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Mapping leachate migration and groundwater risk in Port Harcourt: geoelectrical insights from ten open dumpsites

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Abstract

Dumpsite-induced groundwater contamination remains a pressing environmental and public health issue in urban and peri-urban areas of Nigeria. Leachate infiltration from poorly managed waste disposal sites poses severe threats to aquifer integrity and potable water safety. Given the rapid urban expansion and lack of engineered landfill systems, there is an urgent need to evaluate subsurface pollution patterns using non-invasive geophysical techniques. This study aimed to delineate leachate migration patterns and assess the vulnerability of groundwater resources in the vicinity of selected dumpsites within the Port Harcourt metropolis using electrical resistivity methods. It further sought to compare the extent of subsurface contamination across multiple locations and provide scientific justification for sustainable waste and water resource management. A total of ten dumpsites (Eliozu, Rumuolumeni, Choba, Eneka, Rumepirikom, Rumuagholu, Sasun, Oyigbo, Rumuola, and Eleme) were investigated using Vertical Electrical Sounding (VES) and 2D Electrical Resistivity Tomography (ERT). Schlumberger electrode configurations were employed to generate pseudo-sections and resistivity inversion models. Data interpretation focused on identifying zones of low resistivity associated with leachate-impacted layers. These geophysical outputs were correlated with established hydrological models and previous studies on dumpsite-induced contamination. The geoelectric models revealed varying degrees of subsurface contamination across all sites. Low resistivity zones (as low as 0.3–6.84 Ωm) were identified at shallow to intermediate depths (1–20 m), confirming leachate infiltration into sandy and clayey formations. Sites like Rumuola and Eliozu exhibited deep contamination profiles, reaching 24 m and 20 m, respectively. In contrast, Oyigbo and Rumuolumeni showed shallower contamination (2–6 m), indicating either newer waste deposits or more resistive soil matrices. High resistivity layers (>1000 Ωm), interpreted as potential aquifers, were generally found at depths exceeding 14 m, often beneath the contaminated zones. The findings confirm the widespread vertical and lateral migration of leachate plumes from open dumpsites into the subsurface, threatening the integrity of underlying aquifers. Electrical resistivity profiling proved effective in identifying contamination hotspots and mapping pollution pathways. The spatial heterogeneity in leachate penetration highlights the role of local geology and hydrology in influencing contaminant behavior. Based on the findings, it is recommended that immediate remediation efforts be prioritized at dumpsites with deeper leachate infiltration, such as Rumuola and Eliozu, through the installation of engineered liners and leachate recovery systems to curb further contamination. Borehole drilling for potable water should be strategically planned to avoid vulnerable zones, targeting deeper, uncontaminated aquifer layers. Government and environmental agencies should institutionalize routine groundwater monitoring in communities surrounding dumpsites to detect early signs of pollution. Additionally, transitioning from open dumping to sanitary landfilling with appropriate environmental safeguards must be enforced through updated waste management policies, supported by public awareness campaigns and infrastructure investments aimed at sustainable waste disposal practices. The presence of leachate-impacted zones within shallow aquifers poses serious risks for public health, including exposure to toxic metals, pathogens, and organic pollutants. Consumption of groundwater from these zones can lead to chronic illnesses, reproductive disorders, and developmental toxicity. Protecting groundwater in waste-impacted areas is therefore a critical component of environmental health policy.

Keywords: Geoelectrical Profiling; Groundwater Contamination; Resistivity Tomography; Leachate; Schlumberger Array; Aquifer Protection; Sanitary Landfills; Waste Management; Environmental Health; Port Harcourt; Nigeria

Abbreviations: ANOVA, Analysis of Variance; APHA, American Public Health Association; BOD, Biochemical Oxygen Demand; COD, Chemical Oxygen Demand; EC, Electrical Conductivity; E. coli, Escherichia coli; EIA, Environmental Impact Assessment; ERT, Electrical Resistivity Tomography; Fe, Iron (chemical symbol); GPS, Global Positioning System; HDPE, High-Density Polyethylene; HSD, Honestly Significant Difference (as in Tukey's HSD test); IDW, Inverse Distance Weighting; ISO, International Organization for Standardization; ISO/IEC, International

Organization for Standardization / International Electrotechnical Commission; L, Litre; M, Meter(s), mg/L, Milligrams per Litre; Mn, Manganese (chemical symbol); MSW, Municipal Solid Waste, NDDC, Niger Delta Development Commission; NESREA, National Environmental Standards and Regulations Enforcement Agency (Nigeria); NIST, National Institute of Standards and Technology; NSDWQ, Nigerian Standard for Drinking Water Quality; Pb, Lead (chemical symbol); PCA, Principal Component Analysis; QA/QC, Quality Assurance / Quality Control; RPD, Relative Percent Difference; RMS, Root Mean Square; SDG, Sustainable Development Goal; SPSS, Statistical Package for the Social Sciences; SRM, Standard Reference Material (NIST); TDS, Total Dissolved Solids; USEPA, United States Environmental Protection Agency; VES, Vertical Electrical Sounding; WGS84, World Geodetic System 1984; WHO, World Health Organization; WQ, Water Quality Index; Zn, Zinc (chemical symbol); Ωm, Ohm-meter (unit of electrical resistivity)

Introduction

Port Harcourt's uncontrolled urban and industrial development in recent decades has spurred economic activity at a significant cost. Now, unregulated dumpsites pockmark the landscape, in most instances within meters of homes. These dumpsites leach toxins that endanger groundwater, the lifeline of the local populations that rely on boreholes and wells. Rather obviously, investigating how far these toxins penetrate underground can no longer be discretionary. Groundwater energizes daily life in Port Harcourt. Over 60 % of Nigerians depend on it, and dependence is possibly higher here due to its shallow Niger Delta aquifers.[1–10] However, studies say borehole water near dumpsites contains heavy metals i.e., cadmium, lead, zinc, iron, copper, as well as nutrients and elevated electrical conductivity, all exceeding WHO and Nigerian standards.[11–15] That contamination endangers human health and ecosystem balance.[16–18] Research confirms those suspicions. Eseyin and Osu[19] measured physicochemical parameters around Port Harcourt dumpsites and noted that pollutants, i.e., TDS, BOD, COD, EC, nutrients, and heavy metals, attenuate with distance from the dump, yet remain above safety levels in the adjacent boreholes. Nwachukwu et al.[20] added spatial nuance: lead slightly exceeded standards at 50 m and 100 m from the Aluu dumpsite, even though overall water quality remained "good to very good" hinting at a distance-based contamination gradient without examining depth. Amadi et al.[21] took a step deeper, sampling groundwater at 10 m below Mbodo-Aluu and found acidic pH (~4.2), elevated nitrate (56 mg/L), and high cadmium (0.86 mg/L), nickel (0.42 mg/L), and lead (0.017 mg/L). That clearly shows downward leachate movement.

Yet as with other studies, the sampling lacks systematic depth profiling across layers. Knowing the depth of contamination matters when designing boreholes and mapping risk. Oyelami et al.[22] added radiometric data. Their leachate samples from dumpsites showed heavy metals (Fe, Cu, Cd, Pb, Cr, Zn, Ni) well above WHO limits and some radioactive isotopes. They warned of risk to groundwater and surface water, yet they didn't sample boreholes at multiple depths. Alaye et al.[23] examined seasonal variation. In rainy versus dry season, they found Fe, Cu, Mn, Pb, As, Ni above NSDWQ in boreholes near dumpsites. Health risk assessment flagged elevated Pb risk for females, As risk for children in rainy season. But again, no depth variation was captured. These findings resonate with studies from other polluted areas of Nigeria, like Osun and Bayelsa States. Raimi et al.[1] and Awogbami et al.[24] demonstrated how hydrocarbon contamination, industrial waste, and artisanal mining raise toxic metal concentrations in surface and groundwater, increasing health risks for local populations. In a related context, Clinton-Ezekwe et al.[7] documented significant heavy metal contamination in Mgbede oil fields, showing a clear link between pollution sources and water quality degradation. These works emphasize that leachate pollution is often not only chemical but biological, posing dual threats through heavy metals and pathogenic microbes. Moreover, the Niger Delta's unique hydrogeology and seasonal hydrodynamics influence pollutant transport pathways. Raimi et al.,[1,14] Morufu et al.,[8,9,10] Olalekan et al.[15] and Fubara et al.,[25,26,27] Evans et al.[28] revealed that contaminant mobility, biogeochemical transformations, and aquifer vulnerability vary markedly between rainy and dry seasons. Their use of geostatistics and multivariate techniques further highlights the complexity of tracing pollution sources and predicting exposure risks.

Despite these advances, most assessments overlook vertical stratification, an omission that hampers effective borehole siting and protection strategies. All these works underscore the problem: dumpsites raise groundwater contamination, especially with heavy metals. As they link to SDG 6 (safe water) and SDG 11 (sustainable urban infrastructure). However, they share a critical gap, nearly all focus on shallow sampling or single-depth points, without revealing how deep contaminants penetrate. That matters if your borehole reaches deeper aquifers. While, it is still debatable how contaminants distribute vertically beneath dumpsites in Port Harcourt. Seasonal trends, depth gradients, and complex pollutant mixes (heavy metals, pathogens, and organics) remain unexplored. This study fills that gap by collecting groundwater samples at multiple depths across several dumpsites, profiling key contaminants, comparing with WHO/NSDWQ guidelines, and analyzing horizontal and vertical spread. That will support SDG 6 by targeting clean water sources and SDG 11 by informing safer urban waste-water management. Thus, this study aims to assess how contaminants vary with depth in groundwater beneath selected dumpsites in Port Harcourt. It focuses on measuring heavy metals like lead, cadmium, and mercury, microbial pathogens such as *E. coli*, and organic pollutants including hydrocarbons. By sampling groundwater at multiple depths, the research will evaluate how contaminants spread horizontally and vertically in relation to dumpsite proximity and local hydrogeology. Overall, the study seeks to generate evidence that can support improved groundwater protection under Sustainable Development Goals 6 and 11, which call for safe water access and more sustainable urban waste practices.

Materials and methods

Study design

This study adopted a quasi-experimental research design to evaluate the impact of municipal solid waste dumpsites on groundwater quality across Port Harcourt, Nigeria. The design enabled the comparison of groundwater conditions at varying distances from each dumpsite, thereby providing insights into vertical and lateral leachate migration. Investigations were carried out during both rainy and dry seasons to understand seasonal dynamics in contaminant dispersal. Each site was assessed using both geophysical resistivity surveying and physicochemical/microbiological water analyses.

Study area and sampling sites

The study was conducted across ten active municipal dumpsites and two supplementary locations in Port Harcourt and its environs, including Eliozu, Rumuolumeni, Choba, Eneka, Rumepirikom, Rumuagholu, Sasun (Trans-Amadi), Oyigbo, and Eleme (Figure 1). Three boreholes were selected per site at radial distances of 200m, 400m, and 600m from the dumpsites to evaluate spatial variation in groundwater contamination. Each location was geo-referenced using a Garmin GPSMAP 64s, ensuring ±3m spatial accuracy. The sites were underlain predominantly by the Benin Formation, a high-permeability aquifer system that heightens vulnerability to surface contaminants.

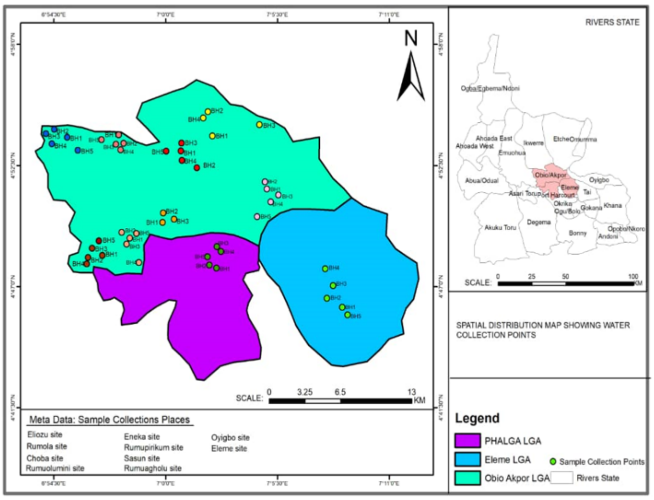

Figure 1 Map of the study Area showing Sampling Locations.

