AQUIFER VULNERABILITY EVALUATION IN SOUTHWESTERN NIGERIA FROM AHP-GODT MODEL USING GEO-ELECTRICAL DERIVED PARAMETERS

Saminu Olatunji[1*], Ahmed Muyiwa Emiola[2] and Adewale Warith Adebisi[3]
[1&2]Department of Geophysics, University of Ilorin, Ilorin, (Applied Geophysicist), (Geophysicist)
[3]Department of Physics, University of Ilorin, Ilorin, Nigeria, (Geophysicist)
**E-mail*: Sam61ng@gmail.com, +2348032892742

Submitted: 10 June 2021 *Revised: 18 July 2021* *Accepted: 2 August 2021*

Abstract

The study aimed to determine the exposure levels of the subsurface aquiferous layers, owing to the alarming rate of contamination of the groundwater within 8.150 ^{0}N - 8.156 ^{0}N and 4.244 ^{0}E - 4.248 ^{0}E. Analytical Hierarchy Process - Groundwater Overlying strata Depth to aquifer and Topography (AHP-GODT) multi-criteria Modeling approach was used. *Thus, aquifers' overlying layers, resistivity, and thickness anomalies were determined to generate an aquifer vulnerability map. A multi-criteria decision method of estimated Groundwater confinement, Overlying strata, Depth to Aquifer, and Topography index approach was implemented. Schlumberger's Vertical Electrical Sounding technique was implemented to acquire 30 Vertical Electrical Sounding points under a maximum half-current electrode separation (AB/2) of 65 m. IP2Win geophysical software packages were used to analyze the varying layer resistivity, depth, thickness, and also the sounding curves of the study area. The geologic 2D models, derived from the equivalence electric layers, revealed a maximum of four geo-electric layers. The layers' resistivity and thickness ranges are clayey silt topsoil (52.5-1104 Ωm; 0.5-9.59 m), weathered layer (10.3-804 Ωm; 0.6-12.1 m), fractured basement (5.5-50832 Ωm; 6.7-18.1 m) and fresh basement (8.3-27348 Ωm; infinity m). On the Groundwater Overlying Strata Depth to Aquifer and Topography model scale, the area is generally characterized by the moderate vulnerability. Implying here is that aquifers have a moderate protective capacity in which the overlying strata above the aquifer are mostly impermeable layers (clay and silt) of high thickness and low porosity.*

Keywords: *Aquifer; Resistivity; Vulnerability; AHP-GODT model*

1. *Introduction*

Water finds its worth in area such as for domestic, agricultural, and industrial purposes. The search for a productive, clean and safe groundwater resources had been on an increase across the globe (earth) due to the fact that surface water is usually contaminated and limited. Also, groundwater is considered all over the world as the safest, most reliable and best source of water apart from the rainwater which is considered rare and seasonal [1].

However, groundwater resource which used to be in a very high state of purity and quality, is now been threatened by contamination from various agents and prolix sources in the area of study. The supply of water within the layers of the earth varies from one geographical location to another and depends on the season of the year. Knowledge of the hydrological functioning of aquifers and the geochemistry of groundwater is one of the crucial means for assessing the quality and natural tracing of water using the isotopic composition [2].

Contamination has come from different sources due to natural and human activities. In an agrarian community for instance, an excessive application of the NPK fertilizer has directly or indirectly affected the groundwater quality in areas of their use. Also nitrate compound is naturally generated from the natural nutrient cycle due to bacterial actions. However, pollution originating from human activity, anthropogenic sources, have mostly increased the nitrate concentration in groundwater resources [3].
Impurities in the groundwater resources in metropolitan areas is due to factors which include; uncontrolled location of accommodations and conveniences, spillage from petroleum products,

underground storage tanks for petroleum and gas products, domestic and industrial dumpsites and septic tanks of various households and hotels [4]. Also, day to day man's activities that also pose threats and dangers to groundwater resources include landfill solid wastes disposal, manufacturing and engineering activities, sewage disposal, septic waste infiltration systems, gasoline service stations and livestock feedlots etc. It is therefore an essential part of present day geophysical studies to look into the protection of environment as an essential part of development in recent time [5]. Thus, the need for evaluation of groundwater vulnerability is very imperative. The distribution of impurities also depend on several factors such as lithology, the hydrodynamic state of the aquifer and climatic conditions [6].

Groundwater reservoirs have been considered predisposed to pollutions and contamination directly or indirectly according to the aforementioned sources. The process of contamination may be slow but its significance is very nasty on both human and animal who may depend on such contaminated groundwater resources for consumption [7] [8]. Aquifer protection thus become an essential phase to which geoscientists are trying their best, notably, in the studying of the vulnerability of the groundwater reservoir for a sustainable use of the groundwater resources and its account for 97% of the world's available freshwater resources.

This research focuses on the use of groundwater hydrological modeling to assess groundwater vulnerability. The objective of this article is to understand the hydrodynamics of the groundwater in the area using an aquifer vulnerability assessment of Groundwater Overlying Strata Depth to Aquifer and Topography model from carefully collected Vertical Electrical Sounding data. Then, simulations from the vulnerability assessment will be used to identify areas that have potentially aquifer vulnerability and apparent exposure level.

