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## ELECTROSTRATIGRAPHIC INVESTIGATION OF VULNERABILITY IN COASTAL AQUIFERS : A CASE STUDY OF FEDERAL COLLEGE OF EDUCATION (TECHNICAL), OMOKU, RIVERS STATE

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### ABSTRACT

An integrated electrostratigraphic investigation was conducted to assess the intrinsic vulnerability of the coastal aquifer at the Federal College of Education, Omoku, Rivers State. Twenty Vertical Electrical Sounding (VES) stations were employed, revealing a heterogeneous subsurface composed of four distinct geoelectric layers. The resistivity and thickness of the topsoil and unsaturated vadose zone were identified as the primary controls on vulnerability. The study utilized three vulnerability models: GOD, GLSI, and DRASTIC. The GOD index classified the area into low (33.3%) and moderate (66.7%) vulnerability classes. In contrast, the GLSI index, derived directly from VES data, provided a higher-resolution assessment, identifying two high-risk points (10%), a majority of moderate vulnerability (80%), and two low-vulnerability points (10%). The DRASTIC model consistently rated the entire area as moderately vulnerable, reflecting the inherent risk of the coastal hydrogeological setting. The comparative analysis concluded that the aquifer system is predominantly moderately vulnerable with localized zones of high vulnerability, particularly where protective layers are thin and conductive. The GLSI model proved most sensitive for pinpointing these high-risk areas. The findings underscore the urgent need for targeted groundwater protection strategies, land-use regulations, and continuous monitoring in the identified vulnerable zones to ensure sustainable water resource management in this coastal environment.

### KEYWORDS

groundwater, geoelectric layers, susceptibility, resistivity, thickness

## 1. INTRODUCTION

Groundwater is a vital component of the hydrological cycle, especially in coastal and deltaic environments where it supports domestic, agricultural, and industrial activities. Studies from around the world indicate that groundwater is increasingly endangered by both human activities and natural factors, putting water security at risk in numerous regions (Nugraha et al., 2021; Shaibur et al., 2024). This crisis is primarily fueled by over-extraction, which depletes aquifers faster than they can recharge, and contamination from agricultural runoff and industrial waste. Addressing these interconnected challenges is essential to ensuring a reliable and safe water supply for the future. In southern Nigeria, including Rivers State, groundwater serves as the principal source of potable water due to the unreliability and contamination of surface water sources. However, rapid urbanization, industrialization, and unregulated land use in these regions increasingly threaten the quality and sustainability of groundwater reserves (Okoroh and Ibuot, 2022; Akakuru et al., 2022; Chinyem and Ovwamuedo, 2024). This is particularly true in low-lying coastal areas like Omoku, situated in the western Niger Delta,

where shallow aquifers are highly susceptible to contamination from both natural and anthropogenic sources.

The vulnerability of groundwater systems in such coastal settings is influenced by a complex interplay of factors including hydrogeological conditions, lithological variations, aquifer depth, recharge mechanisms, and human-induced pressures. In the case of the Federal College of Education, Omoku, the increasing reliance on shallow boreholes and hand-dug wells for water supply raises urgent concerns regarding the vulnerability of the underlying aquifer systems. Given the region's proximity to petroleum operations, the absence of structured waste disposal systems, and the dominance of sandy, unconsolidated sediments, it becomes imperative to conduct a comprehensive vulnerability assessment to inform groundwater protection strategies.

Electrostratigraphic investigation, which integrates geoelectrical techniques with stratigraphic analysis, has been widely used to characterize aquifer geometry, identify lithological units, and evaluate protective capacity of overburden materials (Al-Khafaji, and Al-Dabbagh, 2016; Ibuot et al., 2017; George et al., 2018; Ibuot et al., 2024a). Geophysical methods like Vertical Electrical Sounding (VES) are

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particularly effective for mapping subsurface variations in resistivity, which are proxies for lithology and saturation, thereby providing insight into zones that may be prone to pollutant migration.

In complementing electrostratigraphic data, groundwater vulnerability assessment models such as GOD, DRASTIC, and GLSI offer quantitative means of evaluating the susceptibility of aquifers to contamination. The GOD index an acronym for Groundwater occurrence (G), Overlying lithology (O), and Depth to water table (D) is a straightforward model that categorizes vulnerability based on intrinsic hydrogeological conditions (Foster, 1987). The DRASTIC model, developed by the US Environmental Protection Agency, expands this approach by incorporating seven hydrogeological parameters: Depth to water (D), Net recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (I), and Hydraulic conductivity (C) (Aller et al., 1987; Sadat-Noori and Ebrahimi, 2016; Khosravi et al., 2018). Meanwhile, the GLSI (Goelectrical Layer Susceptibility Index) is a more recent approach that uses resistivity-derived parameters such as layer thickness, resistivity, and depth - to produce a numerical representation of vulnerability potential based solely on geophysical data (Oni et al., 2017; George, 2021; Kirilas et al., 2022).

Using a combined approach that integrates electrostratigraphic profiling with GOD, DRASTIC, and GLSI models offers a robust framework for understanding groundwater vulnerability in a stratified and multi-dimensional way. This study aims to assess the vulnerability of the aquifer system beneath the Federal College of Education, Omoku, through the use of geophysical and index-based techniques. This study is novel in its integrative application of electrostratigraphic methods with three complementary vulnerability models (GOD, DRASTIC, and GLSI) in a single coastal setting within the region. Furthermore, the study leverages geoelectrical data to enhance the parameterization of the vulnerability indices, particularly GLSI, thereby ensuring a more realistic representation of aquifer conditions. This hybridized methodology allows for cross-validation and comparison of model outputs, ultimately leading to more accurate vulnerability zonation and risk-based groundwater management. The findings will inform policy recommendations for groundwater protection and guide future infrastructural development within the Federal College of Education, Omoku and its surrounding communities. The results of this research are expected to support water resource managers, institutional authorities, and environmental planners in making informed decisions for sustainable groundwater development and protection in similar coastal environments.

### 1.1 Location, Geology and Hydrogeology of the Area

Omoku is a rapidly growing town located in the Ogba/Egbema/Ndoni Local Government Area of Rivers State, Nigeria. It lies within the western part of the Niger Delta region and is geographically situated between latitudes 5°20'N to 5°25'N and longitudes 6°38'E to 6°42'E (Figure 1). The town serves as the administrative and commercial hub of the Ogba Kingdom and hosts several strategic facilities, including the Federal College of Education (Technical), oil installations, and residential developments. Omoku is approximately 45 kilometers northwest of Port Harcourt and lies within the low-lying, humid tropical belt of southern Nigeria. The area experiences a tropical rainforest climate, with high annual rainfall averaging between 2,000 mm and 3,000 mm, mainly concentrated between March and October (NIMET, 2022). Relative humidity remains high throughout the year, often exceeding 80%, while temperatures range from 24°C to 32°C. The dense vegetation cover, flat terrain, and swampy characteristics make it hydrologically sensitive and prone to surface flooding and groundwater interaction.

