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Groundwater Assessment and Its Intrinsic Vulnerability Studies Using Aquifer Vulnerability Index and GOD Methods

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Abstract: Groundwater assessment and aquifer/water bearing formation vulnerability studies were carried out in Ose and Owo Local Government areas of Ondo State, Southwestern Nigeria. The groundwater evaluation involved integrated electrical resistivity (vertical electrical sounding), very low frequency electromagnetic, and borehole logging. Aquifer vulnerability assessment was done using Aquifer vulnerability Index (AVI) and GOD approaches. Fifty two (52) vertical electrical soundings (VES) data were acquired with Schlumberger array using current electrode separation (AB/2) of 1 to 225 m. The acquired VES data were qualitatively interpreted to determine the geoelectric parameters (layer resistivity and thickness). The geoelectric sections revealed the lithological sequence comprising topsoil, weathered layer, partly weathered/fractured basement and fresh basement. The most occurring curve types identified are H and KH with % frequency of 30 and 26.9 respectively. The lineament density and interception maps show a low spatial variation as the lineaments are generally sparse in the study area especially in Ose local government area; while Owo area shows a low – moderate variation. The major water bearing units are confined/unconfined fracture basement and weathered layer composing of clay/sandy clay, clay sand and sand aquifers (found in the southern part of the study area with thickness generally above 20 m and could be up to 60 m). However, the fracture basement aquifer is widespread in Owo area with thickness that could up to 30 m. The depth to these water bearing geological formation is between 1.2 m and 15.9 m. The AVI characterized the study area into “extremely low – High vulnerability” with predominant very high vulnerability values. The GOD vulnerability model depicts that the study area is characterized by three vulnerability zones, which are low, moderate and high vulnerable zones. According to the model, about 5% of the area is highly vulnerable while about 45% is of moderate rating, and 50% low vulnerable rating. It is highly recommended that the least vulnerable zone should be the primary target for future groundwater development in the area in order to ensure continuous supply of safe and potable groundwater for human consumption; and more importantly, location of septic tanks, petroleum storage tanks, shallow subsurface piping utilities and other contaminant facilities should be confined to low vulnerable zones.

Keywords: GOD, AVI, Vulnerability, Groundwater, Contamination, Borehole Logging

1. Introduction

Fresh water makes up only 2.5% of all the water on earth, but not all of this water is available for human use. The water in polar ice caps, other forms of ice and snow, soil moisture, marshes, biological systems, and the atmosphere are not readily available. As a result, only the 10,530,000 km³ of groundwater, 91,000 km³ of fresh water in lakes, and the 2,120 km³ of water in rivers are considered attainable for use and comprise a total of 10,623,120 km³. Consequently, groundwater comprises 99% of the earth’s available fresh water [1] and it has now become as a national treasure and the most important natural resources. Despite its abundance, most people still lack fresh water for daily needs in form of drinking, domestic, municipal, industrial and irrigation purposes. Although governments all levels are putting up concerted efforts in making sure this resource becomes readily available in towns and villages in the country, but the results are virtually infinitesimal. In addition, most of the successful drilled boreholes are failing at a very alarming rate [2]; while those that have not failed are highly contaminated. Therefore there's need to carry out comprehensive groundwater assessment studies using integrated approach with state-of-the-art equipment. In this vein groundwater assessment and its vulnerability to contamination was undertaken in Owo and Ose local government areas of Ondo State using hydrogeological measurements, and geophysical methods. The vulnerability of the delineated aquifer/water bearing formation to contamination was evaluated using Aquifer Vulnerability Index (AVI) and GOD (groundwater occurrence/lithology overlying aquifer/depth to water table) methods.

1.1. Description of the Project Environment

The study area is Ose and Owo local government areas of Ondo State, Southwestern Nigeria "Figure 1". It lies within longitudes 5° 20^{l} E and 6° 00^{l} E and latitudes 6° 30^{l} N and 7° 30^{l} N. The study area is easily accessible by roads like Ikare – Owo highway, Benin – Ifon highway and Akure – Owo highways. It is bounded by Kwara, Kogi and Ekiti State in the North, Edo and Delta in the east, Ogun, Oyo and Osun States in the west and in the South by the Atlantic Ocean. Over 60% of the State is underlain by basement migmatites, gneisses and granites which form rugged hills and rolling plains. The area lies geographically within the tropical rain forest belt of hot and wet equatorial climatic region characterized by alternating wet and dry climate seasons [3], which is strongly controlled by seasonal fluctuation in the rate of evaporation.

The available rain data shows that mean annual rainfall ranges from 1000 mm - 1500 mm and mean temperature of 24°C to 27°C. There is rapid rainfall during the month of March and cessation during the month of November. June and September are the critical months when rainfall is usually on the high side. The vegetation is of tropical rainforest and is characterized by thick forest of broad-leaved trees that are ever green. The vegetation of the area is dense and made up of palm trees, kolanut trees and cocoa trees. However teak and Gmelina trees are also predominant in the area "Figure 2".

The Owo local government area has a gently undulating topography as it ranges from 311 m to 363 m above the sea level, while in Ose local government it generally varies between less than 100 m and 260 m except at Ido Ani area where surface elevation is between 300 m and 400 m "Figures 3 and 4", with potential groundwater flow direction of N – S "Figure 5".

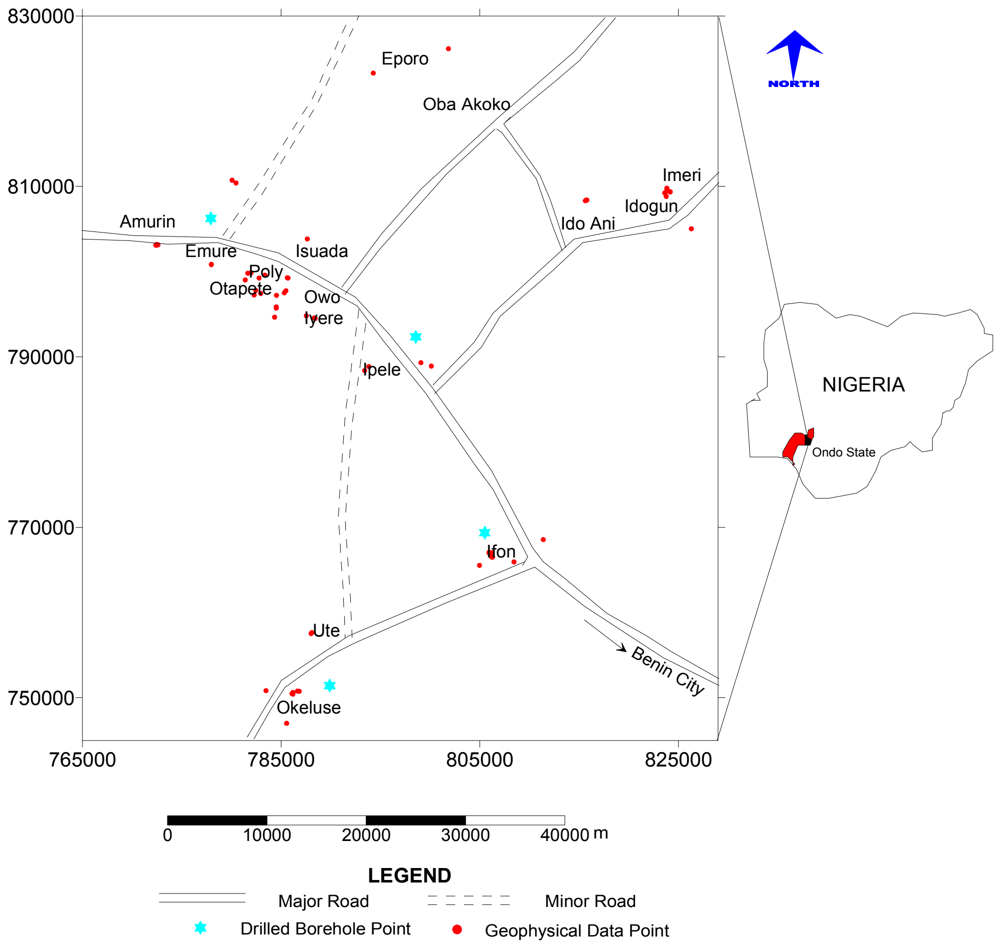


Figure 1. Location/Base Map of the Study Area.