Geophysical survey

To assess subsurface conditions, Vertical Electrical Sounding (VES) using the Schlumberger array configuration was performed. A total of 10 VES points were executed at each site. The ABEM SAS 300B Terrameter was used with stainless steel electrodes, and measurements were taken at increasing electrode spacings (up to 100m) to profile resistivity changes with depth. This technique enabled the detection of leachate plumes based on their characteristic low resistivity signatures in comparison to background geological formations. Control VES points were also conducted at 200m and 400m distances from each dumpsite for baseline comparison.

Hydrogeological and environmental context

The region experiences high annual rainfall (>2500mm), low relief (<20m above sea level), and a shallow water table (<10m), creating conditions conducive to contaminant percolation. Soil types ranged from sandy loams to poorly drained clayey alluvium, influencing the degree of percolation and runoff. Vegetation included remnants of rainforest, freshwater swamps, and oil palm plantations, with drainage systems discharging into the Bonny and New Calabar Rivers.[29]

Data collection

Site selection

A stratified random method was used to select ten functional dumpsites based on size, waste volume, and surrounding well density, following criteria used in similar hydrogeological risk assessments.[30] At each site, three sampling points were positioned radially at 200 m, 400 m, and 600 m.

Field sampling procedure

Pre-sampling:

Sampling bottles (HDPE for metal ions, borosilicate for organics) were acid-washed with 10% HNO_3, then rinsed three times with 18.2 MΩcm deionized water to eliminate residual ions.[31] Wells were purged using a stainless-steel bailer for 3-5 volumes to flush out stagnant water.

Sample collection and preservation:

I. *Physicochemical parameters*: Water was collected in 1 L HDPE containers. In-situ pH and EC measurements were performed immediately using a Hach HQ40D multiprobe calibrated before each field campaign.

II. *Heavy metals*: Water samples were acidified with ultrapure HNO_3 to pH <2 to stabilize analytes and prevent wall adsorption.[31]

III. *Microbiological samples*: Collected in pre-sterilized bottles containing sodium thiosulfate to neutralize residual chlorine, then stored on ice (4 °C) and analyzed within 6 hours of collection.[32]

Geolocation:

All sampling sites were georeferenced using a Garmin GPSMAP 64s (±3 m accuracy, WGS84 datum). Elevation data were logged to assess topographic influences on groundwater flow and potential leachate pathways.[33]

Secondary data sources

Reviewed hydrogeological studies relevant to the Niger Delta region was conducted to obtained baseline data from the Rivers State Ministry of Environment, and accessed archived reports on water quality and land use provided by the Niger Delta Development Commission (NDDC).

Laboratory analysis

All analytical procedures adhered to standard methods outlined by the American Public Health Association[31] and were conducted in ISO/IEC 17025-accredited laboratories.

Physicochemical Parameters

I. **pH and EC**: Measured using calibrated electrometric probes (Hanna HI98107) and standardized buffer solutions (pH 4.01, 7.01, 10.01).

II. **TDS**: Determined gravimetrically after evaporating filtered samples at 180 °C (APHA Method 2540C).

III. **Heavy metals (Pb, Fe, Mn, Cu, Zn)**: Quantified via Flame Atomic Absorption Spectrophotometry (PerkinElmer PinAAcle 900T), with detection limits ranging from 0.01–0.1 mg/L. Quality assurance was ensured using NIST-certified reference material SRM 1643e, with acceptable recovery between 92–107% (*ISO 17294-2:2016*).

Microbial parameters

Escherichia coli counts were assessed using membrane filtration (0.45 µm cellulose acetate filters) on m-FC agar, incubated at 44.5 °C for 24 h, in line with *APHA Method 9222B* and WHO microbial water quality guidelines.[32]

QA/QC Measures

I. **Field blanks**: Comprised 10% of the total sample pool, confirming minimal cross-contamination.

II. **Replicates**: Duplicate samples were processed in parallel, showing <5% RPD.

III. **Instrument calibration**: Carried out after every 10 samples, using multi-point calibration curves ($R^2 \geq 0.999$).

Statistical methods

Statistical analysis, including ANOVA and Tukey's HSD, was conducted using SPSS v26 to test differences in contaminant levels by distance and season. Principal Component Analysis (PCA) was done in R (v4.3.1) to identify major pollution sources. Spatial interpolation using Inverse Distance Weighting (IDW) in ArcGIS 10.8 produced contamination maps and vulnerability heatmaps. Moran's I was computed in QGIS v3.28 to evaluate spatial autocorrelation.

Geospatial analysis

I. Spatial interpolation was performed using Inverse Distance Weighting (IDW) in ArcGIS 10.8 to model contaminant plumes.

II. Buffer analyses determined the extent of zones exceeding WHO guideline thresholds.[32]

III. Moran's I statistic was computed to test spatial autocorrelation using QGIS v3.28.

Software

I. SPSS v26: Inferential statistics.

II. R v4.3.1: Principal Component Analysis (PCA) to identify source patterns.

III. QGIS v3.28: Spatial visualization and autocorrelation analysis.

Ethical considerations

Field blanks and duplicate samples (10%) were used to ensure accuracy, and all instruments were calibrated using multi-point standard curves ($R^2 > 0.99$). All field activities adhered to the Nigeria Standard for Drinking Water Quality (NSDWQ, 2007) and WHO guidelines. Ethical consent was obtained verbally from all well owners prior to sampling. This integrated methodology effectively addressed the study's objectives: characterizing vertical/lateral leachate migration, seasonal contaminant variations, spatial vulnerability, and comparing resistivity-based geophysical profiles with hydrochemical evidence.

Results

The resistivity profile presented in Figure 2 depicts a geophysical survey result conducted at the Eliozu dumpsite, aimed at assessing the extent of subsurface contamination. The curve indicates a three-layer stratification, consistent with an H-type resistivity pattern, where a conductive middle layer is sandwiched between two more resistive layers. The topmost layer, with a moderate resistivity of 10.4 Ωm, likely represents lateritic soil, which may have been partially affected by surface-level contamination. The sharp decrease in resistivity to 0.443 Ωm in the second layer strongly suggests significant infiltration of conductive fluids, most plausibly leachate from the dumpsite into a sandy-clay matrix. This layer, extending from approximately 2.4 m to 20 m in depth, indicates the zone most impacted by subsurface pollution. The third layer reveals a substantial increase in resistivity to 1047 Ωm, indicating a transition to a more competent and likely impermeable geological unit such as basement rock or consolidated sandstone, effectively halting the downward migration of contaminants. This geophysical evidence underscores the need for urgent environmental management at the dumpsite, especially since the leachate plume has penetrated a considerable depth, potentially threatening nearby shallow groundwater resources. The data not only provides a basis for targeted remediation but also serves as a model for similar landfill investigations where assessing vertical contamination spread is essential for protecting human health and groundwater integrity.

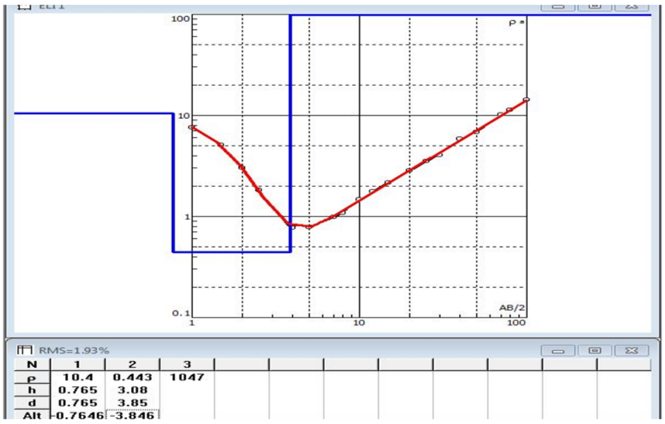

Figure 2 VES of Eliozu Dumpsite Researcher's analysis 2020.

Figure 3 presents both the pseudo and interpreted resistivity cross-sections for the Eliozu dumpsite, surveyed during the rainy season. The pseudo-section (top) displays apparent resistivity distribution with pronounced low-resistivity anomalies (1.87-2.85 Ωm) extending from approximately 2 m to over 19 m depth, especially towards the western section of the profile. These zones, represented by black and dark blue shades, signify areas with high moisture content or contamination, likely due to the infiltration of leachate over time. The gradational transition into green, yellow, and pink tones toward the eastern portion suggests reduced contamination or different lithological characteristics, with resistivity values gradually increasing up to 43.3 Ωm. The resistivity cross-section (bottom) reveals a more resolved subsurface interpretation composed of discrete geoelectric layers. A thin upper layer in the western part shows extremely low resistivity (0.445 Ωm), indicating heavily saturated or leachate-impacted soil. Beneath this, the resistivity increases significantly (1047–1420 Ωm), suggesting a compact, less permeable formation that likely limits vertical contaminant migration. Toward the eastern flank, intermediate zones (7.47 Ωm, 872 Ωm) suggest partially affected or variably conductive materials, while deeper zones with resistivity exceeding 3000 Ωm may correspond to dry, resistive bedrock or highly consolidated formations. This delineation is vital for understanding the extent and direction of leachate transport, and it provides critical input for groundwater protection strategies and remediation planning at the site.

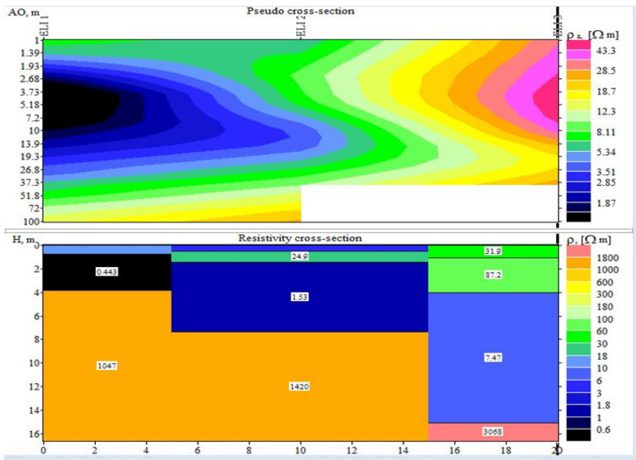

Figure 3 Pseudo section and Resistivity section of Eliozu Dumpsite.

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Figure 4 illustrates the resistivity sounding curve for the Rumuolumeni dumpsite along Profile 1. The curve exhibits an H-type configuration, indicative of a three-layer subsurface structure. The first layer, characterized by a resistivity value of 9.65 Ωm, represents the near-surface material, likely composed of lateritic or sandy soil with minimal contamination. A significant drop in resistivity to 0.49 Ωm is observed in the second layer, extending from approximately 0.67 m to just over 1.7 m depth. This pronounced reduction signals the presence of highly conductive material likely a leachate-saturated zone suggesting substantial infiltration of waste-derived fluids into this shallow subsurface layer. Beneath this, the third layer shows a notable increase in resistivity to 3.57 Ωm, implying a transition into a less contaminated or more consolidated formation. This upward trend indicates that the leachate infiltration is likely confined to the intermediate zone and does not extend significantly deeper. The relatively low RMS error (2.46%) confirms a good fit between the field data and the interpreted model. This geoelectrical characterization is crucial for understanding vertical contaminant migration and highlights the importance of monitoring and mitigating subsurface pollution to protect underlying groundwater resources in the area.

