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## **GEOSPATIAL ANALYSIS OF ANTHROPOGENIC HEAVY METAL SOURCES AND DISTRIBUTION IN SOIL AND GROUNDWATER IN FUNTUA, KATSINA STATE**

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### **ABSTRACT**

Heavy metal contamination of soil and groundwater is an escalating environmental and public health threat in rapidly urbanizing settlements, where overlapping anthropogenic activities complicate risk assessment and constrain effective management. In Funtua, Katsina State, Nigeria, limited geospatial evidence linking contamination sources to observed pollution patterns has hindered evidence-based groundwater conservation. This study spatially characterized anthropogenic heavy metal contamination in soil and groundwater across Funtua metropolis and identified priority zones for intervention. An integrated geospatial framework combining field surveys, systematic sampling and atomic absorption spectrophotometry was employed, and concentration profiles, source-clustering patterns, contamination levels and composite indices were computed and mapped using a Geographic Information System. Anthropogenic pollution sources exhibited statistically significant spatial clustering, including auto-mechanic workshops ( $z = -11.10$ ,  $p < 0.001$ ), filling stations ( $z = -12.36$ ,  $p < 0.01$ ) and dumpsites ( $z = -19.84$ ,  $p < 0.01$ ). Soil concentrations ranged from 0.19-0.26 mg/kg (Cd), 1.80-3.02 mg/kg (Cu), 1.74-7.46 mg/kg (Pb), 4.41-18.90 mg/kg (Fe) and 0.14-0.84 mg/kg (Ni). Groundwater analysis returned markedly elevated lead (up to 74.37 mg/L) and nickel (up to 560.10 mg/L) at several locations; these two extreme values exceed drinking-water guideline values by three to four orders of magnitude and are reported as provisional pending confirmatory re-analysis. The Metal Index ranged from 0.02 to 63.86, with 12.40% of the study area (17.09 km<sup>2</sup>) classified as contaminated, while the combined high- and very-high-risk zones occupied 0.68% (0.93 km<sup>2</sup>) and coincided with dense source overlap. Heavy metal contamination in Funtua is spatially structured and driven primarily by clustering of anthropogenic activities. Targeted monitoring, land-use control and regulatory enforcement at identified hotspots are recommended, and a low-cost biochar-based groundwater treatment system is proposed as a direction for future work.

**Keywords:** Heavy metal contamination; Anthropogenic sources; Soil pollution; Groundwater quality; Geospatial analysis

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## **1. INTRODUCTION**

Heavy metal contamination of soil and groundwater is recognized globally as one of the most intractable forms of environmental degradation, owing to the persistence and bioaccumulative behaviour of metallic pollutants (Kabata-Pendias, 2011). While natural weathering establishes baseline metal concentrations, the sharpest increases are anthropogenically driven, arising from industrial activity, waste disposal, vehicular traffic and unplanned urban expansion (FAO, 2017; Alloway, 2013). Urban and peri-urban settlements are disproportionately affected because informal pollution sources such as auto-mechanic workshops, filling stations and dumpsites are typically spatially concentrated and inadequately regulated.

Studies in China show that soil metal accumulation is governed primarily by land-use intensity and proximity to the urban core (Fang et al., 2011; Huang et al., 2018; Yang et al., 2020), while Nigerian studies in Ijebu-Ode, Lagos and Nsukka have linked localized soil contamination to differential land use, industrial estates and clustered mechanic workshops, respectively (Adedeji et al., 2019; Ololade et al., 2022; Duru et al., 2024). Groundwater, which supplies nearly half of global freshwater withdrawals,

is especially vulnerable once surface contaminants infiltrate through permeable soils and inadequate drainage (Jain, 2023), and aquifers underlying Africa's Sahelian belt, including northern Nigeria, face considerable and spatially heterogeneous pollution risk (Podgorski et al., 2024).

Despite this growing body of research, most existing studies focus on large metropolitan centres and treat soil and groundwater contamination as discrete processes, leaving medium-sized, rapidly urbanizing towns characteristic of northern Nigeria, and integrated source-to-contamination frameworks, comparatively understudied. In Funtua, Katsina State, no such framework has yet been applied, which constrains environmental planning, groundwater protection and risk-based regulatory decision-making.

