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INTEGRATED ASSESSMENT OF AQUIFER CONTAMINATION RISK USING GOD, GODL, AND GLSI MODELS IN SOUTHERN OKIGWE, SOUTHEASTERN NIGERIA

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ABSTRACT: *This study assesses aquifer contamination across fifty VES locations in Okigwe South, Southeastern Nigeria, using the GOD, GODL, and GLSI models. The GOD Index classifies vulnerability based on geological setting, overlying soil, and depth to groundwater. Results show that EHUME falls within the extreme vulnerability category, while locations like UMUOKE and UMUDIMIRE are highly vulnerable, requiring urgent protective measures. Moderate to low vulnerability was observed in several other locations, indicating varying degrees of natural protection. The GODL Index, an extension of the GOD model incorporating resistivity, depth, longitudinal conductance, and location, provided a more detailed classification. Sites such as UMUAWUCHI II and UMUARIAM II recorded high GODL values, suggesting thick, resistive formations, while areas like IKPEREJERE II showed low values, reflecting more conductive and potentially vulnerable subsurface conditions. Comparative analysis shows that GODL values were consistently higher than GOD values, emphasizing the role of human activity and land use in increasing groundwater contamination risk. The GLSI model, based on resistivity and layer thickness, further refined the classification. Locations such as UMUARIAM and AMANZE demonstrated strong natural protection (low vulnerability), while UMUOKE and UMUAWUCHI II were flagged as highly vulnerable zones due to weak protective layers. The integration of these models offers a robust approach for identifying contamination risks and guiding groundwater protection strategies. It highlights the need for targeted monitoring, land-use regulation, and sustainable groundwater development in vulnerable areas.*

KEYWORDS: Aquifer contamination, GOD Index, GODL Index, GLSI model, Groundwater protection.

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INTRODUCTION

Integrated assessment of aquifer contamination risk using GOD, GODL, and GLSI Models refers to a comprehensive approach to evaluating the potential of groundwater contamination by combining three different vulnerability models—GOD, GODL, and GLSI. Each model analyzes different hydrogeological and environmental parameters to provide a multi-dimensional understanding of how susceptible an aquifer is to pollution from surface or subsurface sources. The assessment of aquifer vulnerability has become a critical component in groundwater resource management, especially in regions experiencing increasing land use pressures and contamination risks. Among the models developed to evaluate the intrinsic and specific vulnerability of aquifers, the GOD, GODL, and GLSI indices have proven to be practical and adaptable tools in diverse hydrogeological settings.

The GOD model, developed by Foster and Hirata (1988), is a widely used index-based approach for evaluating intrinsic groundwater vulnerability. It is structured around three core parameters: groundwater occurrence (G), overall lithology of the unsaturated zone (O), and depth to the water table (D). These parameters are combined to provide a vulnerability index that classifies aquifers from negligible to extreme susceptibility to contamination. The simplicity and data efficiency of the GOD model make it suitable for regional-scale studies, particularly in data-limited environments. In southeastern Nigeria, particularly within Imo State, the GOD index has been applied in several studies to identify areas of concern. For instance, studies by Ehirim and Ebeniro (2010) in parts of Okigwe revealed that shallow water tables and permeable overburden materials significantly increase contamination risks. Expanding on the GOD framework, the GODL model introduces land use and longitudinal conductance into the vulnerability assessment. This model acknowledges that anthropogenic activities—such as agriculture, urban development, and industrial processes—can significantly amplify the risk of groundwater contamination, even in areas with naturally low vulnerability. The GODL model therefore integrates both natural hydrogeological conditions and human-induced stressors. In a geophysical vulnerability mapping conducted by Nwachukwu et al. (2016) across parts of Imo State, the GODL index was employed to demonstrate how land use patterns intensified vulnerability, especially in areas with minimal natural protective barriers. Their findings showed that locations with high resistivity but extensive surface activities exhibited elevated vulnerability scores under the GODL classification. The Geoelectric Layer Susceptibility Index (GLSI) is a more recent and field-based model derived from Vertical Electrical Sounding (VES) data. It utilizes the resistivity and thickness of geoelectric layers to quantify the ability of subsurface materials to either impede or facilitate contaminant movement. Unlike the GOD and GODL models, which rely on broader geological and environmental parameters, GLSI offers a detailed lithological perspective based on direct geophysical measurements. In groundwater vulnerability studies conducted in parts of Okigwe South, GLSI has been instrumental in identifying protective clayey layers and permeable sandy formations that control the flow of potential contaminants (Ukaegbu and Ezeh, 2012). These localized assessments have proven vital for siting boreholes and implementing groundwater protection policies. Together, these models—GOD, GODL, and GLSI—offer a complementary and comprehensive framework for evaluating aquifer vulnerability in Imo State. While GOD and GODL provide regional-scale insights, with the latter incorporating land use influence, GLSI refines the analysis by revealing layer-specific protective characteristics. When used in combination, as demonstrated in recent studies across Okigwe and surrounding

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areas, they serve as reliable tools for guiding groundwater management, especially in the face of increasing anthropogenic pressures.

To better reflect human-induced stress, the GODL model incorporates parameters such as land use, resistivity, and longitudinal conductance. In a study around Nsukka, Nwankwo and Odoh (2015) showed how GODL values were significantly influenced by land use changes, with elevated vulnerability linked to farming and waste disposal activities. Umeh et al. (2017) further emphasized the role of urban sprawl in increasing groundwater contamination risk in parts of Enugu using the GODL framework. Complementing these models, the GLSI **a**pproach utilizes Vertical Electrical Sounding (VES) data to evaluate the protective capacity of subsurface layers. Studies in Abia (Okoro et al., 2018). Udeh et al. (2024) assessed the aquifer geo-hydraulic characteristics of Enugu and its surroundings using pumping test and geo-sounding data. Their study provided insights into groundwater potential and aquifer behavior in southeastern Nigeria. In southeastern Nigeria, including parts of Okigwe, integrated use of GOD, GODL, and GLSI has enabled effective zoning of groundwater protection areas (Ehirim & Ebeniro, 2010; Ukaegbu & Ezeh, 2012). These models, when combined, offer a robust framework for identifying vulnerable zones and guiding groundwater development and policy decisions.

Recent geophysical and hydrogeological studies across southern Nigeria have highlighted the effectiveness of combining vertical electrical sounding (VES), electrical resistivity tomography (ERT), and index-based models in assessing groundwater vulnerability. In the Nsukka Sedimentary Basin, Ibuot et al. (2025) utilized AVI, GOD, and GLSI indices to identify aquifer zones with moderate to high vulnerability. Similarly, Obiora et al. (2023) applied index-based models to evaluate groundwater pollution risks in the Igbo-Etiti area, while Obiora and Ibuot (2023) employed geophysical methods to assess flood susceptibility and subsurface conditions at the University of Nigeria, Nsukka. Omeje et al. (2024) expanded this work by applying GOD, GODL, and GLSI models, along with sensitivity analysis, to map vulnerability in both Nsukka and Igbo-Etiti. In Uyo, Ibuot et al. (2024) investigated the geohydraulic behavior of coastal hydro-lithofacies, and later (2025a) assessed the vulnerability of alluvial aquifers in the Niger Delta using pollution-based indices. Collectively, these investigations emphasize the importance of integrating geophysical techniques with vulnerability models to map aquifer integrity, evaluate contamination risks, and support sustainable groundwater management.

Location and Geological Context of the Study Area

The study area, Okigwe South, is geographically located between latitudes 5.570°N and 5.700°N and longitudes 7.230°E and 7.380°E, as illustrated in Figure 1. Geologically, it falls within the Anambra Basin—a prominent clastic sedimentary depocentre in the southern Benue Trough (Oladimeji & Nwajide, 2022). The region is predominantly underlain by the Ajali, Mamu, and Nsukka Formations. The Ajali Formation consists primarily of thick, fine-grained, iron-stained sandstone, while the Mamu and Nsukka Formations are also widely exposed in the area. Okigwe South encompasses three local government areas: Ehime Mbano, Obowo, and Ihitte/Uboma, as shown in Figures 1 and 2.