For studies on a proficient means to protect groundwater resources from contamination, scientists developed aquifer vulnerability techniques for prediction of areas that are most vulnerable to contamination [9]. For the past years, researchers have assessed groundwater vulnerability to pollution using a variety of methods. Some of these techniques include the DRASTIC system by [10], GOD system by [11], AVI rating system by [12], SINTACS method by [13], German method, the EPIK and the Irish perspective [14] [15].

The GOD technique has been successfully used for aquifer vulnerability assessment in the researches by [11] and [16]. The modification to GOD technique by [17] culminated to the multi-criteria decision method termed 'Groundwater Overlying strata Depth to aquifer and Topography (GODT) Modeling. The fourth parameter topography (T) has been added and considered to improve the resulting vulnerability model since the topography of an area has a direct influence on the migration of contaminants. Thus, GODT approach, in conjunction with Analytical Hierarchy Process (AHP) was adopted to evaluate aquifer vulnerability.

The study was carried out during the onset of the raining season (April-May) within Ogbomoso town in southwest of Nigeria. It falls between longitude 4.240 ºE to 4.265 ºE and latitude 8.125 ºN to 8.165 ºN. Ogbomoso is linked to other communities by series of road networks such as Igbeti, Oyo, Osogbo and Ilorin townships. The Ogbomoso metropolitan has been experiencing population increase since the establishment of the Ladoke Akintola University of Technology (LAUTECH). The base map of the study area is presented as shown in Figure 1. Geologically, Ogbomoso Township lies on the Basement Complex region of southwestern Nigeria (Figure 2). The geological substratum of the area consists of rocks of migmatite-gneiss-quartz complex [18].

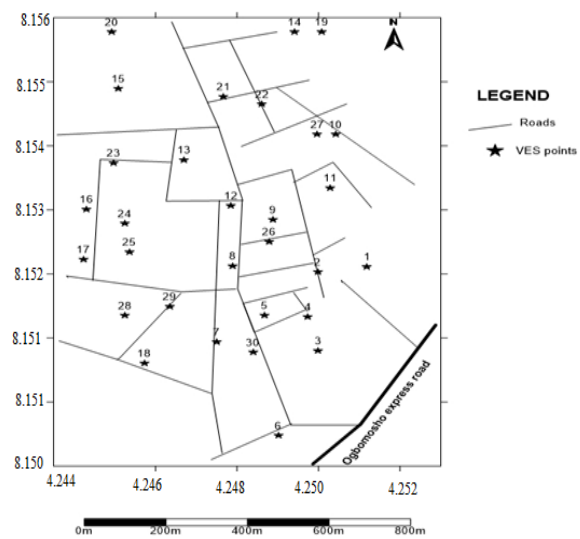

Figure 1. Base map for data collection in the study area

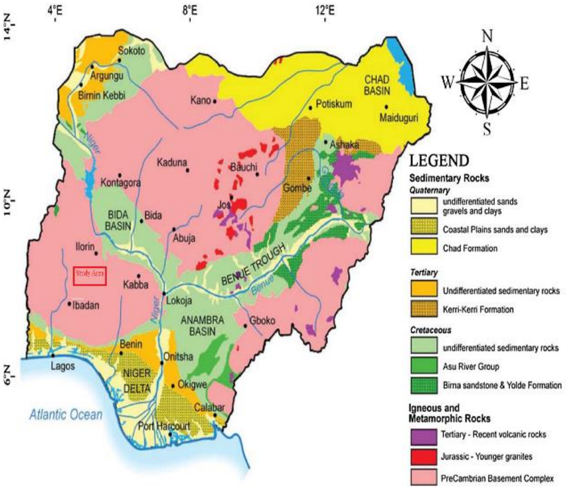

Figure 2. Geological map of Nigeria showing the study area After: [19; modified by [20]

2. *Methods*

Geophysical investigation involving Vertical Electrical Sounding (VES) was carried out using Schlumberger array with maximum current separation (AB) of 200 m. Omega Earth Resistivity Meter was used to occupy a total of thirty (30) VES points. A maximum half current electrode spacing of 130 m for Schlumberger array was used. The VES technique was implemented because of its efficiency in delineating vertical sections of the subsurface geology [21], [22], [23]. The global coordinate of each VES point was recorded from Garmin GPS G-12.

The field process passed current through a twosome of current electrode into the subsurface and measuring the potential difference developed within, through the potential electrodes (Figure 3). The precautions to ensure acquisition of accurate data in geophysical surveys were followed as laid down by [24]. The apparent resistivity of each sounding point was obtained using equation 1.

Where 'K' is the geometric factor obtainable from the sequential electrode spacing used at each VES point and 'R' is the earth's resistance obtained from the resistivity meter used. The sounding data were processed using the *IP2Win* computer software. The geo-electric results were presented as curve types and maps.

