



Evaluation and modeling of a major coastal aquifer's vulnerability to contamination with the use of GOD and AVI models as indicators in South-eastern Nigeria

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Abstract

Geophysical techniques were employed to evaluate the extent of a major coastal aquifer's vulnerability to near-surface and subsurface contamination with the use of GOD and AVI vulnerability models in Akwa Ibom State, Southern-eastern Nigeria. The study area is strongly dependent on groundwater resources, hence it was important to evaluate the extent of aquifer vulnerability. Interpretations of the resistivity inversion models, constrained by well information, indicated the presence of three lithological layers (motley top soil, fine sand, and coarse sand). The resistivities of the first layer were generally larger than those of the underlying subsurface layers, indicating the percolation of contaminant material into the surrounding aquifer.

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The resistivity of the geological layers ranged from 1.3- 626 Ω m. Contour maps were used to illustrate the variations of various geological and geo-electrical parameters obtained at the study location. Resistivity data was also used to generate aquifer hydraulic data from which the aquifer vulnerability indices were determined to evaluate the vulnerability of the aquifer to pollutant contamination. The vulnerability indices used to determine the extent of aquifer vulnerability to contamination were the Aquifer Vulnerability Index (AVI) model and the Groundwater occurrence, Overlying layer and Depth to groundwater (GOD) model. The GOD indices ranged from 0.54 to 0.63 with a mean of 0.55, implying a high vulnerability to near-surface and subsurface contaminants. The AVI values had a range of 0.3 to 1.13 with a mean value of 0.65, and based on AVI classification tables, the aquifer units have a very high vulnerability to contamination. These results corresponded with what was obtained from the

GOD models showing that in general, the research area is highly susceptible to contamination.

Keywords: Aquifer vulnerability index (AVI); GOD index; groundwater; contaminants; resistivity

1.0 Introduction

Groundwater is a major resource whose main source is precipitation from rain or snow that infiltrates land surfaces into rocks via the vadose zone into the zone of saturation. Contaminant solvents typically infiltrate through the vadose zone into the aquifer resources where the water is mined for residential and industrial uses. The infiltration rate of surface water depends on the study area's topography (steeper slopes favor runoff rather than infiltration), the nature of soil or rock (porous rocks increase infiltration), the amount of precipitation (the slower the intensity of precipitation, the greater the infiltration), the vegetation (the presence of lush vegetation causes precipitation to fall slowly, increasing infiltration) and land use (paved floors and roofed buildings reduce infiltration).

An aquifer could either be confined or unconfined. The presence of a confining layer (e.g., clay) reduces ground water flow. An unconfined aquifer, on the other hand, has no confining layer overlying the saturation zone. While groundwater recharge is mostly fueled by precipitation, discharge is more common (e.g., springs, pumping). Degradation of groundwater quality is likely to occur if the resource is pumped from very deep wells that contain soluble minerals. Over the years, the need for potable groundwater has grown significantly due to the problem of greater demand but inadequate supply. Further, degradation of groundwater quality has increased the demand for potable groundwater resources (Egboka et al., 1989; Machiwal et al., 2018; Fienen and Arshad, 2016).

Groundwater flow depends on the hydraulic gradient of the water table and the nature of geo-materials within the subsurface. The water table's hydraulic gradient for an unconfined aquifer is its slope. An aquifer's hydraulic conductivity defines its ability to permit the flow of water, and this is defined as the cubic meters of water (m^3) that passes through a cross-sectional area (m^2) in a day. For example, with saturated sand and gravel that contains no clay; the values of hydraulic conductivity can get very high (up to 5-50cm/h). The values obtained for hydraulic conductivity are dependent on extent, geometry and nature of pore spaces within the rock and their interconnectivity with one another.

Most of the world's population use groundwater as their major potable water source. Hence assessing the vulnerability of groundwater resources is of great importance (Kumar and PramodKrishna, 2020). Anthropogenic activities generate toxic chemicals such as synthetic organic chemicals that are used in industrial process to create pesticides (Ghazavi and Ebrahimi, 2015). Food additives and drugs, heavy metals (such as arsenic, lead, mercury, cadmium), radioactive materials, municipal processes, urban sewage, industrial processes such as mining, leakages of underground reservoirs of oil, agricultural processes such as irrigation, and infiltration of nutrients such as phosphorus and nitrogen from fertilizers and detergents, has led to groundwater degradation (Khan et al., 2008; Vrba and Zaporozec, 1994).

Industrialized areas, due to their high levels of urbanization, are especially prone to problems of groundwater degradation (Neh et al., 2015; Mádl-Szőnyi and Füle, 1998; Brindha and Elango, 2015). These are locations in which the rate of discharge via pumping outperforms the available groundwater resources. In some locations, groundwater is used at rates that exceed the rate

of recharge from precipitation. Consequently, the water level has declined in these areas and groundwater in such locations can be considered a non-renewable resource. In order to effectively manage and exploit groundwater resources, it is important to estimate an aquifer's vulnerability to contamination (Edet, 2014).

Aquifer vulnerability studies measure quantitatively the rate at which contaminants on the surface and near-surface can percolate into an aquifer (Harter and Walker, 2001; Foster et al., 2013). It is important to note that an aquifer's vulnerability to contamination depends on the thickness of the aquifer, the distance from topsoil to aquifer, the hydraulic conductivity (i.e., the rate of fluid flow), the rate of recharge, the properties of the overlying vadose zone, and the chemical properties of the contaminant (Abu-Bakr, 2020). Aquifer contamination also depends on the rate at which the contaminant material permeate through the vadose zone into the aquifer, the ability of the soil materials overlying the water table to filter out the contaminants, and the nature and toxicity of the contaminants. For example, shallow aquifers are more prone to contamination than deeper ones (Daly and Warren, 1998; Maxe and Johansson, 1998).