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Fig. 1: Geological Map of the Study Area

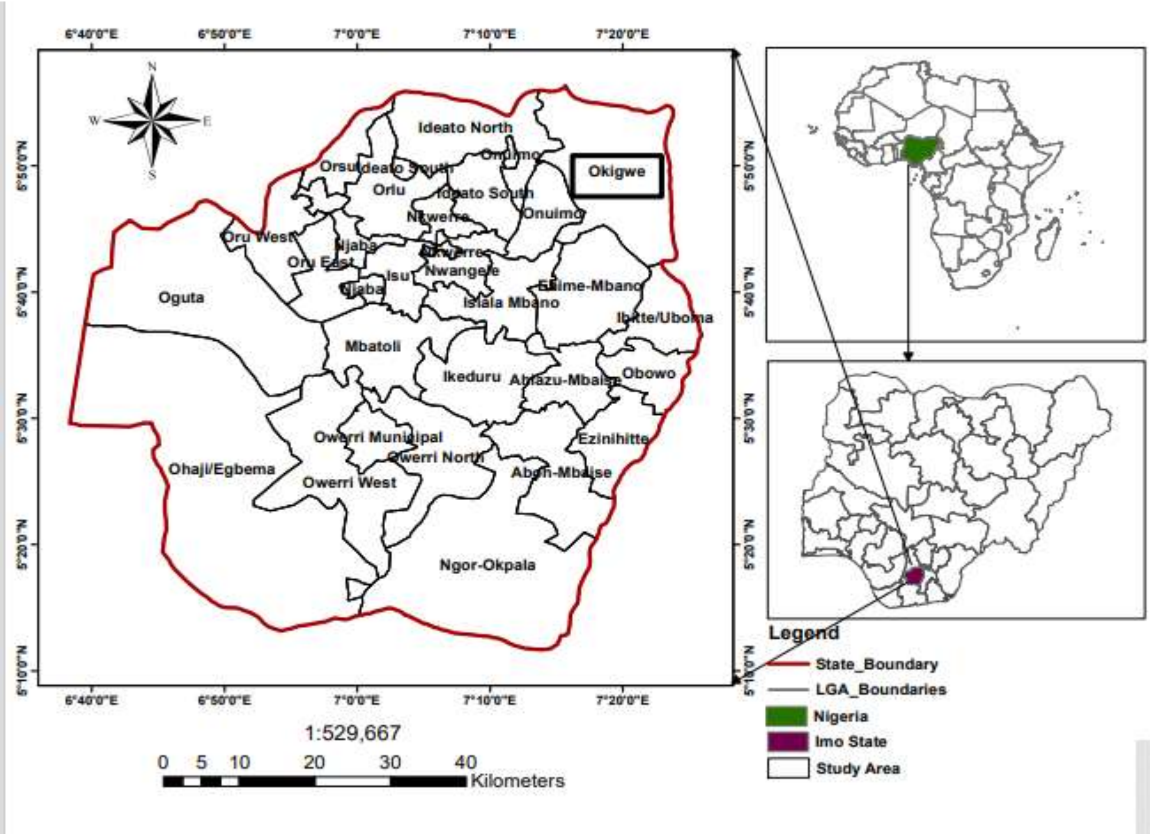
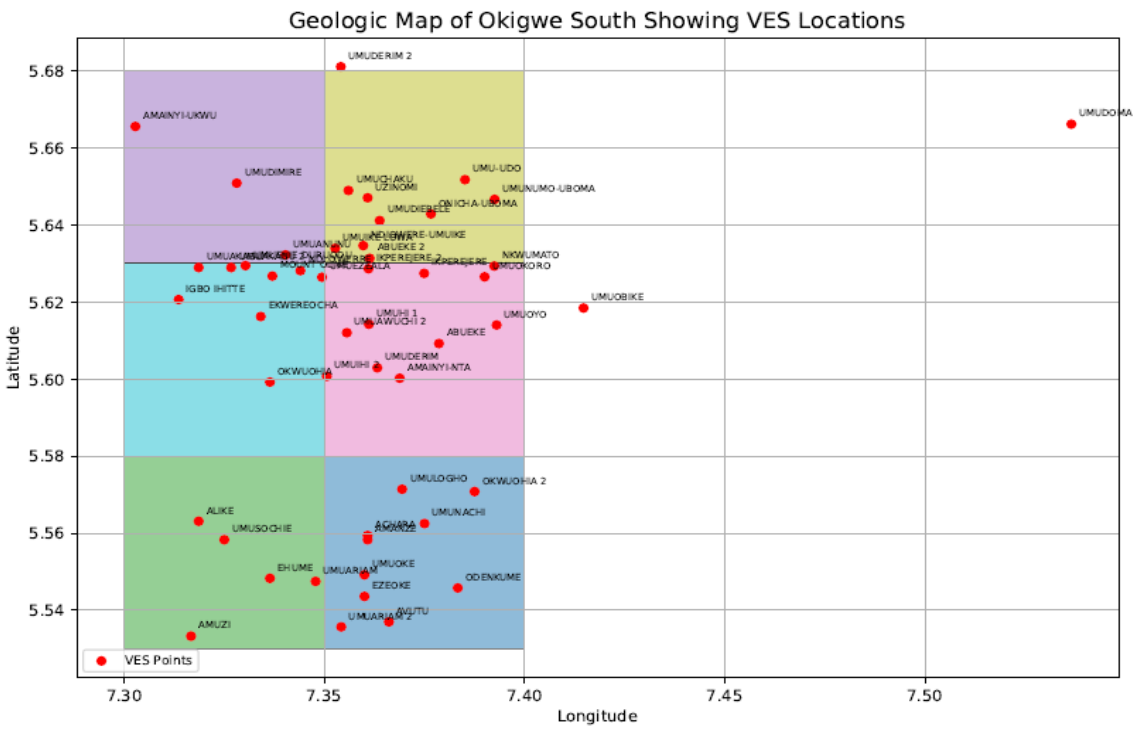


Fig. 2: Location Map of the Study Area



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The Imo Formation, described by Anyanwu and Oguntade (2021), is characterized by bluish-grey shale interbedded with fine-textured clay, ironstone, and thin, indurated sandstone bands that occasionally contain gastropod fossils. Toward the eastern margin of the study area, the Imo Shale transitions laterally into sandstone facies. This lateral variation connects to the Ameki Group, which includes the Nanka Sand, Nsugbe, and Ameki Formations, considered lateral equivalents of the Imo Formation (Nwajide, 1979). As a basal unit of the Niger Delta sequence, the Imo Formation occupies a structurally concave zone that extends southward from the Benin Flank across the Anambra Basin (Whiteman, 1982). This geological framework significantly influences the hydrogeological and geophysical characteristics of the area, which are critical for groundwater vulnerability assessment.

MATERIALS AND METHODS

Geoelectrical Survey Using VES Technique

The geophysical investigation entailed a structured acquisition of subsurface data using the electrical resistivity method, a widely adopted approach in groundwater quality evaluation and environmental studies. In total, 50 Vertical Electrical Sounding (VES) surveys and 8 Water Sample Analyses (WSA) were conducted across selected sites within the Ihitte/Uboma, Ehime Mbano, and Obowo Local Government Areas. Data were acquired using the Integrated Geo-instrument of Resistivity Meter (I.G.R), which comprises a current injection module and a voltage measurement unit tailored for resistivity-based exploration. The field measurements were subsequently processed with WINRESIST software, enabling the derivation of true resistivity values, layer thicknesses, depths, and subsurface lithological structures. Apparent resistivity (ρ_a) was computed using the standard resistivity formula.

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

where AB is the current electrode separation, MN is the potential electrode separation, R_a is the apparent electrical resistance measured in the field. Equation 1 can be written as:

$$\rho_a = GR_a \qquad 2$$

where G is the geometric factor given by:

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

The VES data were plotted on a bi-logarithmic graph, with apparent resistivity (ρ_a) plotted against AB/2 electrode spacings. To improve data quality, the resulting curves were refined by removing anomalous points that could increase the root mean square (rms) error (Ekanem and Udosen, 2023a, b). After this refinement, any remaining variations observed within the curves were interpreted as genuine vertical or lateral changes in subsurface resistivity distribution. Figure 3 presents sample VES models generated by WINRESIST. The resulting geo-resistivity

