Australian Journal of Science and Technology

ISSN Number (2208-6404)
Volume 5; Issue 1; March 2021

Original Article

Aquifer vulnerability assessment using Dar-Zarrouk parameter: A case study of Otofure and Ikhueniro dumpsites, Benin-city, South-South Nigeria

K. K. Oboshenure[1]*, O. J. Airen[2]

[1]Department of Physics, Faculty of Science, Niger Delta University, Wilberforce Island, Nigeria, [2]Department of Physics, Faculty of Physical Sciences, University of Benin, Benin, Nigeria

ABSTRACT

Assessment of the aquifer vulnerability using Longitudinal Unit Conductance, S (Dar-Zarrouk parameter) was carried out in Otofure and Ikhueniro with a view to preventing the exploitation and consumption of contaminated groundwater due to the presence of an old and active dumpsite in each location. Ten Vertical Electrical Sounding (VES) data were acquired from each of Otofure and Ikhueniro. Seven VES data around each dumpsite and three VES data acquired 100 m away from each dumpsite as control data points. The VES results in Otofure and Ikhueniro delineate five geoelectric layers which are indicative of the topsoil, clay/sandy clay, clayey sand, leachate, and sand. The control VES delineate 4–6 geoelectric layers which are only topsoil and sand units (with varying degree of moisture content). The leachate occurs at a depth of from 2.9 to 4 m and 0.6–13.6 m in Otofure and Ikhueniro, respectively. In Otofure, the Total Longitudinal Unit Conductance, S varies from 0.0258 to 0.0915 mhos away from the dumpsite, while S varies from 0.6438 to 1.1562 mhos around Otofure dumpsite. In Ikhueniro, the Total Longitudinal Unit Conductance, S varies from 0.0237 to 0.0273 mhos away from the dumpsite, while S varies from 0.4119 to 4.4206 mhos around the dumpsite. These values indicate that away from the two dumpsites areas, the aquifer protective capacity is poor while in the immediate vicinity of the dumpsites, the protective capacity varies from moderate to good, revealing that aquifers that are away from the dumpsites in both locations are vulnerable to contamination while aquifers in the immediate vicinity of the dumpsites are well protected from contamination. The study has shown that aquifers in the vicinity of both Otofure and Ikhueniro dumpsites have good protective capacity against migrating sources of contamination while the aquifers that are away have very poor protective capacity against migrating sources of contamination. The study has further revealed the importance of deliberate selection of suitable locations for sitting dumpsites and landfills as revealed from the results.

Keywords: Vertical electrical sounding, contamination, Dar-Zarrouk, leachate, conductance

Submitted: 09-02-2021, **Accepted:** 12-02-2021, **Published:** 30-03-2021

INTRODUCTION

The geoelectrical resistivity method has been successfully employed in the delineation of subsurface geological sequence, geological structures/features of interest, aquifer units, types, and depth extent in almost all geological terrains.[1-4] This is because of the significant resistivity contrasts that exist between different earth materials.[5] The resistivity method can therefore map interface along which a resistivity contrast exists. This interface may or may not coincide with geological boundary.[6] In addition, vertical electrical sounding (VES) has been widely used to evaluate groundwater potentials and area of high groundwater yield.[7-9] Geoelectrical methods are also used extensively in groundwater mapping for investigation of the vulnerability of shallow aquifers.[9]

The vulnerability of aquifers is largely dependent on the presence or absence of protective impermeable layer, usually clay. The earth medium acts as a natural filter to percolating fluid; its ability to retard and filter percolating fluid is a measure of its protective capacity.[10] Studies have shown that geoelectrical method is an invaluable tool in mapping aquifer

Address for correspondence: K. K. Oboshenure, Department of Physics, Faculty of Science, Niger Delta University, Wilberforce Island, Nigeria. E-mail: koboshenure@gmail.com

vulnerability because of its capability to distinguish low- and high-resistive formations.[11] The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against natural impacts, especially with regard to contaminants entering the subsurface zone. Consequently, some land areas are more vulnerable to groundwater contamination than others. Henriet[12] showed that the combination of layer resistivity and thickness in the Dar Zarrouk parameters S (longitudinal conductance) and T (transverse resistance) may be of direct use in aquifer protection studies and for the evaluation of hydrologic properties of aquifer. The protective capacity is considered to be proportional to the longitudinal unit conductance in mhos.[1,10,13,14]

Atofure and Ikhueniro dumpsites are active old dumpsites located in Ovia North East and Ikpoba-Okha Local Government Areas (LGA), respectively, in Edo State, South-South, Nigeria. All classes of wastes are deposited on the dumpsites. Over the years, the wastes have gone through episodic decays that had generated leachates and definitely transported deep into the subsurface. It is, therefore, important to assess the vulnerability of the aquifers in these localities to leachate infiltration into the aquifer with a view to alerting the government and cautioning the residents of the areas from consuming contaminated groundwater in situations of vulnerability. In this study, aquifer vulnerability assessment using a Dar-Zarrouk parameter was carried out in Otofure and Ikhueniro areas with a view to preventing the exploitation and consumption of contaminated groundwater in the localities.

METHODOLOGY

Location and Geology

The study areas, Edo State falls within the Niger Delta Basin. The basin is an extensive continental margin basin situated in the Gulf of Guinea built out into the Central South Atlantic Ocean at the mouths of the Niger-Benue and Cross River systems during the Eocene [Figure 1]. It is a wave dominated and tidally influenced delta with sand bodies whose thickness may be influenced by growth faulting.[15]

Otofure dumpsite area is located within Longitudes 005° 35’ 52.56” E - 005° 36’ 02.29” E, Latitudes 06° 27’ 40.48” N - 06° 27’ 48.99” N and elevation of 97–106 m while Ikhueniro dumpsite is located within Longitudes 005° 44’ 40.01” E - 005° 44’ 66.20” E, Latitudes 06° 19’ 15.45” N - 06° 19’ 38.99” N and elevation of 71–86 m. Otofure and Ikhueniro dumpsites are located in Ovia East Local Government Area and Ikpoba-Okha LGA, respectively, both in Benin-City, Edo State, Nigeria. The dumpsites are presumed to have existed for over 20 years and cover an area of 300–500 m^2 with refuse content consisting of various kinds of metallic, organic, and non-biodegradable materials. The areas occupy the Southern part of Edo State which is a sedimentary terrain and is underlain by sedimentary rocks of Paleocene to recent age [Figure 2]. The sedimentary rock contains about 90% of sand stone and shale intercalations.[16] Edo State is situated in south-southern part of Nigeria. It is an important sedimentary basin in Nigeria due to her closeness to the oil fields within the Niger-Delta region.

