

ASSESSMENT OF POTENTIAL LEACHATE-ASSOCIATED ZONES AROUND KABAMA MUNICIPAL SOLID-WASTE DUMPSITE, ZARIA, NIGERIA, USING ELECTRICAL RESISTIVITY TOMOGRAPHY AND INDUCED POLARIZATION TECHNIQUES

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ABSTRACT

To identify buried waste items and potential leachate accumulation in the subsurface of Kabama dumpsite in Zaria, Kaduna State, Nigeria, an interpretation of resistivity and chargeability imaging approach was utilized. A total of 6 profiles were mapped using a Dipole-Dipole configuration with ABEM TERRAMETER SAS 4000, with an electrode spacing of 5.0 m and profile distances of 200 m. The inversions revealed both the lateral and vertical extents of conductive zones, primarily in fractured regions that functioned as the contaminant pathways. The electrical resistivity and chargeability imaging was established using the inverse models produced by a 2D inversion program (RES2DINV). The leachate had low resistivity ($<10 \Omega\text{m}$) and a weak chargeability zone ($<20 \text{ msec}$), whereas the investigations verified a high chargeability unit ($>70 \text{ msec}$) showing waste deposits and a saturated clayey layer. The results obtained in this research highlight the potential application of resistivity and IP methods jointly to monitor the contaminant plume. These non-destructive, efficient, and economically viable geophysical techniques could lead to a robust reconnaissance framework for remediation of solid waste disposal sites.

Keywords: Dumpsite, 2D Electrical resistivity, Induced polarization, Leachate, Contaminants.

INTRODUCTION

Municipal solid waste (MSW) disposal is an increasing environmental challenge in rapidly urbanizing communities, particularly where inadequate waste-management practices result in uncontrolled or poorly managed dumpsites (Boonsakul *et al.*, 2022). The rapid increase in global population and urbanization has intensified the need for effective management and monitoring of dump sites, particularly as urban development continues to expand toward existing and abandoned dumpsites. In many developing countries, however, older dump sites were established without proper engineering designs or containment systems to prevent environmental contamination (Singh *et al.*, 2013; Ojo *et al.*, 2022; Badmus *et al.*, 2022). As a result, leachate generated from these uncontrolled waste disposal sites can infiltrate surrounding soils and groundwater systems, posing serious health risks to nearby communities and causing significant damage to local ecosystems. Therefore, comprehensive characterization and continuous monitoring of landfill sites are essential for effective environmental risk assessment, pollution control, and sustainable waste

management practices. Rapid and non-invasive surface geophysical techniques have become valuable complementary tools to conventional monitoring wells in the investigation and assessment of landfill sites and their surrounding environments. Numerous studies have demonstrated the effectiveness of geoelectrical methods in the monitoring and characterization of dumpsites and contaminated subsurface zones (Chambers *et al.*, 2006; Soupios *et al.*, 2007). These methods are particularly suitable for landfill investigations because leachate plumes typically contain high concentrations of dissolved ions, which significantly decrease the electrical resistivity of contaminated zones relative to the surrounding uncontaminated formations. This resistivity contrast makes it possible to identify and monitor leachate migration pathways using electrical resistivity imaging techniques (Abdulrahman *et al.*, 2013; Islami *et al.*, 2020; Odong *et al.*, 2024).

In situations where the resistivity contrast between a leachate plume and the surrounding subsurface materials is minimal, electrical resistivity methods alone may not provide sufficient resolution for accurate delineation of contamination zones (Carlson *et al.*, 2001). For instance, low resistivity anomalies may result not only from leachate contamination but also from increased moisture saturation, elevated ionic concentration, or the presence of clay-rich formations within sandy sediments. Consequently, distinguishing between these materials using resistivity data alone can be challenging. However, the incorporation of Induced Polarization (IP) measurements provides additional information that improves subsurface discrimination (Dahlin *et al.*, 2014). Saline water, despite exhibiting high electrical conductivity and low resistivity, generally produces low chargeability responses. In contrast, clay-rich materials are characterized by relatively high IP responses due to their electrochemical properties (Gazoty *et al.*, 2012a). Therefore, the combined application of electrical resistivity and IP techniques enhances the ability to differentiate between clay layers and saline or leachate-contaminated sandy formations, even when both exhibit similarly low resistivity values.

Gazoty *et al.* (2012a) observed that electrical resistivity surveys may produce ambiguous results when the groundwater table occurs within waste deposits. This is because the electrical response of subsurface materials is strongly influenced by pore fluid conductivity, thereby introducing significant uncertainty in the interpretation and mapping of landfill environments. Nevertheless,

integrating electrical resistivity and Induced Polarization (IP) techniques helps to reduce the uncertainties associated with the independent application of either method. While resistivity measurements are mainly controlled by fluid saturation and ionic concentration, IP responses are more sensitive to lithology and the presence of chargeable materials commonly associated with landfill waste deposits (Legaz *et al.*, 2010). Consequently, the combined use of resistivity and IP methods provides improved subsurface characterization and enhances the reliability of landfill investigations. Several researchers have demonstrated the effectiveness of integrating these two geophysical techniques for the characterization and monitoring of solid waste disposal sites (Dahlin *et al.*, 2010; Ustra *et al.*, 2012).

