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Geo-electrical assessment of coefficient of permeability and porosity of leachate plume at Asin dumpsite, Iwaro-oka, southwestern Nigeria

Ugotavljanje geoelektričnih lastnosti, količnika prepustnosti in poroznosti na območju izpiranja odpadne deponije pri Asinu v Iwaro-oki v jugozahodni Nigeriji

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Abstract

An integrated geophysical (involving two-dimensional [2D] electrical resistivity) and petrophysical study was conducted in the Precambrian Crystalline Basement area of Iwaro-oka Akoko, southwestern Nigeria. Five 2D resistivity profiles, both around the perimeters and inside the dump, were investigated with maximum lengths of 100 m. Results of the resistivity imaging delineated the leachate plumes as low-resistivity zones, with values ranging from 3 Ω m to 55 Ω m. The coefficient of permeability ranged from 4.33×10^{-6} to 7.82×10^{-3}, and the average porosity ranged from 32 Ω m to 169 Ω m, thus indicating migration of leachate plume to the groundwater due to the high coefficient of permeability and the porosity.

Key words: geophysical, geochemical, coefficient of permeability, porosity, leachate

Izvleček

Na območju deponije odpadkov, ki leži na ozemlju predkambrijske kristalinične podlage pri kraju Iwaro-oka akoko v jugozahodni Nigeriji so izvedli povezano geofizikalno (z uporabo dvodimenzionalne električne upornosti) in petrofizikalno prospekcijo. Na odvalu in v njegovi bližnji okolici so izmerili pet 2D upornostnih profilov dolžine do 100 m. Na podlagi podatkov upornostnih meritev je bilo mogoče omejiti območja širjenja lužine iz deponije kot cone nizke upornosti v razponu 3 Ω m to 55 Ω m. Količnik prepustnosti in povprečna poroznost se gibljeta prvi v mejah od 4.33×10^{-6} do 7.82×10^{-3} in druga od 32 Ω m to 169 Ω m. Visoke vrednosti količnika prepustnosti in poroznosti nakazujejo poti, po katerih odteka lužina v podtalnico.

Ključne besede: geofizika, geokemija, količnik prepustnosti, poroznost, lužina

Introduction

The quantity and indiscriminate disposal of domestic and industrial wastes have increased during the past decades. Land filling is a common and cheap method of waste management, which allows the treatment of 54% of domestic waste in the USA [1] and 39% of that in France [2]. Consequently, environmental laws of the European Union have focused on the water quality through framing of the Water Framework directive (2000/60EC). Despite innovations and improvements, numerous landfill plants continue to pollute groundwater because of several decades of waste disposal [3]. Recent landfills contribute to pollution when leaks from the storage compartment occur. The regular defects are fracture system, jointing and inhomogeneity due to porosity as well as the permeability of the subsurface geology [4].
These subsurface fracture inhomogeneities favour input of leachate into the subsoil, weathered and fractured soil membranes, and unconfined aquifers after percolation. Porosity and coefficient of permeability of the interconnected soil matrix has a direct impact on the hydraulic gradient of leachates. Moreover, sands/ regoliths enable quick exchange between groundwater systems integrated to a Darcy flow [5]. Hence, leachates may be subjected to variable reducing and oxidation reactions within groundwater.
Geophysical methods can furnish useful data for locating the boundaries of landfill sites and for estimating fill thickness. Physical property distribution along the subsurface, which may have geotechnical significance, can be derived from the geophysical data. Additionally, because the geophysical method responds to changes in the physiochemical conditions in the subsurface, useful chemical information may be gleaned from continuous geophysical site monitoring investigation. The electrical resistivity method is a unique geophysical tool used in groundwater and landfill studies [6, 7]. The resistivity method is used for electrical sounding and imaging. Electrical sounding provides information about vertical changes in subsurface electrical properties and, thus, it is useful in the determination of hydrogeological conditions, such as the depth to water table, depth to bedrock and thickness of soil [6]. Electrical resistivity imaging maps groundwater contamination leachate plumes, contaminant source, migration paths and depth [8].
Moreover, high-density electrical resistivity tomography (ERT) is receiving much attention for near-surface geophysical prospecting and subsurface hydrology evaluation [9–13]. Applications based on ERT either use the earth's resistivity to characterize the site and understand the subsurface geological structure and lithology [14, 15] or utilize temporal variations of the earth's resistivity to investigate underlying physical and chemical processes [16–18]. Because usually only earth resistance or electric potential data are available, successful application of ERT requires a suitable inversion algorithm that can convert the measured data to spatial distribution of resistivity.
The reduction and oxidation reactions of autotrophic and heterotrophic bacteria are regulated by dissolved oxygen and concentrations of inorganic carbon; temperature, pH and organic carbon concentration contribute to leachate toxicity. [19]. Moreover, high bioavailability for primary producers and high concentrations are responsible for eutrophication.
This investigation provides a discontinuous subsurface picture and can be a very tedious and expensive procedure [20]. Electrical resistivity is a modified direct current method [21] and is based on the former's dependence on the moisture content, porosity and temperature of different materials [22, 23]. Application of the electrical resistivity method to waste disposal characterization is very popular because the electrical resistivity of the waste in a landfill site varies considerably with time during waste decomposition and leachate formation [22-27].
Predicting the migration of contaminants from a landfill site requires an understanding of the physical factors that control the flow of water through the aquifer as well as the chemical and biochemical reactions that take place between waste components, groundwater and aquifer minerals. Once the physical properties of the aquifer and the chemical and biochemical reactions have been quantified, they must be integrated into a solute transport model in

