



Research Paper

Comparative Geoelectrical Delineation of Potential Leachate-Affected Zones Around Three Abandoned Dumpsites in Rivers State, Nigeria

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ABSTRACT: Abandoned dumpsites can remain potential sources of subsurface pollution because leachate generated within waste deposits may infiltrate the underlying soil and alter its electrical properties. This study comparatively delineates and characterizes potential leachate-affected zones around three abandoned dumpsites at Airport Road, Eneka and Aluu in Rivers State, Nigeria, using Vertical Electrical Sounding (VES). Twelve Schlumberger VES soundings were acquired, comprising three soundings around each dumpsite and one control sounding at each location. The field data were interpreted using one-dimensional geoelectrical inversion, and conductive anomalies were evaluated in terms of resistivity, thickness, maximum vertical extent and control-to-anomaly resistivity contrast. The results revealed distinct geoelectrical responses among the three dumpsites. At Airport Road, the identified conductive intervals had resistivities of 2.25–3.00 Ωm , with a median anomalous resistivity of 2.30 Ωm and a maximum vertical extent of 7.88 m. At Eneka, anomalous resistivities ranged from 9.50–12.70 Ωm , with a median of 11.00 Ωm , a median anomalous-zone thickness of 25.56 m and a maximum vertical extent of 32.89 m. At Aluu, anomalous resistivities ranged from 2.10–4.20 Ωm , with a median of 3.70 Ωm , a median thickness of 13.70 m and a maximum vertical extent of 16.19 m. Control-to-anomaly resistivity contrasts were 402.2, 77.1 and 867.8 for Airport Road, Eneka and Aluu, respectively. The results demonstrate that anomalous resistivity magnitude does not necessarily correspond to vertical extent. The study shows that control-based comparative VES provides a useful approach for characterizing site-specific conductive anomalies around abandoned dumpsites. However, because low resistivity is not uniquely diagnostic of leachate, the identified anomalies are interpreted as potential leachate-affected zones rather than confirmed chemical contamination.

KEYWORDS: Vertical Electrical Sounding, Electrical Resistivity, Leachate, Abandoned Dumpsites, Geoelectrical Characterization.

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I. INTRODUCTION

Uncontrolled disposal of municipal solid waste remains an important environmental concern because waste deposited at the ground surface can alter the physical and chemical conditions of the underlying soil and groundwater system. Infiltration of rainfall through accumulated waste promotes the dissolution and transport of organic and inorganic constituents, producing leachate that may migrate through the unsaturated zone and eventually reach groundwater. The composition and mobility of leachate depend on factors such as waste composition, age of the dumpsite, rainfall, moisture conditions, subsurface lithology and permeability. Consequently, abandoned dumpsites may continue to represent potential sources of subsurface pollution even after active disposal has ceased [1–4].

The investigation of leachate migration is particularly important in areas where groundwater constitutes a major source of domestic water supply. Conventional groundwater monitoring based solely on borehole or water sampling provides information at discrete locations and may not adequately describe the spatial distribution of subsurface anomalies between sampling points. Geophysical methods provide a complementary approach by allowing subsurface properties to be investigated without extensive excavation or drilling. Among

these methods, electrical resistivity techniques have been widely applied to environmental investigations because electrical resistivity is sensitive to changes in lithology, pore-fluid content, saturation and ionic concentration [5–7]. Leachate-affected materials commonly exhibit relatively low resistivity because dissolved ions increase the electrical conductivity of pore fluids. This contrast provides a basis for identifying conductive zones that may be associated with leachate migration [8–10].

Vertical Electrical Sounding (VES), particularly using the Schlumberger electrode configuration, has been extensively employed for investigating the vertical variation of subsurface resistivity around waste disposal sites. VES measurements provide geoelectrical parameters including layer resistivity, thickness and depth, thereby allowing conductive intervals to be related to the subsurface geological framework. In Nigeria, electrical resistivity investigations at dumpsites in Agbara, Ibadan, Lagos, Minna, Eket and other locations have demonstrated the usefulness of the method for identifying low-resistivity zones interpreted as possible leachate-affected materials [8,11–14]. For example, Mosuro et al. [8] used 45 VES stations together with electrical resistivity tomography around a dumpsite in Agbara, southwestern Nigeria, and identified a leachate plume extending to approximately 10 m depth. Similarly, Okunowo et al. [11] identified a low-resistivity zone beneath the Abule Egba dumpsite in Lagos and used resistivity contrasts between the dumpsite area and control soundings to support the interpretation of possible leachate influence. These studies demonstrate the value of resistivity contrasts in environmental assessment of waste disposal sites.

Evidence from other Nigerian investigations further demonstrates the applicability of VES to the characterization of subsurface conditions beneath and around dumpsites. Omolayo and Fatoba [12] used two-dimensional electrical resistivity imaging to delineate a low-resistivity zone associated with leachate migration at an old dumpsite in Ibadan. Okpogo and Wilkie [13] combined VES and two-dimensional resistivity measurements at the Ile Epo dumpsite in Lagos and identified highly saturated and conductive materials extending to several metres below the surface. Muhammad et al. [14] reported substantial resistivity contrasts between a dumpsite and a control area at Maitumbi, Minna, with the anomalous zone extending to approximately 13 m. More recently, Udosen et al. [15] combined VES and electrical resistivity tomography to investigate leachate percolation and aquifer protectivity at a major open dump in Eket, southern Nigeria. These investigations collectively show that resistivity methods can provide useful information on the depth and geometry of subsurface conductive zones associated with waste disposal.

