

RESEARCH ARTICLE

URBANIZATION, SEASONALITY, AND PUBLIC HEALTH RISKS: INTEGRATING HYDROCHEMICAL AND COMMUNITY PERSPECTIVES ON WATER SECURITY IN LIMBE, CAMEROON

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ABSTRACT

Rapid urbanization and unregulated land use are intensifying water quality challenges in sub-Saharan African cities, yet local data to guide effective management remain scarce. This study assessed the spatiotemporal variability of drinking water quality in Limbe, Cameroon, by integrating hydrochemical analyses of the Limbe and Macocar rivers with community-based surveys. Water samples collected at upstream, midstream, and downstream during the dry and rainy seasons were analyzed for physicochemical and microbial parameters, while household surveys captured perceptions of health and socioeconomic impacts. Results revealed pronounced dry-season spikes in electrical conductivity, total dissolved solids, and coliform counts in the Macocar River, while the Limbe River exhibited persistent downstream increases in nutrient and microbial loads. Statistical analyses linked these trends to farming, waste disposal, and unplanned urban expansion. The weighted arithmetic Water Quality Index (WQI) classified several downstream sites as “poor” or “unfit” for drinking, particularly in the dry season. Community responses corroborated laboratory findings, reporting increased health risks, economic burdens, and reliance on untreated surface water among low-income households. These findings underscore the urgent need for context-specific, participatory watershed management strategies to safeguard water security and public health in rapidly urbanizing, resource-limited settings.

KEYWORDS

Water quality, urbanization, spatiotemporal variability, Water Quality Index, Limbe, Cameroon, community perceptions, public health, watershed management

1. INTRODUCTION

Access to safe drinking water is foundational for public health and sustainable development, yet rapid urbanization and intensifying anthropogenic activities are increasingly jeopardizing water quality in data-scarce regions (WHO, 2023; World Bank, 2019). In sub-Saharan Africa, these challenges are compounded by accelerating population growth, inadequate infrastructure, and limited regulatory oversight, all of which amplify pollution and exacerbate inequities in water distribution (Muller et al., 2021). Coastal cities such as Limbe, Cameroon—characterized by a 4.2% annual population growth rate—exemplify these dynamics, where unsustainable land-use practices and insufficient watershed management have led to the degradation of freshwater systems vital for human consumption and local livelihoods (Baba et al., 2020).

Spatiotemporal variability in water quality, shaped by seasonal rainfall patterns and complex human-water interactions, further complicates management strategies. Research highlights that urban runoff, agricultural effluents, and solid waste disposal are principal contributors to elevated pollutant loads in tropical urban watersheds, particularly where rainfall is erratic and infrastructure is lacking (Zhong et al., 2022; Gioce et al., 2019). Notably, increased nitrate concentrations from fertilizer use and microbial contamination from informal settlements illustrate the direct link between land-use changes and heightened health risks (Jozef et al., 2019; James, 2021). In Limbe, riverbank encroachment and climate-driven hydrological variability have intensified salinity, nutrient enrichment, and pathogen prevalence, disproportionately

affecting low-income communities that depend on untreated surface water (Akoachere et al., 2019; Soumyoun et al., 2021).

Despite global advancements in water quality assessment and integrated management frameworks, there remains a pressing need for localized studies that address specific drivers and vulnerabilities. Water Quality Indices (WQI) and participatory monitoring approaches have proven effective in identifying pollution hotspots and guiding interventions, yet their application in rapidly urbanizing, data-limited contexts like Limbe remains limited (Chatterjee et al., 2002; Kristin, 2019). This study addresses this gap by systematically examining the spatiotemporal dynamics of pollution in Limbe’s primary water sources—the Limbe and Macocar rivers—and quantifying the associated health and socioeconomic impacts. By integrating hydrochemical analyses with community perceptions, the research aims to inform actionable, context-specific strategies for mitigating anthropogenic pressures and enhancing water security in urbanizing coastal ecosystems.

2. LITERATURE REVIEW

2.1 Spatiotemporal Variability and Urbanization

Water quality degradation in rapidly urbanizing coastal regions, such as Limbe, Cameroon, is increasingly attributed to the interplay between spatiotemporal variability and anthropogenic pressures (Baba et al., 2020). Seasonal shifts—particularly the alternation between rainy and dry periods—profoundly affect pollutant dynamics in tropical watersheds. Studies have shown that during the dry season, reduced river flows

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concentrate dissolved ions and microbial contaminants, while the onset of rains rapidly dilutes these pollutants but increases runoff-borne nutrient and sediment loads (Zhong et al., 2022; Giuoce et al., 2019). This pattern is evident in the Macocar and Limbe rivers, where dry-season spikes in electrical conductivity (EC), total dissolved solids (TDS), and coliform counts are commonly observed, mirroring findings from similar tropical catchments (Mohini et al., 2013).