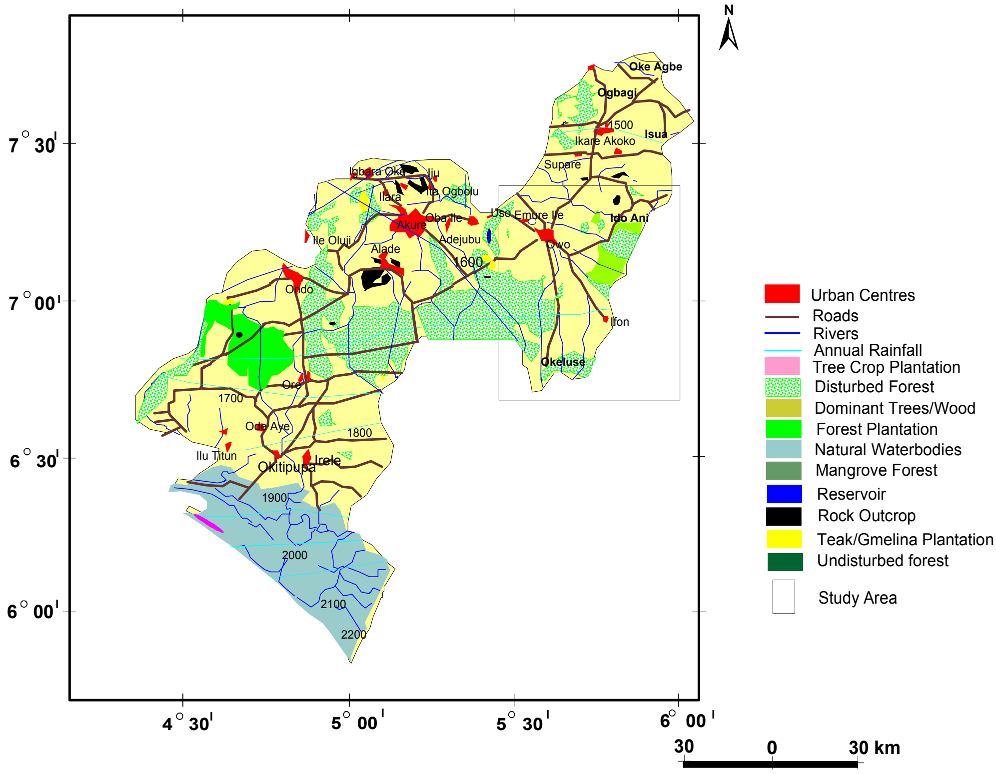


Figure 2. *Land Use Map of Ondo State showing the Study Area.*

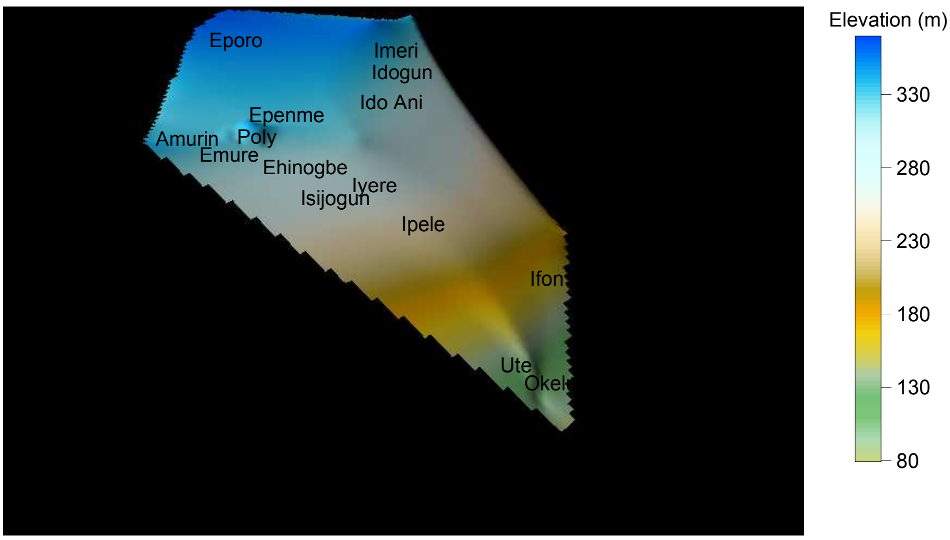


Figure 3. *3-D Surface Map of the Study Area.*

1.2. Geology of the Studied Area

The area of study falls within the Southwestern basement rock, which is part of Nigerian Basement complex. The area is underlain mainly by rocks of the Migmatite - Gneiss Complex which is predominated by quartzite, granite gneiss and schist "Figure 6". Granite gneiss and gneiss are the most widespread rock in the area; which mineralogically contain quartz and feldspar dominating mineral, other minerals such as muscovite, tremolite, microcline and biotite are common as well. Quartzite which are prominent as ridge varies in texture from massive to schistocity due to the presence of flaky minerals like mica. However, the southern area of the study area is basically underlain by cretaceous sediments in Imoru, Arimogija, Ute and Okeluse. These areas are characterized by thick lateritic clay/sand (more than 10 m in places) especially around Imoru and Ute in Ose local government area; and predominant lateritic clay and kaolinite in Okeluse. Also observed are oolitic sand, sharp sands and rounded pebbles which are essentially contemporaneous and uniform in character (lithological, chemical, and physical). These deposits are the derivatives or products of disintegration of the basement rocks, which are transported over a long distance and subjected to erosional processes of attrition, abrasion etc.

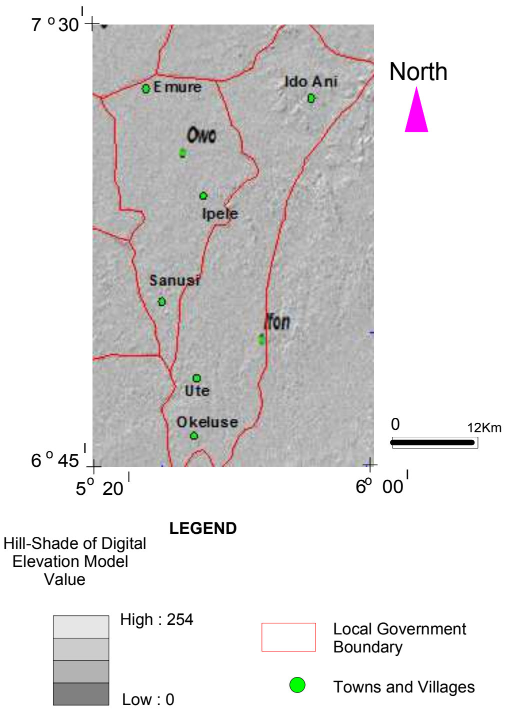


Figure 4. Hill-Shaded Map of the Study Area.

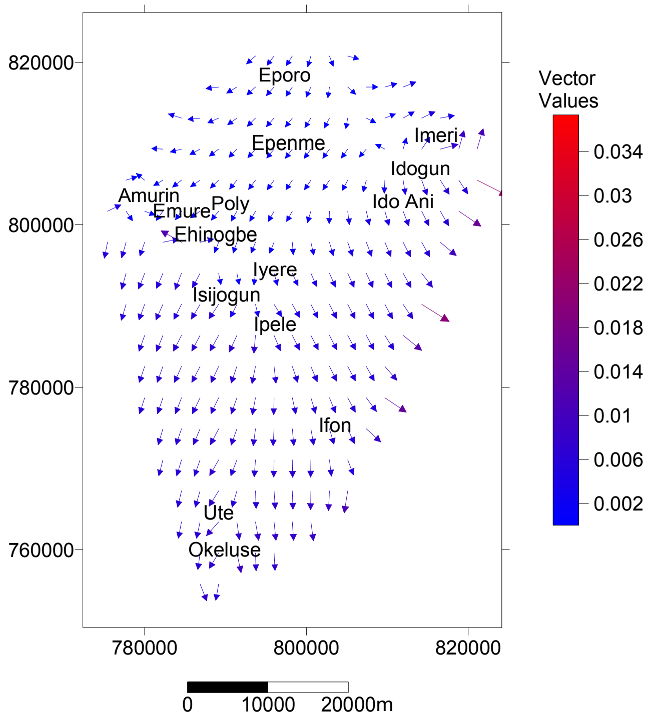


Figure 5. 1-Grid Vector Map showing potential Groundwater flow direction.

