ISSN: 2285-2071
Volume 10, Number 1, 2022
International Journal of Physical Science Research

APPLICATION OF GEOPHYSICAL METHODS IN THE EVALUATION OF VULNERABILITY AND PROTECTIVE CAPACITY OF THE AQUIFER IN ORU AND ENVIRONS, SOUTHEASTERN, NIGERIA.

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ABSTRACT

Evaluation of Vulnerability and Protective Capacity of Aquifer in Oru and Environs, Southeastern, Nigeria was conducted applying geophysical methods to ascertain the protective capacity of the aquifer in the area from possible pollution. Aquifer Vulnerability indices and Hydraulic parameters have been estimated from DRASTIC (an acronym for Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone and hydraulic Conductivity) and surface geoelectrical data, using data sets from Oru west and Oru east and environs in Southeastern Nigeria. The study area is underlain by the Benin Formations. Fourteen (14) vertical electrical sounding (VES) results, using the Schlumberger method were acquired for the study area. A maximum current electrode spacing (AB) of 1000 meters was used for data acquisition. For comparative purposes, seven (7) of the soundings were carried out near existing boreholes to evaluate the interaction of subsurface materials. The layer parameters thus obtained from the analysis were combined with pumping test data from existing boreholes to estimate aquifer hydraulic conductivity including those areas without boreholes and vulnerability index assessment, using the DRASTIC model. From the study, the vulnerability assessment and analysis of the results of the vulnerability map of the study area indicates that Amagu, Omuma, Umuejike and Umuabiah areas fall within the moderate vulnerability zone while the other adjoining areas fall within the high vulnerability zone. The longitudinal conductance of the aquifers range from a minimum of 0.002702 Ω^{-1} at Akwada axis to a maximum of 0.036396 Ω^{-1} at Ofor-Uru area with an average value of 0.015411 Ω^{-1}. The study revealed that the overburden layers within the study area and environs are poorly protected and highly vulnerable to pollution. The regression line of data points obtained in this plot yield an equation: DI = 348.82C + 141.2 with R^2 = 0.043 and a correlation coefficient of R = 0.20736, implying relationship between the two variables.

Keywords: Geophysical, Hydraulic conductivity, Vulnerability, Protective capacity, DRASTIC.

INTRODUCTION

The importance of water resource cannot be over-emphasized, this is because from generation to generation, mankind has continued to bequeath to the upcoming generation with this very resource and has continued to make use of the resource that may be referred to as scarce resource, due to the fact that most times, it is difficult to get water that may be completely free from impurities.

The inhabitants of Oru East and West and environs actually have groundwater supply, but they have health related issues and complaints which is attributed to the source of water. Some attribute it to pollution of the source of water within the environment. The need to investigate groundwater of this locality using the vertical electrical sounding to probe the aquifer parameters such as hydraulic conductivity and longitudinal conductance of the various locations to ascertain if actually the source of water will be polluted is necessary. Irrespective of the various methods in carrying out groundwater exploration and exploitation, the Vertical Electrical Sounding (VES) is

more convenient and reliable to apply in this study. This very method has been in use so extensively in groundwater investigation in the basement complex terrains and also in the sedimentary basins.
Harnessing groundwater resource can sometimes be difficult and tasking and it requires an adequate knowledge, finance and manpower to get this natural endowment for our very utilization. This process and even the water are most times damaged and spoilt by pollution and contamination. This polluted water when consumed by mankind most times result into contacting likely diseases/pathogens.
Geological formations have a property that is heterogeneous and this, as a result, shows that they are not sensitive to pollution related to the activities of man in his environment, thereby determining the different level/amount of vulnerability as a function of hydro-geological conditions and to determine the extent of protection that is needed by each area (Margat and Sauis-Parascandola, 1987). Albinet and Margat (1970) opined that vulnerability is the possibility of contaminants to percolate and diffuse from the ground surface into the natural water table reservoirs, under some natural conditions. According to Olmer and Rezec (1974), vulnerability as regards to groundwater has to do with the extent of endangering or polluting the groundwater which is determined by the natural conditions and independent of the source of pollution. They are of the view that and opinion that vulnerability is a function of vertical permeability in the unsaturated zone, and also on the hydraulic gradient and flow velocity in the aquifer.
Aquifer vulnerability is divided into two: Firstly, by the degree of protection against contamination as a result of the overlying strata and secondly by the potential for the purification of contaminated water I the aquifer (Vierhuff *et al.*, 1981). Vierhuff *et al*. (1981), assed vulnerability on the basis of three (3) parameters: type of aquifer, location of the aquifer in the hydrologic cycle and the characteristics of the unsaturated zone or confining layers.
Bachmat and Collins (1987), postulated that groundwater vulnerability is the sensitivity of its quality to anthropogenic activities, which may prove detrimental to the present and/or intended usage -value of the change in concentration of a given substance per increment of a given human activity. They equally introduced the idea of using a vulnerability map to display the results of vulnerability assessment or estimation in such a way that it will be useful and convenient for actual application in the decision making process.
The U.S.A. National Research Council (1993) on their part has viewed groundwater vulnerability as "the tendency or likelihood for contaminants to reach a specified position in the groundwater system after the introduction at some locations above the very uppermost aquifer". All these different definitions by different authors target at assessing the natural protection capability of the geological formation to maintain the quality of any groundwater by a way of shielding it from the very adverse effects of anthropogenic activities. However all these postulations are subject to the basic principle that states that: "All groundwater is vulnerable" (Mato, 2002). Therefore, there is the need to apply geophysical methods to investigate how potable the groundwater resource is in any given area. This study is therefore aimed at determining the vulnerability of the aquifer and the protective capacity of the overburden layer in the study area.

