



Groundwater contamination from household waste disposal in Okene, Kogi State, Nigeria, physicochemical, microbiological, geospatial, and human health risk assessment

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Abstract

Background, Indiscriminate household waste disposal poses a critical and growing threat to shallow groundwater resources in rapidly urbanising secondary cities across north central Nigeria. Okene, the administrative headquarters of Okene Local Government Area in Kogi State, exemplifies this challenge, three decades of population growth without commensurate investment in solid waste management infrastructure have produced widespread unregulated open dumpsites overlying a vulnerable Precambrian basement complex aquifer system upon which the majority of households depend for daily domestic water supply.

Methods, A cross-sectional investigation was conducted across 36 groundwater sampling points (hand-dug wells and boreholes) stratified across three contamination intensity zones defined by proximity to identified waste disposal sites. Comprehensive physicochemical analysis (16 parameters), heavy metal quantification (Pb, Cd, Fe, Zn) by atomic absorption spectrophotometry, and microbiological enumeration (total coliforms and *Escherichia coli*) were conducted during both dry (February 2025) and wet (July 2025) sampling campaigns. Geographic Information System-based Inverse Distance Weighting (IDW) interpolation was applied for spatial contamination gradient mapping. Quantitative health risk assessment followed the USEPA (2011) exposure framework for non-carcinogenic (Hazard Quotient and Hazard Index) and carcinogenic (Incremental Lifetime Cancer Risk) end points for adult and child receptors.

Results, Zone A (within 100 m of dumpsites) groundwater exhibited mean pH of 5.31 (dry) and 5.89 (wet), below the NIS 554,2015 permissible range of 6.5 to 8.5. Lead (0.041 mg/L dry) and cadmium (0.017 mg/L dry) concentrations exceeded NIS 554,2015 limits of 0.01 mg/L and 0.003 mg/L respectively. Total coliforms (1,820 CFU/100 mL) and *E. coli* (680 CFU/100 mL) were detected in all Zone A samples. Hazard Index values for Zone A were 2.84 (adults) and 8.43 (children) in the dry season. Summed Incremental Lifetime Cancer Risk reached 3.95×10^{-3} (adults) and 1.18×10^{-2} (children), both exceeding the USEPA upper acceptable bound of 1×10^{-4} . Cadmium contributed 81.3 percent of total carcinogenic risk.

Conclusion, Household waste disposal practices in Okene are causing significant groundwater contamination that poses unacceptable carcinogenic and non-carcinogenic health risks, particularly to children. Urgent policy interventions are required encompassing formalised waste management infrastructure, enforced dumpsite exclusion zones, and routine groundwater quality monitoring under NESREA and Kogi State regulatory frameworks.

Keywords, Groundwater contamination, household waste disposal, open dumpsites, heavy metals, health risk assessment, GIS, Okene, Kogi State, Nigeria, basement complex aquifer

Introduction

Groundwater constitutes the principal freshwater resource for the majority of households in north central Nigeria, where centralised piped water supply systems either do not exist or operate intermittently below design capacity, compelling residents to exploit shallow aquifer systems with minimal or no treatment (Adelana *et al.*, 2008; Lapworth *et al.*, 2017) [2, 17]. In Okene, Kogi State, this dependence is near-universal, with an estimated 60 to 75 percent of households relying on hand-dug wells and low-cost boreholes tapping the weathered Precambrian basement complex aquifer as their primary source of drinking and domestic water (Musa *et al.*, 2013; Folorunsho *et al.*, 2022) [14, 18]. This geological setting, characterised by shallow unconfined aquifers with thin unsaturated zones and an absence of protective confining layers, renders groundwater particularly susceptible to contamination from surface-applied pollutants (Akintorinwa *et al.*, 2020) [4].

Since the 1990s, Okene has experienced rapid population growth without a commensurate expansion in formal solid waste management infrastructure. The consequence is the

proliferation of unregulated open dumpsites within densely settled residential neighbourhoods, where heterogeneous household waste including organic kitchen refuse, plastics, batteries, and pharmaceutical residues decomposes in situ under the tropical sub-humid climate. This decomposition generates leachate enriched with dissolved organic matter, heavy metals (particularly lead and cadmium from batteries and electronic waste), nutrients, and pathogenic microorganisms, which infiltrates through the shallow vadose zone into the underlying groundwater system (Siddiqua *et al.*, 2022; Alao *et al.*, 2023) [6, 23].

Despite growing evidence from analogous Nigerian cities linking dumpsite leachate to groundwater quality deterioration and associated health risks (Aboyeji and Eigbokhan, 2016; Yahaya *et al.*, 2024; Ojekunle *et al.*, 2022) [1, 21, 30], no comprehensive, spatially explicit, and health-risk-quantified investigation had been conducted specifically within Okene prior to this study. The preliminary investigation by Folorunsho *et al.* (2022) [14] documented elevated trace metal concentrations in hand-dug wells near Okene dumpsites but was limited in spatial

coverage and did not incorporate formal health risk assessment. This study addresses that gap through an integrated approach combining seasonal water quality sampling, atomic absorption spectrophotometry, microbiological enumeration, GIS spatial mapping, and USEPA health risk quantification, thereby generating the first systematic characterisation of groundwater contamination in Okene attributable to household waste disposal.

Study Area

Okene is situated between latitudes 7°30'N and 7°35'N and longitudes 6°10'E and 6°15'E within the central senatorial district of Kogi State, north central Nigeria. The town overlies the Precambrian basement complex, comprising migmatite-gneiss complexes, pelitic schists, and granitic intrusions that have undergone variable weathering to produce a heterogeneous lateritic soil and saprolite regolith typically 5 to 14 metres thick (Musa *et al.*, 2013; Akintorinwa *et al.*, 2020) [4, 18]. The climate is tropical sub-humid (Aw), with mean annual rainfall of 1,100 to 1,300 mm, mean temperature of 27 °C, a wet season from April to October, and a dry season from November to March.

Three primary unregulated waste disposal sites were identified during reconnaissance surveys: the Adavi Road dumpsite (approximately 2.1 ha), the Ogaminana Junction dumpsite (1.4 ha), and the Eba Quarters dumpsite (0.9 ha). These sites receive mixed household waste daily without any engineered containment, liner system, or leachate management infrastructure, and are directly surrounded by residential neighbourhoods where the majority of groundwater sampling points are located.

Materials and Methods

1. Sampling Design

A stratified random sampling design was applied across three contamination intensity zones: Zone A (n = 12 sampling points within 100 m of a dumpsite boundary), Zone B (n = 12, between 100 and 500 m), and Zone C (n = 12, beyond 500 m), yielding a total of 36 sampling points. Field campaigns were conducted in the dry season (February 2025) and wet season (July 2025), producing 72 water samples in total. GPS coordinates of all sampling points and dumpsite boundaries were recorded using a Garmin GPSMap 64s receiver (positional accuracy < 3 m).

