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Assessment of Aquifer Vulnerability Using Multi-Criteria Decision Analysis around Akure Industrial Estate, Akure, Southwestern Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author ADA designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors SOI and OEB managed the analyses of the study. Author TE managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

This study is aimed at evaluating of aquifer vulnerability in a typical basement complex environment of Akure industrial estate, Akure, Southwestern Nigeria. A multi-criteria model is developed for achieving this aim; the vulnerability model which is based on topsoil resistivity, longitudinal conductance, thickness of layer overlying aquifer, and hydraulic conductivity of each sounding point across the study area is successfully used to evaluate the aquifer vulnerability of the area for future groundwater development programme in the area. Geophysical investigation involving vertical electrical sounding is carried out across the study area. A total of thirty one (31) vertical electrical soundings (VES) data were acquired using Schlumberger array with maximum half-current electrode separation of 100 m. Three to five geoelectric layers were delineated across the study area. The curve types obtained are the A, H, K, KH, HA, AA, QHA and KHA.The map of topsoil resistivity, longitudinal conductance, thickness of layer overlying aquifer, and hydraulic conductivity were generated and synthesized to producing the vulnerability map. The vulnerability map shows that the area is characterized by five zones; very low, low, moderate, high and very

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high. The mid-western, southeastern and closure at the northern part of the study area are delineated to be very low to low vulnerable zones, followed by the eastern and part of the western and central part of the study area which are categorized as moderate vulnerable zones, and finally the southern and northern part of the study area which are characterized by high and very high vulnerable zone.

Keywords: Aquifer vulnerability; hydraulic conductivity; longitudinal conductance; topsoil resistivity.

1. INTRODUCTION

The increasing rate of groundwater contamination, most especially in the developing countries has become a problem that has gained the attention of both academic scholars and stakeholders in the management of water resources in recent times [1,2]. Groundwater is naturally susceptible to contamination from both natural and anthropogenic sources. While there are cases of contamination induced from dissolution of natural minerals as groundwater moves through iron bearing strata, limestone and salty formations. Groundwater contaminations attributed to anthropogenic sources have raised the scale tremendously [1]. One important source of groundwater contamination in the developing countries is the poor solid waste management whereby municipal wastes are disposed off indiscriminately openly and are often subjected to open burning [3]. This unsanitary routine of industrial waste disposal has impact on the quality of groundwater in an area as the poisonous chemicals can be saturated with rainwater and percolates down to pollute the subsurface aquifer system. Researchers have confirmed the potential health hazard a waste disposal constitute for people depending on ambient groundwater as source of drinking water or for other domestic purposes.

In view of the importance of groundwater, prevention of groundwater contamination is critical to effective water resource management as remediation can be very expensive and often impractical [4]. Consequently, it has become imperative to carry out aquifer vulnerability assessment in order to predict areas at potential risk of contamination. Such vulnerable zones could then be enforced with restricted land use or become a focus of attention at preventing contamination of the underlying groundwater resources. Several studies on aquifer vulnerability have revealed that the protection of aquifer centers on the permeability of the overlying media to the transportation of contaminants into underlying aquifer units [3]. In the Basement Complex, numerous attention have been given to the morphology of the vadose zone in assessing the susceptibility of underlying aquifers to infiltration of contaminants [5]. The rate and extent of leachate infiltration is controlled primarily by the ease with which the subsurface layers beneath the area and its surroundings allow contaminants migration. Reports have shown that permeable sandy materials allow rapid infiltration of contaminants while less permeable clayey materials provide geological barrier that impedes its movement [6, 7]. Therefore the need to understand the subsurface soil profile has become pertinent to assess the impact of any overlying leachate on the underlying aquifer system.

The Akure Industrial Estate is characterize by series of industries that are continually disposing their waste product indiscrimately into the surrounding environment. The heterogeneous composition of the waste in the study area are the industrial wastes (such as chemicals, vehicle spare parts e.t.c), and other sources like domestic wastes (such as paper, garbage, wood scrap, nylon, rubber, can, glass, ceramics, aerosol e.t.c.); agricultural wastes (farm manure, animal dung and crop residue). The biodegradation of these wastes generates leachate plume that can contain both chemical and biological constituents [8,9]. These leachates are typical sources of groundwater contamination especially where they infiltrated the subsurface layers to pollute the aquifer system. The vulnerability of underlying aquifers to contaminants infiltrating the subsurface media tend to be varied based on the morphologies of the subsurface in different geological locations.

In the past, groundwater potentials have been evaluated based on consideration of important parameters such as longitudinal conductance, overburden thickness, topsoil resistivity and geology among others and each parameter is considered in isolation. However in this study a multi-criteria decision approach was developed for evaluating aquifer vulnerability in a typical basement complex environment. The vulnerability model was based on four most important parameters; topsoil resistivity, longitudinal conductance, thickness of layer overlying aquifer, and hydraulic conductivity. These parameters were synthesized using an existing approach that has been used in environmental studies.