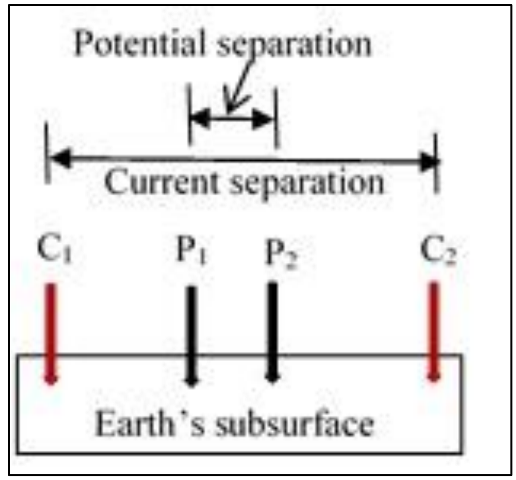

Figure 3. Sketch of the Schlumberger configuration used

$$\rho_a = KR \qquad (1)$$

In the vulnerability assessment, Analytical Hierarchy Process - Groundwater Overlying strata Depth to aquifer and Topography (AHP-GODT) Modeling approach was used. Following the AHP standard technique model of [16] the assigned weight to the GODT parameters are 0.51, 0.15, 0.08 and 0.27 respectively. Hence, AHP multi-criteria decision method yielded vulnerability conditioning parameters as inputs for the GODT model algorithm; as these parameters have individual effect on the vulnerability of an aquifer. So, the geo-electrical layer parameters (i.e. layer resistivity and thickness) were used to define groundwater confinement (G), overlying strata resistivity (O) and depth to aquifer (D). The D parameter is derived from interpreted VES curves using

$$\frac{\sum_1^n \rho_i}{n} \qquad (2)$$

Where ρ_i = layer density, n = number of layers. Topography (T) was the elevation, given by the GPS. Thus, the parameters considered sufficient in enumerating the extent of vulnerability in the area was inferred from geo-electric parameter of GODT, where the lowest level of vulnerability is attributed to values of ≤ 0.1 (negligible) while the highest level is ascribed to ≥ 0.7 (extreme). Rating values from 0 to 1 were assigned to GODT parameters following the priority vector modified by [16] (Table 1).

Table 1. Attribution of Inferences for GODT model parameters (Modified by [16])

Aquifer Type	Inference	Depth to Aquifer (m)	Inferenc e	Lithology/Resistivity (Ωm)	Inference	Topography	Inference
None aquifer	0	< 2	1	< 60	0.4	Ridge	0.7 – 0.8
Artesian	0.1	2 – 5	0.9	60 -100	0.5	Depression	0.9 – 1
Confined	0.2	5 – 10	0.8	100 -300	0.6		
Semi-confined	0.3	10 -20	0.7	300 – 500	0.7		
Free with cover	0.4 – 0.6	20 – 50	0.6	500 – 600	0.8		
Free with cover	0.7 – 1	50 -100	0.5	600 – 2000	0.9		
		>100	0.4	> 2000			

For vulnerability prediction the GODT index estimation is needed. The GODT index was estimated by multiplying the stimuli of the four parameters which include Groundwater occurrence (confinement of the aquifer), Overall lithology overlying the aquifer, Depth to the aquifer and Topography of the area (Equation 3).

$$(\mathrm{AHP-GODT})_I = \mathrm{G}_I \text{ x } \mathrm{O}_I \text{ x } \mathrm{D}_I \text{ x } \mathrm{T}_I \quad (3)$$

$$\text{where } \mathrm{G}_I = \mathrm{G}_R \text{ x } \mathrm{G}_w ,\ \mathrm{O}_I = \mathrm{O}_R \text{ x } \mathrm{O}_w ,\ \mathrm{D}_I = \mathrm{D}_R \text{ x } \mathrm{D}_w, \mathrm{T}_I = \mathrm{T}_R\ x\ \mathrm{T}_w \quad (4)$$

where $_I$ = index, $_R$ and $_w$ are the rating and weight for each parameter. The geospatial data were then synthesized to produce the aquifer vulnerability map using the estimated AHP-GODT index. The vulnerability classification was finally made following the five-class vulnerability rating of [11].

3. *Result and Discussion*

The results of the geo-electric soundings applied in the vulnerability evaluations (GODT modeling) were derived from sounding curves, presented as chart, tables and maps. Typical Schlumberger sounding array curves obtained for 30 VES points, for a 3 and 4 layer case is shown in Figure 4. Thus, the summary of the typical geo-electric parameters obtained for all the 30 VES points are shown in Table 2. The geologic equivalent of the geo-electric sections delineated a range of three to four layers. Geo-electric section revealed that the first layer has resistivity value ranging from 52.5 to 1104 Ωm and thickness ranges from 0.5 to 9.59 m. The second layer has a resistivity value varying from 10.3 to 804 Ωm and thickness ranges 0.586 to 12.1 m. The third layer resistivity value ranges from 5.54 to 50832 Ωm and thickness ranges from 6.67 to 18.1m and the fourth layer has a resistivity value ranging from 8.32 to 27,348 Ωm whose depth extends to infinity. The characteristic curve types obtained in the area are QH, H, AH, HA, KH and A. Figure 5 shows the order of the predominance of the curve types obtained in the area. The QH curve type occurs 9 times representing a 30% of the total, the H type occurs 10 times representing a total of 33.33%, the AH and KH type occurs once signifying 3.33% each. The HA type occurs 5 times which also represents 16.67% and the A curve type occurs 2 times which signifies a 6.67% on a percentage level. The wide range and fluctuating resistivity variations characteristics observed could be associated to occurrence of series of past geological events over geologic age which could have vitiated the electrical faces in the rock component of the area studied.

