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Full Length Research Article

Geo-spatial Classification of Vulnerability Zones using Lithological, Elevation and Geoelectric Parameters in a Typical Basement Complex Environment

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ABSTRACT

Lithology, elevation and four (4) geoelectric parameters were utilized in assessing the groundwater vulnerability at northwestern part of Akure, southwestern Nigeria. Vertical electrical sounding (VES) technique of electrical resistivity method was adopted for this work. A total of 224 VES data was acquired and interpreted both qualitatively and quantitatively. Three to five geo-electric layers were delineated across the area which corresponds to four geologic layers. The resistivity of the layers varies respectively from 6.9 - 550 Ohm-m, 60 - 2500 Ohm-m, 20 - 650 Ohm-m and 220 - 7900 Ohm-m in the topsoil, weathered layer, partially weathered basement/partially fractured basement and presumed fresh basement. Likewise, the layer thicknesses also vary respectively from 0.4 - 4.0 m, 0.7 - 19.0 m and 4.0 - 60 m in the topsoil, weathered layer and partially weathered basement/partially fractured basement. The results were presented as topsoil (resistivity and thickness) and weathered layer (resistivity and thickness) maps. The six parameters consisting of lithology, elevation, topsoil (resistivity and thickness) and weathered layer (resistivity and thickness) were synthesized using an additive model in order to generate the aquifer vulnerability model map. The aquifer vulnerability model map shows that the area is of very low to moderate vulnerability with 5% of the area having very low vulnerability, 30% low vulnerability and 65% moderate vulnerability. This implies that the groundwater resources in the area are moderately safe.

Keywords: Vertical electrical sounding (VES), Groundwater, Aquifer layer, Vulnerability model map, Lithology, Geoelectric parameters.

INTRODUCTION

Aquifer vulnerability is the sensitivity of groundwater quality to an imposed contaminant (Van Stempvoort *et al.*, 1992). Groundwater vulnerability is the measure of how easy it is for pollution or contamination at the earth surface to reach the underlying aquifer layer. Vulnerability of groundwater body can be assessed in three (3) major ways: (1) Physical measurements; distribution of high and low permeability units, (2) Chemical measurements; use of environmental tracers and (3) integrated hydrological modeling (numerical modeling). Aquifer vulnerability can range between very low to very high. Groundwater vulnerability is not an absolute property but a relative indication of where contamination is likely to occur (Bjerg *et al.*, 1992). Therefore, vulnerability is the probability of contamination occurring in an area in the future. The potential for contaminants to percolate through the vadoze zone and get to the water table depends on several factors which include the composition of soils and geologic materials in the unsaturated zone, the depth to water table, the recharge rate, and environmental factors influencing the potential for biodegradation (Bjerg *et al*., 1992).

The effect of the composition of the unsaturated zone on vulnerability is substantiated by the fact that high organic matter or clay (lithology) content increases sorption rate and thus lessens the potential for contamination (Rhoades *et al*., 1989). The depth to the water table can be an important factor because short flow paths decrease the opportunity for sorption and biodegradation, thus increase the potential for many contaminants to reach the ground water (Bjerg *et al*., 1992). Conversely, longer flow paths from land surface to the water table can lessen the potential of contamination by chemicals that degrade along the flow path (Bjerg *et al*., 1992). Recharge rates affect the extent and rate of transport of contaminants through the saturated zone (Van Stempvoort *et al*. 1992). Finally, environmental factors, such as temperature and water content, can significantly influence the degradation of contaminants by microbial transformations. The surface topography has also been found to have effect on the ease at which contamination gets to the groundwater (Adeyemo *et al*., 2015). The type of aquifer obtainable in an area can also influence vulnerability, confined, semi-confined aquifer or leaky aquifer and perched aquifer.

There are two general types of vulnerability assessments. The first addresses specific vulnerability, and is referenced to a specific contaminant, contaminant class, or human activity. The second addresses intrinsic vulnerability and is for vulnerability assessments that do not consider the attributes and behavior of specific contaminants. In practice, a clear distinction between intrinsic and specific vulnerability cannot always be made. Contaminants can enter aquifers by a variety of pathways. Most existing assessment techniques address only transport that occurs by simple percolation and ignore preferential flow paths such as bio-channels, cracks, joints, faults and fracture planes, and solution channels in the vadoze zone (Abdeslam *et. al*., 2017; Guettaia *et. al*., 2017). Some overlay and index methods have attempted to address contamination that might occur by wells and boreholes by mapping those features in combination with the results derived from other assessment methods. The overall utility of a vulnerability assessment is highly dependent on the scale at which it is conducted, the scale at which data are available, the scale used to display results, and the spatial resolution of mapping (Lathamani *et. al*., 2015 and Abdeslam *et. al*., 2017).

