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Article *in* Arabian Journal of Geosciences · June 2014

DOI: 10.1007/s12517-014-1486-8

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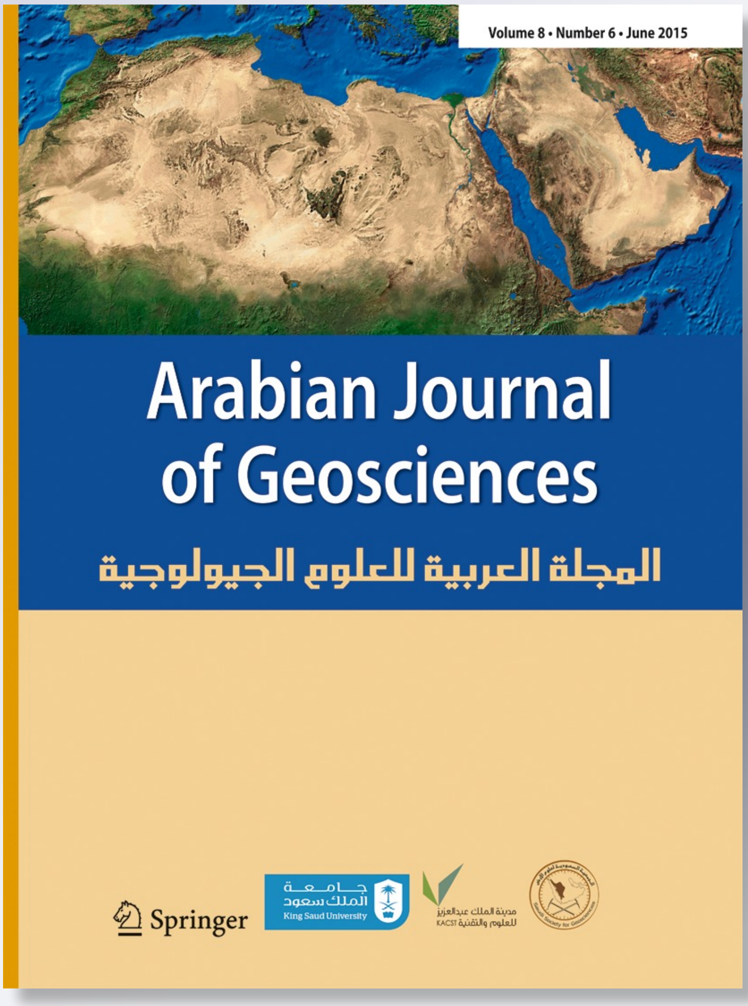
Arabian Journal of Geosciences

ISSN 1866-7511
Volume 8
Number 6

Arab J Geosci (2015) 8:4101-4115
DOI 10.1007/s12517-014-1486-8



Springer

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ORIGINAL PAPER

Integrated geophysical and physicochemical assessment of Olushosun sanitary landfill site, southwest Nigeria

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Received: 26 January 2014 / Accepted: 23 May 2014 / Published online: 17 July 2014

Abstract An integrated surface geophysical and physicochemical study involving 2-D electrical resistivity imaging (terrain conductivity measurement using EM34-3) complimented with measurement of some physical parameters was conducted at Olushosun sanitary landfill site in Lagos metropolis, southwestern Nigeria, with the aim of investigating the lateral extent and depth of the possible subsurface leachate contamination plumes (electrically conductive anomalies) within the area. Fourteen 2-D resistivity imaging lines were investigated with a maximum spread length of 249 m per line. The result of the resistivity imaging delineated the contaminant plume as low-resistivity zones (0.24–36Ωm) to a maximum depth of 59 m. The electrical resistivity tomography (ERT) lines were projected to produce stacked block models of the site which show southeast flow pattern of the leachate and, possibly, the groundwater flow direction. Eleven electromagnetic (EM) profiles were established with a maximum spread length of 150 m per profile using both the vertical and horizontal dipole configurations to measure terrain conductivity of the study area; 10, 20, and 40 m coil separations were deployed for the measurement. Qualitative interpretation of the EM34-3 data reveals high conductivity range of values (30–264 mmho/m) within the dumpsite as compared to conductivity values ranging between 4 and 26 mmho/m for the control site. It delineated the vertical extent of the contaminated zones up to a maximum depth of about 30 m (horizontal dipole configuration) and a maximum depth of about 60 m (vertical dipole configuration). Physicochemical analysis of the water samples taken from wells and boreholes within the precinct of the dumpsite reveal an elevation in concentrations of total dissolved solid (TDS) (range of 513–2,000 mg/l) and electrical conductivity (EC) (range of 1,019–3,999 μS/m) in wells 4, 7, 10, 11, 15, 16, and 19 with the values obtained moderately above the WHO standards. The pH obtained from water samples indicates high acidic content (5.34–6.85). These possibly indicate contamination of the groundwater as a result of solid waste leachate accumulation, thus complimenting the geophysical data. Leachate flow direction was generated from the increasing concentration of TDS and EC in southeast direction which agrees with similar flow pattern deduced from ERT results.

Keywords Leachate · Pollution · Landfill · Electrical resistivity · Physicochemical analysis · Contaminant plume · Terrain conductivity

Introduction

Landfills, most of which are open and uncontrolled dumpsites, are the most common waste disposal systems in Lagos State. Most of these waste landfills are improperly designed due to low capital investment, thus allowing for environmental pollution in those areas where they are located. Landfills are usually accompanied with the presence of either decomposable and/or non-decomposable materials which generate leachate that pollute both the surface and underground water. Most landfills in Lagos are pits formed from the excavation of lateritic soil for construction purposes. These landfills are not protected by the use of impermeable soil materials before dumping of wastes. Increasing amount of municipal solid waste (MSW) emanating from residential, commercial, and

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industrial areas, together with changing nature of waste over time, has led to the degradation of the quality of the environment.

One of the most common demands in metropolitan areas includes detecting the location and extent of contamination in areas as small as landfills. In such circumstance, the integrated use of geophysical methods provides an important tool in the evaluation and characterization of contaminants. No single geophysical tool can effectively determine the characteristics of a landfill. Iterative and integrated data collection and interpretation using multiple geophysical methods provides for a more complete interpretation of data, often resulting in a more accurate model of the complex structures and processes of the subsurface (Dawson et al. 2002). Electrical and electromagnetic geophysical methods are becoming increasingly accepted tools for the initial characterization of contaminant plumes from municipal and hazardous waste landfills (Greenhouse and Harris 1983; Sweeney 1984; Greenhouse and Monier-Williams 1985). The electrical resistivity method provides a veritable tool for mapping the degree and extent of contamination owing to the resistivity contrast between the zone of pollution and the immediate subsurface vicinity. The method is not used to directly detect contaminants. Rather, it is used in the investigation of the geological environment through which the contaminants move, and in the determination of the distribution of pollutant in space and time through monitoring. Many chemical pollutants are associated with dumpsites depending on the sources of contamination. These produce vertical and laterally migrating leachates, commonly reducing resistivity, and the decrease in resistivity can be distinguished from natural, non-saline groundwater using electrical resistivity (Ross et al. 1990), electromagnetic methods (Greenhouse and Slaine 1983), seismic methods (King et al. 1989; Slaine et al. 1990), ground-penetrating radar (Davis and Annan 1989), or other integrated geophysical approach (Slaine and Greenhouse 1982). As a consequence, these methods are commonly used to define the extent of contamination and pollution plumes surrounding landfill sites. The electromagnetic (EM) induction method provides fast and low-cost detection of many subsurface waste materials which change the electrical conductivity where they are deposited. The application of electromagnetic techniques to the measurement of terrain conductivity has been described (Keller and Frischnecht 1966; Wait 1962).

In the present work, electrical resistivity tomography and EM methods have been integrated with some physical parameters from existing wells to investigate possible contamination of groundwater due to leachate emanating from the landfill site and the direction of flow of the contaminants in and around the Olushosun sanitary landfill site at Ojota, southwestern Nigeria.

The study area

Olushosun sanitary landfill site is located at the northern part of the Lagos metropolis in Ikeja Local Government Area of Lagos State (Fig. 1). It is owned and maintained by the Lagos State Waste Management Authority (LAWMA).The landfill was opened in 1989, and it covers an area extent of about 42 ha. Olushosun landfill site has witnessed rehabilitation which consisted of reclamation of land and construction of accessible road for ease of tipping, spreading, and compaction of waste since inception. The site receives waste from entire Lagos metropolis and is accessible by tarred road through the Lagos-Ibadan expressway. It is surrounded by residential, commercial, and industrial setups, and the waste stream is made up of domestic, market, commercial, industrial, and institutional origins. The wastes are of different types, ranging from organic to inorganic, hazardous, and non-hazardous. Waste brought here by private sector partnership (PSP) collection trucks from different parts of the city are dumped haphazardly without segregation. The site is characterized by landfill fires mostly due to spontaneous combustion which are prevalent in the dry season. At present, the laterites excavated are being used to cover up the waste on the active area of the landfill. The wastes are first compacted before being covered with the excavated laterite.

Geology and hydrogeology

Lagos State is basically a sedimentary area located within the western part of Nigeria, a zone of coastal creek and lagoon (Elueze and Nton 2004). The area is also developed by barrier beaches associated with sand deposits (Ogbe 1972). The subsurface geology reveals two basic lithologies: clay and sand deposits. These deposits may be interbedded in places with sandy clay or clayey sand and occasionally with vegetable remains and peat (Ayolabi and Peters 2005). The water-bearing strata of Lagos State consist of sand, gravel, or admixtures from fine through medium to coarse sand gravel (Adeleye 1975).

