Using VES and GIS-Based DRASTIC Analysis to Evaluate Groundwater Aquifer Contamination Vulnerability in Owerri, Southeastern Nigeria

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Abstract. This study assesses groundwater vulnerability in Owerri, Nigeria, using Vertical Electrical Sounding (VES) and Geographic Information System (GIS)-based DRASTIC modeling. The research methodology includes literature review, field survey, geological feature mapping, hydrogeological assessment, geo-electrical sounding, and data interpretation. Owerri, a rapidly developing city with flat topography and a growing population, uses the DRASTIC model to construct a groundwater vulnerability map. The model evaluates the risk of groundwater contamination using seven critical criteria, including depth to water table, net recharge, aquifer media, soil media, topography, vadose zone impact, and hydraulic conductivity. Each parameter was given a weight and rating, and the DRASTIC Index (DI) was calculated by summing the products of the weights and ratings for each factor. The results of the vulnerability assessment indicated that approximately 49% of the study area falls into the high vulnerability category, around 45% is classified as moderate vulnerability, and the remaining 6% is labeled as low vulnerability. The study reveals moderate to high vulnerability zones in Owerri, Nigeria, due to factors like lower slope terrain, permeable aquifer media, and vadose zone impact. The use of VES and GIS-based DRASTIC mapping techniques provides insights into groundwater vulnerability, aiding in sustainable resource management and environmental protection. The findings emphasize the importance of understanding potential risks and the need for effective management strategies to safeguard clean water supplies. Further research and mitigation efforts should focus on highly vulnerable areas.

Keywords: aquifer, sustainable groundwater, hydrogeology, geospatial analysis, vulnerability index.

1. Introduction

Groundwater resources play a critical role in meeting the water demands of many communities worldwide. However, these resources are susceptible to contamination from various anthropogenic and natural factors (Abdulrazzaq et al., 2020). Vulnerability studies for groundwater aquifers are therefore necessary to identify areas that are at risk of contamination and to develop appropriate management strategies (Tirkey et al., 2013; Adewumi et al., 2023). This study focuses on the use of vertical electrical sounding (VES) and GIS-based DRASTIC model to assess the vulnerability of groundwater aquifers in Owerri, South East Nigeria. The study aims to provide insights into the sustainable management of groundwater resources, environmental protection, and water supply in the region.

Water is an essential resource for human life, with many uses including drinking, domestic, industrial, and agricultural purposes. According to Agbasi and Etuk (2016) and Asonye et al. (2007), more than 90% of the world's freely accessible stream resources are made up of groundwater, with the remaining 10% found in lagoons, pools, streams, and swamps. Unlike surface water resources like lakes and rivers, most of the earth's liquid freshwater is stored underground in aquifers (Agbasi et al., 2019; Ahmed et al., 2017). Groundwater is a renewable resource that is globally relevant and highly valued. Anomohanran (2011) defines groundwater as water found beneath the surface of the earth in underground streams and aquifers, which are contained in geological formations. During periods of little rainfall, these aquifers provide a reliable base flow that distributes water to rivers. Due to the growing awareness of the importance of groundwater development and sustainability, there is a need for a quantitative description of aquifers to effectively address hydrogeological issues (Anomohanran, 2013).

Water is an important resource that can contain various toxins, but the characteristics of aquifers are crucial in determining the success of groundwater development and studies (Akaolisa et al., 2022a; Shahsavari et al., 2024). Therefore, conservation efforts are needed to ensure that groundwater can sustain both human populations and ecosystems that rely on it. As populations grow and industrialization increases, the demand for water rises, and sustainable groundwater development becomes increasingly important (Edet & Okereke, 2002). To address this issue, the electrical resistivity method has been employed in this study, and groundwater models have been created to serve as useful tools for managing groundwater in the study area. Groundwater models are scientific simulations that use Darcy’s law to estimate the flow of groundwater through an aquifer and the restraining components of the sub-units (Chowdhury et al., 2010; Igboekwe & Achi, 2011).

Groundwater models are computer simulations that are used to investigate the behavior of groundwater under different scenarios. These models are essential tools for predicting the impact of human actions on groundwater resources (Akaolisa et al., 2022b). The accuracy of these models largely depends on how well they represent the actual field conditions. According to Igboekwe and Udoinyang (2011), groundwater models are indispensable for forecasting the impact of pumping on groundwater levels and predicting the movement of groundwater in an area.

Groundwater modeling is a useful tool in determining the extent of accessible groundwater and predicting the movement of water in underground aquifers. With the use of numerical models, it is possible to simulate various groundwater processes, such as recharge, flow, and discharge (Aladeboyeje et al., 2021). These models can help in identifying potential sources of pollution and in outlining the perimeter of a contaminant plume. Groundwater modeling also plays an important role in groundwater management by providing a quantitative assessment of the resource availability and its sustainability.

In addition, groundwater models can be used to describe the location and extent of a recharge zone. Recharge zones are areas where surface water infiltrates the ground and recharges the underlying aquifers. Identifying recharge zones is essential for understanding the dynamics of groundwater systems, as it can impact the water availability and quality in a region. A recharge zone can also serve as a source of sustainable groundwater supply (Igboekwe & Udoinyang, 2011). Furthermore, groundwater models can aid in the design and optimization of groundwater extraction systems. By simulating the response of the aquifer to pumping, the models can predict the long-term effects of pumping and help in the sustainable management of groundwater resources (Nganje et al., 2017). The use of groundwater models is an essential tool in understanding and managing groundwater resources. It provides a quantitative approach to assessing the groundwater availability, sustainability, and quality, which is crucial in decision-making processes related to water resources management (Ibuot et al., 2022).

The quality of groundwater is also an important consideration in groundwater management. Groundwater can contain dissolved or suspended substances that affect its usability (Amos-Uhegbu et al., 2012). The distribution of subsurface geological materials is an important factor in determining the quality of groundwater (Nwosu et al., 2013). In general, groundwater flow is influenced by the permeability of the subsurface materials and the hydraulic gradient. These factors play a crucial role in groundwater modeling and management.

The availability and quality of freshwater is one of the most crucial environmental and sustainable issues of the 21st century, according to the United Nations Environment Programme

(UNEP, 2002). Groundwater has become a popular source of drinkable water because of its quality and cost-effectiveness compared to other water sources. It is often free from pollutants, which means that little or no decontamination is required before use (Casas et al., 2008; Lawrence & Ojo, 2012). Additionally, groundwater typically lacks odour, colour, and has low levels of dissolved solids. Unlike surface water, groundwater stored in underground aquifers is not usually affected by natural factors such as drought (Lawrence & Ojo, 2012).

Shallow hand-dug wells are more likely to be contaminated than drilled wells, especially those with poor casing materials. In the Imo River basin, most of the shallow wells are hand-driven and constructed with inferior casings. Nwachukwu et al. (2010b) reported that the greatest problem with manual drilling is that operators often terminate the drilling process as soon as they penetrate the water table or run out of energy. According to Ibe et al. (2007), Nwachukwu et al. (2010a), and Nwachukwu et al. (2010c), environmental pollution in the Imo River basin increases from the shale north to the sandy south, and human activities are the primary source of water pollution in the area.

The study aims to address the issue of groundwater vulnerability in the Owerri region of South East Nigeria. Despite being a crucial resource, there is a lack of information on the extent of groundwater contamination and depletion in the area. This study seeks to fill the gap by using VES technology and a GIS-based DRASTIC model to identify areas that are highly vulnerable to contamination from various sources, such as industrial and agricultural activities.

2.Location and Geology of Research Area

The Owerri study area is situated in Imo State, one of the states in Nigeria. Imo State is headquartered in Owerri, a city in the southeast of the nation. According to Figure 1b, the city is roughly located between latitudes 5°28'N and 5°33'N and longitudes 7°00'E and 7°07'E. Two important rivers border Owerri on either side. The Otamiri River forms its eastern border, and the Nworie River forms its western border. These rivers influence the local hydrology by serving as a supply of water for diverse uses and sculpting the terrain (Ibe Sr & Sowa, 2002).

