



# Geospatial aquifer vulnerability mapping using parametric models in Ondo metropolis, Southwestern Nigeria

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## Abstract

This study utilized geographic information system-based overlay and index methods (DRASTIC, DRASTIC-LU, GOD and AVI models) in mapping groundwater vulnerability zones in Ondo town, Southwestern Nigeria. The models' parameters were based on hydrogeological (well/borehole) data, geophysical data, and satellite imageries. The weightage of different parameters was done using analytical hierarchy process. The AVI distinguished the area's vulnerability into two zones as high (94%) and extremely high (6%); GOD distinctly categorized the area into four vulnerability zones, comprising low (42%), moderate (17%), high (25%) and very high representing 16% of the study area. The AVI and GOD showed 60% correlation. On the other hand, the DRASTIC model showed three major zones, as moderately high found in the northwestern part, high, and very high vulnerability zones, constituting 33%, 50%, and 17%, respectively. The DRASTIC-LU based on index values, divided the area into high vulnerability zone (100–120) constituting 87% and very high vulnerability zone (120–145) with 13% aerial coverage. Thus, there is high level of correlation among the models (about 60%), as all displayed high/very high vulnerability zones which characterized the southern part of the study, which was also validated by the nitrate map with nitrate concentration varying from 7 to 15 mg/L. Thus, land use/cover, slope, hydraulic conductivity, net recharge, soil media, and depth to water level are very influential on groundwater quality in the study area, but land use/cover is the most predominant factor. The high percentage of the high vulnerable areas in the south requires prompt action to safeguard the aquifers from further pollution risk.

**Keywords** Groundwater vulnerability · Pollution · Overlay methods · Nitrate · Hydrogeological data

## Introduction

Groundwater is one of the most important components of the planet, yet it is heavily polluted by domestic, agricultural, industrial, and municipal pollution (Falowo 2022; Schwartz and Zhang 2003; Sameer et al. 2021; Omer 2018). Groundwater quality in many Nigerian cities, including Lagos, Port Harcourt, Kano, and Abuja, has deteriorated over the last decade due to a variety of factors, including urbanization and population growth; overexploitation; and indiscriminate drilling of water wells (Tartiyus et al. 2015; Jijingi et al. 2019). As a result, many aquifers or water bearing units

are subjected to undue strain (Nzama et al. 2021; Nas and Berktaş 2010; Ezenwaji and Ezenweani 2019; Chatterjee et al. 2018; Arya et al. 2020; Afshar et al. 2021; Ekwere et al. 2022), with many wells losing 10–50 cm of depth yearly (Falowo 2022; Petters et al. 1989; Edet 2013; Omole 2013; Omole and Isiorho 2011; Longe et al. 2010; Abdullahi 2009), as evident in increasing drawdowns and the threat of pollution being experienced by many aquifer system. Like these aforementioned huge cities, Ondo metropolis has experienced enormous development and expansion in the last 2 decades in the area of housing, industry, market, and hospital. The introduction of health and academic institutions such as Gani Fawehinmi diagnostic Centre, University of Medical Sciences, and conversion of Adeyemi College of Education to a university of Education are big boost to the development of the city. Consequently, all of this has drawn a large number of migrants from surrounding states, towns, and villages, resulting in a population expansion and a spike in groundwater demand. This is causing environmental

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problems owing to an increase in trash output, which can damage groundwater and surface water, which are the primary sources of water supply in the area. As a result, proper precautions must be taken to protect the groundwater system from potential contamination by toxic components and heavy metals in industrial effluents, particularly in shallow aquifers linked with hard rocks in southern Nigeria. Thus, for effective groundwater planning, monitoring, and development, comprehensive groundwater vulnerability assessments must be used to describe likely groundwater contamination zones (USEPA 2014; Yihdego et al. 2016; Yihdego and Drury 2016).

Groundwater vulnerability assessment is an empirical method for mapping or assessing the risk or tendency of groundwater contamination in an area based on a number of physical, chemical, or microbiological parameters that control the flow of contaminants within the unsaturated zone, for groundwater planning, management schemes, and land use management for residential, industrial, and agricultural uses (Eshtawi et al., 2016; Barbulescu 2020; Jang et al. 2017; Khan Jhariya 2019). Groundwater vulnerability to pollution assessment assists in determining the risk of groundwater contamination and is thus required for preserving and protecting groundwater quality (Krenkel 2012; Oseke et al. 2021; Wang and Yang 2014). Many groundwater vulnerability models have been created over the previous 4 decades (such as DRASTIC, SINTACS, SI, GOD, AVI, EPIK, SEEPAGE, DISCO, ISIS, INDICATOR KRIGING, HAZARD-PATHWAY-TARGET) employing geographic information systems, each with its own peculiarities, features, and distinctiveness. Some models are tailored to specific geological environments (Aller et al. 1987; Kozłowski and Sojka 2019; Malakootian and Nozari 2020; Ghazavi and Ebrahimi 2015; Al-Aboodi et al. 2021a; Ribeiro 2000; Vias et al. 2005; Stempvoort et al. 1993; Daly et al. 2002; Vias et al. 2006; Perrin et al. 2004; Mkumbo et al. 2022; Singh et al. 2015; Kuisi et al. 2006; Kumar et al. 2013); and slight modification may be required if a model needs to be employed in another geo-environment (Anane et al. 2013; Denny et al. 2007; Olojoku et al. 2017). These methods are divided into statistical, process-based simulation, and index-based models (Vbra and Zaprorozec 1994; AWRC 1992; Jang et al. 2016). The statistical approach is used to evaluate the statistical relationship or dependency between observed pollutant elements/environmental variables, and observed land uses that may contaminate groundwater. The statistical approach offers the advantage of determining statistical significance directly. The process-based computer simulation focus on recreating the flow and transport patterns within the unsaturated zone or in an actual aquifer and can be used to compute travel times or concentrations of a contaminant in the unsaturated zone in an aquifer; examples of such models are PRZM, LEACH, MODFLOW, GSFLOW, GWM-MODFLOW and

HYDRUS (Vbra and Zaprorozec 1994; Civita 2010; Fetter 1994; Saeft 2000). These models require significant input data to run, and for most users, it is not easy to use the models, because they are fairly complicated. The index-and-overlay methods is based on gathering information on the most important factors affecting aquifer vulnerability such as soil type, geology, and recharge (Kumar et al. 2017). These hydrogeologic parameters are interpreted by scoring, integrating or classifying the information to produce an index rank or class of vulnerability. They are usually suitable for use with computerized geographic information system (GIS) technique, which provides an efficient way for analyses and high capabilities in handling a large quantity of spatial data. Index-based model can categorized into hybrid, non-parametric, and parametric types. The parametric which is the most commonly used or adopted model all over the globe is divided into pragmatic and classical models. The pragmatic includes DRASTIC, SINTACS, SEEPAGE, EPIK (Kumar et al. 2017, 2013; Aller et al. 1987; Foster 1987; Denny et al. 2007; Anane et al. 2013; Kuisi et al. 2006; Agyemang 2017), while classical embraces GOD, AVI, GLA, and PI models (Ribeiro 2000; Oroji 2018; Foster 1998; Agyemang 2017). The choice of method to be adopted depends on several factors, including the scale of the project, the hydrogeological characteristics of the area, and the availability of data. Index-based techniques have the advantages over the rest of the two as it resolves their limitations. Index-based techniques are not encumbered by computational complexities and data shortage. This is the reason that index-based techniques are the most preferred for the groundwater vulnerability assessment.

The most widely used overlay technique is DRASTIC model, which is established for the United States Environmental Protection Agency (EPA) to conduct a systematic evaluation of groundwater contamination potential in any hydrogeological setting and is compatible with a wide range of aquifer types. It generates a vulnerability index map by combining seven rated hydrogeologic factors: depth to water table, recharge, aquifer media, soil media, topography, vadose zone, and hydraulic conductivity (Aller et al. 1987). However, it has substantial limitations, and many researchers have attempted to improve it by adding layers or deleting particular features without jeopardizing the description of the key processes (Singh et al. 2015; Barbulescu 2020; Koesuma et al. 2022; Anane et al. 2013). Furthermore, when compared to other methodologies utilized for karst aquifers, DRASTIC's flaws include erroneous conclusions, which led to the creation of SINTACS (Kuisi et al. 2006; Kumar et al. 2013; Daly et al. 2002; Dörfliker 1996; Vias et al. 2006). The SINTACS model, which has the same parameters as the DRASTIC model but a different name, uses the same parameters. Water depth (S), net infiltration (I), soil media (T),

aquifer media (A), hydraulic conductivity (C), slope (S), and unsaturated zone (N) are all abbreviations for SINTACS. The distinction is in how the weights and relative scores of these criteria are awarded. The SEEPAGE model has been frequently used to forecast the susceptibility of groundwater pollution. The model considers the following parameters: depth to the water table, soil topography, soil depth, influence of the vadose field, aquifer material properties, and attenuation potential. The vulnerability index is calculated using a linear empirical method similar to that used by the DRASTIC model (Foster 1987; Vias et al. 2005), thus SEEPAGE studies soil parameters in more depth than DRASTIC. Among the classical method, GOD is the commonest, based on the fact that it is easy and quick (Olojoku et al. 2017; Ekwere and Edet 2017; Ghazavi and Ebrahimi 2015; Al-Aboodi et al., 2021b; Oroji 2018; Falowo et al. 2017). The model depends on three parameters: the groundwater occurrence, overall lithology of the aquifer and depth to groundwater table. AVI is based on measured density in terms of thickness (T) of sedimentary deposits above the topmost aquifer and approximate hydraulic conductivity (C) of each of these deposits (Falowo et al. 2017). The model calculates a theoretical factor called hydraulic resistance for each deposit above the uppermost. Susceptibility Index (SI) method is an adaptation to the DRASTIC method; it was developed in Portugal by Ribeiro (2000). The vadose zone and hydraulic conductivity are eliminated in this technique, while the Land Use parameter is introduced. According to Ribeiro (2000), it was difficult to assess the distribution of the aquifer hydraulic conductivity; in fact, it is estimated based on rock lithology, which also minimizes the role of the vadose zone (Foster 1987; Vrba and Zaporozec 1994), implying that mitigation processes related to the soil type parameter have no effect on vulnerability. The integration of the "land use" parameter takes the vadose zone parameter into account indirectly in the SI technique.

