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Physicochemical, Nutrient and Microbiological Characteristics of Water from Selected Waterfronts in Calabar, Cross River State, Nigeria

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Abstract

Water quality assessment is important in waterfront communities where surface waters support domestic activities, fisheries, transportation and other livelihoods. This study assessed selected physicochemical, nutrient and microbiological characteristics of water from Adiabo, Nsidung and Ikang waterfronts in Calabar, Cross River State, Nigeria. Water samples were analysed for pH, temperature, turbidity, electrical conductivity, total dissolved solids (TDS), colour, salinity, total hardness, nitrate, nitrite, phosphorus, ammonia, faecal coliform count (FCC) and total coliform count (TCC). Descriptive statistics were expressed as mean ± standard deviation with 95% confidence intervals. Spatial differences were evaluated using one-way analysis of variance (ANOVA), with effect size estimated using eta squared (η^2). Levene's test was used to assess homogeneity of variance, while Tukey's HSD was applied following significant ANOVA results. Welch ANOVA and Games–Howell procedures were specified as alternatives where the homogeneity assumption was violated. Mean pH ranged from 6.32 to 6.42, while turbidity ranged from 10.19 to 12.52 NTU and colour from 66.67 to 71.00 Pt-Co. The overall ANOVA showed no significant spatial differences in pH, temperature, turbidity, electrical conductivity, TDS, colour, total hardness, nitrate, nitrite, ammonia or total coliform count ($p > 0.05$). Phosphorus differed significantly among waterfronts, $F(2,6) = 15.16$, $p = 0.005$, $\eta^2 = 0.835$, with Ikang recording the highest concentration. Faecal coliform counts also differed significantly, $F(2,6) = 24.58$, $p = 0.001$, $\eta^2 = 0.891$, with Nsidung recording the highest count. Tukey HSD confirmed significant differences involving Ikang for phosphorus and Nsidung for FCC. The findings demonstrate persistent physical and microbiological water-quality concerns and support improved sanitation, wastewater management and integrated water-quality surveillance in Calabar waterfront communities.

Keywords: Calabar Waterfronts, Water Quality, Physicochemical Parameters, Nutrients, Faecal Coliforms, Total Coliforms, Nigeria

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INTRODUCTION

Water quality is a multidimensional determinant of ecosystem integrity and human health. It is influenced by physical characteristics, dissolved chemical constituents, nutrients, microorganisms and contaminants introduced through natural processes and anthropogenic activities. In densely settled coastal and estuarine environments, untreated domestic wastewater, stormwater runoff, indiscriminate solid-waste disposal, fishing and fish-processing activities, transportation, agricultural runoff and industrial discharges can alter the chemical and biological characteristics of receiving waters.

The World Health Organization emphasizes risk-based management of drinking-water quality and surveillance from source to consumer. The WHO drinking-water framework recognizes that the safety of water depends on the combined management of microbiological, chemical and operational risks rather than assessment of a single parameter (WHO, 2022, 2026).

Calabar is situated within a hydrologically complex coastal setting associated with the Calabar River, Great Kwa River and Cross River estuarine system. The Calabar River originates in the Oban Hills and drains southward towards the Cross River estuary. The surrounding catchment encompasses urban, peri-urban and waterfront settlements in which population growth, settlement expansion and land-use changes can place increasing pressure on aquatic systems. Njar et al. (2019) reported settlement expansion and associated estuarine degradation along the Calabar River, while Enyenihi et al. (2019) demonstrated the importance of nutrient dynamics within the Cross River estuary and adjacent Gulf of Guinea.

Previous investigations of Nigerian coastal and estuarine systems have documented spatial and seasonal variability in physicochemical characteristics and trace-metal concentrations. Onojake et al. (2017), for example, reported variations in surface-water characteristics and trace metals within the Bonny/New Calabar River estuary. Similarly, Ebong and John (2021) reported elevated physicochemical and selected trace-metal parameters in major estuaries of the Niger Delta. Uzamere et al. (2023) also identified physicochemical concerns in the New Calabar River.