The present study addresses this gap. It integrates a field-based source inventory, systematic soil and groundwater sampling, laboratory analysis and GIS-based spatial and contamination-index modelling in order to characterize the spatial distribution of the three major anthropogenic heavy metal sources in Funtua — auto-mechanic workshops, filling stations and dumpsites — to quantify the associated soil and groundwater contamination, and to identify the priority zones for intervention that follow from their spatial coincidence.

## 2. METHODOLOGY

### 2.1 Study Area

Funtua town lies between latitudes 11.390279°N and 11.580643°N and longitudes 7.244443°E and 7.358793°E in Katsina State, north-western Nigeria, covering approximately 137.72 km<sup>2</sup> across eight wards (Makera, Nasarawa, Anguwan Musa, Sabon Gari, Anguwan Ibrahim, Dandutse, Maigamji and Kusami/Yankwani). As a major commercial and transit hub, the town hosts a dense concentration of filling stations, auto-mechanic workshops and informal dumpsites clustered along its road network and market areas, making it a suitable case for examining the linkage between anthropogenic activity and soil/groundwater contamination. Locality names follow a single gazetteer, applied consistently across the text, tables and figures of this paper; variant spellings encountered in the field records were reconciled to this gazetteer before analysis.

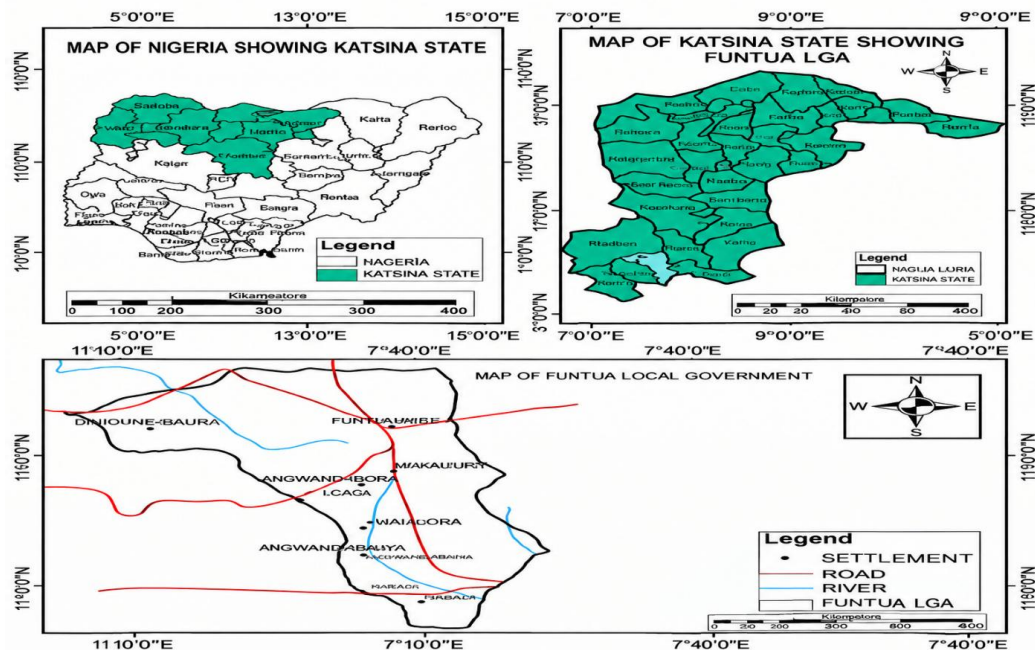


Figure 1: Map of the study area.

