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Assessment of Intrinsic Aquifer Vulnerability Using GODTP Framework at Igbesa-Lusada, Southwestern Nigeria

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ABSTRACT
Groundwater serves as a critical source of potable water in many parts of Nigeria, yet increasing waste generation and inadequate disposal practices continue to threaten its quality. This study applies a modified GODT, which is GODTP vulnerability assessment framework to evaluate the susceptibility of aquifers to contamination in a rapidly urbanizing area – Igbesa-Lusada of southwestern Nigeria. The framework integrates five parameters: Groundwater occurrence (G), Overlying strata characteristics (O), Depth to water table (D), Topography (T), and Protective capacity (P) derived from longitudinal conductance. Hydrogeophysical data from vertical electrical soundings (VES), topographic (elevations), and geological mapping were used to compute the GODTP index and classify the terrain into vulnerability zones. The introduction of the "P" parameter, representing aquifer protective capacity, improved framework sensitivity by capturing the influence of clay-rich or lateritic layers that attenuate contaminant migration. The GODTP results for the Igbesa-Lusada Road (Dump Corridor) indicate high vulnerability, with ~70% of VES stations in both the high and moderate. Frequency analysis further confirms that about 68.57% of the area exhibits low protective capacity, while only 8.57% shows high protection. These findings demonstrate that dumpsite activities significantly increase aquifer vulnerability in the study area, provide a spatially explicit evaluation of aquifer susceptibility, offering a practical tool for groundwater management and land-use planning in the region and highlight the importance of monitoring and remediation planning in this critical zone.

Keywords:
Aquifer Vulnerability,
GODTP Framework,
Groundwater Contamination,
Protective Capacity,
VES.

INTRODUCTION
Rapid urban expansion and increasing waste generation have intensified concerns about groundwater degradation, particularly in areas with poorly developed waste management systems. Open dumpsites and inadequately engineered landfills allow precipitation to infiltrate waste layers, producing leachate enriched with organic compounds, heavy metals, nutrients, and microorganisms. The migration of this leachate through the soil is influenced by subsurface permeability, overlying layer thickness, and contaminant chemistry (Ayolabi *et al.,* 2020; Zghibi *et al.,* 2020; Islam *et al.*, 2021; Onyeagocha *et al*., 2023). These processes collectively determine aquifer susceptibility.

Groundwater is a vital freshwater resource, occupying pore spaces and fracture networks in sedimentary and unconsolidated formations, supporting domestic supply, agriculture, industry, and ecosystems (Adepelumi & Faleye, 2021; Omosuyi, 2021; Akinwumiju *et al.,* 2022; Olatinsu *et al.,* 2023). Climate variability and population growth have increased reliance on groundwater, highlighting its importance for sustainable water supply (Olusola & Awokola, 2020**;** Odekunle, 2021; Aderoju & Olatunji, 2023). Protecting groundwater quality is essential, as remediation is often costly and rarely restores original conditions (Baalousha, 2023).

Aquifer vulnerability is shaped by subsurface characteristics and human activities. Recharge patterns, aquifer geometry, land-use changes, excessive abstraction, and waste pollution alter groundwater quality (Zhang *et al.,* 2021). Understanding these interactions is critical for sustainable groundwater management.

This study applies a GODTP framework—Groundwater occurrence (G), Overlying strata (O), Depth to aquifer (D), Topography (T), and Protective capacity (P)—to assess intrinsic aquifer vulnerability. While the original GODT model is widely applied due to its simplicity and minimal data requirements (Zghibi *et al.,* 2020), the inclusion of the protective capacity (P) parameter enhances the representation of subsurface attenuation processes. In particular, P accounts for the filtering effect of clay-rich and lateritic overburden materials common in the sedimentary terrain of Southwestern Nigeria, using longitudinal conductance derived from VES data (Adepelumi & Faleye, 2021; Ogunyele *et al*., 2022). Longitudinal conductance derived from geoelectric parameters has been widely used to evaluate aquifer protective capacity in sedimentary environments (Adepelumi *et al*., 2011). This concept forms the basis for the protective capacity (P) component introduced in the GODTP vulnerability index.

Location and Geology of the Study Area

Igbesa is accessed via the Lagos–Badagry Expressway near Agbara. It lies between longitudes 3°04′–3°10′E and latitudes 6°31′–6°34′N, within Ado-Odo/Ota LGA of Ogun State. The study focuses on the Igbesa-Lusada corridor (3.10°–3.25°E; 6.52°–6.65°N), part of the eastern Dahomey Basin (Akinwumiju *et al*., 2022; Ogunyele *et al.,* 2022). The terrain is underlain by Coastal Plain Sands (Benin Formation), consisting of unconsolidated sands, clay, alluvium, and lateritic profiles (Figure 1) (Reyment, 1965).

