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RESEARCH ARTICLE

RELIABILITY OF GEOSPATIAL PARAMETRIC MODELS IN AQUIFER SUSCEPTIBILITY MAPPING: CASE STUDY OF ILE OLUJI SOUTHWESTERN NIGERIA

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ABSTRACT

The usefulness of groundwater vulnerability mapping cannot be overemphasized in planning, policy formulation and decision-making for groundwater management and protection. The present study employed geographic information system based overlay and index methods (DRASTIC, DRASTIC-LU, GOD and AVI models) in assessing and mapping groundwater vulnerability zones in Ile Oluji area of Ondo State, Southwestern Nigeria. The models' parameters were prepared using hydrogeological (well/borehole) data, geophysical data, and satellite imageries. The weightage of different parameters was done using analytical hierarchy process. The DRASTIC map classified the area into the low vulnerability (30 % of the area), moderate (4%), high-vulnerability zone (60 %), and very high vulnerability zone (6 %). The DRASTIC-LU distinguished the area into high – very high groundwater vulnerability zone (90 %), while low – moderately low area has 10 % aerial extent. The GOD and AVI models, categorized the vulnerable areas into quite low (<0.03) to low (0.03 – 0.3); and high (0.98 – 1.85) to extremely high (<0.98) vulnerability zones respectively. As a result, the DRASTIC, DRASTIC-LU, and AVI models all showed predominate high vulnerability zone, which was also confirmed by the nitrate map. The index values in the DRASTIC and DRASTIC-LU models revealed significant overlap. Therefore, in the research region, slope, hydraulic conductivity, net recharge, soil medium, and depth to water level are the factors that have the greatest influence on groundwater quality. Due to the significant number of highly vulnerable places, the aquifers must be protected immediately.

KEYWORDS

AHP, geophysical data, hydrogeological measurement, Ile Oluji, DRASTIC-LU

1. INTRODUCTION

One of the most significant sources of fresh water is groundwater, accounting for 0.61% of global water resources and 20% of global fresh water supply (Krenkel, 2012; Delleur, 2010; Adagunodo et al., 2018; Fetter, 2007; Freeze and Cherry, 1979), but many aquifers are facing increased pollution due to human activity, mining, and population growth (Narayanan, 2011; Oyebode et al., 2019; Oyedele et al., 2018; Okorobia et al., 2020). As a result, water quality has emerged as a critical problem in terms of management and monitoring, particularly in urban areas (Mohamed et al., 2016; USEPA, 2014; Cosgrove and Loucks, 2015; Falowo et al., 2020; Jijingi et al., 2019). This has necessitated for the need to carry out groundwater vulnerability studies arose as a result of the fact that contaminants entering the subsurface aquifer might pollute groundwater (Eshtawi et al., 2016; Ezenwaji and Ezenweani, 2019), despite the fact that it is assumed that groundwater is protected from natural or human activities by the physical environment (Schwartz and Zhang, 2003; Domenico and Schwartz, 1990). An aquifer's susceptibility to pollution is known as groundwater vulnerability. or the measure of pollution at the ground surface's tendency to contaminate/reach an aquifer. (Van-Stempvoort, 1992; Jhariya et al., 2019; Mogaji et al., 2014). Alternatively, it is the potential for contaminants to percolate and diffuse from the ground surface into naturally occurring water table reservoirs. This insulation provided by natural and artificial factors helps to keep contaminants out of groundwater. Therefore, groundwater is vulnerable to contamination from operations at the land surface if natural barriers offer little to no protection (Hiscock, 2003; Olojoku et al., 2017; Abad et al., 2017; Jang et al., 2017). Therefore, regardless of the current source of contamination, vulnerability is defined as the level of danger to an aquifer determined by natural conditions (Hiscock, 2003). A non-measurable, dimensionless feature called vulnerability can be utilized to locate polluted places.

The key factors in determining groundwater vulnerability include the nature of the saturated zone, including whether or not it is accessible to the hydraulic penetration of pollutants, the capacity of the strata above the saturated zone to attenuate pollutants through physicochemical retention or reaction, and the thickness and hydraulic characteristics of the geologic formations above the aquifer (Ribeiro, 2000; Oni and Akinlalu, 2017). In actuality, the unsaturated zone regulates an aquifer's susceptibility by preventing pathogenic viruses and bacteria from entering, sorbing, and destroying them; sorbing and degrading many synthetic organic chemicals; attenuating heavy metals and other inorganic chemicals through sorption; complexing with mineral surfaces within the unsaturated zone; and uptake into plants and crops (Ribeiro, 2000; Srivastava et al., 2016). Based on the nature of the contaminants in connection to the aquifer unit, aquifer vulnerability assessments may be separated into two kinds: intrinsic and specific vulnerability studies. While the specific vulnerability assessment describes groundwater vulnerability to pollutants based solely on contaminant properties, the intrinsic groundwater vulnerability mapping defines the aquifer and its susceptibility to pollutants on the basis of its inherent characteristics (geological and hydrogeological parameters) (Khemiri et al., 2013; Falowo et al., 2017). Several groundwater vulnerability techniques have been

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developed over the last five decades, and they may be characterized as statistical models, process-based simulation models, and index-based models, which include hybrid, non-parametric, and parametric models. Parametric models are classified as pragmatic (DRASTIC, SINTACS, SEEPAGE, EPIK) or classical (GOD, AVI, SI, GLA, and PI).

The most widely used ground-water vulnerability mapping method is DRASTIC (Barbulescu, 2020; Kozlowski and Sodja, 2019), named after the seven factors considered in the method: depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone media, and hydraulic conductivity of the aquifer (Malakootian and Nozari, 2020; Paul and Das, 2019; Shah et al., 2021). The DRASTIC technique has been used to create ground-water vulnerability maps in numerous parts of the world and for various aquifer types, but its effectiveness has been variable. The fundamental weakness of the DRASTIC technique is its inherent subjectivity in constructing rating scales and weighting coefficients. SINTACS model evaluates seven parameters (Kumar et al., 2013), which include water table depth (S), effective infiltration (I), unsaturated zone (N), soil media (T), aquifer media (A), hydraulic conductivity zone (C), and topographic slope (S) are all elements included by the SINTACS model (Kuisi et al., 2006). EPIK is a parameter weighting and rating method particularly intended for karst aquifers in order to protect water supply sources (springs and wells). It is recommended for areas having karst features (Saefl, 2000; Doerfliger et al., 1999; Daly et al., 2002; Goldscheider, 2002). A thorough evaluation of these parameters, however, is necessary, which is often complex, costly, and time consuming because it requires field work, geophysical, isotopic, and hydrological research, hydraulic character analysis, and so on. According to Olojoku et al. (2017), the AVI (Van-Stempvoort et al., 1993) uses hydraulic resiliency against vertical water movement through layer of protection to quantify vulnerability. The AVI method is based on the protective layer's characteristics, which have been identified as the key factor in determining aquifer vulnerability (Ekwere and Edet, 2017). Aquifer vulnerability is determined using the suggested hydraulic conductive ability of the protective layer (k) and the hydraulic resistance (c) for every sedimentary layer above the uppermost aquifer, known as (d).

