

Spatiotemporal dynamics and seasonal influence on the microbial and physicochemical integrity of groundwater sources in rural cross river state, Nigeria

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Abstract

The availability of quality water resources is a significant challenge in many part of the world, including Nigeria. This study investigated the spatiotemporal dynamics of groundwater quality in Obudu and Obanliku, Cross River State. Bacteriological and physicochemical characteristics of 120 samples from wells and boreholes were analyzed across wet and dry seasons (January–June, 2025). Independent T-tests and the Weighted Arithmetic Water Quality Index (WQI) were used to determine significant differences and the overall physicochemical status. Physicochemical results generally aligned with WHO and SON standards, though significant seasonal variations occurred. While pH remained stable ($p > 0.05$), turbidity was significantly higher during the wet season in wells (3.15 ± 1.81 NTU) and boreholes (1.56 ± 0.40 NTU). *E. coli* peaked in wells during the wet season (4.76 ± 4.11 cfu/100ml) and was lowest in boreholes during the dry season (0.31 ± 0.36 cfu/100ml). Despite the WQI classifying water status as "Good" (27.30–37.10), all samples exceeded thresholds for total coliform, faecal coliform, and *E. coli* across both seasons. The study concludes that while the physicochemical status appears safe, pervasive bacteriological contamination renders these sources unsuitable for drinking. Household-level water treatment, regular disinfection of existing wells and environmental sanitation are urgently recommended to mitigate public health risks.

Keywords: Water quality; Pollution; *E. coli*; Faecal contamination; Agricultural runoff

1. Introduction

Reliable supply of safe drinking water is fundamental to human health and sustainable development [1,2]. Water plays an essential role in domestic activities such as drinking, cooking, and sanitation; however, its benefits depend largely on its quality [3]. When drinking water becomes contaminated with microorganisms or harmful chemicals, it can pose serious health risks to communities [4,5]. According to the World Health Organization, waterborne diseases account for a significant proportion of the global disease burden and are responsible for millions of deaths annually, particularly in developing countries where access to safe water and sanitation is limited [6,5].

The quality of drinking water is commonly evaluated using physicochemical and bacteriological parameters [7]. Physicochemical characteristics such as pH, turbidity, electrical conductivity, total dissolved solids, and nutrient concentrations provide information about the chemical condition of water and possible sources of contamination [8]. On the other hand, bacteriological indicators, particularly coliform bacteria, are widely used to assess the microbial

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safety of drinking water [9,5]. The presence of these microorganisms often suggests contamination from human or animal wastes, which may introduce disease-causing pathogens into water sources [10].

In many rural and semi-urban areas of Nigeria, communities rely heavily on natural and untreated water sources such as streams, springs, boreholes, and hand-dug wells for their daily water needs. These sources are often vulnerable to contamination from agricultural activities, poor sanitation practices, surface runoff, and geogenic processes that influence water chemistry. As a result, regular monitoring of water quality is necessary to ensure that water intended for consumption meets recommended safety standards [11,12,13,14].

Obudu and Obanliku Local Government Areas are located in the northern part of Cross River State and are characterized by mountainous terrain, rural settlements, and increasing tourism activities associated with the nearby Obudu Mountain Resort [15,16]. Despite the ecological and socio-economic importance of this region, many communities depend on local water sources whose quality is not consistently monitored [14]. Contamination of these sources could have implications for public health and environmental sustainability [10].

2. Materials and methods

2.1. Description of the Study Area

This study was conducted in Obudu and Obanliku Local Government Areas of Cross River State, Nigeria, both located in the northern senatorial district of the state. The area is home to the Obudu Mountain Resort in Obanliku LGA, which hosts the annual Obudu Ranch International Mountain Race and attracts tourists from different parts of the world. Obudu town is located downstream of the Obudu Dam, a condition that has contributed to acute scarcity of drinking water during the dry season [15,16]. Obudu LGA ($6^{\circ}40'5.5''\text{N}$, $9^{\circ}9'52.3''\text{E}$) comprises ten wards: Alege/Ubang, Angiaba/Begiaka, Begiading, Ipong, Obudu Urban I, Obudu Urban II, Ukpe, Utugwang Central, Utugwang North, and Utugwang South [17]. Obanliku LGA ($6^{\circ}36'33''\text{N}$, $9^{\circ}15'1''\text{E}$) also consists of ten wards: Basang, Bebi, Becheve, Bendi I, Bendi II, Bishiri North, Bishiri South, Bisu, Busi, and Utanga [18].

