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INTEGRATED GEOPHYSICAL AND HYDROGEOCHEMICAL ASSESSMENT OF DUMPSITE-INDUCED SOIL AND GROUNDWATER CONTAMINATION IN A FRACTURED SHALE AQUIFER SYSTEM OF ABAKALIKI, SOUTHEASTERN NIGERIA

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ABSTRACT: *Rapid urbanization and indiscriminate waste disposal have intensified soil and groundwater contamination in many Nigerian cities. This study presents an integrated geophysical and hydrogeochemical assessment of subsurface contamination associated with major urban waste dumpsites within Abakaliki Metropolis, southeastern Nigeria, underlain predominantly by fractured and weathered shale of the Asu River Group. Vertical Electrical Sounding (VES) employing the Schlumberger electrode configuration and two-dimensional (2-D) electrical resistivity imaging using the dipole–dipole array were conducted at three major dumpsites: Rice Mill, Umuoghara, and Mechanic Village. The acquired resistivity data were processed using Advanced Geosciences Incorporated (AGI) inversion software and Res2Dinv software to delineate subsurface lithology, fracture systems, aquifer characteristics, and leachate-contaminated zones. The geophysical results revealed low resistivity values ranging from 7–19 Ωm within the topsoil and weathered shale units, indicating highly conductive zones associated with moisture accumulation and leachate infiltration. Moderately to highly resistive layers (118–24,201 Ωm), interpreted as sandstone lenses, silty sand, and siltstone units, were identified at intermediate depths, while deep conductive zones with very low resistivity values (0.18–3.04 Ωm) were interpreted as fractured and saturated shale aquifers vulnerable to contaminant migration. To validate the geophysical interpretation, physicochemical and heavy metal analyses were carried out on soil and surface water samples collected around the investigated dumpsites. Elevated concentrations of heavy metals, including Pb, Cd, Hg, Cr, and Ni, were detected in several samples, with some values exceeding World Health Organization (WHO) permissible limits. The integration of geophysical, physicochemical, and geochemical data confirms the occurrence of leachate-induced subsurface contamination and demonstrates the vulnerability of fracture-controlled aquifer systems within the study area. The study demonstrates the effectiveness of integrating electrical resistivity techniques with hydrogeochemical analyses for environmental assessment and groundwater vulnerability studies in shale-dominated terrains affected by uncontrolled waste disposal activities.*

KEYWORDS: 2-D Electrical Resistivity Imaging; Electrical Resistivity; Fractured Shale Aquifer; Groundwater Vulnerability; Heavy Metal Contamination; Hydrogeochemistry; Vertical Electrical Sounding (VES).

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INTRODUCTION

Rapid urbanization, driven largely by rural-urban migration in search of better opportunities, has led to an unprecedented increase in municipal solid waste generation in many cities (Fatoba et al., 2020). Coupled with population growth and industrial expansion, indiscriminate disposal of refuse has become a pressing challenge. Varma and Sarath (2015) noted that population growth and industrialization are among the principal drivers of escalating solid waste volumes in urban environments. In most developing countries, dumpsites remain the predominant waste disposal option due to limited infrastructure and weak enforcement of environmental regulations. Although dumpsites play a vital role in maintaining urban sanitation, poorly designed and unmanaged sites are associated with severe environmental consequences, including soil and water contamination, greenhouse gas emissions, and long-term ecosystem degradation (Fatoba et al., 2020).

Areas near dumpsites are prone to groundwater and soil contamination because of the presence of leachate originating from the source in the natural environment. The fumes and odour emanating from solid waste can also lead to skin and blood infections, eye and respiratory infections, as well as chronic diseases such as cancers (Nwankwo and Ogoro, 2020). Economic activities are also affected as people would not like to locate their companies, businesses, and houses in toxic areas/environment. Land-Land and waterborne diseases and infections may also occur near such dump sites.

Among geophysical tools used to characterize the subsurface, electrical resistivity methods such as geoelectrical imaging and Vertical Electrical Sounding (VES) remain among the most effective due to their ability to non-invasively delineate subsurface resistivity contrasts associated with lithology, fluid content, and contamination effects. Recent reviews highlight the continued and growing application of electrical resistivity tomography (ERT), electromagnetic (EM), and VES methods in environmental and geo-environmental investigations, including mapping contaminant plumes, delineating hydrogeological units, and monitoring landfill leachate infiltration pathways with high resolution and cost efficiency (Alao, 2025).

The vertical electrical sounding (VES) technique, in particular, has been widely applied in ground-water resource assessment, subsurface geological characterization, and environmental risk studies because of its simplicity of implementation, depth penetration, and sensitivity to changes in electrical properties that relate to fluid saturation and lithologic interfaces (El Makrini, 2022).

Soil and shallow subsurface environments are especially vulnerable to anthropogenic contamination, including waste-disposal-derived leachates and surface pollutants, which can significantly lower subsurface resistivity through increased moisture and dissolved ions. Geophysical surveys combining resistivity measurements with hydrological and physicochemical analyses have been shown to effectively assess groundwater susceptibility to contamination from open dumpsites, providing critical insight for environmental management and remediation planning (Alao, et al., 2023).

Although numerous studies (Ramalho et al., 2011; Lopes et al., 2012; Olla et al., 2015; Siddhardhan et al., 2015; Giang et al., 2018; Mepaiyeda et al., 2019; Zaini et al., 2021; Bernardo et al., 2022; Nwankwoala et al., 2022; Dauda & Ali, 2024; Kevin et al., 2024; Mejida, 2024; Nwachukwu et al., 2024; Odoh et al., 2024) have demonstrated the effectiveness of

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electrical geophysical techniques in delineating leachate migration and groundwater contamination around dumpsites, several methodological, contextual, and interpretational gaps remain.

Early studies such as Ramalho et al. (2011) and Lopes et al. (2012) successfully applied integrated geophysical and hydrochemical methods to delineate leachate pathways and groundwater flow systems. However, these studies were conducted largely in engineered or sealed landfill settings within temperate environments, limiting their direct applicability to unsecured and unmanaged dumpsites typical of many developing urban centers.

Studies carried out in Nigeria and other developing regions, including Olla et al. (2015), Siddhardhan et al. (2015), Giang et al. (2018), and Mepaiyeda et al. (2019), effectively identified contamination zones but often focused on single dumpsites or short investigation depths, with limited emphasis on the structural controls of groundwater occurrence, particularly in shale-dominated terrains where aquifer productivity and contaminant migration are strongly fracture-controlled. Investigations such as Zaini et al. (2021) and Bernardo et al. (2022) incorporated advanced resistivity imaging and temporal analysis but were largely conducted in sedimentary or mixed lithologic environments, leaving a gap in understanding contamination dynamics in intensely fractured shale formations like those of the Abakaliki Anticlinorium.

More recent Nigerian studies, including Nwankwoala et al. (2022), Dauda and Ali (2024), Nwachukwu et al. (2024), and Odoh et al. (2024), have highlighted the vulnerability of shallow aquifers to waste and effluent-derived contaminants. Nevertheless, most of these studies either emphasized effluent discharge points rather than municipal dumpsites, or relied on regional-scale assessments without explicitly linking surface contamination, lithologic variability, and aquifer stratification within a single integrated framework.

Furthermore, while Mejida (2024) and Kevin et al. (2024) adopted multi-method and high-resolution approaches, the application of such techniques remains limited in southeastern Nigeria, particularly within urban shale environments, where groundwater development is already constrained and highly susceptible to contamination.

In this study, an integrated geophysical and hydrogeochemical approach was employed to investigate the impact of urban waste dumpsites on soil and groundwater quality within the fractured shale aquifer system of Abakaliki Metropolis, southeastern Nigeria. Vertical Electrical Sounding (VES) and two-dimensional (2-D) electrical resistivity imaging were used to characterize subsurface lithology, delineate aquifer geometry, identify fracture systems, and map potential leachate migration pathways. The geophysical findings were integrated with physicochemical and heavy metal analyses of soil and surface water samples to evaluate the extent of contamination and validate the geophysical interpretations.

Accordingly, the objectives of this study were to: (i) delineate the subsurface lithologic units and groundwater-bearing zones beneath selected urban dumpsites using electrical resistivity techniques; (ii) identify and characterize potential leachate migration pathways and contamination zones within the fractured shale aquifer system; (iii) assess the physicochemical properties and heavy metal concentrations in soil and surface water surrounding the dumpsites; and (iv) integrate geophysical and hydrogeochemical datasets to evaluate the extent of dumpsite-related contamination and provide baseline information for groundwater protection and sustainable environmental management in Abakaliki Metropolis.

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Geology of the Study Area

The study area lies within the Abakaliki Anticlinorium, which is underlain predominantly by the Abakaliki shale of the Asu River Group belonging to the Albian Stage of the Lower Cretaceous sediments. These shales are well exposed across the area and consist mainly of dark grey to black, calcareous, calcite-cemented shale with occasional intercalations of siltstone. The Asu River Group represents the earliest sedimentary sequence deposited unconformably on a subsiding basement complex within the Benue Trough (Burke, 1972). It comprises an alternating sequence of shale, mudstone, and siltstone, with localized occurrences of sandstone and limestone lenses, and attains a thickness of about 1,500 meters (Agumanu, 1989 and Farrington, 1952). Kogbe (1989) further described the sediments as poorly bedded sandy limestones interbedded with shales and mudstones. Due to prolonged weathering and ferruginization, the original black shales have often been altered to pale grey, with mottled shades of red, yellow, pink, and blue (Orajaka, 1965; Ukpong and Olade, 1979). Structurally, the rocks of the Abakaliki area are intensely fractured, folded, and faulted, reflecting the complex tectonic his-tory of the Benue Trough.