1.1 Description of the Study Area

The study area lies within the Industrial Estate in Northwestern part of Akure, Southwestern Nigeria. It lies between latitude 805000N to 806000N and longitude 738700E to 740200E (Fig. 1). It is well accessible through several road networks within and around the study area.

1.2 Geomorphology, Climate and Vegetation of the Study Area

The study area can be described as moderately undulating and the drainage pattern is dendritic. The climate of the area consists of two seasons; dry season (November to March) and wet season (April to October) seasons. The mean annual rainfall ranges between 1000 and 1500 mm [10]. The mean annual temperature distribution is 27°C [10]. The mean annual temperature ranges between 21.9 to 30.4°C. Humidity is relatively high during the wet season and low during the dry season with values ranging annually from 39.1 to 98.2% [11]. The vegetation is of tropical rain forest which is characterized by thick forest.

1.3 Geology of the Study Area

The study area is underlain by rocks of the Precambrian Basement Complex of Southwestern Nigeria [12]. The geological mapping and other related studies of the area around the Akure Metropolis have been carried out by several workers amongst whom are [13, 14,15,16 and 9]. The area around the Akure Metropolis is underlain by four of the six petrological units of the Basement Complex of Southwestern Nigeria identified by [17] and also described by [13,16,17]. These are the Migmatite-Gneiss Quartzite Complex, Charnockitic and Dioritic rocks, Older Granites and Unmetamorphosed dolerite dykes (Fig. 2). The basement rocks exhibit varieties of structures such as foliation, schistosity, folds, faults, joints and fractures. Generally, the structural trends in the study area are NNW-SSE and NNE-SSW.