Interpretation of electrical resistivity inverse models in landfill investigations is generally considered more straightforward than the analysis of chargeability models obtained from Induced Polarization (IP) surveys. The electrical resistivity of subsurface materials is primarily controlled by factors such as sediment porosity, moisture content, and the resistivity of pore water (Abdulrahman *et al.*, 2016). Materials such as seawater, brackish water, leachate, and clay typically exhibit low resistivity values due to their high ionic content and conductive nature. Moderate resistivity values are commonly associated with fresh groundwater, moist sand, sandstone, and limestone formations. In contrast, high resistivity values usually characterize dry sand, compact rocks, and crystalline basement formations such as granite (Guérin *et al.*, 2004). Although clay-rich materials can generally be distinguished from other unconsolidated sediments because of their relatively high IP responses (Gazoty *et al.*, 2012b), interpreting the

chargeability characteristics of dispersed contaminant plumes often requires more detailed evaluation. Nevertheless, landfill waste materials frequently contain metallic components and biodegraded organic matter that generate elevated chargeability anomalies. This characteristic makes IP surveys particularly useful for identifying and delineating waste boundaries and contaminated zones within landfill environments (Ustra *et al.*, 2012).

This study aims to assess and characterize leachate contamination within the dumpsite soils and the underlying geological formations surrounding the municipal solid waste (MSW) disposal site, with a view to evaluating its potential effects on nearby shallow groundwater systems. The specific objectives of the research are to employ integrated two-dimensional Electrical Resistivity Tomography (2D ERT) and Induced Polarization (IP) techniques to identify zones of leachate accumulation, determine the spatial geometry and migration pathways of the contaminant plume, and assess the likelihood of groundwater contamination within and around the dumpsite environment.

MATERIALS AND METHODS

Site Description and Geological Setting

The study area is the Kabama municipal solid waste disposal site behind the shooting range, Sabon Gari, Zaria metropolis, Kaduna State, North West Nigeria (Fig. 1). The site is geographically located between latitude 11° 08' 38"N to 11° 08' 45"N and longitude 007° 45' 48"E to 007° 45' 56"E. Fig. 1 below presents the geological map of the study area.

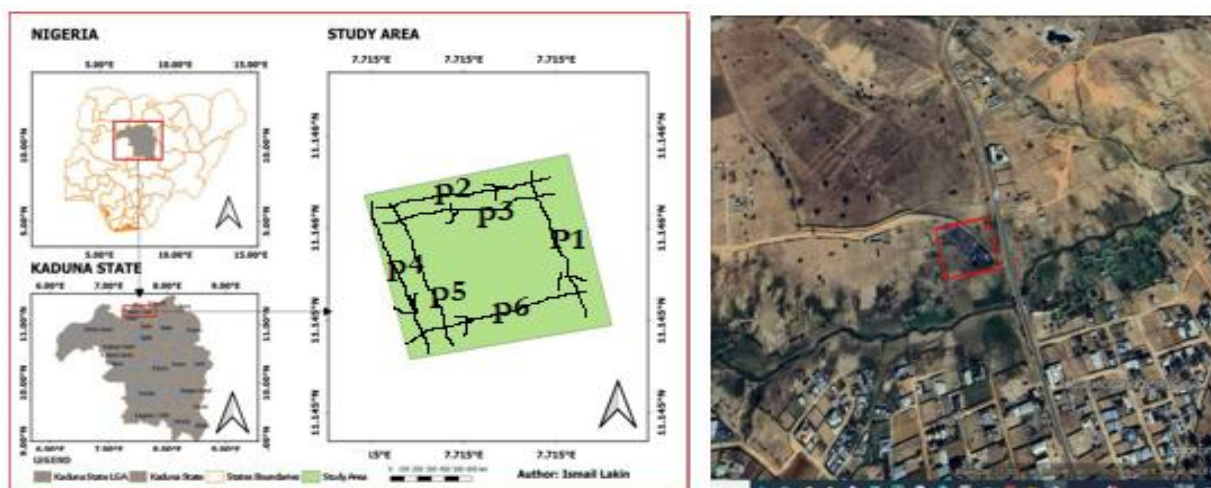


Figure 1: Map of the Study Area

Geologically, the study area is located within the Basement Complex terrain of northern Nigeria. The area is underlain by crystalline basement rocks consisting predominantly of granites, gneisses, migmatites, amphibolites, and quartzites. These rocks are generally mechanically competent and tend to respond to tectonic stresses through brittle deformation and fracturing. Surface water infiltrates through these fractures, thereby enhancing chemical weathering processes within the subsurface. Among the basement rock units, gneisses and migmatites are generally more susceptible to weathering compared to granitic

rocks (Abdullahi *et al.*, 2010). The study area experiences a typical tropical Savannah climate characterized by distinct wet and dry seasons. The dry season generally extends from October to April, while the rainy season occurs between May and September. The region receives about 1270 mm of rain on average each year, with August often seeing the highest amount of precipitation. Seasonal variations in temperature range from below 15°C during the Harmattan period in December and January to roughly 32°C during the warmer months of March and April.

