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Groundwater Quality and Heavy-Metal Contamination Associated with Dumpsite Leachate in Chaza, North-Central Nigeria

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Abstract: *Groundwater contamination by heavy metals from dumpsite leachate poses a potential environmental and public-health concern in rapidly developing communities. This study assessed groundwater quality, hydrochemical characteristics, heavy-metal contamination and associated soil contamination around dumpsites in Chaza, North-Central Nigeria. A total of 21 groundwater samples, comprising 12 hand-dug wells, 8 boreholes and 1 control well, and 10 soil samples were investigated. Field measurements and laboratory analyses were used to determine physicochemical parameters, major ions and selected heavy metals, while contamination factor (CF) and pollution load index (PLI) were applied to evaluate contamination status. Groundwater pH ranged from 5.65–8.30, electrical conductivity from 124–1,679 µS/cm, and TDS from 74–1,010 mg/L. HDW2 exhibited the highest mineralization, with EC of 1,679 µS/cm and TDS of 1,010 mg/L. Hydrochemical interpretation indicated predominantly rock–water interaction, with localized anthropogenic influence. Groundwater CF values showed generally low enrichment for Cu (0.010–0.294) and Zn (0.007–0.383), whereas Pb reached 16.67 and Cd 10.00 at selected locations. Groundwater PLI ranged from 0.134–1.207, with HDW2 representing the only sampling location with PLI >1 in the reported dataset. Soil concentrations ranged from 400–1,314 mg/kg Fe, 103.75–300 mg/kg Cu, 10–411.5 mg/kg Cr and 122.25–540 mg/kg Ni, while Cd reached 20 mg/kg. Soil CF indicated pronounced enrichment, particularly for Cd, Cu, Cr and Ni. The results demonstrate localized groundwater contamination and substantially greater metal enrichment in soil, suggesting that dumpsite-affected soils may serve as reservoirs and potential secondary sources of heavy metals. Improved waste management, protection of shallow wells and continued groundwater and soil monitoring are recommended.*

Keywords: *Groundwater quality; Heavy metals; Dumpsite leachate; Soil contamination; Chaza.*

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1.0 Introduction

Groundwater is one of the most important freshwater resources for domestic consumption, agriculture, industry, and ecosystem support, particularly in regions where surface-water resources are seasonal, inadequate, or vulnerable to pollution. In many developing countries, groundwater provides a substantial proportion of the water used by rural and peri-urban communities and is frequently abstracted through hand-dug wells and boreholes with limited treatment before consumption. Consequently, deterioration in groundwater quality can have direct implications for public health, livelihoods, and environmental sustainability. Groundwater quality is controlled by a combination of natural processes, including mineral dissolution, water–rock interaction, ion exchange, and redox reactions, as well as anthropogenic activities such as agriculture,

industrialization, urbanization, and indiscriminate waste disposal (Edmunds & Smedley, 2000; WHO, 2022). In areas where communities depend heavily on shallow groundwater, uncontrolled waste disposal represents a particularly important pathway through which contaminants can enter subsurface water resources.

Open and unregulated dumpsites constitute a major environmental concern because they provide direct contact between heterogeneous waste materials, infiltrating precipitation, soil, and the underlying geological environment. During waste decomposition, water percolating through the waste mass dissolves and transports soluble inorganic and organic constituents, producing leachate. The chemical composition of leachate varies with waste type, age, moisture content, climatic conditions, decomposition processes, and site characteristics, but it may contain elevated concentrations of dissolved salts, nutrients, organic matter, heavy metals, and potentially pathogenic constituents (Kjeldsen et al., 2002; Christensen et al., 2001). Where dumpsites lack engineered liners, drainage systems, leachate-collection facilities, and groundwater-monitoring networks, leachate can migrate through the unsaturated zone and eventually reach underlying aquifers. The resulting contamination may be particularly persistent where waste contains batteries, electrical and electronic components, metal scraps, paints, construction materials, and other metal-bearing materials.

Heavy metals are of particular concern because many are persistent in the environment and may accumulate in soil and groundwater systems. Metals such as lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), and iron (Fe) may originate from both natural geological materials and anthropogenic sources. Unlike many biodegradable organic pollutants, metals cannot be destroyed through natural degradation processes and may therefore persist in contaminated environments. Their mobility is influenced by pH, redox conditions, organic matter, mineral surfaces, ionic strength, and the physicochemical properties of the soil and aquifer materials. Acidic conditions, for example, can enhance the dissolution and mobility of several potentially toxic metals, thereby increasing their potential transfer from waste and soil into groundwater (Alloway, 2013). Exposure to elevated concentrations of toxic metals through drinking water may result in adverse health effects. Lead is a priority drinking-water contaminant because exposure can affect neurological development and other physiological systems, while cadmium exposure is associated with renal and skeletal effects following prolonged exposure (WHO, 2022). Accordingly, assessment of groundwater contamination around dumpsites should extend beyond determining whether measured concentrations exceed drinking-water standards to include evaluation of potential human-health risks.

The vulnerability of groundwater to dumpsite-derived contamination is strongly influenced by local hydrogeological conditions. This consideration is particularly important in crystalline basement terrains, where groundwater storage and movement are controlled largely by secondary porosity associated with weathered materials, fractures, joints, faults, and other structural discontinuities. Unlike extensive primary-porosity sedimentary aquifers, basement aquifers are often spatially heterogeneous, and groundwater occurrence may vary considerably over relatively short distances. The weathered overburden may constitute a shallow aquifer, while deeper groundwater can occur within fractured or decomposed bedrock. Consequently, the thickness and permeability of the weathered zone, depth to bedrock, fracture connectivity, hydraulic gradients, and groundwater-flow direction can strongly influence the migration and attenuation of contaminants introduced at the ground surface.

Studies of groundwater chemistry in Nigerian Basement Complex terrains have demonstrated that although water–rock interaction contributes substantially to groundwater chemistry, human activities can impose a strong anthropogenic signature on shallow groundwater systems (Olorunfemi & Fasuyi, 1993; Tijani et al., 1996).

Evidence from Nigeria demonstrates that uncontrolled waste disposal can adversely affect groundwater quality. Investigations around the Olusosun open dumpsite in Lagos reported acidic groundwater in a substantial proportion of sampled wells and boreholes and identified several physicochemical and heavy-metal parameters as indicators of possible leachate influence. The study also observed a relationship between groundwater quality and proximity to the dumpsite, indicating increased vulnerability among water sources located closer to the waste-disposal area (Adewole et al., 2017). Similarly, investigations at the Alakahia dumpsite in Port Harcourt identified acidic groundwater and elevated concentrations of selected contaminants, with water quality deteriorating in locations closer to the dumpsite (Nwankwoala & Udom, 2015). More recently, groundwater investigations around the Emirin dumpsite in Ado-Ekiti combined hydrochemical analysis with geophysical delineation of leachate migration and reported elevated concentrations of selected heavy metals, including Pb, Ni, and Fe. The study further demonstrated that leachate migration can be influenced by the weathered and fractured basement environment (Badmus et al., 2022).

The potential health implications of dumpsite-associated groundwater contamination have also been demonstrated in Nigeria. Laniyan and Adewumi (2019) investigated heavy-metal contamination in groundwater around an exposed dumpsite in southwestern Nigeria and assessed potential health effects associated with metal exposure. Their findings demonstrated that indiscriminate waste disposal can constitute a source of potentially toxic metals in groundwater and highlighted the importance of evaluating contamination in relation to human exposure. Similarly, the study of the Emirin dumpsite by Badmus et al. (2022) incorporated health-risk indicators, including average daily intake, hazard quotient, and hazard index, and reported potential non-carcinogenic risks associated with heavy-metal exposure. These findings demonstrate that concentration-based assessment alone may not adequately describe the environmental significance of groundwater contamination; rather, contaminant levels should be interpreted in relation to exposure pathways and potential health consequences.

Despite these studies, important uncertainties remain regarding the interaction between dumpsite leachate, groundwater chemistry, soil contamination, and hydrogeological conditions in North-Central Nigeria. Much of the available Nigerian literature has concentrated on individual dumpsites in southern or southwestern urban environments, while relatively fewer studies have comprehensively investigated dumpsite-affected groundwater within North-Central Nigerian Basement Complex settings. Furthermore, previous investigations have often emphasized physicochemical parameters or selected heavy metals without simultaneously integrating groundwater hydrochemical facies, major-ion chemistry, contamination indices, soil-metal concentrations, spatial distribution, and potential human-health implications. This limitation is significant because the response of a dumpsite-affected groundwater system depends not only on the contaminant load but also on the geological framework, groundwater-flow conditions, water–rock interaction, attenuation processes, and characteristics of the receiving aquifer.

The Chaza area in Suleja, Niger State, provides an important setting for investigating these relationships. The area is underlain by Precambrian Basement Complex rocks and

contains shallow groundwater sources, including hand-dug wells, alongside deeper boreholes that may intersect weathered and fractured bedrock aquifer systems. The presence of unregulated waste-disposal sites within or near residential areas creates a potential pathway for leachate-derived contaminants to enter the shallow subsurface and migrate toward groundwater. The coexistence of heterogeneous waste materials, shallow groundwater abstraction, weathered basement materials, and fractured bedrock therefore raises concerns regarding the quality and safety of groundwater used by surrounding communities. However, site-specific information on the extent of heavy-metal contamination, hydrochemical evolution, contamination status, and potential health implications of groundwater associated with the Chaza dumpsites remains limited.

The knowledge gap addressed by this study therefore concerns the lack of an integrated assessment of groundwater hydrochemistry, heavy-metal contamination, soil contamination, pollution indices, groundwater facies, controlling hydrogeochemical processes, spatial variation, and potential human-health implications in the vicinity of dumpsites within the Chaza Basement Complex environment. Establishing this relationship is necessary to distinguish natural contributions from anthropogenic contamination and to determine whether groundwater sources close to the dumpsites exhibit evidence of deterioration relative to sources farther from the waste-disposal areas.

Accordingly, the aim of this study is to assess groundwater quality and the potential human-health implications of heavy-metal contamination associated with leachate migration from dumpsites in Chaza, North-Central Nigeria. Specifically, the study seeks to: (i) characterize the physicochemical and major-ion composition of groundwater around the dumpsites; (ii) determine the concentrations and spatial distribution of selected heavy metals in groundwater and surrounding soils; (iii) assess the degree of metal contamination using appropriate contamination indices, including the Contamination Factor (CF) and Pollution Load Index (PLI); (iv) determine the dominant groundwater hydrochemical facies and the principal processes controlling groundwater chemistry using hydrochemical classification and graphical techniques; (v) evaluate the relationship between groundwater quality, dumpsite proximity, and the underlying basement hydrogeological setting; and (vi) assess the potential implications of detected heavy-metal concentrations for human health using appropriate exposure and risk-assessment parameters.

The significance of this study lies in its contribution to understanding the vulnerability of groundwater resources to uncontrolled waste disposal in crystalline basement environments. Scientifically, the study provides integrated hydrogeochemical and contamination information that can improve understanding of the interaction between leachate, soil, groundwater, and basement aquifer systems. From a public-health perspective, the assessment provides evidence for identifying groundwater sources that may require treatment, alternative sourcing, or more frequent monitoring. Environmentally, the findings can assist in identifying areas requiring remediation and in establishing priority locations for groundwater-quality surveillance. The results are also relevant to environmental regulators, local authorities, waste-management agencies, groundwater-resource managers, and community planners in developing appropriate waste-disposal and groundwater-protection measures. More broadly, the study provides baseline information that can support the transition from uncontrolled open dumping toward properly engineered sanitary-landfill systems incorporating liners, leachate-collection systems, drainage controls, and groundwater-

monitoring programmes in environmentally sensitive basement-terrain settings.