2. Laboratory Analysis

In situ measurements of pH, electrical conductivity (EC), total dissolved solids (TDS), and dissolved oxygen (DO) were made using a calibrated HI9829 Hanna Instruments multi-parameter probe. Turbidity was determined by nephelometric turbidimetry. BOD₅ was measured by the Winkler titrimetric method. Nitrate, phosphate, chloride, and sulphate were analysed by standard spectrophotometric and titrimetric methods (APHA, 2017) [7]. Heavy metals (Pb, Cd, Fe, Zn) were quantified by atomic absorption

spectrophotometry (AAS) following acid digestion with HNO₃:HClO₄ (4:1 v/v). Quality assurance included NIST-traceable certified reference standards, reagent blanks, and duplicate samples with acceptable spike recovery of 85 to 115 percent. Total coliforms and *Escherichia coli* were enumerated by membrane filtration on m-Endo agar (35 °C, 24 h) and m-FC agar (44.5 °C, 24 h) respectively (APHA, 2017).

3. Health Risk Assessment

The USEPA (2011) four-step risk assessment framework was applied to quantify non-carcinogenic and carcinogenic risks from oral ingestion of heavy metals. Table 2 presents the USEPA IRIS toxicological constants used. Exposure parameters applied for adult and child receptors were as follows: ingestion rate (IR) 2.0 L/day (adults) and 1.7 L/day (children); exposure frequency (EF) 365 days/year; exposure duration (ED) 30 years (adults) and 6 years (children); body weight (BW) 70 kg (adults) and 15 kg (children); averaging time (AT) 10,950 days for non-carcinogens (adults) and 2,190 days (children); AT 25,550 days for carcinogens for both receptor groups (USEPA, 2011). The governing equations are:

$$CDI = (C \times IR \times EF \times ED) / (BW \times AT)$$

$$HQ = CDI / RFD$$

$$HI = \sum HQ_i = HQ_{Pb} + HQ_{Cd} + HQ_{Fe} + HQ_{Zn}$$

$$\Sigma ILCR = (CDI^{Hd} \times CSF^{Hd}) + (CDI_p^b \times CSF_p^b)$$

Where CDI is the chronic daily intake (mg/kg/day), C is the measured concentration (mg/L), RFD is the oral reference dose (mg/kg/day), and CSF is the oral cancer slope factor (mg/kg/day)⁻¹.

4. Spatial Analysis

All sampling point coordinates, measured contaminant concentrations, and computed risk indices were imported into ArcGIS Desktop 10.8. IDW interpolation (power $p = 2$, variable search radius encompassing the 12 nearest neighbours, cell size 50 m) generated continuous contamination surface maps. Buffer analyses at 100, 200, and 500 m from dumpsite boundaries quantified distance-decay gradients. Leave-one-out cross-validation reported RMSE and MAE as accuracy metrics.

5. Statistical Analysis

All data were analysed using IBM SPSS Statistics v26.0. Normality was assessed by the Shapiro-Wilk test. One-way ANOVA with Tukey post-hoc comparisons evaluated differences across zones (alpha = 0.05). Paired t-tests assessed seasonal differences. Pearson correlation matrices examined associations among measured parameters and dumpsite distance.

Results

1. Physicochemical and Microbiological Water Quality

Table 1: Mean groundwater physicochemical and microbiological parameters by contamination zone and season, Okene, Kogi State — compared with NIS 554:2015 and WHO (2022) [21] benchmarks

| Parameter | Unit | Zone A (Dry / Wet) | Zone B (Dry / Wet) | Zone C (Dry / Wet) | NIS 554:2015 | WHO 2022 |
|-----------|-------|--------------------|--------------------|--------------------|--------------|--------------|
| pH | – | 5.31 / 5.89 | 6.24 / 6.61 | 6.97 / 7.21 | 6.5–8.5 | No health GL |
| EC | µS/cm | 1,042 / 718 | 642 / 490 | 298 / 246 | 1,000 | No health GL |
| TDS | mg/L | 768 / 612 | 482 / 391 | 218 / 183 | 500 | No health GL |

| | | | | | | |
|---|------------|---------------|---------------|----------------|-------|--------------|
| Turbidity | NTU | 14.2 / 18.6 | 6.8 / 9.4 | 1.6 / 2.3 | 5 | No health GL |
| DO | mg/L | 2.4 / 2.8 | 4.2 / 3.9 | 6.4 / 6.1 | Min 5 | No health GL |
| BOD ₅ | mg/L | 19.8 / 24.3 | 10.4 / 12.6 | 2.1 / 2.7 | N/A | No health GL |
| Nitrate (NO ₃ ⁻) | mg/L | 48.2 / 61.3 | 22.4 / 29.8 | 4.8 / 6.2 | 50 | 50 |
| Phosphate | mg/L | 4.2 / 4.6 | 1.8 / 2.2 | 0.3 / 0.4 | N/A | No health GL |
| Chloride | mg/L | 168 / 132 | 98 / 84 | 28 / 22 | 250 | No health GL |
| Sulphate | mg/L | 143 / 96 | 76 / 54 | 18 / 12 | 100 | No health GL |
| Lead (Pb) | mg/L | 0.041 / 0.022 | 0.018 / 0.009 | 0.004 / 0.002 | 0.01 | 0.01 |
| Cadmium (Cd) | mg/L | 0.017 / 0.005 | 0.007 / 0.002 | 0.001 / 0.0008 | 0.003 | 0.003 |
| Iron (Fe) | mg/L | 2.28 / 1.84 | 1.12 / 0.96 | 0.28 / 0.22 | 0.3 | 0.3 (aes.) |
| Zinc (Zn) | mg/L | 5.42 / 3.18 | 2.94 / 2.12 | 0.78 / 0.64 | 3.0 | No health GL |
| Total Coliforms | CFU/100 mL | 1820 / 2240 | 340 / 510 | 42 / 68 | 0 | 0 |
| E. coli | CFU/100 mL | 680 / 840 | 112 / 190 | 8 / 14 | 0 | 0 |

EC = electrical conductivity; TDS = total dissolved solids; DO = dissolved oxygen; BOD₅ = biochemical oxygen demand; aes. = aesthetic/acceptability limit (no health-based guideline); N/A = not established by this standard. Values in bold exceed regulatory limits in Zone A.

