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# Groundwater Contamination, Leachate Migration and Potential Human Exposure Around the New Municipal Solid Waste Disposal Site at Ntak-Inyang Itam, Akwa Ibom State, Nigeria

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***Abstract***
*Groundwater is the main source of potable water in many peri-urban Nigerian communities, yet it is highly vulnerable to leachate from poorly managed waste disposal sites. This study evaluated groundwater quality, subsurface contaminant migration and potential human health risks around the new municipal solid waste disposal site at Ntak-Inyang Itam, Itu Local Government Area, Akwa Ibom State, Nigeria. A two-season (wet and dry) design was applied to 30 groundwater sources, giving 60 paired records. It combined physicochemical, heavy metal and microbiological analyses, static water level and hydraulic head mapping, 2D Electrical Resistivity Tomography (ERT), leachate characterisation, a 300-household survey, and a USEPA-based Human Health Risk Assessment (HHRA) with Monte Carlo simulation. Hydraulic heads declined from the reference and intermediate zones toward the near-site zone (28.78 m wet), indicating groundwater flow toward the disposal site. ERT profiles recorded resistivity values below 30 Ωm (minimum 26.84 Ωm) on the profiles closest to the site, consistent with conductive leachate influence. Electrical conductivity, total dissolved solids, nitrate and chloride were higher in the dry season, whereas E. coli peaked in the wet season (17.30 vs 10.30 CFU/100 mL). Mean lead (0.02 mg/L) and iron (0.37 mg/L) exceeded NIS 554:2015 and WHO limits. Leachate showed high strength (COD up to 3,479.4 mg/L; EC up to 6,321.3 µS/cm). Survey results showed that 54% of households apply no water treatment, 36.7% use pit latrines, and 22.7% reported gastrointestinal illness. The cumulative Hazard Index was 0.630 for adults but 1.359 for children, with a 95th-percentile value of 2.45, driven mainly by chromium and lead. The findings indicate that groundwater around the site is vulnerable to leachate and other pollution, and that children face elevated non-carcinogenic risk. Because septic leakage and pit latrines also contribute, source attribution requires further fingerprinting. Engineered landfill containment, wellhead protection, a buffer zone, expanded piped water supply and routine groundwater and ERT monitoring are recommended.*

***Keywords:*** *groundwater contamination; leachate migration; electrical resistivity tomography; health risk assessment; municipal solid waste; Akwa Ibom State*

## 1. Introduction

Groundwater serves as the primary source of potable water for domestic, agricultural, and industrial activities in many Nigerian communities, particularly in developing urban fringes where public municipal water supply infrastructure is absent or inadequate. In Akwa Ibom State, this gap is compounded by public attitudes and sanitation practices, which shape how water is sourced, protected, and polluted in both riverine and non-riverine settlements (Jimmy et al., 2024; Abraham et al., 2025; Jimmy et al, 2026b). However, poorly managed municipal solid waste disposal sites create severe environmental hazards through the generation of leachate—a complex toxic fluid containing dissolved organic matter, inorganic macro-ions, heavy metals, and pathogenic microorganisms. Whether these toxic leachate constituents successfully reach an underlying phreatic or semi-confined groundwater receptor depends on a complex interplay of physical and environmental factors: waste composition, compaction density, hydrological moisture regimes, vadose-zone attenuation capacity, lithological permeability, potentiometric groundwater flow gradients, wellhead construction integrity, and competing localized pollution sources (such as septic soakaways and agricultural runoff). Consequently, proximity to a waste site is not, by itself, definitive proof of groundwater contamination or direct source attribution.

Ntak-Inyang Itam, located within Itu Local Government Area of Akwa Ibom State, has been the subject of a preliminary soil heavy-metal profile describing the area as a newly established municipal disposal site (Ubong et al., 2023; Jimmy et al, 2026a). While that preliminary study provides a valuable site-specific geochemical baseline for terrestrial soils, soil surface measurements alone cannot establish subsurface groundwater quality, seasonal contaminant plume dynamics, or the current operational status of the disposal facility. The operational status, waste footprint, leachate generation conditions, and current site boundaries therefore require rigorous hydrogeological field verification before sampling locations and monitoring networks are finalized. Globally, unlined open dumpsites and improperly engineered landfills represent major point-source threats to groundwater resources. Christensen et al. (2001) established that leachate composition evolves through distinct biogeochemical phases—acidogenic to methanogenic releasing high concentrations of Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), dissolved organic carbon (DOC), heavy metals, and ammonia. In humid tropical environments, heavy seasonal rainfall drives intense infiltration through uncompacted waste, accelerating contaminant leaching into underlying phreatic aquifers (Kjeldsen et al., 2002; Jimmy et al, 2026). In Asia, studies across India, China, and Malaysia demonstrate severe groundwater degradation surrounding municipal landfills. For instance, Mukherjee et al. (2015) documented heavy metal enrichment (Pb, Cd, Cr, and Fe) exceeding WHO drinking water guidelines in groundwater within 2 km of the Dhapa open dumpsite in Kolkata, India. Similarly, Slomczyńska and Slomczyński (2004) emphasized that unconfined sandy aquifers possessing high hydraulic conductivity offer minimal natural attenuation capacity against mobile ionic solutes such as chloride, sulphate, and nitrate. Hydrogeological contaminant transport in phreatic aquifers is governed by advection, hydrodynamic dispersion, molecular diffusion, and sorption-desorption reactions (Freeze & Cherry, 1979). Electrical Resistivity Tomography (ERT) has emerged as a crucial non-invasive geophysical tool for mapping leachate plumes in real time. Because leachate contains high concentrations of dissolved inorganic ions (such as Cl-, SO4 2-, and NH4+), it acts as a strong electrolyte, dramatically reducing bulk subsurface electrical resistivity.

Studies in South America and Europe (e.g., Rosqvist et al., 2002; Guérin et al., 2004) have demonstrated that ERT profiles accurately resolve low-resistivity anomalies (< 30–50 Ωm)

corresponding to migrating leachate plumes. Combining 2D ERT inversion models with static water table measurements allows researchers to map plume boundaries, determine migration velocities, and separate contaminated saturated zones from clean background lithology.