Data Acquisition and Processing

Geophysical investigation

Twenty VES data were acquired from both locations, with seven VES data from each location at different points and three VES data acquired 100 m away from each dumpsite as control data points. The acquired apparent resistivity data were processed both quantitatively and qualitatively. The quantitative interpretation of the depth sounding curves was carried out using the partial curve matching technique.[18] The combination of two or more interpreted VES results along a profile was used to generate a geoelectric section along the profile [Figure 3].

Dar-Zarrouk parameters

Dar-Zarrouk (D-Z) parameters were defined by Maillet.[19] T is the resistance normal to the face and S is the conductance parallel to the face for a unit cross-section area, which plays an important role in resistivity soundings. D-Z parameters are sufficient for computing the distribution of surface potential and hence an electrical resistivity graph.[12]

Suppose that a section consists of N fine layers with thickness $h_1, h_2, \ldots\ldots, h_n$ and resistivity $\rho_1, \rho_2, \rho_3, \ldots\ldots, \rho_n$ for a block of unit square area and thickness $H = \sum_{i=1}^{N} h_i$

These values of S and T are set equal to those for an anisotropic block with unit square area. So that:

Longitudinal Unit Conductance S,

$$S = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \ldots\ldots + \frac{h_n}{\rho_n} = \sum_{i=1}^{N} \frac{h_i}{\rho_i} \quad (1)$$

Transverse Unit Resistance T,

$$T = \rho_1 h_1 + \rho_2 h_2 + \rho_3 h_3 + \ldots\ldots + \rho_n h_n = \sum_{i=1}^{N} \rho_i h_1 \quad (2)$$

Longitudinal Resistivity $R_{S,}$

$$R_s = \frac{H}{S} \quad (3)$$

Transverse Resistivity, R_T

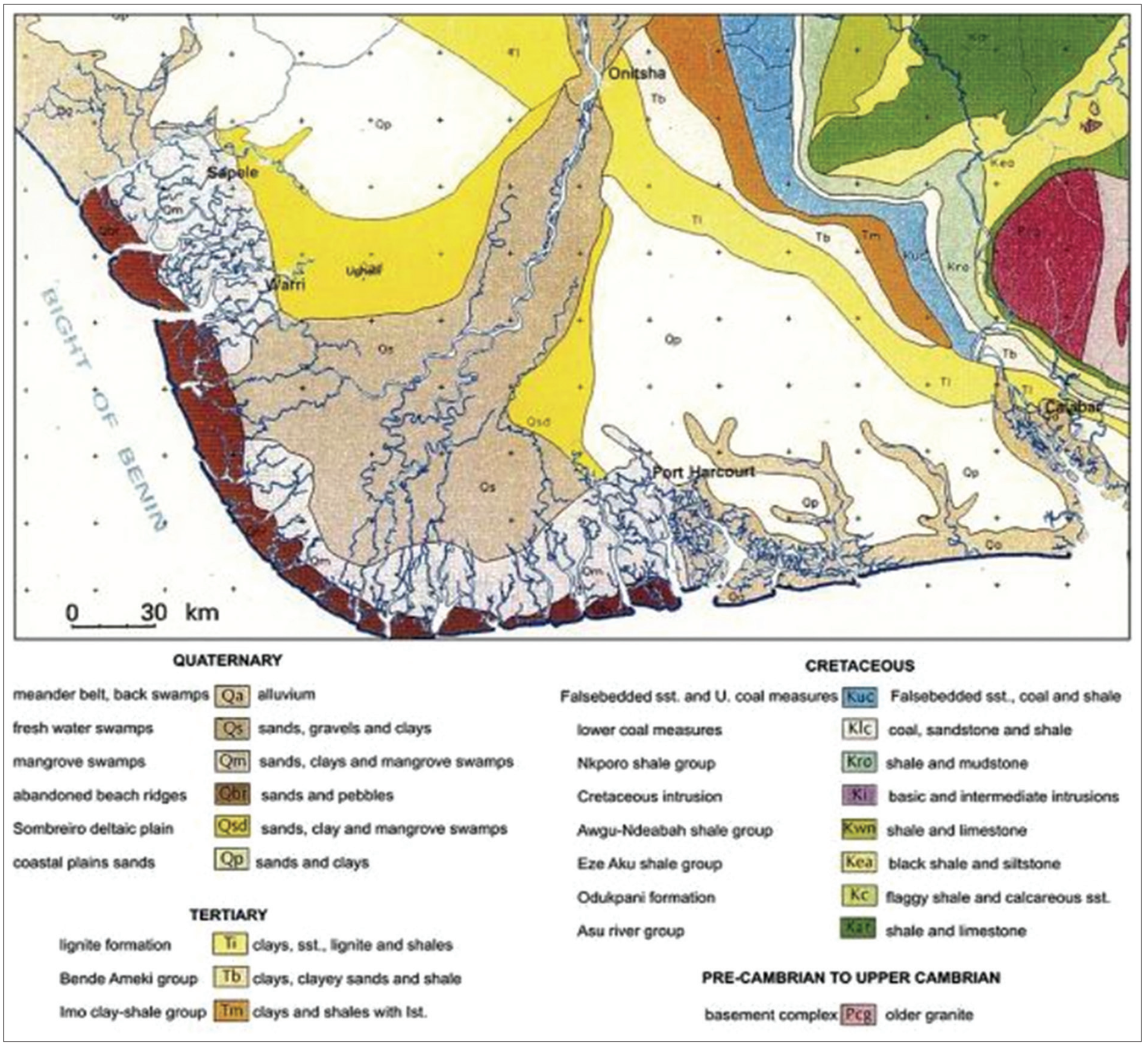

Figure 1: Geological map of Niger Delta[17]