Basically, there are three major aquiferous units that are being tapped for the purpose of water supply in the Lagos metropolis; these are categorized to first aquifer horizon thought to belong to the recent littoral/alluvial deposit of the Benin formation (Longe et al. 1987). This upper aquifer unit is mostly exploited through hand-dug wells, and it is prone to contamination because of its limited depth. The second aquifer horizon is made up of sands and clay thought to be the coarse sandy estuarine deltaic and continental beds of Ilaro formation (Jones and Hockey 1964; Longe et al. 1987), while the third aquifer layer consists of alternating sequences of clayey and sandy strata. Only few boreholes tap water from this aquifer (Jones and Hockey 1964).

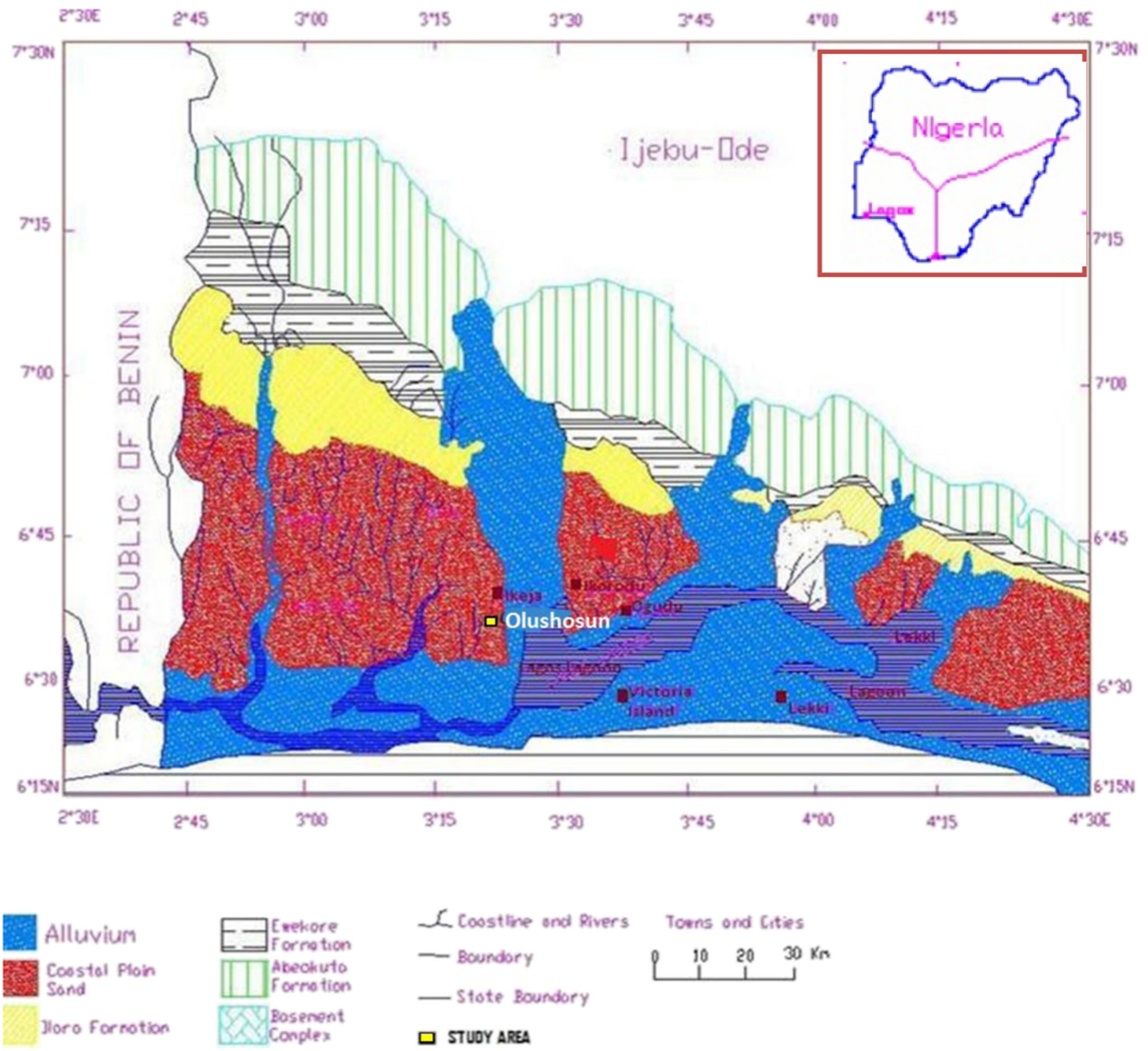


Fig. 1 Geological map of Lagos showing the study area (modified after Billman 1992)

The hydrogeology of the study area falls within the first and second aquifers described above.

Materials and methods of investigation

The research employed both geophysical and hydrogeochemical methods in delineating the effects of the dumpsite on the subsurface hydrogeological unit within the study area. Borehole log data were used for lithological correlation. Detailed reconnaissance survey of the landfill and its immediate neighborhood was carried out before the area was mapped out. These include updating baseline information, locating target areas for geophysical surveys, hydrogeological survey of the area, terrain assessment, and cutting of available traverse lines whose coordinates were taken with the GPS instrument.

Geophysical method

Two-dimensional electrical resistivity imaging and electromagnetic method (terrain conductivity measurement using EM34-3 equipment) were used for the investigation of possible contamination of groundwater by leachate from the landfill. A total of 14 electrical resistivity tomography (ERT) lines were traversed using dipole-dipole array with minimum electrode separation "*a*" of 3 m. The choice of small value for electrode spacing is to capture the near-surface effects of the contamination without necessarily omitting any information (Loke 2004). The maximum spread of each profile is 249 m.

The traverses were oriented in N–S and E–W directions parallel to each other and according to the geometry of the dumpsite (Fig. 2). The 2-D data were processed and inverted using the AGI Earth Imager (an inversion software 2009). These programs generate the inverted resistivity-depth image for each profile line based on an iterative smoothness-constrained least-squares inversion algorithm after deGroot-Heldin and Constable (1990) and Loke and Barker (1996). These inversion routines involve a cell-based inversion technique; it subdivided the subsurface into a number of rectangular cells whose positions and sizes are fixed and then used to determine the resistivity of cells that provides a model response which agrees with the observed data (Loke 2004). The differences between the observed and calculated blocks were minimized to obtain an acceptable agreement of the fitting process (Loke and Barker 1996).

EM measurements were collected using the Geonics EM34-3 ground conductivity meter. The instrument measures terrain conductivity rather than resistivity. It employs electromagnetic (inductive) techniques to measure the field strength and phase displacement of subsurface features. EM34-3 data can be collected in the vertical and horizontal dipole configurations. Thus, it allows for two depth determinations and for average soil conductivities. It uses three frequency/coil spacing pairs which are 10, 20, and 40 m spacings, using frequencies of 6,400, 1,600, and 400 Hz, respectively. A total of 11 profile lines were traversed with the total line length of each profile being 150 m. Profiles 1–9 were carried out within the vicinity of the dumpsite with each profile spaced 20 m apart, while two profiles (10 and 11) were meant to serve as control and were carried out about 500 m away from the dumpsite (Fig. 2). Along each profile, vertical and horizontal dipole measurements were collected. The field data were plotted as line profiles of apparent conductivity (mmho/m) against midstation (m) for both coil orientations and were interpreted to find the ground positions directly above conductive features.

Hydrochemical method

In order to assess the presence and/or degree of possible groundwater contamination by the solid waste leachate, 20 well water samples were analyzed for the content of their total dissolved solid (TDS), pH values, and electrical conductivity (EC). The results of the physicochemical analysis are presented in Table 1. The values of EC and TDS were used to prepare maps of spatial distribution of EC and TDS, respectively, and,