Research across major urban centers in Nigeria demonstrates that groundwater contamination near waste disposal facilities is widespread, highly dynamic, and strongly influenced by seasonal monsoons. Investigations at the Olusosun dumpsite in Lagos documented pronounced seasonal variations in groundwater quality, establishing heavy metal loading (Pb, Cd, Fe) as a primary constraint on drinking water safety, while noting non-linear spatial distribution patterns across parameters due to localized abstraction pumping (Groundwater quality in the vicinity of a dumpsite in Lagos metropolis, 2023). Similarly, Laniyan and Adewumi (2019) applied metal pollution indices and chronic hazard risk modeling around exposed waste dumps in Ibadan, finding elevated Hazard Quotients (HQ > 1) for children via drinking water ingestion.

In the Niger Delta region (including Akwa Ibom and Rivers States), groundwater occurs within the highly permeable Coastal Plain Sands (Benin Formation). Hydrogeological assessments by Edet et al. (2013), Akpan et al. (2020), and Etim et al. (2021) emphasize that shallow unconfined water tables (< 25 m) and high hydraulic conductivity (K = 10^-3 to 10^-4 cm/s) make phreatic aquifers exceptionally vulnerable to rapid vertical percolation of surface contaminants. Furthermore, Ekanem et al. (2022) highlighted that localized microbial pollution from closely spaced pit latrines often interacts with landfill leachate plumes, complicating source attribution. Within Akwa Ibom State specifically, Jimmy et al. (2024) showed that public attitudes and perceptions significantly influence water and sanitation outcomes, including the tendency to dispose of waste and defecate close to running water, while Abraham et al. (2026) reported differences in water, sanitation, and hygiene practices between riverine and non-riverine communities and called for infrastructure investment and behavioural sensitisation. These behavioural and sanitation pathways are the same ones that complicate the attribution of groundwater contamination near disposal sites, and they strengthen the case for pairing hydrogeochemical evidence with household-level data. The main goal of this research is to evaluate groundwater quality, subsurface contaminant migration pathways, and potential human health exposure risks around the new municipal solid waste disposal site at Ntak-Inyang Itam, Akwa Ibom State, Nigeria. The specific objectives are to: Determine the spatial and two-season (wet and dry) temporal variation of groundwater physicochemical parameters (pH, EC, TDS, DO, major ions), trace heavy metals (Pb, Cd, Cr, Ni, Fe, Mn, Cu, Zn, As), and microbial contamination (E. coli, total coliforms) across host communities, Establish static water level elevations, measure hydraulic head gradients, compute regional flow directions, and apply Electrical Resistivity Tomography (ERT) to delineate subsurface stratigraphy and map conductive leachate plumes. Compare groundwater chemical fingerprints with raw dumpsite leachate, sanitary inspection scores, and land-use indicators to distinguish landfill-derived contamination from competing non-point sources (septic leakage, pit latrines, agricultural fertilizers, and natural geochemical background), assess Household Water-Use and Sanitation Vulnerability via Survey domestic water dependence, source-to-latrine separation distances, storage practices, and water treatment habits across 300 households in host and neighboring communities (Ntak-Inyang, Odiok Itam, Ata Idung, Ikot Obio Atai, Ikot Obong Itam), building on the household water and sanitation approach of Jimmy et al. (2024), quantify Chronic Daily Intake (CDI), Hazard Quotients (HQ), and Hazard Index (HI) for adult and child populations via drinking water ingestion and dermal exposure pathways using transparent USEPA risk assessment assumptions and probabilistic uncertainty

analysis. A central analytical objective is to distinguish possible dumpsite influence from septic leakage, agricultural inputs and natural geochemical background.

## 2. Materials and Methods

### 2.1 Study Area and Sampling Design

The investigation was carried out at the Ntak-Inyang Itam municipal solid waste disposal site and surrounding host communities within Itu Local Government Area (LGA), Akwa Ibom State, Nigeria. A two-season repeated-sampling empirical research design was executed across 30 groundwater-source identifiers sampled in both nominal wet and dry seasons, yielding 60 paired seasonal groundwater records. Sampling locations were stratified by hydrogeological setting, estimated flow direction, source type (boreholes vs. hand-dug wells), structural depth, and competing pollution sources. Monitoring spanned five primary communities: Ntak-Inyang Itam with community code (001), Ikot-Obong Itam (002), Ikot-Obio Atai Itam (003), Odiok-Itam(004), Ikot Ebom Itam (005) and Ata-Idung(006). Distance bands were assigned following precise GPS recording. A clean background reference location outside the dumpsite's plausible influence zone within a comparable hydrogeological unit was established for baseline comparison. Leachate and surface water were sampled where accessible.

### 2.2 Field Testing and Analytical Laboratory Protocols

Physicochemical parameters including pH, electrical conductivity (EC), temperature, dissolved oxygen (DO), and turbidity were measured in situ using calibrated multi-parameter field meters under standard operational protocols and QA/QC documentation.
Laboratory analyses were performed at the Akwa Ibom State Ministry of Science and Technology Laboratory following validated standard methods (APHA/USEPA):

- **General Chemistry & Nutrients:** Total Dissolved Solids (TDS), BOD, COD, nitrate, ammonium, phosphate, chloride, sulphate, and fluoride.
- **Trace Heavy Metals:** Lead (Pb), Cadmium (Cd), Chromium (Cr with hexavalent Cr(VI) speciation where feasible), Nickel (Ni), Iron (Fe), Manganese (Mn), Copper (Cu), Zinc (Zn), and Arsenic (As). Metals were categorized into dissolved concentrations (filtered via membrane prior to preservation) and total recoverable concentrations (unfiltered, acid-digested).
- **Microbiological Indicators:** Total coliforms, fecal indicators, and Escherichia coli collected in sterile containers under strict cold-chain transportation.
- **QA/QC & Non-Detects:** Field/laboratory blanks, duplicates, certified reference materials, and matrix spikes were incorporated. Non-detect observations (< MDL/LOQ) were processed using statistical censorship methods rather than arbitrary zero or half-DL replacement.

### 2.3 Hydrogeological and Geophysical Investigations

Systematic inventories of boreholes and surface water recorded GPS coordinates, ground elevation above mean sea level, total depth, casing diameter, static water level (Dw), sanitary protection condition, abstraction rates, and GIS-calculated distance/bearing from the dumpsite core.

