

Integrating Geophysical and Hydrogeologic Layer Susceptibility Indexing for Aquifer Vulnerability Evaluation at Ilere Locality, Akure-Ijare Road, Southwestern Nigeria

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Abstract

Groundwater vulnerability assessment was carried out in the Ilere community on the Akure-Ijare road in Nigeria, aimed at classifying the area into zones of vulnerability. A total of fifty-nine Vertical Electrical Soundings (VES) were obtained by using the Schlumberger array with a maximum half current electrode spacing (AB/2) of 100m. The layer resistivity and thickness (geoelectric properties) of the covering strata were interpreted to characterize the subsurface conditions. Four geoelectric unit layers were identified: topsoil, lateritic layer, weathered/fractured basement and fresh basement. Aquifer vulnerability was analyzed in three models, namely GOD (Groundwater occurrence, Overlying lithology, and Depth to water table), longitudinal conductance, and Geo-electric Layer Susceptibility Index (GLSI). The results show that the overburden has a poor to moderate protective capacity in general, largely as a result of thin topsoil (0.2-5.2m) and variable resistivity values (25.6-1225.5ohm-m). The longitudinal conductance model showed poor to weak protective classes and thus has low attenuation capability against the infiltration of contaminants. The GOD and GLSI models consistently resolve into very low, low, and moderate vulnerability areas, with low vulnerability being dominant. However, moderate vulnerability zones are more noticeable in the Southern region. The combination of several geoelectric models offers a reliable basis for groundwater vulnerability mapping for basement terrains. The findings indicate the need to be careful of the site of potential sources of contamination, such as septic systems and waste disposal facilities, away from vulnerable zones in order to ensure sustainable development of groundwater.

Keywords: Aquifer Vulnerability, Geoelectric Parameters, Basement Complex Terrain, GOD Model, Electrical Resistivity Method, Southwestern Nigeria.

Introduction

Groundwater vulnerability assessment importance is critical for determining the vulnerability of the aquifers to contamination and to ensure sustainable water resource management, water may be found in large or small amounts in living organisms or in non-

living materials which were chemically or genetically assembled. One of the universal necessities of life is groundwater, and the abundance of its search worldwide is a result of its variable amounts in various locations. The search for groundwater has increased worldwide since it is often regarded as the best source of potable and safe water for drinking, agriculture, and industry (Hoque et al., 2009; Enabulele et al., 2024). Several technologies, including geophysics, remote sensing, and geographic information systems (GIS), have been used to accurately locate this valuable resource beneath the subsurface. However, without adequate protection from dangerous contaminants that can deteriorate its quality and make it unfit for consumption by humans, this resource's location is insufficient (Adeyemo et al., 2023). Groundwater development plans that deal with improper pesticide usage and disposal, leaching from septic tanks, waste dumps, petroleum tanks, and pollutants that seep into the subsurface and contaminate groundwater after a considerable amount of time have been abandoned (Ossai et al., 2020). In places without an adequate waste management system, groundwater contamination is inevitable, particularly if a well or borehole is located a short distance from a refuse dumpsite. Additionally, rudimentary methods of disposing of waste are frequently used in impoverished and emerging communities. This trash gradually breaks down and seeps into the earth, poisoning the local groundwater. Additionally, because the underlying earth functions as a selective filter, fluid motions in the subsurface are influenced by porosity and permeability, which can either support or prevent aquifer pollution. The susceptibility of an aquifer to contamination from the earth's surface or subsurface is known as aquifer vulnerability. In groundwater exploration, preventing aquifer contamination is crucial since basement complex regions tend to have shallow water table depths. Groundwater vulnerability to pollution has been the focus of extensive research in recent years, with a range of index approaches created to quantify aquifer vulnerability to contamination. Understanding especially vulnerable zones is one strategy assisting in preventing groundwater pollution. Policymakers can implement successful management techniques for minimizing groundwater pollution, such as altering land use activities according to the risk for groundwater pollution, to guide the allocation and concentration of resources to areas where maximum amounts of exertion are required, and to increase public awareness of the risk for groundwater contamination by using the assessment of aquifer vulnerability (Focazio et al., 2003; National Research Council, 1993). The majority of vulnerability assessment methodologies GOD (Foster, 1987), DRASTIC (Aller et al., 1987), are mostly hydrogeologic in nature and subjective, although a few electromagnetic metrics, such as terrain conductivity and longitudinal conductance, use a geophysical approach to measurement. The hydraulic conductivity and thickness of the layers covering the aquifer are the basis for some of the techniques (McLay et al., 2001; Herbst et al., 2005), while the geoelectric parameters of the geoelectric layers are the basis for others. Longitudinal conductance is a well-known geoelectric approach that measures the vulnerability or susceptibility of the geoelectric layers. Since laterites are known to be

effective protective barriers for the underlying aquifers, other comparative approaches like GLSI and GOD must be used in the vulnerability assessment. However, the method is prone to the possibility of very resistant deposits, such as laterites, and its results are defined by a similar criterion (Oni et al., 2017). The GLSI is a recently developed method designed to address the GOD approach's overemphasis on the impact of geomaterials and its inherent shortcoming of being insensitive to the potential existence of lateritic deposits in longitudinal conductance. By giving the parameters (layer thicknesses and layer resistivity values) index scores, GLSI accords equal weight to the thickness of the vadoze zone and the significance of geomaterials in aquifer protection studies. The GLSI and GOD are index-based parametric techniques; each parameter shows an extensive number associated with its property, categorized into definable and structured zones with particular values that represent their degree of environmental vulnerability (Gogu et al., 2000).

Theoretical Framework

The principles used for assessing the groundwater vulnerability in data-limited basement complex terrains rely fundamentally on the combined interpretation of geophysical theory and the principles of hydrogeology (fluid flow and transport in subsurface). The present study is based on the theoretical assumption that the hydrogeologic parameters that control the ability of contaminant to move through subsurface can be quantitatively correlated with the geophysical (geoelectric) parameters obtained from resistivity survey; which are porous, permeability, hydraulic conductivity, and fluid saturation (George, 2021). Resistivity values vary with changes in lithology and fluid content hence enabling the identification of layers having variable hydraulic properties. The obtained geoelectric parameters are usually transformed to the Dar-Zarrouk parameters (i.e. Longitudinal conductance and transverse resistance) and are taken as a theoretical justification for estimating aquifer protective capacity and hydraulic conductivity values. Low conductive zones indicate fine-grained or porous/fractured rocks and thus higher permeability whereas highly conductive zones indicate fine materials like clay. Highly conductive layers have high longitudinal conductance, but are usually composed of clay materials which are less permeable and act as barriers against contaminant percolation into the subsurface (low hydraulic conductivity). Low conductance corresponds to permeable rocks like sand, fractures which have high permeability and hence high vulnerability to contamination (Oladapo et al., 2004).

The conceptual approach of relating the resistivity to aquifer vulnerability provides the basis for the application of GOD, GLSI and longitudinal conductance models. The GOD model relies on basic hydrogeology in relation to occurrence of groundwater, lithology and depth to water table thereby indirectly taking the cover thickness and material to account; while GLSI model relies directly on geoelectric layer properties to estimate its susceptibility to infiltration and groundwater pollution. The longitudinal conductance derived from Dar-Zarrouk parameters gives quantitative estimation for the protecting capacity of the

subsurface layers against vertical contaminant transport in the overburden and it is an index of the resistance to contaminant movement toward the groundwater (Abdulmalik et al., 2025).

Protective Capacity Theory: Longitudinal Conductance

The protective capacity concept, where the capacity of overburden materials to counteract contaminants is a function of increasing thickness and a function of decreasing resistivity is the concept for the longitudinal conductance S . According to empirical data, a sandy or resistive layer results in a low conductance and an inefficient protection of the aquifer and a clay-rich, conductive layer results in a high conductance and an efficient protection (Olumurewa et al., 2017). Longitudinal conductance represents a direct geophysical model of the vulnerability of aquifer, which is consistent with the contamination migration theory that contaminant migration is controlled by the vertical resistance to flow (Musa et al., 2023).