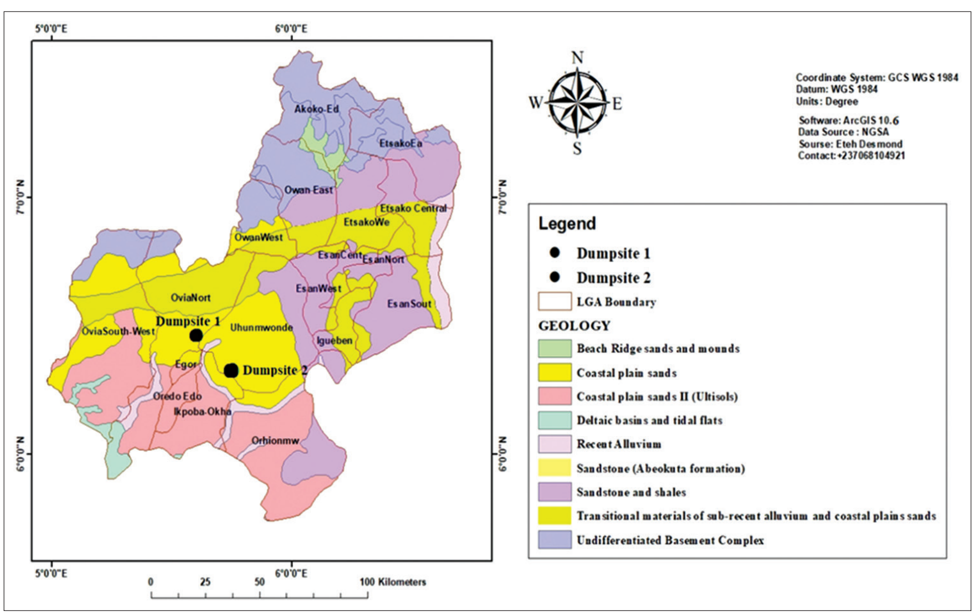

Figure 2: Geologic map of the study areas showing the Otofure and Ikhueniro dumpsites

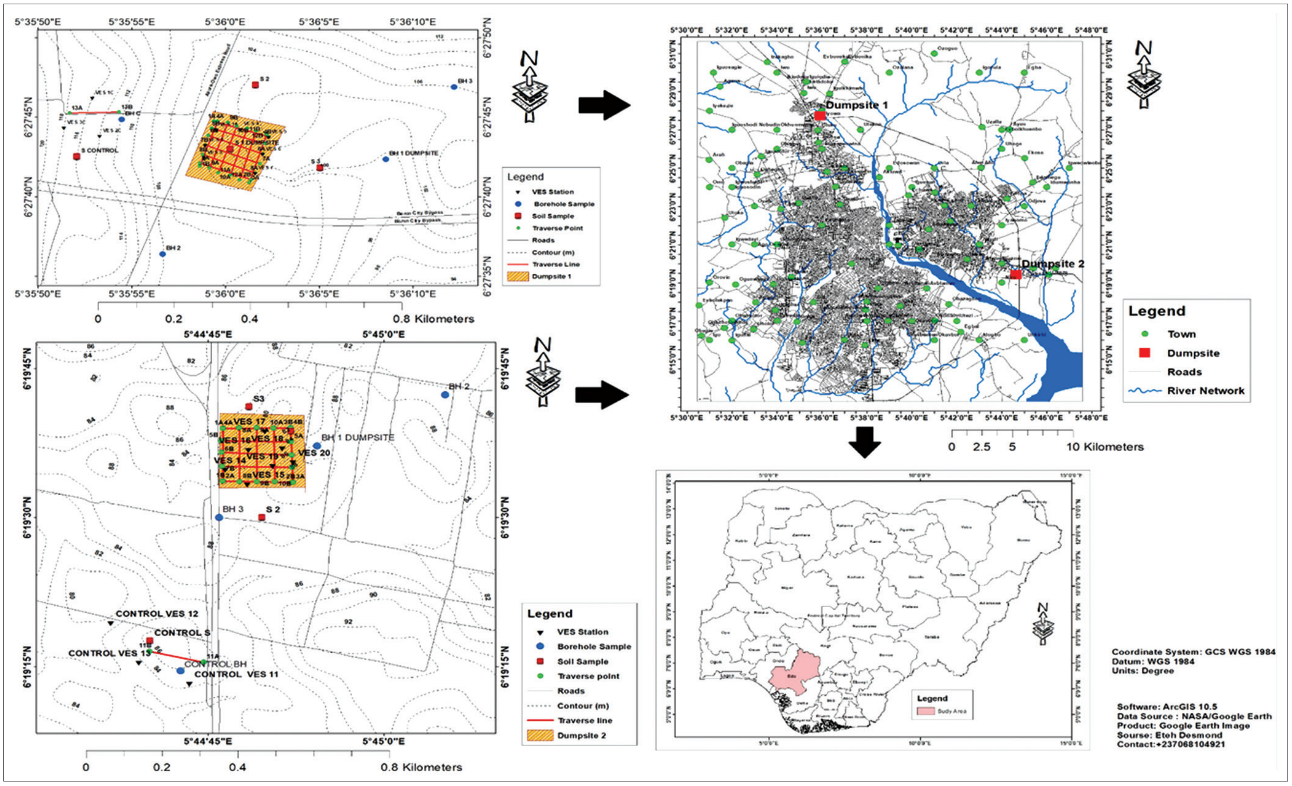

Figure 3: Field basemap of the study areas showing the Otofure and Ikhueniro dumpsites