Fig. 2 Data acquisition map of the study area

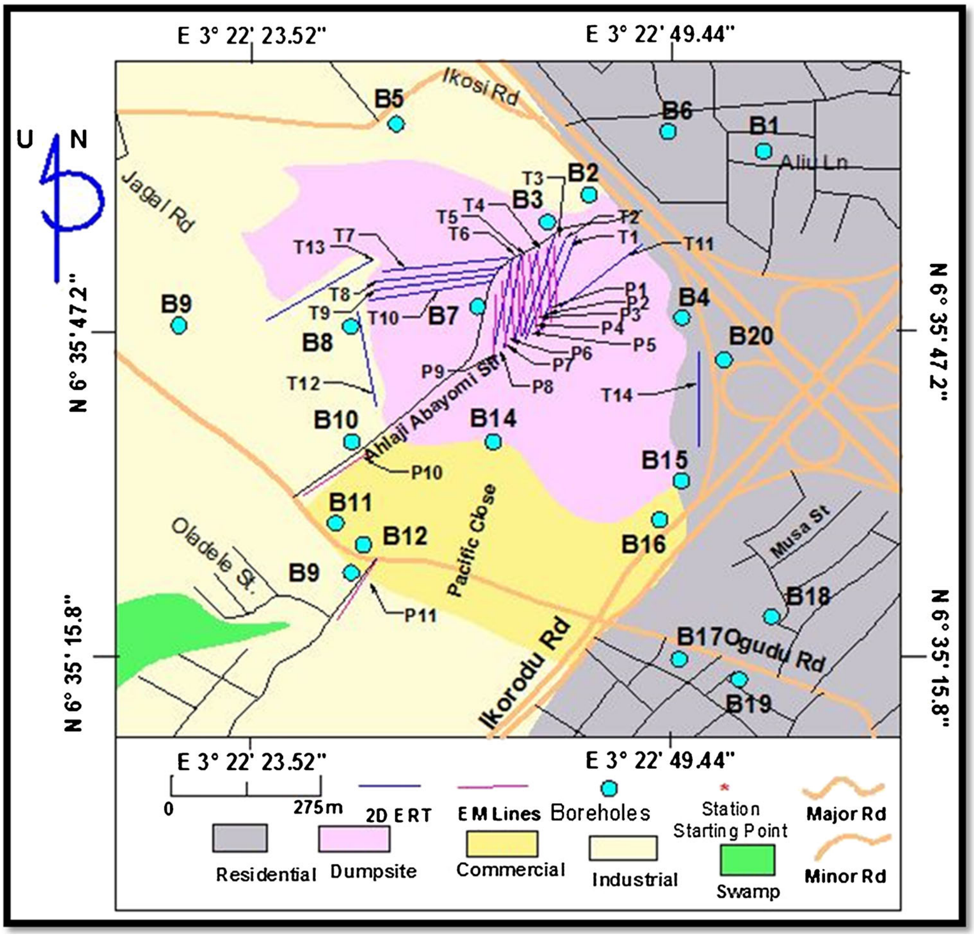


Table 1 Summary of subsurface apparent conductivity for profiles 1–10

Traverse	Variation in apparent conductivity (mmho/m)	
	Horizontal dipole	Vertical dipole
1	40–200	12–180
2	58–247	2–128
3	45–226	11–181
4	51–261	7–198
5	98–265	20–136
6	95–263	9–179
7	91–206	38–161
8	40–200	12–180
9	59–184	45–185
10	14–23	16–24
11	15–28	12–29

consequently, to determine the possible flow direction of contaminant plume within the study area. For this purpose, WinGLink Software (2003 and 2007) was used to produce the maps.

Results and discussion

Two-dimensional ERT results

The resistivity distributions derived from the 2-D inversions of ERT data are presented and discussed here with their resistivity-depth models (Figs. 3, 4, and 5). The inverted models were stacked into three sections. Each section provides useful information on the vertical and lateral spread of the leachate beneath the surface and possible leachate flow direction. The degree of impact of pollution with depth seems to increase from the western to the eastern part of the dumpsite (Figs. 3, 4, and 5). Section 1 consists of stacked inverted models of traverses 1–6, section 2 consists of stacked inverted models of traverses 7–10, while section 3 consists of stacked inverted models of traverses 11–14. Generally, the subsurface below the dumpsite was characterized by low resistivity possibly influenced by contaminants emanating from the dumps with the resistivity sections divided into four geoelectric layers. The first geoelectric layer represents the topsoil, while the third and fourth geoelectric layers correspond to the first and second aquifer units, respectively. The maximum depth

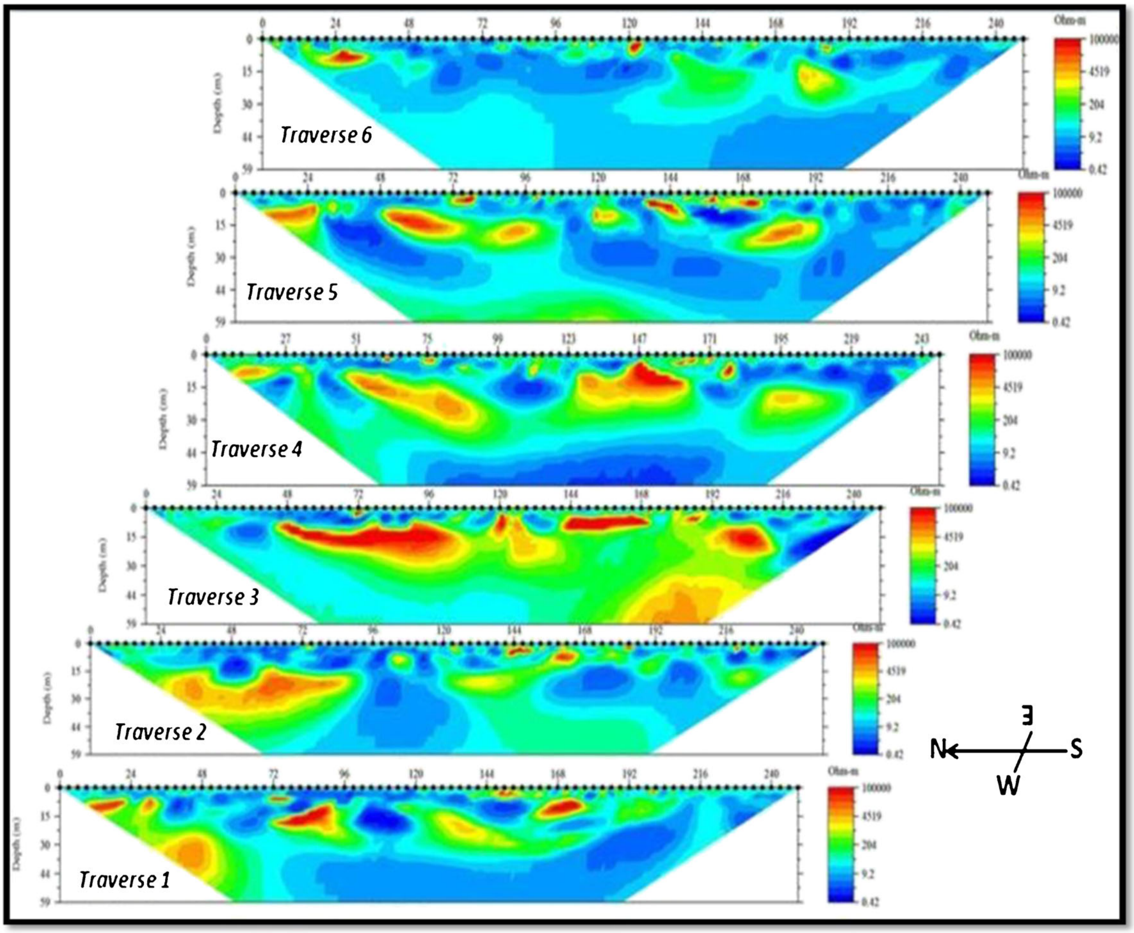


Fig. 3 A block model of the dumpsite projected from 2-D ERT of traverses 1–6

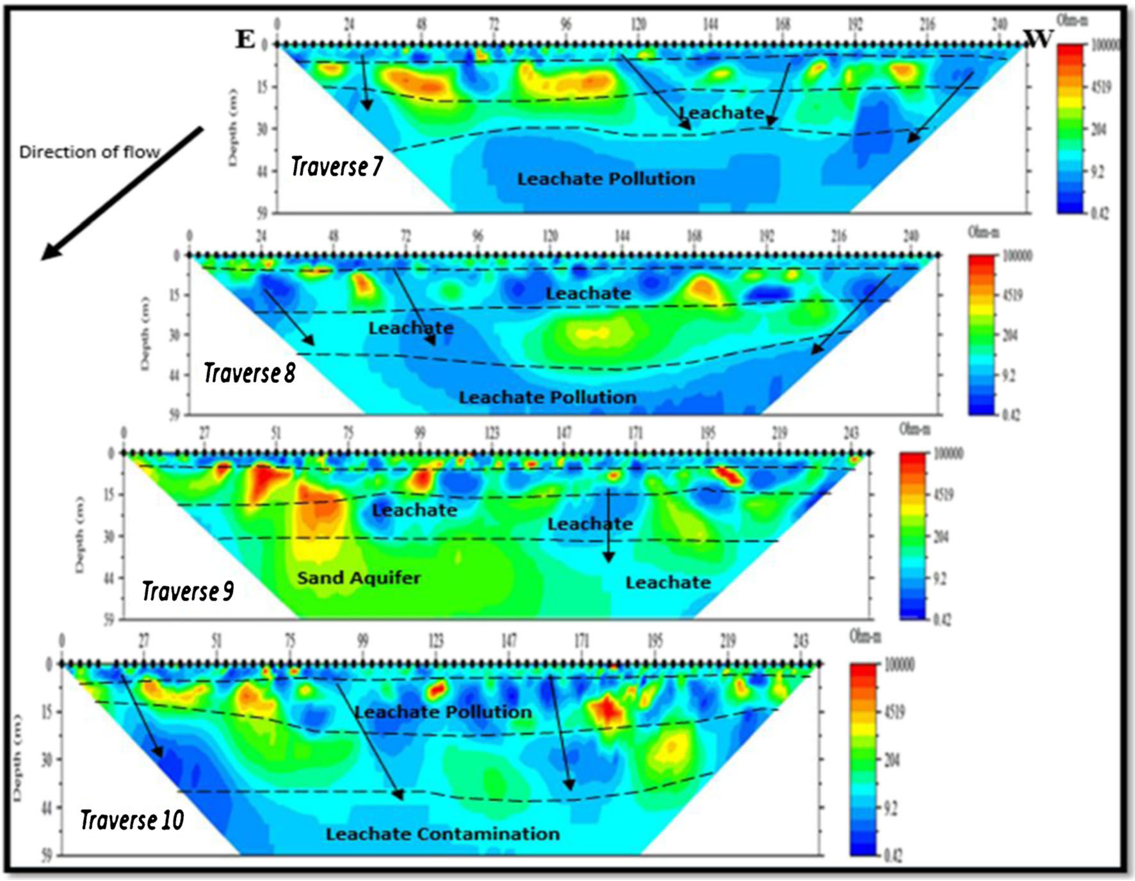


Fig. 4 A block model of the dumpsite projected from 2-D ERT of traverses 7–10

penetrated is 59 m with resistivity values of contaminated layers below 36Ωm. Traverses 1–6 (Fig. 2) represent region where the subsurface (earth material) has been removed up to a depth of about 15–18 m beneath the surface (Ayolabi 2005). The earth material (laterite) was used for road construction, and the pit was reclaimed by dumping refuse there (Ayolabi 2005).

