Application of Geoelectrical Resistivity Method to the Assessment of Groundwater Pollution: A case Study of Onibu-Eja Active Open Dumpsite, Osogbo, Southwestern Nigeria

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Abstract*-Electrical resistivity methods using the dipole – dipole array and Schlumberger Vertical Electrical Sounding (VES) techniques were conducted at the Onibu-Eja active open Dumpsite, Osogbo, Southwestern Nigeria in assessing groundwater pollution. Eight profiles and twenty four VES station measurements were carried out in the eastern and southern accessible area of the dumpsite. The VES data were quantitatively interpreted using the partial curve matching technique and 1-D inversions with WinResist software. The dipole-dipole data were inverted into 2-D resistivity images using the DIPPRO 4.0 software. Subsurface geologic layers delineated include the topsoil (20 to 998 Ωm and 0.4 to 1.0 m thickness), clay/weathered layer (63 to 333 Ωm and 1.2 to 7.6 m thickness), weathered basement (25 to 83 Ωm and 3.0 to 27.0 m thickness) and fractured/fresh basement (31 and 16213 Ωm). The results of the VES from the geosections suggest saturated weathered basement indicative of conductive material/leachate especially in traverse TR6 where resistivity less than 35 Ωm occurred. The aquifer has hydraulic conductivity (K) range 0.326 to 0.720 m/day indicating low conductivity. The transmissivity (T) values ranged between 1.47 m^2/day and 17.40 m^2/day, showing that the area has low to intermediate transmissivity capacity that can meet withdrawals for local water supply. The 2-D profiles distinctly delineated subsurface layers and contamination zones were also found within the aquifer units in the study area. These zones occurred at several traverses with resistivity values less than 31 Ωm and thickness variations from 5 m to 25 m. The leachate seeped to the bottom in vertical motion as seen at the eastern part of the dump site. This could be as a result of the relative permeability of the overburden, possible linear features and the downward sloping of the bedrock topography towards the dumpsite in that area. At the southern part of the dumpsite, the leachate is inferred to migrate laterally, which could imply that the neighboring rocks are relatively porous and permeable. This migration is considered slow because there was no trace of contamination 200 m away from the dumpsite.

Keywords- Electrical Resistivity; Dipole-dipole; Leachate; Hydraulic Conductivity; Transmissivity and Contamination Zone

I. INTRODUCTION

Groundwater, which is a main source of fresh water supply in developing countries, has been found to be highly vulnerable to pollution [1]. Because of the slowness in groundwater movement, once an aquifer is superfluously contaminated, the damage is essentially permanent and efforts to reduce the contamination are extremely costly. As a result, such source of water should be critically examined, because any undetected pollution or contamination of this resource poses a threat to the well-being and continued existence of mankind. Dumpsites, whether landfill or open dump is one of the most common sources of water contamination.

In Nigeria waste disposal management has become a major problem [2] and [3]. Disposal sites are not always properly planned; if planned at all. A common way of disposing waste is by dumping at a site which often for safety reason is located far from human settlements. However, with growing population and urbanization, such locations are becoming habited thereby constituting environmental and health hazards. The environmental and health hazards associated with open dumping of waste are well known [4-6]. For instance, deposited waste materials consume oxygen, undergo changes through chemical reactions and shallow sediments above the water table can be a source of toxic concentrations of leachate thereby contaminating usable aquifers and surface water supplies. The leachate develops when rain falls and infiltrates through the waste dump. This substrate can pervade across the unsaturated zone and transfer pollutants to the aquifer. [7] explained that leachate from municipal dumpsites composed of dissolved organic matter (e.g. vinyl chloride, benzene 1,1,1-Trichloroethene); inorganic ions such as ammonium ($NH4^+$), sodium (Na^+) and sulphate ($SO4^{2-}$) chloride (Cl^-), and heavy metals (manganese (Mn), zinc (Zn), iron (Fe) copper, chromium (Cr), lead (Pb) and cadmium (Cd)) which are harmful. Inorganic leachate increases liquid conductivity owing to the presence of dissolved salts [7]. As a result, the electrical resistivity of leachate is often very much lower than natural groundwater (e.g. the fresh water has a resistivity around 200 Ωm). When the leachate is introduced into the aquifer, the electrical resistivity of the saturated soil is reduced [8]. In this case shallow sources of groundwater, in the form of hand-dug wells are at high risk of contamination. With growing informal settlements, enough and good quality of water

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becomes obvious. For that reason the use of geoelectrical method for groundwater exploration and water quality evaluations has increased over the last few years.

The Vertical Electrical Sounding (VES) has been attested as a popular groundwater prospecting technique because of its simplicity. VES method gives detailed information of subsurface geology as explicitly reported by [9-10] and reemphasized by [11]. This method is regularly used to solve a wide variety of groundwater problems. Some recent studies include: determination of zones with high yield potential in an aquifer [12-13] groundwater exploration in hard rock [14-16]; estimation of aquifer specific yield [17] and delineation of groundwater contamination when electrical resistivity technique is applied across a suspected area identified as the reduced zone [8, 18-19].

The VES is combined with Electrical Resistivity Imaging (ERI), which provides a 2-D resistivity model of the subsurface [20]. 2D electrical resistivity imaging has been effective in hydrogeological investigations notwithstanding the equivalence problem in geoelectrical data associated with some 2-D interpretation software [21-22]. The combined techniques have been used to study the effect of dumpsite leachate on soil and groundwater contamination in parts of southwestern Nigeria and elsewhere [23]. For example, [24] while studying ancient dumpsites in Akure metropolis showed that the weathered layer which constitutes the main aquifer units contains zones with characteristically very low layer resistivity values (< 10 Ωm) that might have been precipitated by conductive leachate from the waste dumpsites. Reference [25] explained that Olubonku dumpsite was characterized by relatively low resistivity values of 25 Ωm which was indicative of polluted topsoil. Reference [26] delineated a layer with low resistivity zone (3-40 Ωm) which was indicative of zone of high leachate activities across the abandoned Gaborone Landfill, Botswana.

The aim of this study is the geophysical characterization around an active open waste dumpsite in Osogbo, Southwestern, Nigeria, with the view to provide geophysical information on the extent of contamination of the groundwater aquifers. This information will be useful in formulating an appropriate land use, management policy and reclaiming the affected land areas and/or re-location of nearby residents.

