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HYDROGEOCHEMICAL CHARACTERIZATION AND EVALUATION OF WATER QUALITY IN PART OF MAKURDI, NORTH CENTRAL NIGERIA

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Abstract: A total of thirty-five water samples were collected from two boreholes, twenty-nine hand-dug wells, and four surface water points (Benue River) for physicochemical and bacteriological analysis. The hydrochemical results were assessed for potable water by comparing with the Nigerian Standard for Drinking Water Quality (NSDWQ) and the World Health Organization's guidelines. The water types were classified with the help of plots to explain the dominant hydrochemical and geological processes influencing water chemistry. Results showed that eleven of the thirty-five samples failed to meet the established drinking water standards, and are therefore deemed unsafe for consumption without adequate treatment. The Piper plot indicated that 57.1% of the samples belonged to the alkaline water type, while 42.9% were classified as alkaline earth. The Durov plot analysis identified simple dissolution or mixing as the principal hydrochemical process, with a subordinate influence from reverse ion exchange. Gibb's plot revealed that rock weathering, with an evaporative influence, was the primary geological process governing the water's chemistry.

Keywords: Hydrogeochemical characteristics, water quality evaluation, rock weathering, Makurdi Basin. .

Introduction

Water is an essential natural resource that sustains human life, ecological balance, and socio-economic development. Groundwater constitutes one of the most reliable sources of freshwater supply for domestic, agricultural and industrial purposes, particularly in developing countries where centralized water supply systems are often inadequate (Gleeson *et al*., 2020). The chemical quality of groundwater is therefore of critical importance because dissolved chemical constituents may influence its suitability for drinking, irrigation, and other domestic uses (Uddin *et al*., 2023). Groundwater quality is influenced by both natural and anthropogenic processes. Natural processes such as mineral dissolution, water-rock interaction, and ion exchange significantly control the hydrochemical composition of groundwater (Chen *et al*., 2019).

In addition, anthropogenic activities including agricultural practices, improper waste disposal, sewage infiltration, and rapid urbanization may introduce contaminants into groundwater systems, thereby degrading water quality and posing potential risks to human health (Krishnamoorthy & Lakshmanan, 2024). Previous studies have shown that poorly sited waste dumps, septic systems, and industrial activities can contribute to groundwater contamination through leachate migration and infiltration of pollutants into aquifers (Ali *et al*., 2024).

These anthropogenic pressures are particularly significant in rapidly expanding urban environments where population growth and infrastructural development increase the demand for groundwater resources. Makurdi metropolis, the capital of Benue State in North-Central Nigeria, has experienced rapid urban growth over the past decades. Due to inadequate public water supply systems, the majority of residents depend on groundwater obtained from privately constructed boreholes and hand-dug wells for their daily water needs (Iwar *et al*., 2021).

In some areas, surface water from the Benue River is also utilized, particularly during periods of water scarcity. Benue State is widely recognized as the "Food Basket of the Nation" because of its extensive agricultural activities. Consequently, water resources in Makurdi are not only essential for domestic consumption, but also play a significant role in agricultural production and irrigation practices. The quality of groundwater used for irrigation, therefore has important implications for crop productivity and food safety, as contaminated irrigation water can introduce pollutants into the food chain and indirectly affect human health.

Hydrogeochemical investigations provide valuable insights into the origin, evolution, and chemical characteristics of groundwater systems. Hydrochemical diagrams such as Piper, Durov, and Gibbs plots are widely used for classifying

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groundwater types and identifying the dominant geochemical processes controlling groundwater chemistry (Shaikh *et al*., 2020). These techniques help in understanding water-rock interactions, ion exchange processes, and the influence of evaporation or anthropogenic activities on groundwater composition.

Although, several studies have investigated groundwater conditions in Makurdi and its surrounding areas, many of these investigations primarily focused on hydrogeological characteristics or localized groundwater quality assessments. Comprehensive hydrogeochemical evaluations that integrate physicochemical analysis, bacteriological assessment, and hydrochemical classification techniques remain limited in the study area.