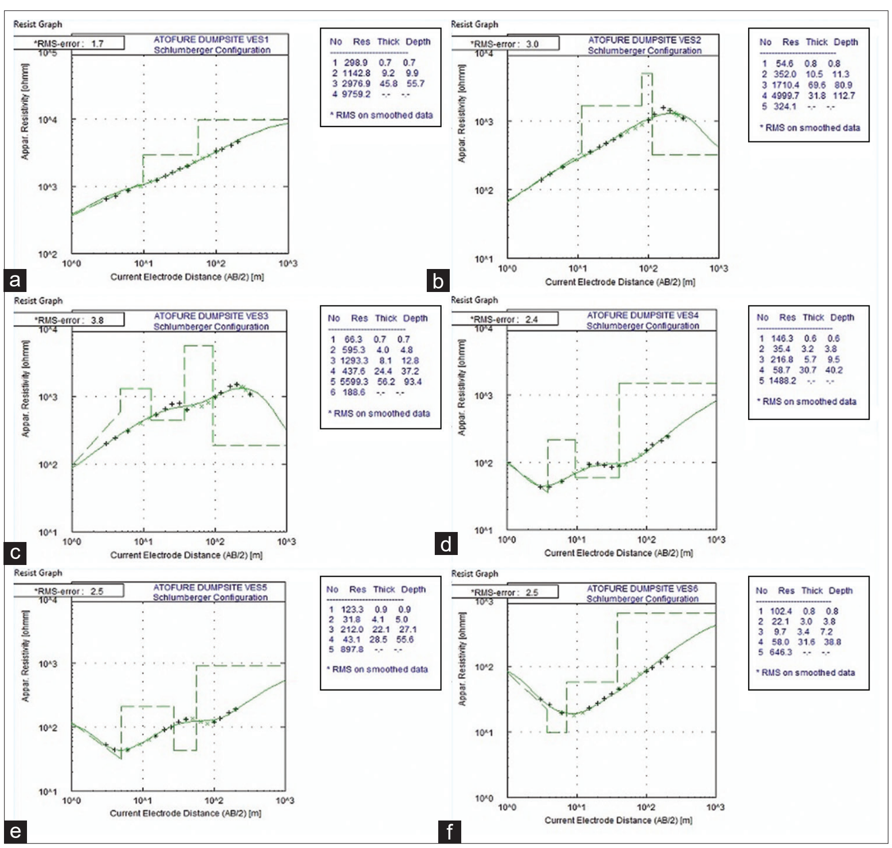

Figure 4a-f: VES curves around Otofure dumpsite

$$R_T = \frac{T}{H} \tag{4}$$

In this study; however, only the Longitudinal Unit Conductance S in mhos (Equation 2) was considered as it is found to be proportional to the protective capacity of the overburden.[1,10,13,14]

RESULTS AND DISCUSSION

Otofure

The VES curves around the Otofure dumpsite are presented in Figure 4a-j. The seven VES data acquired within the dumpsite (i.e., VES 4-10) delineates five geoelectric layers which are indicative of the topsoil, clay/sandy clay, clayey sand, leachate, and sand [Figure 4d-j]. The control VES (1–3) delineate 4–6 geoelectric layers which are only topsoil and sand units (with varying degree of moisture content). There are indications of leachate at VES 6–10 at a depth ranging from 2.9 to 4 m in Otofure dumpsite area [Figure 4d-j].

Evaluation of Aquifer Protective Capacity

Aquifer protective capacity (APC) is the ability of the overlying layers of rock (i.e., the overburden) above the aquifer unit to impede, slow-down, filter and contains percolating ground surface contaminating fluids and run-offs. The second order geoelectric parameter – longitudinal conductance (which is a Dar Zarrouk parameter) was evaluated from the first-order parameters (thickness and resistivity) of the geoelectric layers which were used in the classification of the APC of the 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). While high longitudinal conductance value corresponds to excellent and good APC, low longitudinal conductance values are associated with poor and weak APC [Tables 1 and 2].

Table 1: Longitudinal conductance/protective capacity rating[12]

Total longitudinal unit Conductance (MHOS)	Overburden protective capacity classification
<0.10	Poor
0.1–0.19	Weak
0.2–0.69	Moderate
0.7–1.0	Good

Table 2: Modified longitudinal conductance/protective capacity rating[1]

Total longitudinal unit conductance (MHOS)	Soil protective capacity classification
>10	Excellent
5–10	Very Good
0.7–4.9	Good
0.2–0.69	Moderate
0.1–0.19	Weak
<0.1	Poor