In terms of hydrogeology, previous geophysical investigations and borehole drilling records have revealed the presence of two principal aquifer systems within the area. These include the overburden weathered aquifer, composed mainly of clayey sand and sandy materials, and the fractured crystalline basement aquifer (Dan-Hassan & Olorunfemi, 1999). The overburden aquifer is generally rich in groundwater and is widely exploited through hand-dug wells for domestic water supply. In certain locations, the weathered and fractured aquifers are hydraulically interconnected, forming a continuous groundwater table and a unified hydrogeological system.

Data Acquisition

The 2D resistivity and Induced Polarization (IP) datasets were acquired simultaneously along each survey profile using the multi-electrode ABEM Lund Imaging System (Fig.2) configured in the Dipole-Dipole array with 5m constant electrode spacing. The Dipole-Dipole array configuration was selected for the survey because of its high sensitivity for detecting vertical structures such as faults, leachate plumes, fractures, and buried waste, which enhances data quality and interpretation reliability (Ganiyu *et al.*, 2021). The orientation of the VLF-EM traverses was such that 3 of the 6 traverses trended from north to South, while the remaining 3

traverses trended from east to west across the dumpsite, where profile 1 served as the control profile. The integrated IP acquisition mode enables the concurrent measurement of both resistivity and chargeability data during field operations. The Lund Imaging System comprises an ABEM TERRAMETER SAS 4000, an ES-64 electrode selector, cable reels, connecting units, and stainless-steel electrodes. The electrode selector facilitates the automatic switching and selection of the four active electrodes required for each measurement sequence using standard electrode array configurations (Griffiths *et al.*, 1990). The SAS 4000 Utility software was utilized to convert the field data downloaded from the ABEM TERRAMETER SAS 4000 into readable data files suitable for processing and interpretation. The converted raw resistivity and IP datasets were subsequently processed and inverted using the RES2DINV Geotomo software package to generate two-dimensional subsurface resistivity and chargeability models. The measured resistivity and chargeability data are regarded as apparent values because they represent the combined electrical response of a subsurface volume rather than the true properties of individual geological layers. Therefore, to obtain a more accurate representation of the subsurface resistivity and chargeability distribution, an inversion process must be carried out.



Figure 2: ABEM TERRAMETER SAS 4000

RESULTS AND DISCUSSION

The inverted resistivity sections delineated conductive regions extending to an approximate depth of 33.8 m beneath the dumpsite. These conductive zones were interpreted as areas affected by varying degrees of leachate contamination and were predominantly associated with faulted or fractured subsurface formations. The low resistivity regions ($<10 \Omega\text{m}$), which are represented by blue colour in the inverse models, indicate the leachate-associated zones, which correspond with the shallow localized aquifer (Kaya *et al.*, 2007). Leachate-saturated materials, clayey soils and silty formations with varying moisture contents

exhibited resistivity values ranging from approximately 30–150 Ωm , while fractured basement layers containing different degrees of water saturation showed resistivity values between 50 and 1000 Ωm . Fresh basement rocks were characterized by relatively high resistivity values greater than 1000 Ωm . The interpreted lithological resistivity ranges are consistent with values reported in previous studies conducted within basement complex terrains and landfill environments, confirming the reliability of the geoelectrical interpretation (Kumar *et al.*, 2016).

Table 1: Adopted interpretation scheme of resistivity and chargeability inverse models for selected landfill sites.

Surface section	Resistivity	Chargeability
Mixture of leachate and waste	Low(<10 Ω m) (Dahlin <i>et al.</i> , 2010)	High(>70 msec) (Dahlin <i>et al.</i> , 2010)
Saturated clay (uncontaminated)	Low(<10 Ω m) (Gue'rin <i>et al.</i> , 2004)	High(>70 msec) (Gazoty <i>et al.</i> , 2012b)
Unsaturated waste	High(<10 Ω m) (Dahlin <i>et al.</i> , 2010)	High(>70 msec) (Dahlin <i>et al.</i> , 2010)
Unsaturated soil	High(<10 Ω m) (Leroux <i>et al.</i> , 2007)	Low(<20 msec) (Leroux <i>et al.</i> , 2007)
Leachate plume	Low(<10 Ω m) (Kaya <i>et al.</i> , 2007)	Low(<20 msec) (Gallas <i>et al.</i> , 2011)
Saturated (without leachate)	Intermediate(30-150 Ω m) (Dahlin <i>et al.</i> , 2010)	High(>70 msec) (Dahlin <i>et al.</i> , 2010)
Saturated soil (uncontaminated)	Intermediate(30-150 Ω m) (Dahlin <i>et al.</i> , 2010)	Low(<20 msec) (Dahlin <i>et al.</i> , 2010)