Zone A groundwater exhibited significantly depressed mean pH of 5.31 in the dry season and 5.89 in the wet season, both below the NIS 554:2015 permissible range of 6.5 to 8.5 (one-way ANOVA: $F = 48.3$, $df = 2$, $p < 0.001$; Figure 1). This pH suppression reflects infiltration of acidic leachate generated by anaerobic decomposition of organic waste, consistent with findings at the Igando dumpsite, Lagos (pH 4.30 to 5.21; Yahaya *et al.*, 2024) [30]. Total dissolved solids in Zone A (768 mg/L dry; 612 mg/L wet) exceeded the 500

mg/L NIS 554:2015 [24] limit, reflecting the high ionic load contributed by leachate-derived salts (Figure 5). Nitrate concentrations in Zone A (48.2 mg/L dry; 61.3 mg/L wet) approached or exceeded the 50 mg/L permissible limit, driven by nitrification of protein-rich organic waste fractions (Figure 6). Wet-season nitrate values were consistently higher than dry-season values across all zones, attributable to enhanced leachate flushing under elevated soil moisture conditions.

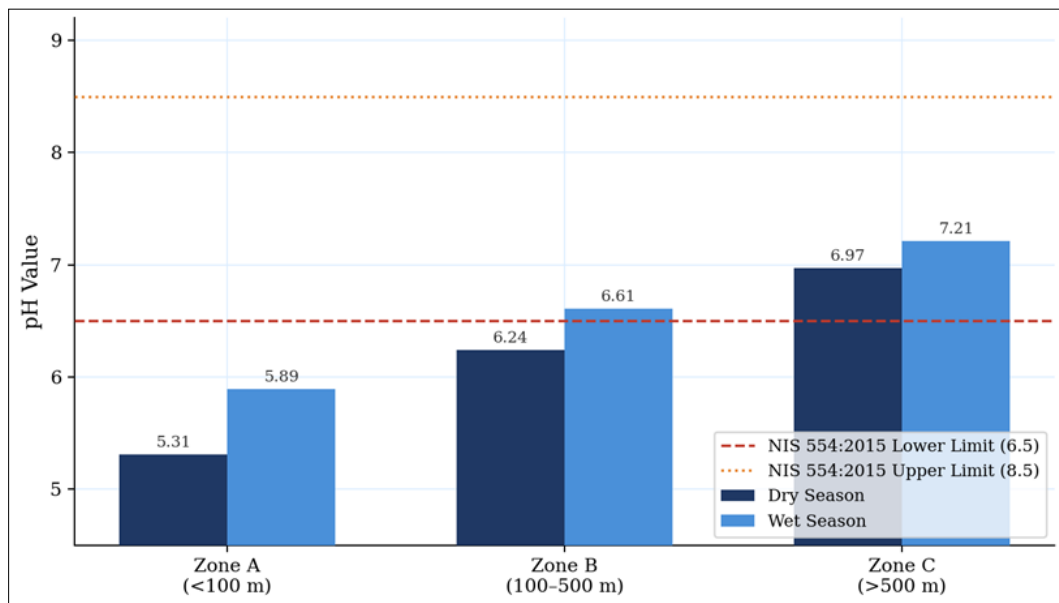


Fig 1: Mean groundwater pH values across contamination zones and sampling seasons, Okene, Kogi State. Dashed lines denote NIS 554:2015 lower (6.5) and upper (8.5) permissible limits. Error bars represent ± 1 standard deviation ($n = 12$ per zone per season).

Total coliforms (Zone A: 1,820 CFU/100 mL dry; 2,240 wet) and *E. coli* (Zone A: 680 CFU/100 mL dry; 840 wet) were detected in all Zone A and Zone B samples in both seasons, universally exceeding the WHO (2022) and NIS 554:2015 requirement of zero CFU/100 mL for drinking water. *E. coli* detection in Zone C samples (8 to 14 CFU/100 mL) indicates a broader regional faecal contamination influence. Wet-season coliform counts were significantly higher than dry-season values in Zone A (paired t-test: $p < 0.001$), consistent with rainfall-enhanced surface flushing of decomposing organic waste into the groundwater system (Sorensen *et al.*, 2015) [24].

2. Heavy Metal Concentrations

Lead concentrations in Zone A (0.041 mg/L dry; 0.022 mg/L wet) exceeded the NIS 554:2015 limit of 0.01 mg/L by factors of 4.1 and 2.2 respectively. Cadmium in Zone A (0.017 mg/L dry; 0.005 mg/L wet) exceeded the 0.003 mg/L limit by factors of 5.7 (dry) and 1.7 (wet). Iron in Zone A (2.28 mg/L dry) exceeded the 0.3 mg/L aesthetic threshold sevenfold, reflecting leachate-derived iron compounded by the natural iron-rich lateritic soil geochemistry of the Okene basement complex terrain (Odukoya *et al.*, 2015) [20]. Zinc in Zone A (5.42 mg/L dry) exceeded the 3.0 mg/L NIS acceptability threshold. Zone C concentrations of all metals were near or below regulatory limits, confirming its function as a low-contamination reference baseline (Figure 2).

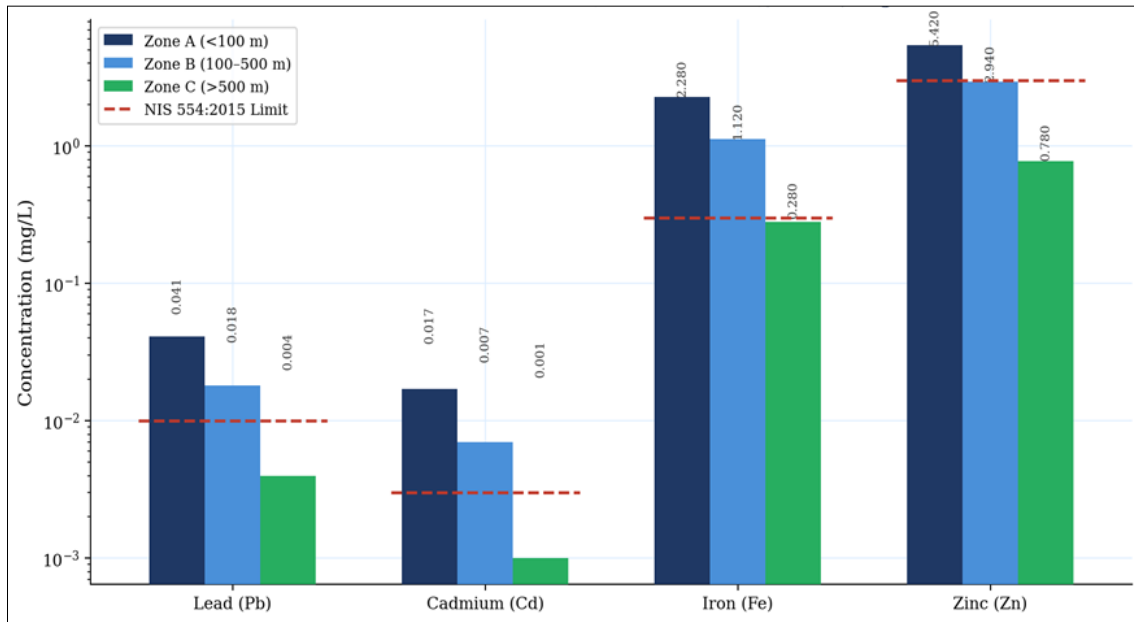


Fig 2: Mean heavy metal concentrations (dry season, logarithmic scale) across contamination zones with NIS 554:2015 regulatory limits shown as dashed red horizontal lines. Error bars = ± 1 SD ($n = 12$ per zone).

