Full length article

Groundwater vulnerability assessment using hydrogeologic and geoelectric layer susceptibility indexing at Igbara Oke, Southwestern Nigeria

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A B S T R A C T

Groundwater vulnerability assessment was carried out at Igbara Oke Southwestern Nigeria, with a view to classify the area into vulnerability zones, by applying the electrical resistivity method, using Schlumberger electrode arrays with maximum electrode separation (AB/2) of 65 m in (41) different locations for data acquisition. Geoelectric parameters (layer resistivity and thickness) were determined from the interpreted data. The study area comprises four geoelectric layers (topsoil, lateritic layer, weathered/fractured layer and fresh basement). The geoelectric parameters of the overlying layers across the area were used to assess the vulnerability of the underlying aquifers to near-surface contaminants with the aid of vulnerability maps generated. Three models were compared by maps using geo-electrically derived models; longitudinal conductance, GOD (groundwater occurrence, overlying lithology and depth to the aquifer) and GLSI (geoelectric layer susceptibility indexing). The total longitudinal conductance map shows the north central part of the study area as a weakly protected (0.1–0.19) area, while the northern and southern parts have poor protective capacity (<0.1); this is in agreement with the GOD method which shows the northern part of the study area as less vulnerable (0–0.1) while the southern part has low/moderate (0.1–0.3) vulnerability to contamination. The longitudinal conductance exaggerates the degree of susceptibility to contamination than the GOD and GLSI models. From the models, vulnerability to contamination can be considered higher at the southern part than the northern part and therefore, sources of contamination like septic tank, refuse dump should be cited far from groundwater development area.

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1. Introduction

As the need for groundwater resources development increases globally due to increase in population, the need for the protection of the resource becomes paramount. Several groundwater developments have been abandoned due to various reasons after a huge investment on such, occasioned by infiltration of pollutants and subsequent contamination of groundwater derived from leaching of septic tank, refuse dump, petroleum tanks, improper use and disposal of pesticides (Sampath, 2000). Huge financial loss (well abandonment) and serious health hazard would have been averted if a well-planned vulnerability assessment had been carried out (Piver et al., 1997). The natural vulnerability is a concept that expresses the sensitivity of an aquifer to be adversely affected by an imposed contaminant load (Van Waegeningh and Van Duijvenbooden, 1987; Foster and Hirata, 1988; Vrba and Zaporozec, 1994). The main parameters considered in the natural vulnerability assessment involve the confinement degree (confined or unconfined), depth to groundwater table and the lithology and consolidation level of the strata above the saturated zone. The contaminants attenuation capacity and hydraulic accessibility of the unsaturated zone is the focus in all vulnerability estimation (Foster and Hirata, 1987). However, aquifers in basement complex terrains often occur at shallow depths, thus exposing the water within to environmental risks, that is, vulnerable to surface or near-surface contaminants (Omosuyi, 2010). The protection of the groundwater reservoirs is given by the covering layers of low

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hydraulic conductivity which offer little or no pathway to contaminant percolation thereby delaying and degrading the contaminant (Aweto, 2011).

Several methods have been developed and applied in the systematic process for assessing the vulnerability of groundwater to contamination. Each method has its advantages and limitations, and none can be considered the most appropriate for all situations (Foster et al., 2002). Most of the vulnerability assessment approaches, (DRASTIC, GOD) are largely hydrogeologic oriented and subjective, while few electromagnetic parameters such as terrain conductivity, longitudinal conductance embrace geophysical approach of measurement. Some of the methods, (Mclay et al., 2001; Herbst et al., 2005) are based on hydraulic conductivity and thickness of the layers overlying the aquifer, while others are based on the geoelectric parameters of the geoelectric layers. Known geoelectric method such as longitudinal conductance does index the susceptibility or vulnerability of the geoelectric layer(s). However, the results are subject to the principle of equivalence and the approach is insensitive to the possible presence of relatively high resistive geological formations like laterites. Laterites are known to be good protective barriers for the underlying aquifers, and thus there is a need for adopting other comparative approaches such as GOD and GLSI in the vulnerability assessment. The GLSI is a newly introduced approach aimed at overcoming the inherent weakness of insensitivity to possible presence of lateritic formations in longitudinal conductance and the over prioritization of the effect of geomaterials in the GOD approach. GLSI gives equal priority to vadoze zone thickness and importance of geomaterials in aquifer protection studies by assigning index scores to the parameters (layer thicknesses and layer resistivity values). The GOD (Gogu and Dassargues, 2000) and GLSI are index-parametric methods; each parameter displays a range relating to its property, subdivided into discrete and hierarchized intervals with specific values, which reflect their susceptibility level to contamination.