The inverted resistivity model for Profile 1 (Fig.3) revealed the lateral migration of conductive zones (50.7 - 118 Ω m) along the profile, extending from the surface to an estimated depth of about 9 m. These conductive regions were interpreted as clayey formations with varying degrees of water saturation. The absence of extremely low resistivity values within this section suggests that the leachate contaminant may not have significantly penetrated to this depth. The resistivity values generally increased with depth, indicating a transition from relatively conductive near-surface materials to more resistive subsurface formations. Fractured basement layers with resistivity values ranging from approximately 250–554 Ω m were identified at depths between 6 m and 11 m, while the fresh basement formation, characterized by much higher

resistivity values ranging from 1238–13447 Ω m, occurred at the deeper portions and base of the model. The observed increase in resistivity with depth suggests reduced moisture content toward the competent basement rock. The inverse model chargeability (Fig.3) shows an indistinguishable, uniformly homogeneous layer with a completely spread chargeability value of 12 msec. Although the geophysical responses obtained from uncontaminated saturated soil zones are similar to those associated with waste deposits, the non-chargeable characteristic of the leachate plume identified in this study provides a clear distinction between the contaminant plume and the saturated clayey formations located outside the landfill waste boundaries (Abdulrahman *et al.*, 2016).

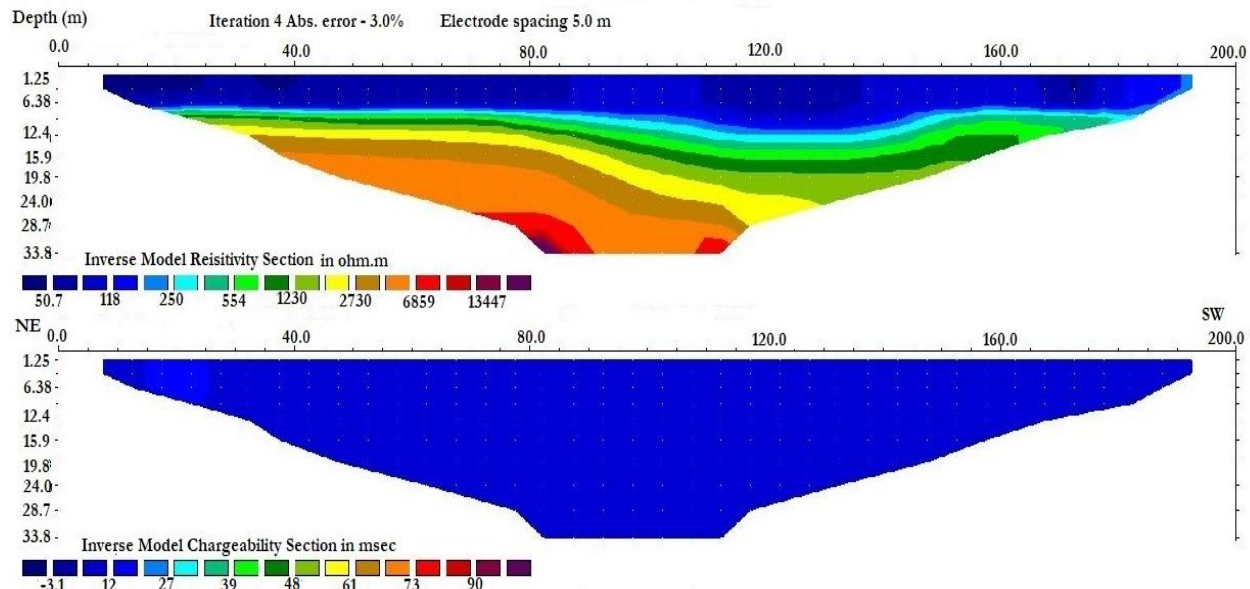


Figure 3: Resistivity and chargeability inverse models of profile 1.

The inverse model resistivity of profile 2 (Fig.4) showed several highly conductive zones (6.75- 13.7 Ω m) saturated with leachate. At lateral distances 10-25, 80-91, 125-130, 153-157, and 178-193 m and depths of 1-9 m. Also, at profile distances 42.5-48 and 162-168 m offset from the model, fractured layers (56.9-116 Ω m) were on the model's surface to a depth of 24 m. The fractured basement layers, characterized by resistivity values ranging from

approximately 236-692 Ω m, were observed across the base of the model at an average depth of about 15.9-33.8 m. The inverse model chargeability section (Fig.4) shows a near-surface spread of moderate chargeability units at a surface distance of 185- 190 m, suggesting that they are likely to be part of the saturated and uncontaminated clayey cover (Abdulrahman *et al.*, 2016).