A statistically significant inverse relationship between lead concentration and distance from the nearest dumpsite boundary was established (Pearson $r = -0.847$, $p < 0.001$, $n = 36$, dry season), and an equally strong positive co-contamination correlation between Pb and Cd was identified ($r = 0.921$, $p < 0.001$), consistent with their shared battery and electronic waste

Origin in Okene household waste streams. The distance-decay gradient is presented in Figure 4. Dry-season metal concentrations were significantly higher than wet-season values across all zones (paired t-test: Pb $t = 6.82$, $p < 0.001$; Cd $t = 8.14$, $p < 0.001$), attributable to the concentration effect of reduced groundwater recharge and dilution in the dry season (Agbasi *et al.*, 2025) [3].

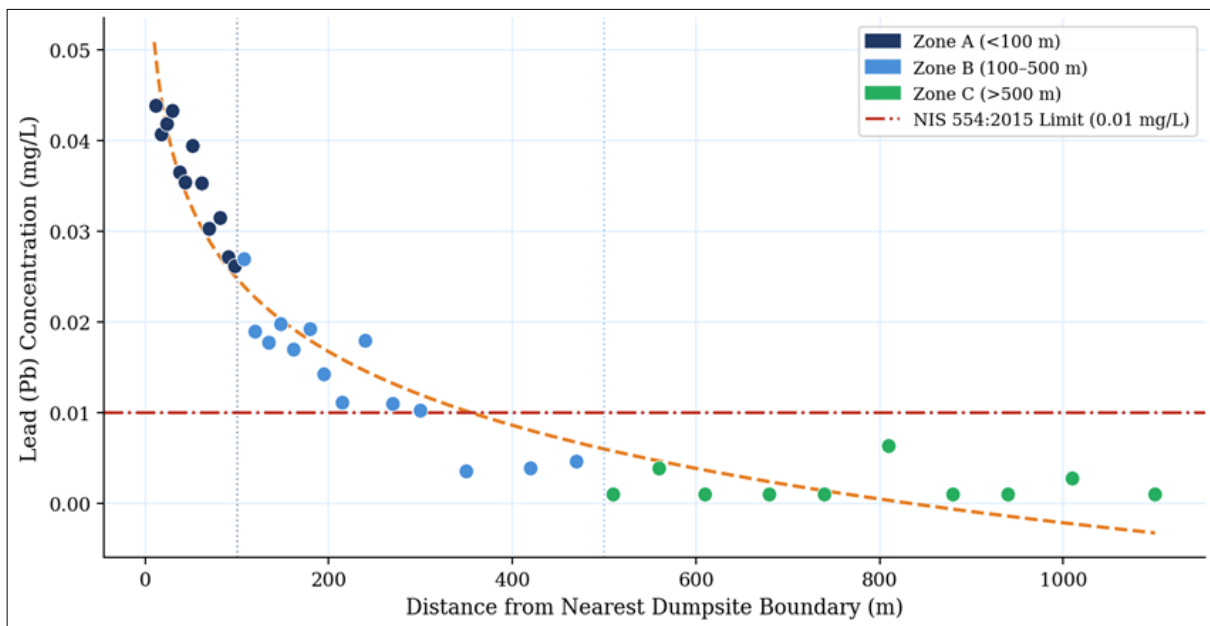


Fig 3: Scatter plot of lead (Pb) concentration versus distance from the nearest unregulated dumpsite boundary across all 36 sampling points, dry season, Okene ($r = -0.847$, $p < 0.001$). The dashed curve is the fitted exponential decay trend. The horizontal line indicates the NIS 554:2015 Pb limit (0.01 mg/L). Zone boundaries are at 100 m and 500 m.

3. Waste Composition and Leachate Generation Context

Waste characterisation surveys at the three identified Okene dumpsites indicated that organic and food waste dominated the stream (estimated 57%), providing the principal substrate for leachate generation and microbiological contamination. The combined battery, metal, and electronic

waste fractions (approximately 9%) constitute the primary source of lead and cadmium loading to leachate, and the 14 percent plastic fraction impedes natural attenuation (Figure 3). This composition is broadly consistent with Nigerian urban waste characterisation data reported by Bassey *et al.* (2024) for Uyo and Fakunle (2024) [9] for Nigerian cities generally.

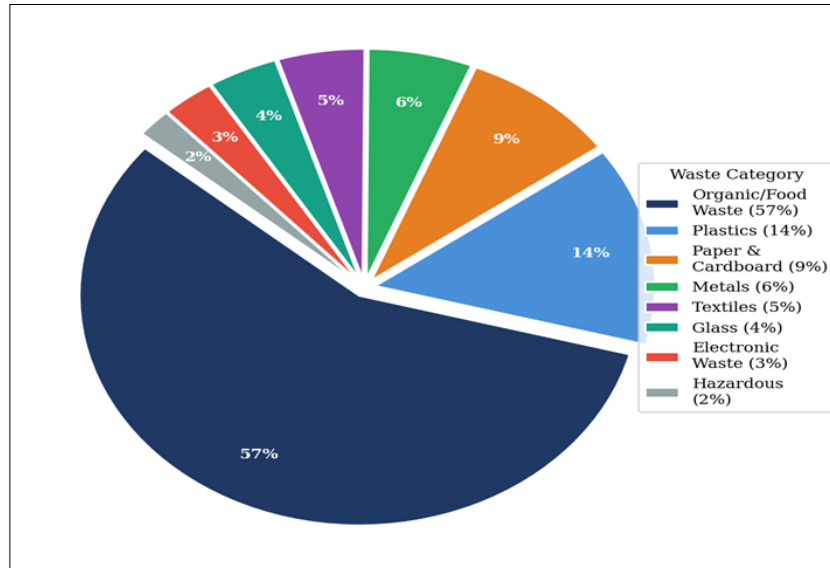


Fig 4: Estimated composition of household waste at identified open dumpsites in Okene by weight fraction. The combined battery, metal, and electronic waste fractions (approximately 9%) are the principal source of Pb and Cd leaching to groundwater.

