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Geophysical investigation of leachate contamination around selected dumpsites in Calabar, Nigeria

Augustine A. Abong[a,*], Samuel I. Ugar[b]

[a] Department of Physics, University of Cross River State, P.M.B. 1138, Nigeria
[b] Department of Geology, University of Calabar, P.M.B. 1115, Nigeria

Abstract

This study employed electrical resistivity tomography (ERT) to investigate leachate contamination around selected dumpsites in Calabar, Cross River State, Nigeria. Seven profiles were surveyed: five close to the dumpsites and two away from the dumpsites as controls. Data were collected using a Wenner array configuration, with spread lengths varying from 55.0 to 105.0 m. The major equipment used was a Resistivity Meter Model SSR-MP-ATS from IGIS (India), with its accessories. The measured subsurface resistance values were converted to apparent resistivity using the appropriate formula. Data analysis was performed using Microsoft Excel and RES2DINV software. The findings revealed the presence of leachate, characterized by low resistivity values (less than 10 Ωm), at the Lemna (profile 2), CROSPIL (profile 4), and UNICROSS (profile 7) dumpsites. Profiles 1, 3, 5, and 6 did not show evidence of leachate contamination. These results imply that the long-term buildup of organic pollutants in leachate may pose a threat to aquatic life, plants, and eventually people. In addition, the introduction of landfill leachate into soil, groundwater, and surface-water bodies poses environmental risks. To mitigate health hazards, it is strongly recommended that groundwater be thoroughly treated before consumption. This approach will help to address the potential health implications associated with leachate from the dumpsites and protect community health and well-being.

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1. Introduction

One of the major problems facing developing countries in this century is the management of open dumpsites. Due to population growth, industrialization, bilateral trade, migration, and urbanization, waste generation has increased significantly [1]. The United Nations Environment Program (UNEP) reported in 2015 that Nigeria ranks first among the 50 countries with the largest active dumpsites, accounting for 12% of the largest active dumpsites globally. According to estimates, the world produces 2.01 billion tons of solid waste annually, and that amount is expected to rise to 2.2 billion tons by 2025 [2, 3].

Poor solid-waste management has detrimental impacts on the environment and human health [4, 5]. Leachate, which is generated when solid waste at a dumpsite decomposes, can seep into groundwater and contaminate it. Because most people in the area rely

*Corresponding author Tel. No.: +234-802-640-8577.
Email address: abongaustine@unicross.edu.ng (Augustine A. Abong)

primarily on groundwater for domestic purposes, contaminated water may cause several water-borne illnesses, including diarrhoea and cholera.

Leachate is created when water from soil moisture, precipitation, snow, and other liquid waste disposed of at a landfill site interacts with the landfill material. In addition, chemical and biological activities within a landfill may produce leachate. Leachate formation causes uneven and sporadic moisture percolation through solid waste in a landfill [6–8]. As a result, soluble components from the waste are removed and added to the leachate. These components may include heavy metals, polycyclic aromatic hydrocarbons (PAHs), phenols, polychlorinated biphenyls (PCBs), chlorinated alkyl phosphates, polyfluoroalkyl and other fluorinated chemicals, pharmaceuticals and personal care products, polybrominated diphenyl ethers (PBDEs), polychlorinated dibenzofurans (PCDFs), polychlorinated dibenzodioxins (PCDDs), and polychlorinated diphenyl ethers (PCDEs). Because leachate contains significant concentrations of different classes of pollutants, it is considered a high-strength wastewater.

Numerous investigations have been carried out across the world. Ugbor *et al*. [9] examined the impact of leachate plumes on groundwater at a dumpsite in Onitsha, Nigeria. Emujakporue [10] examined pollutants in a landfill and found that the leachate zone had a comparatively lower electrical potential. Wijesekara *et al*. [11] evaluated the leachate flow path and observed that it was concentrated near the surface along a low-resistivity zone, with no distinct plume downstream. Ganiyu *et al*. [12] employed electrical resistivity imaging to map leachate-plume movement in the Lapite dumpsite in Ibadan, and their findings showed that the leachate plume was more conductive than the surrounding areas.

Omolara *et al*. [13] examined the Oke–Diya dumpsite using integrated very-low-frequency electromagnetic (VLF-EM), resistivity, and multichannel analysis of surface waves (MASW) methods. Their results showed poor leachate-curtailment capacity and vulnerable subsurface conditions, confirming high contamination risk and supporting recommendations for site evacuation and environmental remediation. Iyoha *et al*. [14] used ERT at Otofure to map leachate plumes. Low resistivity values ($< 38.3\ \Omega$m) indicated contamination down to 13–30 m, while high-resistivity zones reflected waste materials and landfill gases, confirming significant subsurface pollution and the effectiveness of ERT.

