Delineation of Leachate Plume Intrusion at Bwari Dumpsite, Abuja, Nigeria Using Electrical Resistivity Methods

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Abstract: The growing population of the world and Nigeria in particular has led to many environmental crises, spanning from global warming, greenhouse gas emissions, to pollution of all kinds due to an increase in industrial and home wastes. Some of these wastes, both solid and in fluid form, are deposited carelessly around the environment with little concern for how they affect human lives in all ramifications. Some chemical plants have also been shut down with little or no effort to properly remove or dispose of both the raw materials previously used and waste products. These solid wastes decompose to produce contaminant plumes such as leachate. Factors like rain, compression and compaction lead to the leaching of these plumes into the subsurface and eventually into the aquifers. This study employed the resistivity technique to measure the resistivity variation along the Bwari dumpsite using a Wenner array and variation with depth (vertical electrical sounding) via a Schlumberger array. Horizontal profile curve from the Wenner array showed a decrease in resistivity reading towards the middle of the dumpsite. Apparent resistivity as low as 13.19640 Ωm was obtained at the center of the dumpsite. 2-D imaging from win RESIST showed plume intrusion from 5.55m depth downwards. It appears as if gravitational pull has resulted in the distribution pattern of plume presence. The subsurface intrusion was found to be located within 20m and 75m from the position of measurement within 9.2952 oN, 7.3847 oE and 9.2931 oN, 7.3847 oE.

Keywords: vertical electrical sounding, leachate, horizontal profiling, aquifer, plumes, leaching.

1.1 Introduction

Solid waste disposal is one of the problems in the modern world due to a significant increase in waste production. This increase in waste production can be attributed to factors like population surge, urbanisation and industrialisation. Indiscriminate disposal of waste material is a common practice in Nigeria due to inadequate waste disposal facilities and improper enforcement of environmental regulations (Ehirim et al., 2009; Ugbor et al., 2021). Furthermore, places with facilities often lack proper engineering liners or leachate, a toxic liquid produced from decomposition of organic and inorganic waste, collection systems, thereby allowing harmful contaminant plumes to sink into the subsurface and degrade groundwater quality. This infiltration of toxic substances like leachate collectors into the groundwater spells danger to both soil and groundwater, which are important resources for domestic and agricultural use (Maurya *et al.,* 2017; Adeniji *et al.,* 2023). These problems directly violate the United Nations Sustainable Development Goal (SDG) 6, which seeks to ensure the availability and sustainable management of water and sanitation for all (United Nations, 2015).

Geophysical methods such as Electrical Resistivity Tomography (ERT) provide continuous subsurface profiles which can effectively map out zones of leachate migration (Ehirim *et al.,* 2009; Obiabunmo & Obiekezie, 2023). The electrical resistivity technique is one of the available techniques used to characterise subsurface contamination. This technique is preferred because it is reliable and non-invasive in nature. It is based on the principle of variation of electrical resistivity due to moisture content, ion concentration and lithological composition of the subsurface materials.

Recent studies have emphasised the effectiveness of 2-dimensional (2D) and 3-dimensional (3D) resistivity imaging in mapping contaminant plumes around waste sites. Maurya *et al.,* (2017) used high-resolution 2D and 3D to delineate a heavily contaminated landfill in Grindsted, Denmark, and Badmus et al., (2022) employed integrated Electrical Resistivity Imaging (ERI) to map out a dumpsite at Emirin, Ado-Ekiti, Nigeria, among others. The electrical resistivity technique is used to delineate subsurface features using the measured resistivity of the soil influenced by the materials found in and around it.

This work gave a comprehensive geophysical assessment of the Bwari dump site, thereby providing a holistic picture of groundwater vulnerability in the study area. Existing literature has largely centred on other parts of Abuja, such as Gasa, Mpape and Kubwa (Omolara *et al.,* 2023). The resistivity method was selected due to its non-invasive, cost-effective and highly sensitive to subsurface fluid chemistry. It is also helpful for depth profiling and lateral mapping. Furthermore, it can be adopted for complex terrains and heterogeneous geological formations, unlike ground-penetrating radar (GPR), which may be limited by conductive and clay-rich environments (Loke, 2004).