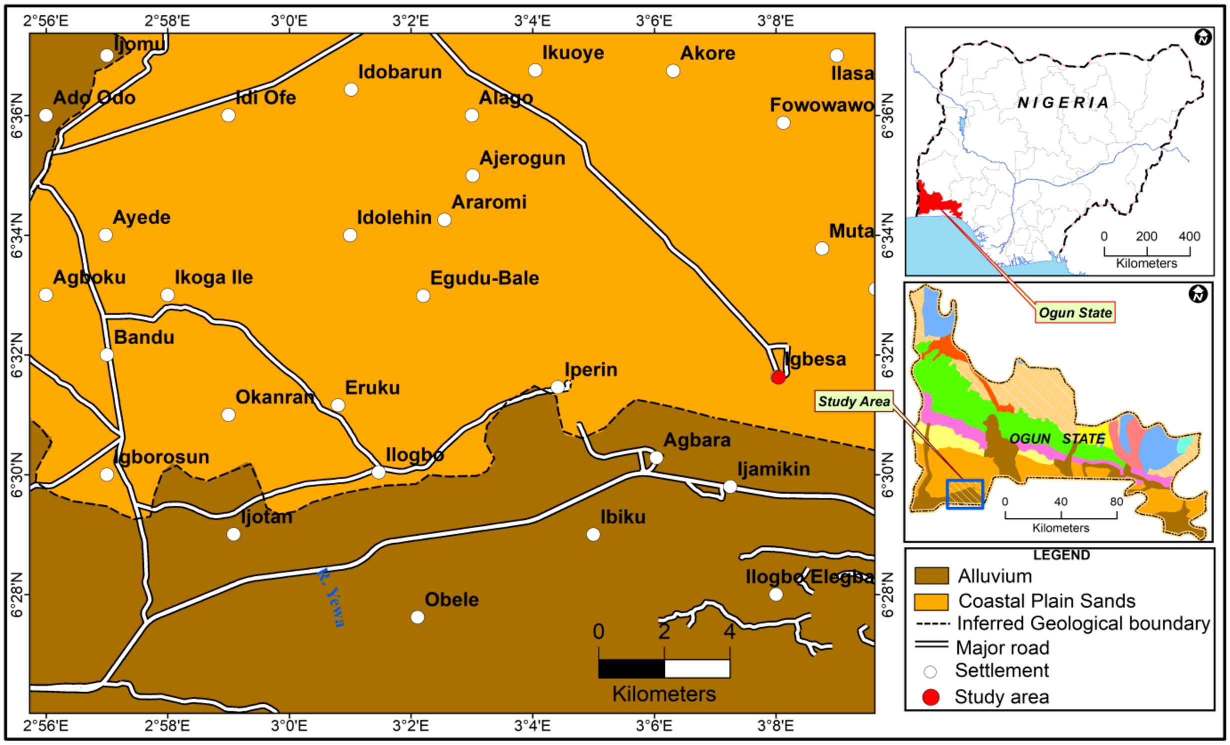

Figure 1: Geological Map of Ogun State Showing Igbesa (Adapted from NGSA, 2020; Sheet 68)

Groundwater occurs in these unconsolidated sands and weathered horizons, with water table depths ranging from 4–10 m in low-lying zones to over 20 m along elevated ridges (Adepelumi & Faleye, 2021; Omosuyi, 2021; Olatinsu *et al.,* 2023).

The corridor has a humid tropical climate, with bimodal rainfall (April–July, September–November) totaling 1,200–1,500 mm annually and temperatures of 26 – 32 °C (Olusola & Awokola, 2020; Odekunle, 2021; Aderoju & Olatunji, 2023). Surface drainage is poorly developed due to permeable sands, causing runoff to channel along roads and infiltrate shallow soils during rainfall (Aderoju & Olatunji, 2023).

The area is dominated by Coastal Plain Sands, with fine-to-medium sands, sandy clays, and discontinuous laterite horizons (Ogunyele *et al.,* 2022). These sediments have moderate-to-high permeability. Groundwater occurs in shallow unconfined aquifers, typically 8–25 m deep (Adepelumi & Faleye, 2021; Omosuyi, 2021; Olatinsu *et al.,* 2023). Thin clay layers increase vulnerability to leachate infiltration (Zhang *et al.,* 2021; Onyeagocha *et al.,* 2023).

Land use is mixed residential–commercial–industrial. Poor formal waste management has led to numerous roadside dumpsites containing household, industrial, and medical wastes (Ayolabi *et al.,* 2020; Adegbola & Akinbile, 2021; Onyeagocha *et al.,* 2023). The Igbesa–Lusada corridor is environmentally sensitive, with shallow aquifers, high rainfall, and unregulated waste disposal magnifying vulnerability (Adepelumi & Faleye, 2021; Omosuyi, 2021; Zhang *et al.,* 2021; Olatinsu *et al.,* 2023). This context is suitable for applying GODTP to evaluate aquifer vulnerability and guide sustainable groundwater management.

MATERIALS AND METHODS

Geophysical data for this study were obtained through Vertical Electrical Sounding (VES) conducted across the Igbesa–Lusada corridor. A total of thirty-five (35) VES stations were established within the study area (Figure 2), with closer station spacing around active and legacy dumpsite to adequately capture subsurface variations associated with waste infiltration. Measurements were carried out using the Schlumberger electrode configuration, with current electrode spacing (AB/2) extended to a maximum of 65 m. A digital resistivity meter (OHMEGA resistivity meter) was used to inject electrical current into the subsurface and record the resulting potential differences.