Location of the Study Area

The study area Oru West and Oru East and environs is in Imo State located within the Latitude of $5^0$39′N through $5^0$50′N and longitude of $6^0$50′E through $6^0$59′E. In the east side of the study area, it shares boundary with Njaba and Orlu L.G.As of Imo state. In the north side, the study area is sharing boundary with Ihiala L.G.A. of Amambra State. In the west, the study area shares boundary with Oguta L.G.A. of Imo State while in the south side, it shares boundary with Mbaitoli L.G.A. of Imo State. The study area falls within the Tropical Rain Forest, the climate is hot and humid, with mean annual rainfall of 152 mm to 203 mm. The dry season is relatively short from

November to March, while rainfall usually lasts from April to October in the study area with a break usually referred to as “August Break”. The temperature in the study area ranges from 27^0C to 34^0C while towards the end of the rains, it is between 18^0C – 21^0C.

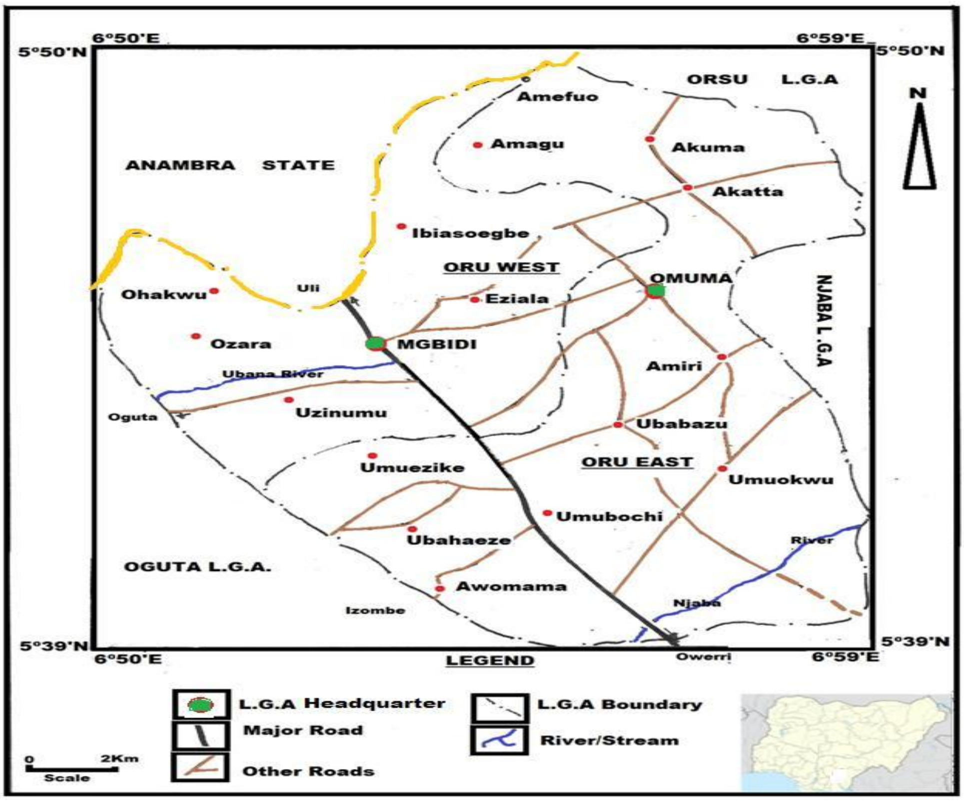


Figure 1: Location Map of the Study Area (Edited from the Nigerian Geological Survey Agency Map of Old Imo State, 1991)

The study area normally experiences a high amount of relative humidity which ranges from 35% to 60% during rainy season and harmattan season (from November through January), while it experiences a low relative humidity ranging from 0% to 35% during the hot (dry) season which starts from January to April. The climate conditions of the study area and environs fall within the warm-horrid tropical climate region where the wet and dry seasons are noticed prominently in the area. The average rainfall is between 1000 mm to 1500 mm with temperature as high as 36.7^0C (Udo, 1970).

Geology and Hydrogeology of the Study Area

The area and its environs is overlain by the Benin Formation which consists of lenticular, unconsolidated and sandy sediments. The Benin Formation has been described as “coastal plain sands”. The Benin Formation is continental in origin. The sediments of the Benin Formation were deposited during the late Tertiary to Early Quaternary Period. The age of the Benin Formation is from Miocene to Recent and it consists of friable sands with intercalations of shale and clay lenses (Onyeaghocha, 1980). It also contains some isolated units of gravels, conglomerates, very coarse-grained sands and sandstone in Owerri area in south-eastern Nigeria. The Formation has a thickness ranging from 0 – 2100 m within the study area and environs close to Owerri. The sands and sandstones are commonly granular in texture and can be partly unconsolidated. The sediments represents upper deltaic plain deposits. The sand may represent braided bars and channel fills. The shales are few and thin and they may represent back swamp deposits. The

shales are the locus of several river systems; these rivers are fed by springs that issue from the margins of sand bodies.
The Benin Formation is underlain by the Ogwashi-Asaba Formation (Reyment, 1965). The Ogwashi- Asaba Formation (Oligocene-Miocene) is an extensive stratigraphic unit in the southern Nigeria sedimentary basins.