Owerri, a 125 square kilometers city in Imo State, is known for its urban development, business sector, and residential neighborhoods. The terrain is mostly level, with elevations ranging from 70 to 120 meters above sea level (Ibe Sr & Sowa, 2002). Owerri is an important economic center, hosting enterprises, governmental agencies, educational facilities, and a market. Its advantageous position and well-developed infrastructure attract visitors from various industries, expanding its economy and reputation. Owerri population has been rapidly increasing, leading to urbanization and infrastructure construction. New residential neighborhoods, business districts, and public amenities have been established to meet citizens' demands.

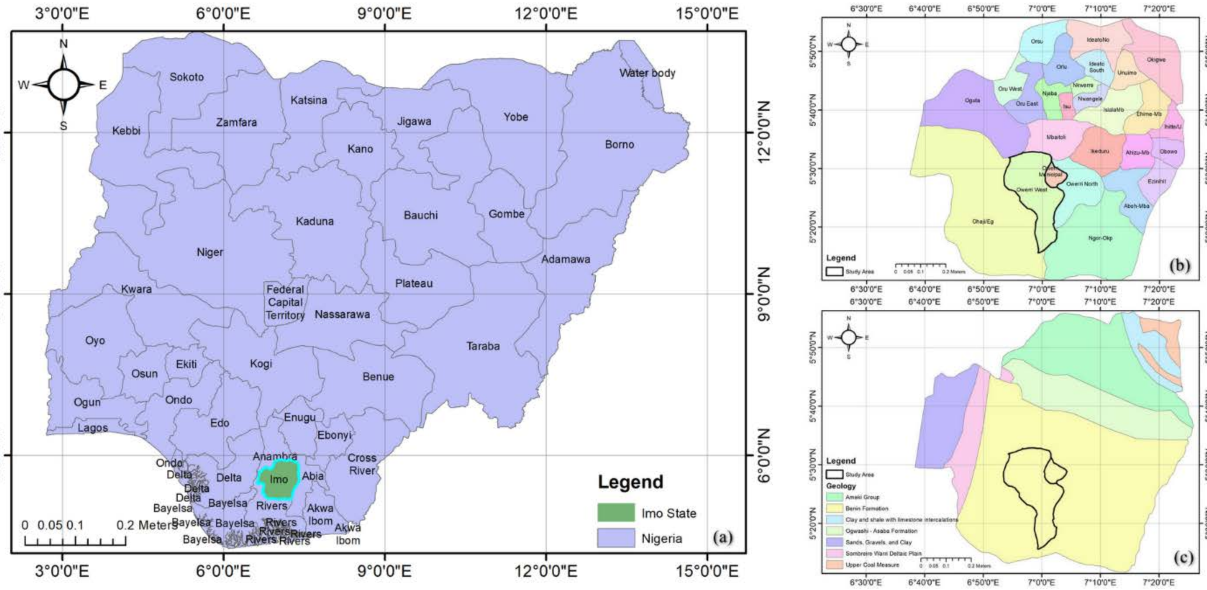


Figure 1. (a) Map of Nigeria, (b) Map of Imo state showing the study area (b) Map of Geology of the study area

Owerri is located in the Niger Delta basin, which is a sedimentary basin that is made up of a variety of rocks, including sandstone, shale, and limestone. The sandstone layers in the basin are particularly important, as they are the main source of groundwater in the area (Emenike, 2001). The groundwater in Owerri is generally of good quality, but it is important to note that the quality of the groundwater can vary depending on the location. Figure 1c shows the geology map of the study area and Imo state.

The geology of Owerri has also had a significant impact on the development of the city. The sandstone layers in the area are particularly well-suited for building, and as a result, Owerri is a relatively well-built city. The city is also home to a number of natural features, such as the Imo River, which provide a scenic backdrop to the city (Ekwe & Opara, 2012). The sandstone layers (mostly Benin Formation) in the area have provided a good foundation for the city, and the natural features in the area have added to the beauty of the city.

3. Materials and Methods

3.1. Methodology

The research methodology included initial literature review and the creation of a study area map. This was followed by conducting a field survey to gather data and observations, mapping the geological features, assessing the hydro-geological aspects, performing geo-electrical sounding, and interpreting both surface geological and geo-electrical data.

3.2. Data Acquisition

The VES (Vertical Electrical Sounding) method was used in geophysical research, with ABEM-Terrameter (SAS1000-Signal Averaging System) equipment in the Schlumberger configuration. The electrical resistivity measurements were carried out at a distance of 800 m (L) between the maximum current electrodes and the depth. This entailed running 400 meters (L/2) on the right side and 400 meters (L/2) on the left side. A grid arrangement of twelve (12) VES stations was constructed. However, offset VES was unavoidable due to the existence of slopes, gullies, and residential development. All required safeguards for geo-electric measurement were taken, ensuring that the task was completed in good weather.

As the distance between current electrodes rises, so does the depth of current penetration (also known as the depth of inquiry). While the distance between the A and B electrodes impacts just the current penetration, the geometric arrangement of all four electrodes influences the depth of investigation.

A systematic adjustment of electrode spacing determines the observed apparent resistivity (ρa) obtained using the Schlumberger array at a certain site.

$$\rho_{a(s)} = R\pi\left(\frac{a^2}{b} - \frac{b}{4}\right) \quad 1$$

Where, a = (AB/2) - (half current electrode spacing), b = MN - (spacing between potential electrodes).

The resistance (R) is derived from the current (I) and voltage (V) values using the relation.

$$R = \frac{V}{I} \quad 2$$

Equation (2) can be written as

$$\rho_{a(s)} = K \times R \quad 3$$

Geometric factor,

$$K = \pi\left(\frac{a^2}{b} - \frac{b}{4}\right) \quad 4$$

K is a geometric factor that depends on the placements of the electrodes in the ground and may be calculated for any electrode arrangement.

3.3. Data Processing

The VES data obtained were processed using the IP2win software. This software was utilized to input the apparent resistivity values along with their corresponding AB/2 values for further modeling and iteration. The iteration process involved multiple computer iterations, ranging from 1 to 29, to minimize errors and improve the goodness-of-fit. Through this iterative procedure, true resistivity layers were derived, along with their respective thickness and depth values.

3.4. Application of The Drastic Model to The Study Area

Groundwater vulnerability assessment is gaining popularity in many parts of the world because it plays an important role in making decisions regarding appropriate groundwater management and conservation (Soupios et al., 2007). For the United States Environmental Protection Agency, Aller et al. (1985), and Aller et al. (1987) developed a systematic technique for measuring groundwater contamination susceptibility. The DRASTIC model was employed in this investigation. The DRASTIC model was used to construct the groundwater vulnerability map for the research region.

In the research area, the Point Count System Model (PCSM) named DRASTIC is applied to assess groundwater vulnerability. This model relies on seven essential criteria to evaluate the risk of groundwater contamination. A detailed analysis of these criteria helps in pinpointing areas that might be at higher risk of groundwater pollution and assists in formulating effective management strategies. The seven critical parameters considered are as follows: Depth to water table, Net recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, Hydraulic conductivity of the aquifer.

3.4.1. Depth to the Water Table

The vertical distance from the ground surface to the water table level is referred to as the depth to the water table. It represents the thickness of the material that any pollution must pass through before reaching the aquifer. When low permeability layers surround the aquifer, they operate as barriers, preventing contaminants from entering the aquifer. Furthermore, deeper water implies longer travel distances, which increases the chance of natural attenuation processes as the water flows through the subsurface.

3.4.2. Net Recharge

The quantity of water per unit area of land that infiltrates the ground and finally reaches the water table is referred to as net recharge. This mechanism transports leached chemicals and pollutants vertically into the water table and can also transport them laterally within the aquifer zone. A greater recharge rate increases the risk for groundwater contamination since more pollutants can enter and damage the groundwater system.