The quality of waterfront water is particularly important because communities may interact directly with these environments through domestic activities, fishing, fish processing, transportation and recreation. Microbial contamination is of particular concern because the detection of faecal indicator organisms can indicate contamination by sewage, animal waste or faecally contaminated runoff and may signal vulnerability to enteric pathogens. For drinking-water supplies, WHO guidance identifies the absence of Escherichia coli in a 100-mL sample as the principal microbiological target (WHO, 2022, 2026).

The present study therefore assessed physicochemical, nutrient and microbiological characteristics of water from three selected waterfronts—Adiabo, Nsidung and Ikang—in Calabar, Cross River State, Nigeria. Specifically, the study examined spatial variation in physical parameters, nutrients and microbial indicators using descriptive and inferential statistical procedures. Composite water-quality and pollution indices reported in the underlying dataset were also considered to provide an integrated assessment of water-quality conditions.

MATERIALS AND METHODS

Study area

The study was conducted at selected waterfronts in Calabar, Cross River State, southeastern Nigeria. The area is associated with the Calabar and Great Kwa rivers and the wider Cross River estuarine system. The Calabar River originates in the Oban Hills and flows southward towards the estuary. The region experiences a tropical humid climate characterized by a pronounced rainy season and a comparatively drier period.

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The waterfront environment supports fishing, transportation, domestic activities, fish processing and other livelihood activities. These activities, together with settlement development and drainage, provide potential pathways for the introduction of organic matter, nutrients, suspended solids and microorganisms into adjoining surface waters.

Study design and water sampling

A comparative environmental water-quality assessment was undertaken at three waterfront locations: Adiabo, Nsidung and Ikang. Water samples were collected for physicochemical, nutrient and microbiological analyses. Three observations were available for each parameter at each waterfront, giving three analytical replicates per location for the statistical comparisons.

Physicochemical analysis

Water temperature, pH, turbidity, electrical conductivity, total dissolved solids, colour, salinity and total hardness were determined using standard water-analysis procedures. pH was measured using a calibrated combined glass-electrode pH meter, turbidity using a turbidity meter, and colour using a Nessler/Lovibond comparator. Electrical conductivity was measured with a conductivity probe, while TDS was estimated from conductivity using the applicable conversion factor. The analytical framework was consistent with the scope of Standard Methods for the Examination of Water and Wastewater, 24th edition (APHA, AWWA, & WEF, 2023).

Nutrient analysis

Water samples were analysed for nitrate, nitrite, phosphorus and ammonia. Results were expressed in mg/L. The original dataset reported nutrient concentrations as mean ± standard deviation.

Microbiological analysis

Faecal coliform count (FCC) and total coliform count (TCC) were determined and expressed as colony-forming units per 100 mL (CFU/100 mL). The presence of faecal indicator organisms was interpreted as evidence of microbiological contamination and possible vulnerability to sewage or faecally contaminated runoff. For drinking-water interpretation, WHO recommends that E. coli, or thermotolerant coliforms where used operationally, should not be detectable in a 100-mL sample (WHO, 2022, 2026).

Water-quality and pollution indices

The study also considered composite indices reported in the source dataset, including Heavy Metal Pollution Index (HPI), Degree of Contamination (Cd), Pollution Load Index (PLI), Water Quality Index (WQI) and nitrate hazard quotient (NHQ). The Nemerow-type pollution approach provides an integrated pollution assessment that emphasizes highly polluted parameters while incorporating the contribution of other parameters (Su et al., 2022).

Because composite indices depend on the parameters, standards, weighting systems and analytical assumptions used in their construction, they were interpreted as supplementary indicators rather than replacements for individual parameter measurements.

Statistical analysis

Data were summarized using means, standard deviations and 95% confidence intervals (CI) for each waterfront.

The following inferential procedures were used:

- One-way ANOVA was used to test whether mean parameter concentrations differed among Adiabo, Nsidung and Ikang.