The litho-stratigraphy of the study area and environs is described as laterites-mudstone-lignite-clay-sand. The laterites overlie the mudstone which in turn overlies the lignite, which is the major reason for the name Ogwashi-Asaba Formation. The lignite overlies the clay which is an impermeable Formation. The clay overlies the sandstone. The mudstone is brownish in colour and is about 0.54 m thick. The lignite is also brownish in colour and is about 1.2 m thick. The clay is about 0.5 m thick and is reddish-brown in colour. The sand is moderately indurated and is the source of some of the springs in the study area.

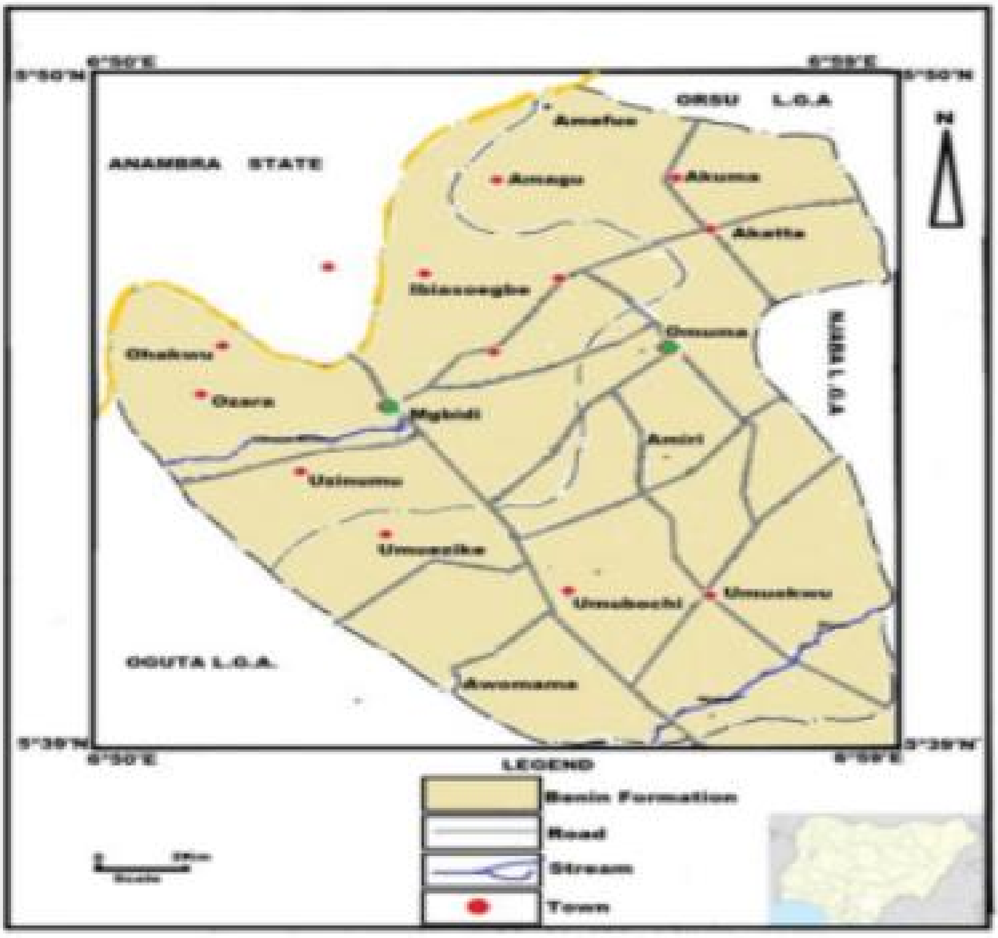


Figure 2: Geology Map of the Study Area (Edited from the Nigerian Geological Survey Agency Map of Old Imo State, 1991)

The source of groundwater in the study area is from the underlying coastal plain sands. This Formation has good groundwater potentials being dominantly sandy with high permeability and porosity. A lot of boreholes have been drilled into the coastal plain sands. Data of an existing borehole drilled in the neighbouring villages and towns indicate that the depth to water table in the borehole is about 40.04 m. The aquifer is quite prolific and groundwater exploration in the study area is quite promising.

Materials and Method

DRASTIC Model

The drastic model was developed in USA for the purpose of protecting groundwater resources (Aller *et al.*, 1985; Aller *et al.*, 1987). Drastic is an empirical groundwater model that estimates groundwater contamination vulnerability of aquifer systems based on the hydrogelogical settings of the area. The drastic model depends on the concept of the hydrogeological setting that is defined as a composite description of all the major geologic and hydrologic factors that affect and control the groundwater movement into, through and out of an area (Aller et al, 1987). The model yields a numerical index that is derived from ratings and weights assigned to the seven model parameters. The significant media types or classes of each parameter represent the ranges, which are rated from 1 to 10 based on their relative effect on the aquifer vulnerability. The DRASTIC index equation is stated as:

$$D_j = \sum_{j=1}^{7} \left(W_j \times R_j\right) \qquad (1)$$

where,

D_j = DRASTIC Index for a mapping unit
W_j = Weight factor for parameter j
R_j = Rating for parameter j

DRASTIC being the seven parameters (**D**epth of water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of vadose zone and hydraulic **C**onductivity) and the subscripts: *r* and *w* are the corresponding rating and weights respectively.