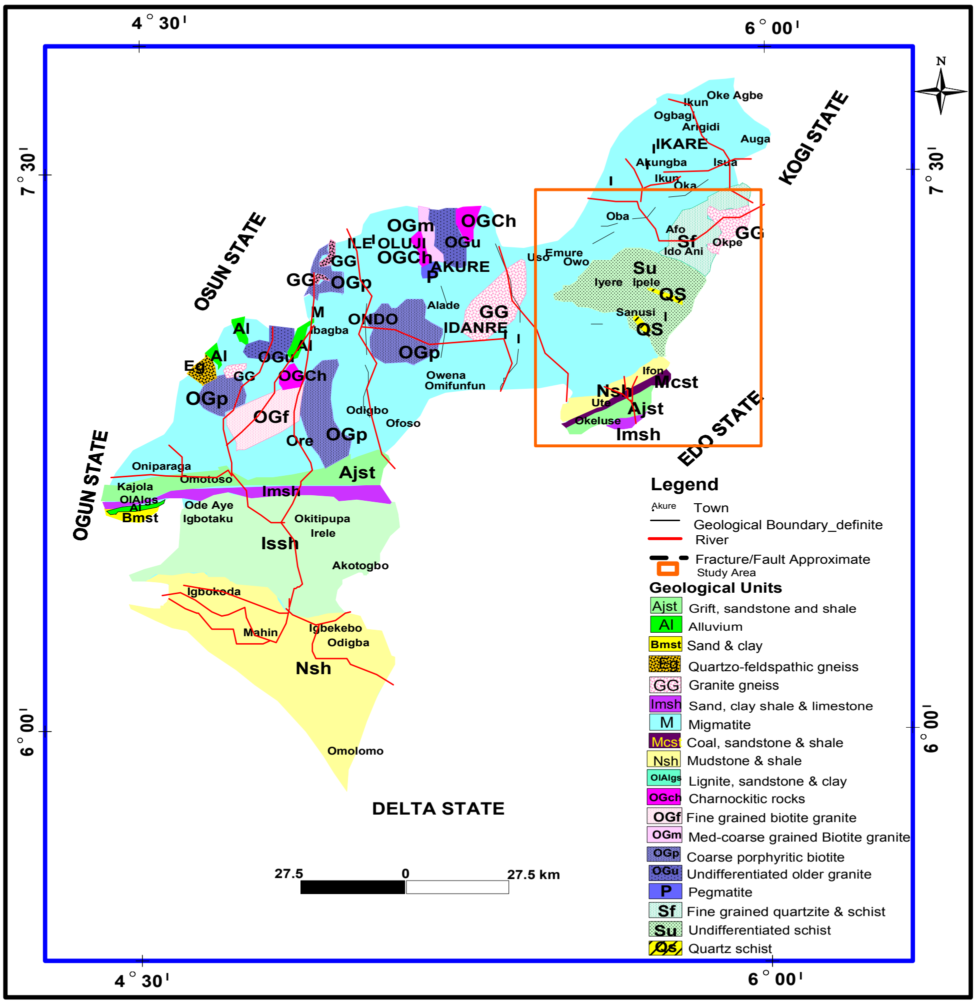


Figure 6. Geological Map of Ondo State showing the Study Area predominately underlain by Migmatite.

2. Material and Methods

Fifty Two (52) Schlumberger vertical electrical soundings (VES) were conducted across the study area using a maximum current electrode separation (AB) of 225 m. "Figure 1" shows the VES locations. Resistivity measurements were made with an Ohmega digital resistivity meter which allows for readout of current (I) and voltage (V). The location of each sounding stations in both geographic and Universal Traverse Mercator (UTM) coordinates was recorded with the aid of the GARMIN 12 channel personal navigator - Geographic Positioning System (GPS) - unit.

The field curves were interpreted through partial curve matching [4] with the help of master curves (Orellana and Mooney, 1966) and auxiliary point charts [5-6]. From the preliminary interpretation, initial estimates of the resistivity and thickness of the various geoelectric layers at each VES location were obtained. These geoelectric parameters were later used as starting model for a fast computer-assisted interpretation [7]. The program takes the manually derived parameter as a starting geoelectric model, successively improved on it until the error is minimized to an acceptable level. The interpreted result was considered satisfactory where a good fit of RMS between the field curves and computer generated curves is generally less than 15%; as it ranges between 1.8 – 10.7. The results were also used to generate the geoelectric/geologic section.

The Very Low Frequency Electromagnetic (VLF– EM) method utilized the inline profiling technique. VLF-EM measurements were also taken at 5 to 10 m interval along each traverse with Geonics EM 16 VLF. The real and quadrature components of the vertical /horizontal magnetic field ratio were recorded at each observation station. The receiver unit was tuned to Rugby in Great Britain. The real and filtered real components were plotted against station positions using 'KHFFILT' software version 1.1. A 2-D inversion of the real component data was carried out using the same software.

Information was also collected on four (4) drilled boreholes in the study area in order to constrain the geophysical interpretation. Also three hundred and two (302) hand dug wells were measured to know estimation of depth to the water level/water table elevation. The surface elevation at different points varies due to topographic variation, the true water level were obtained by subtracting the measured depth to the water level in the hand-dug wells from the surface elevation to get uniform water levels otherwise known as the elevation of the water level or static water level [8].

$$\text{Mathematically, } S_{wl} = E - D_{wl} \quad (1)$$

Where: S_{wl} is the true or uniform water level otherwise known as the static water level in the case of unconfined aquifer; E is the surface elevation with respect to the mean sea level; D_{wl} is the depth from the surface of the earth to the water level (Well Head) in the hand- dug wells (Direct borehole logging).

Therefore in order to evaluate the vulnerability of the aquifers/water bearing units to contamination or pollution, GOD and Aquifer Vulnerability Index (AVI) were used. The Aquifer Vulnerability Index method [9] is a measure of groundwater vulnerability based on two physical parameters:

(a) thickness (d) of layer above the uppermost aquifer surface, and,

(b) estimated hydraulic conductivity (K) of each of these (sedimentary) layers.

The thickness (d) of sedimentary layers (e.g. sand, clay, silt, gravel) was obtained from the geoelectric sections. Since K determinations may not be available for each geologic unit, a table of estimated values "Table 1" was used according to [10]. Based on the two physical parameters, d and K, the hydraulic resistance "c" can be calculated "Table 2", where:

$$C = \sum \frac{d_i}{K_i} \quad (2)$$

for layers 1 to i

The parameter c is a theoretical factor used to describe the resistance of an aquitard to vertical flow [11]. Thus, the weighting of the two factors, thickness and hydraulic conductivity of each sediment layer above the uppermost saturated aquifer surface, is not arbitrary, but is based on physical theory. Hydraulic resistance (c) has dimension of Time, which indicates the approximate travel time for water to move by advection downward through the various porous media above the uppermost saturated aquifer surface. However, it should be noted that, in a strict sense, "c" is not a travel time for water or contaminants. Factors such as hydraulic gradient, diffusion, and sorption are not considered. The calculated "c" or "log(c)" values can be used directly to generate iso-resistance contour maps. However, in this method, each profile (e.g., well) is related to a qualitative.

The AVI method takes into account indirectly the various factors or parameters used by DRASTIC, with the exception of topography, and aquifer media (i.e. type of sediment or rock serving as aquifer media, hydraulic conductivity of aquifer).