Studies conducted in the Niger Delta and its environs are particularly relevant because of the region's extensive sedimentary formations and widespread dependence on groundwater. Kobani et al. [16], using Schlumberger VES in parts of Obio/Akpor and its environs, demonstrated the application of geoelectrical methods to the investigation of possible leachate occurrence around several dumpsites. Other investigations in southern Nigeria have similarly applied VES and complementary geophysical methods to characterize dumpsite-related conductive anomalies [17,18]. These studies provide evidence that geoelectrical methods are applicable to dumpsite investigations within the geological and hydrogeological conditions of southern Nigeria.

Despite the demonstrated usefulness of electrical resistivity methods, interpretation of a low-resistivity anomaly as leachate contamination is inherently non-unique. Low resistivity may also result from clay-rich materials, increased moisture or saturation, saline or mineralized groundwater, and variations in lithology. The relationship between resistivity and leachate therefore depends on the geological and hydrogeological setting of the investigated area [6,7,19]. Recent investigations have also emphasized that variations in soil texture and clay content can substantially influence electrical responses and complicate the interpretation of conductive zones as leachate pathways [20]. For this reason, a low-resistivity layer identified from VES should more appropriately be regarded as a potential leachate-affected zone unless supported by independent hydrochemical, lithological or other geophysical evidence.

An additional limitation in much of the existing literature is that individual dumpsites are frequently investigated independently, making direct comparison of the magnitude and vertical extent of conductive anomalies between different sites difficult. A comparative framework in which similar VES measurements are acquired at multiple dumpsites and interpreted relative to corresponding control locations can provide additional information on how the geoelectrical response varies from one dumpsite environment to another. Such an approach is particularly useful because the magnitude of a resistivity anomaly and its vertical extent do not necessarily vary in the same manner. A site exhibiting the lowest anomalous resistivity may not necessarily have the deepest conductive zone. Differences in waste composition, subsurface lithology, degree of saturation and hydrogeological conditions may produce different resistivity signatures at different dumpsites.

The present study therefore applies a comparative VES approach to three abandoned dumpsites located at Airport Road, Eneka and Aluu in Rivers State, Nigeria. Schlumberger VES measurements were conducted at each dumpsite together with corresponding control soundings outside the immediate dumpsite environment. The study focuses on the identification and characterization of conductive anomalies, their resistivity values, thicknesses and vertical extent, and their contrast with the background geoelectrical conditions represented by the control locations. Rather than treating low resistivity as direct proof of contamination, the anomalies are

interpreted as potential leachate-affected zones, taking into account the known non-uniqueness of electrical resistivity responses.

Accordingly, the objective of this study is to comparatively delineate and characterize potential leachate-affected zones around three abandoned dumpsites in Rivers State using Vertical Electrical Sounding. Specifically, the study aims to delineate the subsurface resistivity structure around the selected abandoned dumpsites, identify and characterize low-resistivity zones that may represent potential leachate-affected materials, determine the thickness and vertical extent of the identified conductive anomalies and comparatively evaluate the magnitude and vertical extent of the anomalies relative to corresponding control soundings.

II. MATERIALS AND METHOD

2.1 Study Area and Site Selection

The study was conducted around three abandoned dumpsites located at Airport Road and Eneka in Obio-Akpor Local Government Area and Aluu in Ikwerre Local Government Area of Rivers State, southern Nigeria. The locations lie within the Niger Delta sedimentary basin and are underlain predominantly by sediments of the Benin Formation, comprising mainly unconsolidated to semi-consolidated sands with subordinate clayey materials. The sandy nature of the formation provides relatively permeable pathways for infiltration and subsurface fluid movement, making the area suitable for investigating possible leachate-related changes in subsurface electrical properties.

The three dumpsites were selected to provide a comparative basis for examining the geoelectrical characteristics of separate abandoned waste-disposal environments. Rather than treating the entire study area as having a single background resistivity, each dumpsite was evaluated against a corresponding control sounding. This approach was adopted because natural subsurface resistivity varies with lithology, saturation, moisture content and pore-fluid chemistry, all of which may produce spatial variations independent of waste disposal [1,4,5,19].

Previous geophysical investigations in southern Nigeria have demonstrated the usefulness of electrical resistivity methods for identifying conductive subsurface zones associated with dumpsites and possible leachate migration [4,8,9,16–18]. The local applicability of the approach is also supported by the investigation of Kobani et al. [16], who used Schlumberger VES to investigate possible leachate occurrence around dumpsites in parts of Obio/Akpor and its environs.