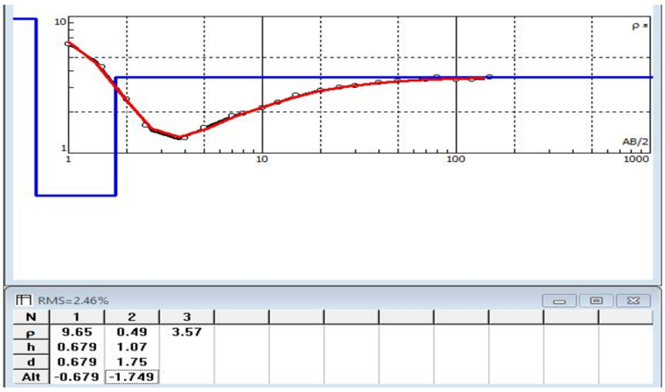

Figure 4 VES Curve of Rumuolumeni Dumpsite.

The Figure 5 below presents the pseudo cross-section and the interpreted resistivity cross-section of the Rumuolumeni dumpsite, providing insights into subsurface resistivity distribution and potential zones of contamination. The pseudo cross-section reveals a low resistivity zone (1.3-3.87 Ωm) occurring between depths of approximately 2.5 m and 10 m, indicative of leachate infiltration from surface waste materials. This accumulation of leachate, which is more pronounced between 14 m and 20 m depths, suggests a downward migration of contaminants, potentially affecting underlying aquifers. These resistivity values are consistent with saturated or polluted zones, underscoring the vulnerability of the subsurface to pollution, especially in areas with shallow groundwater systems. The resistivity cross-section further delineates the geological stratification of the subsurface. The uppermost layer in the rainy and dry seasons has moderate resistivity values (60.2 Ωm and 9.65 Ωm respectively), likely representing contaminated topsoil. A significantly lower resistivity in the second layer (1.6 Ωm and 0.49 Ωm) indicates zones where contaminants have pooled, typically within fine-grained sand layers that can retain leachate. Contrastingly, the third layer in the rainy season exhibits a very high resistivity value (>1000 Ωm), suggesting a clean, coarse sandy formation suitable for groundwater extraction. However, the same layer in the dry season has a resistivity of 3.57 Ωm, implying a possible seasonal shift in saturation or contamination. These findings are critical for environmental monitoring and groundwater management, especially for preventing the spread of pollutants and ensuring the safety of nearby potable water sources.

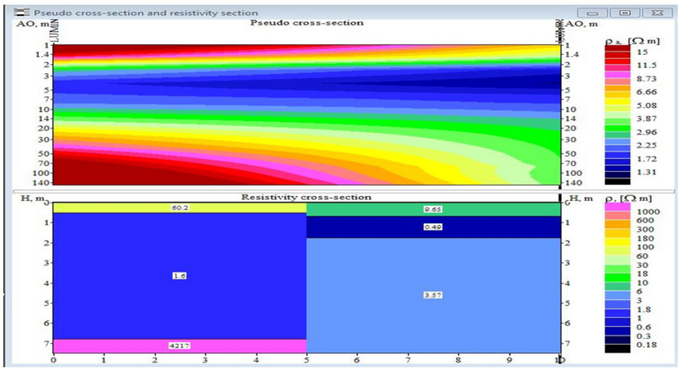

Figure 5 Pseudo/Resistivity section of Rumolumeni Dumpsite.

Figure 6 illustrates a resistivity sounding curve from the Rumuola Dumpsite, showing the characteristic H-type response with three distinct subsurface layers. The first layer, indicated by a relatively high resistivity value of approximately 49.2 Ωm, corresponds to a lateritic topsoil extending to a depth of roughly 4.47 meters. This layer likely represents unsaturated or less-impacted material. The second layer reveals a sharp drop in resistivity to 6.84 Ωm, suggesting the presence of a saturated, leachate-impacted sandy zone that facilitates fluid movement. This zone spans a thickness of about 9.77 meters, reaching depths where contamination is likely concentrated due to percolation. The third layer, with a significantly elevated resistivity of 1122 Ωm, indicates the presence of a more resistive material, such as clean, coarse sand or gravel, which is typical of aquiferous formations. This resistivity rise implies a transition into a more competent, less contaminated layer that may offer potential for groundwater development. However, the depth of this layer, beginning at approximately 14.2 meters, underscores the necessity for proper site assessment before exploitation. The model's low RMS error (1.01%) indicates a good fit between observed and calculated data, enhancing confidence in the interpretation. This geoelectrical signature is crucial for evaluating subsurface integrity and assessing risks to groundwater resources in areas impacted by waste disposal.

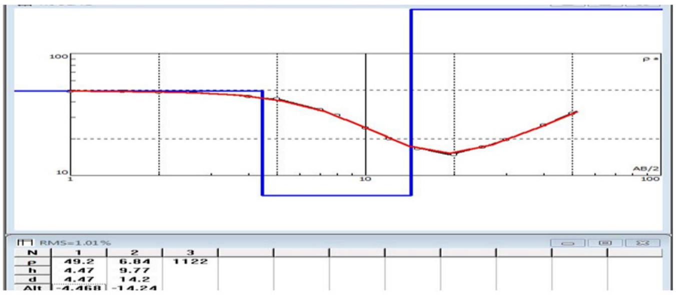

Figure 6 VES Curve of Rumuola Dumpsite.

The Figure 7 illustrates both the pseudo and resistivity cross-sections of the Rumuola borrow pit area, which has been historically used for waste disposal. In the pseudo cross-section, the uppermost zone (approximately 0-3.2 m) exhibits notably low resistivity values ranging between 8.22 Ωm and 10 Ωm, indicative of high moisture content and probable leachate infiltration. A widespread green zone, extending to depths of over 30 m, signifies a permeable sandy formation that likely acts as a conduit for downward contaminant migration. This directional flow pattern aligns with expected subsurface leachate transport influenced by hydrological gradients and the porous nature of the host sediments. In the corresponding resistivity model, a tripartite geologic structure is evident. The surface layer shows moderate resistivity (49.2 Ωm), suggesting lateritic sand with minimal impact from contamination. Beneath this, a lower resistivity zone (6.84 Ωm) marks a leachate-impacted stratum, supporting the interpretation of pollutant accumulation. The final layer, characterized by high resistivity values (1122-1207 Ωm), reflects a dense, coarse sandy deposit, likely functioning as a significant aquifer unit. Its resistivity profile suggests minimal contamination, making it a potential target for clean groundwater extraction. This subsurface characterization is essential for developing appropriate environmental remediation strategies and managing water resource protection in waste-affected areas.

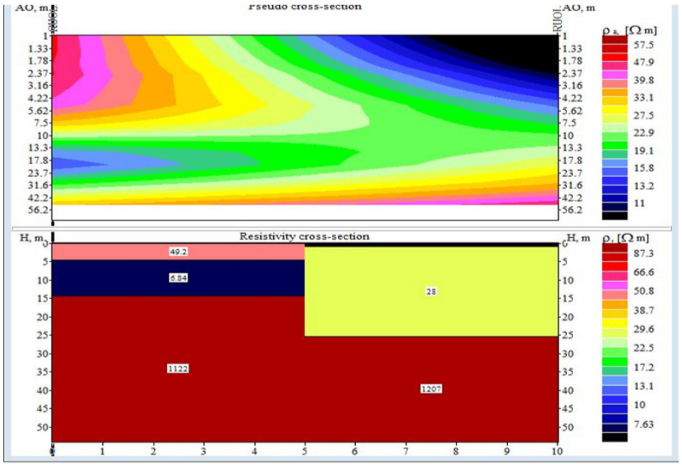

Figure 7 Pseudo section of Rumuola dumpsite.

Figure 8 presents the result of a vertical electrical sounding (VES) survey conducted at the Oyigbo dumpsite, characterized by an H-type resistivity curve. This curve reveals three distinct geoelectric layers, with a significant drop in resistivity observed in the second layer. The topmost layer exhibits moderate resistivity, followed by a markedly low-resistivity layer, indicating the presence of a conductive material. This pattern typically reflects leachate infiltration into subsurface formations, as evidenced by the resistivity drop from 2.39 Ωm to as low as 0.457 Ωm between depths of approximately 1.42 m to 2.15 m. The third layer, however, shows a rebound in resistivity (680 Ωm), suggesting a relatively uncontaminated and more resistive formation below the leachate-impacted zone. The presence of a low-resistivity layer in the subsurface at shallow depth implies potential groundwater contamination due to leachate migration from the dumpsite. Such contamination poses serious health risks to local populations relying on shallow groundwater sources. This VES interpretation is therefore crucial for guiding the planning of waste management interventions, the siting of water boreholes, and the implementation of groundwater protection measures. Moreover, it underscores the importance of geophysical investigations in environmental impact assessments, especially in regions with informal or unregulated waste disposal practices.

The Figure 9 illustrates a pseudo-section and a resistivity cross-section derived from electrical resistivity imaging at the Oyigbo dumpsite. The pseudo-section (top panel) reflects interpolated apparent resistivity values, suggesting a predominantly low-resistivity zone from the near surface to a depth of about 6 meters. This region, dominated by resistivity values typically below 3 Ωm, corresponds to areas of significant electrical conductivity, likely caused by elevated moisture content and ionic concentration due to leachate infiltration. The resistivity cross-section (bottom panel) further refines this interpretation, distinctly showing three layers: a shallow layer with moderate resistivity, an intermediate layer with very low resistivity, and a deeper zone with high resistivity indicative of a more consolidated and potentially uncontaminated formation. These findings highlight the subsurface impact of waste leachate on the geologic profile beneath the dumpsite. The presence of a highly conductive intermediate layer suggests active contamination, raising concerns over the integrity of the subsurface environment, particularly groundwater safety. This stratification emphasizes the necessity for continuous monitoring and possible remediation measures to protect groundwater reserves from further degradation. It also underscores the utility of geophysical methods for environmental risk assessments and the planning of sustainable waste management practices in vulnerable areas.

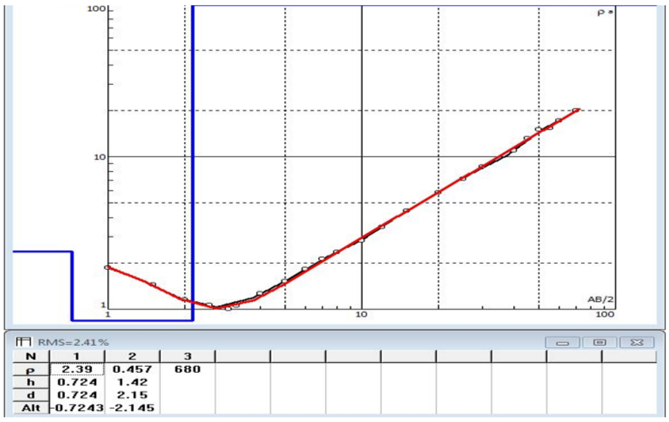

Figure 8 VES of Oyigbo Dumpsite.

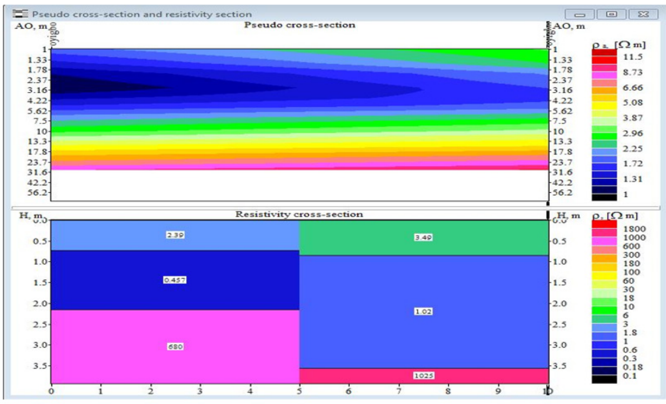

Figure 9 Pseudo/Resistivity- Section of Oyigbo dumpsite.