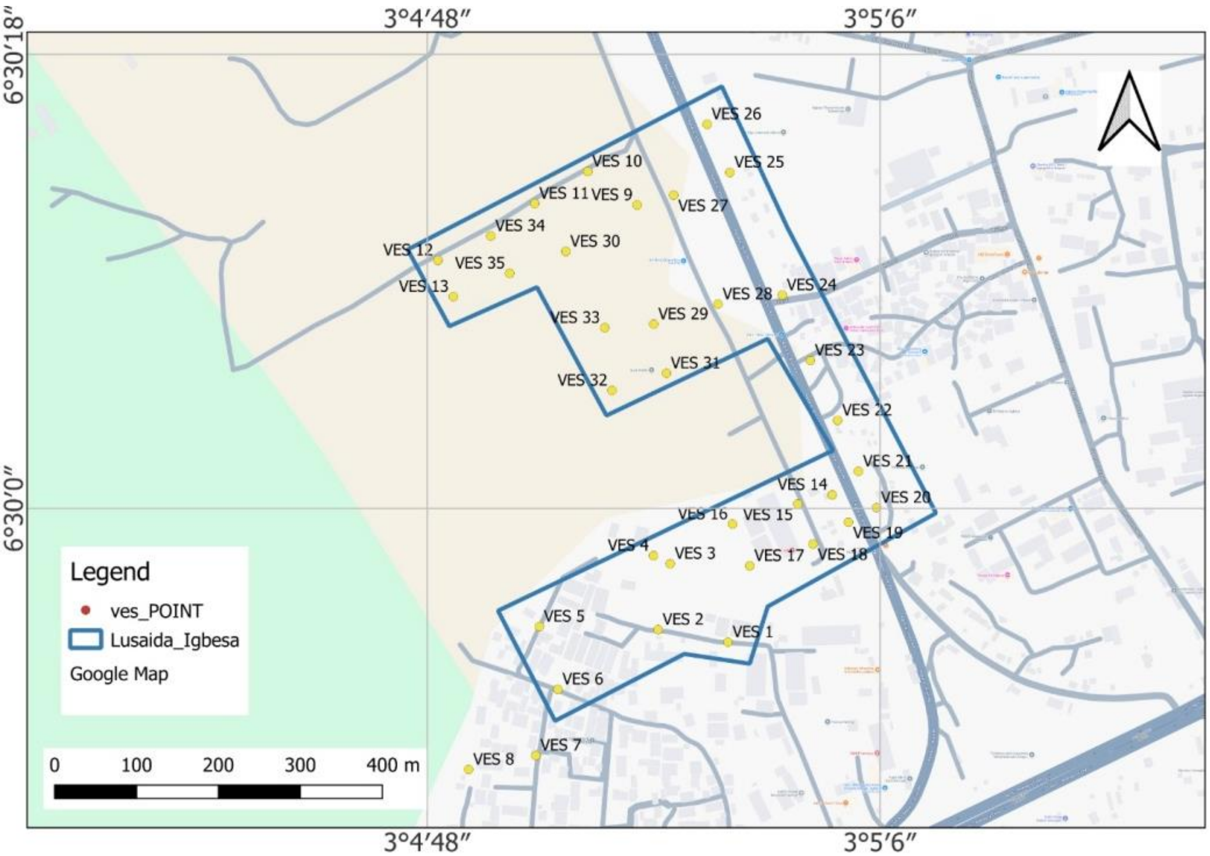

Figure 2: Map Showing the VES Station Distribution along the Dump Corridor in IGBESA-LUSADA Road

The acquired VES data were processed and interpreted using IPI2Win and WinResist software. Interpretation results provided essential geoelectric parameters, including layer resistivity, layer thickness, depth to aquifer, and longitudinal conductance (S). Longitudinal conductance was computed from the resistivity and thickness of the subsurface layers and was used as an indicator of the overburden's ability to attenuate contaminant migration. These parameters constituted the primary inputs for the groundwater vulnerability assessment.

Intrinsic aquifer vulnerability was evaluated using a modified GODT that is GODTP framework, which incorporates Groundwater occurrence (G), Overlying strata (O), Depth to aquifer (D), Topography (T), and Protective capacity (P). The groundwater occurrence parameter characterizes the nature of the saturated zone as unconfined, semi-confined, or confined. Overlying strata describe the lithological materials above the water table, where sandy and highly porous formations are assigned higher vulnerability scores, while clay-rich or lateritic materials reduce vulnerability. Depth to aquifer was derived directly from VES interpretation, with shallower depths indicating higher vulnerability due to increased susceptibility to contaminant infiltration. Topography, expressed in terms of elevation, was used to evaluate the influence of surface runoff and infiltration on groundwater recharge.

The protective capacity (P), introduced in this study, represents the natural filtering ability of the overburden materials. This parameter was quantified using longitudinal conductance (S) computed from the resistivity and thickness of subsurface layers obtained from VES interpretation (Equation 1), with higher conductance values indicating better aquifer protection. The integration of all GODTP parameters enabled a comprehensive assessment of intrinsic aquifer vulnerability within the sedimentary terrain of the study area.

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

Where: S = longitudinal conductance denoted as protective capacity "P", h_i = valid layers thicknesses and ρ_i = valid layers resistivities.

All computations were performed in ArcGIS/QGIS using raster overlay.

The aquifer vulnerability assessment employed a modified GODTP framework, an extension of the traditional GOD and GODT methods. The model integrates five parameters to generate a composite vulnerability index:

Each parameter was assigned a weight (1–6) following standard GODTP scoring guidelines, adjusted for local hydrogeological conditions. The composite vulnerability index (VI) was computed as:

$$GODTP = G_r G_w \ x \ O_r O_w \ x \ D_r D_w \ x \ T_r T_w \ x \ P_r P_w \quad (2)$$

Where: G = Groundwater Hydraulic Confinement, O = Aquifer Overlying Lithology, D = Depth to the aquifer, T = Topography (elevations), and P = Protective capacity.