An array of approaches for predicting ground water vulnerability has been developed and used from an understanding of the factors that affect the transport of contaminants introduced at or near the land surface. These methods fall into three major classes: (1) overlay and index methods that combine specific physical characteristics that affect vulnerability and are often giving a numerical score (Lathamani *et. al*., 2015; Abdeslam *et. al*., 2017; Guettaia *et. al*., 2017; Oni *et. al*., 2017), (2) process-based methods consisting of mathematical models that approximate the behavior of substances in the subsurface environment (Chen, *et al*., 2013; Jang and Chen, 2015; and Javadi *et al*., 2017), and (3) statistical methods that draw associations with areas where contamination is known to have occurred (Armengol *et al*., 2014).

Several approaches have been used by different authors in assessing aquifer layers vulnerability in Akure area and beyond; longitudinal conductance, GOD (Groundwater occurrence, Overlying lithology and Depth to aquifer), GODA (Groundwater occurrence, Overlying lithology, Depth to aquifer and Aquifer geomorphology relief) and GSLI (Geoelectric Layer Susceptibility Indexing) and DRASTIC ([D] depth to water table, [R] recharge, [A] aquifer media, [S] soil media, [T] topography, [I] impact of vadoze zone and [C] hydraulic conductivity) (Chen, *et al*., 2013; Armengol *et al*., 2014; Jang and Chen, 2015; Lathamani *et. al*., 2015; Abdeslam, *et. al*., 2017; Guettaia, *et. al*., 2017; Oni *et. al*., 2017; Javadi, *et al*., 2017). However, this work utilized six parameters which includes lithology and surface elevations and four geoelectrically derived parameters; topsoill (resistivity and thickness) and weathered layer (resistivity and thickness) in assessing aquifer vulnerability. Some of the earlier approaches used many parameters (DRASTIC) or parameters that are not easily come about; but this newly proposed approach includes six (6) parameters; lithology, elevation and topsoil resistivity, topsoil thickness, weathered layer resistivity and weathered layer thickness was developed and proposed because all the parameters are easily derived and can easily be replicated elsewhere.

The Study Area

The study area is part of Akure, Ondo State, Nigeria. The area is bounded in the north by Akure-Ilesha/Akure-Owo Expressway, to the south by Aule Road and to the west by Alaba-Apatapiti road. The area comprises of part of Aule GRA, Alaba-Apatapiti layout and Ondo State Industrial Estate Akure (Figure 1). The area falls within geographic grids of 736237 to 740501 m (Eastings) and 803887 to 808093 m (Northings) along 31N Minna Datum of the UTM (Universal Traverse Mercatum) system and the total surface area is about 7.15 km^2. The area is moderately to highly undulating with surface elevation ranging from 335 to 410 m above sea level (Figure 1). The increase in population of the area and the concomitant increase in refuse disposal will pose serious threat to the groundwater resources of the area, especially if groundwater flow direction was not considered before sitting these dump sites.