Notably, the occurrence of lead–zinc vein mineralization is hosted within the dark shales. The mineralization is commonly associated with ironstone bands, baked shales, and silicified zones along fracture systems (Nnabo, 2011). These mineralized veins represent important economic deposits and provide further evidence of hydrothermal activity within the basin.

MATERIALS AND METHODS

Study Area Description

The study area is located within Abakaliki Metropolis, Ebonyi State, southeastern Nigeria, and lies approximately between latitudes 6°17′N - 6°22′N and longitudes 8°02′E - 8°10′E (Figure1). The area is accessible via major road networks, including the Enugu–Abakaliki expressway, which connects key locations such as the Umuoghara, Rice Mill, and Mechanic Village dumpsites investigated in this study.

The Umuoghara Dumpsite is located along the Enugu – Abakaliki express road with a diversion through the Umuoghara road. The site is strategically positioned and remains accessible at all times of the day. This dumpsite has been in operation for over twenty (20) years.

The Rice Mill Dumpsite is situated within the Abakaliki Rice Mill premises along Old Ogoja Road, Abakaliki. Waste materials deposited at this site consist mainly of rice husk alongside other solid wastes generated from milling activities and the adjoining local market. This dumpsite has existed for more than thirty (30) years.

The Mechanic Village Dumpsite is located along the Enugu–Abakaliki Expressway, before the Central Police Station (CPS), Abakaliki. The site has reportedly been in existence for over twenty (20) years.

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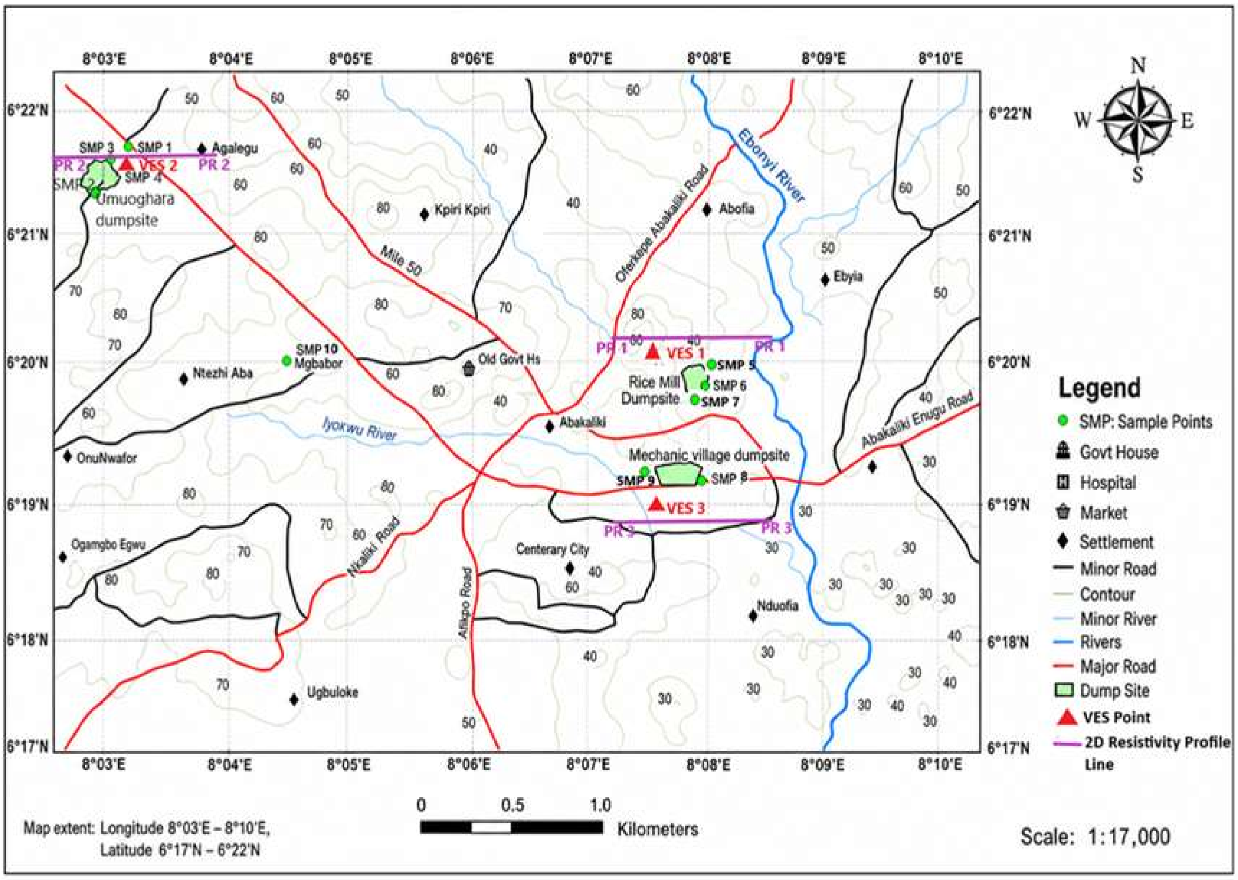
Figure 1. Location map of the study area showing the dumpsites, VES points, 2D Resistivity Profile and Sample points within the study area within the study area



Geophysical and Laboratory Equipment

The geophysical investigation was carried out using the OHMEGA-500 Electrical Resistivity Equipment, which is designed for subsurface resistivity measurements in environmental and engineering applications. The instrument consists of a resistivity meter, current electrodes, potential electrodes, insulated cables, metallic pegs, a measuring tape, and a portable power source. The OHMEGA-500 enables the injection of controlled electrical current into the ground and the measurement of the resulting potential differences required for apparent resistivity computation.

Standard laboratory equipment, including an oven (for drying samples), sieves (2 mm mesh), filtration apparatus, hot plates, glassware (beakers, conical flasks, funnels), and an analytical balance, was employed.

Atomic Absorption Spectrophotometer (AAS) was used for the quantification of heavy metal concentrations in soil, water, cassava, and rice samples.

These laboratory facilities enabled accurate preparation, processing, and analysis of samples to determine the concentrations of heavy metals in different environmental media.

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Survey Design and Field Techniques

The Vertical Electrical Sounding (VES) and two-dimensional (2-D) electrical resistivity imaging methods were adopted in this study to investigate subsurface resistivity variations, delineate aquifer depth, identify fracture systems, and assess possible zones of contamination beneath the investigated dumpsites. The combined application of VES and 2-D resistivity imaging provided both vertical and lateral characterization of the subsurface conditions within the study area.

Vertical Electrical Sounding (VES)

The VES survey was conducted using the Schlumberger electrode configuration, which is effective for vertical subsurface profiling and depth investigation. A maximum total electrode spread length (L) of 240 m was employed at each VES station. The midpoint of the electrode array was fixed, while the current electrodes were symmetrically expanded about the center point during measurements. A distance of 120 m (L/2) was covered on both sides of each traverse.

VES stations were strategically located at suitable positions within the dumpsites, and the traverses were oriented against the natural drainage direction to enhance the detection of leachate migration pathways. Field resistance values were measured directly in ohms (Ω) at each electrode spacing using the digital resistivity instrument operated at a constant current cycle. Electrical current (I) was injected into the subsurface through the outer current electrodes, while the corresponding potential difference (V) was measured across the inner potential electrodes. Measurements were taken at progressively increasing electrode separations to achieve greater depth penetration.

All necessary precautions required for reliable geo-electrical measurements were duly observed. These included ensuring good electrode–ground contact, maintaining straight electrode alignment, minimizing cultural and electromagnetic noise, and avoiding buried metallic objects where possible. Data acquisition was carried out under favorable weather conditions to reduce the influence of soil moisture variability. Each VES location required approximately 1 hour and 30 minutes to complete.

The measured field resistance (R) was used to compute the apparent resistivity (ρ_a) using the standard relation:

$\rho a = K \times R$ (Ω-m), ------------ (1)

Where: K = geometric factor of electrode spread; R = field resistance = I/V (Ohms).

I = current passed to the earth through electrodes, and V = Corresponding voltage

Equation (1) can be expressed as follows:

$$\rho a\ (Ohm - m) = \frac{\pi\left[\left(\frac{L}{2}\right)2 - \left(\frac{l}{2}\right)2\right]}{l} \times \mathrm{R}$$

L = Current Electrode spread, I = Potential Electrode spread

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All VES field data were processed using Advanced Geosciences Incorporated (AGI) 1D resistivity inversion software. The inversion results provided subsurface resistivity models from which lithologic layers, layer thicknesses, aquifer depth, fracture zones, and possible leachate-affected zones were delineated.

Two-Dimensional (2-D) Electrical Resistivity Imaging

In addition to the VES survey, two-dimensional (2-D) electrical resistivity imaging was carried out using the dipole–dipole electrode configuration to investigate the lateral and vertical distribution of subsurface resistivity beneath the investigated dumpsites. The dipole–dipole array was selected because of its high sensitivity to lateral resistivity variations and its effectiveness in mapping fractures, lithologic discontinuities, contaminant plumes, and leachate migration pathways within heterogeneous subsurface environments.

The electrode array consisted of equally spaced electrodes connected through multicore cables to the resistivity meter. Electrical current was introduced into the ground through one pair of electrodes, while the resulting potential difference was measured using another pair of electrodes positioned at varying separations along the survey line. Measurements were acquired systematically along the traverse using progressive electrode expansion to obtain deeper sub-surface information.

The acquired apparent resistivity data were processed and inverted using standard 2-D resistivity inversion software (Res2Dinv software) to generate inverse resistivity sections representing the spatial distribution of subsurface resistivity beneath the dumpsites. The inverted resistivity models were subsequently interpreted to identify conductive leachate-impacted zones, lithologic variations, fractured shale horizons, and groundwater-bearing formations within the study area.