2.2 Land Use, Pollution Sources, and Health Risks

Anthropogenic activities—such as agriculture, construction, and informal waste disposal—are principal drivers of water quality decline in urbanizing settings (Anita and Sangwan, 2009; Erin et al., 2001). Fertilizer application during the rainy season elevates nitrate concentrations, while upstream waste disposal introduces pathogens and organic pollutants, increasing coliform counts downstream (Jozef et al., 2019; James, 2021). Deforestation and bushfires, particularly in the dry season, exacerbate erosion and sedimentation, further elevating TDS and EC levels (Arran et al., 2020; Annie and Naito, 2019). In Limbe, riverbank encroachment and unregulated construction have intensified these impacts, leading to nutrient enrichment and heightened pathogen prevalence—trends also documented in other West African coastal cities (Akoachere et al., 2019; Sounyoun et al., 2021). The health implications of such pollution are severe. Outbreaks of waterborne diseases, including cholera, typhoid, and schistosomiasis, are closely linked to microbial contamination and nutrient-rich, stagnant waters (James, 2021; WHO, 2004). These risks disproportionately affect low-income communities reliant on untreated surface water, compounding existing vulnerabilities (World Bank, 2019).

2.3 Hydrological Alterations and Ecosystem Impacts

Urbanization-driven changes to hydrological processes further complicate water quality management. The expansion of impervious surfaces and unregulated construction increase sediment and pollutant runoff, particularly during heavy rains (Giuoce et al., 2019; Karuppasamy et al., 2003). In Limbe, these factors manifest as pronounced downstream increases in temperature, EC, and TDS—consistent with the urban heat island effect and loss of riparian vegetation (Sounyoun et al., 2021). Such thermal and chemical stressors can exacerbate dissolved oxygen depletion, threaten aquatic biodiversity, and accelerate ecosystem degradation (Isonfuo and Bariweni, 2001).

2.4 Governance, Assessment Tools, and Local Context

Effective water quality management relies on robust assessment tools and governance structures. The weighted arithmetic Water Quality Index (WQI), rooted in framework and refined, integrates multiple physiochemical and biological parameters to provide actionable insights (Horton's, 1965; Chatterjee et al., 2002). WQI has proven effective in sub-Saharan Africa for identifying pollution hotspots and linking water quality to health outcomes (James, 2021). However, regulatory frameworks in data-scarce regions like Limbe remain weak, necessitating participatory approaches that combine hydrochemical data with community perceptions (Din, 2016; UN Water, 2014).

Recent studies in China and tropical Africa emphasize the importance of stakeholder engagement and adaptive governance to mitigate pollution from unplanned urbanization (Li et al., 2014; Kristin, 2019). In Limbe, localized WQI assessments have revealed declining water quality downstream, correlating with increased health risks and economic burdens for affected communities (MPCA, n.d.).

2.5 Synthesis and Study Rationale

Despite global advances in water quality management, context-specific studies remain critical for addressing the unique challenges of rapidly urbanizing, data-limited regions. North America and Europe have long-established regulatory frameworks, but in regions like Limbe, integrated watershed management and participatory monitoring are essential to mitigate diverse anthropogenic pressures (UN Water, 2014; Kristin, 2019; Hering et al., 2010). This study builds on these insights by systematically quantifying spatiotemporal pollution trends in Limbe's rivers, linking them to health and socioeconomic impacts, and advocating for tailored, evidence-based interventions.

3. MATERIALS AND METHODS

3.1 Study Area

Limbe Municipality (Figure 1), located in Cameroon's Southwest Region (4°09'–4°05'N, 9°29'–9°06'E), is a rapidly urbanizing coastal city with a population growth rate of 4.2% annually (Baba et al., 2020). The municipality spans 248.6 km², divided into three councils (Limbe I, II, III), and is bounded by Mount Cameroon to the north and the Atlantic Ocean to

the southwest. Its tropical climate features high annual rainfall (1,500–6,000 mm) and temperatures averaging 26°C, with distinct dry (November–February) and rainy (March–October) seasons. These climatic conditions drive seasonal hydrological shifts, exacerbating pollution risks in freshwater systems like the Limbe and Macocar rivers, which serve as critical drinking water sources for ~50% of the population (Akoachere et al., 2019).