### 2.2 Sampling and Laboratory Analysis

Source coordinates for filling stations, auto-mechanic workshops and dumpsites were captured with a hand-held GPS, imported into Microsoft Excel, converted to shapefiles, and overlaid on the study-area base map in ArcMap 10.3/ArcGIS 10.8. A 50 m buffer was delineated around all mapped

contaminant sources, and sampling was stratified across the eight wards. Within each ward, four soil samples (0–25 cm depth) and four groundwater samples (from hand-dug wells and boreholes) were collected inside the buffer zone, yielding 32 source-proximal soil samples and 32 source-proximal groundwater samples. A further four soil and four groundwater control samples were collected from areas of comparably low anthropogenic activity outside all buffers, giving an overall total of thirty-six soil samples (S1–S36) and thirty-six groundwater samples (W1–W36). The control samples supplied the local geochemical background value used in the geo-accumulation index and the baseline against which source-proximal enrichment was judged.

Soil and groundwater samples were digested by the nitric acid–sulfuric acid procedure of Standard Methods for the Examination of Water and Wastewater, Method 3030 G (APHA, AWWA & WEF, 2005), and analysed for Al, Cd, Cu, Fe, Ni and Pb using an atomic absorption spectrophotometer (Unicam Model 969) at the National Water Quality Reference Laboratory, Sokoto. Groundwater physicochemical parameters (temperature, pH, electrical conductivity, salinity, turbidity and hardness) were determined on separate unacidified aliquots. Analytical quality was controlled through multi-point calibration ( $r^2 > 0.995$ ), reagent blanks, and duplicate and matrix-spike analysis; the numerical QA/QC outcomes are not reported in this paper, so the two extreme groundwater Pb and Ni values discussed in Section 3.3 are treated as provisional pending confirmatory re-analysis.

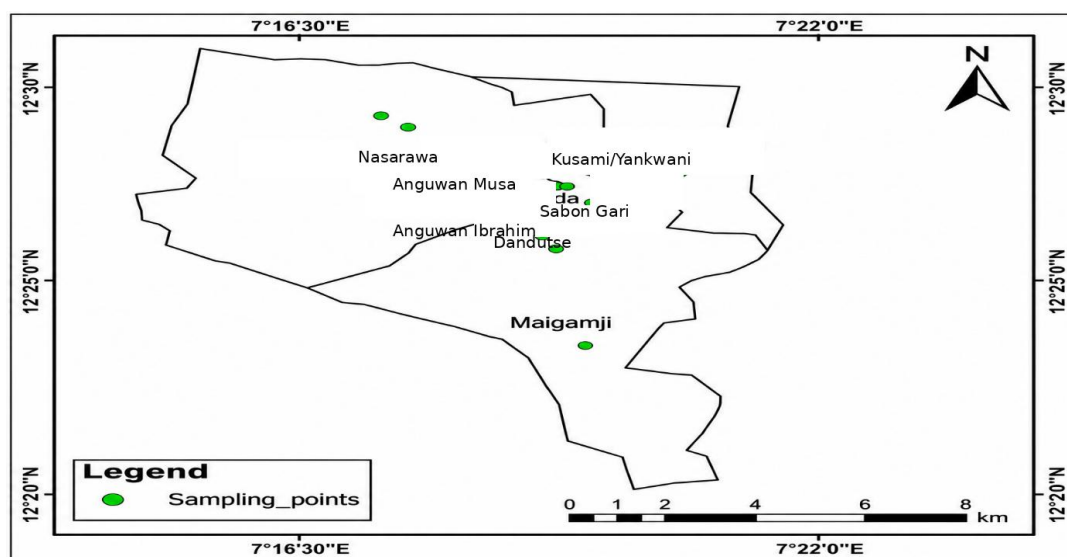


Figure 2: Spatial distribution of soil and groundwater sampling points across the wards of Funtua.

### 2.3 Geospatial and Statistical Analysis

Spatial analysis comprised point mapping, Average Nearest Neighbour (ANN) analysis, buffering, overlay/intersect analysis, and raster interpolation and reclassification in ArcGIS. The ANN statistic compares the observed mean nearest-neighbour distance among source points with the value expected under complete spatial randomness (Clark & Evans, 1954), yielding a Nearest Neighbour Ratio (NNR) and an associated z-score; ratios substantially below 1.0 with large negative z-scores indicate statistically significant spatial clustering (Ebdon, 1976; Mitchell, 2005). Where the NNR was unavailable for a source category, inference in this paper is confined to the significance of the departure from randomness rather than the ranking of clustering intensity.