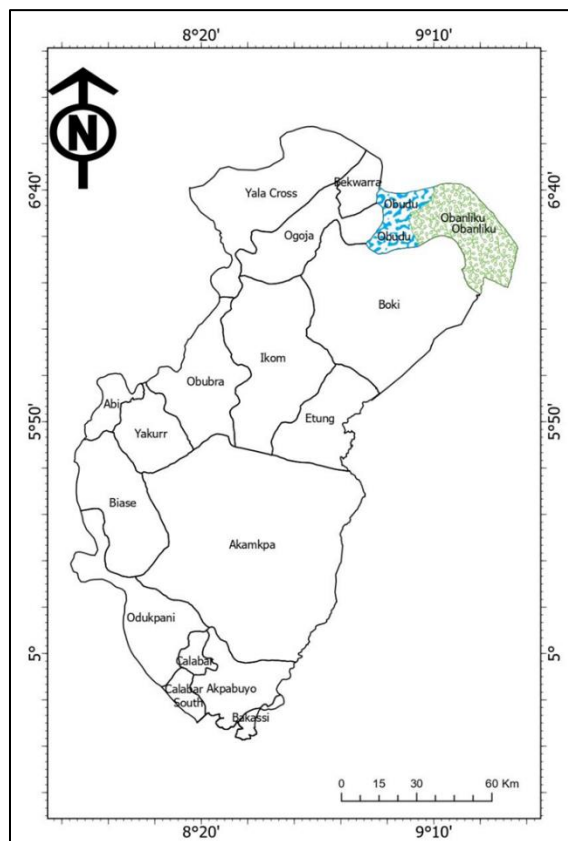


Figure 1 Map of Cross River State, Nigeria, showing Obudu and Obanliku LGAs

2.2. Sampling Technique

A combination of random and purposive sampling methods was used to select 20 drinking water sources (10 wells and 10 boreholes) across the 20 wards in Obudu and Obanliku Local Government Areas to ensure adequate representation of the study area. Sampling points were randomly selected from the ten wards in each LGA. Water samples were collected in both the dry and wet seasons to capture possible seasonal variations in water quality. Sampling was conducted three times in each season: January–March 2025 for the dry season and April–June 2025 for the wet season.

Sampling equipment included water sampling bottles, sampling rods, a pH meter, a turbidity meter, and an 8-in-one digital tester. The collected samples were analyzed for physicochemical parameters and microbiological characteristics.

2.3. Sample Collection and Treatment

Water samples were collected monthly over a six-month period. To reduce the effect of diurnal variations, sampling was conducted between 7:00 a.m. and 12:00 p.m. The samples were collected in new sterile plastic bottles and immediately placed in a cooler with ice packs to maintain a temperature of about 4 °C during transportation to the laboratory. Each sample was properly labeled with the sampling location, date, and time of collection for easy identification and tracking.

Certain parameters, including temperature, pH, dissolved oxygen (DO), and turbidity, were measured *in situ* to prevent changes caused by natural reactions or biological activity. In the laboratory, the samples were filtered using 0.45 µm membrane filters to remove suspended particles. About 1–2 mL of concentrated nitric acid was then added to preserve the samples and prevent microbial growth. The preserved samples were subsequently analyzed for other physicochemical and microbiological parameters using standard analytical methods and equipment.