Physicochemical and Heavy Metal Analysis of Soil Samples

Physicochemical Analysis of Soil Samples

Physicochemical parameters of the soil samples, including pH, electrical conductivity (EC), temperature, and total dissolved solids (TDS), were determined using standard laboratory procedures. Soil pH was measured in a 1:2.5 soil-to-distilled water suspension using a calibrated digital pH meter. Electrical conductivity (EC) and total dissolved solids (TDS) were measured in the soil-water extract using a calibrated conductivity/TDS meter. Soil temperature was determined in situ at the sampling locations using a soil thermometer immediately after sample collection.

Heavy Metal Analysis of Soil Samples

Soil samples were analyzed for selected heavy metals including Pb, Cd, Cr, Zn, Cu, Ni, Fe, Ba, Hg, V, and As using an Agilent FS240AA Atomic Absorption Spectrophotometer (AAS), following standard procedures recommended by the American Public Health Association (APHA, 1995).

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Sample Digestion:

Approximately 2.0 g of homogenized and sieved soil sample was weighed into a pre-cleaned Teflon digestion vessel. About 20 mL of acid mixture comprising concentrated HNO_3, perchloric acid ($HClO_4$), and concentrated H_2SO_4 was added to the sample. For arsenic determination, a separate digestion using HNO_3 and H_2O_2 was adopted to minimize arsenic volatilization during digestion. The mixture was heated on a hot plate at temperatures between 95–120 °C until near dryness to ensure complete digestion of organic matter. After cooling, the digest was diluted with distilled deionized water, filtered, and transferred into a 100 mL volumetric flask.

The digested extracts were subsequently analyzed using Atomic Absorption Spectroscopy (AAS) for quantification of the selected heavy metals. Hydride Generation Atomic Absorption Spectroscopy (HG-AAS) was employed specifically for arsenic determination because of its higher sensitivity for trace arsenic detection. Appropriate hollow cathode lamps were selected for each element, and calibration was carried out using analytical-grade standard solutions. Blanks and standard reference materials were analyzed alongside the samples to ensure analytical accuracy and precision. Metal concentrations in the soil samples were expressed in mg/kg dry weight.

Physicochemical and Heavy Metal Analysis of Surface Water Samples

Physicochemical Analysis of Water Samples

Physicochemical parameters of surface water samples, including pH, electrical conductivity (EC), total dissolved solids (TDS), temperature, and dissolved oxygen (DO), were measured using a portable multi-parameter water quality meter. Turbidity was determined using a nephelometric turbidity meter following standard procedures.

Heavy Metal Analysis of Water Samples

Surface water samples collected from ponds and surface water bodies around the investigated dumpsites were analyzed for selected heavy metals including Pb, Cd, Cr, Zn, Cu, Ni, Fe, Ba, Hg, V, and As.

Sample Preservation:

Immediately after collection, water samples were stored in pre-cleaned acid-washed glass bottles. To prevent microbial activity and adsorption of dissolved metals onto container walls, samples were preserved by acidification with ultrapure HNO_3 to pH values < 2.

Digestion Procedure:

A measured portion of each preserved water sample was transferred into a digestion flask, and 5 mL of concentrated HNO_3 was added. The samples were heated gently at temperatures between 95–120 °C until the volume was reduced. For arsenic determination, additional H_2O_2 treatment was applied to ensure complete oxidation of arsenic species.

After digestion, the samples were cooled, filtered through Whatman No. 42 filter paper, and diluted to 50 mL with deionized water in a volumetric flask.

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Heavy metal concentrations were determined using Flame Atomic Absorption Spectroscopy (FAAS), while arsenic was analyzed using Hydride Generation Atomic Absorption Spectroscopy (HG-AAS) for improved analytical sensitivity. Calibration was performed using multi-element standard solutions, and only calibration curves with correlation coefficients (R^2) ≥ 0.995 were accepted.

The concentrations of heavy metals were expressed in mg/L. Analytical quality assurance was maintained through the use of replicate analyses, reagent blanks, and certified reference water standards.

RESULTS

Vertical Electrical Sounding (VES)

The Vertical Electrical Sounding (VES) data acquired from selected dumpsites in Abakaliki Metropolis, are presented in Tables 1-6 and Figure 2-5. One-dimensional (1D) resistivity inversion of the geoelectrical data delineated subsurface resistivity layers, corresponding layer thicknesses, depths, and inferred lithological units.

Table 1. Geo-electric layers for VES 1 (Rice mill Dumpsite)

Layer	Resistivity (Ω·m)	Thickness (m)	Bottom Depth (m)
1	11.73	0.506	0.506
2	21,611	0.001	0.506
3	364,928	0.000	0.507
4	36,484	0.022	0.529
5	45,070	0.270	0.798
6	1,536	0.121	0.920
7	6,918	0.001	0.921
8	118.44	1.507	2.428
9	1,758	7.140	9.568
10	1,278	17.916	27.484
11	265	8.462	35.946
12	0.18	–	–

Table 2. Constrained Lithologic layers for VES 1

Layer	Resistivity (Ω·m)	Bottom Depth (m)	Lithology
1	11.73	0.506	Topsoil / Weathered shale
2	6,918	0.921	Sandstone (Subsoil)
3	118.44	2.428	Partially Weathered/Fractured Saturated Shale (Subsoil)
4	1,758	9.568	Siltstone
5	1,278	27.484	Siltstone (Upper water table)
6	265	35.946	Sand (Lower water table)
7	0.18	—	Saturated aquifer unit

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Figure 2. VES 1, Location of Dumpsite: Abakaliki Rice Mill, Coordinates: N6.323207; E8.132793, Elevation: 150FT, Direction Layout: Against drainage

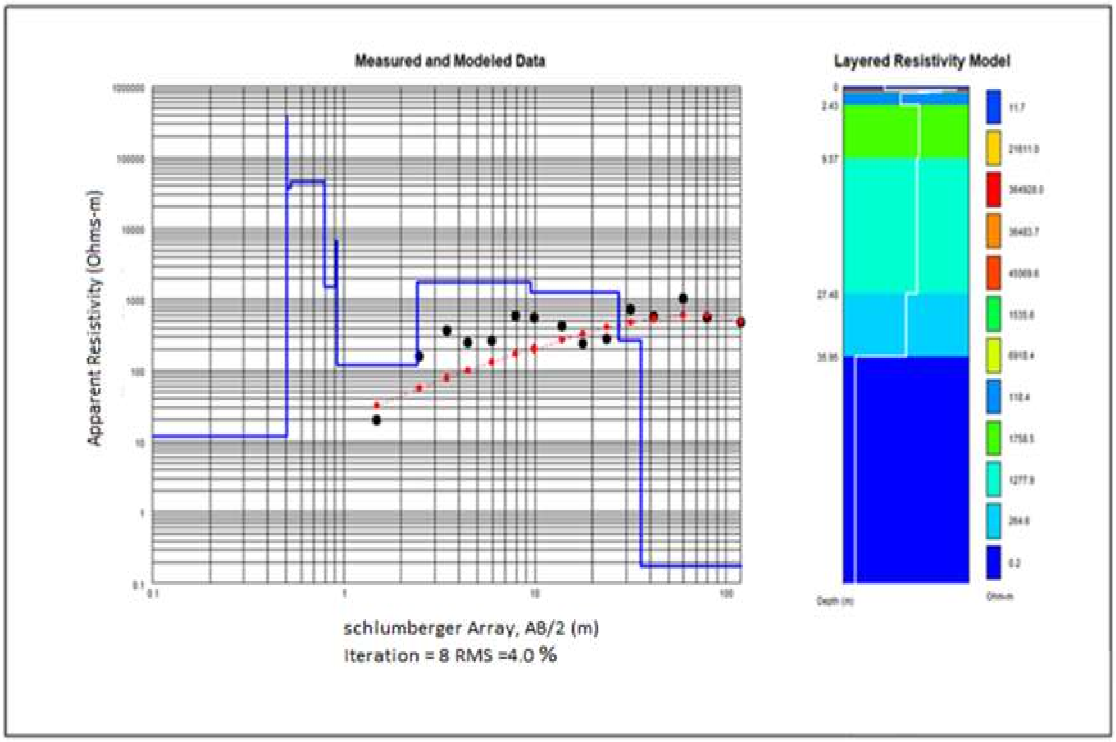

Table 3. Geo-electric layers for VES 2 (Umuoghara Dumpsite)

Layer	Resistivity (Ω·m)	Thickness (m)	Bottom Depth (m)
1	7.20	0.403	0.403
2	6.15	0.210	0.612
3	19.03	0.125	0.738
4	110	0.055	0.793
5	238	0.152	0.945
6	24,201	1.576	2.520
7	16,395	2.049	4.569
8	6,143	0.401	4.971
9	1,234	1.113	6.083
10	3.04	11.378	17.461
11	0.41	38.719	56.180
12	762	–	

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Table 4. Constrained Lithologic layers for VES 2

Layer	Resistivity (Ω·m)	Bottom Depth (m)	Lithology
1	7.20	0.700	Topsoil / Weathered shale
6	24,201	2.520	Sandstone
7	16,395	4.569	Siltstone
9	1,234	6.083	Silty sand
10	3.04	17.461	Fractured saturated shale / sandy layer (Upper water table)
11	0.41	56.180	Sand (Lower water table)
12	762	—	Shale / Sandy clay

Figure 3. VES 2, Location of Dumpsite: Umuoghara Waste Dump Site, Coordinates: N6.3539483; E8.0453599, Elevation: 249ft, Direction Layout: Against Drainage