2. The study area

The study area, Igbara-Oke, is the Headquarter of Ifedore Local Government area of Ondo State, Southwestern Nigeria. It is located along Akure-Ilesha expressway (Fig. 1). It is situated between latitudes 7°24′0″ and 7°25′30″N and longitudes 5°2′0″ and 5°4′0″E with elevation 359 m above sea level. It is linked to the neighboring communities by series of road networks such as Isarun, Igbara-Odo, Ilawe, Ero and Owena. The geology is underlain by the Precambrian rocks of southwestern Nigeria (Rahaman, 1976). It consists of metamorphic and igneous rocks, composed mainly of porphyritic granites, gneisses, schists, politic schists, quartzites, schistose quartzites, charnockites and fine to medium grained biotitic-muscovite granite, with occurrence of quartzite (Fig. 2).

3. Methods of study

The Schlumberger array electrode configuration was used for the resistivity survey at the study area. vertical electrical soundings (VES) were conducted and the apparent resistivity (ρ_a) measurements were plotted against AB/2. The maximum electrode separation is 65 m. Omega campus resistivity meter was used in data acquisition in 41 different locations. The parameters considered adequate in quantifying the degrees of vulnerability in the area were inferred from the geo-electric parameters using three methods; longitudinal conductance, GOD and GLSI.
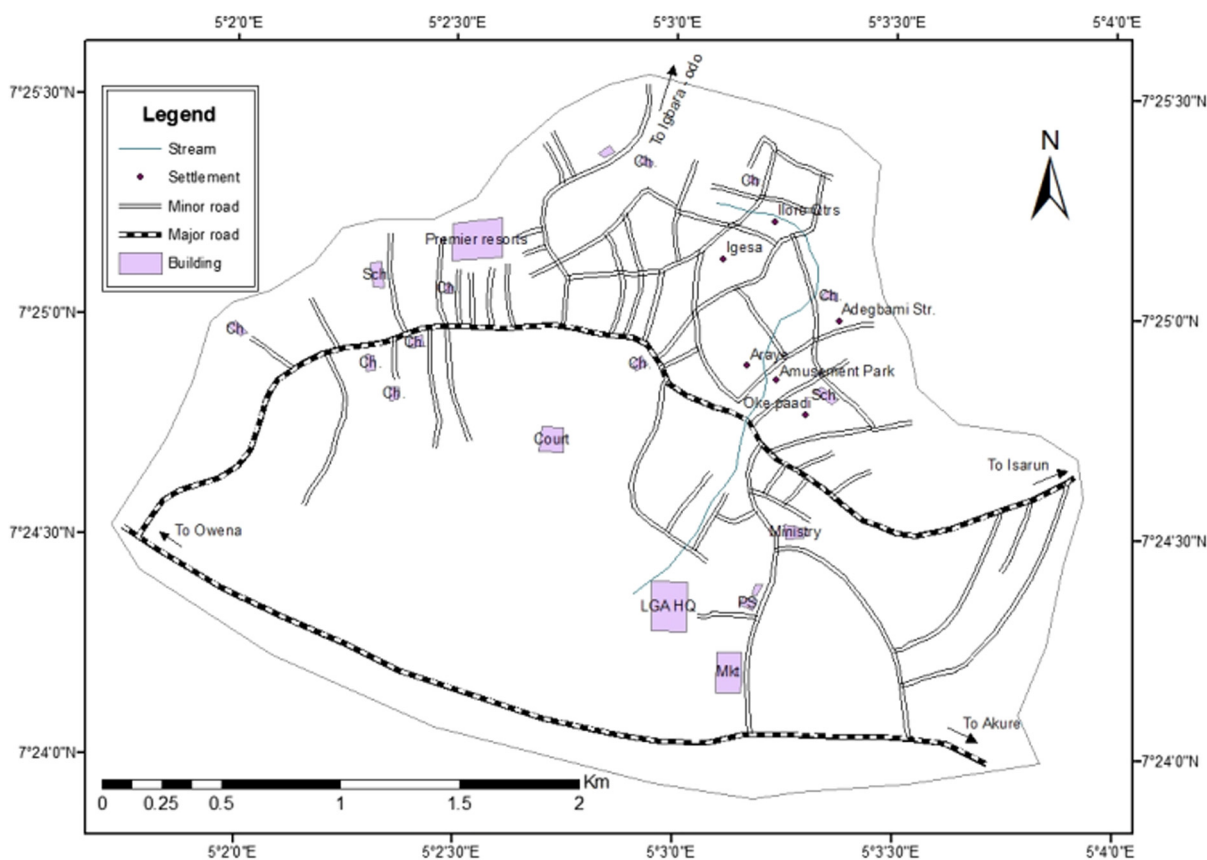