A. The Study Area

The study area, Onibu-Eja Active open dumpsite, is within Osogbo in Osun State, Southwestern Nigeria. It is sited between latitudes N07° 45.505′ and N07° 48.552′ and longitudes E04° 29.611′ and E04° 34.321′ (Fig. 1a). Osogbo has a sub-humid climate with average annual rainfall of 1241 mm [27]. In a year, the warmest month is March with an average temperature of 28.3 °C while August has the lowest average temperature of 23.7 °C. The area has some rivers flowing NW-SE and discharging into river Osun. Although, the nearest river is a few kilometers away from the dumpsite, the direction of groundwater flow might be in the same NW–SE direction.

The study area is situated within the pre-Cambrian basement complex rocks of southwestern Nigeria [28]. One of the three major lithological components that constitute the geology of Nigeria is the Basement Complex. The main metamorphic rock types mapped within the study area are quartzite and banded gneiss (Fig. 1a). The quartzite is highly fractured and outcrops as a massive ridge (Fig. 1b) mostly in the southern part of the area. Bands and joints are the main structures discovered in both rock types.

The Onibu-Eja active open dumpsite is situated along Osogbo-Iwo highway (Fig. 2a.) and is reachable through a dirt road. Dumping of waste started nearly two and a half decades ago without any engineering works and holds an estimated 152 metric tons of waste based on the measured dimensions (Fig. 2b). It serves as the dumpsite where all residents of the Osun state capital, Osogbo and adjoining towns dump different types of materials, including wastes from kitchens, farms, hospitals, offices, workshops and industries (Fig. 2b). Percolating groundwater provides a medium through which waste, particularly organics can undergo degradation into simpler substances through biochemical reactions involving dissolution, hydrolysis, oxidation and reduction processes [29].

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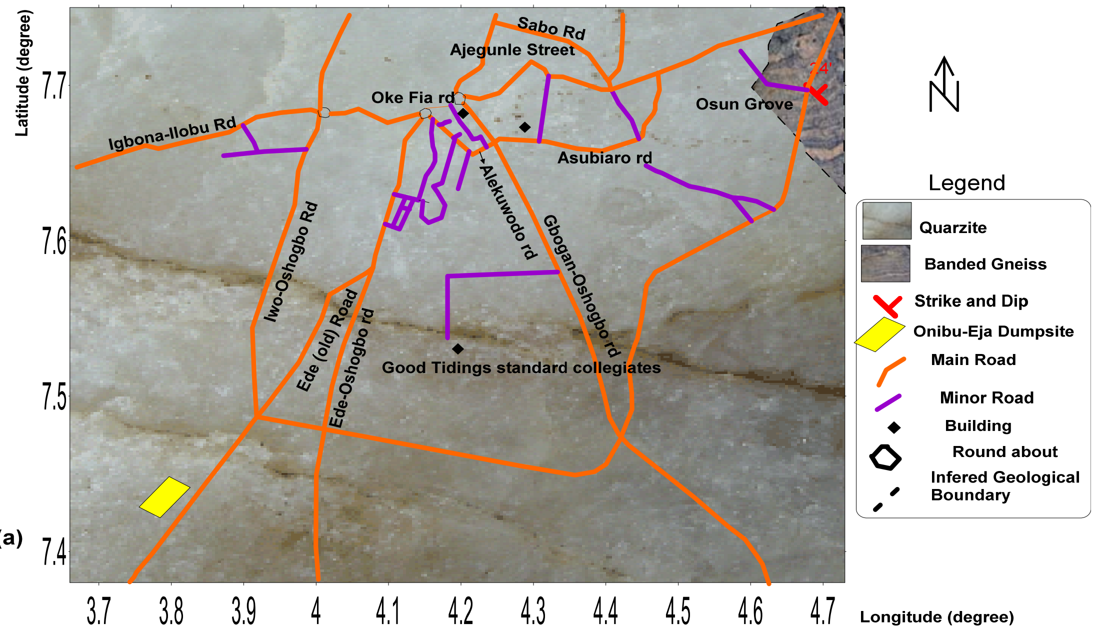
(a)



(b)

Fig. 1 (a) The generalized geology map and (b) Quartzite outcrop seen along traverse TR1 in the study area

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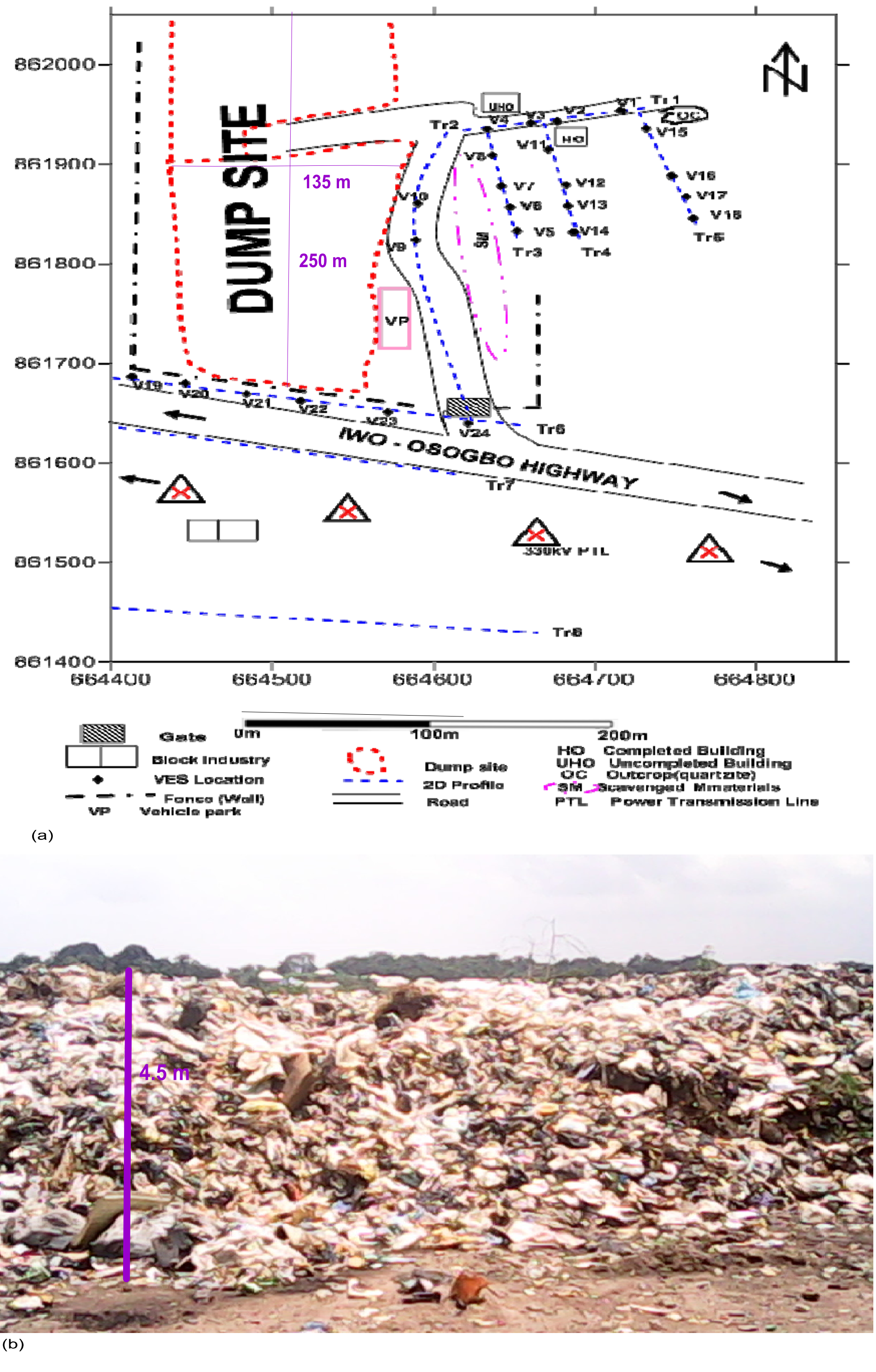