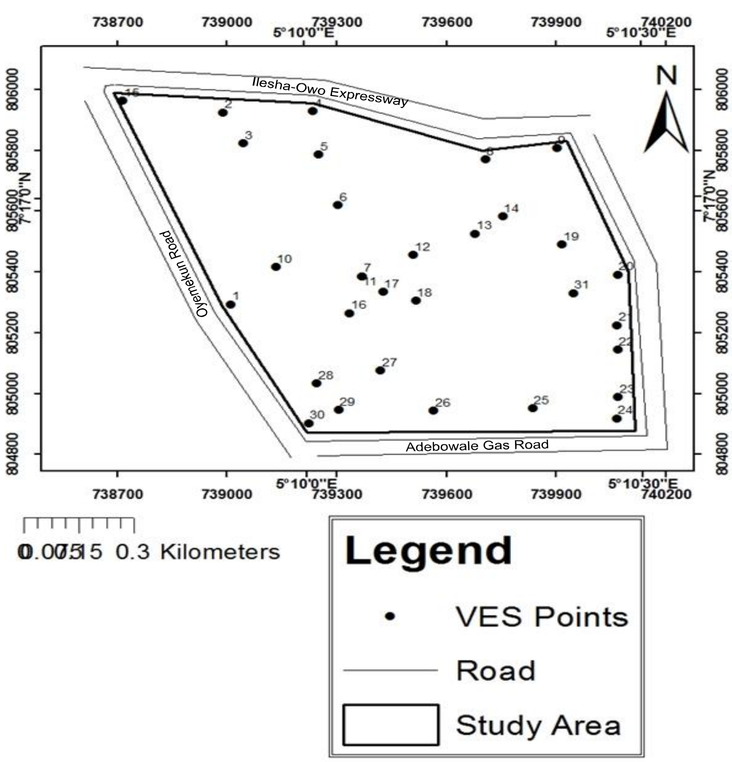

Fig. 1. Location map of the study area

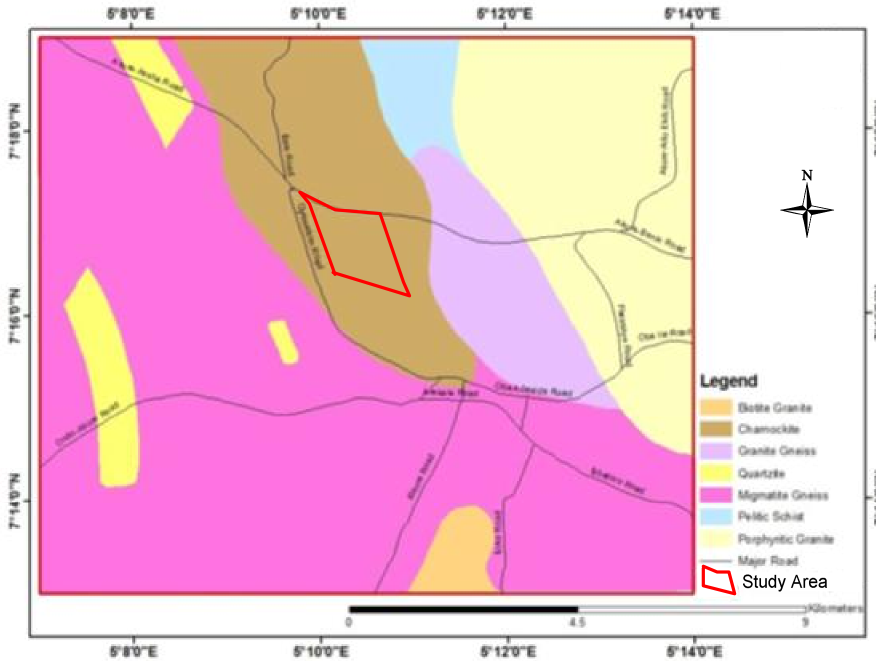

Fig. 2. Geological map of Akure showing the study area

Several minor and extensive fractures, joints and fissure zones which generally trend north south are common. These structural trends fall within the principal basement complex fracture direction identified by [18]. The dominant rock types within the study area is Charnockite (Fig. 2), which weathered slowly to form clay soil.

2. METHODOLOGY

The vertical electrical sounding (VES) field technique utilizing Schlumberger electrode configuration was adopted for this study. Thirty one (31) VES points were occupied across the study area with a view to understanding the characteristic of lithological sequence overlying the aquifers. Analysis and interpretation of the data obtained were made bothquantitatively in order to establish the geo-electric/geologic sequence beneath the study area. The quantitative analysis involving partial curve matching and computer iterations to determine geoelectric parameters of geoelectric sequence beneath the study area.Four factors considered to be of great influence on aquifer vulnerability were derived from the geoelectric parameter which are the topsoil resistivity (TSR), longitudinal conductance (LC), thickness of layer overlying aquifer (TLOA), and the hydraulic conductivity (HC).

The longitudinal conductance (S_i) is computed by the relation;

$$Si = \; hi/\rho i \tag{1}$$

Where S_i = Longitudinal Conductance
h_i= Layer Thickness
ρ_i= Layer Resistivity

The hydraulic conductivity is computed by the mathematical relation;

$$k = 0.0538\, e^{-(0.0072\rho)} \text{ [19]} \tag{2}$$

Where k = Hydraulic Conductivity
ρ = Layer Resistivity

The results of the study were presented as tables and maps.

3. RESULTS AND DISCUSSION

3.1 Field Sounding Curves

Table 1 shows the summary of the interpreted VES results from the study area. The curve types obtained in the study area are the A, H, K, KH, HA, AA, QHA and KHA. The characteristic geoelectric layers depicted by these curves range from three to five layers. The curve types from the study area can be classified into two groups based on the confinement of the ambient aquifers which influence its vulnerability. This includes; Group I, The curve types in this group include A, H, AA, HA and QHA where the ambient aquifers correspond to layer 2 but they are all unconfined in nature by virtue of their respective thin overlying layers. These aquifers are typically those of weathered layer in the subsurface sequence and are possibly vulnerable to near-surface contaminants in the area. While in Group II, we have the K, KH and KHA which are characterized by basement aquifers residing within the layer 3. These aquifers are confined in nature and correspond to the partly weathered/fractured basement within the subsurface. The vulnerability of such aquifers to pollutants is usually low and is equally of good yield [20,21].

3.2 Aquifer Vulnerability Assessment in the Study Area

The assessment of aquifer vulnerability to contaminants have been undertaken by investigating the capacity of the layer overlying the aquifer units in the study area (vadose zone) to offer protection to the underlying aquifer units. Hence, the topsoil resistivity, thickness of layers overlying aquifer, longitudinal conductance and the hydraulic conductivity of the vadoze zone are taken into consideration.

The resistivity of the topsoil ranges from 7 – 383 ohm-m (Table 2). The topsoil resistivity map (Fig. 3) shows that the topsoil in the study area is characterize by very low to low resistivity values at the central, eastern, western and part of the northern parts of the study area. This is an indication that these portion of the study area will have a good protective capacity and aquifer in this sections will be less vulnerable to leachates from the industrial waste products due to its impervious nature. While moderate resistivity value occupied the extreme southern and part of the northern portion of the study area. These portion will show a moderate protective capacity and aquifer in this sections will be more vulnerable to industrial waste products.

The longitudinal conductance of the vadoze zone which also provides a measure of the aquifer protective capacity is presented in Fig. 4. The longitudinal conductance of the vadoze zone in the study area ranges between 0.01 - 1.20 mhos. Table 3 provides the scheme by which the aquifer protective capacity was classified. Accordingly, the vadoze zone in major parts of the study area offers poor to weak protection for the underlying aquifers based on their characteristic low longitudinal conductance (< 0.2). However, moderate protection can be envisaged in few areas in the central and southeastern parts where relatively moderate longitudinal conductance (> 0.2) was observed. And a good longitudinal conductance at the eastern and part of the southern portion of the study area. The longitudinal conductance map (Fig. 4) shows a very low to low longitudinal conductance at the mid-central and closure at part of the northern, eastern and western portion of the study area. While moderate longitudinal conductance occur at the western, central and portion of the southern part of the study area. A high to very high longitudinal conductance at the eastern and closure at the southern part of the study area. Highly impervious materials such as clay and shale usually have high longitudinal conductance values (resulting from their low resistivity values) while pervious materials such as sand and gravels have low longitudinal conductance values (resulting from their high resistivity values). Thus, high longitudinal conductance value corresponds to excellent and good aquifer protective capacity; low longitudinal conductance values are associated with poor and weak aquifer protective capacity [22,23].

