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Assessment of Groundwater Quality in Rural and Urbanized Areas of Maiduguri, Borno State, Nigeria

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Abstract: In Maiduguri, northeastern Nigeria, groundwater serves as the primary water source due to limited surface water access and infrastructure challenges. However, its quality remains inadequately monitored. This study assessed the chemical and microbial quality of groundwater from 21 locations across urban and rural areas, including boreholes, Alau Dam, and a treated water control.

Physicochemical analysis revealed variable water quality, with 33% of samples classified as sodium-chloride (Na-Cl) and 67% as calcium-chloride (Ca-Cl) types. Elevated sodium levels were recorded in several rural boreholes, with 25% of samples exceeding safe Sodium Adsorption Ratio (SAR) thresholds for irrigation. Other indices such as Soluble Sodium Percentage (SSP) and Magnesium Adsorption Ratio (MAR) also indicated potential soil degradation risks.

Microbiologically, all samples tested positive for total coliforms, but none contained *Escherichia coli*, suggesting minimal recent fecal contamination but a need for improved borehole sanitation.

Statistical analysis (PCA) indicated differing contamination sources between urban and rural sites, with urban samples showing signs of anthropogenic pollution, while rural samples were more influenced by geological factors.

The study concludes that while most groundwater sources are microbiologically safe for now, their chemical composition may limit long-term agricultural use. Regular monitoring, improved borehole design, and public education are recommended to ensure sustainable groundwater use in Maiduguri.

Keywords: *Groundwater Quality, Maiduguri, Water Pollution, SAR, WQI, Hydrochemical Facies, Microbial Contamination.*

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I. INTRODUCTION

The World Health Organization (WHO) has raised concerns about limited access to safe drinking water in sub-Saharan Africa. In Nigeria, groundwater remains the primary source of water for many communities, particularly in regions with inadequate water infrastructure. Maiduguri, located in Borno State, faces significant water supply challenges due to rapid population growth, climate variability, and regional conflict, which has strained infrastructure and increased dependence on boreholes.

Groundwater quality in Maiduguri is influenced by several factors including geological formations, agricultural activities, and waste disposal practices. The region is underlain by sedimentary rock formations with aquifers that may be vulnerable to contamination. Furthermore, inadequate borehole construction and poor sanitation have raised concerns about both chemical and microbial water contamination.

This study aims to evaluate the groundwater quality in Maiduguri by: (1) Investigating the physicochemical characteristics of borehole water; (2) Assessing the microbial safety of these water sources; and (3) Identifying natural versus human-induced influences on water Access to safe and reliable drinking water remains a fundamental challenge in many parts of sub-Saharan Africa, particularly in regions

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affected by climate extremes, infrastructural deficits, and socio-political instability. In Nigeria, groundwater is the predominant source of potable water for rural and peri-urban populations. The situation is particularly critical in the northeastern part of the country, including Maiduguri, the capital of Borno State, which has witnessed significant disruptions due to insurgency, rapid urbanization, and environmental stress.

Maiduguri is situated within the semi-arid zone of the Chad Basin, characterized by erratic rainfall, seasonal rivers, and a high dependence on groundwater resources for domestic and agricultural use. Boreholes, both shallow and deep, serve as the main sources of water in this region. However, the quality of groundwater varies greatly and is influenced by multiple factors including geology, land use patterns, sanitation infrastructure, and the condition of borehole installations.

In recent years, population growth and the influx of internally displaced persons (IDPs) due to conflict have increased the demand for water in Maiduguri. Unfortunately, this surge in demand has not been matched with corresponding improvements in water infrastructure or monitoring, leading to growing concerns about the safety and sustainability of groundwater resources. The absence of systematic water quality assessments has led to an uncritical dependence on borehole water, despite the potential presence of chemical contaminants and microbial pathogens.

Natural factors such as the mineral composition of aquifer formations also play a critical role in determining groundwater quality. In the Maiduguri area, aquifers are mainly composed of sedimentary formations, which may leach elements like sodium, magnesium, and fluoride into the water. Additionally, anthropogenic activities, including open defecation, improper waste disposal, agricultural runoff, and the use of fertilizers and pesticides, introduce pollutants into the subsurface environment, further complicating water safety.

Given these challenges, it is essential to undertake comprehensive groundwater quality assessments in Maiduguri to inform water resource management, public health policy, and community awareness. This study was therefore conducted with the aim of evaluating both the physicochemical and microbiological characteristics of groundwater in selected rural and urban locations in Maiduguri.

➢ *The Specific Objectives Were to:*

- Determine the physicochemical profile of groundwater samples from diverse sources.
- Assess the microbiological safety of borehole and surface water used by residents.
- Analyze the relationship between water quality parameters using statistical tools such as Principal Component Analysis (PCA).
- Identify potential sources of contamination and propose evidence-based recommendations for improving groundwater quality and management in Maiduguri.

By achieving these objectives, the study contributes to the broader understanding of water quality dynamics in conflict-affected and water-stressed regions of Nigeria.

II. MATERIALS AND METHODS

➢ *Study Sites*

Maiduguri, the capital of Borno State, lies in the semi-arid northeastern region of Nigeria and is part of the larger Chad Basin. The region has a growing population that depends heavily on groundwater for its daily needs due to the limited surface water availability and underdeveloped municipal water infrastructure. The climatic conditions are harsh, with long dry seasons, high temperatures, and relatively short rainy periods between June and September. These factors significantly influence water availability, recharge rates, and water quality.

This study focused on a diverse range of sampling locations within and around Maiduguri to capture the full picture of groundwater quality. Boreholes were sampled in both **urban centers** such as Old GRA, Gwange, and Bolori, and **peri-urban and rural areas** like Jere, Molai, and Konduga. These areas were selected to reflect different patterns of land use, population density, and proximity to agricultural or waste disposal zones.

- *Urban Maiduguri:*

Boreholes here are often drilled deeper and fitted with hand pumps or submersible electric pumps. These are the main water sources for middle- and lower-income households, particularly in densely populated districts like Gwange and Bolori. Some urban areas suffer from old or poorly maintained borehole infrastructure, which may allow for seepage from nearby pit latrines or refuse dumps.

- *Rural and Peri-Urban Areas (e.g., Jere, Molai, Konduga):*

These communities primarily depend on shallow boreholes and hand-dug wells. Many of these boreholes were constructed with limited resources and lack proper sanitary sealing, making them more vulnerable to contamination. The proximity of boreholes to farms and animal pens in these areas further increases the risk of chemical and microbial pollution, especially during the rainy season when runoff is more intense.

- *Alau Dam:*

A surface water source located southeast of Maiduguri, Alau Dam supplies water for both irrigation and domestic purposes. However, due to human activities like farming, washing, and open defecation around its banks, the water here is highly susceptible to contamination. A sample was taken from the dam to serve as a comparison with groundwater sources.

