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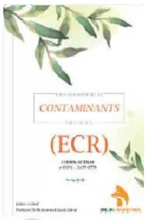

REVIEW ARTICLE

HUMAN-INDUCED HEAVY METAL CONTAMINATION IN GROUNDWATER AND SURFACE WATER: A CASE STUDY OF UGBOMORO AND UGBOLOKPOSO, SOUTHERN, NIGERIA

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ABSTRACT

Water pollution from unregulated human activities remains insufficiently documented in many developing countries, including Nigeria. This study investigates the effects of poor agricultural practices, abattoir waste discharge, indiscriminate waste dumping, and dredging on the water quality of Ugbomoro and Ugbolokposo communities in Delta State. Surface and groundwater samples were collected and analyzed using Atomic Absorption Spectroscopy (AAS) to determine their physicochemical characteristics and heavy metal concentrations. The results revealed acidic pH levels (5.1–6.55), electrical conductivity (EC) values ranging from 54 to 596 µS/cm, and salinity levels between 0.024 and 0.27 mg/L. Total Dissolved Solids (TDS) were low (0–2.1 mg/L), while Chemical Oxygen Demand (COD) ranged from 27 to 255 mg/L, indicating potential organic pollution from animal waste, sewage, or decaying materials. Most samples were clear and free from suspended particles, except sample HWD 12, which showed signs of localized contamination. The acidic pH suggests the water may be corrosive and unsuitable for drinking or irrigation. Elevated EC and salinity point to dissolved ion presence, possibly from chemical runoff or waste. Although most heavy metal concentrations complied with NSDWQ (2007) and WHO (2011) standards, levels of iron (Fe), manganese (Mn), chromium (Cr), cadmium (Cd), and lead (Pb) exceeded safe limits, indicating potential health hazards and contamination from anthropogenic sources like industrial waste and improper disposal practices. Variations in water quality across sites may be linked to underlying geology, groundwater recharge patterns, proximity to pollution sources, and human activities. The findings confirm that water resources in Ugbomoro and Ugbolokposo are significantly impacted by human-induced pollution, posing threats to public health, agriculture, and ecosystems. Continuous monitoring and improved waste management are essential to safeguard these vital water sources.

KEYWORDS

Ugbomoro and Ugbolokposo, Groundwater, Eigenvalues, Contamination

1. INTRODUCTION

The contamination of water bodies (surface water and groundwater) has increasingly become an issue of serious environmental concern. Portable water is an essential ingredient for good health and the socio-economic development of man, but it is lacking in many societies (Udom et al, 2002). Boreholes, wells, rivers and streams are among the important sources of water for man and apart from its function as a source of water for drinking, domestic and industrial uses; freshwater resources serve multiple functions most of them being critical to human settlement and survival. Polluted water is an important vehicle for the spread of diseases. Adequate supply of safe and sanitized freshwater is an inevitable factor for human and economic development. Reports by Food and Agricultural Organisation (FAO) revealed that in African countries, particularly Nigeria, water related diseases had been interfering with basic human development (FAO, 2007). The common sources of water that are available to local communities in Nigeria are fast being severed by a number of anthropogenic factors, of which pollution remain the most dominant problem.

Water abstraction for domestic use, agricultural production, mining, industrial production, power generation, and forestry practices can lead to deterioration in water quality and quantity that impact not only the aquatic ecosystem, but also the availability of safe water for human consumption (UNEP, 2006).

Water is the most significant nutrient that is indispensable to the survival of humanity because it is involved in all body functions and makes up about 75% of total body weight (Shryer, 2007; Mack and Nadel, 2011; Offei Ansah, 2012). About 60% percent of human body is water as life began in water and life is nurtured with water (Amoo et al., 2018). They stated that surface water is generally poor in quality, while ground water is more reliable for domestic and agricultural irrigation needs (Okeola et al., 2010). Berthold (2010) submitted that boreholes and wells change the natural flow field and create a path that opens up an additional possibility of heat and mass transfer between rock, aquifers and surrounding atmosphere. Many authors (Sunnudo-Wilhelmy and Gill, 1999; Egwari and Aboaba, 2002; Lu, 2004) have attributed the contamination of borehole water to indiscriminate waste disposal, poor agricultural practices, poor

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well construction, proximity of septic tanks to boreholes, sitting of pit latrines near boreholes.

The widespread reports on pollutants in groundwater have increased in recent years and have resulted to augmented public concern about the quality of groundwater. Groundwater bodies are prone to contamination from both anthropogenic and natural activities (Okuo et al., 2007). The seepage of waste buried underground such as pit toilets or leachate from fertilizer applications can produce hazardous effects on ground water quality especially within Ugbomoro and Ugbolokposo communities, as they are one of the areas in Delta State that has been long known as agricultural area. Strikingly, the persistent nature of some chemicals used for farming can possibly leach and contaminate the ground water.

Also their proximity to urban areas like Warri and Effurun have facilitated their social economic growth, with the communities witnessing gradual introduction to modern amenities such as market, school and health facilities. However, this development has also contributed to environmental degradation from oil exploration (which has introduced heavy metals like lead, cadmium, mercury into water bodies) to limited or poor waste management issues, hence, the pursuit of understanding the impact of human activities on heavy metals contaminations on surface and ground water in these communities of interest.

They investigated soil and water contamination near auto-mechanic workshops in Warri, South-South Nigeria (Aladin et al., 2024). The soil was slightly acidic, and while most heavy metals met regulatory standards, elevated levels of Fe, Cu, Zn, Cd, and Cr indicated significant contamination. PCA and correlation analyses suggested a common source for many metals. Water samples showed elevated Cu, Cd, and Co, likely from a different source, and exceeded standards for TDS, EC, and salinity. The research highlights the need for proper monitoring and management of pollution from auto-mechanic activities.

They assessed the physicochemical and bacteriological quality of water from six boreholes at the Federal University Dutse campus in North-West Nigeria (Amoo et al., 2018). Results showed pH levels between 6.53 and 7.80, EC from 422 to 690 µS/cm, and temperatures from 31.0 to 33.0°C. Some parameters, including turbidity, total hardness, and nitrite, varied within acceptable ranges, but E. coli was detected in four of the boreholes. While two boreholes were free from coliforms and considered safe, some water quality parameters exceeded WHO and NSDWQ standards. The study recommended regular water testing and routine inspections to ensure water safety on campus.

There is growing concern about the increasing presence of heavy metals in water bodies, particularly in industrialized regions. Delta State, renowned for its extensive industrial activities and oil-rich reserves, faces significant environmental challenges due to these operations. Industrial discharges and oil exploration have contributed to the contamination of local water resources with heavy metals. The communities of Ugbomoro and Ugbolokposo are particularly vulnerable, given their close proximity to oil fields, industrial complexes, and expanding urban centres. Residents in these areas may be exposed to heavy metals through various pathways, including the consumption of crops grown on contaminated land, inhalation of polluted dust, or direct contact with tainted soil and water. Despite the recognized risks, there is a lack of focused research on the specific impacts of heavy metal contamination on water quality and human health within these two communities.

This research aims to fill the existing knowledge gap by quantifying heavy metal concentrations in local water bodies, assessing the potential health risks to residents who depend on these sources, and examining the broader environmental impacts. The goal is to deepen understanding of the environmental and public health challenges in Ugbomoro and Ugbolokposo and to provide a basis for developing effective strategies to manage and reduce the effects of heavy metal pollution on water resources.