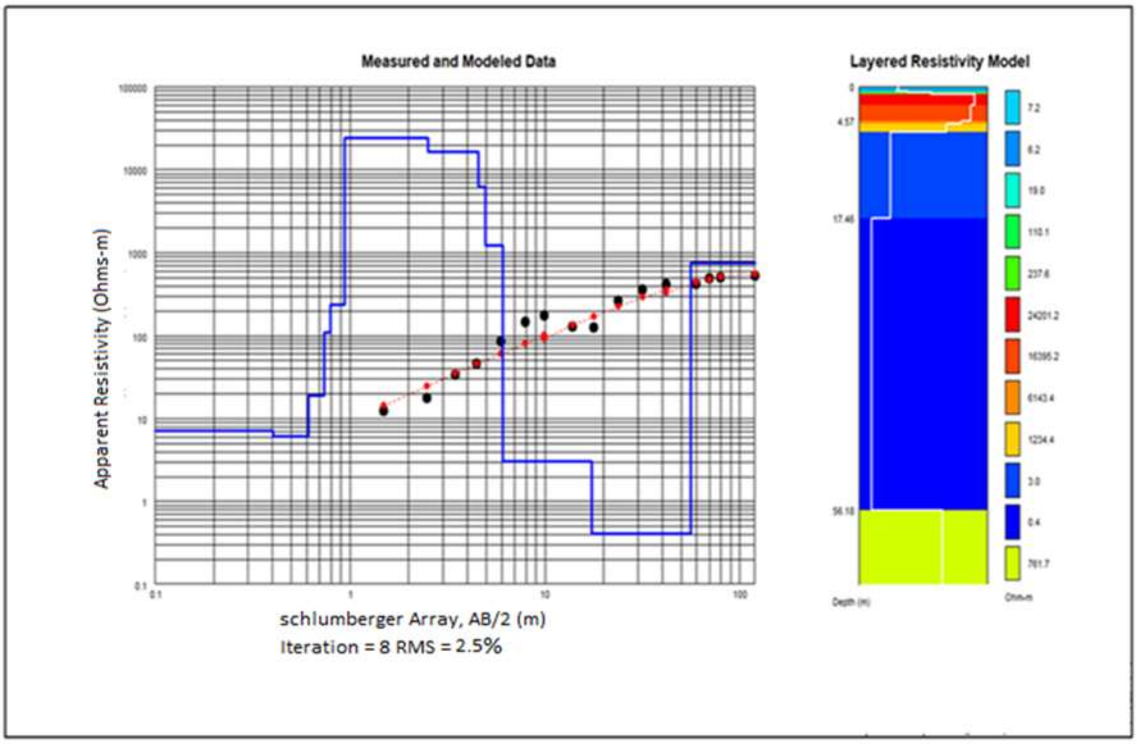

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Table 5. Geo-electric layers for VES 3 (Mechanic Village Dumpsite)

Layer	Resistivity (Ω·m)	Thickness (m)	Bottom Depth (m)
1	12.30	0.700	0.700
2	170	1.300	2.000
3	781	2.200	4.200
4	460	4.010	8.210
5	165	4.410	12.620
6	301	5.610	18.230
7	3,233	6.270	24.500
8	4,113	6.300	30.800
9	6,111	4.200	35.000
10	2,115	3.500	38.500
11	405	1.500	40.000
12	2.50	—	

Table 6. Constrained Lithologic layers for VES 3

Layer	Resistivity (Ω·m)	Bottom Depth (m)	Lithology
1	12.00	1.400	Topsoil / Weathered shale
2	781	4.600	Lateritic sandy clay
3	165	12.620	Weathered shale (Upper water table)
4	3,232	24.230	Sandstone
5	6,111	31.320	Sandstone
6	405	40.000	Fractured shale
7	2.50	—	Fractured shale (Lower water table)

Figure 4. VES 3, Location of Dumpsite: Mechanic Village Waste Dump Site, Coordinates: N6.30839; E8.132407, Elevation: 115ft, Direction Layout: Against Drainage.

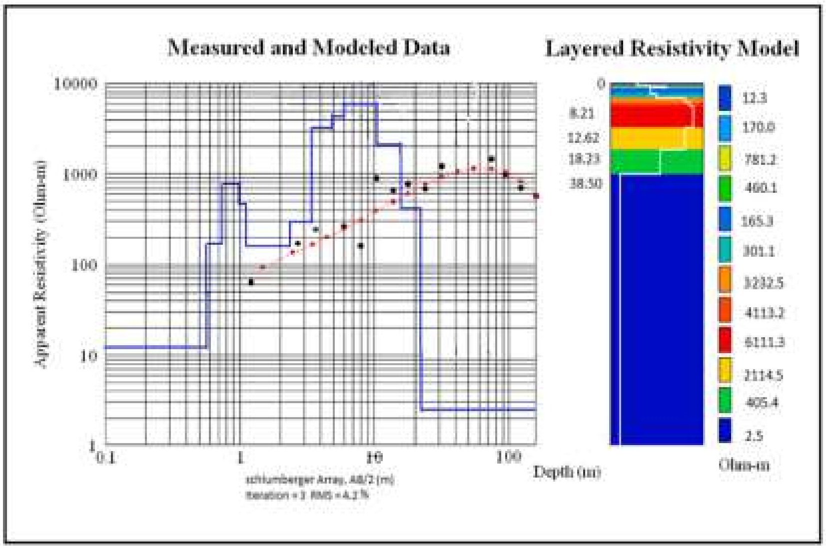

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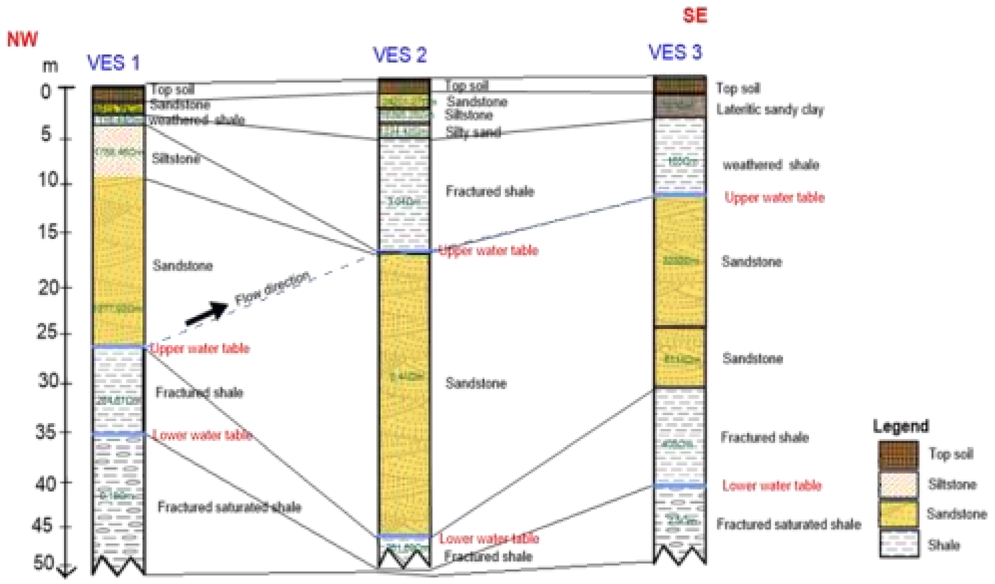
Figure 5. Electrical Resistivity Sections Derived from VES 1, VES 2, and VES 3 Showing Subsurface Lithology and Aquifer Zones (NW–SE Profile).



The summary of resistivity-derived subsurface units and inferred hydrogeological conditions from VES surveys at Abakaliki dumpsites is presented in Table 7, while Figure 6 presents a conceptual model summarizing the inferred subsurface conditions beneath the Abakaliki dumpsites based on VES data.

Table 7. Summary of Subsurface Resistivity Characteristics and Hydrogeological Interpretation at Abakaliki Dumpsites

Unit	Depth (m)	Resistivity (Ω-m)	Inferred Lithology	Hydrogeological Interpretation
Topsoil / Weathered zone	0–0.5 (VES-1) 0–0.7 (VES-2)	7–19; 11.7	Weathered shale / clayey topsoil	Highly conductive, moisture-rich, possible leachate-affected zone
Shallow subsoil	0.9–6.0	118–24,201	Partially weathered shale with localized sandstone lenses	Low–moderate permeability; sandstone lenses act as preferential flow paths
Intermediate subsoil	2.4–27.0	1,277–1,758	Siltstone / consolidated shale	Relatively competent layer; limits flow except where fractured
Upper water table	6.0–17.5	0.4–3.0	Fractured saturated shale / sandy layer	High groundwater saturation; vulnerable aquifer zone