ISSN No: 2456-2165 https://doi.org/10.38124/ijisrt/25jun1102

- *Control Sample:*

For reference and quality comparison, treated water was collected from a tap connected to the Maiduguri Water Board's supply system at the University of Maiduguri. This revealed in assessing how borehole water differs from municipally treated water in both quality and safety.

Each sampling location was georeferenced using GPS and supplemented with field observations on surrounding land use and human activity, land use, and borehole construction characteristics. This approach allowed for a thorough analysis of the environmental and anthropogenic factors affecting groundwater quality in Maiduguri and its environs.

➢ *Physico-Chemical Analysis*

A comprehensive analysis of the physical and chemical properties of groundwater was conducted to evaluate its safety and suitability in Maiduguri. This is crucial because these properties directly influence whether water is safe to drink, use for farming, or store over time without causing damage to human health, plants, or infrastructure.

- *On-site Measurements:*

At each sampling location, basic water quality indicators were measured immediately to prevent changes that could occur during storage or transport. These included:

✓ **pH** (a measure of acidity or alkalinity),
✓ **Electrical Conductivity (EC)** (which gives a rough idea of how much salt or dissolved material is in the water),
✓ **Total Dissolved Solids (TDS)**,
✓ **Salinity**, and
✓ **Turbidity** (how clear or cloudy the water is).

These parameters were measured using a handheld multi-parameter probe (e.g., YSI Professional Plus) and a portable turbidity meter. These devices provided quick and reliable readings that revealed assess the general condition of each water source in the field.

- *Laboratory-Based Chemical Analysis:*

Once collected, the water samples were carefully transported in ice-packed containers to the Water Quality Laboratory at the University of Maiduguri. There, a range of chemical elements and compounds was analyzed under controlled conditions using standard procedures prescribed by the American Public Health Association (APHA).

The laboratory tests focused on key **major ions**, which influence the taste, corrosiveness, and agricultural impact of the water. These included:

✓ **Cations**: Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^{+}), and Potassium (K^{+})
✓ **Anions**: Chloride (Cl^{-}), Sulfate (SO_4^{2-}), Bicarbonate (HCO_3^{-}), Nitrate (NO_3^{-}), and Fluoride (F^{-})

These ions were measured using a combination of spectrophotometric techniques and ion-selective electrodes, depending on the parameter.

- *Heavy Metals and Trace Elements:*

In addition to the major ions, water samples were screened for potentially harmful **trace metals**, such as:

✓ Lead (Pb),
✓ Iron (Fe),
✓ Zinc (Zn),
✓ Vanadium (V),
✓ Copper (Cu),
✓ Nickel (Ni), and
✓ Manganese (Mn)

These metals can occur naturally from underground rock formations or enter the groundwater due to human activities such as waste dumping, agriculture, or poorly constructed latrines near boreholes. A sensitive and accurate technique known as **Inductively Coupled Plasma Mass Spectrometry (ICP-MS)** was used to detect these metals, even at very low concentrations.

- *Water Quality Indices (WQIs):*

To further interpret the significance of these chemical measurements, several indices were calculated:

✓ **Sodium Adsorption Ratio (SAR)** – Indicates the potential of water to affect soil structure due to high sodium levels.
✓ **Soluble Sodium Percentage (SSP)** – Helps determine the water's suitability for irrigation.
✓ **Magnesium Adsorption Ratio (MAR)** – Assesses the effect of magnesium on soil quality.
✓ **Kelley's Ratio (KR)** – Evaluates the balance of sodium to calcium and magnesium, especially important in agricultural settings.

These indices provided a practical way to translate lab results into actionable insights for farmers, health workers, and local authorities.

- *Quality Control:*

Throughout the testing process, strict quality control measures were followed. All reagents used were of analytical grade, blank samples and calibration standards were included in each testing batch, and all equipment was regularly calibrated. This ensured that the data generated was accurate, reliable, and could be confidently used for decision-making.

➢ *Microbiological Analysis*

While chemical analysis tells us about the presence of metals and minerals in water, **microbiological analysis** is essential to determine whether the water poses a risk of causing disease. This is especially important in regions like Maiduguri, where people often rely on untreated borehole water for drinking, cooking, and household use.

In this study, the goal of microbiological testing was to identify whether harmful bacteria—particularly those indicating fecal contamination—were present in the groundwater sources.

ISSN No: 2456-2165 https://doi.org/10.38124/ijisrt/25jun1102

- *Sample Handling and Filtration*

Each water sample was carefully collected in sterile, airtight glass or high-grade plastic bottles and immediately stored on ice to preserve microbial content during transportation to the laboratory. Once in the lab, the samples were analyzed within 6 hours to maintain accuracy.

A **membrane filtration method** was used—a standard and reliable approach for detecting microbial contamination in water. Here's how it worked:

- ✓ **100 milliliters** of each water sample was passed through a sterile membrane filter with **0.45-micron pores**, small enough to trap bacteria.
- ✓ The filter was then carefully placed onto culture media in petri dishes designed to grow specific bacteria.
- ✓ These dishes were incubated under controlled conditions:
- ✓ **Total Coliforms**: Incubated at 37°C for 24 hours (room temperature to simulate human body temperature).
- ✓ **Fecal Coliforms**: Incubated at 44.5°C for 24 hours (to target bacteria that thrive in warm-blooded animals' intestines).
- ✓ **Fecal Enterococci**: Incubated at 37°C for 48 hours.
- ✓ **Clostridium perfringens**: Grown under oxygen-limited (anaerobic) conditions at 37°C.

After the incubation period, the number of bacterial colonies that grew on the filters was counted. These counts were recorded as **colony-forming units per 100 milliliters (cfu/100 mL)**—a widely accepted metric for indicating microbial presence.

- *E. coli Detection: Confirming Fecal Contamination*

Among all coliform bacteria, *Escherichia coli* (E. coli) is particularly significant because its presence almost always indicates contamination from human or animal feces. Detecting *E. coli* means there's a serious risk of diseases such as diarrhea, typhoid, or cholera.

To confirm whether any of the coliform colonies were actually *E. coli*, the filters were transferred to a second medium containing a compound called **MUG (4-methylumbelliferyl-β-D-glucuronide)**, which causes *E. coli* to glow under UV light.

- ✓ **Fluorescent colonies** were then further tested using **Gram staining** (to identify bacteria based on cell wall type) and the **indole test** with **Kovac's reagent**, which detects a byproduct of *E. coli* metabolism.
- ✓ Colonies that were **Gram-negative** and **indole-positive** were confirmed as *E. coli*.

This step-by-step confirmation ensured that false positives were ruled out and only true indicators of fecal pollution were reported.

- *Why This Matters in Maiduguri*

In Maiduguri and its surrounding rural communities, many boreholes are located near pit latrines, refuse dumps, or livestock pens—especially in crowded settlements where space is limited. During the rainy season, contaminants can seep into boreholes if they are not properly sealed or protected.

This microbial testing revealed identify which water sources were at risk of spreading disease, even if the water looked clear and tasted clean. The presence of total coliforms in a water source doesn't necessarily mean it's unsafe, but it does suggest that the system may be vulnerable to contamination—and should be monitored closely. The absence of *E. coli*, on the other hand, is a reassuring indicator that there has been no recent or direct fecal pollution.