order to predict contaminant concentration distributions at various times for a range of possible operating conditions, waste types and input or leaching rates. Obtaining information to describe the physical flow of water usually involves a field investigation of the site geology and measurement of the hydraulic properties of the principal formations or features that control groundwater flow. In its simplest form, this involves the determination of hydraulic conductivity and porosity, which, coupled with hydraulic head information, allows the determination of the velocity and direction of water flow in the saturated zone away from the landfill.

Groundwater resources have been under rapidly increasing stress in large parts of the world due to pollution. Pollution is primarily the result of irrigated agriculture, industrialization and urbanization, which generate diverse wastes, with the attendant impact on the ecosystem and groundwater. Waste may be loosely defined as any material that is considered to be of no further use to the owner and is hence discarded [28]. Characterizing and imaging the underground condition of landfills and the location of subsurface contaminants have always constituted a challenge. Conventional environmental monitoring used to determine the spread of groundwater contamination is performed by the expensive and labour-intensive task of drilling closely spaced boreholes for point sampling [29]. Contaminant plumes usually have a sufficiently high contrast in physical properties relative to the host media due to an increase in dissolved salts in the groundwater and a resulting decrease in bore water resistivity; therefore, they may be detected by the geo-electrical technique [30]. The generation of leachate in landfills results principally from the flow of percolating water through waste materials [31]. Leachate composition is determined by the nature of the waste at a specific site, the amount and rate of flow through the waste as well as the in situ geochemical condition. Attempts have been made to identify leachate attenuation reactions and thereby determine which hydrogeological environments are more suited to waste disposal. This research includes studies of both containment sites and sites where leachates are allowed to migrate, in order to study conditions in the landfill and in the unsaturated and the saturated zones. Where landfills are situated on permeable deposits, the source term is difficult to determine, but if the landfill has been established for some time, such sites provide the opportunity to study the long-term behaviour of contaminants and determine real-scale dispersion parameters.

Here, we present for the first time, the assessment and relationship of two-dimensional (2D) ERT, porosity and coefficient of permeability in terms of leachate migration and toxicity on groundwater. The study focuses on leachate dynamics originating from mature landfills (agricultural waste, sewage, sludge, methane, ammonia, sulphates, etc.) [32], as well as to determine the dynamics of the relationship and changes between conductivity of leachates and porosity, as well as the interaction of porosity with coefficient of permeability, in addition to assessing the fate of the migration effects of leachates on groundwater. In order to achieve these aims, we have applied geotechnical and 2D ERT investigation techniques.

Site description

Site and physiography

Iwaro oka-Akoko is located in Southwest Akoko, Local Government Area of Ondo State, Southwest Nigeria. It lies within the Precambrian Complex and is bounded by longitudes 5 74′E –5 755′E and latitudes 7 445′N –7 485′N; it covers an area of about 66 km^2. The study area can be accessed through a good road network running from Owo-Akungba to Iwaro Oka town. Other roads of secondary category that are not tarred but are motorable also aid accessibility in the area. Road cuts also make the rock units available for study. The northern part of the study area is characterized by a hilly topography, consisting of several east–west trending ridges. Some parts of the studied area are low lying, thus having a low relief (Figs. 1–3). The study area belongs to the tropical rainforest region and can be described as good, and it supports agricultural activities. The vegetation is thick with palm trees growing in the direction indicating the presence of flowing river or stream. The vegetation then causes highly frac-

