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A COMPARATIVE AQUIFER VULNERABILITY STUDY OF THE QUATERNARY SOMBREIRO – WARRI DELTAIC PLAIN DEPOSITS, WESTERN NIGER DELTA, NIGERIA

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ABSTRACT

This paper investigates the effect of two parameters, resistivity and hydraulic conductivity of the vadose zone, and their reliability in assessing aquifer vulnerability. Hence, the vulnerability of the aquifers within the Quaternary – Sombreiro Deltaic deposits to contamination was assessed using two models: longitudinal conductance and hydraulic resistance. The results from the simulation of the models show four vulnerability zones indicated by the longitudinal conductance model, while the hydraulic resistance model revealed five zones. Two-way analysis of variance (ANOVA) reveals that thickness, lithology, and the interactions of the two variables have a significant effect on the two models. The longitudinal conductance and hydraulic resistance models show a closer coincidence of vulnerability in 72% of the study area. The differences in results and delimitations of varying vulnerability zones by the two models depend primarily on the two parameters employed in estimating the vulnerability, with the vadose layer's hydraulic conductivity imposing remarkable influence on the general vulnerability of the study area.

Keywords: Aquifer, Vulnerability, Vadose zone, Longitudinal conductance, Hydraulic resistance.

INTRODUCTION

Groundwater is a precious natural resource; however, contamination has remained an ever-increasing water resource problem. Previous studies in the Niger Delta have shown deterioration in groundwater quality (Akpoborie *et al.*, 2000; Akpoborie and Aweto, 2012; Aweto, 2020; Ohwoghere-Asuma *et al.*, 2020). The sands which are coarse and have good aquifer potential are mostly unconfined, thus making them vulnerable to surface contamination from many potential sources (Aweto, 2012). Human activities have some adverse effects on the quality of groundwater; hence, developing methods that prevent contamination and protect aquifers has become very crucial (Logan, 1990). One such method is aquifer vulnerability assessment; aquifer vulnerability is the tendency for contaminants to infiltrate an aquifer (Natural Resources Council, 1993). An assessment of how vulnerable an aquifer to contaminants is vital in groundwater resource development strategy so as to maintain clean groundwater sources.

Some early methods used in aquifer vulnerability studies based on surface information needed to consider the confining layer's thickness as a relevant parameter in determining aquifer vulnerability to contamination. However, recent methods have been devised considering the confining layer's thickness (Manitoba Natural Resources, 1990; Roeper, 1990; Mclay *et al.*, 2001). These methods usually consider the conditions of the vadose zone as a notable parameter for assessing vulnerability. These methods include DRASTIC (Aller *et al.*, 1987); G.O.D. (Foster, 1987); A.V.I. (Van Stempvoort *et al.*, 1993; SINTACS (Civita, 1994), cation exchange capacity (Holting *et al.*, 1995), integrated conductivity (Rottger *et al.*, 2005), VLF – E.M. (Ohwoghere – Asuma *et al.*, 2018). The parameters employed in various vulnerability studies are usually either qualitative or quantitative. The significance of these parameters is not based on any unprejudiced distinction (Aller *et al.*, 1987). There is, however, a significant overlap or superfluousness in the parameter, such as hydraulic conductivity (Aller *et al.*, 1987).

The vadose zone is part of the subsurface that lies between the ground surface and water table. Groundwater contamination usually begins on the ground surface, the contaminants have to travel through the vadose zone before it reaches the water table (Dahan, 2020). The reduced flow rates leading to longer residence time of contaminants and natural attenuation process of the vadose zone protects the aquifer below from contamination (Dahan, 2015; Panda and Sabarathinam, 2019). Longitudinal conductance, which is regarded as proportionate to the capacity of vadose zone to protect the aquifer beneath (Henriet, 1976), has also found wide application in aquifer vulnerability studies in Nigeria (Oladapo *et al.*, 2004; Atakpo and Ayolabi, 2009; Atakpo, 2013; Aweto and Mamah, 2014; Egbai *et al.*, 2015), this method measures vulnerability by incorporating the resistivity and thickness of the overlying vadose zone above aquifers. Aweto (2014) evaluated the vulnerability in the Western Niger Delta and observed that a clay layer above an aquifer with a resistivity of 90 Ωm and thickness of 10 m; had a corresponding longitudinal conductance of 0.11 mho was thus rated as having weak protective capacity. This layer ideally was expected to have a good protective capacity rating. Two studies were recently conducted in the Niger Delta by Ohwoghere-Asuma *et al.* (2018) and Aweto (2020) to identify lithofacies and aquifer protective capacity. The findings of the studies showed that aquifers underlying impervious geologic materials such as clays tend to retard the migration of contaminants and thus have a good protective capacity (GPC). Thus, the longitudinal conductance model sometimes underrates the vulnerability where the vadose zone is made up of clays.

Maps showing vulnerability of aquifer have become a critical guide in environmental monitoring and groundwater management tool. Therefore, it is imperative to establish reliable mapping techniques that is competent in handling uncertainties associated with producing vulnerability maps. The aquifer vulnerability index method (Van Stempvoort *et al.*, 1993) is another aquifer vulnerability mapping technique based on two non-arbitrary parameters: thickness and hydraulic conductivity of the confining layers. These two parameters were used to determine the hydraulic resistance; the hydraulic resistance indicates the approximate time for the vertical flow of water by advection through the vadose zones above the aquifer. Many factors influence both the longitudinal conductance and the hydraulic resistance of a vadose zone, and the thickness of the zone is just one of them. For example, other factors such as soil texture, structure, and moisture content can also significantly affect the hydraulic resistance of a vadose zone. Suppose it is essential to consider whether the thickness of the vadose zone can be separated from the geological material it is made of. In that case, assessing the interactions of these two sets of properties must also be critical. Therefore, it is vital to recognize the outcome of the interaction between lithology and geological material on longitudinal conductance and hydraulic resistivity separately.

In this context, this study is thus directed at comparing these two vulnerability mapping methods to determine which model best represents the vulnerability of the study area. Furthermore, the interaction of the thickness and soil texture distribution of the vadose zone to aquifer vulnerability is investigated using the conventional statistical method.

Location and Geology

The study area is located within the Niger Delta region of Nigeria, and it comprises eight (8) communities, namely; Ughoton, Ekakpamre, Uvwiamuge, Egbeleku, Otor – Jeremi, Okpara – Inland, Aghalokpe and Sapele (Figure 1). The Cenozoic Niger Delta basin is represented by three diachronous sequences (Short and Stauble, 1967) namely; Akata, Agbada and Benin Formations. These three lithostratigraphic units are generally distinguished based on sand-shale ratios. The oldest formations in the study area is the Akata Formation which lie at the base which consists of holo-marine shales, silts, and clays; followed by the Agbada Formation made up of interbedded sands and shales. Lying on top of these formations is the younger Benin Formation consisting of massive continental/fluvial sands and gravels. Overlying this formation are the Quaternary deposits, which mask the Benin Formation (Oomkens, 1974). These deposits are between 40 – 150 m thick and made up of rapidly alternating sequences of sand, silt, and clay, with the silt and clay becoming conspicuous seawards.

