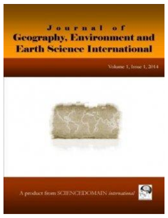

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Assessment of Aquifer Pollution Vulnerability Index at Oke–Ila, South-western Nigeria Using Vertical Electrical Soundings

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Authors' contributions

This work was carried out in collaboration between both authors. Author KEA conceived and designed the study. Author KEA acquired the data and wrote the first draft of the manuscript. Author OOA managed the analyses of the study and the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

The study was undertaken with the aim of estimating vulnerability index of shallow aquifer within weathered crystalline regolith that overlies the basement complex rocks of Oke-Ila, Osun State, South-western Nigeria. Twenty five vertical electrical soundings adopting Schlumberger configuration were used to investigate the subsurface lithology in an area covering 48 km^2. The result revealed four distinct geologic layers which consist of top soil, weathered layer (clayey/sandy saprolite), sand, and fractured/fresh basement rocks. The saprolite, characterized by resistivity in the range of 44 and 471 Ωm with thickness varying from 7 to 16 m, acts as shallow aquifer storing infiltration water. The thickness of the layers above the aquifer, as obtained from quantitative interpretation of resistivity sounding data and estimates of hydraulic conductivities, were used to quantify vulnerability indices. The obtained aquifer vulnerability index shows that, in 70% of the study area, the aquifer has high to extremely-high vulnerability and may be vulnerable to effluents discharge that percolate into the aquifer tapped by hand-dug wells for domestic purposes.

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Keywords: Aquifer vulnerability; groundwater; geoelectric; saprolite; basement; contamination.

1. INTRODUCTION

The rocks in the basement complex of Nigeria are crystalline with low porosity and permeability [1] thus making them poor aquifer. However, most areas that lie within this terrain are underlain by a thin discontinuous layer of weathered soil called saprolite. The average thickness is about 15 m but may in some cases be up to 60 m [2,3]. This layer has porosity up to 40% and specific yield between 13 and 15%. It is the major aquifer for inhabitants living in these areas, storing infiltrate water and releasing it to wells [4]. Beneath this mantle of weathered rocks lie crystalline basement rocks. However, where these rocks are fractured; it is able to store water and transmit water which can be exploited by boreholes. The costs of these boreholes are expensive and usually out of reach for most people living in the area. As a result, most household rely heavily on water sourced from the shallow weathered regolith overlying the fractured/fresh basement rock by hand-dug wells. The hand-dug wells are shallow in nature with static water level less than 11 m with respect to sea level. The shallow nature of this aquifer makes them vulnerable to pollution from surface activities [5]. The growing population and poor land-use of the shallow subsurface as sites for waste disposal has produced frightening harmful effects on the quality of groundwater in a subtle way [6].

Aquifers are protected by overburden layers called protective layers. The likelihood of groundwater to be contaminated by anthropogenic activities at surface and subsurface is known as aquifer vulnerability [7,8]. Vulnerability of an aquifer is dependent on certain properties of the protective layers. One of such property is hydraulic conductivity which is the rate of fluid flow through the subsurface material under the influence of pressure gradient. This property characterizes the dynamics of fluid flow and is a vital parameter that strongly influences the rate at which contaminant laden groundwater spread into and within an aquifer. An aquifer is said to be vulnerable when the subsurface characteristics favours movement of contaminants into and within the aquifer. This may be attributed to protective layers having high hydraulic conductivity, small thickness and shallow water table. Aquifer vulnerability, which is a quantification of aquifer protection, plays a prominent role in groundwater resource management and planning. It is a viable tool that can be used to delineate areas with potential high risk to pollution from anthropogenic activities [9] and also to ensure that activities capable of contaminating groundwater are not located within such areas.

Numerous studies have established electrical resistivity method as a useful tool that can be used to delineate superficial layers within basement terrain [3,10] and quantify aquifer intrinsic vulnerability [11]. Ekwere and Edet [12] used the DRASTIC method of aquifer vulnerability assessment in Oban massif, South-eastern Nigeria. The method, developed by [9], is based on some hydrogeological factors related to spread of contaminants in an aquifer [13].

The present study intends to identify the shallow aquifer within weathered zones overlying the basement crystalline rocks, and to quantify the vulnerability of the aquifer by estimating the hydraulic resistance of the protective layers to vertical flow of fluids.