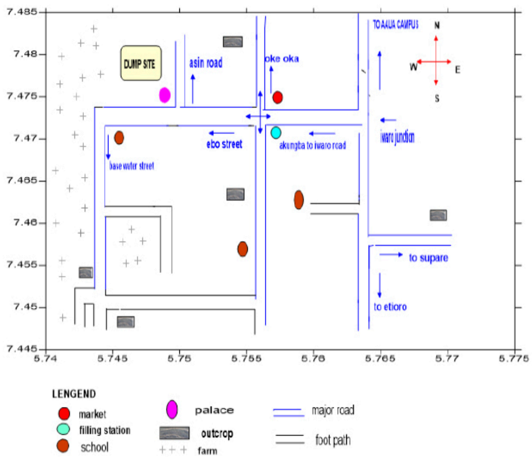


Figure 1*: Location map of the study area.*

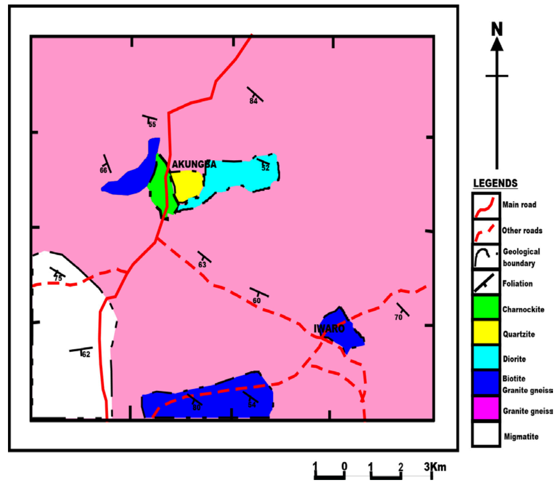


Figure 3: *Geological map of the study area.*

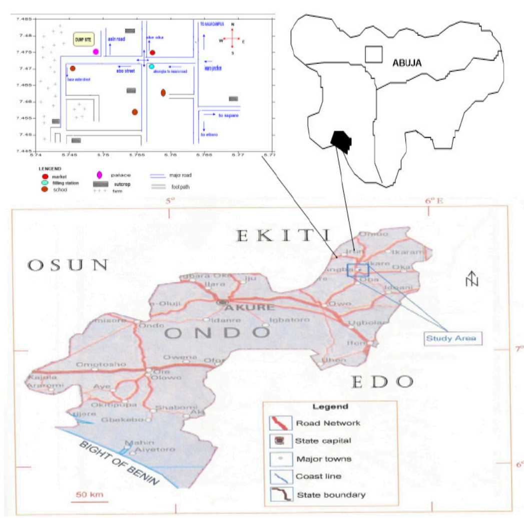


Figure 2: *Map of Ondo State showing the study area and the layout.*

tured openings in rocks. Intense cultivation, habitation and deforestation have modified the vegetation. The climatic condition of the investigated area is similar to that of the general climate of southwestern Nigeria; the rainy season is between March and October, and the dry season is between November and February. The temperature in the area varies between 28°C and 38°C, with high temperature between February and April.

Geology and hydrogeology

The survey area is underlain by the Precambrian basement complex rock of southwestern Nigeria. The basement rock exposures are, however, found as lowland outcrops in a few places within the survey area, particularly where the basement is shallow and erosional activities are active. However, according to Rahaman and Ocan [33], the area is underlain by migmatite–quartzite complex, with granite–gneiss being the major unit, which includes charnockite, quartzite, diorite and biotite. The area is sandwiched between two parallel prominent East – West ridges/inselbergs of granite gneiss composition found at the north, south and eastern ends. This feature creates a broad valley for groundwater resources development. Generally, in a typical basement complex area, groundwater is usually contained in the weathered column and fractured/fissured, sheared or jointed/faulted basement column. The geological processes in the study area enhance the leaching of the contained plumes into the aquifer. Hence, the geological condition of the study area favours groundwater accumulation.