2.0 Materials and Methods

2.1 Study Area and sampling locations

The study area is located in the Suleja area of Niger State, North-Central Nigeria, between latitudes 09°07′30″N and 09°10′30″N and longitudes 07°09′00″E and 07°12′00″E (Figure 1). The area covers approximately 25 km² and encompasses Chaza and adjoining settlements, including St. Peter Catholic Church, Kiddies Choice International School, Chaza Central Mosque, and the Nomadic School. The area experiences a tropical savanna climate characterized by distinct wet and dry seasons. Mean annual rainfall is approximately 1,334 mm, while mean temperatures generally range from about 25°C during the cooler rainy-season period to approximately 30°C during the hotter dry-season period. Relative humidity is generally higher during the rainy season. Vegetation is predominantly savanna, comprising grasses, shrubs, and scattered trees of moderate height.

The topography is variable, ranging from relatively gentle to steep slopes, with elevations of approximately 415–444 m above mean sea level. Surface drainage generally follows the local topographic gradient, with runoff from relatively elevated areas toward lower-lying portions of the study area. These topographic characteristics are important in understanding surface-water movement and the potential transport of contaminants originating from the dumpsites.

Geologically, the study area lies within the Precambrian Basement Complex of Nigeria, which forms part of the Pan-African mobile belt between the West African and Congo Cratons (Black, 1980; Obaje, 2009). The Nigerian Basement Complex consists principally of migmatite-gneiss complexes, schist belts, and Older Granites that record several phases of deformation, metamorphism, and magmatism. Groundwater occurrence within crystalline basement terrains is predominantly associated with secondary porosity and permeability developed through weathering, fracturing, joints, faults, and related structural discontinuities. Thus, groundwater occurrence and movement are strongly influenced by the thickness and hydraulic characteristics of the weathered overburden and the degree and connectivity of basement fracturing (Olorunfemi & Fasuyi, 1993).

The local geology is dominated by granitic gneiss and medium- to coarse-grained granite, with quartz veins occurring locally and generally trending in a NE–SW direction. Granitic gneiss occupies approximately 60% of the mapped area, whereas granite accounts for about 40%. The weathered and fractured nature of the basement provides potential pathways through which surface-derived contaminants may infiltrate and migrate into groundwater. This hydrogeological setting is therefore particularly relevant to assessing the potential movement of leachate from unregulated dumpsites into shallow groundwater systems.

The geographic and hydrogeological characteristics of the groundwater sampling points are presented in Table 1. A total of 21 groundwater sampling points were investigated, comprising 12 hand-dug wells (HDW1–HDW12), eight boreholes (BH1–BH8), and one control/reference well (CRT1). The sampling points were distributed across residential, institutional and commercial locations within the Chaza study area, including areas around the Chaza Clinic, mosques, schools, residential compounds, a motorcycle mechanic workshop, pharmacy, health centre and other community facilities. The spatial distribution of the sampling points was designed to capture groundwater conditions at different locations relative to the dumpsite-affected environment.

The hand-dug wells were generally shallow. For the locations where measurements were available, static water levels ranged from 3.0 to

8.20 m, while well depths ranged from 4.0 to 9.40 m. The shallowest static water level was recorded at HDW6 (3.0 m), whereas the deepest measured static water level was 8.20 m at HDW4. Corresponding well depths ranged from 4.0 m at HDW5 to 9.40 m at HDW4. These shallow groundwater conditions are important because hand-dug wells can be particularly vulnerable to infiltration of surface-derived contaminants and dumpsite leachate.

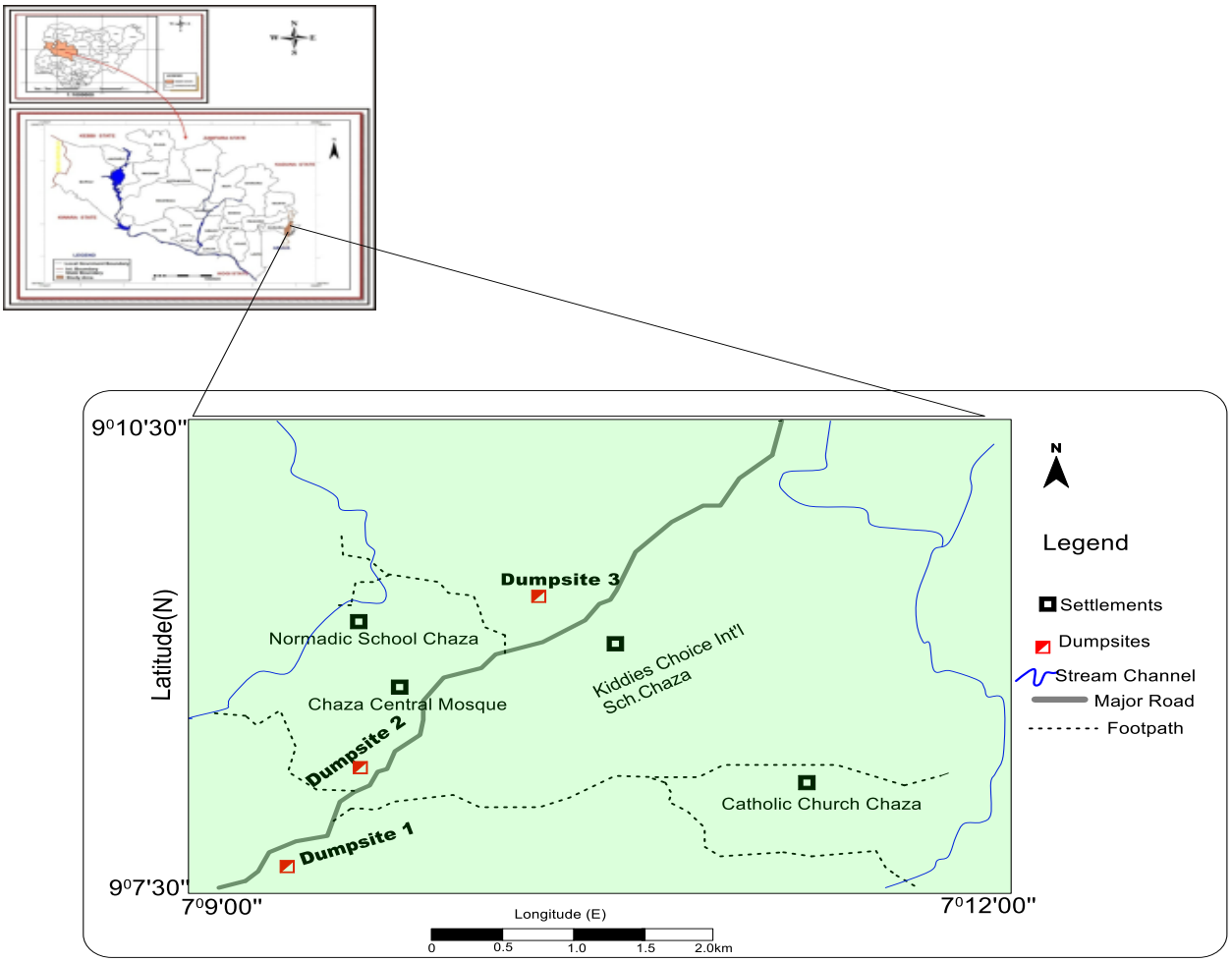

Fig. 1:Location map of the study area

Static water-level and well-depth data were unavailable for HDW7–HDW12, as indicated by the missing entries in Table 1. Consequently, interpretation of groundwater-level variations among the hand-dug wells was restricted to the locations for which field measurements were available. These missing observations should be distinguished from zero values because they represent unavailable measurements rather than absence of groundwater.

The boreholes were substantially deeper than the measured hand-dug wells. BH1 and BH2 had depths of 50 and 55 m, respectively, while BH3 and BH4 had depths of 65 and 60 m, respectively. BH7 had a depth of 50 m, whereas BH8 was the deepest borehole, with a reported depth of 70 m. Static water levels in the measured boreholes ranged from 45 to 60 m, with the lowest recorded values of 45 m at BH1, BH2 and BH7 and the highest value of 60 m at BH8. Static water-level and depth data were not available for BH5 and BH6.

The reported water-table elevations for the measured hand-dug wells ranged from 402.0 m

at HDW1 to 430.8 m at HDW2, while the ground-surface elevations ranged from 408.0 to 447.0 m across the hand-dug-well locations. Among the boreholes with available measurements, water-table elevations ranged from 359 m at BH1 and BH2 to 390 m at BH7, while ground-surface elevations ranged from 409 m at BH1 to 445 m at BH3. The variation in water-table and ground-surface elevations reflects the local topographic and hydrogeological variability of the study area and provides important information for interpreting groundwater flow and potential contaminant migration.

Table 1. Geographic location and hydrogeological characteristics of groundwater sampling points in the Chaza study area

Water Sample ID	Coordinates	Static Water Level (m)	Well Depth (m)	Water Table Elevation (m)	Ground Surface Elevation (m)	Location Name
HDW1	N09°09′3.96″ E07°10′9.05″	5.8	6.0	402	408.0	Behind Chaza Clinic
HDW2	N09°09′5.09″ E07°10′20″	6.6	7.2	430.8	438	Chaza Mosque
HDW3	N09°09′17.09″ E07°10′27.2″	7.2	8.9	421.1	430.0	Opp. Izalzt Mosque
HDW4	N09°09′20.5″ E07°10′28.1″	8.20	9.40	418.6	428	Opp. Chaza Plaza
HDW5	N09°09′17.6″ E07°10′40.07″	3.6	4.0	418	422.0	Household Almadina
HDW6	N09°09′27.17″ E07°10′54.8″	3.0	5.1	410.9	416.0	Household Almadina
HDW7	N09°09′01.7″ E07°10′19.9″	—	—	—	447	Bike Mechanic Workshop
HDW8	N09°09′17.9″ E07°10′27.4″	—	—	—	435	Close to Mosque
HDW9	N09°09′19.5″ E07°10′23.02″	—	—	—	439	Residential New Chaza, Sabon Gari
HDW10	N09°09′07.07″ E07°10′20.09″	—	—	—	447	Jummat Mosque
HDW11	N09°09′10.01″ E07°10′22.08″	—	—	—	442	New Transformer
HDW12	N09°09′22.07″ E07°10′24.04″	—	—	—	436	Behind Plaza Chaza
BH1	N09°09′3.33″ E07°10′14.05″	45.0	50.0	359	409	Chaza Clinic
BH2	N09°09′13.09″ E07°10′21.01″	45.0	55.0	359	414	Main Jummat Mosque

BH3	N09°09′1.09″ E07°10′22.06″	50.0	65.0	380	445	Chaza Primary School
BH4	N09°09′18.02″ E07°10′24.09″	50.0	60.0	372	432	Opp. Bifas School
BH5	N09°09′04.05″ E07°10′22.05″	NM	NM	NM	441	Opp. Brain Tiza Academy
BH6	N09°09′03.09″ E07°10′11.09″	NM	NM	NM	415	Health Center
BH7	N09°09′17.01″ E07°10′24.08″	45.0	50.0	390	440.0	Chybest Pharmacy
BH8	N09°09′20.01″ E07°10′21.08″	60.0	70.0	374	444.0	Sabon Gari Area
CRT1	N09°09′16.06″ E07°10′46.06″	40.0	55	376	431	Almadina

The control/reference well, CRT1, is located at Almadina and has coordinates N09°09′16.06″ E07°10′46.06″. It has a static water level of 40 m, a well depth of 55 m, a water-table elevation of 376 m, and a ground-surface elevation of 431 m. The inclusion of CRT1 provides a reference against which groundwater chemistry at potentially impacted locations can be compared. This is particularly useful when evaluating whether elevated concentrations of dissolved constituents are localized around waste-disposal areas or represent broader natural hydrogeochemical conditions.

