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Research Article

Mapping Groundwater Contamination Plumes Around an Urban Solid Waste Dumpsite Using Two-Dimensional Electrical Resistivity Tomography: A Case Study of Tukur-Tukur, Zaria, Nigeria

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ABSTRACT
Uncontrolled open dumpsites in peri-urban environments generate leachate that poses a persistent threat to shallow groundwater in Basement Complex terrain. This study delineates subsurface leachate plume distribution and the extent of groundwater contamination at the Tukur-Tukur dumpsite, Zaria, Kaduna State, Nigeria, using two-dimensional electrical resistivity tomography (2D-ERT). Eight 200-metre survey profiles were acquired using the ABEM LUND Imaging System with Schlumberger electrode configuration. Apparent resistivity data were inverted using RES2DINV software and correlated with borehole lithological data. The resistivity models resolved a four-layer subsurface consistent with borehole lithology: reddish lateritic clay (0–3 m), brownish sandy granite (3–6 m), weathered/fractured basement (6–36 m), and fresh crystalline basement (>36 m). Low-resistivity anomalies (<100 Ωm) in the uppermost 0–7 m across all profiles indicate pervasive topsoil contamination. Critically, anomalies of 10–80 Ωm at 28–38 m depth in the eastern sector suggest deep aquifer impairment. Root mean square errors ranged from 4.3% to 25.9%. The result indicates that plumes have migrated beyond dumpsite boundaries in all directions, and have reached the principal aquifer horizon. This finding highlights the need for dumpsite engineering upgrades, water quality monitoring, and community health protective measures.

Keywords: Electrical Resistivity Tomography; Groundwater contamination; Leachate plume; Nigeria; Schlumberger array; Solid waste; Zaria

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INTRODUCTION

The global surge in urban solid waste generation, driven by population growth and accelerating urbanisation, has created severe environmental challenges in sub-Saharan Africa (Amuda *et al*., 2014). In Nigeria, inadequate waste management infrastructure has led to the proliferation of uncontrolled open dumpsites within and adjacent to residential communities (Adejobi and Olorunnimbe, 2012). These facilities lack engineered liners or leachate collection systems, functioning as persistent point-sources of groundwater contamination through uncontrolled leachate dispersal—a complex liquid carrying dissolved heavy metals, chlorides, organic compounds, and pathogens (Carpenter *et al*., 2012).

Groundwater provides the primary potable water supply for millions of peri-urban Nigerians, yet the integrity of this resource is increasingly compromised by leachate infiltration in Basement Complex terrain, where weathered and fractured zones form preferential contaminant migration pathways (Jatau *et al*., 2006; Afuwai, 2013). Electrical Resistivity

Tomography (ERT) exploits the markedly reduced resistivity of leachate-saturated zones relative to uncontaminated formations, producing high-resolution subsurface images that delineate plume geometry, estimate contamination depth, and identify flow pathways non-invasively (Abdullahi *et al*., 2011; Ganiyu, 2015).

Tukur-Tukur ward, Zaria Local Government Area hosts a large uncontrolled dumpsite that has operated for over fifteen years without engineering containment. Residents report organoleptic changes in groundwater from adjacent wells and boreholes, yet no geophysical investigation of this specific site has previously been published. This study addresses that gap using 2D-ERT to: (i) map the spatial distribution and depth extent of leachate plumes; (ii) characterise subsurface geo-electrical stratigraphy; and (iii) identify zones of suspected aquifer impairment, thereby providing a scientific basis for remediation planning and public health policy.

MATERIALS AND METHODS

Geological Setting And Hydrogeological Context

Geographic Location

Coordinates: N 11°5′15″, E 7°40′47″ Elevation: 657 meters above sea level (m a.s.l.) Context: Located in Tukur-Tukur, north-central Nigeria (Figure 1).