2. DESCRIPTION OF STUDY AREA

Ugbomoro is located in the Uvwie Local Government Area of Delta State, Nigeria. It lies within the Niger Delta region, near the city of Warri, a prominent urban and economic hub in southern Nigeria. The community is accessible through various major roads connecting it to Warri and other neighboring areas like Effurun, Ekpan, and Ugborikoko. The community is predominantly a semi-urban area with a mix of residential, commercial, and agricultural activities. The community is home to people of diverse ethnic groups, with the Urhobo people being the predominant ethnic group. It is known for its rich cultural heritage, with traditional practices and festivals being integral to the lifestyle of its residents. The community has seen significant growth over the years, with infrastructural developments such as schools, markets, and churches. Despite its proximity to urban centres like Warri, Ugbomoro still retains some rural characteristics, including reliance on small-scale farming, fishing, and trading. However, challenges such as inadequate infrastructure, environmental degradation, and unemployment persist. Ugbomoro is also affected by the broader issues of the Niger Delta, including oil exploration and its associated environmental impacts. The region's development and sustainability efforts often focus on balancing economic growth with preserving its natural environment and cultural heritage.

Ugbolokposo is also located in Uvwie Local Government Area of Delta State, Nigeria. It is situated in the Niger Delta region, known for its oil-rich land, waterways, and cultural diversity. The community is a semi-urban area that has seen significant development due to its proximity to Warri, a major commercial hub in Delta State. Ugbolokposo is strategically positioned near the Effurun-Warri axis, making it easily accessible via major roads connecting it to other parts of Delta State. Its location places it within the oil-producing belt of Nigeria, contributing to the state's economic activities. Ugbolokposo features a blend of traditional and modern lifestyles. The area is known for its vibrant population, which engages in various occupations, including trade, craftsmanship, and services linked to the oil and gas industry. Despite its development, the community maintains aspects of its traditional heritage, reflected in local festivals, customs, and communal living.

Ugbomoro and Ugbolokposo, located in the Niger Delta, share a tropical climate with distinct wet and dry seasons. Their flat, low-lying terrain and proximity to water bodies make them vulnerable to flooding. Agriculture remains the main source of livelihood, supported by small-scale trade, fishing, and oil-related activities. While the communities benefit from economic opportunities, they continue to struggle with inadequate infrastructure, environmental degradation, and high unemployment. However, urbanization is gradually reshaping both areas with growing residential and commercial development.

Plate 1: View showing anthropogenic activities in the study area

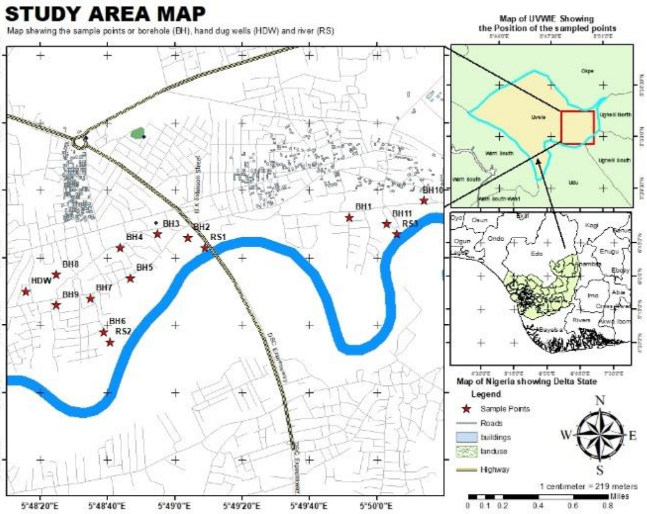

Figure 1: Based map of the study area

3. GEOLOGY OF THE STUDY AREA

Ugbomoro and Ugbolokposo, located within the hydrocarbon-rich Niger Delta Basin, exhibit similar geological and hydrogeological characteristics. Both communities are underlain by sedimentary deposits of sands, clays, and silts formed through deltaic and fluvial processes during the Cenozoic era. These formations include alternating layers of sandstone and shale, which serve as reservoir and seal rocks respectively, supporting oil accumulation. Groundwater in both areas is stored in sandy aquifers that are recharged by rainfall and surface water. These aquifers provide essential freshwater for domestic and agricultural use. However, their shallow nature makes them vulnerable to contamination, particularly from oil exploration and related environmental risks. Sustainable management and regular monitoring are necessary to protect groundwater quality and ensure long-term resource availability.

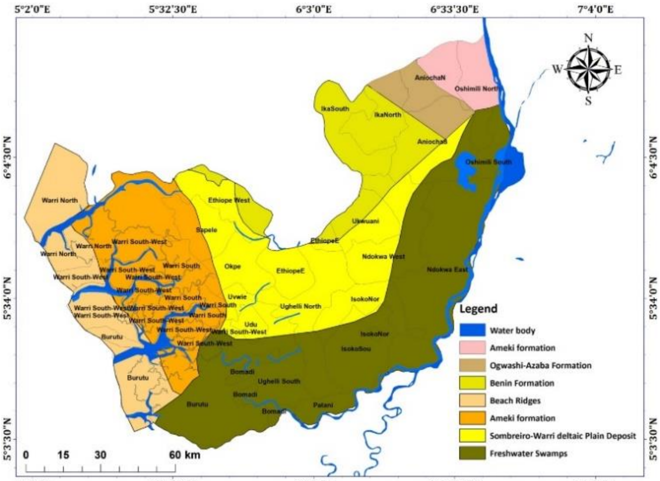

Figure 2: Geology map of the study area (Modified Source: (Komolafe and Aladin, 2023).

4. MATERIALS AND METHODS

4.1 Materials

A total of fifteen (15) water samples were collected from Ugbolokposo and Ugbomoro communities in the Niger Delta region. The samples consisted of groundwater (collected from drilled boreholes) and surface water (obtained from hand-dug wells). Each sample was collected in sterilized plastic bottles, sealed, labeled using masking tape, stored in a cooler containing ice, and immediately transported to Martlet Environmental Research Laboratory Limited for physicochemical and heavy metal analyses, following standard sampling procedures (APHA, 2017).

Materials and equipment used included: Sterilized plastic sample bottles, Ice-filled cooler, Masking tape for labelling, GIS equipment for geolocation, Bacon bags for secure sample containment during transport.

The samples were analyzed for the following parameters: Physicochemical Properties (pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, color (Pt-Co scale), turbidity, total suspended solids (TSS), and chemical oxygen demand (COD), Major Ions and Nutrients: Bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), phosphorus (P), ammonium (NH_4^+-N), nitrite (NO_2^-), nitrate (NO_3^-), calcium (Ca^{2+}), potassium (K^+), sodium (Na^+), magnesium (Mg^{2+}), chloride (Cl^-), and sulfate (SO_4^{2-})) and Heavy Metals (Manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), and vanadium (V)).

4.2 Methods

4.2.1 Sample Digestion and Preparation for AAS Analysis

Water samples were analyzed for metal concentrations using Atomic Absorption Spectrophotometry (AAS), a well-established technique for detecting trace metals in environmental samples (EPA, 2007). Apparatus and materials used: 250 mL digestion tubes, PTFE beakers, Hot plate, Funnels, 25 mL and 50 mL volumetric flasks, Filter paper, Ultrapure water (resistivity ≥ 18.2 MΩ·cm).

Procedure: Measure 25 mL of the water sample into a PTFE digestion beaker; Add 2.0 mL of concentrated nitric acid (HNO_3) and 6.0 mL of concentrated hydrochloric acid (HCl), both of trace metal grade; Heat the mixture gently on a hot plate in a fume hood until near boiling and the solution becomes clear; After cooling, transfer the digested solution to a 50 mL volumetric flask; Rinse the beaker with ultrapure water and add the rinsate to the flask; Make up the final volume to 100 mL with ultrapure water, ensuring a final acid concentration of 10%; Filter or centrifuge the sample if necessary to remove particulates that may obstruct the AAS nebulizer. All glassware and apparatus were acid-washed with dilute HNO_3 prior to use to avoid contamination (APHA, 2017).

