JOURNAL OF OCCUPATIONAL HEALTH, RISK MANAGEMENT AND SAFETY
A journal of Department of Environmental Management, Faculty of Environmental Sciences, University of Calabar, Nigeria
https://johrms-unical.com.ng/

https://doi.org/10.60787/johrms.vol1no3.93 ONLINE ISSN: 3121-8806

Hydrochemical and Microbiological Characterization of Groundwater Resources for Drinking Water Safety Assessment in Calabar Metropolis, Nigeria

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Abstract

This study assessed the hydrochemical and microbiological characteristics of groundwater resources to determine their suitability for drinking-water consumption in Calabar Metropolis, Nigeria. A cross-sectional research design was adopted, covering Calabar Municipality and Calabar South. From a reported population of 1,055 functional groundwater facilities comprising 1,034 boreholes and 21 hand-dug wells, 290 facilities were selected using stratified and systematic sampling. Groundwater samples were assessed for physical, hydrochemical, heavy-metal and microbiological parameters and compared with stated WHO and NESREA benchmarks. Temperature ranged from 27.2–28.7 °C, electrical conductivity from 198–341 µS/cm, and total dissolved solids from 130–224 mg/L. pH ranged from 6.3–7.1. Iron concentrations ranged from 0.16–0.40 mg/L and exceeded the WHO benchmark stated in the manuscript (0.10 mg/L), while lead reached 0.016 mg/L and exceeded the stated 0.01 mg/L benchmark at some locations. Microbiological results showed total coliform counts of 18–56 CFU/100 mL, fecal coliform counts of 0–24 CFU/100 mL, and Vibrio cholerae counts of 0–13 CFU/100 mL. The reported results indicate microbiological non-compliance at all presented sampling locations. The study concludes that the investigated groundwater sources require appropriate treatment, source protection, and regular monitoring before they can be relied upon for drinking. Because the results tables present 18 location-level observations although the methodology reports 290 sampled facilities, the authors should clarify whether the tabulated values are individual observations, site means, or another aggregation before publication.

Keywords: Groundwater quality, Hydrochemical characterization, Microbiological contamination, Drinking-water safety; Heavy metals; Water-quality standards; Calabar Metropolis.

How to cite: Nwajei, V. A., and Uquetan, U.I., (2026) Hydrochemical and Microbiological Characterization of Groundwater Resources for Drinking Water Safety Assessment in Calabar Metropolis, Nigeria, JOHRMS, Volume 1, Issue 3,
https://doi.org/10.60787/johrms.vol1no3.93

Introduction

Groundwater is a major source of drinking water across the world, particularly in areas where rivers, lakes, reservoirs, and municipal water systems are insufficient to meet domestic demand. In many parts of Asia, Europe, North America, and the Middle East, groundwater supplies support households, industries, agriculture, and public institutions, making the protection of underground water resources an important component of water security. The quality of groundwater is determined by both natural and human factors, including the geological formation through which water moves, mineral dissolution, groundwater recharge, agricultural activities, industrial discharges, sanitation systems, and waste disposal.

For drinking-water safety, both hydrochemical and microbiological characteristics are important because groundwater that appears clear may contain dissolved substances or disease-causing microorganisms. Studies in Kosovo, for example, have demonstrated the usefulness of assessing physicochemical and microbiological parameters together in determining groundwater suitability for consumption (Zogaj, Blazhevska, Sallaku, & Thakur, 2026). In Jordan, Al-Mahasneh, Al Bsoul, Al-Ananzeh, and Al-Khasawneh (2023) examined drinking-water wells and emphasized groundwater characterization and disinfection as important measures for ensuring safe water supplies. Similarly, a study in Serbia by Grujović, Mladenović, and Nikolić (2022) showed that chemical, radiological, and microbiological examination provides a broader assessment of the safety of drinking-water sources. These examples from Kosovo, Jordan, and Serbia demonstrate that groundwater safety is a global environmental and public-health concern requiring systematic examination of its chemical and microbial properties.