Table 1 shows the qualitative risk categories of low, moderate, high and very high vulnerabilities, respectively (Aller, 1987, modified Piscopo, 2001).

Table 1: DRASTIC index ranges for qualitative risk categories (Aller, 1987, modified Piscopo, 2001)

	DRASTIC Qualitative Category			
	LOW	MODERATE	HIGH	VERY HIGH
DRASTIC INDEX (DI)	1 – 100	101 – 140	141 – 200	>200

Hydraulic Properties

In order to achieve quantitative information in groundwater flow and contaminant transport modelling, it is imperative to estimate the hydraulic properties of any given aquifer system. Such aquifer hydraulic properties (hydraulic conductivity and transmissivity) are usually obtained either from pumping tests or laboratory experiments when core samples are available. However an alternative approach can be applied adopting non-invasive geophysical information. Geophysicists have understood that a correlation between hydraulic and electrical aquifer properties can be possible, as both properties are related to the pore space structure and heterogeneity (Rubin and Hubbard, 2005).

The Dar-Zarrouk Parameters

The combination of the thickness and resistivity of the geoelectric layers into single variables; the Dar-Zarrouk parameters of transverse resistance (R_T) and longitudinal conductance (C_L), can be adopted as a basis for the evaluation of aquifer properties such as protective capacity of the overburden rock materials (Ekwe *et al.,* 2006; Oladipo *et al*., 2004; Olorunfemi *et al.,* 1998). For a horizontal, homogeneous and isotropic layer, the Dar-Zarrouk parameters of transverse resistance and longitudinal conductance are respectively obtained as:

$$R_{Ti} = \sum_{i=1}^{n} \rho_i h_i \qquad (2)$$

And

$$C_{Li} = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \qquad (3)$$

where ρ_i and h_i are the layer resistivity and thickness of the *ith* layer.

The ability of the overburden to retard and filter percolating fluid is a measure of its protective capacity (Rubin and Hubbard, 2005). Estimating these properties from pumping tests can be very expensive and time consuming. Surface geoelectrical methods offer an alternative, rapid and cost effective approach for aquifer evaluation and groundwater quality assessment using empirical relations between hydraulic and geoelectric parameters (Kelly, 2007).

The longitudinal conductance (C_L) gives a measure of the impermeability of a confining clay/shale layer. Such layers have low hydraulic conductivity (K) and low resistivity. Protective capacity (P_c) of the overburden layers is proportional to its longitudinal conductance.

$$P_C = C_{Li} = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \qquad (4)$$

Table 2: Modified longitudinal conductance/protective capacity rating (Henriet 1976; Oladapo et al. 2004)

Longitudinal Conductance (*Lc*) (mhos’)	Protective Capacity Rating
< 0.1	Poor
0.1 - 0.19	Weak
0.2 – 0.69	Moderate
0.7 – 4.90	Good
5.0 – 10.00	Very Good
> 10	Excellent

Schlumberger resistivity soundings was used in this study to evaluate the aquifer protective capacity of the overburden layers and the vulnerability of the aquifer in the study area. The electrical resistivity survey involved VES, which is based on measuring the potentials between one electrode pair while transmitting direct current (dc) between another electrode pair. The depth of penetration is proportional to the separation between the electrodes in homogeneous ground, and varying the electrodes separation provides information about the stratification of the ground (Dahlin, 2001). The vertical electrical method was chosen for the aquifer characterization of the study area because the instrumentation is simple: field logistics are easy and straightforward and the analysis of data is less tedious and economical (Ujuanbi et al 2005; Okolie et al., 2005).

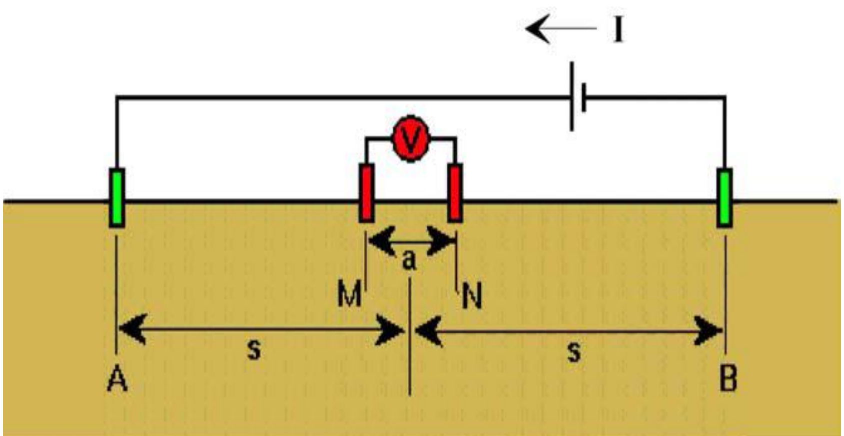


Figure 3: The Schlumberger Configuration.