Fig. 2 (a) The survey map of the study area and (b) a section of the active open dumpsite showing ~4.5 m layer of assorted waste

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II. METHODOLOGY

Eight traverses of lengths ranging between 105 and 240 m were established in directions approximately W-E and N-S (Fig. 2a). Traverses TR1 to TR5 were in the eastern part while TR6 to TR8 were at the southern part of the dump site. 2-D ERI [30] using dipole-dipole configuration and the Schlumberger vertical electrical sounding [31] techniques were adopted for data acquisition. The dipole-dipole survey was used to determine the lateral and vertical variation in apparent resistivity of the subsurface beneath the eight traverses. Dipole-dipole provides the highest resolution and is most sensitive to vertical resistivity boundaries when compared to other arrays [32]. However, it has a low resolution of depth at large electrode spacing and produces noisy data at sites with cultural relics [32-33]. An inter-electrode spacing, ***a*** = 5 m was adopted while inter-dipole expansion factor (n) was varied from 1 to 5. The dipole-dipole data were inverted into 2-D subsurface images using the DIPRO™ 4.0 software [34]. The program automatically creates a 2-D model by dividing the subsurface into rectangular blocks and calculates apparent resistivity using the finite difference method [35-36]. Five iterations were carried out on the resistivity of the blocks to minimize the variation between the measured and the calculated values. The root mean square (rms) errors of the inversion process were between 1.5 to 4.0%.

For the VES, twenty-four sounding stations were carried out along traverses TR1 to TR6 with current electrode spacing (AB/2) varying from 1 to 65 m. The Schlumberger configuration of electrodes provides for high signal-to-noise ratios, good resolution of horizontal layers, and good depth sensitivity [37]. It is easier to use than the Wenner technique because only two of the four electrodes are moved between successive readings, relatively low cost and its capacity to distinguish between saturated and unsaturated layers [38]. The VES data were inverted into 1-D using suitable software to generate resistivity and layer thickness values. The electrical resistivity contrast between lithological units enabled the delineation of geoelectric layers and identification of aquifer units.

A. Estimation of Aquifer Parameters

The estimation of aquifer parameters involves the analysis and interpretation of soil and water samples of drilled boreholes, but due to the fact that there was absent of drilled wells or boreholes in the study area, a noninvasive geoelectrical resistivity method (vertical electrical sounding) is used as an alternative to pumping tests [39]. In the basement complex of Nigeria, the main aquifer components are the weathered basement and fractured basement [40-41]. Well pump tests and well log data are used to obtain parameters; hydraulic conductivity and transmissivity. However, these can be determined using resistivity data by establishing the relationship between aquifer transmissivity (T), hydraulic conductivity (K) and aquifer thickness (h) [42-43] and is given by:

$$T = K\, h \tag{1}$$

In a hardrock aquifer (basement complex)

$$K = 8 \times 10^{-6}\, e^{-0.0013\rho} \text{ [42]} \tag{2}$$

where ρ is resistivity of the aquifer.

III. RESULT AND DISCUSSION

A. Characteristics of the Resistivity Sounding Curves

The observed depth sounding curves were classified into different resistivity type curves and the interpreted layers vary from 3 to 5. Different types of curves representing the distribution of resistivities of subsurface layers (Table 1) were classified for all the VES points. They are H ($\rho_1>\rho_2<\rho_3$), HK ($\rho_1>\rho_2<\rho_3>\rho_4$), KH ($\rho_1<\rho_2>\rho_3<\rho_4$), QH ($\rho_1>\rho_2>\rho_3<\rho_4$) and HKH ($\rho_1>\rho_2<\rho_3>\rho_4<\rho_5$) types. The H-type curve, for example, contains a low resistivity layer being in between more resistant materials [44]. Table 1 depicts the summary of the VES parameters. The KH type curve is the most predominant of all the multilayered curves with the percentage occurrence of 37%. H type curve is the next predominant accounting for 21%. The HK and HKH type curves constitute 17% each while QH type curve has a percentage occurrence of 8%. The percentage of occurrence of each curve type is shown in (Fig. 3).

According to [45-46] the typical lithostratigraphy in a basement complex terrain consists of top layer, highly weathered layer, which are mostly clay/clayey sand and then fractured/fresh basement rock. In the study area, the resistivity of the topsoil varies from 20 - 998 Ωm and the thickness ranges between 0.4 – 1.0 m. The clay/weathered layer have resistivity (63 – 333 Ωm and 1.2 – 7.6 m thickness); the resistivity of the weathered basement varies from 25 – 83 Ωm and 3.0 – 27.0 m thickness, while the resistivity of the fractured/fresh basement ranges between 31 Ωm and 16213 Ωm.