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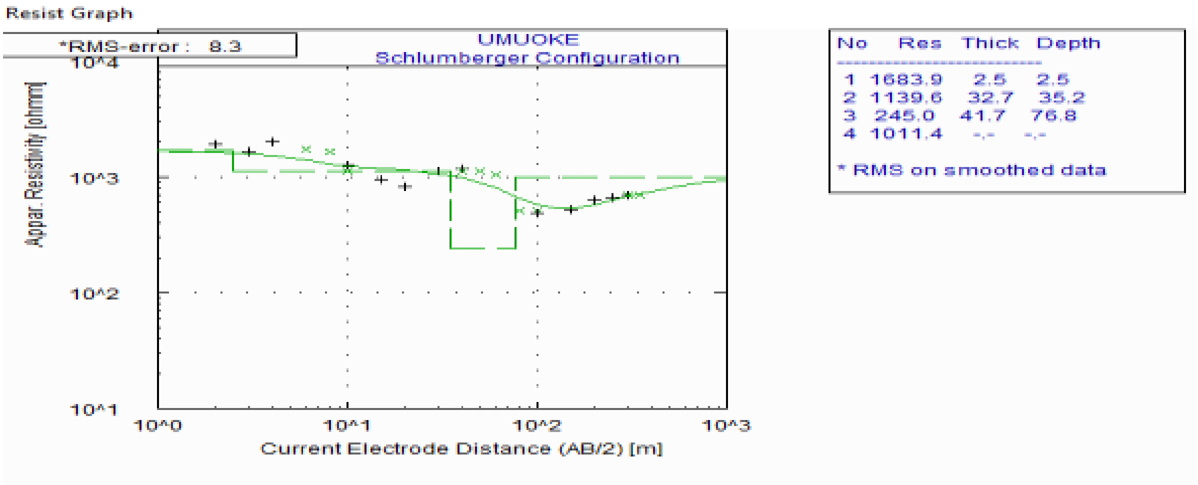
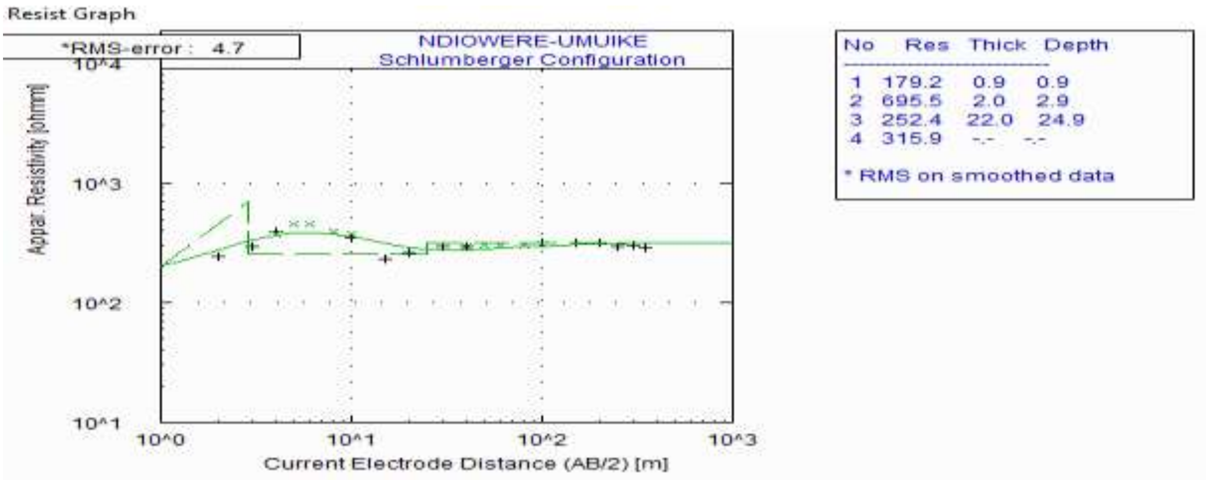
profiles of the subsurface are influenced by factors such as lithology, salinity, moisture content, material density, as well as the size, geometry, and connectivity of pores within the rock matrix.

Fig. 3 (a–b): Representative Inversion Models Generated from Surface Resistivity Data

(a)



(b)



GOD model Aquifer Vulnerability

The GOD model, developed by Foster (1987) in the UK, is widely used to assess aquifer vulnerability based on three hydrogeological parameters: Groundwater occurrence (G), Overlying lithology (O), and Depth to groundwater (D). It is well-suited for broad-scale applications such as land-use planning (Oni et al., 2017). In this study, the GOD index was applied following Foster's method and computed using Equation (4).

$$\text{GOD Index} = G_N \times O_N \times D_N \qquad \textbf{4}$$

N represents the rating assigned to each aquifer vulnerability factor (AVCF) based on the GOD classification. The computed values from Equation (4) were used to categorize vulnerability levels as outlined in Table 1.

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Table 1: GOD parametric index rating (Foster, 1987)

Index rating	Vulnerability class
0.0–0.1	Negligible
0.1–0.3	Low
0.3–0.5	Moderate
0.5–0.7	High
0.7–1.0	Extreme

GODL model Aquifer Vulnerability

The GODL model, developed by Akinlalu et al. (2021), extends the GOD framework by incorporating longitudinal conductance (L) alongside the original G, O, and D parameters. Using a weighted statistical approach, it evaluates aquifer vulnerability based on the combined influence of these factors. In this study, the GODL Index was calculated using the linear additive formula proposed by Akinlalu et al. (2021), as shown in Equation (5).

$$\text{GODL Index} = \sum (G_{NW}G_R + O_{NW}O + D_{NW}D_R + L_{NW}L_R) \quad \textbf{5}$$

N_W and $_R$ represent the normalized weights and ratings of aquifer vulnerability causative factors (AVCFs) as defined by the GODL model (Table 2), while L denotes longitudinal conductance. The GODL model combines elements of the GOD index with longitudinal conductance to enhance vulnerability classification (Akinlalu et al., 2021). Values derived from Equation (5) were used to categorize aquifer vulnerability based on the GODL index rating.

Table 2: AVCFs probability class weights and ratings (Akinlalu et al., 2021)

AVCFs	Classes	Rating (R)	Normalized Weight (NW)
Groundwater Occurrence, G	Unconfined Aquifer	4	0.04
	Semiconfined Aquifer	2	
	Confined Aquifer	3	
	Non-Aquifer	1	
Overlaying Aquifer Lithology, O (Ωm)	35 – 477	2	0.21
	477 – 859	4	
	859 – 1501	3	
	1501 – 5154	1	
Depth of water table, D (m)	0.4 – 4.74	4	0.17
	0.4 – 4.74	3	
	7.75 – 13	2	
	> 13	1	
Longitudinal Conductance, L (Ω^{-1})	0.03 – 0.19	4	0.05
	0.19 – 0.37	3	
	0.37 – 0.83	2	
	>0.83	1	

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Table 3: GODL parametric index rating (Akinlalu et al., 2021)

Index rating	Vulnerability class
<2.0	Low
2.0–3.0	Moderate
3.0–4.0	High
> 4	Extreme

Longitudinal conductance (L)

Longitudinal conductance was used to assess the aquifer's ability to protect against vertical contaminant migration (Oni et al., 2017). According to George (2021), this protective capacity is proportional to the ratio of aquifer thickness to resistivity. As a geophysical parameter, it effectively reflects subsurface composition (Evans et al., 2017). It was computed using Equation (6).

$$L = \sum \frac{h_i}{\rho_i} \quad (6)$$

The symbols h and ρ denote the thickness and resistivity of k individual layers. Essentially, increased layer thickness results in a longer travel time for contaminants to migrate through the subsurface and reach the aquifer (Braga et al., 2016).

GLSI Model Aquifer Vulnerability

According to Oni et al. (2017), the Geoelectric Layer Susceptibility Index (GLSI) evaluates aquifer vulnerability by analyzing variations in electrical resistivity across subsurface lithological layers. It has been recognized as a reliable tool for assessing groundwater contamination risk (George, 2021). In this study, groundwater vulnerability is assessed using the GLSI model, as defined by Oni et al. (2017) in Equation (7).

$$GLSI = \frac{\left(\frac{h_{1r} + \rho_{1r}}{2}\right) + \left(\frac{h_{2r} + \rho_{2r}}{2}\right) + \left(\frac{h_{3r} + \rho_{3r}}{2}\right) + \cdots + \left(\frac{h_{nr} + \rho_{nr}}{2}\right)}{N} \quad (7)$$

Table 4: GLSI Parametric Rating (Oni et al., 2017)

Index rating	Vulnerability class
1.0–1.99	Low
2.0–2.99	Moderate
3.0–3.99	High
4.0	Extreme
Longitudinal conductance	Protective capacity rating

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RESULTS AND DISCUSSION

Electrical Resistivity Sounding

Vertical Electrical Sounding (VES) was carried out at 50 locations using the Schlumberger array, with apparent resistivity plotted against half-current electrode spacing. Data were processed using WINRESIST software, which matched field curves with theoretical models to derive geo-electric parameters, following Akpan et al. (2013) and Ibuot et al. (2013). A low RMSE parameter—resistivity and layer thickness—was used to derive secondary indices for groundwater potential (Bawallah et al., 2018). Table 5 presents variations in resistivity, thickness, depth, and elevation, highlighting the area's subsurface heterogeneity (Obianwu et al., 2011). The contour maps and the single plot were generated using Python in the Spyder environment.

Topsoil resistivity (ρ_1) ranged from 22.2 Ωm at VES 45 (suggesting moist/clayey soils) to 5276.1 Ωm at VES 20 (indicative of dry, lateritic material). The second layer (ρ_2), representing weathered or fractured zones, ranged from 12.8 Ωm at VES 21 to 11,928.4 Ωm at VES 16, reflecting variations from saturated clay to compacted sands. The third layer (ρ_3), often the principal aquifer, showed extremely high values (10,000–31,000+ Ωm) at sites like VES 16, 17, and 26, indicating dry or consolidated formations with limited water potential (Olayinka & Barker, 1990). Basement resistivity (ρ_4) varied from 12.5 to over 30,000 Ωm, reflecting lithological differences. Layer thicknesses (h_1–h_3) also varied widely. Thin upper layers, such as 0.5 m at UMUAWUCHI II, suggest unconsolidated soils, while thick third layers—405.9 m at MOUNT OLIVE and 126.3 m at UMUARIAM II—may indicate deep aquifers or bedrock. These thickness distributions are critical for evaluating groundwater storage potential.