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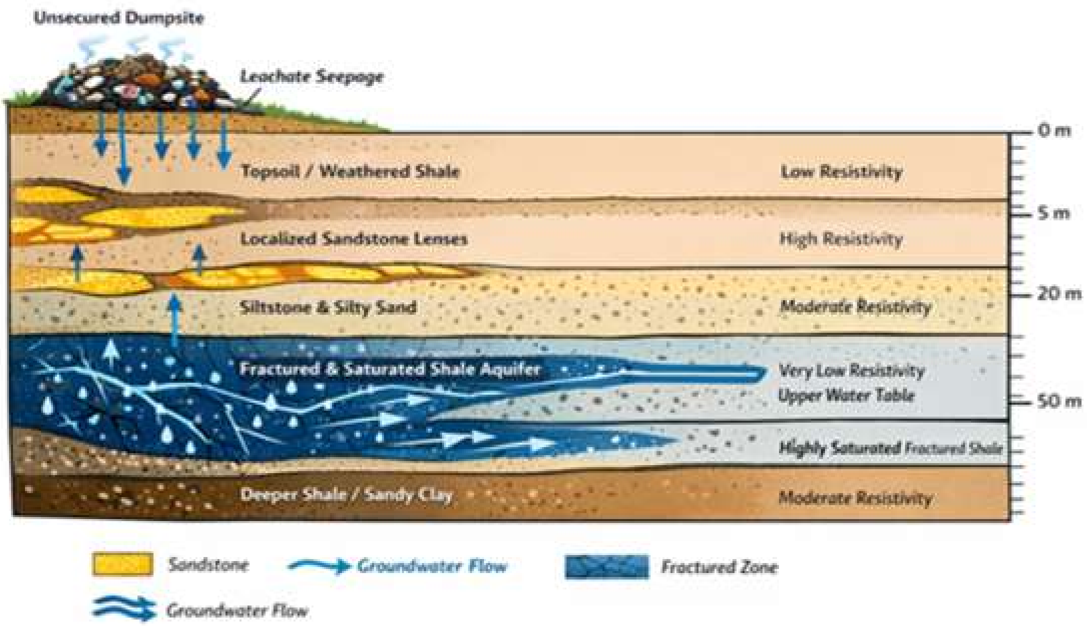
Lower water table	27–56.0	0.18–264	Fractured saturated shale	Principal structurally controlled aquifer
Deep unit	>56.0	~ 760	Shale / sandy clay	Reduced permeability; basal confining layer

Figure 6. Conceptual subsurface model of Abakaliki dumpsite geology showing shale-dominated stratigraphy, localized sandstone lenses, fracture-controlled aquifers, and leachate migration pathways.



The resistivity values obtained from the VES survey were further used to estimate the electrical conductivity of subsurface pore fluids using the inverse relationship between resistivity and conductivity ($\sigma = 1/\rho$). Where,

σ = electrical conductivity (S/m)

ρ = resistivity (Ωm).

The calculated conductivity values provide an indirect assessment of leachate presence and intensity within the subsurface beneath the investigated dumpsites. The estimated leachate conductivity and its classification relative to groundwater quality are presented in Tables 8 and 9, while the spatial distribution of the leachate plume is shown in Figure 7.

Table 8. Groundwater Classification

Water type	Conductivity (µS/cm)
Fresh groundwater	50 – 500
Slightly polluted	500 – 1500
Contaminated	1500 – 3000
Landfill leachate	> 3000

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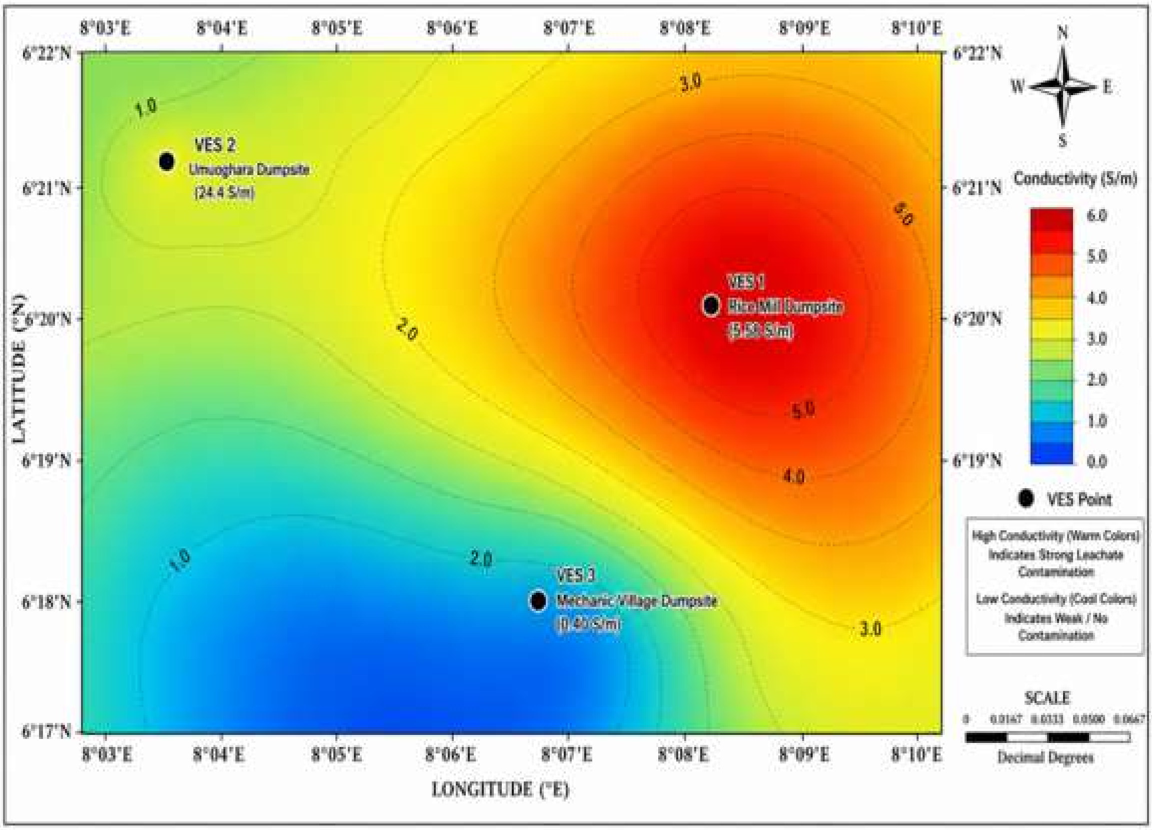
Table 9. Estimated Leachate Conductivity in the Study Area

S/N	VES Point	Location	X (Latitude)	Y (Longitude)	Z (Conductivity) (S/m)	Conductivity (µS/cm)	Inferred Leachate Strength
1	VES 1	Rice Mill Dumpsite	6.32262	8.133473	5.56	55,600	Very strong
2	VES 2	Umuoghara Dumpsite	6.351212	8.045333	2.44	24,400	Strong
3	VES 3	Mechanic Village Dumpsite	6.30839	8.132407	0.40	4,000	Contaminated

Figure 7. Leachate plume map (conductivity distribution)



Two-dimensional (2-D) Electrical Resistivity Imaging

Two-dimensional (2-D) electrical resistivity imaging was carried out across the investigated dumpsites using the dipole–dipole electrode configuration to delineate the lateral and vertical extent of subsurface contamination associated with leachate migration. The dipole–dipole array was adopted because of its high sensitivity to lateral resistivity variations and its effectiveness in mapping fracture zones, contaminant plumes, and lithological discontinuities within heterogeneous subsurface environments.

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The acquired field data were processed and inverted using standard resistivity inversion software (Res2dinv) to generate 2-D inverse resistivity sections representing the spatial distribution of subsurface resistivity beneath the investigated dumpsite. The 2-D inverse resistivity sections obtained from the Rice Mill dumpsite, Umuoghara dumpsite, and Mechanic Village dumpsite are presented in Figures 8, 9, and 10, respectively.