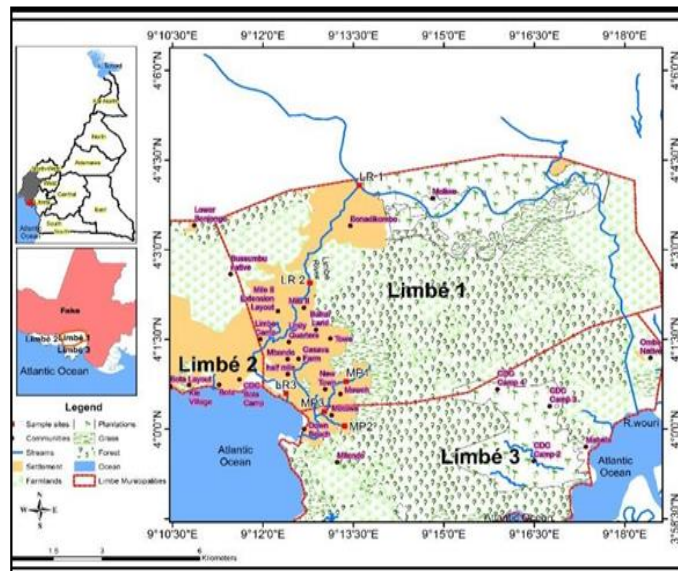


Figure 1: Location of the study area and the sampled streams

The Limbe River, the largest in the municipality, originates from Mount Cameroon and flows through densely populated zones (e.g., Mile 2, Mile 4, Botanic Garden) before discharging into the Atlantic. Its steep slopes (up to 43%) accelerate runoff, increasing sedimentation and pollutant transport during rainy seasons (Mohini et al., 2013). The Macocar River, smaller and primarily managed by local communities, faces similar pressures from unplanned urbanization, including encroachment, agricultural runoff, and solid waste disposal (Sounyoun et al., 2021). Both rivers exhibit spatiotemporal variability in water quality, with upstream areas impacted by farming and construction, while downstream zones suffer from industrial effluents and fecal contamination linked to informal settlements (James, 2021).

Urban expansion has intensified human-water interactions, with 70% of households in riparian zones relying on untreated surface water due to inadequate piped supply (Baba et al., 2020). Seasonal flooding and poor watershed governance further compound pollution, elevating concentrations of nitrates (from fertilizers), coliform (from sewage), and total dissolved solids (TDS) during rainy seasons (Zhong et al., 2022; Giuoce et al., 2019). This context underscores Limbe's vulnerability to water quality degradation, necessitating localized assessments to inform adaptive management strategies.

3.2 Study Design

This study assessed spatiotemporal variability in drinking water quality and its implications on the population of Limbe Municipality, focusing on the Limbe and Macocar rivers—key freshwater sources serving ~50% of the population (Baba et al., 2020). Purposive sampling selected these rivers due to their proximity to human activities, population density, and contrasting management frameworks (CAMWATER for Limbe River vs. community-led systems for Macocar River). Three sampling points were established along each river: source (control site with minimal human influence), human habitation upstream (intensive farming/urbanization), and human habitation downstream (industrial/residential zones). Water samples and household surveys were collected during dry (November–February) and rainy seasons (March–October) to capture seasonal dynamics (Sounyoun et al., 2021).

3.3 Criteria for Site and Stream Selection

Streams were chosen for the study because they are an important source of drinking water for the municipality as they serve a wider population within the municipality despite the existence of other sources like boreholes. The streams selected for the study were purposively sampled that is; Limbe River and Macocar River, The criteria used for their selection were proximity to human influence, population density and dependence on stream use, flow pattern of the stream for easy monitoring and the

general management body of the rivers. Firstly, the streams have the highest proximity to human influence especially with the communities around mile 4, mile 2, Clerks quarters, and Macocar. These areas also have an averagely dense population and the population depends on the stream for farming and other activities. More so, they have different management bodies that is CAMWATER for Limbe River and the community for Macocar river. The two streams selected flow on a permanent basis that is during the dry and rainy season and is due to this yearly discharge, which permitted the study to measure the water quality parameters on a seasonal basis.

