GEOELECTRICAL INVESTIGATION OF GROUNDWATER VULNERABILITY AT THE VICINITY OF A MUNICIPAL DUMPSITE IN AWKA, SOUTHEASTERN NIGERIA

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ABSTRACT: *The vulnerability of overburden aquifers at the vicinity of a municipal dumpsite has been carried out. The survey site is bounded by longitude 7°5′20″E and 7°5′52″E and latitudes 6°13′35″N and 6°13′52″N located within Niger delta basin of Southeastern Nigeria. Two-dimensional electrical resistivity tomography (2DERT) and vertical electrical sounding (VES) techniques were carried out in order to ascertain the extent of the vulnerability of groundwater at shallow subsurface. The registered resistivity values modeled in the 2DERT and VES are in the ranges of about 3.76 Ωm to 11464 Ωm and about 76.79 Ωm to 5665.85 Ωm respectively. With the aid of Res2D inversion version 3.2 and Winglet version 1.62 software, the 2DERT and VES data were modeled respectively. Interpreted 2DERT results showed evidence of the leachate in clayey and sandy topsoil the refuse dump. Inferred fractures in both top and other shallow layers suggest percolation of the leachate into depths beyond the limits probed by the 2DERT. Interpreted results from the VES showed that longitudinal conductivities S_L derived for depths in the study site is in the range of about 0.002161 - 0.101741 mhos. Hence, Dar Zarrouk Parameter (DZP) standard was used to evaluate the protective capacity of groundwater's overburden at the site and its vulnerability. Based on the interpreted 2DERT, there is evidence of leachate percolation through the topsoil and shallow subsurface to depths. The protective capacity of the depths underlain by the groundwater was inferred as weak at NNE and Eastern zones of the dumpsite while at the SSE and the Western zones of the dumpsite was inferred as poor. Consequently, the vulnerability of the groundwater in the vicinity of Awka municipal dumpsite to percolating leachate from refuse dump is moderately high.*

KEY WORDS: Tomography, Sounding, Leachate, Percolation, Vulnerability, Groundwater

INTRODUCTION

Groundwater is an important natural resource which compliments surface sources of water in the provision of portable water for both domestic and industrial applications (Asuerimen, 2014). In most parts of the earth, groundwater resource has been under rapid increasing stress due to pollution and population explosion (Ogungbe *et al*., 2012). Particularly, pollution of groundwater has been a progressively emerging serious challenge in several continents of the world such as Europe, Asia and Africa. Groundwater pollution has, for the past one decade gained an obvious international scientific interest and has been studied using several approaches and techniques (Chukwuma *et.al.*, 2015). The consequences of polluted

groundwater have been found to last from months up to decades and its remedial actions are usually neither practically easy nor cheap. However, measures to circumvent the groundwater pollution are commonly preferred to the consequences afterwards (Hine, 2005). Vulnerability of groundwater qualitatively is the measure of how prone the aquifer is to the pollutants from the ground surface of the earth. The pollutants could be landfill, industrial wastewater discharge, chemical fertilizers, pesticides or herbicides.

A quality and good groundwater protection is commonly assured when aquifers are overlain by protective layers with sufficient thickness and low hydraulic conductivity (Chukwuma *et. al.,* 2015*).* In other words, the factors which control groundwater contamination include; depth to water table, concentration of contaminants and permeability of geologic strata. Sufficiently deep-water table usually amount that the groundwater would be relatively filtered as it percolates downwards through the soil. Conversely, shallow water table would have contaminants percolate and reach the groundwater directly, faster and without sufficient filtration by soil. The extent of how portable groundwater is depends on the earth media which acts as a natural filter to percolating fluid. The ability of the earth to filter fluid is dependent on the overburden thickness, the covering materials and the protective capacity of the overlying overburden of the aquifer (Olorunfemi *et al.,* 1999). Soils such as silts and clays are suitable aquitards which often constitute protective geologic barriers when they are found above aquifers. Such soils constitute good protective cover and thus protect the aquifer from surface and near-surface contamination because their low hydraulic conductivity leads to high residence time of percolating water (Lenkey *et al.,* 2005).

There has been a serious concern on the deteriorating groundwater quality due to the anthropogenic activities (Akpankpo and Igbokwe, 2011). Particularly, in the recent few decades, there was a number of socio-economic upgrading that led to astronomical population explosion in Awka metropolitan city, southeastern Nigeria. These include creation of new Anambra state in Nigeria whereby Awka was made state capital and the establishment and upgrading of the state University in Awka from state to Federal University. Hence, the population explosion invariably led to increase in waste generation and indiscriminate disposal of refuse until the Ministry of Utility and Environment of the State government mapped out the site under study (Plate 1) for municipal refuse disposal. Prior to this use of the site and thereafter, the need for investigation of groundwater at the site's vicinity has been on the increase as a prime concern of indigenous geoscientists. The need for both geoscience and other scientific studies would be on the increase as the number of residential buildings around the study site which would also lead to high demand for groundwater escalates.

Plate 1: Some Side Photographic Views of the Dumpsite

In Awka town, there was discontinuity of functional community water supply and subsequent collapse of the State's Water Board. Hence, individuals sink shallow wells and boreholes to access portable water. The groundwater, if polluted, could amount to serious health risk to the inhabitants. Therefore, it is eminent to investigate the vulnerability of groundwater at the site.

Generally, electrical resistivity survey is geophysical method commonly used in prospecting for hydro-geological investigation *vis-a-vis* depth to aquifer, quality and quantity of groundwater. It is also useful in mining, geotechnical investigations and subsurface environmental studies (Osele, 2013). Moreover, geo-electrical imaging technique has been found to be widely used for delineating minor contrast of subsurface materials based on their electrical conductivity. Refuse dump harbors all kinds of ionic, Ohmic and electrolytic conductive materials. Therefore, application of the techniques in electrical resistivity method for investigating leachate in the subsurface from dumpsite is expected to give plausible results.

This study is therefore aimed at investigating the vulnerability of groundwater at the vicinity of the municipal dumpsite using two-dimensional electrical resistivity tomography (2DERT) and Vertical Electrical Sounding techniques (VES). On one hand, the shallow subsurface 2DERT is meant to delineate the occurrence of pollutants such as leachate in the topsoil and their tendency of percolation to depths. On the other hand, the VES is meant to probe the lithology of deeper subsurface hence estimate the extent of its protective capacity on the groundwater which underlie it. The results from the study will be beneficial to government,

community and researchers for determination of environmental friendliness of the dumpsite hence, aid the future recommendation of other site(s) for same purpose.