Figure 10 presents a resistivity model curve for the Eleme dumpsite, highlighting a four-layer geoelectric structure characterized by an HA-type curve. The resistivity profile reveals a shallow, moderately resistive top layer (85.7 Ωm), underlain by a significantly more conductive zone (11.4 Ωm) extending from approximately 1.9 m to 8.1 m depth. This middle layer marks the most conductive part of the profile, with a pronounced resistivity depression that strongly suggests the presence of leachate accumulation and active contamination. Below this zone, there is a sharp and consistent increase in resistivity, rising to 3300 Ωm and eventually 5360 Ωm at greater depths, an indication of a clean, consolidated formation with minimal or no influence from surface pollutants. This resistivity distribution underscores a clear stratigraphic division between the leachate-impacted zone and the underlying uncontaminated geologic units. The identification of the depth interval most affected by contamination is crucial for environmental planning and remediation efforts. It provides actionable insights for groundwater protection, especially in determining safe depths for borehole drilling and designing containment strategies for waste seepage. The distinctly rising resistivity values at deeper levels also reinforce the potential of the lower layers to serve as viable aquifers, provided they remain isolated from the upper contaminated zones.

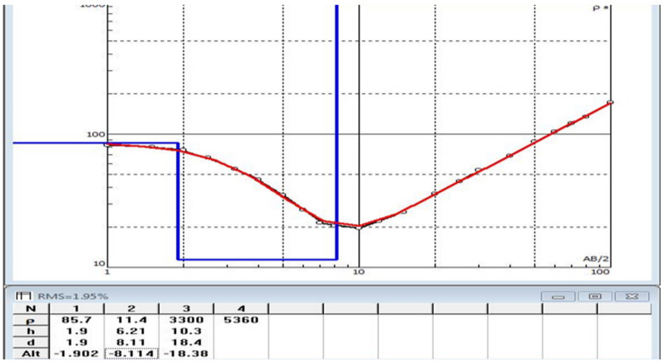

Figure 10 VES of Eleme Dumpsite.

The Figure 11 presents key outputs from a geophysical resistivity survey conducted at the Eleme dumpsite, comprising an apparent resistivity pseudo-section (top) and an interpreted resistivity cross-section (bottom). The pseudo-section visualizes raw resistivity data collected at various depths and lateral positions, using a color gradient to represent resistivity values in ohm-meters (Ω·m). Notably, the pseudo-section reveals a prominent low-resistivity anomaly (blue and green zones) extending from shallow depths to approximately 8 meters. This anomaly corresponds to leachate infiltration, as leachate increases ionic concentration and electrical conductivity in affected soils and groundwater. The interpreted resistivity cross-section refines this data into distinct subsurface layers, highlighting the spatial extent of both contaminated and uncontaminated zones. The intermediate layer, exhibiting very low resistivity values (11.4-15.1 Ω·m), indicates zones impacted by leachate, likely migrating through sandy or clay-rich formations. In contrast, deeper and adjacent zones with significantly higher resistivity values (exceeding 1000 Ω·m, shown in red) are indicative of uncontaminated, consolidated sand or gravel, which may serve as groundwater-bearing formations. This resistivity imaging approach, widely used in environmental and engineering geophysics, is instrumental for site assessments, pollution monitoring, and remediation planning. It enables non-invasive mapping of subsurface conditions, allowing stakeholders to identify contaminant plumes, assess risks to groundwater resources, and inform the development of sustainable waste and water management strategies.

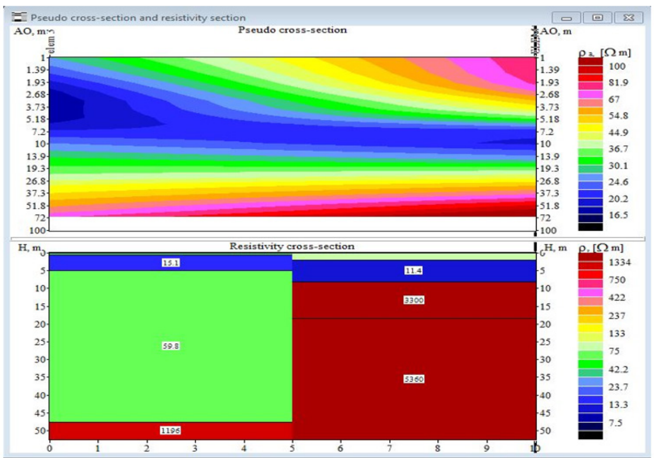

Figure 11 Pseudo/Resistivity- section of Eleme dumpsite.

The Figure 12 presents the vertical electrical resistivity sounding (VES) curve for the Choba Dumpsite, illustrating the variation of apparent resistivity with electrode spacing on a log-log scale. The red curve represents the measured field data, while the blue stepped line indicates the interpreted geoelectric layering. The H-type curve observed is characterized by an initial decrease in resistivity followed by an increase with depth, which is typical in environments where a conductive, contaminated layer is sandwiched between more resistive strata. Additionally, the uppermost zone exhibits moderate resistivity, indicating a slightly contaminated silty-clay surface material. Beneath this, a pronounced low-resistivity layer (approximately 4.49 Ω·m) extends from about 2.3 to 8.35 meters, marking the presence of leachate-impacted, conductive material. At greater depths, the resistivity increases sharply, indicating a transition to consolidated, coarse sand that is likely saturated with relatively uncontaminated groundwater. This stratification is essential for delineating zones of contamination and for informing remediation and groundwater protection efforts in the vicinity of the dumpsite.

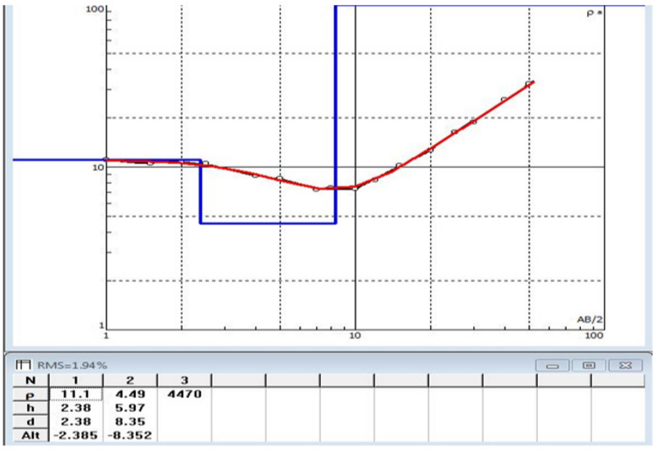

Figure 12 VES of Choba Dumpsite.

Figure 13 displays both a pseudo-section and an interpreted resistivity cross-section for the Choba Dumpsite, offering a clear visualization of subsurface electrical properties. The upper pseudo-section reveals a gradation of resistivity values, with the surface layer exhibiting relatively low resistivity (around 11 Ω·m, indicated by blue shades), consistent with a silty-clay unit affected by contamination. This low-resistivity zone extends from the surface to approximately 0.5 meters, after which an even lower resistivity channel (deep blue) descends to greater depths, highlighting a highly conductive pathway likely associated with significant leachate infiltration and groundwater pollution. In the lower resistivity cross-section, three distinct subsurface layers are delineated. The first layer, with a resistivity of about 11 Ω·m, corresponds to the contaminated silty-clay at the surface. Beneath this, a zone of even lower resistivity (4.45 Ω·m) represents a porous, sandy formation that facilitates the downward migration of contaminants, acting as a conduit for groundwater pollution. The deepest layer, with resistivity values ranging from 59.3 Ω·m up to 4470 Ω·m, is indicative of medium to coarse sand, which is generally suitable for potable water extraction but may still exhibit minor contamination due to total dissolved solids (TDS). The figure underscores the importance of detailed resistivity imaging in identifying critical zones for groundwater protection and guiding remediation strategies at waste disposal sites.

Citation: Abiye T, Ayotamuno A, Ezekwe IC, et al. Mapping leachate migration and groundwater risk in Port Harcourt: geoelectrical insights from ten open dumpsites. *Open Access J Sci.* 2025;8(1):187–201. DOI: 10.15406/oajs.2025.08.00263

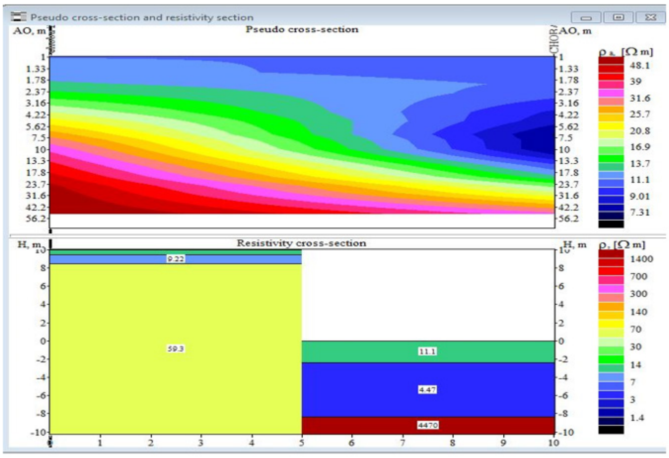

Figure 13 Pseudo/Resistivity- section of Choba dumpsite.

Figure 14 presents resistivity measurements from the Eneka Dumpsite, illustrating a three-layer subsurface formation characterized by an H-curve type. The data reveal a sharp decline in resistivity values from 5.24 Ωm in the topsoil to 1.27 Ωm in the second layer, indicative of leachate infiltration contaminating the subsurface up to a depth of approximately 10 meters. Below this contaminated zone, the third layer exhibits higher resistivity values, suggesting the presence of uncontaminated medium to coarse sand. This layered resistivity profile provides critical insights into the vertical extent of contamination and the underlying geological structure. The findings have significant implications for environmental monitoring and remediation efforts. The abrupt resistivity drop in the second layer serves as a clear marker of leachate migration, highlighting the vulnerability of shallow aquifers to pollution from waste disposal sites. Identifying the uncontaminated third layer is equally important, as it delineates the boundary of contamination and aids in assessing groundwater risks. Such data is essential for designing targeted remediation strategies, such as containment systems or soil treatment, to mitigate further environmental degradation. The study underscores the utility of resistivity surveys in mapping contamination plumes and informing sustainable land-use decisions near waste disposal areas.

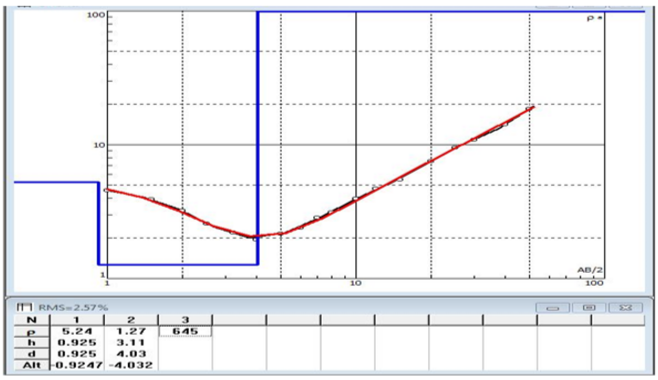

Figure 14 VES of Eneka Dumpsite.

Figure 15 illustrates the geoelectrical interpretation of the Eneka Dumpsite through a pseudo-section and a resistivity cross-section, offering critical insights into subsurface conditions. The pseudo cross-section reveals a progressive reduction in resistivity values from shallow to deeper layers, with contours indicating a transition from relatively resistive zones (above 5 Ωm) near the surface to markedly low resistivity values (as low as 1.27 Ωm) at deeper levels (approximately 14-20 m). These low resistivity zones, primarily depicted in green and blue shades, suggest the infiltration and accumulation of conductive leachate within subsurface strata, an indication of severe contamination possibly extending to the groundwater table. The resistivity cross-section further distinguishes the subsurface into three principal geoelectric layers. The uppermost layer, with moderate resistivity values (4.6–5.24 Ωm), likely represents unsaturated topsoil. The second layer, characterized by significantly reduced resistivity (1.27 Ωm), points to a clayey or sandy formation highly saturated with leachate, corroborating active pollutant transport. Notably, the deepest layer exhibits a sharp resistivity contrast, with values reaching 645 Ωm, suggesting a more consolidated, coarse sand unit with high permeability and potential for groundwater extraction. This profile underscores the environmental risk posed by the dumpsite, particularly the vulnerability of deeper aquifers to contamination, and supports the need for urgent remediation and strategic groundwater monitoring in the area.