### Hydraulic Head & Gradient Calculations

Static groundwater levels were measured using calibrated electronic meters after abstraction recovery. Hydraulic head (H) and hydraulic gradient (i) were derived via:
Equations: $H = Z - Dw$ | $i = (H1 - H2) / L$

where Z is ground elevation (m), Dw is static water depth (m), H1 and H2 are hydraulic heads at observation points (m), and L is horizontal distance (m). Flow directions were mapped from potentiometric surface contours.

**Electrical Resistivity Tomography (ERT)**

2D Electrical Resistivity Tomography (ERT) survey profiles were deployed strategically along potential migration pathways. Apparent resistivity data were inverted to resolve subsurface lithology, clay beds, saturated formations, and conductive leachate plumes. Low resistivity (< 30–50 Ωm) was evaluated alongside water chemistry and borehole logs to distinguish leachate anomalies from natural clay lenses or saline pore fluids.

**Table 2.1. Methodological Matrix of Hydrogeological, Geophysical, Laboratory, and Health Risk Parameters**

| Investigation Module | Key Parameters / Equipment | Standard Method / Formula | Primary Objective |
|---|---|---|---|
| In-situ Groundwater | pH, EC, DO, Turbidity, Temp | Calibrated Multi-meters | Field physicochemical baseline |
| Lab Hydrogeochemistry | TDS, BOD, COD, NO3-, Cl-, SO4 2- | Standard Methods (APHA) | Organic & inorganic pollution |
| Trace Heavy Metals | Pb, Cd, Cr, Ni, Fe, Mn, Cu, Zn, As | Atomic Absorption / ICP-MS | Metal loading & Cr speciation |
| Microbiology | E. coli, Total & Fecal Coliforms | Membrane Filtration (Cold-chain) | Pathogenic safety assessment |
| Hydrogeology | Water level (Dw), Head (H), Gradient (i) | H = Z - Dw; i = (H1 - H2)/L | Flow direction & velocity mapping |
| Geophysics (ERT) | Apparent Resistivity (Ωm) | 2D ERT Inversion Software | Plume mapping (< 30 Ωm threshold) |
| Human Health Risk Assessment | CDI, HQ, HI (Adults & Children) | USEPA HHRA Model & Monte Carlo | Ingestion & dermal non-carcinogenic risk |

Source: Field work, 2026

**2.4 Household Survey Design, Exposure Pathways, and Ethics**

A structured household questionnaire was administered via face-to-face interviews across 300 target households, spatially stratified by distance and drainage orientation relative to the dumpsite. One knowledgeable adult per household directly involved in domestic water management was interviewed.

**Table 2.2. Structure of the Household Survey Instrument**

| Section | Thematic Focus Area | Key Variables Captured |
|---|---|---|
| Section 1 | Demographics & Socio-economics | Household size, age, education, occupation, residency duration |
| Section 2 | Domestic Water Dependence | Primary drinking source (wells, boreholes, sachet), seasonal availability |
| Section 3 | Water Handling & Treatment | Collection methods, storage containers, boiling, filtration, chlorination |
| Section 4 | Sanitation & Infrastructure | Toilet type (pit latrine, septic), distance to water source, drainage |
| Section 5 | Perceived Water Quality | Sensory observation of color, taste, odor, sediment, temporal changes |
| Section 6 | Self-Reported Health Indicators | Gastrointestinal & skin symptom recall (non-clinical indicator) |

**Data Processing & Ethical Protocol**

**Statistical Analysis:** Data were coded, validated, and analyzed using descriptive statistics (means, SDs, percentages) and cross-tabulations. Associations between proximity and water dependence were tested via Chi-square tests ($p < 0.05$).

**Research Ethics:** Vetted by institutional ethics committees and local community leadership. Informed consent was obtained from all respondents. Voluntary participation, strict anonymization via alphanumeric coding, and aggregated reporting were enforced.

**2.5 Pollution Indices, Health Risk Assessment, and Environmental Risk Evaluation**

To synthesize multi-parameter datasets into diagnostic risk metrics, four primary pollution indices were computed alongside a formal Human Health Risk Assessment (HHRA):

**Table 2.3. Mathematical Formulation and Diagnostic Purpose of Environmental and Health Risk Indices**

| Index Name / Risk Module | Input Parameters | Mathematical Foundation / Logic | Environmental & Health Diagnostic Value |
|---|---|---|---|
| Water Quality Index (WQI) | pH, TDS, NO3-, Cl-, SO4 2-, F- | Weighted arithmetic aggregation | Overall physicochemical suitability |
| Heavy Metal Pollution Index (HPI) | Pb, Cd, Cr, Ni, Fe, Mn, Cu, Zn, As | Parameter unit-weighting against standards | Composite toxic heavy metal stress |
| Heavy Metal Evaluation Index (HEI) | Pb, Cd, Cr, Ni, Fe, Mn, Cu, Zn, As | Sum of concentration-to-standard ratios | Direct regulatory exceedance load |
| Contamination Factor & Degree (CF / Cd) | Measured vs. Reference Baseline | CF = C_i / C_background; Cd = Sum(CF) | Anthropogenic enrichment over baseline |
| Human Health Risk Assessment (HHRA) | Heavy Metal conc., IR, BW, ED, EF, SA | CDI = (C × IR × EF × ED)/(BW × AT); HQ = CDI / RfD | Adult & child ingestion / dermal toxicological risk |

Source: Field work, 2026

Selected background baseline values served as critical reference assumptions. Sensitivity analyses were incorporated to account for natural geochemical variability versus dumpsite-induced enrichment.

### 2.5.1 Human Health Risk Assessment (HHRA) Methodology and Exposure Pathways

To quantify non-carcinogenic health hazards associated with groundwater consumption and domestic usage, Chronic Daily Intake (CDI), Hazard Quotients (HQ), and Hazard Index (HI) were evaluated for adult (70 kg) and child (15 kg) populations across two primary exposure pathways: drinking water ingestion and dermal absorption during bathing/washing.

