ASSESSMENT OF HYDROGEOCHEMICAL CHARACTERISTICS OF GROUNDWATER FOR DRINKING AND IRRIGATION PURPOSES IN LAFIA AND ITS ENVIRONS

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ABSTRACT

Groundwater remains a primary source of domestic water supply in Lafia Local Government Area (LGA), yet its quality is increasingly threatened by rapid population growth, inadequate sanitation, and changing hydroclimatic conditions. This study assessed the physicochemical and microbiological characteristics of groundwater during the rainy and dry seasons using 20 representative boreholes and hand-dug wells. Parameters measured included pH, electrical conductivity (EC), total dissolved solids (TDS), major ions, trace metals, and microbial indicators (Escherichia coli and total coliforms). Results were evaluated against the World Health Organization (WHO, 2022) Guidelines for Drinking-water Quality and the Nigerian Standard for Drinking Water Quality (NSDWQ, 2015). Findings show widespread exceedances of permissible limits, notably extremely high concentrations of lead (Pb), cadmium (Cd), chromium (Cr), and arsenic (As), and frequent detection of E. coli. Rainy-season samples exhibited greater microbial contamination and turbidity, whereas dry-season samples recorded higher EC, hardness, and toxic metal concentrations. The combined seasonal trends highlight both anthropogenic contamination—primarily from sanitation sources—and geogenic mobilization of heavy metals. The study concludes that groundwater in Lafia poses substantial acute and chronic health risks, requiring urgent interventions including water safety planning, point-of-use treatment, improved well protection, and strengthened regulatory monitoring.

Keywords: Hydrogeochemical, Groundwater Quality, Seasonal variation, contamination, irrigation suitability.

1. INTRODUCTION

Groundwater serves as the principal source of potable water for many communities in Nigeria, particularly in regions where surface-water supplies are unreliable or insufficient. In Lafia Local Government Area (LGA), dependence on boreholes and hand-dug wells has increased in response to population growth, urban expansion, and limited access to centralized water infrastructure. However, groundwater systems in tropical environments are highly vulnerable to both natural and anthropogenic contamination due to shallow aquifers, permeable soils, high rainfall infiltration, and inadequate sanitary protection (MacDonald *et al.,* 2012).

Safe drinking water is fundamental to human health, and the World Health Organization (WHO, 2022) establishes standards that ensure water is free from harmful microorganisms, harmful concentrations of chemicals, and radiological hazards. The Nigerian Standard for Drinking

Water Quality (NSDWQ, 2015) provides national regulatory thresholds for microbial, physical, and chemical parameters. Deviation from these standards can lead to serious health outcomes, including gastrointestinal diseases, neurological impairment, renal dysfunction, and cancer (Smith *et al.,* 2000; Jarup, 2003; Vahter, 2008).

Previous studies in Nigeria have documented increasing pressure on groundwater resources due to agricultural practices, waste mismanagement, and unregulated settlement patterns (Ajayi & Ogunbode, 2019; Edet & Worden, 2009). Seasonal variation further influences groundwater quality by altering recharge, redox conditions, and contaminant transport. The Lafia region located within the Guinea Savannah transitional zone experiences distinct rainy and dry seasons that can significantly impact water chemistry and microbial contamination pathways.

Although several studies have assessed groundwater quality in parts of northern Nigeria, limited data exist for Lafia LGA, despite its growing population and extensive reliance on shallow groundwater. This study addresses this knowledge gap by providing a detailed seasonal assessment of groundwater quality using internationally accepted standards. The aim is to identify pollution sources, evaluate compliance with WHO and NSDWQ guidelines, and provide evidence-based recommendations for water safety management.

Study Area

Lafia and its environment is located in the eastern part of Nasarawa State, Nigeria, surrounded by Wamba in the north, Nasarawa in the west, Obi in the south and Plateau State in the east (Fig. 1). The study area falls within latitudes 8° 16' 00" N and 9° 11' 00" N and longitudes 8°16' 00" E and 9°20' 00" E with areal extent of 1010 sq.km.

The study terrain of Lafia district generally has an undulating terrain with such a small hill toward the West-South and North-East This region contains few large and small disconnected hills, they are: Konakancae, Monkwar, Shishem and Ngolo hills which are located along the north-eastern district boundaries. Much of the district of Lafia is drained by the Gwayaka and Mada Rivers which flows from north to south along the western and eastern district boundaries. Feferuwa, Ntirim, Rafin Gora, Lange, Ehula and Agbabija are the vital rivulets and tributaries to the Gwayaka and Mada Rivers. The rivers Feferuwa, Ntirim and Rafin Gora are draining in the eastern section of the district and the river Lange, Ehula and Agbabija drains in the western region of the district. The drainage pattern is dendritic (Fig. 2) which shows the geomorphic and geological homogeneity of the area. The drainage is structurally influenced and majority of the streams are seasonal and flow in distinct directions (Ifediegwu , 2022)..

Throughout the year and two seasons the research area experiences relatively warm tropical weather with fairly high temperatures. Temperatures are generally high all year round due to tropical weather conditions with an average monthly value of around 27.5 °C, depending on the location and time of year, the maximum daytime temperatures range from 25 to 30 °C (Ifediegwu , 2022).