A total of fourteen (14) vertical electrical soundings (VES) from locations in part of the study area were acquired with the ABEM terameter based on the Schiumberger configuration with maximum electrode spacing AB/2 = 500m and MN/2 = 50m. Only the current electrodes are moved more often during measurements until the measurable signal becomes very small. The potential electrodes are then expanded along the transverses, mostly along major roads. Resistance values $R(\Omega)$ at each VES point was recorded and apparent resistivity values $\rho_a\ (\Omega m)$ were determined using the appropriate geomectric factor (K). Garmin GPS 72 was used in determining the coordinates in longitude and latitude and elevation height above mean sea level of the locations of sounding points. The apparent resistivity (ρ_a) was calculated using (Ibuot et al. 2013):

$$\rho_a = \pi \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right] R = KR \qquad (9)$$

Where

$$K = \pi \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right] \text{being the geometric factor} \qquad (10)$$

The resistivity values were then processed with computer to produce VES curves.

Data Analysis

Quantitative interpretations of vertical electrical sounding data often lead to the generation of geoelectric layers. The VES curves obtained were interpreted for possible estimation of the aquifer characteristics. The information from these geo-electric layers enhances the identification and interpretation of layer parameters which includes aquifer resistivity, depth, thickness, and frequency. These layer parameters thus obtained together with or without existing pumping test information in drilled wells were then used to calculate the longitudinal conductance (L_C) and the hydraulic conductivity (K) distribution. The longitudinal conductance (C_l) was further applied in the estimation of the protective capacity of the overburden layers while the hydraulic conductivity (K) and other six parameters were used in the DRASTIC model to evaluate the vulnerability. The seven parameters are then assigned weights ranging from 1 to 5 reflecting their relative importance. The Drastic index is then computed by applying a linear combination off all factors according to equation 1:

Results and Discussion

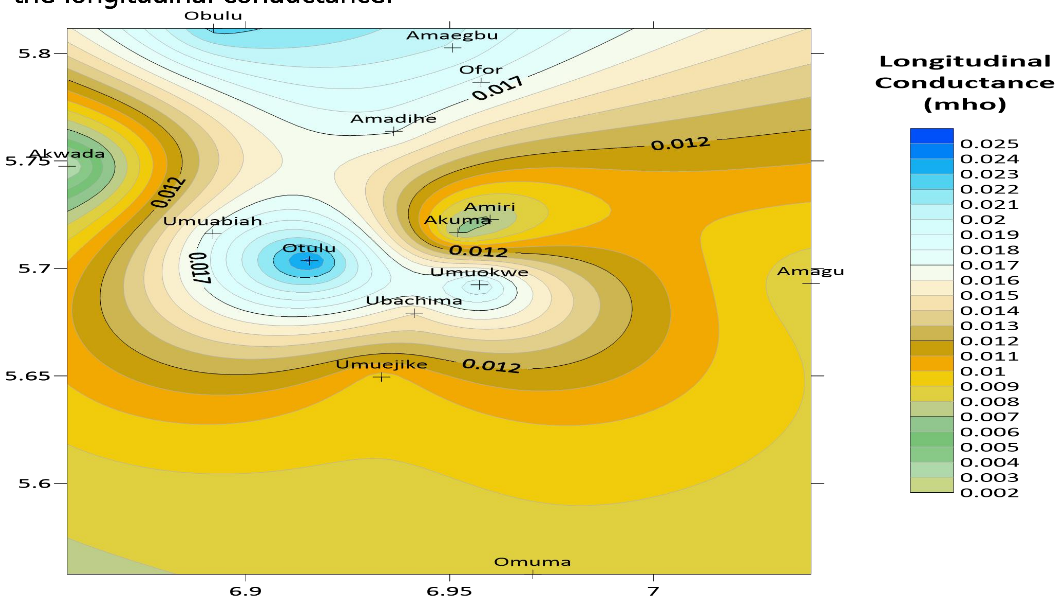
Aquifer Protective Capacity Based on the Overburden Layer

Table 3 shows the summary table of the resistivity, depth and thicknesses of the geo-electric/lithological layers within the subsurface as well as the longitudinal conductance and the transverse resistance of the aquifer. The table also shows the aquifer protective capacity ranges as modified by Henriet 1976 and Oladapo et al. 2004.