Omoku falls within the Niger Delta sedimentary basin, which is one of the most prolific hydrocarbon provinces in Africa. Geologically, the Niger Delta is composed of three major lithostratigraphic units that reflect its depositional history. The surface formation of Omoku is dominated by the Benin Formation (Miocene–Recent). It consists predominantly of coarse-to-medium grained sands, pebbly sands, and minor clay intercalations. The sands are often unconsolidated and highly permeable, making them suitable for groundwater accumulation but also vulnerable to contamination. The thickness of the Benin Formation exceeds 2,000 m in some parts of the delta. The Agbada Formation (Eocene–Miocene): underlies the Benin Formation and comprises alternating sequences of sandstones and shales. It represents the primary oil and gas-bearing unit in the Niger Delta (Ibuot et al., 2017). The Akata Formation (Paleocene–Eocene) is the deepest unit, consisting mainly of marine clays and shales, with minor silt and sand. It functions as the source rock for hydrocarbons in the delta. The Benin Formation is the dominant geologic unit and serves

as the primary aquifer system. The presence of unconsolidated sand layers, often interspersed with clay lenses, significantly influences both groundwater storage and vulnerability to pollution (Short and Stauble, 1967; Avbovbo, 1978; Reijers et al., 1997).

The hydrogeology of Omoku is characterized by the coastal sedimentary aquifer systems. The main aquifers are unconfined to semi-confined and are composed of highly permeable, unconsolidated sands of the Benin Formation. Groundwater occurs under water table conditions in the shallow zones and may transit to semi-confined conditions at greater depths due to interbedded clay layers. Recharge is primarily from direct infiltration of precipitation, which is abundant due to the high rainfall in the region.

The absence of continuous clay confining units in many parts of Omoku renders the aquifer highly susceptible to vertical migration of contaminants, especially from improperly located waste disposal sites, leaking septic tanks, and unlined boreholes. Additionally, the proximity of Omoku to oil production facilities introduces the potential for petroleum hydrocarbon intrusion into the groundwater system.



Figure 1: Map of the study area showing the geographical location of Omoku

## 2. MATERIALS AND METHODS

### 2.1 Vertical Electrical Sounding (VES)

A Vertical Electrical Sounding (VES) survey was carried out at twenty (20) locations within the study area using the Integrated Geo and Instrument Services (IGIS) signal enhancement resistivity meter with model SSR-MP-ATS, a digital geophysical instrument suitable for subsurface resistivity investigations. The Schlumberger electrode configuration was employed, with the half-current electrode spacing ( $AB/2$ ) systematically varied from 1.0 to 300.0 m, enabling deep penetration into the subsurface to characterize multiple geoelectric layers. The half-potential electrode spacing ( $MN/2$ ) ranged between 0.25 and 20 m, optimized to maintain measurement sensitivity while adapting to changes in current electrode spacing.

The measured apparent resistance ( $R_a$ ) values were used to calculate the apparent resistivity ( $\rho_a$ ) using equation 1.

$$\rho_a = \pi \cdot \left[ \frac{(AB/2)^2 - (MN/2)^2}{MN} \right] \cdot R_a \quad (1)$$

where,  $\pi \cdot \left[ \frac{(AB/2)^2 - (MN/2)^2}{MN} \right]$  is the geometric factor  $G$  express in equation as;

$$G = \pi \cdot \left[ \frac{(AB/2)^2 - (MN/2)^2}{MN} \right] \quad (2)$$

The calculated apparent resistivity values are then plotted against the electrode spacing ( $AB/2$ ) on a log-log graph to generate the sounding curves. Interpretation involves matching the field curve with standard

theoretical master curves or using auxiliary curve charts to estimate the number of layers, their resistivities, and thicknesses (Zohdy et al., 1974).

Using WinResist, the field data (AB/2 and apparent resistivity values) were inputted into the software. The program automatically plots the sounding curve and performs an iterative curve-matching process to generate a best-fit with their respective resistivities, depths and thicknesses. Borehole lithological logs obtained from existing were used to constrain the VES data interpretation during the computer modelling stage (Figures 2). The Borehole logs were analyzed to classify lithological units and the VES derived resistivity values were correlated with borehole lithologies to identify distinct subsurface layers. The geological constraints aimed to mitigate the ambiguity problem related to the non-uniqueness in interpreting VES data (LaBrecque et al. 1996; George et al., 2015; Ibuot et al., 2024b). The geoelectric layer parameters (resistivity, thickness and depth) obtained were used to estimate the secondary parameters.

The hydraulic conductivity (K) which is linked to laboratory-measured porosity can be estimated using the Kozeny-Carman-Bear's equation (equation 3).

$$K = \left(\frac{\delta_w \cdot g}{\mu_d}\right) \cdot \left(\frac{d_m^2}{180}\right) \cdot \left(\frac{\phi^3}{(1-\phi)^2}\right) \tag{3}$$

where  $\phi$  is the effective porosity,  $g$  represents the acceleration due to gravity ( $10 \text{ m/s}^2$ ),  $\delta_w$  is the density of water ( $1000 \text{ kg/m}^3$ ),  $d_m$  signifies the site's mean diameter ( $0.00036 \text{ m}$ ) measured using a micrometer screw gauge, and  $\mu_d$  stands for the coefficient of dynamic viscosity of water, approximately  $0.0014 \text{ kg/ms}$  according to Fetters (1994). Permeability is a measure of a material's ability to transmit fluids through its pore spaces or fractures. It's an important property for understanding groundwater flow, contaminant transport, and the behavior of subsurface reservoirs. High permeability materials like gravel and coarse sand allow water to move freely and rapidly, making them good aquifer media. In contrast, clay and shale have very low permeability due to their fine grain size and poor pore connectivity, often acting as confining or protective layers. The Nutting's equation (Hubert, 1940) aid in estimating permeability and is express in equation 4.

$$k_p = \frac{K \mu_d}{\delta_w \cdot g} \tag{4}$$

The effective porosity ( $\phi$ ) is property of geological materials that describes the proportion of void (pore) spaces within a rock, soil, or

sediment, it determines how much water or other fluids a material can hold. It can be calculated using equation 5, according to Ibuot et al. (2019).