Values from GODTP vulnerability evaluation**s** were classified into vulnerability zones—low, moderate, and high.

RESULTS AND DISCUSSION

Interpretation of the Vertical Electrical Sounding (VES) data along the Igbesa–Lusada Road dump corridor revealed characteristic Schlumberger curve types dominated by Q, H, and K forms (Figure 3). These curve types indicate alternating resistive and conductive subsurface layers, which are typical of sedimentary environments and reflect heterogeneous lithological conditions that influence groundwater occurrence and vulnerability.

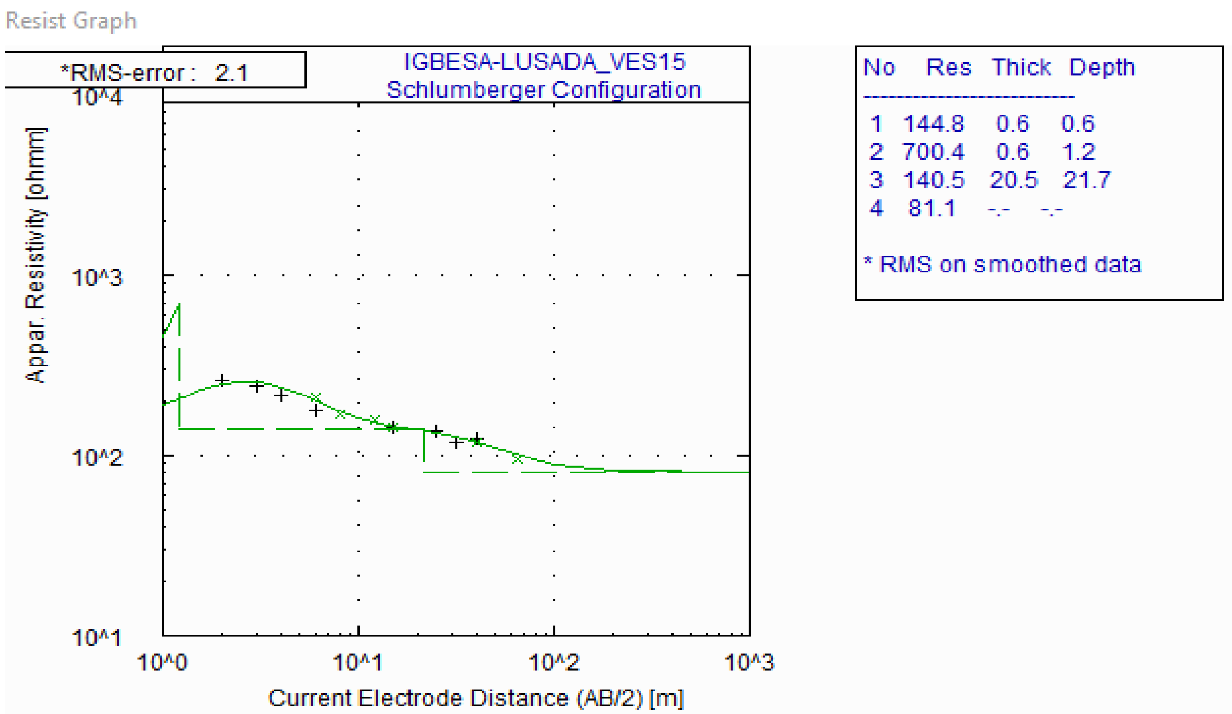

Figure 3: Typical VES Curve - Dump Corridor VES 15

Geoelectric sections generated from representative VES points (VES 3, 10, 17, 23, and 31) along a north–south profile show relatively thin clayey overburden materials underlain by sandy and gravelly units (Figure 4). This lithological arrangement suggests limited natural protection of the aquifer system, particularly in areas where clay layers are discontinuous or thin. The inferred lithological sequence consists of topsoil and clayey sand overlying silty clay and sandy clay units, with deeper gravelly and water-bearing sand layers (Figure 5). Aquifers occur at depths ranging from approximately 1.03 to 23.8 m, although their continuity is affected by the heterogeneous nature of the subsurface. Reflection coefficients (–0.72 to +0.83) and moderate-to-high anisotropy values indicate strong resistivity contrasts and uneven groundwater flow paths, conditions that enhance vulnerability to contaminant migration. Although shallow clay layers provide partial protection, the low-lying topography and absence of thick confining beds increase the susceptibility of the aquifer to leachate infiltration from dumpsite activities.

Groundwater vulnerability was further evaluated using the modified GODTP framework. The groundwater occurrence (G) parameter indicates that aquifers within the dump corridor are predominantly confined to semi-confined (Figure 6), likely resulting from sediment compaction and anthropogenic surface loading. However, the integrity of this confinement is potentially compromised by continuous leachate infiltration. The overlying lithology (O) is dominated by sandy clay, clayey sand, and compacted sands (Figure 7), suggesting moderate to high infiltration risk. Depth to water table (D) values range from approximately 6 to 18 m below ground surface (Figure 8), with shallower depths observed toward the eastern and southern parts of the corridor, thereby increasing vulnerability in these zones. Topographic analysis shows elevations between 4.56 and 20.26 m (Figure 9), where lower elevations favor infiltration over runoff.