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Table 5: **Summary of Interpreted Vertical Electrical Sounding (VES) Data**

VES	Location	Latitude (ON)	Longitude (OE)	Layer resistivity (Ωm)				Thickness (m)			Depth (m)			Elevation(m)	Curve Types
				ρ_1	ρ_2	ρ_3	ρ_4	h_1	h_2	h_3	d_1	d_2	d_3		
1	EHUME	5.5483	7.3364	1178.1	221.1	2926.7	2125.1	1.2	5.1	54.0	1.2	6.3	60.3	88.0	HK
2	OKWUOHIA	5.5992	7.3364	477.2	1174.3	1783.4	2039.8	3.8	3.4	36.0	3.8	7.2	43.1	111.0	AA
3	UMUARIAM	5.5475	7.3478	110.5	4538.2	119.0	2526.2	0.8	4.6	36.2	0.8	5.4	41.6	150.0	KH
4	UMULOGHO	5.5714	7.3694	350.5	987.3	5637.9	1452.7	4.5	3.0	32.1	4.5	7.5	39.6	99.0	AK
5	UMUOKE	5.5492	7.3600	1683.9	1139.6	245.0	1011.4	2.5	32.7	41.7	2.5	35.2	76.8	113.0	QH
6	ACHARA	5.5594	7.3608	201.4	37.8	158.5	518.7	3.6	6.8	52.5	3.6	10.4	62.9	86.0	HA
7	ALIKE	5.5631	7.3186	326.1	315.0	1338.1	4408.2	2.4	8.6	10.4	2.4	11.0	21.4	86.0	HA
8	AMANZE	5.5583	7.3608	67.5	1359.1	288.9	1170.0	2.5	7.4	32.2	2.5	10.0	42.1	172.0	KH
9	AMUZI	5.5333	7.3167	192.7	167.6	825.6	2611.4	4.7	13.2	24.5	4.7	17.9	42.4	98.0	HA
10	AVUTU	5.5370	7.3661	374.5	1318.4	3081.6	1177.7	2.6	20.6	71.1	2.6	23.2	94.3	101.0	AK
11	UMUSOCHIE	5.5583	7.3250	332.0	37.3	2285.4	1137.3	1.0	2.1	34.0	1.0	3.0	37.0	112.0	HK
12	ODENKUME	5.5458	7.3833	379.4	1275.8	934.3	1134.3	1.2	10.1	29.1	1.2	11.2	40.3	118.0	KH
13	OKWUOHIA II	5.5708	7.3875	307.2	51.4	278.4	2199.5	3.4	8.3	13.8	3.4	11.7	25.5	116.0	HA
14	UMUNACHI	5.5625	7.3750	172.7	627.1	6192.8	545.6	2.7	13.2	55.8	2.7	15.9	71.8	114.0	AK
15	UMUARIAM II	5.5357	7.3542	998.0	4228.7	2501.2	1230.2	3.6	10.2	126.3	3.6	13.9	140.2	117.0	KQ
16	UMUAKAGU II	5.6289	7.3267	187.1	11928.4	23539.4	2462.3	1.1	2.5	11.9	1.1	3.5	15.4	184.0	AK
17	MOUNT OLIVE	5.6267	7.3370	191.8	734.6	31032.5	1249.0	2.5	5.4	405.9	2.5	7.9	413.8	179.0	AK
18	UMUANUNU	5.6322	7.3403	322.4	2214.7	8442.1	3060.4	1.5	31.3	64.4	1.5	32.8	97.2	159.0	AK
19	UMUDIMIRE	5.6508	7.3281	3860.5	311.9	43.9	235.3	0.9	14.0	11.2	0.9	14.9	26.1	168.0	QH
20	EZEOKE	5.5436	7.3600	5276.1	418.8	468.9	1880.8	1.0	7.7	41.6	1.0	8.6	50.2	115.0	HA
21	UMUEZEALA	5.6264	7.3494	588.2	12.8	252.4	760.5	0.7	1.0	32.2	0.7	1.7	33.9	171.0	HA
22	NDI OWERRE	5.6281	7.3440	1974.7	9519.1	977.7	30801.2	4.4	7.7	38.1	4.4	12.1	40.2	189.0	KA
23	UMUEHIE DURUODU	5.6294	7.3303	116.7	6731.2	11593.1	1563.3	1.3	3.1	19.6	1.3	4.3	23.9	169.0	AK
24	UMUAKAGU	5.6289	7.3186	76.7	4456.1	2400.6	2444.6	0.9	5.4	38.2	0.9	6.3	44.6	168.0	KH
25	IGBO IHITTE	5.6206	7.3136	128.2	2347.9	55779.1	17521.1	1.6	1.7	22.0	1.6	3.3	25.3	129.0	AK

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26	UMUIKE LOWA	5.6339	7.3527	1776.4	2025.3	10188.6	1774.2	2.1	7.2	15.4	2.1	9.3	24.7	162.0	AK
27	UMUDIEBELE	5.6411	7.3638	1746.2	111.9	346.7	104.2	0.7	20.4	80.3	0.7	21.1	101.4	105.0	HK
28	UMU-UDO	5.6517	7.3851	1123.6	201.6	7721.1	461.2	1.2	5.5	48.2	1.2	6.7	54.9	125.0	HK
29	UMUNUMO-UBOMA	5.6466	7.3925	1341.1	172.4	1678.8	304.3	1.4	2.6	8.2	1.4	3.9	12.1	101.0	HK
30	UZINOMI	5.6470	7.3608	329.1	441.6	8.3	90.5	3.4	4.3	80.7	3.4	7.7	88.4	93.0	KH
31	UMUCHAKU	5.6489	7.3560	459.9	159.5	1194.1	57.5	5.9	24.4	60.4	5.9	30.3	90.7	120.0	HK
32	UMUHI 1	5.6142	7.3611	198.3	3455.8	5574.4	626.9	1.6	34.1	61.1	1.6	37.0	98.1	161.0	AK
33	UMUIHI II	5.6007	7.3506	745.0	2947.4	11697.7	6489.6	1.0	19.7	110.5	1.0	20.6	131.1	158.0	AK
34	UMUAWUCHI II	5.6120	7.3556	4558.4	152.1	9521.3	728.5	0.5	13.6	81.9	0.5	14.1	96.0	164.0	HK
35	UMUDERIM	5.6029	7.3632	979.8	1345.5	4300.1	1001.9	2.2	18.4	50.2	2.2	20.7	70.8	157.0	AK
36	AMAINYI-NTA	5.6002	7.3688	306.9	1301.6	816.5	4890.3	1.4	5.2	9.3	1.4	6.6	15.9	146.0	KH
37	EKWEREOCHA	5.6162	7.3341	267.2	221.9	4611.1	326.9	5.2	9.0	37.1	5.2	14.2	51.4	163.0	HK
38	ABUEKE	5.6092	7.3786	500.4	3791.2	4551.9	780.5	1.3	7.9	57.8	1.3	9.2	67.0	126.0	AK
39	UMUOYO	5.6140	7.3930	735.3	114.0	598.6	787.4	1.5	20.0	132.6	1.5	21.5	154.1	130.0	HA
40	IKPEREJERE	5.6274	7.3749	224.7	72.2	25.8	584.5	2.5	4.8	40.3	2.5	7.3	47.6	118.0	QH
41	UMUOKORO	5.6265	7.3900	873.2	2522.7	1275.4	6853.5	2.9	5.8	12.4	2.9	8.8	21.2	159.0	KH
42	NDIOWERE-UMUIKE	5.6346	7.3597	179.2	695.5	252.4	315.9	0.9	2.0	22.0	0.9	2.9	24.9	115.0	KH
43	AMAINYI-UKWU	5.6655	7.3028	868.8	197.7	3490.3	971.4	6.3	9.6	37.1	6.3	15.9	53.0	123.0	HK
44	NKWUMATO	5.6293	7.3924	621.8	40.8	658.0	398.5	2.5	5.5	8.4	2.5	8.0	16.4	116.0	HK
45	IKPEREJERE II	5.6286	7.3610	22.2	97.1	3224.6	510.5	3.7	1.9	36.1	3.7	5.5	41.6	119.0	AK
46	UMUDERIM II	5.6810	7.3541	94.3	628.6	3530.8	422.9	3.0	2.3	24.1	3.0	5.3	29.4	122.0	AK
47	UMUDOMA	5.6661	7.5365	87.8	65.9	108.0	2792.1	2.1	11.8	20.1	2.1	13.9	34.1	115.0	HA
48	ONICHA-UBOMA	5.6428	7.3766	86.2	601.9	662.3	101.2	0.9	26.6	67.4	0.9	27.4	94.8	131.0	AK
49	UMUOBIKE	5.6184	7.4147	282.1	1907.4	6264.8	10611.9	2.3	3.1	72.6	2.3	5.4	78.0	113.0	AA
50	ABUEKE II	5.6313	7.3613	125.6	30.5	2430.8	12.5	2.0	3.0	23.0	2.0	4.9	27.9	118.0	HK

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Layer depths—calculated as the cumulative thickness from the surface to each subsurface unit—exhibit significant spatial variation. Shallow third-layer depths, such as 12.1 m at UMUNUMO-UBOMA and 15.4 m at UMUAKAGU II, suggest near-surface basement or compact formations, while deeper profiles, like 413.8 m at MOUNT OLIVE and 140.2 m at UMUARIAM II, indicate thick stratified sequences or deeply weathered zones. These variations are essential for determining optimal borehole drilling depths and assessing subsurface stability for engineering purposes. Elevations across the study area range from 86.0 m to 189.0 m, influencing surface runoff, infiltration, and regional groundwater flow. Higher sites like NDI OWERRE (189.0 m) and UMUAKAGU II (184.0 m) represent uplands, while areas like EHUME (88.0 m) lie in the lowlands. VES curve interpretations from Okigwe South display a range of resistivity profiles, reflecting diverse subsurface geology. The KH-type is predominant, characterized by a resistive top layer, a conductive middle (typically aquiferous), and a resistive basement—favourable for groundwater accumulation. Similarly, HK-type curves show aquifer potential, with a resistive upper layer, conductive middle, and resistive base.