2.4. Analytical procedure

2.4.1. Analysis of physicochemical parameters

- **pH measurement:** Water pH was taken in-situ using 8 in 1 digital tester pen pool water quality monitor.
- **Temperature measurement:** The water temperature values was taken in-situ using 8 in 1 digital tester pen pool water quality monitor.
- **Turbidity measurement:** Turbidity was measured using a turbidity meter (Hack Turbidimeter) calibrated with standard turbidity solutions (0, 10, 50, and 100 NTU).
- **Total dissolved solids (TDS) measurement:** TDS was measured in-situ using 8 in 1 digital tester pen pool water quality monitor.
- **Electrical conductivity (EC) measurement:** EC was taken in-situ using 8 in 1 digital tester pen pool water quality monitor.
- **Dissolved oxygen (DO):** DO was taken in-situ using 8 in 1 digital tester pen pool water quality monitor.
- **Biochemical oxygen demand (BOD):** The BOD was determined using standard method as described by APHA (2005).
- **Nitrate:** The concentration of NO₃⁻ was determined using the Phenol-disulphuric acid method.
- **Phosphate:** Phosphate concentrations were determined according to APHA standard method 4500-P E (Ascorbic acid method). Samples were reacted with ammonium molybdate and antimony potassium tartrate to form a phosphomolybdate complex, which was reduced by ascorbic acid to produce a blue color measured at 880 nm.

2.4.2. Bacteriological analysis

- **Total coliform count:** The water sample's total coliform count was determined using the Most Probable Number (MPN) assay, also known as the presence/absence test. The total coliform was cultured on MacConkey agar as medium employing the convectional cultural plating technique
- **Faecal coliform count:** Faecal coliform count was determined using the multiple tube fermentation technique (MTFT) with EC Broth as the medium.
- **E. coli Count:** *E. coli* count was determined using the membrane filtration technique with Chromocult Coliform Agar as the medium.

2.4.3. Water quality index (WQI)

The WQI was determined using the weighted arithmetic method as described by Falola *et al.* [20]. In this study, only key physicochemical parameters will be used for calculation including pH, BOD, TDS, DO and turbidity [21]. The WQI will be calculated using the following steps: S_n

$$K = \frac{1}{\sum S_n} \quad (1)$$

Where S_n is the value (mean) for each parameter; and K is the proportionality constant in equation 2.

$$W_i = \frac{K}{S_n} \quad (2)$$

Where W_i is the unit weight for each parameter.

$$Q_i = \frac{(V_o - V_i)}{(S_n - V_i)} \times 100 \quad (3)$$

V_i (ideal value) for all parameters in water quality analysis is zero, except pH and dissolved oxygen (DO) which have an ideal value of 7 and 14.6 mg/L, respectively. V_o will be the observed (mean) value, while Q_i will be the quality rating of the individual parameter.

$$WQI = \frac{\sum W_i Q_i}{\sum W_i} \quad (4)$$

Table 1 Categories of water quality index: value, ratings and usage

WQI Value	Water Quality Ratings	Usages
0-25	Excellent	Drinking, Irrigation and Industrial
26-50	Good	Drinking, Irrigation and Industrial
51-75	Poor	Irrigation
76-100	Very Poor	Restricted Use for Irrigation
>100	Unfit, Unsuitable for Use	Proper Treatment Required before use

[22,4]

2.5. Statistical Analysis

Descriptive and inferential statistical methods were used to analyze the data obtained from this study. The mean was calculated to determine the average values of the water quality parameters, while standard deviation was used to assess the level of variation among the parameters. In addition, a t-test was applied to compare the mean values of water quality parameters between Obudu and Obanliku Local Government Areas, as well as to examine differences across sampling seasons and water sources.

The Weighted Arithmetic Water Quality Index (WAWQI) was employed to generate a single numerical value representing the overall water quality. Data analysis was carried out using Microsoft Excel and the Statistical Package for Social Sciences (SPSS). The obtained results were compared with the standards provided by the Standards Organisation of Nigeria (SON) and the World Health Organization (WHO) for drinking water quality.

3. Results

3.1. Physicochemical parameters

Results for physico-chemical parameters of drinking water in Obudu and Obanliku Local Government Areas of Cross River State, taken during both dry and wet seasons from wells and boreholes are presented in tables 2a and 2b. The physico-chemical quality of drinking water in the study area showed sensitivity to seasonal and spatial factors. The pH remained relatively stable, with Obudu recording 6.68 ± 0.45 in the dry season and 6.55 ± 0.36 in the Wet season, while Obanliku showed 6.61 ± 0.53 (dry season) and 6.65 ± 0.49 (wet season). Statistically, pH showed no significant spatial or seasonal variation ($p > 0.05$).