GOD method is characterized by a rapid assessment of the aquifer vulnerability; it was developed by [12] for studying the vulnerability of the aquifer against the vertical percolation of pollutants through the unsaturated zone, without considering their lateral migration in the saturated zone. The approach used in this model takes in consideration three parameters:

1. Groundwater occurrence (confinement of the aquifer)
2. Overall aquifer class (lithology overlying the aquifer)
3. Depth to aquifer/water bearing unit

The GOD index which is used to evaluate and map the aquifer vulnerability caused by the pollution, was calculated by multiplication of the influence of the three parameters using the equation (3).

$$\text{GOD Index} = Cl \times Ca \times Cd \quad (3)$$

Where: Ca is the type of aquifer, Cl is the lithology of the unsaturated zone and Cd is the depth to aquifer. These GOD parameters were interpreted from the geoelectric sections. The intervals values of GOD Index and corresponding classes "Table 3", attribution of notes for GOD Model parameters was modified after [13]. The corresponding classes of vulnerability used, which were derived from GOD Index used is presented in "Table 3" and "Table 4".

Table 1. *Hydraulic Conductivity (K) Estimates (mean values) for Various Sediments [10].*

Sediment Type	Standard Code	Hydraulic Conductivity
Gravel	A	1000 m/d
Sand	B	10 m/d
Silty sand	C	1 m/d
Silt	D	10^{-1}m/d
Fracture till, clay or shale (0 to 5 m from ground surface)	E	10^{-3}m/d
Fracture till, clay or shale (0 to 5 m from ground surface)	F	10^{-4}m/d
Fracture till, clay or shale (10 m from ground surface, but weathered based on colour: brown or yellow)	F	10^{-4}m/d
Massive till or mixed sand-silt-clay	G	10^{-5}m/d
Massive clay or shale	H	10^{-6}m/d

Table 2. *Relationship of Aquifer Vulnerability Index to Hydraulic Resistance.*

Hydraulic Resistance	Log(c)	Vulnerability (AV)
0 to 10 y	<1	Extremely High
10 to 100 y	1 to 2	High
100 to 1, 000 y	2 to 3	Moderate
1, 000 to 10, 000 y	3 to 4	Low
>10, 000 y	>4	Extremely Low

Table 3. *Interval values of the GOD Index and corresponding classes (Modified after [14]).*

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

Table 4. *Attribution of notes for GOD Model parameters (Modified after [13]).*

Aquifer Type	Note	Depth to Aquifer / water bearing unit	Note	Lithology (Ω-m)	Note
Non-Aquifer	0	< 2	1	< 60	0.4
Artesian	0.1	2 - 5	0.9	60 – 100	0.5
Confined	0.2 - 0.4	5 - 10	0.8	100 - 300	0.7
Unconfined	0.5 - 1	10 - 20	0.7	300 - 600	0.8
		20 - 50	0.6	> 600	0.6
		50 - 100	0.5		

3. Results and Discussion

In this extant age of geo-information technology, it is almost becoming the norm to combine remote sensing and geophysics in most environmental, groundwater and engineering site investigation [15-16]. The lineament density and interception maps "Figures 7 and 8" show a low spatial variation as the lineaments are generally sparse in the study area especially in Ose local government area; while Owo area shows low – moderate variation.

"Tables 5 – 6" give a summary of the results of the VES curves obtained from the study area. The number of layers varies between three (3) layers and six (6) layers. Ten curve types have been identified: HKH, H, HA, HK, KHKH, KQ, KH, A, KHK, and QH "Figure 9". The most occurring curve types identified are H and KH with % frequency of 30 and 26.9. The root mean square (RMS) error of the generated curve types ranges between 1.8 and 6.1; this shows models of well smoothened, iterated curves [17]. The major water bearing units are confined/unconfined fracture basement and weathered layer. They have thickness that varies between 2.6 m and 64.6 m. The depth to these water bearing geological formation is between 1.2 m and 15.9 m "Figure 10". The major water bearing formations in the study area are clay/sandy clay and clay sand. Sand aquifers are found in the southern areas of the study area with thickness generally above 20 m. However, the fracture basement aquifer is widespread in Owo area with thickness that could be up to 30 m.

Along Traverse 1, the geoelectric section "Figure 11a" delineates four geologic layers comprising the topsoil, weathered layer, fracture basement which is confined within the fresh basement. The topsoil along this traverse is composed of clay sand and sandy clay with resistivity in the range of 100 Ω-m – 300 Ω-m, while clay/sandy clay underlying it as the weathered material. Fracture zones which is also identified on the VLF-EM 2-D model as strong conductive target, suspected to be a water filled geological formation. The weathered layer is generally very thick (>5 m) especially at eastern flang, but its resistivity values suggest a clay/clay sand formation. However the major aquifer along this traverse is the fractured basement. The flow direction is east – west.

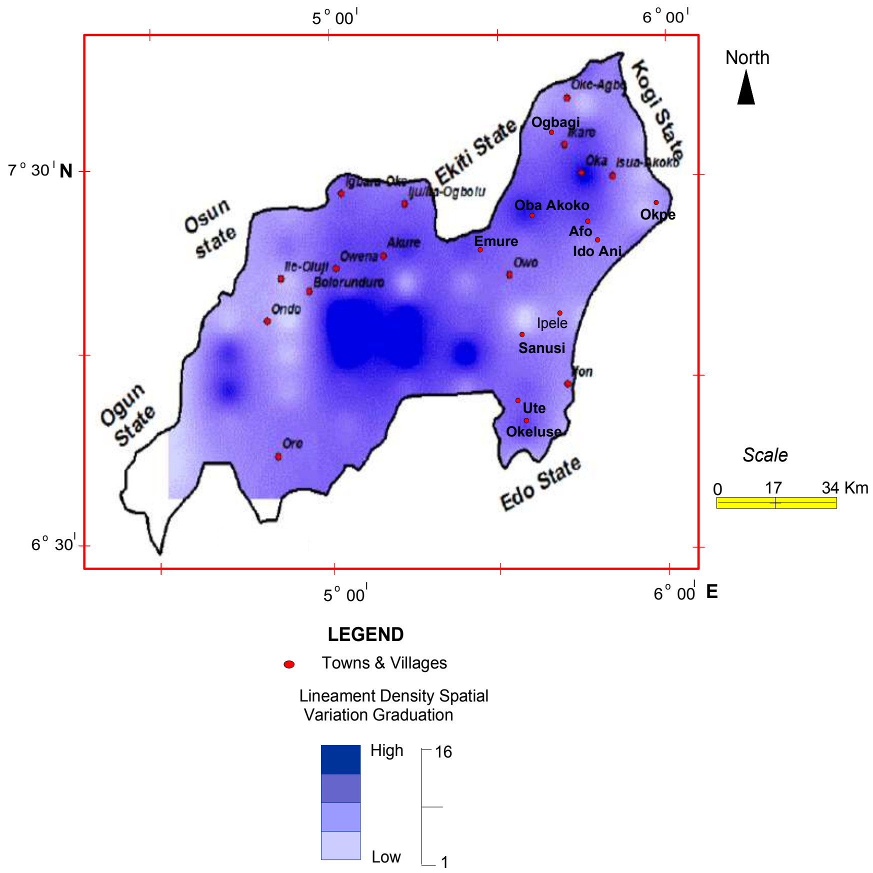


Figure 7. Regional Lineament Density Variation Map of the Study Area [18].

