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Research Article

Analysis of Groundwater Quality and Health Implications: A Case Study of Bisichi and Surrounding Locations, North Central Nigeria

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Abstract

This study investigated the groundwater quality in selected communities within north-central Nigeria encompassing Bisichi, Dunduma, Zira, Rassa, Rahai and Korot where residents depend primarily on shallow hand dug wells for domestic water supply; with the aim of identifying any contaminants that may pose any risks to human health. Twenty (20) water samples were collected from ten (10) locations during the dry season and analyzed for chemical and biological parameters. Microbial quality was determined using the Most Probable Number (MPN) method at 37^{0}C and at 44^{0}C to determine the total coliform count and fecal coliform present while chemical analysis was achieved using the standard operating procedures of Genius-IF Xenemetrix instrument. Results of the microbial analysis revealed the MPN at 37^{0}C ranged from 0-12 coliforms/100ml of water. About 90% of the samples (JAR 1, JAR 2, JAR 4, JAR 5, JAR 6, JAR 7, JAR 8, JAR 9 and JAR 10) revealed low to moderate levels of bacterial contamination which renders same sources of water unfit for consumption whereas, only 10% of the samples (JAR 3) disclosed zero (0) coliform count and considered fit for consumption according to the World Health Organization (WHO) standard. In addition, the MPN at 44^{0}C of fecal coliform at locations JAR 1 and JAR 4 disclosed possible contamination from sewage. The heavy metal analysis revealed elevated concentrations of elements such as aluminum (Al), iron (Fe) and manganese (Mn) in several samples, with the Heavy Metal Pollution Index (HPI) exceeding the critical threshold (>100) in 80% of the sampled locations, indicating significant contamination. While 20% of the sampled locations (JAR 5 and JAR 10) have HPI values below 100 signifying low contamination. The Pearson's correlation matrix and principal component analyses of the chemical parameters revealed contamination is greatly influenced by anthropogenic activities and geogenic influence to a lesser extent. The study concluded that while some groundwater sources may be suitable for consumption after treatment such as boiling, chlorination, filtration and /or ultraviolet disinfection, others may pose potential health risks like diarrhea, nausea, hepatitis, stomach cramps, cancers, organ failure and infections

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especially in vulnerable individuals. Public awareness on the urgent need to safeguard water quality, sanitation practices and treatment measures as well as regular monitoring are recommended.

Keywords: Microbial, Most Probable Number (MPN), Genius-IF Xenemetrix, Elemental analysis, fecal coliform, Heavy Metal Pollution Index (HPI)

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Introduction

The importance of water to the sustainable development of any nation cannot be overemphasized because of its importance to human life and livelihood. Hence, one of the targets of the Sustainable Development Goal (SDG) by 2030 is to improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, thereby improving human health on the whole. Presently, the world is saddled with issues of water pollution whose effects are harmful to the environment and human health (Arif, 2020). While many people worldwide have access to water, it is often neither safe for drinking nor available in sufficient quantities to meet basic health needs in numerous areas (Luvhimbi et al., 2022). The World Health Organization (WHO & UNICEF, 2019) estimates that about 2.2 billion people globally consume unsafe water, thereby contributing to 88% of diarrheal diseases due to unsafe water, poor sanitation and unhygienic practices. To ensure a safe and healthy life, drinking water must be free from pathogens as well as organic and inorganic pollutants (Kraemer et.al., 2001). Most often, water contaminants could originate from natural sources (geogenic) or human activities (anthropogenic) especially of indiscriminate waste disposal, mining and agricultural activities. It is significant to note that deep wells/boreholes are less susceptible to anthropogenic contamination, whereas shallow wells are more vulnerable, potentially leading to various environmental and health issues (Ilyas et al., 2017). However, groundwater could be chemically contaminated due to the water-rock interaction making the concentration of dissolved constituents high (Tahir, 2004). This could also be through infiltration from the surface or cross transmission between aquifer (Rapant and Krcmova, 2007).

The area of investigation was delineated and tagged “High risk potential zone” for more in-depth studies on water contamination (Ramadan and Haruna, 2019). The residents within these communities rely entirely on groundwater obtained through shallow hand-dug wells and a limited number of boreholes for drinking and other domestic purposes.

And because of the increased rate of the population growth and consequent industrialization, mining and agricultural activities, it has become very important and urgent to ascertain the quality of the groundwater within the different localities within the study area and determine how safe the water sources are as it relates to human health. The aim of this proposed research was achieved by chemical and biological analyses of groundwater samples collected, and further comparing the results with the standards which would give an insight to problematic locations. Further computations on pollution /contamination indices was performed and the health implications of ingesting the water discussed. Finally, the possible sources of the contaminations/pollution was ascertained to help in suggesting ways to mitigate contaminations in order to safeguard the water quality of the area.

Aim and Objectives

The aim of the study is to evaluate the quality of groundwater by identifying potential contaminants as well as the impact of human activities to groundwater quality within the area and determine its suitability for consumption and other uses.