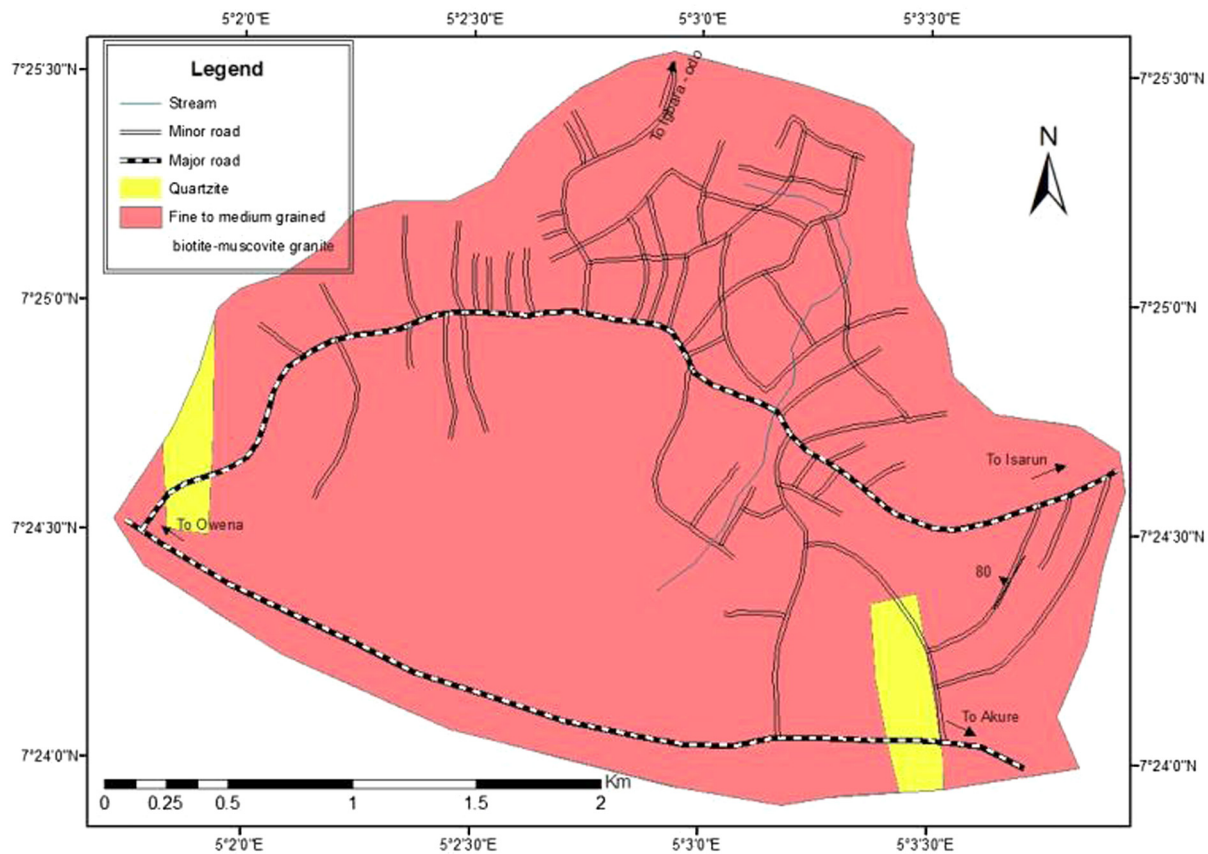**Fig. 1.** Base map of the study area.