The primary goal of this research is to analyze and map the groundwater vulnerability of aquifer units in Ondo metropolis using the combined GOD, AVI, DRASTIC-LU/LC, and SINTACS models to assure the long-term viability of these aquifer resources. The main innovations or contribution of this research are the use of more reliable methods by integrating them, to gain a thorough understanding of the vulnerability potential in the study area, as well as the modification of the existing DRASTIC model to accommodate land use/cover in order to quantify the most important hydrogeological parameters for groundwater vulnerability assessment. These models and their modifications have been used in many literatures with success being recorded (Mkumbo et al. 2022; Musekiwa and Majola 2013; Hamdan et al. 2020; Nzama et al. 2021;

Koesuma et al. 2022; Paul and Das 2021; Malakootian and Nozari 2020; Al-Aboodi et al. 2021a).

## Description of the study area

Ondo metropolis is located in Ondo State, southern Nigeria. In the Universal Traverse Mercator (UTM) coordinate system, it is located between the geographic coordinates of Eastings 754,900 and 756,500 mE and Nothings 859,700 and 860,900 mN in Zone 31N (Minna datum) (Fig. 1). The climate is tropical, with dry and wet seasons. The dry season lasts from November to March, with the wettest months being August and September, with an annual rainfall of 180 cm on average. The yearly temperature ranges from 25 to 31 °C (mean temperature of 24 °C) (Iloje 1981). The region is located in south-western Nigeria's deciduous rain forest. It features evergreen vegetation and urban habitation. The vegetation in the region is rain forest, with dense evergreen forest of towering trees with thick foliage (which may reach a height of 15 m or more) and other species. They are made up of light woods, bushes, dispersed cultivation, trees and plants such as lumber, oil palm, kolanut, rubber, cocoa, and citrus.

The topography of the region is somewhat undulating, with elevations ranging from 300 to 800 m above sea level. The area is located in the broadleaf rain forest of south-western Nigeria (Iloje 1981). It is part of the Precambrian Basement Complex, containing gneiss and migmatite exposures (Fig. 2 and Plate 1). 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, with some being porphyritic. Gneisses are foliated metamorphic rocks that are megascopically crystalline; mineral segregation into layers or bands of differing color, texture, and composition distinguishes them. Obaje (2009) describes gneisses as having bands of mica-ceous minerals alternating with bands of equidimensional minerals such as feldspar and quartz. Migmatites are mixed rocks composed of closely related components of the igneous (granitic rock) and metamorphic (gneisses) rock groups. They are common in the research environment. Figure 3a displays the landuse/land cover of the study region, which is largely built-up and has ferric luvisol soils. (See Fig. 3b). The luvisols are soils with considerable textural differences within the soil profile, with the top horizon drained of clay and clay buildup in a beneath "Argic" horizon. Luvisols contain high activity clays throughout and no abrupt textural shifts, whereas ferric luvisols exhibit ferric features. Figure 4 depicts the drainage system. The land is well drained by several river and stream systems. Figure 4 represents the principal rivers in the research, which have large catchments.

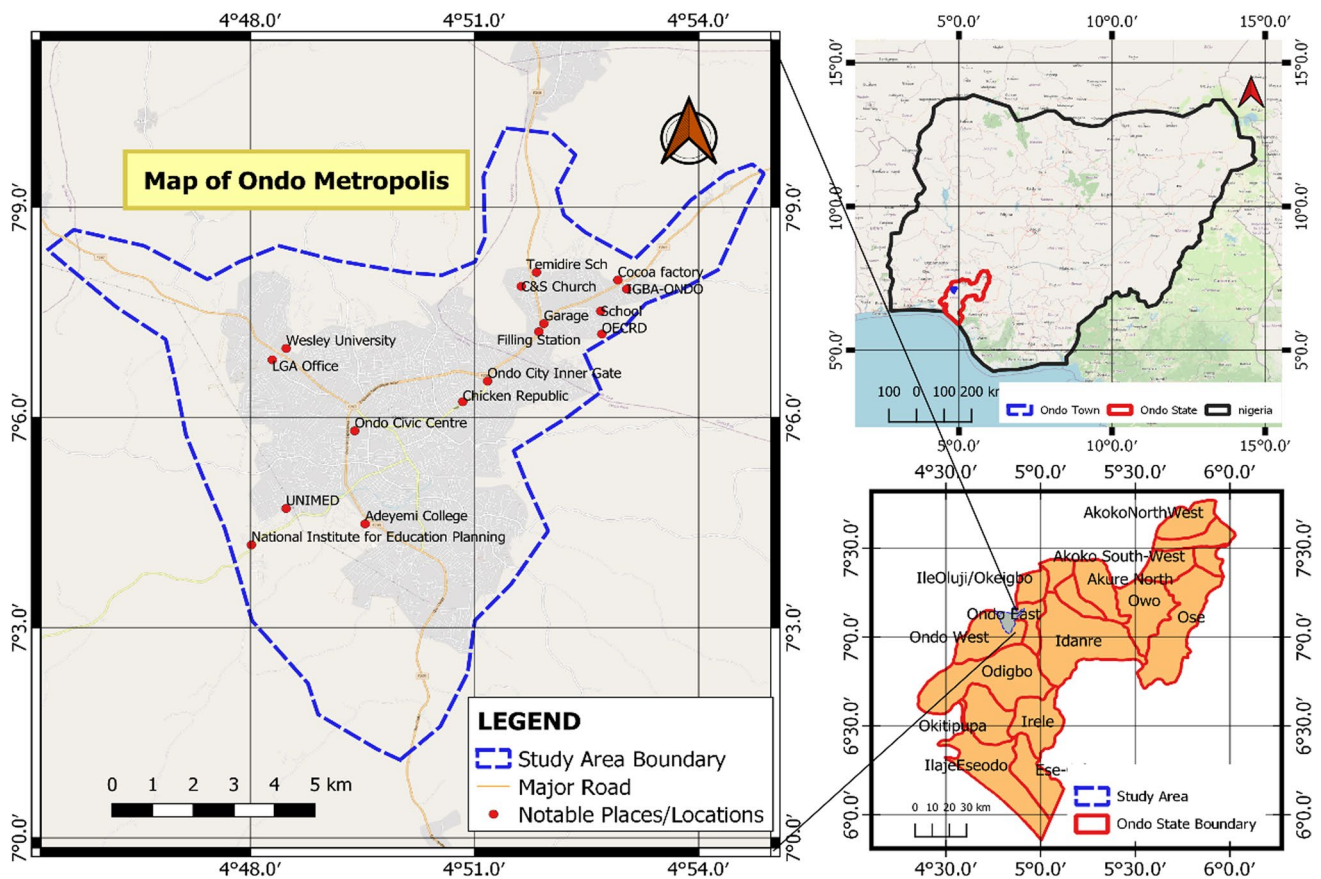


Fig. 1 Location map of the Study Area on map of Ondo State and Nigeria

### Materials and methods

Groundwater vulnerability mapping is a useful tool for implementing groundwater preservation, compatible land-use planning and policies for sustainable socioeconomic development. Vulnerability mapping is used to determine the most susceptible catchment regions and to set criteria for safeguarding groundwater utilized for drinking water supply (Abad et al. 2017; Rizka 2018). The DRASTIC, DRASTIC-LU, GOD, and AVI models were used in this work to estimate the vulnerability of the study region (Olojoku et al. 2017; Barbulescu 2020; Ekwere and Edet 2017; Paul and Das 2021; Falowo et al. 2017). These models are used to compare the region's protective capability of the aquifer units and or vadose throughout the area.