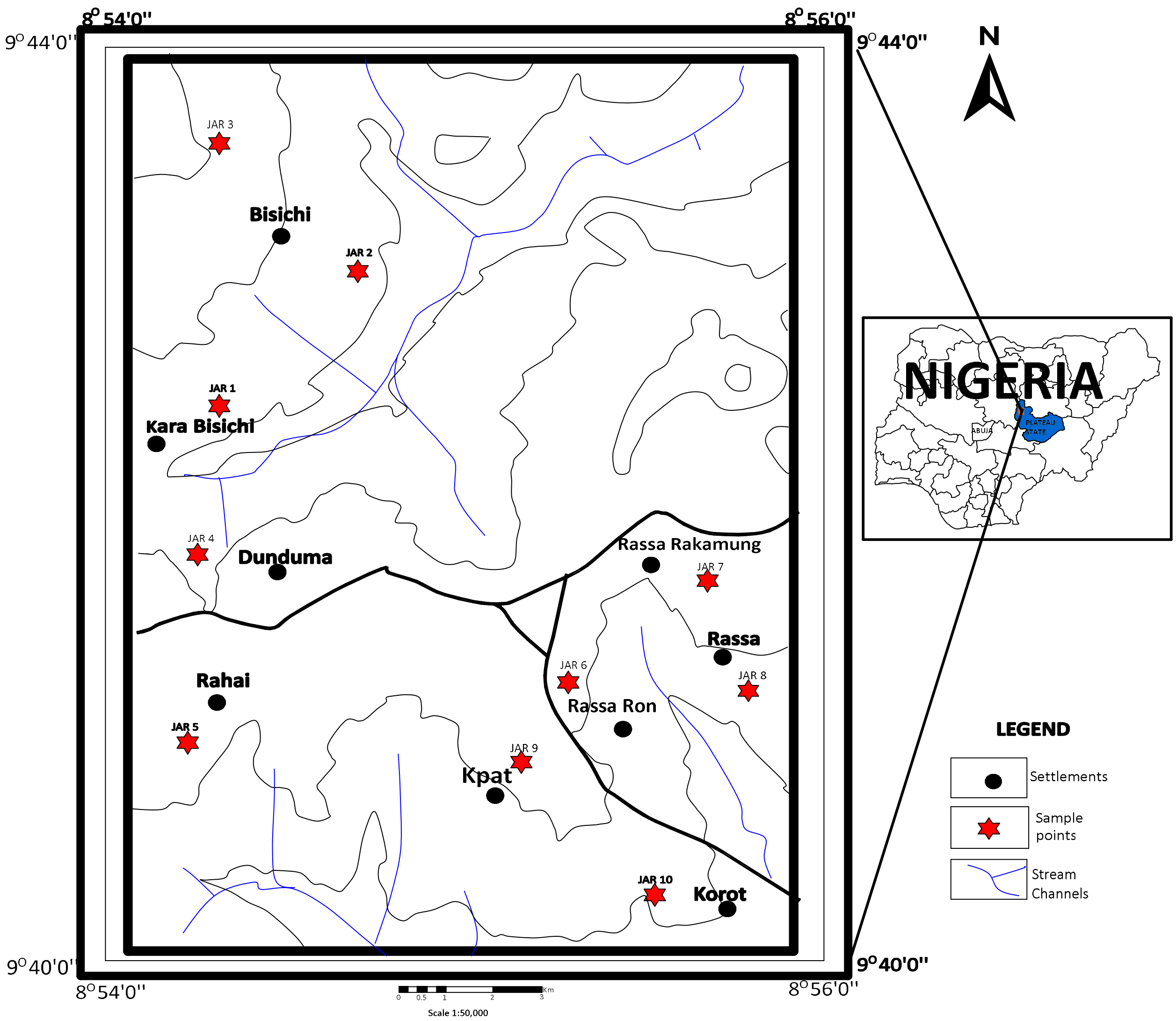
The following objectives used to achieve the aim were as follows:

i. To analyse the chemical and biological characteristics of the groundwater samples that were obtained within the study area.
ii. To identify and quantify the presence of contaminants and other pollutants that may pose risks to human health or the environment.
iii. To compare the groundwater quality against permissible limits for drinking water so as to determine its suitability for consumption.
iv. To investigate the influence of human activities on the groundwater quality within the area.
v. To suggest appropriate measures to mitigate contamination, improve water quality and prevent further degradation of groundwater resources within the area.

Materials and Methods

Description of the Study Area

The study area is located in north-central Nigeria and covers communities like Bisichi, Dunduma, Rassa Zira, Rahai and Korot. It is bounded by latitudes $9^0 40'00''$ N and $9^0 44'00''$ N and longitudes $8^0 54'00''$ E and $8^0 56'00''$ E and it is generally accessible through some tarred feeder roads and footpaths linking the various communities as shown on Figure 1.



A total number of twenty (20) water samples were collected from ten (10) locations in pairs within the study area during the dry season month of January, 2025. These samples (250 ml each) were drawn from hand dug wells and boreholes in polyethylene containers previously washed with distilled water and repeatedly rinsed. Until collection, the containers were kept in sealed polythene bags and at collection point rinsed twice with the sample collected before the final collection. Furthermore, the Garmin Global Positioning System (GPS) was used to locate positions where each sample was taken (Fig. 1).