Several methods have been developed to evaluate aquifer vulnerability. These include the DRASTIC technique (Aller et al., 1987), SI technique (Abdelmadjid and Omar, 2013), the GOD technique (Foster 1987), and the AVI technique (Stempoot et al., 1993). Each of these methods uses different aquifer properties in their evaluation of an aquifer's vulnerability to contamination. For example, the DRASTIC technique (Thirumalaivasan et al., 2003) uses the following parameters to evaluate aquifer susceptibility to contamination: depth to groundwater (D), rate of groundwater recharge (R), aquifer media type (A), soil texture (S),

topography (T), influence of vadose zone (I), and hydraulic conductivity of the aquifer (C), hence the acronym DRASTIC. The Susceptibility Index (SI) technique computes aquifer vulnerability indices with the use of the following parameters: depth to groundwater (D), rate of groundwater recharge (R), topography (T), land (L) and middle aquifer (M). The SI method is mostly used in evaluating the vulnerability of aquifers on lands contaminated by nutrients like phosphorus and nitrogen which are typically used in the manufacture of pesticides. The Aquifer Vulnerability Index (AVI) technique evaluates aquifer susceptibility to contamination using measures of thickness of the subsurface layer overlying the aquifer (T) and measures of aquifer hydraulic conductivity (K). And finally, the GOD method uses the following parameters to evaluate aquifer vulnerability: groundwater confinement (G), overlying strata (O) and depth to groundwater (D).

While it is true that one can simulate aquifer vulnerability when complex geological structures exist, such requires far more complicated data that are expensive and labor-intensive to gather. Such data are typically gotten from meteorology, hydrogeology and climatic information (Gogu and Dassargues, 2000). GOD and AVI methodologies, on the other hand, are fast and effective approaches of quantifying aquifer vulnerability with limited data (Ghazavi and Ebrahimi, 2015; Mfonka et al., 2018). Their use in other studies (e.g. Falowo et al., 2017; Oroji, 2019) has shown their efficacy (Kazakis and Voudouris, 2011) and thereby validates their use in this work for the quantification of aquifer vulnerability. The method in use was geo-electrical surveying (Udosen and George, 2018a; Udosen and Potthast, 2018) which has been found useful in various applications ranging from investigations of saltwater intrusion (Inim et al., 2020), leachate and contaminant mapping

(Udosen, 2022), delineation of anisotropy (Udosen and George 2018b) and delineation of geological and geophysical subsurface features (Ekanem 2020; Ekanem et al. 2020; George et al., 2017; George et al., 2022).

The aim of this work was to use geophysical methods to delineate groundwater vulnerability with the GOD and AVI model methodologies. This work is one of the first to assess aquifer vulnerability indices within this study area. The study's primary goals were to map the zones of pollution in the area and conduct an assessment of groundwater's vulnerability. Groundwater is a critical resource for meeting the residential and industrial needs of the local population within the study area. It therefore becomes critical to evaluate the vulnerability of stratigraphic units within the study area with the goal of determining which locations are vulnerable to contamination by pollutants.

2.0 Location and Geology of the Study Area

This work was carried out in Southern Nigeria's Eket Local Government Area. Eket is located between coordinates 4.33" and 4.45" latitude and 7.52" and 8.02" longitude. Eket is bordered by Nsit Ubium Local Government on the north, Ibeno Local Government on the south, Esit Eket Local Government on the east, and Onna Local Government area on the west (Figure 1). The location map of the study area is indicated in Figure 2. The Cross River, Imo River, and Kwa Iboe River along with their tributaries, drain the study area. The main lithologies in the study area are sands/gravels, with clay and sandy clay interbeddings at some locations. Eket has two distinct climatic seasons which comprise wet or rainy season (April –October), and the dry season (November –March). The area experiences a humid tropical environment with mean annual rainfall values of around 3040 mm and temperatures ranging from 23 to 31°C.

Geologically, the Benin Formation (Coastal Plain Sands) sediments from the Niger Delta are found beneath the study region (Short and Stauble, 1967; Avbovbo, 1978). The Benin formation (the primary aquifer-bearing deposit in the region) comprises sediments made primarily of fluvial sands, clay, and lignite veins. These poorly-sorted sands are fine, medium or coarse grained (Mbipom et al., 1996). The Agbada Formation, an oil-bearing layer in the Niger Delta (Reijers and Petters, 1987), lies beneath the Benin Formation (Stacher 1995).

3.0 Material and Methods

3.1 Field data acquisition

An ABEM SAS 1000 resistivity meter was used to carry the vertical electrical soundings at the study area by employing the Schlumberger configuration, the aim being to delineate the resistivity distribution within the subsurface. The Schlumberger array employs 4 electrodes: two electrodes to inject a known current (I) into geo-materials within the site, and two electrodes to compute the potential gradient (V) between the current electrodes. The VES profiles were acquired at 10 locations with a maximum current electrode separation of 800m. Half the current electrode spacing (AB/2) ranged from 1m to 400m, while half the potential electrode spacing (MN/2) ranged from 0.25m to 20m. The resistivity meter used Ohm's law

$$R_a = \frac{V}{I} \quad (1)$$

to generate the apparent resistance (R_a). After obtaining these raw apparent resistance measurements, these measurements were multiplied with geometric factor G of the configuration in use to obtain the values of apparent resistivity via the formula

$$\rho_a = G * R_a. \quad (2)$$

This geometric factor G depends on the current and potential electrode spacing of the given array type in use and for Schlumberger array, the geometric factor is given by:

$$G = \Pi \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right] \quad (3)$$

where AB = separation between the current electrodes, and MN = separation between the potential electrodes. Hence, the apparent resistivity (ρ_a) for a Schlumberger configuration is obtained using the formula:

$$\rho_a = \Pi \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right] R_a \quad (4)$$