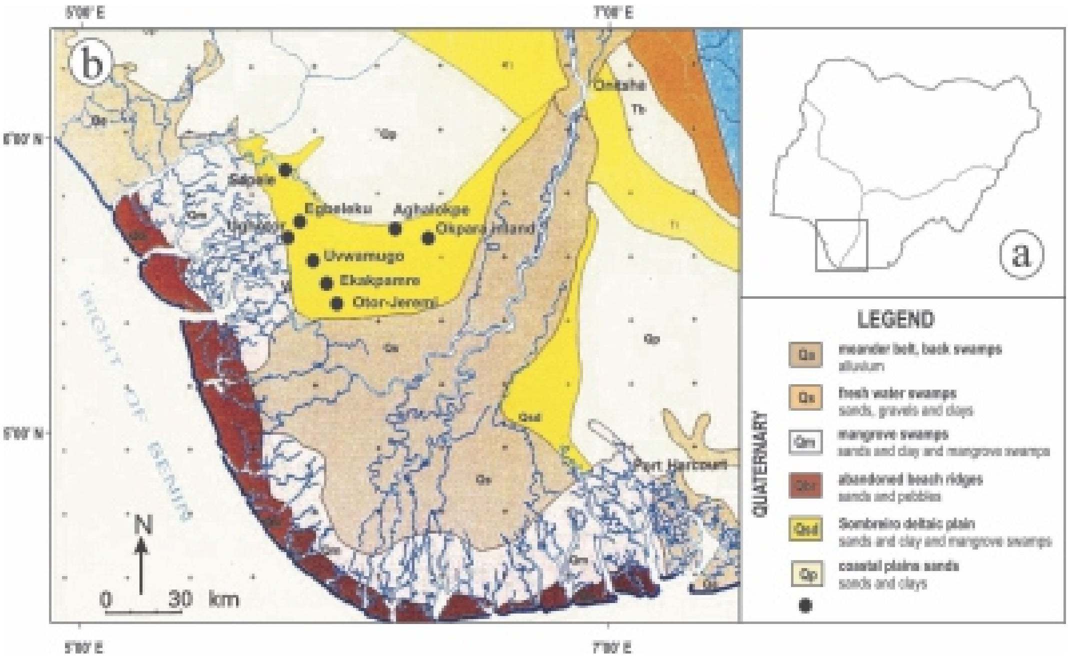


Figure 1: (a) Map of Nigeria showing the Niger Delta (black box). (b) Geological map of the Niger Delta (modified from Reijers, 2011) showing the study area (Sombreiro deltaic plain).

Materials and Methodology

130 Vertical Electrical Sounding (VES) data were obtained at different locations in the study area using the ABEM signal averaging system (SAS) Terrameter model 4000, as shown in Figure 2. The Schlumberger configuration was adopted for the sounding with current electrode separation (AB) of 200 to 600 m. An initial interpretation was made by so it reads made by partial curve partial curve matching, followed by a computer modelling technique using win resist (Vander Valpen, 2004) to obtain the subsurface layer's resistivity and thickness. The results of the resistivity soundings were correlated with lithologic logs from the area.

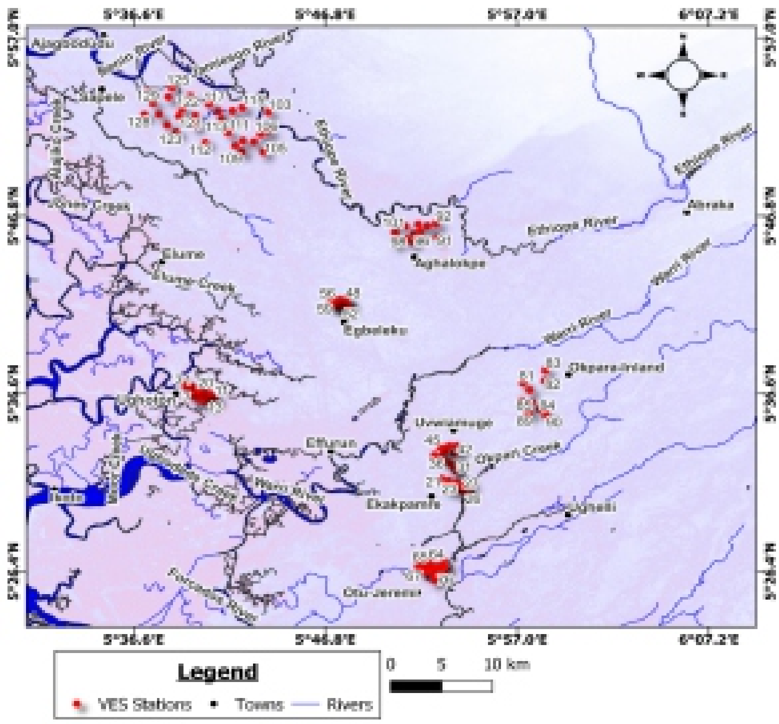


Figure 2: Map of study area showing sounding locations

Longitudinal conductance and Hydraulic resistance

The resistivities and thicknesses of unsaturated layers were used in deriving the total longitudinal conductance, S, given by:

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \quad (1)$$

The thickness of these layers and their estimated hydraulic conductivities were used in estimating the hydraulic resistance, C, given by:

$$C = \sum_{i=1}^{n} \frac{h_i}{k_i} \quad (2)$$

Hydraulic conductivity used in this study was obtained from Aweto and Ohwoghere-Asuma (2018); hydraulic conductivity for sand is 3650 cm/yr, for clay is 0.000365 cm/yr, for clayey sand is 0.365 cm/yr and for sandy clay is 0.0365 cm/yr.

The vulnerability of an aquifer to contamination was evaluated utilizing the total longitudinal conductance values calculated with equation 1 and hydraulic resistance values with equation 2. The rating and index systems given by Oladapo *et al.* (2004) and Van Stempvoort *et al.* (1993), shown in Tables 1 and 2, were then applied.

Table 1: Modified longitudinal conductance (LC)/aquifer protective capacity rating (Oladapo *et al.*, 2004).

Longitudinal Conductance (mho)	Protective capacity rating
> 10	Excellent (EPC)
5 – 10	Very good (VGPC)
0.7 - 4.9	Good (GPC)
0.2 - 0.69	Moderate (MPC)
0.1 - 0.19	Weak (WPC)
< 0.1	Poor (PPC)

Table 2: Relationship of hydraulic resistance (HR) to aquifer vulnerability index (Van Stempvoort *et al.*, 1993).

The logarithm of the C	Aquifer vulnerability index
< 10	Extremely high vulnerability (EHV)
1 – 2	High vulnerability (HV)
2 – 3	Moderate vulnerability (MV)
3 – 4	Low vulnerability (LV)
> 4	Extremely low vulnerability (ELV)

The longitudinal conductance and hydraulic resistance derived from the resistivity and thickness of the vadose zone were used to produce aquifer vulnerability maps using SURFER (2002), a Terrain and 3D surface modelling software.

Statistical analysis

Analysis of Variance (ANOVA) which is one of the most common statistical methods in groundwater vulnerability analysis (Worrall *et al.*, 2002), was used to understand if there is an interaction between two independent variables (called factors) on the dependent variable. The objective was to study the effect of thickness and lithology (independent variables) on longitudinal conductance and hydraulic resistivity (dependent variable) of the vadose zone. The ANOVA technique has been used to find the significant effect level of influencing parameters on response.