However, great changes was observed in the water turbidity at different seasons of sampling. For instance, in Obudu, turbidity rose significantly from 1.15 ± 0.78 VTU in the dry season to 2.70 ± 1.25 VTU in the Wet season ($p < 0.001$). Similarly, there was a significant seasonal change was noted in Obanliku (1.67 ± 1.71 VTU to 2.00 ± 1.71 VTU), which could be due to runoff infiltration into the Wells. Nitrate concentrations showed the most location-based differences. Obudu recorded a combined mean of 5.49 (mg/L), which was significantly higher ($p < 0.001$) than the 3.93 (mg/L) recorded in Obanliku.

Results from the t-test analysis conducted revealed that the choice of water source (Borehole vs. Well) had a greater impact on water chemistry than the change in seasons. There was a significant difference ($p < 0.05$) between boreholes and wells across nearly all chemical markers, including EC ($p = 0.000$), TDS ($p = 0.0016$), and BOD ($p = 0.000$). Boreholes exhibited significantly higher mineralization compared to Wells likely due to longer residence times and rock-water interactions in deeper aquifers.

On the other hand, Wells were found to be significantly more susceptible to nutrient loading and atmospheric interaction. There was a statistically significant difference ($p < 0.05$) in Nitrates, Phosphates, and Dissolved Oxygen (DO) between the two sources. Wells recorded significantly higher Nitrate levels compared to Boreholes, as well as higher DO levels (Mean: 4.62 mg/L), confirming that shallow Wells are more vulnerable to surface contamination and atmospheric aeration. Interestingly, while Temperature fluctuated seasonally, the difference in temperature between Boreholes and Wells was not statistically significant ($p > 0.05$), indicating a uniform temperature map for the drinking water in Obudu and Obanliku LGAs.

Table 2a Seasonal variations of physico-chemical parameters of drinking water in Obudu and Obanliku

Parameter	Obudu (Mean \pm SD)		Obanlikwu (Mean \pm SD)		WHO Guideline	SON Standard
	Dry	Wet	Dry	Wet		
pH	6.67 ± 0.42^a	6.55 ± 0.35^a	6.63 ± 0.52^a	6.65 ± 0.52^a	6.5-8.5	6.5-8.5
Turbidity (NTU)	1.15 ± 0.78^a	2.7 ± 1.25^b	1.67 ± 1.71^a	2.00 ± 1.71^b	5	5
Temperature ($^{\circ}$ C)	29.34 ± 1.33^a	26.86 ± 1.39^b	29.59 ± 1.92^a	27.34 ± 1.49^b	NL	30
TDS (ppm)	78.4 ± 35.29^a	83.26 ± 33.04^a	86.76 ± 31.74^a	100.36 ± 43.46^a	500	500
EC (μ S/cm)	154.85 ± 72.40^a	158.57 ± 69.93^a	175.37 ± 64.59^a	182.53 ± 63.76^a	1000	1000
DO (mg/L)	4.14 ± 1.13^a	3.92 ± 0.99^a	4.00 ± 0.98^a	4.12 ± 1.15^a	NL	7.5
BOD (mg/L)	3.09 ± 1.03^a	3.13 ± 1.14^a	3.51 ± 0.76^a	3.38 ± 0.86^a	5	6
Nitrates (mg/L)	5.55 ± 1.55^a	5.43 ± 1.42^a	3.88 ± 2.42^c	3.99 ± 2.62^c	50	50
Phosphates (mg/L)	0.067 ± 0.24^a	0.10 ± 0.19^a	0.09 ± 0.06^a	0.11 ± 0.08^a	NL	NL

Table 2b Seasonal variations of physicochemical parameters of drinking water in Obudu and Obanliku LGA across sources