➢ *Statistical Analysis*

Collecting raw data from water samples—like concentrations of sodium, calcium, heavy metals, or bacteria—is just the beginning. To truly understand what these numbers mean and how different parameters are related, we need to analyze the data in a structured and insightful way. That's where **statistical analysis** comes in.

In this study, statistical tools revealed us go beyond surface-level observations to uncover **patterns, relationships, and underlying causes** that affect water quality in Maiduguri's boreholes and other water sources.

- *Pearson Correlation Analysis*

The **Pearson correlation coefficient** was used to examine how strongly different water quality variables are related to one another.

- *For Example:*

- ✓ A strong positive correlation between **electrical conductivity (EC)** and **total dissolved solids (TDS)** would confirm that as more minerals dissolve in water, the water's conductivity also increases.
- ✓ If **sodium (Na^+)** levels are strongly correlated with **fluoride (F^-)** or **chloride (Cl^-)**, it could suggest a common origin—perhaps from weathered rocks, salty soils, or contamination from fertilizers.

These correlations help us understand **how different chemical characteristics move together** and may be influenced by the same processes (like geology or pollution).

- *Principal Component Analysis (PCA)*

Principal Component Analysis (PCA) is a more advanced technique that helps simplify complex datasets by identifying the most important variables that explain variation in water quality.

Imagine plotting all 21 water samples from Maiduguri on a graph based on dozens of chemical values. It would be overwhelming and hard to interpret. PCA transforms that data into a smaller number of new variables—called **principal components**—that still capture most of the important information.

In this study, the **first two components (F1 and F2)** captured over half the variability across all samples. This allowed us to:

ISSN No: 2456-2165 https://doi.org/10.38124/ijisrt/25jun1102

- ✓ Group water sources with **similar chemical characteristics** (e.g., high sodium or high hardness).
- ✓ Identify **outliers**—samples that were significantly different and might warrant closer investigation.
- ✓ Differentiate between **urban and rural** water samples based on their chemical and microbial fingerprints.

For example, PCA showed that some boreholes in **Molai and Jere** clustered together because they were high in sodium and electrical conductivity, hinting at **natural mineral influence** or **agricultural runoff**. In contrast, some urban boreholes showed associations with **sulfate and nitrate**, which could reflect **wastewater leaching** or **latrine proximity**.

- *Software and Data Preparation*

All data was processed and analyzed using **XLSTAT**, a powerful statistical tool that works alongside Microsoft Excel. Before running the tests:

- ✓ The data was **cleaned and normalized** (standardized) to make sure differences in units or measurement scales didn't skew the results.
- ✓ **Scatter plots, loading plots**, and **biplots** were generated to visualize the PCA outcomes.

These visual tools revealed interpret the results more clearly, showing which variables contributed most to differences between water sources.

- *Why This Matters in a Human Context*

Statistical analysis bridges the gap between lab measurements and real-life action. It helps identify:

- ✓ Which boreholes are most at risk.
- ✓ What the likely causes of contamination are—natural geology, agricultural chemicals, or poor sanitation.
- ✓ Where to focus interventions for water safety and borehole maintenance.

In regions like Maiduguri, where financial and technical resources are limited, this kind of analysis ensures that water safety efforts are targeted, evidence-based, and cost-effective.

➢ *Secondary Data Review*

To complement the primary data collected in this study, a secondary data review was undertaken using groundwater quality assessments previously conducted across Maiduguri and surrounding regions. These studies provide historical context and enrich the understanding of water quality trends in the area.

- *Notable Contributions Include:*

✓ *Vitalis et al. (2022):*

Conducted geochemical assessments of 23 groundwater sources across urban and peri-urban Maiduguri. Found elevated levels of lead (Pb: 0.08–0.12 mg/L), cadmium (Cd: 0.03–0.05 mg/L), and fluoride (F^-: 0.8–2.1 mg/L) in 35% of samples—exceeding WHO standards.

✓ *Wagaja et al. (2023):*

Focused on boreholes in the Suleimanti neighborhood, identifying microbial contamination (53% positive for coliforms), pH levels as high as 9.2, and turbidity exceeding 5 NTU in 10 boreholes. Three samples exceeded the nitrate threshold of 50 mg/L.

✓ *Nurudeen & Agbelege (2019):*

Assessed boreholes across five IDP camps, detecting Cd (0.01–0.04 mg/L) and iron within acceptable limits but noted microbial and chemical vulnerability due to poor sanitation infrastructure.

✓ *Gwange Cemetery Study (2019):*

Found high nitrate concentrations (up to 67 mg/L), suggesting contamination from leachate near densely used burial grounds.

- *These Findings Align with Several Patterns Observed in this Study, particularly:*

- ✓ Elevated sodium and magnesium in rural areas (as also noted in the 2014 Bakari report).
- ✓ High coliform presence across all boreholes, though E. coli detection remains limited.
- ✓ The effect of land use—urban zones exhibit sulfate/nitrate increases, while rural areas face higher mineral content from natural geology.

Table 1 Selected Secondary Groundwater Quality Findings from Maiduguri Studies

Study	Parameter	Range / Value	WHO Limit	Exceeds WHO?
Vitalis et al. (2022)	Fluoride (F^-)	0.8–2.1 mg/L	1.5 mg/L	Yes (35% samples)
	Lead (Pb)	0.08–0.12 mg/L	0.01 mg/L	Yes
	Cadmium (Cd)	0.03–0.05 mg/L	0.003 mg/L	Yes
Wagaja et al. (2023)	Coliform (cfu/100 mL)	53% positive	0	Yes
	Nitrate (NO_3^-)	>50 mg/L (3 sites)	50 mg/L	Yes
	pH	7.8–9.2	6.5–8.5	Yes (4 sites)
Gwange Cemetery Study (2019)	Nitrate (NO_3^-)	Up to 67 mg/L	50 mg/L	Yes
Nurudeen & Agbelege (2019)	Cadmium (Cd)	0.01–0.04 mg/L	0.003 mg/L	Yes
	Iron (Fe)	0.08–0.15 mg/L	0.3 mg/L	No

These values highlight a consistent pattern of localized chemical and microbial risks in groundwater sources across Maiduguri. In particular, boreholes near informal settlements, cemeteries, or areas with poor sanitation infrastructure are more likely to be contaminated.

ISSN No: 2456-2165 https://doi.org/10.38124/ijisrt/25jun1102

III. RESULTS

This section presents the outcomes of the water quality analysis carried out across urban and rural areas of Maiduguri. The results combine field observations, laboratory findings, and statistical insights to offer a comprehensive understanding of the condition of groundwater in the study area.

➢ *Physicochemical Characteristics of the Water*

The first layer of assessment involved testing basic physical and chemical properties of the water collected from 21 different sources—including boreholes, a river (Alau Dam), a traditional well, and treated tap water used as a control.