1.1 Location and Geology

The study area Oke-Ila, covering an area of 48 km^2, is located in Osun State, Nigeria, between latitude 8°00' N and 8°04' N, and longitude 4°56' E and 4°58' E. The geology of the study area lies within the Precambrian basement complex rocks of South-western Nigeria. It is made up of predominantly Pan-African granites, grey gneiss, granite gneiss, mica schist, migmatites with minor pegmatite vein, and quartz vein intrusions varying in thickness from a few millimetres to about a meter [14]. The area has been affected by barrovian type of metamorphism and grades from green schist to amphibolite metamorphic facies [14].

2. METHODOLOGY

A total of twenty five vertical electrical soundings (VES) were carried in the study area (Fig. 1). Because of the discontinuous nature of the aquifer system in the basement complex, the spacing between each sounding locations varied between 500 to 1500 m.

The ABEM Terrameter SAS 1000 was used, adopting Schlumberger configuration with current electrode separation varying between 1 and 360

m. The observed field data (apparent resistivities and corresponding current electrodes spacing) were used to produce depth sounding curves (Fig. 2). The depth sounding curves were quantitatively interpreted by partial curve matching and computer based iterative modelling technique using the winResist software [15]. This provided fairly accurate estimates of resistivity distribution of the subsurface layers. The existing electrical resistivity contrasts between litho-stratigraphic units were used to delineate the weathered horizon, its overlying materials and their equivalent thickness. The inferred geoelectric parameters were correlated with lithologic logs from two (2) boreholes drilled in the area.