Paramters	Wells		Boreholes		WHO Guideline	Son standard
	Dry	Wet	Dry	Wet		
pH	6.62 ± 0.40^a	6.60 ± 0.37^a	6.67 ± 0.54^a	6.60 ± 0.51^a	6.5-8.5	6.5-8.5
Turbidity (NTU)	2.06 ± 1.65^a	3.15 ± 1.81^b	0.73 ± 0.19^c	1.56 ± 0.40^d	5	5
Temperature ($^{\circ}$ C)	28.99 ± 1.66^a	27.41 ± 1.48^b	29.94 ± 1.50^a	26.79 ± 1.37^b	NL	30
TDS (ppm)	69.80 ± 24.14^a	83.80 ± 42.59^a	95.37 ± 37.00^c	99.83 ± 34.44^c	500	500

EC ($\mu\text{S}/\text{cm}$)	139.50 \pm 50.10 ^a	146.63 \pm 51.07 ^a	190.77 \pm 75.30 ^c	194.47 \pm 73.91 ^c	1000	1000
DO (mg/L)	4.66 \pm 1.23 ^a	4.58 \pm 1.20 ^a	3.47 \pm 0.12 ^c	3.45 \pm 0.17 ^c	NL	7.5
BOD (mg/L)	2.78 \pm 1.06 ^a	2.69 \pm 1.17 ^a	3.83 \pm 0.21 ^c	3.83 \pm 0.20 ^c	5	6
Nitrates (mg/L)	5.64 \pm 2.53 ^a	5.64 \pm 2.64 ^a	3.78 \pm 1.23 ^c	3.79 \pm 1.09 ^c	50	50
Phosphates (mg/L)	0.11 \pm 0.14 ^a	0.16 \pm 0.19 ^a	0.05 \pm 0.04 ^c	0.06 \pm 0.04 ^c	NL	NL

Note: Values are expressed as Mean \pm SD. Means within the same superscript letter are not significantly different, while different letters indicate significant difference at $p < 0.05$ (Independent two-sample t-test). TDS= Total Dissolved Solid, EC=Electrical conductivity, DO=Dissolved oxygen, BOD=Biochemical oxygen demand, NL=Not listed

3.2. Bacteriological parameters of water samples across seasons, LGAs, and sources

Results for the bacteriological analysis of drinking water in Obudu and Obanlikwu LGAs, including Total Coliform, Faecal Coliform, and *E. coli* counts, is presented in tables: 3a and 3b. As shown in Table 3a, all bacteriological parameters across both LGAs exceeded the SON and WHO permissible limits of 0 cfu/100ml. Obanlikwu recorded generally higher microbial loads, with Total Coliform counts peaking at 32.56 \pm 17.81 cfu/100ml in the wet season.

Faecal coliform ranged from 5.47 \pm 8.53 in Obanlikwu during the dry season to 10.04 \pm 7.81 in Obudu during the wet season. *E. coli* levels showed a notable seasonal trend in Obanlikwu, increasing significantly from 1.39 \pm 0.23 cfu/100ml in the Dry season to 2.98 \pm 4.27 cfu/100ml in the Wet season ($p < 0.05$). In Obudu, *E. coli* also increased during the Wet season (2.97 \pm 2.58 cfu/100ml vs 2.00 \pm 2.14 cfu/100ml in the Dry), but this change did not reach the threshold of statistical significance ($p < 0.05$). These findings imply that while both LGAs suffer from microbial contamination, the water sources in Obanlikwu are statistically more vulnerable to seasonal faecal contamination than those in Obudu.

Wells recorded a combined mean for *E. coli* of 3.99 cfu/100ml, which is significantly higher than the 0.75 cfu/100ml found in Boreholes. A seasonally significant difference was observed only in Boreholes, where *E. coli* spiked from 0.31 \pm 0.36 cfu/100ml in the Dry season to 1.19 \pm 0.86 cfu/100ml in the Wet season ($p < 0.001$), and Total Coliform rose from 12.39 \pm 4.47 cfu/100ml to 16.46 \pm 4.64 cfu/100ml ($p < 0.05$). In contrast, Wells showed no significant seasonal difference for *E. coli* (3.21 \pm 2.76 vs 4.76 \pm 4.11 cfu/100ml), ($p > 0.05$) or Total Coliform (36.39 \pm 9.61 vs 40.89 \pm 13.03 cfu/100ml, ($p > 0.05$)), indicating that while contamination is higher in wells, it remains a persistent, year-round issue regardless of rainfall, table 3b.