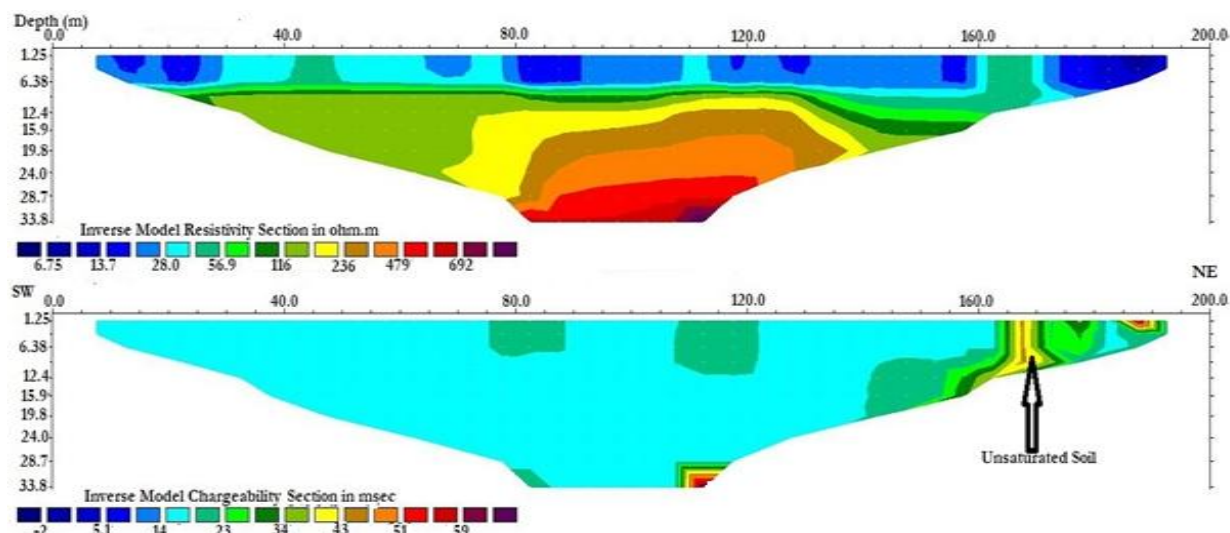


Figure 4. Resistivity and chargeability inverse models of profile 2

The inverse model resistivity of profile 3 (Fig.5) showed resistivity of about 55.6 - 85.1 Ω m at profile distances 7- 16, 31- 68, and 172- 193 m from the model's surface to an approximated depth of 9 m. These regions indicated migration of leachate in the fractured layers. Fractured layers with resistivity values of 138-468 Ω m aided the migration of leachate contaminants (Ganiyu et al., 2015). On

the surface of the inverse model, at a profile distance of 120- 135 m offset, fresh basement layers with a resistivity value of 1097 Ω m were observed. The inverse model chargeability section (Fig.5) presents a surface with a low chargeability value of 2.90 msec, which signifies fractured basement layers.