Table 2: Attribution of Notes for GOD model Parameters (Khemiri et al. 2013)					
Aquifer type	Note	Lithology ( $\Omega\text{-m}$ )	Note	Depth to aquifer (m)	Note
Non-aquifer	0	<60	0.4	<2	1
Artesian	0.1	60 - 100	0.5	2 - 5	0.9
Confined	0.2	100 - 300	0.7	5 - 10	0.8
Semi-confined	0.3 - 0.5	300 - 600	0.8	10 - 20	0.7
Unconfined	0.6 - 1.0	>600	0.6	20 - 50	0.6
				50 - 100	0.5

2.2.2 GLSI index

The Geoelectric Layer Susceptibility Index (GLSI) is an empirical index developed to assess the intrinsic vulnerability of groundwater-bearing formations by integrating geoelectrical parameters obtained from Vertical Electrical Sounding (VES) data (Oni et al., 2017). It quantitatively evaluates the potential of subsurface layers to permit contaminant infiltration based on their resistivity and thickness characteristics. GLSI is calculated by assigning weights to each identified geoelectric layer based on its electrical resistivity ( $\rho$ ) and thickness ( $h$ ), reflecting the layer's ability to impede or permit contaminant migration. Layers with low resistivity and high thickness are considered more vulnerable due to their higher permeability and potential for contaminant retention. Conversely, layers with high resistivity, often indicating consolidated or impermeable materials, are less vulnerable. The GLSI is typically expressed as in equation 7. Table 3 gives the rating for geoelectric layer susceptibility index for resistivity and thickness, while Table 4 is GLSI parametric rating. GLSI complements other vulnerability models (DRASTIC, GOD) by incorporating site-specific subsurface characteristics, enhancing decision-making in groundwater protection, land-use planning, and environmental impact assessments (Ibuot et al., 2025a).

$$\phi = 36.51\rho^{-0.031} \tag{5}$$

2.2 Vulnerability Assessment Models

Three widely accepted models GOD, DRASTIC, and GLSI were applied to assess the intrinsic vulnerability of the aquifer systems within the study area.

2.2.1 GOD Index

The GOD model, a groundwater vulnerability assessment model that evaluates the intrinsic vulnerability of aquifers to contamination based on three main parameters: G (Groundwater occurrence) - type of aquifer (unconfined, semi-confined, or confined), unconfined aquifers are more vulnerable (Foster 1987). O (Overlying lithology) - refers to the type and characteristics of the unsaturated zone, especially its lithology and permeability. More permeable materials like sand or gravel indicate higher vulnerability. D (Depth to water table) - measured from available borehole data and field observations, the shallower the depth, the more susceptible the aquifer is to surface contaminants. Each parameter is rated and weighted according to standard guidelines. Each parameter is assigned a rating from 0 (least vulnerable) to 1 (most vulnerable), and the GOD index is calculated by multiplying the three components: The final GOD vulnerability index was calculated as expressed in equation 6. The Values range from 0 (no vulnerability) to 1 (extreme vulnerability). Tables 1 and 2 show the index rating and the attribution of notes for GOD model parameters. The GOD index is a simple, cost-effective tool used in hydrogeological studies to inform groundwater protection and land-use planning.

$$GOD \text{ Index} = G \times O \times D \tag{6}$$

Table 1: GOD parametric index rating (Foster 1987)	
Vulnerability class	Index rating
Negligible	0.0 - 0.1
Low	0.1 - 0.3
Moderate	0.3 - 0.5
High	0.5 - 0.7
Extreme	0.7 - 1.0

$$GLSI = \frac{\left(\frac{\rho_{1r}+h_{1r}}{2}\right) + \left(\frac{\rho_{2r}+h_{2r}}{2}\right) + \dots + \left(\frac{\rho_{nr}+h_{nr}}{2}\right)}{N} \tag{7}$$

Table 3 : Geoelectric layer susceptibility index rating for resistivity and Thickness				
Resistivity ( $\Omega\text{-m}$ )	Lithology	Susceptibility index rating	Thickness (m)	index rating
<20	Clay/Silt	1	<2	4
20 - 50	Sandy clay	2	2 - 5	3
51 - 100	Clayey sand	3	5 - 20	2
101 - 150	Sand	4	>20	1
151 - 400	Laterite sand	2		
>400	Laterite	1		

Table 4: GLSI parametric rating	
Index rating	Vulnerability Class
1.0 – 1.99	Low
2.0 – 2.99	Moderate
3.0 – 3.99	High
4.0	Extreme

**2.2.3 DRASTIC Index (DI)**

The DRASTIC index is a standardized, widely used model developed by the U.S. Environmental Protection Agency, the intrinsic vulnerability of groundwater to contamination (Aller et al., 1987). It integrates hydrogeological and environmental parameters that influence the movement of contaminants from the surface to the aquifer. The acronym DRASTIC represents seven key hydrogeological parameters: D – Depth to water, R – Recharge (net), A – Aquifer media, S – Soil media, T – Topography (slope), I – Impact of the vadose zone, C – Hydraulic conductivity of the aquifer. Each parameter is assigned a rating based on its characteristics and a weight reflecting its relative importance. The DRASTIC vulnerability index is computed using the expression in equation 8 (Aller et al., 1987);

$$DRASTIC_{Index} (DVI) = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \tag{8}$$

Where r is the rating and w is the weight for each parameter. Each parameter is rated on a scale from 1 to 10 which displays the relative contamination potential of that parameter for that area.

The resulting index is a numerical value indicating the aquifer's vulnerability, with higher values signifying greater vulnerability to surface contamination. DRASTIC is valued for its comprehensive and adaptable framework, making it suitable for diverse geological settings. It is widely applied in land-use planning, groundwater protection, and environmental management (Ibuot et al., 2025b).

Depth to water table (D) refers to the vertical distance between the land surface and the groundwater table. Shallow depths imply a shorter travel

path for contaminants, increasing vulnerability, while deeper water tables provide more filtration and protection.

Net recharge (R) denotes the amount of water per unit area that infiltrates from the surface and reaches the water table. Higher recharge rates can transport contaminants more rapidly into the aquifer. It provides the channel for transportation of surface pollutants into groundwater system. The Net recharge is determined using the Piscopo method which considers the slope, rainfall and soil permeability as express in equation 9 (Piscopo, 2001) and classification done according to his ratings. Table 5 gives the Net recharge classification, ratings and weight

$$Net\ recharge = Slope + Rainfall + permeability \tag{9}$$

Aquifer media (A) describes the consolidated or unconsolidated material composing the aquifer (e.g., sand, gravel, limestone). It is an underground layer of permeable rock or sediment that stores and transmits groundwater. Materials with high permeability like sand or fractured rocks allow easier contaminant flow.

Soil media (S) represents the uppermost weathered zone that affects infiltration and percolation. is the region between the land surface and the water table, where the spaces between soil particles contain both air and water. Soil texture (e.g., clay, loam, sand) determines the filtration capacity; fine-textured soils like clay offer better protection (Babiker, et al., 2005).