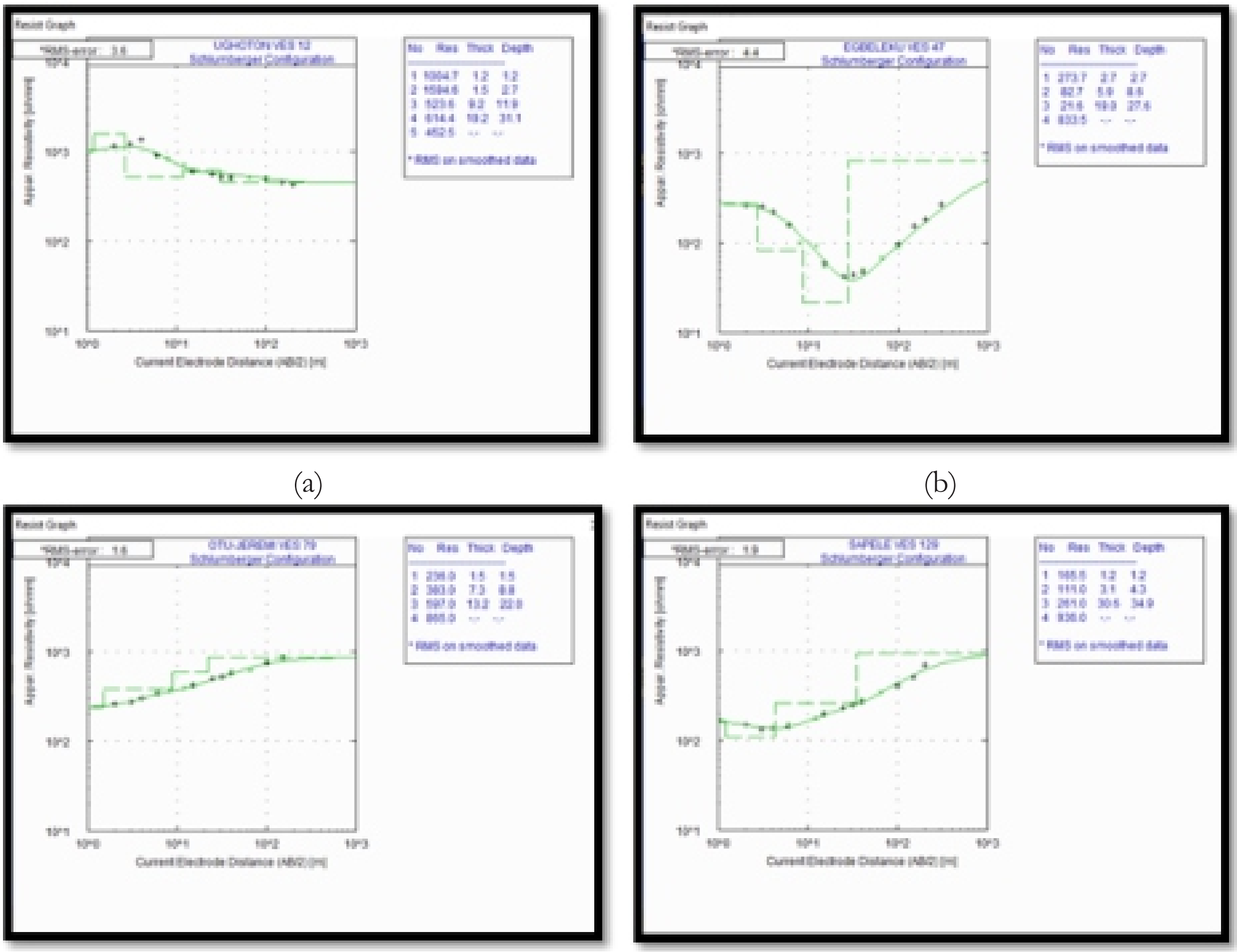
ANOVA models were carried out using Statistical Package or Social Sciences (SPSS 23) to analyze the data statistically.

A normality assumption was first performed using graphical techniques. Then a two-way ANOVA test was performed to decide the P-value for testing the null hypothesis of no significant effect of thickness and lithology on both longitudinal conductance and hydraulic resistivity against the alternative hypothesis of significant effect of thickness and lithology on both longitudinal conductance and hydraulic resistivity.

RESULTS AND DISCUSSION

Geoelectric parameters and sections

Some selected examples of the 130 modelled curves are shown in Figure 3, while Table 3 shows the interpreted layer resisitivities, layer thicknesses, inferred lithologies and aquifer vulnerability rating.



(a) (b) (c) (d)

Figure 3: Computer-generated model data curves for Ughoton, Egbeleku, Otu-Jeremi, and Sapele.

Qualitative interpretation results of the computer-generated model data curves have led to the detection of four to five geoelectric layers (Figures 4 & 5). The resistivity values defined the following sequence: topsoil, clay/sandy clay/clayey sand/sand, fine to medium grained sand and coarse sand. The subsurface layer's resistivities and thicknesses shown in Table 3 is as follows:

The first layer shows resistivity that ranges from 71 – 1129 Ωm and thickness between 0.6 – 2.2 m, representing the topsoil with variable lithologic composition ranging from clays to sands.

Table 3: Summary of iterated Geoectric parameters, lithology, and aquifer vulnerability rating.

V.E.S.	Resistivity (Ωm)	Thickness (m)	Lithology	Long. Cond.	Rating	Hydraulic Resistance	Rating
5	50	1.0	Clay	0.14	WPC	4.02	ELV
	61.1	2.8	Clay				
	151.7	10.3	Clayey sand				
	700	8.5	Sand				
	469.8		Sand				
15	146.3	0.9	Clayey sand	0.21	MPC	3.98	LV
	52	3.5	Clay				
	323.7	43.3	Sand				
	976.3		Sand				
26	401	0.7	Sand	0.05	PPC	-2.57	EHV
	1001	6.2	Sand				
	511	2.9	Sand				
	483	19	Sand				
	610		Sand				
44	103	0.7	Clay	0.13	WPC	3.44	LV
	59	3.3	Clay				
	540	35.8	Sand				
	340		Sand				
47	273.7	2.2	Sand	0.96	GPC	4.83	ELV
	82.7	6.9	Clay				
	21.6	19	Clay				
60	165	1.4	Clayey sand	1.72	GPC	4.45	ELV
	117	3.2	Sandy clay				
	16	11	Clay				
	1015		Sand				
66	131.2	1.5	Sandy clay	0.08	PPC	2.61	MV
	176.1	1.8	Clayey sand				
	560	34.1	Sand				
	221		Sand				
78	73.6	1.1	Clay	0.13	WPC	3.89	LV
	487	12.8	Sand				
	20.1	1.7	Clay				
	374		Sand				
90	299	1.6	Sand	0.2	MPC	4.62	ELV
	578	2.5	Sand				
	84	15.1	Clay				
	956		Sand				
101	538	1.2	Sand	0.0763	PPC	4.31	ELV
	101.3	7.5	Clay				
	311	10.5	Sand				
	527		Sand				
118	82.5	1.1	Clay	0.04	PPC	3.48	LV
	363	1.5	Sand				
	525	12.1	Sand				
	819		Sand				
129	165.5	1.2	Clayey sand	0.0152	PPC	1.95	HV
	111	3.1	Sandy clay				
	261	30.6	Sand				
	936		Sand				

The second layer show resistivity of 15 – 1390.9 Ωm, with thickness ranging from 1.3 – 27.5 m. The variation of resistivity indicates a lateral lithologic change from clay to sand; this layer with the first layer constitutes the vadose zone in the study area; the average thickness is 8 m.

The third layer shows resistivity values of 16 – 988 Ωm and thickness between 5.8 – 50.1 m. It is made of sand and constitutes the aquifer in the area, extending almost over the study area, except at Egbeleku, where they are clayey.

The fourth and fifth layers show resistivity that varies from 151 – 3913 Ωm and 411 – 958 Ωm, respectively. These layers are made up of sands and constitute part of the aquifer; the thickness of these layers could not be ascertained; however, inference from borehole log data indicates a possible thickness of more than 80 m.