GOD model Aquifer Vulnerability

The following interpretation assesses aquifer vulnerability across fifty different locations (VES 1 to 50) based on the GOD Index, which incorporates geological setting, overlaying soil, and depth to groundwater. This index helps classify each region's susceptibility to contamination, ranging from negligible to extreme vulnerability. The analysis provides a clear understanding of areas that require focused groundwater protection and management. EHUME shows extreme vulnerability to groundwater contamination, so urgent protective measures are essential. Areas like UMUOKE, UMUDIMIRE, EZEOKE, UMUSOCHIE, UMUDIEBELE, UMU-UDO, UMUCHAKU, and NDI OWERRE exhibit high vulnerability, indicating significant contamination risks that require immediate attention and management. Places such as OKWUOHIA, UMULOGHO, AMANZE, AVUTU, and IGBO IHITTE have moderate vulnerability, suggesting some susceptibility to contamination and the need for regular monitoring and precautionary steps, as shown in Table 6.

Table 6: Aquifer Vulnerability Classification Using the GOD Index

Location	VES	GN	ON	DN	GOD Index	Vulnerability
EHUME	1	0.7	0.8	0.3	0.168	Low
OKWUOHIA	2	0.7	0.6	0.3	0.126	Low
UMUARIAM	3	0.5	0.6	0.3	0.09	Negligible
UMULOGHO	4	0.7	0.6	0.3	0.126	Low
UMUOKE	5	0.7	0.8	0.3	0.168	Low
ACHARA	6	0.5	0.8	0.3	0.12	Low
ALIKE	7	0.7	0.2	0.3	0.042	Negligible
AMANZE	8	0.3	0.6	0.3	0.054	Negligible
AMUZI	9	0.5	0.4	0.3	0.06	Negligible
AVUTU	10	0.7	0.6	0.3	0.126	Low
UMUSOCHIE	11	0.7	0.2	0.3	0.042	Negligible
ODENKUME	12	0.7	0.4	0.3	0.084	Low
OKWUOHIA II	13	0.7	0.2	0.3	0.042	Negligible

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UMUNACHI	**14**	**0.5**	**0.6**	**0.3**	**0.09**	**Negligible**
UMUARIAM II	**15**	**0.7**	**0.4**	**0.3**	**0.084**	**Low**
UMUAKAGU II	**16**	**0.5**	**0.4**	**0.3**	**0.06**	**Negligible**
MOUNT OLIVE	**17**	**0.5**	**0.8**	**0.3**	**0.12**	**Low**
UMUANUNU	**18**	**0.7**	**0.8**	**0.3**	**0.168**	**Low**
UMUDIMIRE	**19**	**0.7**	**0.4**	**0.3**	**0.084**	**Low**
EZEOKE	**20**	**0.7**	**0.6**	**0.3**	**0.126**	**Low**
UMUEZEALA	**21**	**0.7**	**0.6**	**0.3**	**0.126**	**Low**
NDI OWERRE	**22**	**0.7**	**0.6**	**0.3**	**0.126**	**Low**
UMUEHIE DURUODU	**23**	**0.5**	**0.4**	**0.3**	**0.06**	**Negligible**
UMUAKAGU	**24**	**0.3**	**0.6**	**0.3**	**0.054**	**Negligible**
IGBO IHITTE	**25**	**0.5**	**0.4**	**0.3**	**0.06**	**Negligible**
UMUIKE LOWA	**26**	**0.7**	**0.4**	**0.3**	**0.084**	**Low**
UMUDIEBELE	**27**	**0.7**	**0.8**	**0.3**	**0.168**	**Low**
UMU-UDO	**28**	**0.7**	**0.6**	**0.3**	**0.126**	**Low**
UMUNUMO-UBOMA	**29**	**0.7**	**0.4**	**0.3**	**0.084**	**Low**
UZINOMI	**30**	**0.7**	**0.8**	**0.3**	**0.168**	**Low**
UMUCHAKU	**31**	**0.7**	**0.8**	**0.3**	**0.168**	**Low**
UMUHI 1	**32**	**0.5**	**0.7**	**0.3**	**0.105**	**Low**
UMUIHI II	**33**	**0.5**	**0.7**	**0.3**	**0.105**	**Low**
UMUAWUCHI II	**34**	**0.3**	**0.6**	**0.3**	**0.054**	**Negligible**
UMUDERIM	**35**	**0.5**	**0.7**	**0.3**	**0.105**	**Low**
AMAINYI-NTA	**36**	**0.4**	**0.3**	**0.3**	**0.036**	**Negligible**
EKWEREOCHA	**37**	**0.7**	**0.3**	**0.3**	**0.063**	**Negligible**
ABUEKE	**38**	**0.5**	**0.7**	**0.3**	**0.105**	**Low**
UMUOYO	**39**	**0.5**	**0.7**	**0.3**	**0.105**	**Low**
IKPEREJERE	**40**	**0.4**	**0.3**	**0.3**	**0.036**	**Negligible**
UMUOKORO	**41**	**0.5**	**0.7**	**0.3**	**0.105**	**Low**
NDIOWERE-UMUIKE	**42**	**0.3**	**0.3**	**0.3**	**0.027**	**Negligible**
AMAINYI-UKWU	**43**	**0.5**	**0.3**	**0.3**	**0.045**	**Negligible**
NKWUMATO	**44**	**0.5**	**0.3**	**0.3**	**0.045**	**Negligible**
IKPEREJERE II	**45**	**0.3**	**0.3**	**0.3**	**0.027**	**Negligible**
UMUDERIM II	**46**	**0.3**	**0.3**	**0.3**	**0.027**	**Negligible**
UMUDOMA	**47**	**0.3**	**0.3**	**0.3**	**0.027**	**Negligible**
ONICHA-UBOMA	**48**	**0.3**	**0.6**	**0.3**	**0.054**	**Negligible**
UMUOBIKE	**49**	**0.5**	**0.7**	**0.3**	**0.105**	**Low**
ABUEKE II	**50**	**0.3**	**0.3**	**0.3**	**0.027**	**Negligible**

Locations including UMUARIAM, ACHARA, ALIKE, AMUZI, ODENKUME, OKWUOHIA II, UMUARIAM II, UMUAKAGU II, MOUNT OLIVE, UMUANUNU, UMUEZEALA, UMUEHIE DURUODU, UMUAKAGU, UMUIKE LOWA, ABUEKE, UMUOYO, UMUOKORO, UMUOBIKE, and UMUIHI II show low vulnerability, which means their groundwater is relatively safer but would still benefit from basic protective