4.2.2 Atomic Absorption Spectroscopy (AAS) Analysis Procedure

The prepared samples were introduced into the AAS system for metal quantification. The procedure followed these steps:

The sample is aspirated into the AAS flame, where it is atomized; Atomization: High temperatures convert the metal ions into free atoms; The atomic vapour absorbs light at a characteristic wavelength emitted by a hollow cathode lamp specific to each element; The spectrometer records the absorbance at each element's wavelength; Concentrations were calculated based on calibration curves constructed from standard solutions of known concentrations (EPA, 2007).

4.3 Statistical Analysis

Statistical analysis was carried out using Microsoft Excel and IBM SPSS Statistics (version 26). Principal Component Analysis (PCA) was used to reduce data dimensionality and to identify the major factors influencing water quality parameters (Jolliffe and Cadima, 2016). The PCA results included: Total Eigenvalues (Representing the variance explained by each principal component); Percentage of Variance (The individual variance each component accounts for); Cumulative Percentage (The total variance accounted for by a combination of components); Rotation Sums of Squared Loadings (Enhanced interpretability following Varimax rotation).

5. INTERPRETATION OF RESULTS AND DISCUSSION

5.1 Physiochemical Parameters of Water Samples Collected around Ugolokposo-Ugbomoro Community

The physicochemical parameters of the water samples collected from Ugbomoro and Ugbolokposo communities indicate varied water quality across the locations. The pH values ranged from 5.1 to 6.5, with a mean of 5.73, suggesting mildly acidic conditions. Samples BH 9 UGB (pH 5.1) and BH 4 UGB (pH 5.3) were notably more acidic, while BH 6 UGB (pH 6.5) and HDW 12 (pH 6.4) approached neutrality. The observed acidity may be linked to local soil geochemistry, leachate percolation, or industrial discharge, consistent with environmental conditions reported in the Niger Delta (WHO, 2011; NSDWQ, 2007).

Electrical conductivity (EC) ranged from 54 to 596 µS/cm, with a mean of 222.6 µS/cm, and Total Dissolved Solids (TDS) ranged from 0 to 2.1 mg/L (mean = 80.5 mg/L). Salinity values spanned from 0.024 to 0.27 g/L, with an average of 0.1 g/L. The highest EC and TDS levels were recorded at BH 6 UGB, indicating increased mineralization or ionic contamination, likely from anthropogenic sources. Elevated EC was also observed at HDW 12, BH 14 UGO, BH 9 UGB, RS 2 UGB, and RS 8 UGB, potentially due to subsurface flow of mineral-rich or contaminated water.

Chemical Oxygen Demand (COD) ranged from 7 mg/L at RS 3 UGB to 30.1 mg/L at BH 6 UGB, with a mean value of 13.33 mg/L. The high COD at BH 6 UGB suggests significant organic loading, possibly from domestic wastewater or agricultural runoff such as livestock effluent.

Colour, turbidity, and Total Suspended Solids (TSS) were mostly undetectable, except in HDW 12, which had a colour value of 1.2 Pt.Co., turbidity of 1 NTU, and a TSS value of 2.1 mg/L. Slightly elevated TSS was also found in RS 8 UGB (1.8 mg/L) and BH 9 UGB (2.1 mg/L), possibly resulting from surface runoff or sediment resuspension. The low turbidity and TSS levels across most samples indicate generally good visual clarity and limited particulate contamination.

Although most parameters complied with the NSDWQ (2007) and WHO (2011) guidelines, pH values in all samples except BH 6 UGB and HDW 12 fell below the recommended range of 6.5–8.5. This suggests that the water is slightly acidic and may require treatment before domestic use. The elevated EC, TDS, and COD at BH 6 UGB underscore localized contamination, warranting further investigation and possibly remediation.

Table 1: Physiochemical parameter of water samples collected at study area

Parameter	pH	EC µS/cm	Salinity g/l	Col. Pt.Co	Turb. NTU	TSS mg/l	TDS	COD
BH 1 UGB	5.5	134	0.06	ND	ND	ND	67	9.1
RS 2 UGB	5.4	261	0.118	ND	ND	ND	130	15.2
RS 3 UGB	6.2	54	0.024	ND	ND	ND	27	7
BH 4 UGB	5.3	221	0.099	ND	ND	ND	110	10.1
BH 5 UGB	5.7	229	0.104	ND	ND	ND	114	11.2
BH 6 UGB	6.5	596	0.27	ND	ND	ND	255	30.1
BH 7 UGB	5.3	227	0.103	ND	ND	ND	111	10
RS 8 UGB	5.8	245	0.111	ND	ND	1.8	123	13.2
BH 9 UGB	5.1	273	0.123	ND	ND	2.1	135	18.1
BH 10 UG	5.4	90	0.041	ND	ND	ND	45	8.7
BH 11 UGB	5.7	164	0.074	ND	ND	ND	62	9.3
HDW 12	6.4	360	0.163	1.3	1	1.7	151	22.3
RS 13 UGO	5.9	70	0.032	ND	ND	ND	35	7.4
BH 14 UGO	5.4	353	0.16	ND	ND	ND	176	21
RS 15 UGO	6.4	62	0.028	ND	ND	ND	31	7.2
AVERAGE	5.73	222.6	0.100	0.087	0.067	1.87	104.80	13.33
MIN	5.1	54	0.024	ND	ND	ND	27	7
MAX	6.5	596	0.27	1.3	1	2.1	255	30.1

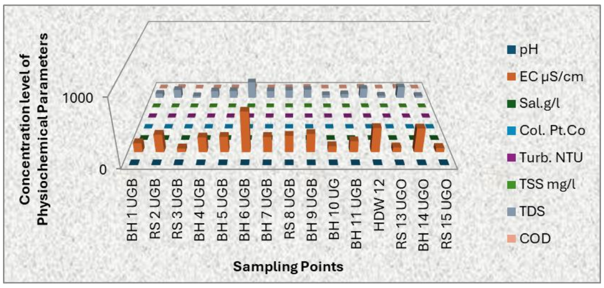

Figure 3: Concentration level of physiochemical parameters and sampling points

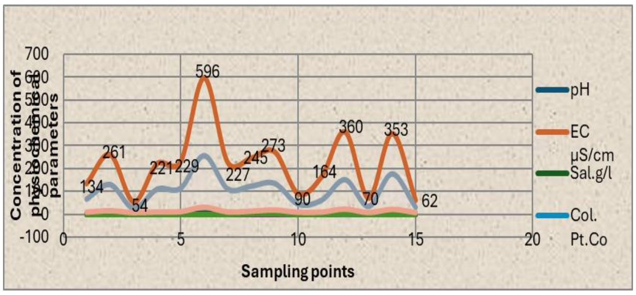

Figure 4: Scatter diagram of physiochemical parameters concentration level

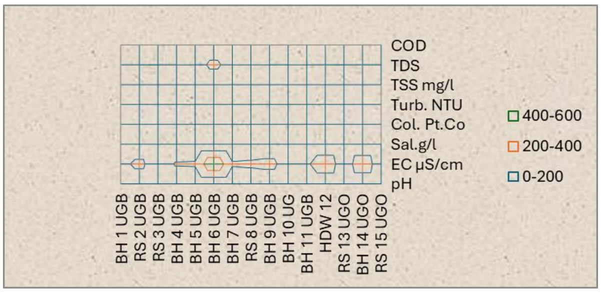

Figure 5: Surface contour showing the concentration level of sampling points of the study area

Table 2: Comparison of Physiochemical parameters with (NSDWQ, 2007; WHO, 2011)

Parameter	pH	EC µS/cm	Salinity g/l	Col. Pt.Co	Turb. NTU	TSS mg/l	TDS	COD
BH 1 UGB	5.5	134	0.06	ND	ND	ND	67	9.1
RS 2 UGB	5.4	261	0.118	ND	ND	ND	130	15.2
RS 3 UGB	6.2	54	0.024	ND	ND	ND	27	7
BH 4 UGB	5.3	221	0.099	ND	ND	ND	110	10.1
BH 5 UGB	5.7	229	0.104	ND	ND	ND	114	11.2