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- The ANOVA F statistic, degrees of freedom and p-value were reported.
- Eta squared (η^2) was calculated as a measure of effect size, representing the proportion of total variability attributable to differences among waterfronts.
- Levene's test was used to assess the homogeneity-of-variance assumption.

Where the ANOVA was significant, Tukey's honestly significant difference (HSD) test was used for pairwise comparisons of:

- Adiabo versus Nsidung;
- Adiabo versus Ikang; and
- Nsidung versus Ikang.

Where Levene's test indicated violation of homogeneity of variance, Welch's ANOVA was to be used instead of conventional ANOVA, followed by Games–Howell pairwise comparisons.

Statistical significance was evaluated at $\alpha = 0.05$.

The analysis covered all available physical parameters (pH, temperature, turbidity, electrical conductivity, TDS, colour, salinity and hardness), nutrient parameters (nitrate, nitrite, phosphorus and ammonia) and biological parameters (FCC and TCC).

Because only three replicate observations were available per waterfront, the inferential results were interpreted cautiously, particularly with respect to assumptions of normality and statistical power.

RESULTS

Physicochemical characteristics

The physicochemical characteristics of water from the three waterfronts are presented in Table 1. Mean pH was 6.42 at Adiabo, 6.34 at Nsidung and 6.32 at Ikang. Mean temperature ranged from 24.97°C at Nsidung to 26.14°C at Ikang. Turbidity exceeded the 5-NTU comparison value at all three locations.

Conductivity and TDS were highest at Ikang, whereas Adiabo had the highest mean total hardness. Colour values were elevated at all three waterfronts relative to the 15 Pt-Co comparison value.

Table 1. Physicochemical characteristics of water from the three waterfronts

Parameter	Reference value	Adiabo Mean ± SD	Nsidung Mean ± SD	Ikang Mean ± SD
pH	6.5–8.5	6.42 ± 0.71	6.34 ± 0.22	6.32 ± 0.12
Temperature (°C)	Ambient	26.10 ± 0.87	24.97 ± 0.76	26.14 ± 1.69
Turbidity (NTU)	<5	12.52 ± 2.01	10.19 ± 4.09	10.39 ± 6.31
Conductivity (µS/cm)	1000	341.20 ± 184.95	259.35 ± 432.71	566.67 ± 155.00
TDS (mg/L)	600	204.72 ± 110.97	155.61 ± 259.62	340.00 ± 93.00
Colour (Pt-Co)	15	66.67 ± 5.77	70.67 ± 3.06	71.00 ± 1.00
Salinity (mg/L)	250	63.60 ± 3.96	32.49 ± 12.17	57.33 ± 33.48
Total hardness (mg/L)	500	48.31 ± 21.54	28.67 ± 9.50	30.70 ± 12.01

Note: SD values for parameters with complete raw triplicate data were recalculated from the supplied observations. Salinity values are retained from the source manuscript because the raw salinity observations supplied for recalculation were incomplete/ambiguous.

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Assumption testing and ANOVA of physicochemical parameters

Levene's test did not indicate significant heterogeneity of variance for pH, temperature, turbidity, conductivity, TDS, colour or total hardness ($p > 0.05$). Consequently, conventional one-way ANOVA was retained for these parameters and Welch ANOVA was not required.

There were no statistically significant spatial differences in pH, temperature, turbidity, conductivity, TDS, colour or total hardness ($p > 0.05$). Although conductivity and TDS showed numerical differences among sites, these differences were not statistically significant.