As a means of determining susceptibility, the GOD model (Foster, 1987; Foster and Hirata, 1988) examines three hydrogeologic parameters: groundwater occurrence, overall lithology, and depth to groundwater (GOD). It is assigned a number between 0 and 1, with the total value determined by combining the three elements together. One advantage of the GOD technique is that, with the exception of karst, it could be utilized to any kind of aquifer formation (Foster, 1998). Factor "D" is overestimated, which is one of the method's disadvantages. All of these models are tools for collecting complicated hydrogeological data into a single piece of literature that design professionals, administrators, geoscientists, and the wider public may utilize because most lithologies have equivalent vulnerability levels.

Ile oluji is one of the fastest developing towns in Ondo State, Nigeria, thanks to the construction of the Federal Polytechnic and other government facilities/infrastructures nearby. Small and medium-sized businesses/industry, as well as residential development, have flocked to the area. As a result, the region's present groundwater delivery system has become overburdened, necessitating groundwater monitoring and conservation. In the area, most toxins soak into the ground and, if hydrogeological conditions permit, may percolate into the aquifer (Nas and Berktay, 2010; Norouzi and Moghaddam, 2020). As a result, determined practical actions, strategies, and solutions are necessary to protect the aquifer system in the study area. Subsequently, the broad objectives of this research is to assess groundwater vulnerability in Ondo State's Ile Oluji area utilizing the AVI, GOD, DRASTIC, and modified DRASTIC models, specifically DRASTIC-LU, with the weights of the elements analyzed established using the analytical hierarchy process (AHP); produce a vulnerability map of the area using overlay analysis to highlight areas of very high, high, moderate, low and very low risk to contamination; and to conduct sensitivity analysis (Ewusi et al., 2017; Maria, 2018) on the effective and theoretical weight of the DRASTIC/DRASTIC-LU parameters.

In addition, all the models would be subjected to comparative analysis and validation (using concentration of nitrate), for the evaluation of groundwater protective capacity in the area (Oroji, 2018). The AHP (Saaty, 1980) has been established based on the separation and breakdown of complex issues into simpler parameters and sub-parameters. In this method, parameters are binary compared to one another and are valued the relative weights of each parameter are calculated from the resulting matrix. The AHP reduces the complexity of the decision problem by considering two parameters/factors at the same time, with each parameter being scored based on its relative influence/importance on the pollution potential assessment. According to Saaty (1980), the comparison scores range from 1 to 9. Thus, the study would delineate the areas of the study area where groundwater is prone to contamination due to anthropogenic and geogenic factors in the form of groundwater vulnerability map using the aforementioned models. The modeled groundwater susceptibility map will separates the area into numerous hydrogeological zones with different vulnerability intensities.

2. Location and geology Setting

The research location is located between 704800 and 708800 meters east, and 793350 and 809900 meters north (Figure 1). It is bounded by Ipetu-Ijesa, Ondo East/West, Ifetedo, Okeigbo, and Ifedore local governments. The region is defined by the Otasun Hills, Ikeji Hills, Okurughu, Oni, and Awo Rivers (Adebawore et al., 2017). It has a population of roughly 300,000 people and a land area of 600 km2. The scenery in Ile-Oluji is separated into three types: plains, undulating hills, and river valleys. The mountains, on the other hand, dominate the landscape. The settlement is well-constructed (Figure 2a), and the soil is ferric luvisols, Figure 2b depicts this. Luvisols are soils with significant textural changes within the soil profile, with clay draining from the top horizon and clay accumulating in a subsurface "Argic" horizon. Luvisols have strong clay activity and no sudden textural alterations, however ferric luvisols have ferric characteristics. The area is surrounded by many granite boulders, including Ota-Ororo, Ota-Akoko, Ota-Didu, Ota-Upote, and Iguruguru (Adebawore et al., 2017). The town serves as the headquarters of Ile-Oluji/Okeigbo Local Government.

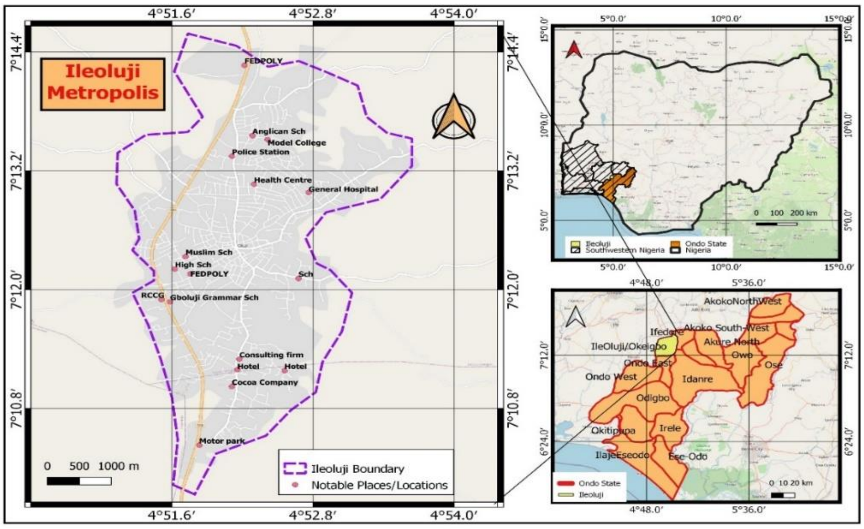


Figure 1: Map showing the Study Area's location in relation to Ondo State and Nigeria

One of Nigeria's major centers for cocoa production and exportation is the agravian town of Ile Oluji. The main crops grown by farmers in the town are cassava, yam, maize, and oil palm. Cocoa Products Ile Oluji Limited is the town's main manufacturer. The Federal Polytechnic, Ile Oluji is a significant tertiary institution in the community, while Gboluji Grammar School—one of the oldest secondary schools in Nigeria—is the area's prominent high school. There are distinct wet and dry seasons in the tropical rain forest where the research region is located. The yearly rainfall ranges from 1400 to 1800 millimeters. According to Iloeje (1981), the average temperature is 27°C and ranges from 24.5°C in July to 29.5°C in February. Precambrian basement rocks are concealed underneath the study area (Figures 2 and 3). Granites, quartzite, and migmatite-gneiss were among the local geological rock types that could be identified from specimens. The two that are most common are granite gneiss and quartzite (ridges), with granite gneiss showing up as intrusive, low-lying formations (Figure 4). Field investigation reveals the presence of joints, fractures, or fissures within the bedrock. As a result, these characteristics are more likely at greater depths since they are a characteristic of the basement complex (i.e., fault, nascent joints, and fracture systems) brought about by ongoing tectonic/orogenic processes. The fractured zone and weathered layer are the primary aquiferous components in typical basement settings. Among the rocks mapped in the research area are granite, gneiss, and migmatite (Figure 4).