The resistivity-depth model obtained in traverse 1 is presented in Fig. 3. The subsurface beneath this traverse is characterized by resistivity value ranging from 0.42 to 20,000Ωm (Fig. 3). Four subsurface geoelectric layers were delineated. The first geoelectric layer represents the topsoil and extends from the surface to a depth of about 6 m, while the second geoelectric layer extends from a depth of 5 m to an average depth of about 22 m. These layers represent the buried refuse material since the pit was reported to have been dug to about 15–18 m before dumping of the refuse (Ayolabi 2005). Low-resistivity structures (0.42–36Ωm) within these layers are reflective of leachate from the decomposed refuse, while regions with high-resistivity structure (>43Ωm) may be associated with the hanging lateritic layer separating the dumpsite into different compartments or may be associated with the presence of non-conductive, non-biodegradable waste materials (such as polythene and rubber) or possibly trapped methane gas from the decomposed refuse materials. The third geoelectric layer extends from a depth of about 15–30 m having resistivity values ranging between 0.42 and 800Ωm. Available borehole data (Fig. 6) show that the layer is composed of sandy clay/sand and represents the first hydrogeologic unit for the study area. Low-resistivity structures (0.42–36Ωm) within the layer represent the possible migrating route of the leachate to the underlying aquifer unit and suggestive of possible pollution of the first aquifer by the leachate. However, resistivity values above 43Ωm found within this layer suggest less impact of leachate on groundwater.

The fourth geoelectric layer is composed of sand and represents the second hydrogeologic unit for the area and extends from a depth of 27–59 m beneath the surface. Leachate effect, suggestive of groundwater pollution within this layer are represented by low resistivity (<36Ωm).

The 2-D resistivity structure in traverse 2 (Fig. 3) reveals sediments with resistivity values ranging from 0.42 to 15,000 Ωm. The first two geoelectric layers to a depth of 17 m are characterized predominantly by low-resistivity structure (0.42–36Ωm) reflective of leachate from the decomposed refuse. Isolated high-resistivity structure (3,000–15,000Ωm) within these layers is suspected to be associated with non-

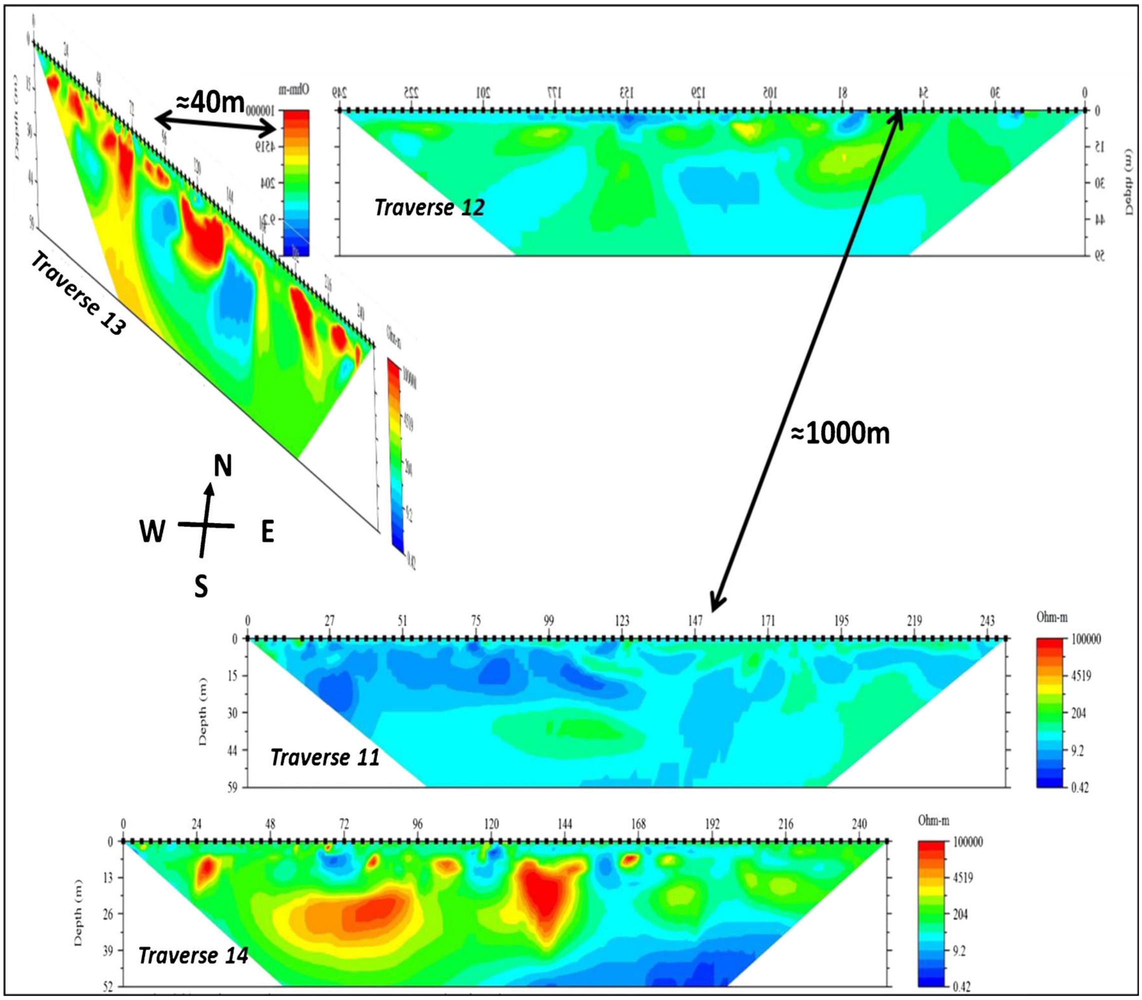


Fig. 5 A block model of the dumpsite projected from 2-D ERT of traverses 11–14

biodegradable refuse materials or trapped methane gas from the decomposed refuse materials. The third geoelectric layer (15–37 m) represents the first hydrogeologic unit and is characterized by resistivity value ranging from 0.42 to 10,000 Ωm. It is composed of sandy clay and sand (Fig. 6). However, the low-resistivity structure (0.42–36 Ωm) between lateral distances of 84–123 and 150–200 m is suggestive of the effect of the leachate on the groundwater; hence, the aquifer unit may have been polluted. The fourth geoelectric layer (37–59 m) represents the second hydrogeologic unit. Leachate effect, suggestive of groundwater pollution within this layer, is represented by low resistivity (<36 Ωm).

In traverse 3, the topsoil is to an average depth of 6 m from the surface and represents the buried refuse materials, and the resistivity distribution reflects the degree of decomposition of the refuse materials. The second geoelectric layer (6–25 m) is characterized with resistivity values ranging between 0.42 and 36,000 Ωm. Regions with high-resistivity structure (1,000–36,000 Ωm) are seen between lateral distances of 45–213 m suggestive of possible standing lateritic layer separating the dumpsite into different compartments. However, low-resistivity structure (0.42–36 Ωm) was observed between lateral distances of 24–42 and 216–240 m suggestive of percolating leachate from the decomposed refuse materials. The third and fourth layers are composed of sandy clay/sand (Figs. 5 and 6). The effect of percolating leachate from the decomposed refuse material within these layers is represented by low-resistivity structure (<36 Ωm).

The 2-D inverted resistivity section along traverse 4 (Fig. 3) can be divided into four geoelectric layers. Within these layers, the effect of leachate from the decomposed refuse materials is represented by low-resistivity structures (<36 Ω m), while the resistivity value range of 204–15,000 Ωm within the layer may be associated with the hanging lateritic layer separating the dumpsite into different compartments or may be associated with the presence of non-biodegradable waste materials (such as polythene and rubber) or possibly trapped methane gas from the decomposed refuse materials.

The resistivity-depth model of traverse 5 (Fig. 3) reveals sediments with resistivity value ranging from 0.42 to 18,000 Ω m. The first two geoelectric layers extend from the surface to a depth of about 20 m beneath the surface. Low-resistivity