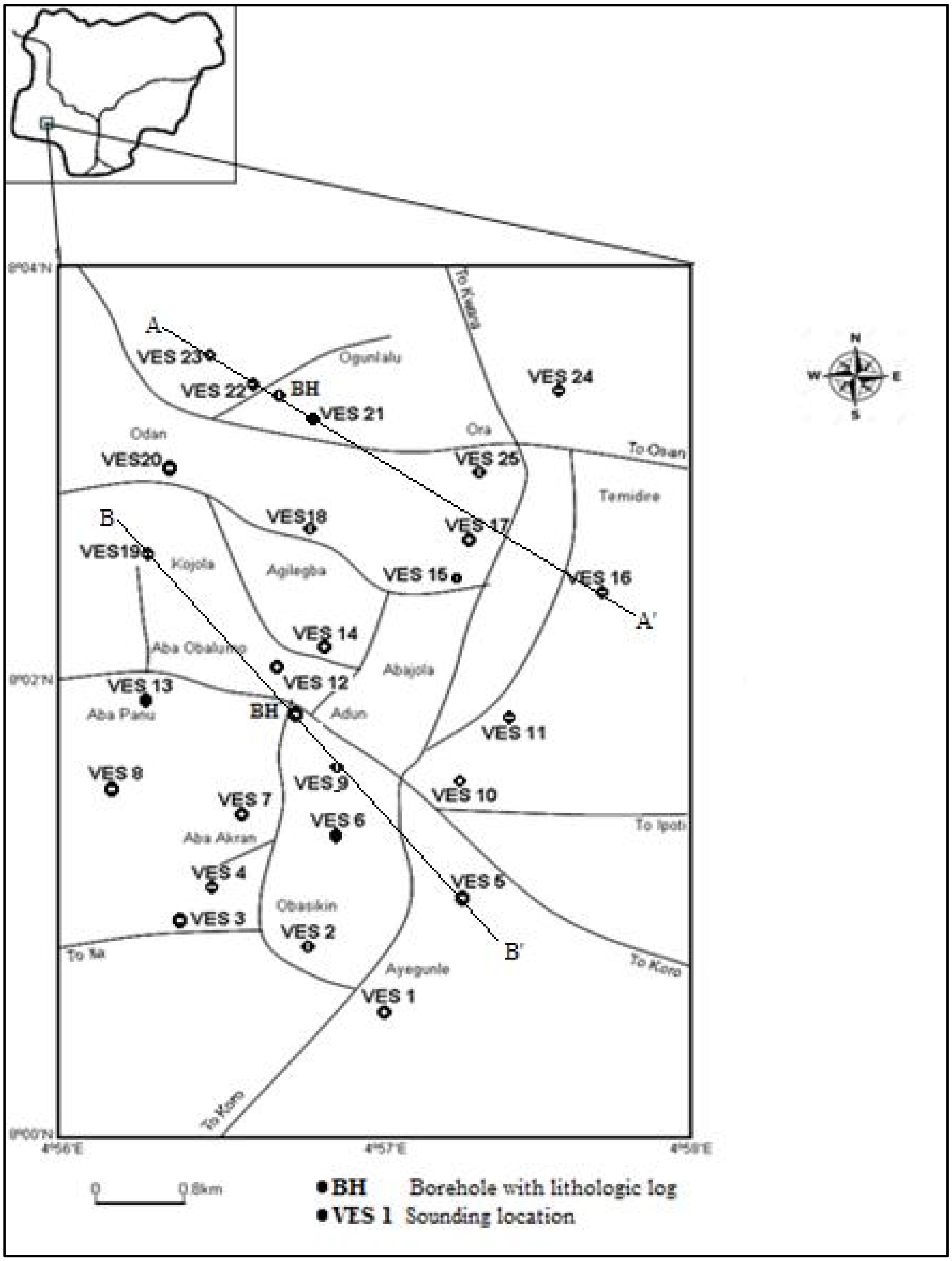


Fig. 1. Location map of study area showing sounding locations

The aquifer vulnerability index (AVI) method for assessment of groundwater vulnerability to pollution was used in this study. The method quantifies vulnerability by determining the hydraulic resistance to vertical flow of fluids through the overlying regolith horizons above an aquifer [16]. For a sequence of *n* horizontal protective layers overlying an aquifer, having thickness d_i and hydraulic conductivity K_i, the hydraulic resistance *C* is given by:

$$C = \sum_i \frac{d_i}{K_i} \tag{1}$$

Table 1. Estimates of Hydraulic conductivity of Protective layers [17,18,19]

Sediments	K (m/y)
Sand	3650
Clay	0.0000365

The thickness (*d*) of the first two (2) geoelectric layers (in meters) from the interpreted resistivity data in Table 3 and estimates of hydraulic conductivity (in meters/year) were used in equation 1 to determine the hydraulic resistance C in years. Typical estimates of hydraulic conductivities for unconsolidated materials overlying the aquifer, based on [17,18,19], are shown in Table 1. According to Van Stempvoort et al. [16], the calculated values of logarithm C can be used in quantification of aquifer vulnerability index as shown in Table 2.

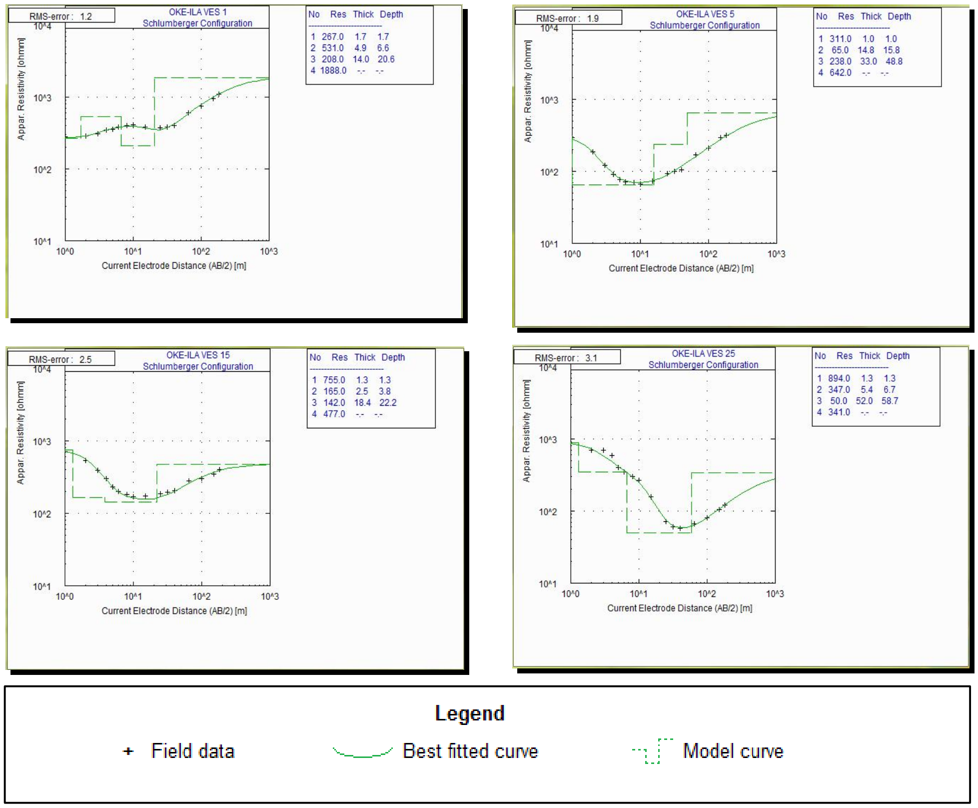
Table 2. Aquifer vulnerability rating based on hydraulic resistance