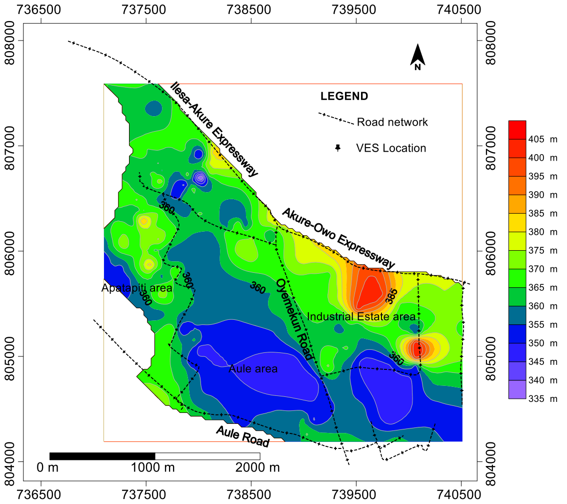

Figure 1: Elevation map of the study area

MATERIALS AND METHODS

This study utilized the vertical electrical sounding (VES) techniques of the electrical resistivity method. The Schlumberger electrode configuration was adopted for the data acquisition (Zohdy, 1965: Koefoed, 1979) with half-current electrode spread varying from minimum of 1 m to maximum of 100 - 150 m. A total of 224 geoelectric sounding data was acquired in order to access the aquifer layer vulnerability of the study area (Figure 2) and the field data were interpreted using the conventional partial curve matching techniques (Zohdy, 1965 and Koefoed, 1979) and the results were further enhanced using Resist Version 1.0 software (Vander Velpen, 2004). Six parameters consisting of lithology, surface elevation, topoil resistivity, topsoil thickness; weathered layer resistivity and weathered layer thickness were used**.** These six parameters were synthesized using an additive model that was first used by Chachadi, (2005) and adapted by Adeyemo *et al*. (2017) to generate the final aquifer vulnerability model map of the area using Surfer 13 software produced by Golden Software.

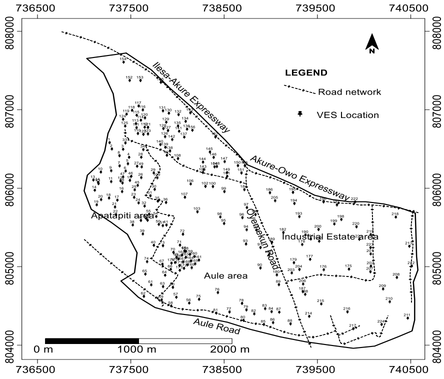

Figure 2: The study area map showing the VES locations

Aquifer Vulnerability Assessment

In evaluating aquifer vulnerability, this study considered factors like geology, surface elevation, topsoil resistivity, topsoil thickness, weathered layer thickness and weathered layer resistivity. Weighting and rating (Table 3) of these factors were done in order to generate aquifer vulnerability model map. The effect of each of the six parameters to vulnerability were weighed on a scale 1 - 10 and the scores were subsequently normalized (Table 3). From the normalized weight, geology was assigned the weight of 0.3, because it determines the subsurface lithology, structures and their contribution to vulnerability, next to geology are surface elevation, topsoil and weathered layer resistivity which were assigned equal weight of 0.15, while topsoil and weathered layer thickness were both assigned equal weight of 0.125.

RESULTS AND DISCUSSION

The VES field obtained data were interpreted qualitatively and quantitatively. The results of the 224 vertical electrical sounding (VES) survey were as presented in Table 1. The highest occurring curve type is KH (82), follow by HA (48), H (41), A (14) and AA (8) while the frequency of other curve types ranges from 1 to

6 (Table 1). Three to five geo-electric layers were delineated across the area which corresponds to four significant geologic layers. The resistivity of the layers varies respectively as 6.9 - 550 Ohm-m, 60 - 2500 Ohm-m, 20 - 650 Ohm-m and 220 - 7900 Ohm-m in the topsoil, weathered layer, partially weathered basement/partially fractured basement and the presumed fresh basement. The layer thickness values also vary respectively as 0.4 - 4.0 m, 0.7 - 19.0 m and 4.0 - 60 m in the topsoil, weathered layer and partially weathered basement/partially fractured basement (Table 1). Fifteen (15) different curve types were delineated across the study area from the VES results (Table 2).