Topography (T) indicates the slope of the land surface. Steeper slopes reduce infiltration due to runoff, lowering vulnerability, whereas flat terrains promote infiltration and increase vulnerability (Barbulescu, 2020; Patel et al., 2022).

Vadose zone impact (I) is the unsaturated zone between the soil and the water table. Its composition influences how contaminants are filtered before reaching the aquifer. Coarse materials (e.g., sand) permit faster contaminant transport. It is an important component of groundwater recharge and contamination.

Hydraulic conductivity (C) measures the aquifer's ability to transmit water. Higher conductivity means water and potential contaminants can move quickly through the aquifer, raising vulnerability. Hydraulic conductivity is computed using equation 4.

Table 6 presents the DRASTIC model parameters classifications, ratings and weight according to Aller et al. 1987, while Table 7 gives the DRASTIC vulnerability class.

Table 5: Net recharge classification, ratings and weight (Piscopo 2001)								
Slope (%)	Rating	Soil permeability	Rating	Rainfall (mm)	Rating	Net recharge	Rating	Weight
< 2	4	Very slow	1	< 5	1	11 to 13	10	4
2 to 10	3	Slow	2	500 to 700	2	9 to 11	8	
10 to 33	2	Moderate	3	700 to 850	3	7 to 9	5	
> 33	1	Moderately	4	> 850	4	5 to 7	3	
		High	5			3 to 5	1	
Slope (%)	Rating	Soil permeability	Rating	Rainfall (mm)	Rating	Net recharge	Rating	Weight

**Table 6: DRASTIC model parameters classifications, ratings and weight (Aller et al. 1987)**

Depth of water (m)	Net Recharge			Aquifer media			Soil media			Topography (%)			Impact of vadose zone			Hydraulic conductivity $\gamma$ (m/s)				
	R	W		R	W		R	W		R	W		R	W		R	W			
< 20	10	5	>0.0252	9	4	Miscellaneous	2	3	Gravel	10	2	0 to 5	10	1	Gravel	10	5	$5.4 \times 10^{-4}$	10	3
20 to 40	9		0.0175 - 0.0255	8		Igneous	3		Sand	9		5 to 15	8		Sand	9		$4.2 \times 10^{-4}$ to $9.4 \times 10^{-4}$		8
40 to 60	7		0.0100 - 0.015	6		Glacial till	5		Laterite	8		15 to 35	6		Laterite	8		$3.2 \times 10^{-4}$ to $4.2 \times 10^{-4}$		6
60 to 80	5		0.005 - 0.0103	3		Sandstone	6		Sandy loam	6		25 to 35	4		Sandy loam	6		$1.6 \times 10^{-4}$ to $3.2 \times 10^{-4}$		4
80 to 100	3		0.0 - 0.005	1		Limestone and shale	6		Loam	5		> 35	1		Loam Silty loam	5		$4.2 \times 10^{-4}$ to $1.6 \times 10^{-3}$		3
100 to 120	2					Sand and gravel	8		Clay loam	3					Clay loam	3		$4.7 \times 10^{-4}$ to $4.7 \times 10^{-4}$		1
> 120	1					Basalt	9													

heterogeneity of the study area. For instance, extremely high resistivity recorded in VES 5 (5104.5  $\Omega$ m) is typical of dry, coarse sands or gravels, which generally provide a good protective barrier. Conversely, very low resistivity values like in VES 16 (34.1  $\Omega$ m) point to the presence of clayey materials that may act as confining or semi-confining layers, impeding vertical percolation. This layer, therefore, plays a crucial role in determining the extent of aquifer vulnerability based on whether it acts as a protective unit or as a conduit for pollutant transport. The third layer represents the saturated aquifer zone and is the primary water-bearing unit in most of the soundings. It records resistivity values between 41.6  $\Omega$ m, suggest a higher clay content or possible contamination, which may reduce aquifer quality and yield. The fourth layer is interpreted as either a consolidated formation, a deep aquifer, or a transition to the resistive basement or paleo-channel sands. The resistivity of this layer ranges from 20.6 to 12,651.0  $\Omega$ m, with considerable depth variations. VES 9, for instance, recorded an exceptionally high resistivity of 12,651.0  $\Omega$ m, which could suggest dry sandstone, or coarse gravel. These high values may indicate limited water saturation but good confinement. Other locations such as VES 1, 2, 8, 14 and 18 also exhibit high fourth-layer resistivity, reflecting the potential for deeper, more protected aquifers.

**Table 7: DRASTIC index vulnerability class (Aller et al.1987; Amiri et al. 2020)**

Vulnerability Class	DRASTIC index
Low	1 – 100
Moderate	101 – 175
High	176 – 200
Very high	>200

The vulnerability of the aquifer systems varies significantly across the area, depending largely on the composition and thickness of the overlying layers. The shallow water tables and low-resistivity upper layers allow contaminants to infiltrate rapidly to the aquifer zone. These findings indicate that while the study area sit atop productive aquifer systems, many areas are susceptible to contamination due to inadequate overburden protection. The implications are critical for groundwater resource management, especially given the coastal and urbanized setting of the study area.

**3. RESULTS AND DISCUSSION**

**3.1 VES**

The results of the VES survey conducted across the Federal College of Education, Omoku, revealed a heterogeneous subsurface structure characterized by multilayered geoelectric sequences. Each of the twenty VES stations delineated four geo-electric layers, interpreted in terms of resistivity and thickness (Table 8), and used to infer lithological composition and assess aquifer vulnerability. The layered resistivity profiles offer insights into the distribution of potentially water-bearing formations and their protective capacities against surface-induced contamination.

The first layer across all VES points corresponds to the topsoil, exhibiting resistivity values ranging from 35.1 to 891.6  $\Omega$ m, with thicknesses and depths between 0.6 and 5.4 m. These variations suggest a mix of sandy loam, lateritic soil, and clayey sand. VES points such as VES 17 (39.7  $\Omega$ m) and VES 18 (35.1  $\Omega$ m) recorded particularly low resistivity, indicative of high moisture content or clay-rich topsoil. Such materials have low filtration capacity and, when shallow, can enhance infiltration of contaminants, rendering the underlying aquifer more vulnerable. On the other hand, locations such as VES 13 (891.6  $\Omega$ m) suggest relatively dry or gravelly surface material, which could offer better protection.