Table 3 shows the typical summary of the GODT model parameters, derived from geo-electric data sets, namely: the groundwater hydraulic confinement, aquifer overlying strata, depth to aquifer and aquifer thickness, which were used as input parameters for establishing the aptness of the GODT in groundwater vulnerability assessment.

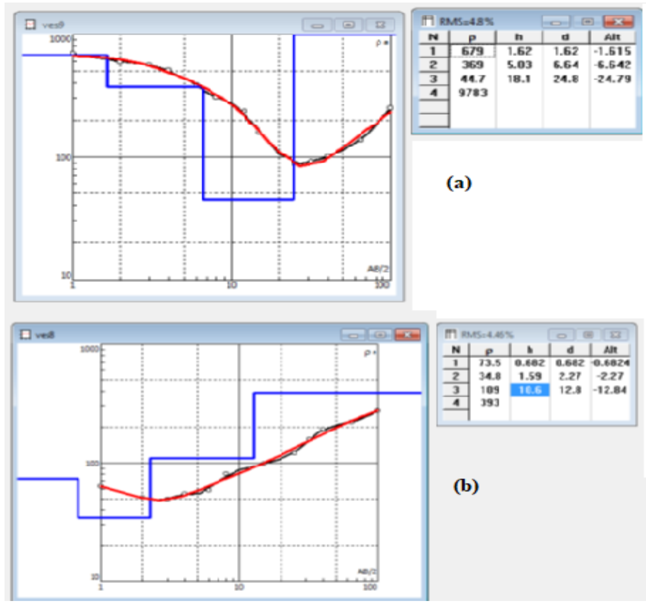

Figure 4. Typical VES field curves (a). 4-layer (b). 3-layer

Table 2. Typical VES interpreted results

VES NO.	Layer resistivity (Ωm)		Thickness (m)		Curve type
1	ρ_1	271	h_1	0.5	QH
	ρ_2	140	h_2	2.76	
	ρ_3	34.6	h_3	10.7	
	ρ_4	1585			
2	ρ_1	268	h_1	0.5	H
	ρ_2	141	h_2	2.59	
	ρ_3	39	h_3	13.6	
	ρ_4	7991			
3	ρ_1	1010	h_1	4.4,	QH
	ρ_2	76.8	h_2	8.06	
	ρ_3	896			
4	ρ_1	1104	h_1	1.27	HA
	ρ_2	804	h_2	3,93	
	ρ_3	67.5	h_3	6.67	
	ρ_4	655			
5	ρ_1	73.4	h_1	0.72	AH
	ρ_2	31.1	h_2	1.22	
	ρ_3	101	h_3	13.4	
	ρ_4	704			

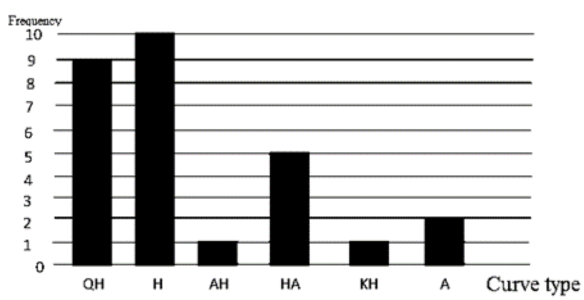

Figure 5. Distribution of VES curve types

Table 3. Typical interpreted geo-electrical Parameters used for AHP-GODT models

Easting	Northing	Elevation (m)	VES NO	G	O	D	T
637719.398	901204.236	355	1	140	34.6	14	355
637597.902	901298.958	350	2	141	39.0	16.7	350
637599.563	900761.55	348	3	1010	76.8	12.5	348
637574.108	901867.26	355	4	804	87.5	11.9	355
637467.000	900871.72	356	5	31.1	101	15.3	356
637501.216	900495.858	354	6	348	45.2	37.6	354
637350.071	900788.447	353	7	397	77.3	17.6	353
637389.393	901026.29	353	8	34.8	109	12.8	353
637488.115	901170.348	353	9	369	44.7	24.8	353
637641.551	901436.211	350	10	242	64.6	13.7	350

Based on the numerical variation of the groundwater confinement G obtained in Table 3, the study area is categorised into five zones (Table 4); each class interval is rated appropriately based on previous works done in the area [25]. The impermeable layer, that are good aquifer confinement, have aquifer resistivity around 100 Ωm and confined in layers whose resistivity is above 1000 Ωm [25]; [26]. The area is characterized with very low (red colour) to moderate (blue colour) vulnerability to contaminants. This confinement cover to contaminant appears in the N, NE, central and SE parts of the area (Figure 6). This confinement cover is less than 40% of the area studied. This shows that it does not provide appreciable protection to the aquifer there.

The overlying strata was generated from the interpreted VES curves obtained using equation 2. The estimated value of O parameter, shown in Table 3, for all the VES points were used to categorise the area into 5 (Table 5). Figure 7 shows it's the spatial variation of the overlying strata resistivity map, dividing the area into five zones based on manual class interval, derived from the table. Figure 7 therefore shows that aquifers in the central part, towards the southern flank in the area are less vulnerable to surface contaminations.