Fig. 2. Local geological map of Igbara-Oke (NGSA, 1965).

Table 1
Modified longitudinal unit conductance/protective capacity rating (Oladapo et al., 2004).

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

3.1. Longitudinal conductance

Henriet (1976) demonstrated that the protection degree of an aquifer may be considered directly proportional to the ratio between the thickness and resistivity $\left(S = \frac{h}{\rho}\right)$, or in other words, the longitudinal conductance (S), enables to define the protection degree of groundwater from contaminants migrating vertically. However, an overlying layer with high longitudinal conductance (generally greater than 1.0) offers a high protection degree to contamination, therefore the bigger the thickness of this layer, the greater the infiltration time of the contaminants (large filter) and the lower the resistivity, the more clayey and less permeable the material will be Braga et al. (2006). Eq. (1) was used in calculating longitudinal conductance;

$$S = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \cdots + \frac{h_n}{\rho_n} \tag{1}$$

where h_1, h_2, h_3 and h_n are layer thicknesses and ρ_1, ρ_2, ρ_3 and ρ_n are layer resistivity parameters. S is the longitudinal conductance. The rated longitudinal conductance protective capacity is shown in Table 1.

3.2. GOD

The G.O.D index used to evaluate the aquifer vulnerability in the area was calculated by multiplication of the influence of the three parameters namely; groundwater occurrence (confinement of the aquifer), overlying lithology of the aquifer, depth to the aquifer.

Table 2
Attribution of notes for GOD model parameters (Khemiri et al., 2013).

Aquifer type	Note	Lithology (Ω-m)	Note	Depth to aquifer (m)	Note
Non-aquifer	0	<60	0.4	<2	1
Artesian	0.1	60–100	0.5	2–5	0.9
Confined	0.2	100–300	0.7	5–10	0.8
Semi-confined	0.3–0.5	300–600	0.8	10–20	0.7
Unconfined	0.6–1	>600	0.6	20–50	0.6
				50–100	0.5
Aquifer type	Note	Lithology (Ω-m)	Note	Depth to aquifer (m)	Note

Table 3
The GOD parameter rating method (Foster, 1987).

Vulnerability class	Index rating
Negligible	0–0.1
Low	0.1–0.3
Moderate	0.3–0.5
High	0.5–0.7
Extreme	0.7–1

Table 4
Geoelectric layer susceptibility index rating for resistivity parameters.

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

Table 5
Geoelectric layer susceptibility index rating for thickness.

Thickness(m)	Index rating
<2	4
2–5	3
5–20	2
>20	1

These GOD parameters were interpreted from the geo-electrical parameters (resistivity and thickness of the interpreted layers).

Table 6
GLSI parameters rating.

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

The GOD index was then calculated by multiplying the influence of the various parameters together in Eq. (2). Tables 2 and 3 show attribution of notes for GOD model parameters and the vulnerability index rating.

$$\text{G.O.D Index} = G \times O \times D \tag{2}$$

where G = Type of aquifer, O = Overlying lithology, D = Depth to the aquifer.