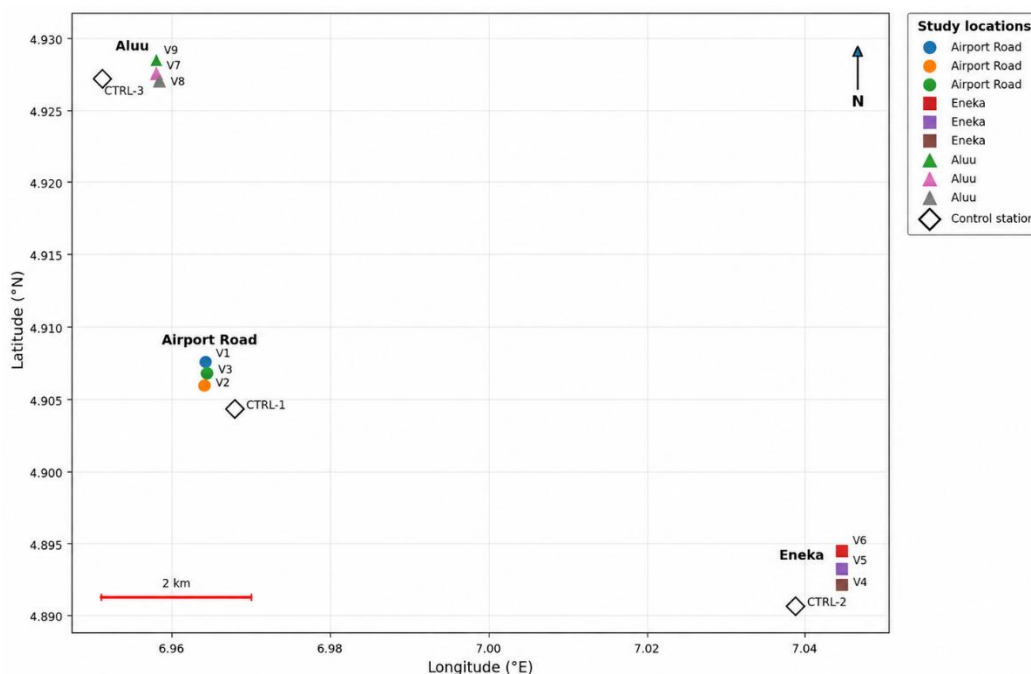


Figure 1: Location of the VES stations and control points around the three abandoned dumpsites in Rivers State, Nigeria.

2.2 Comparative VES Survey Design

The investigation employed a comparative Vertical Electrical Sounding (VES) design consisting of 12 sounding stations (see Figure 1). Three VES stations were investigated around each dumpsite, together with one

control station, giving four soundings per location. Thus, Airport Road comprised VES 1–3 and CTRL-1; Eneka comprised VES 4–6 and CTRL-2; while Aluu comprised VES 7–9 and CTRL-3.

The three soundings at each dumpsite provided within-site replication, while the control sounding provided a local reference against which the resistivity structure of the dumpsite environment could be assessed. This design is particularly relevant to environmental resistivity studies because an absolute low-resistivity value cannot, by itself, establish the presence of leachate. Comparative interpretation with a relatively unaffected background can provide stronger evidence for identifying anomalous conductive intervals [4,8,9,16].

2.3 Geophysical Equipment

The VES measurements were acquired using an ABEM Terrameter SAS 1000 resistivity meter. Four electrodes were used for each sounding, consisting of two current electrodes (A and B) and two potential electrodes (M and N). A Garmin GPS receiver was used to obtain the coordinates of the sounding stations. The use of an ABEM resistivity meter and GPS positioning is consistent with the field methodology reported in the dissertation.

2.4 Vertical Electrical Sounding Data Acquisition

Vertical Electrical Sounding was conducted using the Schlumberger electrode configuration. The method measures the electrical response of the subsurface by injecting current through the two outer electrodes while measuring the resulting potential difference between the two inner electrodes. The electrode arrangement is symmetrical about the centre of the sounding station, and the current-electrode separation is progressively increased to investigate greater depths [19,20].

At each station, a straight measurement traverse was established and the ground surface was prepared to obtain adequate electrode contact. The four electrodes were then positioned symmetrically about the sounding centre. The current electrodes were progressively expanded outward while the potential electrodes remained relatively close to the centre. When the measured potential difference became too small for reliable measurement, the potential-electrode spacing was increased before continuing the sounding. These procedures follow the VES acquisition procedure reported in the dissertation.

For each electrode arrangement, the current-electrode spacing ($\frac{AB}{2}$), potential-electrode spacing ($\frac{MN}{2}$) and measured resistance were recorded. Measurements were repeated where necessary to check the stability of the readings. The field procedure continued until the maximum planned electrode separation was reached. The same basic Schlumberger procedure is commonly employed for vertical investigation of dumpsite-related conductive zones [8,9,16,21].

2.5 Principle of the Schlumberger VES Method

The VES method is based on the variation of electrical resistivity with depth. Electrical current introduced into the subsurface follows paths controlled by the electrical properties of the geological materials. Variations in measured resistance therefore reflect differences in the resistivity of the subsurface materials, which may arise from changes in lithology, porosity, saturation, moisture content and pore-fluid conductivity [19,20].

For environmental investigations, leachate can produce a conductive response because dissolved ionic constituents increase the electrical conductivity of the pore fluid. Consequently, leachate-affected materials may exhibit lower resistivity than surrounding materials under otherwise comparable geological conditions [4,8,9]. However, conductive responses are not unique to leachate. Clay-rich materials, increased saturation and naturally conductive groundwater can also produce low resistivity [1,5,19]. The present study therefore uses low resistivity as an indicator of a potentially leachate-affected zone, rather than treating it as direct proof of chemical contamination.

2.6 Calculation of Apparent Resistivity

The measured resistance values were converted to apparent resistivity using the geometric factor for the Schlumberger configuration. Apparent resistivity was calculated as

$$\rho_a = KR \quad (1)$$

where ρ_a is the apparent resistivity in Ωm , K is the geometric factor and R is the measured resistance in Ω . For the Schlumberger configuration, the geometric factor is given by

$$K = \frac{\pi[(AB/2)^2 - (MN/2)^2]}{MN} \quad (2)$$

where AB represents the separation between the current electrodes and MN represents the separation between the potential electrodes. The resulting apparent-resistivity values represent the bulk electrical response of the subsurface sampled by each electrode configuration and were subsequently used for VES curve generation and inversion [19,20].