Hydrogeological Index Theory: GOD Model

The GOD model is established on the basis of the basic vulnerability theory that the risk of contamination is affected by the following factors: depth to groundwater, overlying lithology, and confinement of aquifer. Recent studies have shown that the model correctly models first-order controls on contaminant transport particularly on the importance of the vadose zone thickness and permeability (Akingboye et al., 2025). In theory, deep, confined aquifers having protective layers lead to low vulnerability whereas, shallow, unconfined aquifers having permeable overburden lead to high vulnerability. GOD is a rational hydrogeological model of processes of vulnerability (Anyanwu et al., 2025).

Layer-Based Susceptibility Theory: GLSI

By introducing layer-specific geoelectric nature, the Geoelectric Layer Susceptibility Index (GLSI) is a way of extending vulnerability theory further and creating a more detailed representation of vertical heterogeneity. According to recent studies, GLSI is an improvement in finding vulnerable zones through the combination of resistivity and thickness of the vadose zone to determine the susceptibility of contamination as well as being sensitive to the change in the properties of individual layers (Anyanwu et al., 2025; Falowo et al., 2023). The basis of the model is the transport of contaminant is not one averaged parameter but is rather an overall functional of stratified media (Akingboye et al., 2025).

Literature Review

Recent Literature (George et al., 2021; Udosen et al., 2024; Olumurewa et al., 2025) broadly categorizes aquifer vulnerability techniques into 3 categories namely: hydrogeological index models (such as GOD representing intrinsic vulnerability),

geophysical/hydrogeophysical models (e.g. Longitudinal conductance and GLSI, representing layer resolved vulnerability) and integrated approaches combining the two aforementioned categories. These categories could be integrated into a multi-scale conceptual system whereby geophysics gives a quantitative view of the subsurface structure while hydrogeology allows for process-based interpretation and integration provides a reliable predictive tool across different types of datasets.

Theoretical basis of the geoelectric assessment of aquifer vulnerability

It is possible to determine the subsurface resistivity, layer thickness and lithology variations through geoelectric techniques such as Vertical Electrical Sounding (VES). It can be reasonably inferred that porosity, permeability and protecting capacity of overburden material is related to the subsurface resistivity, thickness of various geological strata and lithological variations. For basement terrains in which aquifer bodies are limited to the weathered and fractured portions these properties are most significant in mapping contaminant pathways (Hoque et al., 2009; McLay et al., 2001). It can be concluded from the studies reviewed that the resistivity and thickness of the regolith are critically important in any vulnerability assessment, Igboama et al., (2025) highlights the protective capabilities of clayey and resistivity layers because the longitudinal conductance will increase as a result. This will create a protected aquifer if there is a low-resistivity clay layer present, otherwise it suggests a vulnerable aquifer as a result of presence of resistive fractures or sandy layers. Moreover Ewumi (2025) notes that the layer is important as its thickness affects the movement of contamination across the basement complex layers; thin layer would increase vulnerability if it is overlying fractures. Methodologically there is a similarity in all these studies regarding the need for VES derived data however there is a difference in analysis. Some methods are based on simple thresholds whereas others are integrated using index such as Longitudinal Conductance in order to quantify the protective capacity of overburden layers. Threshold-based techniques could be insensitive to some transitional features as compared to integrated index techniques that directly take into account more attributes.

Evolution of Index-Based Vulnerability Model

Index-based models have proven to be popular due to their simplicity and the ease of application in data scarce environments. The GOD model which assesses vulnerability based on aquifer confinement, nature of overlying layers and depth to groundwater seems to be applicable for regional vulnerability assessment in basement complex terrains (Olumuyiwa et al., 2017; Okolo et al., 2024). There have been certain limitations for pure hydrogeological based indices regarding vertical variability in subsurface which had led to inclusion of geophysical methods in order to better represent subsurface protective capacity and consequently leading to generation of geophysical based index such as the GLSI (Akingboye et al., 2025). These models assess vertical vulnerability based on

geoelectrically derived resistivity and thickness of geological strata. The difference between these two types of models can be summarized as follows; The GOD method relies on a conceptual and weighted parameters approach while the GLSI relies on a directly measurable and quantitatively derived process. Hybrid indices exist, such as AHP-GODT (Olatunji et al., 2021) which uses multi-criteria decision analysis for the weighting of parameters and it leads to enhanced consistency in classification as compared to purely hydrogeological based methods in thick clay overburden and yet increases uncertainty associated with weighting schemes.

Comparative Study of GOD And GLSI For Basement Complex Terrains

It has become common place to apply and compare GOD and GLSI models especially for basement complex terrains as is prevalent in many regions in sub-Saharan Africa. Applications in Ondo State show that GOD classifies largely low or insignificant levels of vulnerability while GLSI is more prone to indicate large areas with medium to high vulnerability since it is more responsive to resistivity variations (Akingboye et al., 2025). The reason for such differences in application of GOD and GLSI models are rooted in the two different analysis; the GOD analysis depends on parameters that are closely related to aquifer confinements and aquifer depth while the GLSI analysis is sensitive to geophysical variations of resistivity which in itself represent more local sensitive parameterization of features (Owoyemi et al., 2023). For Nsukka basin (Ibuot et al., 2025) studies shows that the two methods largely agree on low to medium level vulnerability assessment though differs in classification zones. This is in contrast with studies carried out by showing that geophysical parameters are better in indicating the vertical variations in what looks to be otherwise hydrologically homogenous geological layers (Ankeli et al., 2026) In basement complex terrains GOD is a robust model to parameter variation while GLSI appears to be sensitive to parameters that define its framework. This is an advantage and also a disadvantage depending on how one interprets it.

Statement of Problem

The provision of water in the southwestern Nigerian town of Ilere is from the groundwater along the Akure-Ijare road. Ground water is however susceptible to contamination through poor land-use planning, rapid population increase and poor waste management system. Pollution by seepage from soak away pits, latrines and septic tanks, leachate from open dumpsites, surface water which transports surface pollutants such as, rain water carrying fertilizers and pesticides from farmlands, other surface pollutants and the seepage from sewage into the shallow aquifer contaminate the groundwater. They endanger health and the quality of water, introduce hazard components into the ground. It is also observable that Ilere has some problems concerning ground water aquifer susceptibility to contamination; shallow groundwater within Precambrian basement complex, with a thin overburden and weathered fractured zone on topsoil is generally lateritic. Geological

structures provide little or no natural protection from intrusion of contaminants. The presence of poor longitudinal conductance values, a thin aquifer and short time windows at the investigation depth is attributed to a Poor protective capacity and vulnerability to contamination, based on previously undertaken geophysical works and bore data on similar terrain in the region. Also the unpredictability of safe zones in groundwater is due to the spatial variations of subsurface strata.

Against these concerns, present assessment of groundwater hazard in the region is limited to a very few or uses single method approaching, without integrating geophysical and hydrogeological aspects. Existing models (resistivity interpretation or standard index methods) do not consider the detailed characteristics of the subsurface and the synergistic effects responsible for contaminant migration, which therefore leads to low resolution and poor reliability in the vulnerability maps developed that are difficult for decision making. A methodology that considers the combination of the geophysical data and susceptibility indexing of hydrogeologic layers is therefore necessary to clearly identify the vulnerability zones and increase confidence for the sustainable management of groundwater in Ilere.

Research Objective

The objective of this study is to assess the aquifer vulnerability in the Ilere-Ijare region utilizing a combined Geophysical and hydrogeologic technique. In doing so, specific objectives are pursued in this study as stated below:

- To map out and describe subsurface geoelectric layers where the weathered/fractured aquifer bodies exist using the Vertical Electrical Sounding technique.
- To obtain the overburden protective capacity through the use of derived hydrogeological parameters like longitudinal conductance from geoelectric parameters.
- To analyze and compare the aquifer vulnerability using the combined models (GOD, GLSI and longitudinal conductance) to map out aquifer vulnerability zones in the study area.