Furthermore, the thickness of the layer overlying aquifer unit ranges between 0.4– 2.9 m. the thickness map shows that the study area is dominated by a very low to low thickness, indicating a general thin (<1.5 m) vadose zone overlying the aquifer in the area with the exception of an isolated portion in the eastern and western part where relatively thick (> 2 m) vadoze zone is recorded (Fig. 5). Given the general thin nature of the vadose zone, the residence time of the infiltration potential contaminants from the surface to the aquifer unit will be short and the underlying aquifer units can easily be impacted.

The hydraulic conductivity value within the study area ranges from 0.01 to 0.05 mhos. The hydraulic conductivity map (Fig. 6) shows a very low to low hydraulic conductivity dominating the study area. A moderate hydraulic conductivity at the northern and closure at the southern part of the study area. And a high to very high hydraulic conductivity as a closure at part of the northern and southern part of the study area.

The generated maps were used to do the classification and rating of factors as shown in Table 4.

Table 1. VES interpretation results

VES No	Layers	Resistivity (Ohm-m)					Thickness (m)				Curve Type
		ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	h_1	h_2	h_3	h_4	
1	3	225	338	150	-	-	1.7	6.2	-	-	K
2	4	80	443	94	196	-	1.3	3.0	11.8	-	KH
3	3	257	23	634	-	-	1.0	6.7	-	-	H
4	4	383	93	1828	13554	-	1.1	3.1	4.8	-	HA
5	4	180	261	44	347	-	1.3	1.8	12.1	-	KH
6	3	256	13280	9437	-	-	3.4	13.8	-	-	A
7	4	162	310	171	258	-	0.6	2.3	9.4		KH
8	4	52	336	14	154	-	1.0	2.8	16.4	-	KH
9	4	7	20	74	138	-	1.9	3.1	25.0	-	AA
10	3	34	61	285	-	-	1.2	25.8	-	-	A
11	3	162	310	171	258	-	0.6	2.3	9.4	-	KH
12	5	80	361	30	3488	1436	0.4	0.8	2.7	22.2	KHA
13	5	299	181	14	84	103	1.1	0.5	3.0	30.2	QHA
14	4	89	283	5	317	-	0.5	0.7	5	-	KH
15	3	115	27	1154	-	-	1.1	8.8	-	-	H
16	3	36	474	240	-	-	0.7	5.0	-	-	K
17	4	89	721	663	2961	-	0.4	8.6	10.9	-	KH
18	4	107	144	57	286	-	1.1	3.5	19.3	-	KH
19	4	42	11	79	159	-	0.8	4.5	23.9	-	HA
20	4	32	8	39	250	-	0.5	1.7	13.5	-	HA
21	4	22	5	64	134	-	0.6	1.8	14	-	HA
22	3	248	131	1144	-	-	2.9	6.5	-	-	H
23	4	96	297	145	233	-	0.5	2.8	14	-	KH
24	3	175	2176	524	-	-	0.5	19.2	-	-	K
25	4	225	371	31	553	-	1.2	3.4	13.5	-	KH
26	4	216	448	36	834	-	0.9	1.6	12.4	-	KH
27	4	54	533	15	639	-	0.5	2.2	12	-	KH
28	4	114	425	85	472	-	0.6	4.1	34.2	-	KH
29	3	245	531	27	517	-	0.8	3.0	12.3	-	KH
30	4	147	392	92	318	-	0.9	3.2	30.6	-	KH
31	4	11	6	87	150	-	1.0	1.8	32	-	HA

Table 2. Summary of the obtained values for the factors from VES data interpretation

VES no	EASTHING	NORTHING	TSR (Ohm-m)	LC (Mho)	TLOA (m)	HC (m/day)
1	739013	805293	225	0.03	1.7	0.00
2	738991	805924	80	0.14	1.3	0.01
3	739047	805822	257	0.30	1.0	0.04
4	739238	805928	383	0.04	1.1	0.01
5	739253	805786	180	0.29	1.3	0.03
6	739306	805619	256	0.01	-	0
7	739372	805385	162	0.07	0.6	0.00
8	739709	805769	52	1.20	1.0	0.04
9	739904	805806	7	0.76	1.9	0.02
10	739135	805416	34	0.46	1.2	0.02
11	739372	805385	162	0.07	0.6	0.00
12	739512	805455	80	0.10	1.2	0.03
13	739681	805525	299	0.58	1.1	0.01
14	739756	805582	89	1.01	1.2	0.05
15	738717	805963	115	0.34	1.1	0.03
16	739337	805263	36	0.03	0.7	0.00
17	739429	805333	89	0.03	0.4	0.00