The Study Site

The dumpsite is located at the industrial layout of Awka-North where there is also a new residential layout sited. The study site is located at about 500 m off Ring Road junction Awka, Anambra State Nigeria. The area is bounded by latitudes $6°13'35''$N and $6°13'52''$N and longitudes $7°5'15''$E and $7°5'16''$E at the elevation of about 180 m above mean sea level. Figure 1 shows the base map of the survey site showing the VES points (V_1, V_2, V_3 and V_4) and profile lines (P_c, P_1 and P_2). Two main climatic seasons characterize the study area; the rainy season which is associated with the moist maritime southwesterly trade wind from the Atlantic Ocean and the dry season which is associated with the Atlantic Continental northwesterly wind from the Sahara Desert. The average time window for rainy season and dry season are April to October and November to March respectively. Between the two seasons is the occurrence of short-lived cold-dry season which is characterized by low temperature, hazy and dusty atmosphere southeasterly from Sahara Desert.
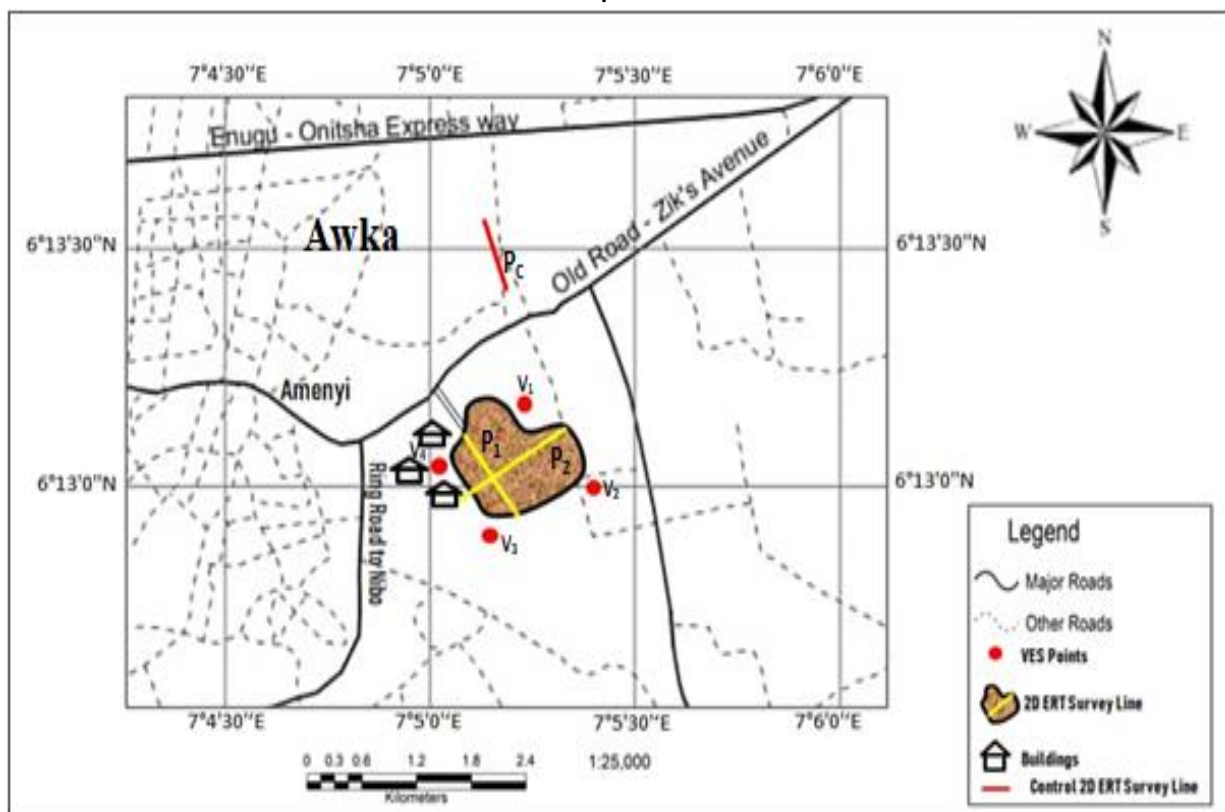
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Figure 1: The Base Map of Awka Showing Dump Site VES Points and 2DERT Profile Lines.

The study site lies within the Niger Delta Basin of Southeastern Nigeria. The Basin is in the Gulf of Guinea in equatorial West Africa, it lies between latitudes 3^oN and 6^oN and longitudes 5^oE and 8^oE (Reijers *et al.,* 1996). Niger Delta is a prograding depositional complex within the Cenozoic Formation of the Southern Nigeria, bounded in the west of it by the Benin flank; the subsurface continuation of the West Africa shield, bounded in the east by Calabar flank; the subsurface continuation of the Oban massif, in the North by Abakaliki and the post-Abakaliki (Anambra Basin) and bounded in the south by Atlantic Ocean (Murat, 1972). The outcropping units of the Niger Delta include Imo formation and Ameki group consisting of Ameki, Nanka, Nsugbe, and Ogwashi-Asaba formations. The subsurface Niger Delta stratigraphic units are classified into three; Benin Formation being the youngest, Agbada Formation and the oldest being Akata Formation (Short and Stauble, 1967). The Akata Formation is about 3,700 metres, composed mainly of marine shales, with sandy and silty beds. The Formation is the major petroleum-bearing unit in the Niger Delta which consists mostly of shoreface and channel sands with minor shales in the upper part, and alternation of sands and shales in equal proportion in the lower part. The Benin Formation is about 280 to 2,100 metres thick in the region of maximum subsidence which consists of continental sands and gravels (Whiteman, 1982; Ajaegwu *et al.,* 2012).