Quartz, feldspar, and accessory mica (muscovite, biotite) are abundant in granitic rocks, as are amphiboles (hornblende), augite, hyperstene, magnetic, apatite, garnet, and tourmaline (Obaje, 2009). Their texture ranged from medium to coarse grained, with some showing porphyritic characteristics (Figure 3a). Gneisses are foliated metamorphic rocks that are megascopically crystalline. Mineral segregation into layers or bands of differing color, texture, and composition distinguishes them. Mica, feldspar, hornblende, and quartz are common minerals. The texture is medium to gritty, and the mineral arrangement is poor. Bands of micaceous minerals alternate with bands of equidimensional minerals such as feldspar and quartz in gneisses (Figure 4). Migmatite are mixed rocks that are extensively dispersed in the research area and consist of closely linked igneous (granitic rock) and metamorphic (gneisses) components. The drainage network and catchment area are depicted in Figure 5. The area is well drained by a few river systems, with a large catchment area, especially in the north.

3. Methodology

In the present investigation, the study area's vulnerability was assessed using the AVI, DRASTIC, GOD, DRASTIC-LU, and GOD. These models are used to compare and analyze the area's aquifer units' and/or vadose zone's protective capabilities.

3.1 DRASTIC and DRASTIC-LU Models

Seven hydrogeological characteristics—Depth of Water Table, Net Recharge, Aquifer Media, Soil Type, Topography, Impact of Vadose Zone, and Hydraulic Conductivity—are used in the DRASTIC model, which control groundwater movement within the subsurface. Land use/cover [LU] is then added to the DRASTIC parameters to produce DRASTIC-LU. The overall pollution potential (DRASTIC and DRASTIC-LU indexes) are established by applying the formula:

$$\text{Drastic Index} = D_R \times D_W + R_R \times R_W + A_R \times A_W + S_R \times S_W + T_R \times T_W + I_R \times I_W + C_R \times C_W$$

$$\text{Drastic} - \text{LU Index} = D_R \times D_W + R_R \times R_W + A_R \times A_W + S_R \times S_W + T_R \times T_W + I_R \times I_W + C_R \times C_W \times LU_R \times LU_W$$

where "W" stands for weight and "R" for rating. Based on these attributes' susceptibility to contaminants, weights and grades are assigned to them. The grading and weighting factors range from 1 to 5, with 1 being the least important and 10 being the most crucial. In the multi-criteria decision analysis (MCDA), all parameters were weighted and rated using the AHP (Saaty, 1980; Vargas, 1990).

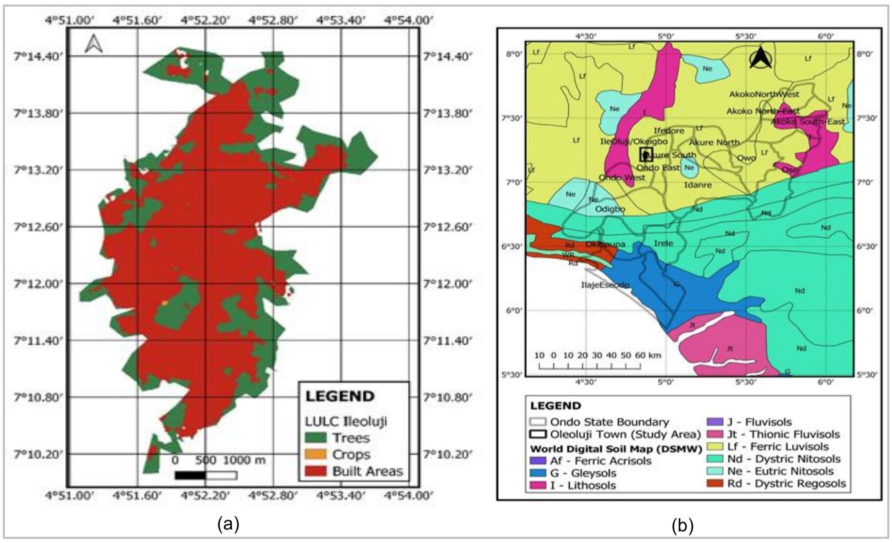


Figure 2: (a) The research area's land use and land cover, which is mostly an urbanized region, is shown in (a); (b) the study area is located on ferric luvisols on the soil map of southwest Nigeria. Adapted from FAO/DSMW and Living Atlas, both of which were published in 2020.

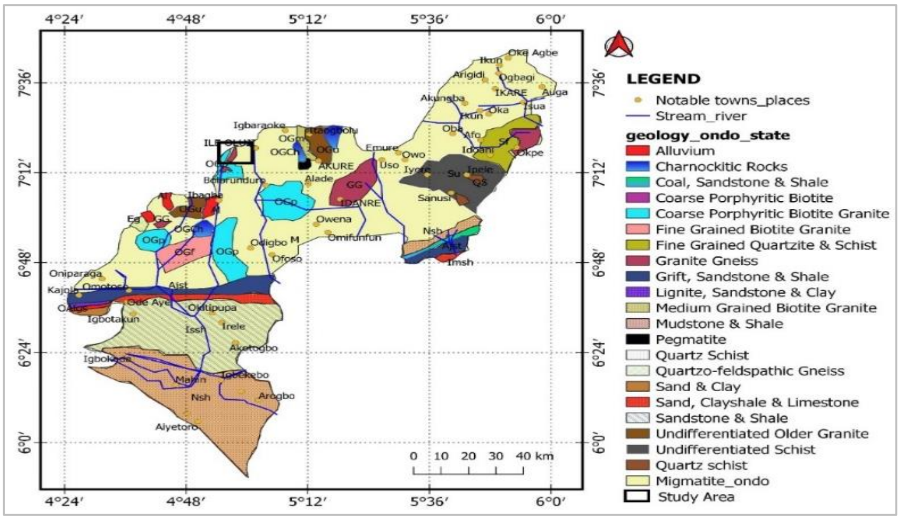
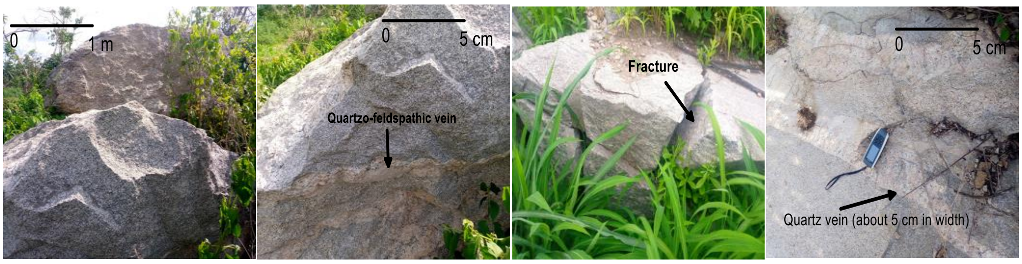


Figure 3: Map of Ondo State's geology highlighting the study area, which is located in Nigeria's Southwestern Basement Complex and has migmatite as its primary rock block. (Modified in light of NGSA, 2006).