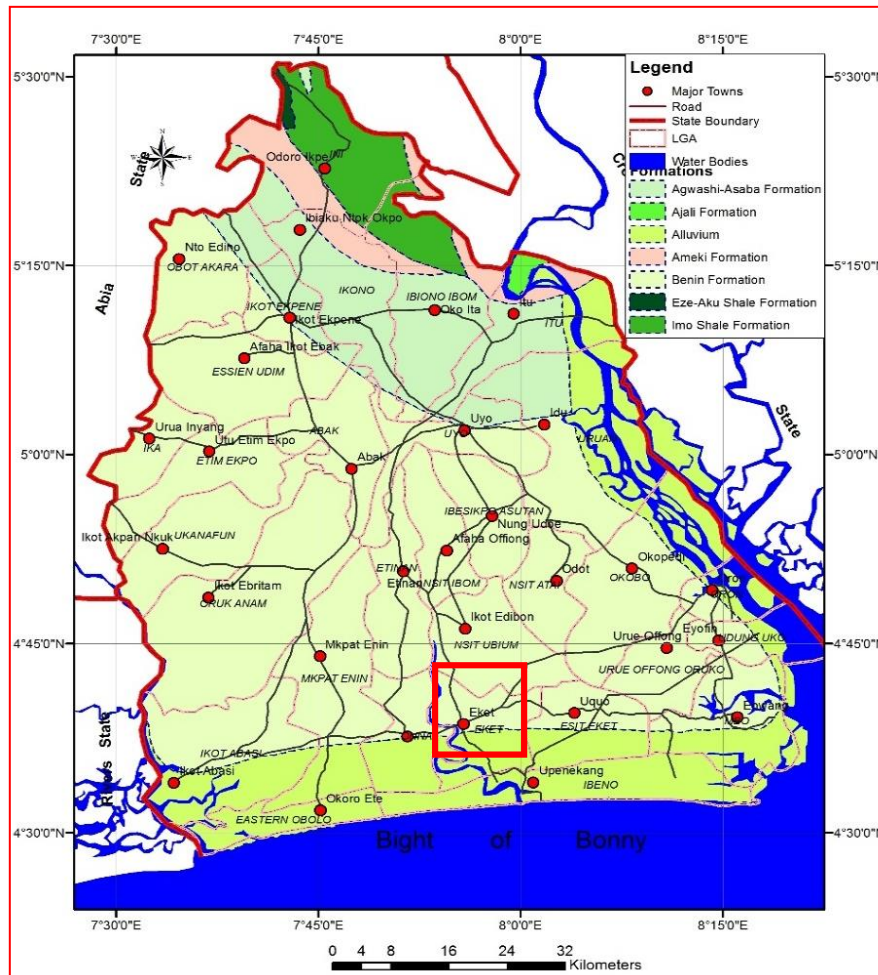


Figure 1: Geologic map of the study area. Eket is highlighted with a red square

The co-ordinates and elevation of each profile line was obtained using a global positioning system (GPS). To generate models of true electrical resistivity distribution within the subsurface, the apparent resistivity values (ρ_a) were plotted on logarithmic curves against AB/2,

where AB describes the spacing between the current electrodes. Manual smoothing of anomalous data points was carried out to reduce the impact of lateral subsurface inhomogenities and consequently the root mean square (rms) error within the measurements (Chakravarthi et al., 2007).



Figure 2: Map of the study area showing location of VES points as denoted by red circles.

This smoothening was carried out by removing deleting anomalous data points and taking the average of readings at cross-over stations. The trend-line of the curves indicated how the subsurface resistivity varied with current penetration depth. Via curve matching, the models of subsurface resistivity and thickness were then obtained. The smoothened apparent resistivity data was input into WinResist least square inversion software, resistivity software that would generate true resistivity curves of the subsurface distribution. The computer models generated from WinResist give the subsurface geoelectric parameters such as resistivity of each layer, the thickness of the layer and its depth. The parameters were generated after the software underwent several iterations in a bid to generate the least rms error. The results obtained from this inversion software were used in computations of hydraulic parameters to quantitatively determine the extent of aquifer vulnerability to contamination. Data (VES 2 and 9) from the nearest boreholes close to the study area (Ibuot et al. 2017) were used to constrain the resistivity data obtained from computer modeling (Fig.3).

4.0 Results and Discussion

4.1 Geo-electrical data results

Via interpretations of the generated VES models obtained from computer inversions modeling, the values of true subsurface resistivity, thickness and depth of each subsurface layer were obtained. Some representative inversion model curves are illustrated in Figure 4(a-c). Table 1 shows that via quantitative interpretation, the study area comprises three geo-electrical units given the maximal current electrode spacing used in the study area. Based on quantitative interpretation, 2 curve types (K and H) were delineated in the study area. It was observed that the study area is predominately made of type H type curves. The results obtained from the VES data was correlated with borehole data obtained in locations around the study area and it indicated that the water table could be found at a depth of approximately 16 m. Further, the first layer was interpreted to be motley topsoil comprising diverse geo-materials.