Table 1: Vertical electrical sounding (VES) results

Ves no	**Layer thickness (m)** $h_1/ h_2/ h_3/ \ldots h_{n-1}/ h_n$	**Layer resistivity (Ω-m)** $\rho_1/ \rho_2/ \rho_3/ \ldots \rho_{n-1}/ \rho_n$	**Curve type**
1	1.1/ 6.3/ 11.5	101/ 120/ 55/ 402	KH
2	6.2/ 1.4/ 1.2	69/ 36/ 105/ 532	HA
3	0.8/ 1.8	54/ 139/ 263	A
4	0.9/ 17.6/ 3.2	42/ 186/ 178/ 2707	KH
5	0.9/ 6.1/ 8.4	53/ 307/ 92/ 1752	KH
6	0.8/ 7.2/ 20.7	71/ 437/18/ 748	KH
7	2.0/ 2.5/ 7.7/ 9.5	72/ 155/ 33/ 144/ 1116	KHA
8	0.8/ 3.5/ 10.0	19/ 500/ 28/ 559	KH
9	1.0/ 9.8/ 2.2	47/ 106/ 153/ 586	AA
10	1.4/ 2.7	59/ 14/ 2789	H
11	6.7/ 3.4	239/ 44/ 1250	H
12	0.9/ 10.8/ 2.2	87/ 135/ 129/ 758	KH
13	0.7/ 2.5/ 14.9	83/ 267/ 46/ 436	KH
14	4.1/ 5.6/ 1.2	106/ 67/ 55/ 2536	AH
15	2.6/ 7.9	282/ 218/ 782	H
16	0.9/ 1.1/ 27.3	124/ 213/ 18/ 317	KH
17	0.8/ 6.3/ 3.2	92/ 172/ 93/ 365	KH
18	0.6/ 3.1/ 11.1	45/ 280/ 76/ 891	KH
19	0.9/ 3.3/ 9.4	76/ 181/ 38/ 788	KH
20	3.1/ 3.6	91/ 27/ 188	H
29	1.7/ 12.3	114/ 36/1315	H
30	3.0/ 2.8/ 14.8	73/ 166/ 1143/ 624	AK
223	0.6/ 1.8/ 14.0	22/ 5/ 64/ 134	HA
224	0.4/ 5.0	358/ 27/ 2024	H

Table 2: Curve types frequency and percentage of occurrence

Serial number	Curve types	Frequency	Percentage (%)
1	KH	82	36.6
2	H	41	18.3
3	HA	49	21.4
4	A	14	6.3
5	K	5	2.2
6	HK	6	2.8
7	KHA	4	1.8
8	KHK	3	1.3
9	HKH	6	2.8
10	HKQ	1	0.4
11	HAK	1	0.4
12	AH	1	0.4
13	AA	8	3.6
14	QH	3	1.3
15	AK	1	0.4

Lithology

The two dominant rock types in the study area are the migmatite-gneiss and charnockite. After alteration by weathering the migmatite-gneiss generally has higher porosity and permeability than charnockite, which weathered essentially into clay and clay has low permeability and high porosity. Migmatite-gneiss is more vulnerable than charnockite due to its greater permeability and higher degree of fracturing and faulting. In view of this, migmatite-gneiss was assigned relatively higher vulnerability rating (0.3) compares to charnockite which was assigned rating of 0.2 (Table 4). Greater part of the study area (Figure 3) which include FUTA area, Embassy area, Industrial Estate area, Oyemekun area and part of Aule area were underlain by charnockite, and these areas will be less vulnerable, while fewer part of the study area; Apatapiti area and part of Aule are underlain migmatite-gneiss will be more vulnerable.

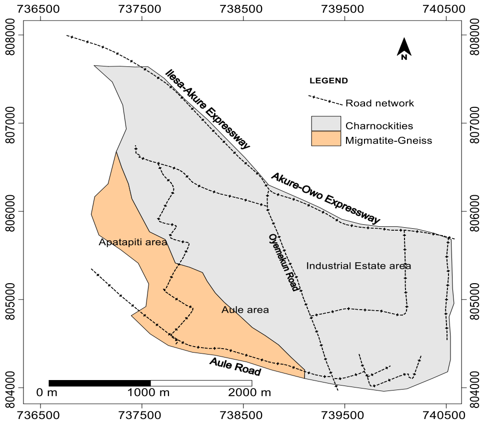

Figure 3: Lithological map of the study area (Modified after Owoyemi, 1996)

Table 3: Weighting of factors for aquifer vulnerability

Parameters	Normalized Weight
Lithology	0.3
Elevation	0.15
Topsoil	0.15
Topsoil	0.125
weathered layer	0.15
weathered layer	0.125

Table 4: Rating of Lithology

Lithology	Rating
Migmatite -	0.3
Charnockite	0.2

Elevation

The altitude of the study area with respect to sea level ranges from 335 - 410 m. Elevation affects surface run-off, at higher elevation run-off will be much while infiltration will be small and conversely at lower elevation, run-off will be small while infiltration will be much. Thus higher infiltration increases groundwater vulnerability, while lower infiltration reduces groundwater vulnerability (Adeyemo *et al*., 2015). The area was grouped into five different ratings based on their surface elevation (Table 5, Adeyemo *et al*., 2017).