Materials and Methods

The surveys involved the use of electrical resistivity method. Particularly, the techniques adopted were vertical electrical sounding (VES) using Schlumberger array and 2DERT which is an electrical imaging technique using Wenner array. Two survey lines-oriented NW-SE and NE-SW were mapped for the 2DERT investigation while four points were selected for the VES (electrical drilling) at the site (Figure 1). The limited number of both the 2D tomography and the 1D sounding is due to restricted confines of the dumpsite's boundary, area coverage and rugged accessible space. On one hand, resistivity imaging was meant for investigating the occurrence of leachate on the ground surface and the extent of its spread at shallow subsurface. On the other hand, the vertical electrical sounding was meant for characterization of various lithology units and provision of data for estimating the vulnerability of the groundwater at the site. Both techniques are based on the response of the subsurface material to the flow of electric current transmitted through two current electrodes and with other two potential electrodes to record the resultant potential difference between them. The measuring instrument used is *ABEM SAS 4000/1000* Terrameter, a composite unit made up of transmitter and receiver units, usually powered by either direct current or low frequency alternating current source. The current was sent into the subsurface through the two outer current electrodes inducing voltage across the two potential electrodes and aligned at the inner part of a profile line. The Terrameter, based on Ohm's law measures the apparent electrical resistivity of the subsurface. The associated ancillary tool of the Terrameter includes; steel electrodes, connecting cables reels, measuring tape, hammer cutlass and GPS.

For the 2DERT survey, the Terrameter was aided by an electrode selector model *ES 10-64*, an automated system which selects four electrodes at a time during each measurement. Forty-two electrodes were inserted into the ground. The multi take-outs were connected to both the electrode array and to transmitter/receiver unit. With the system, two outer electrodes were automatically selected as current terminals while two inner electrodes in the configuration were selected as potential electrodes. Wenner array based on *32SX* protocol was adopted for the field survey whereby the electrode spacing was automatically varied hence the apparent resistivity $'\rho_{aW}'$ (Equation1) for each measured point was registered.

$$\rho_{aW} = 2\pi a \frac{\Delta U}{I} \tag{1}$$

Where a, I and ΔU are the electrodes spacing in the Wenner configuration, current flowing into the earth and the resultant potential difference.

For the VES survey, Schlumberger array was used whereby four vertical electrical soundings were conducted around the dump site. The take-off half-spacing between the current electrodes (AB/2) and potential electrodes MN were 2 cm and 0.5 cm respectively where both pairs are centered at common midpoint. Both the current electrodes' half spacing AB/2 and the potential electrode spacing MN were gradually increased using the Schlumberger's configuration until MN and AB/2 reached 20 m and 100 m respectively. It was ensured that all the electrodes were driven about 2 cm into the ground and aligned on a straight line. A current of 0.5A was passed into the ground through the current electrodes A and B for the measurement of apparent resistivity $'\rho_{aS}'$ (Equation 2) at each point during the sounding.

$$\rho_{aS} = \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right] \frac{\Delta U}{I} \tag{2}$$

Data Processing

Data obtained from the 2DERT were processed using *RES2DINV* (Loke and Barker, 1996). The software automatically determines a two-dimensional resistivity model for the data obtained from electrical survey of the subsurface. The software uses an inversion mathematical model which generates the apparent resistivity data and produces the pseudo section which is 2D inversion after ascertaining that the observed data closely matches the calculated data with minimum absolute (abs) error (Loke and Baker, 1996). For VES, the apparent resistivity values obtained were plotted against half current electrode spacing (AB/2) on a log-log graph using the *WINGLET* version 1.62 software. By the process of iteration, the software finds the line of best fit of the observed data which matches the theoretical resistivity curve type from either type A, K, H or Q. Furthermore, 1-dimensional inversion of the plot was carried out by the software to generate a model curve. The curves obtained for each VES point were meant to find the various lithological units in the subsection associated with the different resistivity values of the subsections.

Having utilized 2D model electrical resistivity sections to confirm the occurrence of leachate in the topsoil and its downward percolation tendency, the protective capacity at depths against the vulnerability of the groundwater follows. In this study, the resistivity parameters of the geoelectric layers underlain by aquiferous zones in the study area were used to assess the vulnerability of the groundwater. For the plausible evaluation, an important parameter in geoelectric prospecting namely Dar - Zarrouk Parameters (DZP) was applied. DZP was evaluated using the longitudinal unit conductance (S_L) in $m\Omega^{-1}$ of a subsurface medium which is layer thickness per resistivity. The combination of the resistivity and thickness in the Dar Zarrouk parameter (longitudinal conductance) have been used by various researchers in groundwater potential and aquifer vulnerability studies (Chukwuma *et al.* (2015), Onuoha and Mbazi (1988), Ezeh (2011), Okonkwo and Ezeh (2013), Ekwe *et al.* (2010), Okonkwo *et al.,* (2014) and Okonkwo and Ugwu (2015)). The total longitudinal conductance (S_L) for geoelectric sounding (VES) stations is given as;

$$S_L = \sum_{i=1}^{n}\left(\frac{h_i}{\rho_i}\right) = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \cdots \; \frac{h_n}{\rho_n} \qquad (3)$$

where S_L is the total longitudinal conductance, h_i is the thickness of the ith layer and ρ_i is the resistivity of the ith layer. The interpretation of all apparent resistivity values obtained from both 2DERT and VES survers were based on the standard range and published previous works as shown by Palacky (1987), Telford *et al.* (1990), Asumerimen, (2014) and Samuoelian *et al.*, (2015).

RESULTS

Result I: 2D ERT Survey

Before the actual pseudo sections obtained from the municipal dump site survey were interpreted, the same obtained from the site control survey at an offset of about 500 m from the dumpsite. The results of the 2D ERT survey of the tomogram obtained from the control profile line Pc is shown in on figure 3a while figures 3b and 3c show the tomograms obtained from profile lines P1 and P2 respectively. This served as a standard for comparison to the tomograms obtained from the vicinity of the dumpsite.