Table 4. Rating Analysis of Overlying Strata values study area modeled [16] Table 4. Rating Analysis of groundwater confinement of the study area modeled [16]

Vulnerability Parameters	Classes (? m)	Rating	Vulnerability Implication
Groundwater hydraulic confinement	0 –100	0.2	Very low
	100 – 300	0.8	High
	300 – 600	1	Very high
	600 – 1000	0.6	Moderate
	> 1000	0.4	Low

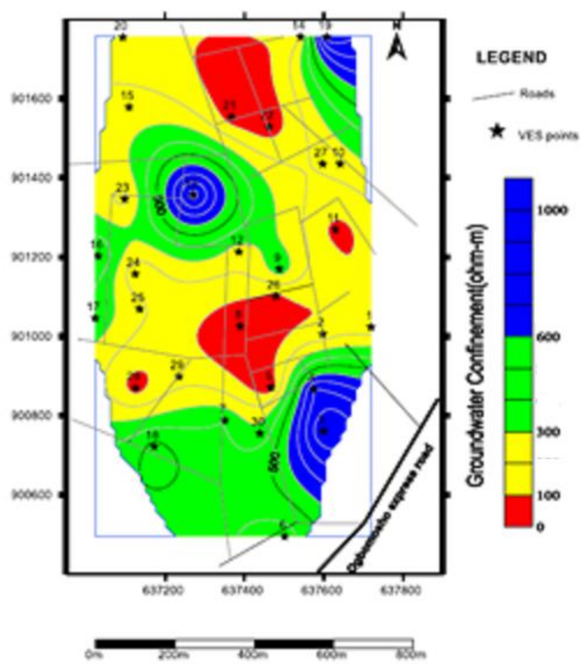

Figure 6. Groundwater confinement map of the area

Table 5. Rating Analysis of Overlying Strata values study area modeled [16]

Vulnerability Parameters	Classes (? m)	Rating	Vulnerability Implication
Overlying strata formation	0 – 60	0.2	Very low
	60 –100	0.4	Low
	100 – 300	0.8	High
	300 – 600	1	Very high
	> 600	0.6	Moderate

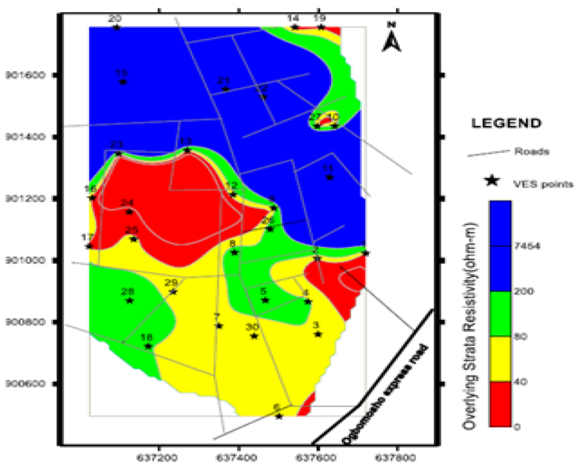

Figure 7. Overlying strata map of the study area

The depth to aquifer obtained quantitatively from the interpreted VES curves was used to categorise and rate the area as shown in Table 6 and used for the generation of map as shown in Figure 8. With the assumption that the deeper the depth the lesser the rate of contamination, a larger part of southwestern region which is indicated with red colour show dip steeping slope. This indicate high risk of contamination i.e. high vulnerability.

Table 6: Rating Analysis of Depth to watertable of the study area modeled [16]

Vulnerability Parameters	Classes (? m)	Rating	Vulnerability Implication
Depth to watertable	0 –2	1	Very high
	2 –5	0.8	High
	5 –10	0.6	Moderate
	10 –20	0.4	Low
	> 20	0.2	Very low

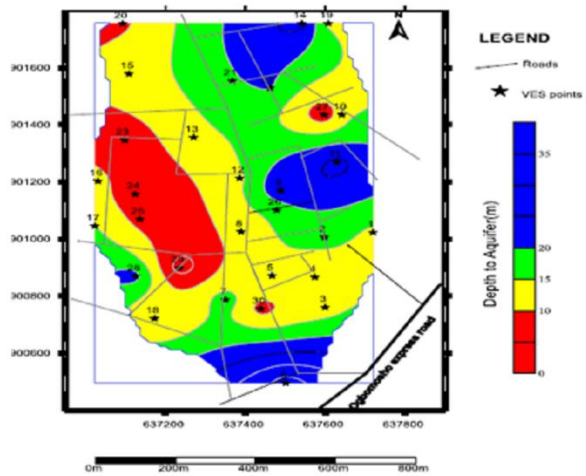

Figure 8. Depth to watertable map of the study area

The elevation distribution for all the VES points rated as shown in Table 7 and the result was applied for the generation of topography map (Figure 9). The study area is divided into five zones based on equal class interval. Based on the surface topography assessment the NE part are region of prominent low elevation where infiltration is expected to be high and the region is more vulnerable to liquid contaminant as a result of high infiltration. Larger part of the NW, trending the western part to the SW corner is region of high to moderate elevation where run-off is expected to be high. Liquid contaminant has little or no chance of percolating into the subsurface. Thus, based on the topographic assessment this region is less vulnerable to liquid contaminant from the earth's surface.