Most Probable Method

A set of ten (10) samples representing ten locations were taken to the microbiology laboratory at the National Veterinary Research Institute (NVRI), Vom in Plateau state, Nigeria for microbial analysis using the most probable number (MPN) method which is a statistical technique used to estimate the concentration of viable micro-organisms present in the sample examined (Li et. al., 2024). Due to the convenience of the MPN method, it is frequently applicable in water analysis, quality testing and assurance of water and liquid products (ALPHA, 2017). In this case, fifteen (15) tubes encompassing five (5) tubes for each of three (3) dilution factors (0.1 ml, 1 ml and 10ml) were used for inoculation. Consequently, three sets each containing five (5) tubes were used in the presumptive test. The first set each of the five (5) tubes containing 10 ml of lactose broth with double strength was inoculated with 10 ml of the water sample. The second set of tubes contain 10 ml of single strength lactose broth were inoculated with 1 ml of water sample and the remaining five tubes containing 10 ml of single strength of lactose broth were inoculated with 0.1 ml of the sample. After that, the tubes were incubated at 37^{o} C for 24 hours for total coliform and 44^{o} C for faecal coliform, after which the tubes were examined for turbidity, gas production and acid production. The results are presented on Tables 3 and 4.

Afterwards, the interpretation for each location was done in accordance with the WHO guidelines for drinking water quality as follows:

Table 1: Interpretation Table for MPN of coliforms in water (WHO, 2022)

MPN/100 ml	Interpretation	Water Quality Status
0	No coliforms detected	Excellent/safe
1-10	Low risk	May be acceptable for drinking after treatment (boiling, chlorination)
10 -100	Intermediate to high risk	Unsafe for drinking without treatment. Indicates possible contamination
>100	Very high risk	Unsatisfactory/unsafe for drinking/ requires immediate/urgent intervention.

The X-Ray Fluorescence Method

Similarly, another set of 10 (ten) samples were taken to National Steel Raw Materials Exploration Agency in Kaduna, Nigeria for chemical analysis using the Standard Operating Procedures (SOP) of Genius-IF Xenemetrix instrument which is designed for multi-elemental analysis across various sample types. Firstly, the water samples were filtered to remove particulate matter that could interfere with the analysis, then acidified with nitric acid to preserve the dissolved elements and prevent precipitation. The prepared water samples were placed in sample cups and introduced in the machine which accommodates multiple positions for efficient analysis. Each of the cups containing the sample is placed with an appropriate X-ray transparent film to prevent leakage and contamination. The heavy metal concentration in the water samples as presented on Table 5 were directly compared with the WHO maximum permissible limit. This aided in highlighting potential risk locations.

Heavy metal Pollution Index

The Heavy metal pollution Index (HPI) is widely used in assessing water quality concerning heavy metal contamination. Water quality and its suitability for drinking purpose can be examined by determining its quality index (Prosad and Mondal, 2008). This method aggregates concentrations of various metals into a single index value and provides an easy-to-interpret measure of pollution severity (Prosad and Bose, 2001). This integrated approach highlights cumulative pollution effects, even when individual metal concentrations appear within permissible limits (Mohan et al., 1996). Furthermore, the HPI provides a practical tool for identifying pollution hotspots, supporting remediation efforts and ensuring compliance with regulatory standards (Sundaray et al., 2006). By tracking HPI values overtime, researchers can also effectively monitor temporal trends in pollution, enhancing long-term environmental management strategies.

The HPI is achieved using a step-by-step approach after the concentration of each metal (C_i) is determined in mg/l or ppm.

The unit weight of each metal is determined using:

$$W_i = \frac{k}{Si} \quad \text{.. .. ..} \quad (1)$$

Where:
W_i = Unit weight of the metal
S_i = Standard permissible limit of the metal
K = Constant (commonly chosen as 1)

The sub-index (Q_i) for each metal is computed using:

$$Q_i = \frac{Ci - Ii}{Si - I} \times 100 \quad \text{.. .. ..} \quad (2)$$

Where:
Ci = measured concentration of the metal
I_i = Ideal Standard (Usually zero)
S_i = Standard permissible limit

The overall HPI is calculated using:

$$HPI = \frac{\sum(Qi \times Wi)}{\sum Wi} \quad .. \quad .. \quad .. \quad .. \quad .. \quad .. \quad .. \quad .. (3)$$

Where:
Q_i = sub-index of the metal i
Wi = unit weight of metal i

The interpretation of HPI is based on established thresholds: values below 100 indicate low heavy metal pollution and safe water quality, values around 100 represent the critical limit and values exceeding 100 suggest considerable contamination and potential health risks (Mohan et al.,1996; Prosad & Bose, 2001; Edet & Offiong, 2002). This classification enables a straight forward evaluation of pollution severity and aids in environmental decision-making.