The geographic coordinates and location descriptions indicate that the sampling points cover several potentially important groundwater-use settings within Chaza, including residential areas and community facilities. The occurrence of shallow hand-dug wells in these populated locations is of particular environmental significance because these wells may have greater susceptibility to contamination from surface activities than deeper boreholes. Conversely, the deeper boreholes provide information on groundwater quality at greater depths and can assist in evaluating the extent to which contaminants have migrated downward through the weathered and fractured basement materials.

Overall, the hydrogeological information in Table 1 establishes the spatial and vertical framework for interpreting the groundwater-quality results presented in subsequent sections. Differences in well depth, groundwater level and elevation are particularly relevant to understanding the observed variations in physicochemical characteristics, major-ion composition, heavy-metal concentrations and contamination indices. The data also provide a basis for assessing the potential vulnerability of shallow groundwater to dumpsite-derived leachate relative to deeper groundwater sourcesThe resulting spatial maps were used to evaluate the distribution of heavy metals in relation to dumpsite location, groundwater-source type, topography, and potential contaminant-migration pathways. Spatial patterns were interpreted together with the hydrogeological and hydrochemical characteristics of the study area rather than being considered independent evidence of contamination sources.

2.2 Sampling and Analytical Procedures

2.2.1 Groundwater Sample Collection and Field Measurements

A total of 20 groundwater samples were collected during the late dry season sampling year]) from 12 hand-dug wells and 8 boreholes within and around the dumpsite-affected area. One of the 20 sampling locations, situated approximately 1 km from the dumpsites and

considered to be outside the immediate influence of the waste-disposal areas, was designated as the control/reference groundwater source. The control location was used for comparison with groundwater samples collected closer to the dumpsites.

The sampling locations were selected to provide spatial representation of groundwater sources at varying distances from the dumpsites. Geographic coordinates and ground elevations of all sampling locations were recorded using a handheld Global Positioning System (GPS). Information on well type, well depth, static water level, and surrounding land use was also recorded where applicable.

Prior to sampling, groundwater from the wells and boreholes was allowed to equilibrate sufficiently to obtain representative samples. Field measurements of pH, temperature, and electrical conductivity (EC) were conducted in situ using calibrated portable meters. A Sartorius PT-10 meter was used for pH measurements, while EC and other relevant field measurements were obtained using a Solinst TLC meter, as applicable. The instruments were calibrated before use according to the manufacturers' instructions, and probes were rinsed with deionized water between sampling locations to minimize cross-contamination.

Water samples were collected in pre-cleaned polyethene bottles. We used separate containers for major-ion and trace-metal analyses. Samples intended for cation and heavy-metal analysis were preserved immediately after collection by acidification with nitric acid to pH <2 to minimize adsorption of metals onto container walls and prevent precipitation during storage. Samples intended for anion analysis were not acidified. All samples were stored under cooled conditions and transported to the National Water Quality Reference Laboratory, Minna, for laboratory analysis within the appropriate holding period.

The laboratory determined total dissolved solids (TDS) from EC using the conversion relationship it adopted. Where calculated from EC, the relationship was expressed according to equation 1

$$TDS = k.EC \quad (1)$$

where TDS is total dissolved solids (mg/L), EC is electrical conductivity (µS/cm), and (k) is the conversion factor appropriate to the water chemistry and analytical procedure used.

2.2.2 Laboratory Analysis of Groundwater

Major cations and selected trace metals were determined using standard laboratory procedures. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) were determined using atomic absorption spectrophotometry (AAS; AA240FS), while sodium (Na^{+}) and potassium (K^{+}) were determined using flame photometry. Major anions, including chloride (Cl^{-}), sulphate (SO_4^{2-}), nitrate (NO_3^{-}), and bicarbonate (HCO_3^{-}), were determined using standard procedures described in the applicable edition of *Standard Methods for the Examination of Water and Wastewater*.

Concentrations of iron (Fe), copper (Cu), zinc (Zn), cadmium (Cd), and lead (Pb) in the groundwater samples were determined using atomic absorption spectrophotometry. The analytical results were reported in mg/L.

Analytical quality assurance and quality control were maintained throughout the analytical procedure. Reagent blanks were analyzed to identify possible laboratory contamination, duplicate samples were analyzed to assess analytical precision, and certified reference materials were analyzed to assess analytical accuracy. The laboratory calibrated the instrument and verified calibration before and during sample analysis. Method detection limits and analytical recoveries were recorded for the respective analytes where applicable.

2.2.3 Soil Sample Collection and Analysis

Ten soil samples were collected from locations representing the dumpsite-affected environment and its immediate surroundings.

Samples were collected from the upper 25–30 cm soil layer using a clean hand auger. Approximately 100 g of soil was collected at each sampling location. We recorded the geographic coordinates and elevations of the sampling points using a handheld GPS.

The soil samples were placed in clean, labelled polyethylene bags and transported to the laboratory. Samples were air-dried under ambient laboratory conditions, gently disaggregated, and passed through a 2-mm sieve to obtain the fine-earth fraction. The processed samples were subsequently homogenized and prepared for X-ray fluorescence (XRF) analysis according to the operating and sample-preparation procedures of the instrument.

We determined the concentrations of manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) using X-ray fluorescence spectroscopy. Instrument calibration was performed using appropriate reference standards. Analytical accuracy and precision were assessed using certified reference materials and replicate analyses. Results were reported in mg/kg or ppm, as appropriate.

2.2.4 Hydrogeochemical Data Processing

The groundwater analytical results were subjected to descriptive and hydrogeochemical analyses to characterize the chemical composition of the groundwater and identify the principal processes controlling its chemistry. We converted major-ion concentrations to milliequivalents per litre (meq/L) before hydrochemical classification and graphical interpretation.

An ionic charge-balance error was calculated to evaluate the internal consistency of the major-ion analytical results using equation 2

$$CBE(\%) = \frac{\sum Cation - \sum Anion}{\sum Cation + \sum Anion} \qquad (2)$$

where the concentrations of the total major cations and anions are expressed in meq/L. The charge-balance results were used as a quality-control check before interpretation of the hydrochemical data.

AquaChem software, version 4.0.254, was used to process the hydrochemical data and construct Piper trilinear diagrams. Piper diagrams were used to classify groundwater into dominant hydrochemical facies based on the relative abundance of major cations and anions.

Gibbs diagrams were also constructed to investigate the principal mechanisms controlling groundwater chemistry. The Gibbs plots were based on the relationships between total dissolved solids and the ionic ratios (Na/(Na+Ca)) and (Cl/(Cl+HCO_3)). The resulting distributions were interpreted in relation to precipitation dominance, rock–water interaction, and evaporation–crystallization processes. Gibbs classification was considered indicative and was interpreted together with the major-ion composition, geological setting, and other hydrogeochemical evidence.

2.2.5 Assessment of Heavy-Metal Contamination

The contamination status of groundwater was assessed using metal-specific contamination ratios and the Pollution Load Index (PLI). Because a drinking-water guideline value represents a regulatory health-protection threshold rather than a natural geochemical background concentration, the reference basis used for the contamination calculation was explicitly distinguished from a natural background value.

Where the concentration in the control groundwater was used as the local reference concentration, the contamination factor for each metal was calculated using equation 4

$$CF_i = \frac{C_i}{C} \qquad (4)$$

where CF_i is the contamination factor for metal, i. C_i is the measured concentration of the metal in the groundwater sample and C is the corresponding concentration in the control/reference groundwater

The contamination factors were interpreted using the classification of Hakanson (1980), in which values less than 1 indicate low contamination, values from 1 to <3 indicate moderate contamination, values from 3 to <6 indicate considerable contamination, and values ≥6 indicate very high contamination.

Where national or international drinking-water guideline values were used instead of the control/reference concentration, the ratio was interpreted as a standard-based pollution ratio rather than as a conventional geochemical contamination factor. This distinction was maintained to avoid equating a regulatory threshold with a natural background concentration.

The overall degree of groundwater pollution by the analyzed metals was assessed using the Pollution Load Index (PLI) according to equation 5

$$PLI = (CF_1 + CF_2 + CF_3 \ldots\ldots + CF_n)^{\frac{1}{n}} \quad (5)$$

where CF_1, CF_2, CF_3 *and* CF_m are the contamination factors for the individual metals, n the number of metals included in the calculation.A PLI value below 1 indicates no overall pollution relative to the selected reference condition, whereas a value greater than 1 indicates an increasing degree of pollution.

For comparison with drinking-water quality requirements, the measured concentrations of individual metals were also compared with the applicable drinking-water guideline or regulatory values. Such comparisons were treated separately from the geochemical contamination-index calculations.

2.2.6 Human Health Risk Assessment

Potential human-health risks associated with exposure to heavy metals through consumption of groundwater were evaluated using a standard exposure and risk-assessment framework. The assessment considered the ingestion of contaminated groundwater as the principal exposure pathway because the sampled wells and boreholes constitute potential sources of domestic water for the surrounding communities.

The chronic daily intake (CDI) of each heavy metal through drinking-water ingestion was estimated using equation 6

$$CDA = \frac{IR \times EF \times ED \times C}{BW \times AT} \quad (6)$$

where C is the concentration of the contaminant in groundwater (mg/L), IR is the daily groundwater ingestion rate (L/day), EF is the exposure frequency (days/year), ED is the exposure duration (years), BW is the body weight (kg), and AT is the averaging time (days).

The potential non-carcinogenic risk associated with exposure to individual metals was estimated using the Hazard Quotient (HQ) given below

$$CDI = \frac{CDI}{RfD} \quad (7)$$

where RfD is the contaminant-specific reference dose. The cumulative potential non-carcinogenic risk associated with exposure to multiple metals was evaluated using the Hazard Index (HI) given below

$$HI = \sum HQ_i \quad (8)$$

where HQ_i is the hazard quotient for the individual metal.Where appropriate toxicological parameters were available for carcinogenic risk assessment, the incremental lifetime cancer risk (CR) was estimated according to equation 9

$$CR = CDI \times SF \quad (9)$$

where SF is the contaminant-specific cancer slope factor.

The exposure parameters and toxicological reference values used in the calculations were obtained from recognized health-risk assessment sources and were applied consistently to the study population. Separate calculations were made for adults and children where the required exposure parameters were available. We compared the resulting HQ, HI, and CR values with accepted risk-interpretation criteria to determine whether exposure to the detected metals may

posepotential non-carcinogenic or carcinogenic health risks.

2.2.7 Spatial Distribution and Mapping

We evaluated spatial distributions of groundwater and soil contaminants using Surfer version 12. We imported geographic coordinates and corresponding analytical concentrations into the software to generate spatial distribution maps.

We used kriging interpolation to estimate the spatial distribution of selected parameters between sampling locations. The interpolation procedure was based on the spatial structure of the observed data and was applied cautiously because of the relatively limited number of sampling points. The selected variogram model and interpolation parameters were kept consistent across comparable

3.0 Results and Discussion

3.1 Physicochemical Characteristics of Groundwater

The physicochemical characteristics of the groundwater samples are presented in Table 2. The measured pH values ranged from 5.75 to 8.30, indicating considerable variation in groundwater acidity and alkalinity across the study area. Approximately 70% of the samples were acidic, with pH values below 7.0. The predominance of acidic groundwater is environmentally important because acidic conditions can enhance the dissolution and mobility of several potentially toxic metals from soils, weathered materials and waste-derived deposits. This is particularly relevant in the study area because the groundwater occurs within weathered and fractured Basement Complex materials that may provide pathways for leachate migration.