Present study aims to evaluate the hydrogeochemical characteristics and water quality of groundwater and surface water in parts of Makurdi, using physicochemical and bacteriological analyses combined with hydrochemical interpretation techniques. Specifically, the study seeks to classify the hydrochemical facies of the water samples and identifying the dominant geochemical processes controlling groundwater chemistry in the area. The findings of this research are expected to provide important baseline information for groundwater quality monitoring, environmental protection, and sustainable water resource management in Makurdi metropolis and other rapidly urbanizing regions with similar hydrogeological conditions.

Study Area

The study area, located in the north western portion of Makurdi, Benue State, is defined by latitudes 07°42'25"N to 07°45'00"N and longitudes 08°30'00"E to 08°32'30"E, encompassing approximately 16.25 km² (Fig. 1). The topography is predominantly low-lying at 70-250 m with some high points reaching 400-600 m. The drainage system is dendritic, with the Benue River serving as the main watercourse and numerous smaller tributaries feeding into it. With a population density exceeding 380 persons per km² (Bakoji *et al*., 2020), the area is well-connected through a network of roads, railways, and footpaths. The region is situated within the Guinea savannah vegetation zone, receiving an annual rainfall of 1,500-2,000 mm, with its peak in July. Climatic data indicate that temperatures range from approximately 27°C in December/January to highs of 38°C and 48°C in March and April, respectively (Shabu *et al*., 2021).

Geologically, the Benue Trough is a long sedimentary basin that extends northeast from the confluence of the Niger and Benue rivers. Basement Complex rocks bound the basin to the north and south of the Benue River. Often described as the longest arm of the Nigerian coastal basin due to its elongated, trough-like shape and continuity with the coastal basin (Ugbor *et al*., 2021), the Makurdi area specifically belongs to the Makurdi Formation. This formation overlies the Albian Shale and consists of thick, coarse-grained sandstone deposits, reaching a thickness of approximately 900 m (Salawu *et al*., 2021). Importantly, the Makurdi Formation also includes the Wadatta Limestone Member, a fossiliferous limestone unit commonly associated with sandstone and calcareous, glauconitic, and micaceous shale interbeds.

This limestone member represents a marine transgressive episode within the otherwise dominantly continental to fluviatile depositional succession of the Makurdi Formation. Therefore, the lithology of this formation in the study area is better described as sandstone-dominated, but locally interrupted by carbonate-rich units, particularly the Wadatta Limestone Member. While the southern part of the Benue Valley is characterized by gently undulating terrain and low hills, and the north-eastern region features more dramatic relief, with hills such as Lammuder and Ligri rising up to 600 m above sea level.

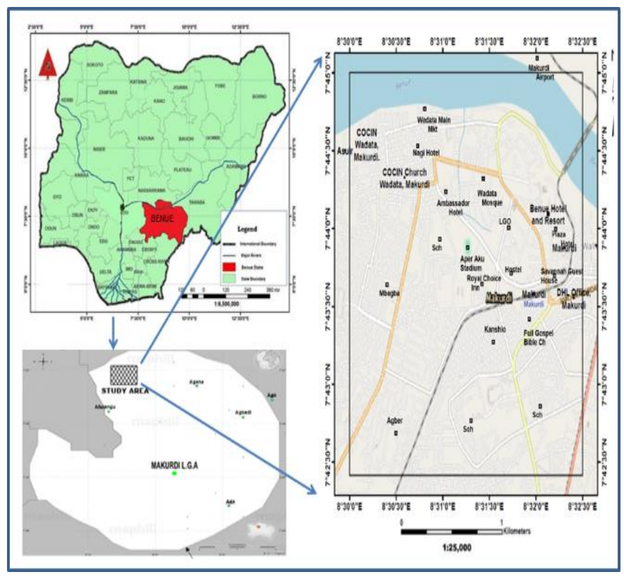

Fig. 1 Study area.

Materials and Methods

Sample Collection and Preservation

A total of thirty-five (35) water samples were collected from different water sources within the study area (Fig. 2) to evaluate the hydrogeochemical characteristics of groundwater and surface water. These samples comprised two (2) borehole samples, twenty-nine (29) hand-dug well samples, and four (4) surface water samples collected from River Benue. Groundwater samples were collected using clean screw-cap high-density polyethylene (HDPE) bottles. Prior to sample collection, each bottle was rinsed two to three times with the water sample to minimize contamination. The geographical coordinates of each sampling location were recorded using a Global Positioning System (GPS) device to enable accurate mapping of the sampling points.