The apparent-resistivity values were plotted against $\frac{AB}{2}$ on logarithmic scales to produce the sounding curves. Increasing $\frac{AB}{2}$ progressively increases the depth range sampled by the electrical field, although the actual depth of investigation depends on the resistivity structure of the subsurface and the electrode geometry [19,20].

2.7 VES Data Processing and Inversion

The field apparent-resistivity data were processed using IPI2Win for computer-assisted one-dimensional inversion. The software was used to obtain the geoelectric parameters of the subsurface, including layer resistivity and thickness. The dissertation reports that the VES curves were subjected to computer-assisted interpretation using IPI2Win and that the resulting models were used to determine the resistivity, thickness and depth of the geoelectric layers.

The inversion procedure involved fitting a layered-earth model to the measured apparent-resistivity curve. The principal parameters obtained from the inversion were:

- true resistivity of each geoelectric layer (ρ , Ωm);
- thickness of each layer (h , m);
- cumulative depth to the base of each layer; and
- geoelectric curve type.

The use of computer-assisted one-dimensional inversion for VES interpretation is consistent with previous dumpsite investigations in Nigeria, including studies that used IPI2Win to derive geoelectric layer parameters from Schlumberger sounding data [18,21,22].

2.8 Identification of Potential Leachate-Affected Zones

Potential leachate-affected zones were identified from the inverted geoelectric models using a combination of resistivity magnitude, vertical position, continuity of conductive intervals and comparison with the corresponding control sounding.

The primary criterion was the occurrence of a relatively low-resistivity interval within the dumpsite soundings that was substantially more conductive than the corresponding background response. This approach follows the general interpretation adopted in previous dumpsite studies, where pronounced conductive anomalies have been associated with possible leachate migration [4,8,9,16,21]. However, the interpretation was not based on a universal resistivity threshold because the resistivity of geological materials varies with lithology and hydrogeological conditions.

Accordingly, a low-resistivity interval was interpreted as a potential leachate-affected zone when it exhibited a marked resistivity contrast with the corresponding control and occurred within the subsurface sequence beneath or around the dumpsite. This terminology replaces the term “contamination layer” used in parts of the original dissertation because VES provides indirect geophysical evidence rather than direct chemical confirmation.

Similarly, the lithological description “leachate sand” used in the original VES tables was not treated as a directly measured lithological unit. In the revised interpretation, such intervals are referred to as low-resistivity sand or potentially leachate-affected sand, depending on the context. This distinction is necessary because resistivity inversion alone cannot uniquely distinguish leachate-bearing sand from other conductive subsurface materials.

2.9 Determination of Anomaly Thickness and Vertical Extent

For each VES model, the upper and lower boundaries of an anomalously conductive interval were determined from the depths of the corresponding layer boundaries. The thickness of an individual conductive layer was calculated as;

$$T = Z_b - Z_t \quad (3)$$

where T is the thickness of the conductive interval, Z_t is its upper boundary depth and Z_b is its lower boundary depth.

Where two or more adjacent low-resistivity layers formed a continuous conductive sequence, their individual thicknesses were summed to obtain the total contiguous thickness of the anomalous interval. The maximum vertical extent was defined as the depth to the lower boundary of the deepest contiguous conductive interval interpreted as potentially leachate-affected.

This parameter was used to describe the vertical extent of the geoelectrical anomaly, rather than the “depth of contamination”. The distinction is important because the lower boundary of a conductive anomaly represents a geophysical model boundary and does not necessarily represent the maximum depth to which chemically confirmed contamination has migrated.

2.10 Control-Based Comparative Analysis

Each dumpsite was compared first with its corresponding control sounding. The control was used to establish the local background resistivity structure and to identify resistivity contrasts that could reasonably be regarded as anomalous. The use of local control measurements is particularly important in sedimentary terrains where natural variations in clay content, saturation and groundwater chemistry can produce substantial changes in resistivity over relatively short distances [4,5,8].

Four parameters were used in the comparison:

1. Anomalous resistivity range (Ωm): the range of true resistivity values associated with the interpreted conductive interval;
2. Anomaly thickness (m): the thickness of the conductive interval at each sounding;
3. Maximum vertical extent (m): the deepest boundary of the contiguous conductive interval; and
4. Control-anomaly resistivity contrast: the relative difference between the representative resistivity of the control interval and the corresponding anomalous interval.

For comparative purposes, the control-to-anomaly resistivity contrast was expressed as;

$$C_\rho = \frac{\rho_c}{\rho_a} \quad (4)$$

where C_ρ is the resistivity contrast, ρ_c is the representative resistivity of the control interval and ρ_a is the representative resistivity of the anomalous interval.

The contrast parameter was used only to describe the magnitude of the geoelectrical difference between each dumpsite and its local background. It was not interpreted as a quantitative measure of contaminant concentration or contamination severity.

2.11 Data Quality Control and Interpretation Limitations

Quality control during field acquisition involved ensuring adequate electrode contact, repeating unstable measurements, avoiding obvious sources of electrical interference and checking equipment operation before data acquisition. Field coordinates and observations were recorded for each station. These procedures are consistent with those described in the dissertation.

The VES interpretation was based on one-dimensional layered-earth models. Such models are inherently non-unique because different combinations of layer resistivity and thickness can produce similar apparent-resistivity responses. Consequently, the inverted parameters should be regarded as model estimates rather than unique descriptions of the subsurface [19,20].

