COMPARATIVE ASSESSMENT OF PHYSICOCHEMICAL AND BACTERIOLOGICAL PARAMETERS IN WATER SOURCES NEAR MAJOR DUMPSITES AND CONTROL AREAS IN KARU-ABUJA AND PARTS OF NASARAWA STATE

ABSTRACT

This study investigated the physicochemical and bacteriological parameters of water samples from boreholes, hand-dug wells, and streams near major dumpsites and control areas in Karu-Abuja and parts of Nasarawa State, Nigeria, to assess their suitability for domestic use. Nine water samples are analysed using Atomic Absorption Spectrophotometry (AAS) and standard methods. Multivariate statistical analysis and water quality indexing were conducted using GRAPHER, SURFER, and XLSTAT tools. Results showed that while most parameters were within permissible limits, heavy metals such as Pb^{2+}, Co^{2+}, Mn^{2+}, Cr^{2+} and Cd^{2+} exceeded these thresholds. The Water Quality Index (WQI) for samples near dumpsites (177.72) indicated poorer quality compared to control areas (62.25). Bacterial analysis revealed elevated coliform counts near dumpsites, while streams had the lowest counts (09-16 cfu/ml) due to continuous flow. *E. coli*, *faecal strep*, and *Pseudomonas spp* were absent in most samples, except for a minor presence of *Pseudomonas spp* in a Keffi hand-dug well. Principal Component Analysis (PCA) accounted for over 92% of the total variance in water quality data. Hydrochemical plots identified mixed water types (Ca-Mg-HCO□ and Ca-Mg-SO□) with temporary hardness. The findings underscore the need for regular water quality monitoring and strategic siting of groundwater sources to mitigate contamination risks and protect public health.

Keywords: Heavy metals, water quality, bacteria, pollution, multivariate analysis

1. INTRODUCTION

The rapid population growth in Abuja, which increased from 378,671 in 1991 to 1,406,239 in 2006, has placed significant pressure on the city's infrastructure, exceeding the original master plan and the capacity of its water supply systems (NPCN, 2016; Jiriko *et al.*, 2024). To address the escalating water demand, residents in Karu-Abuja and parts of Nasarawa State have turned to alternative water sources such as boreholes and hand-dug wells. However, these water sources are often located near open dumpsites, raising concerns about contamination from indiscriminate waste disposal. Open dumpsites generate leachate containing decomposing organic matter, heavy metals, and hazardous pollutants that can seep into groundwater aquifers, potentially

compromising water quality (Obute *et al.*, 2024; Emenike *et al.*, 2024; Singh *et al*., 2024). Contaminants such as heavy metals, including cadmium (Cd), arsenic (As), and lead (Pb), pose serious health risks due to their bioaccumulation in body tissues, despite their trace presence being essential for certain physiological functions (Raimi *et al.*, 2022; Ukah *et al.*, 2019; Egbueri and Chinanu, 2020). These risks necessitate comprehensive evaluations of water quality to safeguard public health and inform effective water management policies.

Globally, studies have underscored the impact of pollution on water quality. For example, Patil and Arya (2024) analysed the Ganga River in Haridwar, India, revealing that dissolved oxygen was below permissible limits and heavy metals such as Fe, Pb, Mn, and Cd exceeded safe levels. Similarly, research in Kano State, Nigeria, linked poor water quality to gastrointestinal illnesses and chronic diseases (Aruf *et al.*, 2024). In Morocco, Hammioui *et al.* (2024) found seasonal correlations between microbial contamination and temperature in well water samples, while Melad *et al*. (2024) used spatial mapping tools to attribute water contamination in the Philippines' Mananga River to industrial activities.

Microbial contamination also presents significant risks. The World Health Organisation (WHO) recommends that safe drinking water be free of pathogens to prevent waterborne diseases such as diarrhea, cholera, and dysentery (WHO, 2000). Indicator microorganisms, including *total coliforms*, *Escherichia coli*, *faecal streptococci*, and *Pseudomonas spp.*, are widely used to detect fecal contamination and assess microbial safety (Odonkor and Ampofo, 2013; Bagordo et al., 2024; Ekiamene et al., 2024). This study aims to evaluate the impact of dumpsites on water quality in Karu-Abuja and Nasarawa State by analysing physicochemical and bacteriological parameters, with a specific focus on contaminant interactions and pollution levels. The findings will provide insights into the suitability of these water sources for domestic use and propose remediation strategies to mitigate health risks while ensuring sustainable water management.

2. LOCATION AND GEOLOGY

The study areas are situated between latitude 8°50'16.7994"N and 8°50'38.4822"N and longitudes 7°53'15.36"E and 7°53'2.5002"E in parts of Karu-Abuja, Goshen City and Keffi in Nasarawa State.

The sampling points include: A Stream under Karu-Abuja Bridge dumpsite (A); A borehole near Junior Sec. School along Jikwoyi-Karachi road, Karu-Abuja dumpsite (control) (B); A Stream adjacent the Karu-Abuja dumpsite along Jikwoyi-Karachi road (C); A Hand-Dug Well near Goshen control (D); Hand-Dug Well near Keffi Control (E); A borehole in Keffi control (F); A Hand-Dug Well near Goshen dumpsite in Aso Kadepe area, Karu LGA, Nasarawa State(G); a borehole near Tipper Garage dumpsite Karu-Abuja (H); and a borehole near the Baptist Church dumpsite, Panteka area in Keffi (I). The study area is underlain by basement complex rocks of Nigeria, including migmatite gneisses, schist belts, Older Granites suite, charnockites, syenites, minor gabbroic, dioritic rocks and undeformed acid and basic dykes. (Dada, 2006**).** The general structures include joints, foliations, and faults (Dada, 2006). The region is characterized by highlands and lowlands with elevations below 260 meters, particularly around the S-E, near the River Uke flow path. The highest relief point, located around S-W, reaches heights of 410 m (asl) and is an intrusive outcrop. The study areas are influenced by two major climatic conditions: the rainy season from April to October and the dry season from February to early-mid April. The annual rainfall average is 145.66 mm (Bashir, 2018). The drainage pattern of the area is dendritic, indicating resistance to erosion by the underlying rock units.

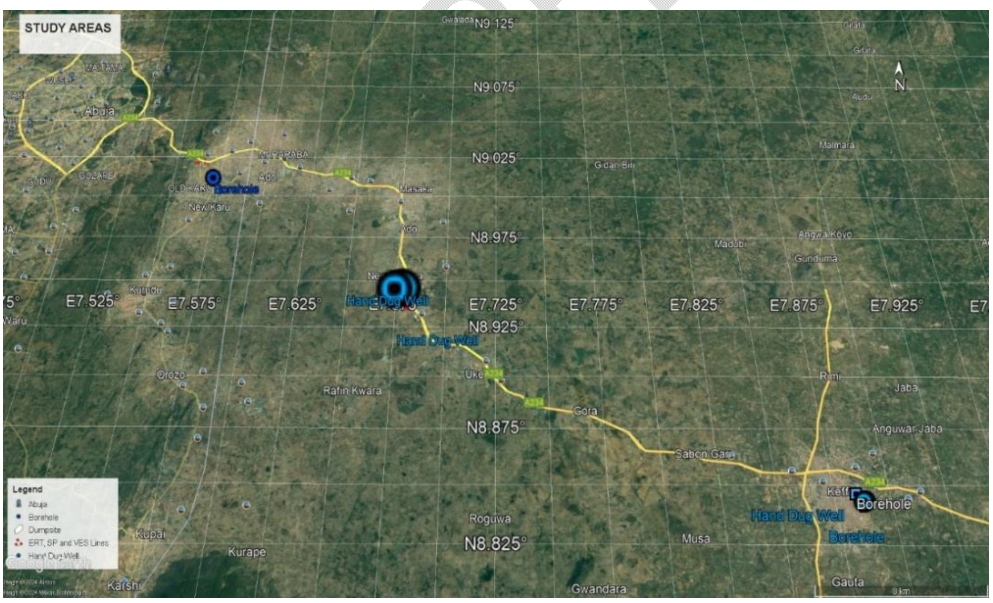


Plate 1: The Study Areas (Source: Google Earth)