Adesokan *et al*. [15] assessed groundwater pollution at a dumpsite in Kuje using geophysical and physicochemical methods. Very low resistivity values ($< 7\ \Omega$m) indicated leachate migration, while water samples showed elevated heavy-metal concentrations above World Health Organization (WHO) limits. The study confirmed contamination from waste materials and emphasized improved waste management for groundwater protection. Ezeh and Maika [16] investigated leachate contamination at Osogbo using integrated vertical electrical sounding (VES), two-dimensional (2D) and three-dimensional (3D) ERT, and time-lapse imaging. Their results showed low resistivity values ($< 100\ \Omega$m), indicating contamination extending to 25 m and beyond aquifers, and confirming that groundwater used for domestic purposes was already polluted.

Ayolabi *et al*. [17] applied integrated geophysical and geochemical techniques to investigate an open dumpsite in Lagos. The study revealed deep leachate migration, groundwater contamination, acidic water conditions, and significant environmental and public-health risks associated with uncontrolled waste disposal. Idowu and Osahon [18] investigated groundwater contamination around the Otofure dumpsite using geoelectrical and X-ray fluorescence (XRF) analyses. Their results showed that leachate migration was confined to shallow depths by impermeable clay layers, while heavy-metal concentrations remained below permissible limits, indicating minimal groundwater-contamination risk.

Ajani *et al*. [19] combined soil physical analysis and geoelectrical VES at the Bowen University dumpsite. Their results showed altered soil properties and increased porosity, indicating leachate-migration potential and possible future groundwater contamination through permeable alluvial soils. Igelle *et al*. [20] assessed leachate penetration at the Lemna dumpsite using ERT, VES, soil, and borehole analyses. The results showed strong resistivity anomalies, significant benzene, toluene, ethylbenzene, and xylene (BTEX) contamination exceeding standards, and very low aquifer protection, indicating severe groundwater vulnerability and an urgent need for remediation. Igelle *et al*. [21] assessed heavy-metal transport and groundwater vulnerability at the Lemna dumpsite using soil and borehole sampling, pumping tests, statistical analysis, and Visual MODFLOW modelling. Their results showed significant contamination by arsenic, lead, cadmium, chromium, nickel, and mercury, with concentrations exceeding regulatory limits. The modelling indicated rapid spatial plume migration (259.2 m^2/day) and extensive annual spread, confirming high groundwater susceptibility and risk to nearby boreholes. The study recommended urgent remediation and strict monitoring to control heavy-metal pollution.

Odoh *et al*. [22] investigated leachate impacts on groundwater in Agu-Akwa using integrated geotechnical, geophysical, and geochemical methods. Their results showed moderate-to-low aquifer protection, elevated heavy metals and contaminants above WHO limits, and confirmed that leachate infiltration significantly degrades groundwater quality, necessitating improved landfill siting and monitoring. Nwachukwu *et al*. [23] assessed groundwater contamination in Awka South Local Government Area. Their results showed leachate impact on groundwater quality, with elevated heavy metals (Pb, Hg, Cr, and As) exceeding WHO limits. Physicochemical parameters were mostly compliant, but the contamination risks require improved waste management and monitoring. Adeniyi *et al*. [24] investigated leachate infiltration at the Ojoou Olayanju dumpsite using dipole–dipole resistivity and natural electric-field methods. Their results showed heterogeneous subsurface conditions, fractured zones, and low-resistivity conductive areas indicating leachate saturation. The findings confirmed widespread topsoil contamination and high groundwater-pollution risk due to continuous leachate migration through permeable pathways.

The increasing volume of waste disposed of at dumpsites in Calabar, Nigeria, raises concerns about leachate leakage and groundwater contamination. Despite these environmental risks, limited geophysical data are available on the extent and movement of