The elevation map (Figure 4) shows that the southern part of the study area, which include Aule area, Ilesha garage area and a part of Apatapiti area are characterized with very low elevation (335 - 365 m) which suggest very high vulnerability, while the northern part which include Oyemekun area, Embassy area and FUTA area has moderate elevation (365 - 375 m) which suggest moderate vulnerability, while a portion of the north-eastern part of the area, the north-western area has very high elevation (385 m and above) which indicate very low vulnerability.

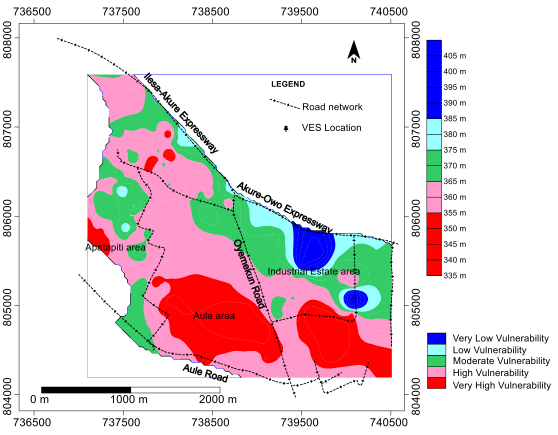

Figure 4: Elevation map of the area showing vulnerability ratings

Table 5: Rating of Elevation

Elevation (m)	Rating
385 and above	0.2
375 - 385	0.4
365 - 375	0.6
355 - 365	0.8
335 - 355	1.0

Topsoil

The topsoil resistivity map (Figure 5) presents the spatial variation of resistivity within the topsoil at the study area in a 2-dimensional form. Resistivity value is a reflection of how clayey a geologic unit is. Clayey materials are less resistive and have a high water holding capacity and low transmissivity and conversely sandy and non-clayey material exhibit relatively high resistivity due to their high transmissivity and poor water holding capacity.

Based on the topsoil resistivity map, the study area was classified into five zones (Table 6); very low (less than 60 Ohm-m), low (60 - 150 Ohm-m), moderate (150 - 250 Ohm-m), high (250 - 350 Ohm-m) and very high (above 350 Ohm-m) vulnerability zones. The extreme eastern part of the area was characterized by very low (less than 60 Ohm-m) vulnerability. The topsoil thickness is another indicator that determines how much protection the topsoil can offer the underlying aquifer layer; the thinner the top soil the more the vulnerability (Bjerg *et al*., 1992; Oni *et al*., 2017).

The topsoil thickness map (Figure 6) was used to classified the study area into five vulnerability zones (Table 7); very high (0 - 1.0 m), high (1.0 - 2.0 m), moderate (2.0 - 3.0 m), low (3.0 - 4.0 m) and very low (5.0 m and above). Larger parts of the study area are classified as high to very high vulnerability due to the thin nature of their topsoil.

Table 6: Rating of Topsoil Resistivity

Topsoil Resistivity (ohm-m)	Rating
0 – 60	0.2
60 – 150	0.4
150 – 250	0.6
250 – 350	0.8
350 – above	1.0

Table 7: Rating of topsoil thickness

Topsoil Thickness (m)	Rating
0 – 5	1.0
5 – 10	0.8
10 – 15	0.6
15 – 20	0.4
20 – above	0.2