Figure 2a shows 2-D inversion model obtained from the selected control site to the study. The profile Pc which trends NNW-SSE is an inversion resistivity tomogram result obtained at the 3rd iteration at minimum abs error of 5.9% whereby a good fit was obtained between the measured and calculated apparent resistivity. The 2DERT inversion tomogram obtained from the profile Pc dimensioned 80 m lateral extent by depth of probe of about 15.0 m is characterized by apparent resistivity ranging from about 40.0 Ωm to 1300 Ωm. This range comprises the values for sand (80-1050 Ωm), sandy clay (30-215 Ωm), sand and gravel (30-225 Ωm), landfill runoff (10-50 Ωm), fresh water (10-100 Ωm), laterite (45-2400 Ωm), gravel and sand (500-10000 Ωm), and shale (10-50 Ωm). This suggests that that the lithology of the control site most probably comprises the materials mentioned in the foregoing whose resistivity values are within the model range for the profile Pc. A significant structural feature of the profile shows that the tomogram is characterized by layered medium having gradual decrease in apparent resistivity from the topsoil to depths.
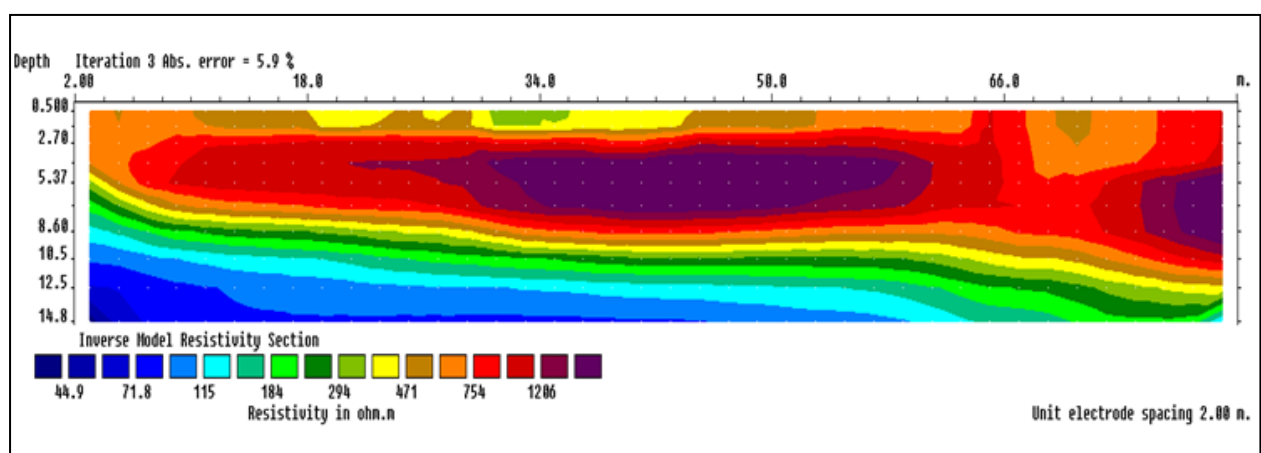

Figure 2a: 2DERT Inversion Model Obtained from the Interpretation Control Site.

Figure 2b is a 2D ERT model section of P1 obtained from the vicinity of the dumpsite. The tomogram trends NW-SE direction across the dumpsite through an existing accessible path. The inversion 2DERT model was obtained at the 3rd iteration at minimum abs error of 1.5% having ensured a good fit between the measured and calculated apparent resistivity data. The resultant tomography model is dimensioned 80 m length by depth of probe of 15.0 m. The fresh basement could not be mapped due to limited profile length. The electrical resistivity value which characterized the 2D tomogram is in the range of about 30 Ωm to 650 Ωm. This range comprises the values for saturated landfill (3-15 Ωm), (15-45 Ωm), unsaturated landfill (15-50 Ωm), sand (80-1100 Ωm), sandy clay (30-215 Ωm), clay (50-150), dry sand(420-10010), laterite (45-2320 Ωm) shale (50-100 Ωm), sand and gravel (30-225 Ωm). A relatively low resistivity zone *A* of range from about 60 Ωm to 200 Ωm is observed almost throughout the topsoil (about 0-3 m deep) of the tomogram. This low resistive (conductive) topsoil is inferred as due to the effect of the leachate to topsoil lea could be at the right side of the tomogram's depths, a relatively high resistivity zone *B* of range 300 Ωm to 650 Ωm occurs hence, there is inferred to be relatively consolidated. At the left side of the same, a relatively low resistivity zone *C* of range about 40 Ωm to 90 Ωm occurs hence, inferred to be relatively unconsolidated and saturated zone in the tomogram. Zones X and Y suggest broken (fractured) leftward continuation of relatively consolidated zone B whereas the contrast between zones B and C suggests occurrence of fracture. The fracture through the maximum depth of the tomogram *M* is an indication that percolation towards the deeper columns is possible.

The uneven features of the tomogram have shown obvious contrast with that obtained from the control site (Pc) whereby high resistivity of the topsoil gradationally decreased down the depths.
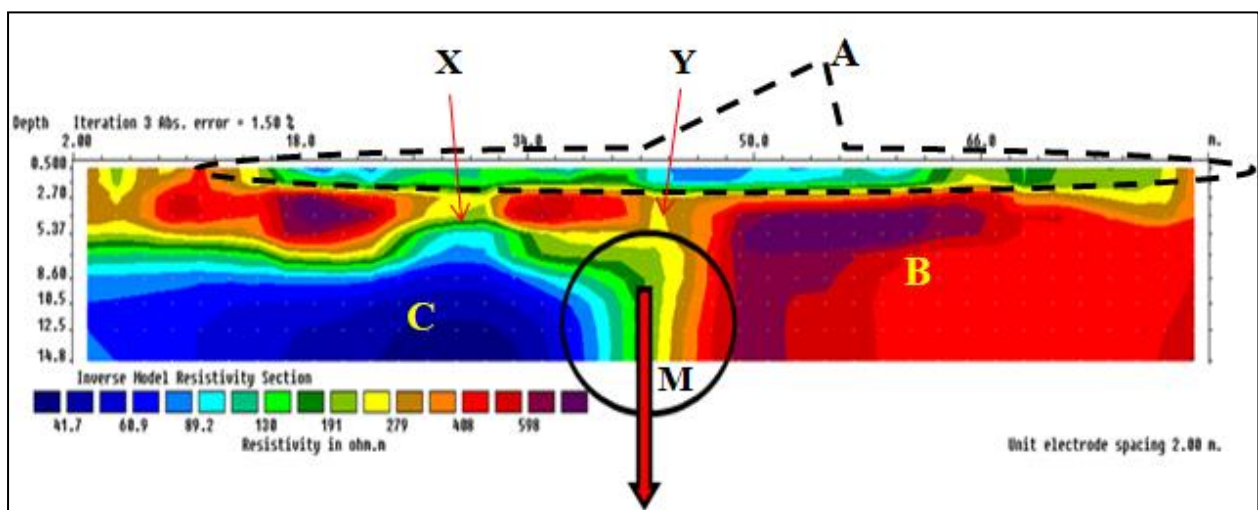

Figure 2b: 2DERT Inversion Model Obtained from the Survey of Profile P1 at the Survey Site.