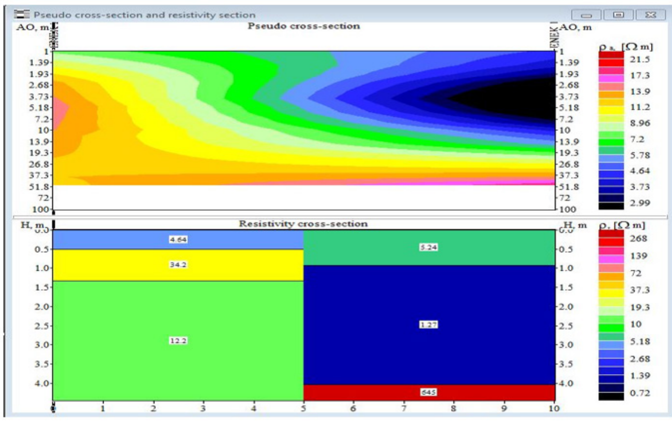

Figure 15 Pseudo/Resistivity- section of Eneka dumpsite.

Figure 16 presents the Vertical Electrical Sounding (VES) curve obtained from the Rumepirikom dumpsite, reflecting the subsurface resistivity variation with depth. The A-type curve progression, characterized by a continuous increase in resistivity, suggests a three-layered subsurface model. Notably, the intermediate layer demonstrates a low resistivity value of approximately 11.6 Ωm, which is indicative of a zone affected by leachate intrusion, likely composed of saturated clay or sandy clay material. This conductive layer lies between 0.5 m and 12.1 m depth, signaling potential environmental risk from surface contaminants percolating into subsurface formations. Beneath this polluted zone, the model reveals a significant increase in resistivity (up to 340 Ωm), suggesting the presence of medium to coarse sand that is likely free of contamination and could serve as a potential aquifer. This contrast in resistivity delineates the transition from a leachate-impacted horizon to a more competent and permeable geological unit. The significance of this data lies in its application for hydrogeological assessments, waste site remediation planning, and groundwater protection strategies. While the current plot effectively communicates the inversion model, its clarity could be improved by redesigning it as a resistivity-depth plot with clearly labeled axes, depth markers, and formation annotations for better interpretability by multidisciplinary stakeholders.

Figure 17 illustrates both the pseudo and resistivity cross-sections of the Rumuepirikom dumpsite, revealing the electrical resistivity distribution of subsurface materials. The pseudo cross-section (top) shows a color gradient indicating resistivity variation with depth and lateral position. A pronounced blue region, extending from near the surface (approximately 1 m) to about 20 m deep, represents zones of low resistivity (0.3–10 Ωm), which strongly suggests the presence of conductive materials, most likely leachate-laden zones within the waste matrix or surrounding soil. The adjacent higher resistivity zones (green to red shades) mark less conductive, potentially drier or unpolluted layers, pointing to differential leachate migration patterns influenced by surface topography or landfill design. The resistivity cross-section (bottom) further distinguishes the subsurface into discrete geoelectrical layers. The uppermost layer, with a very high resistivity value (4700 Ωm), may represent a dry, compacted cover material or resistive fill, possibly unaffected by infiltration. Beneath this lies a moderately resistive layer (247 Ωm), overlying a more conductive zone (9.7 Ωm) that aligns with the suspected leachate-impacted area. The deepest layer, characterized by a much higher resistivity (340 Ωm), is likely a coarse sand or gravel unit that may serve as a clean aquifer. The model emphasizes spatial heterogeneity in contamination and underscores the importance of landfill site characterization for risk assessment, especially in urban groundwater-dependent regions.

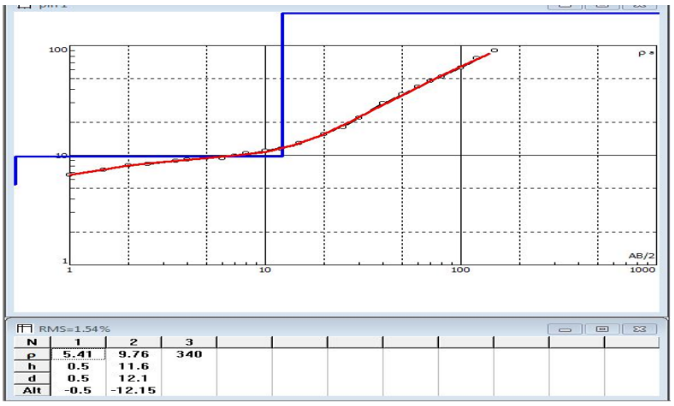

Figure 16 VES of Rumuopirikom Dumpsite.

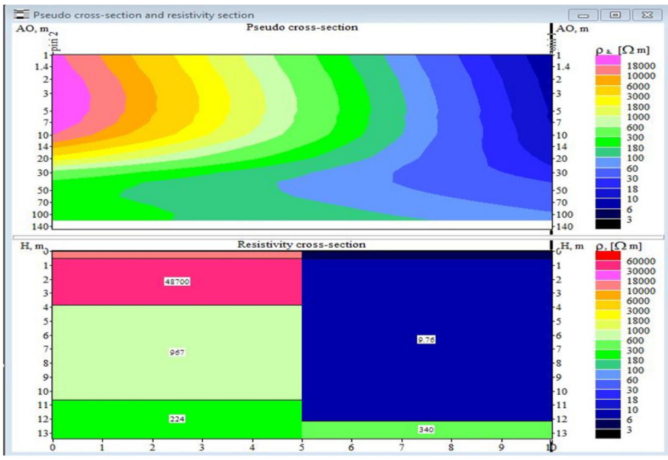

Figure 17 pseudo/Resistivity- section of Rumuepirikum dumpsite.

Figure 18 illustrates both the pseudo cross-section and inverted resistivity cross-section for the Rumuagholu dumpsite, providing insight into subsurface electrical resistivity distribution. In the pseudo section (top), the resistivity values range from approximately 0.7 Ωm (black/blue shades) to over 158 Ωm (pink/red shades), with a visible gradient indicating zones of higher conductivity near the surface between 1 m to 8 m depth. These low resistivity zones suggest significant infiltration of leachate, most likely from organic and inorganic waste decomposition, into shallow subsurface layers. This contamination plume appears to be migrating downwards and laterally, indicating the movement of pollutants across the vertical profile. The resistivity cross-section (bottom) reveals a more constrained conductive anomaly, with a large uniform zone of very low resistivity (~2.03 Ωm) dominating the subsurface from 10 m to 100 m depth. This implies the presence of saturated, possibly polluted, clay or clayey-sand materials that serve as a conductive medium, potentially due to accumulated leachate. The resistivity inversion also identifies a less conductive patch (13.8 Ωm) in the upper part, which may indicate a dry or less contaminated zone. Scientifically, these observations are critical for groundwater protection, as they provide evidence of vertical and lateral contaminant transport. Its applications include informing waste management practices, designing remediation strategies, and guiding environmental impact assessments, particularly in densely populated or hydrologically sensitive areas. The results underline the importance of geophysical surveys in detecting subsurface pollution pathways and safeguarding water resources.

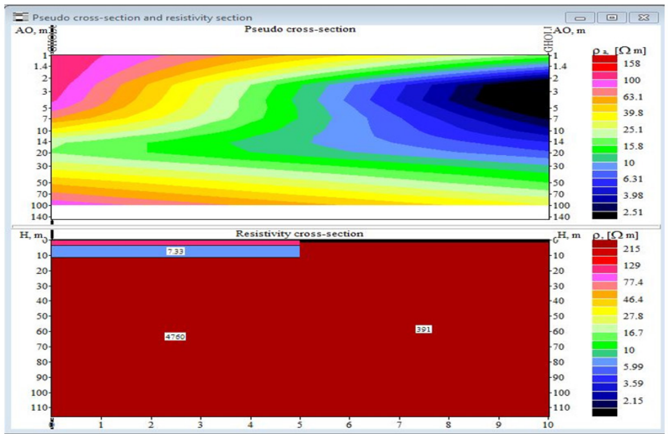

Figure 18 Pseudo/Resistivity- section of Rumuagholu dumpsite.

Figure 19 represents the Vertical Electrical Sounding (VES) curve and model parameters for the Rumuagholu dumpsite using a Schlumberger array. The interpretation curve (red line) fitted to the measured data (black dots) demonstrates a good correlation with an RMS error of 1.46%, indicating a reliable model fit. The curve suggests a three-layer geoelectric structure. The first layer, with a resistivity of 4.32 Ωm and a thickness of 0.512 m, likely represents a surface deposit of fine, moisture-retaining sand. The second layer has a markedly lower resistivity of 1.23 Ωm and a thickness of approximately 1.23 m, indicating a leachate-saturated zone, most likely due to infiltration of waste-related pollutants. Beneath this is a third layer with a significantly higher resistivity value of 3146 Ωm, characteristic of a dry, coarse sand or gravelly formation capable of storing clean groundwater. The sharp contrast between the second and third layers is significant, as it highlights the interface between the contaminated zone and a potentially potable aquifer. This geoelectric structure is crucial for hydrogeological assessment and landfill monitoring, as it aids in understanding subsurface contamination dynamics. In practical terms, the identification of these layers informs decision-making regarding safe borehole placement, groundwater protection policies, and site-specific remediation efforts in urban dumpsite environments.

Figure 20 presents both the pseudo cross-section and resistivity inversion model for the Sasun dumpsite, offering a detailed depiction of subsurface electrical resistivity distribution. The pseudo-section indicates elevated resistivity values from the surface down to approximately 2.5-3.5 meters, suggestive of lateritic or unsaturated sandy soil. A marked decline in resistivity is observed beginning around 2.6 meters and extending to about 16 meters, which corresponds to a conductive zone likely caused by the percolation of

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leachate from the dumpsite. This low-resistivity zone, visualized by blue to black shading, points to significant subsurface contamination. The resistivity inversion cross-section delineates a four-layer geoelectric structure. The first and second layers associated with lateritic and clayey/sandy materials exhibit moderate resistivity values ranging from approximately 69 to 319 Ωm. Beneath these, a third layer characterized by significantly lower resistivity (~4.45 Ωm) represents a leachate-impacted zone, indicating the vertical migration of pollutants. The fourth and deepest layer, with resistivity exceeding 3000 Ωm (depicted in red), corresponds to a dry, coarse sand or sandstone formation, likely serving as a potential aquifer. These findings are critical for environmental monitoring and groundwater management, as they highlight both the depth and extent of waste infiltration, emphasizing the importance of site-specific remediation and safe groundwater extraction planning.

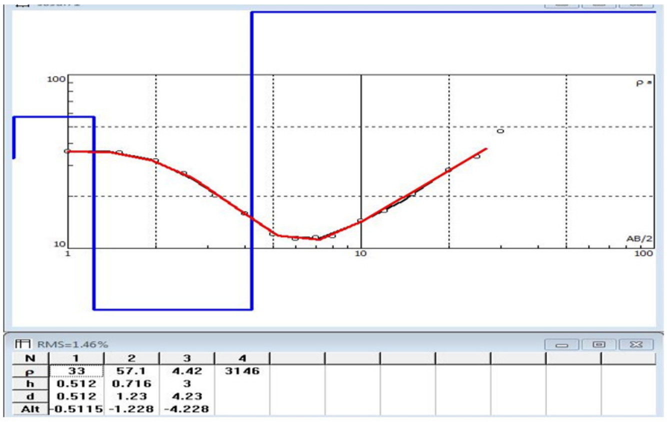

Figure 19 VES Curve of Sasun Dumpsite.