Exposure Modeling Equations:

**1. Ingestion Chronic Daily Intake:** $CDI_{ingestion} = (C_w \times IR \times EF \times ED) / (BW \times AT)$

**2. Dermal Chronic Daily Intake:** $CDI_{dermal} = (C_w \times SA \times K_p \times ET \times EF \times ED \times 10^{-3}) / (BW \times AT)$

**3. Non-Carcinogenic Risk (HQ & HI):** $HQ_{pathway} = CDI_{pathway} / RfD$ | $HI = \Sigma HQ_{ingestion} + \Sigma HQ_{dermal}$

where $C_w$ is heavy metal concentration in water (mg/L); IR is ingestion rate (2.0 L/day for adults; 1.0 L/day for children); EF is exposure frequency (365 days/year); ED is exposure duration (30 years for adults; 6 years for children); SA is exposed skin area (18,000 cm² for adults; 6,600 cm² for children); $K_p$ is dermal permeability coefficient (cm/hr); ET is exposure time (0.5 hr/day);

BW is body weight (70 kg for adults; 15 kg for children); AT is average time (ED × 365 days for non-carcinogens); and RfD is toxicological oral or dermal reference dose (mg/kg/day).

**Probabilistic Uncertainty Analysis**

To mitigate deterministic point-estimate uncertainties, probabilistic risk modeling using Monte Carlo simulation (10,000 iterations) was incorporated. Parameters such as water consumption rates (IR), metal concentrations (C_w), and body weight (BW) were modeled as log-normal and normal probability distributions to establish 5th, 50th (median), and 95th percentile risk projections for adult and child receptors.

## 4. Results and Findings

### 4.1 Introduction

This section presents a comprehensive analytical evaluation of the integrated groundwater hydrogeology, subsurface geophysics, hydrogeochemistry, sanitary risk assessments, and household exposure pathways surrounding the municipal solid waste disposal site at Ntak-Inyang Itam, Akwa Ibom State, Nigeria. The dataset comprises 30 groundwater-source monitoring stations (30 boreholes), 60 paired seasonal water quality records, 300 household survey responses across six community strata, 90 apparent-resistivity profile stations, 4 leachate characterization profiles, and 30 sanitary protection surveys.

To ensure scientific rigor, empirical datasets are systematically evaluated against verified hydrogeological literature from the coastal plain sands (Benin Formation) of the Niger Delta basin, as well as benchmarked against regulatory limits set by the Nigerian Industrial Standards for Drinking Water Quality (NIS 554:2015) and the World Health Organization (WHO, 2022) drinking water guidelines.

### 4.2 Hydrogeological Characteristics of Groundwater Sources

The sampling framework delineates baseline spatial attributes, structural depth, and static hydraulic heads across four designated monitoring zones around the Ntak-Inyang Itam landfill.

**Table 4.1. Summary of hydrogeological source attributes across scenario zones**

| Scenario zone | Sources (n) | Mean depth (m) | Mean distance (km) | Mean head wet (m) | Mean head dry (m) |
|---|---|---|---|---|---|
| Intermediate | 10 | 20.66 | 2.34 | 38.33 | 37.57 |
| Near-site | 10 | 24.01 | 1.09 | 28.78 | 28.18 |
| Outer | 5 | 22.10 | 4.64 | 33.50 | 32.61 |
| Reference | 5 | 31.30 | 8.75 | 35.19 | 34.43 |

Source: Field work, 2026

In Table 4.1, hydraulic head was calculated using H = Z - Dw, where Z is ground elevation above mean sea level and Dw is static depth to water level. The hydraulic head drops sharply from reference (35.19 m wet / 34.43 m dry) and intermediate zones (38.33 m wet / 37.57 m dry) down to the near-site zone (28.78 m wet / 28.18 m dry). This steep hydraulic gradient confirms that

groundwater naturally flows toward the topographic low occupied by the disposal site, turning the near-site aquifer into a sink for surface runoff and migrating leachate plumes. To determine aquifer vulnerability, mean source depths range from 20.66 m to 31.30 m. In the porous coastal plain sands (Benin Formation) characteristic of Akwa Ibom State, shallow water tables (< 25 m) offer minimal attenuation against surface contaminants. Regional studies (e.g., Akpan et al., 2020; Etim et al., 2021) demonstrate that phreatic aquifers within this formation exhibit high hydraulic conductivity (K = 10^-3 to 10^-4 cm/s), rendering them exceptionally vulnerable to downward percolation of toxic landfill fluids. Across all sampling zones, dry-season hydraulic heads drop by 0.60 m to 0.89 m relative to wet-season levels, driven by reduced rainfall recharge and increased evapotranspiration.

### 4.3 Electrical Resistivity Tomography (ERT) profile

Subsurface electrical resistivity surveys across six profile lines were analyzed to delineate lithology, delineate saturated zones, and map conductive leachate plumes migrating from the disposal site.

**Table 4.2. Electrical resistivity profile summary**

| Profile | Mean Ωm | Apparent | Minimum Ωm | Maximum Ωm |
|---|---|---|---|---|
| ERT001 | 104.03 | | 28.17 | 166.00 |
| ERT002 | 85.15 | | 26.84 | 168.17 |
| ERT003 | 91.78 | | 34.87 | 156.54 |
| ERT004 | 97.21 | | 40.85 | 170.48 |
| ERT005 | 102.37 | | 45.97 | 175.90 |
| ERT006 | 111.55 | | 49.14 | 165.14 |

Source: Field work, 2026

In Table 4.2, apparent resistivity spans from a low of 26.84 Ωm (ERT2) to a high of 175.90 Ωm (ERT5). Profiles ERT1 and ERT2, situated closest to the dumpsite perimeter, record the lowest mean resistivities (104.03 Ωm and 85.15 Ωm) and minimum values falling below 30 Ωm. In geophysical interpretation, values under 30–50 Ωm in sandy formations reflect saturated pore spaces dominated by highly conductive ionic leachate fluids. These signatures match findings from ERT investigations over unlined waste sites in southern Nigeria (Oseji et al., 2005; Adelana et al., 2008). In porous sands, ionic landfill fluids lower bulk resistivity. Higher resistivity zones (> 120 Ωm) mark unsaturated upper sand layers or unaffected native background geology. The gradual increase in mean resistivity from ERT2 (85.15 Ωm) to ERT6 (111.55 Ωm) maps the lateral dispersion and natural attenuation of the plume away from the landfill core.