Table 2 (Cont): Comparison of Physiochemical parameters with (NSDWQ, 2007; WHO, 2011)

Parameter	pH	EC μS/cm	Salinity g/l	Col. Pt.Co	Turb. NTU	TSS mg/l	TDS	COD
BH 6 UGB	6.5	596	0.27	ND	ND	ND	255	30.1
BH 7 UGB	5.3	227	0.103	ND	ND	ND	111	10
RS 8 UGB	5.8	245	0.111	ND	ND	1.8	123	13.2
BH 9 UGB	5.1	273	0.123	ND	ND	2.1	135	18.1
BH 10 UG	5.4	90	0.041	ND	ND	ND	45	8.7
BH 11 UGB	5.7	164	0.074	ND	ND	ND	62	9.3
HDW 12	6.4	360	0.163	1.3	1	1.7	151	22.3
RS 13 UGO	5.9	70	0.032	ND	ND	ND	35	7.4
BH 14 UGO	5.4	353	0.16	ND	ND	ND	176	21
RS 15 UGO	6.4	62	0.028	ND	ND	ND	31	7.2
NSDWQ 2007	6.5-8.5	1000		15	5		500	250
WHO 2011	6.5-8.5	900					1000	250

5.2 Major Cations and Nutrient Parameters

The concentrations of major cations and nutrient elements in the water samples varied across the study locations. Sodium (Na$^+$) concentrations ranged from 2.0 to 15.5 mg/L, with an average of 6.073 mg/L. The highest sodium levels were recorded in BH 6 UGB (15.5 mg/L) and HDW 12 (11.1 mg/L). All values fall significantly below the permissible limit of 200 mg/L for sodium in drinking water (NSDWQ, 2007; WHO, 2011). Potassium (K$^+$) levels ranged from 1.2 mg/L (RS 3 UGB) to 11 mg/L (BH 6 UGB), with a mean of 4.487 mg/L. Although there is no maximum standard limit specified for potassium, the levels are considered acceptable for potable water (WHO, 2011).

Calcium (Ca^{2+}) concentrations spanned from 2.0 to 22.3 mg/L, averaging 6.073 mg/L. BH 6 UGB (22.3 mg/L) and HDW 12 (20 mg/L) exhibited the highest concentrations. These values are within the permissible limits of 75 mg/L (NSDWQ) and 100 mg/L (WHO). Calcium contributes to water hardness and is beneficial in moderate concentrations. Magnesium (Mg^{2+}) levels varied between 3.1 and 18.8 mg/L, with a mean of 7.95 mg/L. The highest concentrations were again observed in BH 6 UGB (18.8 mg/L) and HDW 12 (15.3 mg/L), all below the threshold values of 50 mg/L (NSDWQ) and 100 mg/L (WHO), suggesting no significant hardness-related concerns.

Phosphorus (P) concentrations were low, ranging from 0.01 to 0.124 mg/L, with an average of 0.01 mg/L. While there is no established limit for phosphorus in drinking water, elevated levels can indicate anthropogenic pollution or runoff. The highest values were noted at BH 6 UGB and HDW 12. Ammonium (NH_4^+-N) ranged from 1.01 to 5.17 mg/L, with a mean of 3.07 mg/L. Elevated ammonium levels could be linked to agricultural runoff, septic leachate, or organic matter degradation. As shown in Table 3 and Figures 4–6, BH 6 UGB consistently presented the highest concentrations of sodium, potassium, calcium, magnesium, ammonium nitrogen, and phosphorus. This pattern suggests an area with higher mineral or nutrient enrichment, potentially due to local lithology or anthropogenic inputs. Similarly, HDW 12 exhibited elevated levels of these parameters, indicating comparatively higher mineral content. Conversely, RS 15 UGO and RS 3 UGB displayed lower concentrations of the assessed parameters, suggesting less impact from nutrient enrichment or contamination sources.

Table 3: Physiochemical parameters of Major cation

MAJOR CATION						
Parameter	**NH4N**	**P**	**Na**	**K**	**Ca**	**Mg**
BH 1 UGB	2.63	0.022	3.3	2.7	6	4.5
RS 2 UGB	3.78	0.076	7.3	5.1	17.2	9.4
RS 3 UGB	1.01	0.01	2	1.2	4	3.1
BH 4 UGB	2.88	0.047	4.5	3.5	7.4	6.1
BH 5 UGB	3.34	0.058	6.6	4.1	11.5	8.8
BH 6 UGB	5.17	0.124	15.5	11	22.3	18.8
BH 7 UGB	3.15	0.055	5.2	3.8	8.9	6
RS 8 UGB	3.61	0.063	7.1	4.4	15.1	9
BH 9 UGB	4.11	0.087	8.1	6	18.8	10
BH 10 UG	2.51	0.019	3.2	2.6	5.5	4.1
BH 11 UGB	2.79	0.038	3.8	3.3	6.1	5.2
HDW 12	4.44	0.112	11.1	8.7	20	15.3
RS 13 UGO	1.4	0.015	2.8	2.1	5.3	4
BH 14 UGO	4.15	0.11	8.5	7.1	20.1	11.7
RS 15 UGO	1.12	0.011	2.1	1.7	4.8	3.3
AVERAGE	3.07	0.056	6.073	4.487	11.533	7.953
MIN	1.01	0.01	2	1.2	4	3.1
MAX	5.17	0.124	15.5	11	22.3	18.8

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Table 4: Physiochemical parameters of major cation

Parameter	NH4N (mg/L)	P (mg/L)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)
BH 1 UGB	2.63	0.022	3.3	2.7	6	4.5
RS 2 UGB	3.78	0.076	7.3	5.1	17.2	9.4
RS 3 UGB	1.01	0.01	2	1.2	4	3.1
BH 4 UGB	2.88	0.047	4.5	3.5	7.4	6.1
BH 5 UGB	3.34	0.058	6.6	4.1	11.5	8.8
BH 6 UGB	5.17	0.124	15.5	11	22.3	18.8
BH 7 UGB	3.15	0.055	5.2	3.8	8.9	6
RS 8 UGB	3.61	0.063	7.1	4.4	15.1	9
BH 9 UGB	4.11	0.087	8.1	6	18.8	10
BH 10 UG	2.51	0.019	3.2	2.6	5.5	4.1
BH 11 UGB	2.79	0.038	3.8	3.3	6.1	5.2
HDW 12	4.44	0.112	11.1	8.7	20	15.3
RS 13 UGO	1.4	0.015	2.8	2.1	5.3	4
BH 14 UGO	4.15	0.11	8.5	7.1	20.1	11.7
RS 15 UGO	1.12	0.011	2.1	1.7	4.8	3.3
NSDWQ 2007	35		200		75	50
WHO 2011	35		200		200	100

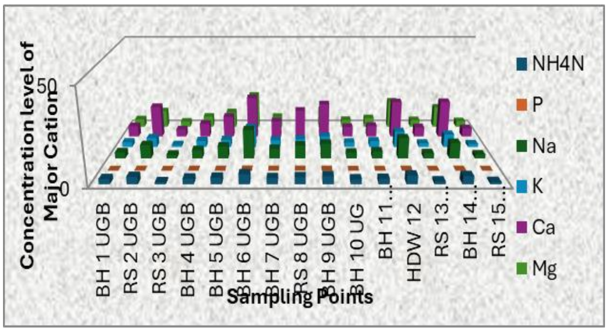

Figure 6: Concentration level of major cation and sampling points

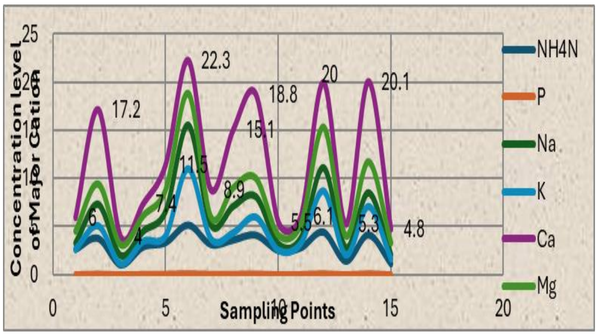

Figure 7: Scatter diagram showing concentration level of major cation and sampling points