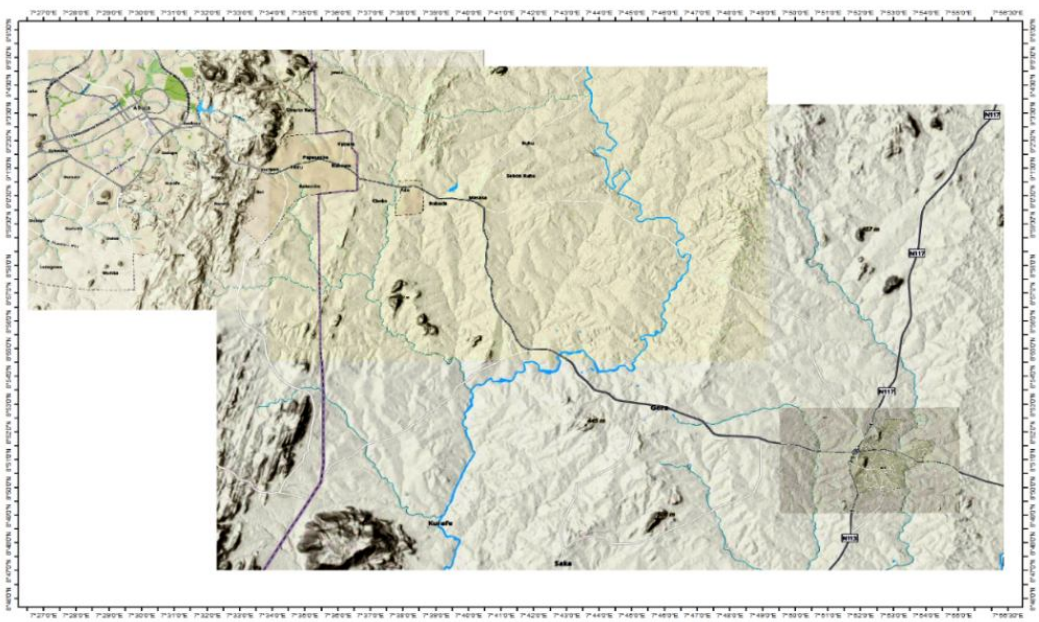


Figure 1: Topographic map of the study areas (after NASRDA, 2018**)**

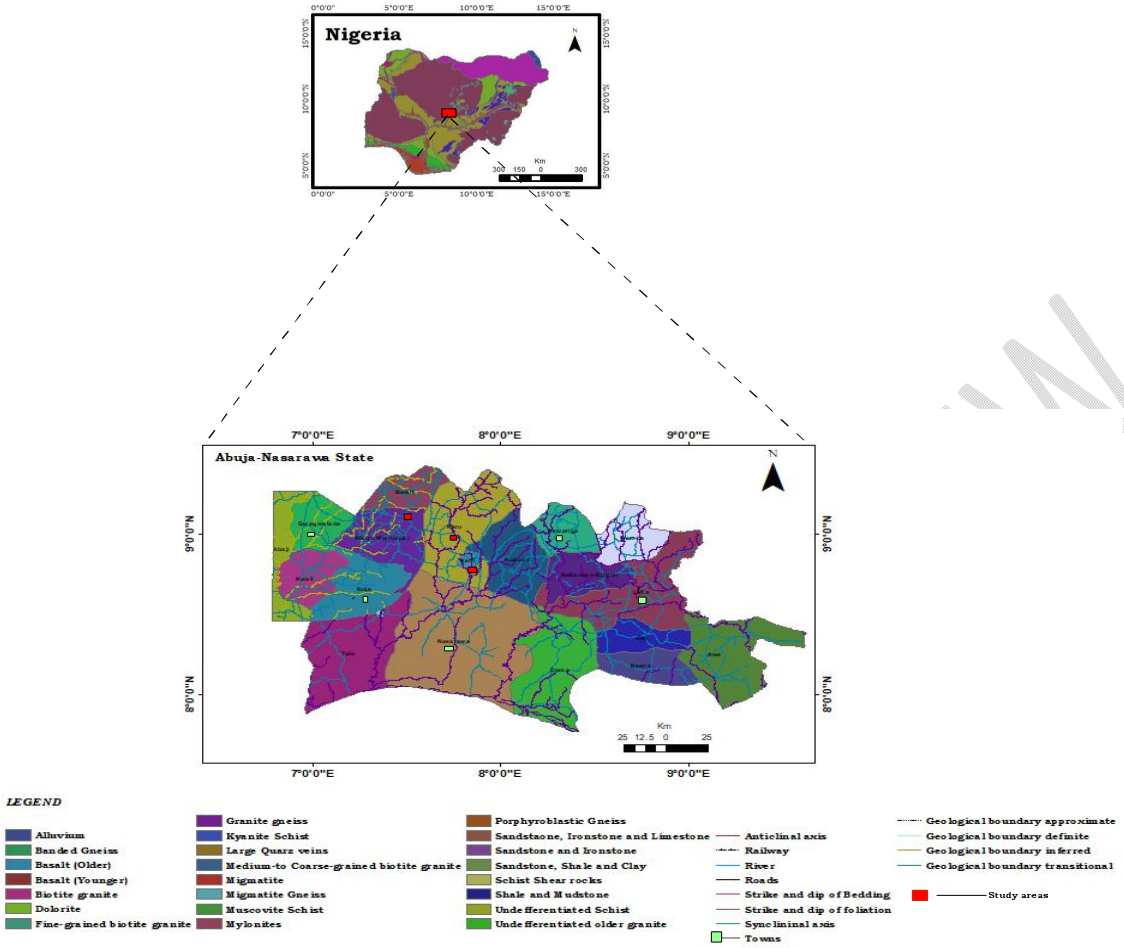


Figure 2: Geological map of the study areas (after NGSA, 2011)

3. MATERIAL AND METHODS

3.1 Water Sample Collection and Processing

Nine water samples were collected from various sources, including boreholes, hand-dug wells, and streams. Five samples were taken near dumpsites, while four were collected from control areas located approximately 700 meters away from the dumpsites. Pre-rinsed polyethylene bottles were thoroughly scrubbed three times with the water sample before collecting representative samples. Prior to sampling, the bottles were sanitized with a solution of 20% nitric acid (HNO□), thoroughly rinsed with distilled water, and air-dried. Each collected sample was labelled appropriately and transported to Sheda Laboratory in Kwali-Abuja in an insulated container filled with ice. Upon arrival, the samples were stored in a freezer at 4 °C to maintain their integrity until analysis.

3.2 Experimental Procedures

To ensure accurate characterization of the physicochemical and microbiological quality of water samples in the study area, we follow a systematic approach from field measurements to the various analyses explained below.

3.2.1 Field Measurements

Temperature is measured on-site using a mercury-in-glass portable thermometer. Turbidity readings are obtained using the nephelometric method with a HACH 2100AN turbidimeter (APHA, 1998), while pH (hydrogen ion concentration) level is determined with HANNA pH meter (Model HI 28129). The Electrical Conductivity (EC) and Total Dissolved Solids (TDS) are measured following standard APHA (2005) procedures.

3.2.2 Chemical Analysis

Major ions like Chloride (Cl^-), carbonate (CO_3^{2-}), sulfate (SO_4^{2-}), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+) are analysed using standard APHA methods (2005). Biochemical Parameters such as Biological Oxygen Demand (BOD), Dissolved Oxygen (DO), and Chemical Oxygen Demand (COD) are measured with a Hanna HI98193 waterproof portable meter and probe. Heavy Metals like Concentrations of Pb, Zn, Cr, Fe, Cu, Co, Cd, and Ni are determined using Atomic Absorption Spectrophotometry (AAS). Iron (Fe^{2+}) and manganese (Mn) are quantified using a Perkin Elmer PinAAcle 500 instrument. While Fluoride ion (F^-) is measured with a potentiometric ion-selective probe (Hanna HI5316).

3.2.3 Bacteriological Analysis

The bacterial load, including total coliform counts, *Escherichia coli*, *faecal streptococci*, and *Pseudomonas spp.*, was assessed using the membrane filtration technique. This method quantified colony-forming units per 100 mL (cfu/100 mL) of water (APHA, 1998). Tools such as GRAPHER, SURFER, and XLSTAT are used to construct Piper and Durov plots for characterizing water composition (Piper, 1944; Durov, 1948). Laboratory results are subjected to multivariate statistical analysis, including indexing, Principal Component Analysis (PCA), and hydrochemical facies analysis. The Pearson's pairwise correlation at a 0.05 significance level is used to evaluate relationships between parameters. The analysed parameters are compared to guidelines from the World Health Organization (WHO, 2011, 2008, and 2004), Standard Organisation of Nigeria (SON, 2015), and Nigeria Standard for Drinking Water Quality

(NSDWQ, 2007). Violation rates of water quality attributes are calculated accordingly. The Kaiser-Meyer-Olkin (KMO) test and Cronbach's alpha coefficient were used to assess sample adequacy and reliability of the data.

(a) (b) (c) (d)

Plate 2: Water sources for samples collected near the dumpsites

(a) (b) (c) (d)

Plate 3: Water sources for samples collected around the control sites

4. RESULT

4.1 Analysed Water Parameters

The results of analysed parameters for water samples collected near the dumpsites and control areas in Karu-Abuja, Goshen areas and Keffi in Nasarawa State, showing the minimum,

maximum, standard deviation, mean values and acceptable concentration limits as prescribed by standard organisations are presented in Tables 1 and 2:

Table 1: The statistics of the analysed parameters of water samples collected around the dumpsites

Parameters	Minimum	Maximum	Standard Deviation	Mean	Standard	Source/Year
Major Cations						
Ca^{2+} (mg/L)	8.690	51.550	16.796	22.510	75.0	WHO, 2011
Pb^{2+} (mg/L)	0.040	1.070	0.407	0.440	0.01	SON, 2015
Co^{2+} (mg/L)	0.000	0.650	0.271	0.256	0.005	WHO, 2008
Ni^{2+} (mg/L)	0.000	0.000	0.000	**0.000**	**0.02**	NSDWQ, 2007
K^{+} (mg/L)	1.740	16.860	6.081	10.988	100.0	WHO, 2011
Mg^{2+} (mg/L)	1.170	41.310	15.185	17.986	50.0	WHO, 2011
Cu^{2+} (mg/L)	0.000	1.060	0.436	**0.704**	**1.0**	NSDWQ, 2007
Mn^{2+} (mg/L)	14.410	37.240	9.623	27.144	0.2	NSDWQ, 2007
Na^{+} (mg/L)	0.610	1.010	0.160	0.890	50.0	WHO, 2011
Cr^{2+} (mg/L)	0.170	1.990	0.672	1.284	0.05	WHO, 2011
Fe^{2+} (mg/L)	0.000	0.210	0.093	0.096	0.3	WHO, 2011
Zn^{2+} (mg/L)	0.370	0.430	0.025	0.400	3.0	NSDWQ, 2007
Cd^{2+} (mg/L)	0.050	0.130	0.032	0.092	0.003	NSDWQ, 2007
Major Anions						
F^{-} (mg/L)	0.850	2.520	0.692	**1.650**	**1.0**	WHO, 2011
SO_4^{2-} (mg/L)	1.000	20.000	8.289	11.800	200.0	WHO, 2011
Cl^{-} (mg/L)	47.920	730.740	282.028	**257.796**	**200.0**	WHO, 2011
CO_3^{2-} (mg/L)	0.000	0.000	0.000	0.000	-	-
pH	6.300	7.600	0.522	**7.006**	**6.50-8.50**	WHO, 2011
EC (µS/cm)	204.800	849.800	278.604	521.120	750.0	WHO, 2011
COD (mg/L)	12.800	29.580	6.310	18.968	80.0	WHO, 2004
Turb (NTU)	0.340	15.600	7.142	**7.038**	**5.0**	WHO, 2011
TDS (µs/cm)	100.400	422.500	138.439	256.460	500.0	WHO, 2011
DO (mg/L)	2.800	6.200	1.332	**4.040**	**5.0**	NSDWQ, 2007
BOD (mg/L)	1.900	5.000	1.114	3.320	5.0	NSDWQ, 2007
Temp. ^{0}C	31.000	34.000	1.182	**32.780**	**30.0**	NSDWQ, 2007