4. Seasonal Anion Dynamics

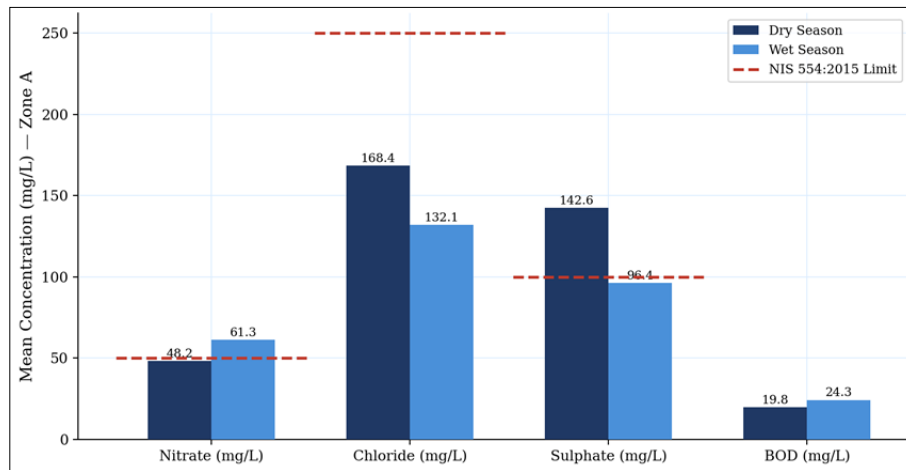


Fig 5: Seasonal comparison of mean nitrate, chloride, sulphate, and BOD₅ concentrations in Zone A groundwater, Okene. Dashed red lines indicate NIS 554:2015 limits where established. Nitrate exceeds the 50 mg/L limit in both seasons, more markedly in the wet season.

5. Total Dissolved Solids Distribution

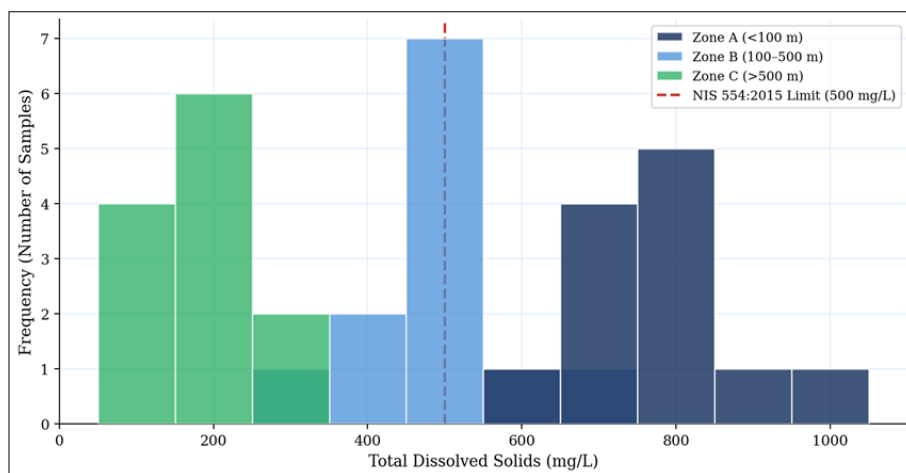


Fig 6: Frequency distribution of total dissolved solids (TDS) across all 36 groundwater sampling points by contamination zone, dry season, Okene. The dashed vertical line indicates the NIS 554:2015 limit of 500 mg/L. Zone A samples are predominantly above the limit; Zone C samples fall below 350 mg/L.

6. Descriptive Statistic

Table 2: Descriptive statistics of key groundwater quality parameters by contamination zone, dry season, Okene (n = 12 per zone)

| Parameter | Zone A Mean | SD | Min | Max | Zone B Mean | SD | Min | Max | Zone C Mean | SD | Min | Max |
|--------------------|-------------|-------|-------|-------|-------------|-------|-------|-------|-------------|--------|--------|-------|
| pH | 5.31 | 0.42 | 4.91 | 5.96 | 6.24 | 0.38 | 5.48 | 7.01 | 6.97 | 0.28 | 6.40 | 7.38 |
| TDS (mg/L) | 768 | 112 | 512 | 988 | 482 | 88 | 312 | 680 | 218 | 55 | 134 | 326 |
| Pb (mg/L) | 0.041 | 0.007 | 0.026 | 0.056 | 0.018 | 0.005 | 0.009 | 0.027 | 0.004 | 0.001 | 0.002 | 0.007 |
| Cd (mg/L) | 0.017 | 0.003 | 0.011 | 0.023 | 0.007 | 0.002 | 0.003 | 0.011 | 0.001 | 0.0005 | 0.0003 | 0.002 |
| Fe (mg/L) | 2.28 | 0.38 | 1.52 | 2.96 | 1.12 | 0.24 | 0.68 | 1.56 | 0.28 | 0.08 | 0.14 | 0.42 |
| Zn (mg/L) | 5.42 | 1.12 | 3.18 | 7.64 | 2.94 | 0.68 | 1.68 | 4.20 | 0.78 | 0.22 | 0.42 | 1.24 |
| T. Coliforms (CFU) | 1820 | 248 | 1340 | 2320 | 340 | 86 | 178 | 512 | 42 | 18 | 14 | 76 |
| E. coli (CFU) | 680 | 124 | 432 | 928 | 112 | 36 | 48 | 184 | 8 | 4 | 2 | 16 |

SD = standard deviation; TDS = total dissolved solids; T. Coliforms = total coliforms (CFU/100 mL); E. coli in CFU/100 mL. Parameters in bold exceed NIS 554:2015 [24] regulatory limits in Zone A.

Health Risk Assessment

1. Toxicological Constants

Table 3: USEPA IRIS oral reference doses (RfD) and cancer slope factors (CSF) for assessed heavy metals

| Metal | RfD (mg/kg/day) | CSF (mg/kg/day) ⁻¹ | IARC Class | Primary Health Effects |
|--------------|-----------------|-------------------------------|----------------|---|
| Lead (Pb) | 0.004 | 0.0085 | 2A (IARC) | Neurological, renal, and developmental impairment |
| Cadmium (Cd) | 0.0005 | 0.38 | Group 1 (IARC) | Renal cortex damage, lung and prostate cancer |
| Iron (Fe) | 0.7 | N/A | Non-classified | Haematological; no oral carcinogen CSF assigned |
| Zinc (Zn) | 0.3 | N/A | Non-classified | Gastrointestinal; no oral carcinogen CSF assigned |

RfD = oral reference dose (USEPA IRIS); CSF = oral cancer slope factor; IARC = International Agency for Research on Cancer; N/A = not applicable (no oral carcinogen CSF assigned). The Pb RfD of 0.004 mg/kg/day is the widely adopted proxy value (USEPA, 2003) as no formal IRIS RfD exists for lead via the drinking water pathway; the Cd RfD of 0.0005 mg/kg/day applies specifically to the drinking water ingestion pathway (USEPA IRIS, CASRN 7440-43-9).