Research Questions

- What are the sub-surface geoelectric properties of the study area and how well do they reveal the weathered/fractured aquifer zones?
- What is the protective capacity of the overburden and how well are aquifer vulnerability related to the geoelectric derived parameters?
- How well do GOD, GLSI and longitudinal conductance model correlate in aquifer vulnerability classification and what patterns do aquifer vulnerability features take in the study area?

Research Hypotheses

H₀₁: The vulnerability classifications derived from the GOD model, the GLSI, and the models based on longitudinal conductance have no significant agreement.

H₁₁: The vulnerability classifications derived from the models have significant agreement.

H₀₂: Overburden protective capacity does not have a significant effect on aquifer vulnerability classification.

H₁₂: Overburden protective capacity has a significant effect on aquifer vulnerability classification.

The Site and Geology Description

The Ilere settlement at Akure-Ijare Road (figure 1) is located between 813037N and 805662N and 1739183E and 737378E. The route is situated between Northings 806719 and 812694 and Eastings 738567 to 739035 in the Universal Traverse Mercator (UTM) coordinates (Figure 2). The road's topography is rather level and slightly declines from the west to the east. There are numerous footpaths, a few unpaved roads, and a large tarmac road leading to this well-developed area. The region's surface elevation ranges from 354 to 398 meters above sea level, and it is moderately to severely inclined (Figure 2). The town is situated on a pleasantly rolling landscape that is encircled by isolated hills with a long, continuous porphyritic granite ridge that trends N-S. This ridge is the cause of the area's noticeable runoff and low infiltration rates. The rain forest in southwest Nigeria contributes to the hot and muggy atmosphere. Rainfall averages 152 mm annually during the rainy season, which runs from April to October. The mean annual relative humidity is approximately 80%, and the average temperature is roughly 27°C during harmattan (December to February) and 32°C in March (Onengiyeofori et al., 2025; Adeyemo et al., 2023). The research region is composed of two rock units: older granite and migmatite-gneiss (Figure 1). While the older granite is found as either charnockites or porphyritic granite, the migmatite-gneiss is found as a sequence of sedimentary debris and crumpled veins with segregation of translucent granitic content (Adeyemo et al., 2024) (figure 1).

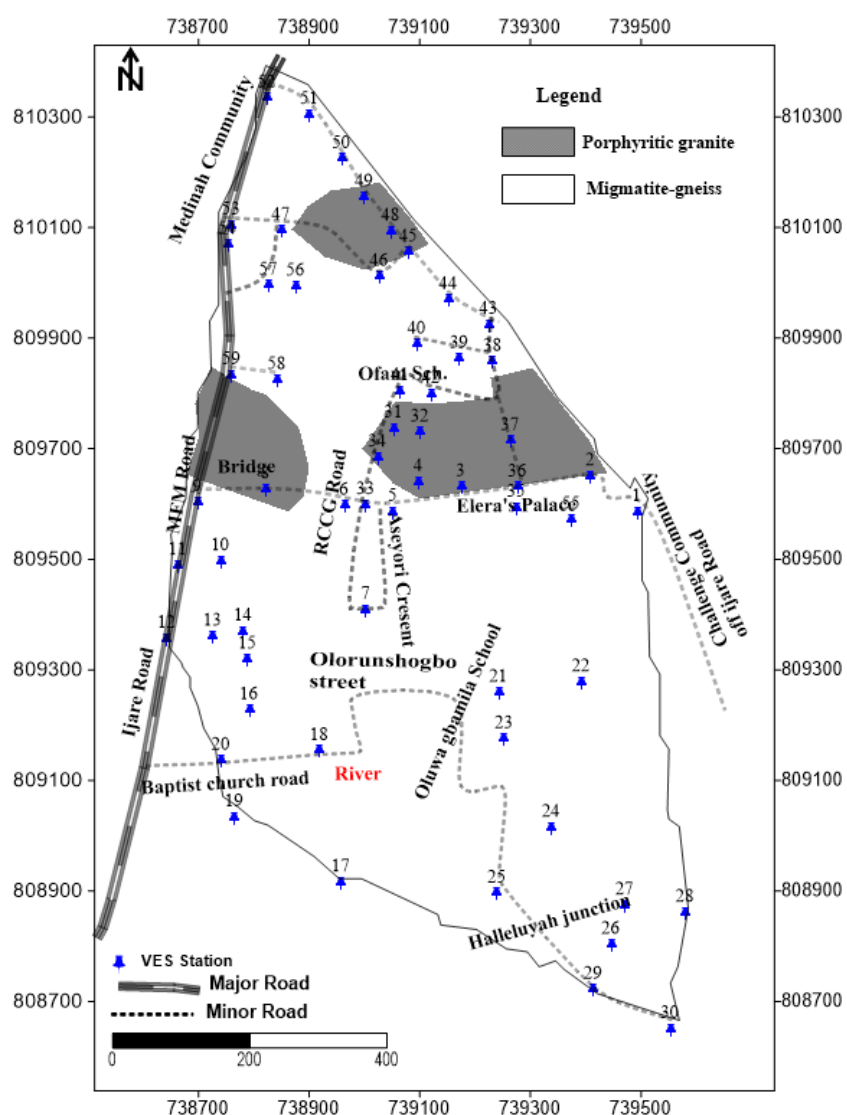


Figure 1: The study area's base map and derived geological map with VES points.

