


Assessment of groundwater vulnerability to leachate infiltration using electrical resistivity method

G. O. Mosuro¹  · K. O. Omosanya² · O. O. Bayewu¹ · M. O. Oloruntola³ · T. A. Laniyan¹ · O. Atobi¹ · M. Okubena¹ · E. Popoola¹ · F. Adekoya¹

Received: 27 June 2015 / Accepted: 2 February 2016 / Published online: 20 February 2016
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Abstract This aim of this work is to assess the degree of leachate infiltration at a dumpsite in Agbara industrial estate, Southwestern Nigeria using electrical resistivity techniques. Around the dumpsite were 45 vertical electrical sounding (VES) stations and 3 electrical resistivity tomography profiles. Current electrode spread varied from 300 to 600 m for the electrical sounding. Electrode configuration includes Schlumberger and Wenner array for sounding and profiling. The state of leachate contamination was tested using parameters such as aquifer vulnerability index, overburden protective capacity and longitudinal unit conductance (S_i) derived from the apparent resistivity values. Four principal geoelectric layers inferred from the VES data include the topsoil, sand, clayey sand, and clay/shale. Resistivity values for these layers vary from 3 to 1688, 203 to 3642, 123 to 388, and 67 to 2201 Ω m with corresponding thickness of 0.8–2.4, 2.5–140, 3–26 m and infinity, respectively. The leachate plume occurs at a maximum depth of 10 m on the 2-D inverse models of real electrical resistivity with an average depth of infiltration being 6 m in the study area. The correlation between longitudinal conductance and overburden protective capacity show that aquifers around the dumpsite have poor protective capacity and are vulnerable to leachate contamination.

Leachate infiltration is favored by the absence of lithological barriers such as clay which in the study area are either mixed with sand or positioned away from the aquifer.

Keywords Leachate · Vulnerability · Resistivity · Tomography · Protective capacity

Introduction

Indiscriminate waste disposal constitutes a major source of pollution in developing countries (Tijani et al. 2004; Olayinka and Olayiwola, 2001; Ariyo et al. 2013). Wastes are mostly dumped in open landfill and abandoned mineral workings which are chosen due to convenience or proximity to the waste source (Desa et al. 2009; Jhamnani and Singh 2009), rather than for environmental, geologic or engineering considerations or recourse to potential bedrock and groundwater contamination (Chambers et al. 2006; Perozzi and Holliger 2008). Infiltration of rainfall into landfill together with the biochemical and chemical breakdown of the wastes produces leachate which is high in suspended solids and of varying organic and inorganic contents. If the leachate enters surface or groundwater before sufficient dilution occurs, serious contamination incidents would transpire (Desa et al. 2009).

The application of geophysical methods for hydrogeological site characterization has increased in the last decade (Vereecken et al. 2004; Herckenrath et al. 2013). Several authors have applied geophysical methods to solve hydrogeological related problems (Faneca Sánchez et al. 2012; Burschil et al. 2012). Since leachate plumes are often more electrically conductive than the surrounding pore waters, they can be detected by electrical geophysical

✉ G. O. Mosuro
motola_abdul@yahoo.com;
mosuro.ganiyu@oouagoiwoye.edu.ng

¹ Department of Earth Sciences, Olabisi Onabanjo University, Ago Iwoye, Nigeria

² Department of Petroleum Engineering and Applied Geophysics, NTNU, Trondheim, Norway

³ Department of Geosciences, University of Lagos, Lagos, Nigeria

method (Bayode et al. 2011). The electrical resistivity method is most frequently used in environmental studies because the electrical resistivity of earth materials is determined by parameters such as fluids, conductivity of the matrix, porosity, permeability, temperature, degree of fracturing, grain size, degree of cementation, rock type and the extent of weathering of the medium (Olorunfemi 2001; Idornigie et al. 2006).

Nigeria generates an average of 0.58 kg solid waste per person daily (Adewumi et al. 2005). With a population of over 170 million people, this huge figure if unabated would lead to serious environmental problems. Hence, it is imperative to provide a proper understanding of the environmental hazards associated with indiscriminate, unguided and open dump waste disposal practices. This study focuses on availability of geological barriers to groundwater pollution and vulnerability of aquifer to leachate contamination in a dumpsite located at Agbara industrial estate, Southwestern Nigeria (Figs. 1a, 2). The paper starts with a succinct introduction to the case study area, the suitability of the electrical method for this investigation, and a discussion on the role of lithology at impeding the flow of leachate in the subsurface. This work is basically a geophysical approach to the interpretation of the leachate and does not include coring or sampling for geochemical analysis purposes.

Location and geology of study area

Agbara estate is located within longitude 3.075° and 3.1° and latitude 6.50° and 6.525° in Eastern Dahomey Basin of Southwestern Nigeria (Fig. 2). The estate covers an average area of c. 454 hectares some c. 31 km west of Lagos on the Lagos-Badagry expressway (Fig. 1b). Localities around the study area include Agbara village, Iperin, and Jako-Petedo (Fig. 2). Agbara estate lies on a laterite outcrop in an area of lowland behind the swamp forest of the Ologe Lagoon. The outcrop is fairly flat at c. 15 m. above the sea level and gently slopes into the River Owo and swampy areas to the south and east while it has an undulating topography to the north and west of the outcrop.

The stratigraphy of the study area has been discussed in Jones and Hockey (1964), Omatsola and Adegoke (1981), Billman (1992) and in the work of Elueze and Nton (2004). The oldest unit in the study area is the Abeokuta group composed of Ise, Afowo and Araromi Formations. The Neocomian to Albian Ise Formation unconformably overlies the basement complex of Southwestern Nigeria (Omatsola and Adegoke 1981). The Afowo and Araromi ranges in age from Maastrichian to Palaeocene. Stratigraphically, the Abeokuta group is overlain by the Imo group, Oshosun Formation, coastal plain sands and recent

alluvium (Jones and Hockey 1964; Omatsola and Adegoke 1981).

The rocks in the area include coastal plain sands and recent alluvial deposits. Both deposits are Quaternary age sediments composed of unconsolidated, coarse to medium grained sands with lenses of clays. The sands are generally moderate to poorly sorted and cemented. The coastal plain sands and recent alluvium are jointly referred to as the Benin Formation (Omatsola and Adegoke 1981). The sands in some places are cross-bedded showing characteristic transitional to continental environment of deposition (Omatsola and Adegoke 1981). The coastal sands are aquiferous layer overlain by lateritic soil and underlain by clay to shaly member of the Akinbo Formation (Omosuyi et al. 2008).