The occurrence of acidic groundwater around the Chaza dumpsites is consistent with observations from other Nigerian dumpsite environments. Badmus et al. (2022), for example, reported predominantly acidic groundwater around the Emirin dumpsite in Ado-Ekiti, where approximately 80% of the sampled groundwater had pH values below 7.0. Their study attributed part of the deterioration in groundwater quality to leachate migration from the dumpsite. Similarly, Laniyan and Adewumi (2019) demonstrated that groundwater around an exposed dumpsite in southwestern Nigeria could be affected by waste-derived contaminants. ScienceDirect

The relatively wide pH range observed at Chaza suggests that groundwater chemistry is not controlled by a single process. Natural water–rock interaction within the weathered basement may contribute to the observed pH conditions, while decomposition of organic waste and generation of acidic leachate may locally lower groundwater pH. The spatial variability is therefore likely to reflect the combined effects of lithology, groundwater residence time, waste decomposition, leachate infiltration and mixing with background groundwater.

Table 2. Physicochemical characteristics of groundwater samples from the Chaza study area.

Water sample ID	Ph	EC(µS/cm)	TDS(mg/l)	Temperature(°C)
HDW1	7.0	139	83	26.7
HDW2	6.40	1679	1010	26.9
HDW3	6.50	526	315	27.3
HDW4	6.50	352	211	26.8
HDW5	6.60	126	75	26.70
HDW6	6.50	366	220	27
HDW7	5.65	456	265	27.8
HDW8	6.46	584	187	26.1

HDW9	5.75	380	229	27.6
HDW10	6.72	568	301	26.4
HDW11	7.75	485	285	27.4
HDW12	6.34	524	290	26.7
BH1	7.70	338	203	26.9
BH2	8.30	599	358	26.9
BH3	8.00	213	127	27.0
BH4	7.90	183	111	26.80
BH5	7.30	124	74	27.0
BH6	6.59	237	96	26.1
BH7	6.68	298	154	26.4
BH8	6.82	304	132	26.1
CRT 1	7.82	240	120	27.1
NSWDQ	6.5-8.5	10 -500C	50mg/l-500mg/l	<700-1000µS/cm
WHO	6.5-8.5	10 -500C	50mg/l-500mg/l	50mg/l –500mg/l

Electrical conductivity (EC) ranged from 124 to 1,679 µS/cm, while total dissolved solids (TDS) ranged from 74 to 1,010 mg/L. The relatively broad EC range indicates substantial spatial variation in the concentration of dissolved ionic constituents. Elevated EC and TDS in groundwater near waste-disposal areas can arise from the dissolution of soluble waste components and subsequent migration of leachate into the subsurface. However, EC and TDS are not, by themselves, definitive indicators of dumpsite contamination because natural mineral dissolution and water–rock interaction can also increase dissolved-ion concentrations.

Approximately 95% of the samples were within the freshwater range based on their TDS concentrations. Nevertheless, the occurrence of samples with substantially higher TDS and EC indicates localized enrichment of dissolved constituents. The highest values should therefore be interpreted together with the spatial distribution of heavy metals and hydrochemical facies. Badmus et al. (2022) similarly reported that most physicochemical parameters around the Emirin dumpsite were within drinking-water limits despite evidence of heavy-metal enrichment. This demonstrates that apparently acceptable general water chemistry does not necessarily exclude contamination by individual toxic metals.

3.2 Major-Ion Chemistry and Hydrochemical Facies

The major-ion concentrations and hydrochemical classifications are presented in Tables 2 and Fig. 2. The groundwater samples exhibit substantial variation in the relative abundance of major cations and anions, reflecting the influence of mineral dissolution, water–rock interaction and anthropogenic inputs.

The Piper trilinear classification identified three principal groundwater facies: Ca/Mg–SO_4/Cl (70%), Na/K–SO_4/Cl (25%), and Ca/Mg–HCO_3 (5%). The predominance of Ca/Mg–SO_4/Cl water indicates that alkaline-earth cations and strong-acid anions constitute the major ionic components in most of the groundwater samples. This hydrochemical character suggests substantial interaction between groundwater and the geological materials through which the water moves, with additional contributions from anthropogenic sources potentially associated with the dumpsites.

The occurrence of the Ca/Mg–HCO_3 facies in a small proportion of the samples is indicative of groundwater that retains a stronger signature of carbonate/bicarbonate-associated weathering processes. In contrast, the Na/K–SO_4/Cl facies may indicate greater ionic exchange and/or contribution from anthropogenic sources. The variation among facies demonstrates that groundwater chemistry is spatially heterogeneous rather than being controlled by a single hydrochemical process.

The predominance of rock-derived ionic signatures is consistent with the Basement Complex setting of Chaza. Groundwater moving through weathered and fractured crystalline rocks interacts with mineral surfaces and dissolves soluble components, thereby acquiring its major-ion composition. However, the presence of sulfate and chloride-dominated facies in groundwater close to waste-disposal areas may also indicate anthropogenic contributions because these ions can occur in relatively high concentrations in municipal and mixed waste leachates.

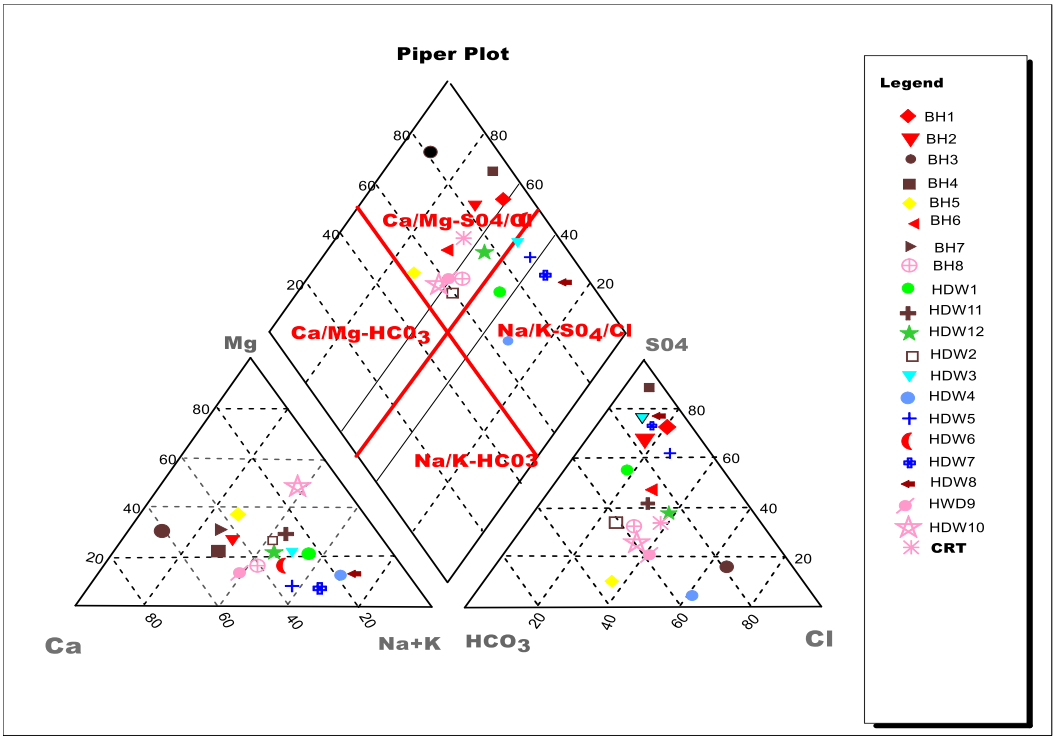

Fig. 2: Piper trilinear diagram of the water samples in the study area.

The concentrations of the major cations and anions determined in the 21 groundwater samples are presented in Table 3. The groundwater chemistry shows considerable spatial variation in the concentrations of Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-} and NO_3^{-}. This variability indicates that groundwater chemistry is influenced by a combination of natural water–rock interaction and localized anthropogenic inputs associated with the dumpsite environment.

Table 3: Major-ion concentrations in groundwater samples from the Chaza study area

Sample	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)	HCO_3^{-} (mg/L)	NO_3^{-} (mg/L)

HDW1	16.02	7.32	11.00	20.00	17.98	44.00	70.00	19.00
HDW2	160.20	24.40	98.00	102.00	199.80	116.00	400.00	60.00
HDW3	80.10	21.96	18.00	10.00	34.96	17.00	160.00	39.00
HDW4	60.07	12.20	4.00	8.00	39.96	20.00	170.60	4.00
HDW5	16.82	5.36	24.00	20.00	24.97	30.00	56.00	ND
HDW6	64.08	14.64	12.00	15.00	39.96	30.00	98.00	8.00
HDW7	44.52	7.65	9.80	17.60	23.10	27.74	75.00	10.49
HDW8	14.04	7.35	12.70	10.80	34.00	25.39	63.00	9.21
HDW9	26.85	5.65	23.20	8.40	18.80	19.76	72.80	11.45
HDW10	12.10	6.08	9.00	7.99	20.80	18.94	64.20	9.07
HDW11	10.04	4.04	6.20	6.20	17.90	17.46	81.40	12.75
HDW12	12.51	5.44	17.60	7.50	21.80	20.31	72.00	10.45
BH1	36.04	26.84	20.00	19.00	18.98	9.00	150.00	14.00
BH2	80.10	24.40	35.00	32.00	29.97	6.00	200.00	30.00
BH3	24.03	4.88	40.00	39.00	19.98	4.00	90.00	15.00
BH4	20.02	7.32	180.00	24.00	14.98	27.00	85.00	6.00
BH5	12.75	4.14	11.10	13.00	9.99	12.00	60.00	10.00
BH6	15.58	7.20	20.80	12.30	8.08	10.21	64.00	9.04
BH7	10.42	8.22	4.70	10.90	10.50	11.46	51.60	16.07
BH8	4.03	7.40	5.60	9.41	7.90	10.44	61.60	12.15
CRT1	17.10	8.40	10.12	8.17	5.30	7.18	50.80	7.07
NSDWQ	200	20	200	10	250	100	250	50
WHO*	200	50	200	10	250	100	250	50

Calcium concentrations range from 4.03 to 160.20 mg/L, with the highest concentration recorded at HDW2, while magnesium ranges from 4.04 to 26.84 mg/L, with the maximum recorded at BH1. The relatively high Ca^{2+} concentration at HDW2 is accompanied by elevated Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-} and NO_3^{-} concentrations, making HDW2 a distinct hydrochemical anomaly within the groundwater system.

All measured Ca^{2+} concentrations are below the 200 mg/L NSDWQ value provided in Table 4, while all Mg^{2+} concentrations are below the listed 20 mg/L NSDWQ value except at HDW2, HDW3 and BH1. Thus, based on the supplied NSDWQ limits, Mg^{2+} shows localized exceedance, particularly in the more chemically enriched groundwater samples.

Calcium and magnesium are commonly released through mineral weathering and water–rock interaction. Their presence is therefore expected in groundwater occurring within weathered and fractured Basement Complex rocks. The elevated values at selected locations, particularly HDW2 and BH1, may additionally reflect localized hydrochemical modification caused by anthropogenic inputs and/or longer water–rock interaction.

Sodium concentrations range from 4.00 to 180.00 mg/L, with the highest value occurring at BH4, while potassium ranges from 6.20 to 102.00 mg/L, with the maximum occurring at HDW2.

The elevated sodium concentration at BH4 is noteworthy because it is considerably higher than the values observed in most other boreholes and hand-dug wells. In contrast, the extremely high potassium concentration at HDW2 represents the most pronounced K^{+} anomaly in the dataset.

Using the NSDWQ reference value of 10 mg/L provided in Table 3, 13 of the 21 groundwater samples (61.9%) exceed the listed potassium value. These samples include HDW1, HDW2,



HDW5, HDW6, HDW7, HDW8, BH1, BH2, BH3, BH4, BH5, BH6 and BH7. However, this result requires careful interpretation because potassium is not generally considered a primary health-based drinking-water parameter by WHO at the same level as toxic metals such as Pb and Cd. The source of the 10 mg/L WHO value in the original table should therefore be verified before describing these samples as exceeding a WHO health guideline.