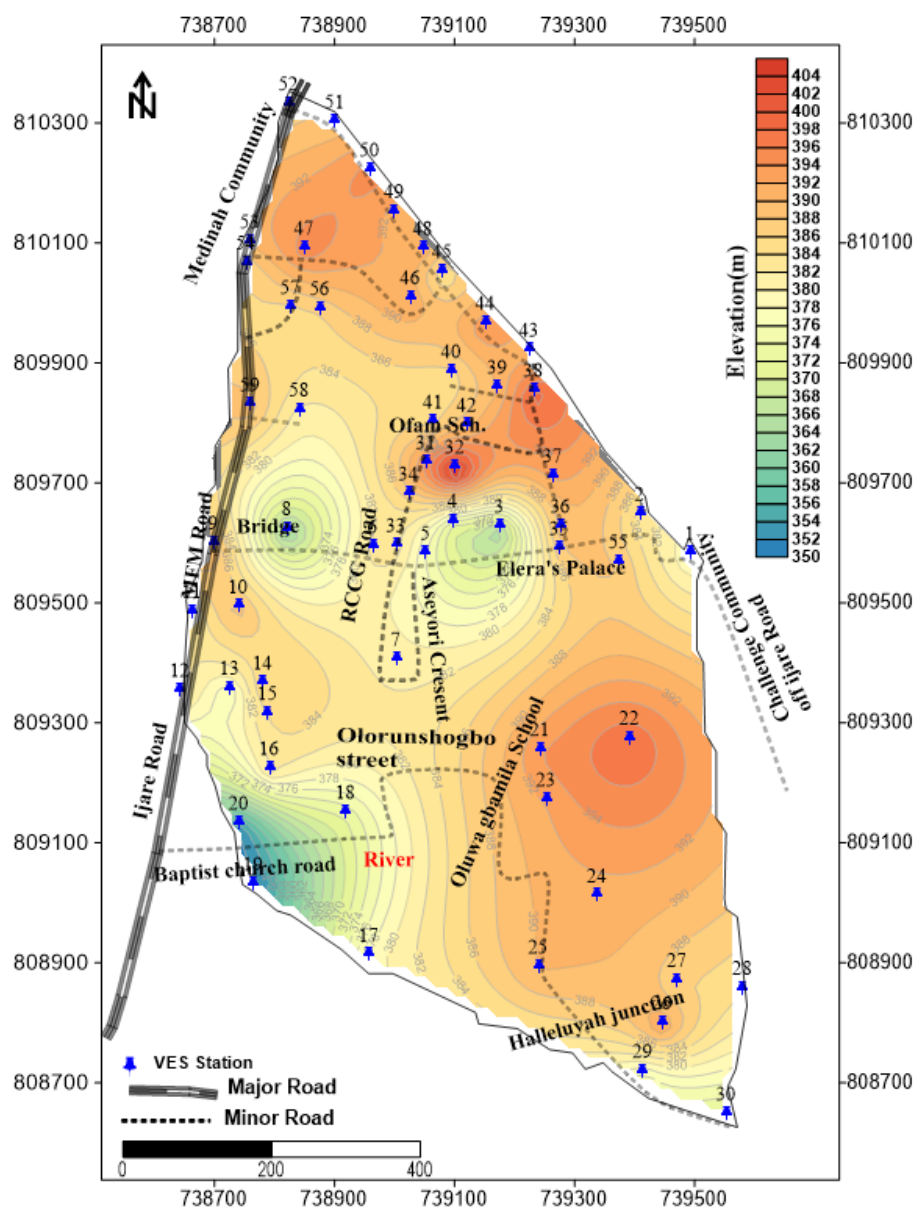


Figure 2: Elevation map of the study area

Materials and Procedures

The data were acquired using an Omega Earth Resistivity Meter. A Schlumberger electrode configuration was used for vertical electrical sounding (VES) data acquisition with the maximum half current electrode separation ($AB/2$) being 100 m. In total fifty-nine (59) VES soundings were carried out over the area of study (Fig 1). Locations for all the VES soundings were chosen such that they cover the area of study considering topography of the area, geology of the area, usage of the land and access through roads. In order to define sub-surface heterogeneity, great care was taken to place VES points on traversable lines

and areas that are suspected to contain hydrogeologically susceptible zones (e.g., fractured/weathered basement rocks) as much as practically possible.

The coordinates of all the VES stations and access roads were collected using a GPS receiver and are plotted in UTM coordinate system. During data acquisition the potential difference was recorded for each station as current electrodes spacing increase while fixing the station center, thereby producing sounding curve (Table 7). As the current electrodes are moved farther, potential difference was found to decrease because the current spread geometry becomes greater, hence to measure an appreciable potential difference, the potential electrodes spacing was increased as much as needed.

Initial interpretation of geoelectric sounding curves was done by matching curves of measured apparent resistivities with standard master and auxiliary curves (Keller et al., 1966; Koefoed, 1979). Although these can give initial estimation on layer parameters, however, it is subject to human bias and dependent on the interpretation experience. To improve these values, forward modeling technique using WinResist software (Vander, 2004) was employed to iteratively refine the layer parameters by matching measured with calculated apparent resistivity values. The good fit was measured in terms of Root Mean Square (RMS) error and in this study; error value is below 5% and for most of the VES below 5% and more in between 1% to 5%. Iterative modeling process was repeated till the RMS value converge to the geologically acceptable parameters. The interpreted layer parameters (resistivity and thickness) were then used to determine other relevant hydrogeophysical indices, namely; longitudinal conductance, aquifer resistivity, GOD index and Geoelectric Layer Susceptibility Index (GLSI). These parameters are interpolated across the area using Surfer 15 software to generate a 2D zonation map of the study area.

The datasets generated and analyzed during the current study (including raw VES field measurements, processed resistivity data, interpreted layer parameters and derived vulnerability indices) are not available from the corresponding author on reasonable request.

Longitudinal Conductance

According to Henriot (1976), the longitudinal conductance (S), or the ratio of thickness to resistivity, can be used to determine the degree of groundwater protection against contaminants that migrate vertically. nevertheless, an underlying layer with a significant longitudinal conductance (typically greater than 1.0) offers an excellent degree of protection against contamination; consequently, the material will be more clayey and less permeable the lower the resistivity, and the thicker the layer, extending the time it requires for contaminants to penetrate (large filter) (Braga et al., 2006). Table 1 displays the prescribed longitudinal conductance protective capability.

Longitudinal unit conductance $S_i = h_i/\rho_i$ When there are n layers, the total longitudinal unit conductance is determined by $S = \sum_{i=1}^n \frac{h_i}{\rho_i} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \dots + \frac{h_n}{\rho_n}$;(1) where p is

the resistivity of every single layer, h represents the thickness of every layer, and S denotes the longitudinal conductance.

Table 1: Adapted from Oladapo et al., (2004) longitudinal unit conductance and protective capacity rating

Longitudinal conductance	Protective capacity rating
>10	Excellent
5-10	Very good
0.7-4.9	Good
0.2-0.69	Moderate
0.1-0.19	Weak
<0.1	Poor

The G.O.D Model

This is used to assess the area's aquifer vulnerability, which is determined by multiplying the impact of the three parameters: depth to the aquifer, overlying lithology of the aquifer, and groundwater occurrence (aquifer confinement) (Onengiyeofori et al., 2025). The resistivity and thickness of the interpreted strata were the geo-electrical parameters that were used to interpret these GOD parameters. Next, the influence of each parameter was multiplied to determine the GOD index. Attribution of remarks for GOD model parameters and the vulnerability index rating are displayed in Tables 2 and 3.

G.O.D index = Aquifer type(G)x Overlying Lithology (O)x Depth to aquifer (D)

GOD index = $G \times O \times D$ (2)

Table 2: Note attribution for the parameters of the GOD model (Oni et al., 2017)

Aquifer type	Note	Lithology (Ωm)	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-Unconfined	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

Table 3: Following Foster (1987), the GOD parameter rating system was developed.

Vulnerability class	Index rating
Negligible	0-0.1
Low	0.1-0.3

Moderate	0.3-0.5
High	0.5-0.7
Extreme	0.7-1.0

Goelectric layer susceptibility indexing (GLSI)

The goelectric parameters generated by the electrical resistivity differential across subsurface lithological sequences are indexed using a hydrogeologic method known as goelectric layer susceptibility indexing (GLSI). It is an empirical concept that was created to support additional methods of vulnerability assessment (Oni et al., 2017). While the longitudinal conductance technique assigns indices to the ratios of the goelectric parameters (layer resistivity and thickness), the GLSI assigns an index to each goelectric parameter (layer resistivity and thickness) (Tables 4 and 5). The MCDA (Multi Criteria Decision Analysis) approach is used by the GLSI for the rating parameters index. After that, the number of goelectric layers (N) found above the aquifer is normalized by dividing it by the given parameter indices.

$$GLSI = \left[\frac{\frac{(h_1 + \rho_1)}{2} + \frac{(h_2 + \rho_2)}{2} + \frac{(h_3 + \rho_3)}{2} + \dots + \frac{(h_n + \rho_n)}{2}}{N} \right] \dots \dots \dots (3)$$

where N is the number of goelectric layers, h is the thickness of each layer, and ρ is the resistivity of each layer.

Table 4: Rating for resistivity values using the goelectric layer susceptibility index.

Resistivity range (Ωm)	Lithology	Susceptibility index rating
<20	Clay/Silt	1
20-50	Sandy clay	2
51-100	Clayey sand	3
101-150	Sand	4
151-400	Lateritic Sand	2
>401	Laterite	1

Table 5: Thickness rating using the Goelectric Layer Susceptibility Index.

Thickness (m)	Index Rating
< 2	4
2-5	3
5-20	2
>20	1

Table 6: Rating of the goelectric layer susceptibility index factors.