Figure 2c shows a 2DERT inversion model section of P2 trending NE-SW direction across the municipal dumpsite. The P2 survey line was accessed by clearing a path through the refuse dump. The 2D inversion resistivity tomogram result was obtained at the 3rd iteration having reached minimum abs error of about 10.5% when a good fit between the measured and calculated apparent resistivity data was obtained. The profile is dimensioned 80 m lateral extent by depth of probe of about 15.0 m based on the electrode spacing of 2.0 m used.
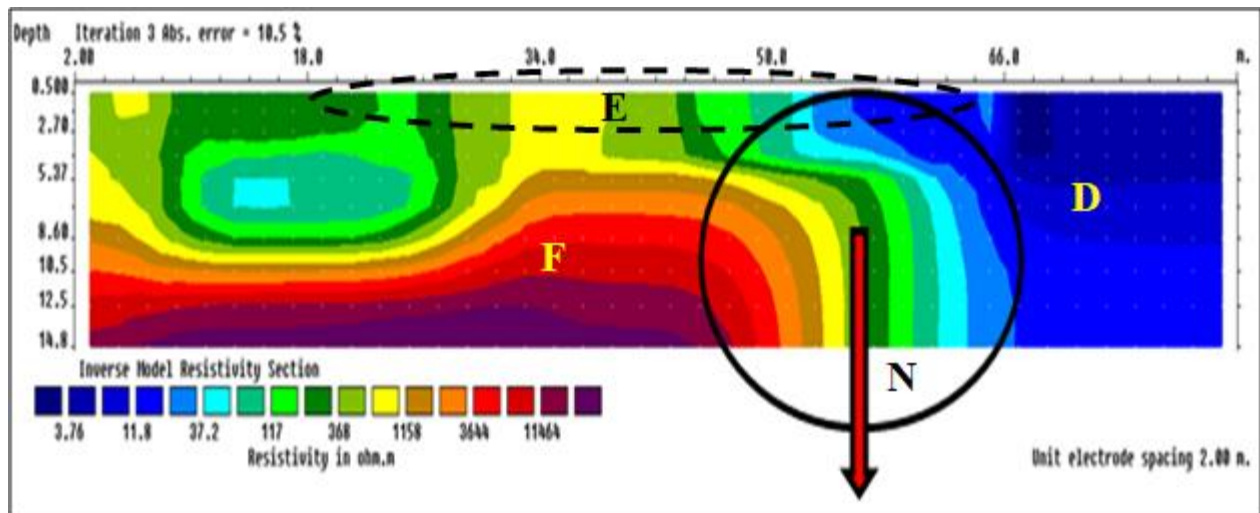

Figure 2c: 2DERT Inversion Model Obtained from the Survey of Profile P2 at the Survey Site

The P2 tomography model is characterized by apparent resistivity value in the range of about 1.00 Ωm to 11500 Ωm. The wide range also comprises the values for saturated landfill (3-15 Ωm), unsaturated landfill (15-50 Ωm), sand (80-1100 Ωm), sandy clay (30-215 Ωm), clay (50-150), dry sand (420-10010), laterite (45-2320 Ωm) shale (50-100 Ωm), sand and gravel (30-225 Ωm). A relatively low resistivity zone D of range about 1.00 Ωm to 3.00 Ωm is shown one end of the tomogram. The zone was observed to be directly underlying the portion of the refuse dump with the highest elevation during the survey. Thus, it is inferred to be due to saturation of the subsurface due to percolation of leachate. There is gradual increase in apparent resistivity with depth at zone **F** of this tomogram. This feature contrasts significantly with that observed from profile (Pc) tomogram of the control site wherein there is decrease in resistivity with depths. Significantly, there is vertical alignment pattern of contrasting resistivity increment from the saturated zone D through E at the topsoil to relatively consolidated F of the tomogram. This is inferred as fracture development having its aligned pattern from the topsoil through to the maximum depth of the tomogram N. This is also an indication that percolation of any leachate from the topsoil towards the deeper columns is possible.

The suspected fractures observed in both P1 and P2 tomograms would invariably enhance percolation of leachate down to deeper horizon in the subsurface. Sequel to this, VES survey results which is expected to probe deeper horizons was required to complement the 2DERT in delineating the lithology and show the vulnerability at deeper horizons.

Result II: VES Survey

The results of the four vertical electrical soundings (V1 to V4) are shown in figures 3 to 6. With the aid of *WINGLET* software, the resistivity curves are shown in log-log graphs whereby apparent resistivity versus half current electrode spacing AB/2 were plotted (Figures 3a to 6a) respectively. Consequently, the software was also used to plot the graphs of the depth of the inferred lithology against the apparent resistivity for the various soundings (Figures 3b to 6b). Hence, the models of the depths-resistivity plots were interpreted based on the adopted ranges from standard resistivity ranges and previous published works as shown by Palacky (1987), Telford *et al.* (1990), Asumerimen (2014) and Samuoelian *et al.*, (2015). The interpretation made shows that the inferred lithologies delineated by the VES surveys encompasses for the ranges of resistivity for laterites, dry sand, clay, sandy clay and aquiferous sandy layer.

Figure 3a shows the apparent resistivity versus AB/2 curve for V_1 whereby $\rho_1 < \rho_2 > \rho_3$ (type K). The interpretation of the sounding shows four layers model in the plot of depth versus apparent resistivity (Figure 3b). The lithology of the layers based on the range of resistivity was inferred to comprise lateritic soil, dry Sand, sandy clay and aquiferous sand. These materials were shown in model plot to be characterized by average resistivity values of 444.61 Ωm, 2362.74 Ωm, 366.52 Ωm and 956.02 Ωm) respectively. Figure 4a shows the apparent resistivity versus AB/2 curve for V_2 whereby $\rho_1 < \rho_2 < \rho_3$ (type A). The interpretation of the sounding shows four layers model in the plot of depth versus apparent resistivity (Figure 4b). The lithology of the layers based on the range of resistivity was inferred to comprise clay, sandy clay, dry sandy and aquiferous sand. These materials were shown in model plot be characterized by average resistivity values of 183.75 Ωm, 76.79 Ωm, 3209.33 Ωm and 792.49 Ωm respectively.