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TABLE 1 QUANTITATIVE INTERPRETATION SHOWS GEOELECTRIC PARAMETERS FROM THE OSOGBO ACTIVE DUMPSITE

Location	Layer1		Layer2		Layer3		Layer4		Layer5		Curve
VES	h_1(m)	ρ_1(Ωm)	h_2(m)	ρ_2(Ωm)	h_3(m)	ρ_3(Ωm)	h_4(m)	ρ_4(Ωm)	h_5(m)	ρ_5(Ωm)	type
1	0.5	805	1.6	333	9.1	54	∞	398			QH
2	0.4	179	6.0	258	24.2	136	∞	16213			KH
3	0.4	119	3.7	73	4.4	271	13.6	31	∞	6555	HKH
4	0.4	168	3.0	243	19.3	52	∞	5648			KH
5	0.5	127	7.9	108	9.2	49	∞	7182			QH
6	0.5	161	2.8	78	3.4	212	27.0	54	∞	7107	HKH
7	0.5	97	5.1	161	22.5	62	∞	8618			KH
8	0.6	227	3.5	91	3.8	210	14.6	47	∞	2824	HKH
9	0.4	114	2.8	151	24.0	43	∞	4993			KH
10	0.5	65	3.5	69	19.8	65	∞	5128			KH
11	0.9	143	18.5	70	∞	3106					H
12	1.0	132	9.0	44	∞	244					H
13	0.5	219	3.1	52	4.9	161	16.5	54	∞	1583	HKH
14	0.7	299	23.9	83	∞	3581					H
15	0.5	269	6.5	57	9.8	252	∞	39			HK
16	0.5	280	1.2	63	6.0	579	∞	145			HK
17	0.6	755	2.1	176	4.2	523	∞	240			HK
18	0.8	998	6.3	126	3.0	1253	∞	36			HK
19	0.5	20	4.0	92	8.6	34	∞	691			KH
20	0.4	67	2.8	158	13.8	52	∞	2813			KH
21	0.3	75	2.9	109	7.9	45	∞	1841			KH
22	0.5	32	1.8	63	8.3	43	∞	1900			KH
23	0.7	82	1.8	82	5.2	25	∞	1280			H
24	0.4	170	12.0	36	∞	307					H

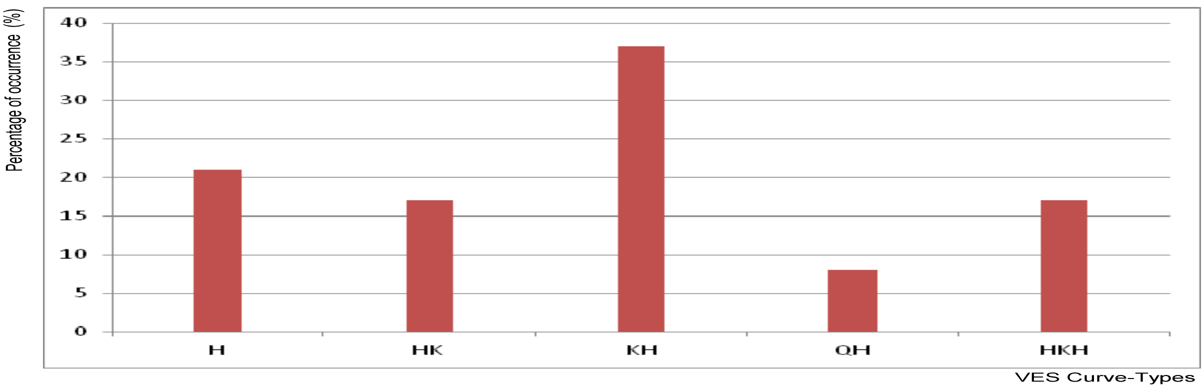

Fig. 3 The frequency of occurrence of the VES type curves in the study area

B. Conceptual geological cross sections

The conceptual geological cross sections present the 2-D view, vertical and lateral variations, of the geoelectric parameters (resistivity and depth) from the electrical resistivity sounding data inversion [47]. One of the significance of the sections is that it enables one to see vividly where there is thin overburden and/or thick overburden within the sounding locations and thereby enhance the understanding of the subsurface geology of the study area. Two geoelectric/geological sections were drawn, (Fig. 4a, b).

The conceptual geological cross section in Fig. 5a was constructed by relating four VES points on traverse TR3 parallel to the dumpsite. The topsoil has resistivity (97 – 227 Ωm, thin thickness ≈ 0.5 m). The geologic interpretation inferred that the topsoil may be clay/sandy clay. Perched clay is delineated on VES 6 and 8. The weathered layer has resistivity (108 to 212 Ωm

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and 3.4 to 7.9 m thickness), indicative of permeable and porous unsaturated sandy clay/clayey sand. The saturated clay/leachate weathered basement (47 - 62 Ωm, thickness 9.2 to 27.0 m) is underlain by the fresh basement of resistivity (2824 - 8618 Ωm).

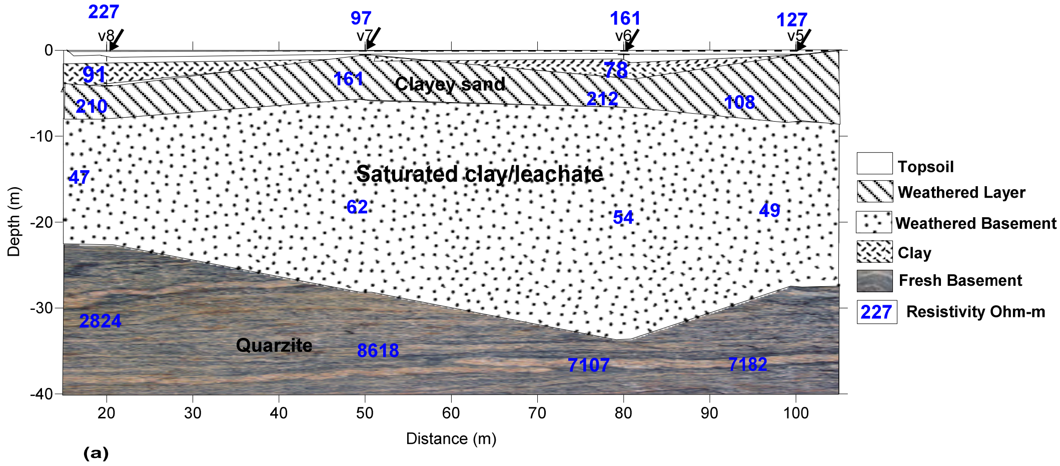

Fig. 4a Conceptual geoelectric/geological cross section along traverse TR 3 in North-South direction. The VES parameters (ρ,h) at each point are interpolated linearly to construct the geosection

The geological/geoelectric section 4(b), drawn relating six VES points along TR6 exhibited four subsurface geologic layers except at VES point 24 that has three subsurface layers. These include topsoil with resistivity (20 - 170 Ωm and 0.3 - 0.7 m thickness) indicative of clay except VES point 24 that may be sandy clay. The topsoil is underlain by a thin weathered layer with resistivity (63 - 158 Ωm and 1.8 - 2.9 m thickness) interpreted to be an unsaturated alternating clay and sandy clay. The weathered basement (resistivity, 25 - 52 Ωm and 5.2 - 13.8 m thickness) is inferred to be highly saturated with conducting material which could be contaminant (leachate) from the dumpsite. The weathered basement is underlain by the basement which may be fractured or fresh basement depending on their resistivity values.