Vulnerability rating	Index
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Low	1.0-1.99
Moderate	2.0-2.99
High	3.0-3.99
Extreme	4.0

Table 7: Summary of all the geoelectric parameters of the study area

Ves No.	Layers	App.Resistivity (ohm-m)	Thickness(m)	Depth(m)	Curve Types
1	1/2/3/4	39.6/1038.3/108.3/4022.8	1.0/1.5/7.8	1.0/2.5/10.4	KH
2	1/2/3	31.0/401.6/4243.6	3.9/4.0	3.9/7.9	A
3	1/2/3	59.2/101/2069.5	0.9/8.0	0.9/8.9	A
4	1/2/3/4	201.4/396.2/111.3/4634.4	2.0/0.4/3.6	2.0/2.4/6.0	KH
5	1/2/3/4	69.3/179.3/822.1/7324.7	4.0/1.0/0.6	4.0/5.0/5.6	A
6	1/2/3/4	64/100.7/41.0/1666.3	3.7/1.0/2.6	3.7/4.7/7.3	KH
7	1/2/3/4	53.3/522.1/22.4/7407	0.4/0.8/3.7	0.4/1.2/4.9	KH
8	1/2/3	205.3/72.4/385.3	2.0/5.9	2.0/7.9	H
9	1/2/3/4	101/270/799/156	1.2/12.1/6.5	1.2/13.3/19.8	K
10	1/2/3/4	380.1/111.6/566.7/213.3	0.6/0.9/6.8/...	0.6/1.5/8.3	HK
11	1/2/3	201/357/243	0.5/14.4	0.5/14.9	K
12	1/2/3/4	85.9/903.9/264.5	2.2/6.9	2.2/9.1	K
13	1/2/3/4	281.4/100.7/556.5/199.1	0.7/0.3/15.2	0.7/1.0/16.2	HK
14	1/2/3/4	533.1/323.5/639.3/180.1	0.6/1.0/9.7	0.6/1.6/11.3	HK
15	1/2/3/4	188.3/429.3/336.7/168.9	0.8/0.5/22.7	0.8/1.3/24.0	K
16	1/2/3/4	69.0/273.2/43.0/805.9	0.3/8.5/0.5	0.3/8.7/9.3	KH
17	1/2/3	47.5/388.6/527.7	0.2/0.7	0.2/0.9	A
18	1/2/3/4	244.1/461.8/254.1/440.4	0.6/1.3/8.0	0.6/1.9/9.9	KH
19	1/2/3	126.0/356.0/146.0	1.2/44.0	1.2/45.2	K
20	1/2/3	78.2/124.1/381.8	2.8/0.3	2.8/3.1	A
21	1/2/3/4	74.7/160.2/61.6/1421.9	0.7/2.2/4.0	0.7/2.9/6.9	KH
22	1/2/3/4	114.3/95.7/108.1/915.0	1.3/0.1/14.2	1.3/1.4/15.6	HA
23	1/2/3/4	144.2/943.8/109.1/954.5	0.3/1.5/7.5	0.3/1.8/9.3	KH
24	1/2/3	37.8/63.7/1656.0	0.4/13.9	0.4/14.3	A
25	1/2/3/4	132.1/602.8/94.1/1088.4	0.2/1.8/7.4	0.2/2.0/9.4	KH
26	1/2/3/4	56.0/596.9/229.0/925.1	0.5/0.7/6.0	0.5/1.2/7.2	KH
27	1/2/3	111.4/273.2/5596.7	2.6/0.6	2.6/3.2/...	A
28	1/2/3	148.4/11106.7/965.1	0.8/5.2	0.8/6.0	K
29	1/2/3/4	61.4/254.1/16.3/306.3	0.4/3.5/1.4	0.4/3.9/5.3	KH
30	1/2/3/4	153.4/30.6/219.8/1487.9	1.0/1.4/1.2	1.0/2.4/3.6	HA

Ves No.	Layers	App.Resistivity (ohm-m)	Thickness(m)	Depth(m)	Curve Types
31	1/2/3	419.5/45.7/1648.5	0.7/5.6	0.7/6.3	H
32	1/2/3	113.3/63.7/886.4	0.9/4.0	0.9/4.9	H
33	1/2/3	408.1/87.8/2747.3	0.2/6.9	0.2/7.1	H
34	1/2/3/4	90.8/23.7/638.9/4603.3	0.7/2.8/2.8/...	0.7/3.4/6.2	HA
35	1/2/3	233.9/29.4/1762.8	0.9/7.4	0.9/8.3	H
36	1/2/3	146.4/34.5/623.0	0.3/4.6	0.3/4.9	H
37	1/2/3/4	98.1/72.0/17.6/1499.5	2.2/0.2/1.4	2.2/2.4/3.7	HA
38	1/2/3/4	127.6/2478.0/476.6/648.3	1.5/0.1/4.2	1.5/1.6/5.8	KH
39	1/2/3/4	86.0/449.3/155.0/875.9	0.6/0.7/11.0	0.6/1.3/12.3	KH
40	1/2/3	297.8/163.4/755.3	1.0/9.9	1.0/10.9	H
41	1/2/3	205.0/96.0/1274.3	0.5/6.0	0.5/6.5	H
42	1/2/3	120.6/128.9/2616.7	1.7/7.3	1.7/9.0	A
43	1/2/3	160.4/252.2/1917.0	5.2/0.2	5.2/5.4	A
44	1/2/3	50.3/125.0/2063.9	0.3/19.1	0.3/19.4	A
45	1/2/3	60.6/154.6/1615.2	0.8/11.0	0.8/11.8	A
46	1/2/3	218.0/168.5/1177.5	0.6/8.4	0.6/9.0	H
47	1/2/3	559.3/178.2/1039.8	0.4/15.9	0.4/16.3	H
48	1/2/3	258.3/116.3/596.5	0.3/5.9	0.3/6.2	H
49	1/2/3/4	239.4/61.4/151.2/793.7	0.7/0.8/10.9	0.7/1.5/12.4	HA
50	1/2/3	1225.5/227.8/862.7	0.5/17.2	0.5/17.7	H
51	1/2/3/4	125.6/33.3/137.8/326.8	2.0/0.6/0.4	2.0/2.6/3.0	HA
52	1/2/3/4	135.1/415.3/24.3/1505.9	0.7/2.3/5.1	0.7/3.0/8.1	KH
53	1/2/3	277.3/113.0/747.9	0.8/2.9	0.8/3.7	H
54	1/2/3	217.5/300.4/1617.0	9.0/10.2	9.0/19.2	A
55	1/2/3/4	25.6/591.8/230.3/1223.6	0.3/0.8/12.1	0.3/1.1/13.2	KH
56	1/2/3	627.6/30.7/1598.6	2.1/2.6	2.1/4.8	H
57	1/2/3/4	248.7/142.8/906.0	3.6/15.4	3.6/19.0	H
58	1/2/3	139.7/209.2/1170.0	1.5/18.8	1.5/20.3	A
59	1/2/3	140.0/134.8/549.9	1.5/9.0	1.5/10.5	H

Results

The VES's qualitative analysis reveals that the research area is dominated by the A, H, K, HK, HA, and KH type curves (figure 3a–3f) (figure 4). Figure 2 below provides typical examples of each type of curve. The area is divided into three (3) to four (4) geoelectric layers, which represent the topsoil, weathered layer, weathered/fractured basement, and the assumed fresh bedrock. The range of layer resistivity values is 25.6-1225.5ohm-m for topsoil, 24-415.3ohm-m for weathered layer, 22-793.9ohm-m for weathered/fractured

basement, and 1223.6-7407ohm-m for the assumed fresh basement. The two main aquifers in the study region are the weathered layer and the partially weathered/fractured basement. On the other hand, the topsoil (figure 5), which is typically thin (0.2–5.2 m) and has relative resistivity values within the range of 25.6–1225.5ohm-m which contains clayey and sandy lithologies provides a very high to moderate protection for the subterranean aquifers.