1.2 Description of the Study Area

The study area, just as the Bwari Area Council where it is situated, is characterised by widespread metamorphism, deformation, and magmatic intrusions underlain by Precambrian Basement complex rocks like gneisses, granites, schists, and migmatites

(Obaje, 2009; Ramadan, 1988). It is located within $9°\ 29'\ 52''N, 7°\ 38'\ 47''\ E$, $7°\ 38'\ 80''\ E$ and $9°\ 29'\ 31''\ N$, $7°\ 38'\ 47''\ E, 7°\ 38'\ 80''\ E$. It lies in the north-eastern part of the Federal Capital Territory and covers a total of about 428718.43 square meters (on the scale of 1:7353 cm). It is a plain terrain which is made up of clusters of rock outcrops.

Figure 1 Map of Study Area (Google Map)

Figure 2: Pictorial View of the Study Area

2.0 Methodology

The materials and methods used in this research are discussed under the subheadings below.

Materials and Methods of Study

The equipment used during this research work includes: 3.5 mm Cables, a 12 V Battery, crocodile clips, a hammer, iron electrodes, 50m measuring tape, a resistivity meter, and 1.0 version WinRESIST software.

The resistivity method was the technique employed in this study. The resistivity method involves the spreading of electrical potential in the ground around a current-carrying electrode to determine the resistivity. This resistivity depends on the electrical resistivities and distribution of the surrounding soil and minerals. The geo-electric technique is a surface geophysical method in which an electrical current is passed into the ground through two pairs of current electrodes, and the potentials caused by this current are measured with another pair of electrodes connected to a voltmeter. The geo-electric technique delineates rocks, materials and minerals in and on the subsurface of the earth by employing electric current flowing on the earth.

The measured resistance is converted into apparent resistivity by multiplying the obtained resistance by the G-factor of the array employed.

Field Procedures

The Schlumberger and Wenner arrays were employed in this study. An inter-electrode spacing of 10m for the Wenner array was used to map the resistivity variation along the site. Two pairs of electrodes were used, with the outer pair as the current electrodes and the inner pair as the potential electrodes. The pairs of electrodes were connected to the ammeter and voltmeter sections of the terameter, respectively. Measurements were taken for one transverse up to 50m.

The distance of separation, in the Schlumberger array, between the current electrodes varied up to 80m, while that of the potential electrodes was kept constant for some readings and varied to get a wider depth. The field procedure was conducted along one traverse; intercurrent electrode spacing was increased gradually for 14 sets of readings from 1 m up to 40 m.

Precautions like hammering the electrodes to the ground properly and tight connections were followed during the field work to reduce uncertainties contributed by gain error and current error.

Theoretical Background

Ohm's law forms the basis for the theoretical background of the resistivity method. This is used to measure the electrical property of the subsurface by inducing current into the ground and measuring the resulting voltage difference. Ohm's law is a direct proportion law that gives the relationship between voltage, resistance and current through a conductor. It is given as:

$$V = IR \quad (1)$$

where V is Voltage (Volts), I is the current (Ampere), and R is the resistance (Ohms).

This law is related to the cross-sectional area of a conductor per unit length through the formula:

$$\rho = \frac{RA}{L} \quad (2)$$

where ρ is the resistivity (Ohm-meter), A is the cross-sectional area (square meters), and L is the length (meters).

In geophysical surveys, factors such as non-uniformity of the subsurface and the weighted average value of resistivity of all materials encountered by the current obtained instead of the exact value of resistivity led to the use of apparent resistivity. This is an estimated value of the resistivities of materials in the subsurface. It is given by (Loke, 1999):

$$\rho_a = \frac{V}{I}G \quad (3)$$

where ρ_a is the apparent resistivity of the material (Ohm-meter), and G, the Geometric factor (meter), defined as the measured resistivity value obtained from

electrical resistivity surveys, which represents an average resistivity of the subsurface material influencing the current electrode (Telford et al., 1990).
Combining equations (1) and (3), we obtain

$$\rho_a = RG \tag{4}$$

a. Electrode arrays:

An electrode array, also called electrode configuration, deals with the various ways in which current and voltage electrodes are arranged in the electrical resistivity method. Electrode arrays were developed to make field measurements more efficient and data interpretation easier (Ohaegbuchu et al., 2019). Electrode configurations adopted in the DC resistivity method for surface investigation include the following: Wenner array, Schlumberger array, Pole-Pole array, Pole-Dipole array, among others.

i. Wenner Array

This is the type of electrode configuration in which four electrodes are placed in line and equidistant from one another.

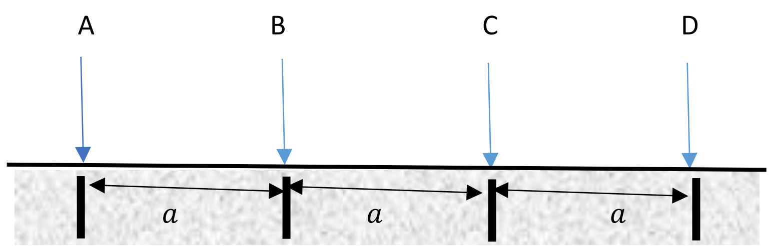

Figure 3 Wenner Array

where a is the distance between the electrodes.
The G-factor of the Wenner array is defined by (Zohdy, 1970),

$$G = 2\pi a \tag{5}$$

From (4), apparent resistivity for the Wenner array is given by,

$$\rho_a = 2\pi a R \tag{6}$$

ii. **Schlumberger array**

The resistivity of the subsurface is measured by moving the current electrodes outward after each measurement, while the potential electrodes stay in the same point until the measured voltage becomes too small. At this point, the potential electrodes' separation is increased outward.

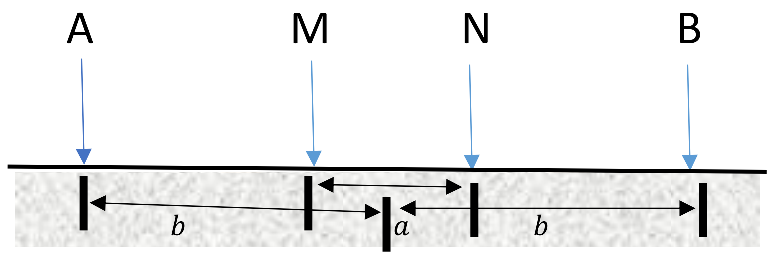

Figure 4 Schlumberger Array

where AB, MN are the distances between current and potential electrodes, respectively.

The G-factor of the Schlumberger array is defined by (Zohdy, 1970):

$$G = \pi \frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \quad (7)$$

From (4), the apparent resistivity for the Schlumberger array is given by:

$$\rho_a = RG = \pi \frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} R \quad (8)$$

3. Discussion of Results

Table 1: Resistivity Table along the Site Using Wenner Array

S/N	Distance, a (m)	R=V/I (Ω)	G=2πa	P=RG (Ωm)
1,	0.00	3.194	62.84	200.71096
2,	10.00	4.102	62.84	257.76968
3,	20.00	1.777	62.84	111.66668
4,	30.00	0.555	62.84	34.87620
5,	40.00	0.210	62.84	13.19640
6,	50.00	0.540	62.84	33.93360

Table 2: Resistivity Table along the Site Using Schlumberger Array

S/N	AB/2 (m)	MN/2 (m)	R=V/I (Ω)	$G = \pi \frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN}$	P=RG (Ωm)
1.	1.00	0.25	2.643	5.89125	15.57057
2.	2.00	0.25	1.043	24.74325	25.80721
3.	3.00	0.25	0.676	56.16325	37.96636
4.	4.00	0.25	0.501	100.15125	50.17578