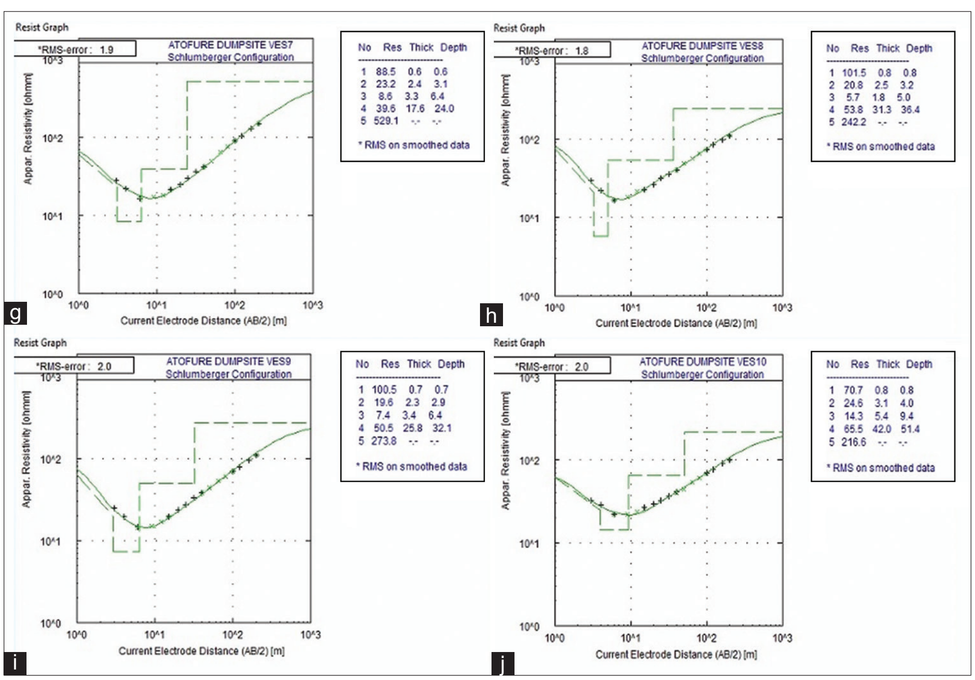

Figure 4g-j: VES curves around Otofure dumpsite

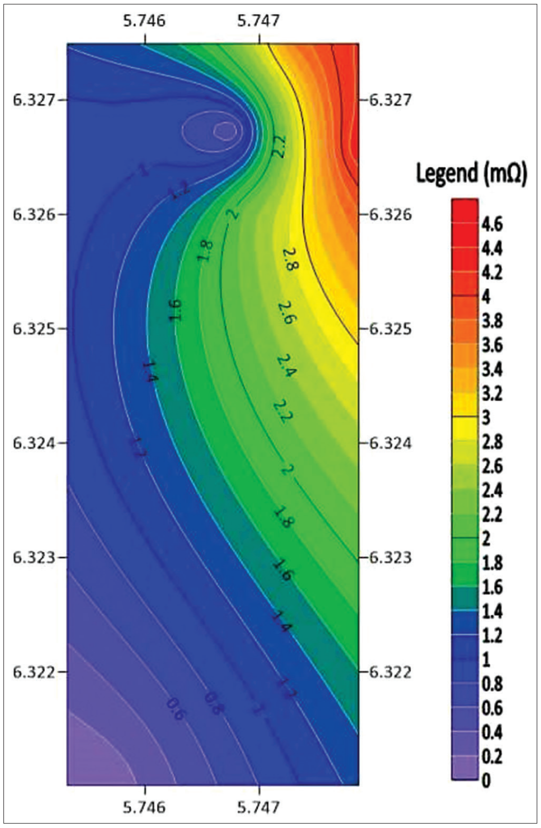

Figure 5: Otofure protective capacity map

Otofure Aquifer Protective Capacity Map

Figure 5 presents the aquifer protective capacity map around Otofure. Western part of Otofure from the north to the south vary in protective rating from 0.2 to 1.4 mhos indicating moderate to good rating.[1,12] In the eastern part of Otofure, from the north to south, the protective capacity ranges from 1.8 to 4.8 mhos [Figure 5] which indicates good protective capacity rating.[1]

Ikhueniro

Figure 6a-j present the VES curves around the Ikhueniro dumpsite. All the seven VES acquired within the dumpsite delineate five geoelectric layers which are the topsoil, clay, clayey sand, leachate, and sand [Figure 6d-j]. The control VES data acquired away from the dumpsite (i.e. VES 1-3) delineates five geoelectric layers which are topsoil and sand [Figure 5a and c]. The sands are suspected to be characterized with varying degree of groundwater saturations and similar type-curve which are very dissimilar from the type-curves of VES data acquired within the dumpsite. VES 4–10 in this location gives both near surface and deeper indications of the presence of leachate migration at a depth range of 0.6–13.6 m [Figure 6d-j].

Ikhueniro Aquifer Protective Capacity Map

Aquifer protective capacity map in Ikhueniro is shown in Figure 7. The northwest of Ikhueniro varies in protective