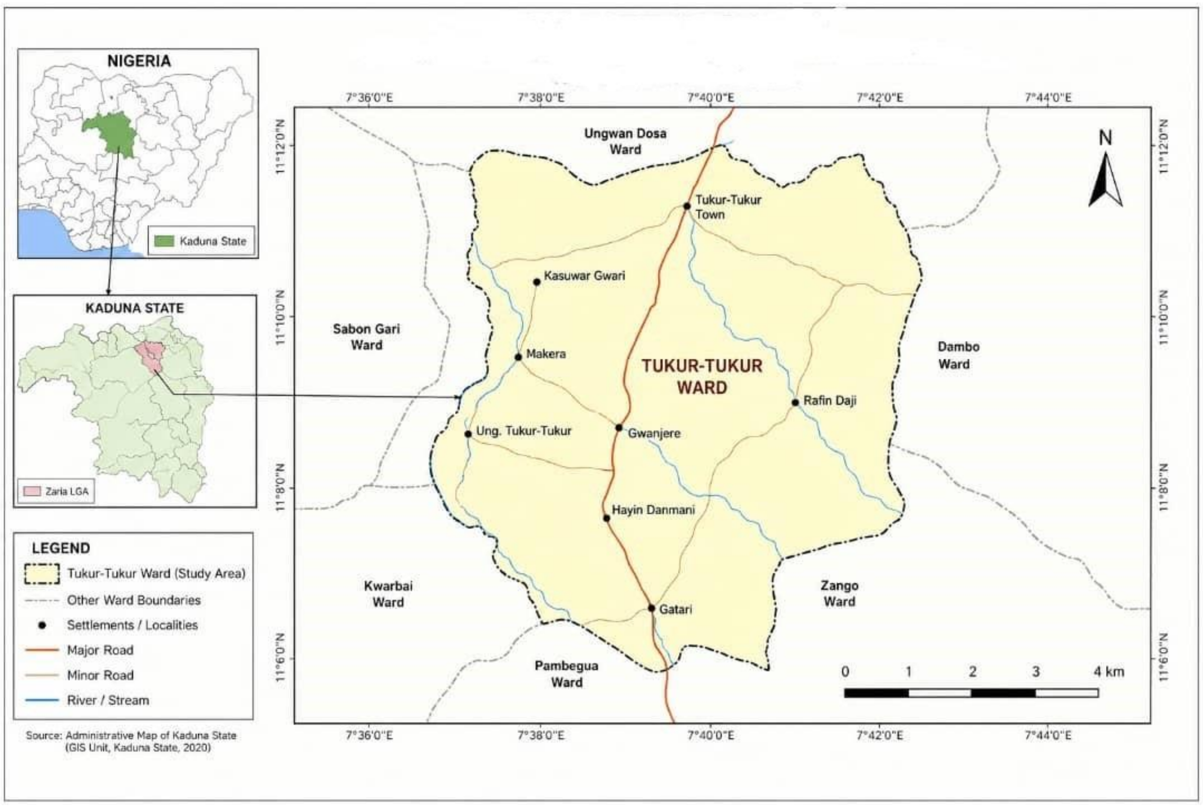

Figure 1: Map of the study area showing Tukur-Tukur ward, Zaria LGA, Kaduna State and Nigeria

Climate

Type: Semi-arid climate. Characteristics: Rainfall is concentrated between May and October, which generates sustained dumpsite saturation and leachate production during the wet season.

Soils

Characteristics: Tropical chemical weathering has developed a characteristic profile featuring a reddish lateritic clay top layer (0–3 m). Properties: The overburden consists of permeable laterite, which, combined with shallow water tables (<10 m), renders the underlying aquifers highly vulnerable to surface-derived contamination.

Geology and Hydrogeology

Geology

Underlain by the Precambrian Basement Complex of north-central Nigeria, specifically migmatites, biotite gneisses, and granitic gneisses of the Migmatite-Gneiss Complex. The weathering profile includes: Reddish lateritic clay (0–3 m) Brownish sandy granite (3–6 m)

Fractured and weathered old granite (6–36 m) Fresh crystalline basement (>36 m)

Hydrogeology

The primary aquifers are formed within the weathered saprolite (brownish sandy granite and fractured/weathered old granite) and fractured basement horizons, which provide the secondary porosity. These aquifers are accessed by hand-dug wells and shallow boreholes. The water tables are shallow (<10 m), making them highly susceptible to contamination.

Survey Design

Eight 200-metre 2D-ERT profiles were deployed around the dumpsite perimeter and interior: Profiles 1–2 (north-western sector, W–N orientation); Profiles 3–4 (southern sector, W–E); Profiles 5–6 (eastern sector); and Profiles 7–8 (northern sector and dumpsite interior). Profile spacing was 30–50 m. Electrode spacing was 5 m throughout, providing investigation depths up to approximately 40 m.

Instrumentation

Data were acquired using the ABEM LUND Imaging System: a Terrameter SAS 4000 resistivity meter and ES 464 multi-channel relay matrix electrode selector. The Schlumberger array was selected for its reduced sensitivity to lateral resistivity variations, efficient field operation, and well-documented performance in Nigerian dumpsite investigations (Abdullahi *et al*., 2011). Four collinear electrodes were deployed with outer current electrodes (AB) and inner potential electrodes (MN) maintained at less than one-fifth AB separation. Stainless steel electrodes, cable jumpers, and an external 12 V power supply completed the setup.