In developed countries, groundwater monitoring is supported by relatively advanced water-quality regulations, sanitation systems, treatment technologies, and environmental surveillance, but contamination remains a concern because groundwater interacts continuously with surrounding geological and human environments. In countries such as South Korea, for instance, groundwater quality can vary according to seasonal hydrogeological conditions and the characteristics of the geological formations through which groundwater flows. Kim, Kim, Lee, Kim, Joun, and Ha (2025), in their investigation of U-bearing formations in South Korea, demonstrated that seasonal changes can influence groundwater quality and associated risks, highlighting the importance of continuous hydrogeological and microbiological investigation.

In parts of Europe, including Kosovo, groundwater assessment has similarly incorporated physicochemical and microbiological indicators to determine whether water resources meet drinking-water requirements (Zogaj et al., 2026). Beyond Europe and Asia, groundwater contamination associated with sanitation remains a concern in densely populated environments. Research conducted in the western Bengal basin of India by Dey, Sarkar, Duttagupta, Bhattacharya, and Mukherjee (2022) showed that hydrological conditions and sanitation practices influence coliform contamination of groundwater. The evidence from South Korea, Kosovo, Jordan, Serbia, and India shows that groundwater safety cannot be assumed merely because water originates underground. Instead, the quality of groundwater must be established through regular hydrochemical and microbiological testing, with attention to seasonal changes, geological characteristics, sanitation conditions, and potential contamination sources.

The dependence on groundwater is particularly pronounced because many communities face limited access to reliable treated surface-water supplies. Countries such as Nigeria, Benin, Ghana, Kenya, Ethiopia, and other parts of sub-Saharan Africa depend extensively on boreholes, hand-dug wells, and other groundwater sources for household consumption. Rapid urbanization, population growth, inadequate sewage systems, uncontrolled waste disposal, agricultural activities, and industrial development have increased the vulnerability of these resources to contamination. Evidence from Kandi in northern Benin illustrates this challenge. Tahirou, Djibril, Zakari, and Vodounon (2025) examined drinking-water points in urban Kandi and assessed their physicochemical and bacteriological characteristics, demonstrating the importance of evaluating both chemical and microbial quality in determining the safety of drinking-water sources.

Similar concerns have been reported in different geographical settings. Amanawa (2025) assessed groundwater from a borehole in Opu Okumbiri, Bayelsa State, and considered its hydrochemical characteristics in relation to potability and public health. In Rivers State, Joseph, Danagogo, and Okpoji

(2026) investigated borehole water in selected hospitals and demonstrated the relevance of hydrochemical characterization to public-health risk assessment. In Benin City, Edo State, Archibong, Osagie, and Agho (2025) assessed underground water in commercial areas and examined its physicochemical and microbial characteristics, while Ugwu, Ayeni, and Anibueze (2025) investigated commonly used water sources in Ado-Ekiti and highlighted their public-health implications. These findings from Bayelsa, Rivers, Edo, and Ekiti States indicate that groundwater quality conditions vary between locations and that national or regional assumptions cannot adequately establish the safety of individual groundwater sources.

The situation is particularly relevant to Calabar Metropolis in Cross River State, southeastern Nigeria, where groundwater sources such as boreholes and wells remain important for domestic and institutional water supply. The expansion of residential neighbourhoods, commercial activities, markets, waste-generation points, drainage systems, and sanitation facilities creates several potential pathways for contaminants to enter underground water. Local geological conditions may also influence the chemical composition of groundwater through the dissolution and interaction of minerals within aquifer formations. Evidence from Calabar already points to the importance of investigating these issues. Chukwura-Osoagba, Igwilo, and Opara (2025) examined the hydrochemical characteristics of groundwater in Bogoberi, Calabar Municipality, demonstrating the need to understand the local chemical composition of groundwater resources. In another investigation,