The weather season is defined by a lengthy-wet season during late-March and July, accompanied by torrential rains and dry weather preceded by a minimal dry season between late July to August and a brief-wet season (September–October) before dry season starts in November (Ifediegwu , 2022). A study of the rainfall data from twelve stations over the 10-year period revealed that the average yearly rainfall across the region ranges from about 1534.6 mm to 1685.4 mm. Nevertheless, within the rainy months of April–September, around 80% of the rainfall falls (Ifediegwu , 2022).
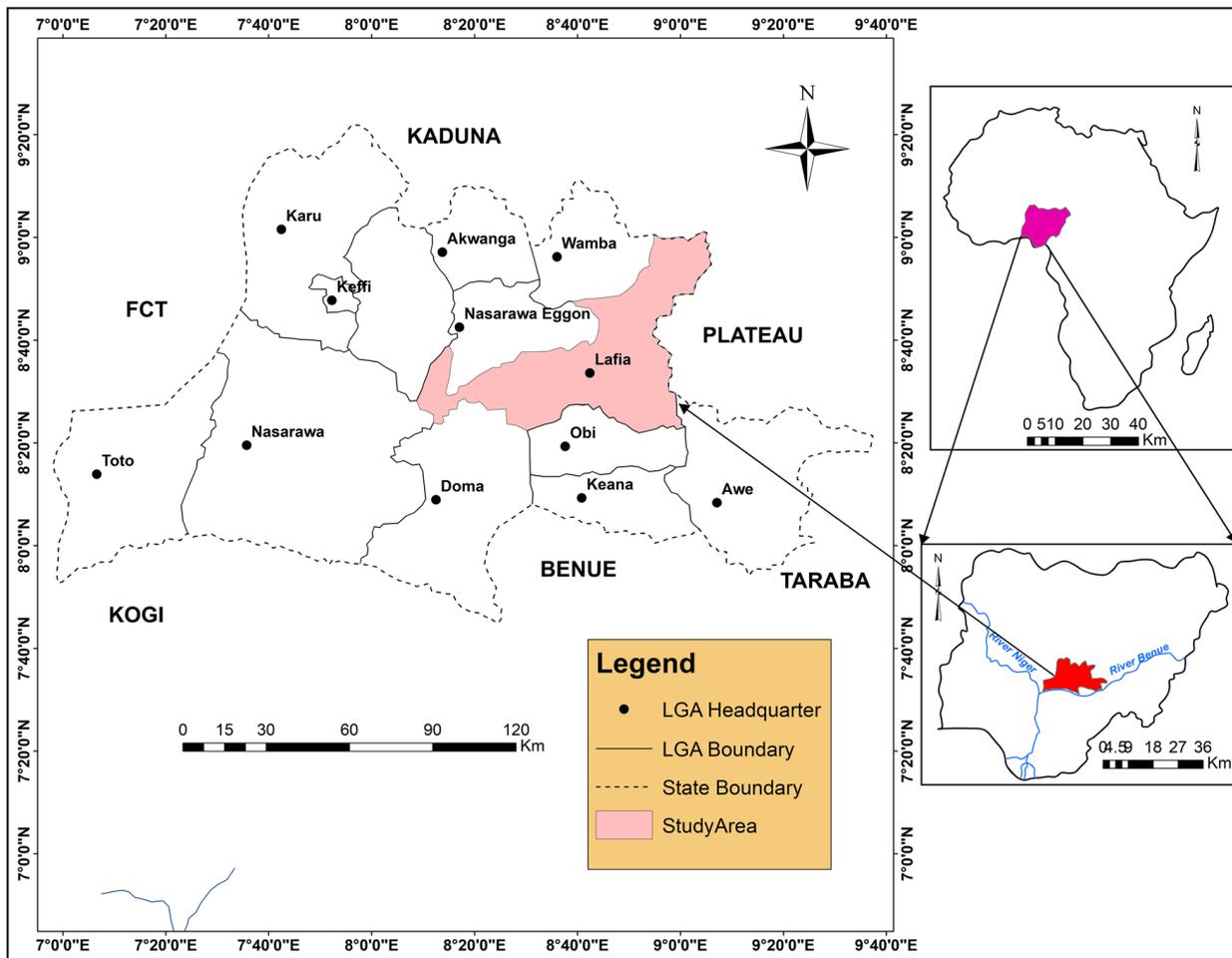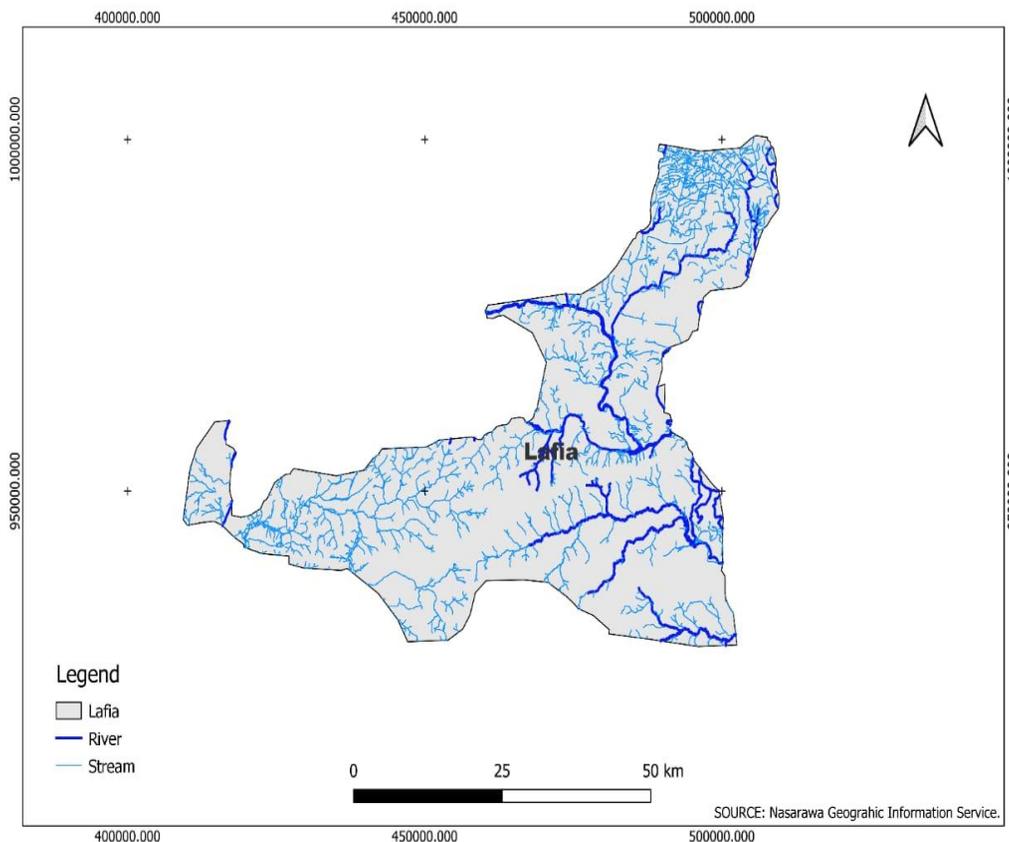
Figure 1: Location Map of the study Area.