Materials and methods

Two-dimensional resistivity surveys were carried out with a digital read-out AbemTerameter SAS 1000C using the dipole–dipole array configuration. A total of five profiles were studied, two each on either side of the landfill, with profile lengths of 100 m, 80 m,75 m and 60 m, interspaced by 10 m each and oriented in the East – West direction. The data obtained from the field were converted to apparent resistivity using the following formula: $G=\pi\,(n+1)(n+2)n$, where $\pi = 3.142$, G=geometric factor, N=number of in-

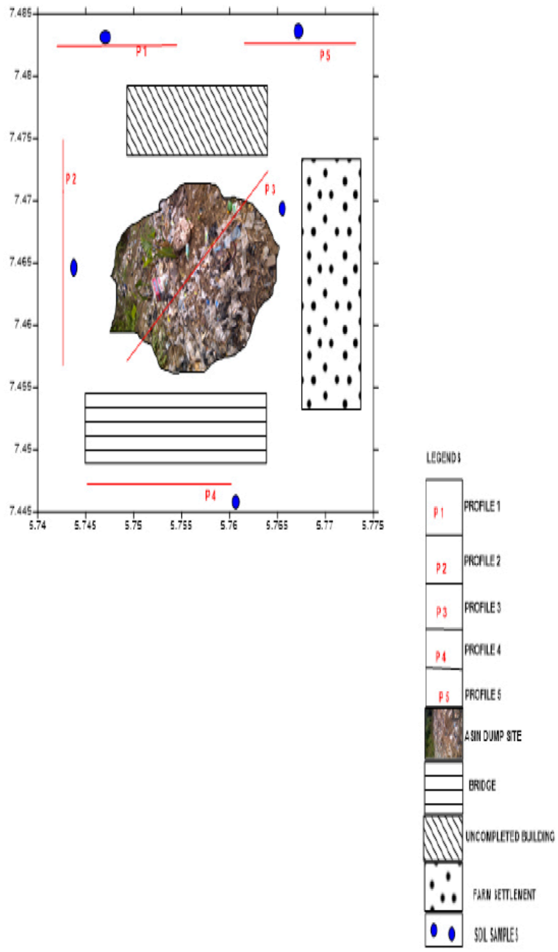


Figure 4: *Acquisition map of the study area.*

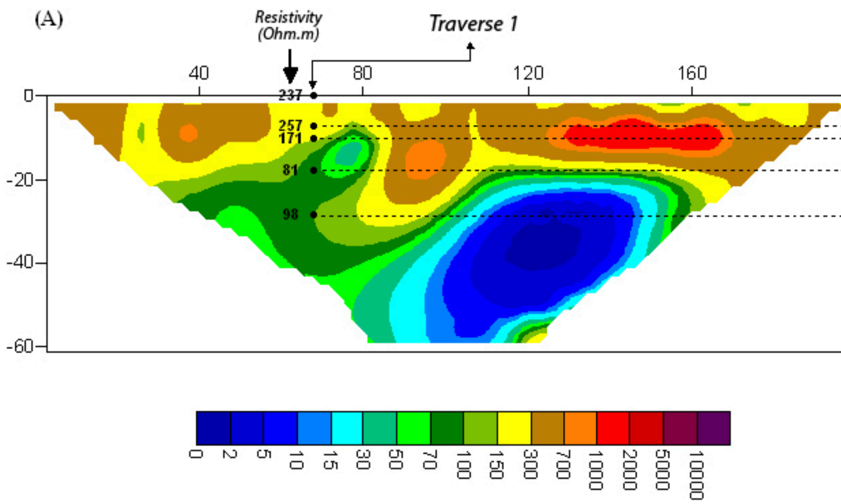
versions and *A*=station spacing. Measurements were made in sequence of increasing offset distances (*A* spacing) along the profile lines ranging from 10 m to 100 m using six stainless steel electrodes. The electrodes were moved from one end of the profile to the other in a leapfrog manner to achieve continuous horizontal coverage of the subsurface. The apparent resistivity measurements were inverted using the Res2DINV inversion software. Porosity determination of the soil in the area of study was based on the result of the resistivity of the area, while the soil permeability test was carried out on some representative samples from the study area.

Results and discussion

The measured 2D resistivity data were processed using RES2DINV inversion software [34].The programme uses the least-squares inversion scheme to minimize the difference between the calculated and the measured apparent resistivity values by an iterative process. The results are displayed as inverted sections of the true resistivity of the subsurface rocks. The sections were subsequently visually inspected to delineate areas of anomalously high or low resistivity related to subsurface structure. Porosity determination of the soil in the area of study was based on the result of the resistivity of the area, while the soil permeability test was carried out on some representative samples from the study area.