5.	6.00	0.25	0.346	225.83125	78.13761
6.	6.00	0.50	0.777	112.3265	87.27770
7.	8.00	0.50	0.561	200.3025	112.36970
8.	12.00	0.50	0.317	451.6625	143.16513
9.	15.00	0.50	0.210	706.1645	148.29455
10.	15.00	1.OO	0.469	351.904	165.04298
11.	20.00	1.00	0.272	626.829	170.49749
12.	30.00	1.00	0.141	1412.329	199.13839
13.	40.00	2.50	0.111	1001.5125	111.16789

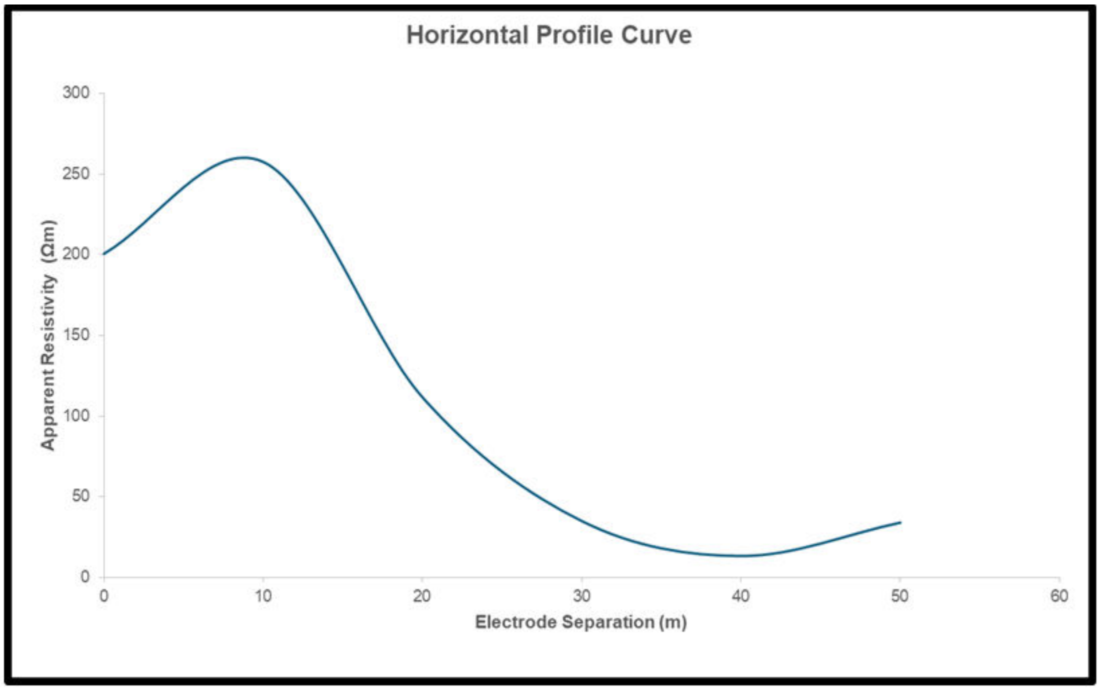

Figure 5 Horizontal Profile Curve

The horizontal profile curve, generated from the Wenner array, showed a sharp decrease in the resistivity along the dumpsite towards the center, with the lowest resistivity value at the center. A very low resistivity of 13.19640 Ωm was recorded. This reduction in resistivity reading showed the presence of conductive materials, salts and ions. These conductive materials are concentrated towards the center of the site.

