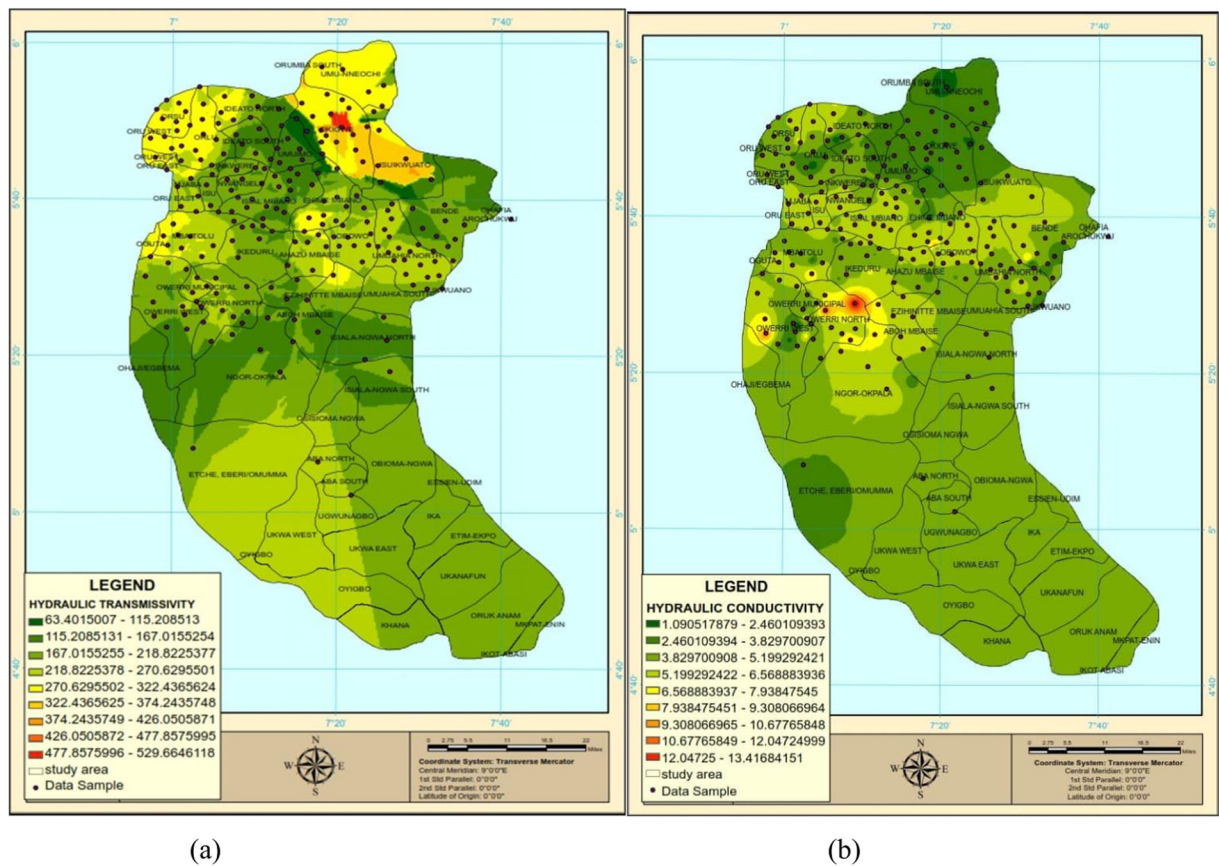


Fig. 9 Spatial variation of aquifer geo-hydraulic parameters of the study area. **a** Hydraulic conductivity. **b** Transmissivity

longitudinal conductance of the study area ranged between 3×10^{-3} and $4.7 \times 10^{-2} \Omega^{-1}$ with a mean value of $4.7 \times 10^{-2} \Omega^{-1}$ while the transverse resistance ranged from 1760 to 445,890 Ωm^2 with a mean value of 66,572 Ωm^2 .

Estimates of the aquifer hydraulic characteristics revealed that the hydraulic conductivity ranged between 0.925 and 13.42 m/day while the transmissivity ranged between 16.20 and 887 m²/day with a mean value of 589 m²/day. Similarly, the storativity values ranged from 6.0×10^{-6} to 3.1×10^{-5} with a mean value of 5.5×10^{-5} . Thus, the ground water potentials of the study area is generally classified into three main groups of low, moderate and high potentials with the southern and north-western parts of the study area falling within the high groundwater potential zone. The Benin and Ogwashi Formations were characterized by moderate to high aquifer hydraulic and transmissivity values. In other words groundwater potential of the two formations can be said to be high. On the other hand, mean aquifer hydraulic conductivity and transmissivity values of

3.02 m/day and 102 m²/day were revealed in the Imo Shale Formation, indicating a fairly low aquifer potential.

Similarly, the layer thickness and the inverse of the layer resistivity values from the first earth layer to the top of the water saturated layer were integrated to estimate the aquifer protective capacity of the study area. The vulnerability estimates from this geophysical approach (IEC) agreed to a reasonable extent with the estimates made using the DRASTIC technique (geological approach) at the same locations. Detailed analysis of the results of the aquifer vulnerability studies revealed that more than half of the study area has low protective capacity and as such 83% of both shallow and deep aquifers of the study area are susceptible to contamination by leachate from dumpsites, heavy metal from automobile mechanic workshops and e-wastes, industrial/domestic sewages and effluents, insecticides, fertilizers, etc. This suggests that care should be taken to reduce soil pollution loads from point/non-point sources in the area. Poor environmental practices like open

waste dumping and excessive application of inorganic fertilizers should be discouraged. Formations with high vulnerability index should be managed properly by ensuring that modern waste disposal methods are adopted in such areas.

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