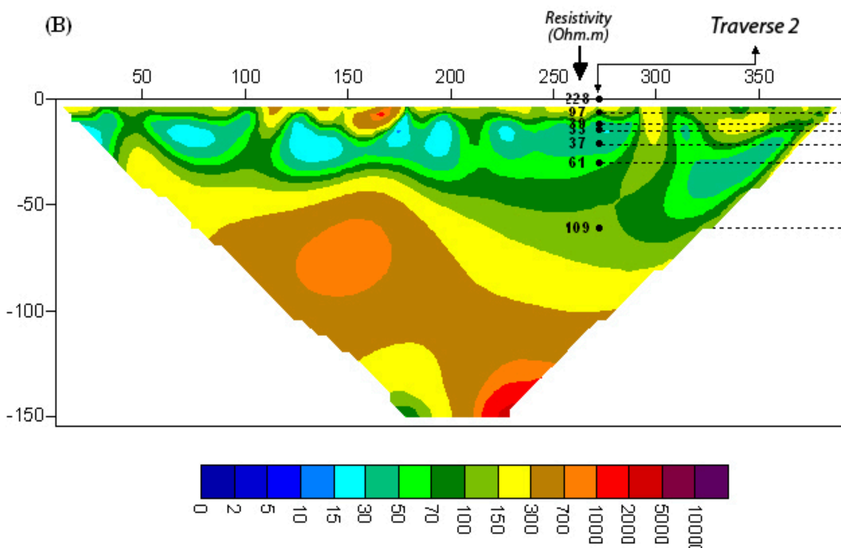
Traverse 1

This traverse lies 20 m away from the edge of the landfill and measurement was taken along the roadside within the vicinity of the landfill. The inverted 2D pseudosection obtained from the constant-separation traversing (CST) survey is shown in Figure 5. In the pseudosection, a high-resistivity zone (red portion) between 1,000 Ω m and 5,000 Ω m) existed near the surface, with spread length between 130 m and 170 m and depth of 5–8 m to the north and the south of the section. This zone is interpreted as having high-resistivity chemical compounds, and leachate migration near the surface is an indication that the leachate is less dense. The result shows fine-to-coarse sand, with resistivity values ranging from 81 Ω m to 257 Ω m at depths of 10–17 m and 7–10 m, respectively. Underlying the zone of high-resistivity chemical compounds is the zone of low resistivity (less than 15 Ω m), with depth ranging between 20 m and 60 m and surface point between 90 m and 150 m. Between the high-resistivity chemical compound zone (these are zones of anomalously high resistivity, containing gases such as methane, ammonia, carbondioxide and hydrogen sulphide from the biodegradation of organic wastes) and low-resistivity zone are sands of varying sizes and thicknesses. The bluish portion shows zones of low resistivity (3–49 Ω m) indicating contaminant leachate



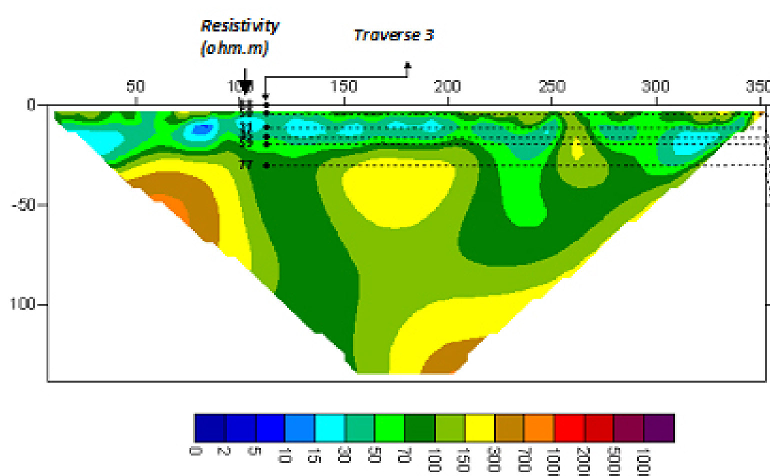
Traverse 1

Depth (m)	Description	Depth of Aquifer
0-7	Sandy Clay	
7-10	Sand	
10-17	Fine Sand	
17-28	Sandy Clay	