3.4 Water Sample Collection and Analysis

Water samples from the respective streams were collected from 3 different points: the source, at the point of encroachment of human activities and further downstream. A Global Positioning System (GPS) was used to take the location of the sampling sites. The source point acted as the control because there is little or no interference and the other two sites served as the treatments. Water samples were collected from six sites (three per river) during peak dry and rainy seasons. At each site, three replicate samples were taken from mid-stream using sterilized 500 mL glass bottles rinsed with distilled water. Samples were coded and transported in ice-cooled containers to IRAD Laboratory (Yaoundé) within 24 hours for physiochemical and biological analysis. Parameters analysed were; temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), nitrates (NO₃⁻), phosphates (PO₄³⁻), and coliform counts, selected for their sensitivity to anthropogenic pressures like agricultural runoff, waste disposal, and deforestation (Zhong et al., 2022; Giuoce et al., 2019).

3.5 Selection of Sample Population

A stratified random sampling approach targeting 150 households across six riparian communities adjacent to the sampled rivers was used. Slovin's formula determined sample size ($n = \frac{N}{1 + N(e)^2}$) with a 95% confidence level (margin of error = ±5%). Surveys assessed perceptions of water quality impacts on health (e.g., cholera, typhoid prevalence), economic costs (treatment expenses, healthcare spending), and availability.

3.6 Statistical Analysis

Descriptive statistics (mean, standard deviation) summarized parameter trends across seasons and sites. ANOVA evaluated significant differences (p<0.05) in water quality parameters between dry and rainy seasons, while independent t-tests compared upstream-downstream variations. Regression analysis quantified relationships between pollution drivers (e.g., nitrate concentrations, coliform counts) and socioeconomic impacts (e.g., water bills, disease prevalence). Chi-square analysis linked anthropogenic activities (farming, construction, waste disposal) to water quality trends, while ANOVA tested seasonal and spatial variability in physiochemical parameters.

3.7 Water Quality Index (WQI) Calculation

The weighted arithmetic WQI method integrated seven parameters (pH, EC, TDS, NO₃⁻, PO₄³⁻, coliform, temperature) to classify water suitability for drinking. Each parameter's quality rating classify water suitability for drinking. Each parameter's quality rating (qn) and unit weight (Wn) were

calculated as:

$$qn = \left(\frac{Vn - Vid}{Sn - Vid} \right) \times 100 \text{ and } Wn = \frac{k}{Sn}$$

Where Vn= mesared value, Vid= ideal value (e.g., 0 for pollutants), Sn= WHO standard, and k= proportionality. Constant. WQI scores categorized water quality as Excellent (0–25), Good (25–50), Fair (51–75), Poor (76–100), or Unfit (>150), guiding recommendations for treatment and governance (Chatterjee et al., 2002).

Figure 2 illustrates the convergent mixed methods design used in this study, highlighting how quantitative and qualitative streams data collected were analyzed and integrated to generate robust and holistic insights.

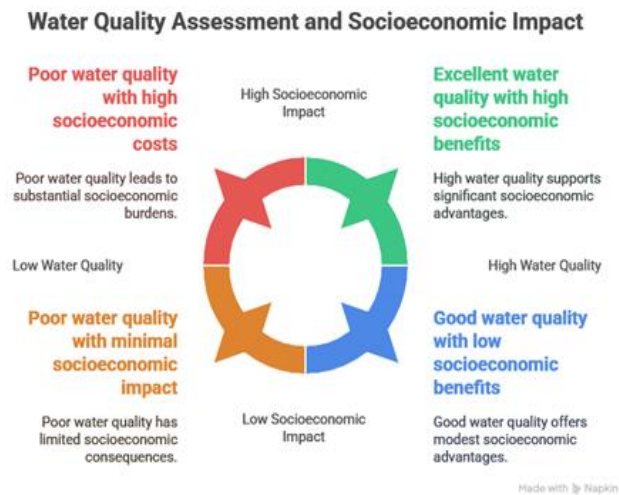


Figure 2: Schematic of the convergent mixed methods design, showing data streams and analytical workflows.