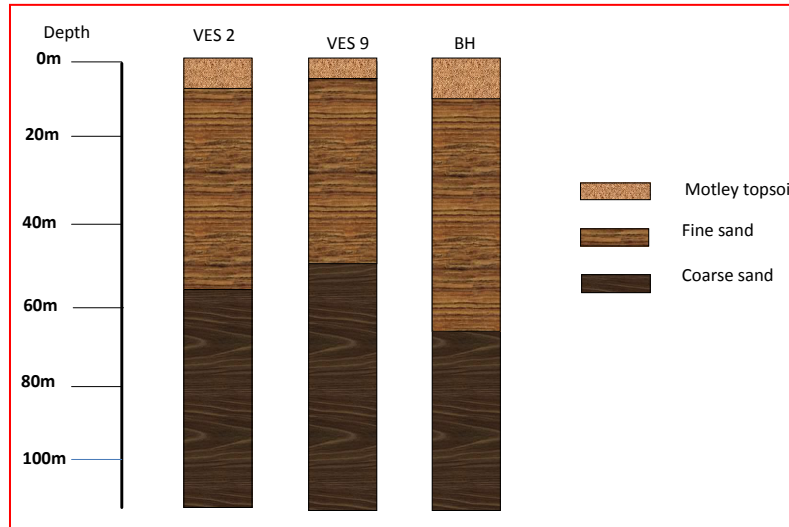


Figure 3: correlation of VES profiles with borehole lithology log

The quantitative values obtained from inversion models showed that this first layer had values of resistivity which ranged from 90 – 626 Ωm with thickness ranging from 0.5 -17.6m. This layer was observed to be more resistive than the underlying layer. Figure 5 shows the electrical resistivity distribution contour map of the first layer. It is observed on the contour map that the subsurface resistivity within this layer decreased as one moved from north-west towards the northeastern part of the study area. The second layer's resistivity ranged from 7.6 – 221.9 Ωm and its thickness ranged from 12.3 – 50.7m. This layer was interpreted from borehole logs to comprise fine sand. The contour map depicted in Figure 6 shows how the resistivity distribution of the second layer varied across the study area. This layer was more conductive than the overlying layer and had a larger layer thickness indicating its saturation with water and its consequent high potential for groundwater abstraction. The contour map showed that the subsurface resistivity within this layer increased as one moved from north-west towards the northeastern part of the study area. The third layer (coarse sands) had resistivity values that

ranged from 11 – 720 Ωm . The depth of this layer was undefined given the maximal current electrode spacing employed in this work. The contour map showing variation of resistivity distribution within this stratum is indicated in Figure 7. Lateral variations illustrated within this map were interpreted to be as a result of the diversity in geo-materials within the stratum.

4.2 Aquifer vulnerability results

As earlier mentioned, the GOD and AVI models were employed to evaluate the extent of the coastal aquifer's susceptibility to contamination. There has been a noticeable increase in the region's population and micro-industrial activity, which has significantly increased the locals' need for water (Uchegbu, 2002). The impact is consequently the degradation in the quality of ground water resources by virtue of environmental contamination (Esu et al., 1999). The GOD and AVI models were used because they do not need too many parameters to determine aquifer vulnerability, yet give values as good as that acquired with models that employ several parameters. In addition, these models were easy to employ and they generated accurate results. The models are considered below.

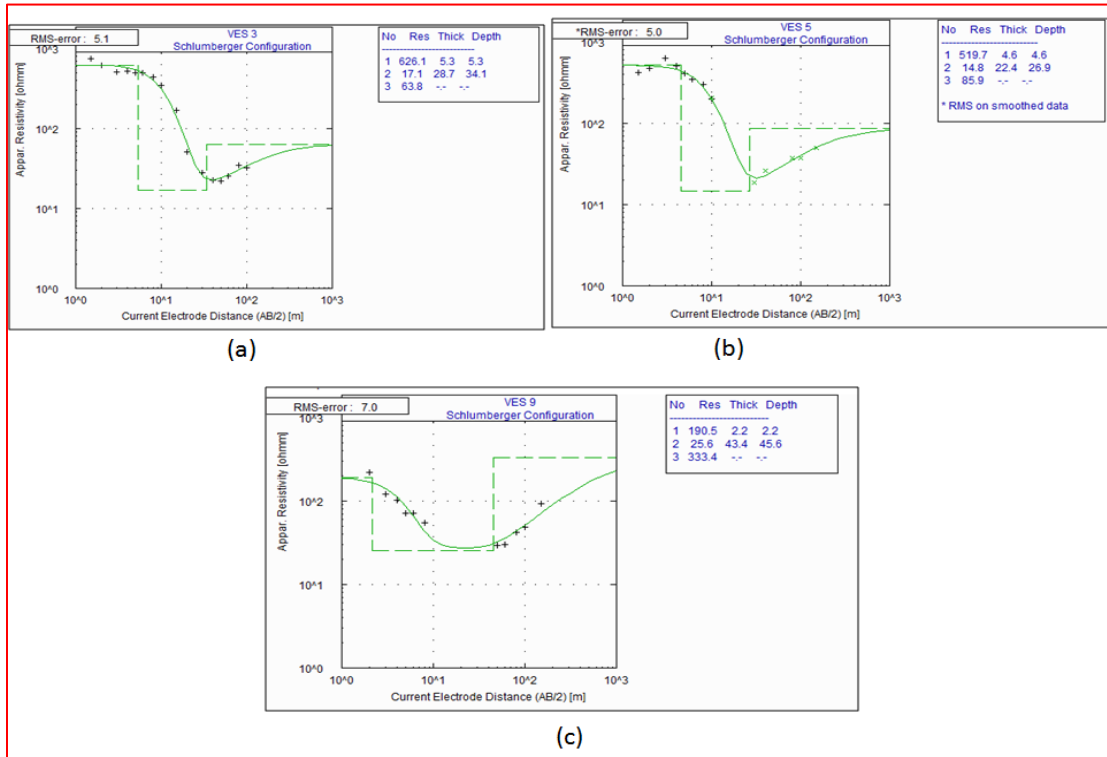


Figure 4 (a-c): Some representative models of the VES profile lines

Table 1: Results of geo-electric parameters obtained from inversion computer modeling