(a) Surface exposures and outcrops of granite at different locations having being subjected to intense weathering, some occuring as boulders with noticeable fractures/fissures. In addition feldspathic and quartzo-feldspathic intrusion are observed

(b) Surface exposures and outcrops of migmatites and granite gneiss at different locations having being subjected to intense weathering, with noticeable fractures/fissures. In addition feldspathic and quartzo-feldspathic intrusion are also observed

Figure 4: Surface exposure/outcrops of (a) granite (b) gneiss, and migmatite observed in the study area

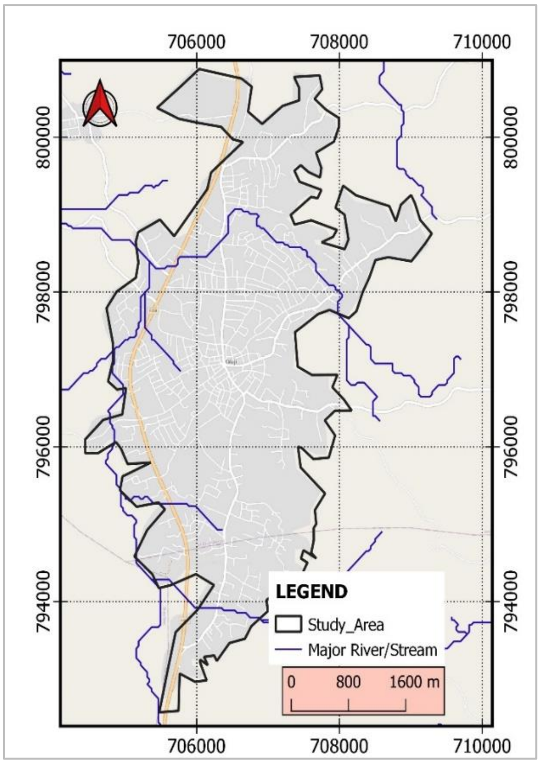


Figure 5: Study's drainage map, highlighting the main river or stream

In the determination of consistency index (CI), equation 1 was adopted (Saaty, 2006). It is the random consistency index of a pairwise comparison matrix (Saaty, 2008, 1990), as illustrated in Table 1.

$$CI = \frac{\gamma_{max} - n}{n-1} \quad (1)$$

where "n" is the number of parameters that are being compared. The acquired weights (w) were then used to rate the parameters (Table 8).

The DRASTIC/DRASTIC-LU parameters were evaluated in the following manner:

a) Depth to Water: This influences how much time a pollutant is required to go through chemical and biological reactions such as dispersion, oxidation, natural attenuation, and sorption. (Karanth, 1989; Hiscock, 2005). Therefore, the lesser the depth, more rapid the transit time, and hence higher the chance of groundwater contamination (Kruseman and de Ridder, 1991). A small depth to water trait corresponds to a greater threat rating, and vice versa. As a consequence, Table 2 displays the degree of importance and value assigned to this attribute. The depth to water values for this study were acquired from 58 water wells and five (5) boreholes (Figure 6), with regions lacking data estimated in QGIS using the Inverse Distance Weighting (IDW) interpolation technique.

b) [N]et Recharge: This is the volume of water that enters the groundwater reservoir, sometimes referred to as the phreatic zone, from the surface of the land. Recharge is a key avenue for contamination transmission because it alters pollutants and toxins that enter the aquifer system (Karanth, 1989; Hiscock, 2005). The Piscopo technique (2001) based on rainfall data, slope and soil permeability, was used to calculate net recharge (Equation 2; Tables 2 and 3).

Recharge = Slope factor + Rainfall factor + Soil permeability factor (2)

c) [A]quifer Media: This is a reference to the consolidated/unconsolidated rock/soil units that will provide enough water below the surface of the earth (Aller et al. 1987). The connection between aquifer media and risk assessment involves several crucial aquifer features, including hydraulic ones as permeability, porosity etc.

Table 1: Random CI Values for The Number of Parameters (N) and Related Random Values (RV) (after Saaty, 2006)

N	1	2	3	4	5	6	7	8	9	10
RV	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

Table 2: The Summary of The Method Used to Assess the Research Area's Sensitivity to Pollution.

Criterion	Classes	Degree of Vulnerability	Rating (AHP standardized values)	Standardized Assigned Weight	Data Sources
Depth to Water (m)	<1.5	Very high	10	5	Well inventory and SWL measurement
	1.5-3.0	High	9		
	3.0-4.5	Medium	5		
	4.5-6.0	Low	3		
	>6.0	Very low	1		
Net Recharge	11-13	Very high	10	4	Slope map, rainfall, hydraulic conductivity data
	9-11	High	8		
	7-9	Medium	5		
	5-7	Low	3		
	3-5	Quite low	1		
Aquifer Media	Fractured rock	Extremely high	10	3	VES
	Sand	High	8		
	Sandy clay	Medium	5		
	Clay sand	Low	3		
	clay	Very low	1		
Soil Media	Gravel	Extremely high	10	2	Soil map (DSMW)
	Sand	Very high	9		
	Shrinking aggregated clay	High	7		
	Clay sand	Moderately high	6		
	Loamy soil	Moderate	5		
	Sandy clay	Low	3		
	Non shrinking/non-aggregated clay	Very low	1		
Topography/ (% Slope)	0-2	Very high	10	1	ASTER DEM
	2-6	High	9		
	6-12	Medium	5		
	12-18	Low	3		
	>18	Very low	1		
Impact of the vadose zone	Sand/Gravel	Very high	10	5	VES / Borehole data
	Sandy clay or silt	High	7		
	Clay sand	Medium	5		
	Laterite	Low	2		
	Clay	Very low	1		
Hydraulic Conductivity (m/day)	<1.0	Very low	1	3	Borehole/well pumping test
	1.0-5.0	Low	3		
	5-20	Medium	5		
	20-50	High	7		
	>50	Very high	10		
Land use / cover	Flooded vegetation	Very High	10	5	Landcover map of the world
	Bare land	High	9		
	Built-up	Moderately high	8		
	Agricultural areas	Moderate	6		
	Grass land	Low	2		

Table 3: Net Recharge Calculation (Modified from Piscopo, 2001)								
Slope %		Rainfall (mm)		Soil Permeability		Net Recharge		
Range	Factor	Range	Factor	Range	Factor	Range	Factor	Vulnerability
<2	4	<500	1	Very slow	1	11-13	10	Very high
2-10	3	500-750	2	Slow	2	9-11	8	High
10-33	2	750-850	3	Moderate	3	7-9	5	Medium
>33	1	>850	4	Moderately high	4	5-7	3	Low
				High	5	3-5	1	Very low