The second layer, interpreted as the unsaturated vadose zone, exhibits more diverse resistivity values (34.1 – 5104.5  $\Omega$ m) and thicknesses up to 16.6 m. These variations highlight the significant lithological

**3.2 GOD Index**

The GOD index provides a semi-quantitative method for assessing aquifer vulnerability by integrating the hydrogeological conditions influencing contaminant transport. The calculated GOD indices (Table 9) for the study area range from 0.21 to 0.38, corresponding to vulnerability classes from low to moderate, with no VES points falling within the high vulnerability category. This range suggests that while aquifer susceptibility exists, most zones benefit from some degree of natural protection against contamination. VES points exhibiting low vulnerability include stations 1, 4, 6, 8, 13, 15, 17, 18, and 20, with GOD index values ranging from 0.21 to 0.29. These areas are typically underlain by moderate to thick unsaturated zones and may possess low-permeability overburden materials, such as lateritic clay or compacted sandy loam, which impede downward migration of contaminants. For instance, VES 17 and VES 18 with GOD index of 0.21 and 0.22 respectively may owe their reduced vulnerability to the limited permeability or protective capacity of its overlying formations. Conversely, moderate vulnerability zones, such as those recorded at VES 2, 3, 5, 7, 9, 10, 11, 12, 14, 16, and 19, show GOD index values ranging from 0.32 to 0.38. These locations are generally associated with moderately deep-water tables, higher aquifer permeability, or reduced natural protective cover, making them more susceptible to contamination from surface sources.

**Table 8: Summary of electrical resistivity survey in the study area**

VES No.	Longitude (°E)	Latitude (°N)	Elevation (m)	Layer Resistivity ( $\Omega$ m)				Layer thickness (m)			Layer depth (m)		
				$\rho_1$	$\rho_2$	$\rho_3$	$\rho_4$	$h_1$	$h_2$	$h_3$	$d_1$	$d_2$	$d_3$
1	6.6506	5.3326	18	186.7	257.9	652.9	6076.8	2.9	5.0	7.9	2.9	14.5	22.4
2	6.6495	5.3327	15	555.0	549.3	177.6	2645.4	3.5	7.0	22.5	3.5	10.5	33.0
3	6.6512	5.3308	17	469.0	624.6	551.7	944.4	0.9	6.5	31.8	0.9	7.4	39.2
4	6.6713	5.3756	15	411.4	1137.3	2948.7	198.7	0.6	8.9	28.4	0.6	9.5	37.9
5	6.6721	5.3778	13	824.4	5104.5	3293.7	230.6	1.4	2.1	10.4	1.4	3.5	13.9
6	6.6498	5.3308	14	773.0	816.8	386.3	55.8	1.2	6.5	9.2	1.2	7.6	16.8
7	6.6488	5.3305	16	523.1	633.9	1475.9	387.4	1.3	16.6	50.3	1.3	17.9	68.2
8	6.6596	5.3428	15	555.0	549.3	177.6	2645.4	3.5	7.0	22.5	3.5	10.5	33.0
9	6.6494	5.3322	13	547.0	643.5	1023.3	12651.0	1.6	12.0	27.0	1.6	13.6	40.6
10	6.6583	5.3359	15	120.3	114.7	269.1	176.2	2.0	5.0	22.6	2.0	7.0	29.6
11	6.6373	5.3318	19	170.8	83.2	66.4	111.3	2.0	4.1	21.7	2.0	6.1	27.8
12	6.6492	5.3314	13	376.7	113.6	209.9	263.4	4.4	6.5	30.9	4.4	10.9	41.8
13	6.6518	5.3320	18	891.6	111.0	834.7	47.4	2.6	8.8	28.6	2.6	11.4	40.1
14	6.6519	5.3311	17	525.7	110.6	861.7	11936.1	4.5	9.7	14.8	4.5	14.2	29.0
15	6.6529	5.3320	18	570.8	836.0	455.5	267.5	1.9	5.0	6.2	1.9	7.0	13.2
16	6.6517	5.3302	16	425.3	34.1	292.7	20.6	1.8	4.4	13.9	1.8	6.1	20.0
17	6.6508	5.3296	10	39.7	106.1	41.6	333.4	5.4	9.5	30.5	5.4	14.8	45.4
18	6.6507	5.3307	17	35.1	733.5	517.1	1002.0	0.6	11.2	45.4	0.6	11.8	57.2
19	6.6472	5.3416	19	170.8	83.2	66.4	111.3	2.0	4.1	21.7	2.0	6.1	27.8
20	6.6467	5.3384	13	376.7	113.6	209.9	263.4	4.4	6.5	30.9	4.4	10.9	41.8

VES 3 and VES 16 both record a GOD index of 0.38, the highest observed in the study, indicating that while the aquifers in these locations may be productive due to the presence of permeable sandy layers, they are more open to contaminant intrusion due to less protective overburden or shallower depths to groundwater. Additionally, the uniformity of the groundwater occurrence parameter ( $G = 0.6$  across all VES points) reflects a consistent aquifer type (unconfined), underlining the importance of depth and overburden characteristics as the principal differentiators in vulnerability classification. Overall, the GOD model underscores a dominance of low to moderate vulnerability classes in the study area, suggesting a manageable but non-negligible risk of aquifer contamination. It can be inferred that there is need for proactive groundwater protection strategies, particularly in zones classified as moderately vulnerable, where industrial, urbanization, waste disposal, and agricultural activities could pose a long-term threat to water quality. The percentage distribution of the GOD index (Figure 2) shows 66.7% as moderate while 33.3% as low, while Figure 3 show the variation of GOD index across the study area.