Logarithm of C	Aquifer vulnerability Index
< 1	Extremely High Vulnerability (EHV)
1 – 2	High Vulnerability (HV)
2 – 3	Moderate Vulnerability (MV)
3 – 4	Low Vulnerability (LV)
> 4	Extremely Low Vulnerability (ELV)

3. RESULTS AND DISCUSSION

3.1 Delineation of Aquifer

The qualitative interpretation of the resistivity sounding curves (Fig. 2) shows the following curve types: Q, KA, HA and QA.



```
No   Res  Thick  Depth
-----------------------
1  267.0   1.7   1.7
2  531.0   4.9   6.6
3  208.0  14.0  20.6
4 1888.0   -.-   -.-
```

```
No   Res  Thick  Depth
-----------------------
1  311.0   1.0   1.0
2   65.0  14.8  15.8
3  238.0  33.0  48.8
4  642.0   -.-   -.-
```

```
No   Res  Thick  Depth
-----------------------
1  755.0   1.3   1.3
2  165.0   2.5   3.8
3  142.0  18.4  22.2
4  477.0   -.-   -.-
```

```
No   Res  Thick  Depth
-----------------------
1  894.0   1.3   1.3
2  347.0   5.4   6.7
3   50.0  52.0  58.7
4  341.0   -.-   -.-
```

Fig. 2. Typical model sounding curves of the study area

Curve type KA represents a subsurface condition in which there is an increase in resistivity values from the top soil to the second layer and then a decrease in the third layer followed by subsequent increase in resistivity with depth. The QA type shows an initial increase in resistivity which could imply dry (vadose) conditions, the general descent in the mid-portion indicates the presence of an aquifer. The HA curve type is the most preponderant in the area. It shows a bell-shaped descending curve, indicating less resistive regolith (clayey layers) underlying the top soil. Curve type A is characterized by succession of the subsurface layers in which resistivity increase with depth, the rightmost end indicates the characteristic high resistivity of crystalline rocks.

The geoelectric sections (Figs. 3 & 4) reveals the presence of four geoelectric layers; the resistivity values defined the following sequence: top soil; weathered layer (saprolite) made of clay/sand, sand, and fractured/fresh bedrock. The distribution of resistivities and thicknesses of the subsurface layers shown in Table 3 is as follows:

- Near the surface, the top soil shows thickness between 0.9 and 1.8 m and resistivity between 107 and 894 Ωm.
- The vadose zone is characterized by resistivity of 15 to 811 Ωm. This layer is mostly made of sandy regoliths, except for location VES 2, VES 7, VES 9, VES 12 and VES 19 where it is clayey. Its thicknesses vary from one location to another, from a minimum of 1.1 m to a maximum of 16 m (VES 14).
- The third layer shows resistivity values of 14 to 4025 Ωm and thickness between 4.4 to 52 m. It is made of sand and constitutes the main aquifer in the area, extending all over the study area, except at VES 10 and VES 17.
- The fourth layer shows resistivity from 150 to 2544 Ωm, and corresponds to fresh/fractured basement rocks.