Figure 2: Map of Lafia Local Government area showing major rivers and Streams

2. MATERIALS AND METHODS

Sampling Design

Groundwater samples were collected from 20 locations in Lafia LGA, consisting of both boreholes and hand-dug wells. Sampling was conducted during the dry season (March, 2025) and repeated during rainy season October, 2025) to capture seasonal variability. Groundwater sampling locations are recorded with GPS (Global Positioning System) and are represented in Figure 3.

Bore wells were pumped for five to ten minutes to eliminate the influence of stagnant water before collecting the groundwater samples, and groundwater samples were collected in 1-liter pre-cleaned polyethylene containers. Each location was assigned a sample ID (Lb1–Lb20) shown in Table 1 and 2. Samples were collected in sterile polyethylene bottles following WHO (2022) recommended procedures for drinking-water sampling.
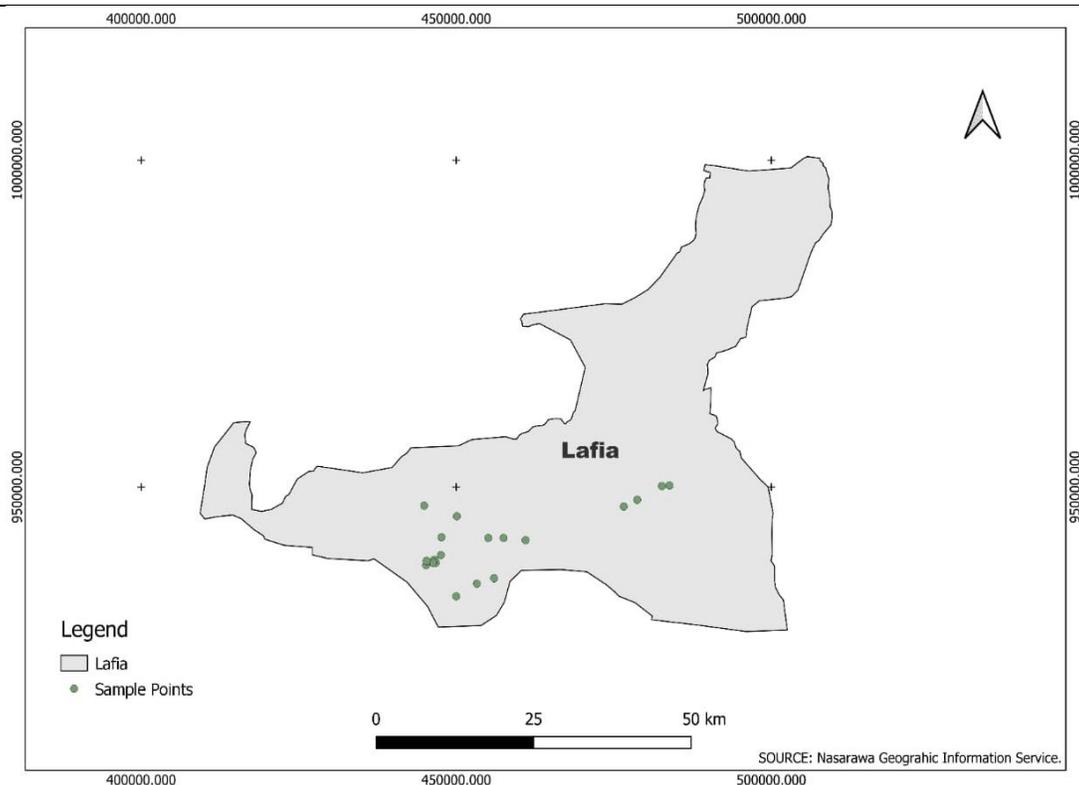
Figure 3: Map of Nasarawa South showing the sample points in Lafia Local Governments.

Field Measurements and Laboratory Analysis

Field parameters including **pH, electrical conductivity (EC), TDS**, and **turbidity** were measured on site using calibrated portable meters. Water samples were transported on ice to the laboratory for further analysis.

Chemical Analysis

Major ions (Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-, F^-) and cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) were quantified using standard titrimetric and spectrophotometric methods. Trace and toxic metals (Fe, Zn, Cu, Mn, Pb, Cr, Cd, As) were analyzed using atomic absorption spectrophotometry (AAS), following APHA Standard Methods.

Microbiological Analysis

Microbial quality was assessed through enumeration of **total coliforms** and *Escherichia coli* using the membrane filtration method. Results were expressed as colony-forming units per 100 mL (cfu/100 mL). All equipment was calibrated before use, field blanks were collected to detect contamination, and duplicate samples were analyzed to ensure data reliability. Analytical methods conformed to WHO (2022) and APHA guidelines.

Data Evaluation

Measured parameters were compared with guideline values provided by: WHO (2022). Guidelines for Drinking-water Quality NSDWQ (2015). Nigerian Standard for Drinking Water Quality. Descriptive statistics were used to summarize data. Seasonal differences were interpreted qualitatively.

Irrigation criteria

The sodium Absorption Ratio (SAR) was calculated based on Richards 1954 using Equation 1, Soluble Sodium Percentage (SSP) were calculated according to the relationships presented by Todd (1980) and Gupta (1987) using Equations 2 , Residual Sodium Bicarbonate (RSC) using 3. The permeability Index (PI) was calculated according to Doneen (1964) using Equation 4, while the Magnesium Adsorption Ratio (MAR) was calculated based on Raghunath 1987, Equation 5. The Kelly's Ratio (KR) (Kelly 1963) is represented in Equation 6. Ion concentrations are expressed in meq/L. Quality The result of the analysis was interpreted under the guidelines and standard specifications outlined by WHO (2022) for drinking water and irrigation quality.