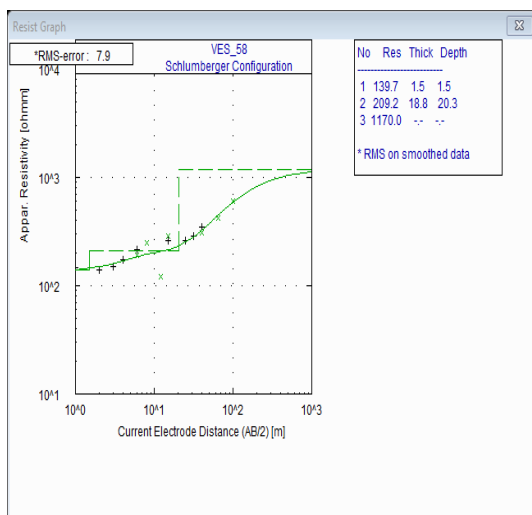


Figure 3a: A CURVE

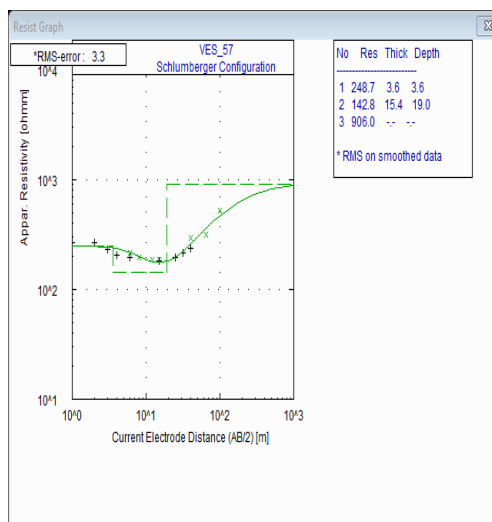


Figure 3b: H-CURVE

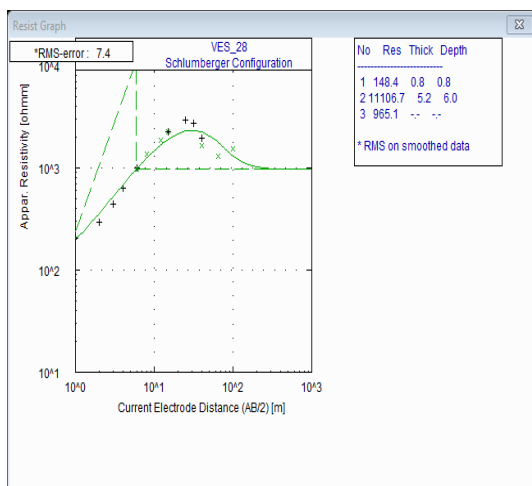


Figure 3c: K-CURVE

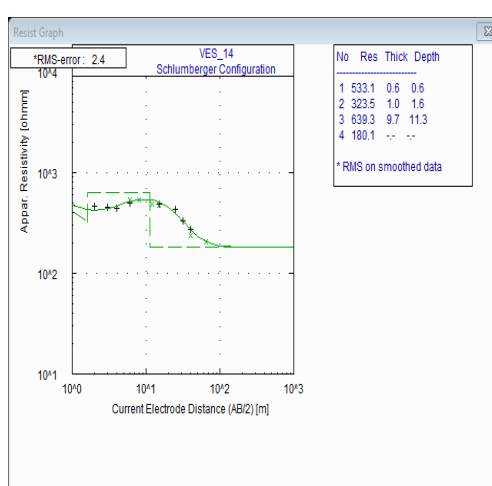


Figure 3d: HK Curve

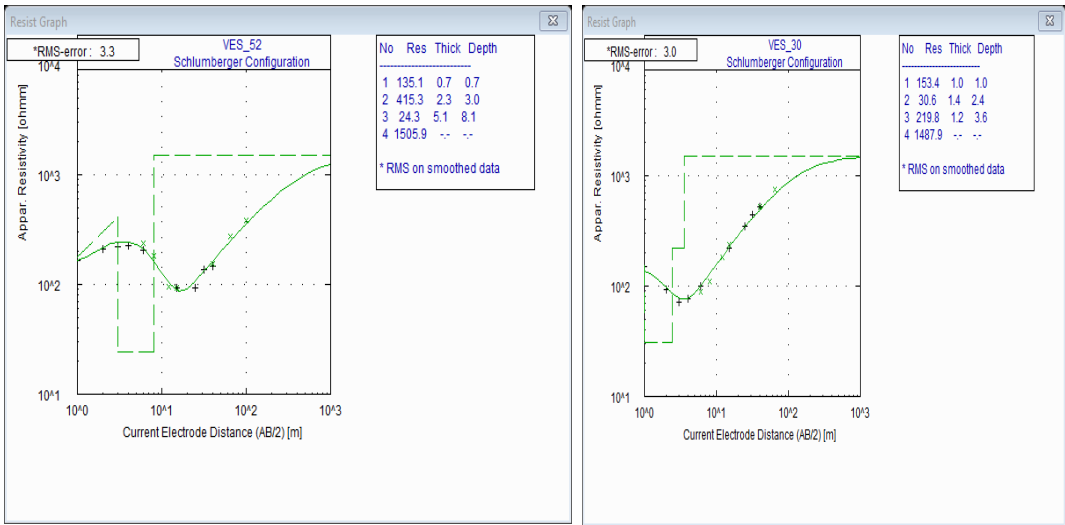


Figure 3e: KH Curve

Figure 3f: HA Curve

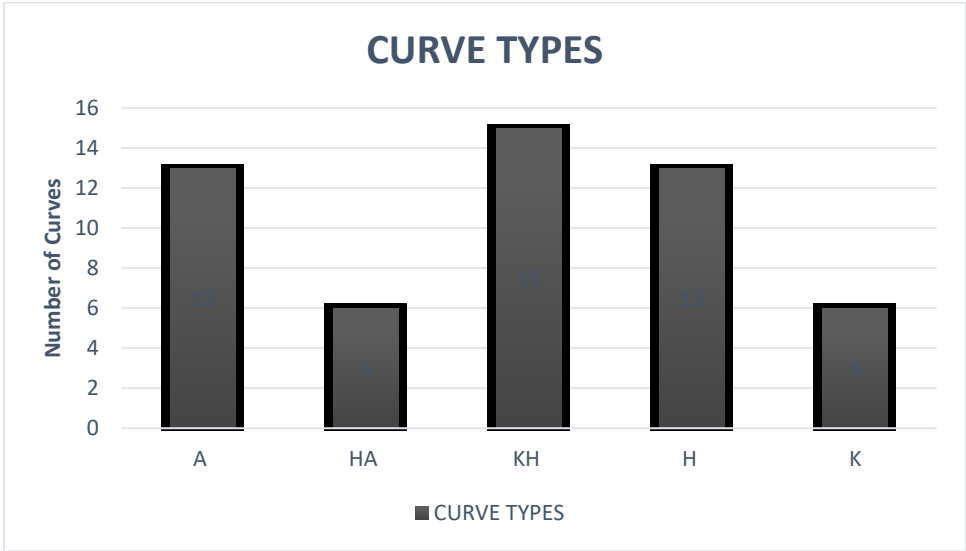


Figure 4: Bar chart showing the total number of each curve types

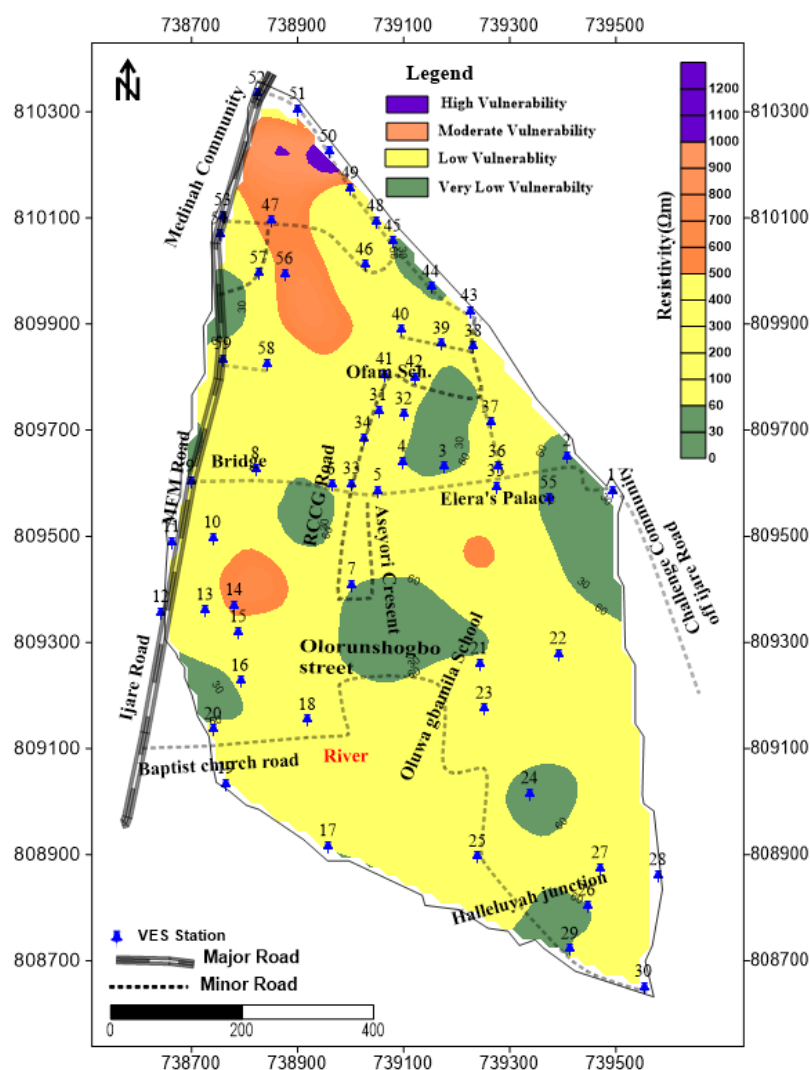


Figure 5: Map showing topsoil resistivity in the research region

Total Longitudinal Unit Conductance

The longitudinal conductance distribution throughout the research area is displayed on the total longitudinal unit conductance map (Figure 6). According to the modelled map, 45% of the study region showed a longitudinal conductance value of 0.1-0.19, revealing a weak protective capacity, and 50% of the study area showed a longitudinal conductance value of less than 0.1, indicating a poor protective capacity. As