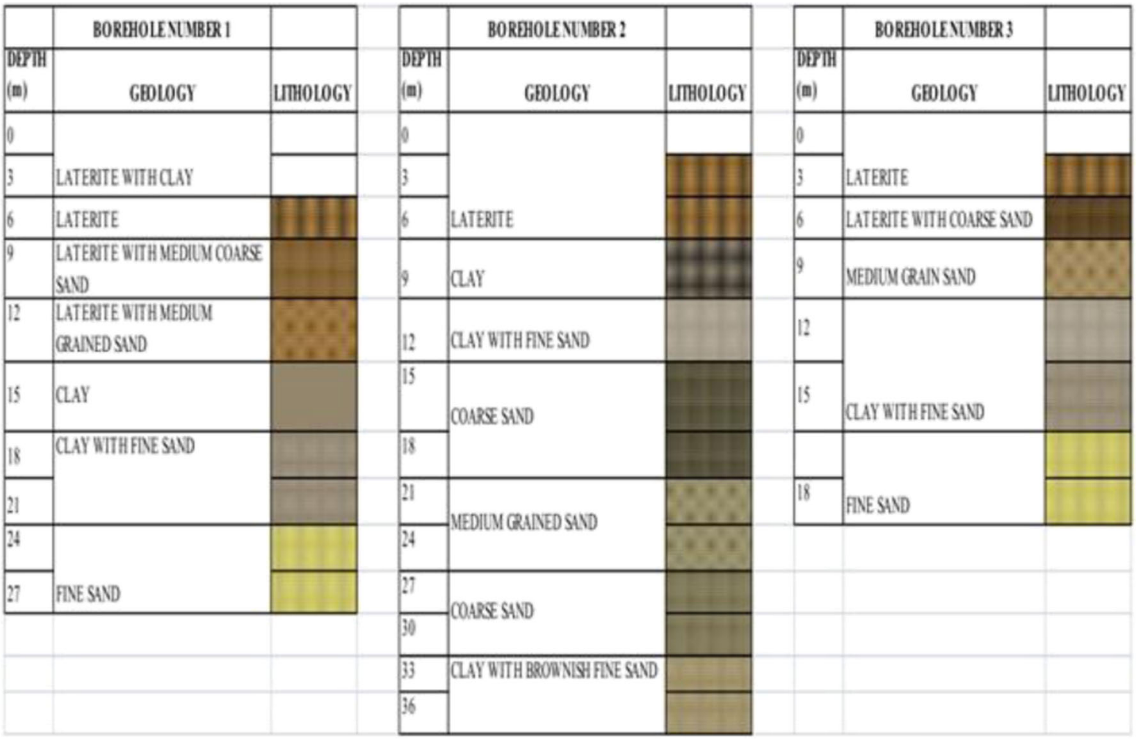


Fig. 6 Hydrogeological profile of boreholes at Olushosun (LMDGP 2009)

structures (0.42–36 Ωm) represent leachate from the decomposed refuse materials, while isolated regions of high resistivity (1,000–9,000 Ωm) may be associated with the presence of non-biodegradable waste materials or possibly trapped methane gas from the decomposed refuse materials. Low electrical resistivity structures within the third and fourth geoelectric layers (18–59 m) are suggestive of possible pollution of the first and second aquifers by the percolating leachate from the decomposed refuse materials.

The 2-D electrical resistivity section on traverse 6 (Fig. 3) shows that the subsurface beneath this traverse is characterized predominantly with low-resistivity structure indicative of varying degrees of decomposition of refuse materials along this traverse. The resistivity structure within this traverse varies from 0.42 to 20,000 Ωm and can be grouped into four geoelectric layers. The first two geoelectric layers represent the decomposed refuse materials and extend from the surface to a depth of about 17 m beneath the surface, while the third and fourth geoelectric layers are composed of sandy clay and sand (Fig. 6) and represent the first and second hydrogeologic units of the study area. These geoelectric layers are characterized predominantly by low-resistivity structure (0.42–36 Ωm) reflective of leachate from the decomposed refuse. Isolated high-resistivity structures (43–12,000 Ωm) are suspected to be associated with the presence of non-biodegradable refuse materials or trapped methane gas from the decomposed refuse materials.

From the geoelectric sections of traverse 1–6 (Fig. 3), the depth of pollution with low-resistivity values shows that the leachate from the decomposed refuse materials has impacted the subsurface, thereby polluting the groundwater, particularly the first and second aquifers. The degree of impact of pollution with depth seems to increase from the western to the eastern part of the dumpsite.

Similarly, models from profiles 7–10 (Fig. 4) reflect resistivity from 0.42 to 36 Ωm for the polluted area. The subsurface delineated under these traverses can be classified into four geoelectric layers indicating vertical and lateral migration of leachate to a depth of 59 m.

The 2-D inverted resistivity structure along traverse 7 (Fig. 4) shows an apparent lateral and vertical migration of the contaminant along this traverse characterized by resistivity values ranging from 0.42 to 4,519 Ωm. The topsoil is composed of lateritic material from the surface to an average depth of 5 m (Fig. 6). It is underlain by subsurface materials with resistivity values ranging from 0.4 to 4,519 Ωm from a depth of 5 m to a depth of 15 m beneath the subsurface. The third and fourth geoelectric layers represent the first and second hydrogeologic units within the study area and are composed of clayey sand and sand when correlated with the available borehole log (Fig. 6). Leachate effects are represented with low-resistivity values ranging between 0.42 and 36 Ωm. However, areas with relatively higher values of resistivity ranging between 90 and 4,519 Ωm within this layer are reflective of the presence of non-biodegradable refuse materials or possibly trapped methane gas beneath the surface.

The 2-D resistivity structure along traverse 8 (Fig. 4) reveals a subsurface structure with resistivity values ranging from 0.42 to 4,600 Ωm. The topsoil is represented by materials with electrical resistivity value ranging between 0.42 and 800 Ωm within an average depth of 5 m from the surface. It is underlain by subsurface materials with resistivity values ranging from 0.4 to 4,519 Ωm from a depth of 5 m to a depth of 18 m beneath the subsurface. The third and fourth geoelectric layers represent the first and second hydrogeologic units within the study area and are composed of clayey sand and sand when correlated with the available borehole log (Fig. 6). Leachate contamination from decomposed refuse materials are represented with low-resistivity values ranging between 0.42 and 36 Ωm. Relatively higher values of resistivity ranging between 90 and 800 Ωm present at a lateral distance of 110 to 213 m within the third geoelectric layer is suggestive of hydrogeologic unit (sand) that has not been impacted by the leachate.

In traverse 9 (Fig. 4), the topsoil is composed of lateritic materials from the surface to an average depth of about 5 m. It is represented by materials with electrical resistivity value ranging between 0.42 and 1,200 Ωm. Geoelectric layer two is characterized by materials with resistivity values ranging between 0.42 and 18,000 Ωm from a depth of 5 m to about 15 m. The third and fourth geoelectric layers extend from 15 to 59 m, and they represent the hydrogeologic units. Within this traverse, plumes of leachate are represented by low-resistivity values (<36 Ωm) indicative of the possibility of groundwater contamination. However, relatively higher values of resistivity (>43 Ωm) within the third and fourth geoelectric layers are suggestive of hydrogeologic unit (sand) that has not been impacted by the leachate.

The 2-D resistivity structure along traverse 10 is shown in Fig. 4. Low-resistivity structure (0.42–36 Ωm) may be indicative of aquifer contamination by the leachate from the decomposing refuse materials. Materials with higher values of resistivity from 70 to 800 Ωm within the third geoelectric layer are suggestive of sand with less impact from the leachate. The presence of leachate to a depth of 59 m indicates that the second aquifer may have been polluted and, therefore, may constitute a potential health hazards to the environment.

The resistivity-depth model obtained in traverse 11 (Fig. 5) shows high infiltration of leachate into the subsurface soil. The subsurface under this traverse was characterized by resistivity between 0.42 and 400 Ωm. Generally, the result reflects a high level of impact of leachate from decomposed materials from the dumpsite with resistivity 0.42–36 Ωm prevalent on the entire traverse. The depth of pollution with low-resistivity values is indicative of the leachate from the decomposed refuse material that has impacted the subsurface, thereby polluting the groundwater particularly the first and second aquifers. Isolated moderate resistivity structures (50–400 Ωm) within this traverse are reflective of less impact by the leachate.

Traverse 12 was run along the western boundary of the landfill perpendicular to traverse 13 (Fig. 5). The subsurface beneath this traverse is characterized by resistivity values ranging between 9.2 and 100,000 Ωm. This may represent the resistivity distribution of the present material beneath the surface. Leachate impact is represented with resistivity values between 0.42 and 36 Ωm, while relatively high-resistivity structure (204–1,000 Ωm) within the layer is reflective of the conductivity of the present soil material (sandy clay/clay sand and laterite).

Correlating the resistivity signature along this traverse with the result of vertical electrical sounding (VES) carried out in 2001 and 2002 by Ayolabi (2005) along this traverse shows that the subsurface along the traverse has been impacted by the leachate from the dumpsite. The variation in resistivity value within the period 2001–2002 (2,167–3,714 Ωm) and 2013 (9.2–1,000 Ωm) confirms the assertion.Traverse 13 was carried out perpendicular to traverse 12 (Fig. 5). It is characterized by electrical resistivity value range of 2.0–36,000 Ωm. The effect of leachate pollution of groundwater is less pronounced along this traverse, and the 2-D resistivity structure along this line may represent the resistivity distribution of the parent soil material beneath the surface. The topsoil has electrical resistivity values between 36 and 4,519 Ωm indicative of lateritic soil material (Fig. 6). The predominance of high-resistivity structure (400–46,000 Ωm) within the second and third geoelectric layers is reflective of parent soil material (sandy clay/clayey sand and laterite) that has not been impacted by the leachate. The high-resistivity signature along this traverse correlates well with the earlier deductions by Ayolabi (2005). However, the low-resistivity value (2–36 Ωm) between electrode positions 75–112 and 132–162 m may be associated with leachate infiltration. The fourth geoelectric layer is from a depth of 40 m to about 59 m. It is characterized by resistivity values ranging between 400 and 3,000 Ωm. This layer represents the second hydrogeologic unit for the study area and may not have been impacted by the leachate.

The 2-D resistivity section of traverse 14 is also presented in Fig. 5. This line was traversed at about 120 m away from the eastern boundary of the dumpsite. A depth of 52 m was probed, and the subsurface is characterized by resistivity values ranging from 0.42 to 36,000 Ωm. The low-resistivity structure (0.42–36 Ωm) within this layer may be associated with the effect of percolating leachate. Deductions from the 2-D resistivity structure also suggest that the leachate from the dumpsite may have been migrating towards the south/southeast direction.

Combining the 2-D ERT view of traverses 11–14 gives a block model of the subsurface under the traverses (Fig. 5). It shows an underground soil that has been impacted by discharge from the overlying decomposed refuse material to a depth above 59 m. The low-resistivity signature seems to increase from west to east and from north to south, suggestive of possible south/southeast leachate flow direction.