#### DRASTIC and DRASTIC-LU models

The model uses seven hydrogeological attributes which regulate the movement of groundwater within the subsurface, which are [D]epth of Water Table, Net [R]echarge, [A]quifer Media, [S]oil Type, [T]opography, [I]mpact of Vadose Zone, and Hydraulic [C]onductivity. The overall 'pollution

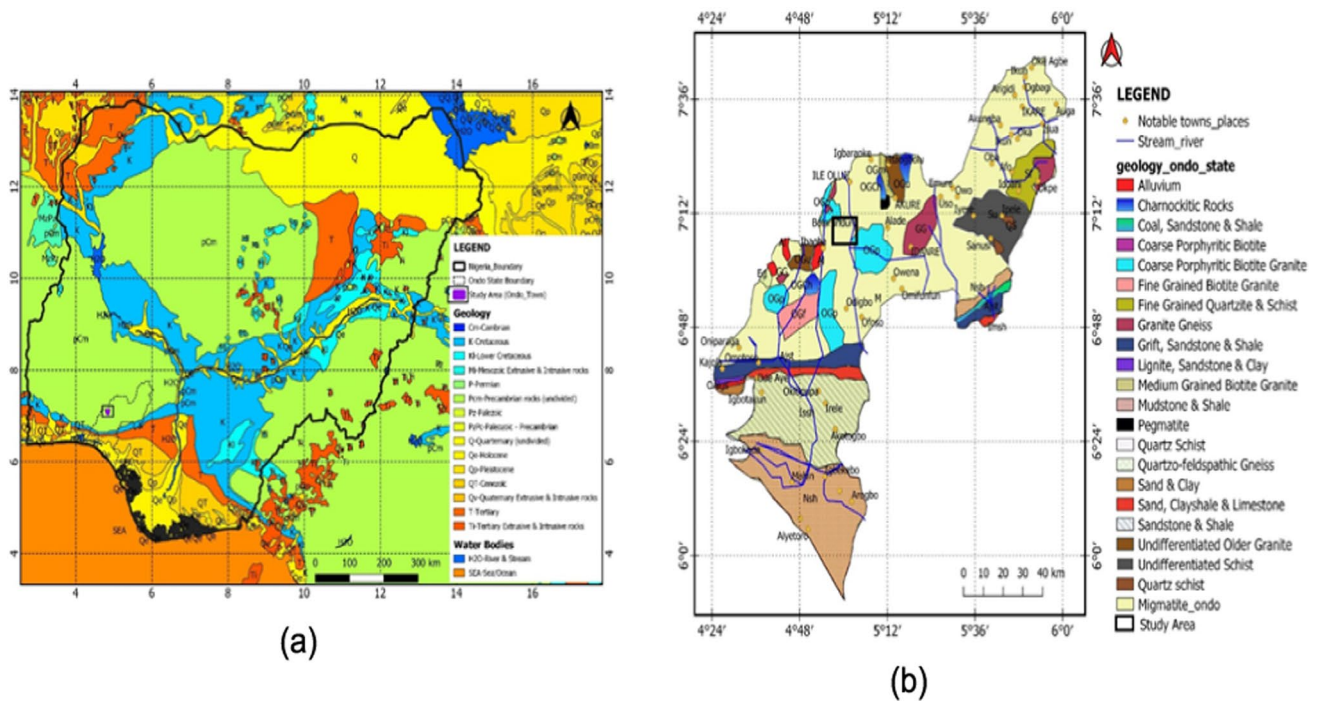
potential' or DRASTIC index is established by applying the formula:

$$\begin{aligned}
 \text{Drastic Index (DI)} = & D_R \times D_W + R_R \times R_W \\
 & + A_R \times A_W + S_R \times S_W \\
 & + T_R \times T_W + I_R \times I_W \\
 & + C_R \times C_W,
 \end{aligned}$$

where *R* is rating, and *W* is weight.

These characteristics are assigned weights and grades based on their sensitivity to contaminants. The weights range from 1 to 5, with 1 being the least important, and 5 being the most important parameter, while the rating varied from 1 to 10 representing very low to very high vulnerability potential, respectively. Saaty (1980) used the analytical hierarchy process (AHP) to do a multi-criteria decision analysis (MCDA) by assigning weights/ratings to all parameters. The AHP is a measurement theory that has found widespread use in decision theory, conflict resolution, and brain models (Vargas 1990). The AHP decision applications are implemented in two stages: hierarchical design and paired comparison assessment. In this study, the standard AHP procedure was used, which involved





**Fig. 2** Geological map of **a** Nigeria and **b** Ondo State showing the study area, which falls within the Southwestern Basement Complex Nigeria with migmatite being the predominant rock unit (modified after Nigeria Geological Survey Agency, 2006)

prioritizing the hydrogeologic parameters based on their importance in groundwater accumulation; the parameters were then pair-wise in a matrix form using Saaty's (1980) scale of importance, where 1, 3, 5, 7, and 9 are equal, moderate, strong, very strong, and extreme importance, respectively; while 2, 4, 6, and 8 are intermediate values; and 1/3, 1/5, 1/7, and 1/9 are values for inverse comparison.

The consistency ratio is calculated by multiplying the pair-wise comparison matrix with the criteria weights calculated for each row and the average value determined to obtain the weighted sum value. The weighted total value is then divided by the criterion weights to generate the consistency ratio for each row. As a result, the average consistency ratio is given as Lambda max ( $\gamma_{max}$ ). The consistency index (CI) is then calculated using Eq. 1.

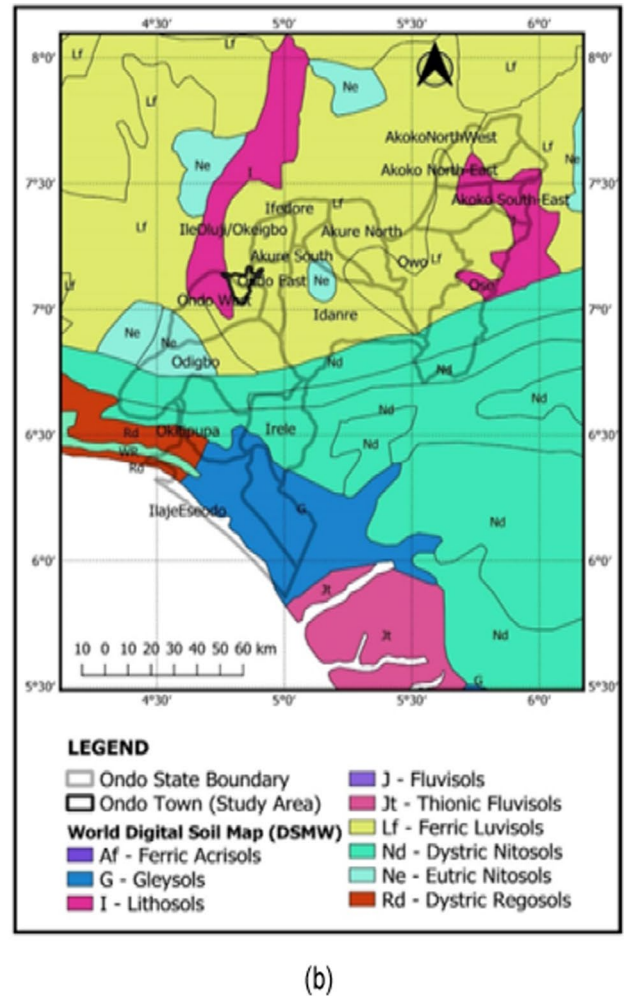
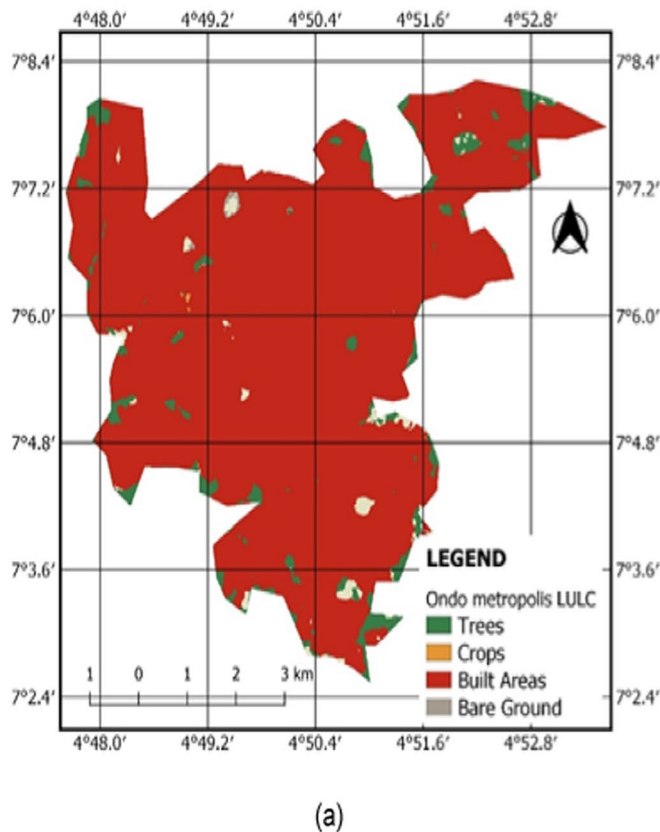
$$CI = \frac{\gamma_{max} - n}{n - 1}, \tag{1}$$

where  $n$  is the number of parameters compared.

The criteria weight was tested to determine its accuracy, reliability, credibility, and consistency (Saaty 1990, 2006) in predicting groundwater yield in the study area, by dividing the CI with the random consistency index value obtained in Table 1 (Saaty 2006), and the resulted value

(0.091) obtained from this study was less than 0.10, which is the standard maximum value. The acquired weights ( $w$ ) were utilized to rate the parameters accordingly. The parameters were evaluated in the following manner:

- (a) [D]epth to Water: This influences the length of time it takes for a pollutant to go through chemical and biological processes including dispersion, oxidation, natural attenuation, sorption, and so on. This means that the lower the depth, the shorter the transit time, and hence the greater the chance of groundwater contamination (Piscopo 2001; Awawdeh and Jaradat 2010). A low depth to water characteristic corresponds to a higher vulnerability rating, and vice versa. As a consequence, Table 2 displays the weight and rating assigned to this attribute. The values of depth to water which represent the static water level, was measured from fifty five (55) water wells and six (6) boreholes (Fig. 5), while areas without data were determined using Inverse Distance Weighting (IDW) interpolation technique in QGIS, which predicts those values based on neighboring values, under the spatial analyst tool. The depth to water level was assigned a weight of 5, and divided into 5 classes with corresponding rating attached, as shown in Table 2.