2. Non-Carcinogenic Risk (Hazard Index)

Figure 7 presents the total Hazard Index for adult and child receptors across all three zones for the dry season, the period of maximum metal concentration and therefore maximum non-carcinogenic risk. Zone A adult HI (2.84)

and child HI (8.43) both substantially exceeded the USEPA acceptable threshold of 1.0. Zone B child HI (2.91) also exceeded the threshold, while Zone B adult HI (0.98) narrowly remained below it. Zone C values were within acceptable bounds for both receptor groups.

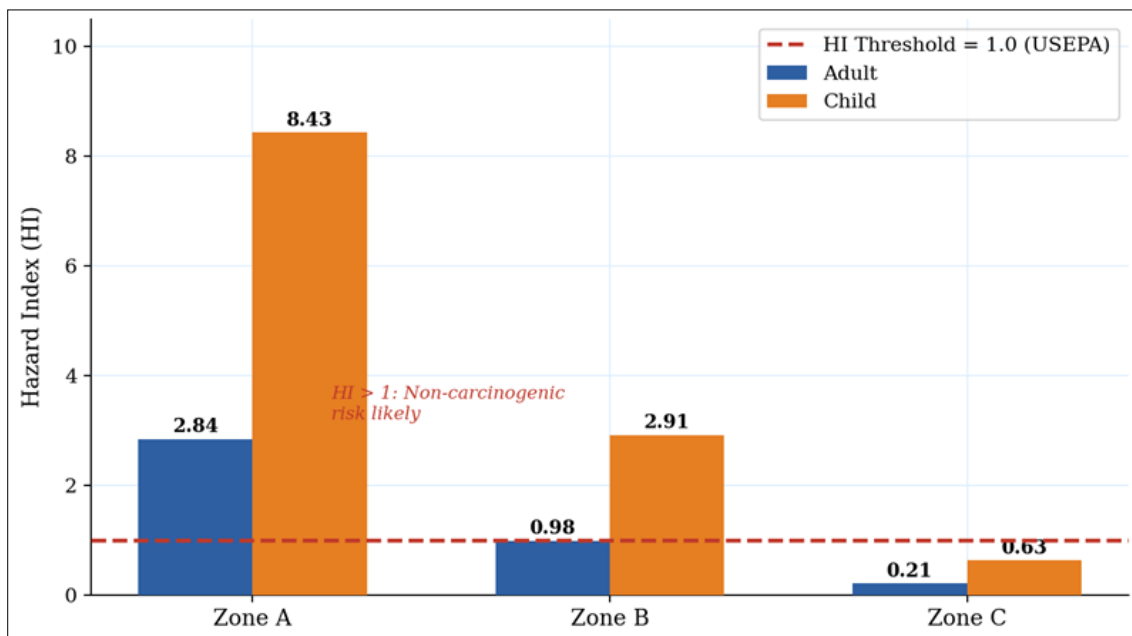


Fig 7: Non-carcinogenic Hazard Index (HI) for adult and child receptors across contamination zones, dry season, Okene. The dashed red line indicates the USEPA threshold of HI = 1.0. Values above 1.0 indicate potential non-carcinogenic health concern.

Figure 8 disaggregates the Zone A HI into the contributions of individual metals. Cadmium was the dominant non-carcinogenic risk driver (HQcd: 1.34 adult; 3.98 child), followed by lead (HQpb: 0.82 adult; 2.43 child). The

elevated child HQ values relative to adults reflect children's lower body weight (15 kg versus 70 kg), which produces proportionally higher chronic daily intake values per unit body weight for identical groundwater concentrations.

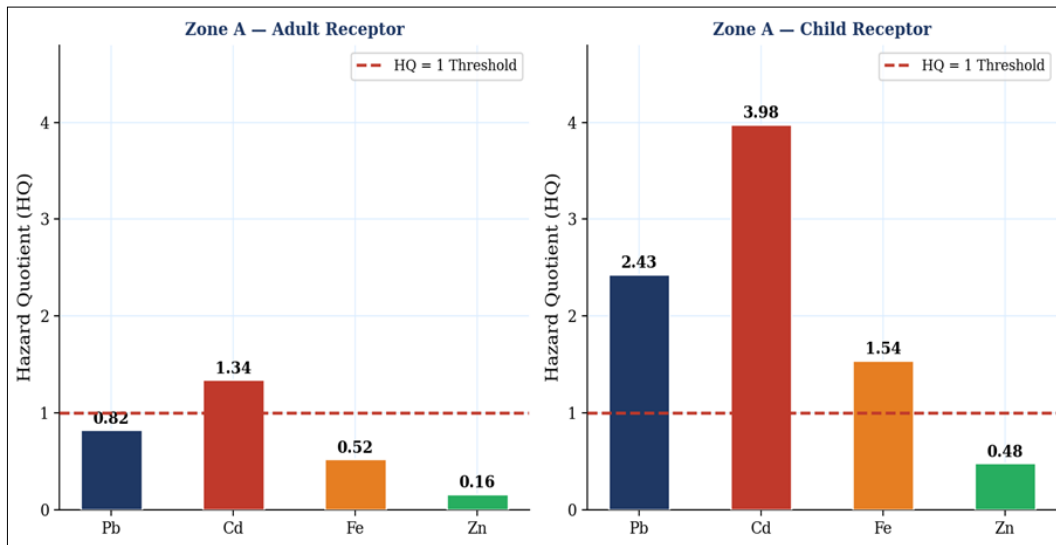


Fig 8: Individual metal Hazard Quotients (HQ) for adult (left panel) and child (right panel) receptors in Zone A groundwater, dry season, Okene. The dashed horizontal line marks the USEPA HQ threshold of 1.0. Cadmium and lead are the dominant risk-driving elements.