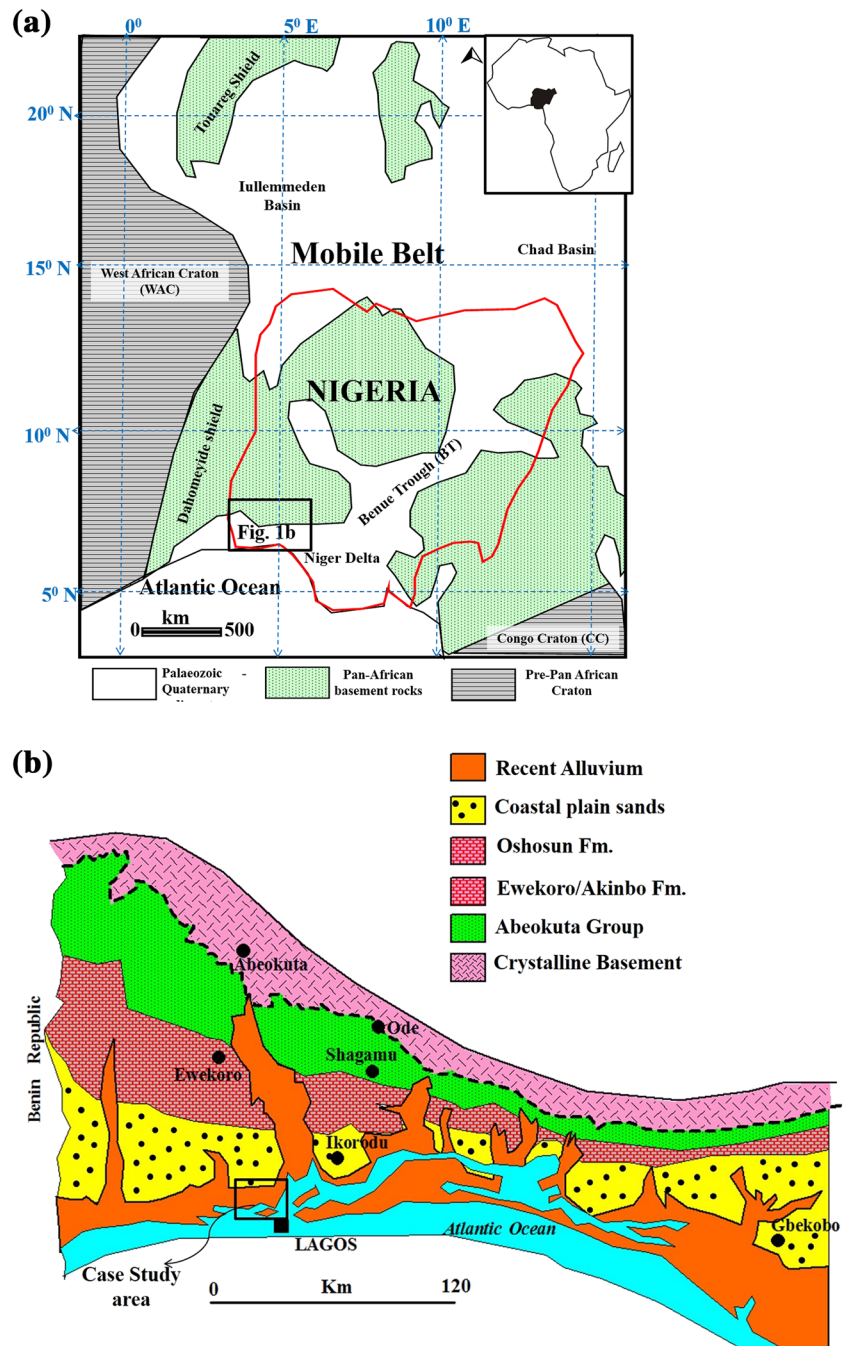
Methods

The methods used for this research include electrical resistivity sounding and tomography. Vertical electrical sounding (VES) uses direct current (DC) injected into the ground surface to investigate the subsurface electrical resistivity (Vladimir et al. 2006). During sounding apparent resistivity of the subsurface materials is measured as a function of depth or position. VES is used in this study to measure variation in resistivity with depth. Schlumberger electrode configuration is used where current and potential electrodes were maintained at the same relative spacing while the whole spread is progressively expanded about a fixed central point (Telford et al. 1976). The progressive increase in the distance between the current electrodes causes the current lines to penetrate to greater depths depending on the vertical distribution of conductivity (Parasnis 1986). Consequently, readings were taken as the current reaches progressively greater depths.

Forty-five VES stations were established within the entire Agbara estate (Fig. 2), three of the station were sited near the dumpsite shown in Fig. 3. The current electrode AB spread was varied between 500 and 600 m. Errors in apparent resistivity are within 2–3 % if the distance between the potential electrodes does not exceed $2/5$ of $AB/2$ (Omosanya et al. 2014). Potential electrode spacing is therefore determined by the minimum value of $AB/2$. As $AB/2$ is increased, the sensitivity of the potential measurement decreases; therefore, at some point, if $AB/2$ becomes large enough, it will be necessary to increase the potential electrodes spacing (Van Nostrand and Cook 1966). The ohmmeter resistivity meter was used for this research.

Furthermore, interpretation of the VES data was done by partial curve matching from which a resistivity and depth model is derived (Fig. 4). The field-derived apparent

Fig. 1 **a** Regional geological map of Nigeria within the context of African cratons (Modified after Woakes et al. 1987). The study area belongs to the Eastern Dahomey Basin in a mobile belt that extends into the Southern Atlantic Ocean (*inset* Map of Africa). **b** Simplified geological map of the Eastern Dahomey Basin (Modified after Billman 1992). The dominant rock types in the case study area are recent alluvial deposits and coastal plain sands



resistivity data was the principal input for computer iteration in WINRESIST software (Vander Velpen 1988). The final resistivity values provided 1D dimensional information about the earth (Omosanya et al. 2014). Resistivity and thickness values were later interpolated to cross sections through the study area. The subsurface resistivity of the area is compared to the similar resistivity values from boreholes in Ijebu-itele and Ijagun (Akinmosin et al. 2013) (Fig. 5), which have similar geology to the study area and to standard resistivity chart of Palacky 1988 (Fig. 6).

Subsequently, electrical profiling was done along three lines shown in Fig. 2. The electrical resistivity tomography (ERT) provides 2D information on subsurface resistivity and thickness. ERT is frequently used for detecting pollution (Chambers et al. 2006; Daily et al. 1998) and characterizing subsurface geologic unit (Daily et al. 1998; Goes and Meekes 2004). In addition, the profiling was used for validating the interpolated resistivity values from the electrical sounding (Omosanya et al. 2014). For the profiling, it was assumed that resistivity does not change in the