3.3. GLSI

Geoelectric layer susceptibility indexing (GLSI) is a hydrogeologic approach that indexes the geoelectric parameters generated from the electrical resistivity contrast between lithological sequences in the subsurface. It is an empirical concept introduced to complement other methods of vulnerability assessment. Unlike the longitudinal conductance approach where the ratios of the geoelectric parameters (layer resistivity and thickness) are assigned indices, the GLSI assigns index to each geoelectric parameter (layer resistivity and thickness) (Tables 4 and 5). GLSI is determined by Eq. (3).

$$\text{GLSI} = \frac{((\rho_{1r} + h_{1r})/2 + (\rho_{2r} + h_{2r})/2 + (\rho_{3r} + h_{3r})/2 + \cdots + (\rho_{nr} + h_{nr})/2)}{N} \tag{3}$$
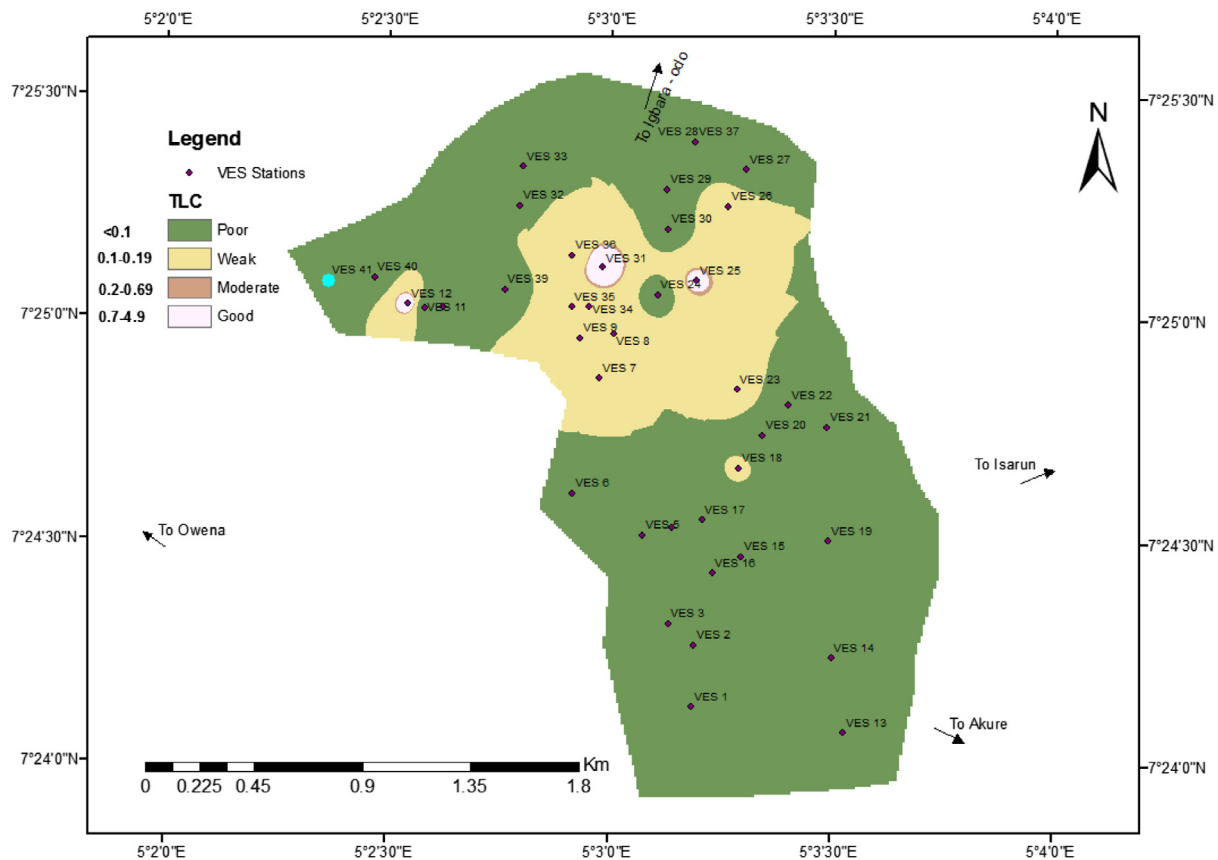