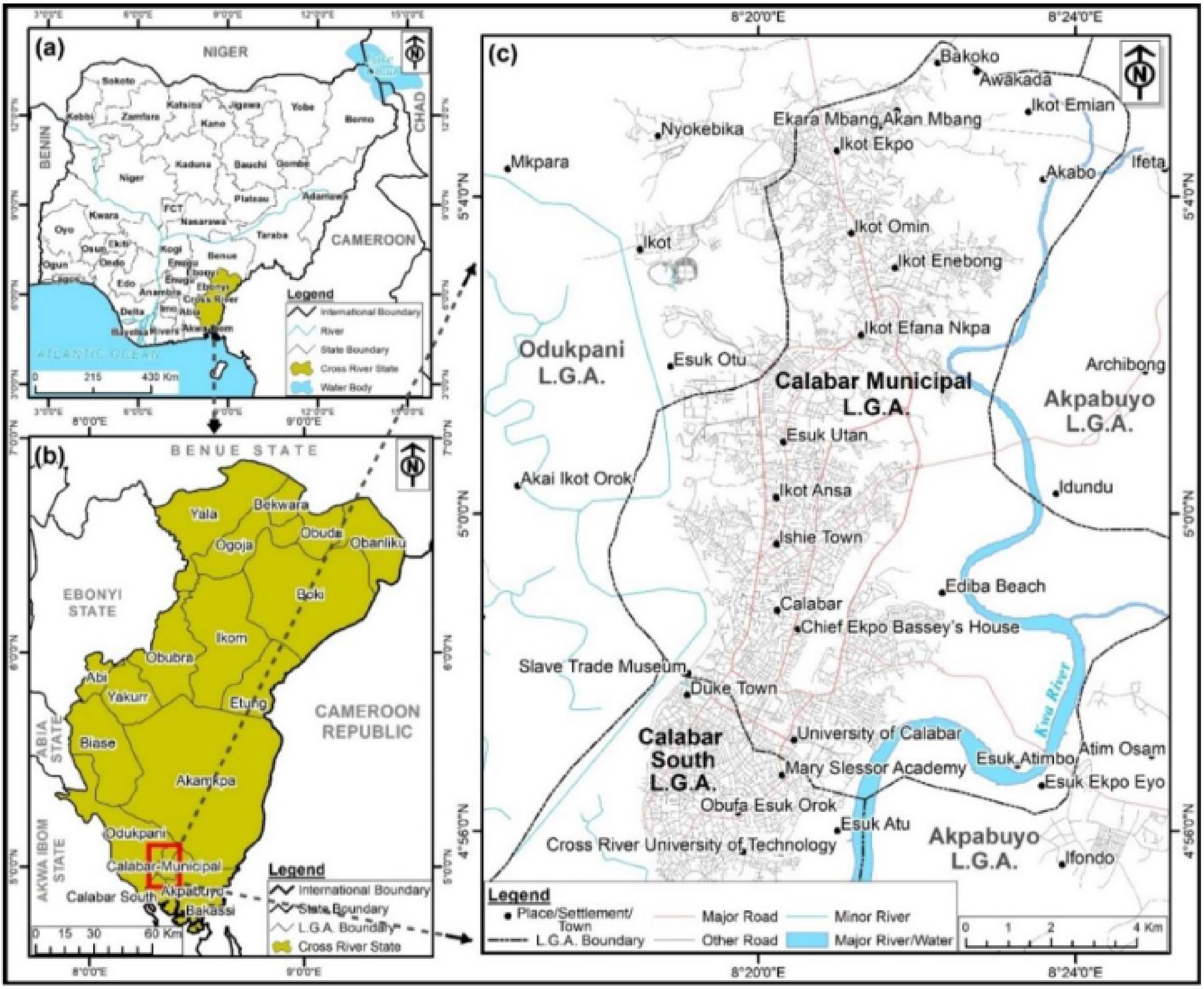

Figure 1: Map of the study area [25].

leachate plumes around these dumpsites. Igelle *et al*. [20] investigated the Lemna dumpsite using geophysical and geochemical methods. However, they focused only on the Lemna dumpsite, while other dumpsites in the metropolis are close to residential areas. This study addresses this gap by investigating leachate contamination using the electrical resistivity tomography method.

2. Description of the study area

Calabar is a city in southern Nigeria that is roughly 158 km^2 in size. It is located between latitudes 4°53′41.10″ and 5°7′37.57″ N and longitudes 8°14′14.90″ and 8°25′14.03″ E. Comprising Calabar Municipal and Calabar South Local Government Areas (LGAs), the city is the capital of Cross River State and a popular tourist destination in Nigeria. As shown in Figure 1, the city shares boundaries with two other LGAs in the state, Odukpani and Akpabuyo.

In Calabar, Calabar South, and Akpabuyo, the dry season lasts from November to March and peaks in January or February, while the rainy season typically lasts from April to October and peaks in July or September. Other months of the year receive little rainfall. January and September have the fewest and most wet days, respectively, with an average monthly rainfall of 50–434 mm and an average monthly temperature of 24.3–27.5°C [25]. The typical vegetation includes parkland, derived savannah, mangrove swamps, and rain forests.