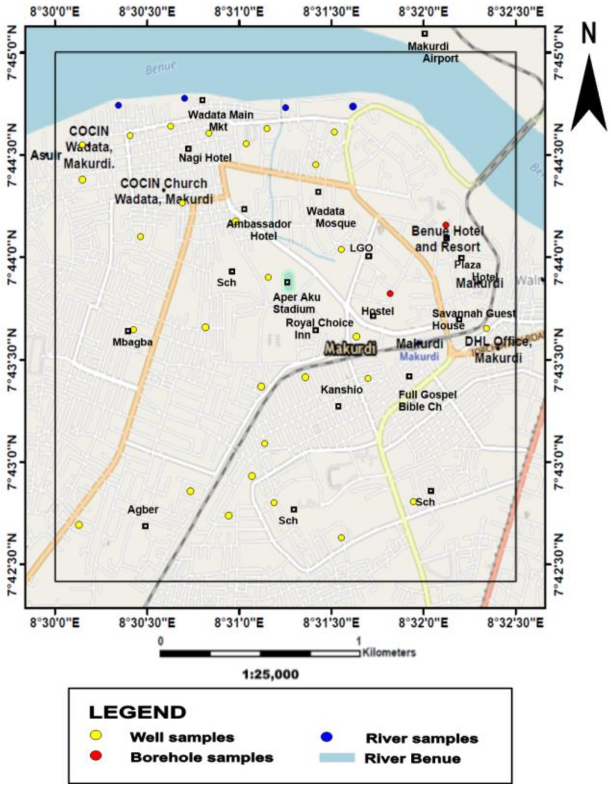

Fig. 2 Water sample locations.

The depths of the sampled hand-dug wells in the study area range from approximately 0.71 m to 8.4 m, with most wells occurring between depths of about 3.5 m and 5.5 m. Water levels in the wells range between 0.3 m and 8.3 m, while the water column ranges between 0 m and 5.5 m. This variation in well depth reflects differences in aquifer conditions and groundwater availability within the study area and may influence groundwater chemistry due to variations in residence time and water-rock interaction processes.

Samples intended for physicochemical analysis were preserved by adding a few drops of concentrated nitric acid to prevent precipitation and adsorption of dissolved metals during storage and transportation. However, samples for bacteriological analysis were collected separately in sterile bottles without acidification to prevent suppression of microbial activity. All collected samples were immediately stored in an ice-packed cooler and transported to the laboratory where they were refrigerated at approximately 4°C prior to analysis to minimize physicochemical and biological changes.

Laboratory Analysis

Laboratory analyses of the water samples were conducted at the Upper Niger River Basin Development Authority Laboratory in Minna, Niger State. The analyses were carried out using standard procedures for the examination of water and wastewater samples. Physical parameters measured include turbidity, electrical conductivity (EC), total dissolved solids (TDS), temperature, and pH. Turbidity was measured using a HACH 2100A turbidimeter, while electrical conductivity and total dissolved solids were measured using a HACH Sension 5 conductivity meter.

Temperature was measured using an analog mercury thermometer, and pH was determined using a calibrated digital pH meter. Chemical parameters analysed include total hardness, dissolved oxygen, sulphate, chloride, nitrate, phosphate, nitrite, fluoride, iron, copper, phosphorus, bicarbonate, sodium, potassium, calcium, and magnesium. These parameters were analyzed using standard laboratory analytical procedures. Bacteriological analysis was carried out to determine total coliform and faecal coliform counts, which are important indicators of microbial contamination in water. For the bacteriological parameters, faecal and total coliforms were determined.

Quality Assurance and Quality Control

To ensure the reliability and accuracy of the analytical results, appropriate quality assurance and quality control procedures were implemented throughout the sampling and laboratory analysis processes. Analytical instruments were calibrated using standard reference solutions prior to analysis. Duplicate samples were analyzed periodically to evaluate analytical precision, while reagent blanks were used to check for possible contamination during laboratory procedures. Standard reference materials were also used to verify the accuracy of the analytical measurements. Furthermore, the ionic charge balance between major cations and anions was evaluated to confirm the reliability of the hydrochemical data prior to hydrochemical interpretation. Samples with acceptable ionic balance errors within recommended limits were considered suitable for hydrochemical analysis.