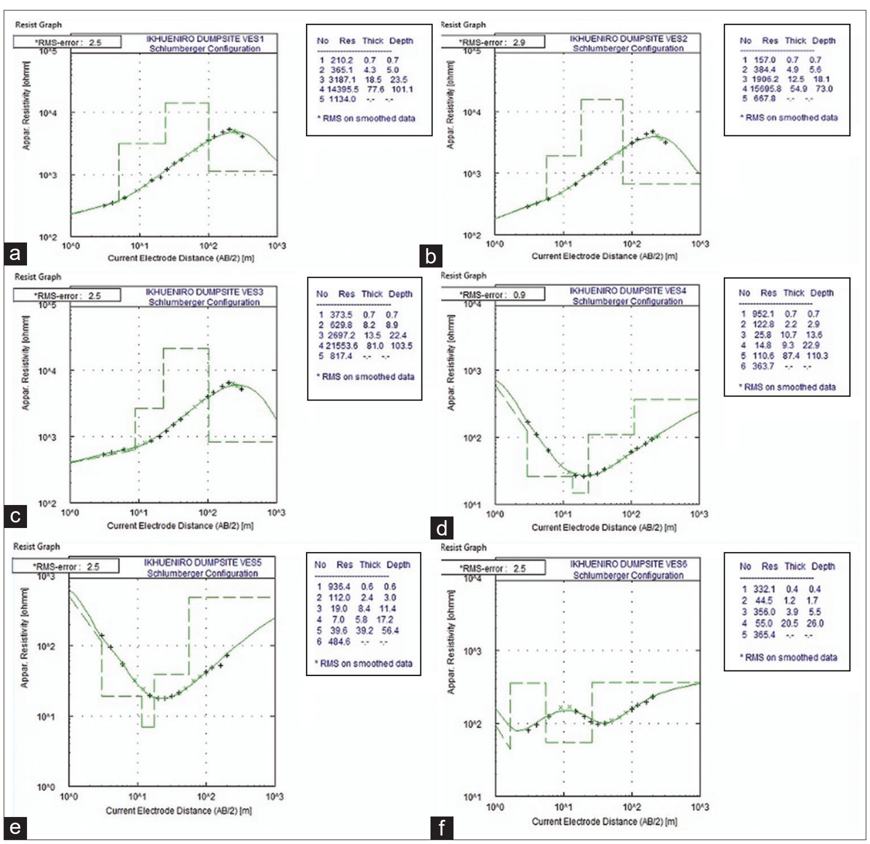

Figure 6a-f: VES curves around Ikhueniro dumpsite

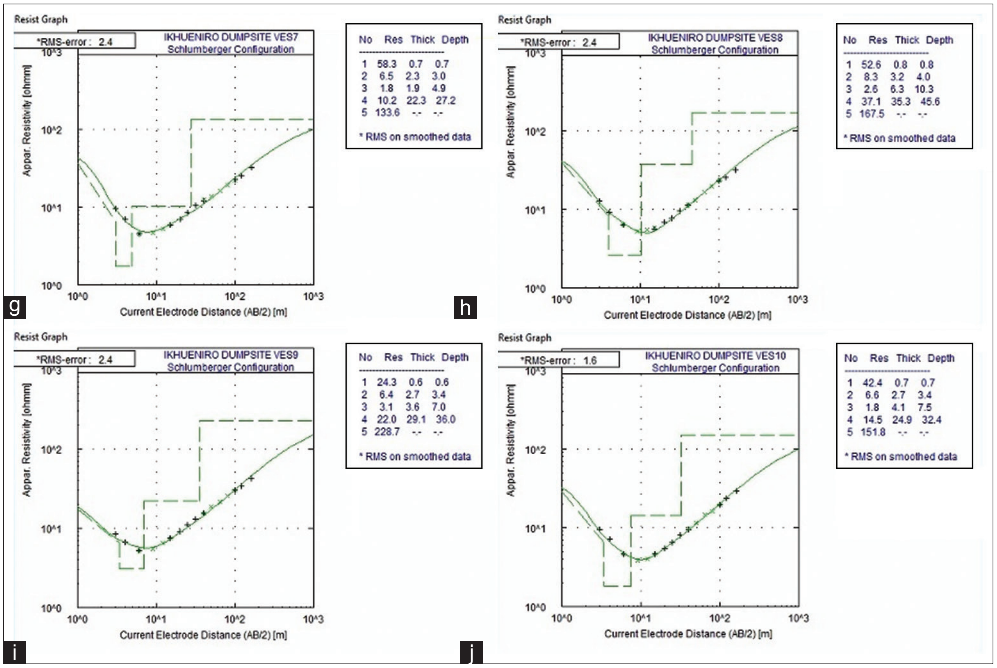

Figure 6g-j: VES curves around Ikhueniro dumpsite

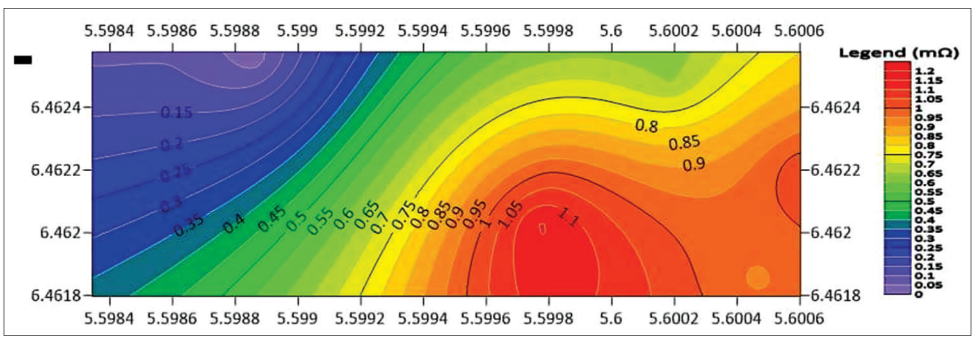

Figure 7: Ikhueniro protective capacity map

rating from 0.15 to 0.45 mhos [Figure 7]. This indicates a weak to moderate rating.[1,12] The central part of Ikhueniro varies in protective rating from 0.5 to 0.75 mhos thus indicating moderate to good protective rating while the eastern to south eastern part of Ikhueniro varies in the protective rating values from 0.8 to 1.1 mhos [Figure 7 and Tables 3 and 4] and thus implying a good protective capacity rating in the study area.[1]

CONCLUSION

Due to growing urbanization around Otofure and Ikhueniro dumpsites and the age-long existence of the dumpsites which has the high possibility of contaminating the regional aquifer with the leachates they have generated over the years, an assessment of the aquifer vulnerability using Longitudinal Unit Conductance, S - a Dar-Zarrouk parameter was carried out in both Otofure and Ikhueniro with a view to prevent the exploitation and consumption of contaminated groundwater in the localities.

Ten VES data were acquired from each of Otofure and Ikhueniro, respectively: Seven VES data from each location and three VES data acquired 100 m away from each dumpsite as control data points. The VES results in Otofure and Ikhueniro delineate five geoelectric layers which are indicative of the topsoil, clay/sandy clay, clayey sand, leachate, and sand. The control VES delineate 4–6 geoelectric layers which are only topsoil and sand units (with varying degree of moisture content). The leachate occurs at a depth of from 2.9 to 4 m and 0.6 to 13.6 m in in Otofure and Ikhueniro, respectively.

In Otofure, the Total Longitudinal Unit Conductance, S varies from 0.0258 to 0.0915 mhos away from the dumpsite, while S varies from 0.6438 to 1.1562 mhos around Otofure

Table 3: Protective capacity rating in Otofure area

VES No	Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology	Longitudinal conductance (mhos) $(\frac{h}{\rho})$	Longitudinal conductance (mhos) $\sum_{i=1}^{n}\frac{h_i}{\rho_i}$	Protective capacity rating
Otofure dumpsite								
Control								
1	1	298.9	0.7	0.7	Topsoil	0.002342	0.025777	Poor
	2	1142.8	9.2	9.9	Lateritic Clayey Sand	0.00805		
	3	2976.9	45.8	55.7	Lateritic Clayey Sand	0.015385		
	4	9759.2	---	---	Lateritic Clayey Sand			
2	1	54.6	0.8	0.8	Topsoil	0.014652	0.091534177	Poor
	2	352.0	10.5	11.3	Sand	0.02983		
	3	1710.4	69.6	80.9	Lateritic Clayey Sand	0.040692		
	4	4999.7	31.8	112.7	Lateritic Clayey Sand	0.00636		
	5	324.1	---	---	Sand			
3	1	66.3	0.7	0.7	Topsoil	0.010558	0.089336071	Poor
	2	595.3	4.0	4.8	Sand	0.006719		
	3	1293.3	8.1	12.8	Lateritic Clayey Sand	0.006263		
	4	437.6	24.4	37.2	Sand	0.055759		
	5	5599.3	56.2	93.4	Lateritic Clayey Sand	0.010037		
	6	188.8	---	---	Sand			
Around Otofure dumpsite								
4	1	146.3	0.6	0.6	Topsoil	0.004101	0.643786452	Moderate
	2	35.4	3.2	3.8	Clay	0.090395		
	3	216.8	5.7	9.5	Sand	0.026292		
	4	58.7	30.7	40.2	Sandy Clay	0.522998		
	5	1488.2	---	---	Lateritic Clayey Sand			
5	1	123.3	0.9	0.9	Topsoil	0.007299	0.901728271	Good
	2	31.8	4.1	5.0	Clay	0.128931		
	3	212.0	22.1	27.1	Sand	0.104245		
	4	43.1	28.5	55.6	Clay	0.661253		
	5	897.8	---	---	Sand			
6	1	102.4	0.8	0.8	Topsoil	0.007813	1.038902156	Good
	2	22.1	3.0	3.8	Clay	0.135747		
	3	9.7	3.4	7.2	Leachate	0.350515		
	4	58.0	31.6	38.8	Clayey Sand	0.544828		
	5	646.3	---	---	Sand			

(Contd....)