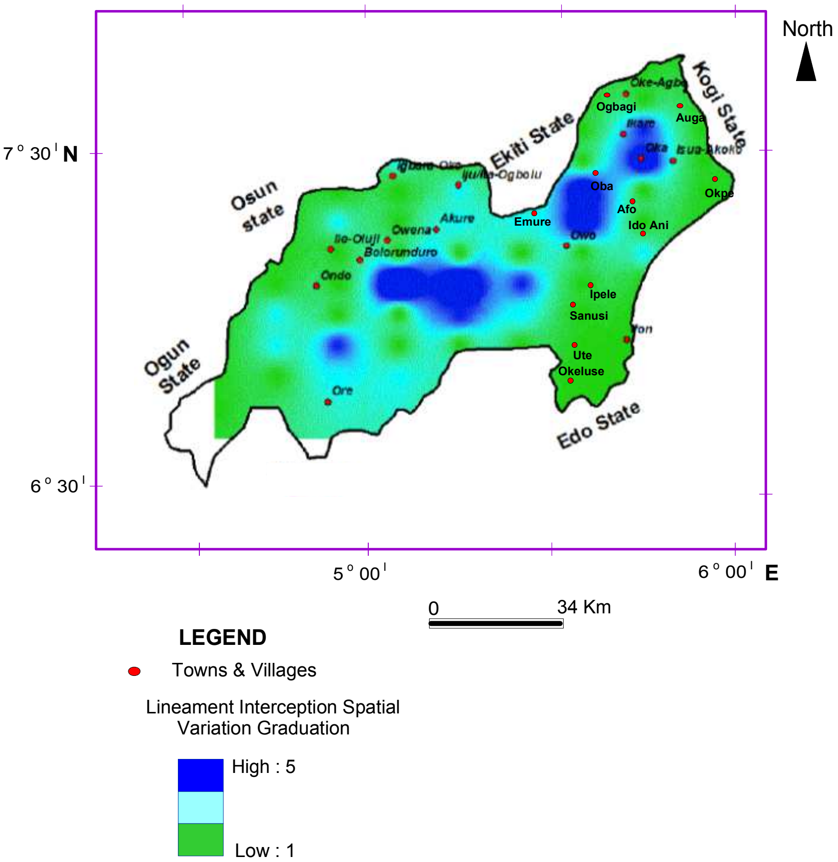


Figure 8. Regional Lineament Interception Variation Map of the Study Area [18).

Along Traverse 2, the topsoil is very thin (about 1.5 m) and composed of sand/clay sand with resistivity range of 420 Ω-m – 464 Ω-m “Figure 12a”. Underlying the topsoil is thick (> 15 m) clayey weathered layer with resistivity of less than 100 Ω-m. The fracture basement is delineated below both VES stations investigated and corroborates the fracture at distance 20 m – 40 m on the VLF-EM 2-D model “Figure 12a” with depth extent greater than/equal to 20 m. Therefore the weathered layer and the fracture basement constitute the major water bearing units along this traverse. This kind of combination is one of the best when prospecting for groundwater resource.

Along traverse 3 “Figure 13”, the geologic succession along this traverse is clay/clay sand/sandy clay, clay, and sand formation. However the major aquifer along this traverse is the deep seated sandy formation, with resistivity values in the range of 500 Ω-m – 2000 Ω-m. The depth to this aquifer is greater than 20 m.

The results of the borehole logging/ sections generated through the recording of the cuttings ejected during drilling are presented in “Figure 14”. Four major geological units are delineated, which comprises sandy clay, clay sand, laterite, sand, and basement rock. In sedimentary terrain (which represents the southern region) there are intercalations of clayey and sand materials. This is generally the case of sedimentary environment.

However the borehole sections agree very well with the geoelectric sections. From the section the uppermost 5 m is made up of clay sand, sandy clay, laterite (in some cases hardpan). The groundwater levels in Owo area is generally less than 10 m (the water bearing unit is clay sand), while greater than 20 m in the southern parts. Ifon and Okeluse show which correspond to Ose area are characterized with sandy aquifers at depth between 15 and 30 m.

Table 5. *Summary of the VES Results obtained in the Study Area.*

VES	RESISTIVITY (Ohm-meter)						THICKNESS (m)					DEPTH (m)					Curve
NO.	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	h_1	h_2	h_3	h_4	h_5	d_1	d_2	d_3	d_4	d_5	Type
1	569	76	1131	72	2566		0.7	0.9	5.3	12.7		0.7	1.6	6.9	19.6		HKH
2	201	40	1212				0.6	9.6				0.6	10.2				H
3	175	21	206	867			0.7	1.4	23.0			0.7	2.1	25.1			HA
4	21	38	1145				2.0	9.1				2.0	11.1				A
5	310	141	457	1717			0.9	3.0	3.3			0.9	4.0	7.2			HA
6	313	57	203				2.5	8.1				2.5	10.6				H
7	258	63	331				2.9	40.2				2.9	43.2				H
8	263	114	540	72			0.9	0.8	24.7			0.9	1.6	26.3			HK
9	238	31	338	87			1.1	0.9	5.5			1.1	2.1	7.6			HK
10	596	200	1243	379			1.6	2.3	15.8			1.6	3.9	19.7			HK
11	420	63	597				0.6	20.0				0.6	20.6				H
12	464	51	321				0.4	9.1				0.4	9.4				H
13	518	182	584				0.5	4.7				0.5	5.2				H
14	296	104	274				1.0	17.7				1.0	18.6				H
15	319	104	2023	180			1.4	1.5	12.1			1.4	2.9	15.0			HK
16	302	3277	1036	1456	314	487	1.9	0.1	1.4	6.5	64.6	1.9	2.0	3.3	9.8	74.4	KHKH
17	327	1031	770	448			0.3	1.7	8.0			0.3	2.1	10.0			KA
18	375	69	363				1.3	2.6				1.3	3.8				H
19	367	46	977				3.9	4.4				3.9	8.4				H
20	136	1127	67	652			0.4	1.0	5.8			0.4	1.4	7.2			KH
21	106	59	323				1.2	5.4				1.2	6.6				H
22	199	51	1942				1.2	21.6				1.2	22.8				H
23	106	812	97	1897	69	868	0.6	0.5	3.1	2.2	24.6	0.6	1.1	4.2	6.4	31	KHKH
24	249	365	86	369			1.0	0.9	13.9			1.0	1.9	15.8			KH
25	361	41	137				1.3	10.2				1.3	11.5				H
26	269	104	244				1.2	3.3				1.2	4.5				H
27	894	378	933	226	541		1.0	2.6	5.5	9.2		1.0	3.6	9.1	18.3		HKH
28	110	164	58	167			1.0	13.2	20.6			1.0	14.2	34.8			KH
29	46	263	48	12330			1.0	6.8	14.1			1.0	7.8	21.9			KH
30	515	587	104	430			1.0	7.4	47.5			1.0	8.4	55.9			KH
31	555	117	3087				1.5	14.2				1.5	15.7				H
32	921	142	4370				0.5	3.8				0.5	4.3				H
33	259	452	69	2396			0.7	0.8	16.9			0.7	1.6	18.5			KH
34	97	108	10441				1.6	44.0				1.6	45.6				A
35	114	318	47	799	41	3536	0.6	0.6	2.1	2.3	21.4	0.6	1.2	3.3	5.6	27.0	KHKH
36	142	143	56	5532	99		1.1	0.5	1.7	8.0		1.1	1.6	3.3	11.3		KHK
37	90	201	60	8199			2.0	1.4	5.4			2.0	3.4	8.8			KH
38	675	207	379	657	1400		0.5	0.4	0.7	23.8		0.5	0.9	1.6	25.4		HAA
39	464	140	125	698			0.7	1.6	11.2			0.7	2.3	13.5			QH
40	384	152	316	283	5203		0.8	1.0	4.5	11.9		0.8	1.8	6.3	18.2		HKH
41	346	32	172	113	5372		0.7	1.1	2.2	14.2		0.7	1.8	3.9	18.1		HKH
42	342	189	154	877			0.9	23.7	15.2			0.9	24.6	39.8			QH
43	236	177	325	69	670		0.9	1.5	21.5	10.3		0.9	2.4	23.9	34.2		HKH
44	689	1277	49	10392			0.7	21.4	30.2			0.7	22.2	52.3			KH
45	3389	11220	7966	207			0.3	3.7	10.3			0.3	4.0	14.3			KQ
46	182	1147	139	28840			0.4	9.8	28.2			0.4	10.1	38.3			KH
47	117	172	60	245			1.5	11.4	19.8			1.5	12.8	32.6			KH

VES NO.	RESISTIVITY (Ohm-meter)						THICKNESS (m)					DEPTH (m)					Curve Type
	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	h_1	h_2	h_3	h_4	h_5	d_1	d_2	d_3	d_4	d_5	
48	46	265	43	13239			1.0	7.0	13.2			1.0	8.0	21.2			KH
49	268	61	1599				4.0	27.6				4.0	31.6				H
50	200	2134	141	436			0.5	0.4	45.7			0.5	0.9	46.5			KH
51	271	353	69	853			1.0	9.6	16.1			1.0	10.6	26.7			KH
52	73	114	69	910			0.5	1.5	35.3			0.5	2.0	37.3			KH

Table 6. *Curve Types and their Statistical Frequency obtained from the Study Area.*