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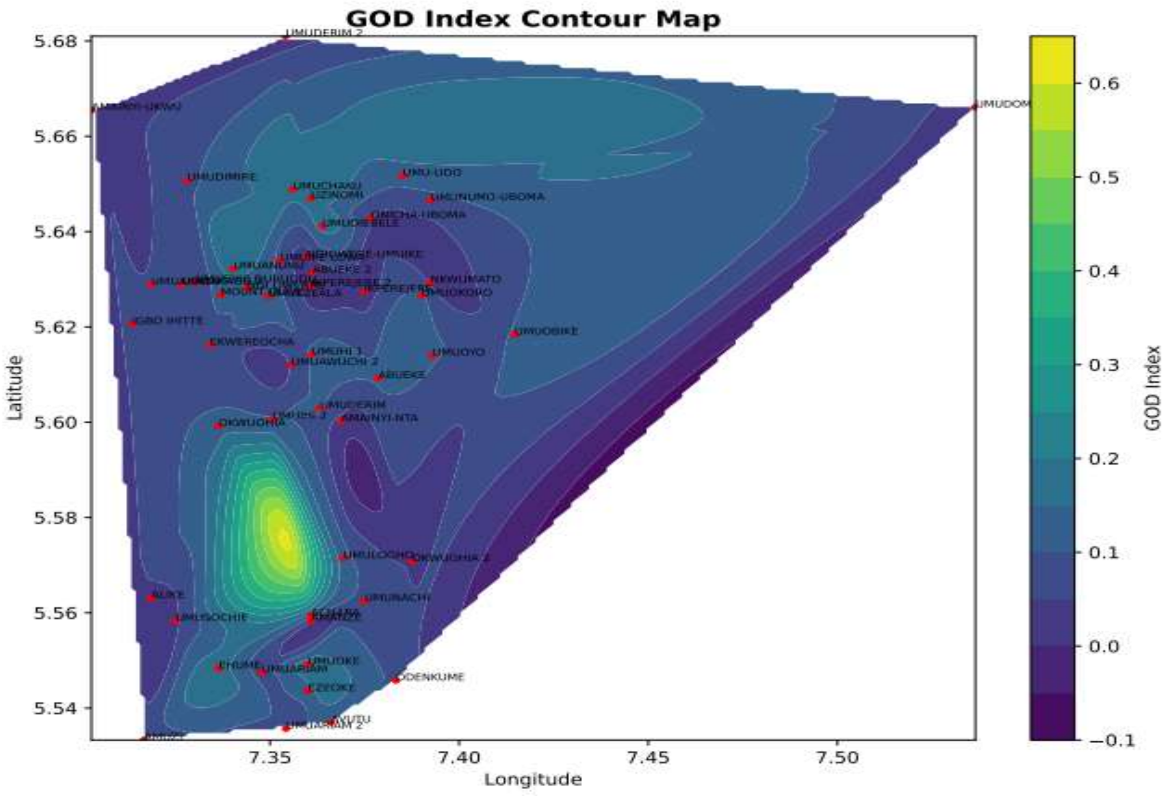
practices. Lastly, areas such as UMUAWUCHI II, AMAINYI-NTA, EKWEREOCHA, IKPEREJERE, NDIOWERE-UMUIKE, AMAINYI-UKWU, NKWUMATO, IKPEREJERE II, UMUDERIM II, UMUDOMA, ONICHA-UBOMA, and ABUEKE II have negligible vulnerability, indicating excellent natural protection of groundwater and minimal contamination risk.

The GOD model evaluates groundwater vulnerability based on three main parameters: the Groundwater occurrence (aquifer type), the Overlying strata, and the Depth to the water table. It is particularly effective for initial vulnerability screening. The contour map in Figure 4 shows that areas with low GOD index values, such as OKWUOHIA and UMUNACHI, are considered to have minimal natural protection and are highly vulnerable to pollution. These areas likely have unconfined aquifers and thin overburden layers, enabling contaminants from the surface to percolate easily into the groundwater system.

Fig 4: Contour map of GOD Index



GODL model Aquifer Vulnerability

The GODL index for the 50 locations reflects the combined influence of resistivity, longitude, depth, and longitudinal conductance on the subsurface geological properties. Locations like UMUAWUCHI II (VES 34) exhibit very high GODL values, indicating thick, highly resistive layers that may correspond to consolidated rock formations or zones with potential mineralization. Similarly, UMUARIAM II (VES 15) shows elevated GODL values, suggesting substantial subsurface layering with significant resistivity and thickness as shown in Table 8.

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Table 8: GODL Vulnerability Index for Surveyed Locations

VES	Location	GN	ON	DN	L	GODL
1	EHUME	1178.1	5.5483	60.3	0.088	30.84
2	OKWUOHIA	477.2	5.5992	43.1	0.111	21.32
3	UMUARIAM	110.5	5.5475	41.6	0.15	10.08
4	UMULOGHO	350.5	5.5714	39.6	0.099	18.19
5	UMUOKE	1683.9	5.5492	76.8	0.113	37.58
6	ACHARA	201.4	5.5594	62.9	0.086	15.66
7	ALIKE	326.1	5.5631	21.4	0.086	14.23
8	AMANZE	67.5	5.5583	42.1	0.172	9.36
9	AMUZI	192.7	5.5333	42.4	0.098	15.6
10	AVUTU	374.5	5.537	94.3	0.101	23.36
11	UMUSOCHIE	332	5.5583	37	0.112	17.34
12	ODENKUME	379.4	5.5458	40.3	0.118	20.29
13	OKWUOHIA II	307.2	5.5708	25.5	0.116	15.38
14	UMUNACHI	172.7	5.5625	71.8	0.114	17.35
15	UMUARIAM II	998	5.5357	140.2	0.117	45.82
16	UMUAKAGU II	187.1	5.6289	15.4	0.184	11.01
17	MOUNT OLIVE	191.8	5.6267	413.8	0.179	73.48
18	UMUANUNU	322.4	5.6322	97.2	0.159	33.37
19	UMUDIMIRE	3860.5	5.6508	26.1	0.168	161.94
20	EZEOKE	5276.1	5.5436	50.2	0.115	213.2
21	UMUEZEALA	588.2	5.6264	33.9	0.1483	30.48
22	NDI OWERRE	1974.7	5.6281	40.2	0.0148	86.99
23	UMUEHIE DURUODU	116.7	5.6294	23.9	0.0404	9.91
24	UMUAKAGU	76.7	5.6289	44.6	0.0815	11.84
25	IGBO IHITTE	128.2	5.6206	25.3	0.0187	10.61
26	UMUIKE LOWA	1776.4	5.6339	24.7	0.0139	76.44
27	UMUDIEBELE	1746.2	5.6411	101.4	0.9697	88.32
28	UMU-UDO	1123.6	5.6517	54.9	0.0416	55.47
29	UMUNUMO-UBOMA	1341.1	5.6466	12.1	0.009	56.89
30	UZINOMI	329.1	5.647	88.4	0.2687	29.39
31	UMUCHAKU	459.9	5.6489	90.7	0.1969	35.01
32	UMUHI 1	198.3	5.6142	98.1	0.1483	20.93
33	UMUIHI II	745	5.6007	131.1	0.013	38.21
34	UMUAWUCHI II	4558.4	5.612	96	0.0213	185.98
35	UMUDERIM	979.8	5.6029	70.8	0.0507	38
36	AMAINYI-NTA	306.9	5.6002	15.9	0.128	15.97
37	EKWEREOCHA	267.2	5.6162	51.4	0.0714	20.79
38	ABUEKE	500.4	5.6092	67	0.0149	29.26
39	UMUOYO	735.3	5.614	154.1	0.0191	45.43
40	IKPEREJERE	224.7	5.6274	47.6	0.054	16.34

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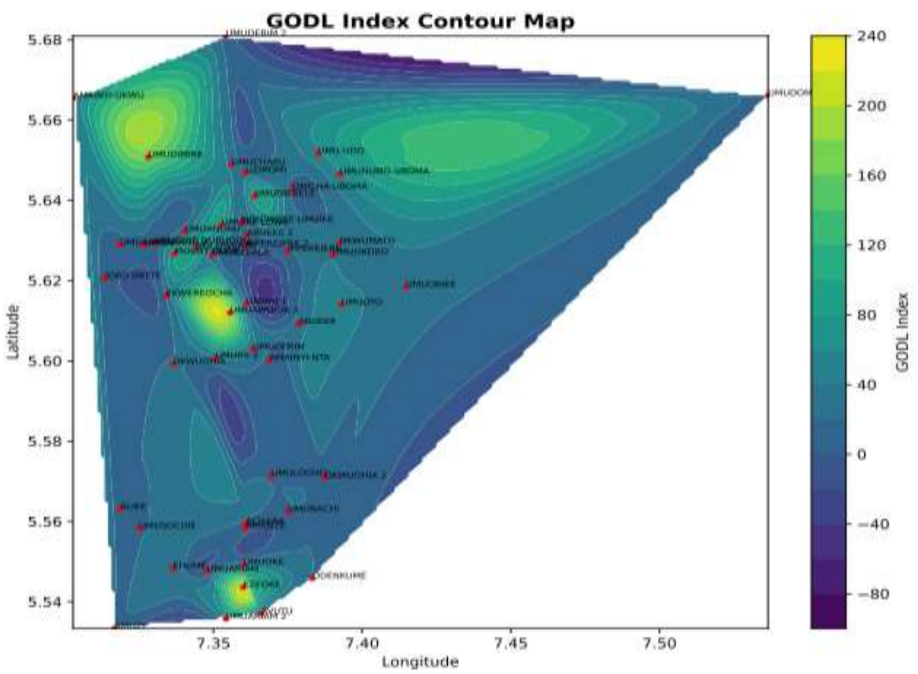
41	**UMUOKORO**	**873.2**	**5.6265**	**21.2**	**0.0843**	**36.88**
42	**NDIOWERE-UMUIKE**	**179.2**	**5.6346**	**24.9**	**0.018**	**11.41**
43	**AMAINYI-UKWU**	**868.8**	**5.6655**	**53**	**0.0844**	**39.08**
44	**NKWUMATO**	**621.8**	**5.6293**	**16.4**	**0.0207**	**27.35**
45	**IKPEREJERE II**	**22.2**	**5.6286**	**41.6**	**0.0217**	**5.65**
46	**UMUDERIM II**	**94.3**	**5.681**	**29.4**	**0.0193**	**11.07**
47	**UMUDOMA**	**87.8**	**5.6661**	**34.1**	**0.0202**	**11.46**
48	**ONICHA-UBOMA**	**86.2**	**5.6428**	**94.8**	**0.0201**	**16.04**
49	**UMUOBIKE**	**282.1**	**5.6184**	**78**	**0.0603**	**29.16**
50	**ABUEKE II**	**125.6**	**5.6313**	**27.9**	**0.0131**	**14.06**