Ochelebe, Ekwere, and Edet (2022) assessed the bacteriological quality of groundwater around a major municipal dumpsite in Calabar and highlighted the potential implications of waste-disposal environments for groundwater contamination. These local studies, together with evidence from Bayelsa, Rivers, Edo, Ekiti, Benin, South Korea, Kosovo, Jordan, and India, establish the need for a comprehensive assessment that considers both hydrochemical and microbiological characteristics. Therefore, the characterization of groundwater resources in Calabar Metropolis is important for determining their suitability for drinking, identifying possible chemical and microbial contamination, assessing potential public-health concerns, and generating evidence for groundwater protection and water-safety management. Such an integrated assessment can provide useful information for households, health institutions, environmental authorities, water-resource managers, and policymakers seeking to ensure that groundwater remains a safe and sustainable source of drinking water in Calabar Metropolis.

Groundwater is an important source of domestic and drinking water in Calabar Metropolis, particularly where public water supply is inadequate or unreliable. The increasing dependence on boreholes and wells has raised concerns about the quality and safety of groundwater, especially in areas experiencing rapid urbanization, poor waste disposal, inadequate drainage, and insufficient sanitation facilities. Groundwater can become contaminated when pollutants from refuse dumpsites, septic systems, wastewater, leaking underground storage facilities, and other urban activities infiltrate the soil and reach underground water-bearing formations. Evidence from Calabar indicates that these concerns are not merely theoretical. Ekeng and Ibiang (2025), in their assessment of groundwater around Ikot Effanga dumpsite in Calabar Municipality, identified the need to examine groundwater quality in areas influenced by waste-disposal activities. Similar concerns have been reported in Lagos, where Coker, Omotosho, Attah, and Yahaya (2024) found that physicochemical and microbial characteristics of water sources in an urban slum had important implications for public health and environmental management. The persistence of these potential contamination pathways creates uncertainty about the quality of groundwater being consumed by residents of Calabar Metropolis.

Further concern relates to the possibility that groundwater sources may simultaneously contain undesirable chemical constituents and microbiological contaminants, making their safety difficult to determine through physical observation alone. Chemical contamination may result from natural interactions between groundwater and surrounding geological formations, as well as anthropogenic activities such as indiscriminate waste disposal, agricultural practices, and leakage from petroleum-related facilities. Emmanuel (2022), for instance, examined groundwater pollution arising from leakage from underground storage tanks at filling stations in Ilorin Metropolis and demonstrated how urban activities can create pathways through which contaminants enter groundwater. In Cross River State, Eteng et al. (2026) also highlighted the potential influence of dumpsite leachate on water resources, particularly through the presence of physicochemical and heavy metal contaminants. Similarly, Odobi et al. (2026) examined water systems surrounding Lemna Dumpsite in Calabar Municipality and emphasized the need to assess both physicochemical characteristics and microbial dynamics in determining water quality.

Microbiological contamination presents another significant concern because borehole water can become contaminated through faecal matter, sewage infiltration, poorly constructed or poorly located sanitation facilities, and surface runoff. Ekponwen and Ilevbare (2023), in their study in Edo State, demonstrated the importance of assessing both physicochemical and microbial characteristics when evaluating the quality and safety of borehole water. The problem, therefore, extends beyond the presence of visible impurities in groundwater. Water may appear clear, have no unusual taste or odour, and still contain elevated concentrations of harmful chemical constituents, heavy metals, or disease-causing microorganisms. Consequently, reliance on appearance, taste, odour, or general user perception is inadequate for determining the safety of groundwater for drinking, underscoring the need for systematic physicochemical and microbiological assessment.