Figure 8. Rice Mill Dumpsite 2-D Inverse Resistivity Section

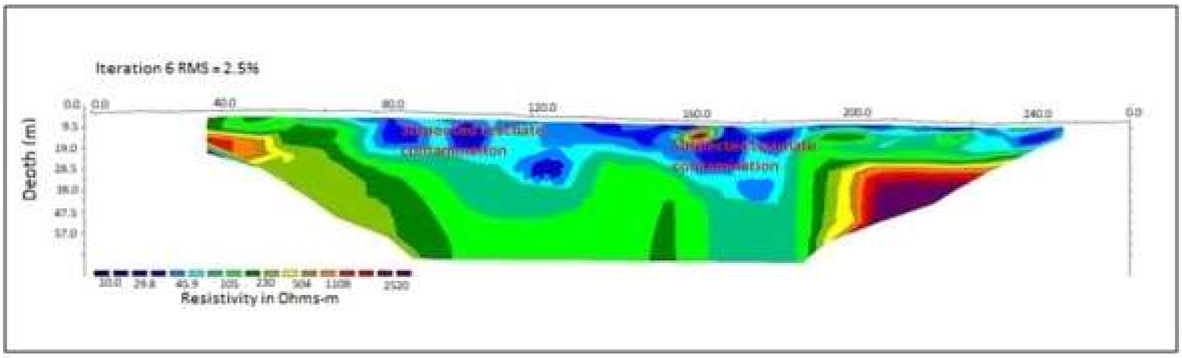


Figure 9. Umuoghara Dumpsite 2-D Inverse Resistivity Section

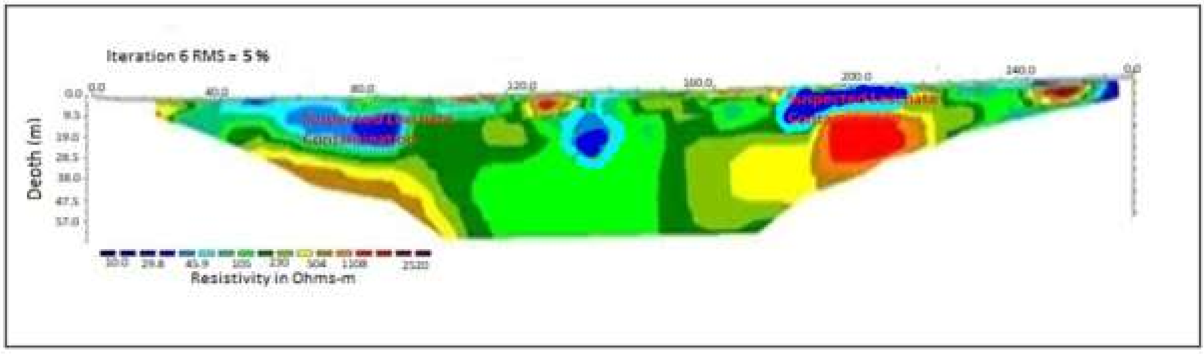
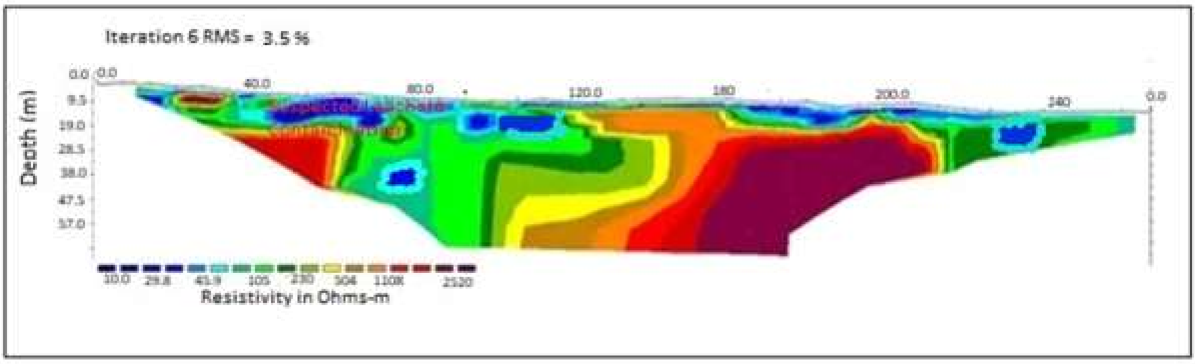


Figure 10. Mechanic Village Dumpsite 2-D Inverse Resistivity Section



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Hydrochemical and Geochemical Validation of Geophysical Results

To complement the geophysical interpretation derived from the Vertical Electrical Sounding (VES) survey, physicochemical and heavy metal analyses were carried out on selected water and soil samples collected from the investigated dumpsites within Abakaliki metropolis. The laboratory results provide additional evidence regarding the extent of subsurface contamination inferred from the resistivity data.

Physicochemical Characteristics of Water Samples

The physicochemical characteristics of water samples collected from the study area are presented in Table 10. The analyzed parameters include electrical conductivity, temperature, salinity, pH, and total dissolved solids (TDS).

The measured conductivity values ranged from 43.20 to 65.10 µS/cm, while TDS values ranged between 14.20 and 27.20 mg/L. Although these values fall within the World Health Organization (WHO) permissible limits for freshwater, slight variations observed among the sampling locations may reflect localized influence of leachate infiltration within the shallow groundwater system. The pH values ranged from 6.47 to 6.67, indicating slightly acidic to near-neutral groundwater conditions.

The relatively low conductivity values recorded in the analyzed water samples compared with the very high conductivity values inferred from the VES-derived pore-fluid conductivity suggest that contamination is more pronounced within the shallow subsurface pore spaces and weathered zones than within the sampled surface water bodies. This observation supports the interpretation that contaminant migration is occurring primarily through fracture-controlled subsurface pathways beneath the dumpsites.

Table 10. Physicochemical Characteristics of Water Samples (WHO, 2017)

Parameter	WSL1	WSL2	WSL3	WHO Guideline	Unit
Conductivity	49.20	43.20	65.10	1000	µS/cm
Temperature	28	28	28	Ambient	°C
Salinity	0.01	0.01	0.01	Freshwater	Psu
PH	6.61	6.47	6.67	6.5–8.5	-
TDS	27.20	14.20	22.18	500	mg/L

Note: WSL1 = Umuoghara dumpsite; WSL2 = Rice Mill dumpsite; WSL3 = Mechanic Village dumpsite.

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Physicochemical Characteristics of Soil Samples

The physicochemical properties of soil samples collected from the dumpsites are presented in Table 11. The measured parameters include electrical conductivity, salinity, pH, total dissolved solids, cation exchange capacity (CEC), and sodium adsorption ratio (SAR).

The soil samples exhibited slightly acidic pH values ranging from 5.98 to 6.10, indicating chemically altered soil conditions possibly associated with prolonged waste decomposition and leachate infiltration. Electrical conductivity values ranged from 190 to 197 µS/cm, while TDS values ranged between 195 and 243 mg/L.

Although the conductivity values fall within the non-saline category according to FAO/WHO standards, the slightly acidic conditions and elevated dissolved constituents indicate progressive geochemical alteration of the near-surface environment. These observations agree with the low resistivity values identified within the topsoil and weathered shale units during the VES interpretation.

The relatively low cation exchange capacity values recorded in the soils further suggest limited buffering capacity against contaminant migration, thereby increasing the vulnerability of the shallow subsurface to pollution.

Table 11. Physicochemical Characteristics of Soil Samples (FAO/WHO, 2007)

Parameter	SSL1	SSL2	SSL3	FAO/WHO Guideline	Unit
Electrical Conductivity	197	190	196	< 4000 (Non-saline)	µS/cm
Temperature	37	36	36	–	°C
Salinity	0.104	0.023	0.123	< 4 (Non-saline)	Psu
PH	6.04	5.98	6.10	6.5–7.5 (Optimal)	–
Total Dissolved Solids (TDS)	195	243	221	–	mg/L
Sodium (Na^+)	0.1298	0.1462	0.1367	< 1	mEq/kg
Calcium (Ca^{2+})	0.0967	0.0978	0.0832	–	mEq/kg
Magnesium (Mg^{2+})	0.1054	0.1267	0.1167	–	mEq/kg
Cation Exchange Capacity (CEC)	0.3319	0.3707	0.3366	> 10 (Good fertility)	cmol/kg
Sodium Adsorption Ratio (SAR)	0.112653	0.120062	0.11781	< 13 (Non-sodic)	–

Note: SSL1 = Umuoghara dumpsite; SSL2 = Rice Mill dumpsite; SSL3 = Mechanic Village dumpsite.

Heavy Metal Concentrations in Water Samples

The concentrations of selected heavy metals in water samples are presented in Table 12. While the variation in heavy metal concentrations among the water samples (WSL1, WSL2, and WSL3) is presented in Figure 11. The analyzed metals include Fe, Zn, Hg, Cr, Pb, Cd, Ni, Cu, Ba, and V.

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The results indicate elevated concentrations of several potentially toxic metals above WHO permissible limits. Particularly significant are the concentrations of mercury (Hg), lead (Pb), cadmium (Cd), nickel (Ni), and chromium (Cr), which exceed recommended drinking water standards in several sampling locations.

Nickel concentrations ranged from 4.154 to 4.455 mg/L, greatly exceeding the WHO permissible limit of 0.07 mg/L. Similarly, cadmium concentrations ranged from 0.022 to 0.086 mg/L, exceeding the allowable limit of 0.003 mg/L. Elevated lead and mercury concentrations were also observed across the investigated locations.

These elevated heavy metal concentrations strongly support the geophysical interpretation of leachate-contaminated groundwater systems beneath the dumpsites. The occurrence of highly conductive, low-resistivity zones within fractured shale aquifers is therefore attributed not only to moisture saturation but also to the presence of dissolved ionic contaminants derived from the decomposition of waste.

Table 12. Heavy Metal Concentrations in Water Samples Compared with WHO Permissible Limits (WHO, 2017)

Metal (mg/L)	WSL1 Umuoghara dumpsite	WSL2 Rice mill dumpsite	WSL3 Mechanic village dumpsite	WHO Permissible Limit
Iron (Fe)	0.2282	2.9374	0.3346	0.30
Sodium (Na)	0.0148	0.0006	0.0031	200
Zinc (Zn)	0.3114	1.1161	0.3456	3.0
Mercury (Hg)	0.015	0.012	0.022	0.006
Chromium (Cr)	0.012	0.027	0.058	0.05
Arsenic (As)	0.001	0.000	0.004	0.01
Lead (Pb)	0.016	0.022	0.019	0.01
Cadmium (Cd)	0.022	0.086	0.033	0.003
Copper (Cu)	0.016	0.022	0.034	2.0
Nickel (Ni)	4.455	4.382	4.154	0.07
Barium (Ba)	0.034	0.027	0.056	0.7
Vanadium (V)	0.007	0.017	0.014	NL

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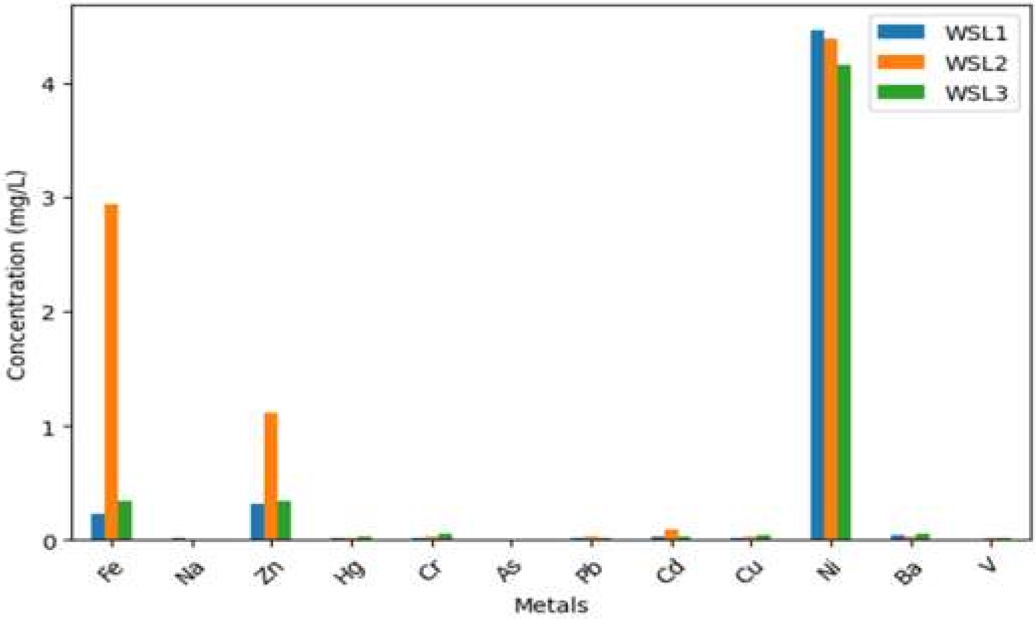
Figure 11. Heavy metal concentrations (mg/L) in water samples across the three study locations relative to World Health Organization standards (2017)