3.4.3. Aquifer Media

The effective surface area with which contaminants can interact is determined by the aquifer media. Permeability has a direct impact on this area, with higher permeability being related with bigger granular particle size and the existence of more fractures or holes within the aquifer. As a result, the pollutant attenuation process is slowed in such instances. The properties of the aquifer media were discovered in this study by assessing the depths at which water was impacted and then connecting those depths with lithological descriptions acquired from VES (Vertical Electrical Sounding) data or other stratum descriptions.

3.4.4. Soil Media

The vadose zone's highest half is made up of soil media, which has a high biological activity. It is widely recognized as the earth's upper weathered layer, reaching a depth of one meter or less from the ground surface. The qualities of the soil influence the amount of recharge that may penetrate into the ground and, as a result, the ability for pollutants to flow vertically into the vadose zone.

3.4.5. Topography

Topography, which includes the various slopes and curves of the ground surface, is critical in lowering the likelihood of pollutants running off, pooling, and remaining on the surface for a lengthy period of time, hence limiting the potential of infiltration. The elevation variety across the terrain generates natural paths for surface water to flow and disperse, reducing the likelihood of pollution buildup in certain regions. Faster surface water drainage is facilitated by steeper slopes, reducing the residence period of possible pollutants and decreasing the possibility of infiltration. Flatter topography, on the other hand, may cause temporary water pooling, but it also allows for enhanced infiltration and natural filtering processes before the water percolates downward into the subsurface.

3.4.6. Impact of Vadose Zone

The vadose zone, also known as the unsaturated or occasionally saturated zone located above the water table, is crucial in determining the attenuation properties of materials both below and above the water table. It operates as a buffer zone, regulating water and pollutant transport through the subsurface. Because this zone is unsaturated, the pores and gaps between particles are not entirely filled with water, allowing for intricate interactions between air and water that affect pollution movement and transformation. Understanding the behavior of the vadose zone is critical for determining the possibility for pollutant migration into the groundwater system and adopting appropriate groundwater quality protection techniques.

3.4.7. Hydraulic Conductivity

The fundamental attribute of hydraulic conductivity determines an aquifer's aptitude or capacity to convey water, determining the speed at which groundwater travels under a certain gradient or slope. It denotes the ease with which water may flow through the aquifer's underlying materials, impacting the pace at which pollutants can move through the groundwater system. A high hydraulic conductivity means that water may travel faster through the aquifer, thus transporting contaminants over longer distances and affecting a broader region. A low hydraulic conductivity, on the other hand, suggests a decreased flow rate, which may result in slower pollutant movement and probable attenuation processes within the aquifer. Understanding hydraulic conductivity is critical for assessing groundwater risk and developing appropriate management measures to protect this essential resource.

3.5. Weights and Ratings for The Drastic Parameters

DRASTIC, an empirical groundwater model, predicts the vulnerability of aquifer systems to groundwater pollution based on the hydrogeological conditions of the area (Prasad & Shukla, 2014). Engel et al. (1996) describe a hydrogeological setting as a mappable unit with shared hydrogeological properties. A numerical ranking technique was used in the model to assign relative weights to various parameters. Each DRASTIC component was given a weight depending on its importance in influencing pollution potential. As stated in the tables below, the ratings vary from 1 to 10, while the weights range from 1 to 5. For each hydrogeological setting, the ultimate outcome is a numerical number known as the DI (Stigter et al., 2006; Kumar et al., 2016). The DI is a measure of pollution potential that is calculated by adding the products of each factor's ratings and weights. The higher the value, the more vulnerable the land is to groundwater contamination. Thus,

$$DI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \qquad 5$$

Where r and w signify the rating and weight of the component under consideration, respectively. The larger the value of DI, the greater the aquifer's sensitivity or relative contamination potential. Engel et al. (1996) classified the calculated DRASTIC indices as low, moderate, high, or extremely high risk.

The weights and ratings attributed to different DRASTIC criteria were shown in Table 1 (Aller et al., 1987). Table 2 depicted the qualitative risk categories of low, moderate, high, and very high vulnerabilities (Engel et al., 1996).

Table 1. Weights and ratings attributed to different DRASTIC criteria.

Factor Weight = 5		Factor Weight = 4		Factor weight = 3		Factor Weight = 2		Factor Weight = 1		Factor weight = 5		Factor weight = 3	
Depth (ft)	Rating	Recharge (inches)	Rating	Aquifer material	Rating	Soil type	Rating	Slope (%)	Rating	Unsaturated material	Rating	Hydraulic Conductivity (gpd/ft^2)	Rating
100+	1	0 – 2	1	Shale	1	Clay/organic soil	1	>18	1	Clay	1	1 – 100	1
75 – 100	2	2 – 4	3	Till	3	Loamy clay	4	16 – 18	2	Shale	2	100 – 300	2
50 – 75	3	4 – 7	6	Silt	3	Clayey loam	5	14 – 16	3	Silt	3	300 – 700	4
30 – 50	5	7 – 10	8	Schist	4	Loam	7	12 – 14	4	Schist	4	700 – 1000	6
15 – 30	7	> 10	9	Sandstone	5	Sandy loam	8	10 – 12	5	Till	4	1000 – 2000	8
5 – 15	9			Limestone	6	Loamy sand	9	8 – 10	6	Green rocks	5	2000+	10
0 – 5	10			Green rocks	6	Sand/gravel	10	6 – 8	7	Sandstone	5		
				Sand	8			4 – 6	8	Limestone	6		
				Sand and gravel	9			2 – 4	9	Sand	8		
				Gravel	10			0 – 2	10	Sand and gravel	9		
										Gravel	10		

Table 2. DRASTIC index ranges for qualitative risk categories (Engel et al., 1996)

	Drastic Qualitative Category			
	Low	Moderate	High	Very High
Drastic Index [DI]	1 – 100	101 – 140	141 - 200	>200

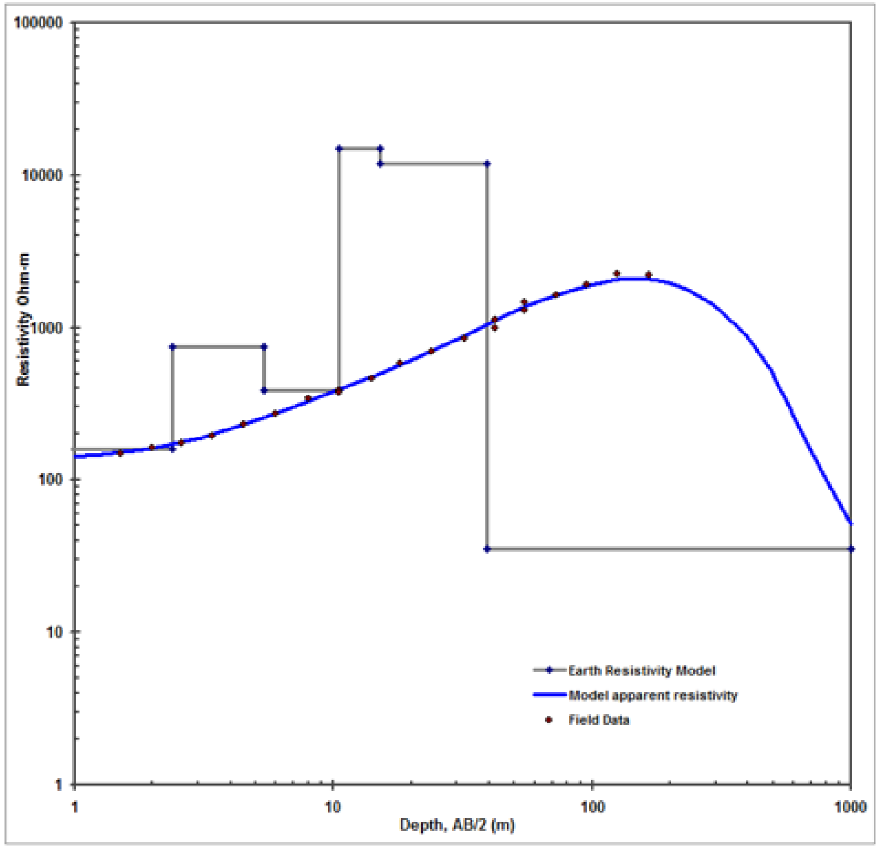
4. Results and Discussion

The findings of field geophysical surveys, such as apparent resistivity, longitude, latitude, and elevation data, are presented in Figure 2. These figures also include the accompanying Schlumberger array. Apparent resistivity serves as an indication when compared to the actual resistivity of the subsurface being studied (George et al., 2022). The iso-resistivity distribution refers to the resistivity distribution seen at a specific depth or electrode spacing, as depicted in these pictures.