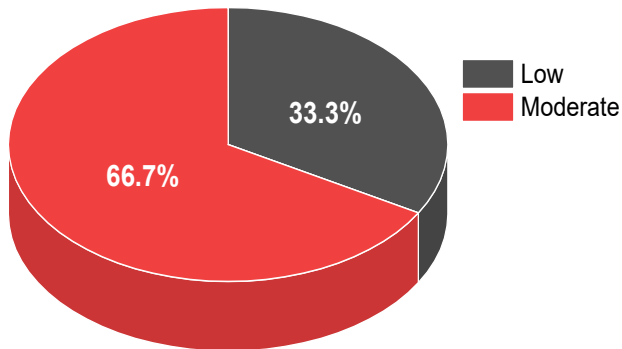


Figure 2: Percentage distribution of GOD index

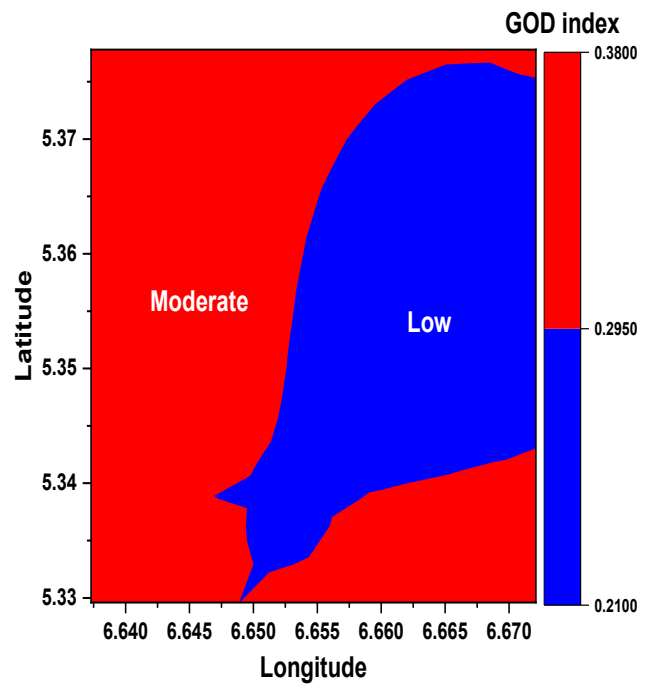


Figure 3: Contour map showing the variation of GOD index

Table 9: Summary of aquifer vulnerability indices using GOD parametric model

VES points	Longitude (°E)	Latitude (°N)	GOD Index			GOD Index	Vulnerability class
			G	O	D		
1	6.6506	5.3326	0.6	0.7	0.7	0.29	Low
2	6.6495	5.3327	0.6	0.8	0.7	0.34	Moderate
3	6.6512	5.3308	0.6	0.8	0.8	0.38	Moderate
4	6.6713	5.3756	0.6	0.6	0.8	0.29	Low
5	6.6721	5.3778	0.6	0.6	0.9	0.32	Moderate
6	6.6498	5.3308	0.6	0.6	0.8	0.29	Low
7	6.6488	5.3305	0.6	0.8	0.7	0.34	Moderate
8	6.6596	5.3428	0.6	0.6	0.7	0.25	Low
9	6.6494	5.3322	0.6	0.8	0.7	0.34	Moderate
10	6.6583	5.3359	0.6	0.7	0.8	0.34	Moderate
11	6.6373	5.3318	0.6	0.7	0.8	0.34	Moderate
12	6.6492	5.3314	0.6	0.8	0.7	0.34	Moderate
13	6.6518	5.3320	0.6	0.6	0.7	0.25	Low
14	6.6519	5.3311	0.6	0.8	0.7	0.34	Moderate
15	6.6529	5.3320	0.6	0.6	0.8	0.29	Low
16	6.6517	5.3302	0.6	0.8	0.8	0.38	Moderate
17	6.6508	5.3296	0.6	0.5	0.7	0.21	Low
18	6.6507	5.3307	0.6	0.6	0.6	0.22	Low
19	6.6472	5.3416	0.6	0.7	0.8	0.34	Moderate
20	6.6467	5.3384	0.6	0.7	0.7	0.29	Low

3.3 GLSI Index

The Geoelectric Layer Susceptibility Index (GLSI) provides a vulnerability assessment framework based on the integration of normalized resistivity and thickness values of the first and second geoelectric layers. It is relevant in hydrogeophysical studies of coastal environments, where lithologic heterogeneity and shallow groundwater conditions often influence aquifer susceptibility. The GLSI results from the study area (Table 10) reflect a vulnerability index range between 1.75 and 3.50, which is categorized into low, moderate, and high vulnerability classes. Out of the twenty VES locations evaluated, two sites (VES 10 and VES 11) fall within the high vulnerability class, with GLSI values of 3.25 and 3.50, respectively. These high indices suggest the presence of shallow, conductive, and thin protective layers in combination with low resistivity values in the first two geoelectric layers. Such conditions enhance the vertical migration of surface contaminants into the aquifer system. The relatively high values in these areas may also indicate limited confinement, porous media, or direct hydraulic connection to surface sources of contamination. Given the urban character and anthropogenic activities in the study area, these locations

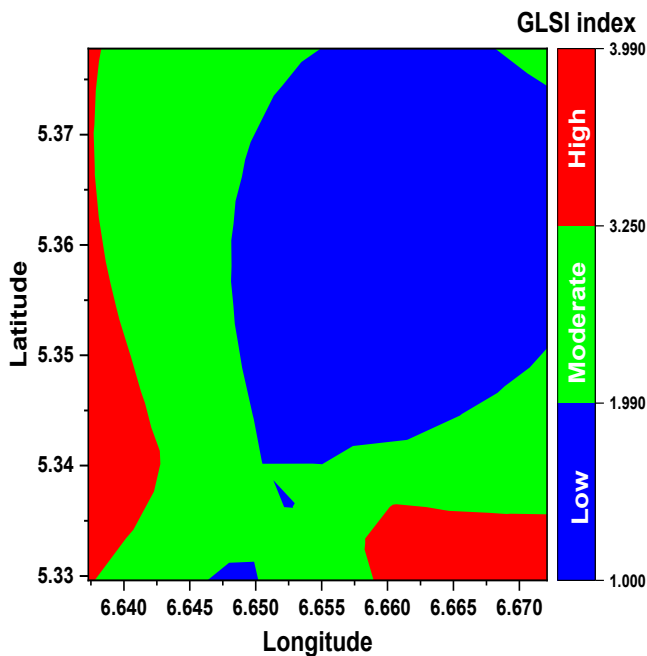
demand urgent monitoring and potentially protective zoning regulations to mitigate contamination risks. The low vulnerability category is represented by VES 2 and VES 8, both recording a GLSI of 1.75. These sites likely benefit from relatively thick and resistive overburden materials or moderately deep-water tables. The combination of higher resistivity in the first layer and greater thickness in the second suggests that the aquifer is effectively shielded by semi-confining or low-permeability strata such as lateritic soils or clayey sand. This protective capacity hinders the rapid percolation of contaminants, thereby enhancing aquifer safety in these zones. The majority of the VES points fall under the moderate vulnerability class, with GLSI values ranging between 2.00 and 2.75. This class reflects a transitional condition, where protective overburden is neither entirely effective nor completely deficient. For example, VES 3, VES 4, VES 6, and VES 7 all report a GLSI of 2.00, indicating moderate resistivity and layer thickness that afford partial protection. Similarly, VES 12, VES 20, and VES 13 show slightly elevated values ( $\geq 2.5$ ), suggesting moderate vulnerability due to thinner or more conductive protective layers. In these areas, the aquifer system is still susceptible to contaminant infiltration, particularly

under stress from land use changes, leakage from waste disposal, or flood-related recharge events. The spatial distribution of GLSI values suggests that while most of the study area is moderately vulnerable, there are localized zones of higher risk, particularly in areas where topsoil and subsurface lithologies favor contaminant percolation. Therefore, the GLSI model highlights that the coastal aquifers of Omoku exhibits moderate to