Table 7. Rating Analysis of elevation values of the study area modeled [16]

Vulnerability Parameters	Classes (? m)	Rating	Vulnerability Implication
Topography	350 –338	0.2	Very low
	338 –326	0.4	Low
	326 –314	0.6	Moderate
	314 –302	0.8	High
	302 –290	1.0	Very high

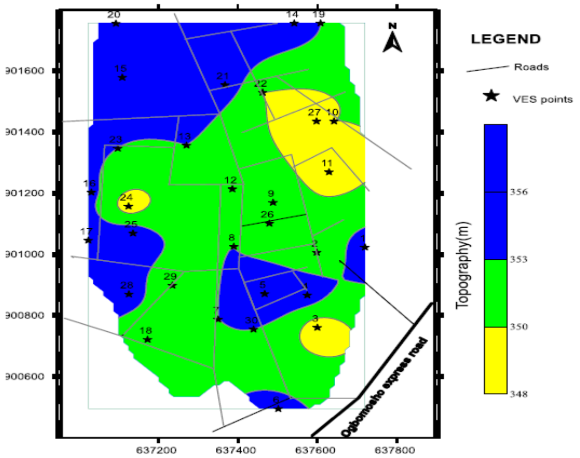

Figure 9. Topography map of the study area

Computed results of AHP-GODT model using equations 3 and 4, needed for vulnerability prediction map, are shown in Table 8. The area is characterized with AHP-GODT index range of 0.314 to 0.842. So, vulnerability in the area is therefore classified based on classes shown in Table 9. The prominent vulnerability integrity, that determines the aquifer protective cover, varies from moderate (yellow colour), low (green colour) to negligible (blue colour) in some areas (Figure 10). The low and negligible vulnerability potentials trend the northwest, en route the west, southwest to the southern flank. The moderate protection trends the northeast, covering the central part and the southeast in the area. Thus, based on the AHP-GODT index approach, over 50% of the water bearing zones in the area is protected from contamination while the remaining portion is relatively moderately protected.

The aquifers in these areas therefore are moderately declared vulnerable to contamination possibly from near-surface pollutants. However, there are pockets of highly vulnerable portions (red colour) posing danger of contamination to the underlying aquifer and the areas are declared very vulnerable and unsafe from contamination in the area.

Table 8. Computed result of AHP-GODT modeling

VES NO	G_R	O_R	D_R	T_R	G_I	O_I	D_I	T_I	$(AHP\text{-}GODT)_I$
1	0.8	0.2	0.4	1	0.408	0.03	0.032	0.27	0.74
2	0.8	0.2	0.4	0.6	0.408	0.03	0.032	0.162	0.632
3	0.4	0.4	0.4	0.4	0.2	0.06	0.032	0.108	0.4
4	0.6	0.4	0.4	1	0.3	0.06	0.032	0.27	0.662
5	0.2	0.8	0.4	1	0.1	0.12	0.032	0.27	0.522
6	1	0.2	0.2	1	0.51	0.03	0.016	0.27	0.826
7	1	0.4	0.4	0.6	0.51	0.06	0.032	0.162	0.764
8	0.2	0.8	0.4	0.6	0.1	0.12	0.032	0.162	0.414
9	1	0.2	0.2	0.6	0.51	0.03	0.016	0.162	0.718
10	0.8	0.4	0.4	0.6	0.4	0.06	0.032	0.162	0.654
11	0.2	0.6	0.2	0.4	0.1	0.09	0.016	0.108	0.314
12	0.8	0.4	0.4	0.6	0.4	0.06	0.032	0.108	0.6
13	0.6	0.2	0.4	0.6	0.3	0.03	0.032	0.108	0.47
14	0.8	0.2	0.2	1	0.4	0.03	0.032	0.27	0.732
15	0.8	0.6	0.4	1	0.4	0.09	0.032	0.27	0.792
16	1	0.2	0.4	1	0.51	0.03	0.032	0.27	0.842
17	1	0.2	0.4	1	0.51	0.03	0.032	0.27	0.842
18	1	0.4	0.6	0.6	0.51	0.06	0.048	0.162	0.78
19	0.6	0.2	0.4	0.6	0.3	0.03	0.032	0.162	0.524
20	0.8	0.2	0.6	1	0.4	0.03	0.048	0.27	0.748
21	0.2	0.8	0.4	1	0.1	0.12	0.032	0.27	0.522
22	0.2	0.6	0.2	0.6	0.1	0.09	0.016	0.162	0.368
23	0.8	0.2	0.6	0.6	0.4	0.03	0.048	0.162	0.64
24	0.2	0.2	0.6	0.4	0.1	0.03	0.048	0.108	0.286
25	0.8	0.2	0.6	1	0.4	0.03	0.048	0.27	0.748
26	0.2	0.8	0.4	0.6	0.1	0.12	0.032	0.162	0.414
27	0.8	0.2	0.6	0.4	0.4	0.03	0.048	0.108	0.586
28	0.2	0.8	0.2	1	0.1	0.12	0.016	0.27	0.506
29	0.8	0.2	0.8	0.6	0.4	0.03	0.064	0.162	0.656
30	1	0.2	0.6	0.6	0.51	0.03	0.048	0.162	0.75