VES Stations	Co-ordinate		Resistivity (Ωm)			Thickness (m)		Depth (m)		Elevation (m)	Curve type
	Latitude ($^{\circ}\text{N}$)	Longitude ($^{\circ}\text{E}$)	ρ_1	ρ_2	ρ_3	h_1	h_2	d_1	d_2		
1	4 $^{\circ}$ 36'55.8"	7 $^{\circ}$ 56'08.7"	90.2	931.2	11.7	3.8	12.3	3.8	16	11	K
2	4 $^{\circ}$ 36'59.2"	7 $^{\circ}$ 56'00.9"	476.6	26.5	251.5	6.4	50.7	6.4	57.2	16	H
3	4 $^{\circ}$ 36'58.8"	7 $^{\circ}$ 56'00.6"	626.1	17.1	63.8	5.3	28.7	5.3	34.1	17	H
4	4 $^{\circ}$ 36'58.3"	7 $^{\circ}$ 56'00.2"	547.6	7.6	720.4	5.2	16.5	5.2	21.7	16	H
5	4 $^{\circ}$ 36'58.1"	7 $^{\circ}$ 55'59.8"	519.7	14.8	85.9	4.6	22.4	4.6	26.9	15	H
6	4 $^{\circ}$ 36'53.6"	7 $^{\circ}$ 56'08.2"	446.3	34	437.5	0.6	24.4	0.6	24.9	14	H
7	4 $^{\circ}$ 36'53.4"	7 $^{\circ}$ 56'08.1"	434	31.1	178.3	0.5	23	0.5	23.5	20	H
8	4 $^{\circ}$ 36'53.5"	7 $^{\circ}$ 56'07.9"	362.3	15.8	143.1	0.9	29.1	0.9	29.9	16	H
9	4 $^{\circ}$ 36'53.8"	7 $^{\circ}$ 56'08.1"	190.5	25.6	333.4	2.2	43.4	2.2	45.6	21	H
10	4 $^{\circ}$ 36'55.0"	7 $^{\circ}$ 56'09.5"	173.2	221.9	56.3	1.3	17.6	1.3	18.9	19	K

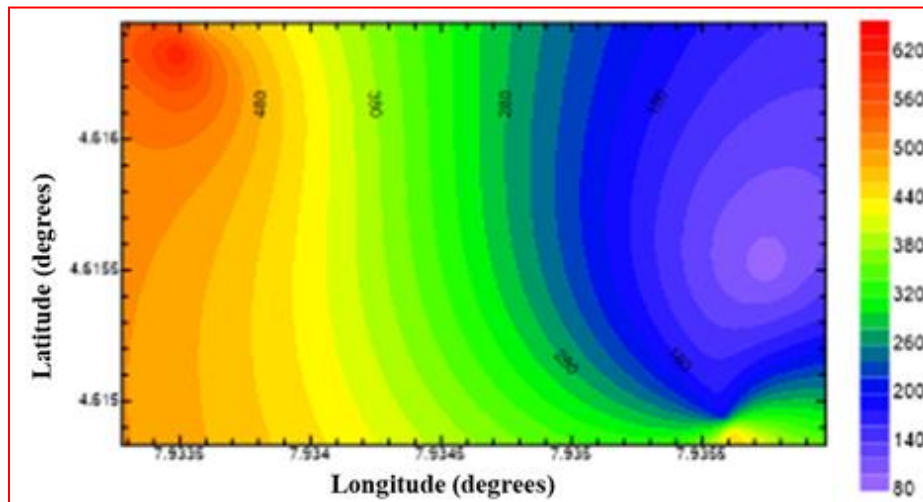


Figure 5: Contour map showing the resistivity distribution within the first layer comprising motley topsoil

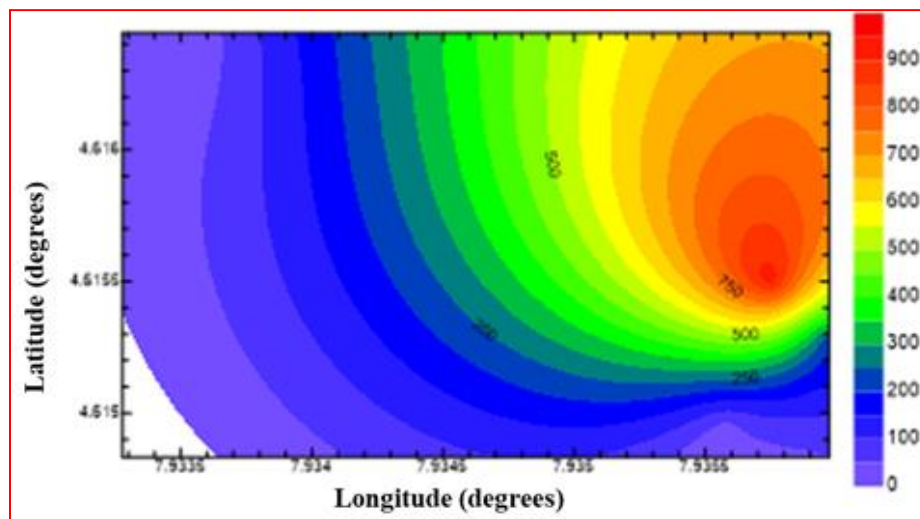


Figure 6: Contour map showing the resistivity distribution within the second layer comprising fine sand

4.3 GOD model results

The GOD model (Foster, 1987) is one of the aquifer vulnerability models developed to evaluate to what extent the aquifer is vulnerable to vertical contamination via the vadose zone. The GOD model employs three parameters in its estimation of aquifer vulnerability to subsurface and near-surface contaminations via the vadose layer which are: Groundwater confinement (G), overlying strata (O) and depth to groundwater (D). The first parameter, groundwater confinement characterizes the type of aquifer by

asking: is the aquifer confined or is it unconfined? An aquifer that is considered confined would have a different vulnerability index than an unconfined aquifer.