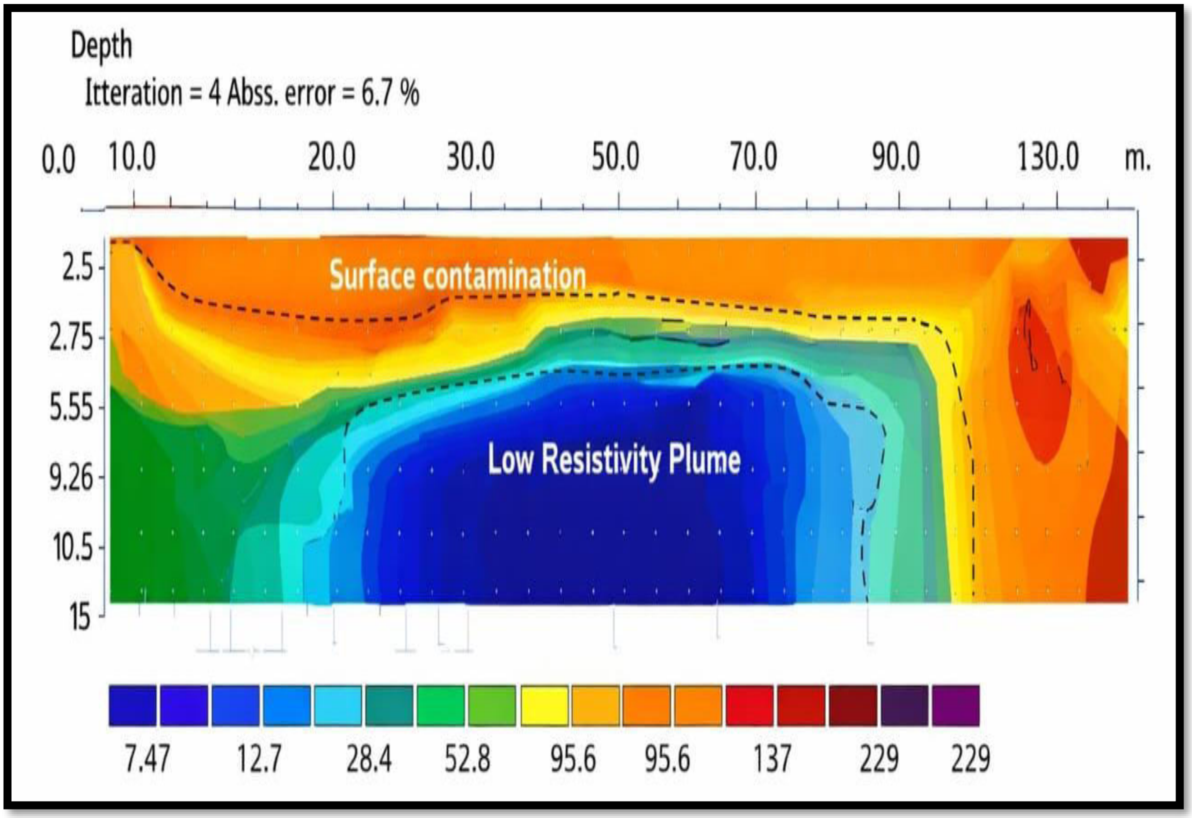

Figure 6 Contoured Pseudo-section – Characterising Dump Impact

The resistivity model gotten after inversion shows values between 7.47 Ωm and 229 Ωm, with a root mean square error of 6.7 %. The near-surface layer (0 m to ~ 3 m) represented by yellow to orange colours is characterized by moderate resistivity values of ~ 95 Ωm to 137 Ωm. This layer is interpreted as contaminated topsoil, likely influenced by infiltration of leachate from the dumpsite. Partial saturation and the presence of dissolved ions enhancing conductivity could likely account for the relatively moderate resistivity obtained at this layer. High resistivity values (> 137 Ωm) represented by orange to red colours are observed at the flanks of the profile.

An eminent low resistivity anomaly of 7 Ωm *to* 30 Ωm is observed between approximately 20 m and 30 m lateral distance, extending to a depth of about 15 m and ~ 5 m to 15 m depth. The very low resistivity values signify high ionic concentration and possible presence of heavy metals. This zone is interpreted as a leachate-contaminated plume. Such low resistivity signatures are common to landfill leachate due to the presence of conductive fluids rich in dissolved constituents (Fetter, 2001). The depth and extent of this anomaly point out that the contamination has migrated vertically into the aquifer and is spreading laterally among permeable pathways.

Engulfing the core plume is a zone of intermediate resistivity values (green to light blue) of 30 Ωm to 70 Ωm. This region signifies a gradual diminishing zone where contaminant concentration decreases due to hydrodynamic dispersion, adsorption onto soil particles, and dilution by groundwater. This is consistent with groundwater flow models where contaminant plumes gradually decrease in concentration away from the source (Freeze & Cherry, 1979).