Note that the second and third layers, mentioned above, correspond to the weathered regolith (saprolite) overlying the crystalline bedrock. Variation of resistivity values within these layers indicates lateral lithologic changes (e.g. from sandy to clayey saprolite). The resistivity of these layers depends on the parent rock type [2] and on the clay to sand ratio [20]. Low resistivity values (less than 20 Ωm) indicate argillaceous regolith, while resistivity greater than 20 Ωm is diagnostic of sand [21]. The ability of argillaceous materials to hold water and its cation exchange capacity generally leads to decrease in their resistivity values. According to Wright [22], saprolite with resistivity values between

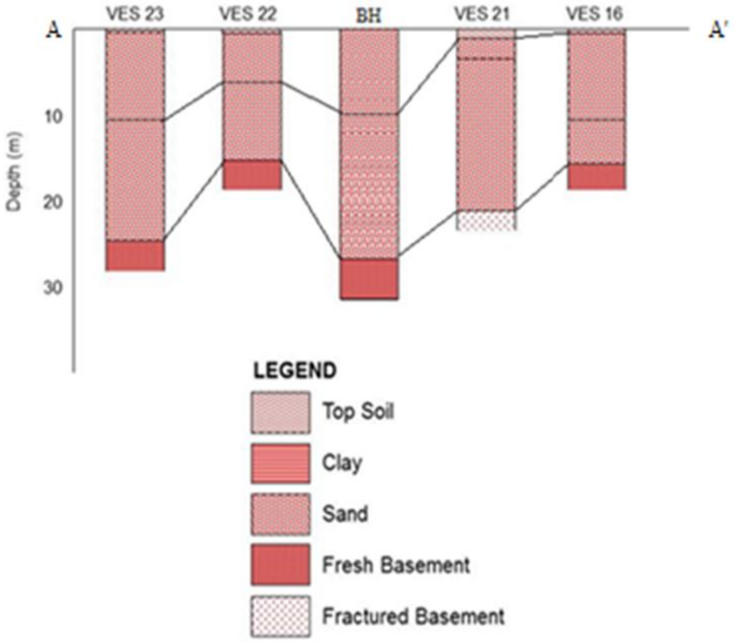


Fig. 3. Geoelectric section along profile A – A'

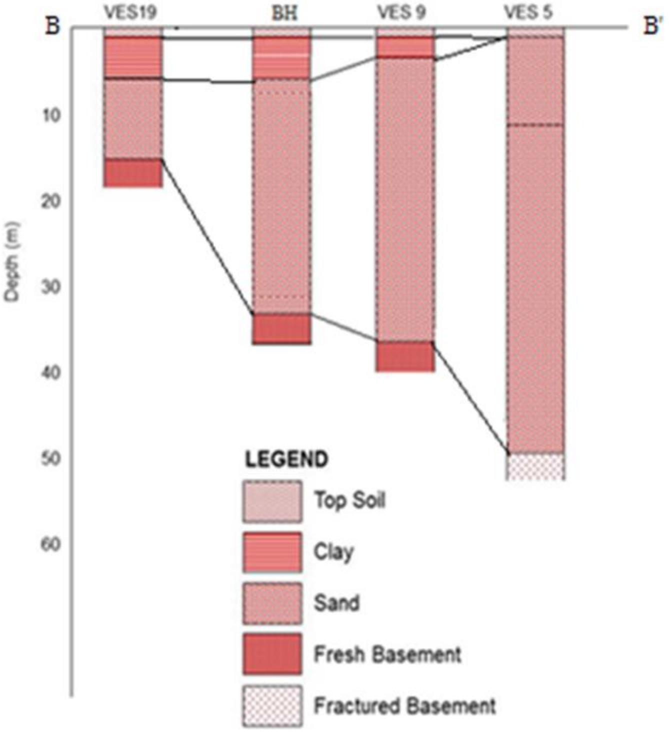


Fig. 4. Geoelectric section along profile B – B '

20 and 100 Ωm are characteristics of optimum groundwater potential. Medium and poor potential saprolites are characterized by resistivities of 100 to 150 Ωm, and 150 to 300 Ωm, respectively. The anomalous extremely high resistivity value of 4025 Ωm at VES 17 is due to the presence of fresh bedrock. Bedrocks exhibiting resistivity value less than 750 Ωm is an indication of high degree fracturing while higher resistivity indicates little or no fracturing [20].

3.2 Aquifer Vulnerability

Indices of aquifer vulnerability are listed in Table 3. The aquifer vulnerability map, shown in Fig. 5, was produced with SURFER 8 Terrain and 3D surface modelling software [23]. The map shows different classes of aquifer vulnerability, from extremely-high (red), to high (ruby red), to moderate (brick red), to low (regal red), and extremely-low (neon red).