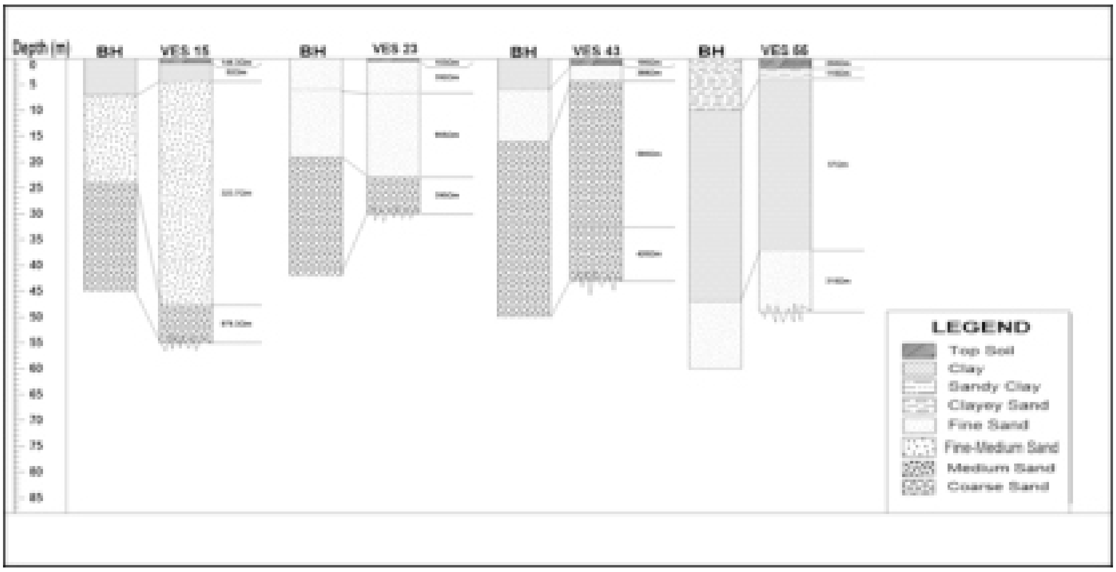


Figure 4: Geoelectric section for Ughoton, Ekakpamre, Uvwiamuge and Egbeleku.

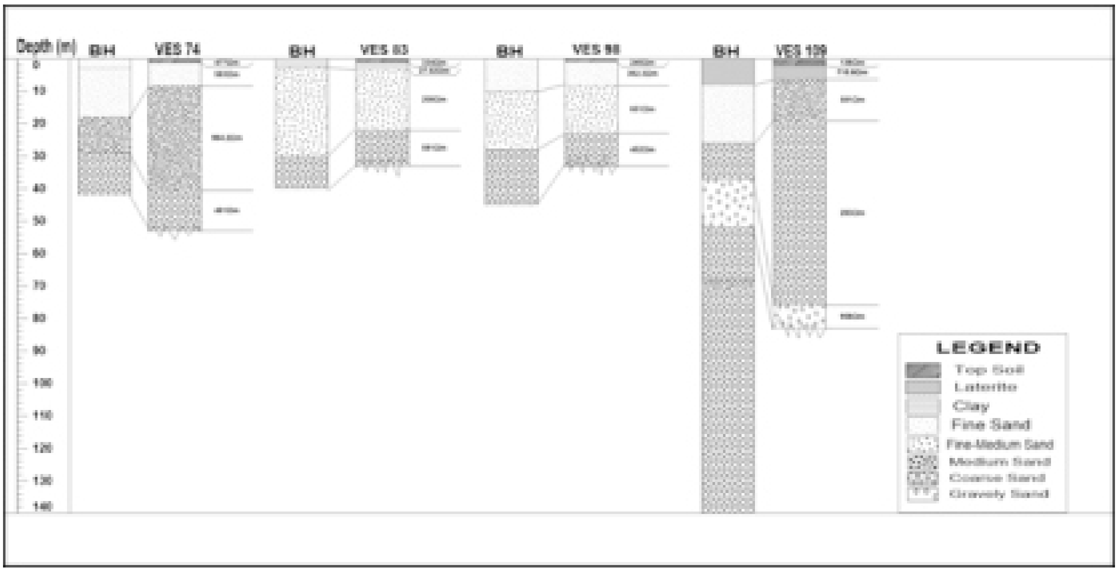


Figure 5: Geoelectric section for Otu-jeremi, Okpara-Inland, Aghalokpe and Sapele.

Aquifer vulnerability

The vulnerability map of Okpara-Inland, Uvwiamuge, Ekakpamre, and Otu-Jeremi based on longitudinal conductance (Figure 6) shows that 87% of the area has PPC. The northern parts around Okpara-Inland have WPC and MPC. Clusters of WPC are located in the western, central, and southwestern parts around Uvwiamuge, Ekakpamre, and Otu-Jeremi. The vulnerability of these areas based on hydraulic resistance (Figure 7) shows a similar pattern, with about 89% of the area having EHV. The northeastern parts show four vulnerability classifications (ELV, LV, MV, and HV), unlike Figure 6, which indicated two classifications; the western and southwestern parts (Figure 7) showed three vulnerability classes (HV, MV, and LV), while Figure 6 indicated mostly WPC and MPC in the southwest around Otu-Jeremi.

The vulnerability map of Sapele, Aghalokpe, Egbeleku, and Ughoton based on longitudinal conductance (Figure 8) show that 61% of the area is dominated by overburden with poor protective capacity, the western, northwestern, eastern, and southwestern region constituting about 19% of the area has weak protective capacity. The central portion representing 16%, has a moderate protective capacity, while the remaining 4% around Egbeleku has an excellent protective capacity. The vulnerability based on hydraulic resistance (Figure 9) also shows that most of the area (59%) is characterized by EHV. Unlike in Figure 8, where the areas located in the western, northwestern, eastern, and southwestern parts have four vulnerability classifications (HV, MV, LV, and ELV). The central portion has MV and HV, while the aquifers at Egbeleku has LV to ELV.

The two vulnerability models show a high level of conformity in areas underlain by sand (Table 3). ELV and LV or WPC and PPC are consistent with regions where the vadose zone is sandy. This was expected due to the presence of highly porous and permeable sandy regolith, thus creating accessible pathways for contaminant load. There were, however, significant discrepancies in the vulnerability classification of the two models where the vadose zone is argillaceous. As seen from the vulnerability maps (Figures 6, 7, 8 & 9), some areas classified as having PPC or WPC by the longitudinal conductance model (Figures 6 & 8) were classified as LV or ELV by the hydraulic resistance model (Figures 7 & 9). This ought not to be because these areas, which were underlain by clays with thickness ranging between 0.6 – 8.2 m, were expected to have MPC to GPC. Two studies were recently conducted in the Niger Delta by Ohwoghere-Asuma *et al.* (2018), Aweto (2020) to identify lithofacies and aquifer protective capacity. The findings of the studies showed that aquifers underlying impervious geologic materials such as clays tend to retard the migration of contaminants and thus have a good protective capacity (GPC).