The elevated Na^+ and K^+ concentrations may arise from feldspar and mica weathering within the Basement Complex, ion exchange processes, or anthropogenic contributions from waste materials and leachate. The particularly high K^+ concentration at HDW2, where several other ions are also elevated, suggests a localized source or enhanced dissolution process rather than a uniform regional geochemical control.

Chloride concentrations range from 5.30 to 199.80 mg/L, while sulphate concentrations range from 4.00 to 116.00 mg/L. The highest concentrations of both Cl^- and SO_4^{2-} occur at HDW2.

All chloride concentrations remain below the 250 mg/L NSDWQ value presented in Table 3. Sulphate concentrations are also below 100 mg/L in all samples except HDW2, which records 116 mg/L. The elevated chloride and sulphate concentrations at HDW2, together with its high Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^- and NO_3^- concentrations, identify this location as a major hydrochemical anomaly.

Chloride is highly mobile in groundwater and is generally less affected by adsorption than many other ions. Consequently, elevated Cl^- can be useful as an indicator of anthropogenic inputs where local geological sources are insufficient to explain the observed concentration. Sulphate can originate from mineral weathering and oxidation processes, but it may also occur in waste-derived leachate. The localized enrichment at HDW2 may therefore reflect the combined influence of natural water–rock interaction and anthropogenic inputs.

Bicarbonate is the dominant major anion in most of the groundwater samples, with concentrations ranging from 50.80 to 400.00 mg/L. The highest concentration occurs at HDW2, followed by BH2 (200 mg/L) and HDW4 (170.60 mg/L).

Using the 250 mg/L value listed in Table 4, only HDW2 exceeds this concentration, with 400 mg/L. The predominance of HCO_3^- in most samples indicates the importance of weathering and water–rock interaction in groundwater evolution. Bicarbonate is commonly generated through the interaction of infiltrating water containing dissolved carbon dioxide with weatherable minerals.

The high bicarbonate concentration at HDW2 is consistent with its overall elevated dissolved-ion content and may reflect enhanced mineral dissolution and/or additional anthropogenic influence. The dominance of bicarbonate in most samples also supports the interpretation from the Gibbs diagram that rock–water interaction is an important controlling process.

Nitrate concentrations range from 4.00 to 60.00 mg/L, with the highest value recorded at HDW2. HDW3 also shows a relatively elevated concentration of 39 mg/L, while BH2 records 30 mg/L.

Using the 50 mg/L value provided in Table 4, only HDW2 exceeds the listed limit, with a concentration of 60 mg/L. The elevated nitrate concentration at HDW2 is particularly important because nitrate is commonly associated with anthropogenic activities, including domestic wastewater, septic systems, agricultural inputs and decomposing organic waste.

The spatial occurrence of the highest nitrate concentration in a hand-dug well is consistent with the greater vulnerability of shallow groundwater to surface-derived contaminants. The nitrate result therefore provides additional evidence that HDW2 is a particularly vulnerable groundwater source. Nevertheless,

nitrate enrichment cannot be attributed exclusively to dumpsite leachate without considering other possible local sources such as sanitation facilities and agricultural activities.

A comparison of the major-ion concentrations among the hand-dug wells, boreholes and control well further illustrates the spatial and hydrogeological variability of groundwater chemistry. The mean concentrations calculated from the supplied data are summarized in Table 4.

The hand-dug wells have higher mean Ca^{2+}, Cl^{-}, SO_4^{2-}, HCO_3^{-} and NO_3^{-} concentrations than the boreholes. This pattern is significant because hand-dug wells generally intercept shallower groundwater and are consequently more directly exposed to infiltration from the land surface. The boreholes, in contrast, have a higher mean Na^{+} concentration, largely influenced by the unusually high Na^{+} concentration at BH4.

Table 4: Mean major-ion concentrations of hand-dug wells, boreholes and control groundwater

Water source	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)	HCO_3^{-} (mg/L)	NO_3^{-} (mg/L)
Hand-dug wells (n=12)	43.11	10.17	20.46	19.46	41.17	32.22	115.25	17.58
Boreholes (n=8)	25.37	11.30	39.65	19.95	15.05	11.26	95.28	14.03
Control well (n=1)	17.10	8.40	10.12	8.17	5.30	7.18	50.80	7.07

The control well has the lowest mean concentration for most of the major ions. Its Ca^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-} and NO_3^{-} concentrations are generally lower than the corresponding means for both hand-dug wells and boreholes. This contrast strengthens the interpretation that groundwater within the dumpsite-affected area has experienced some degree of chemical enrichment relative to the selected reference location.

However, because CRT1 represents a single control sample, the difference should be interpreted cautiously. A single control location cannot fully characterize natural background variability. Future investigations should therefore include multiple reference wells outside the potential influence of the dumpsites.

3.3 Processes Controlling Groundwater Chemistry

The Gibbs diagram is presented in **Fig. 3**. The majority of the groundwater samples plot within or close to the rock-dominance field, whereas a smaller number of samples show positions toward the precipitation- and evaporation-dominance fields. The distribution indicates that rock–water interaction is the dominant natural mechanism controlling groundwater chemistry in the study area.

This finding is consistent with the geological setting of Chaza, where groundwater occurs mainly within weathered and fractured crystalline basement materials. As groundwater moves through the weathered profile and fractures, dissolution and ion exchange involving silicate and other minerals contribute dissolved ions to the groundwater. The dominance of rock–water interaction therefore provides a plausible explanation for the major-ion composition observed in most samples.

Nevertheless, the occurrence of samples outside the principal rock-dominance field suggests that groundwater chemistry is locally modified by other processes. Evaporation can increase dissolved-ion concentrations where groundwater is shallow and exposed to intense dry-season evaporation, while precipitation-related recharge can dilute dissolved constituents. More importantly, the presence of dumpsites introduces an additional anthropogenic source of dissolved ions that may not be adequately distinguished by Gibbs classification alone.

The Gibbs results should therefore not be interpreted as evidence that dumpsites have no influence on groundwater chemistry. Rather, they indicate that natural water–rock interaction provides the dominant regional hydrochemical framework within which localized anthropogenic contamination occurs. This interpretation is consistent with the findings of Badmus et al. (2022), who reported that hydrochemical characteristics around the Emirin dumpsite reflected natural groundwater processes while elevated heavy-metal concentrations indicated localized deterioration associated with leachate intrusion. ScienceDirect

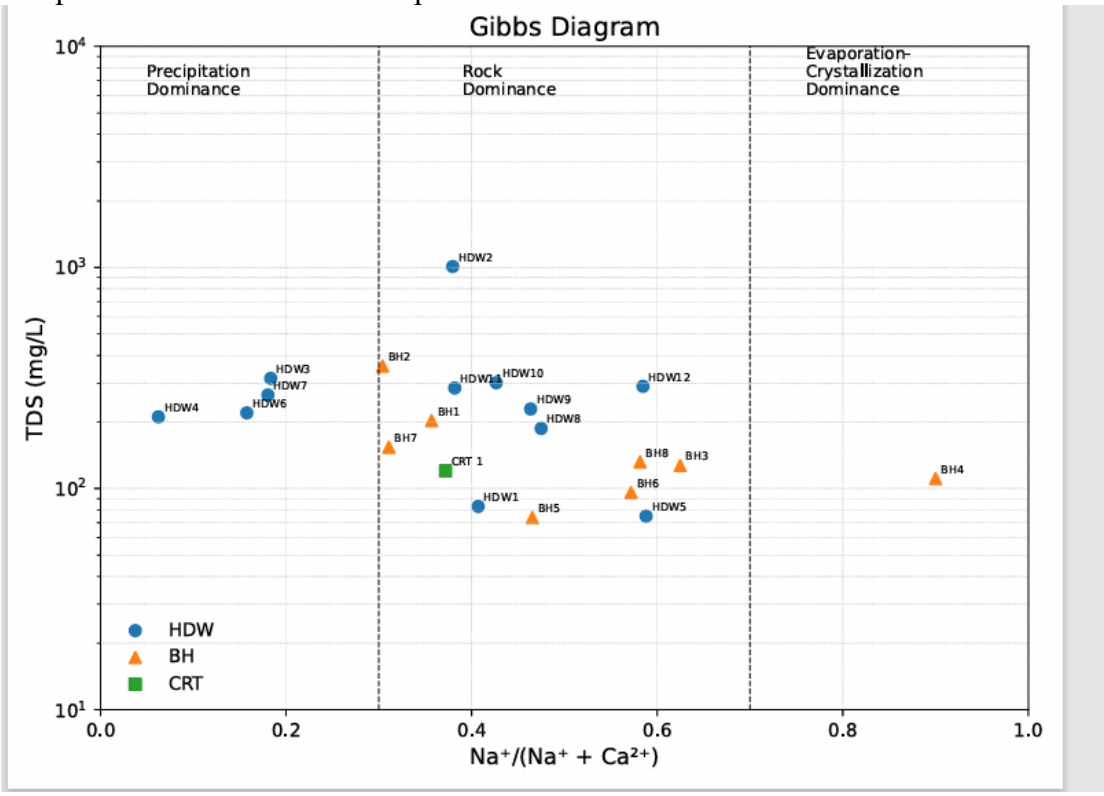

Fig. 3: Gibbs diagram showing the dominant mechanisms controlling groundwater chemistry in the Chaza study area.

3.4 Heavy-Metal Concentrations in Groundwater

Table 5 presents the concentrations of Fe, Cu, Zn, Cd, and Pb in the groundwater samples. The results indicate substantial variation in metal concentrations among the sampled groundwater sources, suggesting heterogeneous contaminant distribution across the study area.

Iron concentrations reached approximately 0.88 mg/L, exceeding the applicable drinking-water guideline at locations with elevated concentrations. **Fig. 4** shows the spatial distribution of iron. The map indicates higher

iron concentrations in parts of the dumpsite-affected area, particularly around the central residential and waste-disposal zones, while relatively lower concentrations occur toward the study area's periphery.

Table 5:Heavy metal concentrations Grouundwater samples from the Chaza study area

Parameters	Fe	Cu	Zn	Cd	Pb
HDW1	0.01	0.15	1.15	0.01	0.01
HDW2	0.88	0.22	0.89	0.04	0.02
HDW3	0.06	0.16	0.74	0.01	ND
HDW4	0.14	0.01	0.77	ND	0.01
HDW5	0.229	0.04	ND	0.01	0.02
HDW6	0.367	0.01	0.05	0.05	ND
HDW7	0.43	0.21	0.32	0.01	0.019
HDW8	0.488	0.26	0.022	0.03	0.0482
HDW9	0.56	0.243	0.037	0.01	ND
HDW10	0.543	0.274	0.031	ND	0.068
HDW11	0.609	0.264	0.052	0.01	0.011
HDW12	0.663	0.243	0.043	ND	0.0489
BH1	0.02	0.03	0.04	0.01	ND
BH2	0.01	0.08	0.11	0.01	ND
BH3	ND	0.11	0.12	ND	0.10
BH4	0.31	0.04	0.68	0.01	ND
BH5	0.17	0.06	0.50	0.01	0.01
BH6	0.22	0.024	0.027	ND	0.005
BH7	0.18	0.026	0.42	ND	0.0039
BH8	0.052	0.293	0.21	ND	0.0052
CRT1	0.091	0.101	0.021	ND	0.076
NSDWQ	0.3	1	3	0.003	0.01
WHO	0.3	2.0	5	0.003	0.01

Iron enrichment may have both natural and anthropogenic origins. Weathering of iron-bearing minerals in the Basement Complex can contribute Fe to groundwater, particularly under acidic or reducing conditions. However, waste decomposition can also release iron-bearing materials into leachate. Therefore, the spatial coincidence between elevated Fe concentrations and the dumpsite environment provides evidence for possible anthropogenic enhancement, although the natural geological contribution cannot be excluded.