Table 3a Seasonal variations of bacteriological parameters in drinking water in Obudu and Obanlikwu LGAs compared with WHO/SON standards

Parameter (cfu/100ml)	Obudu		Obanlikwu		WHO Guideline	SON Standard
	Dry	Wet	Dry	Wet		
Total coliform	21.00 \pm 10.82 ^a	24.79 \pm 12.31 ^a	27.78 \pm 16.40 ^a	32.56 \pm 17.81 ^a	NL	10
Faecal Coliform	7.62 \pm 8.21 ^a	10.04 \pm 7.81 ^a	5.47 \pm 8.53 ^c	8.60 \pm 9.65 ^d	0	0
<i>E. coli</i>	2.00 \pm 2.14 ^a	2.97 \pm 2.58 ^a	1.39 \pm 0.23 ^c	2.98 \pm 4.27 ^d	0	0

Table 3b Seasonal variations of bacteriological parameters in drinking water sources in Obudu and Obanlikwu LGAs compared with WHO/SON standards

Parameter (cfu/100ml)	Wells		Boreholes		WHO Guideline	SON Standard
	Dry	Wet	Dry	Wet		
Total coliform	36.39 \pm 9.61 ^a	40.88 \pm 13.03 ^a	12.39 \pm 4.47 ^c	16.46 \pm 4.64 ^d	NL	10
Faecal Coliform	11.07 \pm 9.36 ^a	14.45 \pm 9.91 ^a	1.29 \pm 1.03 ^c	4.57 \pm 2.68 ^d	0	0
<i>E. coli</i>	3.21 \pm 2.76 ^a	4.76 \pm 4.11 ^a	0.31 \pm 0.36 ^c	1.19 \pm 0.86 ^d	0	0

Note: Values are expressed as Mean \pm SD. Means within the same superscript letter are not significantly different, while different letters indicate significant difference at $p < 0.05$ (Independent two-sample t-test).

3.3. Water quality index (WQI)

The results for the Water Quality Index (WQI) of drinking water across Obudu and Obanliku Local Government Areas (LGAs), as well as by water source, are presented in Tables 4a and 4b. As shown in Table 4a, the WQI values for all studied locations fell within the range of 27.30 to 37.10, which classifies the water status as "Good" across both LGAs and seasons. During the dry season, Obanliku recorded a higher WQI value (32.83) compared to Obudu (27.30).

However, in the wet season, the trend reversed, with Obudu recording the highest overall WQI value of 37.10, while Obanliku recorded 35.20. A consistent seasonal trend was observed in both locations, where WQI values were higher during the wet season than the dry season. This indicates a relative decrease in water quality during the rainy months, although the status remained within the "Good" category.

Table 4b illustrates the WQI based on the type of water source (Well and Borehole). In both seasons, Well water exhibited higher WQI values (31.30 in dry; 38.71 in wet) compared to Borehole water (29.12 in dry; 35.26 in wet). This suggests that Boreholes generally maintained a slightly better quality profile than Wells in the study area.

Similar to the spatial findings, both water sources showed higher WQI values during the wet season. The highest recorded WQI across all sources was observed in Well water during the wet season (38.71), while the lowest was recorded in Borehole water during the dry season (29.12).

Table 4a Water quality index of drinking water across seasons in Obudu and Obanliku LGAs

Location	Season	WQI Value	Water Quality Status
Obudu	Dry	27.30	Good
Obudu	Wet	37.10	Good
Obanliku	Dry	32.83	Good
Obanliku	Wet	35.20	Good

Table 4b Water quality index of drinking water across seasons in Obudu and Obanliku LGAs

SOURCE	Season	WQI Value	Water Quality Status
Well	Dry	31.30	Good
Well	Wet	38.71	Good
Borehole	Dry	29.12	Good
Borehole	Wet	35.26	Good