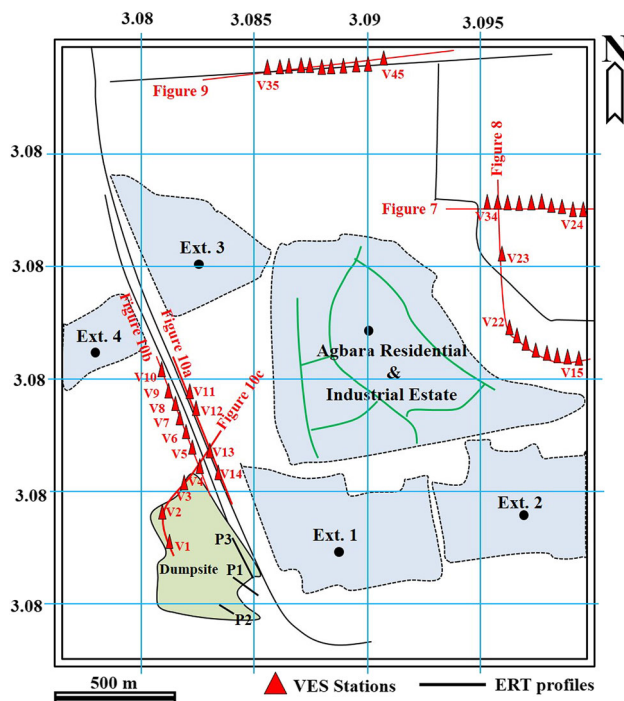


Fig. 2 Survey layout showing the VES stations and lines of transects for the ERT profiles. Electrode configurations for the surveys include Schlumberger for sounding and Wenner array for profiling. Average distance between VES stations is c. 100 m. Note The leaf green polygon shows the approximate outline of the dumpsite

direction that is perpendicular to the survey line. Wenner array configuration was used for the profiling with the survey line located on the dumpsite. The profiling was run from northwest to southeast, with length of survey line being 98, 36 and 145 m for profiles 1–3. Electrode or station spacing is variable among the profiles. For example, 25 stations at spacing of 2 m each was used for profile 2 while 30 stations with individual station spacing of 5 m was used for profile 3. This variation in station number and spacing is due to the rugged topography of the dumpsite and restriction in areas around the swamp.

During the profiling, four electrodes were used namely C1 (first current), P1 (first potential), P2 (second potential electrode) and C2 (the second current electrode) for the first measurement (cf. Ikhane et al. 2012). For the second measurement, electrodes 2, 3, 4 and 5 were used. This process was repeated down to the last measurement with spacing being “2a”. The process was repeated for “3a”, “4a”, “5a”, “6a”, “7a” and “8a” spacing. To obtain the best result, the measurements in this survey were carried out in a systematic manner so that, the possible measurements were made as far as possible (Dahlin and Loke 1998). The derived pseudosection were inverted, a process that allows the apparent resistivity to be plotted against the true depth rather than electrode spacing. The results

obtained from the pseudosection was further interpreted by describing the resistivity of each layer as compared with the standard resistivity of rock types (Palacky 1988, Akinmosin et al. 2013).

The apparent resistivity values were used to calculate parameters such as aquifer vulnerability index (AVI) and overburden protective capacity (Van Stempvoort et al. 1992). The protective capacity of groundwater aquifers is a function of the covering layers usually referred to as the protective layers (Kirsch 2006). Surface water percolates through the protective layers leading to groundwater recharge. During this percolation process, contaminant degradation can occur by mechanical, physicochemical, and microbiological processes. An effective groundwater protection is given by protective layers with sufficient thickness and low hydraulic conductivity leading to high residence time of percolating water. The aquifer vulnerability index (AVI) quantifies aquifer vulnerability by hydraulic resistance which is a function of thickness and hydraulic conductivity of each protective layer to vertical flow of water. Typical values for hydraulic conductivity were based on Freeze and Cherry (1979). Van Stempvoort et al. (1992) subsequently classified aquifers with high hydraulic resistance with low vulnerability to contamination.

Furthermore, the overburden protective capacity in the area was evaluated using longitudinal unit conductance (S_i) derived from the first-order parameters obtained from the VES results (Henriet 1976; Oladapo et al. 2004). S_i is a second-order geoelectric parameter calculated using the Eq. (1)

$$S = \sum_{i=1}^n \frac{h_i}{\rho_i} \quad (1)$$

ρ_i is the layer resistivity, h_i is the layer thickness for the i th layer.

Results

Vertical electrical soundings

The results of the 45 VES soundings are presented as cross section through the subsurface in Figs. 7, 8, 9, 10. Four principal geoelectric layers interpreted from the sounding stations include the topsoil, sand, clayey sand, and clay or shale. The lowest resistivity values were calculated around and on the dumpsite as compared to the other parts of the study area. The topsoil represents the uppermost geoelectric layer with resistivity of 3–1688 Ω m (Fig. 11). Thickness of the topsoil unit varies from 0.8 to 2.4 m. The topsoil is highly resistive in the northern and northern-eastern part of the study. In the southwest of the estate

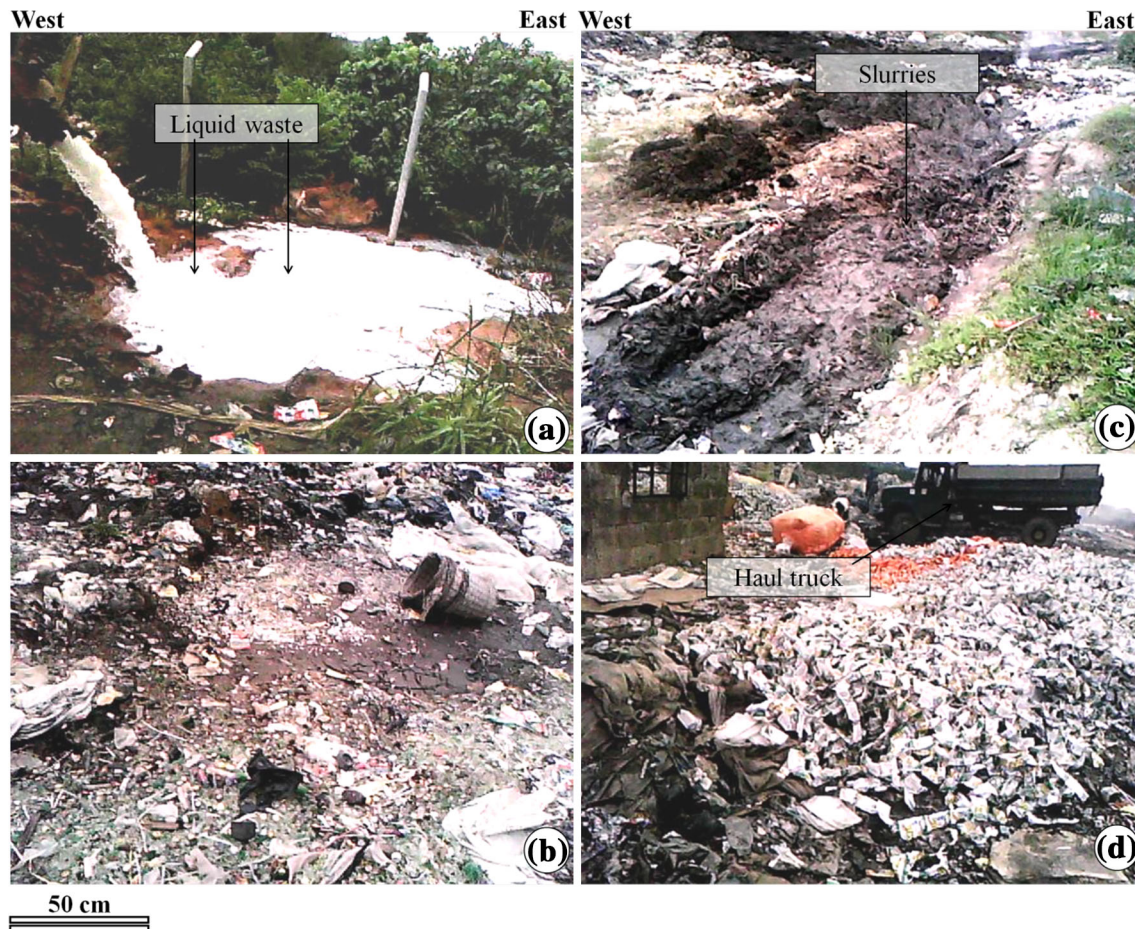


Fig. 3 **a** Example of effluents discharged indiscriminately from a tanker in a nearby industry. The wastes infiltrate the substrate and possibly find its way into groundwater aquifers. **b** Tailings found in the study area include papers, used plastic, rubbers and debris of

wood. **c** Slurries and liquefied waste are possible source of leachate contamination in the study area. **d** Caught in the act, a haul truck indiscriminately dumping refuse at the dumpsite

where the dumpsite is located, low resistivity values were estimated for the topsoil (Fig. 11). For example, the lowest resistivity values for the topsoil are calculated at VES station 1 and 3 (Figs. 2, 9).