The spatial distribution of lead is shown in **Fig. 5**. The map indicates a heterogeneous distribution, with localized zones of elevated Pb concentrations around and near the dumpsite locations and relatively lower concentrations toward some peripheral areas. This spatial pattern is environmentally significant because lead is not normally considered an essential constituent of drinking water and elevated concentrations are associated with adverse health effects.

The observed Pb enrichment is consistent with the composition of heterogeneous municipal waste, which may include batteries, electronic components, metal scraps, paints and other Pb-bearing materials. Leachate generated during decomposition and infiltration can mobilize these constituents and transport them into shallow groundwater. Laniyan and Adewumi (2019) similarly reported heavy-metal contamination and potential health risks in groundwater around an exposed dumpsite in southwestern Nigeria.

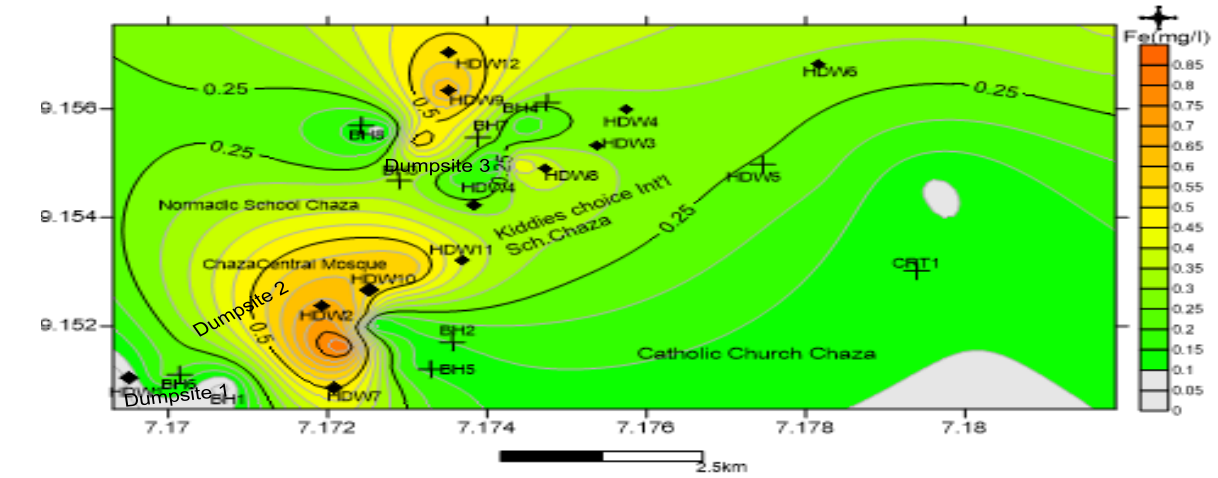

Fig. 4:Spatial distribution of iron concentration in groundwater within the Chaza study area

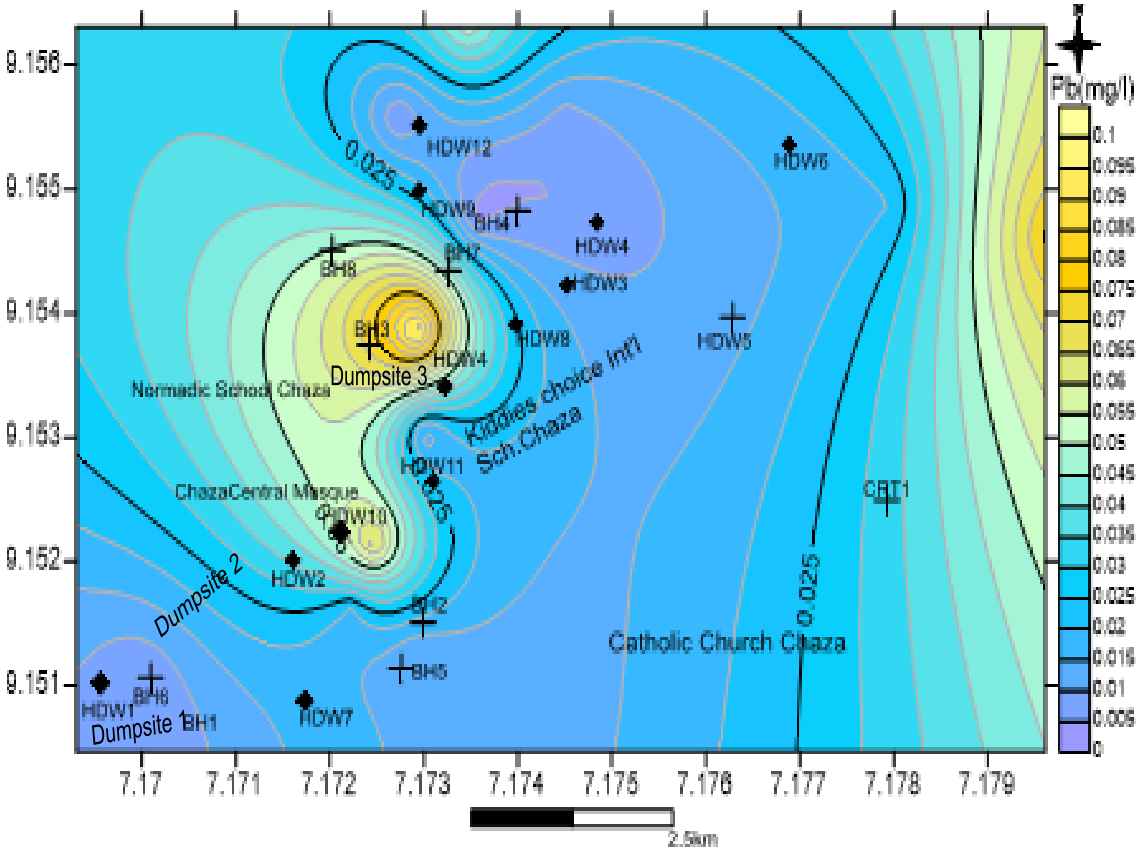

Fig. 5: Spatial distribution of lead concentration in groundwater within the Chaza study area.

The available results indicate that Cd and Pb constitute particular concerns. The maximum reported Cd and Pb concentrations were approximately 0.05 and 0.10 mg/L, respectively. These concentrations are sufficiently elevated to warrant concern when compared with health-based drinking-water criteria. Cadmium is particularly important because its persistence and toxicity mean that long-term exposure to contaminated water can adversely affect renal function and the skeletal system.

The Pb concentration pattern is also important because Pb contamination may arise from several waste streams commonly present in uncontrolled dumpsites. The combination of elevated Pb, Cd and Fe concentrations and the spatial proximity of some high-concentration zones to dumpsites strengthens the interpretation that waste disposal contributes to localized groundwater deterioration.

Copper and zinc were generally less problematic than Cd and Pb in relation to drinking-water quality. However, their spatial variability remains important because both metals can be mobilized from metallic wastes and other anthropogenic materials. Elevated Zn and Cu concentrations can therefore serve as indicators of the influence of mixed waste inputs even where their concentrations do not exceed drinking-water guideline values.

The present pattern is broadly comparable with findings from the Emirin dumpsite in Ado-Ekiti. Badmus et al. (2022) found elevated concentrations of Fe, Pb, Ni and Cr in groundwater around the dumpsite and interpreted the deterioration as being associated with leachate incursion. DOI.org The agreement between the two studies supports the interpretation that unregulated dumpsites can produce localized heavy-metal enrichment even when most conventional physicochemical parameters remain within acceptable ranges.

3.5 Spatial Distribution of Soil Heavy Metals

The soil analyses provided additional evidence for the distribution of potentially toxic elements in the dumpsite environment. Concentrations of Cu ranged from approximately 103 to 300 ppm, Cr from 25 to 411 ppm, and Ni from 122 to 540 ppm. These concentrations demonstrate substantial spatial variability in the soil environment and indicate the presence of localized metal enrichment.

The spatial distribution of zinc is presented in **Fig. 6**. The distribution shows a progressive change in Zn concentration across the study area, with higher concentrations associated with portions of the dumpsite and surrounding residential areas. Zinc is commonly associated with metallic materials, batteries, galvanized products, electronic components and other municipal waste streams. Its presence in elevated concentrations in soil may therefore reflect accumulation from long-term deposition and weathering of waste materials.

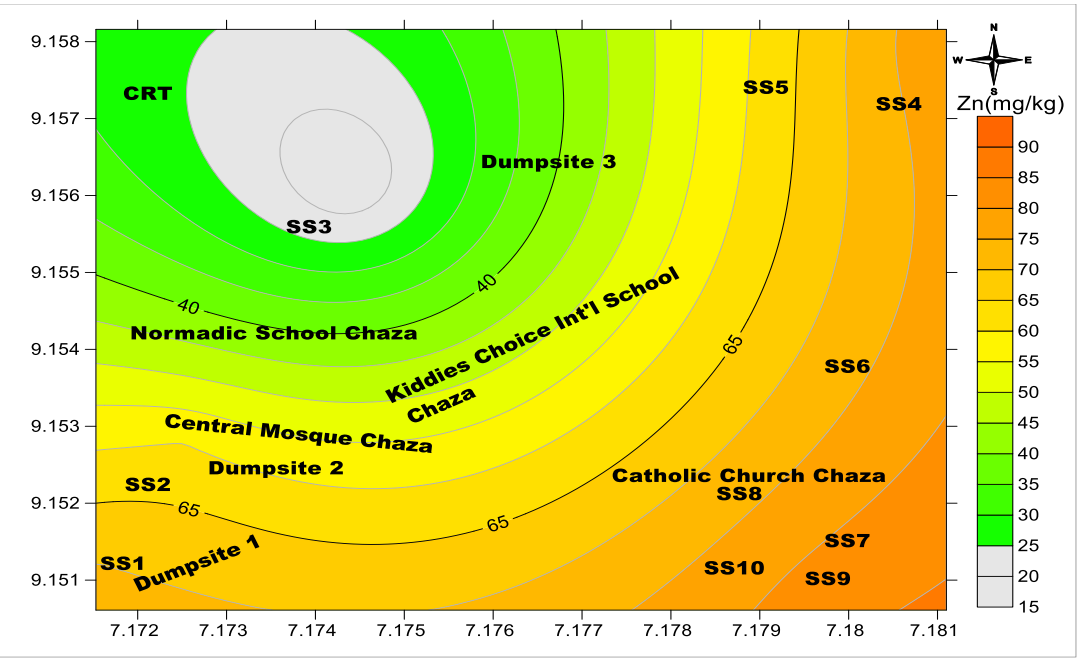

Fig. 6: Spatial distribution of zinc concentration in soil within the Chaza study area

Chromium concentrations ranged from approximately 25 to 411 ppm, as illustrated in Fig.7. The spatial distribution indicates localized areas of relatively elevated Cr concentration. Chromium can occur naturally in soil-forming minerals, but elevated concentrations in dumpsite environments may also originate from metal-containing materials, pigments, leather-related materials, industrial wastes and other anthropogenic sources. The observed range should therefore be interpreted against both local/background soil concentrations and appropriate crustal abundance values rather than assuming that all detected Cr is derived from the dumpsites.

Nickel recorded concentrations of approximately 122–540 ppm, representing one of the more pronounced soil-metal enrichments observed in the study. The spatial distribution shown in Fig. 8 indicates higher Ni concentrations toward parts of the dumpsite-affected environment, with concentration contours changing systematically across the area.