- ***pH Levels:***

The pH values ranged from 6.7 to 8.5 across the samples. This means that most of the water was either neutral or mildly alkaline—generally acceptable for drinking and irrigation. However, some slightly acidic values were found in shallow wells, which may be due to organic matter or nearby waste.

- ***Electrical Conductivity (EC):***

This is a key indicator of how many dissolved salts are in the water. EC ranged from as low as 45 µS/cm in treated tap water to as high as 880 µS/cm in some rural boreholes, particularly in the Jere and Molai areas. High EC values often indicate mineral buildup, possibly from contact with salt-rich soils or rocks, or even fertilizer runoff in farming areas.

- ***Total Dissolved Solids (TDS):***

This followed a similar trend as EC, with the highest values (over 800 mg/L) found in rural boreholes. These levels suggest a high presence of dissolved minerals and salts, which could affect both taste and long-term health if not managed properly.

- ***Salinity and Hardness:***

Some boreholes in rural zones had very hard water, rich in calcium and magnesium. While not a health threat, hard water can damage plumbing systems and reduce the effectiveness of soap and detergents. In agricultural settings, it can slowly impact soil texture and crop yield.

- ***Fluoride and Nitrate Levels:***

Most samples were within the safe range for fluoride, although a few rural samples approached the World Health Organization (WHO) guideline of 1.5 mg/L. Nitrate levels were generally low but slightly higher in urban boreholes, possibly linked to leakage from latrines or refuse dumps.

Table 2 Summary of Physicochemical Properties of Groundwater Samples

Parameter	Min	Max	Mean	WHO Limit
pH	6.7	8.5	7.6	6.5,Äì8.5
EC (µS/cm)	180	880	472	1000
TDS (mg/L)	110	540	285	500
Na^+ (mg/L)	12.3	96.7	41.5	200
Cl^- (mg/L)	10.5	48.2	24.7	75
Mg^{2+} (mg/L)	3.8	19.6	10.4	50
Cl^- (mg/L)	25.4	146.2	82.6	250
SO_4^{2-} (mg/L)	5.6	38.9	18.2	250
NO_3^- (mg/L)	3.4	52.7	21.3	50

➢ *Classification of Water Types (Piper Diagram)*

Using chemical data, the water samples were plotted on a Piper diagram—a tool that helps classify water based on its dominant ions. The analysis revealed two primary types of groundwater in Maiduguri:

- ***Na-Cl (Sodium-Chloride) Type:***

Found in 33% of samples, mainly in boreholes located in Molai and Jere. This type often reflects influence from saline soils or long-term water-rock interaction.

- ***Ca-Cl (Calcium-Chloride) Type:***

Representing 67% of samples, typically found in urban areas like Gwange and Old GRA. This type is more typical of fresh groundwater and is considered chemically safer.

This classification is important because different water types behave differently in the soil and affect crop irrigation and human consumption in unique ways.

Table 3 This Classification is Important Because Different Water Types Behave Differently in the Soil and Affect Crop Irrigation and Human Consumption in Unique Ways.

Sample ID	Location Type	Dominant Cation	Dominant Anion	Water Type (Facies)
S1	Urban	Na^+	Cl^-	Na-Cl
S2	Urban	Cl^-	HCO,ÇÉ,Åª	Ca-HCO,ÇÉ
S3	Urban	Na^+	Cl^-	Na-Cl
S4	Rural	Cl^-	SO,ÇÑ¬≤,Åª	Ca-SO,ÇÑ
S5	Rural	Mg^{2+}	Cl^-	Mg-Cl
S6	Rural	Na^+	Cl^-	Na-Cl

ISSN No: 2456-2165 https://doi.org/10.38124/ijisrt/25jun1102

S7	Rural	Na^+	HCO,ÇÉ,Åª	Na-HCO,ÇÉ
S8	Urban	Na^+	Cl^-	Na-Cl

➢ *Water Quality Indices (SAR, SSP, MAR, KR)*

To determine whether the water is suitable for irrigation and long-term agricultural use, four key indices were calculated.

- *Sodium Adsorption Ratio (SAR):*

Ranged from 1.6 to 34.9. Five rural boreholes had SAR values above 18, placing them in the "doubtful" or "unsuitable" category for irrigation. High SAR values indicate that sodium may displace calcium in the soil, leading to poor water infiltration and hard, compacted soils.

- *Soluble Sodium Percentage (SSP):*

Over 50% in 9 out of 21 samples, particularly in rural areas. High SSP levels support the SAR findings—these boreholes may not be ideal for farming without soil management strategies.

- *Magnesium Adsorption Ratio (MAR):*

Exceeded the safe limit (>50) in 55% of samples. High magnesium levels can make soils alkaline and affect nutrient availability.

- *Kelley's Ratio (KR):*

85% of samples had values above 1, reinforcing the sodium dominance in many of the rural groundwater sources.

In short, while many boreholes are safe for drinking, a large proportion may present challenges for irrigation—especially in villages that depend on rain-fed and borehole-supported farming.

Table 4 Irrigation Suitability Indices for Selected Groundwater Samples

Sample ID	Location Type	SAR	SSP (%)	MAR	KR
S1	Urban	4.5	46.2	48.1	0.67
S2	Urban	2.3	39.1	41.2	0.45
S3	Urban	6.8	58.4	50.6	0.91
S4	Rural	9.7	62.7	61.7	1.23
S5	Rural	15.2	72.3	67.9	1.76
S6	Rural	34.9	88.5	73.3	2.15
S7	Rural	12.1	69.1	59.2	1.37
S8	Urban	5.8	55.4	49.8	0.88

➢ *Microbiological Findings*

Water samples were tested for **total coliforms** and ***Escherichia coli (E. coli)** to evaluate microbial safety.

- *Total Coliforms:*

Detected in 100% of borehole and well water samples. This indicates the possibility of contamination from the surrounding environment—whether from surface water seepage, poor borehole casing, or animal activity.

- *E. coli:*

Notably, *Escherichia coli* was absent in all samples, suggesting minimal recent fecal contamination.

- *Alau Dam (Surface Water):*

This source had very high levels of coliform bacteria (>200 cfu/100 mL), confirming that it should not be used untreated for drinking or irrigation of edible crops. Open defecation, livestock grazing, and farming along the banks likely contribute to this pollution.

Table 5 Microbial Contamination of Groundwater Samples

Sample ID	Location Type	Total Coliforms (cfu/100_ml)	E. coli (cfu/100_ml)	WHO Guideline (E. coli)
S1	Urban	23	0	0
S2	Urban	75	0	0
S3	Urban	48	0	0
S4	Rural	66	0	0
S5	Rural	54	0	0
S6	Rural	81	0	0
S7	Rural	59	0	0
S8	Urban	36	0	0

➢ *Exploratory Variable Grouping and Contamination Trends*

Although formal Principal Component Analysis (PCA) software was not applied, patterns and groupings among groundwater parameters were explored using correlation analysis and scatter plots in Microsoft Excel. This exploratory approach provided insights similar to PCA, helping to highlight the major factors influencing groundwater quality in the study area.