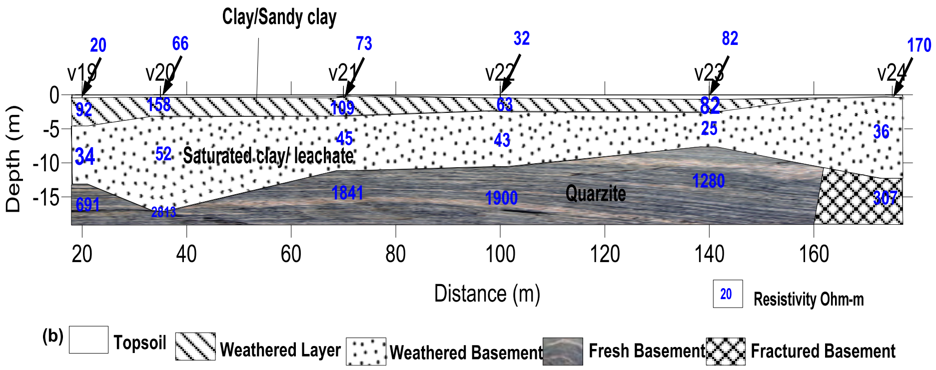

Fig. 4b Conceptual geoelectric/geological cross section along traverse TR6 in West-East direction. The VES parameters (ρ,h) at each point are interpolated linearly to construct the geosection

C. Correlation between VES and Borehole Log

There was neither existing borehole nor log within the dumpsite area. However, a borehole log [48] from a well drilled within Osogbo was comparable with VES 7 obtained along traverse TR3. The total depth of overburden in the surveyed area ranged from 7.7 to 33.6 m which is in correlation with the borehole depth as shown in (Fig. 5a, b). The average depth to water level and depth to bottom of twenty hand dug wells in the neighboring community settlements in the study area is 5.36 m and 7.07 m respectively [49-50]. Correlating the weathered layer depths, borehole log and average depth to water levels, the groundwater table might be between 3.5 m and 5.5 m. It implies that the groundwater table is shallow and therefore could be susceptible to pollution. However, this is also influenced by bedrock depth and basement topography [51-52]. A geoelectric/geological section taken across the middle of traverses TR2 to TR5 in the West – East direction showed a downward sloping basement towards the dumpsite (Fig. 6) which could cause leachate from the dumpsite to accumulate within the peripheries.

The geological structure in basement complex terrain is that the bedrock is overlain by a weathered basement of variable thickness, which forms the main aquifer [53-54]. The parameters of these aquifers were determined as shown in Table 2. Hydraulic conductivity is a measure of the permeability of fluid through a medium [41]. The aquifer hydraulic conductivity (K) varied from 0.326 to 0.720 m/day with an average value of 0.616 m/day. The values indicate low conductivity meaning that groundwater flow in the area is not simple but complex because of the geologic controls of the confined aquifers. The transmissivity (T) values range from 1.47 m^2/day to 17.40 m^2/day with a mean value of 8.76 m^2/day (Table 2). Applying the classification of transmissivity magnitude [55] shown in Table 3, the area has low to intermediate transmissivity capacity that meet withdrawals for local water supply (private consumption, small communities and industrial

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factory). Areas with high transmissivity values can be identified as areas of high water bearing potential, and aquifer materials are highly permeable to fluid movement.

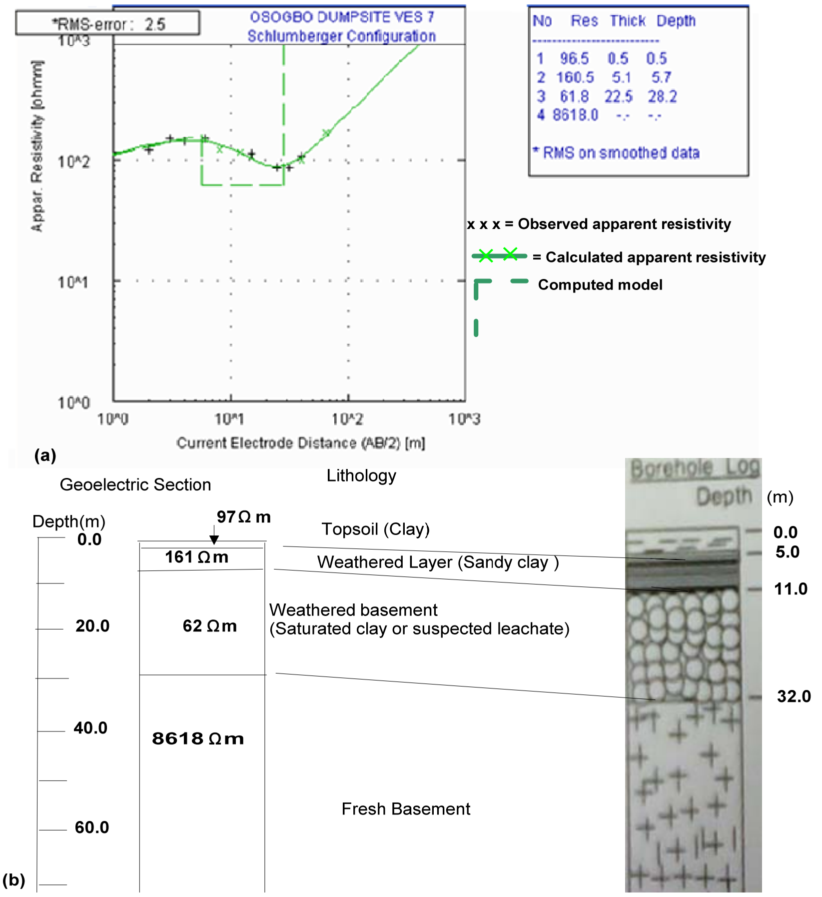

Fig. 5 (a) VES 7 Field Curve compared with a Drilled Borehole at Oshogbo, Osun State, and the study area. (b) Lithologic and Geoelectric Section of the Borehole Site (Modified after [49])