Source: Laboratory analysis

Note: CFU/ML- Colony Forming Unit per milliliter

Table 2: The statistics of the analysed parameters of water samples collected around the control sites

Parameters	Minimum	Maximum	Standard Deviation	Mean	Standard	Source/Year
Major Cations						
Ca^{2+} (mg/L)	2.930	19.570	7.455	11.908	75.0	WHO, 2011
Pb^{2+} (mg/L)	0.240	1.010	0.357	0.488	0.01	SON, 2015
Co^{2+} (mg/L)	0.100	0.630	0.236	0.440	0.005	WHO, 2008
Ni^{2+} (mg/L)	0.000	0.200	0.100	**0.050**	**0.02**	NSDWQ, 2007
K^{+} (mg/L)	1.510	42.700	19.266	14.045	100.0	WHO, 2011
Mg^{2+} (mg/L)	0.580	17.650	7.790	9.218	50.0	WHO, 2011
Cu^{2+} (mg/L)	0.430	1.140	0.372	**0.800**	**1.0**	NSDWQ, 2007
Mn^{2+} (mg/L)	9.860	32.730	9.632	20.730	0.2	NSDWQ, 2007
Na^{+} (mg/L)	0.370	2.480	0.947	1.085	50.0	WHO, 2011
Cr^{2+} (mg/L)	1.170	2.410	0.578	1.683	0.05	WHO, 2011
Fe^{2+} (mg/L)	0.000	0.000	0.000	0.000	0.3	WHO, 2011
Zn^{2+} (mg/L)	0.390	0.440	0.021	0.415	3.0	NSDWQ, 2007
Cd^{2+} (mg/L)	0.070	0.130	0.028	**0.090**	**0.003**	NSDWQ, 2007
Major Anions						
F^{-} (mg/L)	0.020	1.250	0.522	0.518	1.0	WHO, 2011
SO_4^{2-} (mg/L)	4.000	65.000	28.408	27.500	200.0	WHO, 2011
Cl^{-} (mg/L)	39.930	258.550	96.156	135.015	200.0	WHO, 2011
CO_3^{2-} (mg/L)	0.000	0.000	0.000	**0.000**	-	-
pH	6.540	7.010	0.199	**6.820**	**6.50-8.50**	WHO, 2011
EC (µs/cm)	127.40	535.700	183.313	352.925	750.0	WHO, 2011
COD (mg/L)	8.760	25.450	7.487	18.955	80.0	WHO, 2004
Turb (NTU)	0.210	15.200	7.038	**5.060**	**5.0**	WHO, 2011
TDS (mg/L)	62.670	263.000	90.034	173.343	500.0	WHO, 2011
DO (mg/L)	0.400	5.800	2.417	**3.800**	**5.0**	NSDWQ, 2007
BOD (mg/L)	0.010	4.900	2.175	**3.203**	**5.0**	NSDWQ, 2007
Temp. ^{0}C	31.300	34.300	1.484	**32.075**	**30.0**	NSDWQ, 2007

Source: Laboratory analysis

4.1.1 Discussion

The discrimination analysis for water samples collected near the dumpsites and at the control areas presented in (Tables 3 and 4) revealed that the mean values of Ca^{2+}, K^{+}, Mg^{2+}, Cu^{2+}, Na^{+}. Fe^{2+}, Zn^{2+}, F^{-}, SO_4^{2-}, CO_3^{2-}, pH, EC, COD, DO, and BOD fall within the standard permissible limits, while the mean values of Pb^{2+}, Co^{2+}, Mn^{2+}, Cr^{2+}, Cd^{2+} and Temperature exceeded the standard permissible limits. The mean concentration of Ni^{2+} exceeded the standard permissible limits in water samples collected at the control areas while the mean concentration of Turbidity

and Cl^- ion exceeded the standard permissible limits for water samples collected near the dumpsites. The increased levels of toxic metals (Pb^{2+}, Co^{2+}, Mn^{2+}, Cr^{2+}, Cd^{2+} and Ni^{2+}) in both water sources could pose severe health hazards to the population.

a. Ion dominance

The order of ion dominance for water samples collected near the dumpsites is:
$K^+>Ca^{2+}>Cu^{2+}>Ni^{2+}>Na^+>Mn^{2+}>Mg^{2+}>Zn^{2+}>Co^{2+}>Cr^{2+}Pb^{2+}>Cd^{2+}$, while anions is in the order of $F^->SO_4^{2-}>Cl^-$
This hierarchy suggests that K is the most dominant cation, followed by Ca^{2+}, Cu^{2+} and so on.
The order of ion dominance for water samples collected at the control sites is:
$K^+>Mn^{2+}>Ca^{2+}>Mg^{2+}>Cr^{2+}>Na^+>Cu^{2+}>Co^{2+}>Zn^{2+}>Pb^{2+}>Cd^{2+}>Ni^{2+}$ while Anions is in the order of $Cl^->SO_4^{2-}>F^-$
This hierarchy suggests that K^{2+} is the most dominant cation, followed by Mn^{2+}, Ca^{2+}, Mg^{2+} and so on.

The ion dominance pattern in milli-equivalent indicates a natural water system with mineralogical influence, possibly with some anthropogenic input for metals and sulfate levels or geological materials such as feldspar or carbonate rocks as correlated by multivariate statistical analysis.

i. Bacteriological analysis

Table 3 presents bacteriological analysis results, showing Too Numerous To Count (TNTC) coliform counts in samples E, H, I. This were followed by samples D (79 cfu/ml), F (66 cfu/ml), B (39 cfu/ml), G (24 cfu/ml), and C (16 cfu/ml). All water samples tested negative for *E. coli, faecal strep,* and *Pseudomonas spp,* except for *Pseudomonas Spp* (02 cfu/ml) found in a hand-dug well at the Keffi control area. The bacteriological analysis revealed that all water sources had germ colonies above the WHO guideline, except a stream near the Karu dumpsite with Sample ID A (9 cfu/ml) which fell within the WHO limit of 10 cfu/ml due to the dispersive continuous flow of the stream. The study did not definitively prove *E. coli* contamination in samples, but it did not entirely exclude the possibility of faecal contamination.

Table 3: Results of the Bacteriological analysis

S/N	SAMPLE ID	Coliforms (WHO, 2011) limit (10 cfu/ml)	*E. coli* (WHO, 2011) limit (0 cfu/ml)	*Faecal strep.* (WHO, 2011) limit (0 cfu/ml)	*Pseudomonas spp.* (WHO, 2011) limit (0 cfu/ml)
1	A	9	Nil	Nil	Nil
2	B	39	Nil	Nil	Nil
3	C	16	Nil	Nil	Nil
4	D	79	Nil	Nil	Nil
5	E	TNTC	Nil	Nil	2
6	F	66	Nil	Nil	Nil
7	G	24	Nil	Nil	Nil
8	H	TNTC	Nil	Nil	Nil
9	I	TNTC	Nil	Nil	Nil

Source: Laboratory analysis; TNTC = (Too Numerous To Count)

SAMPLE ID.

Stream under Karu-Abuja Bridge dumpsite (A); A borehole near Junior Sec. School (Karu-Abuja dumpsite control) (B); Stream adjacent Karu-Abuja dumpsite (C); a hand-dug well near Goshen control (D); Hand-Dug Well Keffi Control (E); a borehole Keffi control (F); a hand-dug well near Goshen dumpsite (G); a borehole near Tipper Garage dumpsite Karu-Abuja (H); and a borehole near Baptist Church dumpsite Panteka (I).

ii. WQI Analysis

The results of the computed Water Quality Index (WQI) and Heavy Metal Pollution Index (HPI) are shown in Table 4. The Water Quality Index (WQI) for water samples near dumpsites was 177.72, while samples from control areas were 62.25. This suggests that water samples collected near the dumpsites exhibited higher levels of contamination compared to those collected from the control areas. The overall Water Quality Index of water samples collected near the control sites suggests that are suitable for domestic uses. The WQI for F (42.92), B (47.17), D (54.2), I (69.3), H (74.77) were categorized as good and suitable for drinking, with F (42.92) and B (47.17), being the most suitable, while E (127.37), sample G (133.37), C (165.88), and Sample A (199.58) were classified as unsuitable for drinking.

iii. HPI Analysis

The computed HPI values are shown in Table 4. The water samples near dumpsites exhibited higher heavy metal pollution indices, with an overall HPI of 188.53, compared to 176.96 from control sites. The study indicates that both the water sources near dumpsites and control areas have a high heavy metal pollution index. The HPI for water sources near dumpsites shows higher levels of heavy metal contamination compared to control areas. The water samples collected from various locations were found to be highly impacted by leachate and intensive welding activities. Sample H had the highest pollution index (HPI = 300.3), attributed to leachate infiltration and scavenger activities. Samples from C (220.98), A (181), E (165.14), B (162.5), I (104.74), F (102.8), and G (50.71) were classified as high heavy metal pollution indexes due to welding activities. The lowest pollution indices were found in samples from G (50.71) and D (25.14).