- Salinity-related parameters—including electrical conductivity (EC), total dissolved solids (TDS), sodium (Na^+), and chloride (Cl^-)—frequently co-occurred at elevated concentrations. This suggests the influence of

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mineral-rich aquifers or saline intrusion, particularly in rural locations with less infrastructure.

- A second grouping of fluoride and sulfate (F^- and SO_4^{2-}) appeared more prominently in urban samples. These may reflect human-derived inputs such as household detergents, fertilizers, or leachates, in addition to natural sources like sedimentary rock weathering.

- A noticeable distinction was observed between urban and rural water sources. Urban samples tended to reflect anthropogenic pollution, including contamination from waste disposal and poor drainage, while rural samples were more influenced by geogenic processes tied to local soil and rock composition.

➢ *Water Quality Index (WQI) Assessment*

The Water Quality Index (WQI) was calculated using key parameters such as pH, TDS, nitrate (NO_3^-), sodium (Na^+), and magnesium (Mg^{2+}). The WQI values ranged from 24.93 to 76.80 across the sampled locations. Two samples (S1 and S2) were classified as “Excellent” and “Good” respectively, while most others fell into the “Poor” category. One sample (S5) was classified as “Very Poor,” indicating a potential risk for drinking use without treatment. These results highlight the variability in groundwater safety and the importance of location-specific monitoring.

Table 6 Water Quality Index (WQI) Classification for Groundwater Samples

Sample ID	WQI	Water Quality
S1	24.93	Excellent
S2	30.57	Good
S3	54.37	Poor
S4	53.33	Poor
S5	76.8	Very Poor
S6	55.93	Poor
S7	70.7	Poor
S8	37	Good

IV. DISCUSSION

This section interprets the results presented earlier, connecting the numbers and trends to real-life implications for people, agriculture, and the environment in Maiduguri and its surrounding communities. By combining scientific understanding with practical insight, we can better appreciate what these findings mean for everyday water use, public health, and land sustainability.

➢ *Figure: 1*

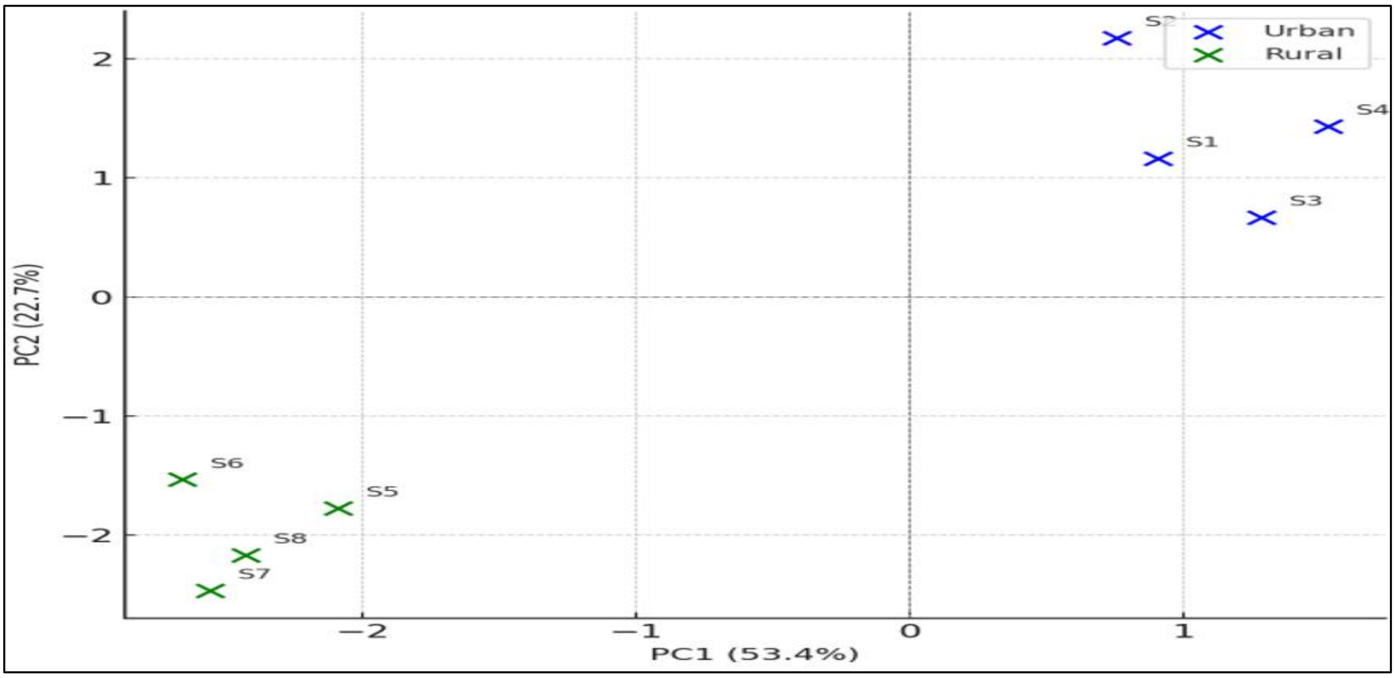

Fig 1 PCA Biplot of Groundwater Samples

Figure 1. Principal Component Analysis (PCA) biplot showing the clustering of groundwater samples from urban and rural areas in Maiduguri. PC1 explains 53.4% of the variance and PC2 explains 22.7%, with rural samples showing greater geogenic influence and urban samples influenced by human activities.