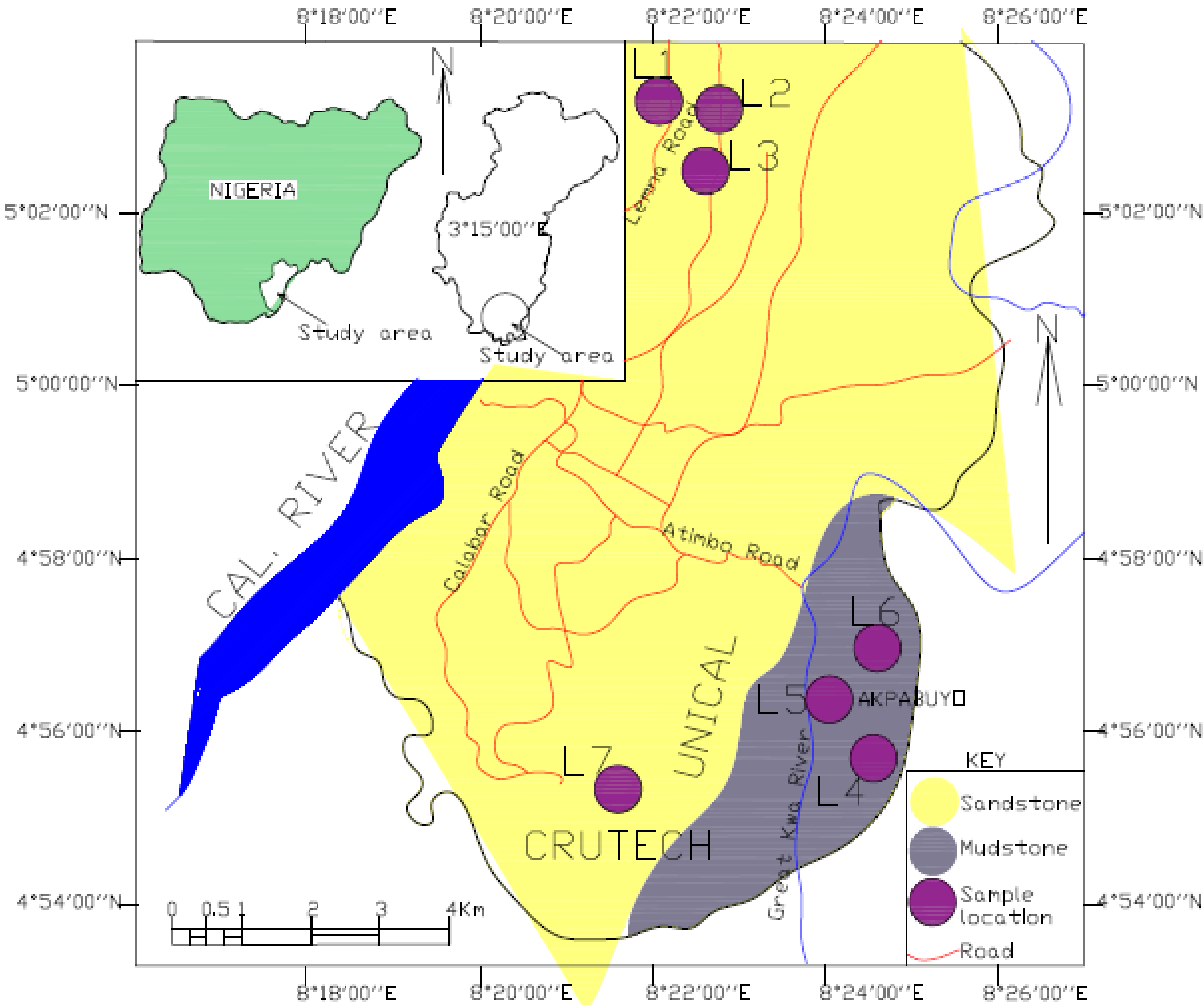

Figure 2: Geologic map indicating sampled points.

2.1. Geological setting

The geology of Calabar Metropolis falls within the Benin Formation, also referred to as the Benin sandstone. The Pliocene-to-Miocene clay/shale lenses that intercalate with the isolated gravel units, conglomerates, very coarse sandstone, and friable sands of the Benin Formation are all present (Figure 2).

3. Materials and methods

A Resistivity Meter Model SSR-MP-ATS from IGIS (India) was the main equipment employed in the study. Hammers, an umbrella, a GARMIN 12-channel personal navigator (GPS unit), 21 electrodes, and measuring tapes were the accessories used with the terrameter.

The spacing between adjacent electrodes in seven ERT profiles was designated as a. Using the Wenner array with an electrode separation of $1a = 5.0$ m, the first step involved recording every possible measurement. For the initial measurement, electrodes 1, 2, 3, and 4 were employed. Specifically, the first current electrode (C_1) was electrode 1, the first potential electrode (P_1) was electrode 2, the second potential electrode (P_2) was electrode 3, and the second current electrode (C_2) was electrode 4. In the second measurement, electrodes 2, 3, 4, and 5 were assigned to C_1, P_1, P_2, and C_2, respectively. This procedure was repeated along the

Table 1: Midpoint coordinates in the study area.

S/N	Name	Label	Latitude	Longitude	Elevation (m); orientation
1	Lemna by Poultry Farm, Calabar Municipality LGA	L1	N05°02′0.8″	E008°21′51.8″	21.0; N–S
2	Lemna Effanga Bassey, Calabar Municipality LGA	L2	N05°02′1.3″	E008°21′57.6″	35.0; N–S
3	Lemna Effanga Bassey, Calabar Municipality LGA	L3	N05°02′00.7″	E008°22′09.0″	14.0; E–W
4	CROSPIL Estate Entrance Gate, Akpabuyo LGA	L4	N04°55′47.7″	E008°24′26.8″	56.0; E–W
5	CROSPIL Estate, opposite Oscar Asinde Drive, Akpabuyo LGA	L5	N04°54′35.9″	E008°24′26.8″	59.0; E–W
6	Brighter Life International Nursery and Primary School, Akpabuyo LGA	L6	N04°56′00.3″	E008°24′41.5″	63.0; N–S
7	UNICROSS opposite St. Joseph Catholic Church, Calabar South LGA	L7	N04°55′50.5″	E008°19′58.9″	10.0; E–W

electrode line until electrodes 18, 19, 20, and 21 were used for the final measurement with $1a$ spacing. For a survey comprising 21 electrodes, there were 18 $(21 - 3)$ potential measurements available with $1a$ spacing in the Wenner array.