The protective capacity (P), derived from longitudinal conductance values (Σh/ρ), reveals predominantly low protective capacity across the dump corridor (Figure 10). Areas with conductance values below 0.1 mhos are indicative of poor natural filtration, typically associated with coarse-grained or sandy overburden materials, whereas higher conductance values reflect better aquifer protection due to clay-rich layers.

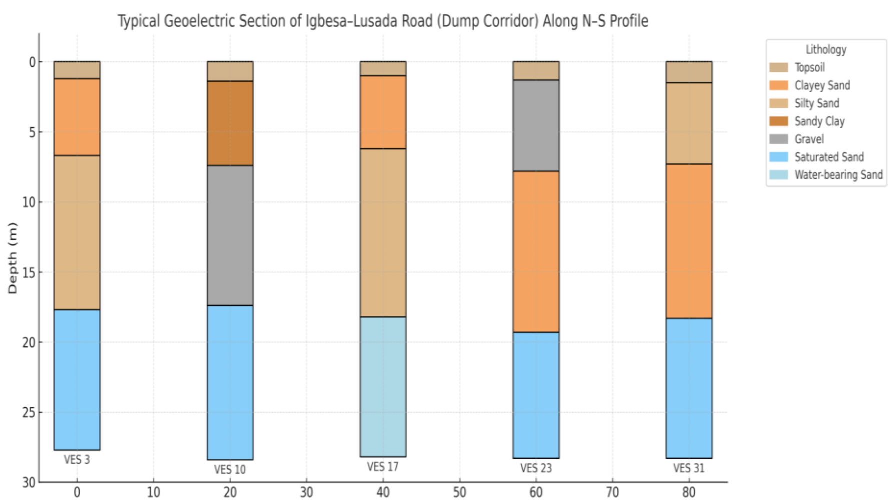

Figure 4: Typical Geoelectric Section of Igbesa-Lusada Road (Dump Corridor) along N–S Profile

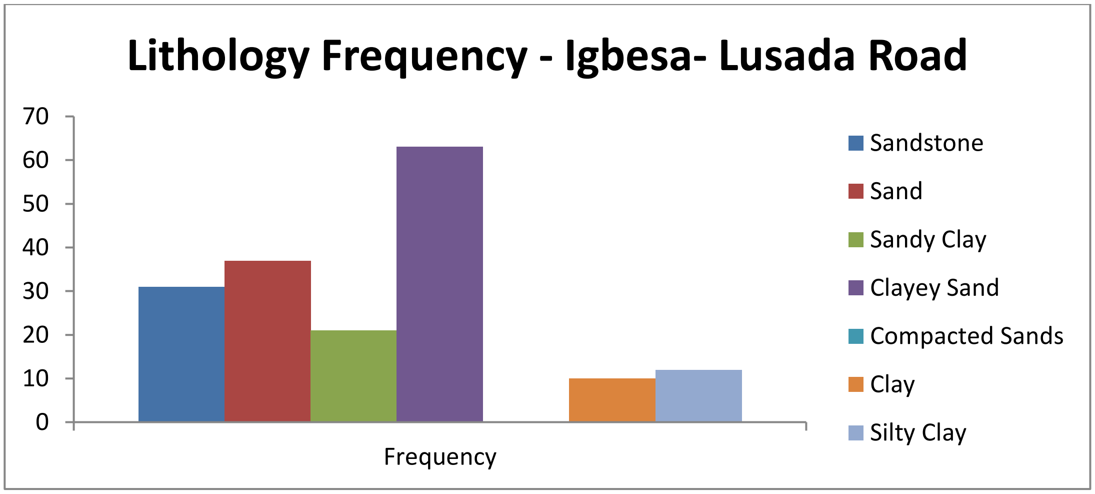

Figure 5: Lithology Frequency – IGBESA-LUSADA ROAD (Dump Corridor)