The second geoelectric layer is sand or sandstone characterized as dry, contaminated and laterite in Fig. 7. Lateritic sand in the study area has resistivity and thickness of 1689 Ω m and 2.5 m, respectively (Fig. 8). At VES stations 9 and 10, the dry sands have resistivity of 3642 and 1718 Ω m with thickness of 15 and 23 m, respectively (Fig. 10b). Contaminated sands are interpreted closest to the dumpsite at VES 1 and 3 (Fig. 10c). These categories of sand have resistivity of 39 and 7 Ω m with thickness of 16 and 5 m at the two stations and their low resistivity value are attributed to leachate infiltration. Sand are the dominant type of rock type in the study area. They are interpreted at all the VES stations (Fig. 7, 8, 9, 10). The sands are presumably composed of fine sand with relatively low resistivity and coarse sand with high resistivity value (Figs. 7, 8, 9, 10). The saturated unit represents the

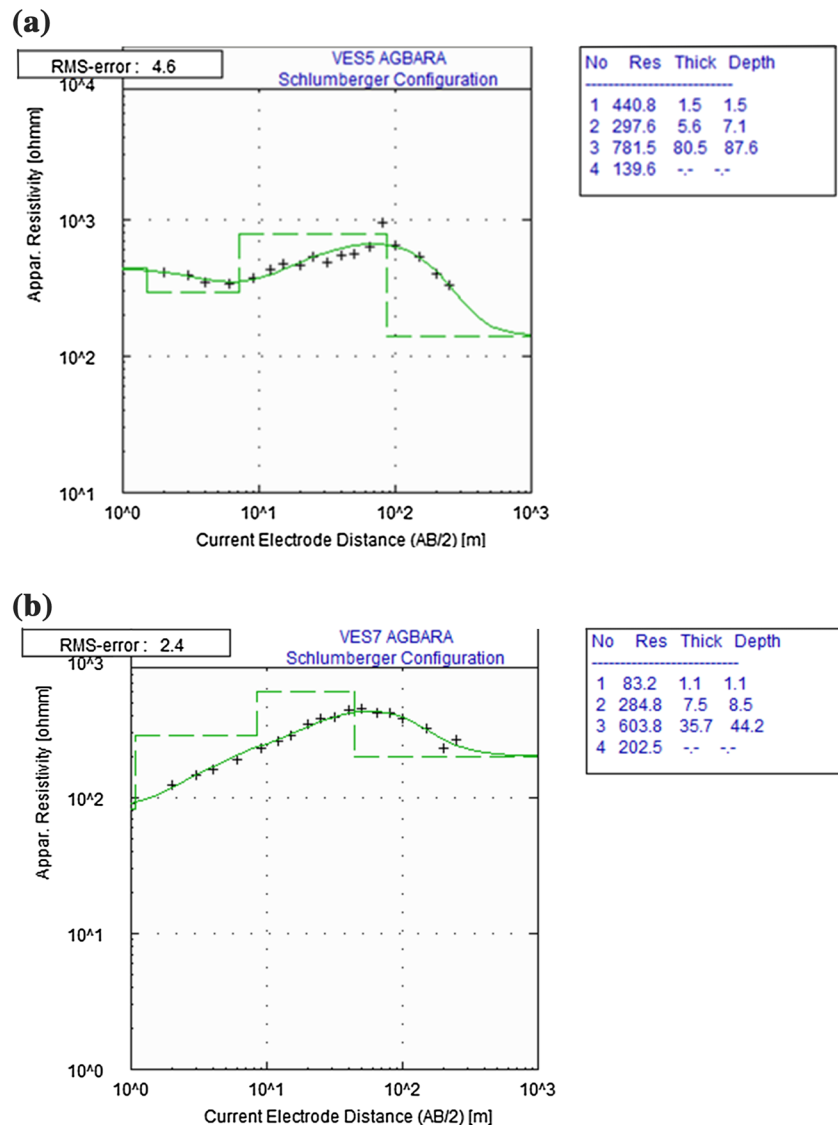
aquiferous unit in the study area with thickness of 14–140 m (Figs. 7, 8, 9, 10). At shallow depth, the sand are interpreted as the vadose zones and as multi-aquiferous layers at deeper stratigraphic levels. The depth to the vadose zone unit ranges from 2 to 24 m (Figs. 7, 8, 9, 10). Underneath the sand are clayey sands with relatively lower resistivity values as compared to the overlying sands.

The fourth geoelectric layer is the clayey or shaly horizon with resistivity of 67 Ω m at VES 11 (Fig. 10a), 1259 Ω m at VES 39 and 215 Ω m at VES 45. The thickness of this layer could not be estimated as they represent the last units on the lithology logs. However, they are estimated at depths of >60 m at these three VES stations.

Electrical resistivity tomography

The electrical resistivity tomography (ERT) was interpreted using the DIPRO software. The 2-D inverse models of the real electrical resistivity are displayed in Fig. 12. They are used to display variation in subsurface resistivity

Fig. 4 Computer iterated curves for **a** VES station 5 and **b** VES station 7. The results of vertical electrical sounding were processed and interpreted by curve matching the raw data from the field and through computer assisted iteration of resistivity model using WINRESIST software



with depth. Areas of extremely low resistivity values are attributed to leachate contamination and in the study are defined on 2-D inverse models as bowl-shaped anomalous zones interpreted as contamination plume.

Profile 1

The south eastern part of profile 1 is located outside the dumpsite and is characterized by relatively higher resistivity values (53–73 Ω m) as compared to the rest of the section (Fig. 10a). Exceptional low resistivity of 6 and 8 Ω m are noticed at two points where they create bowl-shaped anomalous zones from the surface to depth of about 6 m. Beyond this depth, the resistivity ranges from 51 to 85 Ω m up to depth of 10 m. High resistivity value of greater than 160 Ω m was noted at deeper level towards the south eastern end (Fig. 12a). High resistivity zone in the

NW part of the 2-D inverse model is oval-shaped and interpreted as resistive anomaly. The inverse model is divided into three main geoelectric layers corresponding to the topsoil, clayey sand, and sand (Fig. 12a).