EM results

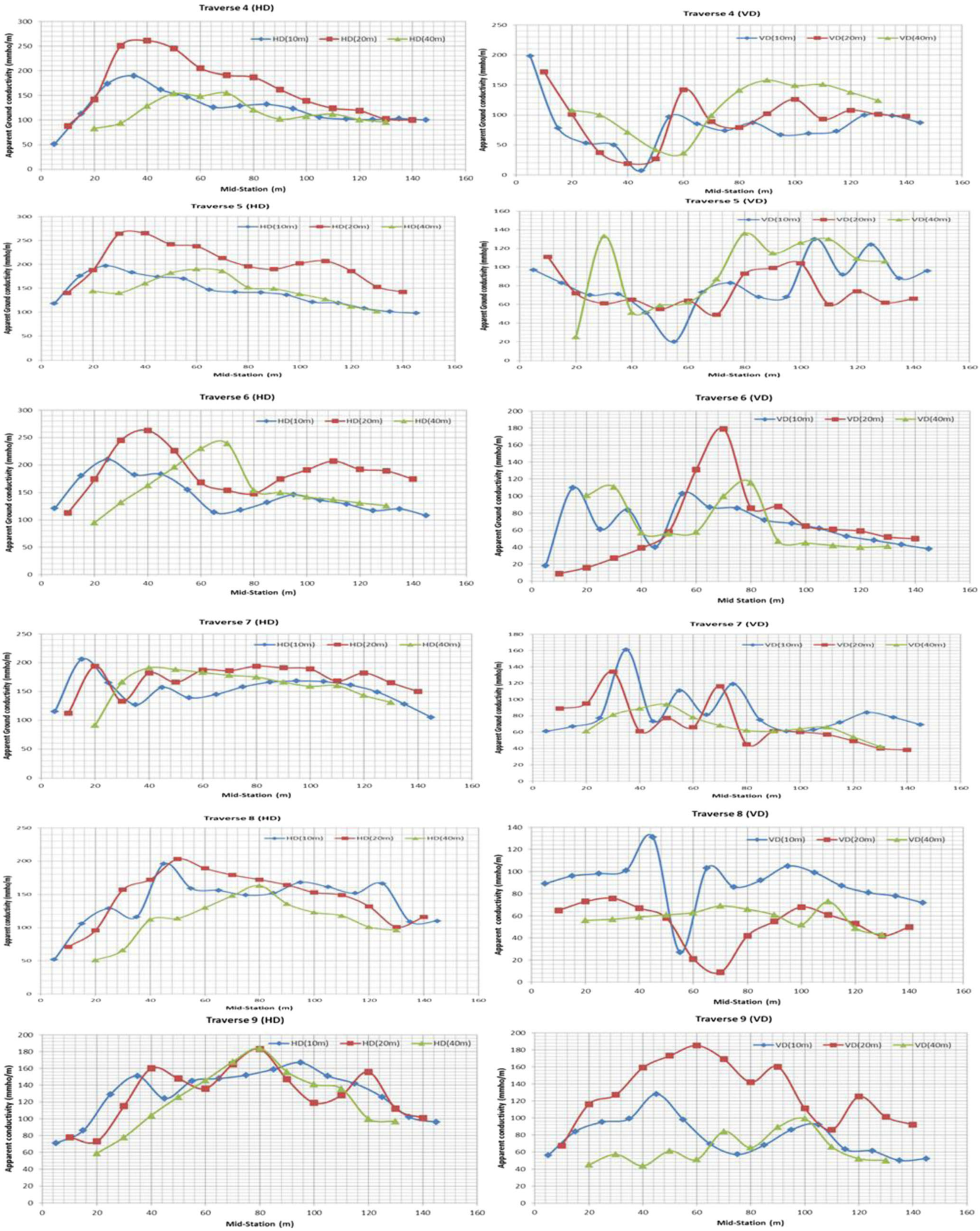
The result of the terrain conductivity measurement for the 11 EM traverses in the study area is presented as a plot of apparent conductivity against station for both vertical and horizontal dipole modes for each traverse (Figs. 7, 8, and 9). The graphical plots (Figs. 7, 8, and 9) show the variation of the terrain conductivity along the 11 profile lines, using the 10, 20, and 40 m intercoil spacing in both horizontal and vertical dipole coil orientations. Traverses 1–9 were carried out within the dumpsite, while traverses 11 and 12 (meant to serve as control) were carried out about 500 m away from the dumpsite. These were used to semiquantitatively deduce the soil conductivity values at 7.5, 15, and 30 m depths for horizontal dipole mode and 15, 30, and 60 m depths for vertical dipole mode.

Apparent conductivity value of 14–26 mmho/m was used as the background value for non-polluted region (Fig. 9), and the EM profiles were interpreted relative to these values.

Table 1 shows the summary of the subsurface apparent conductivity variation for profiles 1–11.Deductions from the EM profiles along traverses 1–9 (Figs. 7 and 8) show that the subsurface may have been impacted by high conductivity (35–270 mmho/m) up to a depth of 60 m (which represents the maximum depth achieved in the vertical dipole mode) as reflected by very high conductivity values at 10, 20, and 40 m coil separations (Figs. 7 and 8). This compared with the threshold value of 14–26 mmho/m (Fig. 9), suggesting that the first and second aquifer units within the dumpsite may have been polluted by the percolating leachate from the decomposed refuse materials.

High conductivity values within the dumpsite (profiles 1–9) indicate the presence of leachate plume beneath the subsurface. Correlation with the lithologic log (Fig. 6) indicates that percolation and migration of leachate plume is further enhanced by the weak protective capacity (laterite/sandy clay) of the subsurface and the fact that the dumpsite is unlined by impermeable materials (such as geomembrane or kaoline).

Fig. 7 Terrain conductivity measurement along profiles 1–3 (vertical and horizontal dipole)



Traverse 4 (HD)
Traverse 4 (VD)
Traverse 5 (HD)
Traverse 5 (VD)
Traverse 6 (HD)
Traverse 6 (VD)
Traverse 7 (HD)
Traverse 7 (VD)
Traverse 8 (HD)
Traverse 8 (VD)
Traverse 9 (HD)
Traverse 9 (VD)

Fig. 8 Terrain conductivity measurement along profiles 4–9 (vertical and horizontal dipole)

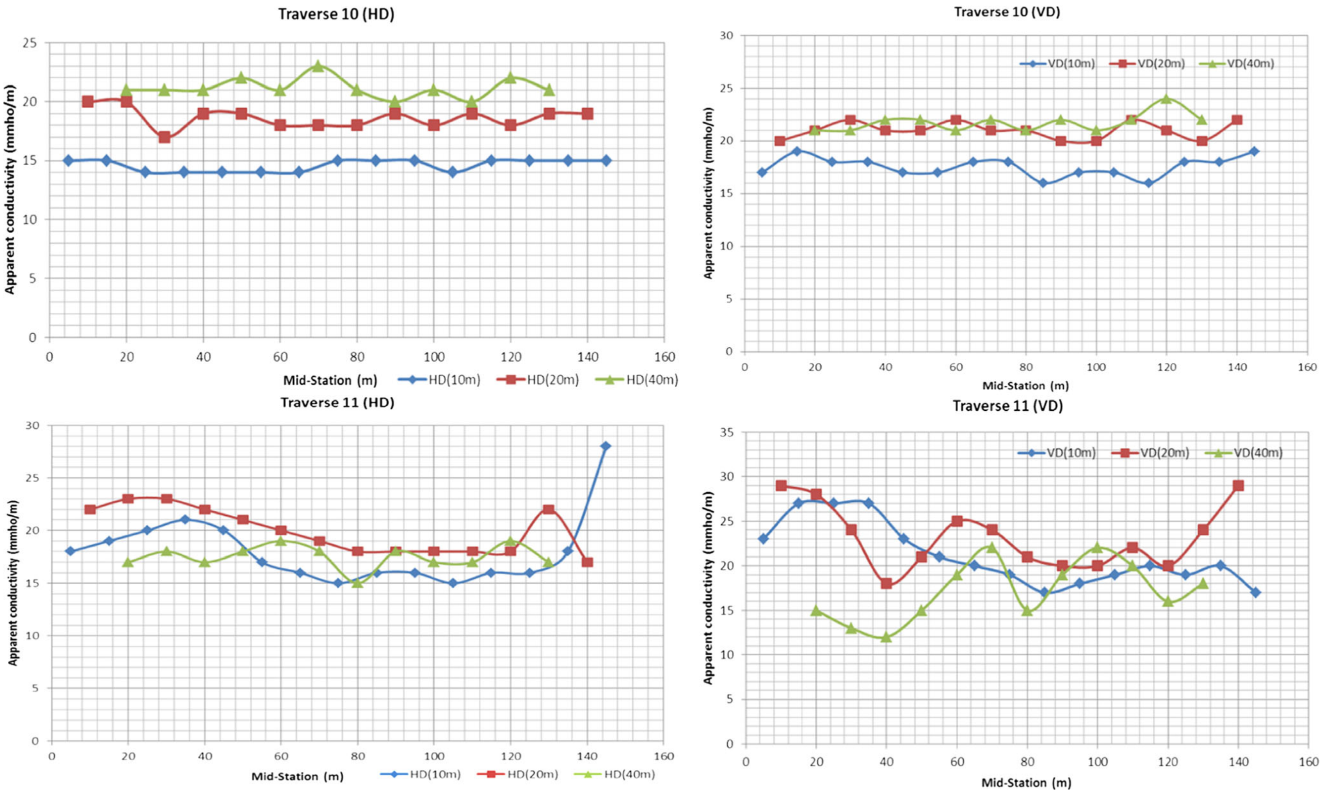


Fig. 9 Terrain conductivity measurement along profiles 10 and 11 (vertical and horizontal dipole)