Hydrochemical Interpretation

Hydrochemical diagrams were used to interpret the chemical characteristics and evolution of groundwater in the study area. Piper diagrams were used to classify groundwater types and identify dominant hydrochemical facies. Durov diagrams were employed to interpret hydrochemical processes and mixing relationships among the sampled water types. Gibbs diagrams were also used to evaluate the dominant mechanisms controlling groundwater chemistry, including precipitation dominance, rock–water interaction, and evaporation processes.

Results and Discussion

The results of the physicochemical and bacteriological analyses of the thirty-five water samples collected from boreholes, hand-dug wells, and surface water (River Benue) are presented in Table 1. The analyzed parameters were compared with the Nigerian Standard for Drinking Water Quality (NSDWQ, 2015) and the World Health Organization (WHO, 2017) drinking water guidelines to evaluate their suitability for domestic consumption.

The total dissolved solids (TDS) concentrations of the analyzed water samples range from 48 mg/L to 1190 mg/L, with a mean value of 378.39 mg/L. Electrical conductivity (EC) values range between 72.5 µS/cm and 1577 µS/cm, with an average value of 539.47 µS/cm. The pH values range from 7.26 to 9.0, indicating that the water samples are generally slightly alkaline in nature. Temperature values recorded during sampling range between 30.0°C and 30.9°C, with an average value of 30.64°C, reflecting the prevailing environmental conditions of the study area. Turbidity values range between 0.55 NTU and 1.54 NTU, which are generally within the acceptable limits for drinking water.

Total hardness values range between 48 mg/L and 461 mg/L, with a mean value of 145.31 mg/L, indicating that the groundwater varies from soft to moderately hard depending on the sampling location. Calcium concentrations range from 6.41 mg/L to 57 mg/L, while magnesium concentrations range from 2.93 mg/L to 94 mg/L. These variations in calcium and magnesium concentrations largely influence the hardness of groundwater in the study area since total hardness is primarily controlled by the presence of these two ions. The concentrations of sodium and potassium range between 5 mg/L and 200 mg/L and 4 mg/L and 41 mg/L, respectively

Bicarbonate concentrations range from 7 mg/L to 112 mg/L, while chloride concentrations range between 4 mg/L and 250 mg/L. Sulphate concentrations range from 3 mg/L to 100 mg/L. Nutrient concentrations also vary across the sampled locations. Nitrate concentrations range between 1.87 mg/L and 69.1 mg/L, while phosphate concentrations range between 0.45 mg/L and 3.65 mg/L.

Nitrite concentrations range from 0 mg/L to 1.3 mg/L, and fluoride concentrations range between 0 mg/L and 2 mg/L. The concentrations of trace metals analyzed in the study area are relatively low. Iron concentrations range from 0.01 mg/L to 0.03 mg/L, while copper concentrations range between 0.14 mg/L and 1.37 mg/L. Bacteriological analysis reveals that total coliform counts range between 5 and 190 counts per 100 mL, while faecal coliform counts range between 0 and 57 counts per 100 mL The presence of coliform bacteria in some sampling locations indicates possible contamination from surface sources such as sewage infiltration, improper waste disposal, and runoff from surrounding areas. Out of the thirty-five water samples analyzed, eleven samples contain one or more parameters exceeding the permissible limits specified by the Nigerian Standard for Drinking Water Quality and the World Health Organization guidelines. These locations include Yanbu, Wadata, Sharp Bend Wadata, Government Day Secondary School Wadata, Federal Medical Center Wadata, Amokachi Lane, Vandekia Street, UBA Bank Wadata, RMC Block Industry, Wadata Market, River Bank Wadata, and Beside Old North Bank Bridge. Water from these locations may therefore require appropriate treatment before being considered suitable for drinking and domestic use. The depths of the sampled hand-dug wells in the study area range from approximately 0.71 m to 8.4 m, with most wells occurring between depths of about 3.5 m and 5.5 m.