4. RESULTS AND DISCUSSION

4.1 Spatiotemporal Variability in Water Quality

The Limbe and Macocar rivers exhibited distinct seasonal patterns in water quality (Table 1), reflecting the interplay of seasonal hydrology and anthropogenic pressures described by (Baba et al., 2020; Giuoce et al., 2019). In the Macocar River, dry-season conditions led to significant increases in electrical conductivity (EC) (Figure 3), total dissolved solids (TDS), nitrate (NO₃⁻), phosphate (PO₄³⁻), and coliform counts (p < 0.05). For example, EC averaged 117.7 μS/cm upstream in the dry season, compared to 52.7 μS/cm during the rainy season, consistent with the concentration effect of reduced flows as highlighted by (Zhong et al., 2022). Conversely, the Limbe River demonstrated muted seasonal variation (p > 0.05), yet pronounced spatial gradients. Downstream coliform counts peaked at 920 MPN/ml, reflecting the influence of informal settlements and waste disposal, as previously observed by (Souneyoun et al., 2021).

Table 1: Seasonal Variation in Key Water Quality Parameters

River	Season	EC (μS/cm)	pH	TDS (mg/L)	Coliform (MPN/ml)	NO ₃ ⁻ (mg/L)	PO ₄ ³⁻ (mg/L)
Limbe	Dry	282.7	7.21	282.7	413.3	23.17	0.1004
Limbe	Rainy	249.7	7.07	249.7	362.0	27.33	0.0137
Macocar	Dry	117.7	6.50	117.7	1600.0	45.28	0.6600
Macocar	Rainy	52.7	8.03	52.7	115.3	5.46	0.0000

The pronounced dry-season spikes in the Macocar River corroborate the findings, who noted similar patterns in tropical catchments where pollutant concentrations rise as dilution capacity declines (Mohini et al., 2013).

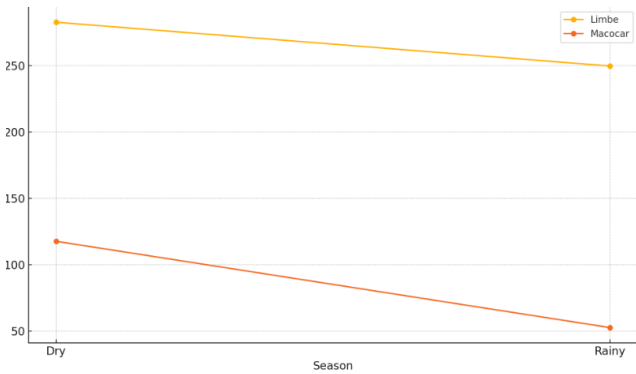


Figure 3: Electrical Conductivity by Season and River

- Macocar River: EC drops sharply from 117.7 µS/cm (dry) to 52.7 µS/cm (rainy), underlining the seasonal concentration-dilution dynamic (Zhong et al., 2022).
- Limbe River: EC remains relatively stable, indicating persistent anthropogenic inputs or sustained baseflow buffering.

The spatial variation in water quality is shown on Table 2. Spatially, both rivers showed increasing temperatures from source (~23.3°C) to downstream (~30°C) (Figure 4), consistent with urban heat island effects and riparian vegetation loss (Sounyoun et al., 2021; Giuoco et al., 2019). TDS and nitrate concentrations also increased downstream, especially in Limbe, where nitrate reached 45.88 mg/L, signaling agricultural runoff and fertilizer leaching as described by (Jozef et al., 2019).

Table 2: Spatial Variation in Water Quality Parameters								
River	Point	Temp (°C)	EC (µS/cm)	TDS (mg/L)	pH	Coliform (MPN/ml)	NO ₃ ⁻ (mg/L)	PO ₄ ³⁻ (mg/L)
Limbe	Source	23.3	237.5	237.5	7.27	70	12.13	0.1506
Limbe	Upstream	26.2	260.5	260.5	7.45	173	17.75	0.0000
Limbe	Downstream	30.0	298.5	298.5	6.70	920	45.88	0.0205
Macocar	Source	23.9	72.5	72.5	7.20	733	30.68	0.1750
Macocar	Upstream	25.0	78.0	78.0	7.00	1050	25.48	0.3600
Macocar	Downstream	29.6	105.0	105.0	7.60	790	19.96	0.4550

The downstream increase in temperature and solute load aligns with the impacts of urbanization and deforestation on riverine systems, as documented by (Isonfu and Bariweni, 2001).