Table 2: Heavy Metal Pollution Index (HPI) Interpretation

HPI Range	Pollution Level	Water Quality	Remarks
< 100	Low	Safe/good	Heavy metals within permissible limits
= 100	Critical Limit	Border line	At threshold; close monitoring needed
> 100	High	unsafe	Heavy metal pollution is significant.

Sources: Mohan et al. (1996); Prosad and Bose, (2001); Edet and Offiong (2002)

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Table 3: Results of Microbial Analysis (Coliform Count 37^0 C) of water Samples

Sample No	Locations	Longitude	Latitude	10 mL	1 mL	0.1 mL	MPN of Coliform/100 mL of water	Bacterial Isolates
JAR 1	Kara Bisichi	489305	1074063	0	1	1	4	*Klebsiella aerogenes*
JAR 2	Bisichi (Com. Health Centre)	490090	1073759	2	0	2	9	*Aeromonashydrophila, Pseudomonas aeruginosa*
JAR 3	Bisichi	490112	1074026	0	0	0	< 2	*Ncl*
JAR 4	Dunduma	490118	1071041	0	2	1	6	*Klebsiella aerogenes, Pseudomonas aeruginosa*
JAR 5	Rahai	490645	1072533	1	1	2	8	*Klebsiella aerogenes, Pseudomonas aeruginosa*
JAR 6	Rassa Ron	492842	1072078	0	2	1	6	*Escherichia coli, Pseudomonas aeruginosa*
JAR 7	Rassa Rakumung	492513	1072683	1	1	0	4	*Pseudomonas aeruginosa*
JAR 8	Rassa	492281	1072594	2	1	1	9	*Klebsiella aerogenes*
JAR 9	Kpat (Borehole)	492073	1069369	2	1	2	12	*Klebsiella aerogenes, Pseudomonas aeruginosa*
JAR 10	Korot (Borehole)	493003	1069139	0	1	1	4	*Escherichia coli, Pseudomonas aeruginosa*

MPN – Most Probable Number; Ncl – No coliform isolate; JAR – Joyce Ayuba Ramadan (sample tag)

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Table 4: Results of Microbial Analysis (Faecal Coliform Count 44^0 C) of water Samples

Sample No	Locations	Longitude	Latitude	10 mL	1 mL	0.1 mL	MPN of Coliform/100 mL of water	Bacterial Isolates
JAR 1	Kara Bisichi	489305	1074063	0	1	0	2	*Klebsiella aerogenes*
JAR 2	Bisichi (Com. Health Centre)	490090	1073759	0	0	0	< 2	NFcl
JAR 3	Bisichi	490112	1074026	0	0	0	< 2	NFcl
JAR 4	Dunduma	490118	1071041	0	1	0	2	*Klebsiella aerogenes*
JAR 5	Rahai	490645	1072533	0	0	0	< 2	NFcl
JAR 6	Rassa Ron	492842	1072078	0	0	0	< 2	NFcl
JAR 7	Rassa Rakumung	492513	1072683	0	0	0	< 2	NFcl
JAR 8	Rassa	492281	1072594	0	0	0	< 2	NFcl
JAR 9	Kpat (Borehole)	492073	1069369	0	0	0	< 2	NFcl
JAR 10	Korot (Borehole)	493003	1069139	0	0	0	< 2	NFcl

MPN – Most Probable Number; NFcl – No faecal coliform isolate; JAR – Joyce Ayuba Ramadan (sample tag)

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Table 5: Metal Concentration in water Samples and HPI in sampled Locations

Sample No	Locations	Al (mg/l)	Cr (mg/l)	Mn (mg/l)	Fe (mg/l)	Ni (mg/l)	Cu (mg/l)	Zn (mg/l)	As (mg/l)	Cd (mg/l)	Ba (mg/l)	Pb (mg/l)	HPI
JAR 1	Kara Bisichi	**1.46**	0.04	0.07	**0.54**	0.02	0.61	0.11	ND	**0.005**	0.09	**0.01**	148.6
JAR 2	Bisichi	**0.83**	0.03	0.05	0.17	0.01	0.24	0.02	ND	0.002	ND	**0.03**	115.5
JAR 3	Bisichi	**0.91**	0.03	0.01	**0.31**	ND	0.17	0.01	ND	**0.003**	ND	**0.03**	128.2
JAR 4	Dunduma	**1.43**	**0.14**	**0.12**	**0.99**	**0.03**	**1.11**	0.09	ND	0.001	ND	**0.02**	101.2
JAR 5	Rahai	**1.12**	0.01	0.05	**0.31**	ND	0.28	0.02	ND	**0.003**	0.03	**0.01**	90.6
JAR 6	Rassa Ron	**0.96**	0.03	**0.12**	**0.49**	**0.07**	0.98	0.14	**0.01**	0.001	ND	**0.03**	118.7
JAR 7	Rassa Rakumung	**0.78**	**0.08**	0.08	**0.80**	**0.08**	0.51	0.06	ND	**0.004**	0.04	**0.05**	239.1
JAR 8	Rassa	**1.41**	**0.09**	0.10	**0.56**	0.01	**1.10**	0.11	ND	0.002	ND	**0.02**	102.1
JAR 9	Kpat (Borehole)	**0.66**	**0.08**	0.09	0.25	0.02	0.49	0.06	**0.02**	**0.005**	0.05	**0.01**	153.9
JAR 10	Korot (Borehole)	**0.67**	**0.06**	0.04	**0.31**	0.01	**1.20**	0.15	**0.02**	**ND**	0.22	**0.01**	61.5
WHO max. Permissible Limit		**0.2**	**0.05**	**0.1**	**0.3**	**0.02**	**1**	**3**	**0.01**	**0.003**	**0.7**	**0.01**	
Maximum Concentration		**1.46**	**0.14**	**0.12**	**0.99**	**0.08**	**1.11**	**0.15**	**0.02**	**0.005**	**0.22**	**0.05**	239.1
Minimum Concentration		**0.66**	**0.01**	**0.01**	**0.17**	**0.01**	**0.17**	**0.01**	**0.01**	**0.001**	**0.03**	**0.01**	61.5
Mean		**1.01**	**0.06**	**0.07**	**0.42**	**0.03**	**0.67**	**0.08**	**0.02**	**0.003**	**0.09**	**0.02**	125.9