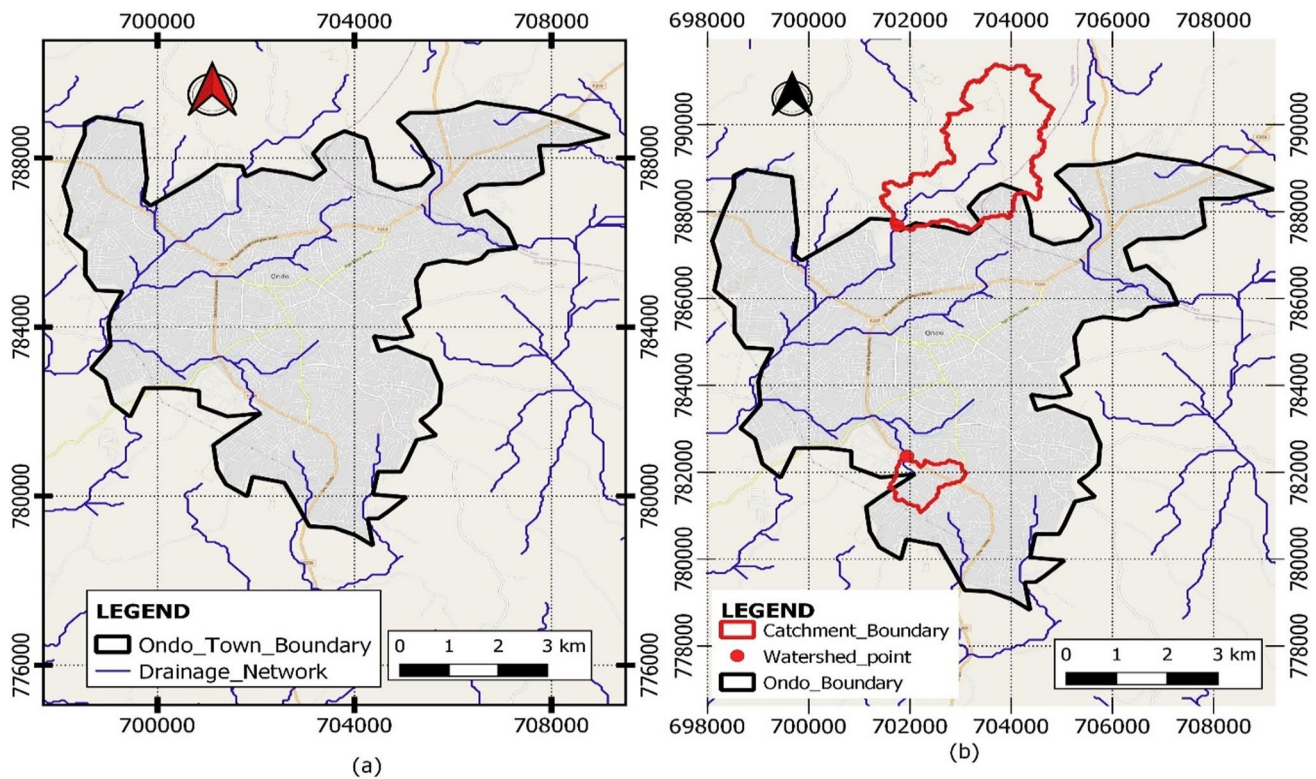


**Fig. 3** a The land use/land cover map of Ondo Metropolis, which is predominantly built up area (Modified after Living Atlas 2020); b Soil map of Nigeria, with the study area falling on Ferric Luvisols (modified after FAO/DSMW 2020)

(b) [N]et Recharge: This is amount of water that flows from the land surface into the groundwater system, also known as the phreatic zone. Rainfall, canals, rivers, irrigation, tanks, ponds, and water conservation facilities are all potential sources of groundwater recharge. Recharge is a main pathway for contaminant transmission, because it dilutes pollutants/contaminants that enter the aquifer system. A greater vulnerability rating is associated with a higher net recharge value; hence, the quantity of recharge positively correlates with the vulnerability rating. For this study, the net recharge was determined using Eq. 2, according to Piscopo method (2001) based on slope, rainfall data, and soil permeability (Eq. 2; Table 3). A weight of 4 was assigned to net recharge, based on its influence on groundwater pollution (Table 2), and divided into five (5) classes with corresponding rating attached, as shown in Table 2.

$$\begin{aligned} \text{Recharge} &= \text{Slope factor} \\ &+ \text{Rainfall factor} \\ &+ \text{Soil permeability factor.} \end{aligned} \tag{2}$$

(c) ([A]quifer Media: This refers to the consolidated or unconsolidated rock units that will provide enough amounts of water at the ground's subsurface (Aller et al. 1987). The relationship between aquifer media and vulnerability assessment is connected to important aquifer qualities like as permeability, porosity, and transmissivity, which are largely hydraulic parameters of the aquifer. This parameter was achieved by a geophysical technique (vertical electrical sounding) at fifty (50) distinct locations, as well as a pumping test in four boreholes (Fig. 5). The Schlumberger array electrode configuration was used for VES with maximum current–current electrode spacing of 150 m. The field



**Fig. 4** Maps showing the **a** drainage networks **b** major rivers with the catchment boundary

**Table 1** Random Consistency Index Table for number of parameter (N) and corresponding random value (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

survey, curve analysis and interpretation followed the procedures of Falowo and Daramola (2023). Area with high permeability or hydraulic conductivity has the tendency to have high vulnerability to contaminants. The aquifer media was assigned a weight of 3, and divided into five (5) classes with corresponding rating attached, as shown in Table 2.

(d) [S]oil Media: The uppermost portion of the earth's weathered zone with an average thickness of 1 m or less is designated as soil. It is an unsaturated zone chemically and biologically active region with the greatest organic matter content and robust biological activity. As a result, the journey time of recharge water that can infiltrate the vadose and phreatic zones is influenced by soil. Depending on its texture or particle size distribution, structure, and mineralogical content, it has the capacity to absorb and attenuate surface and near-surface produced pollutants (Aller et al. 1987; Hiscock 2005; Karanth 1989). The digital soil map of the world (DSMW) was downloaded from UNESCO Food and

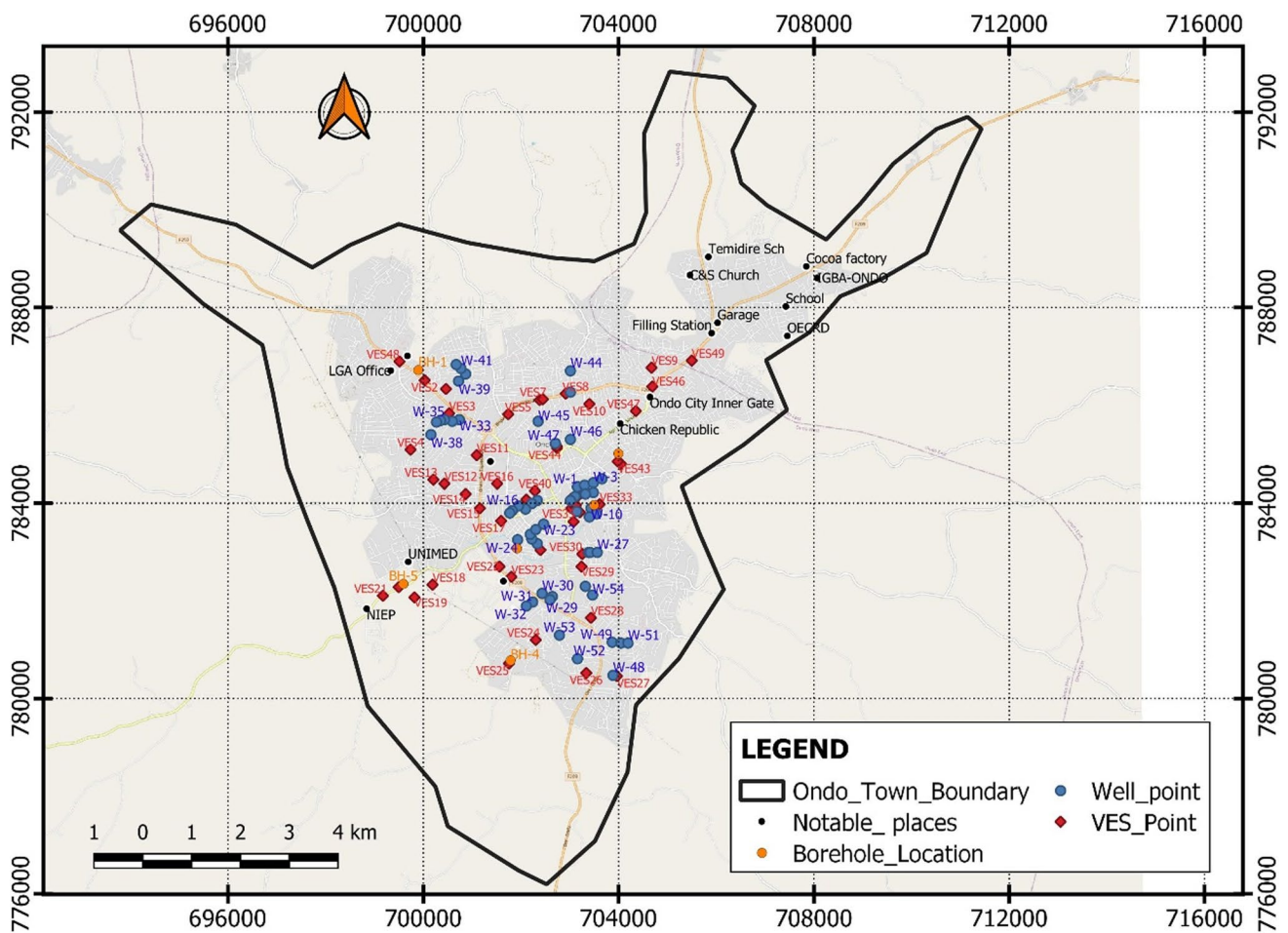
Agricultural Organization of year 2020. The map in raster format was modified in QGIS using the spatial analyst tools, and reclassification by raster calculator. The soil media was assigned a weight of 2, and divided into seven (7) classes with corresponding rating attached, as shown in Table 2.