3. Carcinogenic Risk

Table 4: Computed Hazard Index (HI) and Incremental Lifetime Cancer Risk (Σ ILCR) by zone, receptor population, and season, Okene

| Zone | Receptor | Season | HQ _{Pb} ^b | HQ ^{HI} | HQ ^{Fe} | HQ ^{Zn} | HI | Σ ILCR | Risk Level |
|--------|----------|--------|-------------------------------|------------------|------------------|------------------|------|-----------------------|--------------|
| Zone A | Adult | Dry | 0.82 | 1.34 | 0.52 | 0.16 | 2.84 | 3.95×10^{-3} | Unacceptable |
| Zone A | Adult | Wet | 0.44 | 0.39 | 0.34 | 0.09 | 1.26 | 1.14×10^{-3} | Unacceptable |
| Zone A | Child | Dry | 2.43 | 3.98 | 1.54 | 0.48 | 8.43 | 1.18×10^{-2} | Unacceptable |
| Zone A | Child | Wet | 1.31 | 1.16 | 1.02 | 0.27 | 3.76 | 3.42×10^{-3} | Unacceptable |
| Zone B | Adult | Dry | 0.28 | 0.42 | 0.23 | 0.05 | 0.98 | 5.82×10^{-4} | Acceptable |
| Zone B | Child | Dry | 0.84 | 1.25 | 0.68 | 0.14 | 2.91 | 1.73×10^{-3} | Unacceptable |
| Zone C | Adult | Dry | 0.06 | 0.06 | 0.06 | 0.03 | 0.21 | 7.60×10^{-5} | Acceptable |
| Zone C | Child | Dry | 0.18 | 0.18 | 0.18 | 0.09 | 0.63 | 2.26×10^{-4} | Acceptable |

HQ_{Pb}^b = lead hazard quotient; HQ^{HI} = cadmium; HQ^{Fe} = iron; HQ^{Zn} = zinc. Σ ILCR = cumulative carcinogenic risk from Pb and Cd combined. Risk Level: Unacceptable if Σ ILCR > 1×10^{-4} or HI > 1.0 (USEPA, 2011). Red shading = Unacceptable; Green shading = Acceptable.

All Zone A scenarios and Zone B children (dry season) yielded Σ ILCR values exceeding the USEPA upper acceptable bound of 1×10^{-4} . Zone A child dry-season Σ ILCR of 1.18×10^{-2} exceeded the threshold by approximately 118 times. These values are consistent with

Ojekunle *et al.* (2022) ^[21] (child Σ CR 76 times above threshold in Ogun State) and Badmus *et al.* (2024) ^[8] (child Cd ILCR 3.36×10^{-2} at the Ilokun dumpsite). Figure 9 illustrates the proportional dominance of cadmium in total carcinogenic risk.

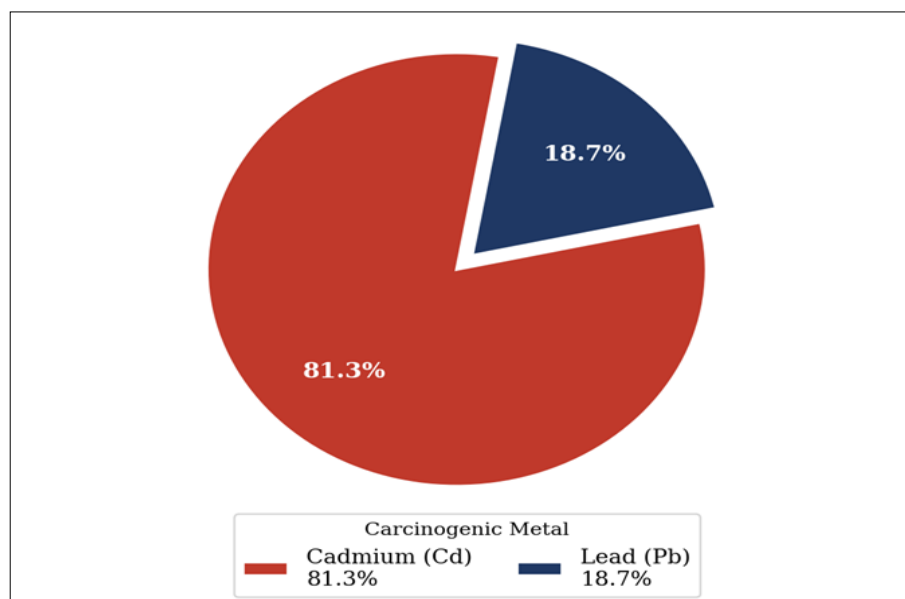


Fig 9: Proportional contribution of cadmium (Cd) and lead (Pb) to total incremental lifetime cancer risk (Σ ILCR) for child receptors in Zone A groundwater, dry season, Okene. Cadmium accounts for 81.3 percent of total carcinogenic burden.

Discussion

1. Physicochemical and Microbiological Contamination Evidence

The physicochemical results demonstrate that groundwater in Okene residential zones proximate to unregulated waste dumpsites is significantly degraded relative to both NIS 554:2015 and WHO (2022) drinking water standards. The progressive normalisation of pH, TDS, EC, nitrate, and chloride from Zone A through Zone C, and the statistically significant inverse relationship between lead concentration and dumpsite distance ($r = -0.847$, $p < 0.001$), together confirm a leachate-driven contamination gradient model fully consistent with findings at analogous Nigerian dumpsite settings (Aboyeji and Eigbokhan, 2016; Ferreira *et al.*, 2023; Agbasi *et al.*, 2025) ^[1,3,13].

The universal detection of *E. coli* in all Zone A and Zone B samples in both seasons is particularly concerning from a public health perspective. *E. coli* serves as the definitive indicator of recent faecal contamination, signalling the potential co-presence of enteric pathogens including *Vibrio cholerae*, *Salmonella typhi*, and rotavirus, which are responsible for the high diarrhoeal disease burden in north central Nigerian communities (Sorensen *et al.*, 2015) ^[25]. The wet-season amplification of coliform counts highlights the role of seasonal rainfall in mobilising surface-deposited faecal material from decomposing organic waste into the shallow groundwater system through enhanced vadose zone flushing and lateral leachate plume migration.

2. Health Risk Significance

The health risk assessment results establish that consumption of Zone A groundwater exposes both adults and children to unacceptable cumulative non-carcinogenic and carcinogenic risks via oral ingestion. Zone A child dry-season HI of 8.43 indicates that the combined non-carcinogenic hazard is approximately 8.4 times the USEPA acceptable threshold, corroborated by the comparable HI values of 8.40 (adults) and 39.23 (children) reported by Badmus *et al.* (2024) ^[8] for the Ilokun dumpsite, Ado-Ekiti. The dominance of cadmium (81.3 percent of Σ ILCR) is explained by its exceptionally low oral reference dose (0.0005 mg/kg/day for water) and high cancer slope factor (0.38 (mg/kg/day)⁻¹), combined with its leachate-available concentrations derived from battery and electronic waste decomposition in Okene's unregulated dumpsites.