VES no	EASTHING	NORTHING	TSR (Ohm-m)	LC (Mho)	TLOA (m)	HC (m/day)
18	739519	805305	107	0.37	1.1	0.02
19	739919	805490	42	0.73	0.8	0.01
20	740071	805390	32	0.57	0.5	0.03
21	740069	805224	22	0.61	0.6	0.02
22	740071	805143	248	0.06	2.9	0.01
23	740073	804988	96	0.11	0.5	0.01
24	740068	804917	175	0.01	-	0
25	739838	804950	225	0.45	1.2	0.03
26	739568	804942	216	0.35	0.9	0.03
27	739422	805074	54	0.81	0.5	0.04
28	739248	805032	114	0.42	0.6	0.01
29	739307	804945	245	0.46	0.8	0.03
30	739225	804901	147	0.35	0.9	0.01
31	739949	805330	11	0.76	1.0	0.01

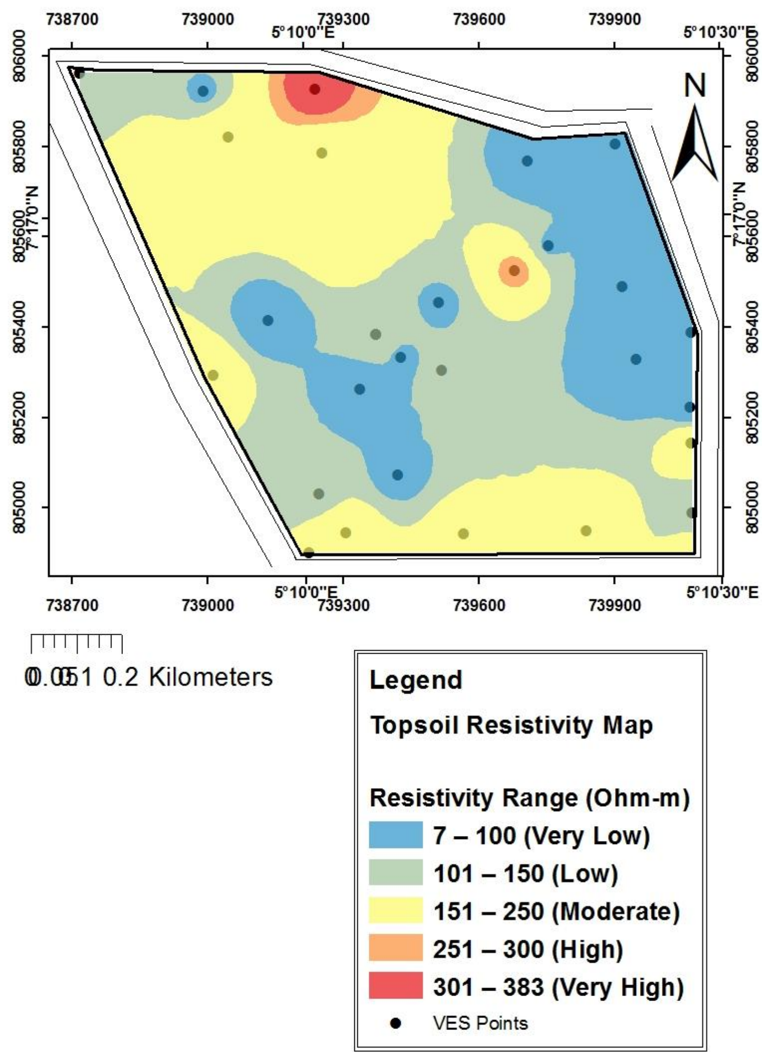

Fig. 3. Topsoil resistivity map of the study area

Table 3. Modified longitudinal conductance/protective capacity rating [22]

Longitudinal Conductance (mhos)	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

3.3 Estimation of the Vulnerability Index (VI)

Vulnerability Index (VI) is the sum of the products of weight (W) and ratings (R) over all the factors used for the evaluation [24].

Weighted linear average technique was used to estimate VI. This technique is usually specified in terms of weightings (W) for each factor as well as rating score (R) for all option relative to each of the factor.

$$VI = \sum WiRi \tag{3}$$

Where W_i is the weight (W) of parameter i and R_i is the rating score of parameter i.

Using the weights (W) and rating (R) of each factor, equation 3 now becomes

$$VI = 0.45\ R_{TSR} + 0.28\ R_{LC} + 0.17\ R_{TLOA} + 0.10\ R_{HC} \tag{4}$$

Where the subscript TSR, LC, TLOA, and HC are the topsoil resistivity, longitudinal conductance, thickness of layer overlying aquifer, and hydraulic conductivity. The Vulnerability Index (VI) for each grid was computed using the equation 4.