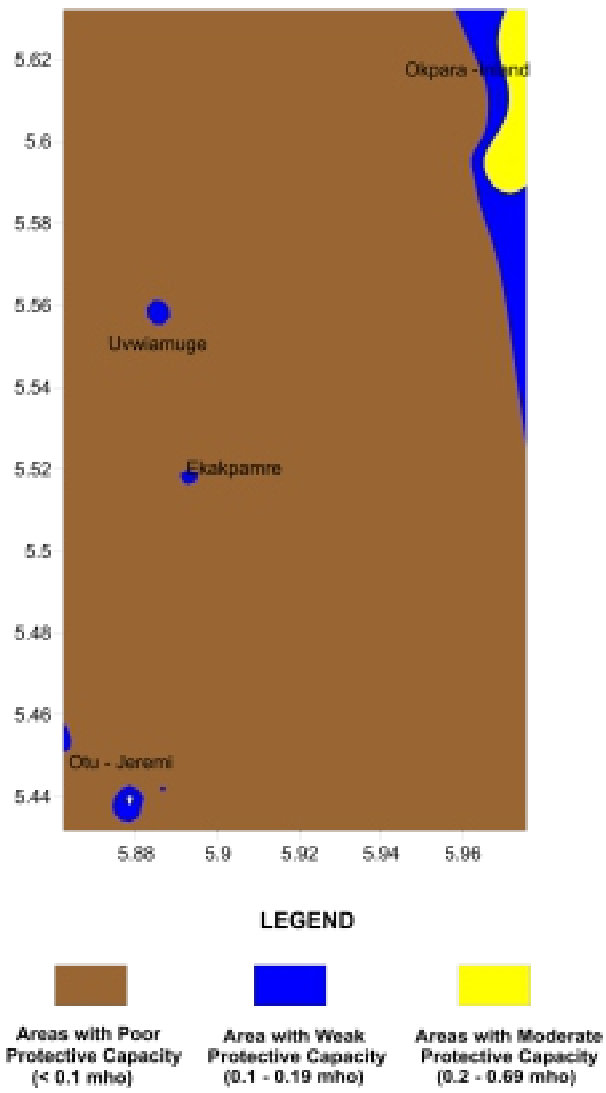


Figure 6: Vulnerability maps of Okpara-Inland, Uvwiamuge, Ekakpamre, and Otu-Jeremi based on longitudinal conductance (LC).

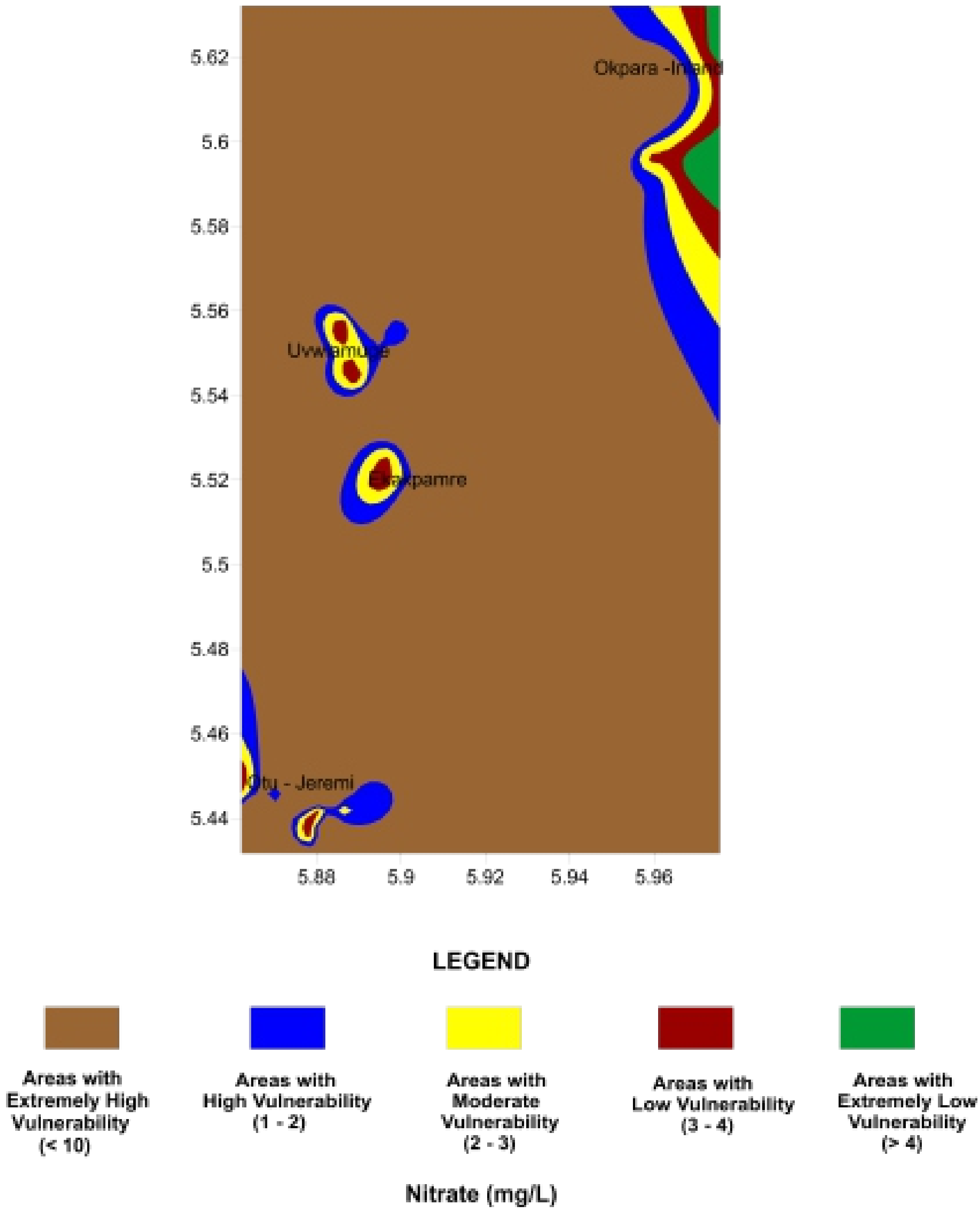


Figure 7: Vulnerability map of Okpara-Inland, Uvwiamuge, Ekakpamre, and Otu-Jeremi based hydraulic resistance (HR).