Shallow wells are generally more susceptible to contamination from surface activities such as waste disposal, sewage infiltration, and runoff, which may partly explain the elevated concentrations of some chemical and bacteriological parameters observed in certain locations. Hydrochemical plots were also generated to further understand the chemical characteristics of the groundwater. The Piper trilinear (Fig. 3) diagram shows that 57.1% of the analyzed samples belong to alkaline water types, while 42.9%fall within the earth-alkaline water category. The diagram also identifies four dominant hydrochemical facies in the study area, namely Ca-Mg-Cl-SO_4, Na-K-Cl-SO_4, Ca-Mg-HCO_3, and Na-K-HCO_3 water types. The Durov hydrochemical plot (Fig. 4) indicates that approximately 85.7% of the samples represent mixed water types with no dominant cation or anion, suggesting that groundwater chemistry in the study area is influenced by mixing processes.

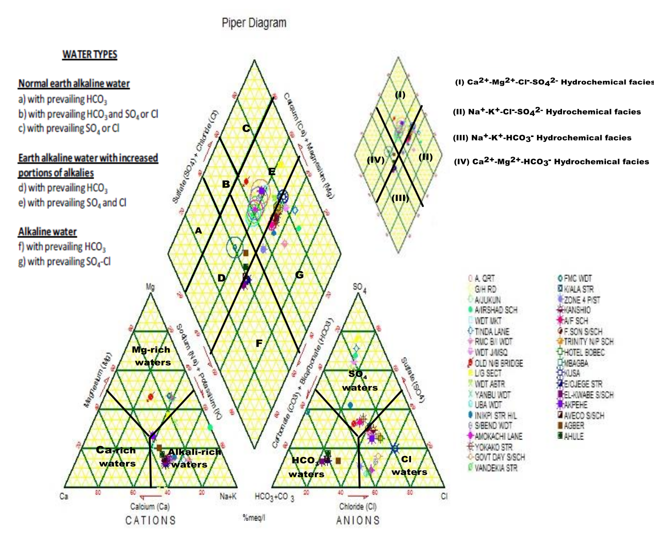

Fig. 3 Piper trilinear plot for the analysed cations and anions (Piper, 1944) Classification of hydrochemical facies using the Piper plot.

The Gibbs diagrams (Figs. 5 & 6) further show that rock weathering is the dominant mechanism controlling groundwater chemistry in the study area, with a minor influence from evaporation processes. This suggests that the chemical composition of groundwater is largely controlled by water-rock interaction processes occurring within the sedimentary formations of the Makurdi Basin. The results from the analysis of the water samples were compared with the Nigerian Standard for Drinking Water Quality (NSDWQ) 2015 and World Health Organization (WHO) drinking water guide 4th edition 2017 (Table 1).

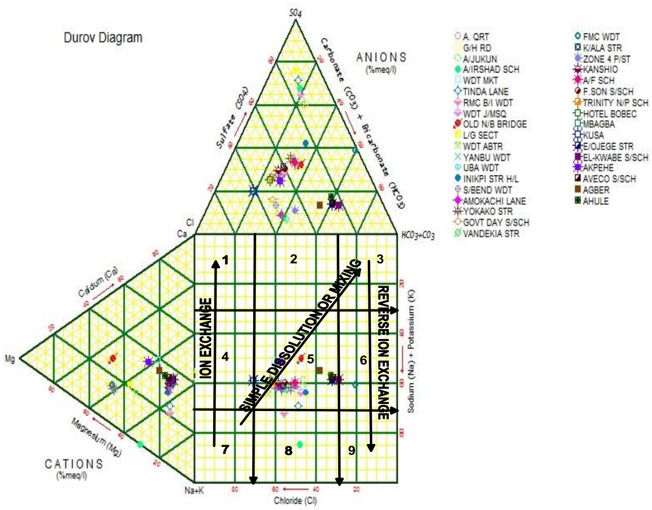

Fig. 4 Durov hydrochemical plot for the analyzed cations and anions (Kehew, 2001). Classification of hydrochemical facies using the Durov plot.