Table 3. Aquifers parameters in the study area.

VES	Depth to water table (m)	Net recharge (m)	Resistivity (Ω)	Hydraulic Conductivity (m/day)
A 1	39.20	2735.00	11794.00	0.5813
A 2	28.80	5491.00	1168.00	0.5821
A 3	91.00	7689.00	3662.00	0.6459
A 4	44.10	9871.00	2200.00	0.6577
A 5	66.00	4312.00	7032.00	0.6179
A 6	30.30	3098.00	7851.00	0.6115
A 7	33.10	6789.00	2200.00	0.5085
A 8	23.40	3456.00	14048.00	0.5642
A 9	85.30	9825.00	5951.00	0.6268
A 10	25.00	7658.00	893.00	0.6029
A 11	36.40	9032.00	910.00	0.6013
A 12	36.40	8170.00	1962.00	0.6603

Number of Layers	7		
Layer NO	Thickness (m)	Depth (m)	ρ (Ω-m)
1	0.79	0.79	139.00
2	1.59	2.38	161.00
3	3.01	5.39	746.00
4	5.11	10.50	391.00
5	4.70	15.20	15016.00
6	24.00	39.20	11794.00
7	-		35.10
-	-		



FIELD DATA	
AB/2 (m)	ρa (Ω−m)
1.5	150.00
2.0	163.70
2.6	174.10
3.4	194.50
4.5	231.90
6.0	270.20
8.0	341.40
10.5	390.10
14.0	462.30
10.5	371.00
14.0	462.50
18.0	578.80
24.0	700.00
32.0	849.60
42.0	1120.30
55.0	1472.90
42.0	992.60
55.0	1295.70
72.5	1635.50
95.0	1902.10
125.0	2261.30
165.0	2219.40
215.0	1674.80

VES NUMBER: 1 DIRECTION LAYOUT: DATE:

LOCATION: LIFE GATE ROAD OBINZE, OWERRI WEST LGA, IMO STATE

COORDINATES: 5.406599"N 6.964956 "E ELEVATION : 60m

Figure 2. Computer modelled curves of VES 1 showing modelled curve, theoretical curve and layered iso-resistivities

Figure 3 displays the spatial distribution of apparent resistivity, specifically highlighting the VES locations within the designated research region. The map illustrates that the core maps inside the research region (A2, A3, A4, A7, A10, A11, and A12) have lower apparent resistivity values, whilst A8 has the greatest apparent resistivity value. The map illustrates a notable disparity in apparent resistivity levels between the southern and northern regions of the research area.

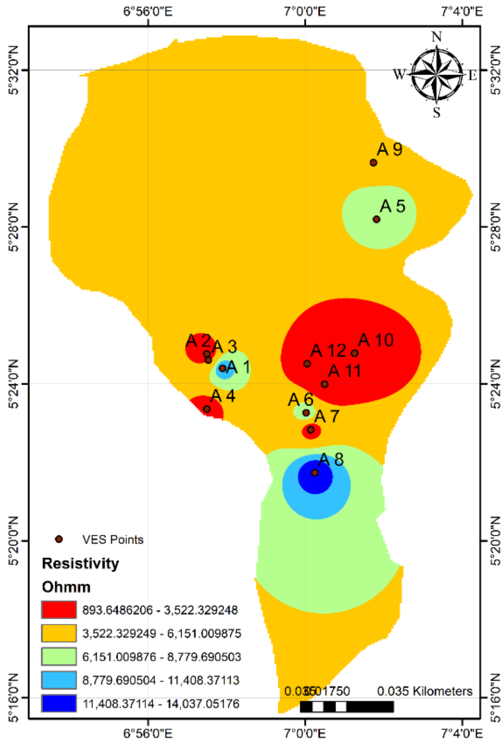


Figure 3. Distribution of apparent resistivity with the VES points in the study area

4.1. Depth to Water Table

The estimation of the depth to the water table was derived from the interpretation of the Vertical Electrical Sounding (VES) data. The findings indicate a range of 23.4 to 91.0 m, as presented in Table 3 and visually depicted in Figure 4a. There exists an inverse relationship between the depth of the water table and the susceptibility of groundwater to surface pollution. The range of depth ratings spans from 3 to 9, as seen in Figure 4b. The predominant feature of the research region is a depth rating of 9, indicating a high vulnerability to groundwater pollution or surface pollutant infiltration.

According to Figure 4, the areas with the most pronounced susceptibility to groundwater are concentrated in proximity to A6, A7, A8, A10, A11, and A12. These regions exhibit a combination of factors including a very close proximity to the water table to the surface, soils with high permeability, and a dense concentration of human inhabitants. certain variables are influential in the heightened susceptibility of certain regions to groundwater pollution.

Regions with limited vertical distances from water tables to surfaces allow for easy infiltration of pollutants into groundwater, while permeable soils facilitate movement. High population density increases susceptibility to pollution from human activities.