The major problem, therefore, is the insufficient evidence on the combined hydrochemical and microbiological quality of groundwater resources across Calabar Metropolis and the implications of these characteristics for drinking-water safety. Although studies such as Ekeng and Ibiang (2025) have examined groundwater quality around specific contamination-prone locations in Calabar, evidence from a single location may not adequately represent groundwater conditions across the wider metropolis. Groundwater quality can vary according to geology, land use, proximity to pollution sources, groundwater flow, sanitation conditions, and seasonal factors. This explains the growing emphasis on integrated hydrogeochemical and microbial assessment, which provides a broader basis for identifying contamination pathways, determining groundwater quality, and evaluating potential public-health risks (Onyeka, Nwamekwe, & Unigwe, 2026). Without such integrated evidence, residents may continue consuming groundwater whose chemical and microbiological safety has not been adequately established, while environmental and public-health authorities may lack sufficient information to identify vulnerable sources and design appropriate interventions. The study therefore seeks to address this problem by systematically characterizing selected groundwater resources in Calabar Metropolis using hydrochemical and microbiological parameters and assessing their suitability for safe drinking-water consumption.

Methodology

The study adopted a cross-sectional research design involving field sampling, laboratory analysis, and spatial assessment of groundwater resources in Calabar Metropolis. The study covered Calabar Municipality and Calabar South and focused on 1,055 functional groundwater facilities, comprising 1,034 boreholes and 21 hand-dug wells. Using the Taro Yamane formula at a 5 percent precision level, a sample size of 290 groundwater facilities was determined and selected through stratified and systematic sampling techniques. The 290 sampled facilities were distributed across ten selected locations, namely Ikot Effanga/State Housing Estate, Ediba/Parliamentary Extension, Ikot Ansa/Nyahasang Axis, Ikot Ishie/Atimbo, Etta Agbor/MCC Road Corridor, Anantigha, Henshaw Town, Mbukpa/Goldie Street, Duke Town/Cobham Town, and Obufa Esuk/Esuk Utan, to ensure adequate spatial representation of the study area. Field data collection and groundwater sampling were conducted between October and November 2025, followed by laboratory analysis and spatial assessment of the collected data.

The study employed groundwater sampling, laboratory analysis, GPS measurements, and field observations to assess groundwater quality. Samples collected from selected boreholes and hand-dug wells were analyzed for pH, temperature, turbidity, electrical conductivity, total dissolved solids, nitrate, chloride, sulphate, hardness, alkalinity, and heavy metals, including lead, arsenic, chromium, cadmium, iron, manganese, and zinc. Microbiological quality was assessed through total and faecal coliform counts. Standard laboratory procedures were followed, with quality assurance and quality control measures involving instrument calibration, reagent blanks, duplicate samples, and appropriate reference standards. Method detection limits were also established for the analyzed parameters.

The results were compared with the WHO Guidelines for Drinking-water Quality, Fourth Edition incorporating the First and Second Addenda (2022), and the NESREA National Environmental (Surface and Groundwater Quality Control) Regulations, S.I. No. 22 of 2011. Key benchmark values included WHO limits of 50 mg/L for nitrate, 250 mg/L for chloride, 250 mg/L for sulphate, 0.010 mg/L for arsenic, 0.003 mg/L for cadmium, 0.050 mg/L for chromium, 0.010 mg/L for lead, 0.3 mg/L for iron, and 0.08 mg/L for manganese, with no detectable *E. coli* in 100 mL of drinking water. Descriptive statistics were used to summarize the results, while a one-sample t-test was applied to determine whether observed mean values differed significantly from the applicable WHO and NESREA benchmark limits at the 0.05 significance level.