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Statistical Analysis

Statistical analysis of the heavy metals in water was carried out using the Jamovi 2.7.4 with particular interest on the Pearson's correlation matrix and principal component analyses to measure and quantify the strength and direction of heavy metals present in the water samples and identify dominant patterns in the data, such as groups, outliers, trends, and so on. The correlation matrix was used to achieve the principal component analysis for the same dataset and the factor components that have Eigen values higher than one (1) were extracted, this is because the Eigen values indicate the significance of the components (Joliffe, 2002). The Principal component analysis helps to group metals that share similar variation patterns, often indicating a common source (Vega et al., 1998). Factor loading values > 0.75 are considered strong, between 0.75 and 0.5 regarded as moderate and between 0.5 and 0.3 considered weak.

Discussion of Results

Biological Parameters

The average value of the most probable number (MPN) of coliform in the water samples collected is approximately 6.9 with the minimum value recorded at JAR 3 of < 2 in 100 ml of water and the maximum value at JAR 9 of 12 in 100 ml of water (Table 3). The public and environmental protection requires safe drinking water to be free of pathogens (Kumar et al., 2013), however, the results of the bacteriological analyses of the samples from the different locations revealed the presence of coliform in varying populations as well as bacterial isolates.

The interpretation of the results of the Most Probable Number (MPN) per 100ml of the samples analyzed which was done with respect to the WHO guidelines for drinking water (2022) reveal that about 90% of the samples (JAR 1, JAR 2, JAR 3, JAR 4, JAR 5, JAR 6, JAR 7, JAR 8, JAR 10) range from low to moderate contamination and by implication pose low health risk. Water from these sources may be acceptable for consumption if there are no alternative sources, but after being subjected to treatment by either boiling for at least 1-3 minutes before use, chlorination and/or the use of filters. On the contrary, the remaining 10% represented by JAR 9 may pose high health risk due to high contamination and consequently, not safe for drinking.

The sources of drinking water within the study area are from the shallow hand dug wells and few boreholes. It was also observed that solid waste disposal is done indiscriminately and open defecation is still practiced within some localities which could lead to the contamination of the drinking water sources with bacteria such as those discovered in the samples collected and analyzed (Table 3). According to the World Health Organization (WHO), the lack of safe water supply and of adequate means of sanitation is blamed for as much as 80% of all diseases in developing countries and very common microbial diseases transmitted through water are

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typhoid fever, dysentery, cholera, hepatitis (Collier et.al., 2005). Drinking water contaminated with bacterial isolates poses several health risks depending on the type and concentration of the bacteria.

Results of the microbial analysis as shown on Table 3, the drinking water samples collected from JAR 1 (Kara Bisichi) and JAR 8 (Rassa) revealed the presence of *klebsiella aerogenes* which could pose gastrointestinal infections, urinary tract infections, respiratory infections and blood stream infections especially in the elderly, infants and individuals whose immune system has been compromised (Sanders and Sanders, 1997; Mezzatesta et al., 2012; Davin-Regli et al., 2019). The sample from JAR 2 representing the community health center in Bisichi showed the presence of *aeromonas hydrophilia* and *pseudomonas aeruginosa* with potential health effects of gastroenteritis, wound infections, sepsis and respiratory infections. Others include skin infections, ear and eye infections. Though the risk level could be low to moderate for healthy individuals, but high for immunocompromised individuals, children, the elderly and those with open wounds (Anaissie et al., 2002). Remarkably, no coliform isolate (Ncl) was discovered in JAR 3 representing Bisichi. However, water samples from JAR 4, JAR 5 and JAR 9 representing Dunduma, Rahai and Kpat in that order revealed the presence of *klebsiella aerogenes* and *pseudomonas aeruginosa*. Likewise, water sample from JAR 7 (Rassa Rakamung) disclosed contamination with *Pseudomonas aeruginosa* which can be harmful especially to individuals with weakened immune system. Possible health effects include gastrointestinal infections, respiratory infections, sepsis and urinary tract infections, besides *Pseudomonas aeruginosa* is resistant to many antibiotics making it difficult to treat (Zhou et al., 2022). Lastly, drinking water samples from JAR 6 (Rassa Ron) and JAR 10 (Korot) disclosed the presence of *Escherichia coli* and *Pseudomonas aeruginosa* which may pose serious health risk because the presence of *Escherichia coli* usually indicates fecal contamination which could cause severe health risks in infants, elderly and immunocompromised individuals of bloody diarrhea, nausea, vomiting, abdominal cramps and fever (WHO, 2017).