Table 2. Levene's test and one-way ANOVA for physicochemical parameters

Parameter	Levene's F	Levene's p	ANOVA F	df	p-value	η^2	Decision
pH	1.192	.367	0.047	2, 6	.954	.015	NS
Temperature	0.180	.839	0.951	2, 6	.438	.241	NS
Turbidity	0.802	.491	0.247	2, 6	.789	.076	NS
Conductivity	0.276	.768	0.929	2, 6	.445	.236	NS
TDS	0.276	.768	0.929	2, 6	.445	.236	NS
Colour	0.425	.672	1.199	2, 6	.365	.285	NS
Total hardness	0.408	.682	1.503	2, 6	.296	.334	NS

Note: NS = not significant at $p < 0.05$. η^2 = eta squared. Welch ANOVA was not required because Levene's test was not significant for these parameters.

The effect sizes varied from very small for pH ($\eta^2 = .015$) to moderate-to-large values for total hardness ($\eta^2 = .334$), although none reached statistical significance at the 5% level.

Nutrient characteristics

The nutrient concentrations are presented in Table 3. Nitrate ranged from 1.20 mg/L at Adiabo to 7.70 mg/L at Ikang. Nitrite ranged from 0.06 mg/L at Nsidung to 0.50 mg/L at Adiabo. Phosphorus showed the largest numerical spatial gradient, increasing from 2.86 mg/L at Adiabo to 8.81 mg/L at Ikang. Ammonia ranged from 0.45 mg/L at Adiabo to 0.64 mg/L at Ikang.

Table 3. Nutrient characteristics of water from the three waterfronts

Table 3. Nutrient characteristics of water from the three waterfronts

Parameter	Reference value	Adiabo Mean ± SD	Nsidung Mean ± SD	Ikang Mean ± SD
Nitrate (mg/L)	50	1.20 ± 0.20	6.25 ± 8.88	7.70 ± 0.87
Nitrite (mg/L)	3	0.50 ± 0.55	0.06 ± 0.06	0.16 ± 0.04
Phosphorus (mg/L)	5	2.86 ± 0.39	4.00 ± 0.22	8.81 ± 2.39
Ammonia (mg/L)	1.0	0.45 ± 0.33	0.61 ± 0.12	0.64 ± 0.10

Statistical analysis of nutrient parameters

Levene's test was not significant for nitrate, nitrite, phosphorus or ammonia ($p > 0.05$); therefore,

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conventional ANOVA was used.

Nitrate, nitrite and ammonia did not differ significantly among the three waterfronts. In contrast, phosphorus demonstrated a statistically significant spatial difference, $F(2,6) = 15.16$, $p = .005$, $\eta^2 = .835$. The effect size indicates that a large proportion of the observed variability in phosphorus was associated with location.

Table 4. Levene's test and one-way ANOVA for nutrient parameters

Parameter	Levene's F	Levene's p	ANOVA F	df	p-value	η^2	Decision
Nitrate	0.954	.437	1.316	2, 6	.336	.305	NS
Nitrite	1.483	.300	1.549	2, 6	.287	.340	NS
Phosphorus	2.683	.147	15.157	2, 6	.005	.835	Significant
Ammonia	1.358	.326	0.702	2, 6	.532	.190	NS

Tukey HSD post-hoc analysis of phosphorus

Tukey HSD demonstrated that the significant overall phosphorus difference was attributable to the substantially higher concentration at Ikang.

The mean phosphorus concentration at Ikang was significantly higher than that at Adiabo (mean difference = 5.95 mg/L, 95% CI: 2.43–9.47, $p = .005$) and Nsidung (mean difference = 4.81 mg/L, 95% CI: 1.29–8.33, $p = .014$). The difference between Adiabo and Nsidung was not statistically significant ($p = .605$).

Table 5. Tukey HSD pairwise comparisons for phosphorus

Pairwise comparison	Mean difference	95% CI	Adjusted p-value	Decision
Adiabo vs Nsidung	-1.14	[-4.66, 2.38]	.605	NS
Adiabo vs Ikang	-5.95	[-9.47, -2.43]	.005	Significant
Nsidung vs Ikang	-4.81	[-8.33, -1.29]	.014	Significant

Note: Mean difference = first waterfront minus second waterfront. Tukey-adjusted p-values are reported at $\alpha = .05$.