A confined aquifer implies that there was an overlying layer (e.g., clay) that lies over the aquifer to make it impenetrable. It is known that clay, though porous, is impermeable, hence the presence of clay over an aquifer would lead to its confinement. On the other hand, an unconfined aquifer implies the presence of sand or sandstone, which is both porous and permeable.

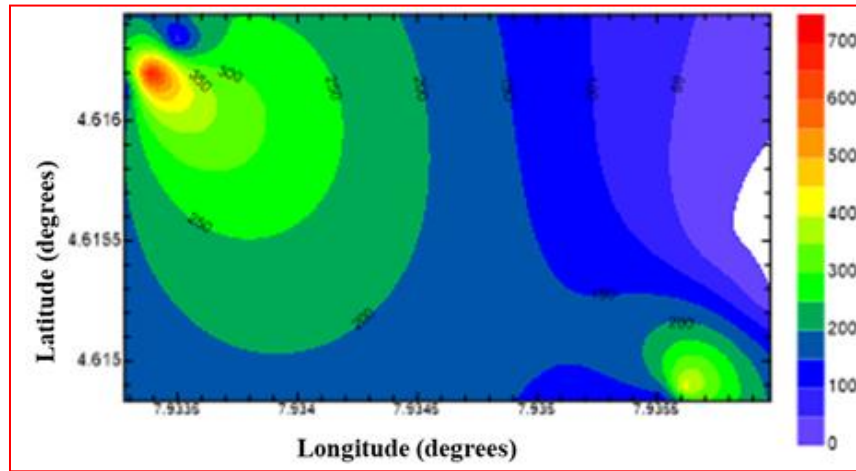


Figure 7: Contour map showing the resistivity distribution within the third layer comprising coarse sand

Hence, under the column for groundwater confinement or occurrence, a confined aquifer had a value of 0, while an unconfined aquifer had a value of 1 (see Table 2).

Overlying strata (O) described the type of lithology overlying the aquifer with regards to their porosity, permeability and hydraulic conductivity. The greater these value of these important factors, the greater the ability of subsurface contaminants to infiltrate the subsurface layers to get to the aquifer. Hence, sandy gravel (which is highly porous and permeable) has an index of 1, sandy gravel with sand =0.9, sand =0.8, sand with clay = 0.7, limestone =0.6, silty sand =0.5, silty clay = 0.4 and clay =0.3. It is observed that the indices get smaller the less porous the geo-material becomes. The implication is with highly porous lithology, the vulnerability of the aquifer to contaminants increases.

The last parameter defined under the GOD model is the depth to groundwater (D) and it is critical in appraisals of aquifer vulnerability. With a shallow aquifer (i.e., less depth to groundwater), vulnerability would increase as contaminants could quickly get to the aquifer compared to an aquifer with a greater depth to groundwater. Hence the GOD model gave varying indices to

depth to groundwater. A greater depth to groundwater meant a lower index for D, while a small depth to groundwater meant a larger value for D. And finally, the depth to groundwater is impacted by the depth of overburden subsurface layers. Hence, the thicker the overburden the less the contamination of the aquifer, while the more shallow the overburden, the more intense the extent of contaminant percolation into the aquifer (Thirumalaivasan et al. 2003). To determine the final GOD index, the formula used was

$$\text{GOD index} = G * O * D \quad (5)$$

In the above equation, G = groundwater occurrence/confinement (i.e., type of aquifer), O = lithology of the overlying strata, and D = depth to aquifer. The indices were evaluated with the aid of equation (5) and values generated were multiplied to give the total GOD index for that particular profile line.

The value of the GOD index derived would determine how vulnerable the aquifer was (Table 3). Hence, a GOD index of 0-0.1 implied the aquifer had very low vulnerability to contamination, 0.3-0.5 implied an average vulnerability, 0.5 – 0.7 implied a high vulnerability, and 0.7 – 1.0 implied a large susceptibility to degradation.

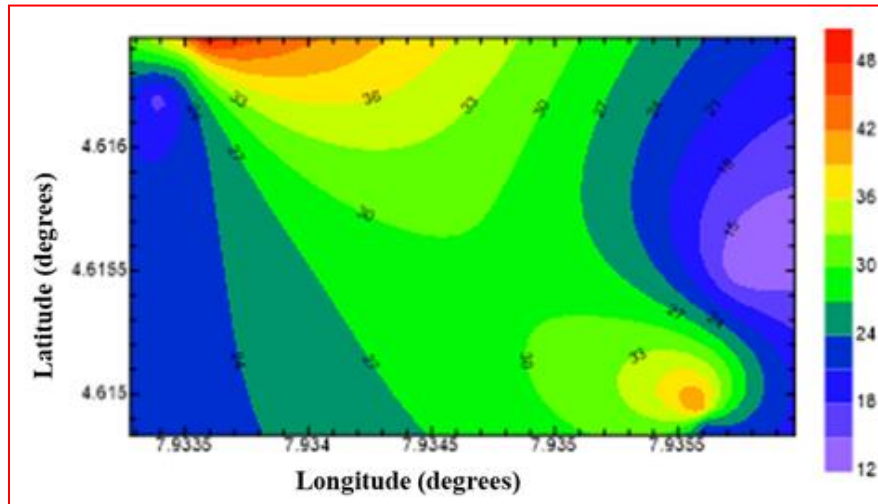


Figure 8: Contour map showing the variation of aquifer thickness within the study area