(e) ([T]opography: This is the slope of the surface (land) area. The amount of runoff and the rate at which the soil can be absorbed by the atmosphere depend on the slope of a region. Low gradients or slopes are likely to diminish runoff, which may increase pollutant infiltration. As a result, locations with a steep slope have a lower risk of pollutant infiltration than areas that are primarily flat (Aller et al. 1987; Hiscock 2005; Karanth 1989). On the other hand, locations with a lesser slope hold water for a longer period of time, allowing contaminants to enter the groundwater through the vadose zone and increase contaminant infiltration. For this study, the Digital Elevation Data (DEM) with accuracy of 30 m, was used to calculate the slope and area aspect

**Table 2** The weights, ratings, and vulnerability classes of the DRASTIC/DRASTIC-LU parameters analyzed

Criterion	Classes	Degree of Vulnerability	Rating (AHP standardized values)	Standardized Assigned Weight	Data Sources
[D]epth 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 [R]echarge	11–13	Very high	10	4	Using slope, rainfall, hydraulic conductivity data
	9–11	High	8		
	7–9	Medium	5		
	5–7	Low	3		
	3–5	Very low	1		
[A]quifer Media	Fractured rock	Very high	10	3	VES
	Sand/Gravel	High	8		
	Sandy clay	Medium	5		
	Clay sand	Low	3		
	clay	Very low	1		
[S]oil 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		
[T]opography (% 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		
[I]mpact of the vadose zone	Sand/Gravel	Very high	10	5	VES / Borehole data
	Sandy/gravel clay or silt	High	7		
	Clay sand	Medium	5		
	Laterite	Low	2		
	Clay	Very low	1		
Hydraulic [C]onductivity (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	Land use map of the world
	Bare land	High	9		
	Built-up	Moderately high	8		
	Agricultural areas	Moderate	6		
	Grass land	Low	2		





**Fig. 5** Field Data acquisition map for determination of depth to water level, Aquifer media, Impact of the vadose zone, and hydraulic conductivity, showing the locations of the boreholes, open wells, and VES

**Table 3** Estimation of Net Recharge from combined factors of Slope, Rainfall, and Hydraulic conductivity data (modified after 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

using QGIS. The topography was assigned a weight of 1, and divided into five (5) classes with corresponding rating attached, as shown in Table 2.

- (f) [I]mpact of Vadose Zone: This is an illustration of the layer of the earth's crust that is unsaturated and typically above the water table (Aller et al. 1987; Hiscock 2005; Karanth 1989; Bisson and Lehr 2004; Wilson 1983). Because highly permeable vadose zones have a significant potential for susceptibility, they directly correlate with groundwater vulnerability. The degree

- to which pollutants are weakened by biological and chemical processes in the vadose determines how far they can travel to the water table. The results of VES, borehole drilling, and hydrogeological measurements of 55 water wells were used to identify the characteristics of the vadose zone. The topography was assigned a weight of 5, and divided into five (5) classes with corresponding rating attached, as shown in Table 2.
- (g) Hydraulic [C]onductivity: The hydraulic conductivity of aquifer sediments is used to determine how much

water may flow through a unit cross-sectional area of the aquifer in a specific amount of time at a specific hydraulic gradient. Hydraulic conductivity controls the speed at which soluble contaminants are conveyed in groundwater flow (Aller et al. 1987; Hiscock 2005; Karanth 1989; Brassington 1988; Bisson and Lehr 2004). The magnitude of the hydraulic conductivity of aquifer sediments increases in proportion to the quantity and degree of interconnectivity of void spaces within the aquifer. Fragmented sand or gravel aquifers are characterized by high fissures, fractures, pore spaces that operate as conduits for fluid movement, and pollutant transmission into the aquifer. Thus, vulnerability and hydraulic conductivity are directly related. The hydraulic conductivity of the aquifer was evaluated in this study using pumping tests from water wells and boreholes (Fig. 5). The hydraulic conductivity was separated into five (5) classes with matching ratings, as shown in Table 2, and given a weight of three.

- (h) [LU]—Land Use: Grassland, agricultural land, built-up land, barren ground, and flooded vegetation were all diverse types of land uses in the region. Based on the local area's predominant land uses, these criteria were selected. While agriculture or grassland is anticipated to have a substantially lower contribution to groundwater pollution due to surface cover, areas with high amounts of flooded vegetation, bare land, and built-up areas are at a higher risk of soil and groundwater contamination (Mkumbo et al. 2022). The digitized map of the world's land cover (created using Landsat satellite imagery) was downloaded in raster format from the Living Atlas (2010) website and opened in QGIS. The study area's land cover and use were then generated utilizing its shape boundary vector file using pertinent raster analysis techniques. The land use/cover was assigned a weight of 5, and divided into five (5) classes with corresponding rating attached, as shown in Table 2.

### GOD model

The abbreviation GOD technique (Foster 1987; Foster and Hirata, 1988) stands for three parameters: groundwater occurrence, overlaying lithology, and water table depth. Groundwater vulnerability across wide regions can be mapped using the GOD overlay/index method. The program provides an instant assessment of groundwater vulnerability. It evaluates the sensitivity of groundwater to pollutant percolation across the vadose zone vertically. With three criteria, each of which has a different weight,

**Table 4** GOD Parameters and respective classes developed for the study area (Khemiri et al. 2013)

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** Interval values of the GOD index and corresponding classes (Falowo et al. 2017)

Index	Vulnerability class
0–0.1	Very Low
0.1–0.3	Low
0.3–0.5	Moderate
0.5–0.7	High
0.7–1.0	Very High

the vulnerability index weight values are grouped accordingly to this method. Equation 3 below is used to determine the GOD:

$$\text{GOD Index} = C_1 \times C_a \times C_d, \quad (3)$$

where  $C_1$  is the lithology of the vadose zone,  $C_a$  is the aquifer type, and  $C_d$  is the depth to aquifer. In order to produce different values for the parameters in this investigation, the results of the electrical resistivity using vertical electrical sounding and hydrogeological measurements, including static water, thickness of the water column, depth of the well, etc. from 55 open wells and 6 boreholes, were both used. The classes and adopted vulnerability interval values are shown in Table 4, while the parameter ratings are shown in Table 5. With the exception of aquifer systems in karst regions, the GOD approach may be used to any aquifer system, making it extremely helpful.

### AVI method

By measuring hydraulic resistance to vertical water flow via the protective layers, the aquifer vulnerability index (AVI) was proposed by Van Stempvoort et al. in 1993. The AVI technique is founded on the properties of the protective layers, which have been acknowledged as the most crucial factor in characterizing aquifer vulnerability. According to this method, aquifer vulnerability is determined by hydraulic resistance ( $c$ ), which is expressed as a ratio between the estimated hydraulic conductivity of the protective layer ( $k$ ) and the thickness of each sedimentary unit above the highest

aquifer, or (d), as shown in Eq. 4. The technique is based on the hydrogeological features of the unsaturated zone, which is a crucial factor in aquifer susceptibility. As a result, for this model, the results of vertical electrical sounding were used to identify the specific soil layers that overlie the aquifer units, and the results of pumping tests from fifty-five (55) water wells and six (6) boreholes were utilized to assess the hydraulic conductivity of the vadose zone. Hydraulic resistance (*c*), which is given in years, is calculated using Eq. 4. This value is explained in Table 6.

$$c = \sum_{i=1}^n \frac{d_i}{k_i}, \tag{4}$$

where *n* is number of sedimentary units above the aquifer, *d<sub>i</sub>* is thickness of the vadose zone, and *k<sub>i</sub>* is hydraulic conductivity of protective layer.

## Results and discussion

### Drastic/drastic-LU parameters

#### Depth to water table

The depths of the boreholes ranged from 35 (gneiss) to 51 m (granite) and an average of 44 m, with static water level ranging from 9 to 26 m (avg. 12.5 m). This information showed that the area has a thick overburden thickness/depth of weathering. The information obtained from 55 open wells with total depth of 5.6 m (granite/gneiss)—13.5 m (gneiss (9.1 m avg.), SWL ranged from 2.5 m (granite; W-20)—7.1 m (gneiss; W-40) with average of 6.4 m. The thickness of the vadose zone which corresponds to the static water level (SWL) is generally moderate i.e. above 5 m, and capable of providing average daily consumption for domestic needs. However, the spatial distribution map of DWT in Fig. 6a showed DWT-Number ranging from 5.0 to 44.0. The map categorized the area’s vulnerability into five classes based on DWT data, as very low (< 5), low (5–14), moderate (14–24.0), high (24.0–34), and very high (34–44) vulnerability zones. However, very low/low commonly found in

the western part (and sporadically observed in the central and southern parts) has an aerial extent of 35%. The moderate vulnerability zone are predominant in the southern and central parts, constituting 40% of the study area. The very high vulnerability zone (with aerial extent of 25%) are conspicuous in the north. Therefore, the high vulnerability are areas where low SWL were recorded. Hence, it can be inferred that the low vulnerability DWT-Number recorded in the western part is as a result of SWL values which is generally greater than 5.0 m. The water table depth may influence groundwater contamination, as pollutants penetrate shallow aquifers more quickly than they do in deep wells. Accordingly, based on DWT, the region has a moderate to low sensitivity to groundwater contamination.