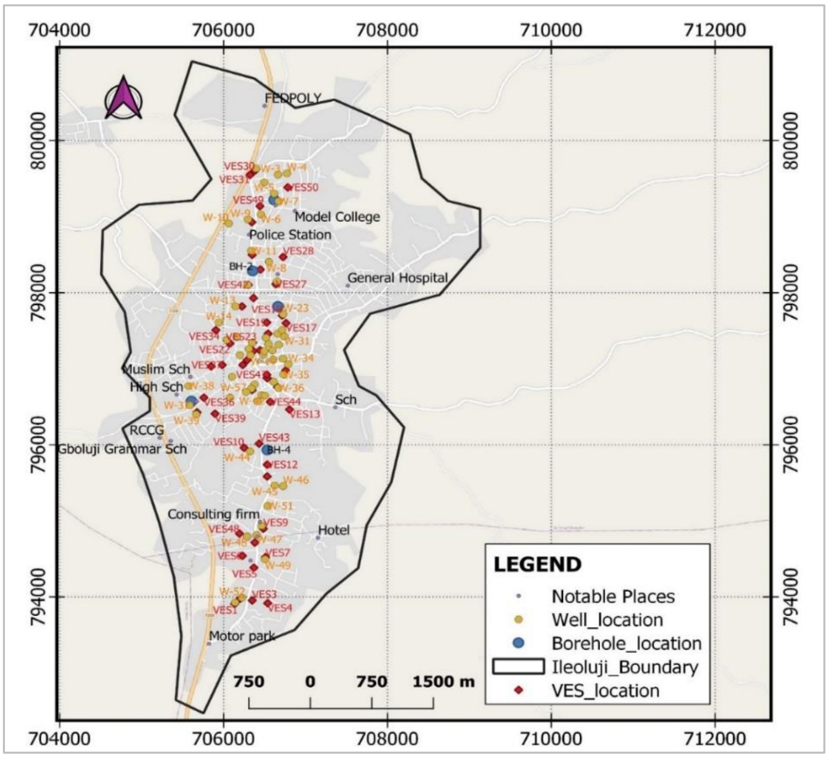


Figure 6: Field Data Collection Map Shows The Locations Of Boreholes, Open Wells, and VES For Determining Depth To Water Level, Aquifer Media, The Impact Of The Vadose Zone, And Hydraulic Conductivity.

This number was obtained by carrying out vertical electrical sounding at fifty different places following Falowo's 2022 procedures, and pumping test in five boreholes (Figure 6). A region with high permeability is more vulnerable to pollutants. Table 2 showed the aquifer media's vulnerability rating, and classification.

d) Soil Media: Soil is the highest section of the earth's weathered zone with an average thickness of 1m. The digital soil map of the world (DSMW, 2020) was modified in QGIS using the spatial analyst tools. The soil media was given a weight of 2, and other assessment indices and class are shown in Table 2.

e) Topography: This is the surface slope. The slope of a location influences the quantity of runoff and the rate of absorption capability of the soil. A low gradient is likely to reduce run-off, thereby boosting pollutants penetration. Areas with a higher gradient, on the other hand, increases run-off, and reduces infiltration; disallowing toxins to flow through the vadose zone and reach the groundwater, hence decreasing contaminant penetration. In this study, digital elevation map with a precision of 30 m was employed using QGIS; while the parameter's assessment was done using Table 2.

f) Impact of Vadose Zone: This is the portion of the earth's crust that is generally above the water table and is unsaturated. The composition of the vadose zone has a direct relationship with groundwater susceptibility because extremely permeable vadose material will have a high vulnerability potential or rating. The degree to which pollutants are attenuated in the vadose by biological and chemical processes determines the extent to which they reach the water table (Wilson, 1983). The vadose zone vulnerability was assessed using Table 2, with the data derived from VES and hydrogeological data of fifty eight water wells.

g) Hydraulic Conductivity: Hydraulic conductivity (K) controls the rate at which soluble contaminants are transported in groundwater flow (Karanth, 1989; Domenico and Schwartz, 1990); and it's a function of void spaces within the aquifer (Fetter, 2007). The "K' of the aquifer was sought out by pumping test from fifty eight open wells and five boreholes (Figure 6). Typical graph is shown in Figure 7. The assessment criteria, classification, and attached rating is shown in Table 2.

h) [LU] - Land Use: The land usage in the region was divided into barren land, flooded vegetation, grassland, built-up area, agricultural area, and flooded vegetation. High concentrations of submerged vegetation, vacant land, and urbanized regions present a high risk of soil and groundwater pollution, whereas agrarian or grassy land is expected to contribute significantly less to groundwater pollution due to surface cover. The digitized Landsat satellite imagery map of the world's land cover was obtained from Living Atlas (2010) and modified in QGIS. The land use/cover was weighted, rated and divided into classes using Table 2

3.2 GOD – Model

The GOD approach refers to three parameters: groundwater presence, overlying lithology, and depth to water table (Foster and Hirata, 1988; Foster et al., 2002). It is an index/overlay technique for mapping groundwater susceptibility as a result of vertical inflow across broad regions that uses an overlay and index technique.

The GOD is determined using equation 3:

$$GOD\ Index = C_l \times C_a \times C_d \quad (3)$$

Where C_l is the lithology, C_a is the aquifer type, and C_d is the depth to aquifer.

For this study, the results of the VES, hydrogeological measurements from fifty eight open wells and five boreholes were used to obtain different values for these parameters. Table 4 shows the accepted vulnerability interval values and accompanying classes, while Table 5 shows the parameter ratings.

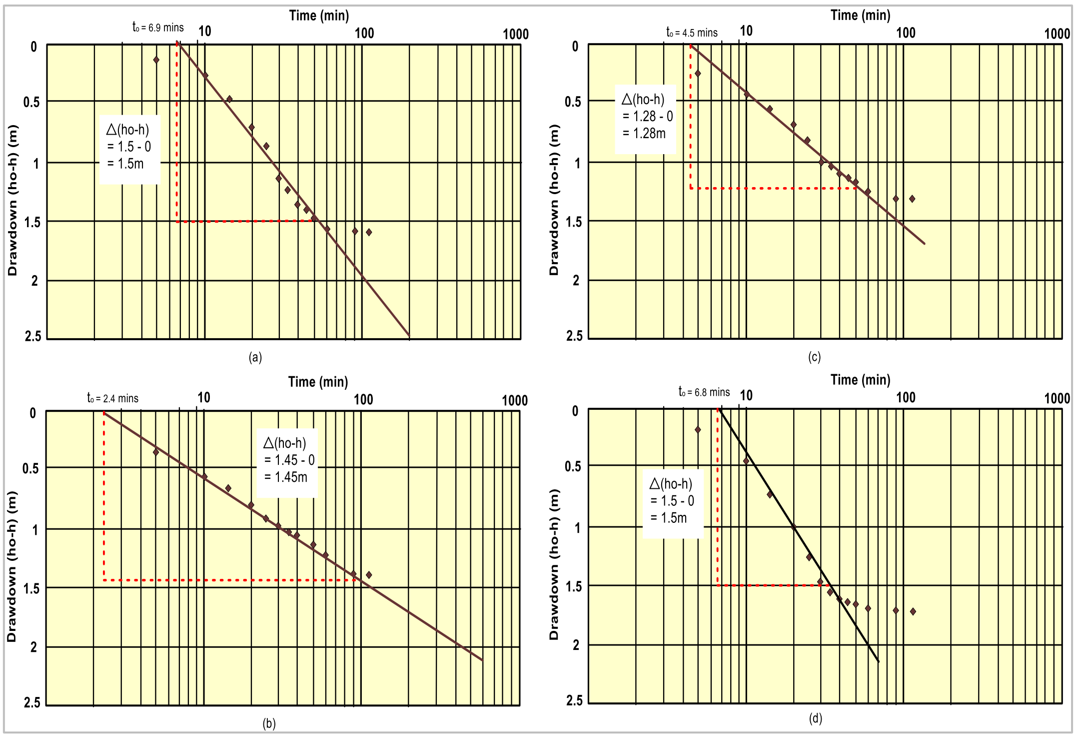


Figure 7: Pumping test curves for wells in the study area's three geological units (a) W-23 -gneiss (b) W-35 – granite (c) W-46 - migmatite (d) W-53 – gneiss

3.3 AVI Method

Protective layer characteristics, which have been found to be the key component in identifying aquifer vulnerability, and this form the foundation of the AVI approach. The method is founded on the hydrogeological characteristics of the unsaturated zone, which play a key role in evaluating the susceptibility of an aquifer. This method calculates the ratio between the projected hydraulic conductivity of the protective layer, written as (k), and the thickness of each unit above the uppermost aquifer, denoted as (d), as shown in equation 4.

$$c = \sum_{i=1}^{n} \frac{d_i}{k_i} \quad (4)$$

Consequently these parameters were determined by pumping test from fifty eight (58) water wells and five (5) boreholes (Figure 6) while the individual soil layers overlying the aquifer units were delineated using the results of VES (Figure 6). Hydraulic resistance (c) in years is determine using equation 4, its interpretation is shown in Table 6.