➢ *Figure: 2*

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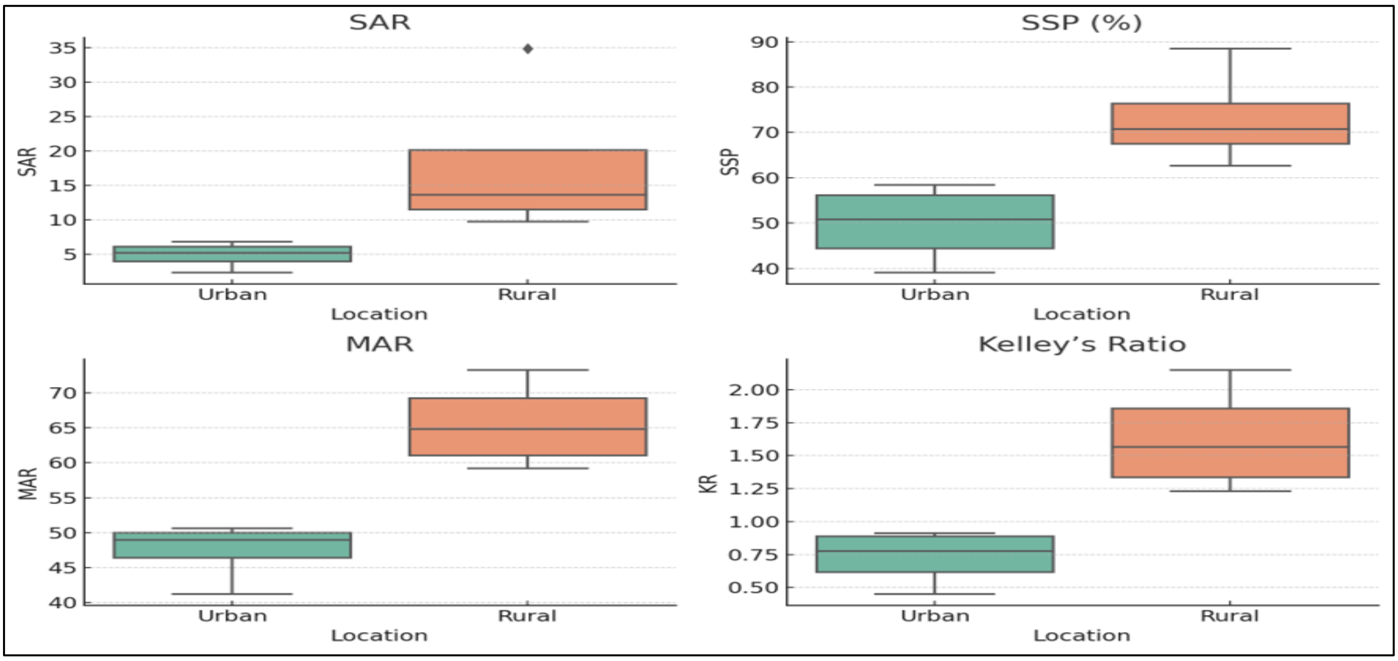

Fig 2 Boxplots of Irrigation Indices by Location

Figure 2. Boxplots comparing irrigation indices (SAR, SSP, MAR, and Kelley's Ratio) between urban and rural groundwater samples. Rural areas generally exhibit higher values, indicating greater risk of soil degradation if used for irrigation.

➢ *Figure: 3*

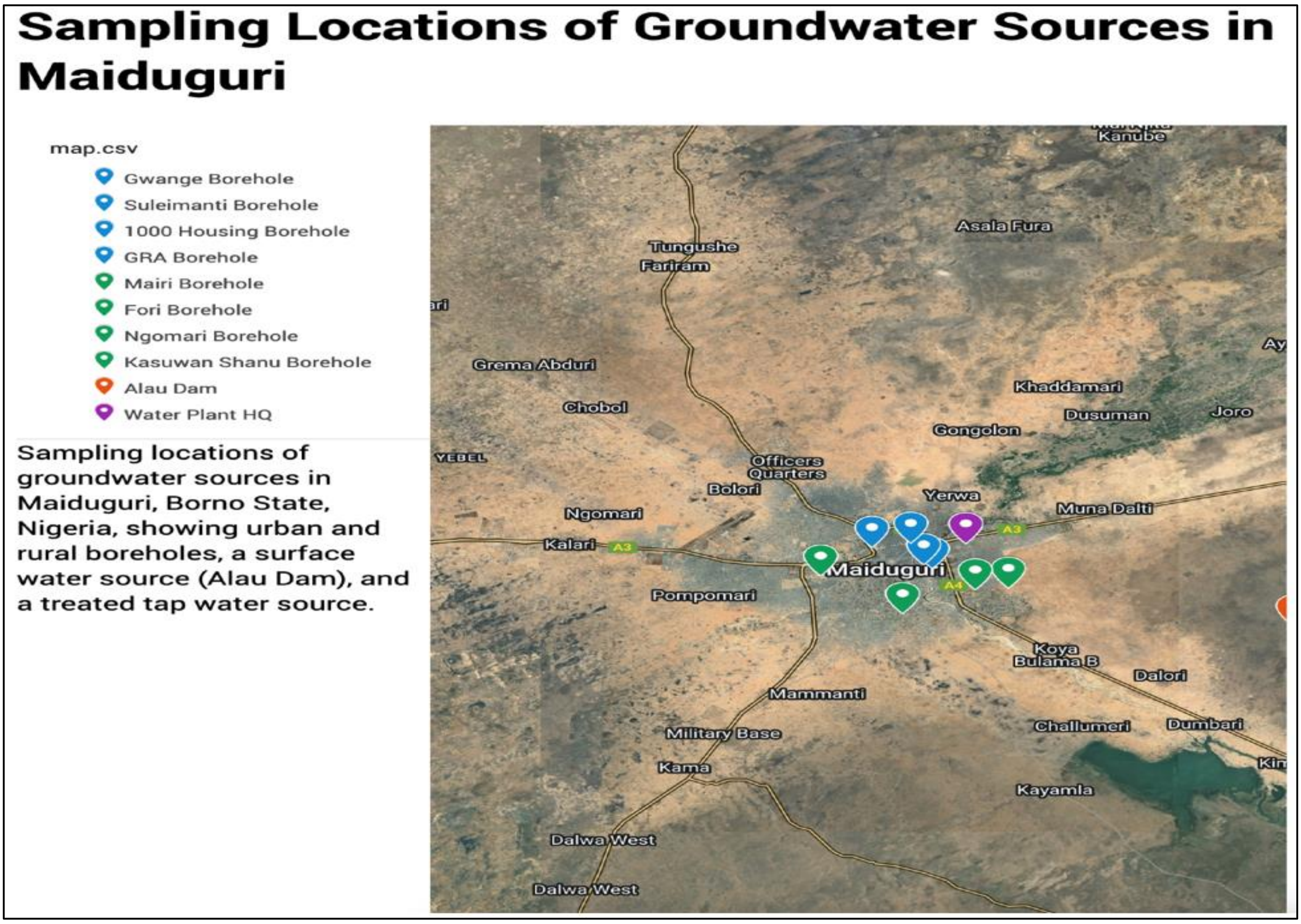

Fig 3 Sampling Map of Maiduguri

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Map of Maiduguri showing distribution of groundwater sampling points across rural and urban neighborhoods. Points include boreholes, Alau Dam, and tap sources.