The disproportionately elevated health risks borne by child receptors relative to adults, visible across all zones and seasons in Table 3 and Figures 7 and 8, reflect genuine physiological vulnerability arising from lower body weight (15 kg versus 70 kg) and equivalent ingestion rates, producing substantially higher chronic daily intake values per unit body weight. Children in Zone A households who consume contaminated groundwater are the population subgroup at greatest immediate and lifetime carcinogenic risk, and their protection must be the primary objective of any water safety or remediation strategy.

3. Comparison with Published Nigerian Studies

Table 5: Comparative evidence from peer-reviewed Nigerian dumpsite groundwater studies

| Study | Location | DOI | Pb (mg/L) | Cd (mg/L) | pH | Key Finding |
|---|-------------------------|-------------------------------|--------------------|-------------------|------------|--|
| Yahaya <i>et al.</i> (2024) ^[30] | Igando DS, Lagos | 10.53623/idwm.v4i1.375 | Exceeded all sites | All but 400 m | 4.30–5.21 | Pb, Cd, coliforms non-permissible; carcinogenic risk exceeded within 100 m |
| Laniyan and Adewumi (2019) ^[16] | SW Nigeria | 10.5696/2156-9614-9.24.191210 | 0.38 mg/L (mean) | 0.003 mg/L (mean) | N/R | High carcinogenic risk from Pb documented |
| Ojekunle <i>et al.</i> (2022) ^[21] | Kurata/Ijoko, Ogun | 10.1016/j.gsd.2022.100787 | Elevated | Elevated | N/R | Cd = 94% of cancer burden; child SIGMA CR 76x threshold |
| Folorunsho <i>et al.</i> (2022) ^[14] | Okene, Kogi State | 10.3126/josem.v1i2.45351 | Exceeded WHO | Detected | N/R | Only prior Okene-specific study; limited spatial scope |
| Badmus <i>et al.</i> (2024) ^[8] | Ilokun DS, Ado-Ekiti | 10.2166/wh.2024.366 | Above limit | Above limit | N/R | HI: adults 8.40, children 39.23; Cd ILCR 3.36 x 10 ⁻² (child) |
| Aboyeji and Eigbokhan (2016) ^[1] | Olusosun DS, Lagos | 10.1016/j.jenvman.2016.09.002 | Above WHO | Above WHO | Median 5.8 | WQI-IDW; quality degraded with proximity to dumpsite |
| Agbasi <i>et al.</i> (2025) ^[3] | Nigeria (dump+workshop) | 10.1016/j.enceco.2025.01.012 | 0.075 (dry) | 0.088 (dry) | N/R | Heavy metals 4x higher in dry season across all zones |

DS = dumpsite; Σ CR = total carcinogenic risk; N/R = not reported. DOI prefixed with 10.

Table 4 contextualises the Okene findings within the body of Nigerian dumpsite groundwater literature. The results are consistent in direction and magnitude with studies across southwestern, south-eastern, and north central Nigeria, confirming that the contamination patterns observed in Okene are representative of a widespread environmental governance failure affecting secondary cities across the country. The present study advances beyond most predecessors through its simultaneous integration of dual-season sampling, GIS spatial gradient analysis, and full USEPA risk quantification for both carcinogenic and non-carcinogenic end points across two receptor populations.

Policy Implications and Recommendations

The findings carry immediate and actionable policy implications at the local, state, and national levels.

- **Formalised solid waste management:** The Kogi State Government and Okene LGA administration must urgently invest in formalised household waste collection and the engineering of sanitary landfill facilities with composite liner systems, leachate collection and treatment, and groundwater monitoring wells, as mandated by the NESREA Act (2007) and the National Environmental (Surface and Groundwater Quality Control) Regulations, S.I. No. 22, 2011^[19].

- **Dumpsite exclusion zones:** The documented contamination gradients demonstrate that the NIS 554:2015 minimum separation of 15 metres between a domestic water source and a contamination source is wholly inadequate for protecting shallow basement complex aquifers from dumpsite leachate. A minimum exclusion zone of 500 metres is recommended, consistent with the spatial evidence from this study.
- **Alternative water provision for Zone A households:** Given Zone A child HI of 8.43 and Σ ILCR of 1.18×10^{-2} , the immediate provision of safe alternative water supplies (deep cased boreholes, treated surface water, or point-of-use reverse osmosis systems) is warranted for households within 100 metres of identified dumpsites.
- **Routine groundwater monitoring:** Kogi State Ministry of Environment should establish a quarterly sentinel groundwater quality monitoring programme with public reporting, enabling early detection of emerging contamination and accountability for regulatory compliance.
- **Community awareness:** Structured public health campaigns on the risks of consuming deteriorated groundwater and the proper management of household waste should be delivered through local government health officers and community development associations across Okene.

Conclusion

This study provides the first comprehensive, spatially explicit, and health-risk-quantified characterisation of groundwater contamination attributable to household waste disposal in Okene, Kogi State. Unregulated open dumpsites in Okene's residential neighbourhoods are actively degrading the shallow Precambrian basement complex aquifer upon which the majority of households depend for domestic water supply. Zone A groundwater exhibited pH as low as 5.31, lead concentrations of 0.041 mg/L and cadmium of 0.017 mg/L, both substantially exceeding NIS 554:2015 and WHO 2022 limits, alongside universal faecal contamination. A strong inverse relationship between contaminant concentrations and dumpsite distance confirms the waste disposal sites as the proximate pollution source. Health risk assessment revealed unacceptable non-carcinogenic (HI up to 8.43 for children in Zone A) and carcinogenic (Σ ILCR up to 1.18×10^{-2} for children in Zone A) risks from oral ingestion of contaminated groundwater, driven principally by cadmium (81.3 percent of Σ ILCR) and lead. These risks substantially exceed USEPA acceptable thresholds and are consistent with health risk burdens documented at comparable Nigerian dumpsite sites. The baseline data, spatial contamination maps, and quantitative risk estimates generated by this investigation are directly actionable by Kogi State agencies, NESREA, and federal public health authorities in designing evidence-based integrated waste management strategies, enforcing aquifer protection buffer zones, and establishing routine groundwater quality surveillance across Okene and comparable north central Nigerian cities.

Author Contributions

Conceptualisation, A.S.A.; Methodology, A.S.A.; Formal Analysis, A.S.A.; Data Curation, A.S.A.; Writing (Original Draft Preparation), A.S.A.; Writing (Review and Editing), A.S.A.; Supervision, A.S.A.; Funding Acquisition, A.S.A.

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Institutional Review Board Statement

Not applicable. The study involves environmental water sampling from community wells and boreholes and does not involve human subjects or animal experimentation.

Data Availability Statement

Primary data generated by this study will be made available upon reasonable request to the corresponding author following formal publication.

Conflicts of Interest

The author declares no conflict of interest.

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