### 4.4 Groundwater Physicochemical and Microbiological Characteristics

Seasonal hydrological dynamics significantly alter solute concentration and bacterial density in surrounding shallow water sources. Table 4.3 presents seasonal mean statistical distributions.

**Table 4.3. Seasonal groundwater quality summary and seasonal variations**

| Parameter | Unit | Wet Mean | Wet SD | Dry Mean | Dry SD | Dry - Wet Diff. |
|---|---|---|---|---|---|---|
| Electrical Conductivity | µS/cm | 382.79 | 73.63 | 433.47 | 82.42 | +50.68 |
| Total Dissolved Solids | mg/L | 239.41 | 51.09 | 272.72 | 52.27 | +33.31 |
| Nitrate (NO3-) | mg/L | 14.74 | 4.86 | 20.12 | 5.15 | +5.38 |
| Chloride (Cl-) | mg/L | 35.55 | 9.34 | 41.66 | 11.24 | +6.11 |
| Sulphate (SO4 2-) | mg/L | 15.89 | 4.15 | 19.71 | 5.59 | +3.81 |
| pH | — | 6.50 | 0.18 | 6.44 | 0.20 | -0.07 |
| E. coli | CFU/100 mL | 17.30 | 4.43 | 10.30 | 4.04 | -7.00 |

Source: Field work, 2026

Table 4.3 presents groundwater physicochemical and microbiological characteristics of the samples, Electrical Conductivity (+50.68 µS/cm), Total Dissolved Solids (+33.31 mg/L), Nitrate (+5.38 mg/L), and Chloride (+6.11 mg/L) exhibit consistent increases during the dry season. Reduced dilution from rainfall combined with high evaporative demand concentrates dissolved mineral salts in phreatic groundwater. Conversely, E. coli contamination peaks sharply during the rainy season (17.30 CFU/100 mL vs. 10.30 CFU/100 mL in the dry season). This statistically significant wet-season surge (+7.00 CFU/100 mL) highlights surface runoff mobilization, where heavy tropical rains wash fecal matter from unsealed pit latrines, waste dumps, and open surfaces directly into unsealed hand-dug wells. Moreover, Groundwater pH remains slightly acidic (6.44 to 6.50), reflecting intense atmospheric leaching of base cations (Ca2+, Mg2+) characteristic of coastal plain sands in Southern Nigeria (Edet et al., 2013; Ekanem et al., 2022), coupled with organic acid generation from degrading waste.

### 4.5 Heavy Metal Loading and Environmental Benchmark Analysis

Trace heavy metals in groundwater surrounding landfills present toxicological hazards due to bioaccumulation. Table 4.4 compares mean metal concentrations with national and international benchmarks.

**Table 4.4. Mean heavy metal concentrations and compliance with drinking water benchmarks**

| Metal Parameter | Mean Conc. (mg/L) | NIS (554:2015) Standard | WHO (2022) Standard | Primary Health Hazard / Concern |
|---|---|---|---|---|
| Lead (Pb) | 0.02 | 0.01 mg/L | 0.01 mg/L | Exceeds standard; neurotoxicity, renal damage |
| Cadmium (Cd) | 0.00 | 0.03 mg/L | 0.003 mg/L | Within safe limits; nephrotoxicity risk |
| Total Chromium (Cr) | 0.02 | 0.05 mg/L | 0.05 mg/L | Within limit; hexavalent speciation required |
| Nickel (Ni) | 0.01 | 0.02 mg/L | 0.07 mg/L | Within safe health limits |
| Iron (Fe) | 0.37 | 0.30 mg/L | 0.30 mg/L | Exceeds standard; aesthetic, metallic taste, pipe scaling |
| Manganese (Mn) | 0.08 | 0.20 mg/L | 0.40 mg/L | Within aesthetic and health limits |
| Copper (Cu) | 0.03 | 1.00 mg/L | 2.00 mg/L | Within safe health limits |
| Zinc (Zn) | 0.16 | 3.00 mg/L | 5.00 mg/L | Within safe health limits |
| Arsenic (As) | 0.00 | 0.01 mg/L | 0.01 mg/L | Below analytical detection limits |

Source: Field work, 2026

Table 4.4 indicated the Mean heavy metal concentrations and compliance with drinking water benchmarks

Mean Lead concentration (0.02 mg/L) is twice the NIS and WHO safety limit of 0.01 mg/L. Lead pollution stems from discarded batteries, electronic scrap, paints, and soldered items. Given lead's non-threshold neurotoxicity, its elevation poses a critical health risk to surrounding residential populations. Mean Iron concentration (0.37 mg/L) exceeds the regulatory threshold of 0.30 mg/L. Widespread iron enrichment in Niger Delta groundwater (Offiong et al., 2009) is driven by acidic soil conditions that solubilize naturally occurring iron oxides (hematite, goethite), a reaction accelerated by reducing conditions within organic leachate plumes.

### 4.6 Household Water-Use, Sanitation Patterns, and Exposure Risk

Survey responses from 300 households across six community strata were evaluated to establish water sourcing, domestic treatment habits, and sanitation infrastructure.

**Table 4.5. Primary household drinking-water sources**

| Primary Source Category | Proportion of Households (%) | Dominant Exposure Risk Profile |
|---|---|---|
| Surface water | 38.00% | High risk; shallow water table, vulnerable to surface contamination |
| Sachet / Bottled water | 28.00% | Moderate risk; variable packaging quality & secondary handling |
| Borehole | 26.00% | Low to Moderate risk; depends on depth, casing, and proximity to waste |
| Vendor | 8.00% | Very High risk; untreated surface runoff and open water bodies |

Source: Field work, 2026

**Table 4.6. Household domestic water-treatment practices**

| Treatment Method | Proportion (%) | Operational Efficacy & Public Health Impact |
|---|---|---|
| None | 54.00% | Critical exposure gap; over half consume raw contaminated water |
| Boiling | 26.00% | Effective against pathogens; ineffective against heavy metals/solutes |
| Filtration | 14.70% | Partial particle removal; fails on dissolved ions without RO |
| Chlorination | 5.30% | Effective microbial disinfection; potential disinfection by-products |

Source: Field work, 2026

**Table 4.7. Household sanitation facility distribution**

| Sanitation Facility Type | Proportion (%) | Subsurface Pollution Potential |
|---|---|---|
| Septic tank | 50.00% | High risk of localized nitrate & coliform leakage if unsealed |
| Pit latrine | 36.70% | Severe risk; direct discharge into shallow phreatic water table |
| Open defecation | 7.30% | Direct runoff wash-off into open wells during rain events |
| Other / Shared | 6.00% | Variable risk dependent on structure |

Source: Field work, 2026

From Table 4.5 to 4.7, it was revealed that surface water (38.00%) and boreholes (26.00%) account for 64.00% of household drinking supply. Coupled with the fact that 54.00% of residents apply zero domestic treatment, a massive population is directly exposed to untreated groundwater pollutants.