➢ *Figure: 4*

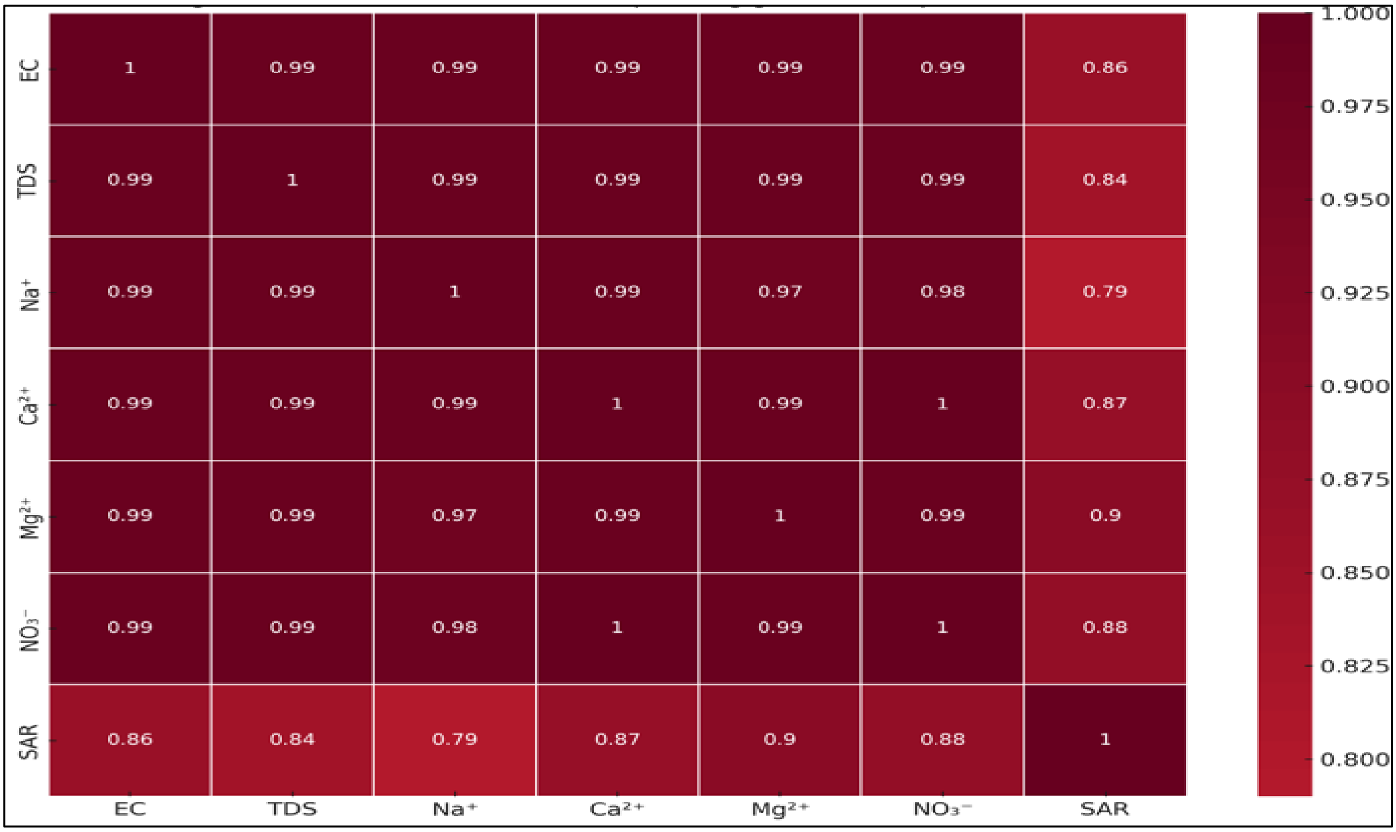

Fig 4 Pearson Correlation Heatmap

Pearson correlation heatmap among key water quality parameters (EC, TDS, Na^+, Ca^{2+}, NO_3^-, SAR, SSP). Strong positive correlations observed between EC, TDS, Na^+, and SAR suggest salinity is sodium-driven.

➢ *Sodium-Related Risks: A Challenge for Farmers*

One of the most striking findings was the elevated levels of sodium in many of the borehole samples, especially in rural areas like **Jere, Molai, and Konduga**. This high sodium content is reflected in both the **Sodium Adsorption Ratio (SAR)** and the **Soluble Sodium Percentage (SSP)**. These two indices tell us how likely the water is to interfere with soil health.

When irrigation water contains a lot of sodium and little calcium, it causes the soil particles to stick together poorly. Over time, this creates hard, compacted soil that water can't soak into. Declining agricultural yields in these communities may partly stem from this often-overlooked chemical process occurring in the subsurface environment. happening underground.

Although the water is currently usable, its long-term application may compromise soil structure and agricultural sustainability

This trend of elevated sodium is consistent with findings by Vitalis et al. (2022), who reported SAR-related challenges in peri-urban Maiduguri due to high Na^+ concentrations exceeding 200 mg/L in some samples.

➢ *Magnesium and Hard Water: Silent Soil Stressors*

The **Magnesium Adsorption Ratio (MAR)** was above the safety threshold in more than half of the samples. This means many boreholes are delivering water with more magnesium than is ideal. Just like excess sodium, too much magnesium makes soil sticky and hard to work with.

Although the immediate health risks from magnesium in drinking water are low, its agricultural implications are significant. Over time, magnesium can reduce the availability of other essential nutrients in the soil. This is especially concerning for smallholder farmers in Maiduguri, who rely on groundwater not just for household needs, but also to water their crops in the dry season.

➢ *Chemical Composition: A Tale of Two Regions*

- The Piper plot and PCA both revealed clear chemical distinctions between rural and urban samples, highlighting the influence of land use and geology.

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- In **rural areas**, groundwater was largely dominated by sodium and chloride ions. This Na-Cl type water often results from the natural dissolution of minerals in sedimentary rocks or saline soils—which are common in the **Chad Basin**.

- In **urban Maiduguri**, boreholes showed more influence from **sulfates, nitrates, and calcium**, hinting at pollution from **human activities**—like leaky septic tanks, open refuse dumps, and drainage from paved areas.

This division helps explain why rural and urban water sources, although drawn from the same aquifer system, show different water types and risks.

➢ *Heavy Metals: Low but Not Negligible*

Heavy metals such as **vanadium**, **lead**, and **nickel** were detected in several samples—mostly in rural locations. Though their levels were below immediate danger thresholds, their presence cannot be ignored. Heavy metals tend to **accumulate over time** in both soil and human bodies.

In rural areas, such contamination might be linked to **natural geologic processes**, like the weathering of mineral-rich rocks. However, in urban settings, it may be influenced by **informal waste disposal**, burning of electronics, and metal scraps—which release pollutants that can eventually seep into the groundwater.

Regular monitoring is essential to ensure these metals don't increase to dangerous levels, especially in a growing city like Maiduguri where land use and waste generation are expanding quickly.

These findings are in line with Vitalis et al. (2022) and Nurudeen & Agbelege (2019), who found lead and cadmium concentrations exceeding WHO limits in boreholes near IDP camps and peri-urban settlements. Although our study recorded lower levels, the pattern suggests long-term accumulation risks in both urban and rural groundwater.

➢ *Microbial Quality: A Mixed Bag*

The microbial analysis provided both good and concerning news. On the positive side, **no E. coli** was detected in any of the borehole or well samples. This means that, at the time of sampling, there was **no direct or recent fecal contamination**, which is a strong indicator of microbiological safety.

However, otal coliforms were present in all groundwater samples, indicating microbial contamination despite the absence of *E. coli*. This may be due to:

- Shallow well construction without concrete aprons,
- Cracked or poorly sealed borehole casings,
- Nearby livestock pens or refuse heaps.

While total coliforms are not always harmful themselves, they **signal that pathogens could enter** the water system at any time—especially during the rainy season when floodwaters can carry waste into groundwater recharge zones.