A further limitation is that VES primarily resolves vertical changes beneath individual sounding points and provides limited information about the lateral geometry of a conductive body. Electrical resistivity tomography or three-dimensional resistivity imaging would provide stronger lateral constraints where detailed plume geometry is required [21,23]. The present study was therefore designed specifically to compare the vertical geoelectrical characteristics of three abandoned dumpsites rather than to produce a three-dimensional map of leachate migration.

Since low resistivity is not uniquely diagnostic of leachate, interpretation in the present study is based on the combined evidence of resistivity contrast, layer position, thickness, vertical continuity and comparison with the corresponding control sounding. This conservative interpretation is consistent with the limitations identified in previous electrical investigations of dumpsite environments [1,4,5,8,9].

III. RESULTS

The results of the VES interpretation and comparative analysis are presented in Figures 2–5.

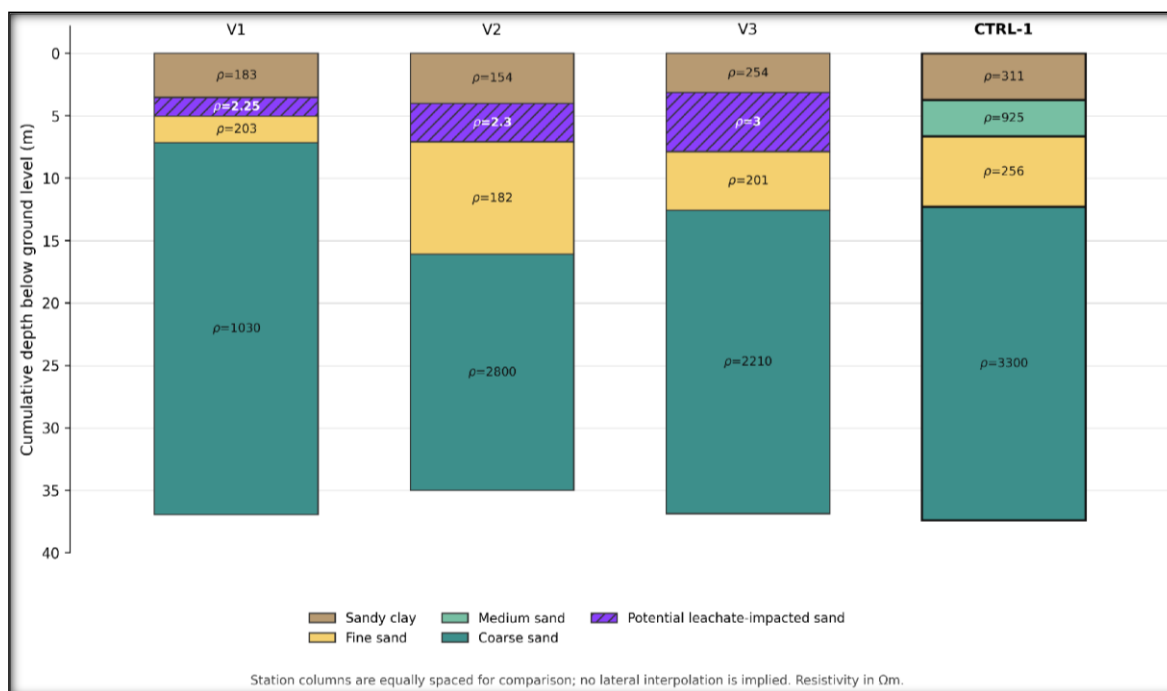


Figure 2: Geoelectric station models for Airport Road dumpsite and control

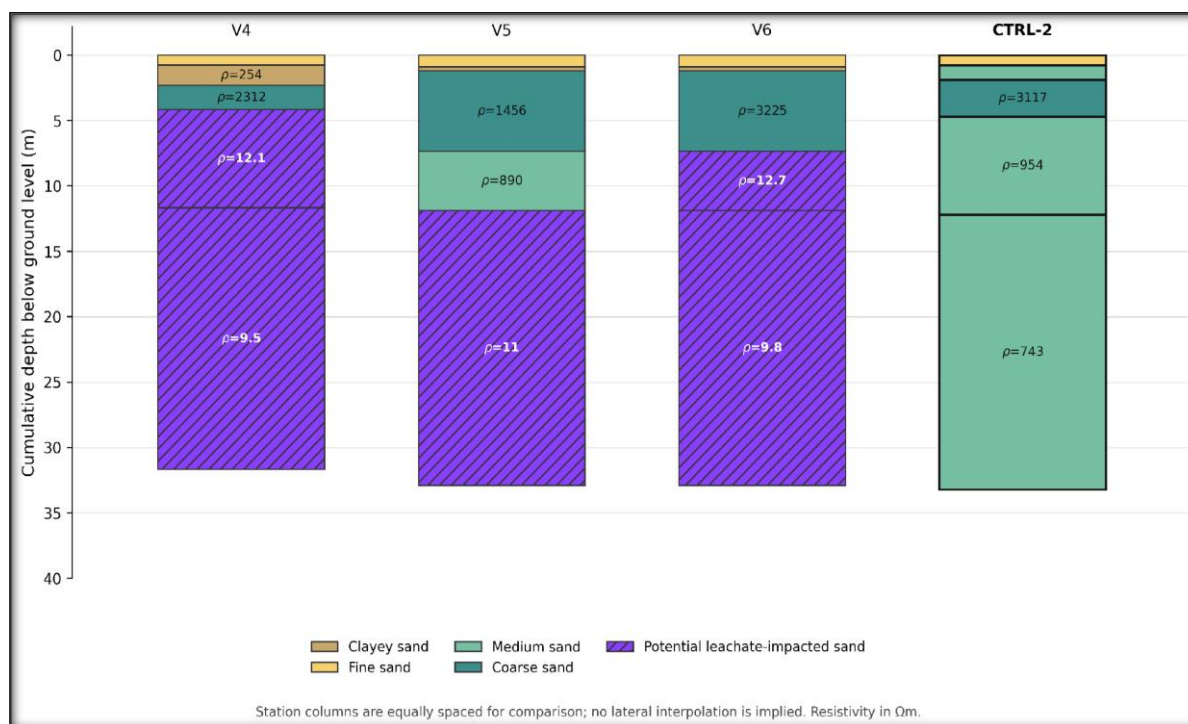


Figure 3: Geoelectric station models for Eneka dumpsite and control.

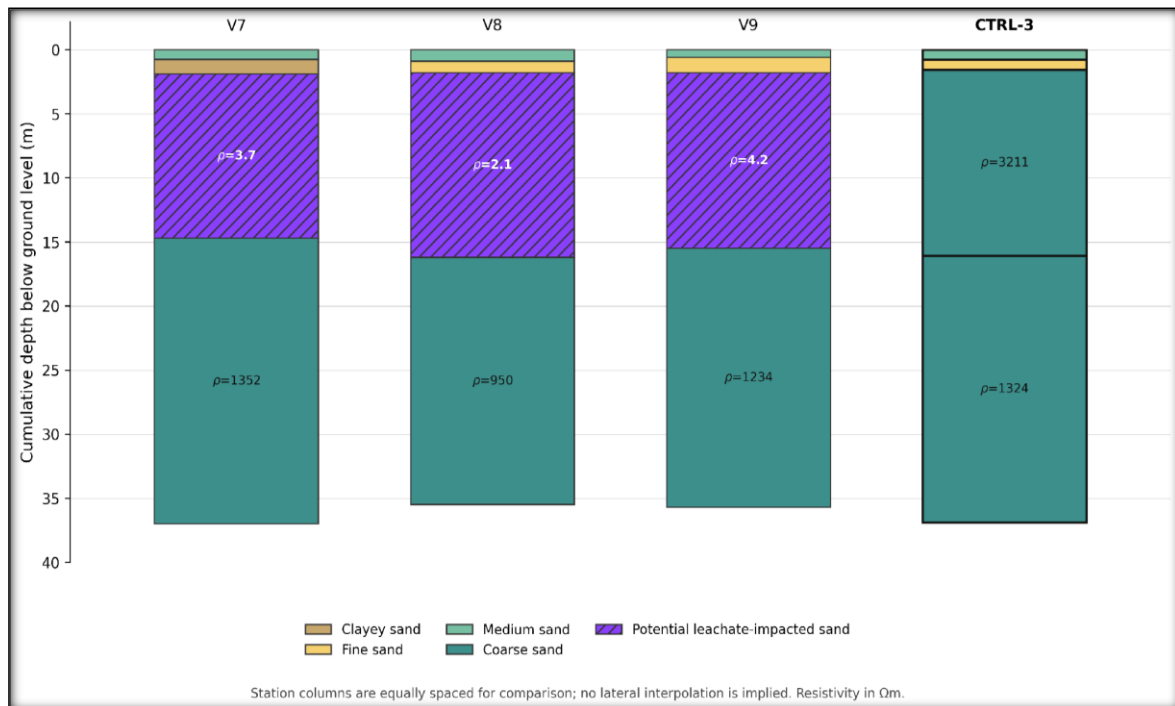


Figure 4: Geoelectric station models for Aluu dumpsite and control.