Table 4: Results of the Water Quality Index (WQI) and Heavy Metal Pollution Index (HPI)

S/N	SAMPLE ID.	WQI	Rating Class	HPI	Rating Class
1	A	199.58	Unsuitable for drinking	181	High heavy metal pollution
2	B	47.17	Good	162.5	High heavy metal pollution
3	C	165.88	Unsuitable for drinking	220.98	High heavy metal pollution
4	D	54.2	Poor	25.14	Low heavy metal Pollution
5	E	127.37	Unsuitable for drinking	165.14	High heavy metal pollution
6	F	42.92	Good	102.8	HM pollution on the threshold

					risk
7	G	133.37	Unsuitable for drinking	50.71	Low heavy metal Pollution
8	H	74.77	Very Poor	300.3	High heavy metal pollution
9	I	69.3	Poor	104.74	HM pollution on the threshold risk

Source: Laboratory analysis

b. Multivariate statistical analysis

i. Inter-elemental relationships between chemical parameters for water samples collected near dumpsites

The study reveals strong ($r > 0.8$) and moderate positive correlations ($r > 0.5–0.79$) between parameters in water samples near dumpsites, providing insights into water quality, pollution sources, and environmental interactions.

The strong correlation between EC-TDS (almost indistinguishable with $r = 1$) indicate the presence of dissolved salts or ions in water (Fu *et al.* 2024), while a strong correlation between Mn^{2+} and EC (0.985), suggests that Mn^{2+}contributes to the overall ionic content (Machado *et al.* 2024). The correlation between Mn^{2+} and Total Dissolved Solids (TDS) is strong ($r = 0.984$) indicating that Mn^{2+} is a significant component of the total dissolved solids in water. The correlation between DO and COD (0.983) indicates a strong connection between oxygen availability and organic/inorganic pollution levels (Melad *et al.* 2024). The strong correlation between Mg^{2+}- Cl^{-} (0.969) indicates a common origin, possibly due to anthropogenic activities (Sghiouer *et al.* 2024). The strong correlation between BOD and COD (0.960) indicates a significant increase in oxygen consumption, potentially causing oxygen depletion and harming aquatic ecosystems (Melad et al. 2024). Pb^{2+} - Mg^{2+} (0.95) correlation is a common ion in water due to their similarity in entering water through processes like mineral weathering or industrial discharge. A strong correlation between Pb^{2+} and Cl^{-} (0.92) suggests that Lead contamination may be linked to chloride, possibly from industrial processes, road salts, or saline intrusion. Pb^{2+} - Zn^{2+} (0.922) are common environmental metals, often found in areas impacted by mining, smelting, or industrial pollution, indicating a strong correlation between the two metals. The strong correlation between magnesium and BOD (0.915) suggests that magnesium may be linked to organic matter in water, possibly from agricultural runoff or wastewater. The strong correlation between magnesium and COD (0.913) indicates that magnesium may be linked to inorganic or organic pollutants that increase oxygen demand in water. The strong correlation between chloride and COD suggests that it may be linked to pollutants with high chemical oxygen demand, such as industrial waste or sewage. The strong correlation between Pb^{2+} - DO (0.892) suggests that lead's presence may impact water oxygen levels due to chemical reactions or pollution depleting oxygen. The correlation between potassium and BOD (0.883) indicates that potassium is strongly linked to organic matter in water (Sghiouer *et al.* 2024). The correlation between BOD and chloride levels in water is strong BOD - Cl^{-} (0.87) indicating that organic pollution, as measured by BOD, is linked to chloride levels. Magnesium significantly

influences water's ionic content, as indicated by a strong correlation between Mg and EC (0.857). which measures water's ability to conduct electricity based on dissolved ions. The correlation between Pb^{2+} -BOD (0.853) suggests that lead contamination may be linked to organic pollution. The correlation between Mg^{2+} and Total Dissolved Solids (TDS) is strong (0.85) indicating that magnesium significantly contributes to the total dissolved solids in water. The strong correlation between Zn2+ - Cl- (0.844) suggests a shared source or similar behavior in the water system. The strong correlation between sodium levels and pH Na^{+} - pH (0.836) indicates that the acidity or alkalinity of water may influence or affect sodium levels. The strong correlation between DO - Cl^{-} (0.831) suggests that chloride levels in water may be influencing dissolved oxygen levels, possibly due to pollution sources or chemical reactions. Parameters with moderate positive correlation (r > 0.5–0.79) were observed in Cr^{2+} - F^{-} (0.786), K^{+} – DO (0.784), EC - Cl^{-} (0.778), SO_4^{2-} - Temp (0.775), K^{+} – COD (0.776), Mn^{2+}- Cl^{-} (0.772), Ca^{2+} - TDS (0.771), TDS – Cl^{-} (0.77), Ca^{2+} - EC (0.762), Cd^{2+} - Cl^{-} (0.757), pH – F^{-} (0.754), Zn^{2+} - COD (0.748), Zn^{2+} - BOD (0.748), Mn^{2+} – BOD (0.74), K^{+} – Temp. (0.733), Pb^{2+} – Mn^{2+} (0.730), Ca^{2+} - Mn^{2+} (0.728), Zn^{2+} - DO (0.678), Ca^{2+} – SO_4^{2-} (0.67), EC - BOD (0.662), TDS - BOD (0.652), Pb^{2+} – K^{+} (0.604), Co^{2+} – Na^{+} (0.631), K^{+} – Mg^{2+} (0.657), pH - Temp. (0.653), Turb.- SO_4^{2-} (0.645), Na^{+} - F^{-} (0.641), Mn^{2+} – COD (0.627), Mg^{2+} - Cd^{2+} (0.623), Cd^{2+} - EC (0.623), Cd^{2+} - TDS (0.622), Cu^{2+} – Fe^{2+} (0.6), Turb.- F^{-} (0.599), Na^{+} - Turbidity (0.596), EC - COD (0.578), pH - SO_4^{2-} (0.57), TDS - COD (0.567), Co^{2+} - F^{-} (0562), K^{+}- Mn^{2+} (0.552), K^{+} – Cl^{-} (0.539), Mn^{2+} – Cd^{2+} (0.535), Ca^{2+} - Zn^{2+} (0.526), Zn^{2+} - Cd^{2+} (0.522), Pb^{2+} - Cd^{2+} (0.519), Mn^{2+} – DO (0.502). This suggests that these chemical parameters originated from similar sources (geogenic or anthropogenic process) and can therefore have influence over one another (Melad *et al*. 2024).

Specifically, EC correlates with (TDS, DO, SO_4^{2-}, Temp, Cl^{-} and COD), while TDS correlates with (DO, SO_4^{2-}, Temp, Cl^{-} and COD). DO correlates with (BOD, SO_4^{2-} and COD). BOD correlates with (SO_4^{2-} and COD). Temp correlates with Cl^{-}. Cl^{-} correlates with COD. Ca^{2+} correlates with (Mn^{2+}, Zn, EC, TDS and SO_4^{2-}). Pb^{2+} correlates with (K^{+}, Mg^{2+}, Mn^{2+}, Zn^{2+}, Cd^{2+}, DO, BOD and Cl^{-}). Co^{2+} correlates with Na^{+} and F^{-}. K^{+} correlates with (Mg^{2+}, Mn^{2+}, DO, BOD, Temp. Cl^{-}, and COD).

Mg^{2+} correlates with Mn^{2+}, Zn^{2+}, Cd^{2+}, EC, TDS, BOD, Temp. Cl^{-} and COD. Cu^{2+} correlates with Fe. Mn^{2+} correlates with Zn^{2+}, Cd, EC, TDS DO, BOD, Cl^{-} and COD; Na^{+} correlates with pH, Turbidity and F^{-}. Cr^{2+} correlates with F^{-}. Zn^{2+} correlates with Cd^{2+}, EC, TDS, DO, BOD, Cl^{-} and COD. Cd^{2+} correlates with EC, TDS and Cl^{-}. pH correlates with Turbidity, F^{-}, SO_4^{2-} and Temp. EC correlates with TDS, F^{-}, SO_4^{2-} and COD. TDS correlates with BOD, Cl^{-} and COD. Turbidity correlates with F^{-}, SO_4^{2-} and Temp. DO correlates with Cl^{-} and COD. BOD correlates with Cl^{-} and COD. SO_4^{2-} correlates with Temp. Cl^{-} correlates with COD. The correlation between chemical parameters around the control sites suggests that these parameters share common origin and similar sources attributed to mineral deposits, percolation of organic and inorganic pollutants into the subsurface, agricultural activities and discharges from poorly treated sewage which often contain high levels of dissolved solids (TDS), organics (increasing COD), and salts like Mg and Cl (Gyabaah *et al.* 2024).

ii. Inter-elemental relationships between chemical parameters for water samples collected from control sites