Table 3. Model geoelectric parameters, inferred lithology and aquifer vulnerability index

VES	Layer	Resistivity (Ωm)	Thickness (m)	Lithology	C = d/k (years)	Log C	AVI
1.	1.	267	1.7	Top Soil	0.00048	0.00176	- 2.75
	2.	531	4.9	Sand	0.0013		EHV
	3.	208	14.0	Sand			
	4.	1888		Fresh Basement			
2.	1.	116	0.9	Top Soil	0.00025	30136.99	4.48
	2.	18	1.1	Clay	30136.99		ELV
	3.	44	35.0	Sand			
	4.	1072		Fresh Basement			
3.	1.	474	1.0	Top Soil	0.00027	0.00254	- 2.59
	2.	192	8.3	Sand	0.00227		EHV
	3.	79	31.0	Sand			
	4.	1642		Fresh Basement			

VES	Layer	Resistivity (Ωm)	Thickness (m)	Lithology	C = d/k (years)	Log C	AVI
4.	1.	127	1.1	Top Soil	0.000301	0.00414	- 2.38
	2.	425	14.0	Sand	0.003836		EHV
	3.	78	10.2	Sand			
	4.	1685		Fresh Basement			
5.	1.	311	1.0	Top Soil	0.000274	0.00433	- 2.36
	2.	65	14.8	Sand	0.004055		EHV
	3.	238	33.0	Sand			
	4.	642		Fractured Basement			
6.	1.	190	1.4	Top Soil	0.000384	0.00227	- 2.64
	2.	32	6.9	Sand	0.00189		EHV
	3.	471	22.0	Sand			
	4.	1625		Fresh Basement			
7.	1.	240	1.1	Top Soil	0.000301	131506.85	5.12
	2.	16	4.8	Clay	131506.84		ELV
	3.	429	27.6	Sand			
	4.	1921		Fresh Basement			
8.	1.	315	1.3	Top Soil	0.00036	0.00337	- 2.47
	2.	176	11.0	Sand	0.00301		EHV
	3.	202	21.0	Sand			
	4.	2114		Fresh Basement			
9.	1.	687	1.1	Top Soil	0.000301	32876.71	4.52
	2.	15	1.2	Clay	32876.71		ELV
	3.	313	30.5	Sand			
	4.	2544		Fresh Basement			
10.	1.	272	1.7	Top Soil	0.000466	0.00277	- 2.56
	2.	171	8.4	Sand	0.00230		EHV
	3.	14	6.3	Clay			
	4.	607		Fractured Basement			
11.	1.	138	1.1	Top Soil	0.000302	0.00238	- 2.62
	2.	68	7.6	Sand	0.00208		EHV
	3.	194	18.4	Sand			
	4.	1517		Fresh Basement			
12.	1.	195	1.1	Top Soil	0.000301	172602.74	5.28
	2.	15	7.1	Clay	194520.55		ELV
	3.	101	15	Sand			
	4.	1826		Fresh Basement			
13.	1.	791	1.1	Top Soil	0.000301	0.00112	- 2.95
	2.	651	3.0	Sand	0.000822		EHV
	3.	75	13.0	Sand			
	4.	2158		Fresh Basement			
14.	1.	355	1.5	Top Soil	0.000411	0.00479	- 2.32
	2.	811	16.0	Sand	0.00438		EHV
	3.	452	4.4	Sand			
	4.	3518		Fresh Basement			
15.	1.	755	1.3	Top Soil	0.000356	0.00104	- 2.98
	2.	165	2.5	Sand	0.000685		EHV
	3.	142	18.4	Sand			
	4.	477		Fractured Basement			
16.	1.	198	1.2	Top Soil	0.000329	0.00334	- 2.48
	2.	77	11.0	Sand	0.00301		EHV
	3.	53	9.2	Sand			
	4.	2457		Fresh Basement			
17.	1.	133	1.8	Top Soil	0.000493	0.00463	- 2.33
	2.	600	15.1	Sand	0.00414		EHV
	3.	4025		Fresh Basement			