Figure 5a also shows the apparent resistivity versus AB/2 curve for V_3 whereby $\rho_1 < \rho_2 < \rho_3$ (type A). The interpretation of the sounding shows four layers model in the plot of depth versus apparent resistivity (Figure 5b). The lithology of the layers based on the range of resistivity was inferred to comprise sand, Sandy, clay, dry sandy and aquiferous sand. These materials were shown in model plot as being characterized by average resistivity values of 1063.84Ωm, 154.07Ωm, 1479.63Ωm and 565.85 Ωm respectively. Figure 6a also shows the apparent resistivity versus AB/2 curve for V_4 whereby $\rho_1 < \rho_2 < \rho_3$ (type A). The interpretation of the sounding also shows four layers model in the plot of depth versus apparent resistivity (Figure 6b). The lithology of the layers based on the range of resistivity was inferred to comprise sandy clay, dry sandy, aquiferous sands and sandy. These materials were shown in model plot to be characterized by average resistivity values of 143.03Ωm, 2314.78 Ωm, 1076.50 Ωm and 5665.85Ωm respectively.
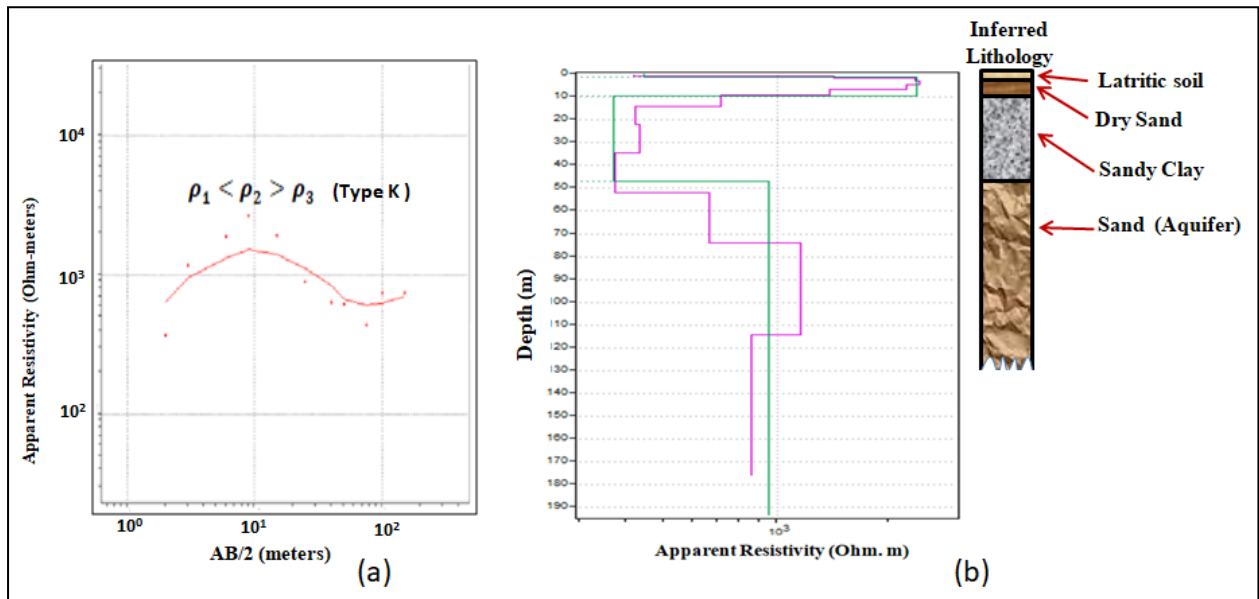
Figure 3: (a) Log-Log Graph of Apparent Resistivity against AB/2 for VES 1