The water samples collected at control areas show a strong positive correlation between EC-TDS, almost indistinguishable with a r = 1 value. Other parameters with strong positive correlation with (r > 0.8) include: The strong positive correlation between Ni^{2+} -Temp. (0.999). This suggests that higher temperatures may facilitate the dissolution or mobility of Ni in water or from industrial or natural sources. The correlation between Ca^{2+} - EC (0.999) indicates that an increase in Ca2+ concentration also enhances the water's ability to conduct electricity. A strong correlation between Ca^{2+} -TDS (0.999) indicates that Ca is a major component of dissolved solids in the water in areas with hard water or limestone geology. DO - COD (0.997), Na^{+} - Temp. (0.985). A strong correlation between Na and temperature could indicate that higher temperatures increase solubility or mobility of Na in water, either from natural weathering processes or anthropogenic sources such as industrial effluents or road salt runoff. Others include: Mn^{2+}- Cl^{-} (0.989), Pb^{2+} - Temp. (0.983), Ni^{2+} - Na^{+} (0.982). A strong correlation between Na and Ni could indicate that both Ni and Na share a common source, such as industrial pollution or groundwater contamination. Pb^{2+} - Ni^{2+} (0.976), DO-BOD (0.974), Ca^{2+} - Mn^{2+} (0.971), Mn^{2+}- EC (0.965), Mn^{2+}—TDS (0.965), Ca^{2+} - Cl^{-} (0.96), BOD-COD (0.954), TDS - Cl^{-} (0.951), EC - Cl^{-} (0.951), Pb^{2+} - Cl^{-} (0.947), K^{+} - F^{-} (0.94), Pb^{2+} - Mn^{2+} (0.922), Mg^{2+} - EC (0.922), Mg^{2+} - TDS (0.923), Mg^{2+} - SO_4^{2-} (0.953), Na^{+} - Cl^{-} (0.928). Mn^{2+}- Na^{+} (0.919), Cd^{2+} - F^{-} (0.917), Ca^{2+} - Mg^{2+} (0.916), pH - COD (0.9), pH – BOD (0.893), Cr^{2+} – Zn^{2+} (0.888), Ca^{2+} - Pb^{2+} (0.821), Ca^{2+}- Na^{+} (0.802), Pb^{2+} - EC (0.804), Pb^{2+}- TDS (0.804), Co^{2+} - Cu^{2+} (0.818), Ni^{2+} - Mn^{2+} (0.831), Ni^{2+} - Cl^{-} (0.856), K^{+} - Cd (0.898), Temp - Cl^{-} (0.871), Mn^{2+} - Temp. (0.845). Parameters with moderate positive correlation (r > 0.5–0.79) were observed in Co- F^{-} (0.799), Mg^{2+} - Cl^{-} (0.796), Mg^{2+} - Mn^{2+} (0.795), SO_4^{2-} - COD (0.79), Na^{+} - EC (0.786), Na^{+} - TDS (0.785), TDS - SO_4^{2-} (0.768), EC - SO_4^{2-} (0.767), Ca^{2+} - SO_4^{2-} (0.761) (suggests that the calcium in groundwater is not only from calcium sulfate minerals but also from other sources such as weathering of carbonate rocks). DO - SO_4^{2-} (0.747), Cu^{2+} - F^{-} (0.732), Mg^{2+} - COD (0.715), Ca^{2+} - Temp. (0.706), Ca^{2+} - Ni (0.685), TDS-Temp. (0.685), EC - Temp. (0.685), Pb^{2+} - pH (0.677), Cr^{2+} - SO_4^{2-} (0.662), Ni^{2+} - EC (0.665), pH –Temp. (0.65), Ni^{2+} - TDS (0.664), BOD - SO_4^{2-} (0.636), Cl^{-} - COD (0.628), K^{+} - Cu^{2+} (0.623), SO_4^{2-} - Cl^{-} (0.617), pH - Cl^{-} (0.624), Ni - pH (0.637), Ni^{2+} - Cu^{2+} (0.609), Ca^{2+} - COD (0.608), Co^{2+} - Cd^{2+} (0.599), TDS - COD (0.595), Cu^{2+} - Temp (0.593), EC - COD (0.593), Mn^{2+} - SO_4^{2-} (0.591), Mg^{2+} - Cr^{2+} (0.588), Na^{+} - pH (0.58), DO - Cl^{-} (0.578), Pb^{2+} - Mg^{2+} (0.565), Co^{2+} - K (0.557), Ca^{2+} - DO (0.546), Pb^{2+} - COD (0.538), TDS - DO (0.531), EC - DO (0.529), Mn^{2+} - COD (0.525), Pb^{2+} - Cu^{2+} (0.52), Mg^{2+} - Na^{+} (0.514), Pb^{2+} - DO (0.503). The correlation between chemical parameters around the control sites suggests that these parameters share common origin and similar sources attributed to geogenic or anthropogenic process. This can provide valuable insights into water treatment needs, potential impacts on human and environmental health (Nayak *et al.* 2024).

Generally, Ca^{2+} correlates with (Pb^{2+}, Ni^{2+}, Mg^{2+}, Mn^{2+}, Na^{+}, EC, TDS, DO, SO_4^{2-}, Temp, Cl^{-} and COD). This suggests that Ca^{2+} originated from the dissolution of salts in groundwater. Pb^{2+} correlates with (Ni, Mg^{2+}, Cu^{2+}, Mn^{2+}, Na^{+}, pH, EC, TDS, DO, Temp. Cl^{-}, COD). Co^{2+} correlates with (K^{+}, Cu^{2+}, Cd^{2+}, and F^{-}. Ni^{2+} correlates with Cu^{2+}, Mn^{2+}, Na^{+}, pH, EC, TDS Temp. and Cl^{-}). K^{+} correlates with Cu^{2+}, Cd^{2+} and F^{-}. Mg^{2+} correlates with (Mn^{2+}, Na^{+}, Cr^{2+}, EC, TDS, DO, SO_4^{2}, Cl^{-} and COD), these values suggest the participation of both carbonate and silicate minerals during the weathering process. Cu^{2+} correlates with Na, F, and Temp. Mn^{2+} correlates with Na^{+}, pH, EC, TDS, SO_4^{2-}, Temp. Cl^{-} and COD. Na^{+} correlates with pH, EC, TDS, Temp. and Cl^{-}. Cr^{2+}

correlates with Zn and SO_4^{2-}. Cd correlates with F^-. pH correlates with DO, BOD, SO_4^{2-}, Temp. and COD. EC correlates with TDS, DO, SO_4^{2-}, Temp., Cl^- and COD. TDS correlates with DO, SO_4^{2-}, Temp. Cl^- and COD. DO correlates with BOD, SO_4^{2-}, and COD. SO_4^{2-} correlates with Cl^- and COD. Temp. correlates with Cl^-. Cl^- correlates with COD as shown Tables 5 and 6:

Table 5: Matrix of correlation for water variables collected near dumpsites

Parameters	Ca	Pb	Co	K	Mg	Cu	Mn	Na	Cr	Fe	Zn	Cd	pH	EC	TDS	Turb	DO	BOD	F	SO4	Temp	Cl	COD
Ca	**1**																						
Pb	0.162	**1**																					
Co	-0.015	-0.186	**1**																				
K	-0.002	**0.604**	-0.387	**1**																			
Mg	0.324	**0.950**	-0.426	**0.657**	**1**																		
Cu	0.140	-0.474	-0.670	-0.356	-0.227	**1**																	
Mn	**0.728**	**0.730**	-0.380	**0.552**	**0.871**	-0.058	**1**																
Na	0.011	-0.835	**0.631**	-0.490	-0.883	-0.025	-0.612	**1**															
Cr	-0.884	-0.012	0.160	0.339	-0.195	-0.472	-0.550	0.054	**1**														
Fe	-0.621	-0.183	-0.571	-0.244	-0.140	**0.600**	-0.414	-0.336	0.230	**1**													
Zn	**0.526**	**0.922**	-0.105	0.511	**0.927**	-0.405	**0.894**	-0.681	-0.337	-0.441	**1**												
Cd	0.291	**0.519**	-0.551	-0.085	**0.623**	0.405	**0.535**	-0.779	-0.558	0.397	**0.522**	**1**											
pH	-0.147	-0.594	0.503	0.049	-0.650	-0.288	-0.473	**0.836**	0.410	-0.443	-0.535	-0.982	**1**										
EC	**0.762**	0.730	-0.323	0.417	**0.857**	-0.040	**0.985**	-0.614	-0.636	-0.393	**0.910**	**0.623**	-0.562	**1**									
TDS	**0.771**	0.723	-0.315	0.405	**0.850**	-0.038	**0.984**	-0.605	-0.646	-0.399	**0.907**	**0.622**	-0.560	**1.000**	**1**								
Turb	-0.119	-0.398	0.218	0.392	-0.391	-0.260	-0.238	**0.596**	0.452	-0.426	-0.368	-0.906	**0.927**	-0.374	-0.376	**1**							
DO	-0.210	**0.892**	-0.336	**0.784**	0.837	-0.449	**0.502**	-0.829	0.371	0.046	**0.678**	0.315	-0.426	0.446	0.434	-0.162	**1**						
BOD	0.089	**0.853**	-0.541	**0.883**	**0.915**	-0.236	**0.740**	-0.831	0.108	-0.059	**0.748**	0.378	-0.421	**0.662**	**0.651**	-0.084	0.919	**1**					
F	-0.706	-0.516	**0.562**	-0.147	-0.711	-0.383	-0.848	**0.641**	**0.786**	0.023	-0.683	-0.844	**0.754**	-0.892	-0.893	**0.599**	-0.245	-0.488	**1**				
SO4	**0.670**	-0.078	0.223	0.336	0.020	-0.213	0.413	0.417	-0.299	-0.860	0.213	-0.461	**0.570**	0.341	0.345	**0.645**	-0.201	0.057	-0.080	**1**			
Temp.	0.145	0.149	0.168	**0.733**	0.148	-0.539	0.265	0.202	0.319	-0.691	0.207	-0.648	**0.653**	0.130	0.126	**0.832**	0.266	0.374	0.247	**0.775**	**1**		
Cl	0.196	**0.921**	-0.519	**0.539**	**0.969**	-0.097	**0.772**	-0.967	-0.178	0.092	**0.844**	**0.757**	-0.798	**0.778**	**0.770**	-0.559	**0.831**	**0.870**	-0.725	-0.215	-0.073	**1**	
COD	-0.072	0.920	-0.447	**0.776**	**0.913**	-0.328	**0.627**	-0.899	0.207	0.054	**0.748**	0.448	-0.533	**0.578**	**0.567**	-0.248	**0.983**	**0.960**	-0.416	-0.171	0.211	**0.911**	**1**