4. Results and Discussion

4.1 DRASTIC/DRASTIC-LU Parameters

4.1.1 Depth to Water Table

The depth to water level ranged from 2.5 – 8.8 m (5.8 m avg.) in open wells and 9.5 – 15.9 m (12.7 m avg.) in boreholes. The spatial distribution map of DWT in Figure 8a showed DWT-Number ranging from 5.0 – 43.0. The map categorized the area's vulnerability into five classes based on DWT data, as low (<5), moderately low (5 – 14.5), moderate (14.5 – 24.0), moderately high (24.0 – 33.5), and high (33.5 – 42.0). However, three susceptibility zones are prominent in the map i.e. low, moderately low, and moderate. The moderately low area constitutes 90% of the area; while moderate accounts for 8%, and 2% aerial extent for moderately high. Some notable areas such as health, educational centres are characterized with moderate – moderately high vulnerability. Therefore, it can be inferred that the low vulnerability DWT-Number recorded is as a result of SWL values which is generally greater than 5.0 m. The depth to water table can affect groundwater pollution in such a way that if the aquifer is shallow, pollutants reach the aquifer in a shorter period than deep wells. Thus, based on DWT, the region is moderate/lowly vulnerable to groundwater pollution.

4.1.2 Net Aquifer Recharge

The primary source of groundwater recharge is precipitation, which infiltrates through the land surface and percolates to the subsurface (through the vadose zone to phreatic water zone). Consequently, the more the recharge (Piscopo, 2001). The greater the risk for contaminants to get to water table. From the net recharge map (Figure 8b), it area's vulnerability tendency is categorized into three classes, as low (<8) common in the southern and northern area and constitutes 15%; high (8 – 28) which sporadically dotted the area in several places, and accounts for 5% of the area; and very high (28 – 36) which is the most dominant and constitute 80% of the study area. As a result, the area's high sensitivity zones may be ascribed to high rainfall intensity/frequency (1500 - 1800 mm) per year, and soil conducting capacity, which is often sandy or mixed sand-clay, with mild to strong hydraulic conductivity.

Table 4: GOD Parameters and Their Corresponding Classes

Aquifer Type	Note	Depth to aquifer	Note	Lithology (ohm-m)	Note
Non-aquifer	0	<2	1	<100	0.1
Artesian	0.1	2 – 5	0.9	100-200	0.2
Confined	0.3	5 – 10	0.8	200– 350	0.3
Unconfined	0.75	10 – 20	0.7	350 – 750	0.4
		20 – 50	0.6	>750	0.1
		50 - 100	0.5		

Table 5: GOD Index Interval Values and Associated Classes

Index	Vulnerability class
<0.1	Very Low
0.1 – 0.3	Low
0.3 – 0.5	Moderate
0.5 – 0.7	High
0.7 – 1.0	Very High

Table 6: Hydraulic Resistance and the Aquifer Vulnerability Index		
Hydraulic resistance	Log (c)	Vulnerability
0 to 10y	<1	Extremely High
10 to 100y	1 – 2	High
100 to 1,000y	2 – 3	Moderate
1,000 to 10,000	3 – 4	Low
>10,000y	>4	Extremely Low

4.1.3 Aquifer Media

This is the type of the consolidated or unconsolidated rock/soil material that serves as an aquifer (Delleur, 1999). The higher the conductivity and consequently susceptibility, the larger the texture/grain size or fissure/fracture. The aquiferous unit in the studied region is composed of unconfined fissured basement and water table aquifer (weathered layer aquifer). The aquifer media spatial map classified the area into five susceptibility zones based on Aquifer media-Number: extremely low (six), moderately low (6-ten), moderate (10-14), high (14-20), and very high (14-24). Low/very low and moderate susceptibility account for approximately 95% and 5% of the territory, respectively (Figure 8c). This is due to the aquifer media's sand-clay combination, and in most situations, the clay component is greater. As a result, the addition of clay to sandy soil will probably diminish permeability. As a result, pollutant penetration and percolation into the aquifer will take longer through this media.

4.1.4 Soil Media

Figure 8a depicts five classifications of susceptibility based on soil media-Number: 6 (low), relatively low (6 - 9), moderate (9 - 12), high (12 - 15), and extremely high (12 - 18). According to the soil media map (Figure 9a), a large portion of the study area (85%) is vulnerable. The loamy soil discovered in the research area's outskirts, occurring in plantation/agricultural regions, is sandy in texture, indicating a high infiltration rate and hence a high groundwater vulnerability potential.

4.1.5 Topography

The slope DRASTIC Number varied from 0 to 10, indicating extremely low to high slope. The slope map (in%) revealed vulnerability index values ranging from 5 to 10 (very high vulnerability) as the most prevalent, accounting for 75% of the study area; notable very low to low groundwater contamination areas are spotted in the southern and northwestern parts, accounting for 10% of the aerial extent; and moderate vulnerable places account for 15% (Figure 9b). As a result, high elevation (slope >18%) is rare in the research region; hence, drainage is modest, resulting in considerable water retention, hence extremely vulnerable to groundwater pollution.

4.1.6 The Impact of The Vadose Zone

The vadose zone is the region of unsaturated water above the water table (Delleur, 1999; Hiscock, 2005). Its composition and texture affect or determine the time it takes pollutants to move through it to the phreatic zone. The vadose zone map (Figure 9c) has the effect of categorizing the region into five susceptibility zones: 5 (very low), 5 - 11 (low), 11 - 18 (moderately low), 18 - 23 (moderate), and 23 - 30 (high).

It was observed that the very low to moderately low zones constitutes 21 %, high zone accounts for 5%, while moderate zone constitutes 73 %. The unsaturated part is composed of predominantly sand-clay mixture, hence gives moderate impact, with medium contamination risk.