Table 3: Borehole Lithological log with Resistivity values of various Subsurface (Adapted from Freeze & Cherry, 1979; Offodile, 2002; Telford et al., 1990; Keller & Frischknecht, 1966)

S/N	Lithology/Material	Resistivity Range (Ωm)	Hydrological Significance
1.	Topsoil (clay/sandy clay)	10 – 100	Unsaturated zone, infiltration layer
2.	Lateritic Clay	50 – 150	Low permeability; acts as an aquitard
3.	Weathered Basement	100 – 500	Moderate permeability; potential aquifer
4.	Fractured Basement	300 – 1000	High permeability; main aquifer zone
5.	Fresh Basement	> 1000	Impermeable; no groundwater storage
6.	Leachate-contaminated zone	< 10 - 50	Highly conductive due to dissolved ions

The different zones obtained when compared to the borehole lithological log are;

1. Surface layer (0 m to ~ 3 m) characterized by moderate resistivity values between 95 Ωm and 137 Ωm corresponding to moist, contaminated topsoil, inferring infiltration of leachate at shallow depth.
2. Low resistivity plume (~ 5 m to 15 m depth) characterized by a saturated sandy layer (aquifer) which shows moderate to high resistivity when clean. However, the observed very low resistivity shows contamination. This signifies contamination of the aquifer by leachate infiltration, increasing ionic concentration and decreasing resistivity (Fetter, 2001).
3. Transition zone with resistivity values between 30 Ωm and 70 Ωm surrounding plume. This is a gradual diminishing zone characterized by partial saturation made up of weathered/fractured materials, where contaminant concentration is diluted.

4. High resistivity zone indicated by orange-red at flanks. This is a fresh basement rock indicating low porosity, minimal fluid content, and absence of contamination, confirming they are uncontaminated, competent formations (Todd & Mays, 2005).
5. Clay layer (~ 2 m to 6 m) characterized by low to moderate resistivity due to high cation exchange capacity and surface conduction mechanism. The clay layer acts as a temporary barrier or sink, slowing vertical migration but not completely preventing it (Freeze & Cherry, 1979).

Table 4: Borehole Lithological log with Resistivity values of various Subsurface

S/N	Depth (m)	Lithology/Material	Resistivity Range (Ωm)	Hydrological Significance
1.	0 – 2.5	Topsoil	95 – 137	Moderately resistive; surface contamination zone
2.	2.5 – 5.5	Clay	10 – 30	Naturally low resistivity; possible contaminant retention
3.	5.5 – 12	Saturated sand	7 – 30	Very low resistivity; leachate-contaminated aquifer (plume zone)
4.	12 – 15	Weathered Basement	30 – 70	Transition zone; diluted contamination
5.	> 15	Fresh Basement	> 100 - 229	High resistivity; uncontaminated formation

The identified anomaly signifies plume intrusion at equal to or greater than 5.55m. It appears as if gravitational pull has resulted in the distribution pattern of plume presence. That is, conductivity increases with an increase in depth. The subsurface intrusion is located within 20m and 75m from the position of measurement. This delineated zone is located within 9.2952 °N, 7.3847 °E and 9.2931 °N, 7.3847 °E.

4. Conclusion

The contaminant plume intrusion delineation at the Bwari dumpsite gives an insight into the effect of uncontrolled waste disposal on the subsurface. VES and horizontal profiling were employed to ascertain the variation in resistivity with depth and along the dumpsite, respectively. The identification of resistivity anomalies attributed to conductive leachate seen easily in the region highlights the vulnerability of groundwater within and around the site. The results provided resistivity anomalies as low as 13.19640 Ωm along the site, with 2-D mapping showing surface contamination and depth contamination from 5.55 m below the surface level.

This finding highlights the need for controlled waste deposits and proper waste management to prevent soil and groundwater contamination. Deliberate actions to properly manage waste disposals will, in turn, reduce groundwater contamination from leachate infiltration, ensuring safe, sustainable management of water resources and reducing contamination risks, advancing SDG 6.

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