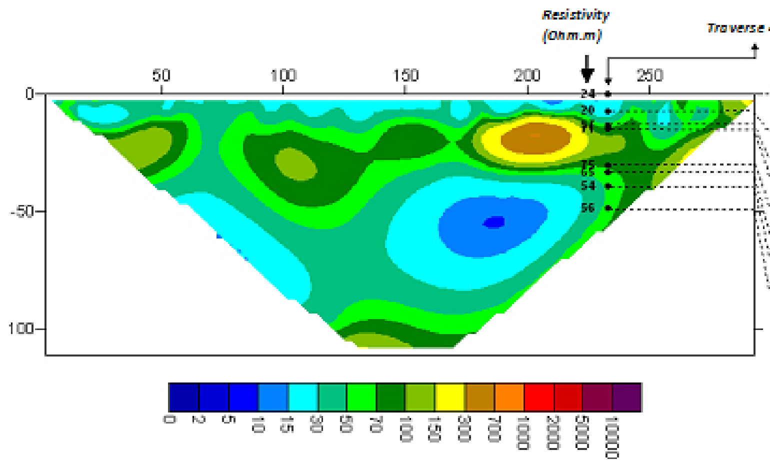
Traverse 2

Depth (m)	Description	Depth of Aquifer
0-6	Clay	
6-12	Clay, Silt & Sand	
12-15	Clay/Sand	
15-21	Clay/Sand	
21-30	Sand	Water bearing zones
30-60	Bedrock	



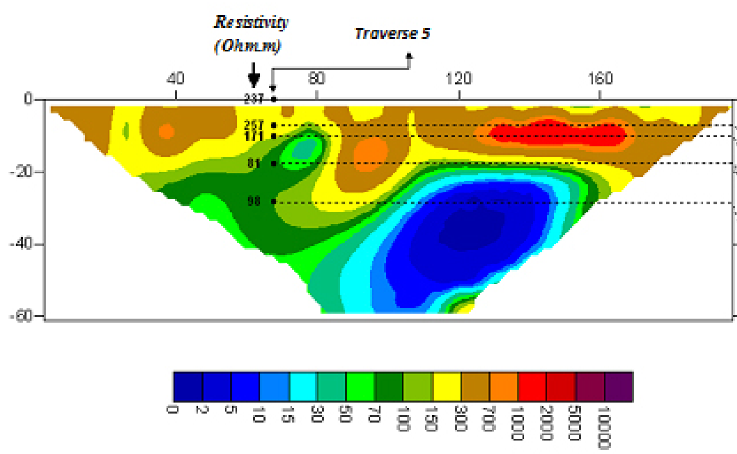
Traverse 3

Depth (m)	Description	Flow Rate
0-4.0	Lateritic soil	
4-11	Clay and Sand	Leachate Plume zones
11-15	Silty Clay and Sand	
15-40	Weathered rock	
40-80	Basement rock	Aquifer



Traverse 4

Depth (m)	Description	Flow Rate
0-10.0	Lateritic soil	Leachate Plume
10-20	Salt and Sand	
20-29	Clay and Sand	
29-40	Silty Clay and Sand	
40-50	Basement rock	Aquifer
50-60	Weathered and Bed rock	



Traverse 5

Depth (m)	Description	Depth of Aquifer
0-7	Sandy Clay	
7-10	Sand	
10-17	Fine Sand	
17-28	Sandy Clay	

Figure 5: *Pseudosections of traverses 1 –5 in the study area.*

plumes changing from blue to light blue, which reflects the changes in the concentration of the leachate as it seeps down due to filtration by the sediment, while the yellow portion shows zones of water-bearing zone (sands). Migration of the contaminant leachate plumes to the bottom is an indication that the leachate is denser. The greenish portion within the interpreted pseudosection of the traverse in the area of the study with low resistivity (less than 80 Ω m) represents the trash cell zone in the study area. The trash cell zone is the area where dump waste materials are located, and leachate activity in the environment is very high. The deep blue colour band shows that the leachate is highly concentrated in the area, while the light blue colour band shows the characteristic of leachate-polluted area. The cover material in this traverse is very thick and also exists within the upper layer. It includes sandy clay, sand and fine sand with depths ranging from 0 m to 28 m.

Traverse 2

The inverted 2D pseudosection, as shown in Figure 5, delineates three subsurface layers. These are the top soil, the weathered layer and the basement bedrock. The result shows that the top soil has virtually merged with the weathered layer due to overlapping low/high-resistivity values. The top soil is characterized with light bluish, greenish and very light yellow-coloured bands. The greenish colour band with low resistivity (less than 80 Ω m), representing the trash cell area of the study area in which the dump wastes are located, exists at the depth of 10–30 m with surface point at 10–350 m. The bluish colour band exists between the depths of 10 m and 30 m, and the surface point is at 30–300 m, which indicates leachate saturation. The result shows the intercalation of clay and clay sand, with resistivity values ranging from 39 Ω m to 97 Ω m and 37 Ω m to 61 Ω m, respectively, which prevents these leachates from migrating downwards to contaminate the water-bearing zone (yellow band). The second layer is the weathered layer characterized by the yellow colour band indicating the water-bearing zone (sand). The last layer is the basement bedrock, characterized by brown – red colour, ranging from depths of 30 m to 60 m. The light blue colour bands indicate the occurrence of leachate, but the concentration is not very high.