Microbiological characteristics

Faecal coliforms were detected at all three waterfronts (Table 6). Nsidung recorded the highest mean FCC (78.90 CFU/100 mL), followed by Ikang (32.90 CFU/100 mL) and Adiabo (25.47 CFU/100 mL). Total coliform counts ranged from 15.59 CFU/100 mL at Ikang to 22.07 CFU/100 mL at Adiabo.

Statistical analysis of microbiological parameters

Levene's tests showed no significant evidence of unequal variances for either FCC or TCC (see Table 7). One-way ANOVA revealed a statistically significant spatial difference in FCC, $F(2,6) = 24.58$, $p = .001$, $\eta^2 = .891$. In contrast, TCC did not differ significantly among the waterfronts, $F(2,6) = 1.59$, $p = .279$, $\eta^2 = .347$.

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Table 6. Microbiological characteristics of water from the three waterfronts

Parameter	Reference	Adiabo Mean ± SD	Nsidung Mean ± SD	Ikang Mean ± SD
Faecal coliform (CFU/100 mL)	0	25.47 ± 4.43	78.90 ± 14.41	32.90 ± 8.92
Total coliform (CFU/100 mL)	0	22.07 ± 5.82	16.18 ± 2.14	15.59 ± 5.84

Table 7. Levene's test and one-way ANOVA for microbiological parameters

Parameter	Levene's F	Levene's p	ANOVA F	df	p-value	η^2	Decision
Faecal coliform count	0.404	.685	24.579	2, 6	.001	.891	Significant
Total coliform count	0.610	.574	1.593	2, 6	.279	.347	NS

Tukey HSD post-hoc analysis of faecal coliform count

Tukey HSD showed that Nsidung had significantly higher FCC than both Adiabo and Ikang. The difference between Adiabo and Ikang was not statistically significant (Table 8).

Welch ANOVA and Games–Howell analysis

Levene's tests for the parameters with complete triplicate observations did not indicate statistically significant heterogeneity of variance at $\alpha = .05$. Consequently, Welch's ANOVA was not required as the primary inferential procedure, and Games–Howell post-hoc comparisons were not triggered.

This does not imply that the small replicate number provides strong evidence that the underlying population variances are identical. Rather, it indicates that the available data did not provide sufficient statistical evidence to reject the equal-variance assumption.

Integrated water-quality and pollution indicators

The composite indicators reported in the source dataset are presented in Table 9.

Table 8. Tukey HSD pairwise comparisons for faecal coliform count

Pairwise comparison	Mean difference (CFU/100 mL)	95% CI	Adjusted p-value	Decision
Adiabo vs Nsidung	-53.43	[-78.77, -28.10]	.002	Significant
Adiabo vs Ikang	-7.43	[-32.77, 17.90]	.660	NS
Nsidung vs Ikang	46.00	[20.67, 71.33]	.003	Significant

Note: Mean difference = first waterfront minus second waterfront.

Table 9. Integrated water-quality and pollution indicators reported in the source dataset

Index/indicator	Adiabo	Nsidung	Ikang	Interpretation reported in source
Degree of Contamination (Cd)	6.03	4.63	3.46	High
PLI	1.21	1.13	0.89	Polluted/near threshold
WQI	214	248	271	Very poor water quality
Nitrate hazard quotient	0.024	0.125	0.154	<1; no nitrate toxicity risk
Faecal coliform (CFU/100 mL)	25.47	78.90	32.90	Unacceptable contamination

Note: Cd = Degree of Contamination; PLI = Pollution Load Index; WQI = Water Quality Index. Composite-index classifications are retained from the source dataset and depend on the standards, weights and parameters used in their calculation.

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DISCUSSION

The present study demonstrates a mixed water-quality pattern across the three selected Calabar waterfronts. Several parameters, including conductivity, TDS, hardness and the measured inorganic nutrients, had relatively low absolute concentrations compared with the comparison values used in the source dataset. However, turbidity and colour were consistently elevated, while faecal coliforms were detected at all three waterfronts. The inferential analysis further identified significant spatial differences specifically in phosphorus and faecal coliform concentration.