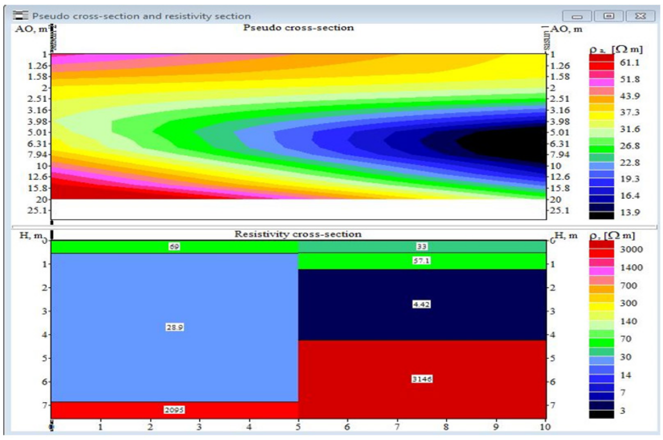

Figure 20 Pseudo/Resistivity- section of Sasun dumpsite.

Summarily, Figure 21 illustrates the depth range of subsurface leachate contamination across ten locations within the study area, highlighting variations in the extent of vertical leachate infiltration from dumpsites. Sites such as Rumuola and Eliozu exhibit the deepest contamination zones, extending from approximately 13-24 meters and 2.4-20 meters respectively, indicating prolonged and significant leachate migration. In contrast, Oyigbo, Rumuolumeni, and Rumuagholu show shallower contamination depths (typically under 10 meters), which may reflect newer dumpsites, less permeable subsurface materials, or early-stage leachate development. These variations point to localized geologic and hydrologic differences influencing contaminant behavior. A key takeaway is the variability in the depth of contaminant penetration, which emphasizes that leachate impact is not uniform across locations. Sites like Eneka, Eleme, and Sasun Hotels have intermediate contamination depths ranging between 10 and 16 meters, suggesting partial leachate percolation through clay-sand sequences into deeper sandy or gravel layers. This is significant for hydrogeological assessments, as deeper contamination increases the risk of aquifer pollution, particularly if the underlying formations are unconfined or poorly protected. Furthermore, the presence of leachate in deeper layers could mean that natural attenuation or biodegradation processes at shallower depths are insufficient to prevent vertical pollutant migration. In real-world terms, these findings have important implications for landfill site management, groundwater protection policies, and environmental risk assessments. Areas with deeper leachate penetration may require immediate intervention, such as engineered liners, leachate recovery systems, or relocation of waste activities. For groundwater studies, this provides vital data for delineating pollution vulnerability zones, guiding borehole placement, and determining appropriate monitoring well depths. Overall, this analysis supports proactive strategies to safeguard water resources and protect public health in urban and peri-urban communities affected by open dumping practices.

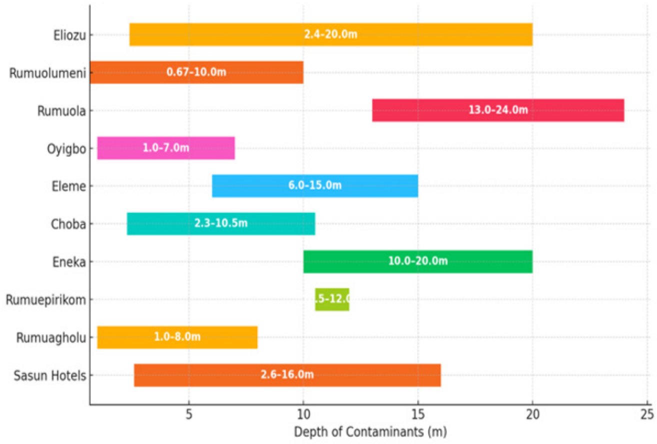

Figure 21 Depth Range of Subsurface Leachate contamination across various Locations.

Source: *Researcher Fieldwork (2021)*

Discussion

The resistivity profiles across multiple dumpsites in Nigeria reveal consistent geophysical signatures of leachate contamination, underscoring the pervasive environmental risks posed by unregulated waste disposal. To begin with, the Eliozu dumpsite exhibits an H-type resistivity curve, featuring a highly conductive middle layer (0.443 Ωm) indicative of leachate-saturated zones, consistent with findings from Raimi et al.,[1] Abiye & Raimi[11,12], and others. This pattern aligns with studies in Port Harcourt and Lagos, where similar low-resistivity anomalies were linked to leachate infiltration into permeable sandy-clay layers.[8–10,34] Moreover, the sharp contrast (>1000 Ωm) between contaminated and basal layers suggests the presence of an impermeable boundary, reinforcing the role of vertical stratification in delineating pollution extents.[35–55] Expanding on this, seasonal variations significantly influence leachate distribution, as evidenced by pronounced low-resistivity anomalies (1.87–2.85 Ωm) during the rainy season at Eliozu. This observation is supported by studies in South-South Nigeria, where rainfall intensifies contaminant transport.[14,25–28] Additionally, the spatial asymmetry in resistivity values suggests directional flow, likely driven by hydraulic gradients, a phenomenon also documented in Benin dumpsites.[56,57] Furthermore, heterogeneity in soil composition affects leachate dispersion, with resistivity

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variations (up to 43.3 Ωm) highlighting localized contamination hotspots.[1,14,15,25–28] Thus, geoelectrical profiling proves indispensable for targeted remediation and groundwater monitoring.[11,12,47] Similarly, at the Rumuolumeni dumpsite, shallow leachate infiltration (0.49 Ωm within 1.7 meters) confirms rapid contaminant migration, a trend echoed in urban landfills across Nigeria.[8–10,37,51] However, resistivity recovery in deeper layers (3.57 Ωm) suggests partial confinement, though residual contamination persists.[7,46] This pattern mirrors findings from oil-impacted zones in Rivers State, where geoelectrical models effectively delineated pollution boundaries.[8–10,14] Importantly, the low RMS error (2.46%) validates the reliability of these methods for groundwater protection planning.[41,43] Transitioning to seasonal dynamics, resistivity at Rumuolumeni fluctuates dramatically, exceeding 1000 Ωm in rainy seasons but dropping to 3.57 Ωm in dry periods, underscoring rainfall's role in leachate mobility.[7,13,39]

These temporal shifts corroborate prior studies linking heavy rainfall to enhanced aquifer vulnerability.[1,36] Notably, partially saturated sandy layers retain contaminants, as observed in biogeochemical studies.[25–28,47] Consequently, seasonal monitoring is critical for optimizing remediation timing and prioritizing intervention zones.[38,41,43,50] Shifting focus to Rumuola, the H-type resistivity curve (6.84 Ωm mid-layer) confirms leachate percolation, consistent with findings by Aiyesanmi & Imoisi[56] and Clinton-Ezekwe et al.[7,13] Meanwhile, the underlying resistive layer (1122 Ωm) suggests aquifer protection, aligning with studies on deep geologic barriers.[8–12] Similarly, at the Rumuola borrow pit, low-resistivity zones (8.22-10 Ωm) within 3.2 meters highlight shallow contamination, while permeable sandy layers facilitate deeper migration.[7,13,25–28] These findings reinforce the need for vertical stratification analysis in remediation strategies.[42,48] At the Oyigbo dumpsite, the H-type response (0.457 Ωm) reveals shallow leachate plumes (1.42-2.15 m), posing direct aquifer threats.[35,36] However, deeper resistivity rebounds (680 Ωm) indicate uncontaminated zones, supporting borehole siting in consolidated formations.[11,12] Likewise, resistivity imaging at Eleme delineates a four-layer HA-type curve, with contamination (11.4 Ωm) confined to 1.9-8.1 meters, while deeper strata (3300-5360 Ωm) remain pristine.[25–28,47] Such stratification is critical for groundwater extraction planning, as seen in Ebocha-Obrikom and Mgbede.[7–10,13] Broadening the perspective, regional analysis reveals variable leachate depths extending up to 24 meters in Rumuola and 20 meters in Eliozu reflecting site-specific hydrogeological conditions (Figure 22, 23).[58,59] These variations underscore the urgency of tailored remediation, particularly in high-permeability zones.[60,61] Most critically, conductive leachate zones (2-20 m) threaten shallow aquifers, with hydrochemical studies confirming toxic metal infiltration (Figure 24).[8–10,45] In conclusion, the integration of geophysical and chemical data provides a robust framework for risk assessment and intervention. To mitigate these risks, immediate measures such as engineered landfills, bioremediation, and seasonal monitoring are essential.[34,62–74] Furthermore, policy reforms and stricter enforcement by agencies like NESREA are imperative to curb further groundwater degradation.[37,52,63–74] Ultimately, this study highlights the need for multidisciplinary collaboration to safeguard water resources and public health in Nigeria's rapidly urbanizing landscapes.

Implications for policy and interventions

The geophysical evidence of extensive vertical and lateral leachate migration from multiple dumpsites in Port Harcourt and surrounding areas calls for a robust review and enforcement of environmental waste management policies. Existing legislation should be updated to mandate geophysical surveys and Environmental Impact Assessments (EIAs) before the siting or expansion of waste disposal facilities. The clear detection of contamination in shallow and, in some cases, deep aquifers demands that groundwater protection zones be legislated, monitored, and enforced. Policy frameworks should prioritize the conversion of open dumpsites into engineered sanitary landfills with impermeable liners and leachate collection systems. Integrated interventions, including community education, routine groundwater surveillance, and health risk assessments, are essential to mitigate the long-term public health impacts associated with uncontrolled waste leachate infiltration.

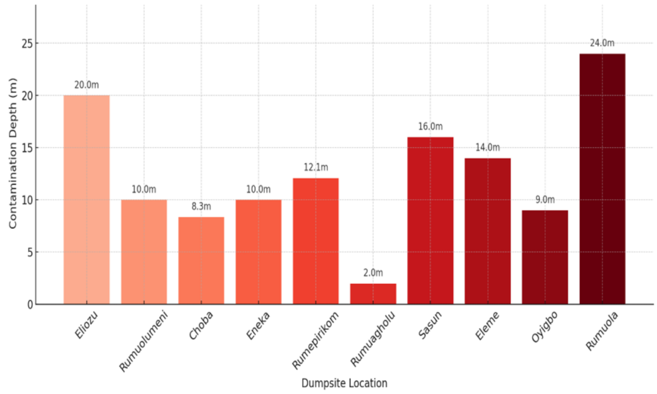

Figure 22 A bar chart showing the vertical extent of subsurface leachate contamination across the ten studied dumpsites. The depth values (in meters) reflect the extent to which pollutants have infiltrated the subsurface, based on geoelectrical resistivity results. Darker red shades indicate deeper contaminant penetration, with Rumuola (24 m) and Eliozu (20 m) being the most affected.

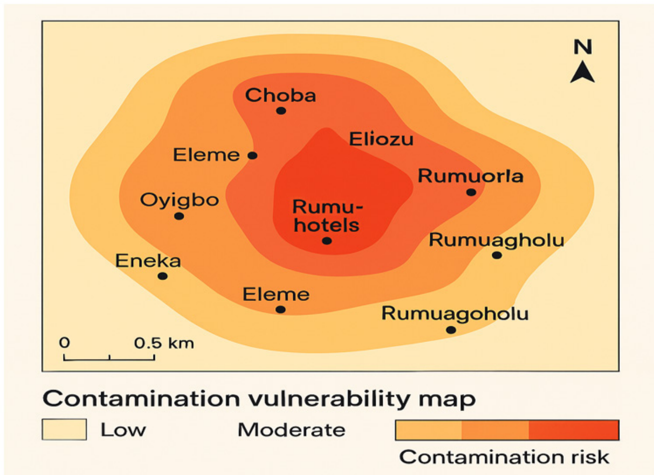

Figure 23 Contamination Vulnerability Map.