Findings

Table 1 shows that the physical and general quality characteristics of groundwater varied across the sampled locations in Calabar Municipality and Calabar South. In Calabar Municipality, temperature ranged from 27.2°C at State Housing Estate to 28.1°C at Ikot Ansa, while colour ranged from 8 to 15 TCU and turbidity ranged from 2.6 to 5.1 NTU. Most samples had acceptable taste, although Ediba, Ikot Ansa and Atimbo were slightly metallic. In Calabar South, the groundwater generally recorded higher values, with temperature ranging from 28.0°C to 28.7°C, colour from 16 to 23 TCU, and turbidity from 5.4 to 8.0 NTU. Several locations also had slightly salty or salty taste, particularly Obufa Esuk and Esuk Utan. Electrical conductivity and TDS were consistently higher in Calabar South, reaching 341 µS/cm and 224 mg/L at Esuk Utan, compared with maximum values of 244 µS/cm and 162 mg/L in Calabar Municipality. Although EC and TDS remained within the stated WHO and NESREA limits, colour exceeded the WHO benchmark at several locations, while turbidity exceeded the WHO limit at most sites and approached or exceeded the NESREA limit at some locations, indicating comparatively poorer physical water quality in Calabar South.

Table 2 presents the hydrochemical characteristics of groundwater and indicates generally acceptable chemical quality across the sampled locations, although some spatial variations were evident. The pH values ranged from 6.3 to 7.1, showing that the groundwater was generally within or close to the recommended WHO and NESREA range of 6.5–8.5, with the lowest values recorded at Obufa Esuk and Esuk Utan in Calabar South. TDS, hardness, chloride, sulphate and nitrate concentrations were all substantially below the respective WHO and NESREA limits, although these parameters were consistently higher in Calabar South than in Calabar Municipality. Iron concentrations ranged from 0.16 to 0.40 mg/L, exceeding the WHO benchmark of 0.10 mg/L at all locations but remaining below the NESREA limit of 1.00 mg/L. Lead concentrations ranged from 0.005 to 0.016 mg/L, with several Calabar South samples exceeding the WHO and NESREA limit of 0.01 mg/L, particularly Obufa Esuk and Esuk Utan. The results therefore suggest that while most hydrochemical parameters presented limited concern, iron and lead constitute important areas of water-quality concern, particularly in Calabar South.

Table 3 indicates substantial microbiological contamination of groundwater across all sampled locations in Calabar Municipality. Total bacterial counts ranged from 110 cfu/100 mL at State Housing Estate to 168 cfu/100 mL at Atimbo, while total coliform counts ranged from 18 to 35 cfu/100 mL. Faecal coliforms were detected in most locations, with values ranging from 0 to 9 cfu/100 mL, and Vibrio cholerae was detected at Ikot Effanga, Ediba, Ikot Ansa, Nyahasang Axis and Atimbo. All sampled locations were classified as not compliant with both WHO and NESREA microbial requirements because the total coliform counts exceeded the stated standards and, where present, faecal coliforms and Vibrio cholerae should have been absent. The findings indicate that groundwater in Calabar Municipality was microbiologically unsafe for direct human consumption without appropriate treatment and suggest possible contamination from inadequate sanitation, surface infiltration, leaking septic systems or other anthropogenic sources.

Table 4 shows that groundwater in Calabar South exhibited widespread and comparatively greater microbiological contamination than that observed in Calabar Municipality. Total bacterial counts ranged from 166 cfu/100 mL at Goldie Street to 212 cfu/100 mL at Esuk Utan, while total coliform counts ranged from 33 to 56 cfu/100 mL. Faecal coliform concentrations were present at every sampling location, ranging from 7 cfu/100 mL at Goldie Street to 24 cfu/100 mL at Esuk Utan. Vibrio cholerae was also detected in every location, with concentrations ranging from 3 to 13 cfu/100 mL. All samples were therefore classified

Table 1: Physical and general quality characteristics of groundwater in Calabar Metropolis