Significance bold values are $p < 0.5$

Table 6: Matrix of correlation for water variables collected around the control sites

Parameters	Ca	Pb	Co	Ni	K	Mg	Cu	Mn	Na	Cr	Zn	Cd	pH	EC	TDS	Turb	DO	BOD	F	SO4	Temp	Cl	COD
Ca	**1**																						
Pb	**0.821**	**1**																					
Co	-0.262	0.154	**1**																				
Ni	**0.685**	**0.976**	0.339	**1**																			
K	-0.148	-0.269	**0.557**	-0.222	**1**																		
Mg	**0.916**	**0.565**	-0.615	0.373	-0.268	**1**																	
Cu	0.305	**0.520**	**0.818**	**0.609**	**0.623**	-0.063	**1**																
Mn	**0.971**	**0.922**	-0.041	**0.831**	-0.105	**0.795**	0.483	**1**															
Na	**0.802**	**0.992**	0.258	**0.982**	-0.149	**0.514**	**0.625**	**0.919**	**1**														
Cr	0.308	-0.289	-0.672	-0.476	0.230	**0.588**	-0.328	0.094	-0.304	**1**													
Zn	-0.116	-0.653	-0.726	-0.801	0.103	0.255	-0.641	-0.344	-0.686	**0.888**	**1**												
Cd	-0.567	-0.575	**0.599**	-0.471	**0.898**	-0.639	0.399	-0.512	-0.465	0.033	0.113	**1**											
pH	0.483	**0.677**	-0.328	**0.637**	-0.890	0.445	-0.219	**0.504**	**0.583**	-0.342	-0.411	-0.948	**1**										
EC	**0.999**	**0.804**	-0.269	**0.665**	-0.126	**0.922**	0.304	**0.965**	**0.786**	0.336	-0.090	-0.549	0.457	**1**									
TDS	**0.999**	**0.804**	-0.271	**0.664**	-0.127	**0.923**	0.302	**0.965**	**0.785**	0.337	-0.089	-0.550	0.458	**1.000**	**1**								
Turb	-0.931	-0.611	0.240	-0.459	-0.167	-0.886	-0.361	-0.869	-0.620	-0.551	-0.113	0.278	-0.138	-0.942	-0.942	**1**							
DO	**0.546**	**0.503**	-0.677	0.386	-0.901	**0.657**	-0.476	0.467	0.389	0.049	-0.013	-0.995	**0.914**	**0.529**	**0.531**	-0.276	**1**						
BOD	0.343	0.340	-0.693	0.244	-0.969	0.493	-0.619	0.262	0.217	-0.022	0.022	-0.962	**0.893**	0.325	0.327	-0.061	**0.974**	**1**					
F	-0.286	-0.201	**0.799**	-0.086	**0.940**	-0.499	**0.732**	-0.169	-0.074	-0.115	-0.192	**0.917**	-0.802	-0.273	-0.275	0.046	-0.946	-0.985	**1**				
SO4	**0.761**	0.360	-0.824	0.153	-0.425	**0.953**	-0.362	**0.591**	0.281	**0.662**	0.445	-0.705	0.467	**0.767**	**0.768**	-0.722	**0.747**	**0.636**	-0.679	**1**			
Temp.	**0.706**	**0.983**	0.310	**0.999**	-0.236	0.402	**0.593**	**0.845**	**0.985**	-0.453	-0.782	-0.492	**0.650**	**0.685**	**0.685**	-0.479	0.409	0.265	-0.109	0.184	**1**		
Cl	**0.960**	**0.947**	-0.096	**0.856**	-0.245	**0.796**	0.397	**0.989**	**0.928**	0.031	-0.377	-0.624	**0.624**	**0.951**	**0.951**	-0.811	**0.578**	0.389	-0.290	**0.617**	**0.871**	**1**	
COD	**0.608**	**0.538**	-0.683	0.410	-0.863	**0.715**	-0.437	**0.525**	0.427	0.098	0.002	-0.991	**0.900**	**0.593**	**0.595**	-0.352	**0.997**	**0.954**	-0.927	**0.790**	0.434	**0.628**	**1**

Significance bold values are $p < 0$.

c. Groundwater types and evaluation

The hydrochemical facies of groundwater explains the relation between major anions and cations and their behaviour. Hydrochemical facies help in establishing the classification of different water types (Piper, 1994) and in understanding the origin and geochemical evolution of groundwater.

i. Piper Trilinear plot

ii. Facie for water samples collected near the dumpsites

The piper diagram (Figure 3) shows Ca-Mg-HCO_3 (20%) and Ca–Mg– SO_4 (60%) mixed water type for samples near the dumpsites, which is mainly influenced by the recharged water from the streams or perhaps caused by rock-water interaction associated with intermediate EC values. Also, the dissolution of dolomite and calcite may cause this water type. The plotted cations indicate the dominance of Ca^{2+} and Mg^{2+}, and in anions, CO_3^- and SO_4^{2-} dominance indicating temporary hardness.

iii. Facie for water samples collected around the control sites

Piper diagrams (Figure 4) shows Ca-Mg-HCO_3 (40%) and Ca–Mg– SO_4 (90%) mixed water type for samples near the control areas. The plotted cations indicate the dominance of Ca^{2+} and Mg^{2+} and in the anion plot, CO_3^- and SO_4^{2-} indicating temporary hardness.

iv. Durov plot

The Durov plot of the water samples indicates that there are mainly two geochemical processes that could affect the genesis of water in the study area (Figures 5 and 6). Samples from dumpsites show HCO_3^- and Ca^{2+} dominance (60 %) and control sites (86 %), suggesting mixing, uncommon dissolution influences, and reverse ion exchange processes.

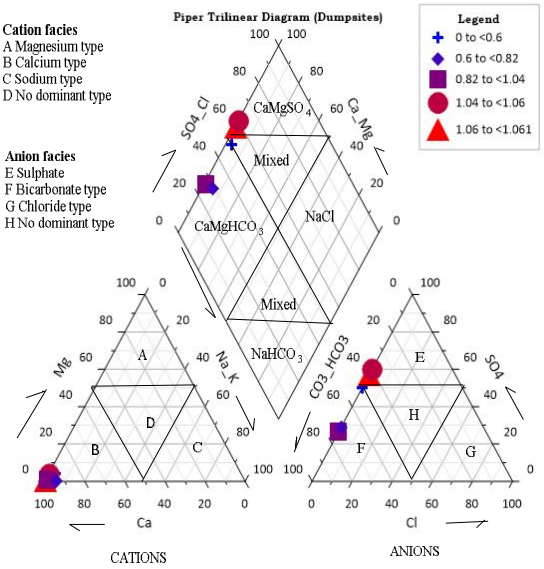


Figure 3:

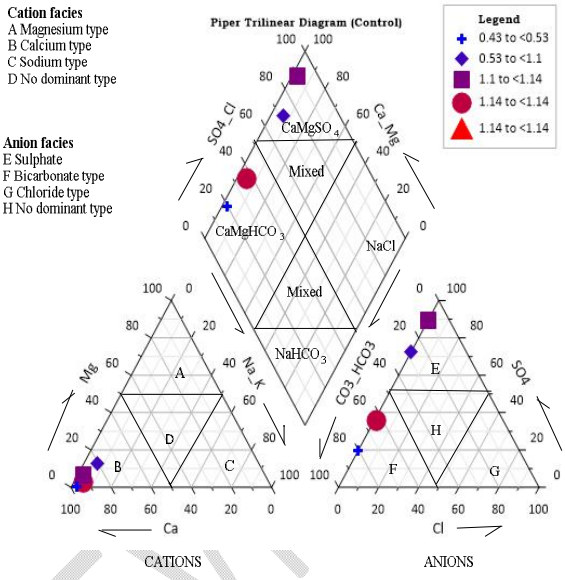


Figure 4:

Figures 3 and 4: Piper trilinear diagram showing the hydrochemical characteristics and hydrochemical facies of water samples collected near the dumpsites and control sites

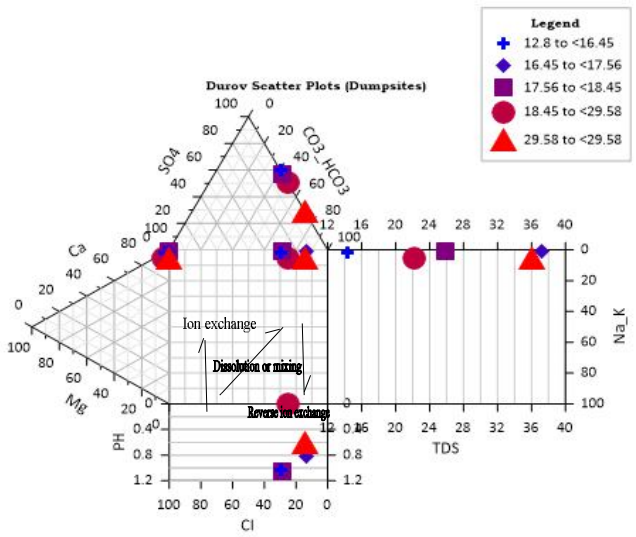


Figure 5:

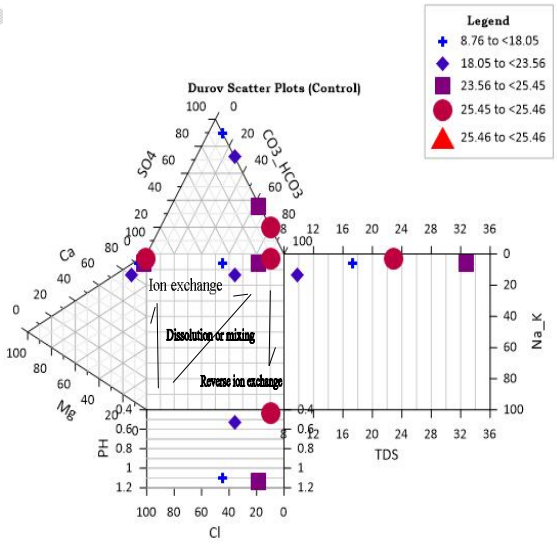


Figure 6:

Figures 5 and 6: Durov diagram showing the dominant chemical processes affecting groundwater chemistry near dumpsites and control sites

d. Comparative Analysis of Principal Components Analysis (PCA)

The Principal component analysis (PCA) results comparing the 3-D tri-plots, 3-D bar plots, and scree plots for the analysed water samples collected near the Dumpsites and samples collected around the control sites are shown in figures 7 to 8:

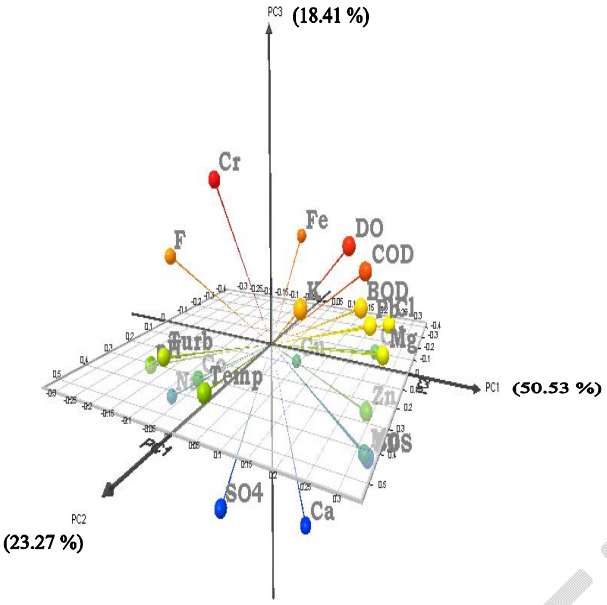


Figure 7:

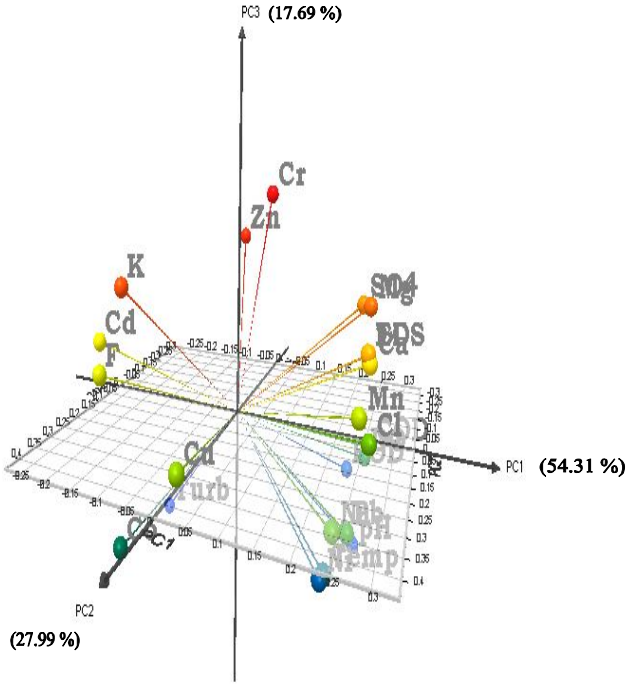
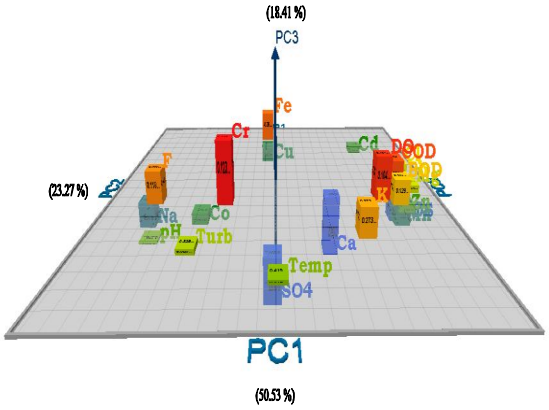


Figure 8:

Figures 7 and 8: 3-D tri-plots score showing PC1, PC2 and PC3 for: a) water samples collected near dumpsites b) analysed water samples collected near control sites.



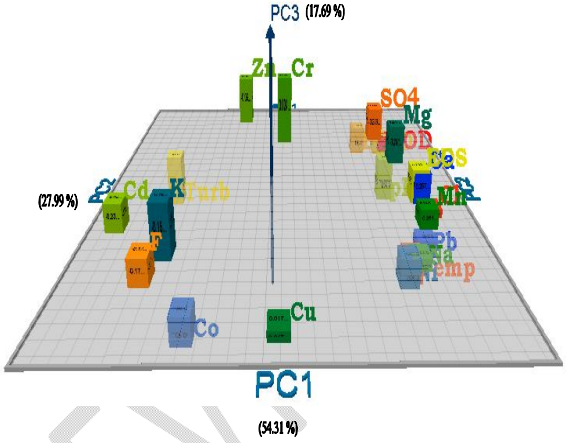
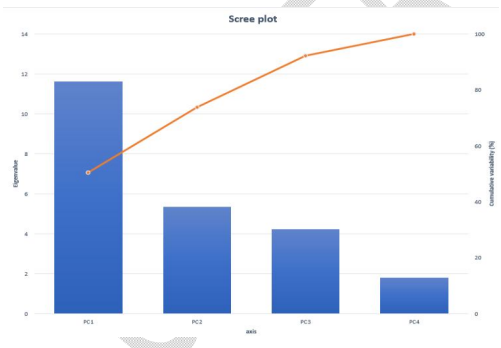


Figure 10: Figure 11:

Figures 10. and 11: 3-D bar-plots score showing PC1, PC2 and PC3 for: c) water samples collected near dumpsites d) analysed water samples collected near control sites.



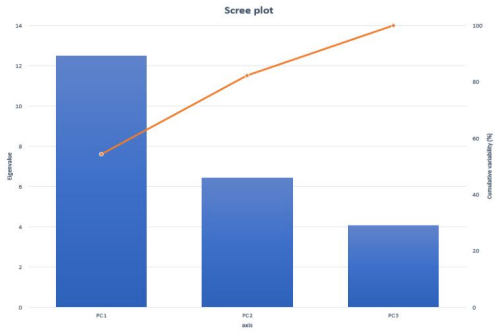


Figure 11: Figure 12:

Figures 11 and 12: 3-D bar-plots score showing PC1, PC2 and PC3 for: e) water samples collected near dumpsites f) analysed water samples collected near control sites.

Table 7: Extracted Principal Components and their total variance for water samples collected within dumpsites

Loadings	**PC1 (50.527%)**	**PC2 (23.269%)**	**PC3 (18.407%)**	**PC4 (7.797%)**
Ca^{2+}	0.119	0.082	**-0.434**	-0.021
Pb^{2+}	**0.263**	0.086	0.126	**0.221**
Co^{2+}	-0.146	0.162	-0.075	**0.572**
K^{+}	0.160	**0.274**	0.192	-0.285
Mg^{2+}	**0.288**	0.062	0.055	0.026
Cu^{2+}	-0.021	**-0.300**	-0.154	**-0.481**
Mn^{2+}	**0.262**	0.111	-0.171	-0.083
Na^{+}	-0.263	0.109	-0.178	0.033
Cr^{2+}	-0.101	0.124	**0.435**	0.018
Fe^{2+}	-0.021	**-0.351**	0.242	-0.219
Zn^{2+}	**0.266**	0.122	-0.062	**0.216**
Cd^{2+}	**0.218**	**-0.283**	-0.064	0.044
pH	-0.219	**0.279**	-0.015	-0.114
EC	**0.263**	0.065	-0.201	0.005
TDS	**0.262**	0.064	-0.207	0.009
Turb.	-0.148	**0.329**	0.039	-0.299
DO	**0.218**	0.104	**0.302**	0.039
BOD	**0.251**	0.129	0.175	-0.168
F^{-}	-0.242	0.119	**0.229**	0.117
SO_4^{2-}	-0.005	**0.337**	**-0.284**	-0.165
Temp	0.003	**0.419**	0.028	-0.177
Cl^{-}	**0.286**	-0.038	0.098	0.031
COD	**0.248**	0.075	**0.244**	-0.012
Eigen values	11.621	5.352	4.234	1.793
Variability (%)	50.527	23.269	18.407	7.797
Cumulative (%)	50.527	73.796	92.203	100.000