Data Processing and 2D Inversion

Apparent resistivity data were converted from native .s4k format to RES2DINV-compatible .dat format using SAS 4000 Utilities software. Outlier 'bad data points' were identified by visual inspection of profile plots and removed manually. Two-dimensional inversion was performed using RES2DINV (Loke and arker, 1996). The standard least-squares L2 norm inversion was applied as the primary algorithm; robust L1 norm inversion was applied where outlier data were present Inversion iterated until RMS error convergence below 5% or stabilisation between iterations, achieved within three iterations for all profiles. Inverted models were correlated with NWRI (2000) borehole lithology.

RESULTS

Profile 1 (RMS 7.6%) revealed low-resistivity zones (<50 Ωm) at 0–6 m depth, interpreted as leachate-contaminated topsoil, with fresh basement (>2,500 Ωm) at depth and fracture-related colour transitions in intermediate zones. Profile 2 (RMS 19.8%) showed persistent low-resistivity (<100 Ωm) contamination extending to 3 m, 30 m from the dumpsite boundary, confirming plume migration beyond the waste footprint.

Profiles 3 and 4 (southern sector) identified a critically low resistivity zone (~25 Ωm) at 55–80 m distance and 6.3–18.5 m depth in Profile 4, interpreted as a contaminated aquifer. Widespread lateritic clay (~200 Ωm) appears to partially retard downward plume migration. Profiles 5 and 6 (eastern sector) revealed pervasive low-resistivity zones (<100 Ωm) across nearly the full 200 m length at 1.25–8 m depth. Critically, approximately 10 Ωm at 34 m depth (Profile 5) and ~80 Ωm at 28–38 m depth (Profile 6) indicates suspected deep aquifer contamination approaching the principal groundwater horizon. Profiles 7 and 8 confirmed topsoil contamination across the northern sector and dumpsite interior, with the simplified two-layer model of Profile 8 (contaminated overburden over fresh basement) reflecting the excavated nature of the site.

Table 1. Summary of ERT profile parameters and RMS inversion errors

Profile	Orientation	Location	RMS Error (%)
1	W–N	North-western	7.6
2	W–N	North-western +30 m	19.8
3	W–E	Southern	16.7
4	W–E	Southern (parallel)	25.9
5	S–N	Eastern	9.3
6	W–E	Eastern (parallel)	10.8
7	WN–SE	Northern	4.3
8	WN–SE	Dumpsite interior	4.4

DISCUSSION

The 2D-ERT results provide compelling evidence of widespread leachate-induced contamination that has migrated substantially beyond the Tukur-Tukur dumpsite boundaries in all directions. Low-resistivity anomalies in the shallow subsurface (<100 Ωm at 0–7 m depth, all profiles) reflect leachate-induced ionic enrichment of pore fluids, particularly elevated chloride and dissolved metals typical of mixed municipal waste leachate (Carpenter *et al*., 2012; Eugeniusz, 2016). The detection of deep anomalies (10–80 Ωm at 28–38 m) in Profiles 5 and 6 is the most critical finding: it implies that leachate has penetrated to the weathered/fractured basement aquifer horizon supplying residential wells.

Fractures identified by resistivity colour transitions in Profiles 1, 7, and 8 likely provide preferential vertical migration pathways, bypassing the partial protection offered by clay-rich horizons (Mike, 2014). The excavated dumpsite interior (Profile 8) eliminates natural overburden filtration, maximising leachate–basement contact. Comparable findings of dumpsite plumes reaching principal aquifer horizons in Basement Complex terrain have been reported by Abdullahi *et al*. (2011) at Kaduna North, Ekeocha (2012) in Rivers State, and Mike (2014) at Gonin-Gora, Kaduna, all emphasising the urgent need for engineering intervention and comprehensive water quality monitoring in affected communities.

The most critical finding of this study is the identification of deep low-resistivity anomalies (10–80 Ωm) at depths of 28–38 m in Profiles 5 and 6 (eastern sector). These depths correspond to the weathered/fractured basement aquifer horizon documented by Jatau *et al*. (2013), which constitutes the primary shallow groundwater resource accessed by local boreholes and hand-dug wells. The presence of such anomalies strongly suggests that leachate has not only migrated vertically through the unsaturated zone but has also penetrated the saturated zone, impairing aquifer quality. This observation is particularly alarming given that the water table in the area is typically less than 10 m, indicating rapid vertical transport and limited natural attenuation capacity (Jatau & Ajodo, 2006).