Figure 6: Groundwater Occurrence– Igbesa-Lusada Road

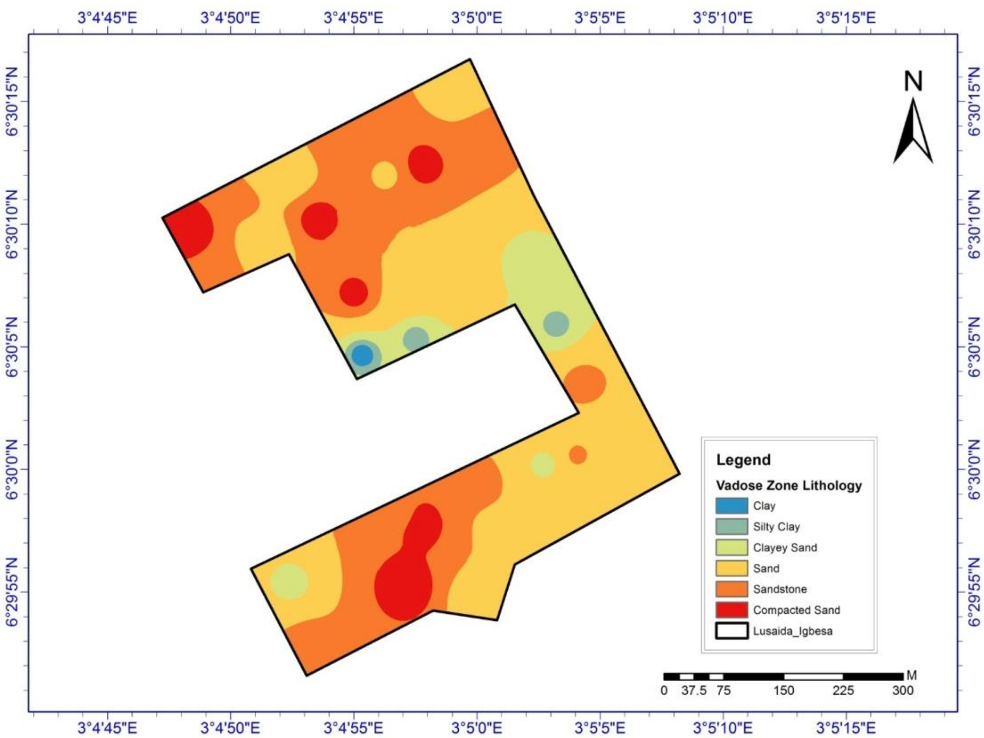

Figure 7: Overlying Lithology/ Vadose Zone Map– Igbesa-Lusada Road

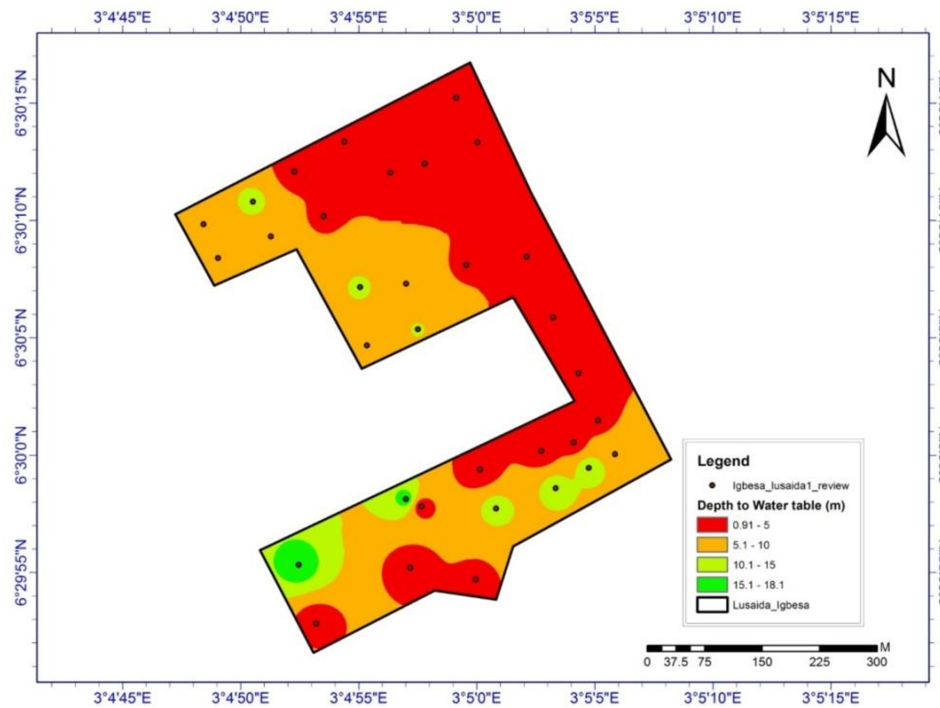

Figure 8: Depth to Water Table Map – Igbesa-Lusada Road

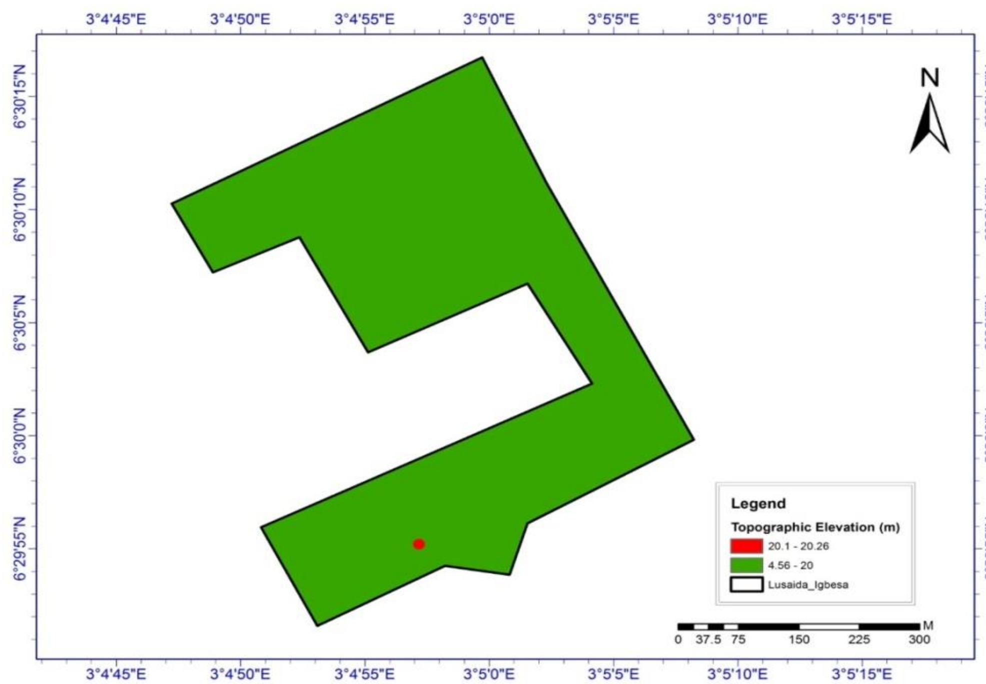

Figure 9: Topography Map– Igbesa-Lusada Road

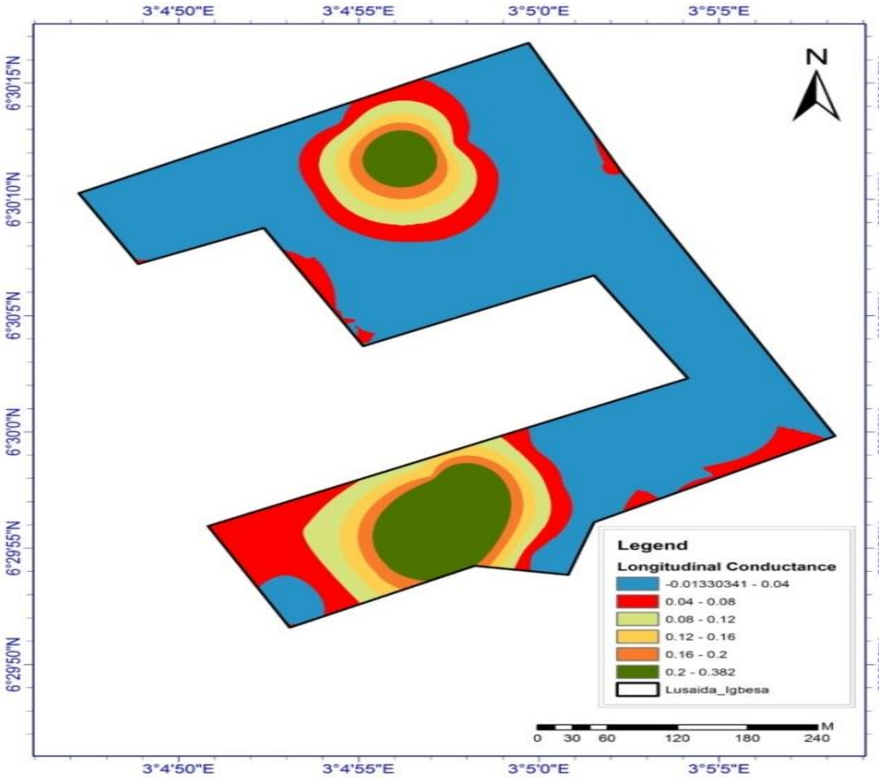

Figure 10: Longitudinal Conductance (P) – Igbesa-Lusada Road

The table of results (Tables 1a & 1b) for GODTP reveals the values interpreted and characterization from the survey. Each parameter was assigned a rating (on a scale of 1 to 5) based on its characteristics, and a weight (ranging from 1 to 6) reflecting its relative importance to vulnerability from the study.

Table 1a: Parameter Characterization for GODTP Framework

Parameter	Range	Rating	Weight
Groundwater Occurrence [G]	0.25 - 0.35 (Confined)	1	
	0.35 - 0.85 Semi-Confined	2	
	0.85 - 1.00 (Unconfined)	3	3(15%)
Overlying Lithology [O]	Sandy Clay	1	
	Clayey Sand	2	
	Sand	5	5(25%)
	Sandstone	4	
	Compacted Sands	3	
Depth to water table [D]	<5.0	5	
	5.1 – 10.0	4	
	10.1 – 15.0	3	5(25%)
	15.1 – 20.0	2	
	>20.0	1	
Topography (%) [T]	< 20.0	5	