VES	Layer	Resistivity (Ωm)	Thickness (m)	Lithology	C = d/k (years)	Log C	AVI
18.	1.	195	1.4	Top Soil	0.000384	0.0021	- 2.68
	2.	52	6.2	Sand	0.0017		EHV
	3.	86	5.4	Sand			
	4.	1978		Fresh Basement			
19.	1.	107	1.6	Top Soil	0.000438	112328.77	5.05
	2.	19	4.1	Clay	112328.77		ELV
	3.	52	10.4	Sand			
	4.	2158		Fresh Basement			
20.	1.	204	1.1	Top Soil	0.000301	0.00337	- 2.47
	2.	50	11.2	Sand	0.00307		EHV
	3.	422	30.4	Sand			
	4.	1763		Fresh Basement			
21.	1.	359	1.6	Top Soil	0.000438	0.00126	- 2.90
	2.	57	3.0	Sand	0.000822		EHV
	3.	92	16.9	Sand			
	4.	150		Fractured Basement			
22.	1.	364	1.2	Top Soil	0.000329	0.00211	- 2.68
	2.	66	6.5	Sand	0.00178		EHV
	3.	130	10.4	Sand			
	4.	1152		Fresh Basement			
23.	1.	308	0.9	Top Soil	0.00025	0.00299	- 2.52
	2.	94	10.0	Sand	0.00274		EHV
	3.	229	12.6	Sand			
	4.	3458		Fresh Basement			
24.	1.	124	1.3	Top Soil	0.000356	0.00199	- 2.70
	2.	39	6.0	Sand	0.00164		EHV
	3.	52	28.7	Sand			
	4.	271		Fractured Basement			
25.	1.	894	1.3	Top Soil	0.000356	0.00184	- 2.74
	2.	347	5.4	Sand	0.001479		EHV
	3.	50	52.0	Sand			
	4.	341		Fractured Basement			

The aquifer vulnerability assessment shows a large sector of extremely-high vulnerability in the northern part (VES 15, VES 16, VES 17, VES 18, VES 20, VES 21, VES 22 and VES 23), in the central part (VES 11, VES 13 and VES 14), and in the southern part (VES 1, VES 3, VES 4, VES 5, VES 6 and VES 10) of the study area. These sectors represents about 70 % of the study area, and are characterized by surficial pervious sand deposits overlying the aquifer, as seen from the geoelectric section (Fig. 3). In such areas, the aquifer may be susceptible to pollution from percolating contaminants. Effluents from anthropogenic activities at surface can reach the groundwater with relative ease, due to high hydraulic conductivity of sands.

There is a significant change in the pattern of aquifer vulnerability in the southern part (around VES 2), south-western part (around VES 7, VES 9 and VES 12), and north-western part of the study area. A concentric pattern of vulnerability, from high (blue) to moderate (yellow), to low (green), to extremely low (brown) can be appreciated. This change is due to the heterogeneity of the surficial geology: in fact, here the composition of the second geoelectric (protective) layer changes from arenaceous to argillaceous. In such zone, constituting 20 % of the entire study area, the aquifer is protected from contamination by infiltrating effluent by thick layers of clays. Here, groundwater is given adequate protection by protective layers of clays having sufficient thickness (ranging from 1.1 to 7.1 m) and high hydraulic resistance (low hydraulic conductivity). According to Holting et al. [24], the percolating time through the unsaturated protective layers in these areas may exceed 10 years, resulting in high residence time of percolating fluid.

An aquifer is given protection by geologic layers having sufficient thickness and low hydraulic conductivity [25]. The travel time of contaminants through such geologic layers can be related to the properties of the layers. Such properties