Chemical Parameters

The mean concentration of heavy metals in the water samples analyzed follow the order: Al > Cu > Fe > Ba > Zn > Mn > Cr > Ni > Pb as displayed in Table 5. Health hazards were already identified as all the sampling locations show heavy metal exceedances when compared with the WHO permissible limits. This is a pointer to the fact that the contamination is widespread and also suggests a shared contamination source (Nagaraju et al., 2022). Furthermore, the HPI was computed which was aimed at capturing the cumulative impact of metals to give an overall assessment of the pollution levels. The computed outcome of the HPI (Table 5) was compared with the standard for interpretation given in Table 2. This was further supported

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by the chart and map (Figure 2 and Figure 3 respectively) which highlighted key insights at a glance.

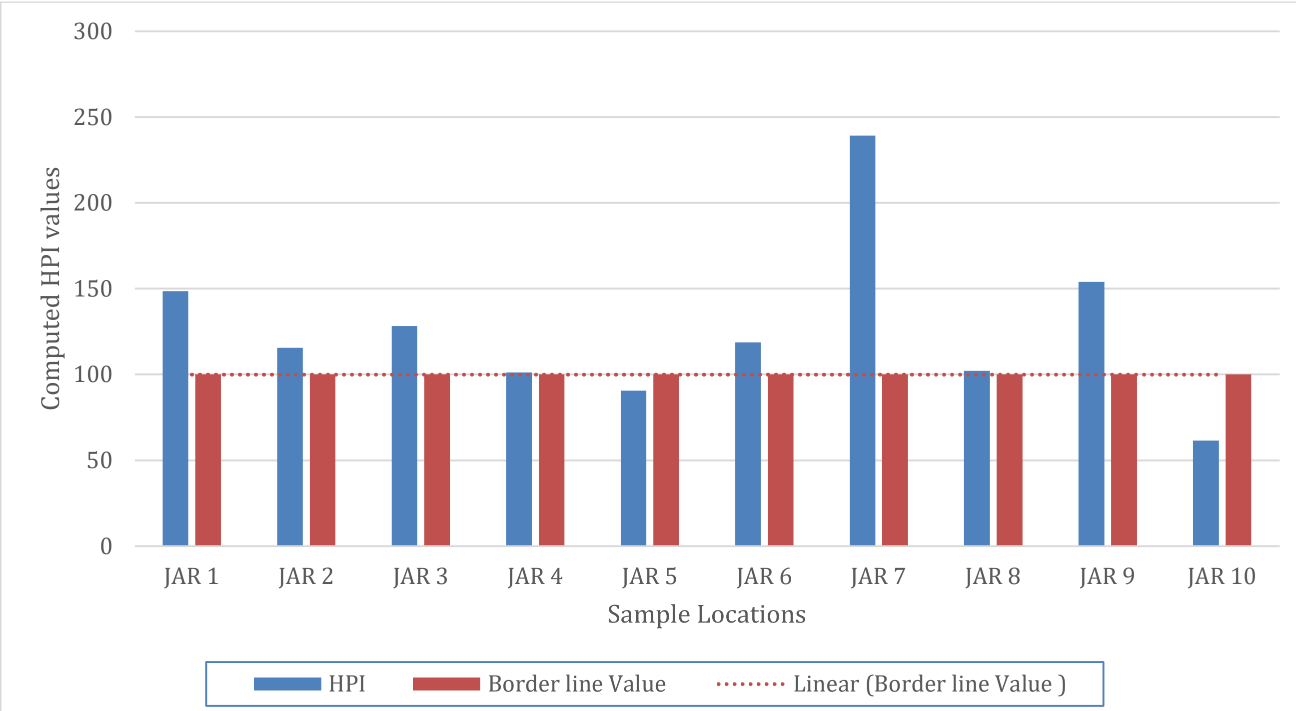

Figure 2: Bar Chart of Computed HPI values Versus Sample Locations

Rahai and Korot where samples of water labelled JAR 5 and JAR 10 have HPI values of 90.6 and 61.5 respectively which fall within the low pollution category since the HPI values are below 100. Although, the value of HPI for JAR 5 is close to the borderline and would require constant monitoring. For this low level of contamination, the water sources could be considered safe for consumption. Whereas JAR 4 (Dunduma) and JAR 8 (Rassa) with HPI values of 101.2 and 102.1 respectively fall within the critical limit of contamination and requires close monitoring.