Table 2 Physicochemical analysis of water samples from wells/boreholes at Olushosun landfill

No of well	Location	Coordinate	TDS (ppm/mg/l)	EC (µS)	pH	Temp (°C)
1	Ikosi High School	06° 35′ 55.6″, 003° 22′ 55.0″	84	168	5.73	30
2	Lagbus Park	06° 35′ 51.51″, 003° 22′44.03″	112	226	5.58	32.1
3	Beside LAWMA office	06° 35′ 49.07″, 003° 22′41.79″	53	105	5.35	30.1
4	*Volvo area beside landfill*	*06° 35′ 41.61″, 003° 22′50.06″*	*862*	*1,733*	*6.6*	*30.3*
5	Union Bank beside 7up	06° 35′ 57.61″, 003° 22′31.85″	92	184	6.01	30.4
6	Ikosi Road	06° 35′ 57.25″, 003° 22′49.14″	80	162	5.77	30.6
7	*Inside landfill*	*06° 35′ 52.53″, 003° 22′37.35″*	*896*	1,783	*5.18*	*33.5*
8	Supreme Road	06° 35′ 41.2″, 003° 22′ 29.1″	222	452	5.34	29.2
9	UAC drive	06° 35′ 40.99″, 003° 22′18.59″	81	162	5.85	29.4
10	*Alh. Abayomi Dr*	*06° 35′ 28.64″, 003° 22′26.95″*	*563*	*1,126*	*6.1*	*31.9*
11	*Olushosun B/S*	*06° 35′ 25.43″, 003° 22′28.38″*	*520*	*1,030*	*5.85*	*30.2*
12	Kudirat Abiola way	06° 35′ 23.02″, 003° 22′29.71″	81	163	6.09	30.5
13	Anisere Street	06° 35′ 32.02″, 003° 22′38.25″	40	75	5.2	29.7
14	Bewaji close	06° 35′ 34.55″, 003° 22′38.68″	76	153	5.24	32.5
15	*Ojota Motor Park*	*06° 35′ 28.63″*, 003° 22′49.77″	*2,000*	*3,999*	*6.85*	*33.4*
16	*Agofure Motors*	*06° 35′ 25.12″*, 003° 22′49.23″	*513*	*1,019*	*6.31*	*37.2*
17	Ogudu Road	06° 35′ 14.95″, 003° 22′50.34″	372	746	5.55	31.6
18	Aina Str	06° 35′ 18.42″, 003° 22′55.60″	251	541	5.58	35.5
19	*Ogudu Car Wash*	*06° 35′ 13.60″*, 003° 22′53.43″	*1,925*	*3,871*	*6.15*	*32.2*
20	LAWMA garden	06° 35′ 37.77″, 003° 22′52.02″	280	559	6.6	28.7

Those in italics represent wells with high values of TDS and EC above the WHO Standard

TDS total dissolved solid, *EC* electrical conductivity

Hydrochemical analysis

From the hydrochemical analysis results obtained in this study, it is deduced that, besides the vertical infiltration of leachate from the solid waste, the hydrological groundwater flow possibly plays a prominent role in contaminant distributions beneath the subsurface of a landfill or dumpsite (Pastor and Hernández 2012). This explains the moderate to high values of the physicochemical properties obtained. It is inferred that the contamination of groundwater aquifer not directly located on dumpsites or landfills is directly related to these high anomalous values. The physical parameters measured on the water samples collected from wells and boreholes in the precinct of the dumpsite are provided in Table 2. For water to be potable, the concentrations of the substances must not exceed the level set by the World Health Organization (WHO 2006).

Because of the persistent and indiscriminate burning coupled with heterogeneous nature of the waste, pH value in the acidic domain is expected since the residue after burning dissolves and percolates into the subsurface making the water more acidic. The pH obtained from water samples indicates high acidic content (5.20–6.85).

The total dissolved solute (TDS) values obtained from well locations 4, 7, 10, 11, 15, 16, and 19 were high (range of 513–2,000 mg/l), above the maximum permissible levels proposed by WHO (2006) which was 500 mg/l. This may be an indication of the presence of inorganic salts (such as calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulfates). The spatial distribution of TDS (Fig. 10) shows a general increase towards the southeastern part of the study area.

The electrical conductivity (EC) is a reflection of the degree of dissolved matters in water. Chemically pure water has a very low EC. The EC in the study area has elevated values (range of 1,019–3,999 μS/m) in wells 4, 7, 10, 11, 15, 16, and 19 having electrical conductivity values above 1,000 μS/m. This may be considered to be high when compared with the WHO standard values between 400 to 1,500 μS/cm and thus implies a high level of pollution. The spatial distribution of EC is shown in Fig. 11. It also shows a general increase towards