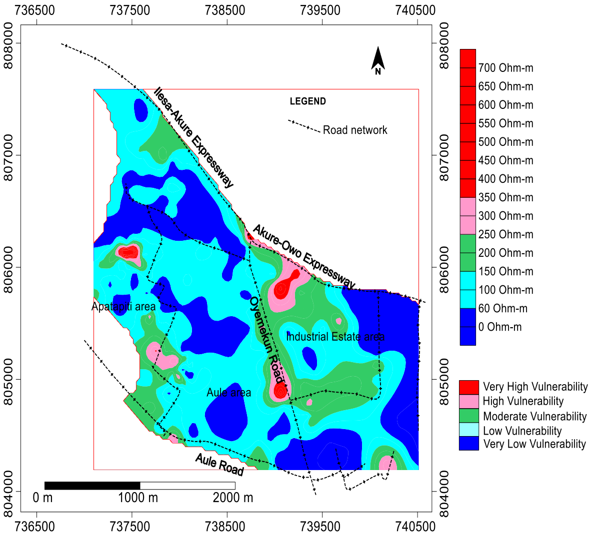

Figure 5: Topsoil resistivity map of the area

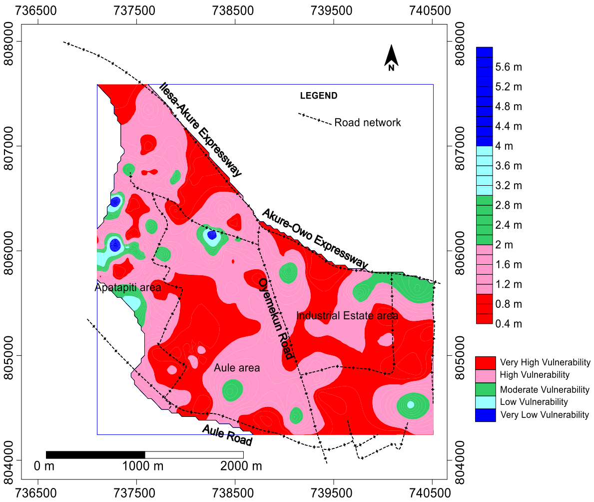

Figure 6: Topsoil thickness map of the area

Weathered Layer

Weathered layer refers to geologic materials between the topsoil and the basement rock. Resistivity value is a reflection of the material constituting any geologic layer; sandy materials are more resistive due to their low water holding capacity or high transmissivity and this makes sandy materials highly vulnerable. Conversely, clay is less resistive because of its high porosity and low permeability these makes clayey materials less vulnerable to contamination. Clay is also noted for its special ability to conduct electric current. As shown in the weathered layer resistivity map (Figure 7) the eastern part of the study area is characterized by high resistivity which suggest possible sandy, lateritic and clayey sand materials which are highly permeable; these high resistivity values therefore reflect high vulnerability. The western part of the area has low resistivity which is a reflection of more clay and sandy clay content and it suggest less permeability and less vulnerability. Table 8 shows the five vulnerability classifications of the study area based on weathered layer resistivity map (Figure 7).

The weathered layer thickness also determines the extent of protection offers by the weathered layer to the underlying aquifer layer; just as it was in the case of topsoil the thinner the weathered layer the more the vulnerability (Adeyemo *et al*., 2015 and Oni *et al*., 2017). The weathered layer map (Figure 8) indicated that the area is classified into five vulnerability zones (Table 9); very high (0 - 1.0 m), high (1.0 - 2.0 m), moderate (2.0 - 3.0 m), low (3.0 - 4.0 m) and very low (5.0 m and above). Larger parts of the area (80 %) are classified as high to very high vulnerability due to the thin nature of their weathered layer. Weathered layer thickness is considered to be a major deciding factor on groundwater susceptibility to contamination. The thicker the weathered layer the less vulnerable the underlying aquifer and conversely the thinner the weathered layer the more vulnerable the underlying aquifer (Adeyemo *et al*., 2015 and Oni *et al*., 2017). Weathered layer thickness map (Figure 8) shows that about 80% of the study area has thin weathered layer (less than 5 m thick) and this suggest possible high vulnerability in those area.

Table 8: Rating of weathered layer resistivity

Weathered Layer Resistivity (ohm-m)	Rating
0 - 60	0.2
60 - 150	0.4
150 - 250	0.6
250 - 350	0.8
350 - above	1.0

Table 9: Rating of weathered layer thickness

Weathered Layer Thickness (M)	Rating
0 - 5	1.0
5 - 10	0.8
10 - 15	0.6
15 - 20	0.4
20 - above	0.2