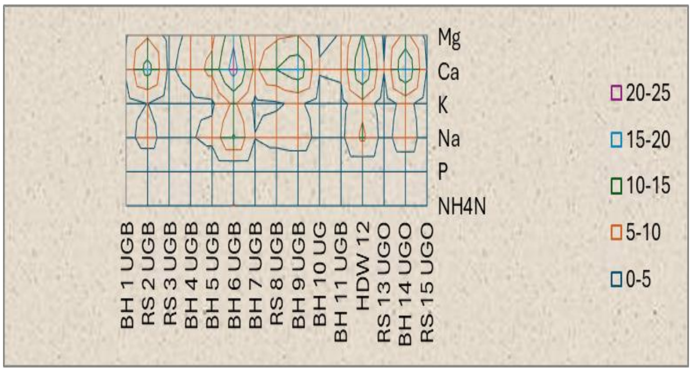

Figure 8: Concentration level of major cation and sampling points

5.3 Major Anion Of Water Samples Collected From The Study Area

Chloride (Cl) concentrations range from 66.3 to 556.1 mg/L, with an average of 216.09 mg/L. Nitrite (NO_2) levels vary from 0.251 to 1.674 mg/L, averaging 0.947 mg/L, while Nitrate (NO_3) ranges from 2.28 to 15.22 mg/L, with a mean value of 8.611 mg/L. Sulphate (SO_4) concentrations fall between 1.44 and 12.87 mg/L, with an average of 6.701 mg/L. Carbonate (HCO_3) levels vary from 18.7 to 101.2 mg/L, with a mean of 44.713 mg/L, as shown in Table 6 and Figure 7. Figures 8 and 9 illustrate the concentration levels of major anions in the study area. Chloride is a common ion in water, and elevated concentrations can affect the taste. The NSDWQ and WHO both set a limit of 250 mg/L for chloride. Some samples, such as BH 6 UGB (556.1 mg/L) and HDW 12 (336 mg/L), exceed this limit, indicating potential salinity or contamination issues. Additionally, BH 9 UGB (277.1 mg/L) and BH 14 UGO (301.1 mg/L) approach or exceed the recommended limit, while the other samples remain within acceptable ranges.

Nitrite, which indicates organic pollution, has a standard limit of 3 mg/L. All samples fall well below this threshold, with BH 6 UGB recording the highest value at 1.674 mg/L. Nitrate, which can be harmful at high concentrations, especially for infants, has a limit of 50 mg/L. All samples remain within safe limits, with BH 6 UGB showing the highest nitrate concentration at 15.22 mg/L, suggesting no significant nitrate pollution.

Sulphates, which can impact taste and cause gastrointestinal issues in high concentrations, have a limit of 100 mg/L (NSDWQ) and 250 mg/L (WHO). All samples fall significantly below these limits, with BH 6 UGB showing the highest sulphate concentration at 12.87 mg/L.

Bicarbonate (HCO_3) contributes to water alkalinity and can neutralize acids. Concentrations range from 18.7 mg/L (RS 3 UGB) to 101.2 mg/L (BH 6 UGB).

BH 6 UGB and HDW 12 have notably higher bicarbonate levels, which could affect the pH balance and buffering capacity of the water.

Among the samples, BH 6 UGB exhibits elevated levels of chloride, nitrite, nitrate, sulphate, and bicarbonate compared to the others, though nitrite, nitrate, and sulphate concentrations remain within safe limits. HDW 12 and BH 14 UGO also show higher chloride and bicarbonate levels, indicating richer mineral content. Conversely, RS 3 UGB, RS 13 UGO, and RS 15 UGO have lower levels of most parameters, indicating cleaner water sources with fewer dissolved ions. While most samples comply with NSDWQ and WHO standards, the chloride levels in BH 6 UGB, HDW 12, and BH 14 UGO exceed the recommended limit, indicating potential contamination or natural mineralization in these water sources.

Table 5: Physiochemical parameters of Major Anion

Parameter	Cl	NO_2	NO_3	SO_4	HCO_3
BH 1 UGB	160.4	0.718	6.53	4.65	26.6
RS 2 UGB	245.4	1.211	11.01	8.01	56.3
RS 3 UGB	66.3	0.251	2.28	1.44	18.7
BH 4 UGB	188.7	0.848	7.71	6.54	33.1
BH 5 UGB	218.7	1.049	9.54	7.15	44.2
BH 6 UGB	556.1	1.674	15.22	12.87	101.2
BH 7 UGB	201.1	0.884	8.04	6.69	40.4
RS 8 UGB	223.1	1.083	9.84	7.77	47
BH 9 UGB	277.1	1.29	11.73	8.74	61
BH 10 UG	141.1	0.696	6.33	4.88	22.1
BH 11 UGB	161	0.814	7.4	6.32	28.5
HDW 12	336	1.442	13.11	10.7	85.2
RS 13 UGO	95.2	0.459	4.17	2.78	20.1
BH 14 UGO	301.1	1.434	13.04	10.1	66.3
RS 15 UGO	70.1	0.357	3.21	1.87	20
AVERAGE	216.09	0.947	8.611	6.701	44.713
MIN	66.3	0.251	2.28	1.44	18.7
MAX	556.1	1.674	15.22	12.87	101.2

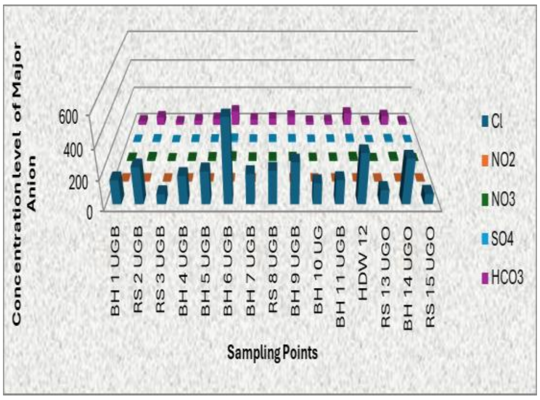

Figure 9: Concentration level of major anion

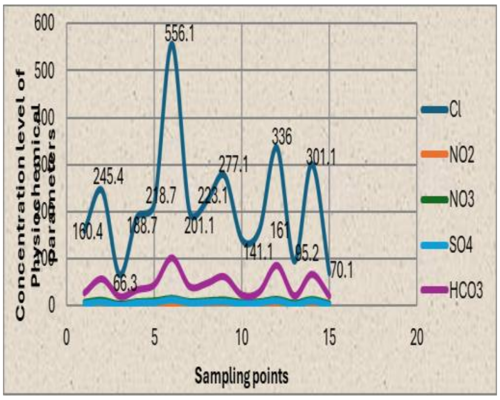

Figure 10: Scatter diagram showing concentration level of major anion

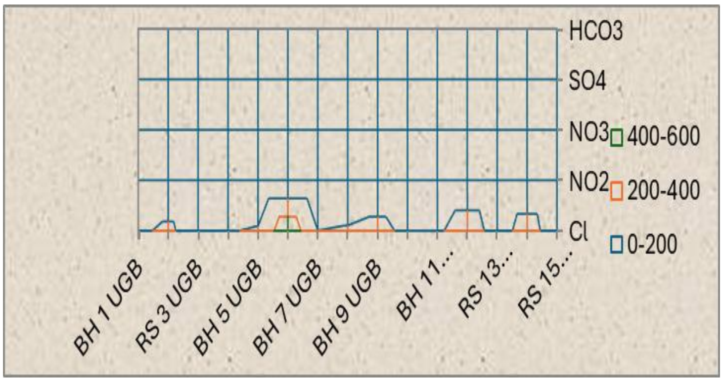

Figure 11: Surface contour plot showing the concentration level of major anion in the sampling points