The mean pH values of 6.32–6.42 indicate mildly acidic water at the three waterfronts. The values were slightly below the 6.5–8.5 range used in the source manuscript. However, pH requires careful interpretation because WHO does not primarily establish it as a health-based chemical guideline. Rather, pH is an important operational parameter affecting treatment efficiency, corrosion and the behaviour of other constituents (WHO, 2022).

The absence of a significant difference in pH, $F(2,6) = 0.047$, $p = .954$, suggests that the observed spatial variation was small relative to within-location variation. The very small eta squared ($\eta^2 = .015$) further indicates that location explained little of the observed variation in pH.

Temperature also did not differ significantly among the waterfronts, $F(2,6) = 0.951$, $p = .438$. The observed temperatures are consistent with a tropical aquatic environment. Temperature can influence chemical reaction rates, dissolved oxygen dynamics and microbial processes, but the present dataset does not permit direct assessment of these relationships.

Turbidity exceeded the 5-NTU comparison value at all three locations. Mean turbidity was highest at Adiabo (12.52 NTU), although the spatial difference was not statistically significant, $F(2,6) = 0.247$, $p = .789$. The absence of a statistically significant difference should not be interpreted as an absence of environmental concern because the mean values at all three sites exceeded the comparison value.

Elevated turbidity may result from suspended mineral particles, organic matter, bank erosion, runoff, resuspension of bottom sediments and human activities along the waterfront. In coastal and estuarine environments, rainfall and runoff can transport particulate matter from surrounding settlements into receiving waters. Similar physicochemical concerns have been documented in Nigerian estuarine systems (Ebong & John, 2021; Uzamere *et al.,* 2023).

Colour was similarly elevated at all three waterfronts. Mean colour ranged from 66.67 to 71.00 Pt-Co compared with the 15-Pt-Co comparison value. Although the spatial difference was not statistically significant, $F(2,6) = 1.199$, $p = .365$, the consistently elevated values indicate a widespread rather than site-specific physical water-quality concern.

Elevated colour may reflect dissolved organic matter, humic substances, suspended particles or anthropogenic inputs. The finding has implications for aesthetic quality and water treatment. Thus, the fact that conductivity and TDS were below their respective comparison values should not be interpreted as evidence that the water is suitable for direct consumption.

Conductivity ranged from 259.35 µS/cm at Nsidung to 566.67 µS/cm at Ikang, but the spatial difference was not statistically significant, $F(2,6) = .929$, $p = .445$. Similarly, TDS showed no significant spatial difference. Conductivity is a useful indicator of ionic content, although it is not itself a direct measure of toxicity. The higher numerical values at Ikang may indicate greater ionic enrichment, potentially associated with local hydrological or land-use conditions.

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Total hardness was also not significantly different among the waterfronts, $F(2,6) = 1.503$, $p = .296$. The relatively low hardness values suggest that hardness was not a dominant water-quality constraint in the sampled waters. Nevertheless, hardness does not provide evidence of microbiological safety.

The original manuscript treated 250 and 500 mg/L as WHO limits for salinity and hardness. These values should be carefully verified before final publication because they should not be presented as equivalent to health-based WHO guideline values without identifying the precise source and basis of the standards.

Nitrate concentrations were relatively low compared with the reference value reported in the source dataset. Although Ikang recorded the highest mean nitrate concentration (7.70 mg/L), the spatial difference was not significant, $F(2,6) = 1.316$, $p = .336$.

The large standard deviation observed at Nsidung was attributable to the unusually high replicate value of 16.5 mg/L relative to the other two observations. This illustrates why reporting only means can obscure the variability within a sampling location. The 95% CI around the Nsidung mean was consequently wide.

Nitrite also showed no statistically significant spatial difference, $F(2,6) = 1.549$, $p = .287$. The relatively high nitrite value at Adiabo was associated with considerable within-site variation.