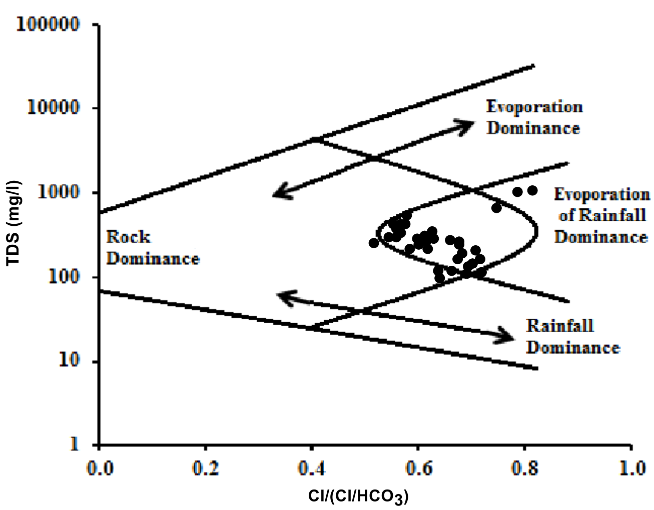

Fig. 5 Gibb's hydrochemical plot using anion ratio (Gibbs, 1970).

The physicochemical and bacteriological analyses of the groundwater and surface water samples provide important insights into the hydrochemical characteristics and water quality of the study area. Although the mean values of most parameters fall within the permissible limits of the Nigerian Standard for Drinking Water Quality (NSDWQ, 2015) and the World Health Organization (WHO, 2017) guidelines, a more detailed examination of individual sampling locations reveals significant variations in water quality across the study area.

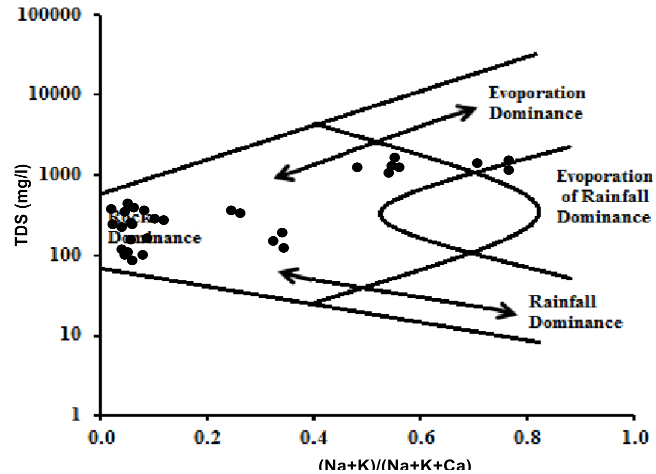

Fig. 6 Gibb's hydrochemical plot using cation ratio (Gibbs, 1970).

Electrical conductivity (EC) and total dissolved solids (TDS) are important indicators of the overall mineralization of groundwater. The EC values observed in this study show a positive relationship with TDS concentrations, indicating that the ionic content of the groundwater is largely responsible for the dissolved solids present in the water samples. This relationship suggests that mineral dissolution and water-rock interaction processes play a significant role in controlling groundwater chemistry within the Makurdi Formation. The hardness of groundwater is largely controlled by the concentrations of calcium and magnesium ions derived from the dissolution of carbonate and silicate minerals within aquifer materials. In the present study, variations in total hardness correspond closely with the concentrations of calcium and magnesium observed in the water samples. This confirms that calcium and magnesium ions are the major contributors to groundwater hardness in the study area and explains the variations observed in hardness values across different sampling locations.

The concentrations of nitrate and phosphate recorded in some of the sampled locations exceed recommended drinking water limits. Elevated nitrate concentrations in groundwater are often associated with anthropogenic activities such as agricultural fertilizer application, sewage infiltration, and improper waste disposal. The presence of elevated nitrate and phosphate concentrations in certain locations, therefore suggests possible contamination from anthropogenic sources within the study area. Bacteriological contamination was also observed in several water samples, as indicated by the presence of total coliform and faecal coliform bacteria. The occurrence of coliform bacteria in groundwater is an indication of possible contamination from human or animal waste, which may enter groundwater systems through poorly constructed wells, leaking septic systems, or infiltration from surface runoff. This contamination is of significant public health concern because it indicates the possible presence of disease-causing microorganisms.