Heavy Metal Concentrations in Soil Samples

The concentrations of heavy metals detected in soil samples collected from the investigated dumpsites are presented in Table 13. While graphical representation of the distributions of heavy metals across the sampling locations is illustrated in Figure 12. The results indicate detectable concentrations of several metals, including Fe, Zn, Hg, Cr, Pb, Cd, Ni, Cu, Ba, and V. Although most measured values remain below FAO/WHO soil guideline limits, the occurrence of elevated nickel concentrations across all sampling locations suggests progressive accumulation of trace metals within the topsoil environment. The presence of mercury, lead, and cadmium further indicates anthropogenic influence associated with prolonged waste disposal activities.

These geochemical observations corroborate the low-resistivity conductive topsoil conditions identified in the VES models and support the inference of chemically enriched leachate-affected zones beneath the dumpsites.

Table 13. Heavy Metal Concentrations in Soil Samples Compared with FAO/WHO Soil Guidelines (2007)

Metal (mg/kg)	SSL1 Umuoghara dumpsite	SSL2 Rice mill dumpsite	SSL3 Mechanic village dumpsite	FAO/WHO Guideline
Iron (Fe)	5.0776	6.0602	5.1030	200–500 mg/kg
Sodium (Na)	0.00636	0.1243	0.1477	Not Specified
Zinc (Zn)	1.6933	3.1806	3.6232	50–300 mg/kg

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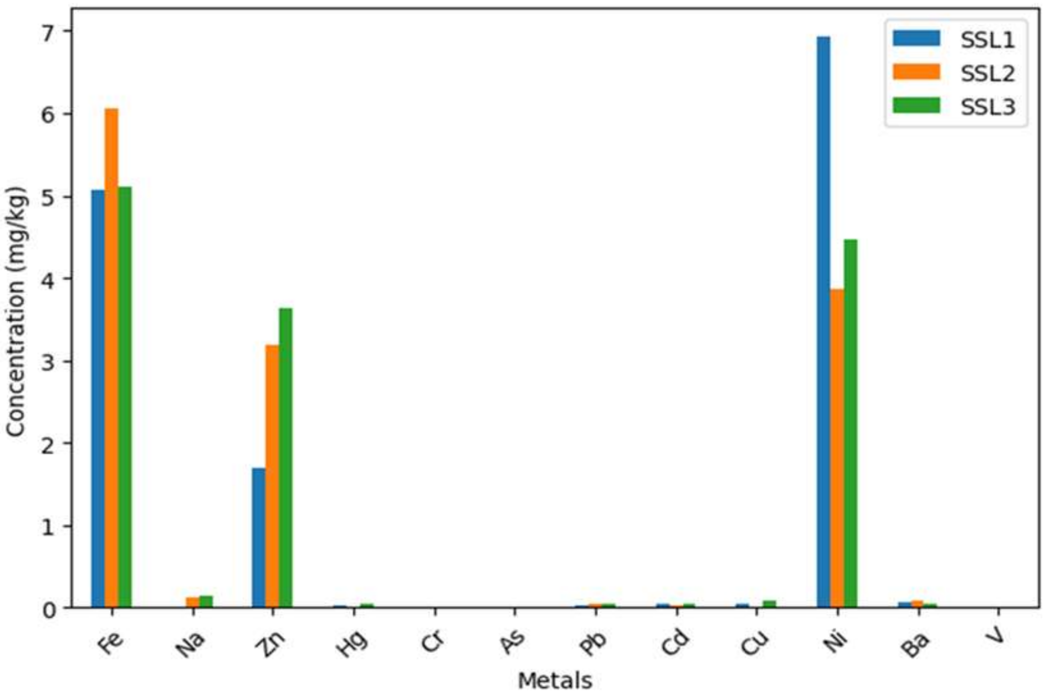
Mercury (Hg)	0.020	0.010	0.034	1 mg/kg
Chromium (Cr)	0.011	0.008	0.012	100 mg/kg
Arsenic (As)	0.003	0.010	0.007	20 mg/kg
Lead (Pb)	0.018	0.035	0.035	50 mg/kg
Cadmium (Cd)	0.040	0.032	0.034	3 mg/kg
Copper (Cu)	0.037	0.011	0.089	100 mg/kg
Nickel (Ni)	6.927	3.873	4.465	50 mg/kg
Barium (Ba)	0.055	0.086	0.048	750 mg/kg
Vanadium (V)	0.013	0.006	0.009	50 mg/kg

Figure 12. Heavy metal concentrations in soil samples from the investigated dumpsites relative to FAO/WHO soil guideline values.



DISCUSSION

The Vertical Electrical Sounding (VES) surveys conducted at the dumpsites within Abakaliki metropolis provide insight into subsurface lithology, groundwater occurrence, and the susceptibility of the area to contamination. The Abakaliki area is predominantly underlain by shale of the Lower Benue Trough, where groundwater occurrence is mainly controlled by secondary porosity associated with fractures, joints, and weathered zones. The geoelectric characteristics obtained in this study are consistent with this regional geological framework.

The interpreted sounding curves predominantly exhibit H- and K-type characteristics, typical of multilayer sedimentary environments and indicative of alternating conductive and resistive subsurface materials. The Rice Mill dumpsite (VES 1) shows a KHK-type curve, reflecting

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alternating resistive and conductive layers associated with sandstone units separated by fractured shale horizons. The Umuoghara dumpsite (VES 2) exhibits an HKH-type curve characterized by a conductive near-surface layer, an underlying resistive unit, and a deeper conductive zone. The Mechanic Village dumpsite (VES 3) also displays a KHK-type curve, indicating successive resistive and conductive layers corresponding to lateritic material, weathered shale, sandstone, and deep fractured shale. These curve types reflect alternating competent and conductive layers typical of fractured shale formations with moisture-bearing horizons.

VES 1 (Rice Mill Dumpsite)

At the Rice Mill dumpsite, the very low resistivity values observed in the near-surface layer indicate the presence of conductive materials within the topsoil and shallow subsurface. Such low resistivity conditions are commonly associated with moisture-rich and chemically enriched soils, which are typical beneath long-term waste disposal sites. The occurrence of highly resistive units at shallow depths suggests localized lithologic variations within the shale sequence, consistent with the presence of competent sandstone or siltstone layers.

At intermediate depths, the alternating moderate to high resistivity layers suggest relatively compact and less conductive units, which may act as partial barriers to vertical fluid movement. However, the presence of a lower resistivity zone at greater depth indicates a saturated subsurface interval capable of transmitting fluids. The extremely low resistivity value recorded in the deepest layer strongly suggests a highly conductive zone, which is characteristic of saturated fractured media. In dumpsite environments, such zones are particularly vulnerable to contamination because they can serve as preferential pathways for downward migration of leachate-derived contaminants.

VES 2 (Umuoghara Dumpsite)

The Umuoghara dumpsite exhibited a similar but more pronounced resistivity pattern. Very low resistivity values in the shallow subsurface indicate highly conductive topsoil conditions, likely influenced by prolonged waste deposition and leachate infiltration. The identification of a distinct high-resistivity layer at shallow depth suggests localized competent lithologies embedded within the dominant shale sequence. Of particular significance is the presence of extensive low-resistivity zones at intermediate and greater depths. These zones reflect highly conductive subsurface conditions, consistent with saturated and fractured shale horizons. The vertical continuity of low resistivity from shallow to deeper layers at Umuoghara indicates enhanced permeability and connectivity within the subsurface, which facilitates downward movement of fluids. This condition implies a higher susceptibility of the subsurface environment to contaminant transport when compared with more resistive and compact geological settings.

VES 3 (Mechanic Village Dumpsite)

The geo-electric sequence obtained from VES 3 shows strong resistivity contrasts with depth, reflecting marked variation in subsurface materials beneath the dumpsite. The very low resistivity recorded in the uppermost layer indicates highly conductive near-surface conditions. Such low values at shallow depth are characteristic of moisture-rich and ion-concentrated materials commonly associated with refuse dumps, where infiltrating fluids increase the electrical conductivity of the soil.

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Below the surface, resistivity values increase within the intermediate layers and then fluctuate, suggesting alternation of relatively compacted and less compacted subsurface materials. The moderate resistivity zone around 12.62 m depth represents a water-bearing horizon. Because this horizon occurs at relatively shallow depth and lies directly beneath the conductive topsoil, it is highly susceptible to downward percolation of infiltrating fluids from the surface. At greater depths, the very high resistivity zones indicate more competent and consolidated formations. However, the subsequent reduction in resistivity below about 38–40 m depth signifies the presence of another saturated zone. The occurrence of this deeper conductive layer suggests groundwater accumulation within fractured materials.

However, the electrical characteristics reveal that infiltration from the dumpsite has influenced the shallow subsurface, creating conductive conditions in the upper layers and increasing the vulnerability of the shallow groundwater horizon. Although deeper layers show relatively higher resistivity, the presence of fractures provides potential pathways for vertical migration of fluids, indicating a possible risk of groundwater quality deterioration at depth.