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^2 + Mg^{2+}}{2}}} \tag{1}$$

$$SSP = \frac{Na^+}{(Ca^{2+} + Mg^{2+} + K^+)} \times 10 \tag{2}$$

$$RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+}) \tag{3}$$

$$PI = \frac{Na^+ + (\sqrt{HCO_3^-})}{(Ca^{2+} + Mg^{2+} + Na^+)} \times 100 \tag{4}$$

$$MAR = \frac{Mg^{2+}}{Mg^{2+} + Ca^{2+}} \times 100 \tag{5}$$

$$KR = \frac{Na^+}{(Ca^{2+} + Mg^{2+})} \tag{1}$$

3. RESULTS
3.1. Physicochemical Characteristics
pH, EC, and TDS

The pH profile across seasons ranges from 4.83 to 7.17 in the rainy season and 5.30 to 11.57 in the dry season (Table1). WHO (2022) recommends a pH range that is generally between **6.5 and 8.5** for acceptable drinking-water quality, noting that values outside this range can increase corrosion and enhance metal solubility. NSDWQ (2015) adopts similar acceptability criteria. The strongly acidic rainy-season samples, and the single highly alkaline dry-season sample, suggest disturbances in aquifer buffering, possibly influenced by acid infiltration or leaching from borehole construction materials. Acidic conditions are known to increase the mobility of trace metals such as iron, manganese, cadmium, and lead (Alloway, 2013), reflecting patterns observed in Table 1.

Electrical conductivity (EC) and total dissolved solids (TDS) show a consistent seasonal trend, with substantially higher values in the dry season. This aligns with decreased recharge and enhanced evaporative concentration commonly documented in tropical aquifers (Edet & Worden, 2009). Although all TDS values remain below the NSDWQ limit of 500 mg/L, their seasonal rise signals increasing mineralization pressure on the groundwater system.

Turbidity and Alkalinity

Turbidity values far exceed the NSDWQ limit of **5 NTU**, particularly during the rainy season when several samples surpass 100 NTU. Elevated turbidity is frequently associated with surface run-off, inadequate wellhead protection, and particulate mobilization (WHO, 2022). High turbidity not only reduces aesthetic quality but also shields pathogenic microorganisms from inactivation during treatment.

Measured alkalinity and bicarbonate levels indicate a carbonate-influenced hydrogeochemical regime. However, samples showing high acidity with low alkalinity point to poor buffering capacity, making the aquifer susceptible to pH-driven mobilization of metals and contaminants.

3.2. Major and Trace Inorganic Chemicals
Major Ions

Chloride and sulfate concentrations remain well below WHO (2022) and NSDWQ (2015) guideline values, indicating low salinity and minimal industrial or anthropogenic sulfate input. Fluoride values are likewise consistently below the WHO guideline of **1.5 mg/L**, suggesting no risk of dental or skeletal fluorosis (WHO, 2022).

Calcium and magnesium concentrations, however, reveal significant hardness in several samples—particularly in the dry season, where Ca^{2+} exceeds 200 mg/L in some cases. Such elevations indicate active water–rock interaction within a carbonate-rich geological matrix, a process well documented in Nigerian basement and sedimentary aquifers (Ajayi & Ogunbode, 2019).

Table 1: Physicochemical and Microbiological Characteristics of Lafia Local Government Area

parameter	n	min	max	mean	median	min	max	mean	median
		Rainy Season				**Dry Season**			
pH	20	4.83	7.17	5.888	5.8	5.3	11.57	6.4945	6.415
EC	20	9.72	264.33	67.647	56.135	10.26	300.1	82.9895	57.85
TDS	20	4.79	159.73	39.374	31.265	6.56	192.07	53.1135	37.025
Cl	20	2.36	23.63	8.6905	7.74	0	11.82	4.654	4.73
HCO3-	20	0.05	0.28	0.1025	0.075	0.08	0.26	0.1315	0.11
Total alkalinity	20	2.33	16.67	5.1185	4.205	1.33	4.07	2.7405	2.67
Total acidity	20	0	26.67	10.175	10	0	16.67	8.6665	10
Ecoli	20	0.33	3.33	1.706	1.67	1.33	4.67	2.817	2.835
Total coliform	20	0	3	1.596	1.67	0	9.33	3.267	3
Turbidity	20	0	8.67	1.666	1	1	12.67	2.8835	2
NO3-	20	44.58	216.09	101.8035	90.74	25.44	327.99	114.384	54.03
SO43-	20	2.96	5.82	4.438	4.57	7.46	25.78	10.9065	10.045
F	20	0.03	0.23	0.136	0.135	0.15	0.43	0.2785	0.26
Ca2+	20	0.48	90.19	23.562	10.12	8.37	241.48	71.167	51.29
Mg2+	20	0.27	7.62	3.4135	3.555	1.2	12.32	7.088	7.9
Fe	20	0.1	0.28	0.1765	0.17	0.05	1.17	0.246	0.23
Zn	20	0	0.05	0.0185	0.02	0.03	0.06	0.0405	0.04
Cu	20	0.07	0.39	0.1765	0.16	0.14	0.45	0.241	0.24
Mn	20	0.05	0.31	0.128	0.1	0.14	0.77	0.2625	0.21
Pb	20	0	0.55	0.1305	0.095	0.1	0.54	0.205	0.185
Cr	20	0	0.12	0.061	0.065	0.01	0.15	0.09	0.095
Cd	20	0	0	0	0	0.03	0.13	0.076	0.07
As	20	0	0.12	0.0505	0.055	0.02	0.15	0.083	0.075

Toxic Heavy Metals

The most critical finding as shown in Table 1 is the widespread exceedance of WHO and NSDWQ limits for multiple toxic metals:

• **Lead (Pb)** levels (~0.5 mg/L) exceed the WHO guideline of **0.01 mg/L** by more than fifty-fold.

• **Cadmium (Cd)** concentrations (~0.12–0.13 mg/L) far surpass the WHO provisional guideline of 0.003 mg/L.