Table 1. Mean and range of values for the analysed parameters in comparison with the NSDWQ 2015 and WHO, 2017

S. No.	Parameter	Range	Mean value	NSDWQ 2015	WHO 2017
1	TDS (mg/L)	48 – 1190	378.39	500	500
2	Conductivity (μS/cm)	72.5 – 1577μS/cm	539.47	1000	400
3	Dissolved Oxygen (mg/L)	5.49 – 7.65	6.48	-	-
4	Temperature (ºC)	30.0 – 30.9	30.64	Ambient	Ambient
5	pH	7.26 – 9.0	8.03	6.5-8.5	6.5-8.5
6	Turbidity (NTU)	0.55 – 1.54	1.90	5	5
7	Total Hardness (mg/L)	48 – 461	145.31	150	100
8	Total alkalinity	12 – 66	40.83	-	20-200
9	Iron (mg/L)	0.01 – 0.03	0.16	0.3	0.3
10	Copper (mg/L)	0.14 – 1.37	0.41	1	2
11	Sulphate (mg/L)	3 – 100	26.08	100	200
12	Phosphate (mg/L)	0.45 – 3.65	2.51	-	0.3
13	Phosphorus (mg/L)	0.12 – 1.43	0.89	-	-
14	Nitrate (mg/L)	1.87 – 69.1	21.7	50	50
15	Bicarbonate (mg/L)	7 – 112	39.31	-	125-350
16	Nitrite (mg/L)	0 – 1.3	0.24	0.2	3
17	Fluoride (mg/L)	0 – 2	0.16	1.5	1.5
18	Chloride (mg/L)	4 -250	38.28	250	250
19	Sodium (mg/L)	5 – 200	50.06	200	200
20	Potassium (mg/L)	4 – 41	22.34	-	1 – 2
21	Calcium (mg/L)	6.41 – 57	27.12	-	75
22	Magnesium (mg/L)	2.93 – 94	21.19	20	50
23	Total coliform (per 100mL)	5 – 190	40.36	10	10
24	Faecal coliform	0 – 57	6.29	Nil	Nil

The shallow depths of many of the hand-dug wells in the study area further increase their vulnerability to contamination. Shallow wells are more susceptible to infiltration of surface pollutants compared to deeper boreholes because they are directly influenced by surface activities such as waste disposal, sanitation practices, and agricultural runoff. Hydrochemical diagrams were also used to interpret the origin and evolution of groundwater chemistry in the study area. The Piper diagram indicates that the majority of the water samples fall within the alkaline and earth-alkaline water types. The dominant hydrochemical facies identified include Ca-Mg-Cl-SO_4 and Na-K-Cl-SO_4 water types, which suggest the influence of mineral dissolution and ion exchange processes. The Durov hydrochemical diagram indicates that most of the sampled groundwater belongs to mixed water types, with no single dominant cation or anion. This suggests that groundwater chemistry in the study area is influenced by mixing processes, possibly involving interactions between groundwater, surface water, and mineralized aquifer materials. The Gibbs diagrams further indicate that rock weathering is the dominant mechanism controlling groundwater chemistry in the study area. This implies that water-rock interaction processes within the sedimentary formations of the Makurdi Basin are the primary factors influencing the chemical composition of groundwater, with minor contributions from evaporation processes.

Conclusion

It is concluded that most of the analyzed water samples fall within acceptable drinking water limits when considering average parameter values. However, a more detailed examination of individual sampling locations shows that 11 out of the 35 sampled locations contain one or more parameters exceeding recommended limits, indicating that water from these locations may not be suitable for direct consumption without treatment. Hydrochemical analysis using Piper, Durov, and Gibbs diagrams revealed that groundwater in the study area is dominated by alkaline and earth-alkaline water types. The hydrochemical facies identified include Ca-Mg-Cl-SO_4, Na-K-Cl-SO_4, Ca-Mg-HCO_3, and Na-K-HCO_3 water types. The results further show that rock weathering and water-rock interaction processes are the dominant mechanisms controlling groundwater chemistry in the study area, with minor influence from evaporation processes.

The presence of elevated concentrations of nitrate, phosphate, and bacteriological contaminants in some sampling locations suggests the influence of anthropogenic activities such as improper waste disposal, sewage infiltration, agricultural activities, and urban development. These findings highlight the vulnerability of shallow groundwater systems to contamination in rapidly urbanizing environments. The results of this study provide important baseline information for groundwater quality monitoring and management in Makurdi metropolis, where groundwater serves as a major source of water for domestic use and agricultural activities. Ensuring the protection of groundwater resources is therefore essential for safeguarding public health and supporting sustainable urban and agricultural development in the region.

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