On the other hand, JAR 1 (Kara Bisichi), JAR 2 (Community health centre, Bisichi), JAR 3 (Bisichi), JAR 6 (Rassa Ron), JAR 7 (Rassa Rakamung) and JAR 9 (Kpat) comprise HPI values of 148.6, 115.5, 128.2, 118.7, 239.1 and 153.9 respectively which fit into the high pollution category with significant heavy metal pollution which renders the water sources unsafe for direct consumption.

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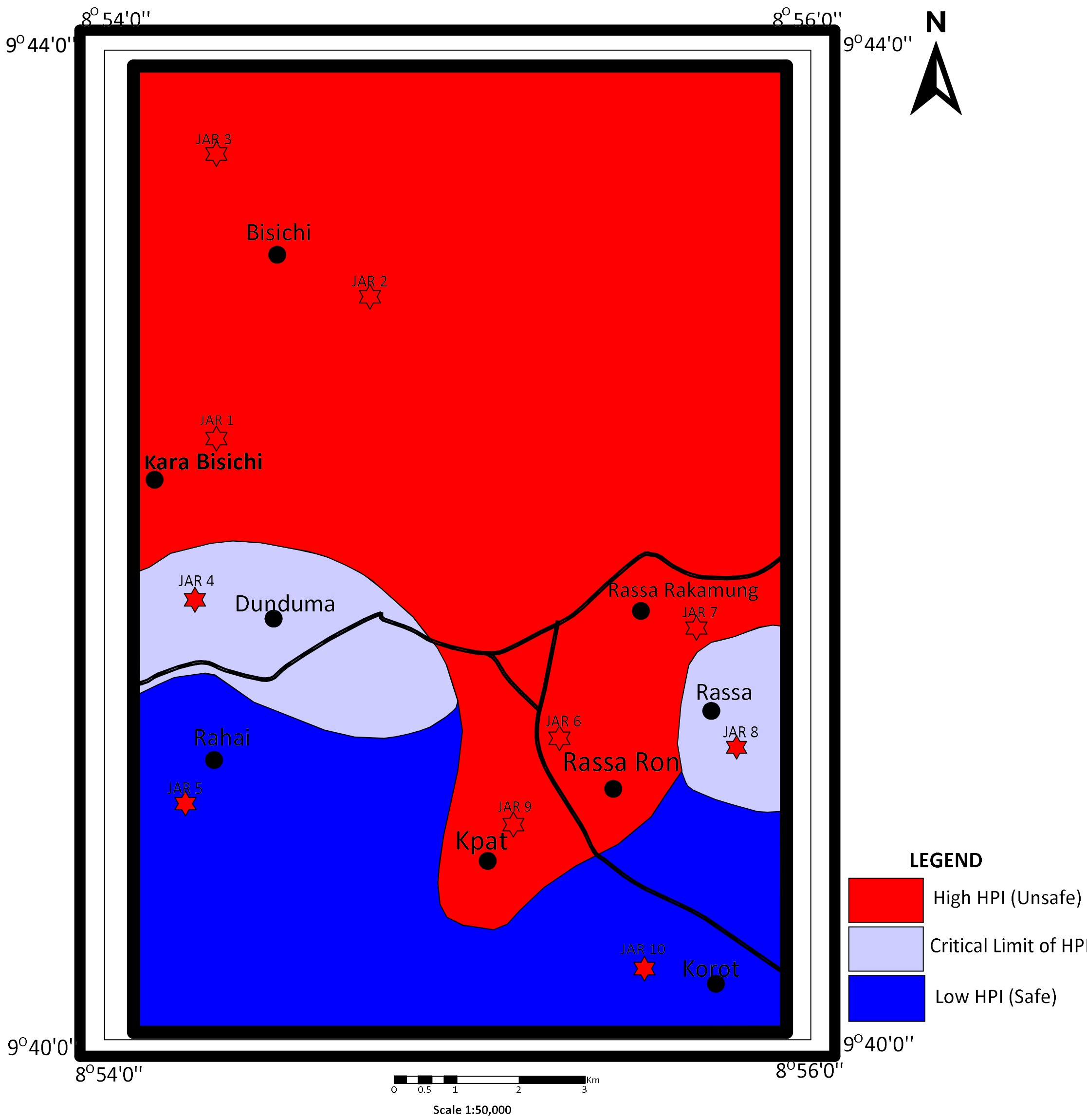

Figure 3: Map of the study area showing zones of High, Critical Limit and Low HPI

The Pearson's correlation matrix of heavy metals in groundwater is shown in Table 6 and it reveals that Mn, Fe and Cu correlate positively with Cr, similarly Fe, Ni and Cu correlate positively with Mn. There exists also a strong correlation between Zn and Cu: Pb and Ni. These strong positive intercorrelations between heavy metals forming groups as suggests that each group of metals have an identical source. The Principal Component (PC) analysis for the

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correlation matrix disclosed three (3) factors (Table 7). PC 1 with strong factor loadings for Cr (0.748), Mn (0.815), Fe (0.817), Cu (0.849) and Zn (0.693) suggests they originate from a common or related source which could be possibly industrial discharges. They may likely represent anthropogenic sources from both industrial and urban activities such as the use of arsenic based herbicides, pesticides and fertilizers in farming, and through mining and processing of cassiterite and other related minerals within the study area.