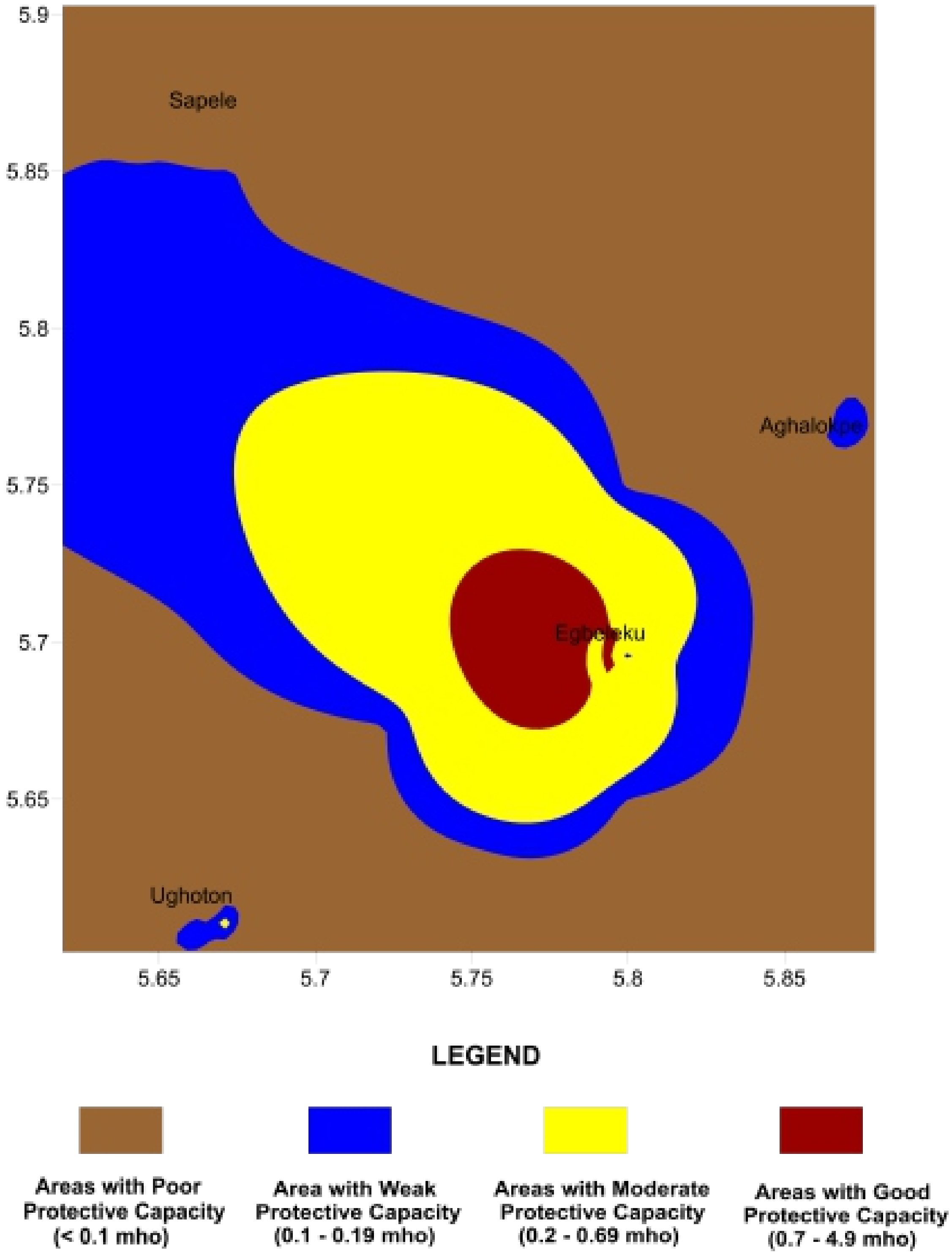


Figure 8: Vulnerability map of Sapale, Aghalokpe, Egbeleku, and Ughoton based on longitudinal conductance (LC).

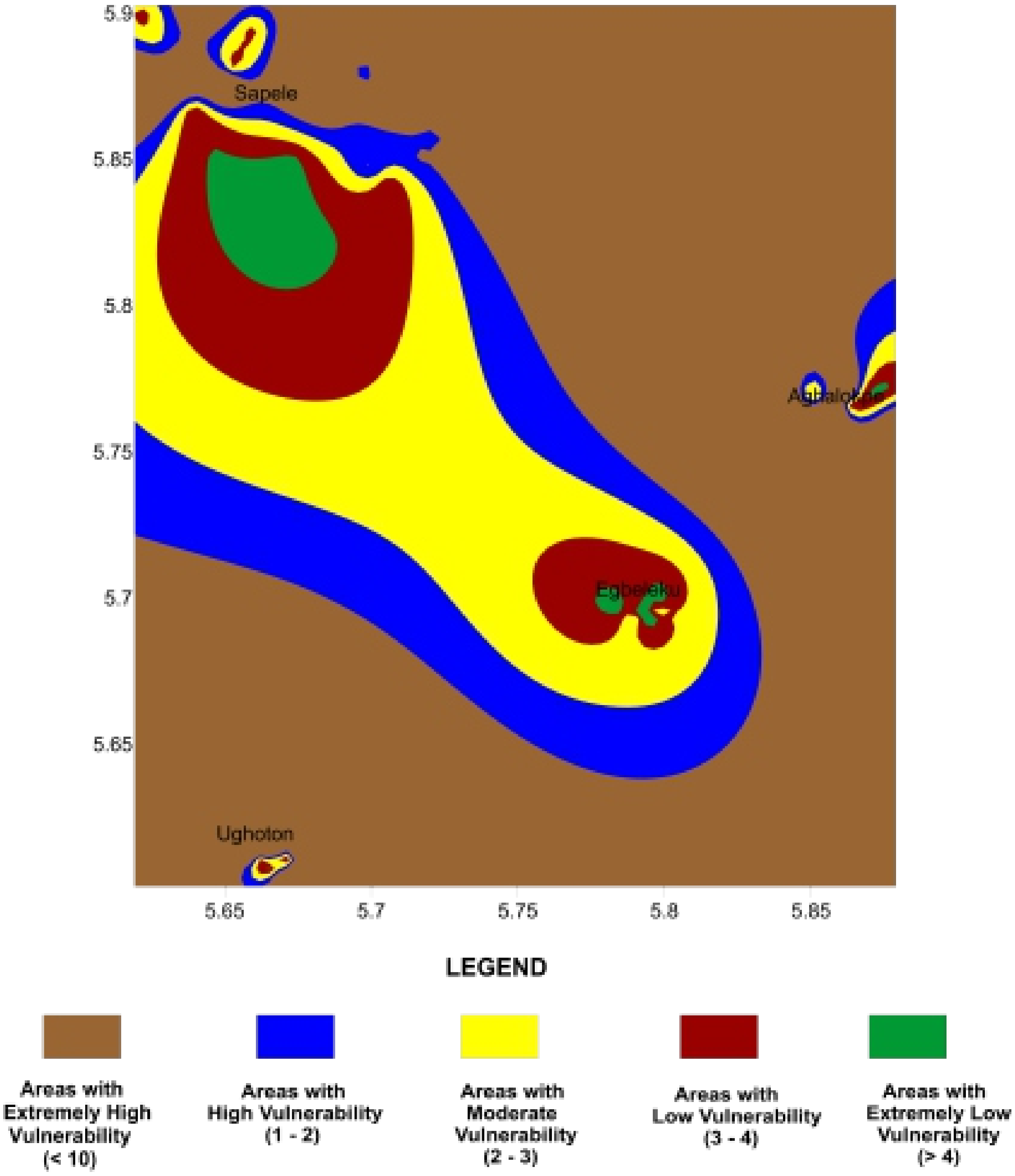


Figure 9: Vulnerability map of Sapale, Aghalokpe, Egbeleku, and Ughoton based on hydraulic resistance (HR).

According to Ravbar and Goldscheider (2009), there are no standard means of validating intrinsic vulnerability that is cognizance of physical parameters but often ignores anthropogenic activities. This study used nitrate levels to validate the two models' vulnerability maps; the area is inhabited with nitrate being a major source of contamination from farmlands and fish farms. Nitrate concentrations (ranging between 0.0 – 3.85 mg/L) from wells were plotted on the vulnerability maps of the two models (Figures 10 & 11). Observations from the maps and cross-correlation of nitrate in wells and vulnerability classification suggests that the hydraulic resistance model better represents the concentration of nitrate across the study area (R^2 = 0.6573) compared to the longitudinal conductance model (R^2 = 0.0494). Thus, the hydraulic resistance model provides a more effective measure of vulnerability in the study area than the longitudinal conductance model.

The effect of lithology and thickness of the vadose zone on the longitudinal conductance and hydraulic resistance models was assessed through a two-way analysis of variance (ANOVA). In this study, the significance of the independent variable was determined through two hypotheses:

H_0 is a null hypothesis: no significant relationship exists between the models and the thickness of the vadose zone or lithology.

Ha is an alternative hypothesis: a significant relationship exists between the models and the thickness of the vadose zone or lithology.

Firstly, the p-value of 0.00 in Table 4 is less than the critical significance level (0.05), meaning the null hypothesis should be rejected. The ANOVA results suggest that there are strong significant effects of lithology and thickness of the vadose zone on the longitudinal conductance. Thin vadose zones (2 – 3 m) generally have poor protective capacity irrespective of lithology type (Figure 12). The longitudinal conductance increases as the thickness of the vadose zone increases in each type of lithology (Figure 12). Thicker vadose zones (> 40 m) characterized by sand are observed to give good progressive capacity compared to relatively thinner vadose zone characterized by clay.