### Net aquifer recharge

The main source of groundwater recharge is precipitation, which seeps through the surface of the land and percolates to the subsurface (through the vadose zone to phreatic water zone). Consequently, the more the recharge, the greater the risk for contaminants to get to water table. From the DRAS-TIC-net recharge map (Fig. 6b), the values ranged from 20 to 36, hence the area’s susceptibility to groundwater pollution is majorly categorized into two prominent classes, as moderate vulnerability zone (< 20) constituting about 95%; and high vulnerability zone (20–28) constituting about 5% of the study area. Definitely from the map, the moderate vulnerability zones are in the process of gradating into high vulnerability zone. The vulnerability zones were based on sum of factors ascribed to slope, rainfall, and soil permeability. Consequently, the high vulnerability zones that is prominent in the area can be attributed to high rainfall intensity/frequency (1500–1800 mm) per year, and soil conductivity which in most places are sandy or mixed sand-clay, which are usually of moderate to high hydraulic conductivity.

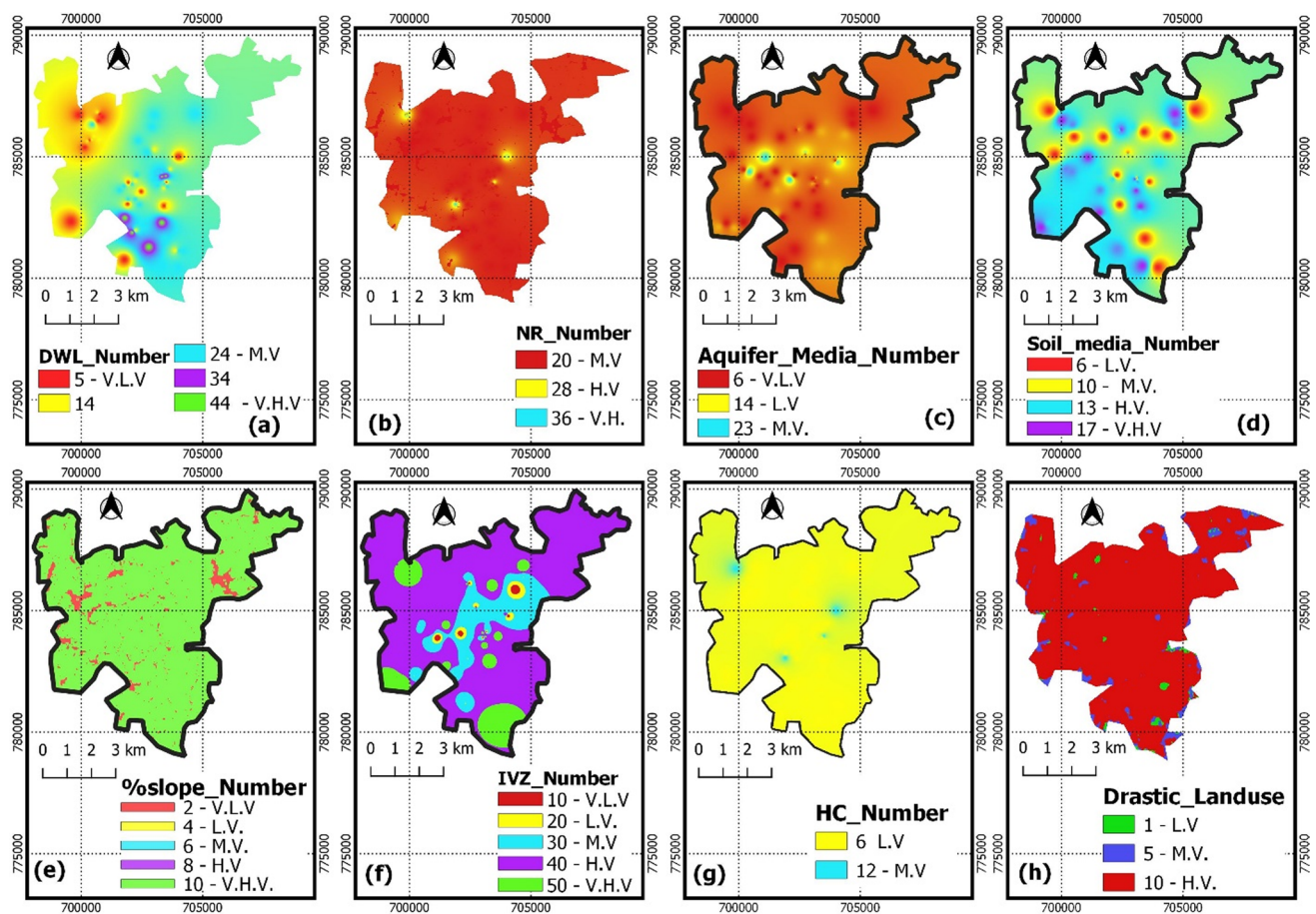
### Aquifer media

The term "aquifer media" refers to the kind of rock or soil, whether it is consolidated or unconsolidated, that acts as an aquifer. With texture/grain size or basement fissure/fracture, conductivity rises, increasing vulnerability. Weathered layer aquifer and unconfined fractured basement make up the aquiferous unit in the area under study. The aquifer media spatial map (Fig. 6c) showed two prominent vulnerability zones based on Aquifer media number as, very low (< 6), and low (6–14), as both constitute 98% of the area. The moderate vulnerability representing 2% of the study area are commonly found in the central part. Therefore, the very low/low vulnerability prevalent on the map can be attributed to sand-clay mixture of the aquifer media, and in most cases

**Table 6** Relationship of aquifer vulnerability index to hydraulic resistance

Hydraulic resistance	Log ( <i>c</i> )	Vulnerability
0–10 years	< 1	Extremely High
10–100 years	1–2	High
100 to 1,000y	2–3	Moderate
1,000 to 10,000	3–4	Low
>10,000 years	> 4	Extremely Low





**Fig. 6** Spatial Distribution maps for DRASTIC/DRASTIC-LU Parameters **a** depth to water table **b** net recharge **c** Aquifer media **d** soil media **e** slope **f** impact of the vadose zone **g** hydraulic conductivity **h** land use/cover

the composition of the clay is higher (as observed during the borehole drilling). Thus, the infiltration and percolation of contaminants will take longer time to occur into the aquifer through this media.

### Soil media

Based on soil media number ranging from 6 to 17, four zones of vulnerability are observed, as < 6 (low), moderate (6–10), high (10–13), and very high (13–17), constituting 12%, 15%, 28%, and 45%, respectively. From the soil media map (Fig. 6d), it can be observed that a large part of the study area is of high vulnerability (comprises of sand, shrinking/aggregated clay, clay sand, and loamy soil), which has high potential for groundwater contamination due to their high infiltration capacity and high permeability. The loamy soil, which is observed on the periphery of the study area, occurring in the plantation/agricultural areas, are sandy in texture, hence has a high infiltration rate resulting in high groundwater vulnerability potential.

### Topography

The DRASTIC Number for slope ranged from 2 (relatively flat surface or terrain) to 10 (steep topography), signifying very low to high vulnerability zones, respectively (Fig. 6e). The slope map (in %) showed vulnerability index values in the range of 0–2 (very high vulnerability) as the most preponderant as it constitutes 90% of the study area; while notable low groundwater contamination areas of values between 8 and 10 are spotted in many places, accounting for aerial extent of 10%. Consequently, it is found that high elevation (slope > 18%) is few in the study area; thus, the runoff is low, resulting in high water retention. Thus, based on the topography parameter, the area is highly vulnerability to groundwater contamination.

### The impact of the vadose zone

The area of unsaturated water above the water table is known as the vadose zone. Contaminants' transit times through it to the phreatic zone are influenced or determined



by its composition and texture. The impact of the vadose zone map (Fig. 6f) classified the area into five vulnerability zones, as < 10 (very low) found in the central part and constitute 1% of the area, 10–20 (low) with aerial extent of 2%, 20–30 (moderate) accounting for 18% aerial coverage, 30–40 (high) with 67% coverage, and 40–50 (very high) representing 12% of the study area. Hence, the high and very high zones constitute 79% of the study area. Therefore this result is expected, since the vadose zone is composed of predominantly sand-clay mixture, hence gives moderate–high impact, with medium/high contamination risk.

**Hydraulic conductivity**

The hydraulic conductivity ranged from 0.22 to 0.52 m/day on migmatite (0.33 m/day avg.), with DRASTIC hydraulic conductivity number ranging from 6 to 12. The spatial map of hydraulic conductivity (Fig. 6 g) two noticeable

vulnerability zones: low vulnerability (<6) and moderate vulnerability zone (6 to 12), with corresponding 95% and 5% aerial extent. Therefore, the area is less vulnerable to groundwater contamination as a result of dominant clayey soil material in the topsoil.

**Land use/land cover**

Based on the DRASTIC Number of land use/cover (1–10), the area is categorized into four zones: 1–5 (low), 5–10 (moderate), and > 10 (high) with percent aerial coverage of 2%, 6%, and 92%, respectively (Fig. 6 h). Consequently, the area is highly prone to contamination. Since the area is predominantly a built-up, industrial and domestic wastes, use of organic and inorganic fertilizers, and the poor design of latrine systems and septic tanks will be usual occurrence, which can endanger groundwater quality.