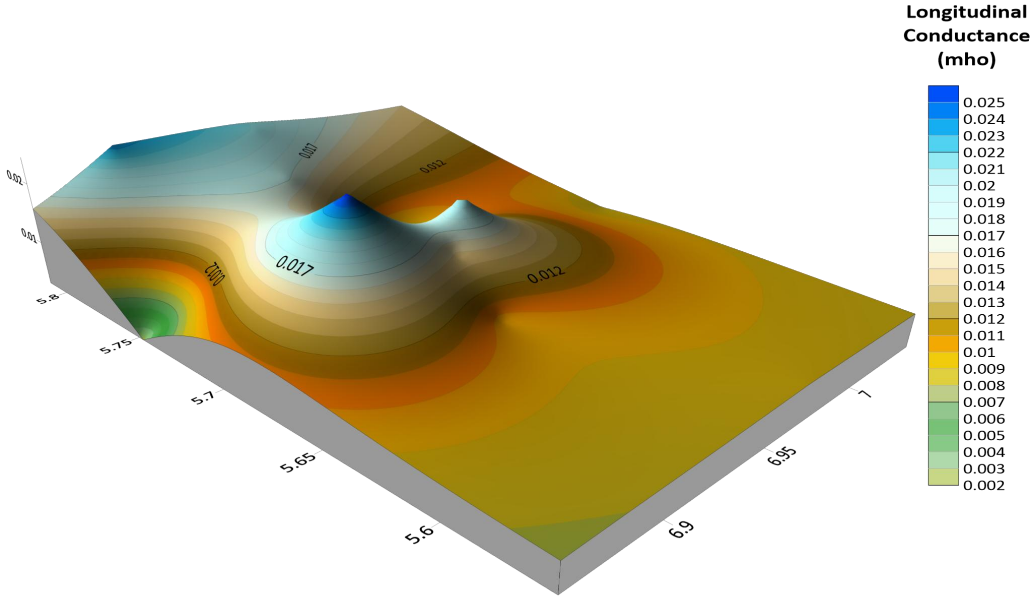
Table 3: Summary Results of Aquifer Parameters

VES Location	Aquifer Depth *(m)*	Aquifer Thickness *(m)*	Aquifer Resistivity *ρ (Ω.m)*	Transverse Resistance R_T *(Ω.m²)*	Longitudinal Conductance C_L *(Ω⁻¹)*	Protective Capacity P_C
Akuma	130.0	91.0	13720.0	1248520.0	0.006633	Poor
Amagu	97.5	81.5	9904.4	807208.6	0.008229	Poor
Omuma	123.5	83.5	9558.0	798093.0	0.008736	Poor
Amiri	111.5	96.5	14177.2	1368099.8	0.006807	Poor
Akwada	87.5	64.5	23871.0	1539679.5	0.002702	Poor
Umuejike	109.0	55.6	5832.5	324287.0	0.009533	Poor
Amadihe	197.0	84.7	4950.0	419265.0	0.017111	Poor
Ubachima	170.0	124.0	8266.6	1025058.4	0.015000	Poor
Obulu	104.1	82.6	3682.3	304158.0	0.022432	Poor
Umuokwe	232.5	203.9	10059.6	2051152.4	0.020269	Poor
Otulu	201.0	154.7	6323.5	978245.5	0.024464	Poor
Umuabiah	121.5	90.4	5142.5	464882.0	0.017579	Poor
Amaegbu	119.3	91.0	4580.0	416780.0	0.019869	Poor
Ofor,Uru	226.0	161.6	4440.0	717504.0	0.036396	Poor

The ability of the overburden to retard and filter percolating fluid is a measure of its protective capacity. Protective capacity (*Pc*) of the overburden layers is proportional to its longitudinal conductance (Rubin and Hubbard, 2005). The longitudinal conductance of the aquifers range from a minimum of 0.002702 Ω^{-1} at Akwada (light green color) in the northwest axis to a maximum of 0.036396 Ω^{-1} at Ofor,Uru (blue color) area with an average value of 0.015411 Ω^{-1}. The study revealed that the overburden layers within the study area and environs are poorly protected. Figures 4a & b display the spatial distribution map of the longitudinal conductance and the 3D model of the longitudinal conductance.



(a)



(b)

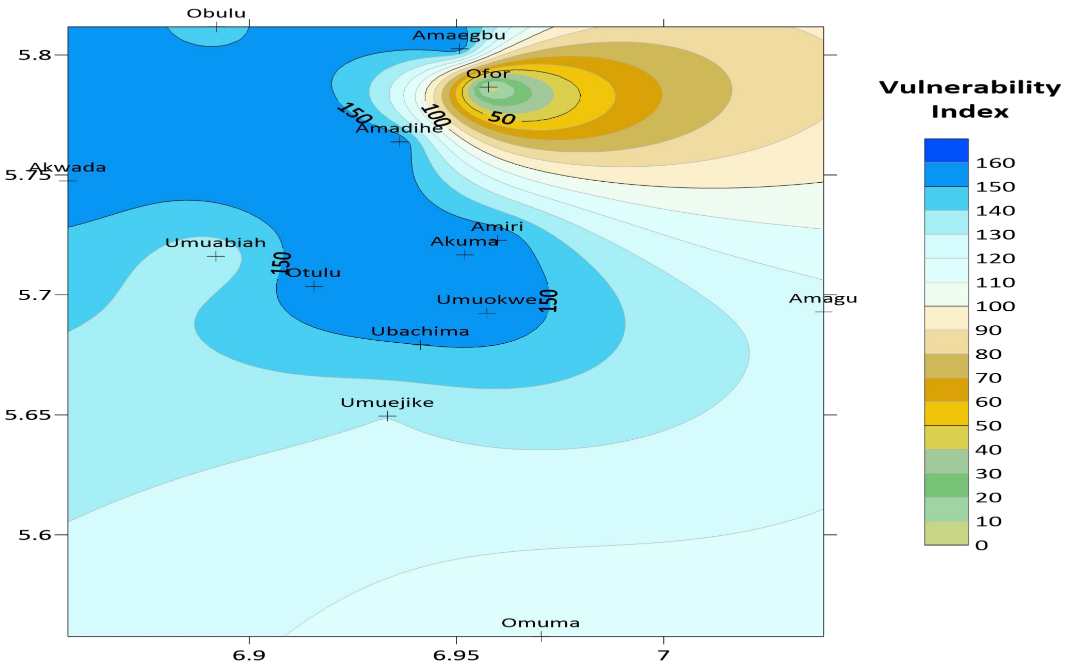
Figure 4: (a) Protective Capacity Distribution Map of the Study Area, (b) 3D Map of the Protective Capacity of the Study Area.