Profile 2

When compared to the other 2-D inverse models, profile 2 shows marked low resistivity values suggesting the presence of highly conductive fluid or rock type (Fig. 12b). The topsoil on this profile is also characterized by very-low resistivity bowl-shaped anomalies. These anomalies extend to depth of 3 and 5 m on the NW and SE parts of the profile. Resistivity in these zones ranges from 1.5 to 2.8 Ω m (Fig. 12b). Low values on the south eastern part of the profile might not be unconnected with the presence of a swamp. At deeper depth, high resistivity values of up

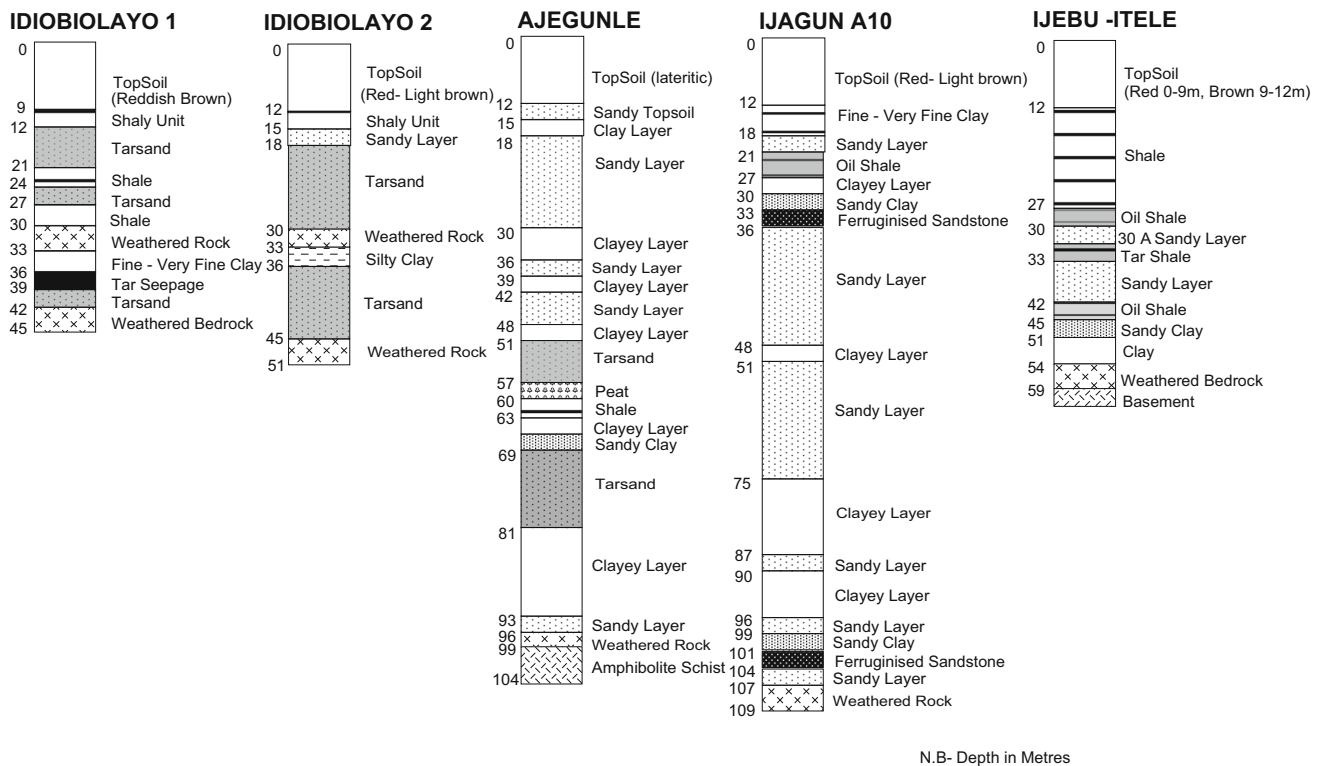
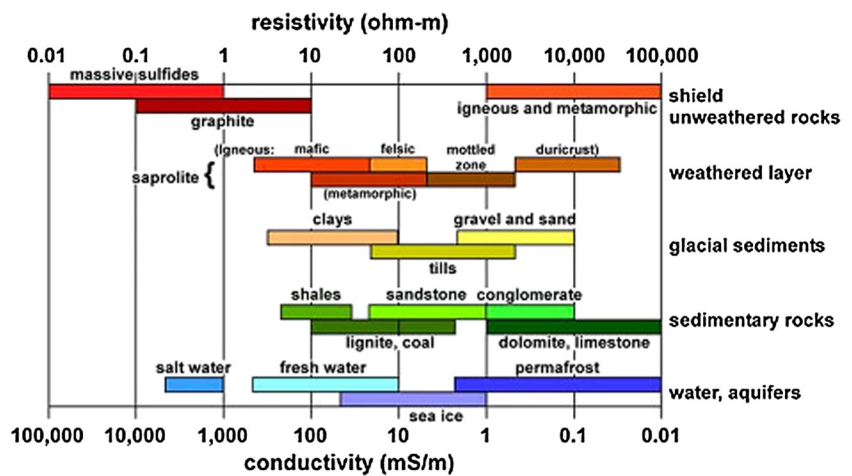


Fig. 5 Interpreted resistivity of rocks from BEECON boreholes in Ijebu-itele and Ijagun. Sandstones or sands from the boreholes have resistivity values of 200 Ω m and more. The shale and clay in their study area have values of less than 100 Ω m (Akinmosin et al. 2013)

Fig. 6 Typical ranges of electrical resistivity (Ω m) or conductivity (mS/m) for selected Earth materials (Palacky 1988)



53 Ω m are estimated in a mounded anomalous zone that extends from the northwest to southeastern part of the profile (Fig. 12b). In addition, three geoelectric layers were interpreted from this profile; topsoil, clayey sand and sand.

Profile 3

This profile is characterized by four geoelectric layers; the topsoil, clayey sand, sand and coarse dry sand (Fig. 10c).

The resistivity values along this profile generally increases with depth. The lowest values are interpreted between 0 and 5 m depth where the topsoil and clayey sand layers are inferred. At depth below 10 m where the coarse dry sand is present, high resistivity value of 1463 and 7680 Ω m were observed on the section (Fig. 10c). Similarly, this profile is characterized by several bowl-shaped low resistivity zones within the topsoil. Resistivity within these zones varies from 6 Ω m at the northwest to 2.7 Ω m at the southeastern

Fig. 7 Two-dimensional cross section through VES 24 to VES 34 revealed four principal lithology, topsoil, lateritic sand, sand and clayey sand. The cross section is located in the eastern part of the industrial estate