• **Chromium (Cr)** values (~0.23–0.27 mg/L) exceed the WHO guideline of **0.05 mg/L.**

• **Arsenic (As)** concentrations (~0.12–0.15 mg/L) are more than ten times the WHO limit of 0**.01 mg/L.**

Chronic exposure to these contaminants is associated with cancer, neurological impairment, renal dysfunction, and cardiovascular disorders (Smith et al., 2000; Jarup, 2003; Vahter, 2008). Their presence suggests a combination of geogenic mobilization (e.g., redox-driven release of As and Fe) and anthropogenic contributions such as waste disposal, agricultural inputs, or use of non-certified borehole construction materials.

Iron and manganese levels, especially during the dry season, exceed aesthetic and health-related thresholds. High Fe and Mn in reducing aquifers are widely reported in tropical groundwater systems (Smedley & Kinniburgh, 2017) and are often linked to the reductive dissolution of Fe/Mn oxides.

Microbiological Contamination

Microbiological analyses show widespread detection of Escherichia coli and total coliforms, with several samples showing extremely high counts. WHO (2022) and NSDWQ (2015) both mandate zero detectable E. coli per 100 mL, making any positive result an immediate health hazard. The presence of E. coli confirms fecal contamination, likely arising from the infiltration of surface run-off, proximity of wells to latrines, poor sealing of hand-dug wells, and inadequate sanitation practices.

The rainy season exhibited the highest microbial load, consistent with earlier research demonstrating seasonal vulnerability of African rural aquifers to fecal contamination due to high rainfall infiltration and land-surface interactions (Trevett et al., 2004).

Irrigation Water Quality Indices

The result of Table 2. Shows Season-dependent variations, but the overall pattern indicates that groundwater in Lafia LGA tends to be marginal to unsuitable for irrigation, especially in locations with extremely high sodium or magnesium hazard.

Sodium Adsorption Ratio (SAR) Standard: 10–18 (good), >18 (unsuitable) (Source: Richards, 1954; Wilcox, 1955). Dry Season (SAR Range: 2.47 – 160.73; Mean = 19.85) as shown in Table 2, Most samples fall within acceptable limits. One extreme outlier (160.73) indicates dangerous sodium hazard, capable of causing severe soil sodification. High SAR values cause clay swelling, poor permeability, and destruction of soil structure. Rainy Season (SAR Range: 0.96 – 49.87; Mean = 9.99) Rainy season averages are lower (mean ≈ 10), indicating relatively safer sodium levels. However, several samples exceed 18, and the extreme value 49.87 suggests high sodium risk in specific locations. Dry season SAR is worse because evapoconcentration increases Na^+. Rainy season dilution reduces Na^+. Soils irrigated with high SAR water risk becoming sodic, reducing infiltration and crop yield.

Table 2: Irrigation water quality Indices in dry and rainy season for Lafia LGA

Parameter	SAR	SSP	RSBC	PI	MAR	KR	RSC	SAR	SSP	RSBC	PI	MAR	KR	RSC
	Dry Season							**Rainy Season**						
1	3.24	20.51	-73.97	0.17	7.71	0.18	-79.92	3.18	11.81	-159.95	0.13	5.51	0.12	-169.21
2	2.65	16.97	-51.02	0.20	6.46	0.18	-54.38	1.51	6.38	-144.70	0.08	5.88	0.06	-153.74
3	21.14	64.77	-30.22	0.65	16.52	1.75	-35.97	23.00	60.03	-51.73	0.62	14.36	1.48	-60.40
4	17.95	88.22	-0.54	1.17	53.29	7.12	-1.19	8.14	56.45	-8.11	0.74	22.78	1.24	-10.50
5	9.51	84.61	-0.44	1.30	37.24	5.28	-0.47	1.98	22.65	-9.78	0.40	20.18	0.28	-12.18
6	11.85	86.08	-0.54	1.26	34.72	6.04	-0.77	4.92	44.23	-8.71	0.62	11.98	0.78	-9.88

7	11.79	86.53	-0.52	1.24	33.55	6.29	-0.68	0.96	5.02	-82.07	0.09	7.18	0.05	-88.43
8	9.40	75.38	-1.41	1.02	46.39	2.74	-2.55	4.01	31.46	-13.61	0.41	41.70	0.41	-23.45
9	3.21	19.78	-61.64	0.19	9.33	0.19	-67.75	2.09	7.96	-185.63	0.08	4.40	0.08	-194.11
10	12.70	55.48	-23.61	0.56	19.79	1.17	-29.17	10.44	37.41	-70.78	0.39	11.56	0.58	-80.02
11	16.37	56.22	-41.23	0.54	14.02	1.18	-47.89	13.77	40.41	-107.24	0.40	6.69	0.64	-114.90
12	38.45	90.36	-2.31	0.93	46.81	9.11	-4.33	15.97	52.44	-50.59	0.53	9.09	1.07	-55.55
13	22.58	78.48	-5.81	0.80	43.13	3.52	-10.15	18.49	64.56	-20.47	0.66	26.49	1.75	-27.87
14	7.50	47.83	-14.30	0.56	20.57	0.88	-17.87	5.00	25.89	-48.65	0.28	14.27	0.33	-56.76
15	15.20	59.75	-24.80	0.60	15.41	1.40	-29.16	14.75	48.51	-55.99	0.50	14.00	0.91	-65.10
16	16.18	55.27	-40.46	0.55	13.35	1.18	-46.50	13.79	39.24	-117.79	0.40	2.57	0.63	-120.83
17	8.42	70.75	-2.52	0.89	22.27	2.31	-3.16	3.22	25.98	-18.98	0.35	15.91	0.34	-22.59
18	5.62	52.19	-5.86	0.69	23.08	1.01	-7.44	3.56	26.94	-16.07	0.36	39.08	0.34	-26.45
19	2.47	15.16	-91.17	0.15	7.77	0.12	-98.69	1.13	5.06	-241.23	0.05	4.85	0.04	-253.48
20	160.73	98.95	-0.33	1.04	35.56	93.21	-0.28	49.87	86.08	-8.61	0.90	46.29	6.16	-16.15
Site Mean	**19.85**	**61.16**	**-23.64**	**0.73**	**25.35**	**7.24**	**-26.92**	**9.99**	**34.93**	**-71.03**	**0.40**	**16.24**	**0.86**	**-78.08**
**Standards	10-18 Good >18 Bad	<50 Good >50 Bad	*<1.2 - 2.50* Good >2.5 Bad	25-75 Good >75 Bad	*<50 Good* *>50 Bad*	*1-2 Good* *>2 Bad*	0.50-9.07 meq/l. go **>10 bad**	10-18 Good >18 Bad	<50 Good >50 Bad	*<1.2 - 2.50* Good >2.5 Bad	25-75 Good >75 Bad	*<50 Good* *>50 Bad*	*1-2 Good* *>2 Bad*	0.50-9.07 meq/l. go **>10 bad**