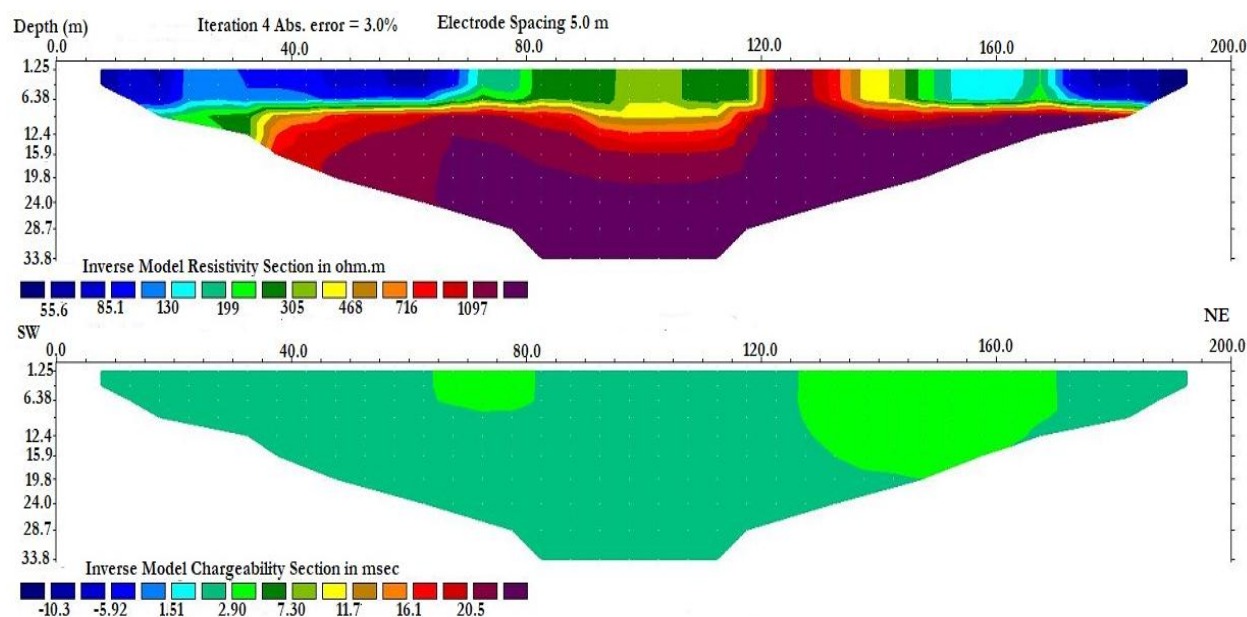


Figure 5: Resistivity and chargeability inverse models of Profile 3.

The inverted resistivity model for Profile 4 (fig.6) revealed relatively conductive regions with resistivity values ranging from approximately 49.6–86.7 Ω m, interpreted as water-bearing zones. These conductive regions extended from the surface to an estimated depth of about 10.5 m and were observed mainly between profile distances of 7.5–50, 62–68, and 163- 193 m. Underlying these conductive zones are fractured basement layers characterized by resistivity values ranging from 152–265 Ω m.

These fractured formations displayed relatively consistent thicknesses along the surface section between 52- 58 m, 70- 80 m, and 120- 150 m and extended downward across the model toward the deeper portions of the profile. The moderate resistivity values suggest partially weathered and fractured basement materials with varying degrees of water saturation. The deeper part of the inverse model is dominated by fresh basement formations with high resistivity values ranging from approximately 811–2481 Ω m. These

highly resistive zones occur predominantly at the base of the model and are interpreted as competent crystalline basement rocks. The inverse model chargeability section (Fig.6) shows a uniformly

homogeneous layer with a completely spread chargeability value of 83 msec. This is in agreement with fresh basement formations with a high resistivity value of approximately 1419 Ω m.

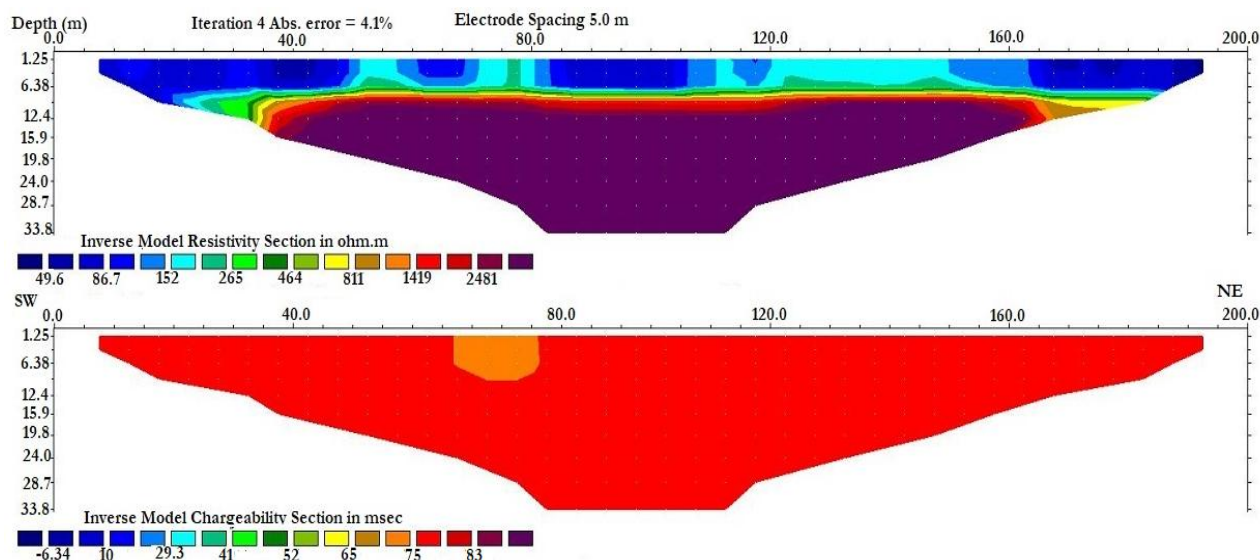


Figure 6: Resistivity and chargeability inverse models of profile 4.