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Table 6: Comparison of major anion with (NSDWQ, 2007 and WHO, 2011)

Parameter	Cl	NO_2	NO_3	SO_4	HCO_3
BH 1 UGB	160.4	0.718	6.53	4.65	26.6
RS 2 UGB	245.4	1.211	11.01	8.01	56.3
RS 3 UGB	66.3	0.251	2.28	1.44	18.7
BH 4 UGB	188.7	0.848	7.71	6.54	33.1
BH 5 UGB	218.7	1.049	9.54	7.15	44.2
BH 6 UGB	556.1	1.674	15.22	12.87	101.2
BH 7 UGB	201.1	0.884	8.04	6.69	40.4
RS 8 UGB	223.1	1.083	9.84	7.77	47
BH 9 UGB	277.1	1.29	11.73	8.74	61
BH 10 UG	141.1	0.696	6.33	4.88	22.1
BH 11 UGB	161	0.814	7.4	6.32	28.5
HDW 12	336	1.442	13.11	10.7	85.2
RS 13 UGO	95.2	0.459	4.17	2.78	20.1
BH 14 UGO	301.1	1.434	13.04	10.1	66.3
RS 15 UGO	70.1	0.357	3.21	1.87	20
NSDDWQ 2007	250	3	50	100	250
WHO 2011	250	3	50	250	250

5.4 Heavy Metal Concentration Level Of The Study Area

Iron concentrations range from 0.332 mg/l (BH 6 UGB) to 0.72 mg/l (RS 3 UGB) with mean concentration value of 0.539 mg/L. Elevated iron levels could be due to natural sources, such as weathering of iron-rich rocks, or anthropogenic sources like industrial discharges. Higher iron levels can cause staining and may affect water taste. Manganese concentration values range from 0.136 mg/l (BH 6 UGB) to 0.295 mg/l (RS 3 UGB) with mean concentration value of 0.221 mg/L. Like Iron, Manganese occurs naturally in the environment but can also come from industrial and agricultural activities. Elevated manganese concentrations can affect water clarity and taste. Zinc concentrations vary between 0.176 mg/l (BH 6 UGB) and 0.382 mg/l (RS 3 UGB) with mean concentration value of 0.286 mg/L. Zinc levels in this range are generally low and are not likely to cause health problems. However, elevated zinc might come from metal pipes, industrial waste, or natural deposits. Copper levels range from 0.071 mg/l (BH 6 UGB) to 0.154 mg/l (RS 3 UGB) with mean concentration value of 0.115 mg/L. Copper can enter water through corrosion of pipes, agricultural runoff, or industrial waste. Low copper levels like these are not typically harmful but are worth monitoring if they increase. Chromium concentrations range from 0.047 mg/l (BH 6 UGB) to 0.103 mg/l (RS 3 UGB) with mean concentration value of 0.077 mg/L. Elevated chromium may originate from industrial sources like metal plating or from naturally occurring minerals. Even low levels of chromium can be toxic, particularly in its hexavalent form (Cr (VI)). Cadmium values range from 0.004 mg/l (BH 6 UGB) to 0.01 mg/l (RS 3 UGB) with mean concentration value of 0.007 mg/L. Cadmium is a toxic heavy metal that can originate from industrial discharges, batteries, or contaminated soils. Even at low concentrations, cadmium can pose health risks. Nickel levels are relatively constant, mostly 0.001 mg/l, except for HDW 12 where it is 0.005 mg/l. Low concentrations of nickel are not typically harmful, but prolonged exposure to higher levels can cause skin reactions or other health issues. Lead concentrations are low, ranging from 0.016 mg/l (BH 6 UGB) to 0.034 mg/l (RS 15 UGO) with mean concentration value of 0.026 mg/L. Even low levels of lead can be harmful, especially to children. Its presence could indicate contamination from industrial activities, lead pipes, or lead-based materials. Vanadium levels are very low and consistent at 0.001 mg/l, except for HDW 12 where it is 0.002 mg/l. Vanadium is naturally occurring, and its concentrations in this range are not typically of concern for health as shown in Table 7 and Figure 10. Figure 11 and 12 shows high concentration level of Fe, Zn, Cd and Mn in the study area. This indicates that the study area is highly contaminated with these heavy metals. RS 3 UGB and RS 15 UGO generally have the highest concentrations of most heavy metals (Fe, Mn, Zn, Cu, Cr, Cd and Pb), which might indicate localized contamination from anthropogenic activities or geochemical conditions that enhance metal solubility. BH 6 UGB shows consistently lower concentrations of heavy metals, suggesting a relatively lower influence of contamination in this location. Elevated levels of metals like cadmium, chromium, and lead, even at low concentrations, are a concern for human health and require monitoring due to their potential toxicity. These results suggest varying levels of heavy metal contamination across the study sites, which could be attributed to natural geochemical processes or human activities such as industrial emissions, agricultural runoff, and improper waste disposal. All the heavy metals conform to standard expects Fe, Mn, Cr, Cd and Pb which is above the acceptable standard values as shown in Table 8 (NSDWQ, 2007; WHO, 2011). Elevated levels of Fe, Pb, Cd and Cr indicate potential health risks and may stem from anthropogenic sources like industrial activities and waste disposal.

Table 7: Heavy metal parameters of the study area

Parameters	Fe	Mn	Zn	Cu	Cr	Cd	Ni	Pb
BH 1 UGB	0.666	0.273	0.353	0.142	0.095	0.009	ND	0.031
RS 2 UGB	0.473	0.194	0.251	0.101	0.068	0.006	ND	0.022
RS 3 UGB	0.72	0.295	0.382	0.154	0.103	0.01	ND	0.034
BH 4 UGB	0.552	0.226	0.293	0.118	0.079	0.007	ND	0.026
BH 5 UGB	0.491	0.201	0.26	0.105	0.07	0.006	ND	0.023
BH 6 UGB	0.332	0.136	0.176	0.071	0.047	0.004	ND	0.016
BH 7 UGB	0.513	0.21	0.272	0.109	0.073	0.007	ND	0.024
RS 8 UGB	0.488	0.2	0.259	0.104	0.07	0.006	ND	0.023
BH 9 UGB	0.41	0.168	0.217	0.087	0.059	0.005	ND	0.019
BH 10 UG	0.671	0.275	0.356	0.143	0.096	0.006	ND	0.032

Table 7 (Cont): Heavy metal parameters of the study area

Parameters	Fe	Mn	Zn	Cu	Cr	Cd	Ni	Pb
BH 11 UGB	0.601	0.245	0.319	0.128	0.086	0.009	ND	0.028
HDW 12	0.381	0.156	0.202	0.081	0.054	0.008	0.005	0.018
RS 13 UGO	0.693	0.284	0.367	0.148	0.101	0.005	ND	0.033
BH 14 UGO	0.388	0.16	0.206	0.083	0.055	0.009	ND	0.021
RS 15 UGO	0.711	0.292	0.377	0.152	0.102	0.009	ND	0.034
AVERAGE	0.539	0.221	0.286	0.115	0.077	0.007	0.005	0.026
MIN	0.332	0.136	0.176	0.071	0.047	0.004	0.005	0.016
MAX	0.72	0.295	0.382	0.154	0.103	0.01	0.005	0.034