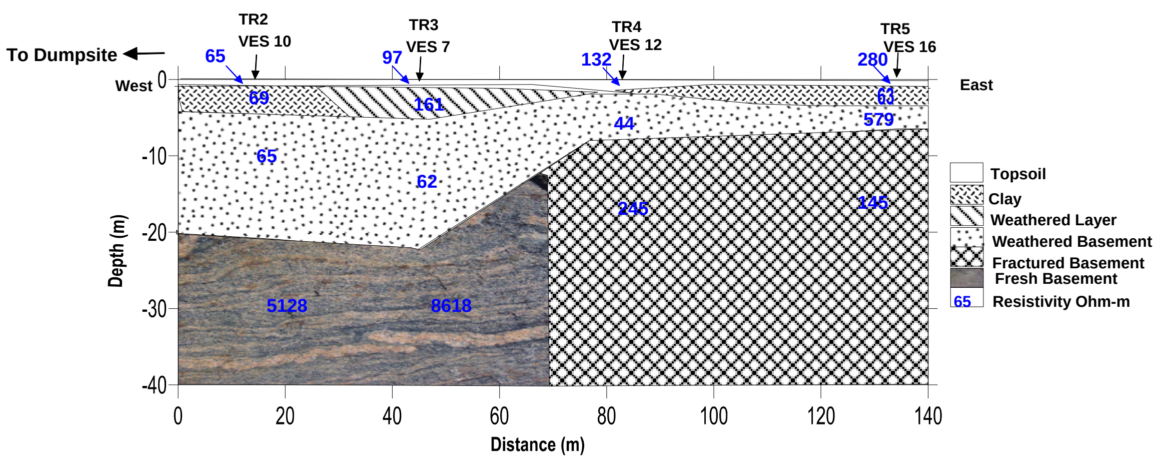

Fig. 6 Geoelectric/geological section across traverses TR2-TR5 showing sloping basement towards the dumpsite. The VES parameters (ρ,h) at each point are interpolated linearly to construct the geosection

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TABLE 2 SUMMARY OF RESULTS OF AQUIFER PROPERTIES OF VES POINTS

VES point	Aquifer thickness (m)	Layer resistivity (Ωm)	Hydraulic conductivity (m/s) x 10^{-6}	Hydraulic conductivity (m/day)	Transmissivity (m^2/day)
1	9.1	54	7.46	0.644	5.86
2	24.2	136	6.70	0.579	14.02
3	13.6	31	8.33	0.720	9.79
4	19.3	52	7.48	0.646	12.47
5	9.2	49	7.51	0.649	5.97
6	27.0	54	7.46	0.645	17.40
7	22.5	62	7.38	0.638	14.35
8	14.6	47	7.53	0.650	9.49
9	24.0	43	7.57	0.654	15.69
10	19.8	65	7.35	0.635	12.58
11	18.5	70	7.99	0.690	12.77
12	9.0	44	7.56	0.653	5.87
13	16.5	54	7.46	0.645	10.63
14	23.9	83	7.18	0.620	14.83
15	9.8	252	5.77	0.499	4.88
16	6.0	579	3.77	0.326	1.95
17	4.2	523	4.05	0.350	1.47
18	6.3	126	6.79	0.587	3.70
19	8.6	34	7.65	0.661	5.69
20	13.8	52	7.48	0.646	8.92
21	7.9	45	7.55	0.652	5.15
22	8.3	43	7.57	0.654	5.43
23	5.2	25	7.74	0.669	3.48
24	12.0	36	7.63	0.659	7.92
Average			**7.12**	**0.616**	**8.76**

TABLE 3 CLASSIFICATION OF TRANSMISSIVITY MAGNITUDE (KRASNY, 1993)

Transmissivity (m^2/day)	Description	Groundwater yielding capacity
>1000	Very high	Withdrawal of great regional importance
100 – 1000	High	Withdrawal of lesser regional importance
10 – 100	Intermediate	Withdrawal of local water supply (eg.small community)
1 – 10	Low	Smaller withdrawal for local water supply (private consumption)
0.1 – 1	Very low	Withdrawal of local water supply with limited consumption
< 0.1	Impermeable	Sources for local water supply are difficult

D. 2-D Resistivity Structure for the Active Dumpsite

The 2-D resistivity structure was set up to have a vivid view of the subsurface because it shows an interpretation of unilateral data and its contours. In the 2-D resistivity structure, the subsurface resistivity depicts a wide variation in the rock or lithology resistivity at various depths along the profiles. Four profiles (TR1, TR2 in the east and TR6, TR7 in the south) close to the dumpsite are discussed.

Fig. 7(a) shows the 2-D resistivity structure along traverse TR1. The first layer with a resistivity varying from 50 to 1880 Ωm and thickness below 2 m is interpretative of topsoil depicting clay/sand and dried laterite at the far end of the eastern part might be linked with the quartzite outcrop in the area (cf. Fig. 1b). The weathered layer has resistivity ranging from 37 to 627 Ωm, thickness less than 4 m. The weathered/fractured basement was delineated at a depth of approximately 17 m with resistivity ranging from 16 to 589 Ωm. The low resistivity value recorded especially towards the west of the profile, close to the dumpsite, could be an indication of accumulation of leachate and contamination of saturated clay/sand.

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The 2-D resistivity structure profile presented in (Fig. 7b) is on average 3 m away from the dumpsite and covers a distance of 240 m along traverse TR2. The topsoil/weathered layer has resistivity values varying from 57 to 328 Ωm with thickness ranges between 0.5 and 10 m. The weathered basement has resistivity (5 to 301 Ωm, 10 to 20 m thickness. These very low resistivity zones (in blue) are suspected pollution zones [25-26, 56-58] in clay/sand soil. The low resistivity is attributed to many anions from the leachate which resulted in an increase in dissolved salts in the ground; subsequently increase in its conductivity [23]. The leachate plume infiltrated vertically to the bottom as seen at the eastern part of the dumpsite. This could be as a result of the relative permeability of the overburden. The downward sloping nature of the bedrock towards the dump site (Fig. 6) might have caused the contaminant to concentrate close to dumpsite (Fig. 8) thereby increasing the density [59-60]. It could also be inferred that the majority of the VES points (1 – 18) located in the eastern part of the dumpsite the aquifers have moderate transmisssivity which might have caused the presence of leachate plume.