Soil contamination was assessed using the Geo-accumulation Index (Igeo), computed as:

$$I_{geo} = \log_2 (C_m / 1.5B_n) \quad (1)$$

where  $C_m$  is the measured concentration of the metal and  $B_n$  is the local geochemical background value, taken as the geometric mean of its concentration in the control soils; the factor 1.5 corrects for lithogenic variation (Müller, 1969). Values were classified into seven standard Müller classes, from uncontaminated ( $I_{geo} \leq 0$ ) to extremely contaminated ( $I_{geo} > 5$ ).

Groundwater contamination was assessed using the Metal Index (MI), computed as:

$$MI = \sum (C_i / MAC_i) \quad (2)$$

where  $C_i$  is the measured concentration of metal  $i$  and  $MAC_i$  is the WHO maximum allowable concentration for that metal (Table 1);  $MI > 1.00$  denotes contaminated groundwater and  $MI \leq 1.00$  denotes uncontaminated groundwater (Tamasi & Cini, 2004). Fifty-metre source buffers were also intersected to classify groundwater risk zones as low, high or very high according to the degree of overlap among source-influence zones.

Table 1: WHO maximum allowable concentrations (MAC) used for Metal Index calculation.

| Metal            | Cu   | Ni   | Cd    | Pb   | Fe   | Al   |
|------------------|------|------|-------|------|------|------|
| WHO limit (mg/L) | 2.00 | 0.07 | 0.003 | 0.05 | 3.00 | 2.90 |

### 3. RESULTS AND DISCUSSION

#### 3.1 Spatial Clustering of Anthropogenic Sources

The ANN analysis showed that anthropogenic sources within the study area are not randomly distributed but exhibit statistically significant spatial clustering (Table 2), concentrated around Anguwan Musa, Sabon Gari, Dandutse, Kusami/Yankwani and the surrounding central corridor (Figure 3). Auto-mechanic workshops returned an NNR of 0.42 ( $z = -11.10$ ,  $p < 0.001$ ), indicating strong clustering consistent with Nigerian GIS-based studies of workshop clusters (Ajeh et al., 2022; Duru et al., 2024; Iwegbue et al., 2024). Filling stations ( $z = -12.36$ ,  $p < 0.01$ ) and dumpsites ( $z = -19.84$ ,  $p < 0.01$ ) also departed significantly from randomness, although their NNR values were unavailable in the ANN output, so inference for these two categories is limited to statistical significance rather than clustering intensity or ranking. Sabon Gari, Anguwan Ibrahim and Nasarawa together accounted for approximately 77% of the mapped source density, indicating that environmental pressure is concentrated in a small part of the study area rather than evenly distributed, and that monitoring based on the area-wide average could underestimate conditions within these clusters.

Table 2: Average Nearest Neighbour (ANN) results for anthropogenic source categories.

| Source category         | NNR  | z-score | p-value   | Pattern                 |
|-------------------------|------|---------|-----------|-------------------------|
| Auto-mechanic workshops | 0.42 | -11.10  | $< 0.001$ | Highly clustered        |
| Filling stations        | —    | -12.36  | $< 0.01$  | Significantly clustered |
| Dumpsites               | —    | -19.84  | $< 0.01$  | Significantly clustered |