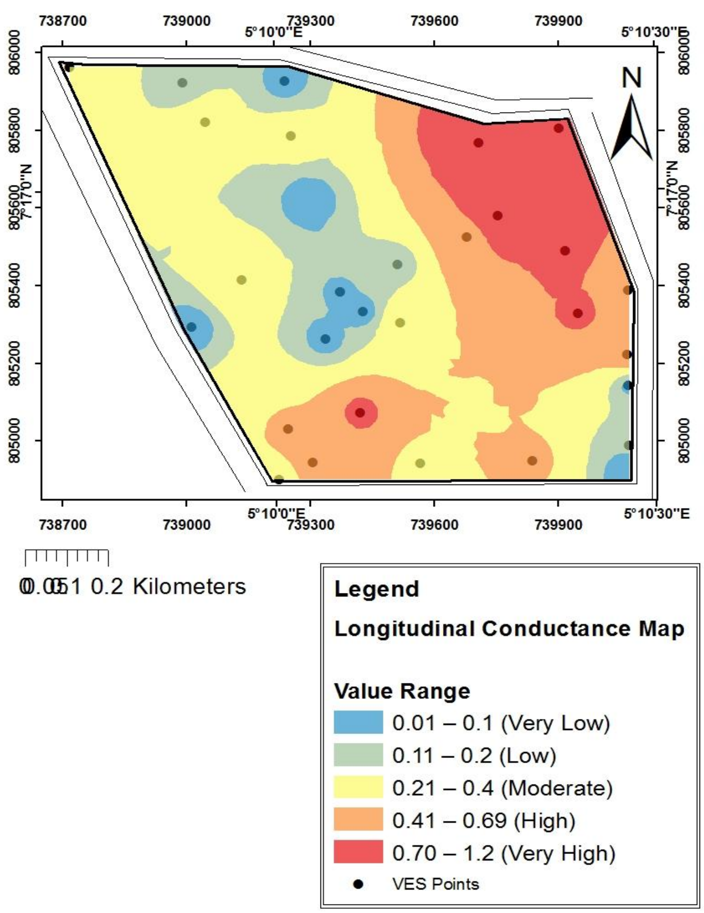

Fig. 4. Longitudinal conductance map of the study area

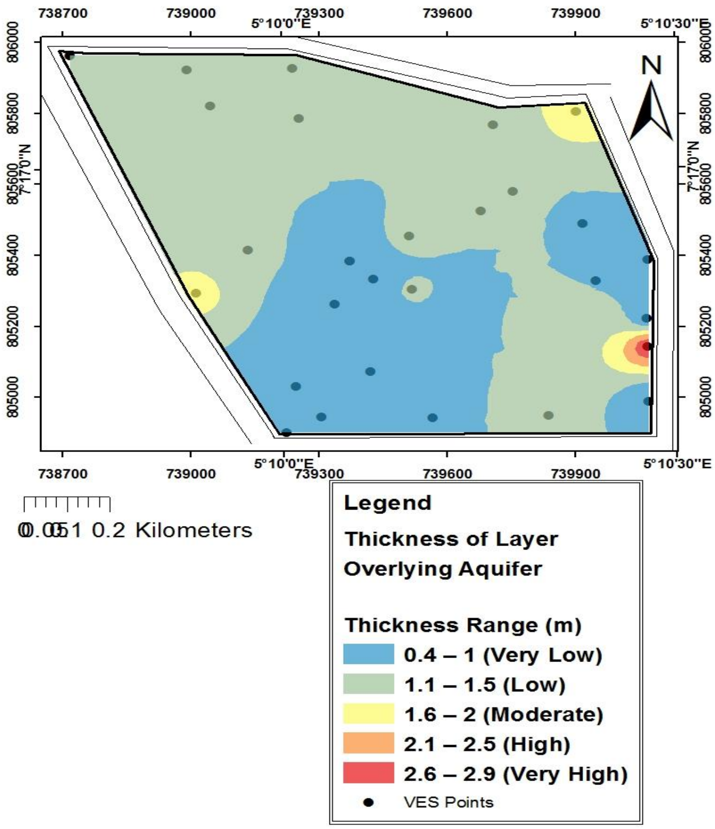

Fig. 5. Map of thickness of layer overlying aquifer in the study area

Table 4. Rating for classes of factors

Influencing Factor	Category Classes	Potentiality for Aquifer Vulnerability	Rating	Normalize Weighting
TSR	7 – 100	Very Low	0.2	0.45
	101 – 150	Low	0.4	
	151 – 250	Moderate	0.6	
	251 – 300	High	0.8	
	301 - 383	Very High	1.0	
LC	0.01 – 0.1	Very Low	0.2	0.28
	0.11– 0.2	Low	0.4	
	0.21 – 0.4	Moderate	0.6	
	0.41 – 0.69	High	0.8	
	0.70 – 1.20	Very High	1.0	
TLOA	0.4 – 1.0	Very High	1.0	0.17
	1.1 – 1.5	High	0.8	
	1.51 – 2.0	Moderate	0.6	
	2.1 – 2.5	Low	0.4	
	2.51 – 2.9	Very Low	0.2	
HC	0.01 – 0.028	Very Low	0.2	0.10
	0.029 – 0.04	Low	0.4	
	0.041 – 0.046	Moderate	0.6	
	0.047 – 0.048	High	0.8	
	0.049 – 0.05	Very High	1.0	