After the measurements with $1a$ spacing were completed, a subsequent series of measurements with $2a$ electrode spacing was conducted. For the initial measurement in this series, electrodes 1, 3, 5, and 7 were selected, ensuring that $2a$ represented the distance between neighbouring electrodes. The second measurement utilized electrodes 2, 4, 6, and 8. This process was repeated until the final measurement with $2a$ spacing was conducted using electrodes 14, 16, 18, and 20. In a configuration with 21 electrodes, there were 15 $(21 - 2 \times 3)$ possible measurements with $2a$ spacing. The same methodology was applied for measurements with spacings of $3a = 15.0$ m, $4a = 20.0$ m, $5a = 25.0$ m, $6a = 30.0$ m, and $7a = 35.0$ m.

During the field survey, measurements were systematically recorded to ensure that, as far as possible, every measurement was taken to achieve optimal results. The quality of the interpretation model generated from the inversion of the apparent resistivity measurements is influenced by this procedure [26]. The Wenner array configuration was chosen over other arrays because of its effective performance in heterogeneous tropical landfills, where fluctuations in waste compaction and moisture content create significant resistivity contrasts [27, 28]. Furthermore, as noted by Godio and Chiampo [29], the vertical resolution of the Wenner array is essential for detecting leachate-saturated zones.

After the data-collection process, measured resistance was converted to apparent resistivity using Eq. (1):

$$\rho_a = 2\pi a R = KR, \tag{1}$$

where

$$K = 2\pi a. \tag{2}$$

In Eqs. (1) and (2), ρ_a is the apparent resistivity, a is the spacing between the electrodes, R is the resistance of the subsurface, and K is the geometrical factor.

RES2DINV software was used to analyze the data. To generate 2D cross-sections, the data from each 2D survey line in the x–y directions were initially inverted separately. The subsurface was divided into several rectangular blocks based on the distribution of the observed data. During the iterations, the modelled calculated data were modified to align with the observed data. The inversion challenge was to determine the resistivity of the blocks that reduced the discrepancy between the calculated and observed apparent resistivity values. Using the observed apparent resistivity measurements, the software automatically constructed a 2D resistivity model of the subsurface through nonlinear least-squares optimization.

The inversion problem addressed by the program was the determination of the resistivity of the blocks that reduced the difference between the estimated and observed apparent resistivity values. The 2D data were inverted using the least-squares inversion technique with a standard least-squares constraint, which aims to minimize the square of the difference between the calculated and observed apparent resistivity values. The conventional Gauss–Newton method was employed to solve the least-squares equation. Only the model perturbation vector was subjected to a smoothness constraint to mitigate significant and unrealistic alterations in the output models, with appropriate damping values selected through trial and error. This inversion method is more effective for delineating the targeted leachate than the robust inversion method [14]. Data gathered from the seven profiles were used to generate two-dimensional inverted sections. The midpoint coordinates of the profiles are shown in Table 1.

4. Results

Figures 3–9 show the inverse model resistivity sections of the profiles. As shown in Figure 3, which was measured in the N–S direction, the resistivity value across profile 1 at the Lemna dumpsite is less than 50 Ωm to a depth of 12.4 m, with a root mean square (RMS) error of 2.9%; this can be interpreted as clayey sand. The lithology consists of clayey/laterite, coarse sand, medium sand, fine sand, light brown fine sand, and brownish-white fine sand (Table 2). There is no leachate in this profile.

In profile 2 (Figure 4) at the Lemna dumpsite, measured in the N–S direction, the top layer is characterized by patches of clay with resistivity values > 11.0 Ωm at horizontal distances between 7.0–40.0 m and 80.0–85.0 m to a depth of 3.75 m. Beneath this is a low-resistivity zone with values ≤ 10.0 Ωm between depths of 6.38 and 12.4 m. This can be interpreted as leachate from decomposed refuse materials in the dumpsite.

Table 2: Borehole lithology log in the Lemna dumpsite.

Depth (m)	Lithology
0.00–1.39	Clayey/laterite
1.39–2.37	Coarse sand
2.37–6.03	Medium sand
6.03–6.46	Fine sand
6.46–42.88	Light brown to fine sand
42.88–66.00+	Brownish-white fine sand

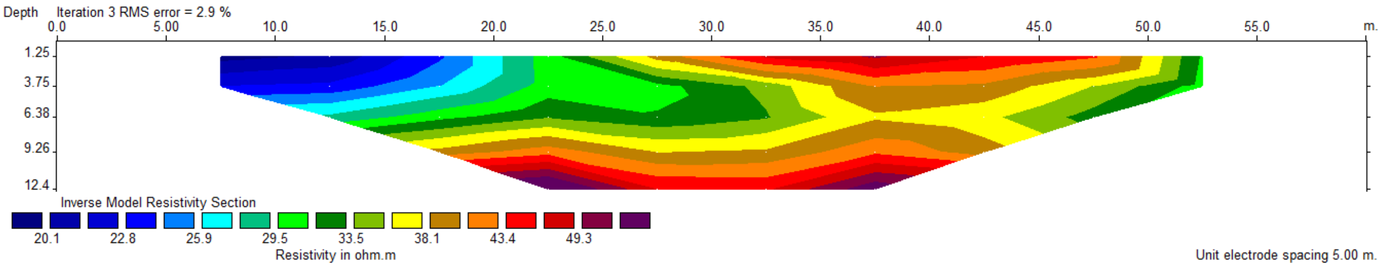

Figure 3: Profile 1 - Lemna L1 (active dumpsite) by Poultry Farm, Calabar Municipality LGA, inverted 2D electrical resistivity tomogram at the entrance to the dumpsite.