Location/Curve Type	HKH	H	HA	HAA	HK	KHKH	KQ	KH	A	KHK	QH	Total No. of VES Curves
Owo Area	2	15	2	-	4	3	1	6	2	-	-	35
Ose Area	3	1	-	1	-	-	1	8	-	1	2	17
Frequency (unit)	5	16	2	1	4	3	2	14	2	1	2	-
Frequency (%)	9.6	30.8	3.9	1.9	7.7	5.8	2.9	26.9	2.9	1.9	2.9	-

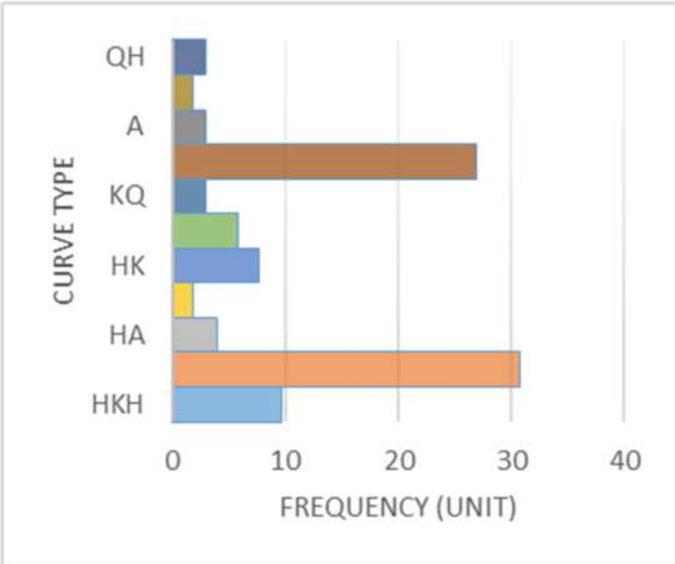


Figure 9. *Histogram of the Curve Types.*

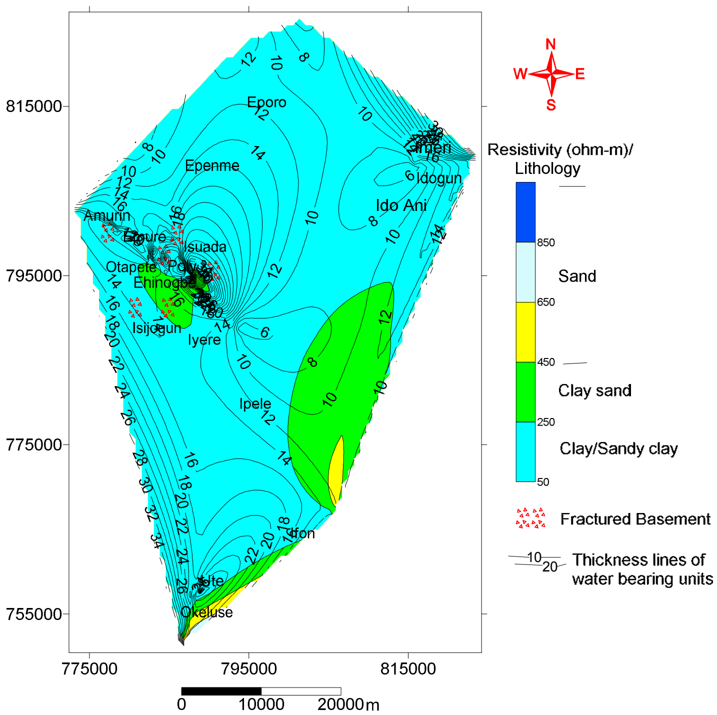
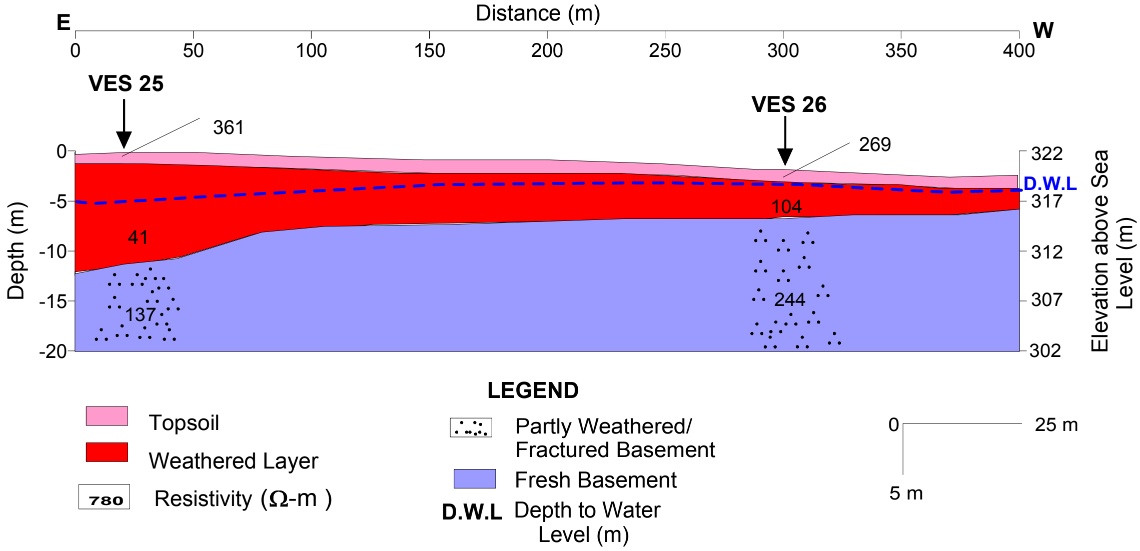
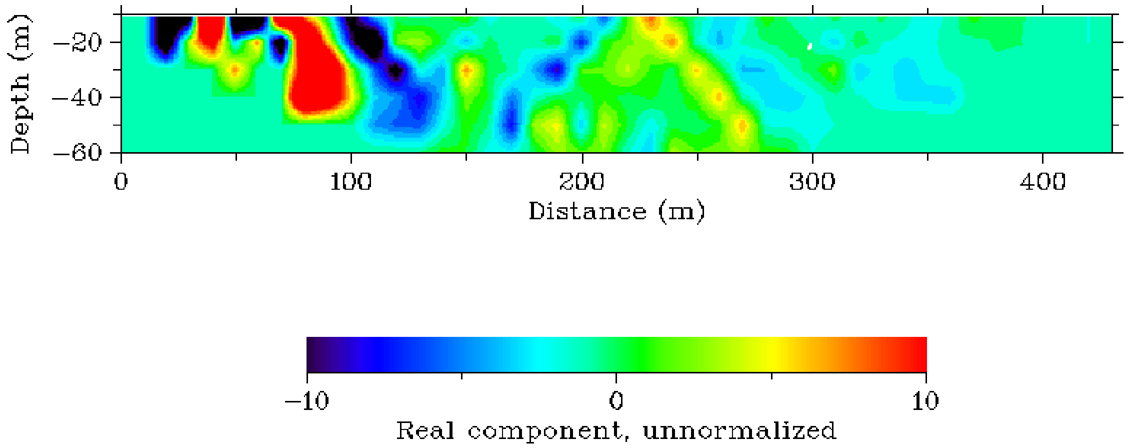