(b) Interpreted Model plot of Depth against Apparent Resistivity for VES 1

Figure 4: (a) Log-Log Graph of Apparent Resistivity against AB/2 for VES 2

(b) Interpreted Model plot of Depth against Apparent Resistivity for VES 2

Figure 5: (a) Log-Log Graph of Apparent Resistivity against AB/2 for VES 3

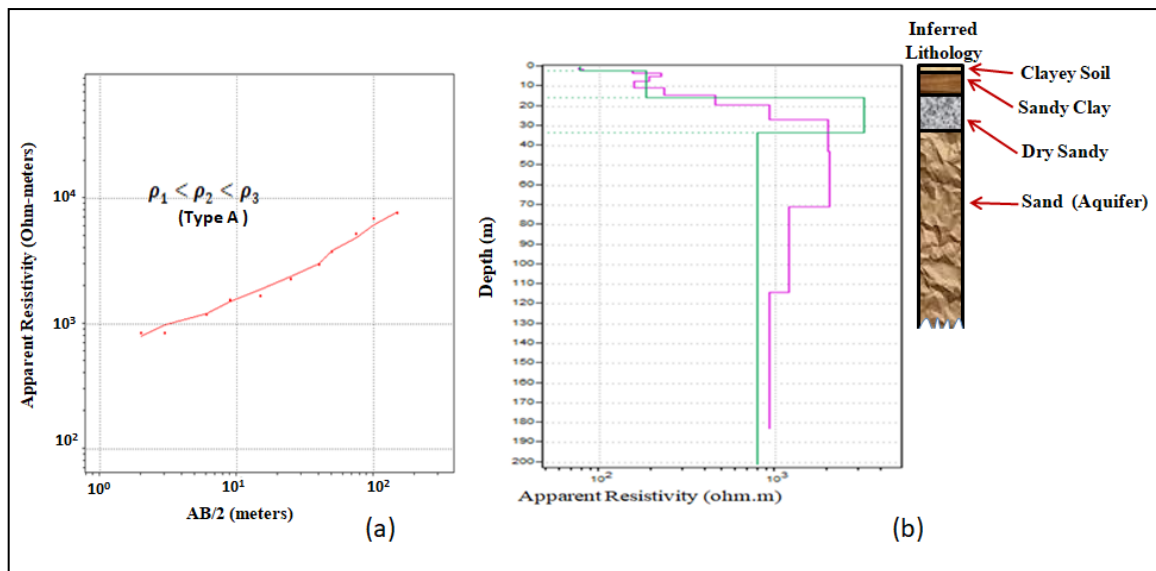**(b) Interpreted Model plot of Depth against Apparent Resistivity for VES 3**
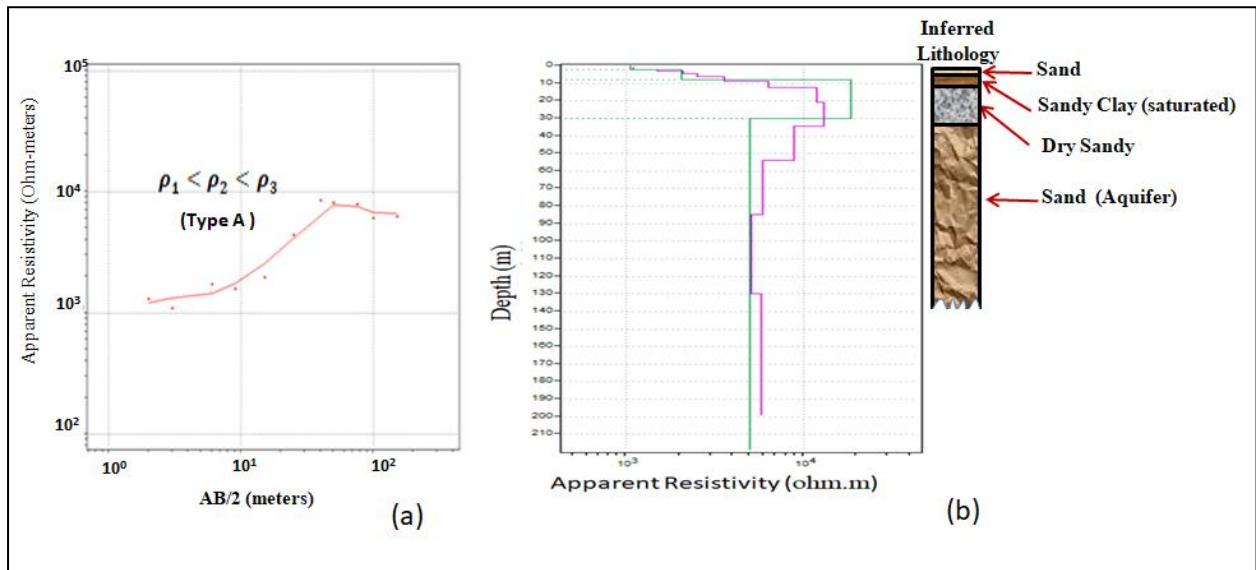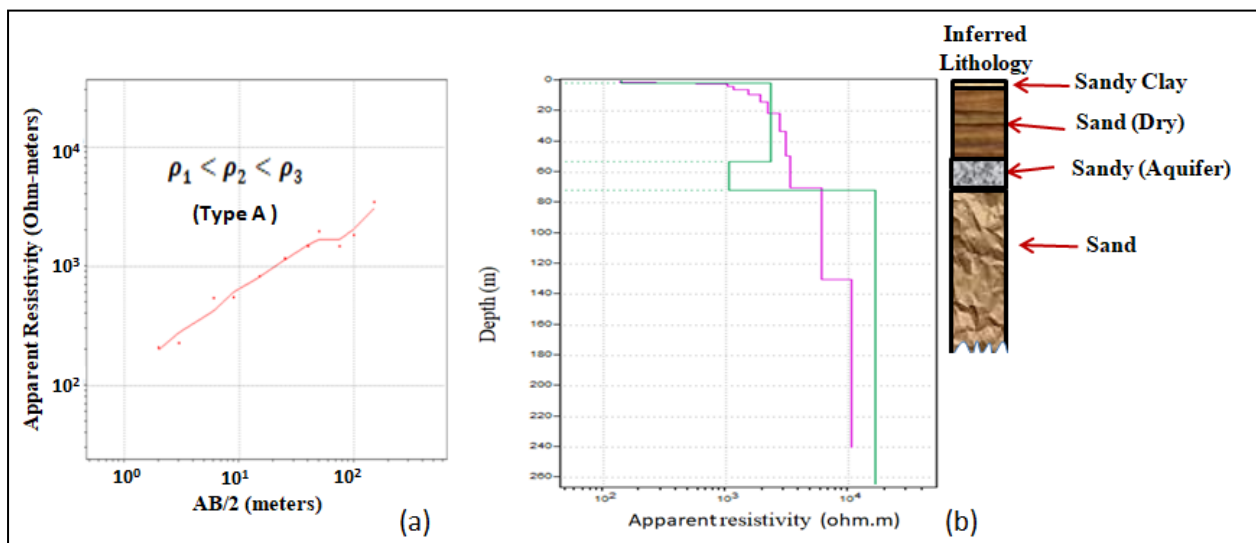

Figure 6: (a) Log-Log Graph of Apparent Resistivity against AB/2 for VES 4

(b) Interpreted Model plot of Depth Against Apparent Resistivity for VES 4.

DISCUSSION

The vulnerability of the groundwater at the dumpsite was calculated based on Dar-Zarrouk (DZP) parameters defined by longitudinal conductance which is layer thickness per unit resistivity. Based on equation 3 and the averages of the each layer average resistivity, the longitudinal conductance S_L was calculated hence the total S_L for the four VES points

$\left(\sum_{i=1}^{n}\left(\frac{h_i}{\rho_i}\right)\right)$ were computed. The total longitudinal conductance computed for each VES location is used for evaluation of overburden protective capacity of the earth materials underlain by aquiferous depths. Henriet (1976), classified the protective capacity ratings of earth materials based on their longitudinal conductance values. The protective capacity rating of earth materials into various grades range from rating ranges from good (0.70-1.00 mhos), moderate (0.20-0.69 mhos) to weak (0.10-0.19 mhos) and poor (<0.10 mhos). Based on the rating, the vulnerability of the site's subsurfaces was interpretation and accentuated. The total longitudinal conductance obtained for each VES location was recorded and compared with the DZP standard in order to ascertain their protective capacities (PC) respectively. Table 1 shows the summary of the protective capacity for the VES surveys carried out based on their total longitudinal capacities for the four-sounding calculated.