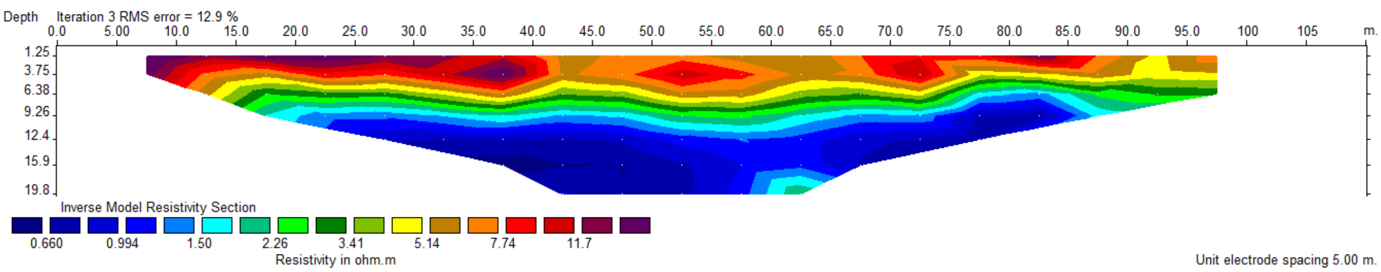

Figure 4: Profile 2 - Lemna L2 (active dumpsite) inverted 2D electrical resistivity tomogram at Effanga Bassey by Assembly of God Church, Calabar Municipality LGA.

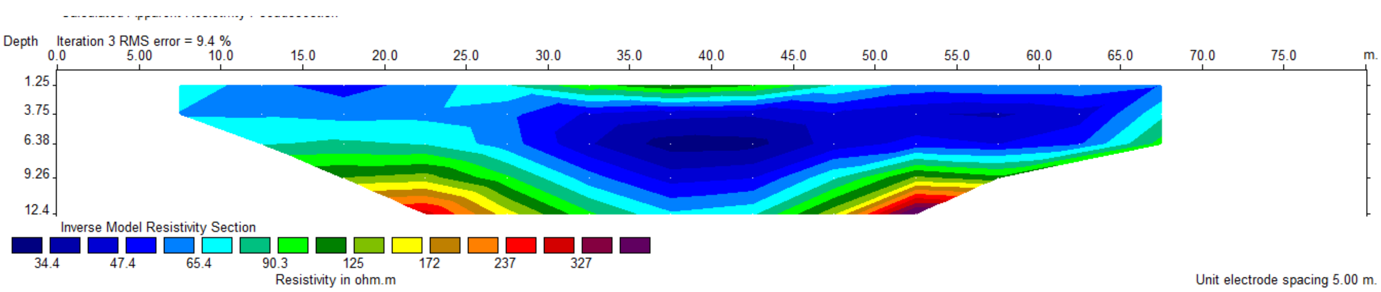

Figure 5: Profile 3 - Lemna L3 (control) inverted 2D electrical resistivity tomogram at Effanga Bassey Close.

Profile 3 (Figure 5) was taken 150 m away from the dumpsite, oriented in the E–W direction, and was used as a control to check whether leachate had migrated. The top layer, with resistivity values between 34.0 and 90.0 Ωm, indicates clayey soil at depths of 6.30 m between horizontal distances of 7.0–25.0 m, 50.0–65.0 m, and at 12.4 m, respectively. Between horizontal distances of 17.0 m and 57.0–58.0 m, resistivity values range from 125 to > 327 Ωm at depths between 11.0 and 12.4 m. This can be interpreted as light brown to fine sand. The absence of leachate in the profile indicates that leachate has not migrated 150 m away from the dumpsite.

In profile 4 (Figure 6) at CROSPIL Estate, oriented in the E–W direction, the lithology comprises topsoil/clayey/laterite, fine-to-medium sand, medium-to-coarse sand, clay/sandy clay, and coarse gravelly sand (Table 3). The top layer has resistivity values between 102.0 and > 1226.0 Ωm at depths of 8.00 and 9.25 m. This can be interpreted as sandy clay. Patches of leachate are observed

Table 3: Borehole lithology log in CROSPIL Estate, Akpabuyo.