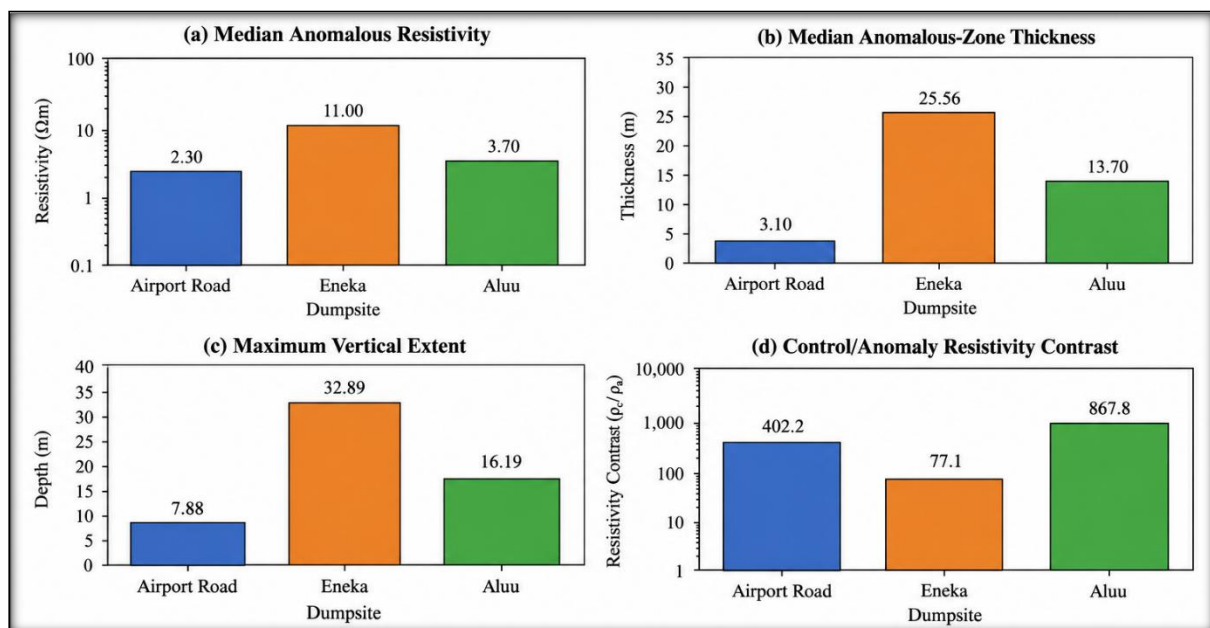


Figure 5: Comparative Geoelectrical Characteristics of Potential Leachate-Affected Zones at the Three Abandoned Dumpsites in Rivers State, Nigeria.

IV. DISCUSSION

The VES results demonstrate marked differences in the geoelectrical characteristics of the three abandoned dumpsites investigated. Figures 2–4 show that the dumpsite soundings contain comparatively conductive intervals that are substantially different from the corresponding control soundings. These contrasts provide the principal basis for interpreting the identified intervals as potential leachate-affected zones. Similar contrasts between low-resistivity zones beneath dumpsites and higher-resistivity control areas have been reported in Nigerian studies, including investigations at Abule Egba, Ibadan and the Onitsha expressway dumpsite [24–26].

At Airport Road, the three dumpsite soundings (V1–V3) exhibit conductive intervals with resistivities of approximately 2.25–3.00 Ωm , whereas the corresponding control sounding has substantially higher resistivity, including a representative value of about 925 Ωm (Figure 2). The strong resistivity contrast supports the interpretation of the shallow conductive intervals as anomalous relative to the local background. Comparable low-resistivity responses have been reported in dumpsite environments where leachate-affected materials were interpreted from their contrast with surrounding or control materials. For example, Okunowo et al. [25] identified resistivities as low as 1.9–2.4 Ωm beneath the Abule Egba dumpsite and contrasted these values with substantially higher resistivities at control soundings.

The Airport Road anomaly, however, is relatively limited vertically, with thicknesses of approximately 1.50–4.73 m and a maximum vertical extent of 7.88 m. This shallow extent is comparable with the relatively shallow leachate-related conductive zones reported in several Nigerian dumpsite investigations. Mosuro et al. [23], for example, reported an average leachate infiltration depth of about 6 m and a maximum depth of approximately 10 m around a dumpsite in Agbara. The similarity should not be interpreted as evidence of identical contamination processes because the depth reached by a conductive anomaly depends on local lithology, saturation, hydraulic conditions and the distribution of conductive pore fluids.

The Eneka models exhibit a different geoelectrical response (Figure 3). The identified conductive intervals have resistivities of approximately 9.50–12.70 Ωm and considerably greater thicknesses than those observed at Airport Road. The median anomalous-zone thickness is 25.56 m and the maximum vertical extent reaches approximately 32.89 m (Figure 5b–c). The corresponding control sounding contains substantially higher-resistivity material, with reported values of 743 and 954 Ωm . The persistence of the conductive interval through a considerable vertical thickness indicates that the anomalous response at Eneka is not restricted to a very shallow surface layer.

The greater vertical extent observed at Eneka is consistent with the broader observation from environmental resistivity studies that conductive anomalies associated with waste disposal can extend several metres into the subsurface where conditions permit downward migration. Ugbor et al. [26], for example, identified low-resistivity zones extending from the surface to several metres depth around a dumpsite in southeastern Nigeria, while Okpogo and Wilkie [9] reported conductive materials extending to tens of metres at the Ile Epo dumpsite in Lagos. The Eneka result therefore falls within the range of vertical extents reported from other dumpsite investigations, although direct comparison of depths must be made cautiously because survey configurations, geological settings and inversion procedures differ among studies.

The Aluu models (Figure 4) show another distinct response. The interpreted conductive intervals have resistivities of approximately 2.10–4.20 Ωm , with thicknesses of 12.80–14.40 m and a maximum vertical extent of 16.19 m. The corresponding control sounding has a substantially higher representative resistivity of approximately 3,211 Ωm . The relatively large contrast between the Aluu dumpsite and its control is reflected in the control-to-anomaly resistivity ratio of 867.8 shown in Figure 5d. Similar large resistivity contrasts have been used in previous dumpsite studies as supporting evidence for identifying conductive zones associated with possible leachate influence [24–26].

An important outcome of the comparison is that anomalous resistivity magnitude and vertical extent do not vary proportionally among the three dumpsites (Figure 5). Airport Road has the lowest median anomalous resistivity (2.30 Ωm), but its maximum vertical extent is only 7.88 m. In contrast, Eneka has a higher median anomalous resistivity of 11.00 Ωm but the greatest maximum vertical extent, reaching 32.89 m. Aluu has an intermediate median anomalous resistivity of 3.70 Ωm and a maximum vertical extent of 16.19 m. Thus, the most conductive anomaly is not necessarily the deepest anomaly. This distinction is important because electrical resistivity responds to several interacting properties of the subsurface rather than to contaminant concentration alone.

Laboratory investigations have demonstrated that the electrical resistivity of sandy soils affected by leachate depends strongly on water content and the electrical properties of the pore fluid, while fine-particle content can also substantially influence the measured resistivity [27]. Consequently, differences in saturation, pore-fluid ionic content and fine-material content can produce different resistivity magnitudes even where conductive zones are generated by broadly similar processes. This provides a basis for interpreting the contrasting resistivity magnitudes observed at Airport Road, Eneka and Aluu without assuming that the site with the lowest resistivity necessarily has the greatest vertical leachate influence.