Phosphorus was the nutrient showing the strongest spatial differentiation. The mean concentration increased from 2.86 mg/L at Adiabo to 4.00 mg/L at Nsidung and 8.81 mg/L at Ikang. The ANOVA demonstrated a significant difference, $F(2,6) = 15.157$, $p = .005$, with a very large effect size ($\eta^2 = .835$).

Tukey HSD demonstrated that Ikang differed significantly from both Adiabo and Nsidung, whereas Adiabo and Nsidung did not differ significantly. The pattern therefore indicates that the overall phosphorus difference was primarily associated with the higher concentration at Ikang.

The ecological interpretation of the phosphorus findings requires caution because the source manuscript reports phosphorus simply as "P" and the analytical species and units should be confirmed. Phosphorus may be reported as elemental phosphorus, phosphate-P, orthophosphate or another analytical fraction. Before publication, the laboratory method and reporting basis should therefore be explicitly stated.

Where elevated phosphorus reflects anthropogenic nutrient loading, possible sources include domestic wastewater, surface runoff, organic waste and other land-based inputs. Nutrient dynamics in the Cross River estuarine system are also influenced by river discharge, rainfall, sediment-water interactions and biological uptake (Enyenihi et al., 2019).

Ammonia was below the comparison value used in the source dataset and did not differ significantly among locations, $F(2,6) = .702$, $p = .532$. Ammonia behaviour in aquatic systems is influenced by pH and temperature, particularly through their effects on the proportion of unionized ammonia.

The microbiological findings represent one of the clearest public-health concerns in the study. Faecal coliforms were detected at all three waterfronts, demonstrating microbiological contamination of the sampled waters. The highest mean FCC occurred at Nsidung (78.90 CFU/100 mL).

The spatial difference in FCC was highly significant, $F(2,6) = 24.579$, $p = .001$, with a very large effect size ($\eta^2 = .891$). Tukey HSD confirmed that Nsidung had significantly higher FCC than both Adiabo and Ikang. Adiabo and Ikang did not differ significantly.

This pattern suggests substantial spatial heterogeneity in faecal contamination. Possible explanations include differences in drainage, sewage disposal, settlement density, animal waste, fish-processing activities and runoff. However, the current dataset does not permit identification of the specific contamination source. Microbial source tracking, sanitary inspection and additional microbiological analyses would be necessary to distinguish human, livestock, wildlife and mixed sources.

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The detection of faecal indicator organisms is particularly important because the WHO drinking-water framework uses the absence of E. coli in 100 mL as a key microbiological target. Consequently, the presence of faecal coliforms in the sampled waterfront waters reinforces the need for appropriate treatment before drinking-water use (WHO, 2022, 2026).

Total coliform count did not differ significantly among the three locations, $F(2,6) = 1.593$, $p = .279$. The different statistical pattern for FCC and TCC illustrates the importance of distinguishing between general coliform contamination and faecal contamination when interpreting microbiological water quality.

The Degree of Contamination values were classified as high, while PLI values indicated pollution at Adiabo and Nsidung and a value near the threshold at Ikang. The WQI values ranged from 214 to 271 and were classified as very poor in the source analysis.

These composite indices provide a useful summary of overall environmental conditions, but they should be interpreted cautiously. HPI, WQI and related indices depend on the parameters selected, reference standards, weighting procedures and mathematical formulations. Consequently, they should complement rather than replace presentation of individual parameter concentrations and analytical quality-control information.

The reported NHQ values were below one at all locations, indicating no nitrate toxicity risk under the assumptions used in the original calculation. However, a low nitrate hazard quotient does not imply overall water safety because microbiological, physical and other chemical hazards remain relevant.

An important finding from the recalculated analysis is that not every numerical difference among waterfronts was statistically significant. Conductivity was numerically highest at Ikang, colour was slightly higher at Ikang, and turbidity was highest at Adiabo, but none of these differences achieved statistical significance.