longitudinal conductance increases, aquifer protection increase. With a longitudinal conductance range of 0.2-0.69, Ves 35 and Ves 24 provide moderate protection.

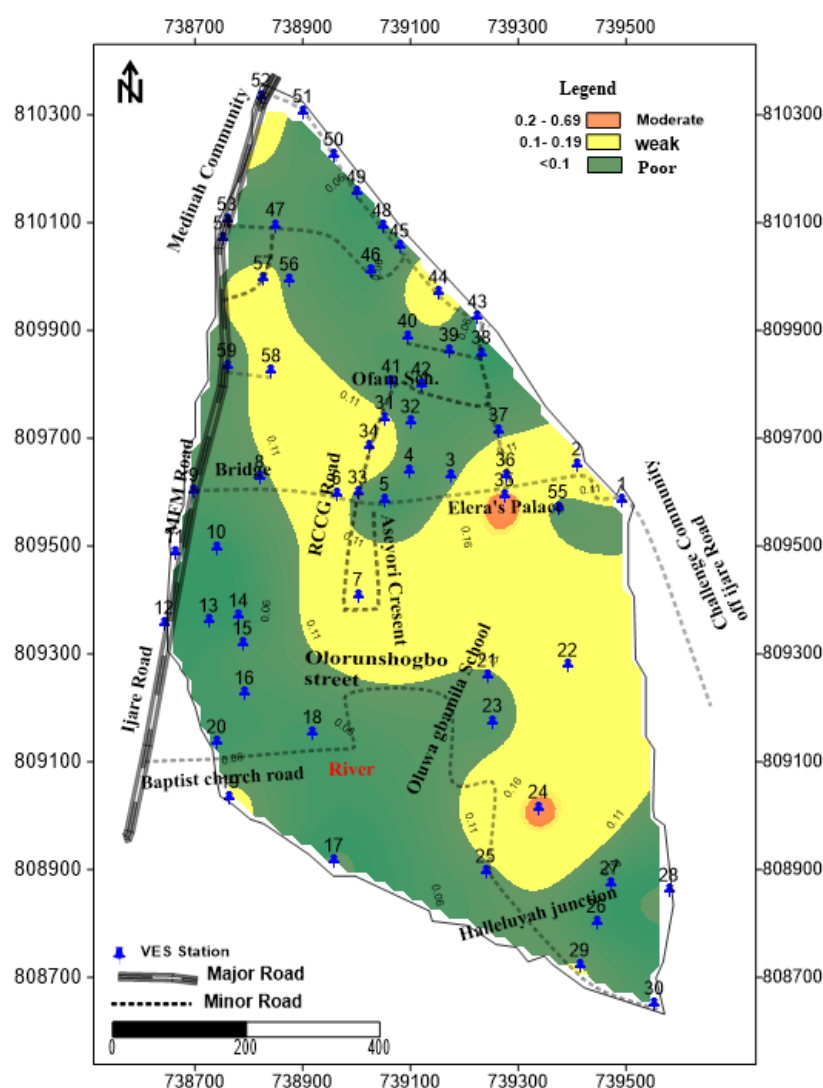


Figure 6: Modified longitudinal unit conductance/protective capacity rating.

The GOD vulnerability index

The GOD modelling parameter were combined to create the Vulnerability index map (figure 7) in order to assess the aquifer susceptibility to contamination within the research area. The map (figure 7) displays a range of vulnerability levels classified as low and insignificant. A minimal vulnerability range of 0-0.1 and a low vulnerability value range of 0.1-0.3, which denotes a low amount of contamination, predominate in the research area. The northern end of the chart at Ves 50 shows significant sensitivity, suggesting that the area is vulnerable to high levels of contamination.

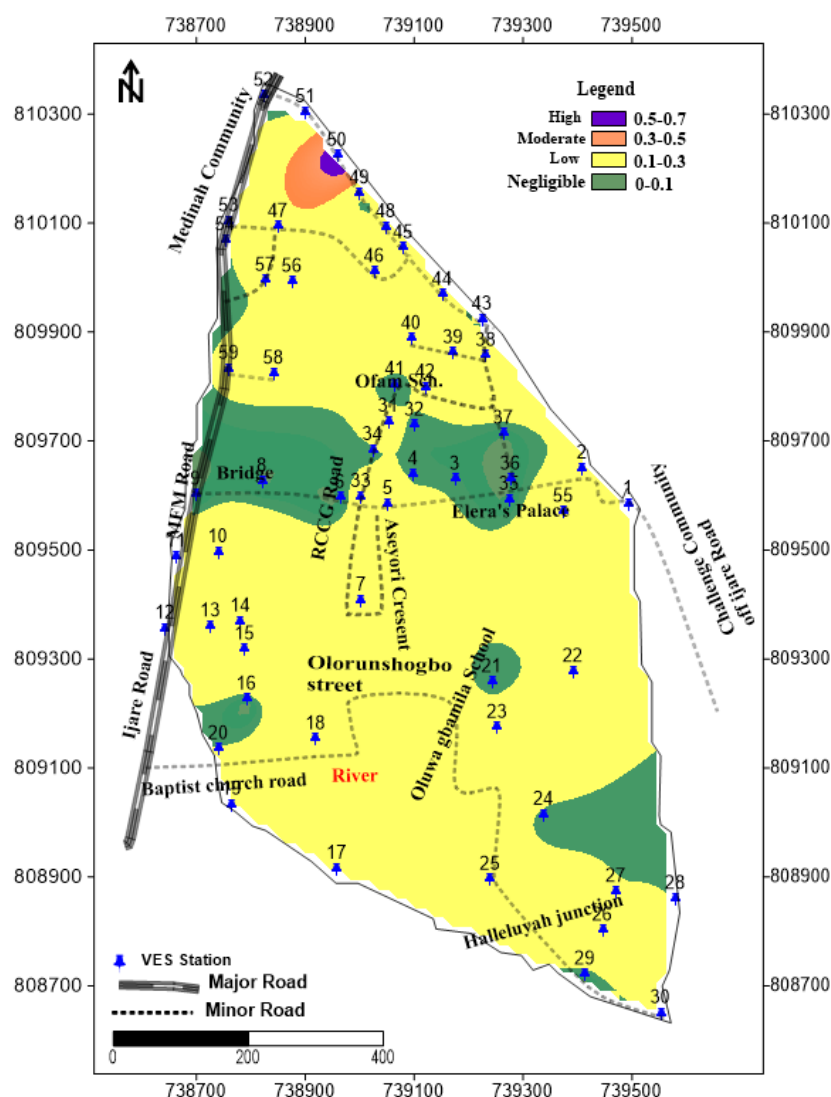


Figure 7: GOD vulnerability index map of the study area.