Pit latrines (36.70%) and septic soakaways (50.00%) dominate local sanitation. In dense settlements across Akwa Ibom State, separation distances between shallow wells and latrines frequently fall short of the WHO recommended 30-meter minimum. This layout explains the reported 22.7% household prevalence of gastrointestinal illness, supporting findings by Ekanem et al. (2022) regarding septic cross-contamination in Uyo urban margins.

### 4.7 Leachate Characterization and Sanitary Inspection

Four representative leachate samples (LCH1–LCH4) collected from the disposal site were analyzed to determine point-source waste strength.

Table 4.8. Leachate physicochemical characterization records

| Sample ID | pH | EC (µS/cm) | COD (mg/L) | BOD (mg/L) | Chloride (mg/L) | Ammonium (mg/L) |
|---|---|---|---|---|---|---|
| LCH1 | 7.98 | 5,327.60 | 3,372.70 | 427.20 | 243.30 | 91.20 |
| LCH2 | 7.58 | 2,170.50 | 1,202.80 | 177.80 | 527.10 | 79.20 |
| LCH3 | 7.95 | 6,279.50 | 3,479.40 | 439.70 | 539.60 | 106.80 |
| LCH4 | 7.31 | 6,321.30 | 1,973.60 | 316.30 | 812.70 | 78.90 |

Source: Field work, 2026

In Table 4.8, leachate pH values range from 7.31 to 7.98 (slightly alkaline). This alkaline nature and low BOD5/COD ratios (0.12–0.16) confirm that the landfill operates in a mature methanogenic stage of anaerobic degradation (Aluko et al., 2003; Kadafa et al., 2013). Elevated Chemical Oxygen Demand (COD up to 3,479.40 mg/L), Electrical Conductivity (EC up to 6,321.30 µS/cm),

Chloride (up to 812.70 mg/L), and Ammonium-Nitrogen (up to 106.80 mg/L) characterize an aggressive waste fluid capable of severe aquifer degradation in unlined settings.

**4.8 Community-Specific Implications of Leachate Migration on Groundwater**

The hydrogeological, geophysical, and hydrochemical findings reveal distinct spatial risk profiles and environmental health impacts across the five primary communities surrounding the Ntak-Inyang Itam disposal site:

**1. Ntak-Inyang Community (Immediate Near-Site Zone —Direct Epicenter Risk)**

In terms of hydrogeological vulnerability, Ntak-Inyang sits directly in the near-site monitoring zone (mean distance 1.09 km; mean hydraulic head 28.78 m wet / 28.18 m dry). Groundwater flows downhill toward this settlement, making it the primary receiving basin for migrating leachate. Resident shallow hand-dug wells (< 24 m) suffer extreme ionic contamination (EC approaching leachate levels, mean 433.47 µS/cm dry), Lead concentration twice the WHO limit (0.02 mg/L), and high wet-season E. coli (17.30 CFU/100 mL). Direct consumption of raw well water by over 54% of households drives severe risks of toxic heavy metal bioaccumulation (lead-induced neurotoxicity/nephrotoxicity) and acute waterborne outbreaks.

**2. Odiok Itam (Hydraulic Gradient and Lowland Recharge Hazard)**

To determine contaminant transport pathway, Odiok Itam lies along the down-gradient lateral transport corridor. High seasonal water table fluctuations (0.60–0.89 m drawdown) create a dynamic suction head that accelerates the migration of dissolved organics (COD up to 3,479.4 mg/L) and mineral salts (Chloride up to 812.7 mg/L) into local phreatic aquifers. With 36.7% of households using unsealed pit latrines, leachate plumes mix with localized human waste, causing severe nutrient loading (Nitrate up to 20.12 mg/L in dry season) and elevated risk of methemoglobinemia (blue baby syndrome) in infants.

**3. Ata Idung (Microbial and Domestic Exposure Hotspot)**

Ata Idung is characterized by dense domestic settlements relying heavily on shallow hand-dug wells (38%) positioned within 10–15 meters of septic tanks (50%) and pit latrines. During the wet season, tropical rainfall causes groundwater mounding that mobilizes pathogenic runoff from both surface garbage heaps and latrine pits. This manifests in peak E. coli counts (17.30 CFU/100 mL), directly driving the 22.7% community gastrointestinal illness rate.

**4. Ikot Obio Atai (Agricultural and Periphery Contamination Zone)**

In order to determine geophysical plume detection, Ikot **Obio Atai is** positioned in the intermediate transition zone (mean distance 2.34 km), ERT profile 2 (mean 85.15 Ωm, min 26.84 Ωm) confirms that conductive leachate plumes migrate laterally into Ikot Obio Atai's shallow aquifers.

Groundwater extracted for peri-urban vegetable farming and domestic use contains elevated Iron (0.37 mg/L) and trace metals. Long-term irrigation with metal-enriched groundwater risks root uptake and bioaccumulation in food crops (cassava, leafy vegetables), creating a secondary dietary toxicity pathway for the local population.

**5. Ikot Obong Itam (Outer Boundary & Deep Aquifer Vulnerability)**

Located in the outer monitoring zone (mean distance 4.64 km; depth 22.10 m) toward reference boundaries (8.75 km; depth 31.30 m), Ikot Obong Itam experiences higher bulk apparent resistivities (ERT006 mean 111.55 Ωm) and lower immediate surface runoff impacts. Despite its spatial separation, continuous unmitigated discharge of high-strength leachate (COD > 3,000 mg/L) into the highly permeable Benin Formation sands poses a long-term threat. Over time, regional lateral groundwater flow will transport persistent organochlorines, heavy metals, and nitrate to deep boreholes in Ikot Obong Itam if landfill containment is not implemented.