	20.1 – 40.0	4	
	40.1 – 60.0	3	1(5%)
	60.1–80.0	2	
	>80.0	1	
Longitudinal Conductance [S]	0.002 – 0.04	5	
Or Protective Capacity [P]	0.041– 0.08	4	
	0.081– 0.12	3	6(30%)
	0.121– 0.16	2	
	0.161– 0.20	1	

Table 1b: The Mapped Aquifer Types Characterization in Igbesa-Lusada Road

S/N	Aquifer Overlying Resistivity (Ωm)	Groundwater Hydraulic Confinement	Symbol
1	<750	Unconfined	U
2	≥232 or <750	Semi-Confined	SC
3	<232 or ≥1200	Confined	C
4	0	Non-Aquifer	NN

Integration of all GODTP parameters produced the aquifer vulnerability map (Figure 11) for the Igbesa–Lusada Road dump corridor. The results indicate that approximately 70% of the area falls within the high to very high vulnerability classes, largely due to shallow water tables, permeable overburden materials, low protective capacity, and sustained anthropogenic pressure.

This advanced; GODTP framework provides a comprehensive groundwater vulnerability profile for the Igbesa–Lusada Road corridor. The dumpsite corridor is characterized by low longitudinal conductance ($S < 0.3$ S) and a shallow sandy overburden thickness ($h < 10$ m), indicating poor natural filtration capacity and high susceptibility of the underlying aquifer to contamination.