Table 9. Aquifer Vulnerability Classification [12]

AHP-GODT Index	Vulnerability class
0 – 0.4	Negligible
0.4 – 0.6	Low
0.6 – 0.8	Moderate
0.8 – 1.0	High
1.0 – 2.0	Very high

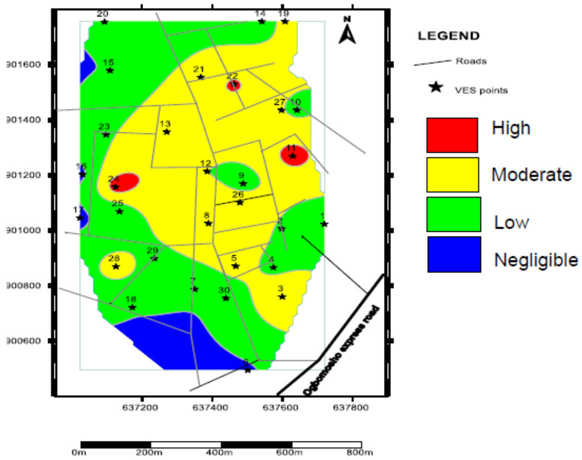

Figure 10. Vulnerability prediction map based on AHP-GODT Model Approach

4. *Conclusion*

Results of the assessment of aquifer vulnerability indicate that the aquifers in this area have an average protective capacities which are not thick enough to give adequate protection. This is because the overburden above the aquifer are mostly impermeable layer (clayey and silt) except for some VES points like 5, 8, 17, 26 etc. where there are lenses of sand. At VES's 6, 11, 14, 15 and 21 the aquifer is protected by silts and clays with thickness ranging from 6.42 to 12.1 m. The overburden at VES 5, 21and 28 on the aquifer is categorized as a moderate protection and this is probably due to the sandy component of the overburden. The poor and weak protective zones are prone to surface and near-surface contamination, while in the moderately protected zones, the aquifer is protected from contaminated percolating fluids. The moderate protective capacity tallies with the thick silt and clay overburden. The topmost layers are mostly clayey silt which protect the aquifer and provide protection for the aquifer underneath. This indicates that the overburden above the aquifer in Ogbomoso Northern area, generally have moderate protective capacity.

Suggestion. The protective covers are moderately vulnerable in some areas and some parts a highly vulnerable. This calls for a caution in the usage of probable exploited underground water in this area. It may be imperative to carry out chemical analysis to ascertain the suitability of exploited underground water from the area of study.

Acknowledgement. The authors appreciate the assistance rendered by the concerned members of staff of the Department of Geophysics, University of Ilorin during the field processes of this work.

References

[1] M. A. Hoque, A. A. Khan, M. Shamsudduha, M. S. Hossain, T. Islam, and S. H. Chowdhury, “Near Surface Lithology and Spatial Variation of Arsenic in the Shallow Groundwater, Southeastern Banglandesh,” In *Environmental Geology*. 56: 1687-1695, 2009.

[2] E. Madene, H. Meddi, A. Boufekane and M. Meddi, “Contribution of Hydrogeochemical and Isotopic Tools to the Management of Upper and Middle Cheliff Aquifers”, In *Journal of Earth Science, Vol. 31, No. 5, p. 993–1006.* https://doi.org/10.1007/s12583-020-1293-y, 2020.

[3] S. Chand, M. Ashif, M. Y. Zargar, and B. M. Ayub, “Nitrate Pollution: A menace to Human, Soil, Water and Plant” Universal Journal of Environmental Research and Technology. 1(1): 22-32, 2011.

[4] M. J. Afonso, A. Pires, H. I. Chamine, J. M. Marques, L. Guimares, L. Guilhermino, and F. T. Rocha, “Aquifer Vulnerability Assessment of Urban Areas Using A GIS-Based Cartography: Paranhos Groundwater Pilot Site, Porto, NW, Portugal,” 33rd Int. Geological Symposium: Hydrogeology, Oslo (Norway), 2008

[5] T. A. Adagunodo, and L. A. Sunmonu, “Geoelectric Assessment of Groundwater Prospect and Vulnerability of Overburden Aquifers at Adumasun Area, Oniye, Southwestern Nigeria,” In Arch. Appl. Sci. Res. 4(5):2077-209, 2012.

[6] M. S. Ghebouli, M. Bencheikh Elhocine, “Origine de la Salinité des Eaux Souterraines cas de Hautes Plaines Setifiennes (Nord-Est Algérien),” In Sciences & Technologie, 28: 37–46, 2008.

[7] A. Baghvand, T. Nasrabadi, G. Nabibidhendi, A. Vosoogh, A. Karbassi, and N. Mehradadi “Groundwater Quality Degradation of an Aquifer

in Iran central desert," Desalination 260(3):264-275, 2010.

[8] L. A. Sunmonu, T. A. Adagunodo, E. R. Olafisoye, and O. P. Oladejo, "The Groundwater Potential Evaluation at Industrial Estate Ogbomoso, Southwestern Nigeria," RMZ Mater. Geoenviron. 59:363–390. 2012.