Fig. 3. Modified longitudinal unit conductance/protective capacity rating.

where GLSI is the geoelectric layer susceptibility indexing, ρ_{1r} is the first layer resistivity index rating, h_{1r} is the first layer thickness index rating, ρ_{2r} is the second layer resistivity index rating, h_{2r} is the second layer thickness index rating, ρ_{nr} is the nth layer resistivity index rating, h_{nr} is the nth layer thickness index rating, N is the number of geoelectric layers overlying the aquifer.

The GLSI adopts the MCDA (Multi Criteria Decision Analysis) approach for the rated parameters index. The assigned parameter indices are then normalized by dividing with the number of geoelectric layers (N) delineated above the aquifer. Table 6 shows the vulnerability index rating for GLSI.

4. Results and discussion

4.1. Total longitudinal unit conductance

Oladapo et al. (2004) classified the protective capacity of vadoze zone, as >10 excellent, 5–10 very good, 0.7–4.9 good, 0.2–0.69 moderate, 0.1–0.19 weak and <0.1 poor. The total longitudinal unit conductance map (Fig. 3) shows the distribution of the longitudinal conductance within the study area. The map shows closures of very low longitudinal conductance (<0.1) at the southern and the northern parts. The north central part exhibits a weak protective capacity (0.1–0.19), which is fairly higher than other parts of the study area categorized to be of poor protective capacity. The higher the longitudinal conductance, the higher the aquifer protective capacity.

4.2. The GOD vulnerability index

The GOD map is an overlaid index map that combines the influence of individual GOD parameters. The final GOD index map produced is influenced by the contributions of individual GOD parameters. The GOD vulnerability map (Fig. 4) is used to evaluate the groundwater susceptibility to contamination in the study area. The map shows a varied degree of vulnerability designated as negligible and low. The northern part of the study area shows a negligible range of vulnerability (0–0.1) values. The southern part ranges between 0.1 and 0.18 indicating a low degree of vulnerability (low level of contamination).

4.3. The geoelectric layer susceptibility index (GLSI)

Fig. 5 shows the overlay index map of lithology and vadoze zone thickness of the study area. The effect of vadoze zone thickness in aquifer vulnerability assessment is of high importance because, a sufficiently thick vadoze zone can delay contaminant travel to the aquifer zone, thereby degrading the contaminant. These parameters combined were used to prepare an overlay index map of GLSI. The map shows medium (2.0–2.99) vulnerability at the northern part of the study area. High (3.0–3.99) vulnerability zones occur at the north-eastern and north-western parts of the area. The southern part has low (1.0–1.99) vulnerability to contamination.