Table 2: Allocation of values to various parameters in the GOD model

Groundwater Occurrence (G)	Value	Overlying strata (O)	Value	Depth to Groundwater (D)	Value
Confined Aquifer	0	Sandy gravel	1	< 2	1
Un-confined Aquifer	1	Sandy gravel with sand	0.9	2-5	0.9
		Sand	0.8	5-10	0.8
		Sand with clay	0.7	10-20	0.7
		Limestone	0.6	20-40	0.6
		Silty sand	0.5	40-70	0.5
		Silty clay	0.4	70-100	0.4
		Clay	0.3	>100	0.3

The results of computations obtained for the GOD model is shown in Table 4. Based on these GOD indices, the vulnerability of the aquifer was either classified as very high, high, moderate, low or very low. In the study area, indices generated from GOD model ranged from 0.54 – 0.81 with a mean of 0.68. Distribution map of GOD indices within the site is illustrated in Figure 9. The

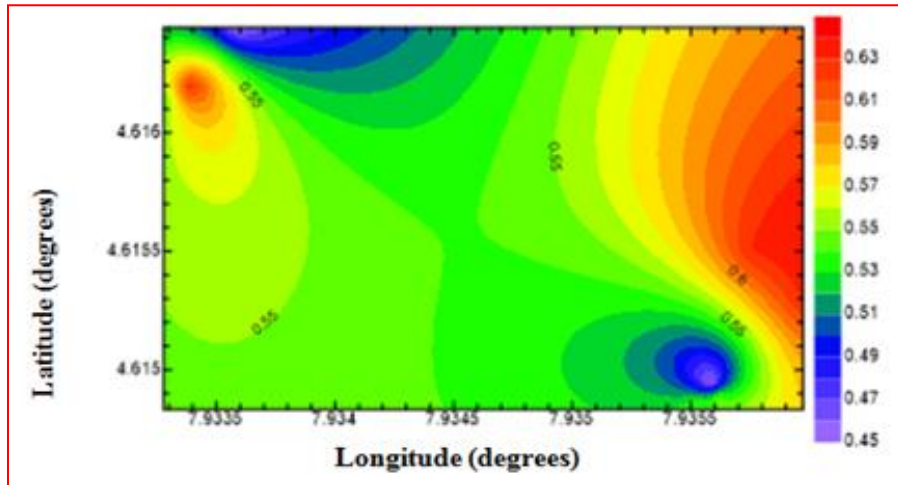
image map shows that in general the area has high susceptibility to aquifer pollution. The north-east and north west sections are seen to be highly susceptible to contamination. Table 4 shows that out of 10 profile lines, 8 lines indicated high aquifer vulnerability and 2 lines indicated average aquifer vulnerability. The general conclusion is that the aquifer is highly susceptible to contaminants.

Table 3: The GOD indices and the class of vulnerability arising from each index

GOD Index	0.0 – 0.1	0.1 – 0.3	0.3 – 0.5	0.5 – 0.7	0.7 -1.0
Class of vulnerability	Very low	Low	Average	High	Very high

Table 4: Determination of GOD indices over the various profiles lines in the study area

VES NO	Latitude (°)	Longitude (°)	Aquifer bulk resistivity ρ_a (Ωm)	Aquifer thickness h_a (m)	GOD Index	Vulnerability rating
1	4°36'55.8	7°56'08.7"	931.2	12.3	0.63	High
2	4°36'59.2"	7°56'00.9"	26.5	50.7	0.45	Average
3	4°36'58.8	7°56'00.6"	17.1	28.7	0.54	High
4	4°36'58.3"	7°56'00.2"	7.6	16.5	0.63	High
5	4°36'58.1"	7°55'59.8"	14.8	22.4	0.54	High
6	4°36'53.6"	7°56'08.2"	34	24.4	0.54	High
7	4°36'53.4"	7°56'08.1"	31.1	23	0.54	High
8	4°36'53.5"	7°56'07.9"	15.8	29.1	0.54	High
9	4°36'53.8"	7°56'08.1"	25.6	43.4	0.45	Average
10	4°36'55.0"	7°56'09.5"	221.9	17.6	0.63	High

**Figure 9:** Distribution map of GOD indices across the study area

4.4 The AVI model results and analysis

The Aquifer Vulnerability Index (AVI) employs thickness of the overburden h and hydraulic conductivity K of each subsurface layer overlying the aquifer to characterize the susceptibility of an aquifer to degradation. The relationship between the two is defined by hydraulic resistance C defined as:

$$C = \sum_i^n \frac{h_i}{K_i} \quad (6)$$

where $i = 1, 2, \dots, n$. The hydraulic resistance (in seconds or days, depending on the unit used for

hydraulic conductivity) estimates the time it takes for fluids to infiltrate the overburden. The aquifer vulnerability index (AVI) is generated via taking the logarithm of C as follows:

$$AVI = \log(C) \quad (7)$$

The value of the AVI index derived would determine how vulnerable the aquifer was. Table 5 illustrates the classes of aquifer vulnerability depending on their AVI values. With an AVI value of < 1 , the aquifer has a very high vulnerability, index values of 1-2 implied a high vulnerability, values ranging from 2-3 implied a

moderate vulnerability, values ranging from 3-4 implied a low vulnerability and a value of > 4 implied a very low vulnerability to contamination.