In contrast, areas such as IKPEREJERE II (VES 45) have low GODL values, which likely indicate more conductive materials such as clay-rich or water-saturated layers, representing less resistive and potentially softer geological formations. Most locations fall in the moderate GODL range, signifying a mix of geological conditions with varying degrees of resistivity, depth, and conductivity. The longitude component plays a notable role in the index, with locations further east generally showing higher GODL values, while depth and longitudinal conductance further refine the assessment by highlighting areas with thicker and better-conducting layers. Overall, the GODL index serves as a useful indicator to differentiate between sites with strong resistive properties and those dominated by more conductive geological materials, guiding priorities for further exploration or study. The GODL model extends the GOD framework by integrating land use data into the assessment. This approach accounts for anthropogenic pressures, such as urbanization, agriculture, and industrial activities. On the contour map (Fig. 5), areas like UMULOGHO and AVUTU appear as hotspots with increased vulnerability.

Fig 5: Contour map of GODL Index



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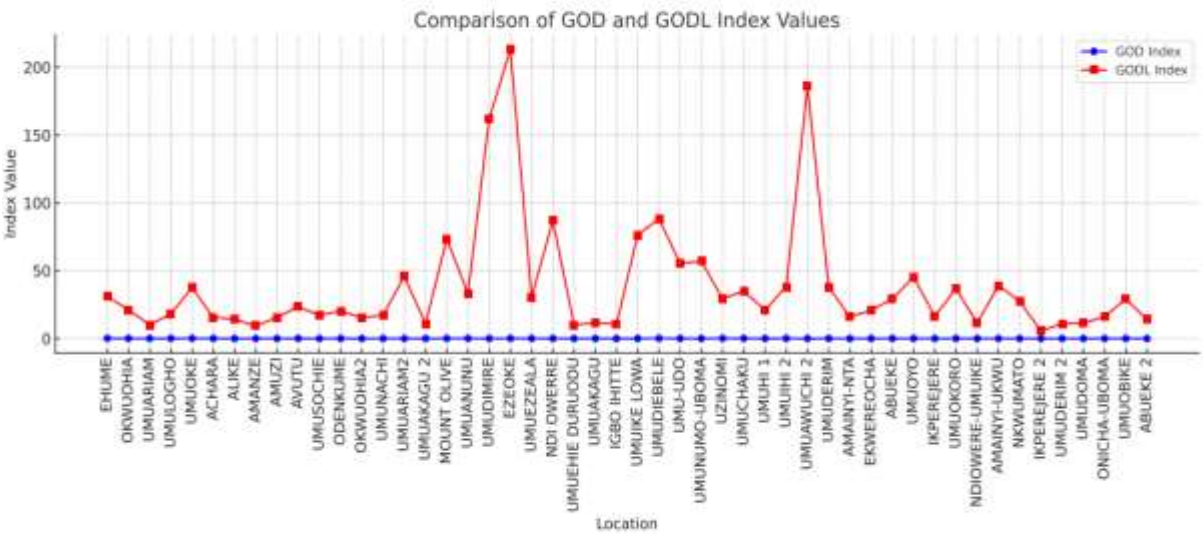
The elevated vulnerability in these areas is attributed not only to unfavorable hydrogeological conditions but also to intensive land use practices—such as agriculture, urban development, and waste disposal—that significantly enhance the risk of pollutant infiltration. The GODL map effectively captures the influence of human activities, making it a valuable tool for informed urban planning, environmental management, and groundwater protection strategies.

GOD and GODL Indices

This chart in Figure 6 compares the GOD and GODL indices across 50 locations in Okigwe South. The GOD Index is a basic model used to evaluate the vulnerability of groundwater to pollution, while the GODL Index is an extended version that considers land use in addition to geological and hydrological factors. From the chart, it is clear that the GODL values are consistently higher than the GOD values at all locations. This is expected because land use often increases the pressure on groundwater systems. For example, locations like UMUDIMIRE, EZEOKE, and UMUAWUCHI II have very high GODL values (above 150), even though their GOD values remain moderate. This suggests that human activities in those areas are significantly increasing the risk of groundwater contamination.

Fig 6: Comparison of GOD and GODL Index Values



While the GOD Index consistently remains below 0.2 across all locations—indicating low to moderate natural vulnerability—it suggests that, in the absence of human interference, the aquifers may not face significant risk. However, the GODL Index, which incorporates land use factors, reveals a different reality by showing how human activities can substantially increase groundwater vulnerability. This makes the GODL Index a more sensitive and realistic tool for assessing actual risk levels. Although the GOD Index provides a solid baseline for evaluating natural protection, the GODL Index offers a more comprehensive perspective. Areas where GODL values are high despite low GOD scores should be prioritized for protection, as they are likely under increasing pressure from agriculture, urban development, or industrial operations.

GLSI Model Aquifer Vulnerability

The Geoelectric Layer Susceptibility Index (GLSI) is used to evaluate the vulnerability of subsurface layers to contamination. It is derived from resistivity and thickness values of geoelectric layers obtained from Vertical Electrical Sounding (VES). By analyzing GLSI

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across the 50 surveyed locations, we can classify each area based on its susceptibility to surface contaminants—ranging from low to extreme vulnerability. This interpretation helps identify areas with strong natural protection for groundwater and those requiring careful environmental management. The areas categorized under low vulnerability have strong natural protection for their groundwater. This means the subsurface materials — such as clay, sandy clay, and thick resistive layers — form a solid barrier against pollutants from the surface. In simple terms, if contaminants like agricultural runoff or waste materials are spilled or dumped on the surface, it would be difficult for them to reach the underground water. These locations are ideal for groundwater development and are less likely to suffer from contamination problems. Locations in this category include UMUARIAM, AMANZE, UMUSOCHIE, ODENKUME, UMUAKAGU II, NDI OWERRE, UMUEHIE DURUODU, UMUAKAGU, AMAINYI-NTA, EKWEREOCHA, NDIOWERE-UMUIKE, IKPEREJERE II, ONICHA-UBOMA, and ABUEKE II. These areas as shown in Table 9 are highly suitable for siting boreholes and public water supplies. However, responsible land-use practices such as safe waste disposal and limited use of chemicals should be encouraged to help maintain the natural protection these zones already possess.

Table 9: GLSI Findings and Their Implications

VES	Location	GLSI Value	Vulnerability Class
1	EHUME	26,764.85	Extreme
2	OKWUOHIA	11,668.06	Extreme
3	UMUARIAM	4,211.99	Extreme
4	UMULOGHO	30,919.29	Extreme
5	UMUOKE	8,615.20	Extreme
6	ACHARA	1,550.56	Low
7	ALIKE	2,901.31	Moderate
8	AMANZE	3,254.78	High
9	AMUZI	3,890.87	High
10	AVUTU	41,205.75	Extreme
11	UMUSOCHIE	13,018.99	Extreme
12	ODENKUME	6,754.83	Extreme
13	OKWUOHIA II	885.5	Low
14	UMUNACHI	59,050.38	Extreme
15	UMUARIAM II	60,437.85	Extreme
16	UMUAKAGU II	51,690.95	Extreme
17	MOUNT OLIVE	2,100,090.38	Extreme
18	UMUANUNU	102,245.78	Extreme
19	UMUDIMIRE	1,388.79	Low
20	EZEOKE	4,667.85	Extreme
21	UMUEZEALA	1,425.30	Low
22	NDI OWERRE	19,872.69	Extreme
23	UMUEHIE DURUODU	41,373.86	Extreme
24	UMUAKAGU	19,305.81	Extreme
25	IGBO IHITTE	205,222.83	Extreme