[9] B. Oroji, "Groundwater vulnerability assessment using GIS-based DRASTIC and GOD in the Asadabad Plain," In J. Mater. Environ. Sci. 9(6): 1809-1816 doi.org/10.26872/jmes.2018.9.6.201, 2018.

[10] L. Aller, T. Bennet, J. H. Lehr, R. J. Petty, and G. Hackhett, "DRASTIC: A Standard System for Evaluating Groundwater Potential Using Hydrogeologic Settings," EPA/600/2-85/018US Environ. Protec. Agency, Ada Oklahoma Report 622 p455. 1987.

[11] S. S. D. Foster, "Fundamental Concepts in Aquifer Vulnerability Pollution Risk and Protection Strategy," In Vulnerability of Soil and Groundwater to Pollution: Proceedings and Information. TNO Committee on Hydrological Research. 38: 69-86. 1987.

[12] D. Van Stempvoort, L. Ewert, and L. Wassenaar, "Aquifer Vulnerability Index (AVI): A GIS Compatible Methodfor Groundwater Vulnerability Mapping," In Can Water Res J 18:25–37. 1993. 1993.

[13] M. Civita, "Le Carte della Vulnerabilita degli acquiferi all inquinamento: Teoria and pratica," PitagoraEditrice, Bologna. 1994.

[14] N. Doerfliger, P. Y. Jeannin , and F. Zwahlen, "Water Vulnerability assessment in Karst Environments: A New Method of Defining Protection Areas Using a Multi-Attribute Approach and GIS tools (EPIK Method)," In Environment Geology 39: 165-175, 1999.

[15] D. Daly, A. Dassargues, D. Drew, S. Dunne, N. Goldscheider, S. Neales, C. H. Popescu, and F. Zwahlen, "Main Concepts of the European Approach for Karst Groundwater Vulnerability and Assessment and Mapping," In Hydrogeol Journal.10:340 – 345, 2002.

[16] S. Khemiri, A. Khnissi, B. A. Alaya, S. Saidi, and F. Zargrouni, "Using GIS for theComparison of Intrinsic Parameter Methods Assessment of Groundwater Vulnerability to Pollution in Scenarios of Semi-Arid Climate. The case of Foussana Groundwater in the Central of Tunisia," In J. Water Resource Prot., 835–845, 2013.

[17] I. A. Adeyemo, T. S. Olowolafe, and A. O. Fola-Abe, "Aquifer Vulnerability Assessment at Ipinsa-Okeodu Area, Near Akure, Southwestern Nigeria, Using GODT," In Journal of Environmental and Earth Science 6(6): 9-18, 2016.

[18] N. G. Obaje, "Geology and Mineral Resources of Nigeria," Published by Springer London 14-60. 2009.

[19] N. B. Salawu, S. Olatunji, M. M. Orosun, and T. Y. Abdulraheem, "Geophysical Inversion of Geologic Structures of Oyo Metropolis, Southwestern Nigeria from Airborne Magnetic Data. Geomechanics and Geophysics for Geo-Energy and Geo-Resources 5(2): 143-157, 2018.

[20] B. R. Onawola, S. Olatunji, O. Ologe, and R. O. Jimoh, "Determination of Aquifer Parameters from Resistivity Data: A Case of University of Ilorin Campus, Northcentral Nigeria," In Tanzania Journal of Science 47(1) https://www.ajol.info/index.php/tjs/article/view/203428, 2021.

[21] A. T. Tizro, K. Voudouris, and Y. Basami, "Estimation of Porosity and Specific Yield by Application of Geoelectrical Method – A Case Study in Western Iran," In J. Hydrol. 454–455:160–172. doi: 10.1016/j.jhydrol.2012.06.009, 2012.

[22] O. Anomohanran, M. O. Ofomola, and F. O. Okocha, "Investigation of Groundwater in Parts of Ndokwa District in Nigeria Using Geophysical Logging and Electrical Resistivity Methods: Implications for Groundwater Exploration," In m. J. Afr. Earth Sc. 129:108–116, 2017.

[23] T. A. Adagunodo, M. K. Akinloye, L. A. Sunmonu, A. P. Aizebeokhai, K. D. Oyeyemi, and F. O. Abodunrin, "Groundwater Exploration in Aaba Residential Area of Akure, Nigeria," In Front Earth Sci. 6:66, 2018.

[24] A. A. Adeniji, "Integrated Geophysical Techniques for Investigating Subsurface Structural Analysis Around Ogbagba, Southwestern Nigeria," M. Tech. Thesis, Ladoke Akintola University of Technology, Ogbomoso," 2014.

[25] K. A. Mogaji, and O. B. Omobude Modeling ofgeoelectric parameters for assessing groundwater potentiality in a multifaceted geologic terrain,Ipinsa Southwest, Nigeria – A GIS-based GODT approach," In NRIAG Journal of Astronomy and Geophysics, 6:2, 434-451, DOI: 10.1016/j.nrjag.2017.07.001, 2017.

[26] G. O. Omosuyi, and A. Oseghale, "Groundwater Vulnerability Assessment in Shallow Aquifers using Geoelectric and Hydrogeologic Parameters at Odigbo, Southwestern Nigeria," In Am. J. Sci. Ind. Res., 3(6):501-512, 2012.