Figure 6 shows the inverse resistivity model of profile 7. It revealed relatively conductive zones with resistivity values ranging from 61.9–92.5 Ω m, interpreted as water-bearing zones. These conductive regions extended from the surface to an estimated depth of about 14 m and were observed mainly between profile distances of 32–87 and 147–158 m. In addition, fractured basement layers characterized by resistivity values ranging from 147–347 Ω m were observed. These fractured formations displayed relatively consistent thicknesses along the surface section between 17–32, 92–145, and 160–193 m and extended downward across the model toward the deeper portions of the profile. The moderate resistivity values suggest partially weathered and fractured

basement materials with varying degrees of water saturation. The deeper part of the inverse model is dominated by fresh basement formations with high resistivity values ranging from approximately 534–1266 Ω m. These highly resistive zones occur predominantly at the base of the model and are interpreted as competent crystalline basement rocks. The inverse model chargeability section (Fig.7) reveals almost a block of moderate chargeability values in the range of 67.1–78 msec dominating the profile, with some pockets of intermittently distributed chargeability of 86 msec at profile distances 57, 155–167 m. The near-surface spread of these moderate chargeability units suggests that they are likely to be part of the saturated waste (without leachate).

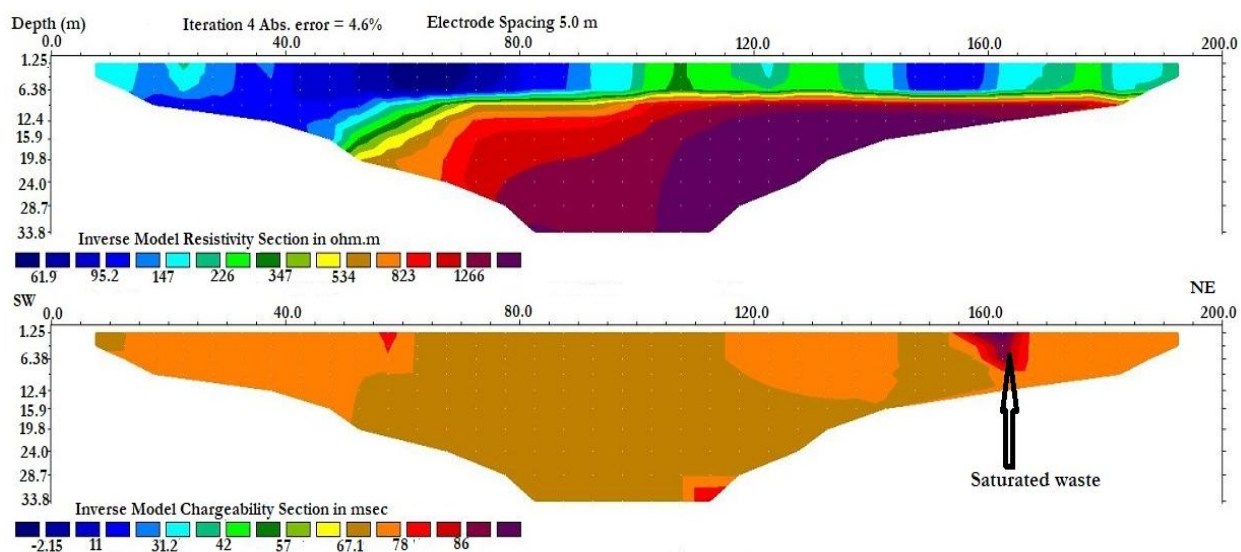


Figure 7: Resistivity and chargeability inverse models of profile 5.

Figure 8 depicts the inverse resistivity model of profile 6. It revealed relatively conductive zones with resistivity values ranging from 12.0–19.9 Ωm at profile distances 7–79 m and depths of 1–12 m. A trace of a low-conductivity zone was also observed around profile distance 190–193 m. These conductive zones suggest leachate-saturated materials, clayey soils and silt formations. Fractured basement layers characterized by resistivity values ranging from 32.2–92.2 Ωm were observed. These fractured formations were observed along the surface section between 80–190 m and extended downward across the model toward the deeper portions of the profile. The base of the inverse model is dominated by

formations with intermediate resistivity values ranging from approximately 154–427 Ωm . The moderate resistivity values suggest partially weathered and fractured basement materials with varying degrees of water saturation. The inverse model chargeability section (Fig.8) presents low chargeability values ranging from 36.1–48 msec dominating the profile. The profile's far right shows a considerable amount of solid waste without leachate. Most of the surface of the profile is uncontaminated saturated soil (intermediate resistivity and low chargeability), with a few areas that are dry land (high resistivity and low chargeability).