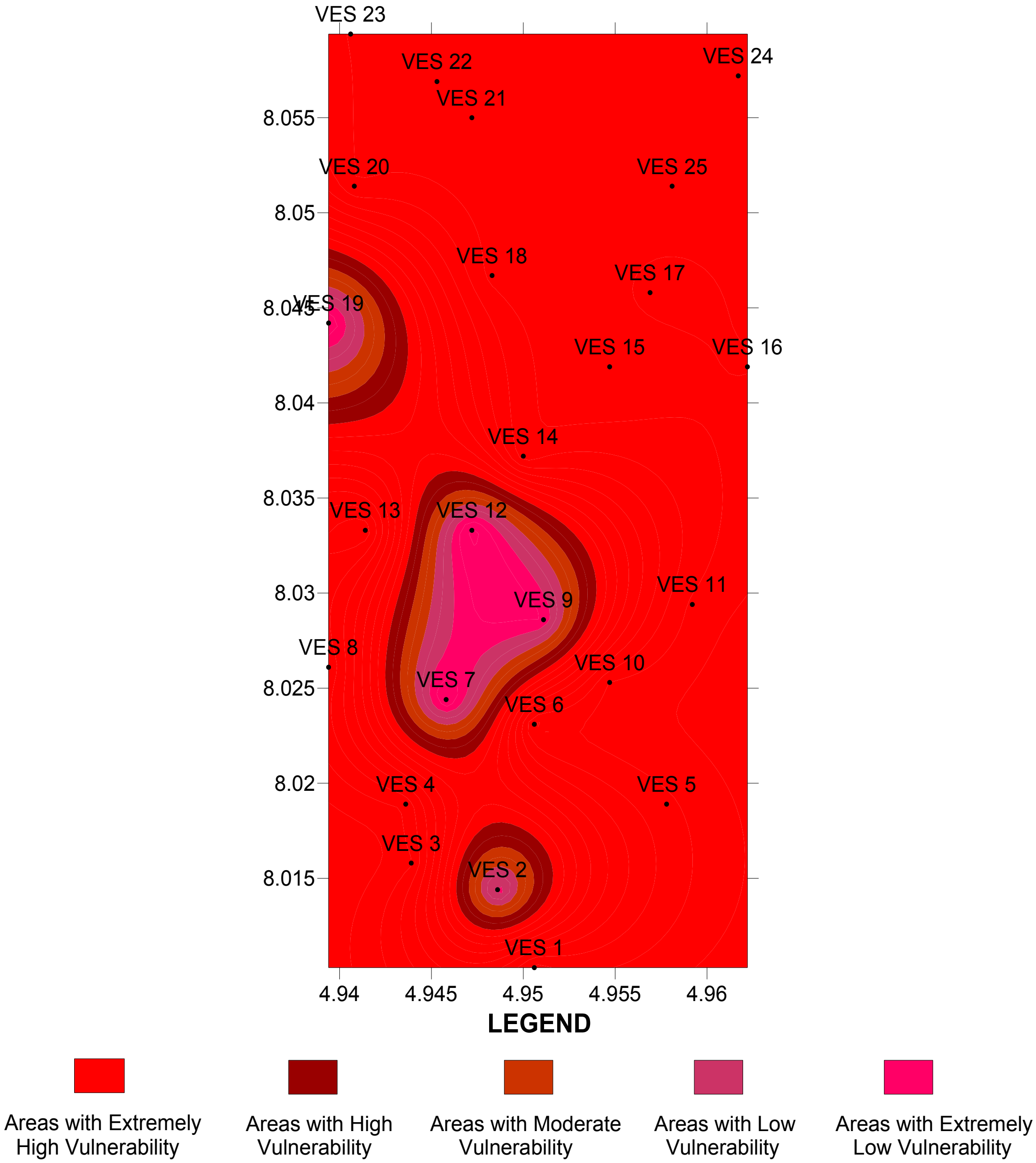


Fig. 5. Aquifer vulnerability map of Oke – Ila

include porosity for sandy regolith and clay content for clayey overburden. Near surface layers of clays often offer such type of protection where they confine an aquifer [26] by precluding potentially contaminated effluent from reaching groundwater.

4. CONCLUSION

Oke-Ila lies within the humid tropical climatic setting; as a result the rocks have been subjected to intense chemical weathering, producing weathered layers that may serve as suitable zones for shallow groundwater accumulation. The results of this study have shown four geoelectric layers namely: top soil, upper weathered layer, lower weathered layer, fresh/fractured basement. The third layer, made of weathered crystalline rocks, serves as aquifer for most inhabitants; the depth to this aquifer is shallow (between 7 and 16 m). It is overlain by mostly pervious sandy regolith, thus making the aquifer highly susceptible to contamination in about 70 % of the entire study area. However, clayey near-surface materials confining the aquifer at some locations gave the aquifer either low vulnerability or extremely-low vulnerability status. Boreholes should be drilled at low and extremely-low vulnerability sites, such as VES 2, VES 7, VES 9, VES 12 and VES 19. Areas with deep weathering profiles could also be good prospect for groundwater development. The thick weathered regolith can in fact provide natural filtration that can prevent effluents from anthropogenic activities from getting into the groundwater system. Contaminants in groundwater tend to be reduced in concentration with travelled distance (through the layers overlying the aquifer) and with time, by means of different mechanisms - such as filtration, sorption, dilution and microbial decomposition.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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