Traverse 3

In this traverse, the leachate effect is mapped out in the region with relatively low resistivity (29–39 Ω m), which is identified in a light blue colour band, as shown in Figure 5. The low-resistivity variation is indicative of the degree of decomposition of the refuse material and denotes the saturated zones starting from the ground surface. The contaminated leachate plumes exist at the surface point of 0–250 m and 261–350 m and at depths of 0–15 m. The presence of the leachate could not be seen at the surface point of 251–260 m along the surface of the traverse. The trash cell area (greenish portion), representing the areas where the dump wastes are located, exists at depths of 30–120 m, infiltrating the water-bearing zone (yellow portion). The water-bearing zone exists at the depth of 30–70 m and at the surface point of 150–200 m. The identification of the trash cell zone (greenish portion) in the traverse suggests that the subsoil and the groundwater may have been contaminated by the leachate. The results also show that the cover material is very thick, and that the cover material includes lateritic soil, clay and sand as well as silty clay and sand at depths of 0–4 m, 4–11 m and 11–15 m, respectively.

Traverse 4

The interpreted pseudosection shown in Figure 5 reveals two pronounced zones. These include the top zone and the groundwater (water-bearing) zone. The top zone (light blue) is indicated as the zone of leachate plume concentration, with resistivity values ranging from 20 Ω m to 56 Ω m and depths of 40–100 m. The result shows that the cover material of the dump site has been infiltrated by the contaminant leachate plumes. The lower the resistivity of this zone, the higher is the conductivity, the more porous it is and the more permeable is the underlying soil. The cover material, such as sand, at the depth of 10–29 m signifies the groundwater zone (yellow portion), which has been partly infiltrated by the contaminant leachate plume. The lithology of this dumpsite enhances the migration of the leachate plume because sand is highly porous and highly permeable, therefore allowing the leachate to migrate downwards. Migration of the contaminant leachate plume to the bottom is an indication that the leachate is denser. The trash cell zone (greenish portion), which represents areas where dump wastes are located, is seen to move in the direction of the leachate plumes, which signifies the characteristic polluted area. The characteristic polluted area influenced by the leachate plumes also infiltrates the groundwater zone, therefore moving in the same direction as the leachate plume.

Traverse 5

This traverse lies 25 m away from the edge of the landfill and measurement was taken along the roadside within the vicinity of the landfill. The inverted 2D pseudosection obtained from the CST survey is shown in Figure 5. In the pseudosection, the high-resistivity zone (red portion) between 1,000 W m and 5,000 W m exists near the surface, with spread length between 130 m and 170 m and depth of 5–8 m to the north and the south of the section. This zone is interpreted as having high-resistivity chemical compounds, and leachate migration near the surface is an indication that the leachate is less dense. The result shows the zone as having fine-to-coarse sand with resistivity values ranging from 81 W m to 257 W m at depths of 10–17 m and 7–10 m, respectively. Underlying the zone of high-resistivity chemical compounds is the zone of low resistivity (less than 15 W m), at depths ranging between 20 m and 60 m and surface point between 90 m and 150 m. Between the high-resistivity chemical compound zone and low-resistivity zone are sands of varying sizes and thicknesses. The bluish portion shows the zones of low resistivity (contaminant leachate plumes) changing from blue to light blue, reflecting the changes in the concentration of the leachate as it seeps down due to filtration by the sediment. The yellow portion shows the water-bearing zones (sands). Migration of the contaminant leachate plumes to the bottom is an indication that the leachate is denser. The greenish portion within the interpreted pseudosection of the traverse in the area of the study with low resistivity (less than 80 W m) represents the trash cell zone where the dump waste materials are located, and leachate activity in the environment is very high here. The deep blue colour band shows that the leachate is highly concentrated in the area, while the light blue colour bands shows the characteristic of a leachate-polluted area. The cover material in this traverse is very thick and also exists within the upper layer. It includes sandy clay, sand and fine sand, with depth ranging from 0 m to 28 m.