5. Conclusion

Electrical resistivity method involving vertical electrical sounding (VES) using Schlumberger configuration was successfully applied in aquifer vulnerability assessment of Igbara-Oke. Geoelectric parameters obtained from the VES assists in the production of the vulnerability index maps. The maps enabled the area to be categorized into different vulnerability zones (high, medium, low). The protective capacity/vulnerability of the area was deter-
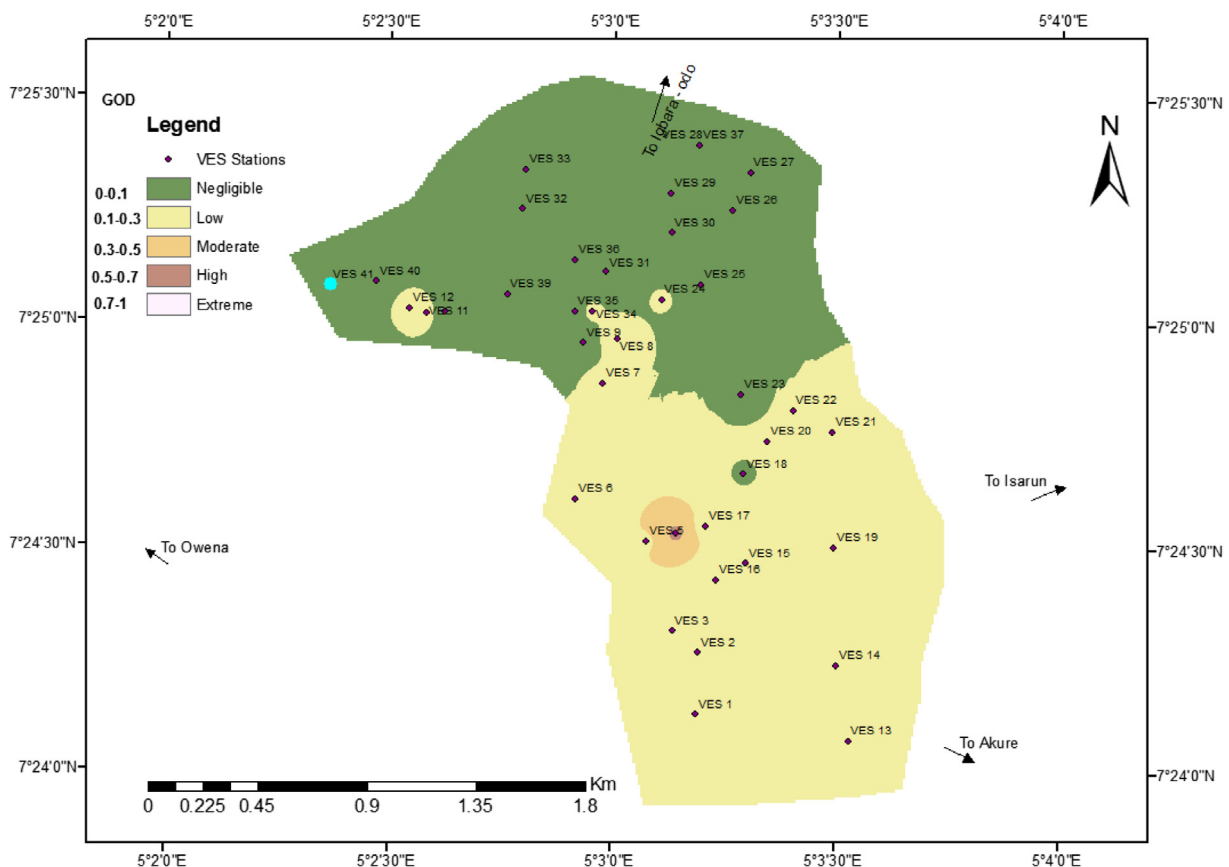