Note: SAR = Sodium Adsorption Ratio, SSP = Soluble Sodium Percentage, RSBC = Residual Sodium Bicarbonate,
PI = permeability index, MAR = Magnesium Adsorption Ratio, KR = Kelly's Ratio, RSC = Residual Sodium Carbonate, PS = potential salinity.
** = Source: Eaton, (1950); Richard, Wilcox, (1955); Mireles, (2010); Taqveem and Adil, (2013); Amin et al., (2016); Ammar et al., (2025)

2. Soluble Sodium Percentage (SSP) Standard: <50% (good), >50% (bad) (Source: Wilcox, 1955). Dry Season (SSP Range: 15.16 – 98.95; Mean = 61.16) Mean SSP >50% → majority unsuitable. Highest values (up to 98.95%) indicate severe sodium hazard. Rainy Season (SSP Range: 5.02 – 86.08; Mean = 34.93). Mean SSP <50%, as shown in Table 2 suggesting better water quality. However, some samples exceed 50%, indicating localized sodium dominance. SSP indicates sodium toxicity risk to plants and soil permeability issues. Rainy season water is generally safer due to dilution.

3. Residual Sodium Bicarbonate (RSBC / RSC). Standard: <1.25 meq/L (good), >2.5 (bad) (Source: Eaton, 1950) Dry Season (RSBC Range: −91.17 to −0.33; Mean = −23.64) Rainy Season (RSBC Range: −241.23 to −8.11; Mean = −71.03). All values are highly negative,

meaning Ca^{2+} and Mg^{2+} dominate over HCO_3-, which is very good for irrigation. Negative RSBC prevents carbonate precipitation and soil alkalinity. RSBC indicates that bicarbonate does not pose a hazard in Lafia LGA. Negative RSBC = irrigation-safe with respect to carbonate precipitation.

4. Permeability Index (PI). Standard: 25–75% (Class II = good) (Source: Doneen, 1964) Dry Season (PI Range: 0.15 – 1.30; Mean = 0.73) Rainy Season (PI Range: 0.05 – 0.90; Mean = 0.40) All values are far below the recommended 25–75% range. Indicates potential long-term decline in soil permeability due to ionic imbalance. PI results suggest that most groundwater may gradually impair soil hydraulic conductivity, especially in clayey or poorly drained soils.

5. Magnesium Adsorption Ratio (MAR) Standard: <50% (good), >50% (hazardous)
(Source: Raghunath, 1987; Amin et al., 2016). Dry Season (MAR Range: 7.71 – 53.29; Mean = 25.35) Most values <50% → acceptable. Some high values (e.g., 53.29) indicate magnesium hazard. Rainy Season (MAR Range: 2.57 – 46.29; Mean = 16.24). All within safe limits (<50%). Rainy season appears better due to reduced Ca^{2+} and Mg^{2+} concentration through dilution. Only isolated areas show high magnesium risk, more pronounced in the dry season.

6. Kelly's Ratio (KR) Standard: KR < 1 (good), >1 (unsuitable) (Source: Kelley, 1963). Dry Season (KR Range: 0.12 – 93.21; Mean = 7.24). Many samples exceed KR=1. KR = 93.21 is dangerously high → severe sodium hazard. Rainy Season (KR Range: 0.04 – 6.16; Mean = 0.86). Most samples in rainy season fall below KR=1. A few exceed KR=1, indicating moderate sodium hazard. Dry season groundwater is largely unsuitable according to KR, suggesting dominance of Na^+ over Ca^{2+} and Mg^{2+}.

7. Residual Sodium Carbonate (RSC). Standard: RSC <1.25 meq/L (good), 1.25–2.5 marginal, >2.5 bad. (Source: Eaton, 1950). Dry Season (RSC Range: −98.69 to −0.28; Mean = −26.92). Rainy Season (RSC Range: −253.48 to −9.88; Mean = −78.08) as shown in Table 2. All values are negative, meaning excellent irrigation quality with respect to carbonate balance. Negative RSC indicates no tendency for carbonate deposition, no risk of soil alkalinity, and good long-term irrigation compatibility.

Contamination Assessment and Systemic Challenges
the seasonal data of the groundwater in Lafia LGA is compromised by a confluence of four primary factors:

1. Widespread Microbiological Contamination: The pervasive presence of E. coli and total coliforms, particularly during the rainy season, points to inadequate sanitation infrastructure and the vulnerability of water sources to surface runoff. This poses an immediate and severe risk to public health, including the transmission of waterborne diseases.

2. Heavy Metal Pollution: The elevated levels of both geogenic (Fe, Mn) and potentially toxic (Pb, Cd, As) metals represent a significant chemical hazard. This is driven by a combination of natural mineral weathering and potentially anthropogenic inputs, with the problem being exacerbated by the groundwater 'slow alkalinity and limited buffering capacity. This acidic

predisposition prevents the precipitation of metals, keeping them in a bioavailable and mobile aqueous phase.

3. Anthropogenic Nitrate Enrichment: The consistently high nitrate levels are a clear marker of anthropogenic impact, stemming from the intensive use of nitrogenous fertilizers and the widespread contamination from onsite sanitation systems. This poses a direct threat of methemoglobinemia in infants and contributes to nutrient pollution.