Secondly, the ANOVA result generated for hydraulic conductance (Table 4) indicates a p-value of 0.000, again suggesting that the null hypothesis of no significant effect between the model and thickness of the vadose zone or lithology should be rejected.

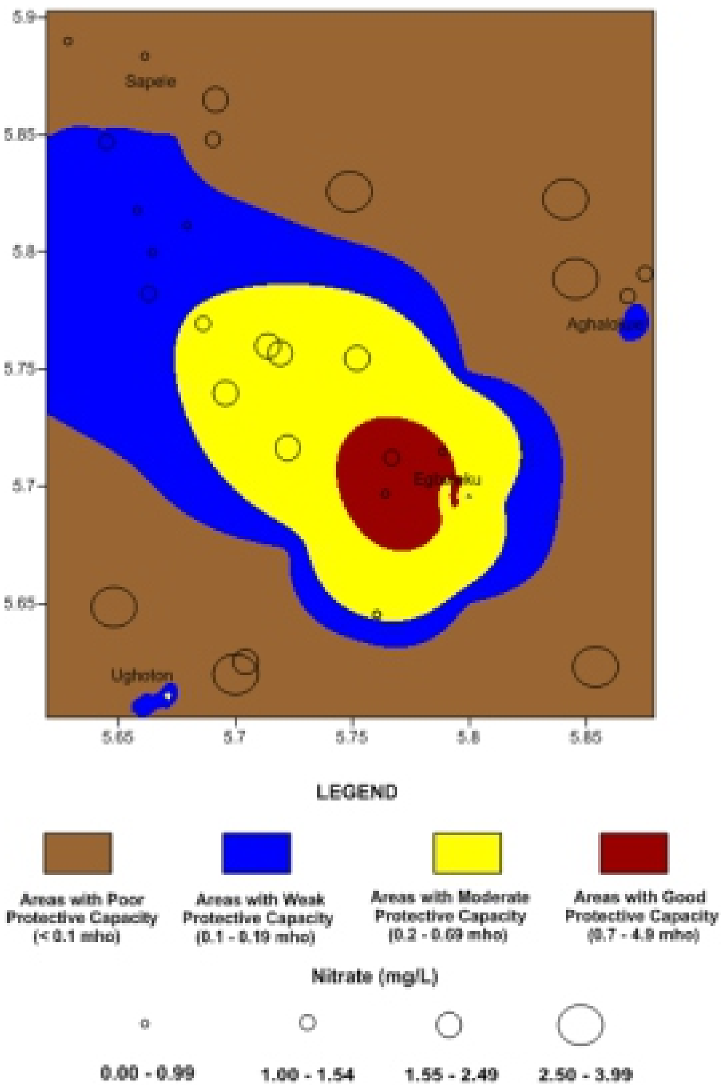


Figure 10: Maximum nitrate concentrations over vulnerability map based on longitudinal conductance.

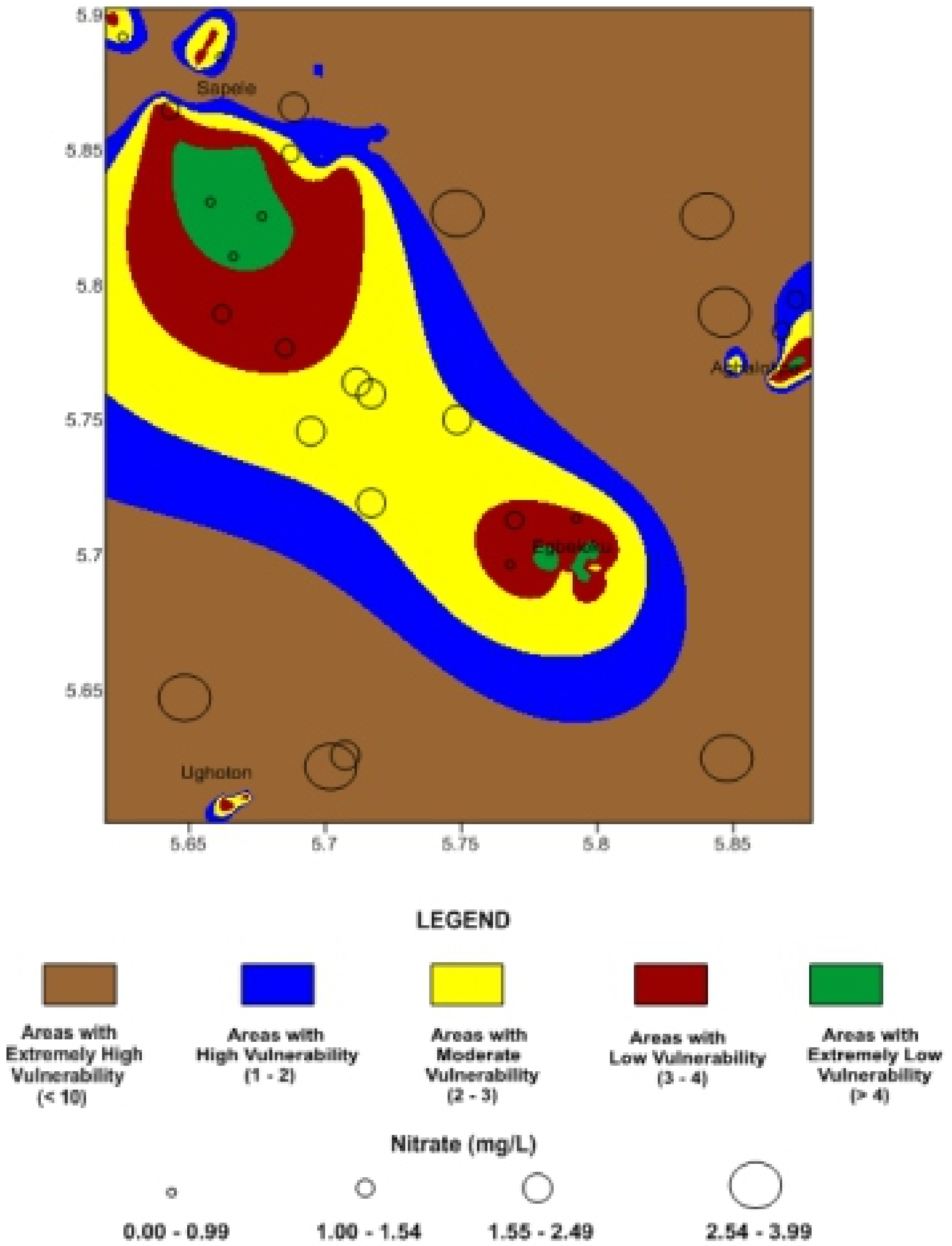


Figure 11: Maximum nitrate concentrations over vulnerability map based on hydraulic resistance

Table 4: ANOVA statistical results of longitudinal conductance for the vadose zone.