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26	**UMUIKE LOWA**	**29,202.84**	**Extreme**
27	**UMUDIEBELE**	**5,224.19**	**Extreme**
28	**UMU-UDO**	**62,435.69**	**Extreme**
29	**UMUNUMO-UBOMA**	**2,681.99**	**Moderate**
30	**UZINOMI**	**614.61**	**Low**
31	**UMUCHAKU**	**13,121.48**	**Extreme**
32	**UMUHI 1**	**2546.52**	**Extreme**
33	**UMUIHI II**	**4870.53**	**Extreme**
34	**UMUAWUCHI II**	**1225.31**	**Extreme**
35	**UMUDERIM**	**2783.83**	**Extreme**
36	**AMAINYI-NTA**	**729.61**	**Extreme**
37	**EKWEREOCHA**	**922.37**	**Extreme**
38	**ABUEKE**	**1845.7**	**Extreme**
39	**UMUOYO**	**3359.47**	**Extreme**
40	**IKPEREJERE**	**543.24**	**Extreme**
41	**UMUOKORO**	**744.15**	**Extreme**
42	**NDIOWERE-UMUIKE**	**174.61**	**Low**
43	**AMAINYI-UKWU**	**870.8**	**Extreme**
44	**NKWUMATO**	**268.79**	**Low**
45	**IKPEREJERE II**	**180.96**	**Low**
46	**UMUDERIM II**	**213.57**	**Low**
47	**UMUDOMA**	**166.36**	**Low**
48	**ONICHA-UBOMA**	**189.79**	**Low**
49	**UMUOBIKE**	**3246.5**	**Extreme**
50	**ABUEKE II**	**87.52**	**Low**

Areas falling under moderate vulnerability offer a fair level of natural protection to the groundwater. The thickness and resistivity of the subsurface layers here provide some resistance to pollution, but not enough to be completely secure. In these areas, pollutants could still make their way to the groundwater, particularly if land use is not well-regulated. Farming, poor waste management, or leaking septic tanks can contribute to groundwater contamination over time. Locations with moderate vulnerability include EHUME, OKWUOHIA, UMULOGHO, ACHARA, ALIKE, AMUZI, UMUOKE, OKWUOHIA II, UMUARIAM II, MOUNT OLIVE, UMUANUNU, UMUEZEALA, IGBO IHITTE, UMUIKE LOWA, UMUDIEBELE, UMU-UDO, UZINOMI, UMUCHAKU, UMUIHI II, UMUDERIM, ABUEKE, UMUOYO, IKPEREJERE, UMUOKORO, AMAINYI-UKWU, NKWUMATO, UMUDERIM II, UMUDOMA, and UMUOBIKE. These areas are generally safe for groundwater development, but users should be cautious. Monitoring of water quality, better sanitation, and good farming practices are essential to ensure that the groundwater remains safe for use. The high vulnerability areas are those where the groundwater is at considerable risk of contamination. In these places, the protective geologic layers are either too thin or have low

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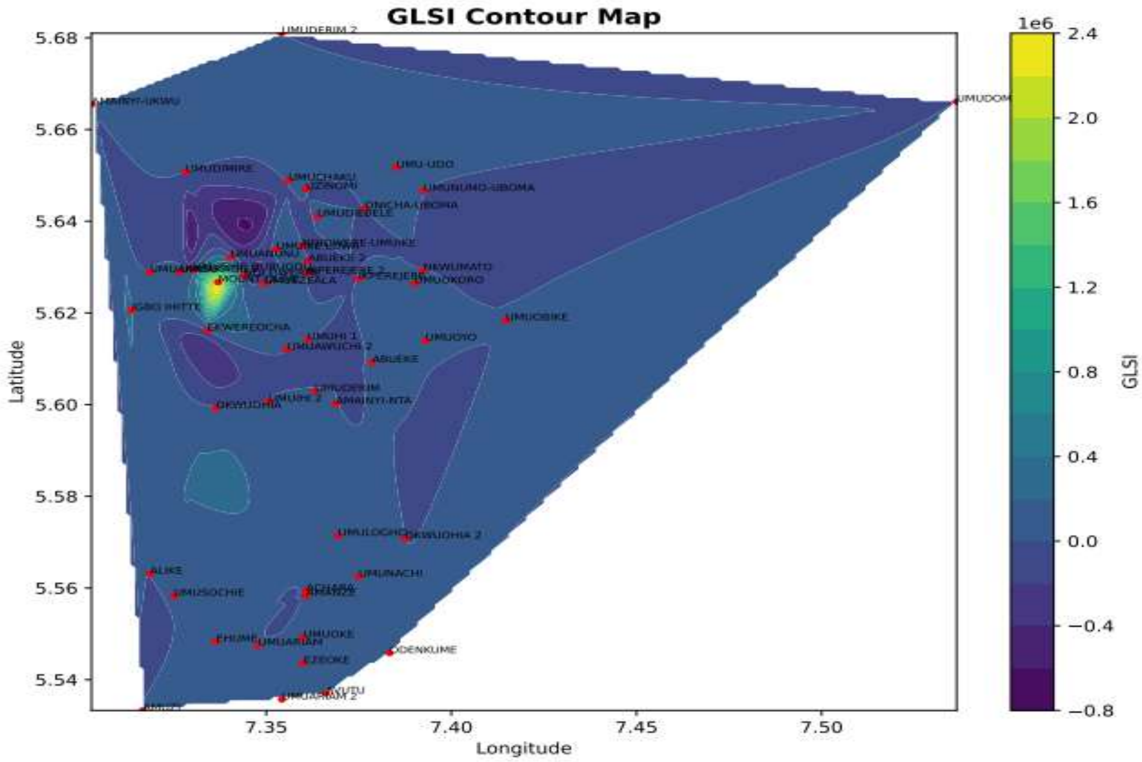
resistivity, making it easy for pollutants to infiltrate the subsurface and reach the aquifer. This means any contamination from surface sources such as chemical fertilizers, leaking sewage, or improperly managed waste can quickly find its way into the groundwater. Locations with high vulnerability include UMUOKE, AVUTU, UMUNACHI, UMUDIMIRE, EZEOKE, UMUHI 1, and UMUAWUCHI II. In these areas, special care must be taken when drilling boreholes or using groundwater for drinking or irrigation. Protective measures like proper casing, sealing, and regular water quality testing are essential. Human activities in these zones should be strictly regulated to avoid introducing harmful substances into the water system. It is important to note that no location in this dataset falls into the extreme vulnerability category, which would have meant the groundwater is highly exposed and virtually unprotected from contamination. This is a positive outcome, showing that with proper management and awareness, most of these areas can safely support groundwater usage for domestic and agricultural purposes.

The GLSI model measures how sensitive groundwater levels are to external stresses like extraction, land use changes, and recharge variability. High GLSI values in Figure 7 indicate that groundwater levels in those areas are highly responsive, and thus, more likely to be quickly affected by contamination or depletion. Regions such as UMUARIAM II**,** UMUDIMIRE, and AMUZI show higher GLSI values, suggesting that any pollution event or excessive withdrawal in these zones could rapidly impact the aquifer system. These areas require monitoring and sustainable groundwater management strategies to prevent long-term degradation.

Fig 7: Contour map of GLSI Index



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CONCLUSION

The integrated assessment of aquifer vulnerability using the GOD, GODL, and GLSI models across 50 locations in Okigwe South has revealed significant spatial variations in susceptibility to groundwater contamination. The GOD model classified areas such as EHUME, UMUOKE, and UMUDIMIRE as having high to extreme vulnerability due to shallow groundwater and limited protective cover, highlighting the urgent need for groundwater protection strategies in these zones. Moderate vulnerability levels were identified in places like OKWUOHIA and UMULOGHO, suggesting a moderate risk of contamination that requires regular monitoring. Conversely, several areas—including UMUARIAM, ALIKE, and UMUAKAGU—exhibited low to negligible vulnerability, implying stronger natural protection but still warranting basic preventive measures. The GODL model provided deeper insights by incorporating resistivity and longitudinal conductance, further differentiating the vulnerability potential of each site. It confirmed the elevated risk in areas like UMUAWUCHI II and UMUARIAM II, while also identifying low-risk zones such as IKPEREJERE II with more conductive, protective subsurface materials. The GODL model consistently produced higher vulnerability scores than GOD, emphasizing the impact of land use on aquifer health. Finally, the GLSI model reinforced these findings by classifying sites based on subsurface geoelectric parameters. While no location showed extreme vulnerability, several areas—including UMUOKE, EZEOKE, and UMUDIMIRE—were flagged as highly vulnerable, mainly due to thin or low-resistivity layers. Conversely, locations like ABUEKE II and ONICHA-UBOMA were identified as low-risk zones, suitable for sustainable groundwater development. Overall, the combined models offer a comprehensive framework for prioritizing groundwater protection and land-use regulation in the region.

Author Contributions

- **Jude M. Anyanwu**: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review and editing.
- **Daniel N. Obiora**: Methodology, Investigation, Resources, Project administration, Writing – review and editing.
- **Desmond O. Ugbor**: Investigation, Data curation, Validation, Resources, Writing – original draft.
- **Johnson C. Ibuot**: Software, Data curation, Resources, Formal analysis, Writing – original draft.
- **James O. Sampson**: Supervision, Conceptualization, Methodology, Validation, Writing – review and editing, Project administration.

Data Availability Statement

No new data were created in this study. The datasets supporting the results are not publicly available due to proprietary restrictions and sensitive information, but are available from the corresponding author upon reasonable request.

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Declaration of Competing Interest

The authors declare that they have no competing interests related to this work.

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