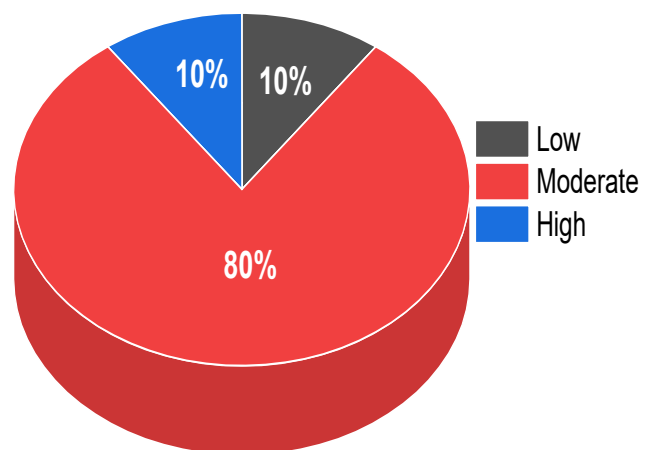
high susceptibility, particularly where shallow, permeable formations dominate. These insights underscore the importance of integrating geophysical data with vulnerability indexing to inform groundwater protection policies. The variation of GLSI index is shown in Figure 4, while Figure 5 is the pie chart showing the percentage distribution of GLSI index.

**Table 10:** Summary of aquifer vulnerability indices using GLSI parametric model

VES points	Longitude (°E)	Latitude (°N)			GLSI Index	Vulnerability Class
			$\frac{(\rho_{1r} + h_{1r})}{2}$	$\frac{(\rho_{2r} + h_{2r})}{2}$		
1	6.6506	5.3326	2.5	2	2.25	Moderate
2	6.6495	5.3327	2	1.5	1.75	Low
3	6.6512	5.3308	2.5	1.5	2.00	Moderate
4	6.6713	5.3756	2.5	1.5	2.00	Moderate
5	6.6721	5.3778	2.5	2	2.25	Moderate
6	6.6498	5.3308	2.5	1.5	2.00	Moderate
7	6.6488	5.3305	2.5	1.5	2.00	Moderate
8	6.6596	5.3428	2	1.5	1.75	Low
9	6.6494	5.3322	2.5	1.5	2.00	Moderate
10	6.6583	5.3359	3.5	3	3.25	High
11	6.6373	5.3318	4	3	3.50	High
12	6.6492	5.3314	2.5	3	2.75	Moderate
13	6.6518	5.3320	2	3	2.50	Moderate
14	6.6519	5.3311	2	3	2.50	Moderate
15	6.6529	5.3320	2.5	1.5	2.00	Moderate
16	6.6517	5.3302	2.5	2.5	2.50	Moderate
17	6.6508	5.3296	2	2	2.00	Moderate
18	6.6507	5.3307	3	1.5	2.25	Moderate
19	6.6472	5.3416	2.5	2.5	2.50	Moderate
20	6.6467	5.3384	2.5	3	2.75	Moderate



**Figure 4:** Contour map showing the variation of GLSI



**Figure 5:** Percentage distribution of GLSI index

**3.4 DRASTIC Result**

The DRASTIC model integrates hydrogeological parameters - Depth to water (D), Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (I), and Hydraulic Conductivity (C) - to assess

the intrinsic vulnerability of aquifers to contamination. In the present study, the computed DRASTIC Vulnerability Index (DVI) for all VES points (Table 11) ranges from 124 to 163, classifying the entire area within the moderate vulnerability class according to standard DRASTIC index thresholds. The relatively narrow range of DVI values across all twenty VES locations suggests a spatially consistent hydrogeological setting, characterized by shallow water tables, moderately permeable soils and aquifer media, and limited topographic variability. Notably, VES 5 and VES

9 recorded the highest DVI value of 163, indicating the most vulnerable zones within the study area. This facilitates downward contaminant migration, highlighting the need for careful land-use control in these zones.

Conversely, VES 17 registered the lowest DVI value (124), suggesting comparatively lower aquifer susceptibility, this implies reduced permeability and contaminant mobility. Despite this relatively lower index, the site still falls within the moderate vulnerability class, emphasizing that no part of the study area is inherently protected from contamination, likely due to its flat terrain, porous geologic formation, and

across the study area reveals the intrinsic sensitivity of the Omoku aquifer system to surface-derived pollutants. This finding is expected in a coastal sedimentary environment where high water tables, sandy aquifer formations, and limited clay layers are common. Furthermore, anthropogenic activities in and around the study area, such as unlined waste disposal, farming activities, fuel storage, and surface runoff from built-up areas, can exacerbate the vulnerability indicated by the model. Although DRASTIC does not directly factor in contaminant sources or land use, its parameter structure effectively captures the natural susceptibility of groundwater to contamination, which serves as a baseline for regulatory or preventive planning.

**Table 11: Computed DRASTIC vulnerability index (DVI)**

VES Points	Coordinates		Weight														DVI	DVC
			5		4		3		2		1		5		3			
	Longitude (°E)	Latitude (°N)	$D_r$	$5D_r$	$R_r$	$4R_r$	$A_r$	$3A_r$	$S_r$	$2S_r$	$T_r$	$1T_r$	$I_r$	$5I_r$	$C_r$	$3C_r$		
1	6.6506	5.3326	10	50	9	36	6	18	5	10	6	6	5	25	1	3	148	Moderate
2	6.6495	5.3327	10	50	9	36	6	18	6	12	6	6	6	30	1	3	155	Moderate
3	6.6512	5.3308	10	50	9	36	6	18	6	12	6	6	6	30	1	3	155	Moderate
4	6.6713	5.3756	10	50	9	36	8	24	6	12	6	6	6	30	1	3	161	Moderate
5	6.6721	5.3778	10	50	9	36	8	24	6	12	8	8	6	30	1	3	163	Moderate
6	6.6498	5.3308	10	50	9	36	6	18	6	12	8	8	6	30	1	3	157	Moderate
7	6.6488	5.3305	10	50	9	36	8	24	6	12	6	6	6	30	1	3	161	Moderate
8	6.6596	5.3428	10	50	9	36	6	18	6	12	6	6	6	30	1	3	155	Moderate
9	6.6494	5.3322	10	50	9	36	8	24	6	12	8	8	6	30	1	3	163	Moderate
10	6.6583	5.3359	10	50	9	36	6	18	3	6	6	6	3	15	1	3	134	Moderate
11	6.6373	5.3318	10	50	9	36	2	6	5	10	6	6	5	25	1	3	136	Moderate
12	6.6492	5.3314	10	50	9	36	6	18	5	10	8	8	5	25	1	3	150	Moderate
13	6.6518	5.3320	10	50	9	36	6	18	6	12	6	6	6	30	1	3	155	Moderate
14	6.6519	5.3311	10	50	9	36	6	18	6	12	6	6	6	30	1	3	155	Moderate
15	6.6529	5.3320	10	50	9	36	6	18	6	12	6	6	6	30	1	3	155	Moderate
16	6.6517	5.3302	10	50	9	36	6	18	5	10	6	6	5	25	1	3	148	Moderate
17	6.6508	5.3296	10	50	9	36	2	6	3	6	8	8	3	15	1	3	124	Moderate
18	6.6507	5.3307	10	50	9	36	6	18	5	10	6	6	5	25	1	3	148	Moderate
19	6.6472	5.3416	10	50	9	36	2	6	5	10	6	6	5	25	1	3	136	Moderate
20	6.6467	5.3384	10	50	9	36	6	18	5	10	8	8	5	25	1	3	150	Moderate

coastal hydrological influences. The dominance of moderate vulnerability

Despite the absence of high vulnerability classifications in the current data, the close proximity of many DVI values to the high-risk threshold is noteworthy. This emphasizes the urgent need for land-use regulation, pollution source control, and water quality monitoring, especially in VES zones 5, 7, and 9, which demonstrate relatively elevated vulnerability indices.