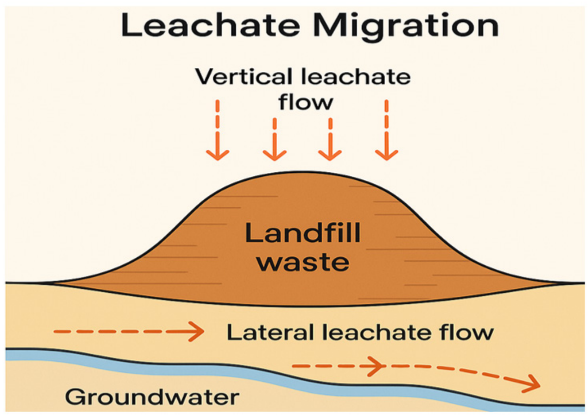

Figure 24 A leachate migration flow diagram showing typical vertical and lateral flow patterns.

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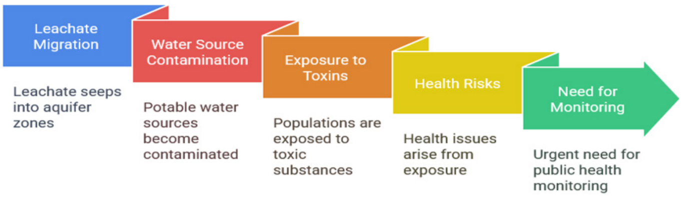

Figure 25 Leachate Migration and Health Risks.

Conclusion

This study has established that indiscriminate waste disposal practices at several urban and peri-urban dumpsites in Rivers State, Nigeria, have resulted in significant subsurface contamination, with leachate plumes migrating to depths ranging from 2 to over 24 meters. The electrical resistivity method employed effectively delineated contaminated zones, highlighting areas where pollutants threaten groundwater resources. These results reveal a pressing need for environmental remediation, sustainable dumpsite engineering, and strategic public health interventions to safeguard water quality in affected communities.

Summary of the findings

I. All surveyed dumpsites, including Rumuola, Eliozu, Choba, Eneka, Oyigbo, and Rumuagholu, exhibit vertical and lateral leachate migration, confirmed through low resistivity zones (0.3-15 Ωm).

II. Resistivity curves (H-type and A-type) consistently indicated three to four subsurface layers, with leachate-impacted zones sandwiched between more resistive strata or underlying unpolluted aquifers.

III. Dumpsites such as Rumuola and Eliozu show deeper contaminant penetration (13-24 m), whereas others like Oyigbo and Rumuolumeni exhibit shallower leachate profiles (<10 m).

IV. High resistivity zones (>1000 Ωm) identified at depth indicate potential aquifers that remain uncontaminated but are at risk without intervention.

V. The findings correlate strongly with previous studies on landfill leachate behavior and groundwater pollution.

Recommendation

It is recommended that dumpsites with evidence of deep contamination be prioritized for remediation through containment strategies such as geomembrane liners, clay barriers, and leachate drainage systems. Groundwater monitoring wells should be installed at regular intervals and depths around each site to track contaminant migration. Waste management policy must shift from open dumping to engineered landfilling, supported by strict enforcement of waste segregation and recycling. Public health authorities should also conduct epidemiological studies in high-risk communities to understand the health implications and develop context-specific responses. Finally, interdisciplinary collaboration between geoscientists, health professionals, urban planners, and policymakers is essential for long-term environmental and health security.

Significant statement

The detection of leachate migration into aquifer zones signifies a direct threat to potable water sources used by urban and peri-urban populations. This can lead to exposure to toxic substances such as heavy metals, pathogens, and dissolved solids, which are known to cause gastrointestinal infections, reproductive disorders, developmental issues in children, and even carcinogenic outcomes over prolonged exposure. These findings underscore the urgent need for public health monitoring and risk communication, especially in communities relying on shallow hand-dug wells or boreholes in proximity to dumpsites. Thus, graphically it is represented as Figure 25.

Study limitations

While the electrical resistivity method provided reliable subsurface imaging, it is inherently interpretative and best validated through complementary data such as borehole logging, water chemistry analyses, and microbial assessments, which were not covered in this study. Furthermore, the spatial resolution is limited by electrode spacing and terrain constraints at some sites. Seasonal variability in water table levels and leachate migration was not accounted for, suggesting that repeat surveys across dry and rainy seasons would yield a more comprehensive contamination profile. Despite these limitations, the findings offer critical baseline data for environmental and public health action.

Author contributions

All authors collaboratively developed the concept and design of the study. They were collectively involved in data collection and analysis, ensuring a comprehensive approach to the research. Each author contributed to drafting the initial article, bringing their unique perspectives and expertise to the writing process. Furthermore, all authors participated in interpreting the data, providing critical insights that shaped the study's conclusions. They thoroughly reviewed the content of the article, ensuring accuracy and coherence, and ultimately approved the final version for publication. This collaborative effort highlights the integral contributions of each author at every stage of the research.

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Competing interests

The authors affirm that they have no competing interests to declare. There are no conflicts of interest that could influence the objectivity or impartiality of the research findings presented in this study.

References

1. Raimi MO, Sawyerr HO, Ezekwe IC, et al. Toxicants in water: Hydrochemical Appraisal of toxic metals concentration and seasonal variation in drinking water quality in oil and gas field area of rivers state, Nigeria. In: Saleh PH, Hassan PAI, eds. *Heavy Metals - New Insights*. IntechOpen; 2022.

2. Olalekan RM, Adedoyin OO, Ayibatonbira A, et al. "Digging deeper" evidence on water crisis and its solution in Nigeria for Bayelsa state: a study of current scenario. *International Journal of Hydrology*. 2019;3(4):244–257.

3. Raimi MO, Omidiji AO, Adeolu TA, et al. An analysis of Bayelsa state water challenges on the rise and its possible solutions. *Acta Scientific Agriculture*. 2019;3(8):110–125.

4. Olalekan RM, Vivien OT, Adedoyin OO, et al. The sources of water supply, sanitation facilities and hygiene practices in oil producing communities in central senatorial district of Bayelsa state, Nigeria. *MOJ Public Health*. 2018;7(6):304–312.
5. Raimi MO, Sabinus CE. An assessment of trace elements in surface and ground water quality in the Ebocha-Obrikom oil and gas producing area of rivers state, Nigeria. *International Journal for Scientific and Engineering Research*. 2017;8(6):10–25.
6. Raimi MO, Pigha TK, Ochayi EO. Water-Related problems and health conditions in the oil producing communities in central senatorial district of Bayelsa state. *Imperial Journal of Interdisciplinary Research*. 2017;3(6):780–809.
7. Clinton-Ezekwe I, Raimi MO, Ezekwe IC, et al. Ensuring safety: groundwater quality and its potential health effects in the Mgbede oil fields environment of south-south Nigeria. *JMIR Preprints*. 2024;64294.
8. Morufu OR, Clinton IE, Bowale A. Statistical and multivariate techniques to trace the sources of ground water contaminants and affecting factors of groundwater pollution in an oil and gas producing wetland in Rivers state, Nigeria. *medRxiv*. 2021;2021.12.26.21268415.
9. Morufu OR, Henry OS, Clinton IE, et al. Many oil wells, one evil: potentially toxic metals concentration, seasonal variation and human health risk assessment in drinking water quality in Ebocha-Obrikom oil and gas area of rivers state, Nigeria. *medRxiv*. 2021;2021.11.06.21266005.
10. Raimi MO, Olawale HS, Clinton IE, et al. Quality water not everywhere: exploratory analysis of water quality across Ebocha-Obrikom oil and gas flaring area in the core Niger delta region of Nigeria. *Research Square*. 2021.
11. Abiye T, Raimi MO. Assessing groundwater contamination near dumpsites in port Harcourt using water quality index (WQI): insights from seasonal and distance-based variations. *Int J Hydro*. 2025;9(1):35–44.
12. Abiye T, Raimi MO. Unlocking the secrets beneath: utilizing the Water Quality Index (WQI) to assess groundwater contamination near dumpsites – A case study of port Harcourt. *JMIR Preprints*. 2025;73643.
13. Clinton-Ezekwe I, Raimi M, Ezekwe I, et al. From oil to health: groundwater quality and its potential health effects in mgbede oil fields of south-south Nigeria. *Open Journal of Yangtze Oil and Gas*. 2024;9(4):95–118.
14. Raimi MO, Oyeyemi AS, Mcfubara KG, et al. Geochemical background and correlation study of ground water quality in Ebocha-Obrikom of rivers state, Nigeria. *Trends Appl Sci Res*. 2023;18(1):149–168. doi:10.17311/tasr.2023.149.168.
15. Olalekan MR, Olawale HS, Clinton IE, et al. Quality water, not everywhere: assessing the hydrogeochemistry of water quality across Ebocha-Obrikom oil and gas flaring area in the core Niger delta region of Nigeria. *Pollution*. 2022;8(3):751–778.
16. Saliu AO, Komolafe OO, Bamidele CO, et al. The value of biodiversity to sustainable development in Africa. In: Izah SC, Ogwu MC, eds. *Sustainable Utilization and Conservation of Africa's Biological Resources and Environment*. Springer; 2023.
17. Raimi MO, Abiola OS, Atoyebi B, et al. The challenges and conservation strategies of biodiversity: the role of government and non-governmental organization for action and results on the ground. In: Izah SC, ed. *Biodiversity in Africa: Potentials, Threats, and Conservation*. Springer; 2022.
18. Raimi MO, Austin-AI, Olawale HS, et al. Leaving no one behind: impact of soil pollution on biodiversity in the global south: a global call for action. In: Izah SC, ed. *Biodiversity in Africa: Potentials, Threats and Conservation*. Springer; 2022.
19. Eseyin O, Osu IC. Effect of Municipal Solid Waste (MSW) Leachate on groundwater quality in port Harcourt, Nigeria. *Journal of Geography, Environment and Earth Science International*. 2019;19(3):1–12.
20. Nwachukwu MA, Feng H, Alinnor J. Assessment of heavy metal pollution in soils and groundwater around a municipal solid waste dump in Port Harcourt, Nigeria. *International Journal of Environmental Science & Technology*. 2010;7(1):155–162.
21. Amadi AN, Olasehinde PI, Okosun EA. An assessment of the impact of a dumpsite on groundwater quality in Port Harcourt municipality, Nigeria. *J Environ Prot*. 2012;3(2):162–167.
22. Oyelami AC, Aladejana JA, Agbede OO. Assessment of groundwater contamination by leachate near a municipal solid waste landfill in Lagos, Nigeria. *J Health Pollut*. 2016;6(10):28–41.
23. Alaye AS, Ogbonna DN, Abere SA, et al. Heavy metal contamination and health risk assessment of groundwater sources to waste dumpsites in Port Harcourt. *International Journal of Environment and Pollution Research*. 2022;10(2):34–49.
24. Awogbami SO, Ogunyemi O, Adebayo PA, et al. Protecting the health of black communities: assessing the impact of environmental hazards from gold mining activities on health outcomes among residents of Osun State, Nigeria. *JMIR Preprints*. 2024;66508.
25. Fubara GE, Dokuboba A, Ilemi JS, et al. The Niger Delta is under a pollution warning: hydrocarbon profiles in crude oil polluted soil remediated with Pleurotus ostreatus and Eisenia fitida. *bioRxiv*. 2024;2024.06.04.597352.
26. Fubara GE, Ukoima HN, Dokuboba A, et al. Evaluating Bioremediation Strategies on Microbial Diversity in Crude Oil-Contaminated Soil Over Three to Six Months in Port Harcourt, Nigeria. 2024b.
27. Fubara G, Amachree D, Soberekon I, et al. From Crisis to Recovery: Addressing Hydrocarbon Pollution in Niger Delta Soils Treated with *Pleurotus ostreatus* and *Eisenia fitida*. *Open Journal of Yangtze Oil and Gas*. 2025;10:1–29.
28. Evans FG, Nkalo UH, Amachree D, et al. From Killer to Solution: Evaluating Bioremediation Strategies on Microbial Diversity in Crude Oil-Contaminated Soil over Three to Six Months in Port Harcourt, Nigeria. *Adv Environ Eng Res*. 2024;5(4):023.
29. Eti-Efeotor JO, Akpokodje EG. Hydrogeochemical characteristics of groundwater in the Niger Delta. *Journal of Mining and Geology.* 1990;26(1):41–48.
30. United States Environmental Protection Agency (USEPA). *Groundwater sampling guidelines* (EPA 540-R-06-001). 2006.
31. APHA. *Standard methods for the examination of water and wastewater 19th edn*. Prepared and Published Jointly by: APHA, AWWA and WEF; Joint Editorial Board; American Health Association, Washington, DC. 2009.
32. World Health Organisation (WHO). Water for Pharmaceuticals Use. In: Quality Assurance of Pharmaceuticals: A Compendium of Guidelines and Related Materials. 2nd Updated Edn. *World Health Organization. Geneva*. 2007;2:170–187.
33. Fetter CW. *Applied Hydrogeology.* Fourth Edition, Prentice Hall, New Jersey. 2021.
34. Adewole AT. Waste management towards sustainable development in Nigeria: A case study of Lagos State. *International NGO Journal.* 2009;4(4):173–179.
35. Stephen OA, Solomon OA, Henry OS, et al. Comprehensive Understanding of Hydrogeochemical evaluation of seasonal variability in groundwater quality Dynamics in the Gold Mining Areas of Osun State, Nigeria. 2022.
36. Awogbami SO, Solomon OA, Sawyerr OH, et al. Comparative Assessment of Seasonal Variations in the Quality of Surface water and its associated health hazards in Gold Mining Areas of Osun State, South-West Nigeria. 2022.
37. Afolabi AS, Morufu OR. Investigating Source Identification and Quality of Drinking Water in Piwoyi Community of Federal Capital Territory, Abuja Nigeria. 2021.