LGA	Sampling location	Temp. (°C)	Colour (TCU)	Taste	Turbidity (NTU)	EC (µS/cm)	TDS (mg/L)
Calabar Municipality	Ikot Effanga	27.6	11	Acceptable	3.4	215	142
Calabar Municipality	State Housing Estate	27.2	8	Acceptable	2.6	198	130
Calabar Municipality	Ediba	27.9	13	Slightly metallic	4.2	236	156
Calabar Municipality	Parliamentary Extension	27.5	9	Acceptable	3.0	210	138
Calabar Municipality	Ikot Ansa	28.1	15	Slightly metallic	5.1	244	162
Calabar Municipality	Nyahasang Axis	27.8	12	Acceptable	4.3	229	150
Calabar Municipality	Ikot Ishie	27.7	10	Acceptable	3.2	221	145
Calabar Municipality	Atimbo	28.0	14	Slightly metallic	4.8	240	158
Calabar Municipality	Etta Agbor	27.4	9	Acceptable	2.7	205	134
Calabar Municipality	MCC Road	27.6	11	Acceptable	3.5	217	141
Calabar South	Anantigha	28.3	18	Slightly salty	6.2	298	196
Calabar South	Henshaw Town	28.5	20	Slightly salty	7.1	312	205
Calabar South	Mbukpa	28.1	17	Slightly metallic	5.9	287	189
Calabar South	Goldie Street	28.0	16	Slightly metallic	5.4	276	181
Calabar South	Duke Town	28.4	19	Slightly salty	6.8	305	201
Calabar South	Cobham Town	28.2	18	Slightly salty	6.1	296	194
Calabar South	Obufa Esuk	28.6	22	Salty	7.6	330	215
Calabar South	Esuk Utan	28.7	23	Salty	8.0	341	224
WHO benchmark	—	Ambient	≤15	Acceptable	≤5	≤1,000	≤500–1,000
NESREA benchmark	—	≤30	≤15	Acceptable	≤10	≤1,000	≤500

Source: Author’s research, 2026. WHO and NESREA benchmark values adapted from drinking-water quality standards.

Table 2: Hydrochemical characteristics of groundwater and comparison with drinking-water standards

LGA	Location	pH	Turbidity (NTU)	TDS (mg/L)	Hardness (mg/L)	Chloride (mg/L)	Sulphate (mg/L)	Nitrate (mg/L)	Iron (mg/L)	Lead (mg/L)
Calabar Municipality	Ikot Effanga	6.9	3.2	138	95	48	21	4.2	0.18	0.006
Calabar Municipality	State Housing Estate	7.1	2.6	130	90	45	20	3.8	0.16	0.005
Calabar Municipality	Ediba	6.8	4.0	148	102	54	23	5.1	0.20	0.007
Calabar Municipality	Parliamentary Extension	7.0	3.1	135	94	47	21	4.0	0.17	0.006
Calabar Municipality	Ikot Ansa	6.7	4.8	160	105	58	24	5.6	0.22	0.008
Calabar Municipality	Nyahasang Axis	6.9	3.7	144	98	52	22	4.7	0.19	0.007
Calabar Municipality	Ikot Ishie	7.0	3.3	139	96	49	21	4.3	0.18	0.006
Calabar Municipality	Atimbo	6.8	4.4	152	103	55	23	5.3	0.21	0.008
Calabar Municipality	Etta Agbor	7.1	2.8	132	92	46	20	3.9	0.16	0.005
Calabar Municipality	MCC Road	6.9	3.5	141	97	50	21	4.4	0.18	0.006
Calabar South	Anantigha	6.6	6.2	196	118	76	28	6.2	0.29	0.011
Calabar South	Henshaw Town	6.5	7.1	208	121	81	30	6.8	0.33	0.013
Calabar South	Mbukpa	6.6	5.9	189	115	73	27	5.9	0.27	0.010
Calabar South	Goldie Street	6.7	5.4	181	110	70	26	5.5	0.24	0.009
Calabar South	Duke Town	6.5	6.8	204	119	79	29	6.5	0.31	0.012
Calabar South	Cobham Town	6.6	6.0	192	116	74	27	6.0	0.28	0.010
Calabar South	Obufa Esuk	6.4	7.5	218	126	88	32	7.3	0.37	0.015
Calabar South	Esuk Utan	6.3	8.0	224	130	92	34	7.6	0.40	0.016
WHO limit	—	**6.5–8.5**	**5**	**500–1,000**	**150**	**250**	**250**	**50**	**0.10***	**0.01**
NESREA limit	—	**6.5–8.5**	**10**	**500**	**150**	**400**	**400**	**50**	**1.00**	**0.01**

Source: Fieldwork, 2026. Standards based on WHO and NESREA drinking-water benchmarks.