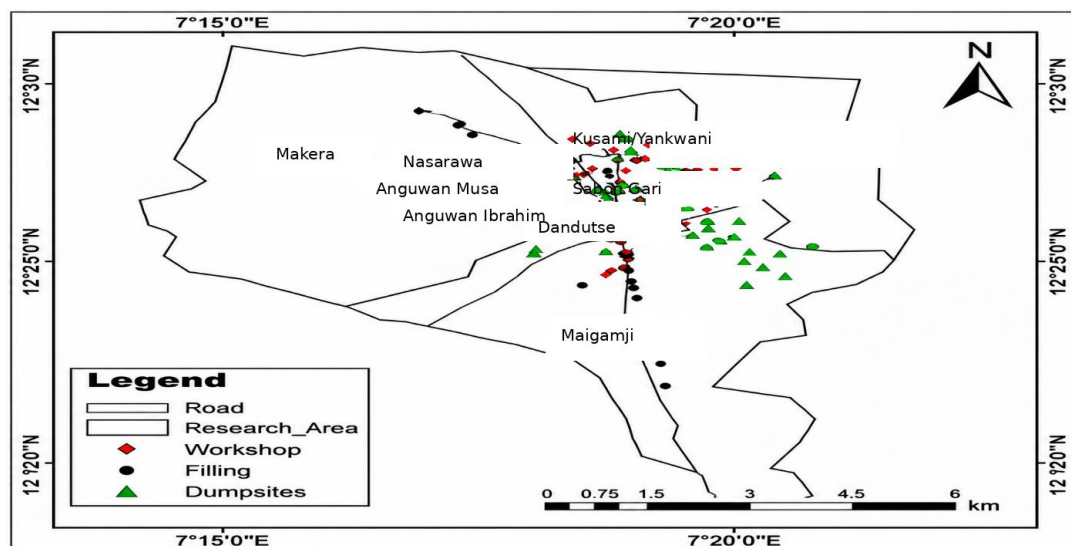


Figure 3: Spatial clustering of anthropogenic sources — auto-mechanic workshops, filling stations and dumpsites — in Funtua.

#### 3.2 Soil Contamination (Geo-accumulation Index)

Soil Pb concentrations ranged from 1.74 to 7.46 mg/kg, with 92.13% of the study area (126.90 km<sup>2</sup>) classified as uncontaminated by Igeo (Figure 4); higher contamination was localized around

Kusami/Yankwani, consistent with Nigerian studies linking metal enrichment to automobile-related activities (Ajeh et al., 2022; Duru et al., 2024; Iwegbue et al., 2024). The remaining metals fell within comparatively narrow ranges (Cd 0.19–0.26 mg/kg, Cu 1.80–3.02 mg/kg, Fe 4.41–18.90 mg/kg, Ni 0.14–0.84 mg/kg). Elevated soil Pb values coincided spatially with the wards of highest anthropogenic-source density, supporting an anthropogenic rather than purely geogenic origin, although a lithogenic contribution cannot be entirely excluded for Fe and Ni.