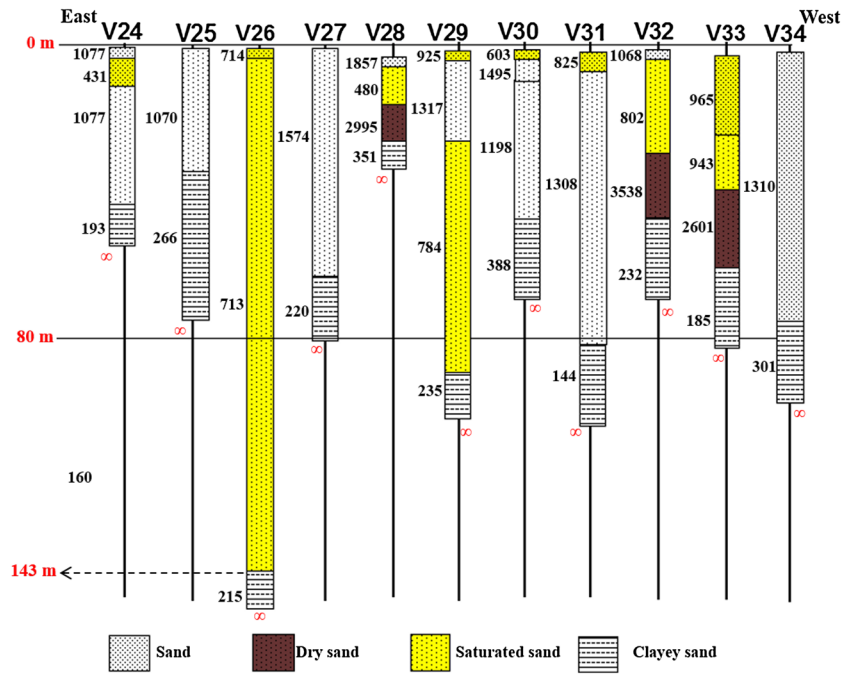
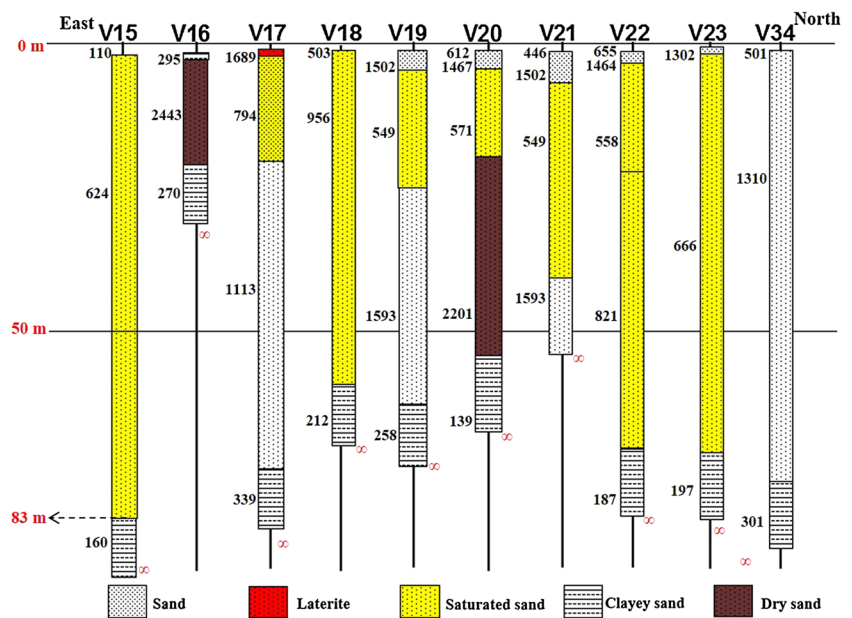


Fig. 8 Two-dimensional geoelectric section through the eastern to northern part of the study area revealed no leachate contamination. Sand in the study area are the aquiferous layer. Other geoelectric layers in from the section include topsoil, sand and clayey sand



part of the 2-D inverse model. The anomalous zones are estimated to depth of 4–8 m in the subsurface (Fig. 10c).

Aquifer vulnerability and overburden protective capacity

The inferred degree or state of leachate contamination for profiles 1–3 is presented in Tables 1 and 2. At depth of 0–3 m, profile 1 revealed extreme to moderate contamination with resistivity values of 6–36 Ω m. On the other hand,

the likelihood of extreme to moderate contamination or presence of effluent is noted at depth of 0–10 m for profile 2 and 3, respectively. Only profile 3 shows no contamination at depth >20 m (Fig. 10c; Table 1). The values of the estimated longitudinal conductance (S_i) range from 0.00 to 0.04 mho using Eq. (1). The highest value of S_i was obtained at VES stations 7, 11 and 12. When correlated with the values of overburden protective capacity of Table 2, it shows that aquifers in the study area have poor protective capacity and are thus vulnerable to leachate pollution when

Fig. 9 Cross section through V35 to V45 show that the northern part of the industrial estate is devoid of leachate contamination. Geoelectric layers in this part of the study area include sand, shale, sand and clayey sand

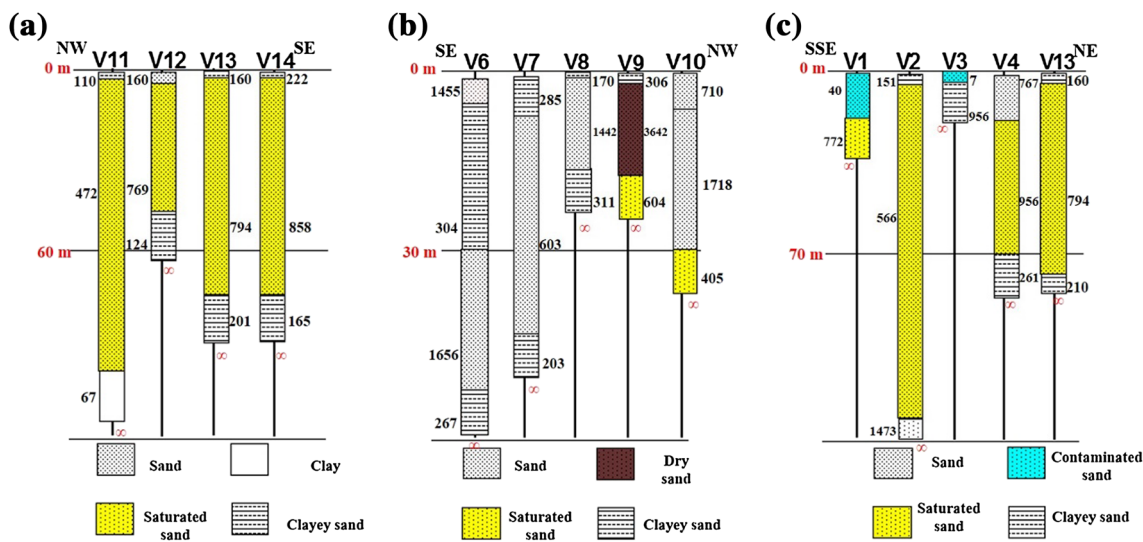
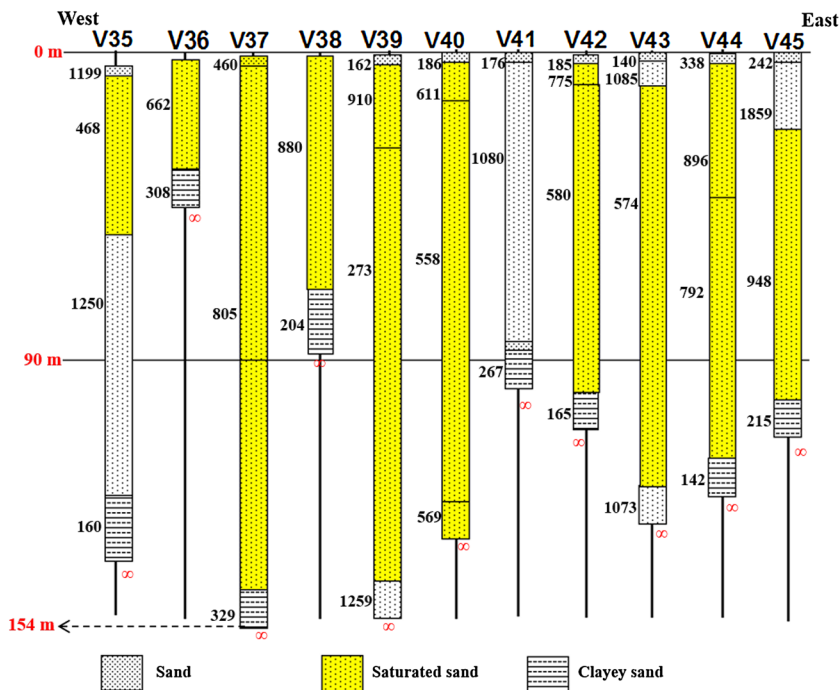