The geoelectric layer susceptibility index (GLSI)

An overlay index map of GLSI (figure 8) was created using the apparent resistivity, thickness and number of each VES layer combined. The resulting map is dominated by low vulnerability zones (1.0–1.99), which are depicted in green, and intermediate vulnerability zones (2.0–2.99), which are represented in yellow. The map shows high vulnerability zones with an index between 3.0 and 3.99. The lithology and vadoze zone thickness overlay index map of the research area is displayed in Figure 8. A suitably thick vadoze zone can delay pollutant transport to the aquifer zone, thereby degrading the contaminant, the role of vadoze zone thickness in aquifer vulnerability evaluation is crucial.

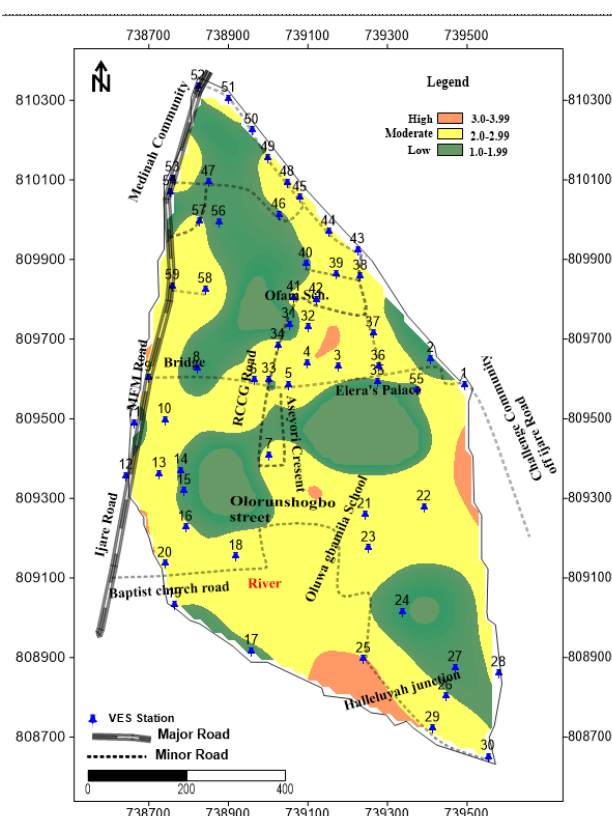


Figure 8: The study area's geoelectric layer susceptibility indexing (GLSI) map.

Discussion of GOD model, Longitudinal conductance and GLSI approaches

The geoelectric parameters obtained from VES data enabled the creation of vulnerability maps, which were used to classify study area into low, moderate and relatively higher vulnerability zones (Davies et al., 2025). The GOD model, GLSI and longitudinal conductance were compared with each other to assess the aquifer protection capacity.

Interpretation of Vulnerability Patterns in Relation to Geology

Poor and weak longitudinal conductance regions occur where overburden thickness is thin and lithologies are resistive, like sands and fractured basement rocks which give low impedance to flow of contaminants. In contrast the moderate conductance region probably reflects thick weathered zones with relatively conductive clay lithologies which offers protection to the aquifer.

The classification in the GOD model reflects the hydrogeological conditions in regional context, thus it generally underestimates the small geological differences that exist and these have significance in cases where overburden is thin and the bedrock is fractured although it classified the study region into negligible and low vulnerability zones. Areas with lower GLSI values indicate a thicker layer and more conductive material thus increased ability of overburden to protect it. VES 25 show relatively higher values of GLSI and thus is more prone to contamination. The results are supported by the geoelectrical features of the

study area where the high value of resistivity and low thickness suggest coarser and/or fractured basement condition that allows for fast movement of contaminant.

Comparative Analysis of Three Methods.

Agreement: The three methods consistently indicate that the entire study area is generally characterized by low to moderate vulnerability, thus indicating no imminent danger of contamination of underlying water table aquifer at a regional scale.

Divergence

1. Most of the area is considered to be low or negligible vulnerability under the GOD model due to reliance on regional hydrogeological properties and insensitive to localized deviations.
2. The GLSI model shows areas of moderate vulnerability particularly where the top soil resistivity map represents thinner or more permeable units and indicates strong ability to detect localized changes in lithology.
3. A number of zones are depicted with moderate/high vulnerability under longitudinal conductance as thickness and conductance of the entire conductive section is considered, without considering aquifers and whether or not there are overlying conductive layers to impede recharge to them or how far they are below surface. The results from longitudinal conductance appear to over-estimate vulnerability where thickness is not equal to permeability.

Contextualization with Previous Studies

This study is in line with several other research works where different methods have been used in comparison. In Ifedore (Akingboye et al., 2025) the results of GOD model similarly revealed generally low vulnerability over most of the area while GLSI produced areas of moderate vulnerability related to resistivity differences and depth. The study by Ibuot et al., (2025) in Nsukka Basin shows a agreement on general vulnerability categories, though the spatial variation differs for both models with more sensitivity by GLSI and is comparable with my finding. This gives more confidence on the methods that I used to calculate vulnerability zones.

Vadose Zone Consideration

According to this study the protective capacity of vadose zone has been assessed to be poor to moderate based on derived geoelectric parameters like electrical resistivity and layer thickness. Although thicker vadose zone could increase the time taken by any contaminants to reach aquifer, the current study is only confined to the physical geoelectric aspect so, interpretation is taken only from this regard (Khemiri et al., 2013; Samson et al., 2025).

Limitations of the Study

The Ground truth data was not used, no borehole logs and pumped test were available, ambiguity in interpretation of geo-electrical data from resistivity method, assumed a set of general parameters for GOD, assumed relationship between electrical parameters and protection capacity (in GLSI & longitudinal conductance). Assumed constant condition with time in calculation and limited stations for VES survey in the study area and they do not cover the entire study area adequately for high resolution spatial prediction of vulnerability.

Conclusion

According to the research, the weathered layer and confined and unconfined fracture basement, which range in thickness from 0.2 to 22.7 meters, are the main aquifer/water carrying units. These units are between 5.2 and 1.3 meters deep. Clay and sandy clay make up the lithology of water-bearing formations. All three methods gave consistent result at regional scale of analysis of aquifer vulnerability to contamination, especially in differentiating between moderate and low vulnerability areas, while they vary in producing details of relatively higher vulnerability zones which are influenced by thickness and resistivity of overburden rocks. This study confirms that the combination of different approaches of vulnerability mapping is a promising method to overcome the shortcomings of each model, allowing for more holistic and robust assessment. In conclusion, the site's protective capacity rating is largely low, and as component of groundwater resource management, efforts must be taken to evaluate the targeted aquifers' susceptibility to pollution.

Recommendation

Effective groundwater protection in the study area requires zone-specific management strategies based on the mapped vulnerability patterns.

High-Vulnerability Zones The region identified by poor longitudinal conductance and high GLSI values, requires strict protection due to its limited natural attenuation capacity:

1. Land-use restrictions should be enforced to limit potentially contaminating activities such as fuel storage, waste disposal, and intensive construction.
2. Setback distances should be established between groundwater sources (e.g., wells, boreholes) and pollution sources such as septic tanks, petroleum storage facilities, and refuse dumps.
3. Underground storage tanks and pipelines should either be avoided or designed with enhanced containment systems (e.g., double-lining and leak detection).
4. New borehole development in this zone should include protective casing and proper sealing to minimize direct contaminant entry.

Moderate-Vulnerability Zones Areas classified as moderate vulnerability (as indicated by GLSI and longitudinal conductance values) require controlled development and active monitoring:

5. Monitoring wells should be strategically installed in these zones to enable early detection of groundwater contamination.
6. Land-use activities should be regulated, with emphasis on proper waste management and controlled siting of sanitation systems.
7. Periodic groundwater quality assessments should be conducted to track changes over time.

Low-Vulnerability Zones These areas, characterized by weak and poor longitudinal conductance and thicker overburden, offer relatively better natural protection but still require precautionary measures:

8. Standard environmental protection guidelines should be maintained to prevent long-term degradation.
9. These zones are more suitable for less sensitive land uses, but activities with high contamination risk should still be regulated.

They may serve as preferred locations for future groundwater development, provided proper engineering practices are followed.

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