Table 3: ***(Continued)***

VES No	Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology	Longitudinal conductance (mhos) $(\frac{h}{\rho})$	Longitudinal conductance (mhos) $\sum_{i=1}^{n}\frac{h_i}{\rho_i}$	Protective capacity rating
7	1	88.5	0.6	0.6	Topsoil	0.00678	0.938393312	Good
	2	23.2	2.4	3.1	Clay	0.103448		
	3	8.6	3.3	6.4	Leachate	0.383721		
	4	39.6	17.6	24.0	Clayey Sand	0.444444		
	5	529.1	---	---	Sand			
8	1	101.5	0.8	0.8	Topsoil	0.007882	1.025647941	Good
	2	20.8	2.5	3.2	Clay	0.120192		
	3	5.7	1.8	5.0	Leachate	0.315789		
	4	53.8	31.3	36.4	Clayey Sand	0.581784		
	5	242.2	---	---	Sand			
9	1	100.5	0.7	0.7	Topsoil	0.006965	1.094662661	Good
	2	19.6	2.3	2.9	Clay	0.117347		
	3	7.4	3.4	6.4	Leachate	0.459459		
	4	50.5	25.8	32.1	Clayey Sand	0.510891		
	5	273.8	---	---	Sand			
10	1	70.7	0.8	0.8	Topsoil	0.011315	1.156175429	Good
	2	24.6	3.1	4.0	Clay	0.126016		
	3	14.3	5.4	9.4	Clay	0.377622		
	4	65.5	42.0	51.4	Clayey Sand	0.641221		
	5	216.6	---	---	Sand			

Table 4: Protective capacity rating in Ikhueniro area

VES No.	Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology	Longitudinal conductance (mhos) $(\frac{h}{\rho})$	Longitudinal conductance (mhos) $\sum_{i=1}^{n}\frac{h_i}{\rho_i}$	Protective capacity rating
Ikhueniro dumpsite								
Control								
1	1	210.2	0.7	0.7	Topsoil	0.00333	0.02630298	Poor
	2	365.1	4.3	5.0	Sand	0.011778		
	3	3187.1	18.5	23.5	Lateritic Clayey Sand	0.005805		
	4	14395.5	77.6	101.1	Lateritic Clayey Sand	0.005391		
	5	1134.0	---	---	Sand			

(Contd....)

Table 4: ***(Continued)***

VES No.	Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology	Longitudinal conductance (mhos) $(\frac{h}{\rho})$	Longitudinal conductance (mhos) $\sum_{i=1}^{n}\frac{h_i}{\rho_i}$	Protective capacity rating
2	1	157.0	0.7	0.7	Topsoil	0.004459	0.027261037	Poor
	2	384.4	4.9	5.6	Sand	0.012747		
	3	1906.2	12.5	18.1	Lateritic Clayey Sand	0.006558		
	4	15695.8	54.9	73.0	Lateritic Clayey Sand	0.003498		
	5	667.6	---	---	Sand			
3	1	373.5	0.7	0.7	Topsoil	0.001874	0.023657433	Poor
	2	629.8	8.2	8.9	Sand	0.01302		
	3	2697.2	13.5	22.4	Lateritic Clayey sand	0.005005		
	4	21553.6	81.0	103.5	Lateritic Clayey Sand	0.003758		
	5	817.4	---	---	Sand			
Around ikhueniro dumpsite								
4	1	952.1	0.7	0.7	Topsoil	0.000735	1.061757587	Good
	2	122.8	2.2	2.9	Clayey Sand	0.017915		
	3	25.8	10.7	13.6	Clay	0.414729		
	4	14.8	9.3	22.9	Clay	0.628378		
	5	110.6	87.4	110.3	Sand			
	6	363.7	---	---	Sand			
5	1	936.4	0.6	0.6	Topsoil	0.000641	2.282645005	Good
	2	112.0	2.4	3.0	Clayey Sand	0.021429		
	3	19.0	8.4	11.4	Clay	0.442105		
	4	7.0	5.8	17.2	Leachate	0.828571		
	5	39.6	39.2	56.4	Clayey Sand	0.989899		
	6	484.6	---	---	Sand			
6	1	332.1	0.4	0.4	Topsoil	0.001204	0.411853078	Moderate
	2	44.5	1.2	1.7	Clay	0.026966		
	3	356.0	3.9	5.5	Sand	0.010955		
	4	55.0	20.5	26.0	Sandy Clay	0.372727		
	5	365.4	---	---	Sand			

(Contd....)