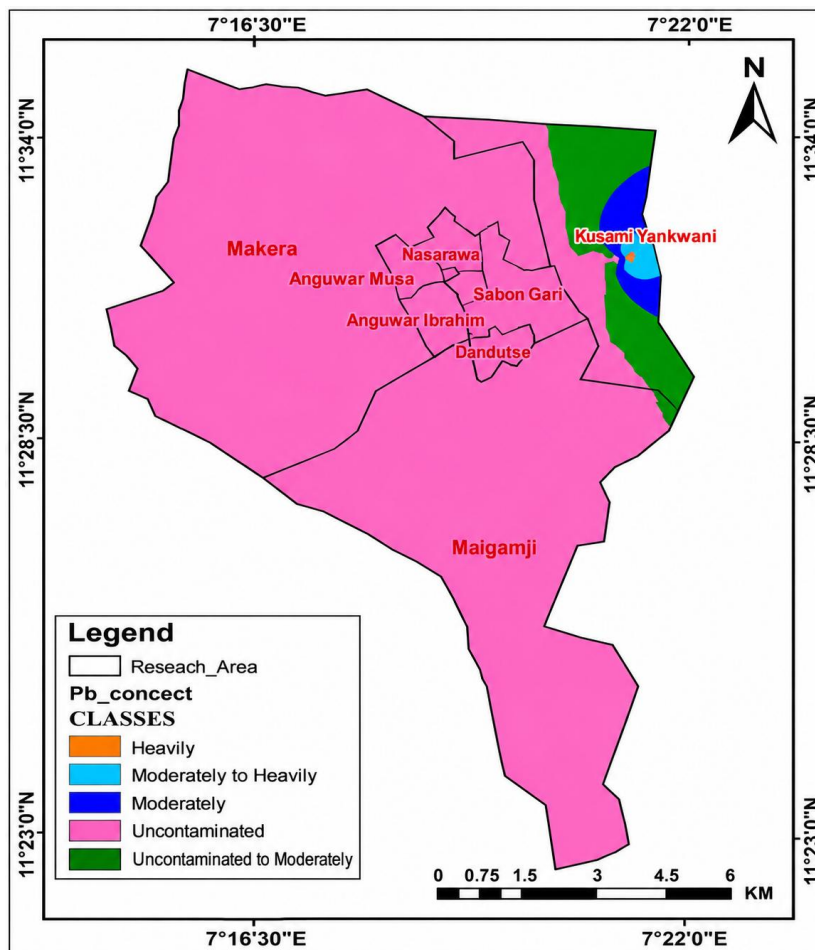


Figure 4: Spatial distribution of lead (Pb) contamination in soil across the study area, classified by the geo-accumulation index (Igeo).

### 3.3 Groundwater Contamination Level (Metal Index)

The groundwater Metal Index ranged from 0.02 to 63.86, with 87.60% of the mapped area (120.63 km<sup>2</sup>) classified as not-contaminated (MI ≤ 1.00) and 12.40% (17.09 km<sup>2</sup>) classified as contaminated (MI > 1.00) (Table 3, Figure 5). The contaminated zone was tightly concentrated in the north-eastern sector, coinciding with the densest aggregation of mapped sources and with the 700–740 m topographic band, suggesting that topographically controlled infiltration compounds the anthropogenic signal (Podgorski et al., 2024).

Maximum groundwater Pb (74.37 mg/L) and Ni (560.10 mg/L) exceeded current WHO drinking-water guidelines (0.01 mg/L and 0.07 mg/L, respectively) by three to four orders of magnitude (World Health Organization, 2022). These concentrations lie above the calibrated working range of the analytical method and were drawn from wells with turbidity up to 169 NTU, so unfiltered, particulate-rich digestion may have inflated the apparent dissolved concentration; both values are therefore reported as provisional pending confirmatory resampling with filtered/unfiltered splits, duplicate digestion and graphite-furnace AAS or ICP-MS analysis. No management or health-risk conclusion is drawn from their absolute magnitude until that confirmatory analysis is completed; the spatial pattern to which they contribute is corroborated independently by the buffer-overlay risk zoning in Section 3.4.

Table 3: Groundwater contamination level in the study area (Metal Index classification).

| Class            | MI range            | Area (km <sup>2</sup> ) | Percentage (%) |
|------------------|---------------------|-------------------------|----------------|
| Not contaminated | ≤ 1.00 (0.02–1.00)  | 120.63                  | 87.60          |
| Contaminated     | > 1.00 (1.01–63.86) | 17.09                   | 12.40          |
| Total            | —                   | 137.72                  | 100.00         |