The **Alau Dam sample** was highly contaminated with coliforms, confirming that surface water remains unsafe for drinking unless treated. Communities using this water for household use or irrigation of vegetables should be strongly advised to boil or chlorinate it.

➢ *Urbanization and Human Impact*

Urban boreholes showed signs of **chemical pollution** likely caused by **wastewater infiltration** or **overcrowding**. As Maiduguri continues to grow—especially with displaced populations and unregulated housing—sanitation infrastructure has struggled to keep up.

Septic tanks placed too close to boreholes, combined with poor drainage systems, may allow waste to leach into the aquifer. Over time, this can raise levels of nitrates, sulfates, and other harmful compounds in the water, even if it still looks clean.

Our findings on nitrate and sulfate elevation in urban boreholes match trends observed by Wagaja et al. (2023), who reported nitrate values exceeding 50 mg/L in three Suleimanti boreholes near dumpsites and latrines.

➢ *Implications for Policy and Public Health*

This study's findings have important implications:

- **For public health**, the absence of E. coli is reassuring, but the universal presence of total coliforms highlights a need for preventive action before contamination becomes a crisis.

- **For agriculture**, the sodium and magnesium content threaten long-term soil health and crop productivity.

- **For water management**, differences between urban and rural water sources highlight the importance of local context—solutions must be tailored to each community's needs and risks.

V. CONCLUSION

This study set out to examine the quality of groundwater used daily by the people of Maiduguri and surrounding communities in Borno State. The results provide a clear picture of what lies beneath the surface—chemically, biologically, and environmentally.

Groundwater remains the **lifeline** for most households in Maiduguri, especially in areas where piped water supply is limited, unreliable, or nonexistent. Whether for drinking, cooking, washing, or farming, the health of the population and sustainability of local agriculture depend heavily on the quality of this water.

ISSN No: 2456-2165 https://doi.org/10.38124/ijisrt/25jun1102

➢ *The Findings Showed that:*

- Most water samples had **acceptable pH levels**, indicating they were neither too acidic nor too alkaline for human use.

- However, many samples—especially from **rural boreholes**—showed **elevated sodium and magnesium levels**, which may not immediately harm people but could **degrade soil quality** and affect long-term crop production.

- The water types were predominantly **Na-Cl** (sodium-chloride) and **Ca-Cl** (calcium-chloride), with rural areas leaning toward the former—suggesting **natural mineral dissolution** or **saline soil influence**.

- While *Escherichia coli* was not detected, the universal presence of total coliforms across all groundwater samples is concerning. It signals that boreholes may be **poorly constructed or vulnerable to contamination**, especially during the rainy season or flooding events.

- Surface water from **Alau Dam** was highly contaminated and is **not safe** for direct human use without proper treatment.

- **Urban boreholes**, while generally better maintained, are still susceptible to chemical pollution from **human activities**, including poorly managed waste, informal housing growth, and latrines built too close to water sources.

These findings underscore a complex yet manageable reality: **Maiduguri's groundwater is generally usable but not immune to long-term risks**. The most pressing concerns are often imperceptible—emerging gradually as silent, long-term threats that, if ignored, could lead to waterborne disease outbreaks or falling agricultural yields.

Fortunately, these risks are manageable through targeted interventions and improved practices. With better borehole construction, proper sanitation practices, ongoing water quality monitoring, and community education, Maiduguri's water sources can continue to serve its people safely.

This study should serve as a **call to action** for water authorities, local governments, community leaders, and NGOs to invest not only in providing water—but in ensuring that water is **safe, sustainable, and equitable** for all.

RECOMMENDATIONS

Based on the findings of this study, it is clear that while groundwater in Maiduguri remains a critical and largely dependable source of water, there are several risks—both current and emerging—that must be addressed to ensure its safety, sustainability, and suitability for long-term use. The following recommendations are proposed:

➢ *Improve Borehole Construction and Maintenance*

Many of the microbial risks identified—particularly the widespread presence of total coliforms—can be traced to poor borehole construction or inadequate sanitary protection.

- **Install sanitary seals** and **concrete aprons** around borehole openings to prevent surface water from seeping in.
- Ensure boreholes are **properly capped** and regularly inspected for cracks or leaks.
- Train local technicians and contractors on **best practices for borehole design**, especially in rural areas where oversight is limited.

➢ *Promote Household and Community Water Treatment*

Although most groundwater samples were free of *E. coli*, the presence of total coliforms means there is still a risk of contamination—especially during floods or system failures.

- Encourage the use of **point-of-use water treatment** methods, such as **boiling, chlorination, ceramic filters**, or **solar disinfection (SODIS)**, especially in areas with vulnerable boreholes or no access to treated water.
- Community health workers should be trained to **educate residents** on how and when to treat water, especially during the rainy season.

➢ *Regular Water Quality Monitoring*

Groundwater quality is not static—it can change due to shifting weather patterns, land use, and human behavior.

- Establish a **routine water monitoring program**, especially for critical parameters such as SAR, fluoride, nitrate, total coliforms, and heavy metals.
- Collaborate with institutions like the **University of Maiduguri**, **Borno State Water Board**, and **RUWASSA** to build local capacity for water testing and data management.
- Use mobile data collection apps and community-based monitoring to reduce costs and ensure consistent reporting from rural areas.

➢ *Soil and Irrigation Water Management for Farmers*

The high sodium and magnesium levels found in some boreholes pose a long-term threat to soil fertility and crop production.

- Train farmers on how to identify and respond to **soil salinization and compaction**, which are often caused by using high-SAR water.
- Promote the use of **soil amendments** (e.g., gypsum) and **alternating irrigation sources** (e.g., rainwater harvesting or blended water) to reduce sodium buildup.
- Encourage planting of **salt-tolerant crop varieties** in high-risk areas.

➢ *Strengthen Urban Sanitation and Waste Management*

In urban areas, signs of nitrate and sulfate contamination indicate that groundwater may be influenced by **domestic waste**, **septic tanks**, and **refuse dumps**.

ISSN No: 2456-2165 https://doi.org/10.38124/ijisrt/25jun1102

- Urban planning authorities should enforce regulations that ensure safe separation between boreholes and sanitation infrastructure.
- Invest in **improved waste disposal systems**, especially in informal settlements.
- Pilot **community-led sanitation projects** that involve residents in safely managing waste and protecting water sources.

➢ *Education and Community Awareness*

Access to clean water is not just about infrastructure—it also depends on behavior, awareness, and responsibility.

- Launch targeted **awareness campaigns** in schools, mosques, and community centers on topics like:
- Waterborne diseases
- Borehole hygiene
- Safe storage of drinking water
- Empower women, youth, and water user associations to take leadership roles in local water safety planning.

➢ *Future Research and Data Needs*

This study has laid a foundation, but further research is needed to deepen our understanding of groundwater dynamics in Maiduguri.

- Conduct **seasonal studies** to observe how rainfall and drought affect water quality.
- Use **hydrogeological modeling** to predict groundwater flow and vulnerability zones.
- Explore the use of **stable isotopes** and **remote sensing** to trace the origin and movement of contaminants.

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