Fig. 10 Cross section through a VES 11–14 b VES 6–10 and c VES 1–V4 and V13. The VES stations are located in the south western part of the estate. VES 1 to VES 3 are directly sited on the dumpsite. Geoelectric layers interpreted from these stations include sand, clay,

clayey sand, dry sand and contaminated sand. Only VES 1 and 3 show leachate contamination of their uppermost sand layer with resistivity of 40 and 7 Ω m, respectively

compared to the standard of Oladapo et al. (2004). The overburden layers are thus zones of probable risks to aquifer contamination. These layers are underlain by porous and permeable sand formation of varying thickness, grain sizes and moisture content. The underlying sand constitutes the aquifer in the study area. Hence, the contamination inferred within these zones along profiles 1 and 3 might be the result of percolating leachate from the topsoil.

Discussion

The results from both profiling and sounding shows that the topsoil is characterized at shallow depth by zone of abnormally low resistivity values suggestive of the presence of a highly conductive fluid or rock type. This observation was made along the three profile lines and on two of the VES stations. Hence, we interpret the anomalous

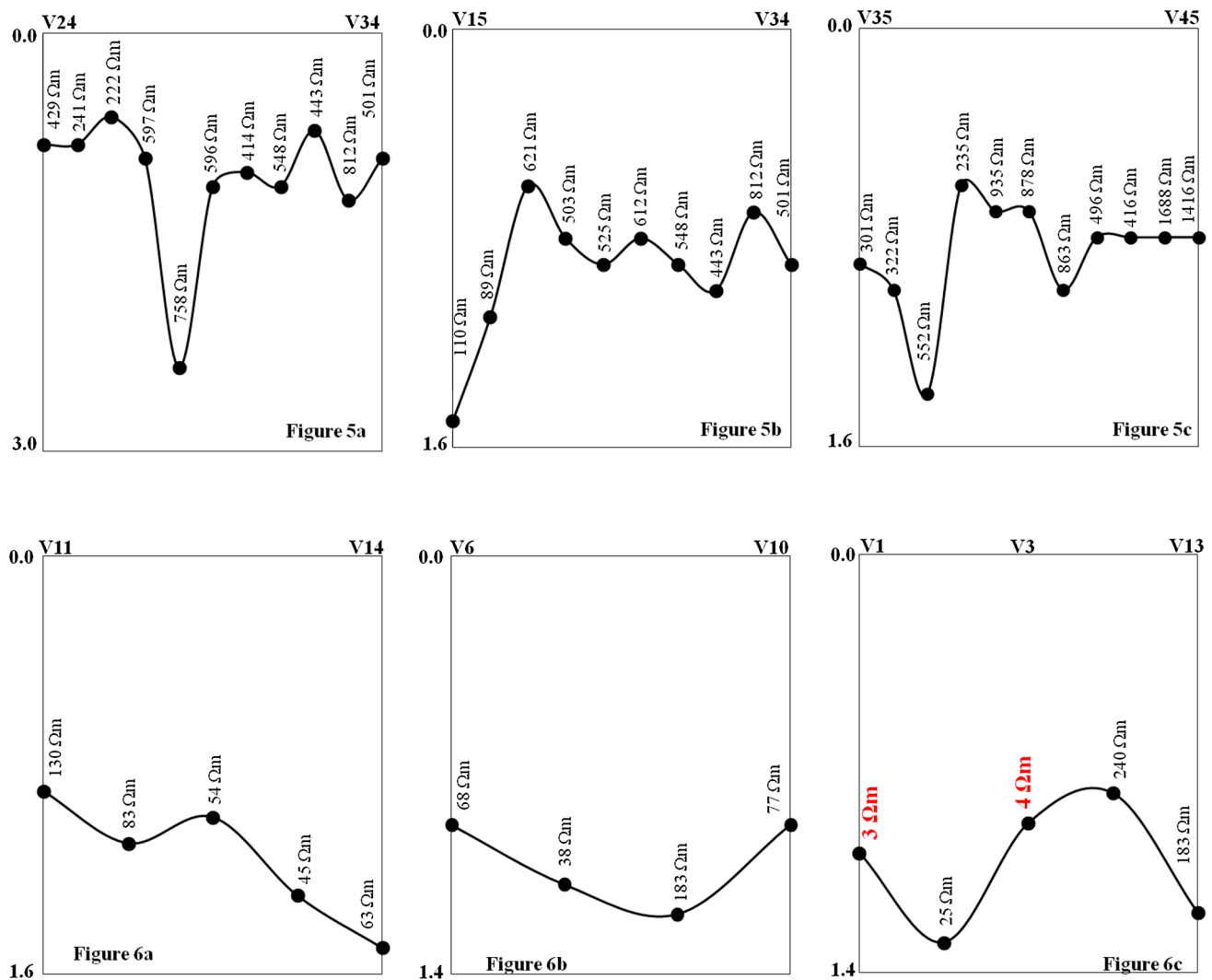


Fig. 11 Topsoil profile in the study area. The maximum thickness of the topsoil is estimated at VES stations 28 with a thickness of 2.4 m. VES 1 and 2 revealed leachate contamination of the topsoil with

resistivity values of 3 and 4 Ω m respectively. At the other VES stations, the topsoil is characterized by high resistivity suggestive of lateritic sand. *Note vertical axis is the depth in meters*

zone as areas of leachate contamination. Leachate plumes normally have low resistivity values because of high ion concentration (Rosqvist et al. 2003). In this work, the leachate plume have resistivity of 1.5–9 Ω m while for electrical sounding, the resistivity of the leachate is 7–40 Ω m (Fig. 10a, b). The resistivity of the leachate plume in this work is in accordance with the result obtained by previous workers such as Hamzah et al. (2014) 1–10 Ω m and Ariyo et al. (2013) <6 Ω m.