The control-to-anomaly resistivity contrast provides an additional basis for comparing the three sites (Figure 5d). The calculated ratios are 402.2 at Airport Road, 77.1 at Eneka and 867.8 at Aluu. The particularly large contrast at Aluu results primarily from the very high resistivity of its control relative to the low-resistivity anomalous interval. However, this ratio should be regarded as a geoelectrical contrast parameter rather than a quantitative contamination index. Electrical resistivity values have overlapping ranges among different earth materials, and low resistivity can result from clay-rich materials, high moisture or saturation, and conductive groundwater as well as leachate [19,20]. The U.S. Environmental Protection Agency similarly notes that natural

materials have overlapping resistivity ranges and that resistivity alone cannot uniquely identify lithology or contaminants.

The geological interpretation of the anomalous intervals therefore requires particular caution. The present study identifies the conductive zones as potential leachate-affected zones rather than chemically confirmed contamination zones. This interpretation is appropriate because the VES method provides indirect information about subsurface electrical properties. Previous investigations have likewise noted that low-resistivity zones may contain contributions from clayey materials and saturation in addition to leachate. For example, investigations around the Emirin dumpsite in Nigeria identified isolated low-resistivity structures interpreted as clayey material alongside other conductive zones considered potentially influenced by leachate [28].

The spatial comparison among the three sites nevertheless demonstrates the usefulness of incorporating control soundings into dumpsite VES interpretation. A low-resistivity value considered in isolation provides limited information because its significance depends on the background geoelectrical structure. At Airport Road and Aluu, the conductive intervals contrast strongly with their respective controls, while Eneka exhibits a lower control-to-anomaly ratio but a substantially greater vertical extent (Figure 5). The combined consideration of resistivity, thickness, vertical extent and local background therefore provides a more informative basis for comparing the three sites than a single resistivity threshold.

The results also have implications for the interpretation of abandoned dumpsites. Although disposal has ceased, the presence of substantial conductive intervals beneath the investigated locations indicates that the subsurface geoelectrical effects associated with the waste-disposal environments are not restricted to the immediate ground surface. Similar observations have been reported at abandoned or closed dumpsites, where resistivity investigations have identified conductive zones extending into the underlying soil and groundwater-bearing formations [24,26]. However, the present VES data do not independently establish the chemical composition of the pore fluids or demonstrate active contaminant transport. Such conclusions would require corroboration using hydrochemical sampling, time-lapse monitoring, or higher-resolution two-dimensional/three-dimensional resistivity imaging.

Overall, the comparative results indicate that the three dumpsites possess different geoelectrical signatures and different vertical extents of potential leachate-affected zones. Airport Road is characterized by a shallow conductive anomaly with very low resistivity, Eneka by the greatest vertical and thickness extent despite a comparatively higher anomalous resistivity, and Aluu by a strong resistivity contrast with its local control and an intermediate vertical extent. These differences demonstrate the value of a comparative control-based VES approach for distinguishing site-specific geoelectrical responses around abandoned dumpsites. At the same time, the non-uniqueness of electrical resistivity requires that the identified anomalies be regarded as potential leachate-affected zones rather than direct measurements of contamination concentration or confirmed contamination depth.

V. CONCLUSION

The comparative VES investigation successfully delineated and characterized conductive subsurface zones around the three abandoned dumpsites at Airport Road, Eneka and Aluu in Rivers State. The results demonstrate clear differences in the geoelectrical responses of the three sites relative to their corresponding control soundings. The identified conductive intervals were therefore interpreted as potential leachate-affected zones, rather than confirmed contamination zones, consistent with the non-uniqueness of electrical resistivity responses.

At Airport Road, the potential leachate-affected zones exhibited the lowest median anomalous resistivity of 2.30 Ωm , but were relatively shallow, with a maximum vertical extent of 7.88 m. Eneka exhibited a higher median anomalous resistivity of 11.00 Ωm , but had the greatest anomalous-zone thickness and maximum vertical extent, with median thickness and maximum extent of 25.56 m and 32.89 m, respectively. Aluu recorded a median anomalous resistivity of 3.70 Ωm , a median anomalous-zone thickness of 13.70 m, and a maximum vertical extent of 16.19 m. These results demonstrate that the magnitude of a conductive anomaly does not necessarily correspond to its vertical extent.

The control-to-anomaly resistivity contrasts of 402.2, 77.1 and 867.8 for Airport Road, Eneka and Aluu, respectively, further demonstrate substantial differences between the dumpsite environments and their local geoelectrical backgrounds. However, these ratios represent geoelectrical contrast parameters and not quantitative measures of contaminant concentration or contamination severity. Their principal value lies in strengthening the identification of anomalous subsurface zones when interpreted together with resistivity, thickness, vertical continuity and local background conditions.

Overall, the study demonstrates that a control-based comparative VES approach provides a practical means of characterizing and comparing the vertical geoelectrical signatures of abandoned dumpsites. Nevertheless, because low resistivity can also result from clay-rich materials, increased saturation and naturally

conductive groundwater, the identified anomalies should be regarded as potential leachate-affected zones. Confirmation of leachate chemistry, contaminant concentration and active migration would require complementary hydrochemical investigations and, where detailed plume geometry is required, higher-resolution two- or three-dimensional resistivity imaging.

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