Results of porosity and permeability tests

Table 1: *Average porosity of the soil.*

Soil samples	Average porosity Ω
1	169
2	63
3	55
4	32
5	155

Table 2: *Coefficient of permeability values.*

Soil sample	Coefficient of permeability, K (m/s)
1	7.82×10^{-5}
2	4.75×10^{-8}
3	4.33×10^{-8}
4	3.47×10^{-7}
5	6.74×10^{-6}

The results of the geophysical survey carried out on the area of study using dipole–dipole array revealed varying degrees of weathering (porosity), with resistivity values ranging from 32 W m to 169 W mW (Table 1), indicating porous zones due to secondary porosity or water content. The results of the hydraulic conductivity *K* determination, presented in Table 2, show high values of *K*, confirming that the sample areas are highly permeable and hence allow free flow of leachate to the groundwater in the area of study. The values of permeability obtained may be influenced by the packing of the soil types, viscosity of the fluid, the amount of or-

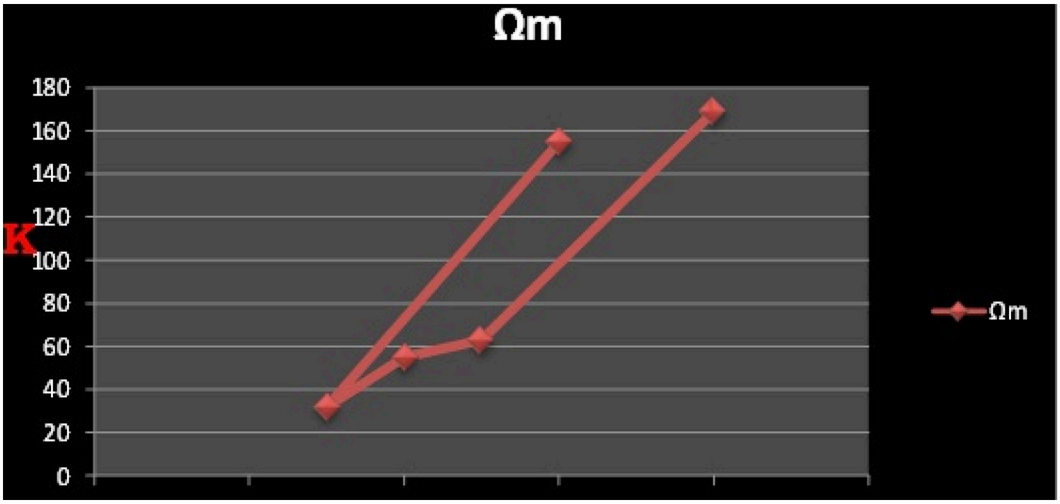


Figure 6: *The statistical plot of the average porosity values of each traverse against the permeability result.*

ganic matter, the porosity and the clay content. From the calculated hydraulic conductivity values, it could be deduced that the more the clay content of the soil samples, the lesser is the flow rate and, consequently, the lesser is the value of *K*; the larger the diameter of the soil sample (the coarser the soil sample), the more is the flow rate, and hence, the higher is the value of *K*. However, the statistical plot of the average porosity values of each traverse against the permeability result (Figure 6) (after Folk [35]) falls within the first quadrant. This plot shows that the higher the porosity of the soil, the more permeable it is and the more is the accumulation of the leachate.

Conclusion

The 2D electrical resistivity models successfully delineated the lateral and vertical extents of the contaminated zones as well as fractures as subsurface contaminant pathways. The result of the 2D resistivity imaging showed the various lithological units in the study site based on the respective depths of the investigation. The geologic interpretation shows that the site is dominantly underlain by clay and sandy formations of varying grain sizes, which constitute the hydrogeologic unit of the area. The study showed that parts of the dumpsite had been contaminated. This contamination (leachate plume) was also observed to have infiltrated to a depth of 60 m in the dumpsite. This could pose serious health risks to the inhabitants of the area who depend largely on wells and shallow boreholes for their drinking water supply. The 2D resistivity models were unable to distinguish the sources of the contamination as resulting from either electrolytic or metallic invasion because they have similar resistivity values. The permeability test result proved that the soil samples within the study area are permeable. This is an indication that the leachate within the area of study can have free access to the groundwater in the area due to the high coefficient of permeability of the soil. However, the porosity of the soil is also high and tends to be across the NE –SE axis of the area of study, and this implies that the leachate effect in the area will be more severe in the NE –SE regions of the area.

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