Depth (m)	Lithology
0.00–1.50	Topsoil/clayey/laterite
1.50–6.00	Fine to medium sand
6.00–15.00	Medium to coarse sand
15.00–22.00	Coarse sand + gravel
22.00–28.00	Clay/sandy clay
28.00–45.00+	Coarse gravelly sand

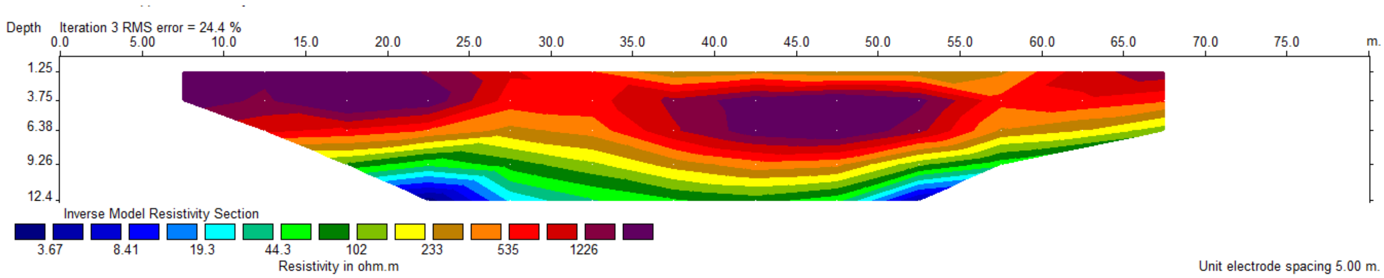

Figure 6: Profile 4 - L4 (inactive dumpsite) inverted 2D electrical resistivity tomogram at the CROSPIL second Estate Entrance Gate, Akpabuyo LGA.

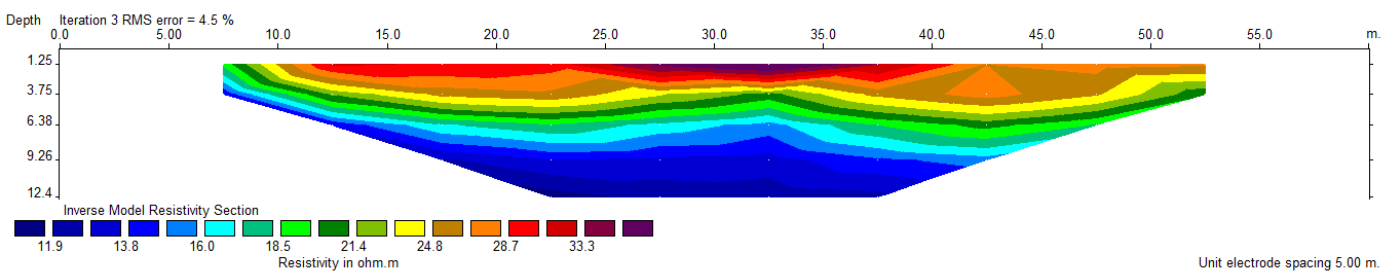

Figure 7: Profile 5 - L5 (inactive dumpsite) inverted 2D electrical resistivity tomogram at CROSPIL, opposite Oscar Asinde's Drive Phase II Road.

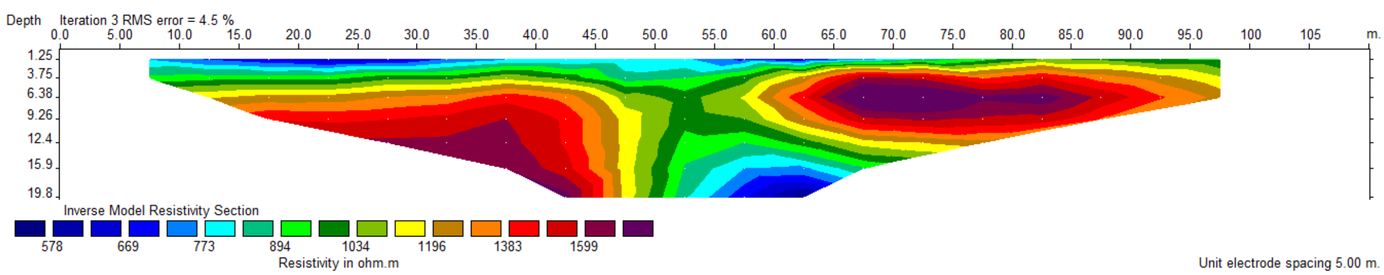

Figure 8: Profile 6 - L6 (control) inverted 2D electrical resistivity tomogram at Brighter Life International Primary School, Akpabuyo.

at horizontal distances between 20.0–25.0 m and 50.0–55.0 m at depths between 11.0 and 12.4 m. There is an indication of leachate in this profile.

In profile 5 (Figure 7) at CROSPIL Estate, oriented in the E–W direction, low resistivity values between 11.0 and 33.0 Ωm were observed across the profile at a depth of 12.4 m; these can be interpreted as clay. This indicates an absence of leachate in the profile.

Profile 6 (Figure 8), measured in the N–S direction at Brighter Life International Primary School, Akpabuyo, was taken about 170 m away from the dumpsite and used as a control. The top layer has resistivity values ranging from 579 to 894 Ωm, with another zone ranging from 1034 to > 1599 Ωm. These are interpreted as clayey sand/laterite and fine-to-medium sand and gravel. The implication is that leachate is absent in the profile.

Table 4: Borehole lithology log in UNICROSS, Calabar.