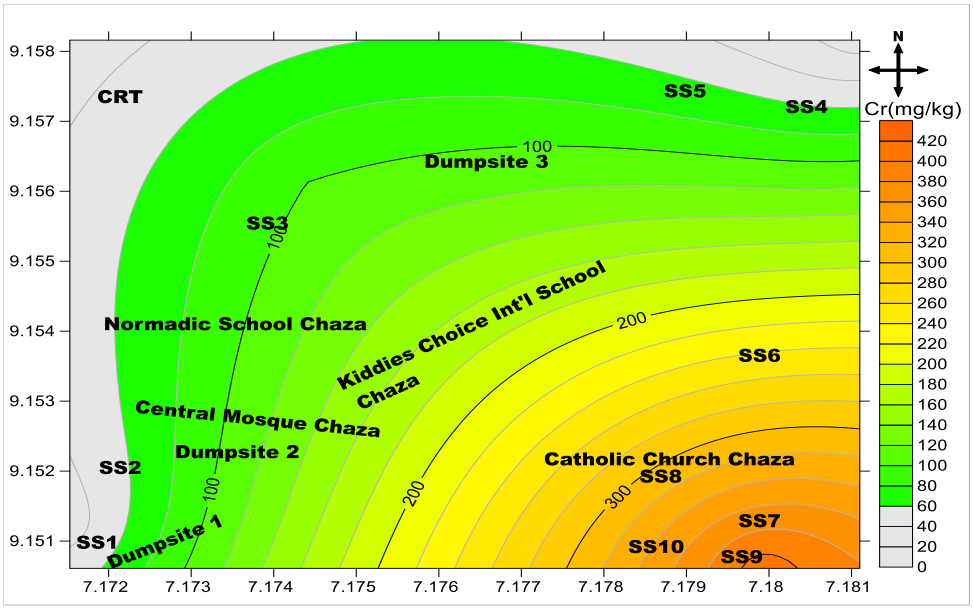

Fig. 7:Spatial distribution of chromium concentration in soil within the Chaza study area

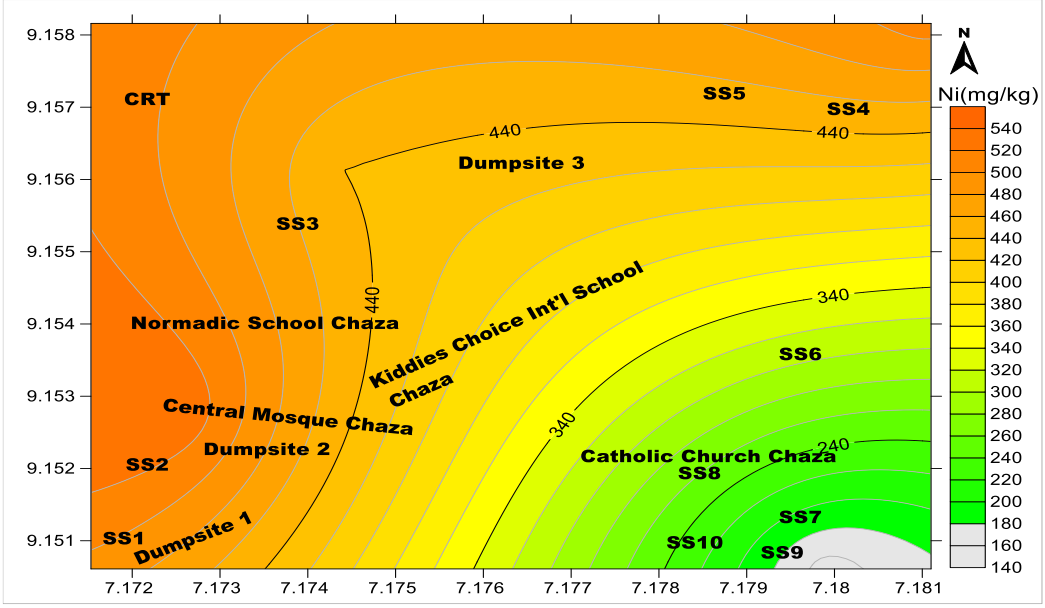

Fig. 8:Spatial distribution of nickel concentration in soil within the Chaza study area

The high Ni concentrations are potentially significant because nickel can originate from metallic materials, batteries, alloys, discarded machinery and other components of mixed waste. Nevertheless, because Ni can also occur naturally in parent materials, source attribution should be supported by comparison with local background concentrations and, where available, multivariate statistical analysis.

The soil results complement the groundwater findings. Metals retained in the soil may constitute a secondary reservoir from which contaminants can be released during rainfall infiltration and transported toward the groundwater system. This is particularly relevant in the Chaza Basement Complex setting, where the shallow weathered zone can facilitate infiltration and where fractures may

provide preferential pathways to deeper groundwater.

3.6 Comparison of Groundwater and Soil Contamination

The combined groundwater and soil results demonstrate that contamination in the study area is spatially heterogeneous rather than uniformly distributed. Groundwater contamination is reflected particularly by the elevated concentrations of Fe, Cd and Pb, whereas the soil results indicate substantial enrichment of Cu, Cr and Ni.

The difference in dominant metals between soil and groundwater is not unexpected. Metal mobility depends strongly on pH, redox conditions, mineral adsorption, organic matter and the chemical composition of the infiltrating water. Some metals may be strongly retained in soil through adsorption and precipitation, whereas others may be more readily mobilized into groundwater. Consequently, high concentrations in soil do not necessarily produce equally high groundwater concentrations at the same location.

The acidic groundwater conditions observed in approximately 70% of the samples may increase the mobility of some metals by promoting mineral dissolution and reducing adsorption onto negatively charged mineral surfaces. Thus, the combination of acidic groundwater, elevated soil-metal concentrations and spatial association with dumpsites provides a plausible mechanism for continued metal migration from waste-affected soils into groundwater.

The observed pattern is consistent with the conceptual model of landfill leachate migration described by Christensen et al. (2001), in which contaminant concentrations are modified by dissolution, sorption, ion exchange, precipitation, dilution and redox processes during movement through the subsurface. The results also agree with Badmus et al. (2022), who demonstrated that leachate migration in a Nigerian basement environment can result in localized groundwater deterioration.

3.7 Contamination Factor

The contamination factors calculated for the groundwater samples are presented in Table 6. The reported results indicate that cadmium had the most pronounced contamination, with reported CF values ranging from approximately 6.80 to 16.67, corresponding to the very-high contamination category under the adopted classification. Lead also showed elevated contamination, with reported CF values of approximately 3.33–13.33, ranging from considerable to very-high contamination.

Table 6: Contamination factors of selected heavy metals in groundwater from the Chaza study area

Water sample ID	Contamination factor (CF)					
	Fe	Cu	Zn	Pb	Cd	PLI
HDW1	0.033	0.150	0.383	3.33	1	0.362
HDW2	2.933	0.220	0.297	13.33	2	1.207
HDW3	0.200	0.160	0.297	3.333	Nil	0.403
HDW4	0.467	0.010	0.257	3.333	Nil	0.186
HDW5	0.763	0.040	Nil	3.333	2	0.671
HDW6	1.223	0.010	0.017	16.667	Nil	0.242
HDW7	1.433	0.210	0.107	3.333	Nil	0.754
HDW8	1.627	0.260	0.007	10.000	0.482	0.505
HDW9	1.867	0.243	0.012	3.333	nil	0.367

HDW10	1.810	0.294	0.010	Nil	6.800	0.428
HDW11	2.030	0.264	0.017	3.333	1.100	0.508
HDW12	2.210	0.243	0.014	Nil	4.890	0.438
BH1	0.067	0.030	0.013	3.333	Nil	0.171
BH2	0.033	0.080	0.037	3.333	Nil	0.134
BH3	Nil	0.110	0.040	Nil	10.0	0.353
BH4	1.033	0.040	0.227	3.33	Nil	0.420
BH5	0.567	0.060	0.167	3.333	1	0.465
BH6	0.733	0.024	0.009	Nil	0.500	0.167
BH7	0.600	0.026	0.140	Nil	0.390	0.171
BH8	0.173	0.293	0.070	Nil	0.520	0.207

The predominance of Cd and Pb in the contamination assessment is important because these metals have relatively high toxicological significance compared with essential elements such as Fe, Cu and Zn. Their elevated contamination factors indicate that the occurrence of these metals cannot be considered solely from the perspective of natural background variability.

3.8 Pollution Load Index

The overall pollution status of the groundwater samples is illustrated in Fig. 9. The PLI values vary substantially among the sampling locations. Most samples have PLI values below 1.0, indicating no overall pollution relative to the reference condition used in the calculation. The highest visible PLI occurs at HDW2, with a value of approximately 1.20, indicating an overall pollution level above the selected reference condition at this location.

Several other hand-dug wells have intermediate PLI values, generally below 0.8, whereas the borehole samples show comparatively low values, mostly below approximately 0.5. This pattern suggests that the shallow hand-dug wells are generally more vulnerable to localized contamination than the deeper boreholes.

The greater vulnerability of hand-dug wells is hydrogeologically reasonable because they commonly intercept shallow weathered groundwater that is more directly connected to surface infiltration. Boreholes that penetrate deeper fractured basement aquifers may have greater separation from the contaminant source, although fractures can also provide preferential pathways for contaminant migration. Therefore, depth alone does not guarantee protection from dumpsite-derived contamination.

The PLI pattern provides an important contrast with the individual-metal contamination factors. A groundwater sample may have a high CF for one metal but still produce a PLI below 1 when the geometric mean of all metals remains low. Consequently, PLI should not be used to dismiss the significance of individual toxic-metal contamination. In the present study, the elevated Cd and Pb concentrations remain environmentally important even where the overall PLI is below unity.

3.9 Soil Contamination Indices

The contamination factors calculated for the soil samples are presented in Table 7. The results show pronounced differences among the investigated metals. Fe generally had CF values below unity, indicating low enrichment relative to the adopted background concentration. This pattern suggests that Fe is largely associated with the natural mineralogical composition of the Basement Complex soils and the weathering of Fe-bearing minerals.

Zinc (Zn) similarly showed generally low contamination, although isolated values slightly above unity occurred in some samples. The relatively limited Zn enrichment indicates that Zn is not a dominant contaminant in the

investigated soils compared with Cu, Cd, Cr and Ni.

Copper showed more substantial enrichment, with CF values ranging from approximately 1.89 to 5.45. The elevated Cu values indicate moderate to considerable contamination at several locations. The enrichment may be associated with anthropogenic waste inputs, including metallic materials, electrical/electronic wastes and other discarded materials. The persistence of Cu in soil is also consistent with its tendency to become associated with organic matter and mineral surfaces.Cadmium exhibited the strongest enrichment pattern. CF values ranged from 0 to 100, with values of 40–100 occurring at several sampling locations. This represents very high contamination where Cd was detected. The exceptionally high CF values result partly from the very low background concentration used for Cd and indicate that even relatively small absolute Cd concentrations can represent substantial enrichment relative to the background. Given the environmental mobility and toxicity of Cd, its elevated soil enrichment is of particular concern. Potential sources include batteries, electronic waste, pigments, metal-containing materials and other components of municipal waste.