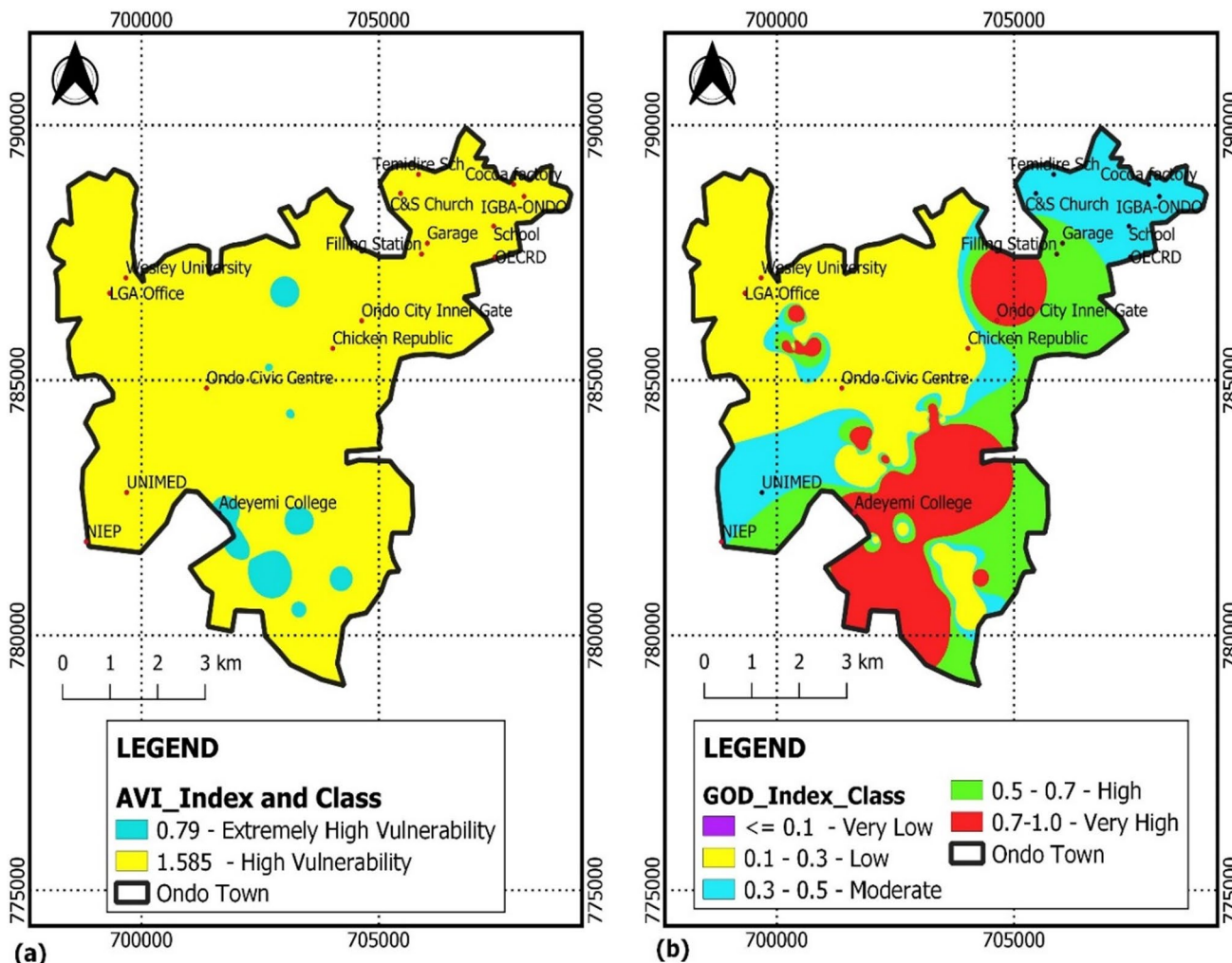


Fig. 7 Spatial Distribution of a AVI b GOD groundwater vulnerability models

### Vulnerability index map

The GOD and AVI models is shown in Fig. 7. The AVI distinguished the area’s vulnerability into two zones as high (1–2) and extremely high (< 1), accounting for 94% and 6%, respectively (Fig. 7a). The delineated vulnerable zones were at variance with what was obtainable by Olojoku et al. (2017), who carried out vulnerability assessment of shallow aquifer hand-dug wells in rural parts of northcentral Nigeria using AVI and GOD methods, from their study, AVI values varied from – 0.32 to 1.78; with the high vulnerable zones having the large percentage of aerial coverage, as also recorded in this study. Similar study by Falowo et al. (2017) in the basement terrain of Southwestern Nigeria using aquifer vulnerability index and GOD methods, recorded two vulnerability zones of extremely high and high, while the high pollution risk zone predominated.

In this study, GOD categorized the area into five vulnerability zones, comprising very low (<0.1) not distinctly represented on the map, low (0.1–0.3) with 42% aerial extent, moderate (0.3–0.5) accounting for 17% aerial coverage, high (0.5–0.7) with 25% aerial extent, and very high (0.7–1.0) representing 16% of the study area (Fig. 7b). Consequently, the combined high and very high vulnerability zone account for 41% of the study area, which is at 60% variance with AVI model. In related study, the result of GOD model by Falowo et al. (2017) in Akoko area of Ondo State delineated three vulnerable zones of low (50%), moderate (45%), and high (5%), but differed widely from the result of Falowo and Omorogieva (2020) which recorded very high and moderate vulnerability indices covering 60% and 40%, respectively, over Ilaje Local Government Area of Ondo State, even though the very high pollution risk in the area was due to salt water intrusion and anthropogenic sources. Thus, the GOD result of this study corroborated or agreed with

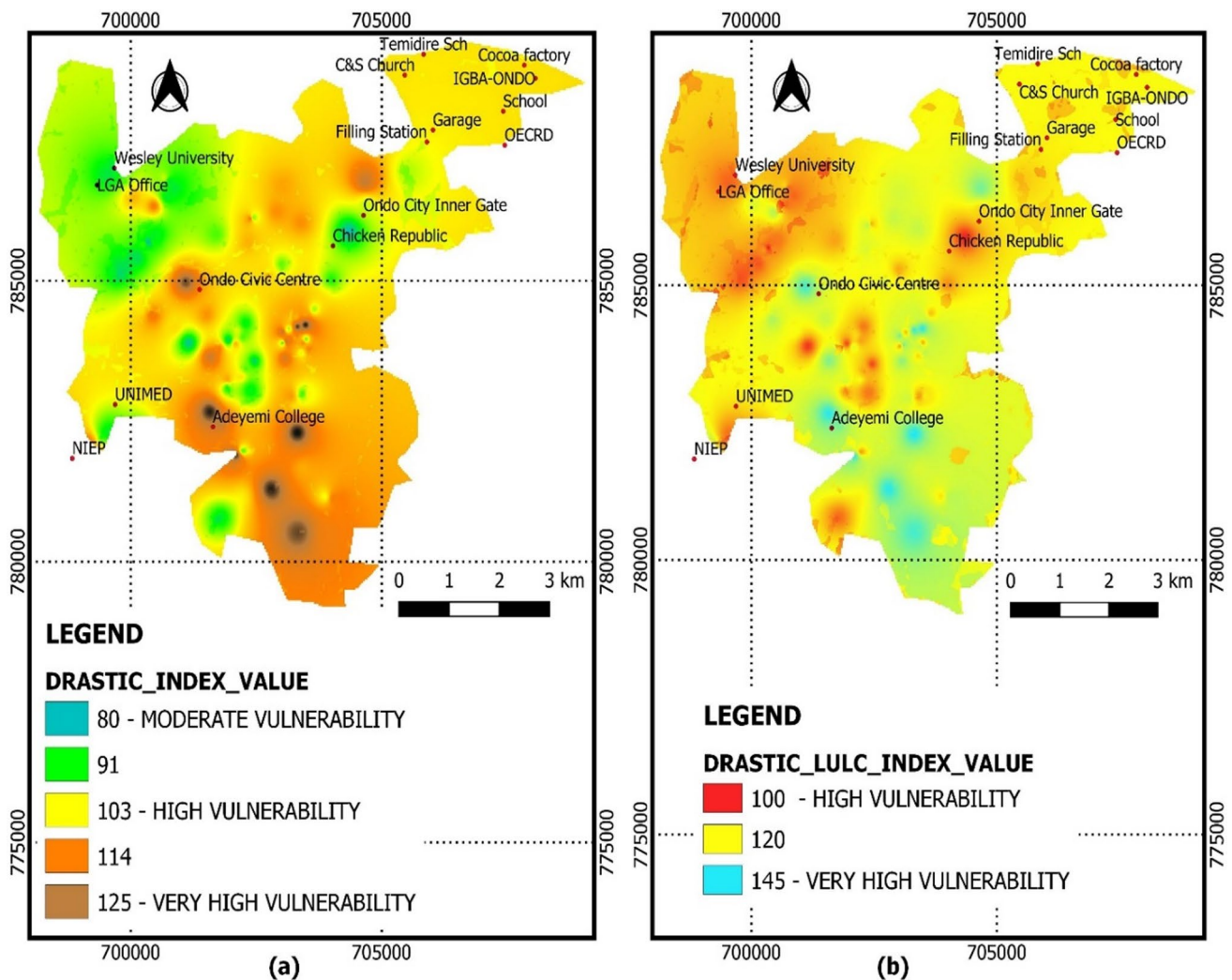


Fig. 8 Spatial Distribution of a DRASTIC b DRASTIC-LU groundwater vulnerability zones

Falowo et al. (2017); with that of Oni et al. (2017) carried out at Igbara-oke in Ondo State Southwestern Nigeria; and Olojoku et al. (2017) done in northcentral Nigeria. Some of the factors responsible for the similarity observed in their results are moderate depth to water table, and clayey subsoil/vadose zone.