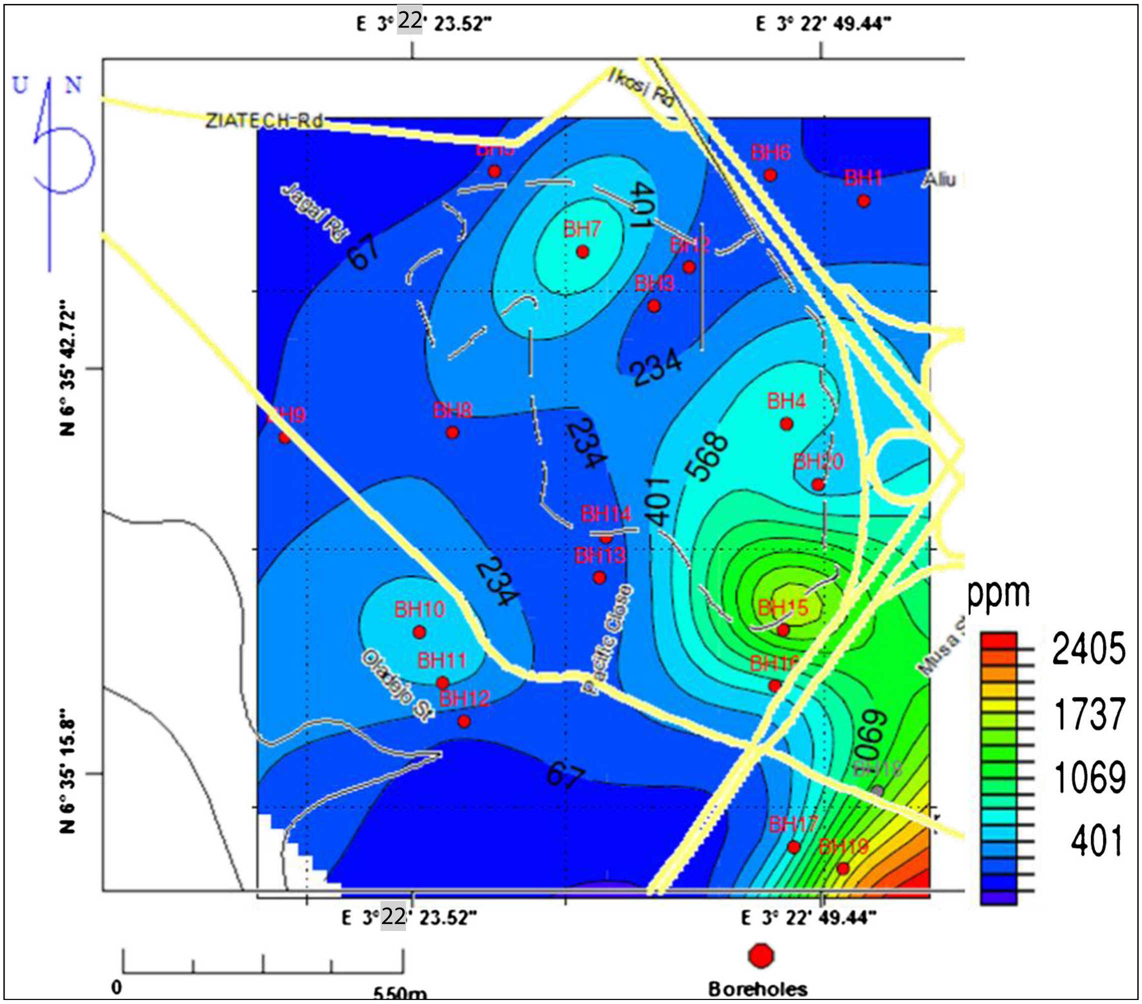


Fig. 10 Spatial distribution of total dissolved solid within the study area

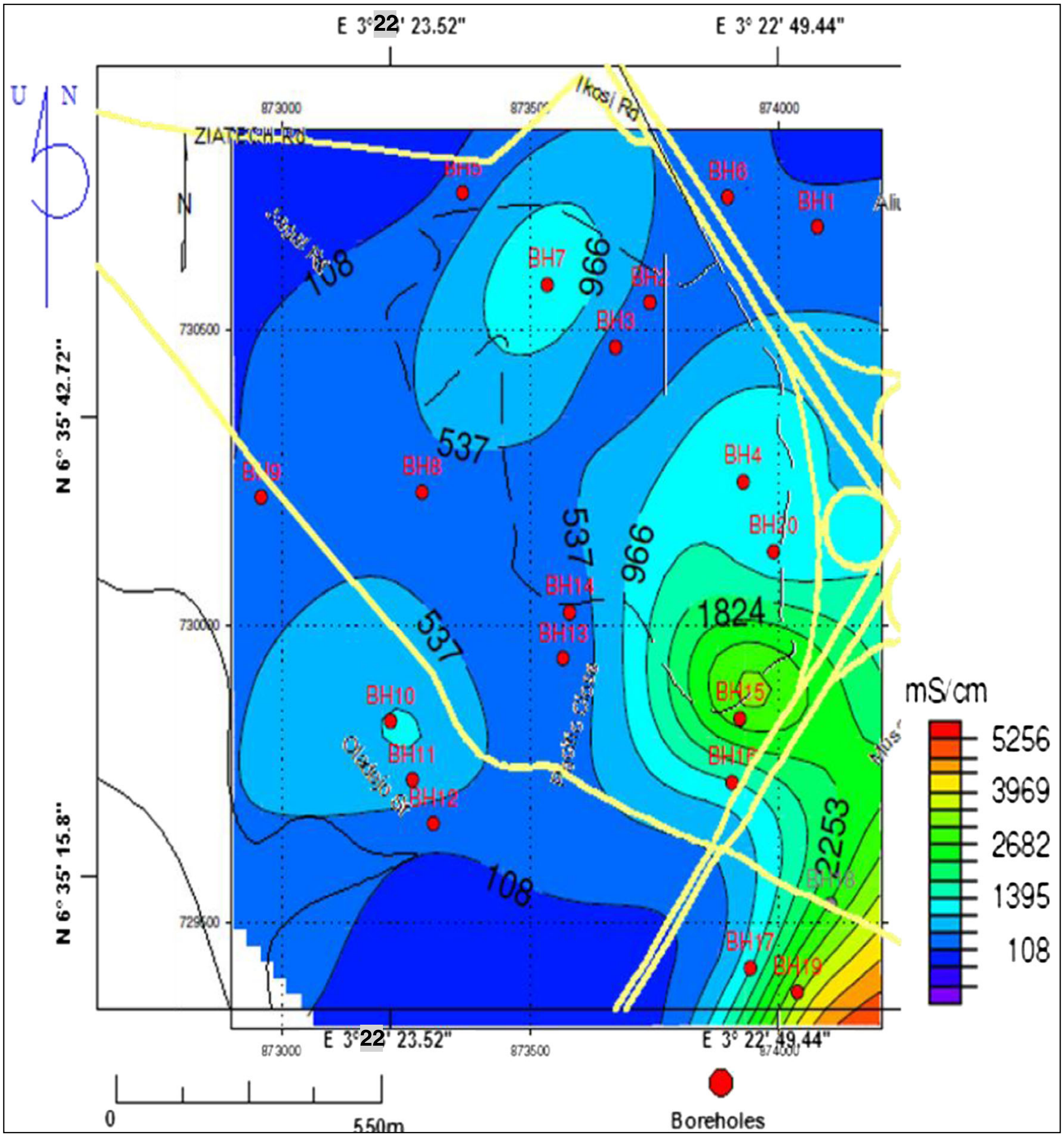


Fig. 11 Spatial distribution of electrical conductivity within the study area

the southeastern part of the study area which conforms to the map of TDS.

Conclusions

Integration of geophysical and physicochemical methods has been used to assess the subsurface conditions of Olushosun sanitary landfill. The ERT and terrain conductivity measurement indicate a polluted depth of over 59 m beneath the surface which coincides with that of the first and second aquifers in the study area. The result of the resistivity imaging delineated leachate plumes as low-resistivity zones (0.42–36 Ωm). It reveals that leachate from the decomposed refuse materials has polluted the subsurface to a depth of about 59 m which suggests possible pollution of the first and second hydrogeologic units within the study area. This correlates quite well with the result of the terrain conductivity measurement which delineated the vertical extent of the contaminated zones up to a maximum depth of about 30 m for the horizontal dipole configuration and a maximum depth of about 60 m for the vertical dipole configuration. In the same vein, statistical analyses of physical parameters determined in situ on groundwater from wells, and boreholes located in the precinct of this site also agreed to the contamination status of the site, having elevated concentrations of TDS (513–2,000 ppm) and EC (1,019–3,999 μS) in wells 4, 7, 10, 11, 15, 16, and 19. The pH obtained from water samples indicates high acidic content (5.34–6.85). Concentrations of TDS and EC measured follow a south and southeast increasing trend suggesting the possible flow of the leachate and consequently of the groundwater, which also agrees with similar flow pattern deduced from ERT results.

This high level of pollution has been accelerated by the weak protective capacity of the thick laterite delineated within the study area. Urgent remedial measures and proper monitoring programs for leachate, surface water, groundwater, and landfill gas control are, therefore, required so as to prevent the site from becoming a potential fountain of disease and death for the next generation.

References

Adeleye DR (1975) Nigeria late cretaceous stratigraphy and paleography. AAPG Bull 59(12):2302–2313

AGI inversion software (2009)

Ayolabi EA (2005) Geoelectric evaluation of Olushosun landfill site, southwest Nigeria and its implications on groundwater. J Geol Soc India 66:318–322

Ayolabi EA, Peters DY (2005) Hydrochemical and electrical resistivity assessment of the impact of solid waste on the groundwater at Oke-alfa refuse dumpsite, Lagos, Nigeria. J Sci Eng 12(1):5936–5946

Billman HG (1992) Offshore Stratigraphy and Paleontology of the Dahomey Embayment, West Africa, N.A.P.E. Bulletin 7(2):121–130

Davis JL, Annan AP (1989) Ground penetrating radar for high-resolution mapping of soil and rock stratigraphy. Geophys Prospect 37(5):531–551

Dawson CB, Lane JW Jr., White EA, Belaval M (2002) Integrated geophysical characterization of the Winthrop landfill southern flow path, Winthrop, Maine: Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) 2002 annual meeting of EEGS, Las Vegas, Nevada, February 10–14, 2002

deGroot-Hedlin C, Constable C (1990) Occam's inversion to generate smooth two-dimensional models from magnetotelluric data. Geophysics 55(12):1613–1624

Elueze AA, Nton ME (2004) Organic geochemical appraisal of limestones and shales in part of Eastern Dahomey Basin, Southwestern Nigeria. J Min Geol 40(1):29–40

Greenhouse JP, Harris RD (1983) DC, VLF and inductive resistivity surveys, in migration of contaminants in groundwater at a landfill: a case study. J Hydrol 63:190–197

Greenhouse JP, Monier-Williams M (1985) Geophysical monitoring of groundwater contamination around waste disposal sites. Groundw Monit Rev 5(4):47–59

Greenhouse JP, Slaine DD (1983) The use of reconnaissance electromagnetic methods to map contaminant migration". Ground Water Monit Rev 3(2):47–59

Jones HA, Hockey RD (1964) The geology of the part of southwestern Nigeria. Geological Survey Nigeria Bulletin, No 31, pp 101

Keller GV, Frischnecht FC (1966) Electrical methods in geophysical prospecting. Pergamon, Oxford, p 523

King WC, Witten AJ, Reed GD (1989) Detection and imaging of buried wastes using seismic wave propagation". J Environ Eng 115(3): 527–540

Lagos Metropolitan Development and Governance Project LMDGP (2009) Solid waste management component. Environmental and Social Impact Assessment (ESIA). Ministry of the Environment Lagos State Secretariat, Alausa, pp 11–70

Loke M H (2004) Tutorial: 2-D and 3-D electrical imaging surveys. 2004 revised edition. www.geometrics.com

Loke MH, Barker RD (1996) Practical techniques for 3D resistivity surveys and data inversion. Geophys Prospect 44:499–524

Longe EO, Malomo S, Olorunniwo MA (1987) Hydrogeology of Lagos metropolis. J Afr Earth Sci 6(3):163–174

Ogbe FGA (1972) Stratigraphy of strata exposed in the Ewekoro quarry, southwestern Nigeria. In: Dessauvagie TFJ, Whiteman (eds) African geology. University Press, Nigeria, p 305

Pastor J, Hernández AJ (2012) Heavy metals, salts and organic residues in old solid urban waste landfills and surface waters in their discharge areas: determinants for restoring Their impact. J Environ Manag 98: S42–S49. doi:10.1016/j.jenvman.2011.06.048

Ross HP, Mackelprang CE, Wright PM (1990) Dipole-dipole electrical resistivity surveys at waste disposal study site in Utah. In: Ward SH (ed) Geotechnical and environmental geophysics, vol 2. Society of Exploration Geophysicists, Tulsa, pp 145–152

Slaine DD, Greenhouse JP (1982) "Case histories of geophysical contaminant mapping at several waste disposal sites." Proceedings of the Second National Symposium on Aquifer Restoration and Ground Water Monitoring. 26–28 May, 1982. Columbus, pp 299–315

Slaine DD, Pehme PE, Hunter JA, Pullan SE, Greenhouse JP (1990) Mapping overburden stratigraphy at a proposed hazardous waste facility using seismic reflection methods. In: Ward SH (ed) Geotechnical and environmental geophysics, vol. 2. Environmental and Groundwater. Society of Exploration Geophysicists, Tulsa, pp 273–280

Sweeney JJ (1984) Comparison of electrical resistivity methods for investigation of groundwater conditions at a landfill site. Groundw Monit Rev 4(1):52–59

Wait JR (1962) A note on the electromagnetic response of a stratified earth. Geophysics 27:382–385

Winglink (2003) Integrated interpretation software. Geosystem, Italy

Winglink (2007) Integrated interpretation software. Version 2.20.01. Geosystem Corporation, Milan

World Health Organization-WHO (2006) Guidelines for drinking water quality. Geneva. www.lawma.gov.ng/landfill