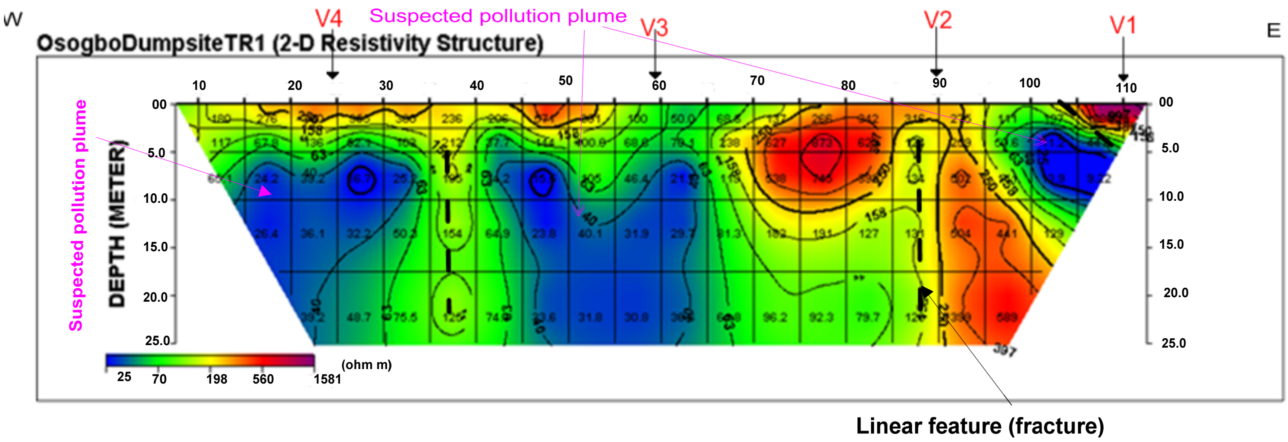

Fig. 7a 2-D Resistivity structure profile along traverse TR1

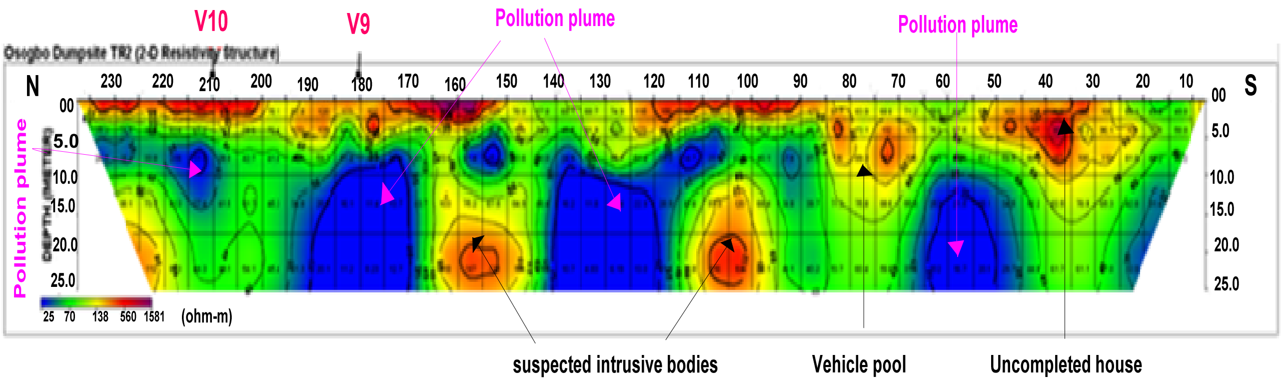

Fig. 7b 2-D Resistivity structure profile along traverse TR2

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Fig. 8 Percolated leachate close to the dumpsite along TR2

The profile shown in Fig. 9a was at a distance of 2 m south of the dumpsite and covered a distance of 195 m along traverse TR6. The topsoil/weathered layer has resistivity varying from 27 to 245 Ωm within 5 m thickness. This is indicative of clay/sandy clay. The weathered basement has a very low resistivity ranging from 16 to 47 Ωm, and thickness 5 to 10 m and it is seen in blue color covering almost the entire length of the traverse. The zone is the suspected pollution plume and the direction is as indicated in Fig.9a. A narrow zone with resistivity as low as 7 Ωm occurred in blue color towards the eastern part which implied highly fractured rocks saturated with conducting materials. Two zones of high resistivity ranging between 629 and 1396 Ωm, descriptive of fresh basement are seen in reddish color. The zones are separated by a suspected linear feature (fracture).

The profile in Fig. 9b was taken approximately 55 m away from the fence along traverse TR7 and covered a distance of 180 m. The topsoil at depth below 3 m has a resistivity ranging from 40 to 134 Ωm and this is descriptive of clay/sandy clay. The weathered layer is dominated by low resistivity varying from 9 to 47 Ωm which is an indication of saturated conducting materials suspected to be a pollution plume. The direction is seen as indicated in the profile. A very low resistivity zone (in blue) between 12 to 24 Ωm descriptive of highly weathered basement is at the eastern part between lateral distances 135 to 180 m. Two zones of high resistivity between 556 to 2176 Ωm possibly fresh basements are separated by a suspected linear feature (fracture).

The leachate in the southern part is inferred to migrate laterally as indicated in TR6 and TR7. This could imply that the neighboring rocks are porous and permeable. The fractured basement is saturated with conducting materials with resistivity values < 24 Ωm.

The interpretation of geoelectric/geological cross section from VES Fig. 4b shows a close coincidence with the 2D inverse model of Fig. 9a comparing the values of the resistivity for the topsoil, weathered layer and weathered basement. However, 2D imaging technique is more accurate, and it is better at recognizing more layers especially horizontal heterogeneities than that of the VES. It gives a clearer and detailed picture of the subsurface lithology than that of the VES resistivity technique.