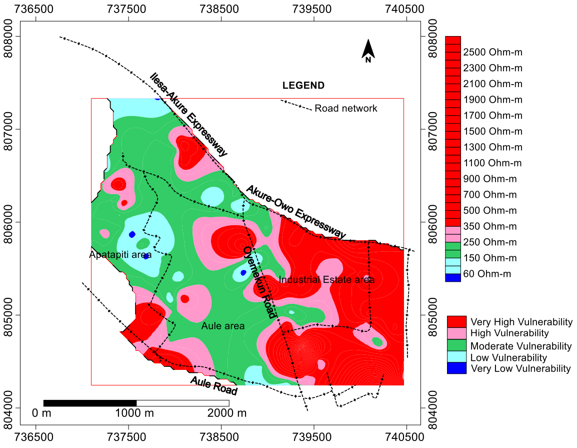

Figure 7: Weathered layer resistivity map of the area

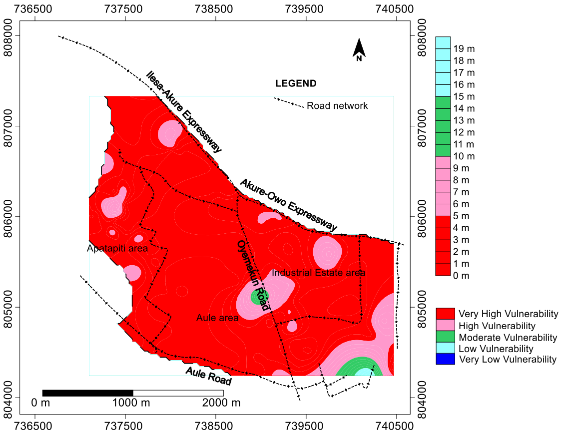

Figure 8: Weathered layer thickness map of the area

Aquifer Vulnerability Map

The aquifer vulnerability map of the area was generated by synthesizing geology, elevation and the four (4) geoelectric parameters (topsoil resistivity, topsoil thickness, weathered layer thickness and weathered layer resistivity) using the additive model (Chachadi, 2005 and Adeyemo *et al*., 2017) The final vulnerability index values were subsequently used to generate the final aquifer vulnerability model map. Each of these parameters were subdivided into different ratings and the results of the results of the weighting and rating factors were integrated using the following relationship

$$\text{GETW} - \text{index value} = [(\text{Wt}_{\text{geo}}{}^{*}\text{Rt}_{\text{geo}}) + (\text{Wt}_{\text{elev}}{}^{*}\text{Rt}_{\text{elev}}) + (\text{Wt}_{\text{soil\_resist}}{}^{*}\text{Rt}_{\text{soil\_resist}}) + (\text{Wt}_{\text{soil\_thick}}{}^{*}\text{Rt}_{\text{soil\_thick}}) \; (\text{Wt}_{\text{weath\_resist}}{}^{*} \text{Rt}_{\text{weath\_resist}}) + (\text{Wt}_{\text{weath\_thick}}{}^{*}\text{Rt}_{\text{weath\_thick}})] \quad (1)$$

Where, Wt = Weight, Rt = Rating geo = geology, elev = elevation, resist = resistivity, thick = thickness
weath = weathered layer

The aquifer vulnerability (GETW-index) model map (Figure 9) categorised the area into four zones, very low vulnerability (0 - 0.2), low vulnerability (0.2 - 0.4), moderate vulnerability (0.2 - 0.4) and high vulnerability (0.6 - 0.8). The aquifer vulnerability model map (Figure 9) shows that the vulnerability of the study area is very low to moderate. About 5% of the area has very low vulnerability, 30% are of low vulnerability and 65% have moderate vulnerability. This is a huge relief because it indicates that the study area is not highly prone to surface pollution and the groundwater resources in the area are moderately safe.

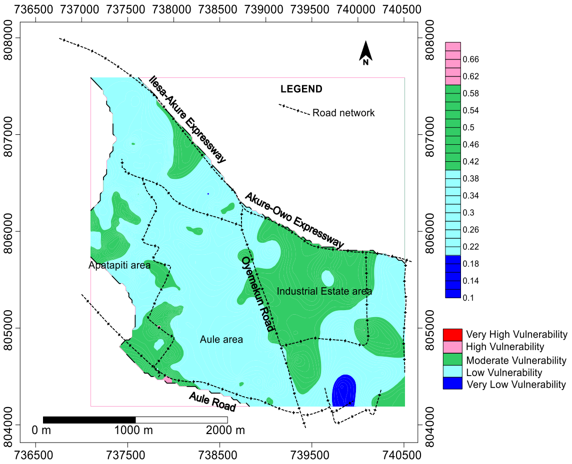

Figure 9: Aquifer vulnerability model map of the area

CONCLUSION

Aquifer layer vulnerability assessment of the north-western part of Akure was carried using a combination of six parameters comprising lithology, elevation, topsoil (resistivity and thickness) and weathered layer (resistivity and thickness). The six parameters were synthesized used to determine LETW– index values which were utilized in generating the aquifer vulnerability model map. The model map shows that the groundwater in the study area is moderately safe.

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