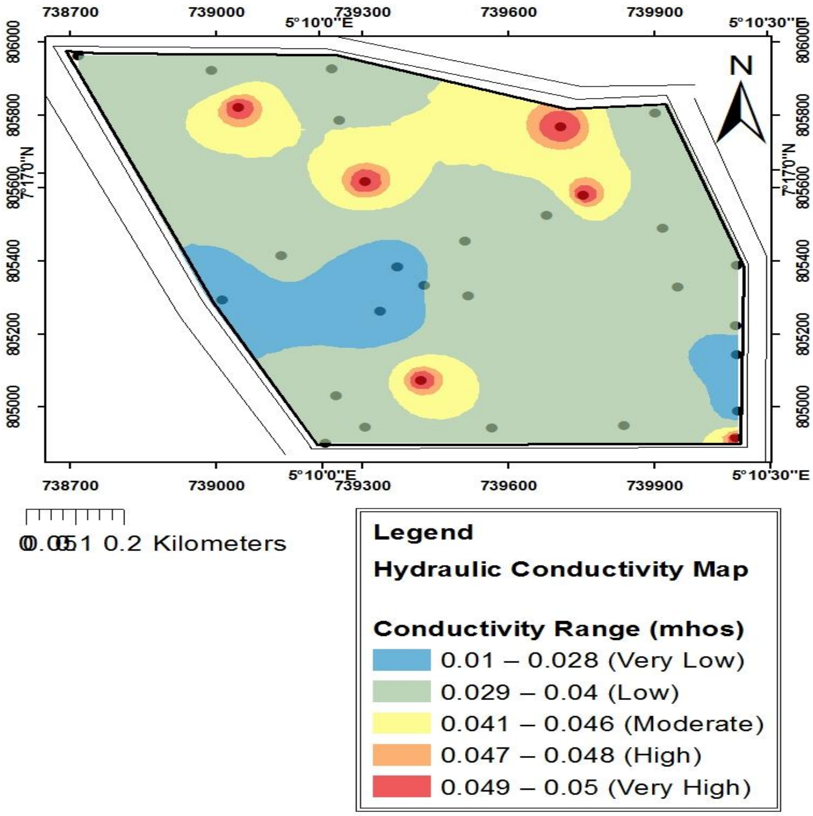

Fig. 6. Hydraulic conductance map of the study area

3.4 Preparation of Aquifer Vulnerability Model

The vulnerability index (VI) obtained for each VES station was used to produce the vulnerability model. It was observed from the model that the VI value for the study area vary between 0.2 and 0.64 (Table 5) hence, the composite vulnerability model, upon consideration of the topsoil resistivity, longitudinal conductance, thickness of layer overlying aquifer and hydraulic conductivity of the vadoze zone is presented in Fig. 7. The vulnerability model has categorized the study area into five classes which include very high, high, moderate, low and very low.

Table 5. Vulnerability index estimation for all the VES stations

VES No	Location (UTM)		TSR (Ωm) (W=0.45)		LC (mho) (W=0.28)		TLOA (m) (W=0.17)		HC(m/day) (W=0.10)		VI
	Easting	Northing	R	W*R	R	W*R	R	W*R	R	W*R	$\sum W * R$
1	739013	805293	0.6	0.27	0.2	0.06	0.6	0.102	0.2	0.02	0.448
2	738991	805924	0.2	0.09	0.6	0.17	0.8	0.136	0.4	0.03	0.434
3	739047	805822	0.8	0.36	0.6	0.17	1	0.17	1.0	0.05	0.798
4	739238	805928	1.0	0.45	0.2	0.06	0.8	0.136	0.4	0.03	0.682
5	739253	805786	0.6	0.27	0.6	0.17	0.8	0.136	0.4	0.04	0.614
6	739306	805619	0.8	0.36	0.2	0.06		0	1.0	0.05	0.516
7	739372	805385	0.6	0.27	0.2	0.06	1	0.17	0.2	0.02	0.516
8	739709	805769	0.2	0.09	1.0	0.28	1	0.17	1.0	0.05	0.64
9	739904	805806	0.2	0.09	1.0	0.28	0.6	0.102	0.4	0.03	0.512
10	739135	805416	0.2	0.09	0.8	0.22	0.8	0.136	0.4	0.03	0.49