Table 8: Comparison of Heavy metal concentration with NSDWQ 2007 and WHO 2011

Parameters	Fe	Mn	Zn	Cu	Cr	Cd	Ni	Pb
BH 1 UGB	0.666	0.273	0.353	0.142	0.095	0.009	ND	0.031
RS 2 UGB	0.473	0.194	0.251	0.101	0.068	0.006	ND	0.022
RS 3 UGB	0.72	0.295	0.382	0.154	0.103	0.01	ND	0.034
BH 4 UGB	0.552	0.226	0.293	0.118	0.079	0.007	ND	0.026
BH 5 UGB	0.491	0.201	0.26	0.105	0.07	0.006	ND	0.023
BH 6 UGB	0.332	0.136	0.176	0.071	0.047	0.004	ND	0.016
BH 7 UGB	0.513	0.21	0.272	0.109	0.073	0.007	ND	0.024
RS 8 UGB	0.488	0.2	0.259	0.104	0.07	0.006	ND	0.023
BH 9 UGB	0.41	0.168	0.217	0.087	0.059	0.005	ND	0.019
BH 10 UG	0.671	0.275	0.356	0.143	0.096	0.006	ND	0.032
BH 11 UGB	0.601	0.245	0.319	0.128	0.086	0.009	ND	0.028
HDW 12	0.381	0.156	0.202	0.081	0.054	0.008	0.005	0.018
RS 13 UGO	0.693	0.284	0.367	0.148	0.101	0.005	ND	0.033
BH 14 UGO	0.388	0.16	0.206	0.083	0.055	0.009	ND	0.021
RS 15 UGO	0.711	0.292	0.377	0.152	0.102	0.009	ND	0.034
NSDWQ 2007	0.3	0.2	3	1	0.05	0.003	0.01	0.01
WHO 2011	0.3	0.4	5	2	0.05	0.003	0.01	0.01

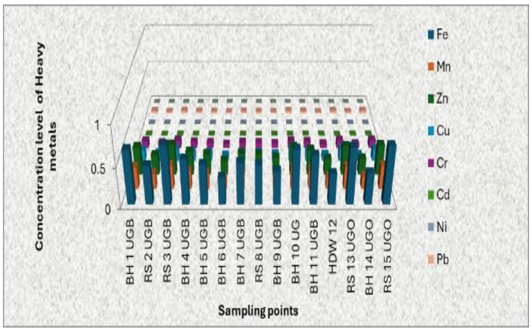

Figure 12: Concentration level of heavy metals and sampling points

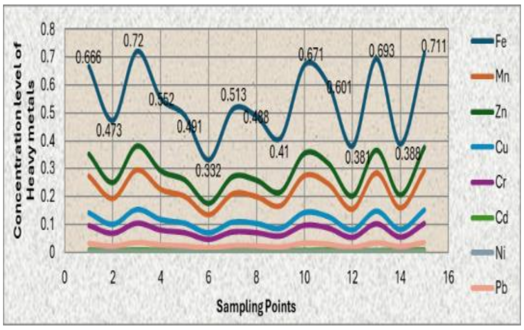

Figure 13: Scatter diagram showing the concentration level of heavy metals in the study area.

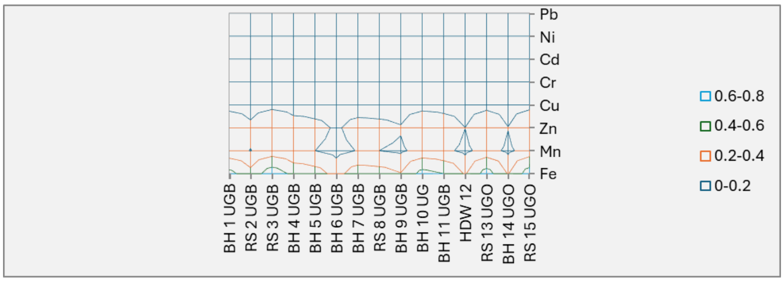

Figure 14: Surface contour showing the concentration level of heavy metal in sampling points

5.5 Heavy Metals Correlation Matrix, Hierarch Cluster And Principal Component Analysis (PCA)

Pearson correlation analysis was conducted to assess the relationships between heavy metals in the water samples. The correlation coefficient between iron (Fe) and manganese (Mn) was 0.99996, indicating an almost perfect positive relationship. Similarly, Fe exhibited very high correlations with zinc (Zn) (r = 0.999993), copper (Cu) (r = 0.999955), and chromium (Cr) (r = 0.99963). These near-perfect correlations suggest that these metals likely share a common geogenic or anthropogenic origin, possibly from industrial discharges, mineral weathering, or other diffuse sources (WHO, 2011). Lead (Pb) also showed a strong positive correlation with Fe (r = 0.9926), reinforcing the hypothesis of a shared contamination source.

However, cadmium (Cd) exhibited a weaker correlation with Fe (r = 0.419), indicating that Cd may originate from a separate source or behave differently geochemically. In contrast, nickel (Ni) showed negative correlations with Fe (r = -0.334) and Pb (r = -0.346), suggesting that Ni is likely derived from a distinct source or influenced by different environmental factors.

These results, summarized in Figure 9, highlight that Fe, Mn, Zn, Cu, Cr, and Pb are closely associated and may be influenced by similar geochemical processes or pollution pathways. In contrast, Cd appears to act more independently, while Ni exhibits a divergent geochemical behaviour, possibly originating from lithogenic sources or localized contamination such as corrosion or industrial waste (NSDWQ, 2007).

Dendrogram analysis based on hierarchical clustering of the sampling points revealed two distinct clusters: Cluster 1 includes sampling points BH 4, BH 5, BH 6, BH 7, BH 11, BH 9, BH 14, RS 2 UGB, RS 8 UGB, and HDW 12, all of which exhibited strong interrelationships and similar contamination profiles, suggesting a common or overlapping source of heavy metal contamination and Cluster 2 consists of points such as BH 1, BH 10, RS 3, RS 15, and RS 13 UGO, which also demonstrate strong internal correlation, indicating a separate but consistent contamination pattern (Figure 9).

Similarly, cluster analysis of the heavy metals grouped them into two clusters based on their inter-correlations: Cluster 1 includes Ni, Pb, Cr, Cu, vanadium (V), and Cd, which displayed strong interrelationships and are likely influenced by similar pollution sources and Cluster 2 includes Zn and Mn, which also exhibited a strong positive correlation, suggesting a different but shared source. Notably, Fe correlated strongly with all analyzed metals, positioning it as a key indicator of heavy metal contamination in the study area (Figures 13 and 14).

These findings point toward multiple sources of contamination, including anthropogenic inputs (industrial effluents, agricultural runoff) and natural geochemical processes. The clustering of metals and sampling points enables a better understanding of contamination pathways and can aid in targeted remediation strategies.