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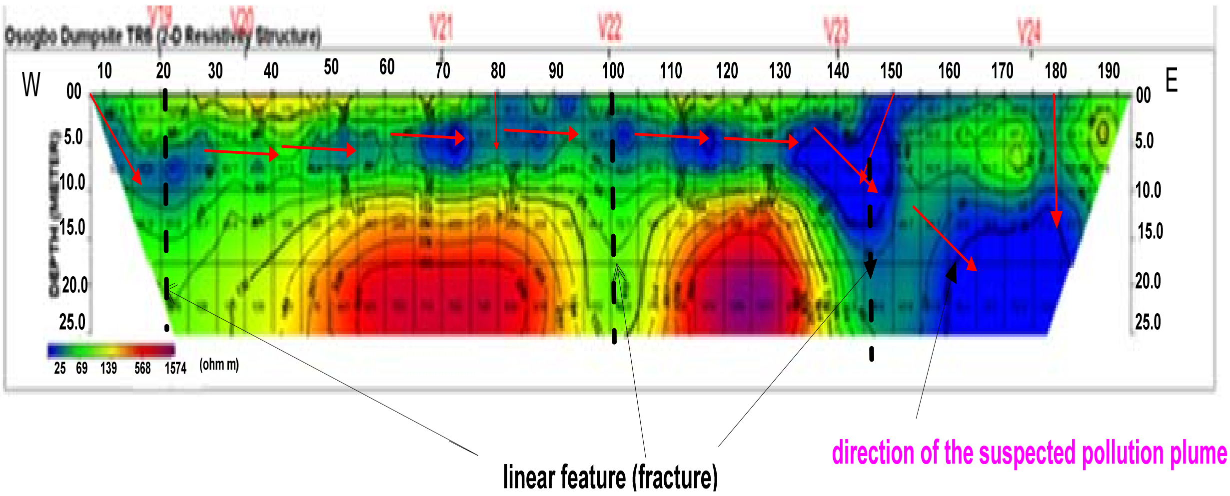

Fig. 9a 2-D Resistivity structure profile along traverse TR6

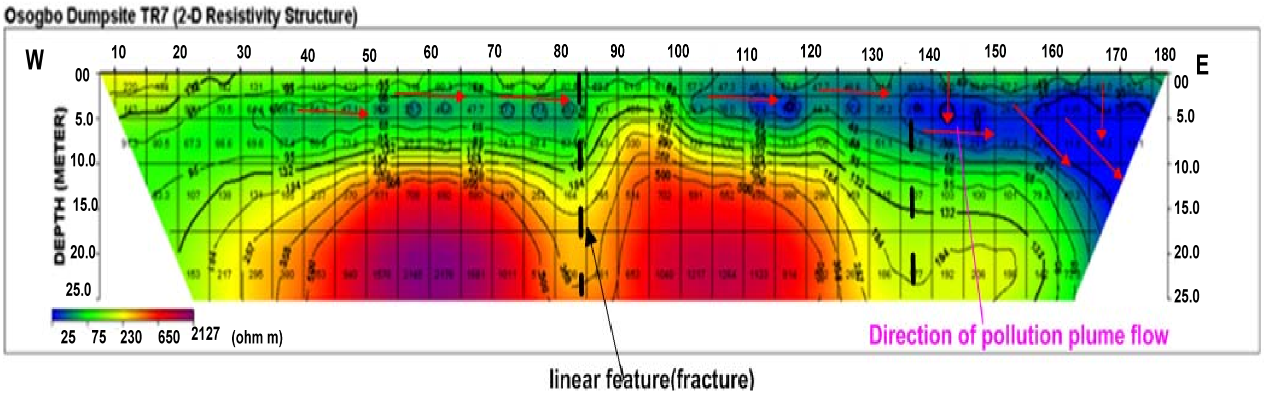

Fig. 9b 2-D Resistivity structure profile along traverse TR7

IV. CONCLUSIONS

The geoelectric method was used in the assessment of environmental conditions and groundwater contamination in an active open dumpsite at Onibu-Eja, Osogbo, Southwestern Nigeria. Eight traverses established around the dumpsite were surveyed using electrical resistivity sounding and 2-D profile imaging. The result of the VES has helped to characterize the subsurface geology around the dumpsite. The geologic layers delineated were characterized into three to five subsurfaces. These include the topsoil, clay/weathered layer, weathered basement and fractured/fresh basement. Topsoil has resistivity range of 20 to 998 Ωm, and 0.4 to 1.0 m thickness, weathered layer of resistivity 63 to 333 Ωm and 1.2 to 7.6 m thickness weathered basement (resistivity and thickness range from 25 to 83 Ωm and 3.0 to 27.0 m) and fractured/ fresh basement with resistivity range between 31 to 16213 Ωm. The bedrock was sloping towards the dumpsite at the eastern part which could cause leachate from the dumpsite to accumulate within the nearby surroundings. Conceptual geoelectric/geological sections of the VES could suggest saturated weathered basement contaminated as a result of leachate accumulation or the presence of in situ weathered clay material. The former is favored as the traverses are close to the dumpsite. Also low to intermediate transmissivity groundwater yielding capacity able to meet withdrawals for local water supply (private consumption, small communities and industrial factory) was obtained in the study area.

2-D profiles also delineated the subsurface layers and some contamination zones were interpreted within the aquifer units for the study area. These zones occurred as low resistivity with values < 31 Ωm and thickness < 5 m to 25 m. The leachate plume leaked to the bottom as observed at the eastern part of the dumpsite. This could be as a result of the relative permeability of the overburden, linear features and the downward sloping topography of the bedrock towards the dumpsite. At the southern part of the dumpsite, the leachate is seen migrating laterally, which could imply that the neighboring rocks are relatively porous and permeable. Further, hydro-chemical analysis of water samples and streams spanning few kilometers away fell within the tolerable range of the World Health Organization (WHO) with the exception of streams very close to the dumpsite [49-50]. Although the pollutant has not migrated far, it is good to carry out regular assessment of the dumpsite and its environs.

A multidisciplinary technique of hydrogeological, geochemical and geophysical techniques should be adopted, as a follow up on the dumpsite, to be able to characterize it effectively. The geophysics could include Induced Polarization (IP) and Self-

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polarization (SP) which have been shown at many waste disposal sites to delineate and possibly to some extent characterize the buried waste [61-62] as well as locate and characterize sources generated by flows of fluid or ions [63]. Drilling of boreholes in some selected positions could help to ascertain the lithological formations and thereby characterize the subsurface. Soil and water sample analysis could be carried out to determine the presence of heavy metals, conductivity, total dissolved solid, suspended solids, color, smell, biological parameters like total coliforms, faecal coliforms and helminth eggs etc.

Even though there has not been any reported outbreak of waterborne disease linked to the dumpsite, it would be in the best interest of the community to recommend decommissioning of site because it has been surrounded by residential settlements. It should be relocated to properly construct, highly effective hydraulic barrier or engineered liner systems that would provide resistance to advective/diffusive migration of contaminants, thereby giving excellent protection to the environment and the public [64-66]. On the present dumpsite, barriers such as trenches, cutoff or defense walls should be maintained where leachate migration threatens or contaminates the aquifer [67] while further remediation is planned.

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