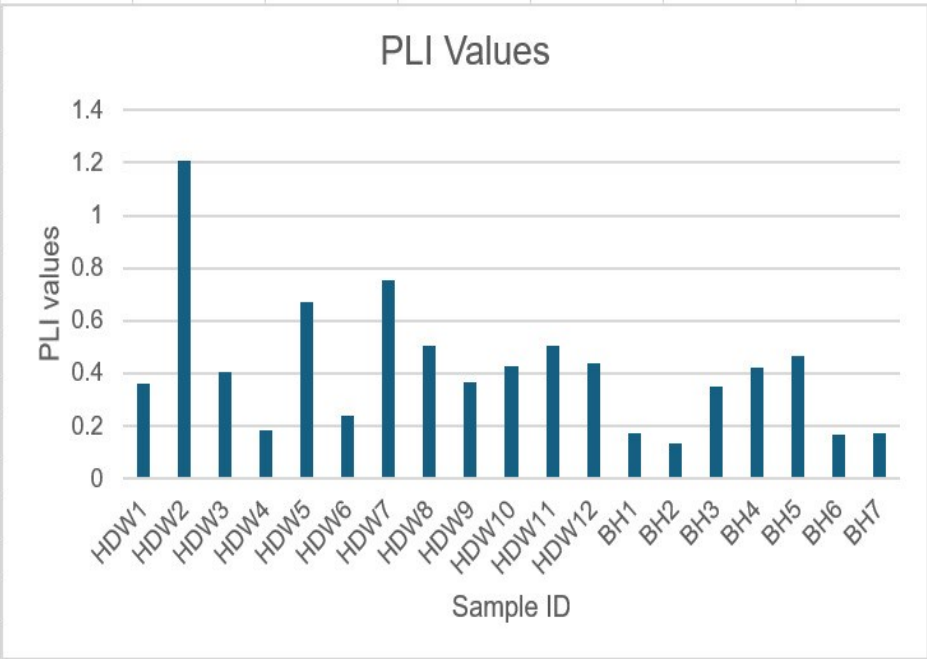

Fig. 9: Pollution Load Index (PLI) values for groundwater samples in the Chaza study area

Chromium displayed variable contamination, with CF values ranging from 0.10 to 4.11. The highest values occurred in SS007, SS008 and SS009, each with a CF of 4.11, indicating considerable contamination at these locations. The spatial concentration of the highest Cr CF values may indicate localized accumulation of Cr-bearing wastes or differential retention of the metal in the soil. However, natural contributions from Cr-bearing minerals should also be considered before assigning the enrichment exclusively to the dumpsite.

Nickel was also enriched in the soil, with CF values ranging from 1.62 to 7.20. The relatively elevated Ni values across the samples indicate widespread enrichment compared with the adopted background concentration. Nickel may originate from metallic wastes, batteries, alloys, discarded machinery and other anthropogenic materials, although its natural

occurrence in parent rocks may also contribute to the measured concentrations.

Taken collectively, the soil CF results demonstrate that Cd, Cu, Cr and Ni constitute the principal soil contamination indicators, whereas Fe and Zn generally exhibit lower levels of enrichment. The contrast between the strongly enriched soil metals and the comparatively low groundwater PLI suggests that the soil/waste interface may act as an important reservoir for metals. Metals retained in the soil can potentially be remobilized during prolonged rainfall, changes in pH or redox conditions, and continued leachate generation, thereby providing a secondary source to groundwater.

Table 7. Soil contamination factors and pollution load index in the Chaza study area

Soil sample	Fe	Mn	Cu	Zn	Cd	Cr	Ni	PLI
Background (BM)	56,300	950	55	70	0.200	100	75	—
SS001	0.0071	1.09	5.272	1.000	50.00	0.30	6.80	1.53
SS002	0.0062	0.98	5.454	0.857	100.00	0.70	7.20	1.89
SS003	0.0079	0.92	4.909	0.214	100.00	1.00	5.86	1.67
SS004	0.0051	0.07	5.090	1.142	50.00	0.10	6.80	0.86
SS005	0.0053	0.68	3.454	0.928	40.00	0.25	4.26	1.01
SS006	0.0171	0.34	2.240	0.246	45.00	0.30	1.62	0.96
SS007	0.0204	0.25	2.127	1.200	50.00	4.11	2.00	1.16
SS008	0.0192	0.25	2.127	1.200	40.00	4.11	2.00	1.12
SS009	0.0233	0.25	2.127	1.200	0.00	4.11	2.00	0.00
SS010	0.0217	0.61	1.886	0.571	0.00	1.73	1.62	0.00

The combined groundwater and soil results indicate that contamination in the Chaza environment is spatially heterogeneous and strongly metal-dependent. The groundwater system generally exhibits low integrated pollution based on PLI, while individual Pb and Cd contamination factors identify localized areas of concern. In contrast, the soil exhibits substantially stronger enrichment, particularly for Cd, Cu, Cr and Ni. This pattern is environmentally significant because soils surrounding waste-disposal sites can retain metals released from solid waste and leachate and subsequently act as long-term reservoirs.

The stronger contamination signal in soil relative to groundwater may reflect several attenuation processes operating between the waste source and the aquifer. Metals released from wastes can be retained through adsorption onto clay minerals and Fe/Mn oxides, complexation with organic matter, precipitation and incorporation into secondary minerals. These processes can temporarily reduce metal transport into groundwater. Conversely, acidic conditions and changes in redox state can increase metal mobility and promote subsequent downward migration.

The localized groundwater anomalies, particularly the elevated Pb and Cd CFs, are therefore consistent with a potential source–pathway–receptor relationship involving dumpsite wastes, leachate migration through the weathered/fractured basement materials and interception by shallow wells. The influence of natural weathering should nevertheless be recognized because the study area is underlain by Basement Complex rocks capable of contributing Fe, Mn and other elements to groundwater through water-rock interaction.

The results further demonstrate why contamination indices should be interpreted alongside hydrochemical characteristics, spatial distribution, geology and measured

concentrations. A low PLI does not eliminate the possibility of health concerns from an individual toxic metal. In particular, Pb and Cd require attention because of their toxicity at relatively low concentrations. Consequently, the contamination-index results provide evidence of localized environmental contamination, but they should be integrated with the groundwater heavy-metal concentrations and the quantitative human-health risk assessment before concluding whether the water poses unacceptable risks to consumers.

3.10 Spatial Relationship Between Dumpsites and Groundwater Contamination

The spatial distribution maps provide additional evidence for interpreting the relationship between waste-disposal sites and groundwater contamination. The Pb and Fe maps show localized concentration anomalies around portions of the dumpsite-affected environment, while the soil maps demonstrate spatially variable enrichment of Zn, Cr and Ni. The coincidence of contaminant anomalies with dumpsite locations is consistent with a potential source–pathway–receptor relationship in which the dumpsites represent the contaminant source, precipitation and infiltration provide the transport mechanism, weathered and fractured basement materials provide migration pathways, and shallow groundwater represents the principal environmental receptor.

However, spatial coincidence alone cannot conclusively establish that all detected metals originated from the dumpsites. The Basement Complex itself can contribute naturally occurring metals through weathering and mineral dissolution. The strongest evidence for anthropogenic influence therefore comes from the combined interpretation of metal concentrations, contamination indices, spatial patterns, groundwater hydrochemistry and comparison with the control/reference groundwater.

This integrated interpretation is consistent with Badmus et al. (2022), who used hydrochemical and geophysical evidence to demonstrate leachate migration around the Emirin dumpsite and identified elevated heavy metals in affected groundwater. ScienceDirect

3.11 Implications for Groundwater Quality and Human Health

The results indicate that although most groundwater samples retain freshwater characteristics based on TDS, localized contamination by potentially toxic metals is evident. The coexistence of acceptable general physicochemical characteristics with elevated Pb, Cd, and Fe concentrations shows that general water-quality parameters alone are insufficient to assess the safety of groundwater around unregulated dumpsites.

The potential significance of Pb and Cd is particularly high because both metals can produce adverse effects following prolonged exposure. Laniyan and Adewumi (2019) demonstrated that heavy-metal contamination around an exposed Nigerian dumpsite can result in potential long-term health risks, emphasizing the importance of combining chemical monitoring with exposure assessment. PubMed

Similarly, Badmus et al. (2022) reported elevated Pb and other metals around the Emirin dumpsite and found that health-risk indices were particularly important for assessing exposure to contaminated groundwater. Their study reported hazard-index values above unity for both adults and children, with children experiencing greater potential risk. DOI.org

For the Chaza study, however, a definitive statement concerning human-health risk should be based on the HQ, HI and/or CR values generated from the actual exposure assessment. The concentration results demonstrate potential concern, but concentration exceedance alone should not be described as a quantified health risk. The final interpretation should therefore distinguish clearly between contamination,

exceedance of drinking-water standards, and calculated health risk.

3.12 Integrated Discussion

Overall, the results demonstrate that groundwater quality in the Chaza area is controlled by the interaction of natural hydrogeological processes and localized anthropogenic contamination. The predominance of rock-dominance signatures in the Gibbs diagram indicates that water–rock interaction remains the principal regional control on groundwater chemistry. Nevertheless, the occurrence of elevated heavy metals and localized contamination anomalies near the dumpsites indicates that natural hydrogeochemical processes are superimposed by anthropogenic inputs.

The predominance of acidic groundwater is of particular concern because low pH can enhance the mobility of several potentially toxic metals. The occurrence of Cd and Pb enrichment in groundwater, together with elevated Cu, Cr and Ni concentrations in soils, indicates that the waste-disposal areas constitute important potential sources of metal contamination. The spatial distribution of contaminants further indicates that contamination is not uniformly distributed but occurs in localized zones associated with the dumpsite environment and shallow groundwater system.

The comparatively lower PLI values observed in most boreholes relative to several hand-dug wells suggest that shallow groundwater sources are generally more vulnerable to contamination. This observation is consistent with the hydrogeological characteristics of Basement Complex terrains, where shallow weathered materials are more directly exposed to surface infiltration. Nevertheless, the presence of contamination in deeper sources demonstrates the need for continued monitoring because fractures can provide preferential contaminant pathways.

The findings are broadly consistent with previous Nigerian investigations. Badmus et al. (2022) documented leachate migration and elevated heavy metals around the Emirin dumpsite, while Laniyan and Adewumi (2019) demonstrated the potential health implications of heavy-metal contamination in groundwater around an exposed dumpsite. The present study extends these observations to the Chaza Basement Complex environment of North-Central Nigeria, where the interaction between dumpsite-derived contaminants and weathered/fractured basement aquifers creates a distinct groundwater vulnerability scenario.

The results consequently support the need for improved waste-management practices around Chaza, including controlled waste disposal, prevention of indiscriminate dumping, proper leachate management, periodic groundwater monitoring, and protection of shallow wells located close to waste-disposal sites. Particular attention should be given to groundwater sources showing elevated Pb and Cd concentrations because these contaminants have greater potential public-health significance than the general freshwater classification suggested by TDS.

4.0 Conclusion

This study assessed groundwater quality and heavy-metal contamination associated with dumpsite environments in Chaza, North-Central Nigeria. The results demonstrate considerable spatial variation in groundwater chemistry, with pH ranging from 5.65 to 8.30 and EC from 124 to 1,679 µS/cm. Several hand-dug wells were mildly acidic, while HDW2 exhibited particularly high EC and TDS, indicating localized mineralization and possible influence from surface-derived contaminants. Major-ion chemistry and hydrochemical facies indicated that groundwater composition is controlled principally by water–rock interaction, with localized anthropogenic influence. Heavy-metal assessment revealed greater concern for Pb and Cd than for Cu and Zn, with elevated contamination factors occurring at selected groundwater points. Soil contamination was more pronounced, particularly for Cd, Cu, Cr

and Ni, suggesting that the dumpsite environment acts as an important reservoir for potentially toxic metals. The contrast between generally low groundwater PLI values and elevated soil contamination indicates attenuation and retention of metals within the soil and weathered zone, although continued leaching could facilitate future groundwater contamination. Overall, the findings highlight the vulnerability of shallow groundwater around the Chaza dumpsite and the need for improved waste management, periodic groundwater and soil monitoring, protection of shallow wells, and appropriate treatment of groundwater intended for domestic consumption.

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Declarations

Ethical Approval and Consent to Participate

Not applicable

Availability of Data and Materials

Data shall be made available upon request

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Authors' Contributions

Both authors contributed to all aspects of the work