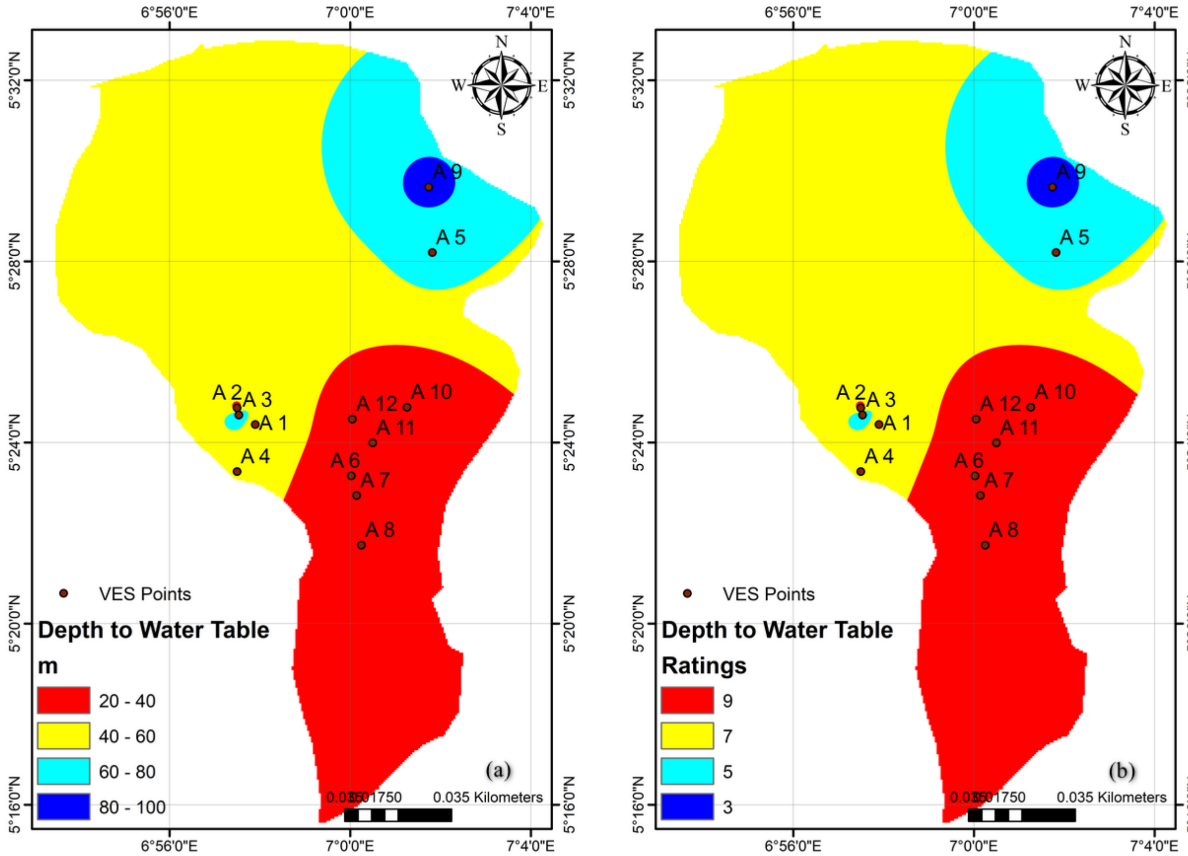


Figure 4. Distribution of (a) and (b) rating of depth to water table with the VES points in the study area

4.2. Net recharge

Net recharge refers to the cumulative amount of water from precipitation and human-induced sources that can refill the groundwater table, exposing aquifers to groundwater pollution (Saha & Alam, 2014). Higher net recharge areas are more vulnerable to contamination, as it acts as a key conduit for surface contaminants. Table 3 and Figure 5a show that the net recharge values in the research zone vary from 2735.00 mm to 9871.00 mm. This means that an anticipated yearly quantity of 9871.00 mm of water infiltrates into the water table from both natural precipitation and human-caused sources. The observed net recharge in the research region is significant, indicating a greater sensitivity to future groundwater contamination. Rainfall is the primary method for replenishing groundwater supplies in the studied region.

The net recharge rating is a quantitative measure of the yearly volume of water that recharges an aquifer. The rating scale runs from 3 to 7, with 3 indicating the lowest rating and 7 representing the highest. In the study region, the net recharge rating for A1, A6, and A8 is 3. As a result, these areas have the least capability for groundwater replenishment. Figure 5b shows that the net recharge rating for A4, A12, A11, and A9 is 7. This means that these areas have the highest potential for groundwater replenishment. The study area has net recharge rates ranging from 3 to 7. This means that the region's capability for groundwater replenishment varies. Certain regions have a significant capacity for recharging, whilst others have a restricted capacity.

The rainfall factor measures the amount of precipitation on Earth's surface, with plant cover and reduced impermeable surfaces reducing this issue. Soil permeability, a quantitative measure of soil hydraulic conductivity, indicates water infiltration capacity. High permeability soils permit greater water infiltration.

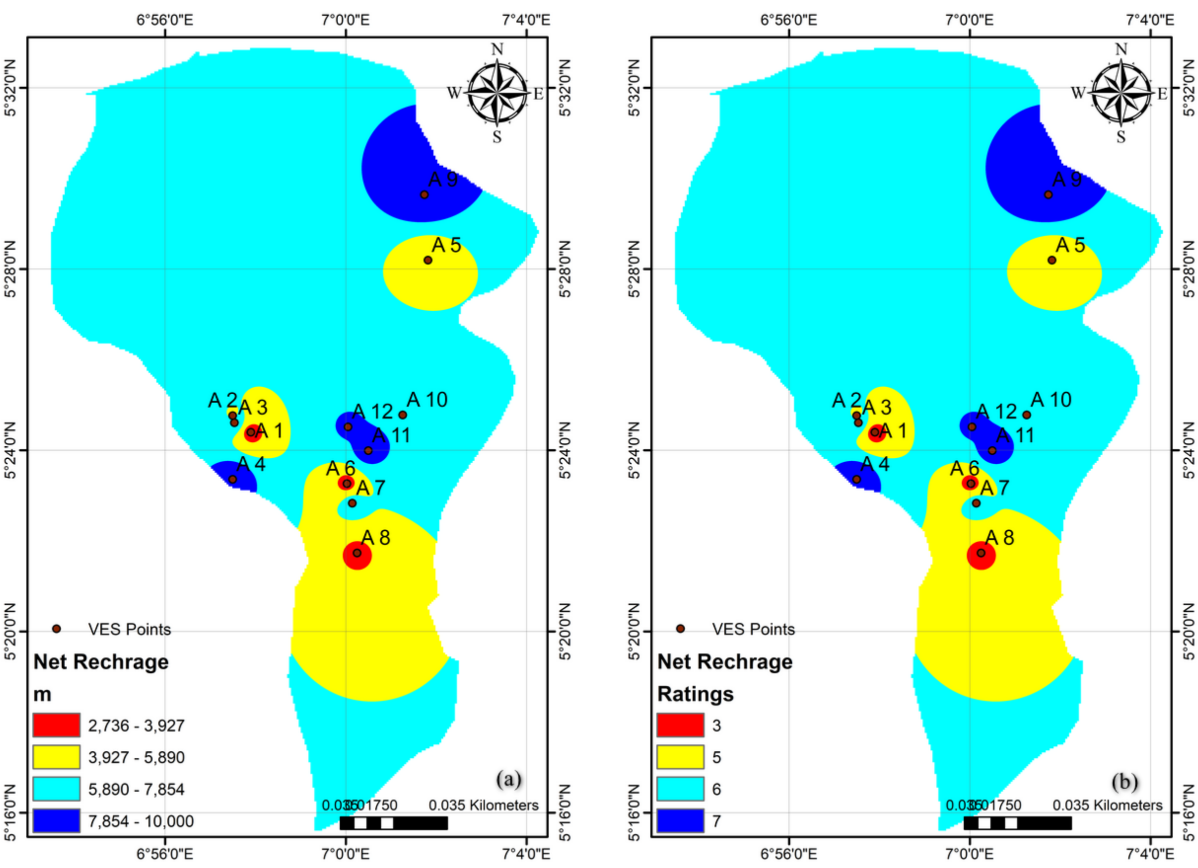


Figure 5. Distribution of (a) net recharge (b) net recharge ratings with the VES points in the study area

4.3. Aquifer media

Aquifer media, consisting of geological elements, control the attenuation of pollutants based on their permeability, determined by the grain size of the aquifer's materials, with higher permeability geomaterials resulting in poorer attenuation capacity (Saha & Alam, 2014).

The aquifer media utilised in this investigation were acquired by the analysis of VES data, with consideration given to the constraints imposed by the geological characteristics. The aquifer media consists of gravelly sands at all sites, as seen in Figure 6a. The material of the gravelly sands aquifer was given a constant rating of 8, as seen in Figure 6b.