Figure 10. *Map showing water bearing units and their corresponding thickness.*

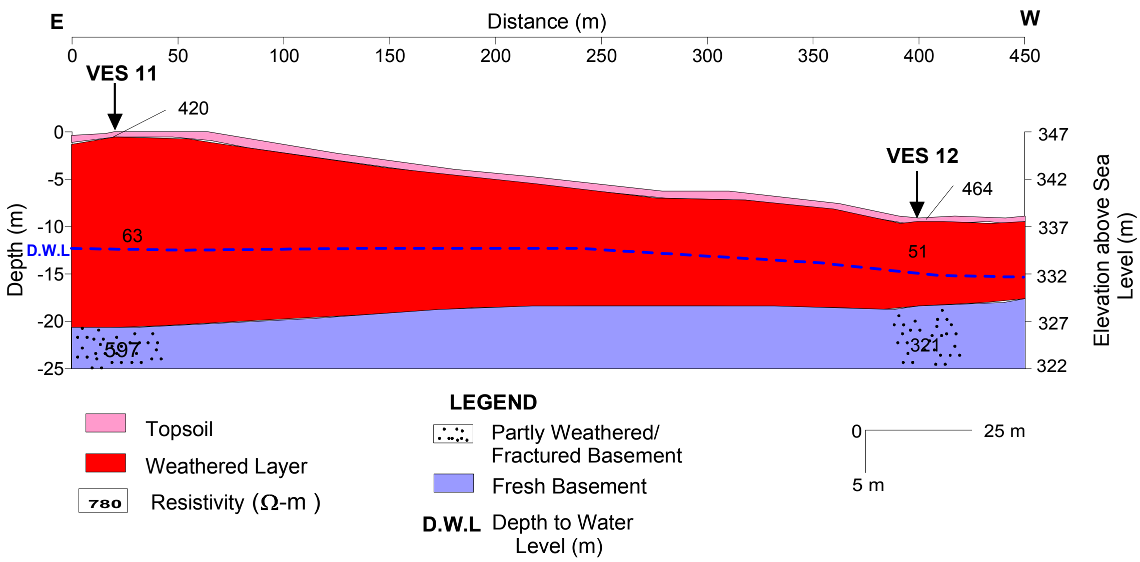


(a)

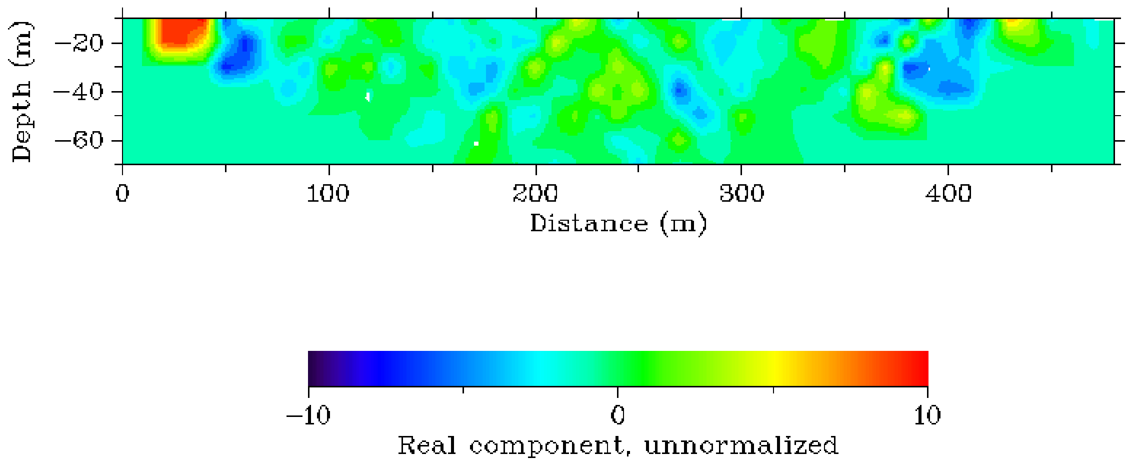


(b)

Figure 11. *Geoelectric section and VLF-EM along Traverse 1.*

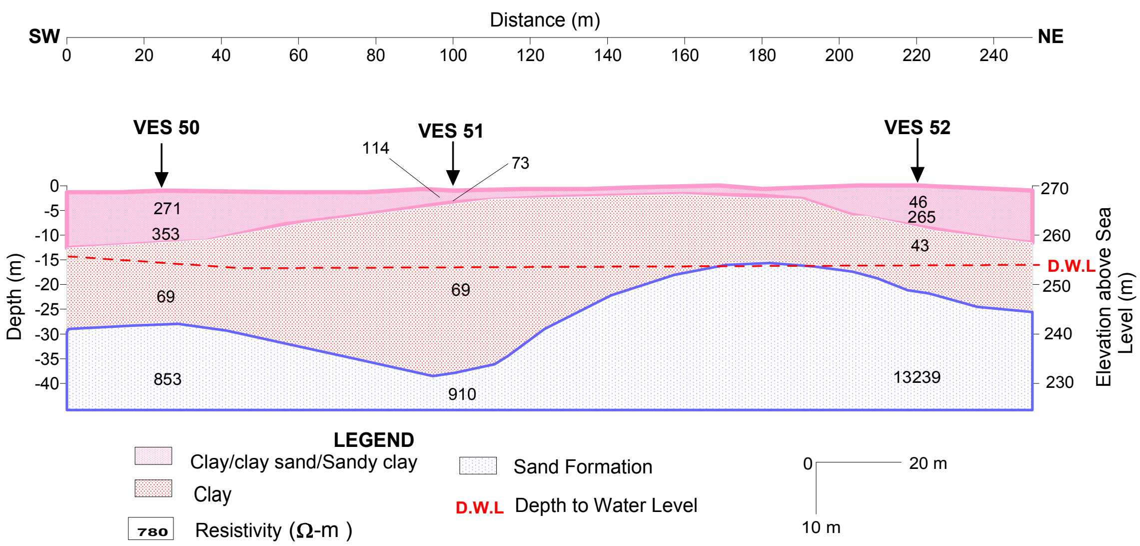


(a)

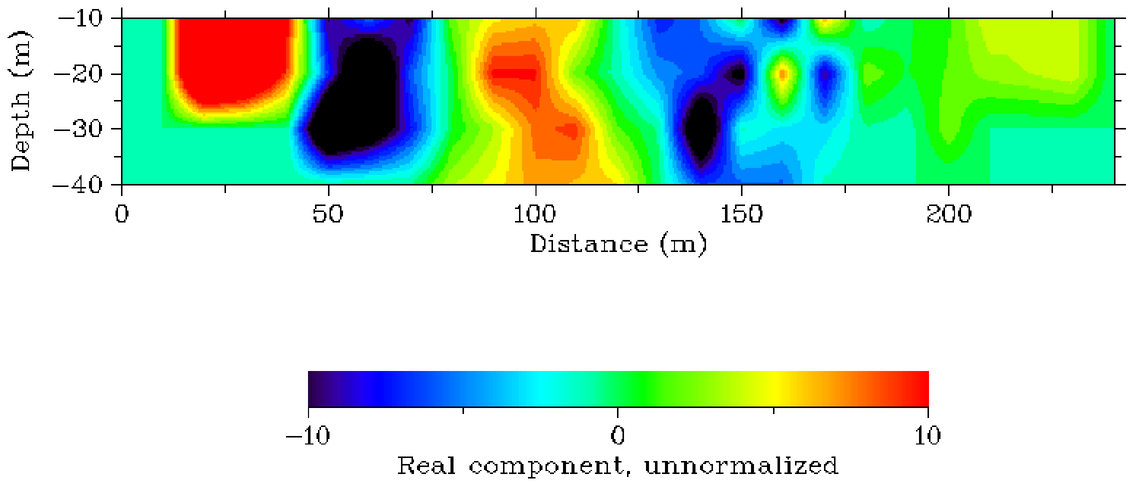


(b)

Figure 12. *Geoelectric section and VLF-EM along Traverse 2.*



(a)



(b)