PC 2 which showed strong positive loadings for As (0.913) and Ba (0.796) suggests a common source and distinct pollution pathway influencing their presence in the groundwater samples. This pattern may indicate geogenic origin where both elements are naturally leached from rocks into groundwater. Alternatively, the loadings may reflect agricultural activities, particularly the use of pesticides and Ba- containing fertilizers.

PC 3 marked by strong factor loadings for Ni (0.860) and Pb (0.869), likely reflects localized contamination linked to mining and associated industrial activities. Given that the area is known for cassiterite mining, these metals (Ni and Pb) may be released during ore extraction, crushing and processing where same often occur as associated trace elements. In addition, agricultural practices in the community may contribute to metal accumulation through the use of agrochemicals. Therefore, PC 3 suggests a combination of mining-related geogenic input and agrochemical influence as probable sources of Ni and Pb in the groundwater.

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Table 6. Pearson's Correlation Matrix for Heavy metals in Groundwater

	Al (mg/l)	**Cr (mg/l)**	**Mn (mg/l)**	**Fe (mg/l)**	**Ni (mg/l)**	**Cu (mg/l)**	**Zn (mg/l)**	**As (mg/l)**	**Cd (mg/l)**	**Ba (mg/l)**	**Pb (mg/l)**
Al (mg/l)	–										
Cr (mg/l)	0.268	–									
Mn(mg/l)	0.379	**0.589***	–								
Fe (mg/l)	0.535	**0.727****	**0.620***	–							
Ni (mg/l)	0.149	0.219	**0.580***	0.549	–						
Cu(mg/l)	0.286	**0.581***	**0.593***	0.479	0.230	–					
Zn (mg/l)	0.182	0.301	0.511	0.309	0.332	**0.898*****	–				
As (mg/l)	0.623	0.050	0.055	0.380	0.023	0.336	0.451	–			
Cd(mg/l)	0.017	-0.140	-0.105	0.087	0.023	-0.613	0.424	-0.153	–		
Ba (mg/l)	0.324	-0.044	-0.317	0.203	-0.146	0.344	0.500	**0.615***	0.158	–	
Pb (mg/l)	0.246	0.048	0.056	0.329	**0.663***	-0.213	0.239	-0.397	0.010	0.435	–

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Table 7. Principal Component Analysis for heavy metals in Groundwater

	Component		
	1	2	3
Al (mg/l)	0.590	-0.586	-0.487
Cr (mg/l)	**0.748**		
Mn (mg/l)	**0.815**		
Fe (mg/l)	**0.817**	-0.330	
Ni (mg/l)	0.395		**0.860**
Cu (mg/l)	**0.849**	0.473	
Zn (mg/l)	**0.693**	0.606	
As (mg/l)		**0.913**	
Cd (mg/l)	-0.359	-0.382	
Ba (mg/l)		**0.796**	
Pb (mg/l)		-0.315	**0.869**

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Conclusion

This study critically assessed the quality of groundwater within selected communities in north-central Nigeria, focusing on both microbial and heavy metal contamination. The results from the chemical and microbial analyses highlight significant concerns regarding groundwater safety, with varying levels of pollutants detected across the sampled locations.

Microbiological analysis revealed that while most samples showed low to moderate coliform contamination, indicating potential faecal and environmental pollution, only a few met the WHO standard for safe drinking water without treatment. The detection of pathogens such as *Escherichia coli, Pseudomonas aeruginosa* and *Klebsiella aerogenes* further underscores the health risks associated with direct consumption of untreated groundwater in the area.

Similarly, the chemical analysis and subsequent computations of the Heavy Metal Pollution Index (HPI) revealed that the majority of the groundwater samples had HPI values above the safe threshold of 100. This indicates a high level of heavy metal contamination, particularly from elements such as aluminum, iron, lead and manganese which exceed the WHO permissible limits in several locations. These contaminants pose long-term health risks, including organ damage and developmental issues especially with prolonged exposure.

The findings based on the Pearson's correlation matrix and subsequent principal component analysis suggest that the contamination of groundwater in the study area is significantly influenced by anthropogenic activities majorly of mining, waste disposal and agricultural practices. Therefore, there is an urgent need for interventions including:

1. Regular monitoring of groundwater quality
2. Public sensitization on the dangers of improper wastes disposal
3. Promotion of point-of-use water treatment techniques
4. Enforcement of environmental protection regulations to safeguard water sources.

In conclusion, while groundwater remains a critical resource for the local population, its current state in many parts of the study area is not entirely suitable for direct consumption without treatment. Prompt and coordinated efforts are essential to mitigate pollution, ensure water safety and protect public health.

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Conflict of Interest
There is no conflict of interest.

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