Table 4: ***(Continued)***

VES No.	Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology	Longitudinal conductance (mhos) $(\frac{h}{\rho})$	Longitudinal conductance (mhos) $\sum_{i=1}^{n}\frac{h_i}{\rho_i}$	Protective capacity rating
7	1	58.3	0.7	0.7	Topsoil	0.012007	3.60768308	Good
	2	6.5	2.3	3.0	Leachate	0.353846		
	3	1.8	1.9	4.9	Leachate	1.055556		
	4	10.2	22.3	27.2	Clayey Sand	2.186275		
	5	133.6	---	---	Sand			
8	1	52.6	0.8	0.8	Topsoil	0.015209	3.775310697	Good
	2	8.3	3.2	4.0	Leachate	0.385542		
	3	2.6	6.3	10.3	Leachate	2.423077		
	4	37.1	35.3	45.6	Clayey Sand	0.951482		
	5	167.5	---	---	Sand			
9	1	24.3	0.6	0.6	Topsoil	0.024691	2.930583953	Good
	2	6.4	2.7	3.4	Leachate	0.421875		
	3	3.1	3.6	7.0	Leachate	1.16129		
	4	22.0	29.1	36.0	Clayey Sand	1.322727		
	5	228.7	---	---	Sand			
10	1	42.4	0.7	0.7	Topsoil	0.016509	4.4206195	Good
	2	6.6	2.7	3.4	Leachate	0.409091		
	3	1.8	4.1	7.5	Leachate	2.277778		
	4	14.5	24.9	32.4	Clayey Sand	1.717241		
	5	151.8	---	---	Sand			

dumpsite. These show that away from the dumpsite, the aquifer protective capacity is poor while in the immediate vicinity of dumpsite of the dumpsite, the protective capacity varies from moderate to good, implying that aquifers that are away from the dumpsite are vulnerable to contamination while aquifers in the immediate vicinity of the dumpsite are well protected from contamination either from the migrating leachate from the dumpsite or from other sources of contamination. In Ikhueniro, the Total Longitudinal Unit Conductance, S varies from 0.0237 to 0.0273 mhos away from the dumpsite, while S varies from 0.4119 to 4.4206 mhos around Otofure dumpsite. These values indicate that away from Ikhueniro dumpsite, the aquifer protective capacity is poor while around the dumpsite, the protective capacity varies from moderate to good, implying that aquifers that are away from the dumpsite are vulnerable to contamination while aquifers in the immediate vicinity of the dumpsite are protected from contamination similarly to Otofure.

The study has shown that aquifers in the vicinity of both Otofure and Ikhueniro dumpsites have good protective capacity against migrating sources of contamination while those away have very poor protective capacity against migrating sources of contamination. The study has further revealed the importance of deliberate selection of suitable locations for sitting dumpsites and landfills as revealed in the results.

ACKNOWLEDGMENTS

The authors are grateful to staff of Physics Department, University of Benin, Benin City Nigeria for access to equipment and manpower used for this research. Special recognition must also go to staff of Geoscience Department, University of Lagos for the release of the software employed for interpretation in this research.

CONFLICTS OF INTEREST

There are no conflicts of interest associated with this work.

REFERENCES

1. Oladapo MI, Mohammed MZ, Adeoye OO, Adetola BA. Geoelectrical investigation of the ondo state housing corporation estate, Ijapo Akure, Southwestern Nigeria. J Min Geol 2004;40:41-8.
2. Ako BD, Ajayi TR, Arubayi JB, Enu EI. The groundwater and its occurrence in the coastal plains sands and alluvial deposits of parts of Lagos State. Niger Water Resour 2005;16:7-17.
3. Lashkaripour GR, Sadeghi H, Qushaeei M. Vertical electrical soundings for groundwater assessment in Southeastern Iran: A case study. J Appl Geophys 2005;5:973-7.
4. Hassanein H, El-Kaliouby H, Al-Garni MA. The use of DC resistivity to outline the subsurface hydrogeological and structural setting beneath a proposed site for subsurface DAM building, Makkah Al-Mukarramah, Saudi Arabia. J King Abdul Aziz Univ Earth Sci 2007;18:117-38.
5. Olorunfemi MO, Fasuyi SA. Aquifer types, geoelectric and hydrogeologic characteristics of part of the central basement Terrain of Niger State Nigeria. J Afr Earth Sci 1993;16:309-17.
6. Telford WM, Geldart LP, Sheriff RE. Applied Geophysics. Cambridge: Cambridge University Press; 1990. p. 770.
7. Ako BD, Osondu VC. Electrical resistivity of the Kerri-Kerri formation, Darazo, Nigeria. J Afr Earth Sci 1986;5:527-34.
8. Abdulaziz MA. Resistivity methods for groundwater exploration in the cretaceous-tertiary sedimentary sequence, East of Jeddah, Saudi Arabia. J Environ Hydrol 2005;13:1-11.
9. Abiola O, Enikanselu PA, Oladapo MI. Groundwater potential and aquifer protective capacity of overburden units in Ado-Ekiti, Southwestern Nigeria. Int J Phys Sci 2009;4:120-32.
10. Olorunfemi MO, Ojo JS, Oladapo MI. Geological Hydrogeological and Geophysical Investigations of Exposed 20, Escravos Lagos Pipeline Technical Report; 1998.
11. Sørensen KI, Auken E, Christensen NB, Pellerin L. An integrated approach for hydrogeophysical investigations: New technologies and a case history. In: Butler DK, editor. Near-Surface Geophysics 2, Investigations in Geophysics, 13. Society of Exploration Geophysics; 2005. p. 585-603.
12. Henriet JP. Direct application of Dar-Zarrouk parameters in ground water surveys. Geophys Prospect 1976;24:344-53.
13. Ayolabi EA. Geoelectric evaluation of olushosun landfill site southwest Nigeria and its implication on groundwater. J Geol Soc India 2005;66:318-22.
14. Atakpo EA, Ayolabi EA. Evaluation of aquifer vulnerability and the protective capacity in some oil producing communities of Western Niger Delta. Environmentalist 2009;29:310-7.
15. Avbovbo AA, Ayoola O. Petroleum prospects of southern Nigeria's Anambra Basin. Oil Gas J 1981;4:335-47.
16. Alile OM, Ujuanbi O, Evbuomwan IA. Geoelectric investigation of groundwater in Obaretin-Iyanomon locality, Edo state, Nigeria. J Geol Min Res 2011;3:13-20.
17. Reijers TJ. Stratigraphy and sedimentology of the Niger Delta. Geologos 2011;17:133-62.
18. Bhattacharya AP, Patra HP. Direct Current Geoelectric Sounding: Principles and Interpretations: Methods of Geochemistry and Geophysics. Amsterdam: Elsevier Publishing Company; 1968. p. 135.
19. Maillet R. The fundamental equation of electrical prospecting. Geophysics 1947;12:529-56.