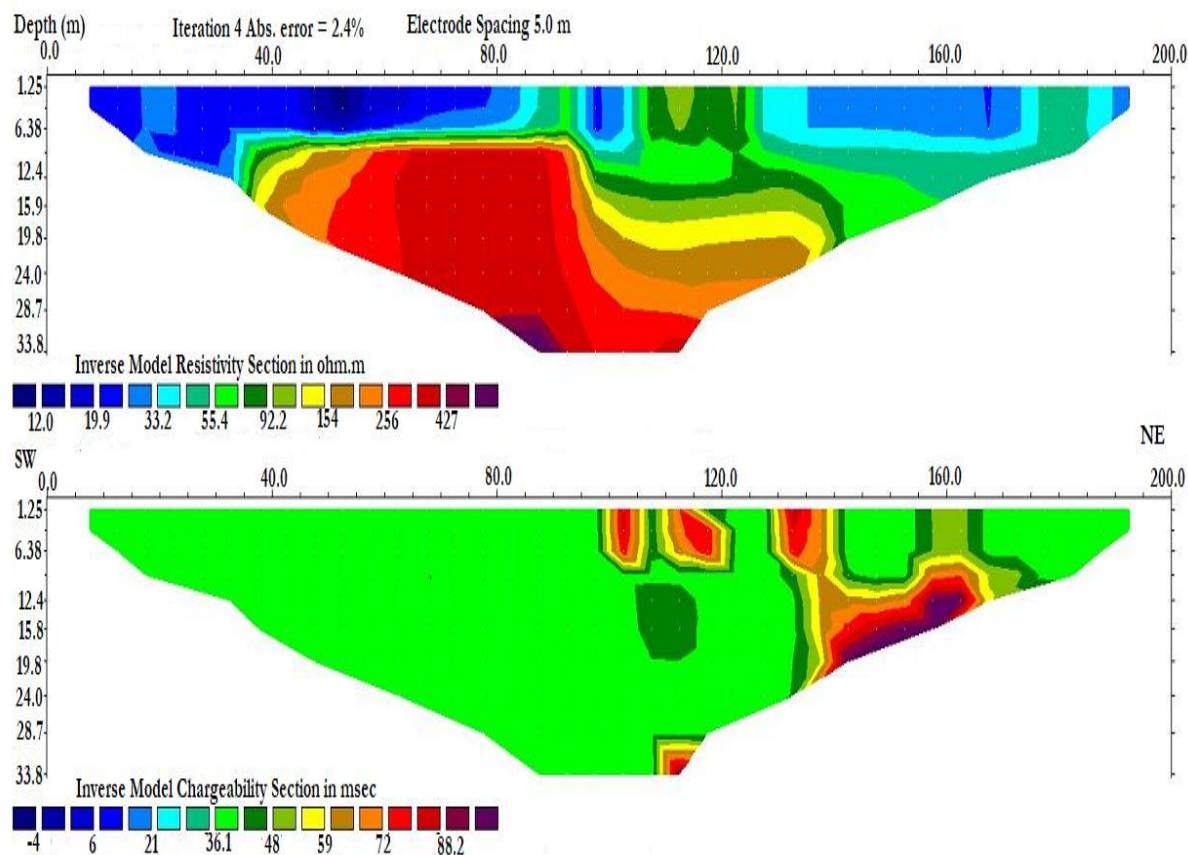


Figure 8: Resistivity and chargeability inverse models of profile 6.

The integrated 2D ERT–IP results indicate that the Kabama dumpsite contains low-resistivity conductive zones associated with possible leachate-affected materials, saturated soils, and clay-rich formations, with the most pronounced anomalies generally occurring at shallow to intermediate depths. Resistivity values <10 Ωm were particularly associated with potential leachate-saturated zones, while intermediate values of 30–150 Ωm mainly represented saturated or fractured materials. The IP results provide additional discrimination: low chargeability (<20 msec) is consistent with leachate-dominated zones, whereas high chargeability (>70 msec) is associated mainly with waste deposits and saturated clay. For example, Profile 2 contains low-resistivity zones of 6.75–13.7 Ωm extending to about 9 m, while Profile 6 shows conductive zones of 12–19.9 Ωm down to approximately 12 m. The combined resistivity and chargeability patterns delineate potential leachate-

affected zones, waste deposits, saturated/fractured formations, and possible migration pathways beneath the dumpsite. However, there is similarity between some leachate/waste zones.

Conclusion

Integrating electrical resistivity and the time-domain IP techniques evidently allowed distinguishing waste deposits from the leachate plumes and validates the zones of the mixture of the two sections. The low resistivity and high IP responses in the profiles made it easier to identify the direction of leachate flow and detect the waste borders. Analysis of the inverted model sections produced at the dumpsite determined the differences in the spread of the contaminant plumes between the six profiles. The inverse model sections from the six profiles and the assessment lines displayed similar patterns in resistivity and chargeability distribution, which is

in line with the findings of previous research. In addition, this research used an analysis chart to interpret resistivity and chargeability models when characterizing the subsurface of the chosen dumpsite. The resistivity values assigned by this scheme are low ($<10 \Omega\text{m}$), intermediate ($30\text{--}150 \Omega\text{m}$), and high ($>1000 \Omega\text{m}$). The chargeability values of the IP responses are high ($>70 \text{ msec}$) and low ($<20 \text{ msec}$), and the values missing from the chart are thought to be transition regions between neighbouring strata. The similarity between the resistivity and chargeability values of the waste combined with leachate and the uncontaminated saturated clay, however, limits the application of the interpretation method.

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