The DRASTIC map (Fig. 8a) was categorized into three major zones, based on the calculated DRASTIC number, which is the overall addition of parameters N-number, as moderately high (60–80) found in the northwestern part, high (80–103), and very high (103–125) vulnerability zones, constituting 33%, 50%, and 17%, respectively (Fig. 8a). This is in sharp contrast with the result of vulnerability assessment of shallow groundwater in Basement Complex Area of Southwestern Nigeria carried out by Adewumi et al. (2018) using DRASTIC model, from their result two vulnerable zones were delineated as low (accounted for 83% aerial coverage) and moderate (with aerial coverage of 17%). However, Emberga et al. (2022) in their work which had to do with groundwater risk assessment in Imo River Basin of Southeastern Nigeria using GIS-based DRASTIC and GOD models, recorded closely related range of values of DRASTIC number (76–192) similar to this present study. However, Ekwere et al. (2022) recorded a low DRASTIC vulnerability index in parts of the Precambrian Oban Massif, Southeastern Nigeria. The DRASTIC-LU (Fig. 8b) divided the area into high vulnerability zone (100–120) constituting 87% of the study area, and very high vulnerability zone (120–145) with 13% aerial coverage. The use of DRASTIC-LU/LC model for assessing groundwater vulnerability to contamination in Nigeria is very scarce in the literature, however, similar work by Mkumbo et al. (2022) in Morogoro Municipality, Tanzania recorded three distinct vulnerable zones of low (having 29.2 km<sup>2</sup>), moderate (120.4 km<sup>2</sup>) and high (124.4 km<sup>2</sup>), and thus agreed with vulnerability zones recorded in this present study. Hence, for the purpose of synthesizing the vulnerability maps, there is high level of correlation among the models (about 60%) as all were able to map the high/very high vulnerability zones/areas. However, those areas which hitherto recorded moderate vulnerability on the DRASTIC model map, are changed to high vulnerability on the DRASTIC-LU and AVI maps. Therefore, the major contributing factors for groundwater pollution in the study area are land use/cover, depth to water level, net recharge, hydraulic conductivity and soil media, with land use pattern being the leading contributing factor.

## Validation

The nitrate analysis was done in order to validate the vulnerability maps (Boris et al. 2016; Huan et al. 2012; Mkumbo et al. 2022; Obeidat et al. 2012; Panno et al. 2006). Therefore, fifty-five (55) and six (6) borehole groundwater

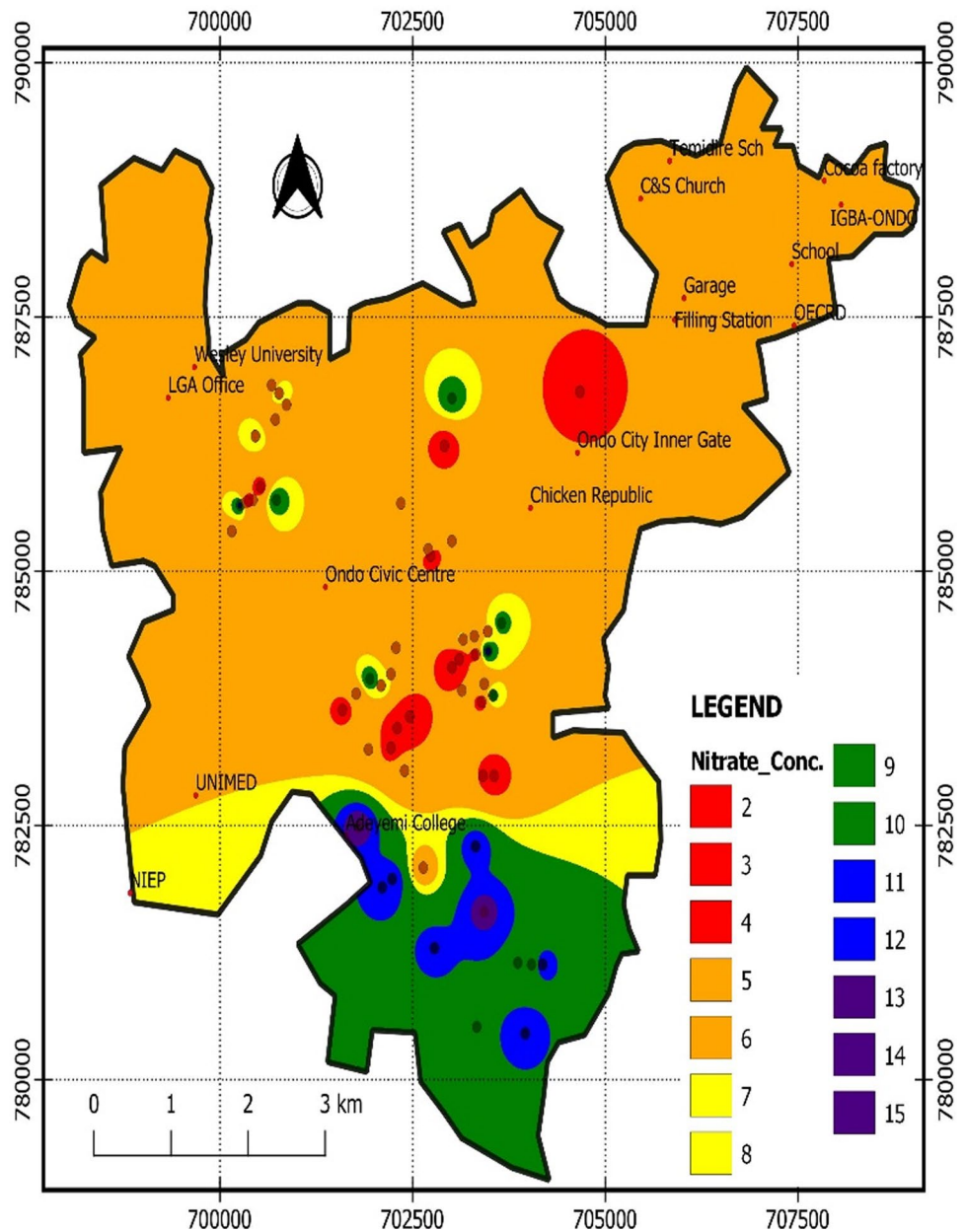
samples were collected in October 2022 (a time of relatively low rainfall, as the rainfall season was winding down), using 500 mL prewashed, high-density polyethylene bottles. Before taking the samples, the wells and boreholes were pumped for some time, enough to ensure that the stagnant water in the wells/boreholes has been replenished by fresh water from the aquifer, thus water samples were taken and analyzed using APHA (2006) procedure. The nitrate map is presented in Fig. 9, and displayed variation of 2 to 15 mg/L, with most of the values less than 10 mg/L maximum permissible of World Health Organization (2004). The relatively high nitrate values of 7–15 mg/L are found in the southern part constituting about 25%, areas identified as extremely high/high vulnerability zone on AVI, GOD, DRASTIC and DRASTIC-LU model maps. Most of the educational, industrial, and business centres are characterized by moderately high/high nitrate values, especially in the south. Thus, the result of the nitrate analysis further corroborates the earlier conclusion.

## Conclusions

This study applied GOD, AVI, DRASTIC and DRASTIC-LU models/methods for groundwater pollution vulnerability in Ondo metropolis, Southwestern Nigeria. The AVI distinguished the area's vulnerability into two zones into high and extremely high accounting for 94% and 6% aerial extent, respectively. The GOD categorized the area into five vulnerability zones, comprising very low, low with 42% aerial extent, moderate (17%), high with 25% aerial extent, and very high (16%). The AVI and GOD has 40% corroboration. The DRASTIC model categorized into three major zones as moderately high, found in the northwestern part; high; and very high vulnerability zones, constituting 33%, 50%, and 17%, respectively. The DRASTIC-LU divided the area into high vulnerability zone constituting 87% of the study area, and very high vulnerability zone with 13% aerial coverage. Therefore is high level of correlation among the models (about 60%) as all were able to map the high/very high vulnerability zones/areas. The nitrate map validated the high/extremely high vulnerability zones delineated on all the maps especially in the southern part. Hence, high level of monitoring is advocated in the zone to forestall break out of "groundwater borne diseases". Therefore, it can be concluded that land use/cover, slope, hydraulic conductivity, net recharge, soil media, and depth to water level are most influential parameters on groundwater quality in the study area, however, land use/cover is the most predominant factor influencing the groundwater vulnerability potential in the study, since land use acts as the source of contaminants during the use of manure and fertilizers, use of latrine and sewage systems. The limitation observed in this study has



**Fig. 9** Spatial Distribution of Nitrate concentration across the study area



to do with limited data or maps availability in the area of groundwater vulnerability studies using different models, especially DRASTIC and DRASTIC-LU/LC models. In Nigeria, except for few studies that utilized the electrical resistivity parameters, AVI, and GOD, many studies had not been carried out using DRASTIC model and/or in its modifications. Thus, it limits the study in the area of comparison with existing literatures especially within Nigeria.

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**Author contributions** Author OOF designed, wrote the protocol, arranged experimental processes, and managed the literature searches. Author OOO analyzed and interpreted the data. Both authors OOF and OOO prepared and approved the manuscript.

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**Availability of data and materials** The author declares that all the data supporting the findings of this study are available within the article.

**Code availability** Not applicable.



## Declarations

**Conflicts of interest** The authors declare no competing interest exists.

**Ethics approval** Not applicable.

**Consent to participate and consent to publish** Not applicable.

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