Depth (m)	Lithology
0.00–1.20	Topsoil/lateritic clay
1.20–8.00	Fine to medium sand
8.00–18.00	Medium to coarse sand
18.00–25.00	Coarse sand + gravel
25.00–32.00	Clay/sandy clay
32.00–50.00+	Coarse gravelly sand

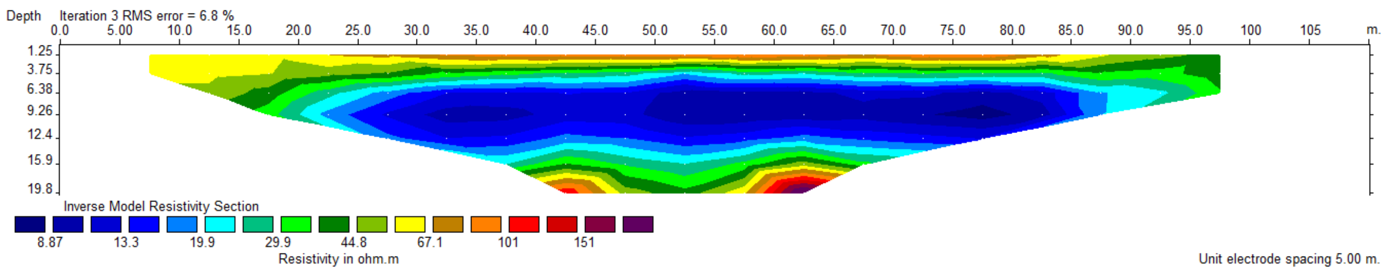

Figure 9: Profile 7 - L7 (inactive dumpsite) inverted 2D electrical resistivity tomogram at UNICROSS, opposite St. Joseph Catholic Church, Calabar South LGA.

In profile 7 (Figure 9) in the E–W direction at the UNICROSS dumpsite, the top layer has resistivity values ranging from 101.0 to > 151.0 Ωm at depths between 0 and 1.25 m; this can be interpreted as clayey/lateritic soil. Beneath this are low resistivity values < 10.0 Ωm at depths of 6.35 and 12.4 m. This indicates leachate in the profile. The borehole lithology log is shown in Table 4.

5. Discussion

The findings of this study indicate the presence of leachate contamination in profiles 2, 4, and 7, and the absence of leachate contamination in profiles 1, 3, 5, and 6.

In profile 2 at the Lemna dumpsite, there is a low-resistivity zone with a value < 10.0 Ωm between depths of 6.38 and 12.4 m; this can be interpreted as leachate contamination. The control taken 150 m away from the dumpsite showed resistivity ranging from 125 to > 327 Ωm. The absence of leachate in the control section of the Lemna dumpsite indicates that leachate has not migrated 150 m away from the dumpsite. In profile 4 at the CROSPIL dumpsite, patches of leachate were observed at horizontal distances of 20.0–25.0 m and 50.0–55.0 m, at depths between 11.0 and 12.4 m, respectively. Profile 6, which served as a control for the CROSPIL dumpsite, was taken 170 m away from the dumpsite and showed high resistivity values ranging from 579 to 894 Ωm and from 1034 to > 1599 Ωm, indicating that leachate contamination was absent 170 m from the dumpsite. In profile 7 at the UNICROSS dumpsite, a low resistivity value < 10.0 Ωm at depths of 6.35 and 12.4 m indicates leachate contamination.

The findings of this study agree with those of Ganiyu *et al*. [12], who found that a low-resistivity region with resistivity < 10 Ωm indicates a leachate plume from a decomposed dumpsite. Similarly, low resistivity values of 1.9–2.4 Ωm at a depth range of 14.5–29.0 m showed the presence of leachate contamination when compared with other delineated materials, such as clay, with resistivity > 10.0 Ωm [30]. In a similar study, Adesokan *et al*. [15] found that very low resistivity (< 7 Ωm) indicated leachate migration. The findings are also in consonance with the work of Trujillo-Romero *et al*. [31], who showed that extensive low-resistivity zones (< 2.1 Ωm) are considered leachate accumulation zones. The implication of these findings is that the persistent accumulation of organic contaminants present in leachate can potentially endanger aquatic life, plants, and, ultimately, humans [32, 33]. Furthermore, the introduction of landfill leachate into groundwater, surface-water bodies, and soil clearly creates environmental hazards [34].

6. Conclusion

This study found that leachate is present in both active and inactive dumpsites at Lemna, CROSPIL Estate, and UNICROSS in Calabar Metropolis, Cross River State, Nigeria. This poses environmental and health risks to inhabitants of the area.

6.1. Recommendations

Based on the findings of this study, the following recommendations are made. Boreholes and other sources of water within the area may be contaminated by leachate; therefore, water should be properly treated before use to avoid water-borne diseases in the area. Dumpsites should be regularly monitored to avoid leachate infiltration. Modern waste-management techniques, including remediation, should be introduced. In addition, awareness campaigns and sensitization programs should be conducted on the dangers and risks associated with dumpsites and their effects on human body.

Data availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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