Aquifer Vulnerability Assessment Based on the DRASTIC Index

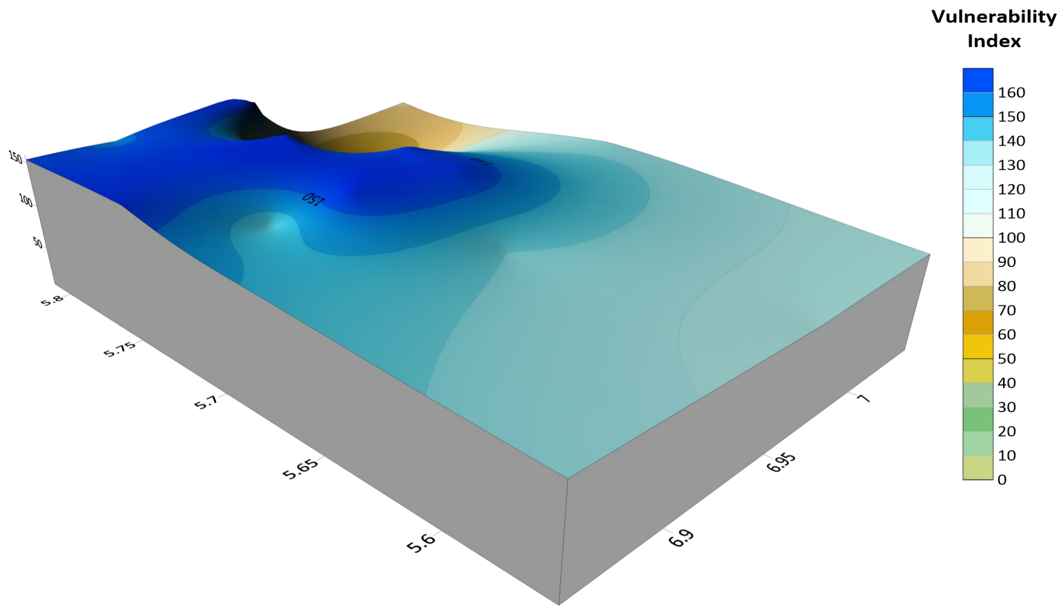
Table 4: Summarized Results of the DRASTIC Model

Location	D		R		A		S		T		I		C		DI	Vulnerability
	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		
Akuma	1	5	9	4	8	3	8	2	10	1	8	5	8	3	155	High
Amagu	1	5	9	4	8	3	8	2	10	1	2	5	8	3	125	Moderate
Omuma	1	5	9	4	8	3	5	2	9	1	1	5	8	3	113	Moderate
Amiri	1	5	9	4	9	3	8	2	10	1	8	5	8	3	158	High
Akwada	1	5	9	4	8	3	10	2	10	1	8	5	8	3	159	High
Umuejike	1	5	9	4	3	3	4	2	8	1	8	5	8	3	130	Moderate
Amadihe	1	5	9	4	8	3	10	2	10	1	8	5	8	3	159	High
Ubachima	1	5	9	4	9	3	4	2	10	1	8	5	8	3	150	High
Obulu	1	5	9	4	8	3	4	2	10	1	8	5	8	3	147	High
Umuokwe	1	5	9	4	9	3	8	2	10	1	8	5	8	3	158	High
Otulu	1	5	9	4	8	3	10	2	10	1	8	5	8	3	159	High
Umuabiah	1	5	9	4	8	3	10	2	9	1	3	5	8	3	133	Moderate
Amaegbu	1	5	9	4	8	3	10	2	10	1	8	5	8	3	159	High
Ofor,Uru	1	5	9	4	8	3	4	2	10	1	8	5	8	3	147	High

Information from pumping test data was used together with values obtained from the study area. The hydraulic conductivities were converted from m/day to gpd/ft^2 before using them to calculate the drastic index. The individual data elements for the DRASTIC indices are as shown in table 4 above and the plot is shown in figure 5a and b. Based on Navulur *et al.* (2006), and to facilitate interpretation, the study area has been classified into Moderate (101 – 140) and High Vulnerability zones (141 – 200). Analysis of the results of the vulnerability map showed that Amagu, Omuma, Umuejike and Umuabiah areas fall within the moderate vulnerability zone while the other adjoining areas fall within the high vulnerability zone. The study revealed that 72% of the studied area is of high vulnerability, which could be the reason of the health related issues and complaints are attributed to the source of water. The vulnerability indices are related to the depth of water table and the nature of the protective material. Shallow unconfined aquifers are more susceptible to pollution than deeper aquifers, all other factors being constant. Figures 5a & b display the spatial distribution map of the vulnerability and the 3D model of the vulnerability of the study area.