Fracture-controlled vertical migration pathways are evident from resistivity colour transitions observed in Profiles 1, 7, and 8. These fractures, likely associated with basement tectonics, bypass the relatively low-permeability lateritic clay horizons (∼200 Ωm) that might otherwise retard leachate movement (Mike, 2014). The excavated nature of the dumpsite interior (Profile 8), which shows a simplified two-layer model, further exacerbates vulnerability by eliminating the protective lateritic overburden entirely. Similar fracture-enhanced leachate migration has been documented in other Basement Complex settings in sub-Saharan Africa, including Kaduna North (Abdullahi *et al*., 2011) and southern Ghana (Patrick, 2015), reinforcing the argument that open dumpsites in fractured crystalline terrain pose disproportionately high groundwater risks.

The variable RMS inversion errors (4.3% to 25.9%) merit discussion. Profiles 7 and 8 (RMS <5%) produced high-confidence models, while Profile 4 (RMS 25.9%) exhibited poorer data fit, likely attributable to lateral resistivity heterogeneity near the dumpsite–background interface or to electromagnetic coupling effects. However, the L1 norm robust inversion applied to noisier profiles improves resistance to outlier data points (Loke & Dahlin, 2003), and the consistency of low-resistivity patterns across multiple profiles strengthens the overall interpretation (deGroot-Hedlin and onstable, 1990).

From a public health perspective, the delineation of deep contamination in the eastern sector raises immediate concerns. Residents report organoleptic changes (taste, odour) in groundwater from adjacent wells, consistent with leachate intrusion. Without hydrogeochemical confirmation, however, the precise contaminants hether heavy metals (e.g., Pb, Cd, Cr), nitrates, or microbial pathogens—remain unknown. Comparable studies at closed landfills in southwestern Ontario and Warsaw, Poland, have shown that low resistivity (<30 Ωm) in aquifer zones often correlates with elevated total dissolved solids and ammonium concentrations, both of which pose chronic health risks (Siddharth, 2013; Eugeniusz, 2016). Long-term exposure to leachate-contaminated groundwater can lead to gastrointestinal diseases, neurological disorders, and heavy metal toxicity, particularly in children and pregnant women. While 2D-ERT provides high lateral resolution, it cannot fully resolve three-dimensional plume geometry without data from multiple azimuths. The absence of direct hydrogeochemical sampling (e.g., borehole water analysis for pH, EC, heavy metals, coliforms) means that the resistivity anomalies are interpreted proxies rather than confirmed contaminants. Furthermore, the reliance on NWRI (2000) borehole lithology—over two decades old—may not capture recent weathering or anthropogenic alterations to subsurface stratigraphy.

To address these limitations, an integrated approach is urgently required. First, 3D-ERT and induced polarisation (IP) methods should be deployed to better resolve plume geometry and to differentiate leachate plumes from clay-rich lithologies (Gideon, 2019). Second, a comprehensive hydrogeochemical sampling programme targeting boreholes and wells along and beyond the transects is necessary to validate resistivity interpretations and quantify contaminant concentrations against WHO (2022) drinking water guidelines. Third, time-lapse ERT monitoring during and after wet seasons would illuminate seasonal plume dynamics and recharge-controlled dilution effects. Fourth, a community-based health survey should assess potential exposure pathways and inform targeted interventions.

CONCLUSION

Eight 2D-ERT profiles at the Tukur-Tukur dumpsite resolved a four-layer Basement Complex stratigraphy and mapped extensive leachate contamination plumes extending beyond the dumpsite footprint. Shallow topsoil contamination is pervasive; deep aquifer impairment is evidenced in the eastern sector. These findings underscore the urgent need for: dumpsite engineering upgrade with leachate containment; mandatory hydro-geochemical monitoring of adjacent water points; community health education; and integration of 3D-ERT and induced polarisation methods for refined plume characterisation. The study validates 2D-ERT as a powerful, cost-effective tool for groundwater contamination assessment in Basement Complex terrain of sub-Saharan Africa. This study reaffirms that 2D-ERT is a cost-effective, non-invasive screening tool for groundwater contamination assessment in data-sparse peri-urban environments of sub-Saharan Africa. However, its maximal utility is realised when integrated with hydrogeochemical and hydrological data. Given the proliferation of uncontrolled dumpsites across Nigerian cities—from Lagos to Kano—the methodological framework demonstrated here offers a replicable model for environmental risk assessment and prioritisation of remediation investments

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