4. Infrastructural and Source Vulnerability: Although boreholes generally demonstrate better water quality than hand-dug wells due to their deeper construction and better integrity, a significant number still exceed safety standards for both microbes and chemicals. This indicates that contamination is not merely a shallow aquifer issue but a systemic challenge. The pollutants have permeated various aquifer layers, suggesting that the entire hydrogeological system is affected by the compounding pressures of land use practices and natural geochemical conditions.

4. CONCLUSION

The groundwater in Lafia LGA is a resource facing a dual burden: acute microbiological pollution linked to sanitation, and chronic chemical contamination from both geogenic and anthropogenic sources. The seasonal shifts alter the dominant risk profile but do not eliminate the fundamental threats. This underscores the necessity for a multi-pronged management strategy that addresses source protection, improved sanitation, and targeted water treatment.

The integrated assessment of multiple indices reveals a clear pattern. While the groundwater is free from carbonate-related hazards (as shown by negative RSC/RSBC), its overall quality for irrigation is compromised, particularly during the dry season. The high sodium hazard (evident from SAR, SSP, and KR) and the very low Permeability Index values are the most significant constraints. The rainy season offers a temporary reprieve through dilution, but the underlying geochemical signature of the aquifer remains a concern. Therefore, the groundwater in Lafia LGA must be classified as marginal to unsuitable for irrigation. Continuous use, especially of dry season water, requires careful management strategies such as appropriate soil amendments (e.g., gypsum), selection of salt-tolerant crops, and efficient irrigation practices to mitigate the risks of soil sodification and permeability loss.

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Appendix A1: Rainy-Season Physicochemical and Microbiological Characteristics of Lafia Local Government Area

Sample ID	pH	EC	TDS	Cl	HCO$_3^-$	Total alkalinity	Total acidity	Ecoli	Total coliform	Turbidity	NO$_3^-$	SO$_4^{3-}$	F	Ca^{2+}	Mg^{2+}	Fe	Zn	Cu	Mn	Pb	Cr	Cd	As
Lb1	6.57	104.13	60.87	2.36	0.06	2.33	6.67	1.33	2.33	1.00	97.92	5.28	0.13	73.68	6.10	0.10	0.02	0.18	0.09	0.00	0.07	0.00	0.01
Lb2	6.77	57.53	35.38	2.36	0.17	3.40	3.33	0.67	1.00	0.33	72.54	5.82	0.17	51.13	3.47	0.18	0.04	0.22	0.06	0.00	0.12	0.00	0.02
Lb3	5.27	106.07	69.89	9.45	0.12	8.07	13.33	2.33	0.00	1.00	87.80	4.83	0.14	30.11	5.99	0.15	0.01	0.39	0.09	0.00	0.11	0.00	0.02
Lb4	6.37	29.87	15.58	2.36	0.19	3.27	10.00	1.33	0.67	0.67	112.73	5.41	0.17	0.71	0.82	0.26	0.00	0.31	0.09	0.04	0.08	0.00	0.06
Lb5	5.80	13.52	4.79	7.09	0.06	4.20	20.00	1.67	1.67	2.00	114.54	4.32	0.18	0.51	0.30	0.15	0.00	0.17	0.08	0.01	0.00	0.00	0.00
Lb6	5.63	9.72	5.86	11.82	0.08	4.53	10.00	0.33	3.00	0.33	175.74	4.50	0.23	0.62	0.34	0.16	0.05	0.13	0.11	0.07	0.04	0.00	0.03
Lb7	7.17	18.20	8.62	9.45	0.07	3.00	6.67	2.00	2.00	1.67	76.16	4.77	0.11	0.57	0.30	0.18	0.02	0.13	0.12	0.06	0.05	0.00	0.03
Lb8	5.80	24.75	14.62	2.36	0.15	4.33	0.00	1.00	0.67	1.00	93.54	4.74	0.10	1.49	1.26	0.19	0.02	0.15	0.18	0.23	0.04	0.00	0.07
Lb9	6.20	74.00	36.97	9.45	0.08	3.00	3.33	1.33	0.00	4.33	78.58	4.85	0.17	61.70	6.05	0.23	0.03	0.19	0.16	0.23	0.12	0.00	0.07
Lb10	6.50	56.50	30.18	11.82	0.07	3.27	13.33	1.67	0.00	5.33	89.30	4.35	0.16	23.67	5.65	0.19	0.03	0.21	0.29	0.19	0.07	0.00	0.07
Lb11	4.90	138.97	82.34	14.18	0.05	4.21	10.00	1.33	2.67	8.67	92.18	4.86	0.11	40.92	7.08	0.13	0.03	0.11	0.05	0.21	0.06	0.00	0.07
Lb12	5.20	40.13	22.67	21.27	0.06	5.93	10.00	3.00	1.00	0.33	87.94	2.96	0.10	2.15	2.03	0.16	0.04	0.25	0.27	0.11	0.07	0.00	0.06
Lb13	4.83	40.90	22.80	23.63	0.05	7.47	13.33	2.33	1.67	0.33	140.38	3.39	0.03	5.58	4.47	0.28	0.03	0.28	0.31	0.20	0.07	0.00	0.05
Lb14	5.57	55.77	32.35	11.82	0.14	3.93	6.67	2.67	2.33	1.67	126.93	4.64	0.12	14.28	3.64	0.20	0.01	0.14	0.10	0.07	0.07	0.00	0.06
Lb15	6.33	70.80	42.43	2.36	0.07	3.00	3.33	0.67	3.00	0.00	84.17	4.21	0.12	24.77	4.40	0.18	0.02	0.21	0.14	0.55	0.11	0.00	0.12
Lb16	5.57	114.07	66.67	7.09	0.06	3.80	20.00	2.00	1.00	2.00	98.22	3.46	0.13	40.14	6.00	0.17	0.00	0.11	0.12	0.14	0.00	0.00	0.11
Lb17	4.90	22.10	11.93	4.73	0.06	16.67	26.67	3.33	2.00	0.33	61.50	3.40	0.14	2.58	0.73	0.14	0.00	0.10	0.08	0.24	0.05	0.00	0.10
Lb18	5.80	45.37	25.24	7.09	0.13	6.47	10.00	1.33	3.00	0.00	44.58	3.46	0.12	5.96	1.75	0.15	0.01	0.08	0.06	0.12	0.01	0.00	0.02
Lb19	6.67	264.33	159.73	4.73	0.28	6.47	6.67	2.00	2.33	2.33	216.09	5.72	0.14	90.19	7.62	0.16	0.00	0.07	0.06	0.06	0.06	0.00	0.02
Lb20	5.91	66.21	38.56	8.39	0.10	5.02	10.17	1.80	1.58	0.00	85.23	3.79	0.15	0.48	0.27	0.17	0.01	0.10	0.10	0.08	0.02	0.00	0.02