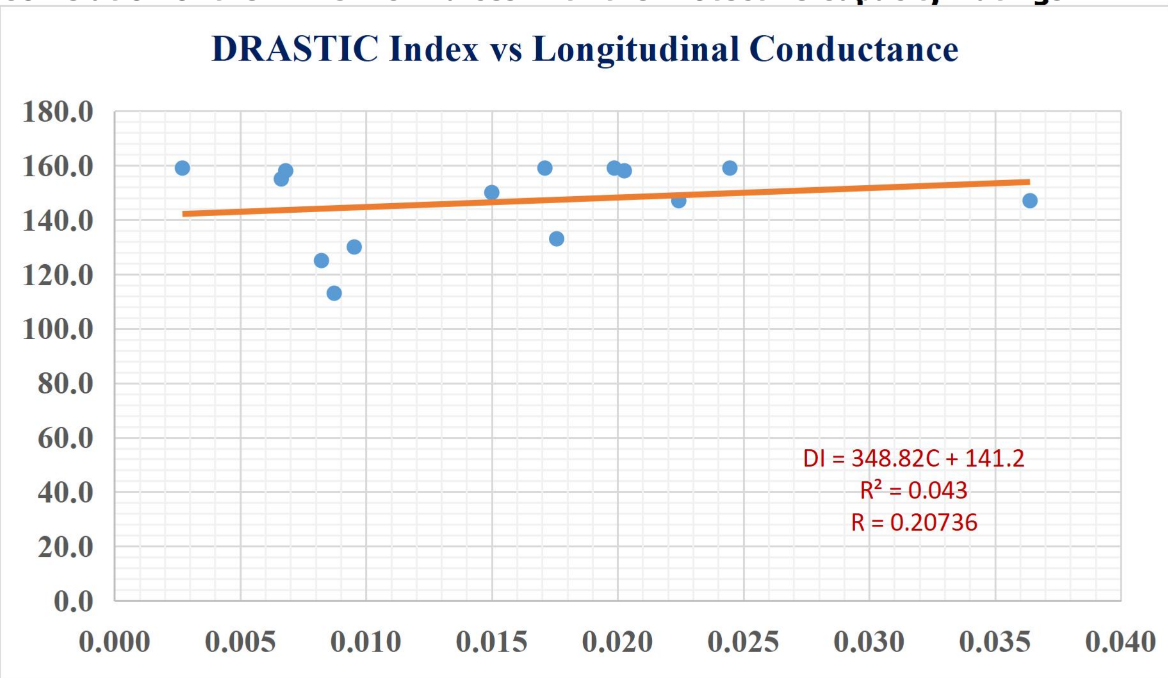
(a)



(b)

Figure 5: (a) Vulnerability Distribution Map of the Study Area,
(b) 3D Map of the Vulnerability of the Study Area.

Correlation of the DRASTIC Indices with the Protective Capacity Ratings



In order to relate the DRASTIC Index (DI) and the protective capacity (P_C) encountered in the study area, results from the DRASTIC Indices and Protective Capacity Ratings determined have been used. The purpose of this is to obtain an equation which will be used to describe how the DRASTIC Indices varies with the Protective Capacity Ratings within the study area. This is done by plotting the DRASTIC Indices against the Protective Capacity Ratings. The regression line of data points obtained in this plot yield an equation: $DI = 348.82C + 141.2$ with $R^2 = 0.043$ and a correlation coefficient of $R = 0.20736$, implying relationship between the two variables. It is worth noting that a low correlation coefficient somewhere near zero does not imply that there is no relationship between the variables rather it means that there is no linear relationship between the variables (Mac' Odo, 1997).

Conclusion

Evaluation of Vulnerability and Protective Capacity of Aquifer in Oru and Environs, Southeastern, Nigeria was conducted applying geophysical methods to ascertain the protective capacity of the aquifer in the area from possible pollution. Aquifer Vulnerability indices and Hydraulic parameters have been estimated from DRASTIC and surface geoelectrical data, using data sets from Oru west and Oru east and environs in Southeastern Nigeria. The study area is underlain by the Benin Formations. The layer parameters thus obtained from the analysis were combined with pumping test data from existing boreholes to estimate aquifer hydraulic conductivity including those areas without boreholes and vulnerability index assessment, using the DRASTIC model. From the study, the vulnerability assessment and analysis of the results of the vulnerability map of the study area indicates that Amagu, Omuma, Umuejike and Umuabiah areas fall within the moderate vulnerability zone while the other adjoining areas fall within the high vulnerability zone. The longitudinal conductance of the aquifers range from a minimum of 0.002702 Ω^{-1} at Akwada axis to a maximum of 0.036396 Ω^{-1} at Ofor, Uru area with an average value of 0.015411 Ω^{-1}. Correlation of the drastic indices with the protective capacity ratings shows that there is a relationship between the DRASTIC indices and the protective capacity ratings. The study revealed that the overburden layers within the study area and environs are poorly protected and highly vulnerable to pollution. The regression line of data points obtained in this plot yield an equation: $DI = 348.82C + 141.2$ with $R^2 = 0.043$ and a correlation coefficient of $R = 0.20736$, implying relationship between the two variables.

The calculated hydraulic parameters are very useful for further studies of the groundwater regime in the area. The estimated aquifer parameters could also be used to derive input parameters for contaminant migration modeling and to improve the quality of model. Finally, we should mention that the calculated aquifer parameters are well defined within the range of observed aquifer parameters.

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