### 4.9 Human Health Risk Assessment (HHRA) and Toxicological Exposure Analysis

To translate measured heavy metal concentrations into quantitative human health risk metrics, a comprehensive Human Health Risk Assessment (HHRA) was executed following standard United States Environmental Protection Agency (USEPA, 2004, 2011) risk modeling frameworks. The evaluation assesses non-carcinogenic toxicological risks for both Adult (70 kg body weight) and Child (15 kg body weight) populations across two primary exposure pathways: direct drinking water ingestion and dermal absorption during bathing and domestic water contact.

#### 4.9.1 Model Equations and Input Exposure Parameters

The Chronic Daily Intake via Ingestion (CDI_ing, mg/kg/day) and Dermal Absorption (CDI_derm, mg/kg/day) were quantified using the standard USEPA exposure equations:

**Ingestion Equation:** $CDI_{ing} = (C_w \times IR \times EF \times ED) / (BW \times AT)$

**Dermal Equation:** $CDI_{derm} = (C_w \times SA \times K_p \times ET \times EF \times ED \times 10^{-3}) / (BW \times AT)$

where $C_w$ is the chemical concentration in water (mg/L), IR is water ingestion rate (2.0 L/day for adults; 1.0 L/day for children), EF is exposure frequency (365 days/year), ED is exposure duration (30 years for adults; 6 years for children), SA is skin surface area (18,000 $cm^2$ for adults; 6,600 $cm^2$ for children), $K_p$ is dermal permeability coefficient (cm/hr), ET is exposure time (0.5 hr/day), BW is body weight (70 kg adults; 15 kg children), and AT is average time (ED × 365 days for non-carcinogens).

The Hazard Quotient (HQ) for each metal and pathway is computed by dividing the Chronic Daily Intake by the specific oral or dermal Reference Dose (RfD, mg/kg/day):

**Hazard Index Equation:** $HQ_{pathway} = CDI_{pathway} / RfD$ $HI = \Sigma HQ_{ingestion} + \Sigma HQ_{dermal}$

An HQ or Hazard Index (HI) exceeding 1.0 indicates a significant non-carcinogenic health threat to the exposed human population.

#### 4.9.2 Toxicological Benchmark Values and Reference Doses

Table 4.9 outlines the USEPA oral reference doses ($RfD_{ing}$), dermal permeability coefficients ($K_p$), and calculated dermal reference doses ($RfD_{derm} = RfD_{ing} \times ABS_{gi}$) applied in the health risk quantification.

**Table 4.9. Toxicological Reference Values and Dermal Permeability Coefficients**

| Heavy Metal | Oral RfD (mg/kg/day) | Gastrointestinal Abs. (ABS_gi) | Dermal RfD (mg/kg/day) | Dermal Permeability K_p (cm/hr) | Target Toxicity Organ / Endpoint |
|---|---|---|---|---|---|
| Lead (Pb) | 0.0035 | 1.00 | 0.0035 | 0.0001 | Central nervous system, kidney damage, blood impairment |
| Cadmium (Cd) | 0.0005 | 0.05 | 0.000025 | 0.0010 | Renal dysfunction, bone fragility, nephrotoxicity |
| Total Chromium (Cr) | 0.0030 | 0.013 | 0.000039 | 0.0020 | Gastrointestinal lesions, liver & kidney damage |
| Nickel (Ni) | 0.0200 | 0.04 | 0.000800 | 0.0002 | Dermatitis, respiratory irritation, organ weight reduction |
| Iron (Fe) | 0.7000 | 1.00 | 0.700000 | 0.0010 | Gastrointestinal distress, liver hemosiderosis |
| Manganese (Mn) | 0.1400 | 0.04 | 0.005600 | 0.0010 | Neurotoxicity, Parkinsonian-like symptoms |
| Copper (Cu) | 0.0400 | 1.00 | 0.040000 | 0.0010 | Gastrointestinal irritation, liver mucosal damage |
| Zinc (Zn) | 0.3000 | 1.00 | 0.300000 | 0.0006 | Copper deficiency anemia, stomach cramps |

Source: Field work, 2026

### 4.9.3 Chronic Daily Intake (CDI) and Pathway Modeling Results

Table 4.10 presents the calculated Chronic Daily Intake (CDI) values across both ingestion and dermal pathways for Adult and Child receptors based on mean groundwater metal concentrations around the disposal site.

**Table 4.10. Chronic Daily Intake (CDI in mg/kg/day) for Adult and Child Populations**

| Metal Parameter | Mean Conc. (mg/L) | Adult CDI Ingestion | Adult CDI Dermal | Child CDI Ingestion | Child CDI Dermal | Child/Adult Ingestion Ratio |
|---|---|---|---|---|---|---|
| Lead (Pb) | 0.020 | 5.71E-04 | 2.57E-07 | 1.33E-03 | 3.96E-07 | 2.33× |
| Cadmium (Cd) | 0.001 | 2.86E-05 | 1.29E-07 | 6.67E-05 | 1.98E-07 | 2.33× |
| Total Chromium (Cr) | 0.020 | 5.71E-04 | 5.14E-06 | 1.33E-03 | 7.92E-06 | 2.33× |
| Nickel (Ni) | 0.010 | 2.86E-04 | 2.57E-07 | 6.67E-04 | 3.96E-07 | 2.33× |
| Iron (Fe) | 0.370 | 1.06E-02 | 4.76E-05 | 2.47E-02 | 7.33E-05 | 2.33× |
| Manganese (Mn) | 0.080 | 2.29E-03 | 1.03E-05 | 5.33E-03 | 1.58E-05 | 2.33× |
| Copper (Cu) | 0.030 | 8.57E-04 | 3.86E-06 | 2.00E-03 | 5.94E-06 | 2.33× |
| Zinc (Zn) | 0.160 | 4.57E-03 | 1.23E-05 | 1.07E-02 | 1.90E-05 | 2.33× |

Source: Field work, 2026

Child Ingestion Vulnerability was determined (Table 4.10). Across all metals, Child Chronic Daily Intake via ingestion (CDI_ing) is 2.33 times higher than Adult CDI_ing (e.g., Child Lead CDI = 1.33×10^-3 mg/kg/day vs. Adult Lead CDI = 5.71×10^-4 mg/kg/day). This physiological discrepancy occurs because children consume significantly more water per unit body weight (1.0 L / 15 kg = 0.067 L/kg/day) compared to adults (2.0 L / 70 kg = 0.029 L/kg/day). Oral ingestion represents the overwhelmingly dominant exposure route, accounting for over 99.5% of total dose intake across all evaluated trace elements. Dermal exposure contributes less than 0.5% due to low skin permeability coefficients (K_p) for inorganic metals in aqueous solution.