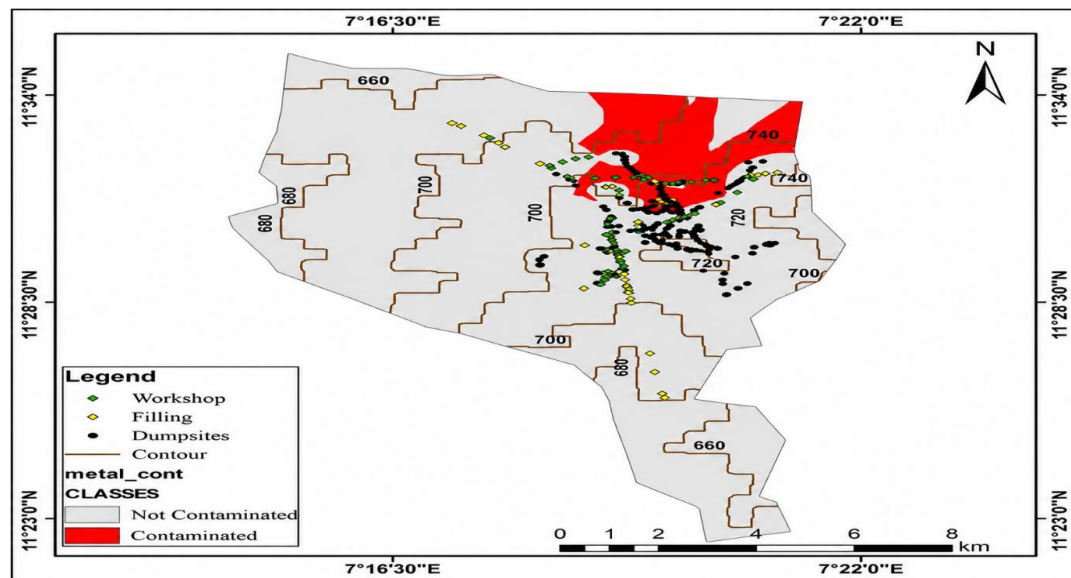


Figure 5: Groundwater contamination level (Metal Index classification) in the study area.

### 3.4 Groundwater Contamination Risk Zones

Buffer-overlay risk classification (Figure 6) showed that the low-risk class dominates the landscape (99.32%, 136.78 km<sup>2</sup>), while the high-risk and very-high-risk classes occupy 0.53% (0.73 km<sup>2</sup>) and 0.15% (0.20 km<sup>2</sup>) respectively, a combined footprint of 0.68% (0.93 km<sup>2</sup>) concentrated in and around Sabon Gari, Dandutse and Anguwan Ibrahim. This footprint coincides with both the highest source density (Section 3.1) and the Metal-Index-defined contaminated zone (Section 3.3); the convergence of these independently derived indicators provides internal validation that these three wards constitute genuine, high-confidence contamination hotspots (Duru et al., 2024; Guan et al., 2013). The small areal extent of the high-risk classes reflects the point-source-driven nature of urban groundwater risk rather than an absence of contamination pressure, consistent with continental-scale assessments of Sahelian aquifer vulnerability (Podgorski et al., 2024).

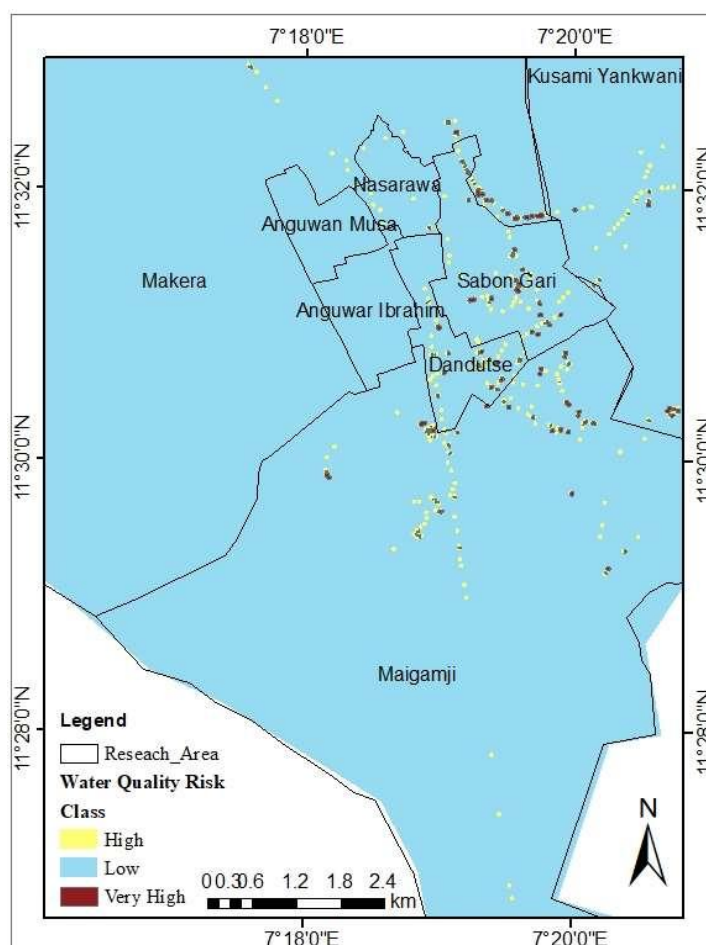


Figure 6: Delineation of groundwater contamination risk zones in the study area.