**3.5 Comparative Analysis of VES, GOD, GLSI, and DRASTIC Vulnerability Assessments**

The integration of geophysical (VES) and parametric (GOD, GLSI, DRASTIC) models in this study has provided a robust, multi-dimensional understanding of aquifer vulnerability in the study area. Each model contributes unique insights based on different conceptual frameworks and parameters. While the VES method offers a direct geoelectrical visualization of the subsurface, the GOD, GLSI, and DRASTIC models offer structured vulnerability ratings based on hydrogeological and environmental parameters.

The Vertical Electrical Sounding (VES) survey revealed that the subsurface consists of four distinct layers, with resistivity and thickness values indicative of varying degrees of aquifer protection and vulnerability. Locations with low resistivity in topsoil and shallow aquifers were interpreted as more vulnerable due to minimal protective cover and

higher permeability. In contrast, locations with thick resistive layers and deeper aquifers, indicate lower susceptibility to contamination. The VES results thus reflect spatial heterogeneity in aquifer vulnerability across the area, identifying both risk-prone and protected zones.

The GOD model classified aquifer vulnerability into low and moderate classes only, with no high-risk zones identified. Out of 20 VES locations, 9 points were categorized as low and 11 points as moderate vulnerability. The model is sensitive to depth to water and overlying lithology, and it generally agreed with the VES findings in identifying shallow, conductive layers as more vulnerable. However, GOD does not account for aquifer transmissivity or contaminant pathways explicitly, which may limit its diagnostic precision in complex hydrogeological settings.

The GLSI Index, derived directly from VES resistivity and layer thickness data, provided a more fine-grained representation of vulnerability. Most locations were classified as moderately vulnerable, while 2 locations showed low vulnerability, and 2 locations were identified as highly vulnerable. These high GLSI values correlated well with VES data indicating thin or conductive topsoil and low-resistivity shallow layers, suggesting high contaminant migration potential. Thus, GLSI appears to offer greater sensitivity to localized geoelectrical variations than the GOD model.

The DRASTIC index yielded moderate vulnerability classification for all VES points, with DVI values ranging from 124 to 163. Despite the absence of high-risk zones, the upper end of the moderate range (VES 5 and 9 with

DVI of 163) signals near-critical vulnerability, particularly in zones with shallow groundwater, permeable soils, and high recharge potential. The uniformity of the DRASTIC classification across all sites suggests that the model, while comprehensive, may smooth out micro-level variability due to its reliance on broad hydrogeologic parameter ratings.

From the comparison, it is inferred that:

- VES and GLSI often align in detecting zones of localized vulnerability, particularly where protective layers are thin or resistive values are low.
- GOD model appears less sensitive to shallow geologic variations and may underestimate vulnerability in areas like VES 10, 11, and 18.
- DRASTIC, while comprehensive, offers broader-scale assessment and classifies all locations as moderately vulnerable—potentially masking subtle variations picked up by VES and GLSI.
- GLSI shows the highest sensitivity, identifying both low and high vulnerability zones, making it a valuable tool when high-resolution geophysical data are available.

In conclusion, the integrated use of VES, GOD, GLSI, and DRASTIC models enhances the reliability of aquifer vulnerability assessments in coastal sedimentary terrains. While all methods agree on the general moderate vulnerability of the Omoku aquifer, the GLSI model - supported by VES profiles - emerges as the most diagnostic tool for detecting micro-level variations in vulnerability due to its direct use of resistivity and layer thickness. This comparative analysis confirms that parametric models should not be used in isolation; instead, coupling them with geophysical investigations like VES provides a more accurate and spatially nuanced framework for groundwater protection and management in vulnerable coastal regions.

#### 4. CONCLUSION

This electrostratigraphic investigation has delineated the subsurface architecture and evaluated the intrinsic vulnerability of the coastal aquifer system underlying the Federal College of Education, Omoku, Rivers State. By integrating Vertical Electrical Sounding (VES) with vulnerability models (GOD, GLSI, and DRASTIC), the study provides a robust multi-criteria assessment that captures both the general hydrogeological framework and the fine-scale heterogeneities governing contamination risk. The VES survey revealed a four-layer geoelectric sequence with marked variability in resistivity and thickness of the topsoil and vadose zone, the primary protective layers. Low-resistivity and thin overburden zones were identified as highly vulnerable, while areas with higher resistivity and thicker protective cover demonstrated stronger natural protection.

Model comparisons highlighted complementary insights. The GOD model classified the area into low and moderate vulnerability classes, reflecting the unconfined aquifer setting but overlooking localized risks. The GLSI index, derived directly from VES parameters, pinpointed high-vulnerability points at VES 10 and 11, demonstrating sensitivity to lithological nuances. Meanwhile, the DRASTIC model assigned uniform moderate vulnerability, capturing regional-scale risks but smoothing over site-specific variations.

Overall, the aquifer system is moderately vulnerable but exhibits localized high-risk zones where thin, conductive overburden allows rapid contaminant percolation. These areas are critically exposed to threats from septic seepage, waste disposal, agricultural runoff, and hydrocarbon storage. Protection strategies must therefore move beyond broad classifications to site-specific interventions. Accordingly, the study recommends implementing continuous water quality monitoring through strategically placed sampling wells, and integrating findings into institutional and community land-use planning. In conclusion, while the aquifer beneath the study area remains a viable resource, its sustainability depends on targeted, science-based management. The vulnerability maps produced serve as vital decision-support tools for policymakers, environmental managers, and the college administration in safeguarding long-term groundwater quality.

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#### CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

#### AUTHORS CONTRIBUTIONS

(M.M.M.E. (Principal Researcher) developed the concept, methodology, and wrote the manuscript. J. C. I, (Co-researcher) was involved in developing the concept, methodology, and wrote the manuscript.

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