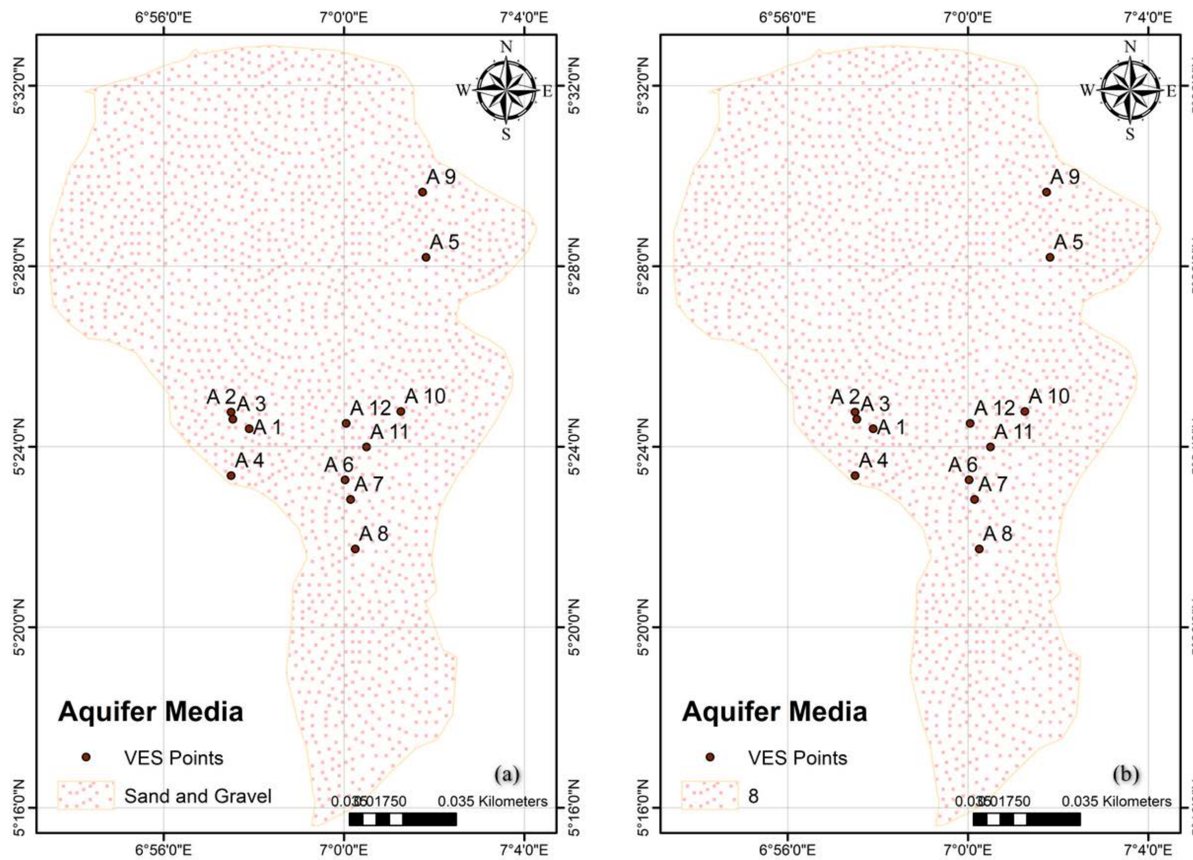


Figure 6. Distribution of (a) aquifer media and (b) aquifer media rating with the VES points in the study area

4.4. Soil Media

Soil media, the Earth's uppermost layer of weathered soil, significantly influences rainwater recharge and pollution movement. Gravel, sand, and gravelly sand soils have high permeability, making them more susceptible to pollution and affecting hydrogeological units.

The soil samples were acquired based on the interpretation findings of the lithological restricted Vertical Electrical Sounding (VES) data. The predominant soil composition in the studied region consists mostly of Xanthic Ferralsols (Clay-Loam) found within the A1 to A8 and A10 to A12 soil horizons. A9 consists of Dystric Nitosols with a sandy-loam texture, as shown by the research regions depicted in Figure 7a. In Figure 7b, the Xanthic Ferralsols (Clay-Loam) parameter was given a rating of 2, but the Dystric Nitosols (Sandy-Loam) parameter was awarded a value of 6.

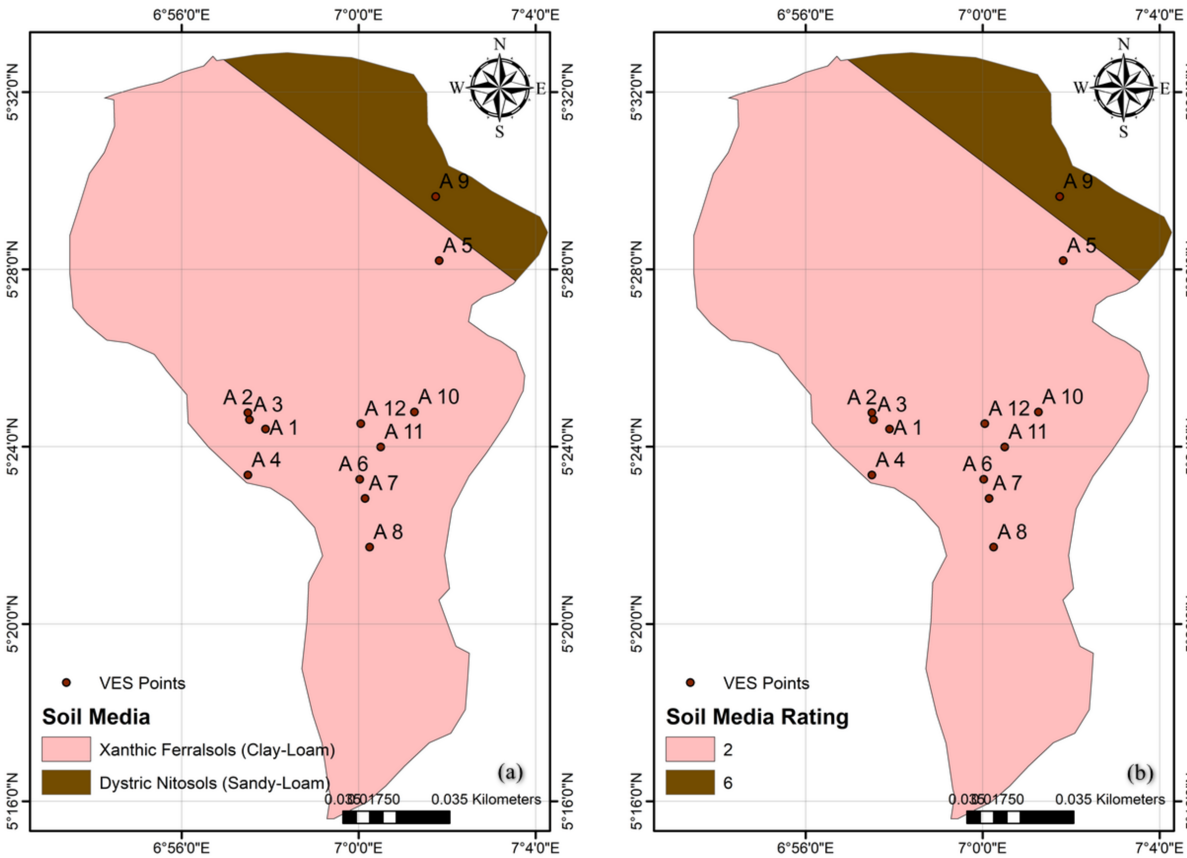


Figure 7. Distribution of (a) soil media and (b) soil media rating with the VES points in the study area

4.5. Topography

Topography refers to the Earth's surface's inclination, with regions with little incline preventing precipitation movement, resulting in slower water flow and facilitating pollutant infiltration into the water table, making these regions more susceptible to contamination based on soil substrate characteristics.

The slope percentage in the research region was derived using the ASTER digital elevation model (DEM). The slope was subsequently assigned numerical values ranging from 1 to 10. The picture map presented in Figure 8a depicts the topographical index within the designated research region. Figure 8b illustrates the presence of a diverse topographical index within the area, which ranges from values of 1, 3, 6, 9, and 10.

The findings suggest that a significant portion of the research region exhibits a low rate of runoff water. This phenomenon will facilitate the efficient infiltration of pollutants into the water table, thereby resulting in a heightened susceptibility of groundwater to contamination.