The statistically significant variables were phosphorus and FCC. The phosphorus pattern was characterized by a high concentration at Ikang, whereas the microbiological pattern was characterized by substantially higher faecal contamination at Nsidung.

These contrasting spatial patterns suggest that different environmental processes may influence different water-quality indicators. Nutrient enrichment at Ikang may reflect local nutrient inputs or hydrological processes, whereas the elevated FCC at Nsidung may reflect localized faecal contamination. These interpretations remain hypotheses because the study design did not include sanitary source tracing.

The combination of elevated turbidity and colour with widespread faecal contamination indicates that the waterfront waters should not be regarded as suitable for untreated drinking-water use. Importantly, the absence of statistically significant differences for several physical and chemical parameters does not eliminate the public-health concern created by microbiological contamination.

Waterfront residents may potentially be exposed through domestic contact, fishing, fish processing, recreational activities and other interactions with surface water. However, the present study did not directly measure human exposure or disease outcomes; consequently, health implications should be presented as potential risks rather than demonstrated causal effects.

The findings are consistent with broader evidence of anthropogenic pressure on Nigerian coastal and estuarine waters. Onojake et al. (2017) documented spatial and seasonal variation and trace-metal concerns in the Bonny/New Calabar River estuary, while Ebong and John (2021) reported physicochemical and trace-metal concerns in Niger Delta estuaries. Njar et al. (2019) also documented settlement expansion and estuarine degradation along the Calabar River.

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A major strength of the study is its integrated assessment of physical, chemical, nutrient and microbiological characteristics across three waterfront locations. The inclusion of multiple indicators provides a broader assessment of water quality than reliance on a single parameter.

A further strength is the use of inferential statistics incorporating Levene's test, ANOVA, effect sizes and post-hoc comparisons. This provides a more rigorous assessment of spatial differences than descriptive comparison of means alone.

However, the study has important limitations. First, only three analytical replicates were available for each waterfront, resulting in very small within-location sample sizes. Consequently, confidence intervals are wide for several parameters and the statistical power to detect moderate spatial differences is limited.

In conclusion, water from the Adiabo, Nsidung and Ikang waterfronts demonstrated a combination of physical, nutrient and microbiological water-quality concerns. Turbidity and colour were elevated at all three waterfronts, while faecal coliforms were detected throughout the study area. Although most physical and nutrient parameters did not demonstrate statistically significant spatial differences, phosphorus showed a significant and large spatial effect, with Ikang recording significantly higher concentrations than Adiabo and Nsidung. Faecal coliform count also differed significantly among locations, with Nsidung recording significantly higher contamination than both Adiabo and Ikang. Total coliform count did not differ significantly among waterfronts. The findings indicate that assessment of waterfront water quality should not rely solely on physicochemical compliance with individual reference values. Microbiological contamination, particularly faecal contamination, remains an important determinant of potential water-use risk. The reported composite indices further suggest broader environmental impairment, although these indices require interpretation in relation to their underlying standards and calculation methods.

It is therefore recommended that routine integrated water-quality monitoring should be established at Adiabo, Nsidung and Ikang, incorporating physicochemical, nutrient and microbiological parameters. Monitoring should be conducted during both dry and rainy seasons to capture seasonal variability. Sanitation and wastewater management should be strengthened in waterfront communities to reduce faecal contamination. Particular attention should be given to Nsidung because of its significantly higher faecal coliform count. Sanitary inspections and microbial source-tracking studies should be undertaken to identify the dominant sources of faecal contamination. Also, solid-waste disposal and drainage systems should be improved to reduce particulate and nutrient inputs. Raw waterfront water should undergo appropriate treatment before domestic or drinking-water use. Future investigations should increase the number of independent sampling events and include seasonal and tidal replication to improve statistical power.

Declarations

***Ethics approval*:** Not applicable.

***Data availability*:** The study is based on the water-quality observations and analytical results described in the manuscript/source dataset.

***Conflict of interest*:** The authors declare none

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