VES No	Location (UTM)		TSR (Ωm) (W=0.45)		LC (mho) (W=0.28)		TLOA (m) (W=0.17)		HC(m/day) (W=0.10)		VI
	Easting	Northing	R	W*R	R	W*R	R	W*R	R	W*R	$\sum W*R$
11	739372	805385	0.6	0.27	0.2	0.06	1	0.17	0.2	0.02	0.516
12	739512	805455	0.2	0.09	0.2	0.06	0.8	0.136	0.4	0.04	0.322
13	739681	805525	0.8	0.36	0.8	0.22	0.8	0.136	0.4	0.03	0.76
14	739756	805582	0.2	0.09	1.0	0.28	0.8	0.136	1.0	0.05	0.606
15	738717	805963	0.4	0.18	0.6	0.17	0.8	0.136	0.4	0.04	0.524
16	739337	805263	0.2	0.09	0.2	0.06	1	0.17	0.2	0.01	0.336
17	739429	805333	0.2	0.09	0.2	0.06	1	0.17			0.316
18	739519	805305	0.4	0.18	0.6	0.17	0.8	0.136	0.4	0.04	0.524
19	739919	805490	0.2	0.09	1.0	0.28	1	0.17	0.4	0.03	0.58
20	740071	805390	0.2	0.09	0.8	0.22	1	0.17	0.4	0.04	0.524
21	740069	805224	0.2	0.09	0.8	0.22	1	0.17	0.4	0.03	0.524
22	740071	805143	0.6	0.27	0.2	0.06	0.2	0.034	0.2	0.02	0.38
23	740073	804988	0.2	0.09	0.4	0.11	1	0.17	0.2	0.02	0.392
24	740068	804917	0.6	0.27	0.2	0.06		0	1.0	0.05	0.426
25	739838	804950	0.6	0.27	0.8	0.22	0.8	0.136	0.4	0.04	0.67
26	739568	804942	0.6	0.27	0.6	0.17	1	0.17	0.4	0.04	0.648
27	739422	805074	0.2	0.09	1.0	0.28	1	0.17	1.0	0.05	0.64
28	739248	805032	0.4	0.18	0.8	0.22	1	0.17	0.4	0.03	0.614
29	739307	804945	0.6	0.27	0.8	0.22	1	0.17	0.4	0.04	0.704
30	739225	804901	0.6	0.27	0.6	0.17	1	0.17	0.4	0.03	0.648
31	739949	805330	0.2	0.09	1	0.28	1	0.17	0.4	0.03	0.58

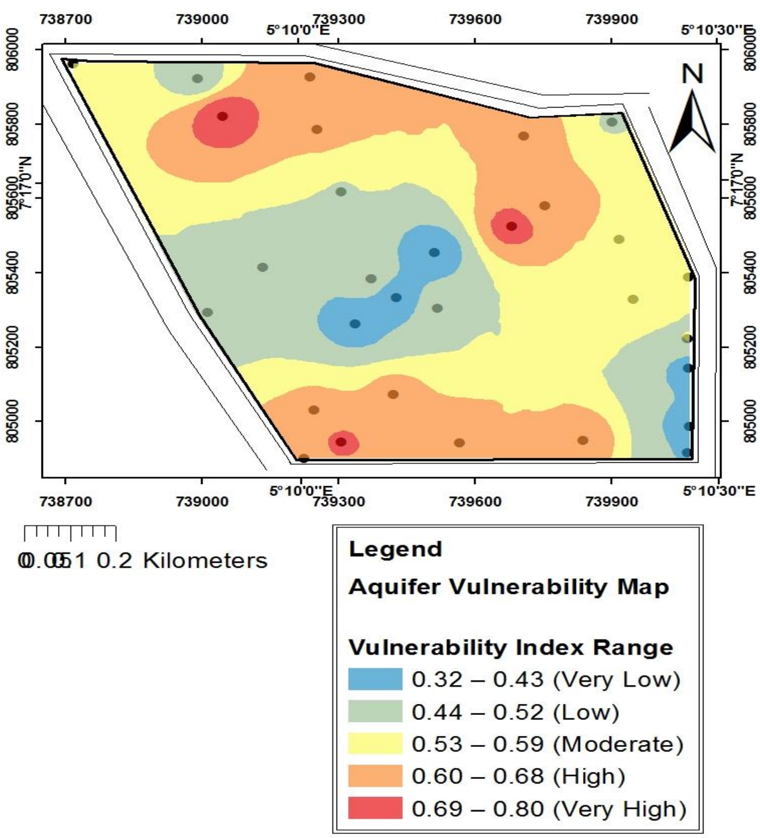

Fig. 7. Vulnerability map of the study area

4. CONCLUSION

The Akure Industrial Estate is located on a gently undulating terrain. The area is underlain by the Charnockitic rocks. Thirty One (31) Vertical Electrical Sounding data sets were acquired within the study area, processed and interpreted quantitatively. The maps of topsoil resistivity, longitudinal conductance, thickness of layer overlying aquifer and the hydraulic conductivity of the study area were generated and integrated in the vulnerability map. The mid-western, southeastern and closure at the northern part of the study area are delineated to be very low to low vulnerable zones, followed by the eastern and part of the western and central part of the study area which are categorized as moderate vulnerable zones, and finally the southern and northern part of the study area which are characterized by high and very high vulnerable zone. In view of the observed reliability of this model it is therefore recommended that aquifer vulnerabilityassessment in any geologic setting should always be done using a multi-criteria approach.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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