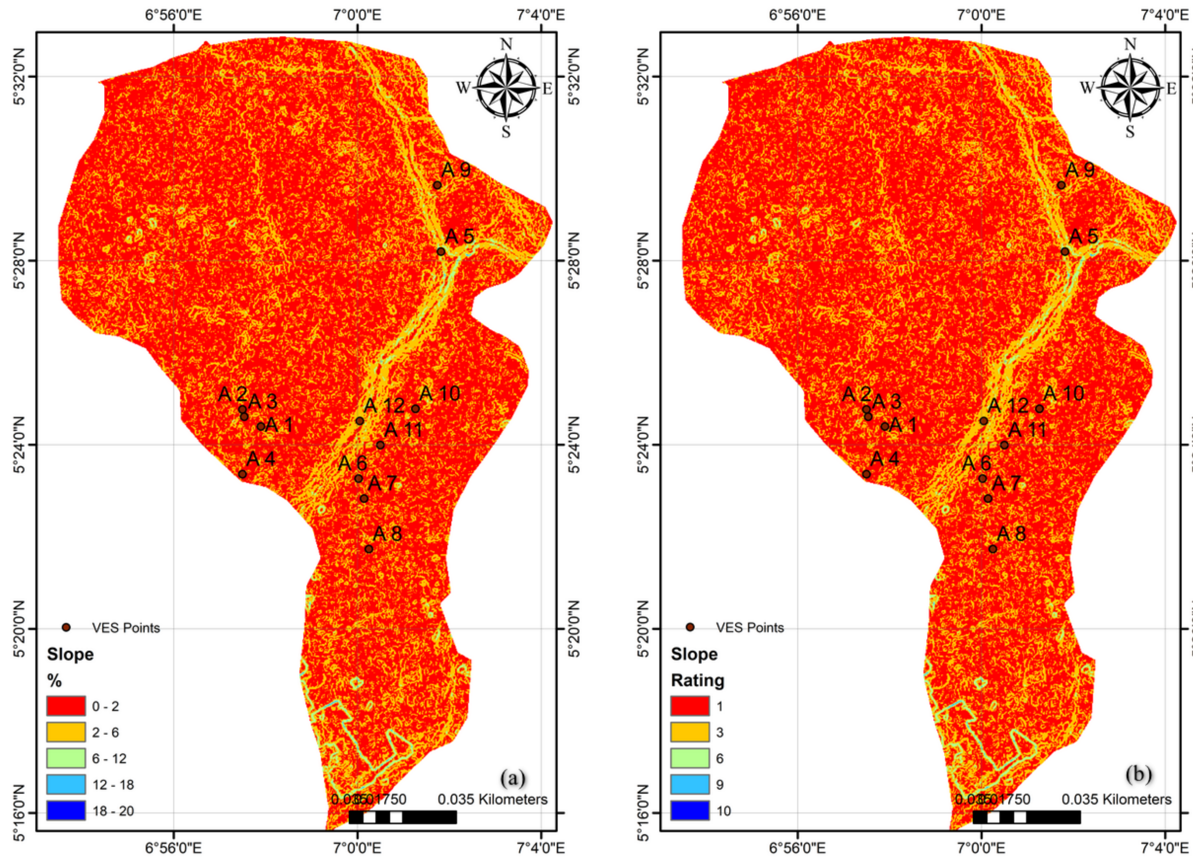


Figure 8. Distribution of (a) slope and (b) slope rating with the VES points in the study area

4.6. Impact of Vadose Zone

The vadose zone, above the water table, is crucial for rainwater percolation into the aquifer layer. It can significantly influence the movement of polluted fluids if it contains porous or permeable substances like sand and gravel. The present study aimed to analyse the geomaterials present in the vadose zone. This analysis was conducted by interpreting the geological lithological data obtained from the VES interpretation. It was observed that the studied region predominantly consisted of sand, as seen in Figure 9a. The vadose zone index within the research region has a range of 8, as seen in Figure 9b.

The studied region has a high vadose zone index, suggesting a significant susceptibility to surface pollutants. The significantly elevated indices are indicative of a proportionally elevated level of pollutants present in the water table, therefore resulting in a heightened susceptibility of groundwater.

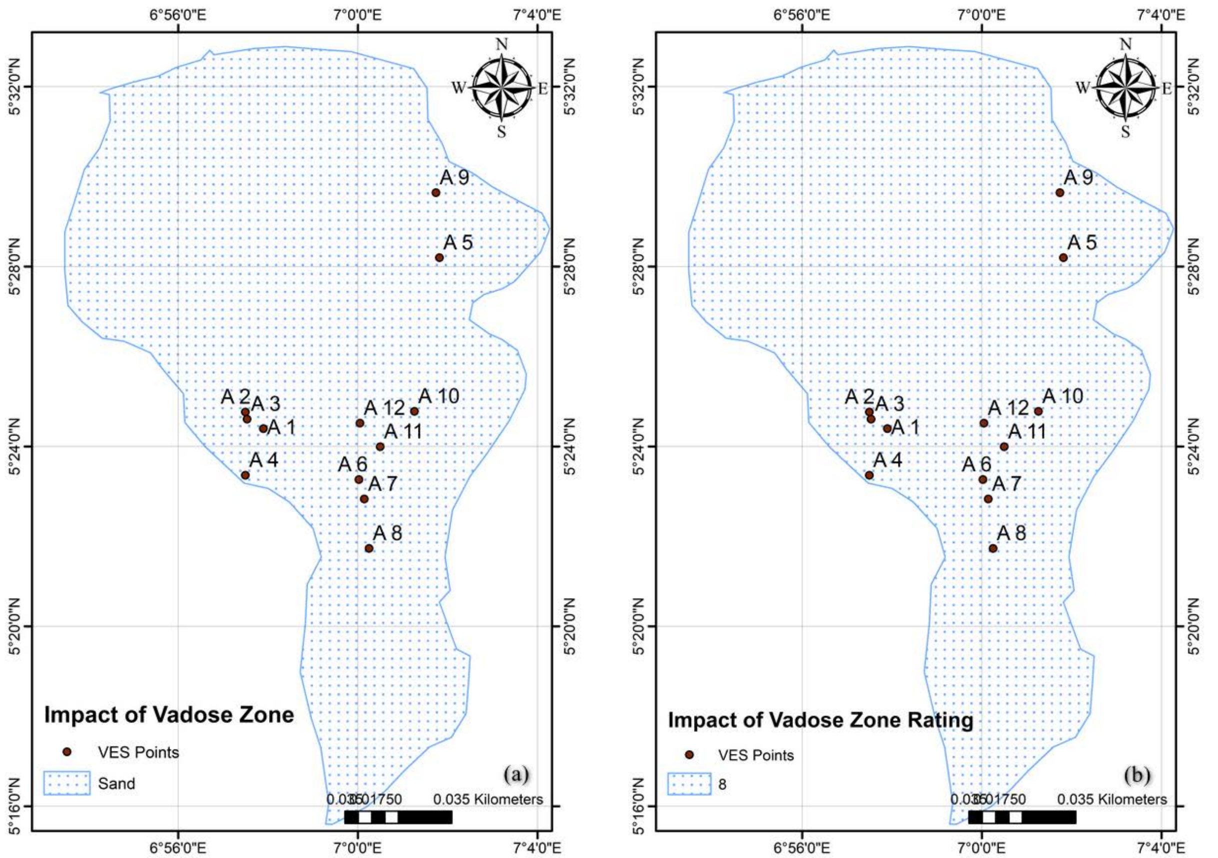


Figure 9. Distribution of (a) impact of vadose zone and (b) impact of vadose zone rating with the VES points in the study area

4.7. Hydraulic Conductivity

The hydraulic conductivity of an aquifer is a fundamental characteristic that governs the flow rate of groundwater and the transport of pollutants within it. The study's estimation of the range of values for the variable in question was found to be between 0.5085 and 0.6603 metres per day, as indicated in Table 3. The distribution of hydraulic conductivity with the VES locations in the research region is illustrated in Figure 10a. The parameter in question has a weight of 3, as indicated by the VES points depicted in Figure 10b within the designated research region.

The presence of a wide range of hydraulic conductivity values suggests a corresponding variety in the grain size of the geomaterial elements within the aquifer units in the studied region. The studied region has a low hydraulic conductivity index, which is indicative of a high sensitivity of groundwater.