In comparison, the total longitudinal conductance of VES 1 0.107981 Ω^{-1} is found to have fallen within the range (0.1-0.19) which is the range for weak PC. VES 2 has a total longitudinal conductance of about 0.106999 Ω^{-1}. This also falls within the range (0.1-0.19) which is the range for weak PC. VES 3 has a total longitudinal conductance of about 0.086513 Ω^{-1}. This falls below the value 0.1 (< 0.10) which is considered to be of poor PC. VES 4 has a total longitudinal conductance of about 0.033966 Ω^{-1}. This also falls below the value 0.1 (< 0.10) which is considered to be of poor PC. Table 1 shows the summary of the protective capacity for the VES surveys carried out at the study site.

Table 1: Summary of the Protective Capacity for the VES Surveys Carried out at the Study Site.

VES No. & Coordinate Point	Layer number	Resistivity (ρ) Ωm	Thickness (m)	Depth to bottom (m)	Inferred lithology	longitudinal conductance (Ω^{-1})	Protective Capacity
$V1$ $6°13'53''N$ and $7°5'49''E$	1	444.16	1.22	1.22	Wet top sandy soil	0.002744	0.107981 (weak)
	2	2362.74	8.26	9.48	Dry sandy layer	0.003496	
	3	366.52	37.29	46.77	Sandy clay	0.1-01741	
	4	956.02	X	X	Sandy aquiferous layer		
$V2$ $6°13'60''N$ and $7°5'59''E$	1	76.79	2.14	2.14	Wet clay soil	0.027868	0.106999 (weak)
	2	183.75	13.52	15.66	Sandy Clay layer	0.073578	
	3	3209.33	17.82	33.48	Dry sandy soil	0.005553	
	4	792.49	X	X	Wet sandy and aquiferous		
$V3$ $6°13'60''N$ and $7°5'15''E$	1	1063.84	2.13	2.13	Sandy topsoil	0.002161	0.086513 (poor)
	2	154.07	5.84	8.15	Sandy clay	0.037750	
	3	1479.63	26.37	34.52	Dry sandy layer	0.046602	
	4	565.85	X	X	Wet sandy aquiferous layer		
$V4$ $6°13'53''N$ and $7°5'15''E$	1	143.03	1.70	1.70	Top clay soil	0.011886	0.033966 (poor)
	2	2314.78	51.11	52.18	Dry sandy layer	0.022080	
	3	1076.50	18.76	70.94	Wet aquiferous sand		
		5665.85	X	X	Probably sand		

The model 2DERT obtained from Pc at offset of about 500 m from the dumpsite showed a gradual decrease in resistivity down the depths. However, the tomography models obtained from profiles P1 and P2 at the dumpsite have some peculiarities which distinguish them from that of Pc of the control site. First, it is observed that 2DERT of P_1 and P_2 show outstandingly low resistivity values at their topmost layer which directly underlay the dumpsite. The low resistivity range of about 41.7 – 68.9 Ωm and 3 Ωm to 40 Ωm respectively obviously contrast with that obtained from the control site (p_c) at the range of 470 Ωm to 1000 Ωm. The contrast suggests that the topsoil of P_1 and P_2 has evidence of the presence of leachate. This is in agreement with the works of Akankpo and Igbokwe (2011), Ehilenboadiaye *et al. (*2018), Jegede *et al. (*2013), Ehirim *et al.* (2009), Umar *et al.* (2014), Abdullahi *et al*. (2013), Ekeocha *et al*. (2012), Ogungbe *et al*. (2012), Mohamed *et al*. (2012), and Adeoti *et al. (*2011) in which the presence of leachate was associated with distinctly low resistivity range less than 50 Ωm.

It was also observed that the 2D resistivity tomograms of profiles P_1 and P_2 show evidence of developing fractures. The fracture occurrences inferred at the topsoil of the tomography models suggests easy percolation into the subsurface. Furthermore, the inferred fractures through to the base of the tomograms suggest vulnerability of the depths beyond the limit of probe by tomography models. The presence of sandy soil horizons associated with high porosity observed in the 2DERT models could also have contributed to the vulnerability of the groundwater at depths. The interpreted VES survey lithology has also shown the presence of sandy soil which could enhance percolation of the inferred leachate. Furthermore, the rating of the total longitudinal conductance computed for the four VES survey fall within the range for both weak and poor protective capacity of the depths probed. VES 1 and 2 located at the NNE and eastern zones of the site showed weak protective capacity ($0.1 – 0.19 \ \Omega^{-1}$) characteristics. This suggests that the subsurface at NNE and eastern zones where VES 1 and 2 were carried out are moderately vulnerable. Whereas VES V_3 and V_4 located at the SSW and the western zones of the sites are characterized by poor protective capacity (< 0.1) range.

This suggests that the subsurface at SSW and western where VES 3 and 4 were carried out are grossly vulnerable to groundwater. In a nutshell, the aquiferous depths underlying the dumpsite are vulnerable to pollutants hence; the possibility of percolation of leachate down the depths to groundwater underlying the dumpsite is relatively high.

CONCLUSIONS

Ascertaining the vulnerability level of groundwater underlying the municipal dumpsite in Awka, Southeastern Nigeria in the foregoing study has involved two techniques in electrical method. While the 2DERT interpreted results showed evidence of percolated leachate both in the topsoil and in other shallow subsurface layers, the VES interpreted results showed weak and poor protective capacity at deeper layers underlain by groundwater. The shallow subsurface lithology underlying the dumpsite as determined from the two survey techniques is predominantly characterized by sandy soil which enhances percolation of the percolating leachate. Also, the inferred developing fracture delineated by the 2DERT showed that the percolation of the pollutants into the subsurface enhanced. The estimated range of weak to poor protective capacity of layers based on the DZP scale has shown the possibility of high

percolation of leachate into the groundwater at the site's vicinity. Therefore, the groundwater delineated at the municipal dumpsite is vulnerable to pollution.

This survey is not exhaustive in that the extent of lateral percolation of the pollutants beyond the site's vicinity was not investigated. Thus, it is eminent that for further studies, other geophysical methods of high resolution are applied at the site. Such methods include seismic refraction tomography (SRT) and very low frequency (VLF) surveys for further confirmation of the findings in this study and to know further other hydraulic contacts between the leachate and the groundwater. For this and other areas of similar occurrences, it is recommended that government should ensure and strictly adhere to construction of standard landfills for the safety of groundwater in the municipality. Other studies such as geochemical analyses of soil samples and physicochemical analyses of water samples from the area are viable investigations for evaluating the level of pollution or contamination at the site studied.

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