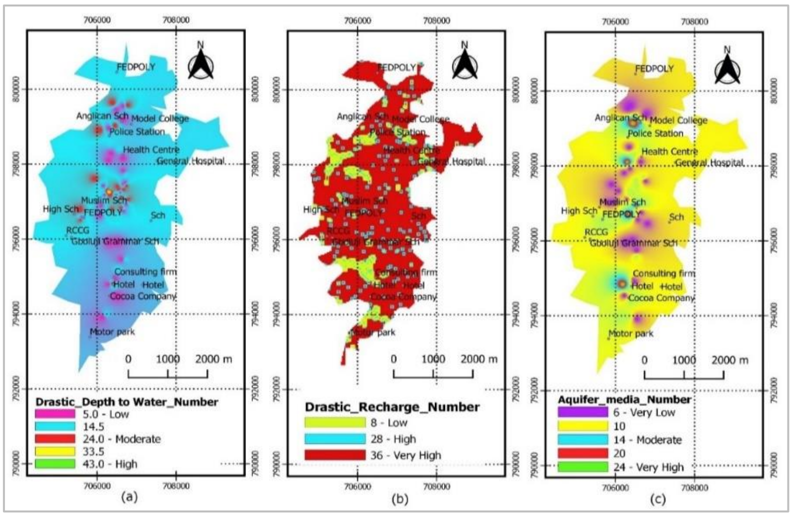


Figure 8: DRASTIC-Number Spatial Distribution for (a) DWT (b) Net Recharge (c) Aquifer media

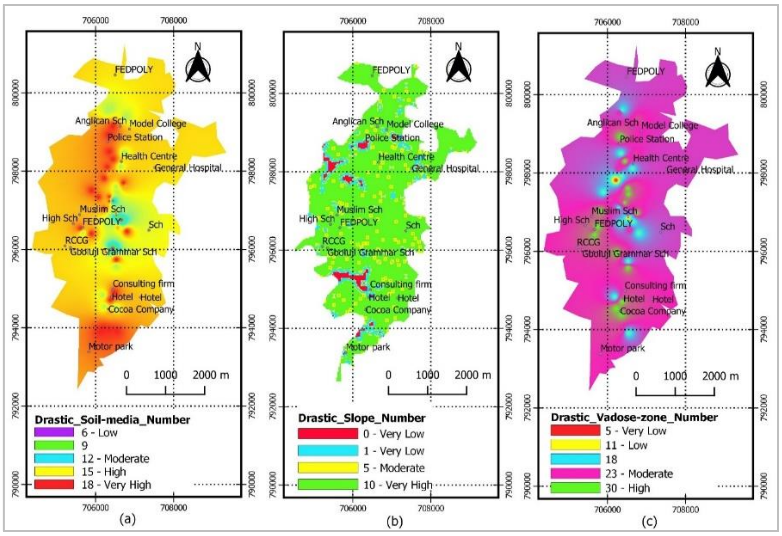


Figure 9: The distribution of the DRASTIC-Number for (a) soil medium, (b) slope, and (c) vadose zone

4.1.7 Hydraulic Conductivity

The "K" ranged between 0.41 and 0.55 m/d (0.48 m/d on average). The hydraulic conductivity geographic map revealed noticeable low/very low vulnerability with "K" less than 3.0 m/d (Figure 10a). As a result, the region is less susceptible to groundwater pollution.

4.1.8 Land Use/Land Cover

The region is divided into four parts based on the DRASTIC-Number of land use/cover: 25 (moderate), 25 - 30 (moderately high), 30 - 40 (high), and 40 - 45 (extremely high). Only the moderate, high, and extremely zones are highly represented, accounting for 27%, 69%, and 4% of all zones, respectively (Figure 10b). As a result, the region is very susceptible to pollution. Because the region is largely built-up, hence industrial/home wastes, and the inadequate construction of latrine systems and septic tanks are very common in the study area, putting groundwater quality at risk.

4.2 Groundwater Vulnerability Maps

Figure 11 depicts the GOD and AVI models, which classified the area as very low (0.03) to low (0.03 - 0.3) and high (0.98 - 1.85) to extremely high (0.98) susceptibility zones, respectively. The spatial map difference can be traced to parameters assessed in both models. The GOD recorded very low/low vulnerability potential because critical parameters (such as hydraulic conductivity) that impact aquifer sensitivity to pollution are not taken into account or reflected in the GOD model. The vulnerability zones on the DRASTIC map (Figure 12a) were classified as low (0 - 60), moderate (60 - 102), high (102 - 115), and extremely high (115 - 150) according to the DRASTIC-Number, which is the total sum of parameters N-number. Consequently, the low vulnerability (constitute 30 % of the area), moderate (4 % aerial extent), high-vulnerability zone (accounts for 60 % of the area), and very high vulnerability zone (6 %). All the potential zones showed high level of overlap, as there is no distinct regional zone for a particular vulnerability zone. Figure 12b depicted the distribution of DRASTIC-LU/LC - Number over the research region and classified it into five groups: low (88), moderately low (88 - 113), high (113 - 138), considerably high (138 - 163), and very high (163 - 188). As a result, the high - very high groundwater risk zone accounts for 90% of the research area, whereas the low - moderately low area accounts for 10% of the aerial extent. Furthermore, there is a strong association between the AVI, DRASTIC, GOD, and DRASTIC-LU modeled maps, since they all exhibited a high vulnerability zone.

5. VALIDATION OF GROUNDWATER VULNERABILITY MAPS

The nitrate analysis (of fifty eight open well and five borehole water samples) was used to validate the vulnerability models (Boris et al., 2016; Huan et al., 2012; Neema et al., 2022) using APHA (2006) procedure. Figure 13 shows the nitrate map, which indicated a range of 1 to 11 mg/L. Nitrate levels ranging from 9 to 11 mg/L have been discovered in locations categorized as extremely high or high vulnerability zones on the AVI, DRASTIC and DRASTIC-LU modeled maps. The majority of educational, industrial, and business centers have relatively high nitrate levels. Thus, there is a substantial association with around 70% agreement between the nitrate map, DRASTIC, and DRASTIC-LU maps. The sensitivity of groundwater to nitrate pollution is arguably related to the geochemical redox state of the groundwater and the depth of the aquifer. As a result, most of the high-vulnerability zones are characterized with shallow water table. Therefore depth to water level, slope, and landuse are the most important parameters influencing groundwater pollution in the study area.