Shale-Dominated Near-Surface Conditions

Both VES locations reveal very low resistivity values at shallow depths (7.20–19.03 Ωm in VES 2 and ~11.73 Ωm in VES 1), which are interpreted as topsoil and weathered shale. Shale-derived soils are typically clay-rich and retain moisture, resulting in low resistivity values. The extremely low resistivity at the surface around the dumpsites may also reflect enhanced conductivity due to leachate infiltration, given the proximity to unmanaged waste disposal.

Localized Sandstone Occurrence within Shale

Despite the dominance of shale, the VES results clearly identify localized high-resistivity layers (>6,000 Ωm to >24,000 Ωm) at shallow to intermediate depths. These layers are interpreted as sandstone or sandy lenses interbedded within the shale sequence. In VES 2, a sandstone unit was encountered between depths of approximately 0.95 m and 2.52 m, while in VES 1, thin but highly resistive layers occur just beneath the weathered shale.

These sandstone bodies are not laterally extensive but occur as localized units controlled by sedimentary variation and structural deformation. Within the Abakaliki area, such sandstone interbeds play a crucial role in enhancing groundwater movement, especially where they intersect fractured shale zones.

Fracture-Controlled Aquifer Systems

A major finding of this study is the identification of deep, very low-resistivity zones interpreted as fractured and saturated shale aquifers. In VES 1, a resistivity value as low as 0.18 Ωm was recorded at depth, while VES 2 recorded 0.41–3.04 Ωm within the upper and lower water table zones. These extremely low values indicate high moisture content and conductive pore fluids.

In shale terrains such as Abakaliki, primary porosity is negligible; therefore, groundwater accumulation is controlled by fracture networks and weathered zones. The thickness and depth extent of the low-resistivity layers observed in this study confirm the presence of structurally controlled aquifer systems, rather than uniform porous aquifers.

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Leachate Migration and Groundwater Contamination Inferred from VES Conductivity

The electrical conductivity values estimated from the resistivity data provide further insight into the hydrogeochemical condition of the subsurface beneath the investigated dumpsites. The calculated conductivity values ranged from approximately 3,300 µS/cm to 55,600 µS/cm, which are far above the typical conductivity range of natural freshwater (50–500 µS/cm). Such elevated conductivity values are characteristic of dumpsite leachate–impacted groundwater and indicate the presence of ion-rich pore fluids within the subsurface.

The highest conductivity was recorded beneath the Rice Mill dumpsite, followed by the Umuoghara dumpsite, while comparatively lower but still elevated values were obtained at the Mechanic Village dumpsite. The vertical occurrence of these conductive zones within the fractured shale horizons suggests downward migration of leachate from the surface through permeable pathways such as weathered zones, fractures, and localized sandy interbeds. In shale-dominated terrains, groundwater storage is largely controlled by secondary porosity, and therefore any infiltrating leachate can easily accumulate within these fracture networks.

Two-Dimensional (2-D) Electrical Resistivity Imaging

The 2-D electrical resistivity imaging results provide detailed insight into the lateral and vertical distribution of subsurface contamination beneath the investigated dumpsites. The dipole–dipole resistivity sections complement the Vertical Electrical Sounding (VES) interpretation by delineating conductive leachate-impacted zones and identifying possible contaminant migration pathways within the fractured shale terrain. The 2-D electrical resistivity imaging results obtained from the Rice Mill, Umuoghara, and Mechanic Village dumpsites reveal significant variations in subsurface resistivity associated with lithologic heterogeneity, moisture distribution, and contaminant migration within the shale-dominated terrain of the study area. The in-verse resistivity sections generally show extensive low-resistivity anomalies within the near-surface and intermediate subsurface layers, indicating highly conductive zones associated with leachate infiltration from prolonged waste disposal activities.

These conductive anomalies are interpreted as leachate-impacted zones enriched with dissolved ionic constituents derived from decomposing waste materials. The low resistivity values observed within the weathered shale and fractured subsurface units suggest elevated moisture content and enhanced electrical conductivity resulting from contaminant accumulation within the pore spaces and fracture systems. The strong lateral continuity of some conductive zones further indicates active subsurface migration of leachate beneath the investigated dumpsites.

Moderately to highly resistive zones identified at intermediate depths are interpreted as relatively competent lithologic units including sandstone lenses, lateritic materials, siltstone, and partially consolidated shale formations embedded within the dominant shale sequence. These resistive units exhibit varying degrees of lateral continuity and may influence the movement and distribution of contaminants within the subsurface environment.

At greater depths, the reoccurrence of low-resistivity anomalies suggests the presence of saturated fractured shale horizons serving as groundwater-bearing zones. The persistence of conductive pathways extending from the near-surface into deeper subsurface levels indicates downward migration of leachate through weathered zones, fractures, and structurally

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controlled pathways. This condition increases the vulnerability of the underlying groundwater systems to contamination.

Among the investigated locations, the Rice mill dumpsite exhibits the most extensive conductive anomalies, suggesting relatively higher levels of subsurface contamination and enhanced permeability associated with fractured and weathered shale materials. The Umuoghara dumpsite also displays pronounced conductive zones extending into deeper subsurface layers, while the Mechanic Village dumpsite shows comparatively less extensive conductive anomalies but still indicates evidence of contaminant infiltration within shallow and deep fractured zones.

Integrated Geophysical and Hydrogeochemical Interpretation of Subsurface Contamination

The integration of geophysical, physicochemical, and geochemical data significantly strengthens the interpretation of subsurface contamination beneath the investigated dumpsites. The low resistivity values delineated by the VES surveys correspond closely with elevated electrical conductivity and detectable heavy metal concentrations observed in both water and soil samples.

The combined results indicate that leachate generated from prolonged waste accumulation has infiltrated the weathered shale and fractured subsurface units, thereby increasing pore-fluid conductivity and facilitating the transport of dissolved contaminants through structurally controlled pathways. The shale-dominated geology of the Abakaliki area, characterized by fracture-controlled groundwater occurrence, further enhances the vulnerability of the aquifer systems to contamination.

This integrated approach demonstrates the effectiveness of combining geophysical and hydro-geochemical techniques for environmental assessment and groundwater vulnerability studies in complex shale terrains.

CONCLUSIONS

This study employed integrated geophysical and hydrogeochemical approaches to investigate subsurface contamination associated with major urban waste dumpsites within Abakaliki Metropolis, southeastern Nigeria. The combined application of Vertical Electrical Sounding (VES), 2-D electrical resistivity imaging, physicochemical analysis, and heavy metal assessment provided detailed insight into the hydrogeological conditions and contaminant migration processes within the shale-dominated terrain of the study area.

The geophysical results revealed extensive low-resistivity anomalies within the topsoil, weathered shale, and fractured subsurface units beneath the investigated dumpsites. These conductive zones are interpreted as leachate-impacted formations enriched with dissolved ionic constituents derived from prolonged waste decomposition and infiltration. The occurrence of deep conductive zones within fractured shale horizons further indicates the vulnerability of the underlying groundwater systems to contamination through structurally controlled pathways.

The 2-D resistivity imaging results demonstrated that contaminant migration within the study area is strongly controlled by fracture systems, weathered shale horizons, and localized

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permeable sandstone interbeds within the Asu River Group formation. Among the investigated locations, the Umuoghara dumpsite exhibited the most extensive conductive anomalies, indicating relatively higher levels of subsurface contamination and enhanced permeability associated with fractured and weathered shale materials.

Hydrochemical and heavy metal analyses of soil and surface water samples further validated the geophysical interpretation. Elevated concentrations of heavy metals, including Pb, Cd, Hg, Cr, and Ni, were detected in several samples, with some values exceeding World Health Organization (WHO) permissible limits. The slightly acidic soil conditions and elevated conductivity values also indicate progressive geochemical alteration of the near-surface environment resulting from prolonged leachate infiltration.

Field observations and information obtained from local farmers revealed adverse effects on agricultural productivity around the dumpsites, particularly at the Umuoghara dumpsite, where premature cassava tuber decay was reported. These observations corroborate the geophysical and geochemical results, suggesting that prolonged exposure to leachate-contaminated soils may negatively affect crop growth, soil quality, and potentially food safety within the surrounding communities.

Collectively, the study demonstrates the effectiveness of integrating electrical resistivity techniques with hydrogeochemical analyses for environmental assessment and groundwater vulnerability studies in fractured shale terrains affected by uncontrolled waste disposal activities. The results highlight the urgent need for improved waste management practices, groundwater monitoring, environmental regulation, and remediation strategies within Abakaliki Metropolis to reduce the risk of long-term soil and groundwater contamination.

Further studies involving detailed hydrochemical characterization, seasonal monitoring, microbiological assessment, and groundwater quality evaluation are recommended to better understand the long-term environmental and public health implications of leachate contamination within the study area.

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Author’s Contributions

Conceptualization: J.C.E.; J.I.N.; J.N.O.; I.E.M. and M.A.N. **methodology:** J.C.E.; software, J.C.E.; **validation:** J.C.E.; J.I.N.; I.E.M. and M.A.N, formal analysis, J.C.E.; investigation, J.C.E..; resources, J.C.E; data curation, J.C.E.; **writing—original draft preparation:** J.C.E.; **writing—review and editing:** J.I.N.; J.N.O.; I.E.M. and M.A.N.; **visualization:** J.C.E..; **supervision:** J.I.N.; J.N.O. and I.E.M., **project administration:** J.I.N.; J.N.O. and I.E.M. All authors have read and agreed to the published version of the manuscript

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Data Availability Statement

The data supporting the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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