### 3.5 Groundwater Physicochemical Characteristics

Table 4 summarizes five physicochemical parameters across the thirty-six groundwater samples (W1–W36) relative to WHO (2017) and NSDWQ (SON, 2015) guideline values. pH (6.94–8.33, mean 7.8) fell entirely within guideline limits, and this near-neutral to slightly alkaline regime favours reduced solubility of  $\text{Pb}^{2+}$ ,  $\text{Cd}^{2+}$  and  $\text{Ni}^{2+}$ , suggesting that the elevated Pb and Ni concentrations reported in Section 3.3 more plausibly reflect direct, source-proximal loading than pH-driven mobilization. Electrical conductivity (112–1,624  $\mu\text{S}/\text{cm}$ , mean 500  $\mu\text{S}/\text{cm}$ ) exceeded the guideline in only 6% of samples, while turbidity (0–169 NTU, mean 20 NTU) exceeded the 5 NTU guideline in approximately 50% of samples the most significant deficiency identified consistent with the shallow, structurally unprotected nature of hand-dug wells (Jain, 2023). Total hardness (64–414 mg/L as  $\text{CaCO}_3$ , mean 180 mg/L) remained below the 500 mg/L guideline throughout. Overall, Funtua groundwater is predominantly fresh and near-neutral, with turbidity representing the principal water-quality concern and a plausible additional pathway for particulate-bound metal transport.

Table 4: Summary statistics of groundwater physicochemical parameters ( $n = 36$ ).

| Parameter                                 | Min  | Max  | Mean | WHO limit | % exceeding |
|-------------------------------------------|------|------|------|-----------|-------------|
| Temperature ( $^{\circ}\text{C}$ )        | 33.2 | 35.2 | 33.8 | N/A       | N/A         |
| pH                                        | 6.94 | 8.33 | 7.8  | 6.5–8.5   | 0           |
| EC ( $\mu\text{S}/\text{cm}$ )            | 112  | 1624 | 500  | 1500      | 6           |
| Turbidity (NTU)                           | 0    | 169  | 20   | 5         | 50          |
| Total hardness (mg/L as $\text{CaCO}_3$ ) | 64   | 414  | 180  | 500       | 0           |

#### 4. CONCLUSIONS

This study provides a GIS-based assessment of anthropogenic heavy-metal contamination in Funtua, integrating source mapping, laboratory analysis and contamination-index modelling. Auto-mechanic workshops, filling stations and dumpsites showed statistically significant spatial clustering (workshops:  $NNR = 0.42$ ,  $z = -11.10$ ,  $p < 0.001$ ; filling stations:  $z = -12.36$ ,  $p < 0.01$ ; dumpsites:  $z = -19.84$ ,  $p < 0.01$ ), concentrated around Sabon Gari, Anguwan Ibrahim, Nasarawa, Dandutse and Kusami/Yankwani. Soil Pb ranged from 1.74–7.46 mg/kg, with 92.13% of the study area classified as uncontaminated by Igeo; groundwater showed greater concern, with Metal Index values of 0.02–63.86 and 12.40% (17.09 km<sup>2</sup>) classified as contaminated. Maximum groundwater Pb (74.37 mg/L) and Ni (560.10 mg/L) exceeded WHO guideline values by three to four orders of magnitude but remain provisional pending confirmatory analysis. Risk mapping identified a combined high-risk and very-high-risk footprint of 0.68% (0.93 km<sup>2</sup>) around source-overlap zones, particularly Sabon Gari, Dandutse and Anguwan Ibrahim. Overall, contamination in Funtua is spatially heterogeneous and driven primarily by the clustering of anthropogenic activities rather than by diffuse regional processes. Priority monitoring should focus on Kusami/Yankwani, Sabon Gari, Dandutse and Anguwan Ibrahim, supported by improved land-use regulation, confirmatory sampling of the extreme groundwater values, and seasonal monitoring. A limitation of this study is that batch-level QA/QC metrics for the analytical procedure are not reported here; a low-cost biochar-based groundwater treatment system is identified only as a direction for future work, not as a system designed or evaluated in the present study.

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