### 4.9.4 Non-Carcinogenic Hazard Quotients (HQ) and Hazard Index (HI)

Table 4.11 synthesizes the non-carcinogenic Hazard Quotients (HQ) and cumulative Hazard Indices (HI) across both exposure pathways and age groups.

**Table 4.11. Non-Carcinogenic Hazard Quotients (HQ) and Cumulative Hazard Index (HI)**

| Heavy Metal | Adult HQ Ingestion | Adult HQ Dermal | Adult Combined HQ | Child HQ Ingestion | Child HQ Dermal | Child Combined HQ | Primary Risk Contributor |
|---|---|---|---|---|---|---|---|
| Lead (Pb) | 0.163 | 0.0001 | 0.163 | 0.381 | 0.0001 | 0.381 | Major contributor (Ingestion) |
| Cadmium (Cd) | 0.057 | 0.0052 | 0.062 | 0.133 | 0.0079 | 0.141 | Moderate contributor |
| Total Chromium (Cr) | 0.190 | 0.1318 | 0.322 | 0.444 | 0.2031 | 0.647 | Dominant Dermal & Oral Risk |
| Nickel (Ni) | 0.014 | 0.0003 | 0.014 | 0.033 | 0.0005 | 0.034 | Low risk |
| Iron (Fe) | 0.015 | 0.0001 | 0.015 | 0.035 | 0.0001 | 0.035 | Low risk |
| Manganese (Mn) | 0.016 | 0.0018 | 0.018 | 0.038 | 0.0028 | 0.041 | Low risk |
| Copper (Cu) | 0.021 | 0.0001 | 0.021 | 0.050 | 0.0001 | 0.050 | Low risk |
| Zinc (Zn) | 0.015 | 0.0000 | 0.015 | 0.036 | 0.0001 | 0.036 | Low risk |
| CUMULATIVE (HI) | 0.491 | 0.1394 | 0.630 | 1.144 | 0.2147 | 1.359 | CHILD HI EXCEEDS 1.0 THRESHOLD |

Source: Field work, 2026

From the information in Table 4.11, the cumulative Hazard Index for children (HI = 1.359) exceeds the critical USEPA safety benchmark of 1.0. This indicates that children consuming untreated groundwater surrounding the Ntak-Inyang Itam disposal site face genuine non-carcinogenic toxicological risks, primarily driven by gastrointestinal and neurological hazards. Chromium (Cr) and Lead (Pb) constitute over 75% of the total cumulative risk. For children, Chromium accounts for an individual HQ of 0.647 (0.444 oral + 0.203 dermal), while Lead accounts for an HQ of 0.381. Because Lead is a non-threshold neurotoxin that impairs cognitive development and renal function in young children, its concentration (0.02 mg/L) twice exceeding WHO/NIS standards represents an urgent toxicological intervention point.

For adults, the cumulative Hazard Index (HI = 0.630) remains below the 1.0 threshold, indicating acceptable non-carcinogenic risk under current mean concentration levels. However, long-term chronic bioaccumulation over an assumed 30-year exposure duration warrants continued monitoring.

Deterministic point estimates tend to introduce uncertainty. Probabilistic Monte Carlo simulations (10,000 iterations) incorporating log-normal distribution assumptions for metal concentrations and body weights reveal that the 95th percentile Hazard Index for children reaches 2.45, demonstrating that children in high-consumption households (IR > 1.5 L/day) face elevated non-carcinogenic health hazards.

## 5.0 Conclusion

The integrated hydrogeological, geophysical, chemical, and community exposure evaluation around the Ntak-Inyang Itam disposal site yields four major conclusions:

**1. Unconfined Aquifer Vulnerability:** The shallow phreatic aquifer within the Coastal Plain Sands (Benin Formation) lacks a protective confining layer, permitting rapid downward infiltration of toxic leachate fluids (COD up to 3,479.4 mg/L; EC up to 6,321.3 µS/cm).

**2. Subsurface Plume Mapping:** ERT profiles confirm active, low-resistivity (< 30 Ωm) conductive leachate plumes migrating laterally toward Ntak-Inyang, Odiok Itam, and Ikot Obio Atai.

**3. Regulatory Non-Compliance:** Groundwater quality fails NIS 554:2015 and WHO (2022) drinking water benchmarks for Lead (0.02 mg/L vs 0.01 mg/L limit), Iron (0.37 mg/L vs 0.30 mg/L limit), and rainy-season E. coli loading (17.30 CFU/100 mL).

**4. Severe Community Health Exposure:** Over 54% of households consume untreated groundwater, with shallow well proximity to pit latrines driving a 22.7% community gastrointestinal illness rate across Ntak-Inyang, Odiok Itam, and Ata Idung.

## 6.0 Policy Recommendations

**i.** Transition the Ntak-Inyang Itam open dumpsite into an engineered sanitary landfill equipped with HDPE geomembrane liners, leachate collection sumps, and an onsite biological treatment facility.

**ii.** Enforce a mandatory 500-meter sanitary buffer zone around the landfill prohibiting new shallow well construction. Priority wellhead sealing (concrete aprons, drainage channels) should be carried out immediately in Ntak-Inyang and Odiok Itam.

**iii.** The Akwa Ibom State Water Corporation (AKSWC) should expand reticulated municipal water distribution networks across Ntak-Inyang, Odiok Itam, Ata Idung, Ikot Obio Atai, and Ikot Obong Itam to eliminate reliance on raw groundwater.

**iv.** Establish a quarterly groundwater quality and ERT monitoring program managed by the Akwa Ibom State Environmental Protection and Waste Management Agency (AKSEPWMA) to monitor trace metal transport and prevent food chain bioaccumulation.

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