Tests of Between-Subjects Effects

Dependent Variable: LC RATING

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	100.166[a]	162	.618	24.403	.000
Intercept	258.274	1	258.274	10193.198	.000
THICKNESS	70.483	108	.653	25.757	.000
LITHOLOGY	2.813	3	.938	37.011	.000
THICKNESS * LITHOLOGY	5.523	51	.108	4.274	.000
Error	3.750	148	.025		
Total	537.000	311			
Corrected Total	103.916	310			

a. R Squared = .964 (Adjusted R Squared = .924)

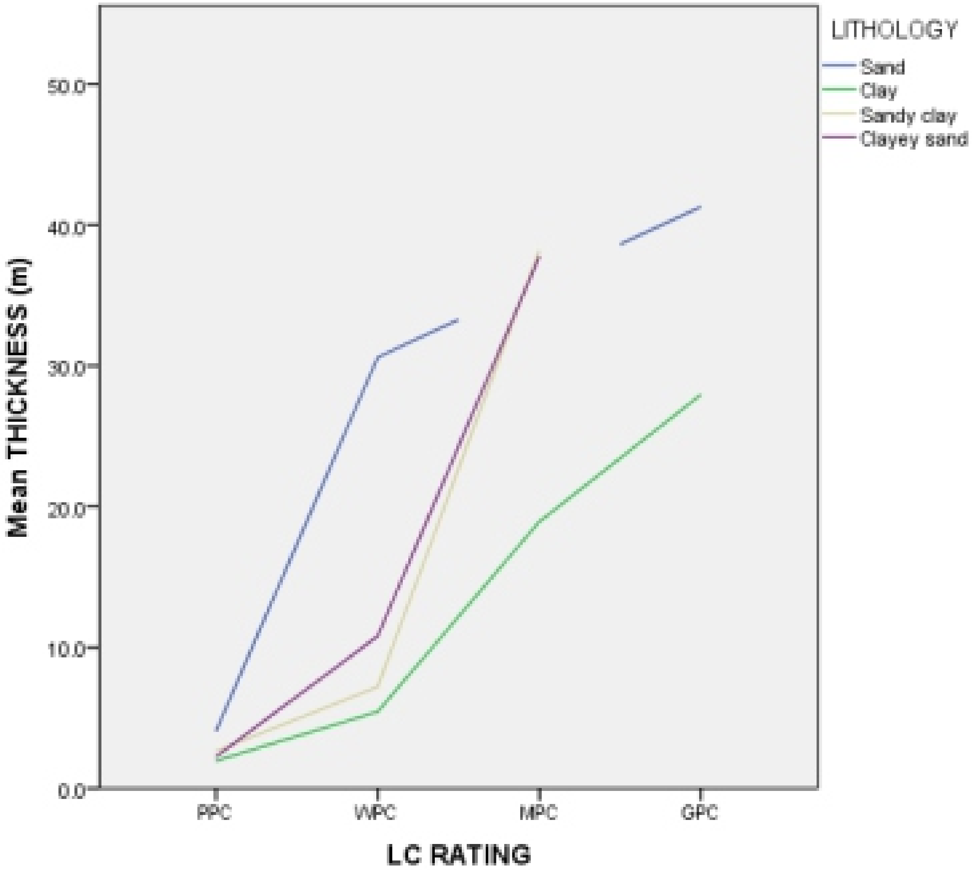


Figure 12: Effects of lithology and thickness on longitudinal conductance (LC)

Table 5: ANOVA statistical results of hydraulic resistance for the vadose zone.

Tests of Between-Subjects Effects

Dependent Variable: HR RATING

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	529.405[a]	162	3.268	20.574	.000
Intercept	1547.807	1	1547.807	9744.699	.000
THICKNESS	52.108	108	.482	3.038	.000
LITHOLOGY	180.715	3	60.238	379.248	.000
THICKNESS * LITHOLOGY	12.484	51	.245	1.541	.024
Error	23.508	148	.159		
Total	6147.000	311			
Corrected Total	552.913	310			

a. R Squared = .957 (Adjusted R Squared = .911)

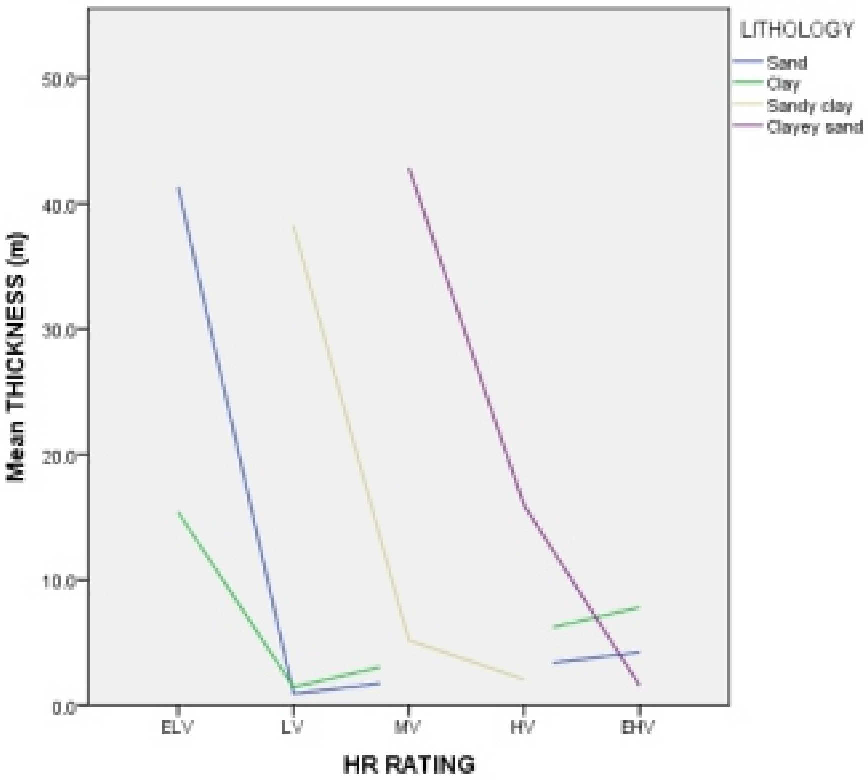


Figure 13: Effects of lithology and thickness on hydraulic resistance (HR)

The vulnerability of the vadose zone generally increases as it's thickness decreases in each type of lithology (Figure 13). However, there is a slight increase in vulnerability as the thickness of the vadose zone increases (above 2 – 3 m) in sand and clay. This effect may be due to the presence of preexisting geological structures (such as fractures and faults) that could affect the permeability of the vadose zone and thus make the aquifer vulnerable to contamination.

As seen from Table 3, areas with thick protective layers of clays between 1.1 – 5.5 m, 1.2 – 6.5 m, and 1.1 – 33.9 m ideally should not be rated as having poor protective capacity, weak protective capacity, and moderate protective capacity, respectively, as assigned by the longitudinal conductance model. These thick aquicludes were, however, expected to give these areas good protective capacity to excellent protective capacity, equivalent to low vulnerability and extreme vulnerability assigned to these localities by the hydraulic resistance model.

The longitudinal conductance model is inadequate and sometimes underrates the vulnerability of aquifers, especially where the vadose zone consists of clayey regolith. Overall, the thickness of the vadose zone is one of many factors that can influence its longitudinal conductance and hydraulic conductance, and a comprehensive understanding of the soil properties and environmental conditions is necessary to accurately predict the behaviour of water flow through the vadose zone before using any aquifer vulnerability model.

CONCLUSION

In this study, two models, longitudinal conductance and hydraulic resistance were used to assess the vulnerability of aquifers within the Quaternary deposits and mangrove swamps of the Niger Delta to contamination. The longitudinal conductance model indicates four vulnerability zones, while the hydraulic resistance model reveals five zones of groundwater vulnerability. The longitudinal conductance and hydraulic resistance models show a closer coincidence of vulnerability in 72% of the study area. The performances of these models are primarily dependent on the parameters used. Though both methods have applications in determining aquifer vulnerability, the hydraulic resistance model better describes the vulnerability of the study area and is likely to be more reliable. It relies on the hydraulic conductivity of the soil media whose intrinsic property influences the amount of water percolating into the groundwater zone through the vadose zone. Clayey regoliths have low hydraulic conductivity, and when they overlie an aquifer, they impede movement once contaminant enters the vadose zone, thus giving the aquifer low vulnerability. Therefore, there is need to modify the longitudinal conductance which sometimes underrates vulnerability of clayey lithology.

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