The outcome of computations generated for the AVI model is illustrated in Table 6. The Aquifer Vulnerability Index (AVI) values ranged from 0.30 to 1.13 with an average value of 0.65. The map showing the AVI distribution within the surface area is indicated in Figure 10. The AVI model indices are observed to increase from the southern parts of the map towards to the north-

eastern sections. The AVI values based on the AVI classification shown in Table 3; show that the aquifer unit has a high susceptibility to contamination. This coincided with results obtained from the GOD models showing that in general, the aquifer was highly vulnerable to contaminant pollution. The implication is that effective groundwater management and conservation strategies should be adopted within the study area to prevent the worsening of groundwater pollution within the study area.

Table 5: The AVI indices and the class of vulnerability arising from each index value

Hydraulic resistance C	AVI (Log C)	Class of vulnerability
0 -100	< 1	Very high
10-100	1 -2	High
100-1000	2-3	Moderate
1000-10000	3-4	Low
> 10000	> 4	Very low

Table 6: Determination of AVI indices over the various profiles lines in the study area

VES Stations	Co-ordinates		Aquifer thickness ha (m)	Hydraulic conductivity K (m/day)		Hydraulic resistance C	AVI	Vulnerability rating
	Latitude ($^{\circ}$)	Longitude ($^{\circ}$)		Layer 1	Layer 2			
1	4 $^{\circ}$ 36'55.8"	7 $^{\circ}$ 56'08.7"	12.3	5.2481	0.9592	13.5468	1.1318	High
2	4 $^{\circ}$ 36'59.2"	7 $^{\circ}$ 56'00.9"	50.7	1.5620	12.8017	8.0576	0.9062	Very high
3	4 $^{\circ}$ 36'58.8"	7 $^{\circ}$ 56'00.6"	28.7	1.2807	17.6104	5.7682	0.7610	Very high
4	4 $^{\circ}$ 36'58.3"	7 $^{\circ}$ 56'00.2"	16.5	1.4118	31.7802	4.2023	0.6235	Very high
5	4 $^{\circ}$ 36'58.1"	7 $^{\circ}$ 55'59.8"	22.4	1.4666	19.5632	4.2814	0.6316	Very high
6	4 $^{\circ}$ 36'53.6"	7 $^{\circ}$ 56'08.2"	24.4	1.6386	10.6776	2.6513	0.4235	Very high
7	4 $^{\circ}$ 36'53.4"	7 $^{\circ}$ 56'08.1"	23	1.6722	11.3936	2.3177	0.3651	Very high
8	4 $^{\circ}$ 36'53.5"	7 $^{\circ}$ 56'07.9"	29.1	1.9072	18.6538	2.0319	0.3079	Very high
9	4 $^{\circ}$ 36'53.8"	7 $^{\circ}$ 56'08.1"	43.4	3.0453	13.1278	4.0284	0.6051	Very high
10	4 $^{\circ}$ 36'55.0"	7 $^{\circ}$ 56'09.5"	17.6	3.2638	2.7251	5.8695	0.7686	Very high

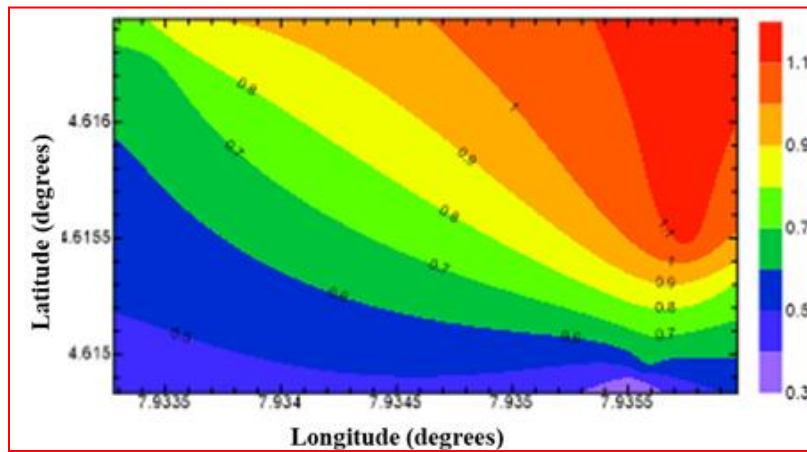


Figure 10: Distribution map of AVI across the study area

5.0 Conclusion

The electrical resistivity surveying technique was applied to evaluate the extent of aquifer vulnerability in Eket Local Government, South-East Nigeria with the aid of vertical electrical profiles employing the Schlumberger array with a maximal current array separation of 800m. Results as interpreted from the resistivity sounding curves and constrained from borehole lithological logs indicate that the study location comprises 3 subsurface layers. The first layer (motley top soil) has resistivity values that ranged from 90 - 626 Ω m. The thickness of this layer ranged from 0.5 - 17.6m. The second layer (fine sand) had resistivity values which ranged from 7.6 - 221.9 Ω m with thickness ranging from 12.3 - 50.7m, while resistivity of the third layer (coarse sand) ranged from 11.7 - 720 Ω m.

The GOD index ranged from 0.54 to 0.81 with a mean of 0.68. Computed GOD indices showed that in general, the area has a high vulnerability to contamination. The AVI value ranged in value from 0.30 to 1.13 with a mean of 0.65. From these values and based on the AVI classification table, it is observed that layers within the research site had contamination vulnerability indices that ranged from high to very high. This coincided with results obtained from the GOD models showing that in general, the area has a

high vulnerability to aquifer contamination. This study, being one of the first to assess vulnerability indices within major coastal aquifer in this area, has shown that electrical resistivity surveying has a great potential in determining the extent of aquifer contamination.

Data availability statement

Data from this work will be made available on reasonable request

Conflict of interest statement

There was no conflict of interest that could influence the results obtained in the study.

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