The first component has an eigenvalue of 6.469, accounting for 71.879% of the total variance. This suggests that metals such as Fe, Mn, Cu, Zn, and Cr are dominant in the study area. The second component has an eigenvalue of 1.881, explaining 20.905% of the variance. Together, these two components explain 92.784% of the total variance, indicating that the majority of the dataset's information can be captured by focusing on these two components. The remaining components contribute only 7.216% of the variance, which is not significant enough to warrant attention. Figures 12 and 13 illustrate the strong correlation and relationship between the heavy metals in the study area. After rotation, Component 1 explains 68.648% of the variance, while Component 2 adds another 24.136%, maintaining the cumulative variance at 92.784%. The rotation improves interpretability by distributing the variance more evenly across components. Communalities, which represent how much variance in each variable is accounted for by the components, range from 0 to 1. High communalities (close to 1) indicate that the components capture most of the variance for those variables. For Fe, Mn, Zn, Cu, Cr, and Pb, the communalities are near 1 (e.g., 0.992, 0.991), meaning these variables are well-represented by the components. Cd has a lower community of 0.480, indicating less of its variance is explained by the components. Ni, with a communality of 0.962, shows notable positive and negative loadings across components. The loadings indicate how strongly each variable correlates with the components. Fe, Mn, Zn, Cu, Cr, and Pb have high loadings on Component 1, indicating a strong association with this component. Cd has moderate loadings on both components but a higher loading on Component 2 (0.537). Ni has a negative loading on Component 1 (-0.435) and a high positive loading on Component 2 (0.879), suggesting it is more closely related to Component 2. Component 1 represents the higher concentrations of Fe, Mn, Zn, Cu, Cr, and Pb, indicating a common source or factor driving these elements. Component 2 is more associated with Ni and Cd, which may reflect different sources or behaviours in the system as shown in Table 10

The scree plot shows a clear "elbow" at Component 2, where the slope flattens, indicating that the first two components capture most of the variance. Components 1 and 2 have the highest eigenvalues, highlighting their importance. After Component 2, the eigenvalues drop sharply, meaning the remaining components contribute little to the variance, as illustrated in Figures 15 and 16.

Table 9: Correlation of Heavy metal parameters of the study area

	Fe	*Mn*	*Zn*	*Cu*	*Cr*	*Cd*	*Ni*	*Pb*
Fe	1							
Mn	0.99996	1						
Zn	0.999993	0.999951	1					
Cu	0.999955	0.999952	0.999953	1				
Cr	0.99963	0.999597	0.999575	0.999585	1			
Cd	0.419009	0.41987	0.420665	0.41978	0.403108	1		
Ni	-0.33397	-0.33483	-0.3341	-0.33586	-0.33698	0.141019	1	
Pb	0.992556	0.993256	0.992662	0.99304	0.991994	0.452559	-0.34645	1

Table 10: Principal Component Analysis (PCA) of Heavy metals of the study area

EXTRACTION AND ROTATION : PCA						
Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	6.469	71.879	71.879	6.469	71.879	71.879
2	1.881	20.905	92.784	1.881	20.905	92.784
3	0.639	7.102	99.886	Rotation Sums of Squared Loadings		
4	0.010	0.109	99.995	Total	% of Variance	Cumulative %
5	0.000	0.004	99.999	6.178	68.648	68.648

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Table 10 (Cont): Principal Component Analysis (PCA) of Heavy metals of the study area

EXTRACTION AND ROTATION : PCA						
6	4.939 X 10^5	0.001	100.000	2.172	24.136	92.784
Communalities (Extraction)		Component				
		1	2			
Fe	0.992	0.992	0.091			
Mn	0.992	0.992	0.091			
Zn	0.992	0.992	0.091			
Cu	0.992	0.992	0.090			
Cr	0.989	0.991	0.084			
Cd	0.480	0.437	0.537			
Ni	0.962	-0.435	0.879			
Pb	0.990	0.991	0.088			

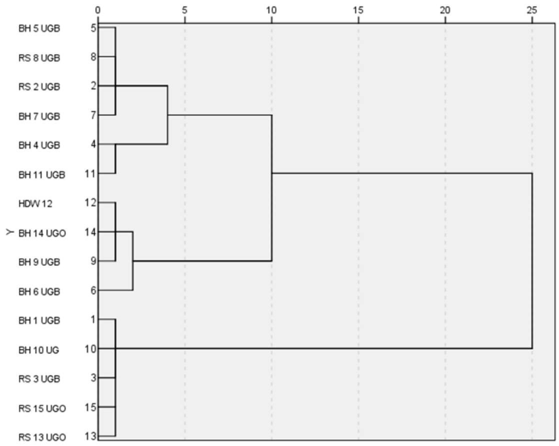

Figure 15: Dendrogram using average linkage (between groups) to show the relationship between sampling points

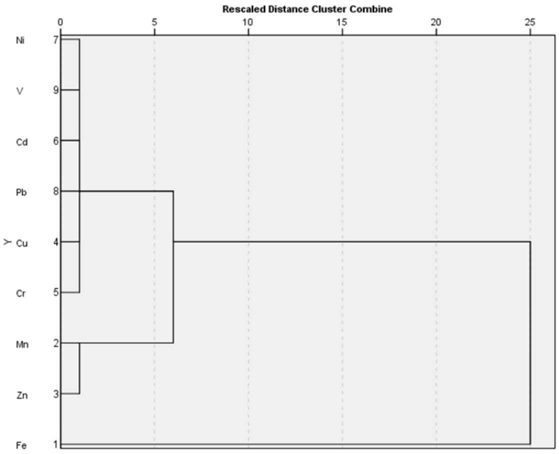

Figure 16: Dendrogram using average linkage (between groups) to show the relationship between heavy metals

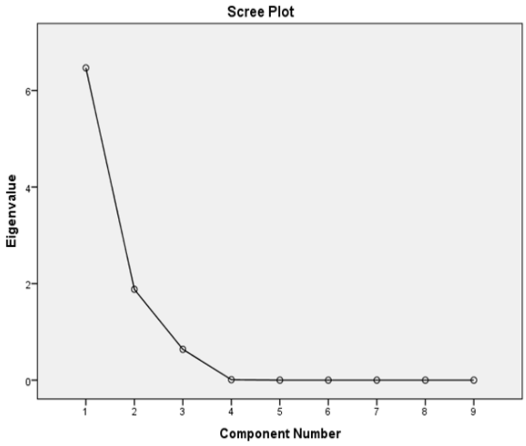

Figure 17: Scree plot of heavy metal of the study area

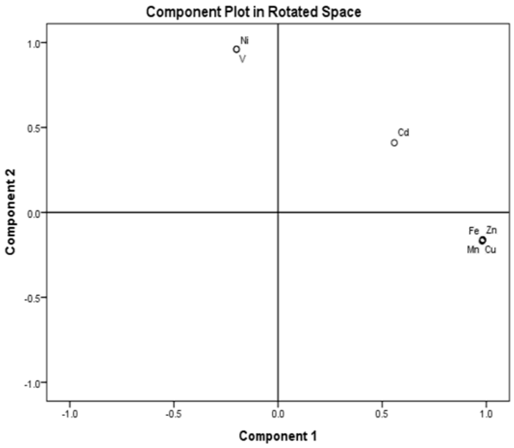

Figure 18: Component plot of heavy metal of the study area

6. SUMMARY AND RECOMMENDATIONS

The groundwater samples analyzed in the study area are slightly acidic, with BH 6 UGB and HDW 12 showing the highest signs of contamination based on elevated levels of electrical conductivity (EC), TDS, COD, anions, and turbidity, suggesting influence from anthropogenic activities or natural mineralization. Lower contamination levels were observed at RS 3 UGB and RS 15 UGO.

All the heavy metals conform to standard expects Fe, Mn, Cr, Cd and Pb which is above the acceptable standard values as shown in Table 8 (NSDWQ, 2007; WHO, 2011). Elevated levels of Fe, Pb, Cd and Cr indicate potential health risks and may stem from anthropogenic sources like industrial activities and waste disposal.

Heavy metals such as Fe, Mn, Zn, Cu, and Cr showed strong positive correlations, indicating they likely originate from the same source or are controlled by similar geochemical processes. In contrast, Cd showed weak correlation and Ni showed negative correlations with Fe and Pb, suggesting different sources or behavior. PCA confirmed two main components driving the variability: the first dominated by Fe, Mn, Zn, Cu, Cr, and Pb (likely anthropogenic), and the second by Ni and Cd. I recommend continuous monitoring and enforcement of waste disposal from industrial and agricultural sources, promote sustainable agriculture

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to minimize runoff and establish community-level water treatment systems in high-risk areas.

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