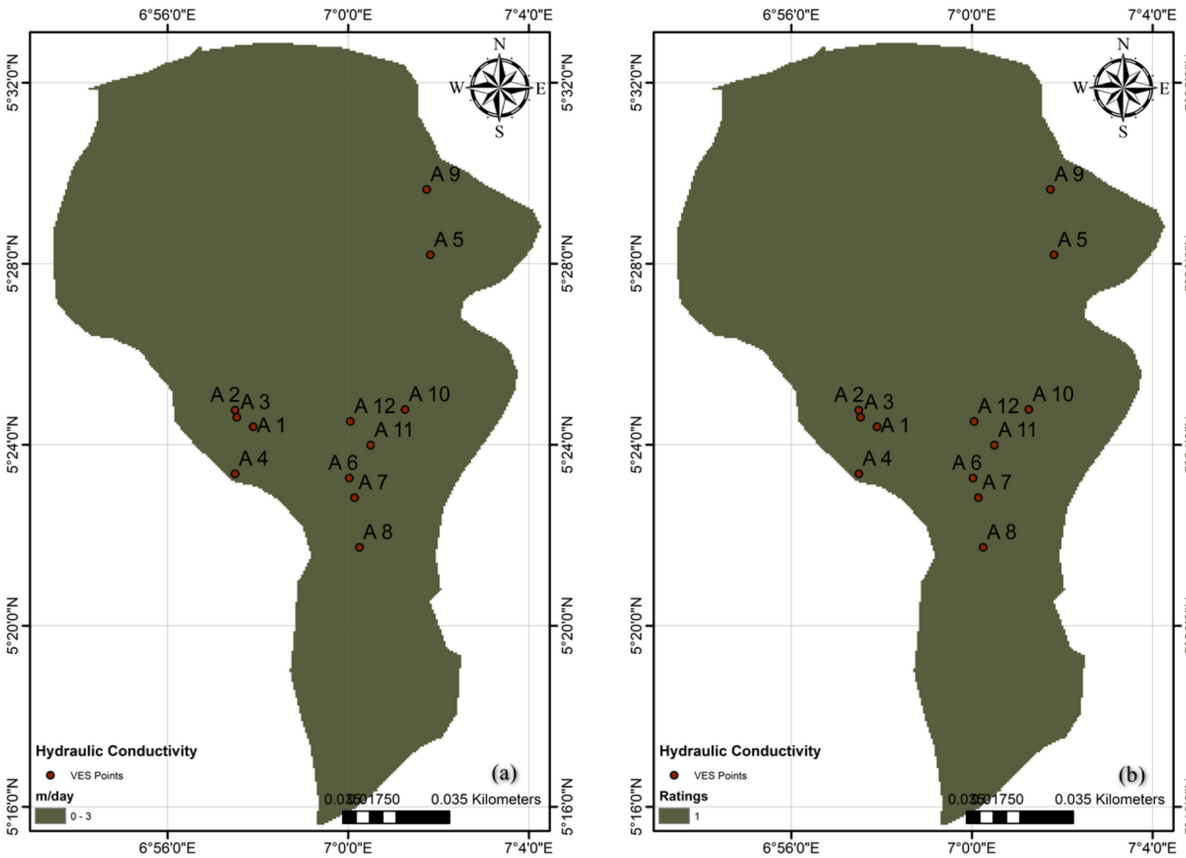


Figure 10. Distribution of (a) hydraulic conductivity and (b) hydraulic conductivity rating with the VES points in the study area

4.8. DRASTIC Index (DI)

The susceptibility of groundwater in the research region was assessed by calculating the DI and Groundwater vulnerability rating (GVR) using the seven criteria previously mentioned. The DI was determined by doing separate evaluations of each VES point, as seen in Figure 11.

The DI values were subsequently classified into three distinct categories based on their vulnerability levels: low vulnerability, moderate vulnerability, and high vulnerability. Based on the findings of the GVR analysis, it is seen that almost 49% of the designated research area can be categorised as exhibiting high vulnerability, around 45% can be classed as demonstrating moderate vulnerability, while the remaining 6% is characterised as displaying low vulnerability.

Moderate to high sensitivity zones in a region are caused by lower slope terrains and high permeability of sands above the aquifer, which allow pollutants to permeate rapidly, increasing groundwater vulnerability to pollution or contamination. Understanding hazards and implementing efficient management and monitoring techniques are crucial to protect the integrity and accessibility of groundwater resources, especially in areas highly susceptible to contamination.

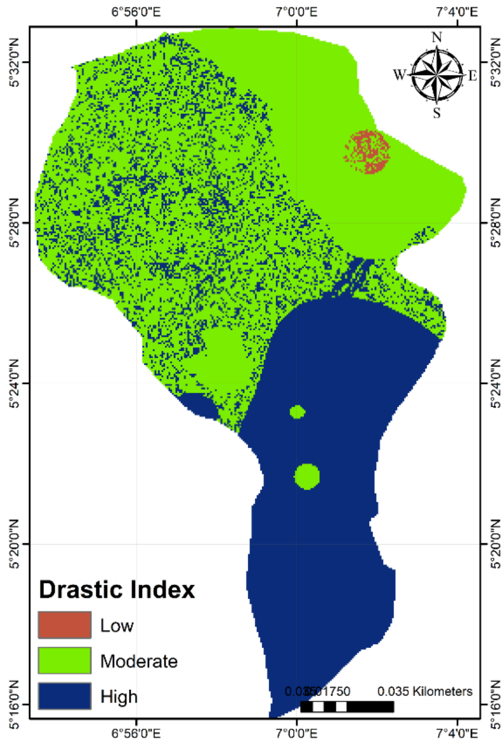


Figure 11. DRASTIC Index in the study area

The combination of DI and GVR mapping approaches offers significant contributions to understanding the spatial patterns of groundwater vulnerability. This integration facilitates the acquisition of crucial information necessary for making well-informed decisions about the sustainable management of groundwater resources and the preservation of the environment. To guarantee the preservation of clean and secure groundwater resources for present and future generations, it is imperative to prioritise further research and mitigation measures in regions that have been identified as extremely susceptible.

5. Conclusion

The primary purpose of this study was to determine how vulnerable the groundwater was in southern Nigeria's Owerri town and adjacent regions. This assessment was carried out using the

DRASTIC model and Geographic Information System (GIS) techniques. The research area consisted of six to seven sand-filled layers, with the sixth layer being the most economically viable for extraction. The DRASTIC model considered seven critical environmental characteristics, including hydraulic conductivity, net recharge, aquifer medium, terrain, and water table depth. The analysis discovered that 49% of the chosen research territory had a considerable level of groundwater vulnerability (GVR). The area's topography, which is defined by a low slope landscape composed mostly of sandy shallow strata with high permeability located above the water table, might be the primary cause of this sensitivity. Because of the geological properties of the location, surface pollutants might easily enter groundwater, increasing the danger of pollution.

According to an analysis of numerous environmental conditions, the key elements that substantially impact groundwater sensitivity are aquifer media, depth to the water table, and terrain. The aquifer medium was shown to be the second most significant likely source of groundwater pollution, after the depth to the water table. On the other hand, it can be proved that the hydraulic conductivity of the aquifer had the least impact on the final DRASTIC score. The GVR map was constructed by merging the DI data gathered from each VES location. The obtained DI values were then classified into three vulnerability categories: low vulnerability, moderate vulnerability, and high vulnerability. According to the GVR study, 49% of the research area was classed as high risk, while 45% was rated as intermediate susceptibility. The remaining 6% of the research region was assessed low vulnerability.

The vulnerability rating map identified high groundwater susceptibility areas in Owerri, highlighting areas where aquifers are not adequately protected from pollution. The vulnerability rating map is useful for identifying regions at risk of groundwater pollution, but it doesn't replace site-specific hydrogeological studies. More research is needed to improve the validity of these studies and understand groundwater quality. Local governments can protect water sources, public health, and the environment by implementing proactive groundwater management strategies. Monitoring and reassessing groundwater sensitivity is crucial for adaptation to changing conditions and pollution sources.

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