Table 8: Extracted Principal Components and their total variance for water samples collected within control sites

Loadings	**PC1 (**54.313%)	**PC2 (**27.993%)	**PC3 (**17.693%)
Ca^{2+}	**0.257**	0.084	0.177
Pb^{2+}	**0.24**	0.19	-0.09
Co^{2+}	-0.107	**0.346**	-0.144
Ni^{2+}	**0.208**	**0.237**	-0.156
K^{+}	-0.152	**0.236**	**0.295**
Mg^{2+}	**0.242**	-0.067	**0.243**

Cu^{2+}	0.018	**0.391**	0.051
Mn^{2+}	**0.251**	0.161	0.106
Na^{+}	**0.225**	**0.234**	-0.065
Cr^{2+}	0.025	-0.170	**0.445**
Zn^{2+}	-0.064	**-0.277**	**0.334**
Cd^{2+}	-0.240	0.166	0.159
pH	**0.227**	-0.084	**-0.278**
EC	**0.254**	0.083	0.192
TDS	**0.254**	0.082	0.192
Turb	-0.199	-0.099	**-0.330**
DO	**0.233**	-0.198	-0.132
BOD	0.191	**-0.246**	-0.193
F^{-}	-0.170	**0.293**	0.143
SO_4^{2-}	**0.218**	-0.181	**0.219**
Temp	**0.214**	**0.229**	-0.148
Cl^{-}	**0.266**	0.130	0.051
COD	**0.243**	-0.186	-0.099
Eigen values	12.492	6.438	4.069
Variability (%)	54.313	27.993	17.693
Cumulative(%)	54.313	82.307	100.000

Table 9: The Kaiser-Meyer-Olkin measure of sampling the adequacy for water samples collected near the dumpsites

Variable	KMO sampling adequacy
Ca^{2+}	0.424
Pb^{2+}	0.609
Co^{2+}	0.406
Ni^{2+}	0.000
K^{+}	0.484
Mg^{2+}	0.724
Cu^{2+}	0.346
Mn^{2+}	0.641
Na^{+}	0.664
Cr^{2+}	0.417
Zn^{2+}	0.638
Cd^{2+}	0.667
pH	0.605
EC	0.653
TDS	0.649
Turb.	0.465
DO	0.562

BOD	0.614
F^-	0.629
SO_4^{2-}	0.388
Temp.	0.445
Cl^-	0.686
COD	0.611
KMO	0.574
Cronbach's alpha	0.693

Table 10: The Kaiser-Meyer-Olkin measure of sampling the adequacy for water samples collected near the control centres

Variable	KMO sampling adequacy
Ca^{2+}	0.567
Pb^{2+}	0.614
Co^{2+}	0.493
Ni^{2+}	0.561
K^+	0.424
Mg^{2+}	0.554
Cu^{2+}	0.428
Mn^{2+}	0.579
Na^+	0.591
Cr^{2+}	0.303
Zn^{2+}	0.384
Cd^{2+}	0.577
pH	0.514
EC	0.557
TDS	0.558
Turb.	0.454
DO	0.581
BOD	0.503
F^-	0.503
SO_4^{2-}	0.561
Temp.	0.569
Cl^-	0.633
COD	0.614
KMO	0.534
Cronbach's alpha	0.811

i. PCA for water samples collected near dumpsites

PC1 for water samples collected around the dumpsites explains approximately (50.527% of the total variance, eigenvalue of 11.62) and has strong positive correlation value with Mg^{2+} and Cl^{-} and a moderately positive correlation with Pb^{2+}, Mn^{2+}, Zn^{2+}, Cd^{2+}, DO, BOD and COD which reflects the role of lithogenic and anthropogenic factors in influencing the water chemistry. Strong correlation of Cl^{-} ions with alkali and alkaline earth metals Mg, indicated the natural weathering sources.

PC2 (23.269% of total variance, eigenvalue of 5.35) has strong positive correlation with Temperature, SO_4^{2-}, and Turb. Has moderate positive correlation with pH and K^{+} and strong negative correlation with Cu^{2+} and Fe^{2+}. The significant inverse relationship between Cu^{2+} and Fe^{2+} indicates the diverse source of chemical origin.

PC3 (18.407% of total variance, eigenvalue of 4.23) was strongly positive weighted on Cr^{2+} and DO, and moderate positive score on COD and F^{-}.

PC4 explains (7.797%of the total variance, eigenvalue of 1.79) observed and has strong positive correlation with Co^{2+} and a moderately strong positive correlation with Zn^{2+}. It has strong negative correlation with Cu^{2+}, Turbidity and K^{+}.

ii. PCA for water samples collected near the control sites

PC1 for water samples collected around the control sites explains approximately (54.3 % of the total variance, eigenvalue of 12.49), and has strong positive correlation value with Ca^{2+}, Cl^{-} and EC, Mn^{2+}, COD, Pb^{2+} Mg^{2+}, Na^{+}, DO, SO_4^{2-}, pH and TDS which reflects the role of lithogenic factors in influencing the water chemistry, and a moderately strong positive correlation with Temp. and Ni^{2+}. Strong correlation of Cl^{-} ions with alkali and alkaline earth metals Mg^{2+}, indicated the natural weathering sources. A high positive loading of Ca^{2+}, Na^{+} and Cl^{-} and SO_4^{2-}, is attributed to various natural processes such as - weathering of rock minerals (limestone and calcium carbonate bearing rocks) and to various ion-exchange processes taking place in the groundwater system.

PC2 (23.269% of total variance, eigenvalue of 6.44) has strong positive correlation with Cu^{2+} and Co^{2+}, has moderate positive correlation with Ni^{2+}, K^{+}, F^{-} and Temperature and strong negative correlation with Zn^{2+} and BOD.

PC3 **(**17.693% of total variance, eigenvalue of 4.07) was strongly positive weighted on Cr^{2+} and Zn^{2+} and moderate positive score on K^{+}, Mg^{2+} and SO_4^{2-} and strong negative correlation with Turbidity and pH, hence, diverse origin.

5. CONCLUSION

This study evaluated and compared the physicochemical and bacteriological parameters in water sources located near major dumpsites and control areas in Karu-Abuja and parts of Nasarawa State, using multivariate statistical analysis, indexing approach, Principal Component Analysis and hydrochemical facie analysis. Twenty-five physico-chemical and four bacteriological parameters from nine water samples collected from boreholes, hand-dug wells and streams were analysed to determine the extent of environmental pollution and potential health risks using the

Atomic Absorption Spectrophotometry (AAS), colorimetric and standard techniques alluded by APHA. The data were analysed with the aid of Grapher, Surfer and XLSTAT statistical tools. Discrimination analysis revealed that the mean concentration of Ca^{2+}, K^{+}, Mg^{2+}, Cu^{2+}, Na^{+}, Fe^{2+}, Zn^{2+}, F-, SO_4^{2-}, CO_3^{2-}, pH, EC, COD, DO and BOD fall within permissible limits, while Pb^{2+}, Co^{2+}, Mn^{2+}, Cr^{2+}, Cd^{2+} exceeded permissible limits for both water sources (collected near dumpsites and control areas). The overall WQI evaluation for water samples collected near the dumpsites was 177.72, while samples collected at the control sites was 62.25. This suggests that water samples collected near the dumpsites exhibited higher levels of contamination compared to samples collected from the control areas. Results also revealed that only the water samples collected from boreholes located at the control areas were suitable for domestic purposes with (WQI < 48), in contrast to water samples from streams and hand-dug wells situated near the dumpsites with (WQI > 100). The overall HPI for water samples collected near the dumpsites was 188.53, while samples collected from the control sites was 176.96, indicating higher heavy metal pollution indices for water sources near the dumpsites. Bacteriological analysis showed that the coliform count for water samples collected from boreholes situated near the dumpsites were Too Numerous To Count (TNTC), while samples from the streams revealed the lowest coliform counts of (9 to 16 cfu/ml), attributed to continuous flow which disperses bacteria. There was no detection of E. coli, faecal strep and Pseudomonas spp in all the water samples, except (02 cfu/ml) Pseudomonas Spp detected in a hand-dug well at the Keffi control area. The decreasing order of dominance for major cations and anions near dumpsites include: $K^{+}>Ca^{2+}>Cu^{2+}>Ni^{2+}>Na^{+}>Mn^{2+}>Mg^{2+}>Zn^{2+}>Co^{2+}>Cr^{2+}Pb^{2+}>Cd^{2+}$, and in anions: $F^{-}>SO_4^{2-}>Cl^{-}$, while control sites showed: $K^{+}>Mn^{2+}>Ca^{2+}>Mg^{2+}>Cr^{2+}>Na^{+}>Cu^{2+}>Co^{2+}>Zn^{2+}>Pb^{2+}>Cd^{2+}>Ni^{2+}$ and in anions: $Cl^{-}>SO_4^{2-}>F^{-}$, attributed to agricultural practices, smelting, septic tanks, leaching and weathering. Three Principal components (PCs) explained 92.2 % and 95.3 % of the total variance of water samples near the dumpsites and control sites respectively. Piper trilinear and Durov diagram reflects mixed water types Ca-Mg-HCO_3 and Ca-Mg-SO_4 for both water samples, indicating temporary hardness. The findings emphasised the importance of regular water testing and the siting of boreholes and hand-dug wells at safe distances from potential contamination sources to safeguard public health.

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Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist

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