38. Deinkuro NS, Charles WK, Raimi MO, et al. Oil Spills in the Niger Delta Region, Nigeria: Environmental Fate of Toxic Volatile Organics. 2021.

39. Olalekan AS, Adewoye SO, Henry SO, et al. Comprehensive understanding of hydrogeochemical evaluation of seasonal variability in groundwater quality dynamics in the gold mining areas of Osun state, Nigeria. *Int J Hydro*. 2023a;7(5):206–220.

40. Olalekan RM, Bukola RW, Omowunmi FO, et al. The application of biomaterials in ecological remediation of land pollution: bioremediation of heavy metals in cement contaminated soil using white-rot fungus Pleurotus. sajor-caju. *J Environ Chem Toxicol*. 2023b;7(1):1–6.

41. Kader S, Raimi MO, Spalevic V, et al. "A concise study on essential parameters for the sustainability of Lagoon waters in terms of scientific literature," *Turkish Journal of Agriculture and Forestry*. 2023;47(3):Article 3.

42. Glory R, Sylvester CI, Morufu OR, et al. Public and environmental health implications of artisanal petroleum refining and risk reduction strategies in the Niger Delta region of Nigeria. *Journal of Biological Research & Biotechnology*. 2023;21(1):1836–1851.

43. Kader S, Jaufer L, Bashir O, et al. Comparative study on the stormwater retention of organic waste substrates biochar, sawdust and wood bark retrieved from Psidium guajava L. species. *Agriculture and Forestry*. 2023;69(1):105–112.

44. Stephen OA, Olayinka AS, Olawale HS, et al. Comparative Assessment of Seasonal Variations in the Quality of Surface Water and Its Associated Health Hazards in Gold Mining Areas of Osun State, South-West Nigeria. *Adv Environ Eng Res*. 2023;4(1): 011.

45. Ifeanyichukwu CE, Christian LO, Morufu OR, et al. Hydrocarbon-Based Contaminants in Drinking Water Sources and Shellfish in the Soku Oil and Gas Fields of South-South Nigeria. *Open Journal of Yangtze Gas and Oil*. 2022;7(4):213–230.

46. Olalekan MR, Albert O, Iyingiala AA, et al. An environmental/scientific report into the crude oil spillage incidence in Tein community, Biseni, Bayelsa state Nigeria. *J Environ Chem Toxicol.* 2022;6(4):01–06.

47. Raimi O, Ezekwe C, Bowale A, et al. Hydrogeochemical and Multivariate Statistical Techniques to Trace the Sources of Ground Water Contaminants and Affecting Factors of Groundwater Pollution in an Oil and Gas Producing Wetland in Rivers State, Nigeria. *Open Journal of Yangtze Oil and Gas*. 2022b;7:166–202.

48. Raimi M, Sawyerr H. Preliminary Study of Groundwater Quality Using Hierarchical Classification Approaches for Contaminated Sites in Indigenous Communities Associated with Crude Oil Exploration Facilities in Rivers State, Nigeria. *Open Journal of Yangtze Oil and Gas*. 2022;7:124–148.

49. Raimi OM, Sawyerr OH, Ezekwe CI, et al. Many oil wells, one evil: comprehensive assessment of toxic metals concentration, seasonal variation and human health risk in drinking water quality in areas surrounding crude oil exploration facilities in rivers state, Nigeria. *International Journal of Hydrology.* 2022c;6(1):23–42.

50. Deinkuro NS, Charles WK, Raimi MO, et al. Environmental Fate of Toxic Volatile Organics from Oil Spills in the Niger Delta Region, Nigeria. *International Journal of Environment, Engineering and Education*. 2021;3(3):89–101.

51. Afolabi AS, Raimi MO. When Water Turns Deadly: Investigating Source Identification and Quality of Drinking Water in Piwoyi Community of Federal Capital Territory, Abuja Nigeria. *Online Journal of Chemistry.* 2021;1:38–58.

52. Suleiman RM, Raimi MO, Sawyerr HO. A Deep Dive into the Review of National Environmental Standards and Regulations Enforcement Agency (NESREA) Act. *International Research Journal of Applied Sciences.* 2019.

53. Odipe OE, Raimi MO, Suleiman F. Assessment of Heavy Metals in Effluent Water Discharges from Textile Industry and River Water at Close Proximity: A Comparison of Two Textile Industries from Funtua and Zaria, North Western Nigeria. *Madridge Journal of Agriculture and Environmental Sciences.* 2018;1(1):1–6.

54. Olalekan RM, Omidiji AO, Nimisngha D, et al. Health Risk Assessment on Heavy Metals Ingestion through Groundwater Drinking Pathway for Residents in an Oil and Gas Producing Area of Rivers State, Nigeria. *Open Journal of Yangtze Gas and Oil*. 2018;3:191–206.

55. Raimi MO, Sabinus CE. Influence of Organic Amendment on Microbial Activities and Growth of Pepper Cultured on Crude Oil Contaminated Niger Delta Soil. *International Journal of Economy, Energy and Environment.* 2017;2(4):56–76.

56. Aiyesanmi, F, Imoisi OB. Understanding Leaching Behaviour of Dumpsite Leachate in Benin-City, Edo State, Nigeria through Dumpsite Monitoring. *British Journal of Environment & Climate Change*. 2011;1(4):190–200.

57. Al-Rashed AA, Mukhopadhyay M, Al-Senafy H, et al. Contamination Of Groundwater From Oil Field Water Disposal Pits In Kuwait. *The Arabian Journal for Science and Engineering.* 2010;35(1B):105–123.

58. Ezekwe IC, Odubo E, Chima GN, et al. Groundwater Occurrence and flow Patterns in the Ishiagu Mining Area of Southeastern Nigeria. *Frontiers of Earth Science*. 2012;6(1):18–28.

59. Aphale O, Tonjes D. Groundwater Flow Simulation Model for a Dumpsite Site in the Town of Brookhaven, Long Island, New York, a thesis by Department of Technology and Society Stony Brook University. 2008.

60. Beetseh CI, Abrahams JO. Dangers of Bioaccumulation of some heavy metals consumed in sardine and mackerel (ice fish) in Benue State Nigeria. *Civil and Environmental Research*. 2013;3(5).

61. Kachalla B, Maidoki AD, Liman A, et al. Impact of Municipal Solid Waste Dumpsite Leachate on Groundwater Quality in Nigeria: Critical Review. 2018.

62. Raheem WB, Fadina OO, Idowu OO, et al. The Application of Biomaterials in Ecological Remediation of Land Pollution: Bioremediation of Heavy Metals in Cement Contaminated Soil Using White-Rot Fungus Pleurotus sajor-caju. 2023.

63. Christopher OE, Adenike BA, Babatunde TO, et al. The Silent Poison: National Strategies to Protect Health and Ecosystems from Toxic Threats. *Authorea.* 2025.

64. Opaminola Nicholas D, Raimi MO. Groundwater Contamination in Bayelsa's Oil-Producing Communities: Physico-Chemical Quality, WHO Standards, and Health Implications. *JMIR Preprints*. 2025.

65. Tomquin A, Ayotamuno A, Ezekwe IC, et al. Ten Dumpsites, One Crisis: Geoelectrical Evidence of Widespread Subsurface Contamination and Groundwater Vulnerability in Port Harcourt. *JMIR Preprints*. 2025.

66. Enang OT, Azeez BO, Ogunyemi BT, et al. Innovative Water Purification for Hemodialysis: TiO_2 Nanoparticle-Based Microporous Filter Development and Analysis. *JMIR Preprints*. 2025a.

67. Enang OT, Azeez BO, Ogunyemi BT, et al. Revolutionizing Hemodialysis Water Quality: Development and Evaluation of TiO_2 Nanoparticle-Enhanced Microporous Filters. *Advances in Nanoparticles*. 2025b;14:12–36.

68. Tano DA, Odafivwotu O, Morufu OR. Residents' Perception and Adjustment to Floods in Yenagoa Metropolis, Nigeria. *Advance.* 2024.

69. Agusomu TD, Ohwo O, Raimi MO. Living with the waters: perception, adaptation, and policy implications of flooding in Yenagoa metropolis, Nigeria. *Open Access J Sci*. 2025;8(1):117–131.

70. Akayinaboderi AE, Tano DA, Okoro E, et al. World Environment Day 2024 Initiatives in Bayelsa State: Promoting Environmental Stewardship and Sustainable Practices - A Collaboration Between Federal University Otuoke, Niger Delta University, and the Nigerian Environmental Society. *Advance.* 2024a.

71. Sarah SJ, Morufu OR, Josephine DK, et al. Assessing Air Quality at Waste Dump Site of Plateau State University, Bokkos, Nigeria: Evaluating Socio-Economic and Health Implications for the Community. *Authorea.* 2024.

72. Raimi MO, Ezekwe IC, Agusomu TD, et al. Enhancing Methane Emissions Management in Nigeria's Oil and Gas Sectors: A Comprehensive Policy and Strategic Framework. *Open Journal of Yangtze Oil and Gas*. 2025;10:31–62.

73. Akayinaboderi AE, Tano DA, Okoro E, et al. World Environment Day 2024 Initiatives in Bayelsa State: Promoting Environmental Stewardship and Sustainable Practices - A Collaboration Between Federal University Otuoke, Niger Delta University, and the Nigerian Environmental Society. *Sustainability in Environment.* 2024b;10(1).

74. Omoyajowo KO, Raimi MO, Omoyajowo KA, et al. Towards a Reduced Pollution Society: Systematic Review on the Role of Storytelling, Social Media, Humor and Celebrities' Influence for Research Communication. *J Appl Sci Environ Manage.* 2024;28(2):603–623.