4. Discussion

Water is an important resource for daily life; although, the quality of water available on earth has been compromised due to various factors including physicochemical and bacteriological contaminants [23-25]. Groundwater in Obudu and Obanliku demonstrated high physicochemical compliance with WHO [10] and SON [26] standards, suggesting minimal industrial impact [27]. The slightly acidic to near-neutral pH (6.5–8.5) favors ionic stability and aligns with regional tropical aquifer profiles [28,29]. Low TDS and EC values further indicate minimal mineralization [30]. Notably, turbidity remained below 5 NTU, contrasting with the high suspended solids found in nearby surface waters like the Abakpa and Ekulu Rivers [31,32]. While nutrient levels (Nitrate/Phosphate) were generally low, the significant spatial variation in phosphate ($p < 0.05$) points to localized agricultural runoff or soil erosion differences between the two LGAs.

In contrast to the chemical results, microbial quality was universally poor, with all samples exceeding the 0 CFU/100 mL limit for *E. coli* and fecal coliforms [10]. This "microbial-chemical divergence" proves that clear water in these LGAs is not necessarily potable. The peaking of coliform counts during the wet season confirms a strong seasonal influence, where rainfall facilitates the vertical percolation of fecal matter from latrines into the shallow water table [33,34].

The spatiotemporal dynamics are most visible in the source comparison: shallow wells exhibited the highest microbial loads due to poor casing and proximity to waste [14]. Although boreholes were safer, their slight contamination suggests septic infiltration or unhygienic handling at the point of collection [35]. The lack of statistical difference between the two LGAs ($p > 0.05$) implies shared sanitary challenges, primarily driven by the high prevalence of open defecation in rural Cross River State [36]. Ultimately, the data suggests that groundwater degradation in the region is a function of poor sanitation infrastructure rather than mineralogical or industrial factors.

The Weighted Arithmetic WQI [22] was employed to evaluate the physicochemical stability and aesthetic palatability of the water sources. Most samples across both LGAs were classified as "Good," indicating an acceptable physicochemical quality. This aligns with findings by [21], who reported similar safety ratings for boreholes and piped water in the region. However, a slight seasonal increase in WQI values was observed during the wet season, likely reflecting the influx of agricultural residues and dissolved ions via surface runoff [37,38]. Such seasonal fluctuations are typical in tropical rural aquifers where rainfall events trigger the migration of suspended solids [39].

A critical finding of this study is the divergence between these results and those of Iorliam *et al.* [14], who rated Obudu groundwater as "Fair to Poor." This discrepancy is attributed to the specific indexing methodology employed. While Iorliam *et al.* [14] utilized the Oregon Index, which integrates heavy metals directly into the final score, this study applied the Brown *et al.* [22]. method, focusing on five core physicochemical markers. Because these markers remained within regulatory limits, the WQI reflects a chemically balanced and aesthetically clear water profile. This distinction underscores that while the water in Obudu and Obanliku is physically and chemically "Good," its overall safety remains compromised by the microbial loads.

5. Conclusion

This study confirms a significant divergence between the physicochemical and bacteriological integrity of groundwater in Obudu and Obanliku LGAs. While the Water Quality Index (WQI) classifies the majority of sources as "Good" due to stable pH, low mineralization, and minimal nutrient loading, this aesthetic clarity masks a severe microbial risk. All sampled sources, including deep boreholes, exceeded regulatory limits for *E. coli* and fecal coliforms, indicating persistent fecal contamination across the region.

The spatiotemporal dynamics of the area reveal that the wet season acts as a critical trigger, significantly increasing microbial loads through vertical percolation and surface runoff. Shallow wells were identified as the most vulnerable infrastructure, while boreholes offered better, though not absolute protection. Ultimately, the degradation of water quality in these rural communities is driven by poor sanitation infrastructure, surface runoff and the prevalence of open defecation rather than industrial pollution.

To mitigate these risks, it is recommended that local authorities prioritize the construction of deeper, properly cased boreholes and implement community-led total sanitation programs to separate waste streams from the groundwater table. Future research should integrate Geographic Information Systems (GIS) to map these high-risk "Red Zones" for targeted governmental intervention.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declares no conflict of interest.

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