Consequently, the low resistivity values could have been attributed to clayey rock in the topsoil. However, the topsoil in the study area is generally lateritic and composed of coarse sands. An important observation is that the lowest resistivity values were estimated around the dumpsite when compared to the rest of the industrial estate. As a consequence, leachate contamination in the study area is limited

only to the southwestern part. The other regions revealed presence of highly resistive geoelectric layers without any indication of leachate infiltration.

An important aspect of leachate contamination is the generation and migration. Previous authors favoured infiltrated rainfall as the principal source of leachate generation in landfills (Desa et al. 2009). In the study area, secondary sources may include effluents such as liquid waste and slurries which may account for the restricted spread of the leachate to the dumpsite (Fig. 3). As for migration, it is hard to predict the direction of flow or drainage for the leachate. Nonetheless, we surmise an eastward transport of the leachate from elevated areas where VES stations 1 and 2 are located to areas of lower elevation where profile 3 is. Hence, the deepest influence of the leachate is interpreted areas with low elevation (Figs. 2, 8, 10).

Fig. 12 Resistivity tomography along profile lines 1–3. Leachate contamination is restricted to the topsoil where they are revealed as bowl-shaped anomalies on the 2-D inverse models of real electrical resistivity. Average resistivity of the leachate plume is 2 Ω m on profile 2, and 9 Ω m on profile 1. Four principal geoelectric layers interpreted from the ERT include topsoil, clayey sand, sand and dry sand. Profile length is 98, 45 and 145 m for profile 1, 2, and 3, respectively

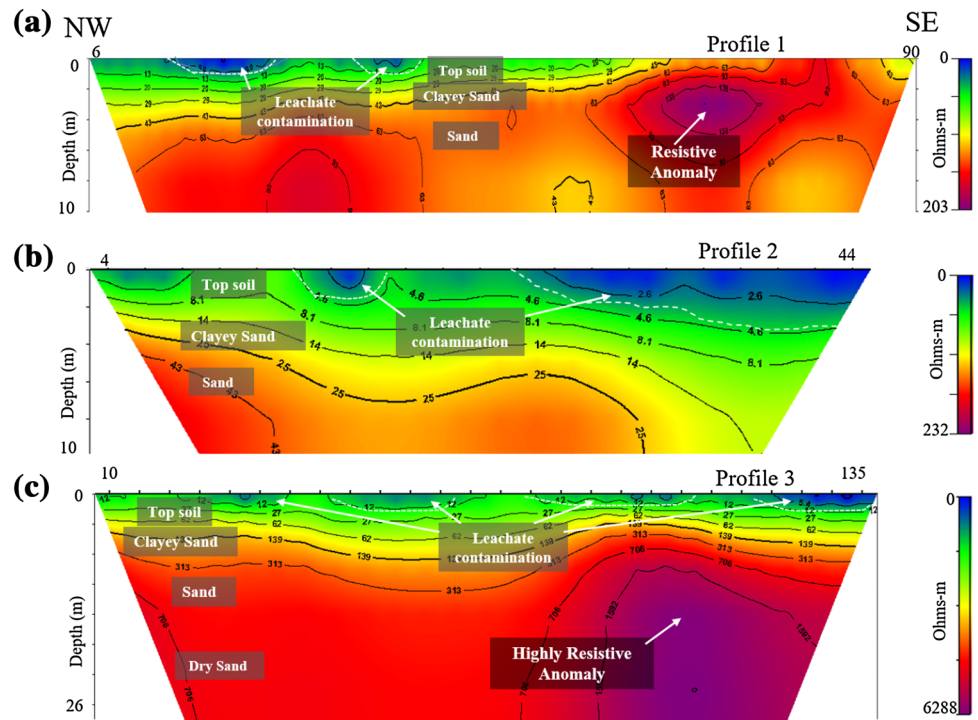


Table 1 Inferred degree of leachate contamination for ERT profile 1 to 3

Profile	Depth	Resistivity (Ω m)	Rate of contamination
1	0–1	5.7–14	Extremely contaminated
	1–2.5	14–36	Moderately contaminated
	2.5–10	36–90	Contaminated
	>10	90–227	Less contamination
2	0–1.5	0–5	Extremely contaminated
	1.5–2.7	5–17	Moderately contaminated
	2.7–5.0	17–56	Contaminated
	>5	56–187	Less contaminated
3	0–2.5	2.25–18.2	Extremely contaminated
	2.5–10	18.2–177	Moderately contaminated
	10–20	177–429	Less contaminated
	20–25	420–536	Not contaminated

Table 2 Standard values for longitudinal conductance/protective capacity rating and classification of Aquifer Vulnerability on the basis of hydraulic resistance

Si (mho)	Protective capacity rating (Oladapo et al. 2004)	Log (hydraulic resistance) in years	Vulnerability (Van Stempvoort et al. 1992)
>10	Excellent	>4	Extremely low vulnerability
5–10	Very good	3–4	Low vulnerability
0.7–4.9	Good	2–3	Moderate vulnerability
0.2–0.69	Moderate	1–2	High vulnerability
<0.1–0.19	Poor–weak	<1	Extremely high vulnerability

Aquifer vulnerability index in the study area shows that the degree of contamination decreases with depth along the three profiles and that soil and aquifers of the study area are vulnerable to leachate contamination at shallow levels. Since we interpreted the topsoil as being lateritic soils with less clayey content, leachate infiltration in the study area is enhanced by the lack of protective layers as shown by the correlation between longitudinal conductance and overburden protective capacity. The topsoil in the southwestern part of the study area is porous and permeable and is therefore conduits for leachate. Hence, the soils and groundwater resources around the dumpsite might be polluted by the leachate. Although, there is no direct geochemical analysis to prove that the soils and groundwater are toxic. We hypothesize that with time the leachate contamination may contribute to pollution of the groundwater and this is of great threat to farming and future exploitation of underground water resources in the area.

This work shows that leachate contamination is limited to the dumpsite around Agbara industrial estate. To forestall further pollution of the soil and groundwater aquifers in the study area, we recommend planned and engineered landfill and also enlightenment campaign to stop indiscriminate dumping practices. The government has huge responsibility of ensuring compliance with existing landfill laws and the provision of suitable dumpsite for the industrial estate.

Conclusion

The major conclusions from this work are:

- The study area is characterized dominantly by five geoelectric layers. Topsoil, laterite, sandy clay/clayey sand, sand (possibly saturated at some levels and very dry at others), and sand intercalated with clay. The third and fourth layers are the vadose and aquifer zones.
 - The lowest resistivity values were estimated around the dumpsite. The results from electrical sounding for VES 1 and 3 correlate positively with those of ERT as zones of leachate contamination are characterized by very low resistivity values relative to the background resistivity of rocks.
 - Leachate plumes are interpreted as bowl-shaped anomalies on the ERT profiles with the maximum depth of infiltration at about 10 m. On the VES cross sections, the estimated depth of contamination is 17 m.
 - Aquifers in the study area are not naturally protected by any lithological barrier to leachate seepage. Clayey geoelectric layers in the study area are located farther from the aquifer zone and are mixed variably with coarse and fine sands.
- Although the history of the dumpsite is unknown, the site remains an active source of leachate generation.

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