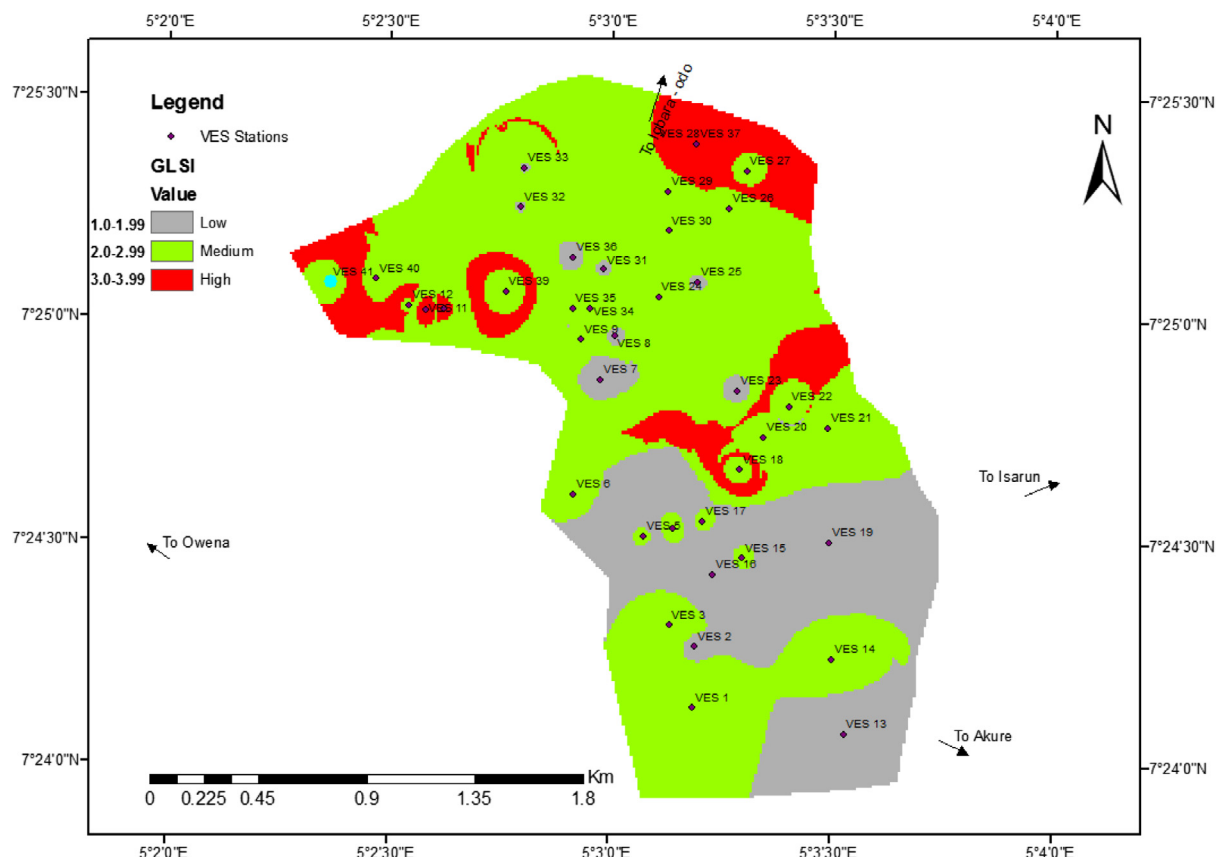Fig. 4. GOD vulnerability index map of the study area.

Fig. 5. Geoelectric layer susceptibility indexing (GLSI) map of the study area.

mined by comparing three different models from hydro-geophysical and hydrogeological points of view (i.e. longitudinal unit conductance, GOD and GLSI models). The study showed that the protective capacity of the vadoze zone ranges from poor to moderate in the study area. The GOD categorises the northern and southern parts of the study area respectively as negligible and low vulnerability zones. The GLSI also classified the northern and southern parts of the study area respectively as moderate to low vulnerability zones. The GOD and GLSI showed low vulnerability to contamination in areas around the southern part of the studied location. Longitudinal conductance exaggerates the degree of susceptibility than the GOD and GLSI models because it gives higher preference to the thickness of geo-material more than the constituent properties of the geo-material. GOD reported low degree of vulnerability than the longitudinal conductance and the GOD methods because it gives higher preference to the inherent properties of the geo-materials in terms of grain size distribution, degree of compaction and consolidation, etc. The study has shown the efficacy of GLSI as an important tool in identifying aquifers susceptible/vulnerable to contamination particularly due to the priority given to the effect of the vadoze zone thickness. Appreciably thick vadose zone could increase the travel time of contaminants, thereby delaying and degrading such contaminant due to the properties of the geo materials and biological activities in the vadoze zone thus making such areas less susceptible to contamination. The consideration given to vadoze zone thickness makes this technique very unique. By relating the various resistivity and vadoze zone thickness maps with the three approaches, the northern part of the study area could be considered less vulnerable to contamination than the southern part.

Therefore, development activities must be well planned around the southern part to avoid contamination from sources such as septic tanks, and petroleum tanks. Contamination must be anticipated and therefore underground services must be cited away from groundwater sources.

Conclusively, in groundwater resources management, efforts must be made to investigate the susceptibility of the delineated aquifers to pollution, this will assist in mitigating against threat contaminated water poses to health and the environment.

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