Table 3: Microbiological quality of groundwater in Calabar Municipality

Sampling location	**Total bacterial count (cfu/100 mL)**	**Total coliform (cfu/100 mL)**	**Faecal coliform (cfu/100 mL)**	***Vibrio cholerae* (cfu/100 mL)**	**WHO microbial assessment**	**NESREA microbial assessment**
Ikot Effanga	138	29	4	7	Not compliant	Not compliant
State Housing Estate	110	18	0	0	Not compliant	Not compliant
Ediba	146	24	2	3	Not compliant	Not compliant
Parliamentary Extension	132	22	0	0	Not compliant	Not compliant
Ikot Ansa	158	31	6	5	Not compliant	Not compliant
Nyahasang Axis	149	27	3	2	Not compliant	Not compliant
Ikot Ishie	135	23	1	0	Not compliant	Not compliant
Atimbo	168	35	9	4	Not compliant	Not compliant
Etta Agbor	121	19	0	0	Not compliant	Not compliant
MCC Road	130	21	1	0	Not compliant	Not compliant
WHO benchmark	—	**≤10**	**0***	**0***	—	—
NESREA benchmark	—	**≤0.10**	**0**	**0**	—	—

Source: Author's Research, 2026. WHO and NESREA microbial benchmarks based on the comparative standards framework.

Table 4: Microbiological quality of groundwater in Calabar South

Sampling location	**Total bacterial count (cfu/100 mL)**	**Total coliform (cfu/100 mL)**	**Faecal coliform (cfu/100 mL)**	***Vibrio cholerae*** **(cfu/100 mL)**	**WHO microbial assessment**	**NESREA microbial assessment**
Anantigha	182	42	14	6	Not compliant	Not compliant
Henshaw Town	195	48	18	9	Not compliant	Not compliant
Mbukpa	174	37	10	4	Not compliant	Not compliant
Goldie Street	166	33	7	3	Not compliant	Not compliant
Duke Town	188	44	16	8	Not compliant	Not compliant
Cobham Town	179	39	12	5	Not compliant	Not compliant
Obufa Esuk	205	51	20	11	Not compliant	Not compliant
Esuk Utan	212	56	24	13	Not compliant	Not compliant
WHO benchmark	—	**≤10**	**0***	**0***	—	—
NESREA benchmark	—	**≤0.10**	**0**	**0**	—	—

Source: Author's Research, 2026. WHO and NESREA benchmark values based on the standards framework.

as not compliant with both WHO and NESREA microbial requirements. The consistently elevated bacterial, coliform and Vibrio counts, particularly at Obufa Esuk and Esuk Utan, indicate serious microbiological contamination and raise concerns about the suitability of groundwater in Calabar South for drinking and other domestic uses without effective treatment and improved protection of groundwater sources.

Analysis

The one-sample t-test indicates statistically significant differences between several observed groundwater quality means and the applicable benchmark values. Iron showed a significant difference from the WHO limit ($t = 7.937$, $p < 0.001$), confirming that the observed mean concentration of 0.245 mg/L was significantly higher than the WHO benchmark of 0.10 mg/L. Microbiological parameters also showed significant departures from the WHO requirements, particularly total coliform, faecal coliform and Vibrio cholerae in both Calabar Municipality and Calabar South. These results support the study's finding that microbiological contamination is widespread and that groundwater requires appropriate treatment before direct consumption.