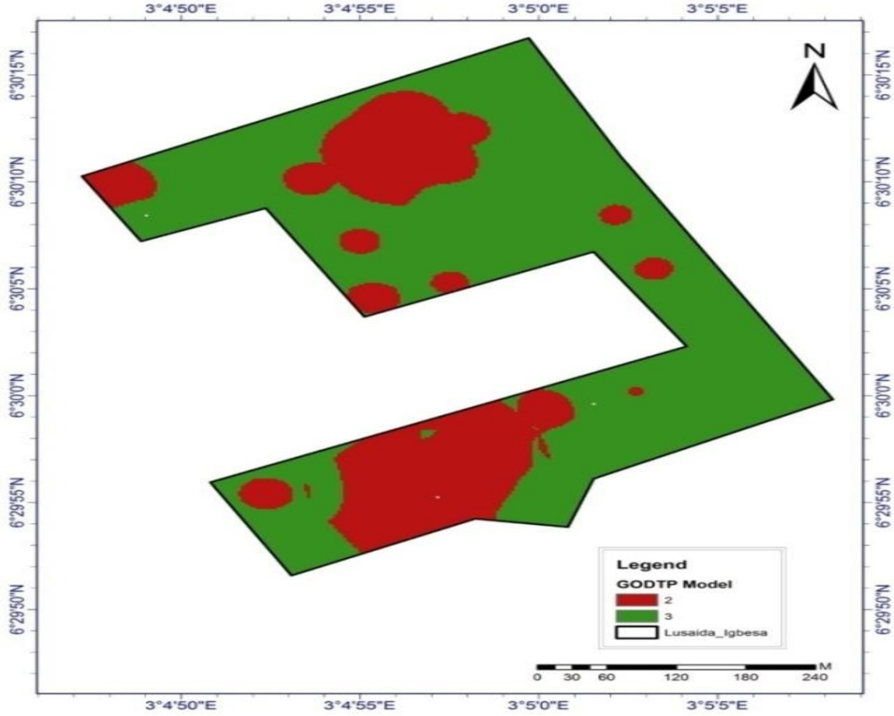

Figure 11: GODTP Parameters – Igbesa-Lusada Road

Table 2 presents the classification of GODTP values obtained in this study.

Table 2: Classification of GODTP Values from the Study

Class Range	Assigned Value	Classification	Remarks
0 – 4	3	High Vulnerability	Low Protection
4 – 13	2	Moderate	Moderate Protection
>13	1	Low Vulnerability	High Protection

The GODTP results for the Igbesa–Lusada Road dump corridor indicate generally high vulnerability, with approximately 70% of the VES stations classified within the moderate to high vulnerability categories. Frequency analysis further shows that about 68.57% of the area exhibits low protective capacity, while only 8.57% is characterized by high protection (Table 3). These results reflect the combined effects of shallow groundwater conditions, thin sandy overburden, and limited natural filtration capacity within the study area.

Table 3: GODTP Frequency (Protective Capacity)

Classification	Igbesa/Lusada Rd Dump	Percentage (%)
High Protection	3	8.57%
Moderate Protection	8	22.86%
Low Protection	24	68.57%

The GODTP framework employed in this study is an intrinsic vulnerability assessment approach rather than a predictive groundwater quality model. Parameter weights were assigned based on established vulnerability assessment schemes and adapted to reflect the hydrogeological characteristics of the sedimentary terrain. As with other index-based frameworks, uncertainty arises from data resolution, parameter generalisation, and the subjective nature of weighting. Consequently, the results should be interpreted as relative vulnerability patterns rather than absolute predictions of groundwater contamination.

Validation of the GODTP results was achieved through comparison with established groundwater vulnerability models, including DRASTIC, GOD, and GODT, all of which similarly identified the dump corridor as a zone of high to extreme vulnerability. While these models captured general vulnerability patterns, the GODTP framework provided improved discrimination by explicitly incorporating protective capacity, thereby quantifying the weak natural attenuation potential of the aquifer system. Independent support for the GODTP results is further provided by available physicochemical characteristics of groundwater within the study area, where surface and shallow groundwater samples exhibit elevated electrical conductivity and total dissolved solids, strongly alkaline stream water (pH ≈ 10.1), and moderately acidic borehole water. These hydrochemical indicators suggest limited natural attenuation and progressive contamination with proximity to surface waste sources, consistent with the vulnerability patterns delineated by the GODTP framework.

The high vulnerability observed within the dump corridor demonstrates that dumpsite activities significantly exacerbate aquifer susceptibility in the area. The transitional geological setting, characterized by poor-to-moderate protective cover, further amplifies the risk of contaminant migration into groundwater systems. These findings underscore the importance of continuous groundwater monitoring and proactive remediation planning within this environmentally sensitive zone.

CONCLUSION

This study applied a modified GODT, that is, GODTP framework to evaluate intrinsic aquifer vulnerability along the Igbesa–Lusada Road dump corridor. The results confirm the presence of extensive high-vulnerability zones and further demonstrate that a large proportion of the area is characterized by weak protective capacity, thereby increasing susceptibility to groundwater contamination.

By integrating protective capacity derived from geoelectric parameters into the conventional GODT approach, the GODTP framework provided a more realistic representation of subsurface conditions and contaminant attenuation potential. This enhancement improved vulnerability differentiation and strengthened the linkage between lithology, hydrostratigraphy, and land-use impacts in the sedimentary terrain.

Overall, the integration of VES data with the GODTP framework enabled a robust evaluation of dumpsite impacts on aquifer vulnerability in the study area. The findings highlight the need for protective zoning, effective environmental regulation, and continuous groundwater monitoring within the Igbesa–Lusada Road dump corridor. The GODTP model is therefore recommended as a reliable decision-support tool for groundwater protection in sedimentary environments experiencing intense anthropogenic pressure.

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