Figure 13. *Geoelectric section and VLF-EM along Traverse 3.*

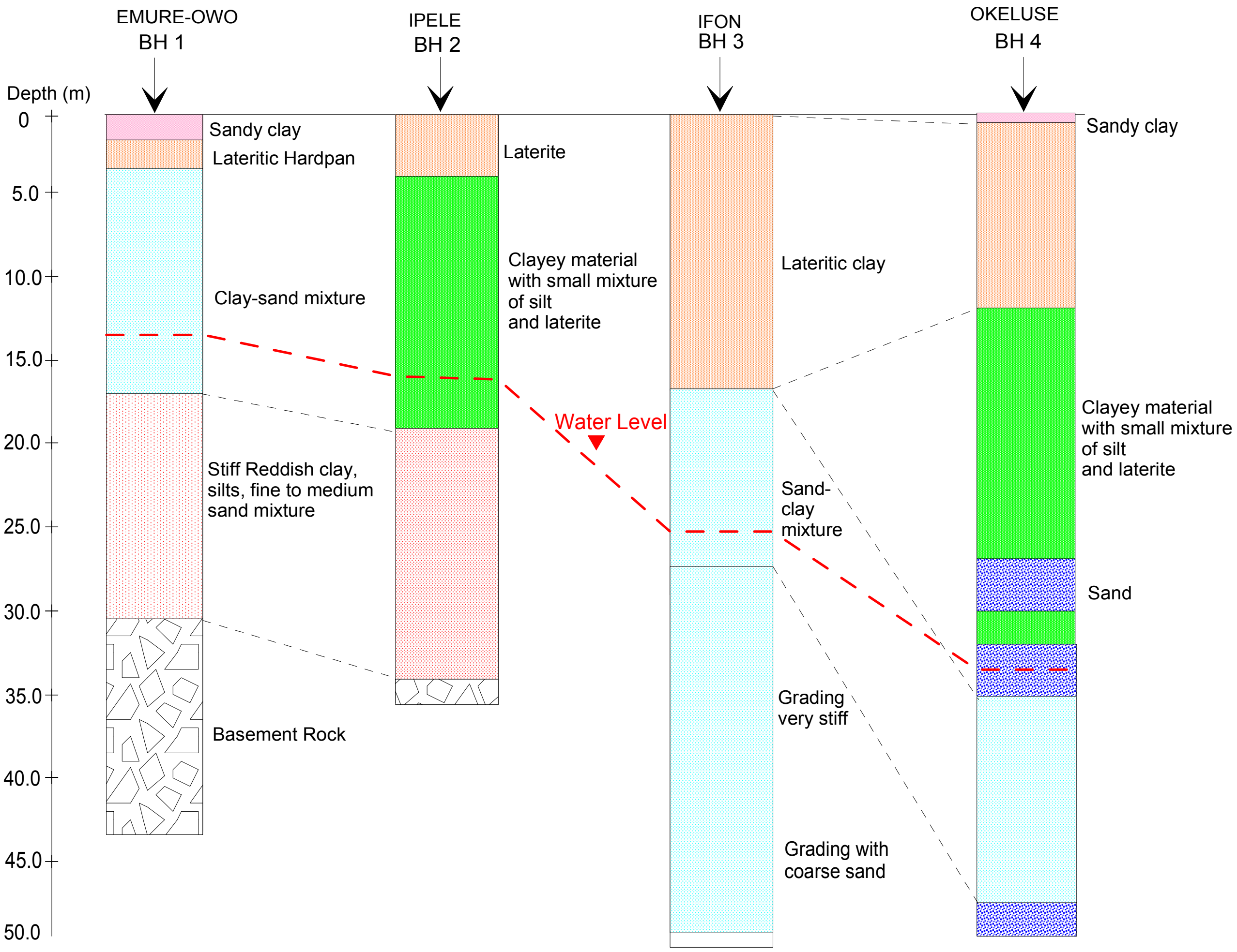


Figure 14. *Geologic sections of the drilled Borehole wells.*

Aquifer protection is essential for a sustainable use of the groundwater resources, protection of the dependent ecosystems, and a central part of spatial planning and action plans. The key expression for a quantification of aquifer protection is vulnerability. It is in view of this that this research was undertaken to effectively characterize the vulnerability of the underlying aquifers to near surface contaminants. "Figures 15 and 16" show the aquifer protective capacity or vulnerability maps using AVI and GOD respectively. The AVI characterized the study area into extremely low – High vulnerability, with predominant very high vulnerability values around the central parts, while small closures of low vulnerability values are observed around Owo and Ido Ani areas. However, the GOD classified the area into low – moderate – high vulnerability, with predominant high vulnerability. The GOD vulnerability model depicts that the study area is characterized by three vulnerability zones which are low, moderate and high vulnerable zones. According to the model, about 5% of the area is highly vulnerable while about 45% is of moderate rating, and 50% low vulnerable rating.

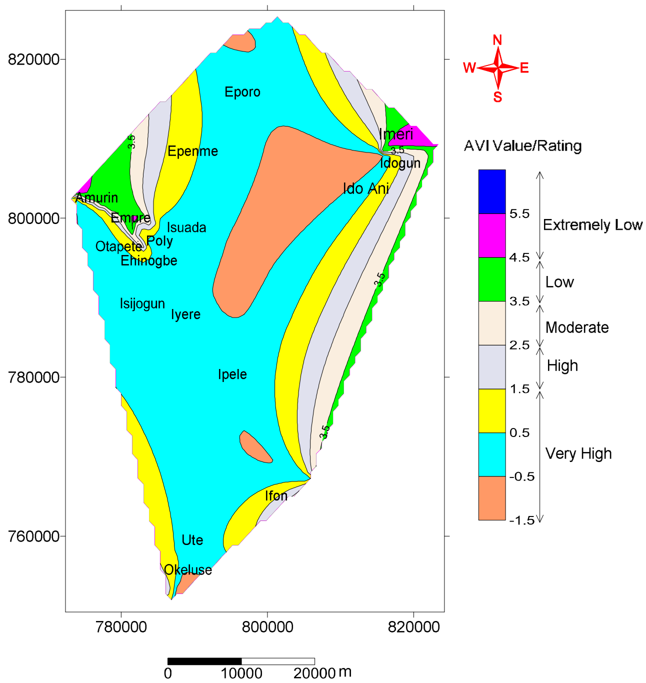


Figure 15. *Spatial Distribution of AVI in the study Area.*

It is observed that the GOD characterized the area better than AVI due to:

(i) Hydraulic conductivity (K) for various sediment types are approximations. In reality it may vary by several orders of magnitude;

(ii) It considers only near surface aquifers, and consider each aquifer to be of equal value.

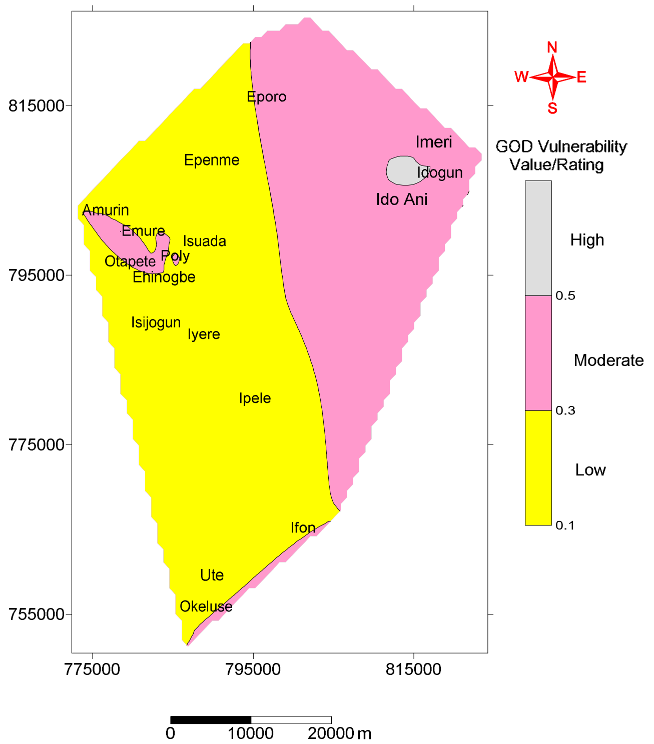


Figure 16. *Spatial Distribution of GOD Vulnerability values in the study Area.*

It is highly recommended that the least vulnerable zone should be the primary target for future groundwater development in the area in order to ensure continuous supply of safe and potable groundwater for human consumption in the area and more importantly, location of septic tanks, petroleum storage tanks, shallow subsurface piping utilities and other contaminant facilities should be confined to these low vulnerable zones.

4. Conclusion

The study showed that the major aquifer/water bearing units are weathered layer, and confined/unconfined fracture basement, with thickness that varies from 2.6 m to 64.6 m. The depth to these units is between 1.2 m and 15.9 m. The fracture basement is predominant in Owo area with thickness that could be up to 30 m in places. However density of the lineaments is very low/sparse. The lithology of water bearing formation is clay/sandy clay. The GOD vulnerability map/model clearly characterized the area into highly vulnerable (about 5%), moderate rating (45%), and low vulnerable rating (50%).

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