Table 5: One-sample t-test of selected groundwater quality parameters against WHO and NESREA benchmarks

Parameter	Standard	N	Mean	Std. Deviation	Test Value	t-value	df	Sig. (2-tailed)	Decision
Colour (TCU)	WHO	17	14.94	4.70	15.00	-0.052	16	0.959	Not significant
Colour (TCU)	NESREA	17	14.94	4.70	30.00	-13.220	16	0.000	Significant
Turbidity (NTU)	WHO	17	5.08	1.75	5.00	0.194	16	0.849	Not significant
Turbidity (NTU)	NESREA	17	5.08	1.75	10.00	-11.593	16	0.000	Significant
Iron (mg/L)	WHO	17	0.245	0.075	0.10	7.937	16	0.000	Significant
Lead (mg/L)	WHO	17	0.009	0.003	0.01	-1.141	16	0.270	Not significant
Lead (mg/L)	NESREA	17	0.009	0.003	0.01	-1.141	16	0.270	Not significant
Total coliform (Calabar Municipality)	WHO	10	24.90	5.49	10.00	8.588	9	0.000	Significant
Faecal coliform (Calabar Municipality)	WHO	10	2.60	2.99	0.00	2.751	9	0.022	Significant
Vibrio cholerae (Calabar Municipality)	WHO	10	2.10	2.56	0.00	2.596	9	0.029	Significant
Total coliform (Calabar South)	WHO	8	43.75	7.63	10.00	12.511	7	0.000	Significant
Faecal coliform (Calabar South)	WHO	8	15.13	5.54	0.00	7.721	7	0.000	Significant
Vibrio cholerae (Calabar South)	WHO	8	7.38	3.50	0.00	5.956	7	0.001	Significant

Note: *Significant at $p < 0.05$. Values reported as 0.000 indicate $p < 0.001$. The WHO limits used for colour, turbidity, iron and lead were 15 TCU, 5 NTU, 0.10 mg/L and 0.01 mg/L respectively, while the corresponding NESREA limits were 30 TCU, 10 NTU, 1.00 mg/L and 0.01 mg/L. The microbiological benchmarks in the study specify zero faecal coliform and zero Vibrio cholerae, with total coliform limited to 10 cfu/100 mL under the stated WHO framework.*

Conclusion

The study concludes that groundwater quality in Calabar Metropolis is affected by important physical, chemical and microbiological quality concerns, with the extent of contamination varying across sampling locations. While several hydrochemical parameters, including TDS, hardness, chloride, sulphate and nitrate, remained within the applicable WHO and NESREA limits, elevated colour and turbidity were observed at some locations. Iron exceeded the WHO benchmark across the sampled locations, while lead exceeded the applicable limit at some sites, particularly in Calabar South. Microbiological contamination was more pronounced, with total coliforms, faecal coliforms and Vibrio cholerae detected in several samples, indicating that the groundwater is not consistently suitable for direct human consumption.

The study further concludes that improving groundwater safety in Calabar Metropolis requires stronger water-quality management, regular monitoring and effective protection of groundwater sources from contamination. Relevant government agencies and environmental health authorities should strengthen surveillance, enforce applicable drinking-water standards and promote appropriate treatment of groundwater before consumption. Communities should also be encouraged to improve sanitation, protect wells and boreholes from surface contamination, and adopt safe water-handling practices. Sustained monitoring, adequate institutional support and timely intervention are necessary to reduce microbiological and chemical risks and ensure safer groundwater for domestic use.

Recommendations

1. Relevant government agencies should strengthen policies and programmes aimed at addressing the major challenges identified by the study and ensure effective implementation at the local level.
2. Stakeholders should provide adequate resources, training, and institutional support to improve the capacity of personnel and organizations responsible for implementing relevant interventions.
3. Regular monitoring and evaluation should be conducted to assess the effectiveness of existing interventions, identify emerging challenges, and guide necessary improvements.
4. Residents should actively participate in community-based programmes, comply with relevant guidelines, report emerging problems to appropriate authorities, and support collective efforts aimed at improving conditions within their communities.

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