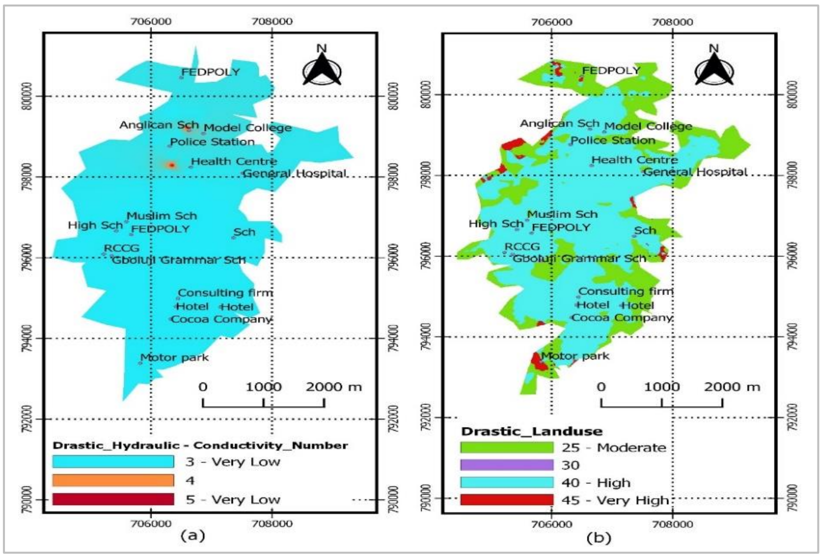


Figure 10: DRASTIC-Number Distribution for (a) K (b) Land Use/Cover

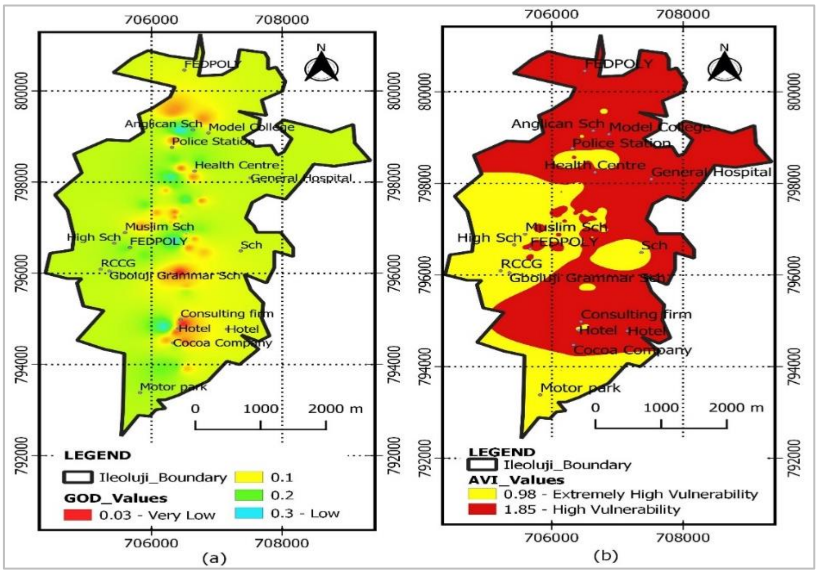


Figure 11: (a) GOD; and (b) AVI groundwater vulnerability maps

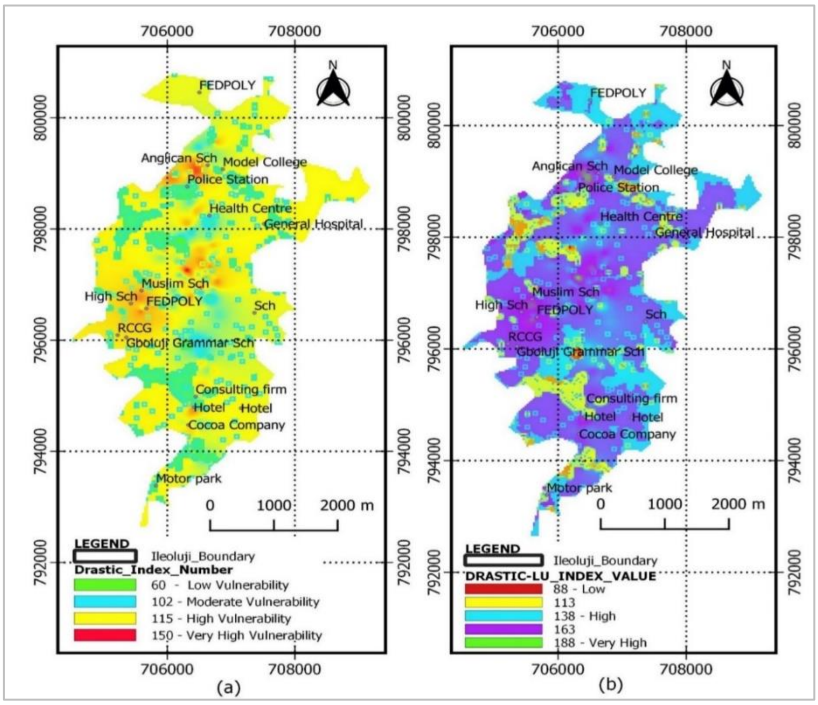


Figure 12: The spatial spread of (a) DRASTIC (b) DRASTIC-LU groundwater risk zones

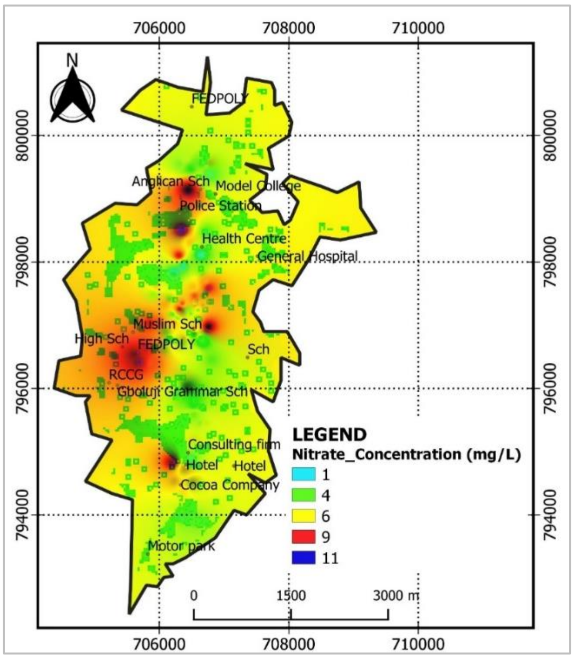


Figure 13: Nitrate concentration distribution over the research area

6. Conclusion

Groundwater vulnerability assessment and mapping is an important strategy in evaluating intrinsic groundwater vulnerability to contamination; as it helps government and decision makers in sustainable management of water resources. This study applied GOD, AVI, DRASTIC and DRASTIC-LU models/methods for groundwater pollution vulnerability in Ile Oluji area of Ondo State, Southwestern Nigeria. The GOD model distinguished the area into very low – low; AVI model categorized the area into high (60%) to extremely high vulnerable zones (40%); DRASTIC model classified it into, low vulnerability (constitute 30 % of the area), moderate (4 % aerial extent), high-vulnerability zone (accounts for 60 % of the area), and very high vulnerability zone (6 %). The DRASTIC-LU classified the region as high - extremely high groundwater risk zone, which accounts for 90% of the research area, and low - moderately low groundwater sensitivity zone, which accounts for 10% of the aerial extent. Subsequently, there is a strong association between the DRASTIC, AVI, and DRASTIC-LU modeled maps, since they all exhibited a high vulnerability zone.

Therefore there are similarities between the groundwater vulnerability maps (with about 70 % agreement) and nitrate map except GOD models which showed high to very high vulnerability for the study area. As a result, the groundwater in the area is highly susceptible to pollution from human-caused contaminants (dumpsite leachate, heavy metals, industrial, domestic sewage and effluents, and other substances), as evidenced by relatively high nitrate concentration values in some locations. The most influencing characteristics on groundwater quality in the research region, however, are slope, land use/cover, soil media, and depth to water level. As a result, by implementing tight environmental monitoring and management in the research area, necessary efforts must be made to minimize the region's point and non-point pollution sources. In addition, there should be discouragement of open waste disposal and overusing inorganic fertilizers, hence embracing modern / contemporary waste disposal techniques. Therefore this study has shown the effectiveness and versatility of combined use of geospatial parametric models with MCDA (utilizing AHP technique) and geographical information system (GIS); with nitrate validation (for anthropogenic pollution source) as veritable tools in groundwater vulnerability assessment in the complex hydrogeological terrain of Southwestern Nigeria.

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