Appendix A2: Rainy-Season Physicochemical and Microbiological Characteristics of Lafia Local Government Area

Sample ID	pH	EC	TDS	Cl	HCO$_3^-$	Total alkalinity	Total acidity	Ecoli	Total coliform	Turbidity	NO$_3^-$	SO$_4^{3-}$	F	Ca^{2+}	Mg^{2+}	Fe	Zn	Cu	Mn	Pb	Cr	Cd	As
Lb1	6.77	148.03	94.74	0.00	0.11	3.43	6.67	1.67	0.00	1.33	124.95	11.52	0.26	160.06	9.33	0.28	0.03	0.24	0.16	0.10	0.09	0.03	0.03
Lb2	6.40	105.75	67.68	0.00	0.09	4.07	10.00	2.33	0.00	2.00	212.26	9.65	0.34	144.80	9.04	0.26	0.06	0.26	0.23	0.11	0.13	0.08	0.04
Lb3	5.37	93.38	59.76	3.45	0.18	3.00	16.67	3.67	1.00	2.00	37.30	8.93	0.43	51.91	8.71	0.33	0.03	0.45	0.21	0.11	0.14	0.07	0.06
Lb4	6.20	25.76	16.49	0.00	0.26	3.00	6.67	3.67	2.33	3.67	327.99	12.57	0.30	8.37	2.47	1.17	0.04	0.35	0.21	0.16	0.15	0.06	0.08
Lb5	6.40	11.38	7.28	0.00	0.09	3.33	6.67	1.33	2.00	3.33	25.44	11.12	0.36	9.87	2.49	0.38	0.03	0.25	0.22	0.14	0.01	0.06	0.02
Lb6	6.40	10.26	6.56	7.09	0.11	2.67	10.00	1.33	2.33	2.00	60.55	10.30	0.38	8.83	1.20	0.23	0.06	0.20	0.14	0.22	0.10	0.07	0.06
Lb7	6.47	35.50	22.72	0.00	0.13	2.67	3.33	2.00	3.33	2.00	233.62	9.19	0.19	82.20	6.36	0.23	0.04	0.16	0.15	0.12	0.06	0.05	0.07
Lb8	6.70	48.30	30.91	0.00	0.20	3.33	0.00	3.33	4.67	1.33	33.45	13.16	0.18	13.81	9.88	0.24	0.04	0.21	0.24	0.26	0.06	0.06	0.14
Lb9	6.60	187.34	119.90	3.45	0.11	3.00	0.00	4.67	4.33	12.67	281.07	11.90	0.36	185.73	8.55	0.26	0.05	0.24	0.22	0.24	0.15	0.07	0.09
Lb10	7.10	150.60	96.39	7.09	0.11	2.33	3.33	4.00	4.00	10.67	229.93	7.46	0.30	70.89	9.27	0.32	0.05	0.25	0.32	0.22	0.09	0.06	0.13
Lb11	5.50	128.74	82.39	9.45	0.08	2.33	16.67	3.33	2.67	1.00	34.74	11.21	0.26	107.32	7.69	0.15	0.05	0.16	0.18	0.23	0.10	0.10	0.11
Lb12	5.57	64.09	41.02	4.73	0.08	3.00	13.33	2.67	3.67	2.00	36.35	8.65	0.20	50.67	5.07	0.07	0.06	0.33	0.28	0.18	0.11	0.11	0.07
Lb13	5.77	31.32	20.05	4.73	0.09	2.33	13.33	1.67	3.67	2.00	33.26	8.62	0.15	20.55	7.41	0.11	0.05	0.34	0.36	0.26	0.09	0.08	0.08
Lb14	6.57	51.61	33.03	11.82	0.08	2.33	10.00	3.00	2.33	2.67	52.00	9.79	0.22	48.73	8.11	0.15	0.03	0.28	0.76	0.17	0.10	0.06	0.10
Lb15	5.53	79.71	51.02	4.66	0.13	2.33	10.00	4.33	1.67	1.00	35.54	10.91	0.26	56.12	9.14	0.17	0.04	0.31	0.17	0.54	0.15	0.13	0.14
Lb16	5.30	118.38	75.76	4.73	0.10	3.33	13.33	2.67	2.67	1.33	52.54	25.78	0.26	117.89	3.11	0.10	0.03	0.18	0.14	0.19	0.02	0.11	0.14
Lb17	6.43	16.51	10.56	7.09	0.09	2.33	10.00	3.33	9.33	2.00	55.52	8.59	0.26	19.07	3.61	0.23	0.03	0.14	0.77	0.27	0.07	0.09	0.15
Lb18	6.47	22.72	14.54	7.09	0.15	2.67	6.67	3.00	5.67	1.00	145.69	8.77	0.21	16.23	10.41	0.06	0.03	0.16	0.16	0.18	0.04	0.13	0.05
Lb19	6.77	300.10	192.07	11.82	0.24	2.00	13.33	2.67	4.67	2.67	246.70	9.36	0.36	241.48	12.32	0.13	0.03	0.14	0.14	0.22	0.10	0.04	0.05
Lb20	11.57	30.31	19.40	5.88	0.20	1.33	3.33	1.67	5.00	1.00	28.78	10.65	0.29	8.81	7.59	0.05	0.03	0.17	0.19	0.18	0.04	0.06	0.05