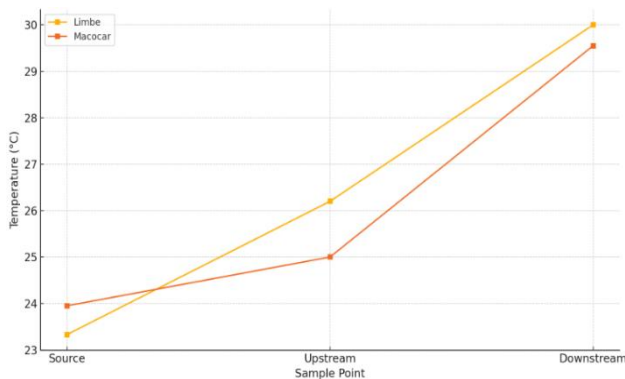


Figure 4: Water Temperature Gradient from Source to Downstream

- Both rivers exhibit a ~7°C increase downstream, a trend linked to reduced riparian shading and urban heat retention (Sounyoun et al., 2021).
- Elevated temperatures downstream may exacerbate biogeochemical processes and dissolved oxygen depletion, threatening aquatic health (Giuoco et al., 2019).

4.2 Anthropogenic Drivers of Water Quality Change

Figure 5 shows the anthropogenic drivers of water quality change. Chi-square analysis confirmed that farming, construction, waste disposal, and bushfires significantly influenced pollution trends (p < 0.05). Farming was the dominant driver during the rainy season, elevating nitrate and phosphate levels (Anita and Sangwan, 2009). Construction activities in the dry season contributed to increased TDS and turbidity, consistent with findings from (Kristin, 2019). Waste disposal remained a critical, year-round source of microbial contamination, particularly downstream, where coliform counts reached 1,600 MPN/ml in the Macocar River (Ritesh, 2018). Bushfires, primarily a dry-season phenomenon, exacerbated erosion and nutrient fluxes, as highlighted by (Arran et al., 2020).

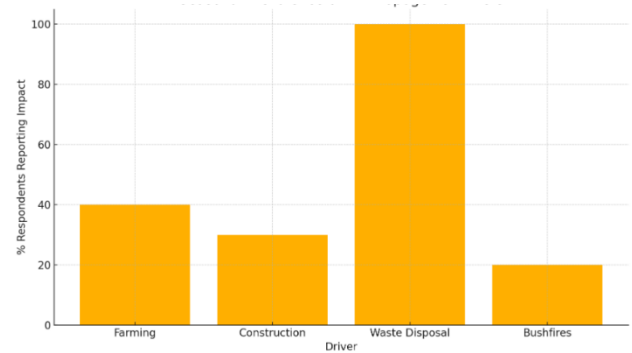


Figure 5: Seasonal Prevalence of Anthropogenic Drivers

- Waste disposal (100% of respondents) is the most pervasive pollution source.
- Farming (40%) and construction (30%) display strong seasonality.
- Bushfires (20%) are episodic but impactful.

Figure 6 shows the peak pollutant concentration associated with four different environmental drivers: farming, construction, waste disposal, and bushfires. Results highlight waste disposal as the most critical target for pollution mitigation efforts, followed by construction. Interventions in waste management could significantly reduce peak pollutant levels and improve environmental health.

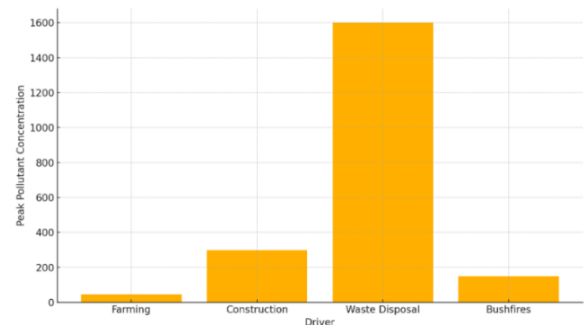


Figure 6: Peak Pollutant Levels by Driver

- Coliform (waste disposal) far exceeds other pollutants, underscoring severe microbial risk (James, 2021).
- TDS (construction) and TSS (bushfires) reflect physical-chemical impacts.
- Nitrate (farming) highlights nutrient enrichment during the rainy season.

The spatiotemporal and anthropogenic patterns observed in the Limbe and Macocar Rivers closely mirror those reported in other rapidly urbanizing tropical catchments (Baba et al., 2020; Zhong et al., 2022). The integration of hydrochemical data and community perceptions, as

advocated, underscores the need for context-specific, participatory watershed management strategies (Kristin, 2019; UN Water, 2014). These findings reinforce the urgency of targeted interventions to safeguard water quality and public health in data-scarce, urbanizing regions

4.3 Health and Socioeconomic Impacts

The observed water quality decline translated into significant health and economic burdens, echoing the nexus between environmental degradation and public health risks established is shown in Figure 7 (James, 2021; World Health Organization, 2004). Cholera and typhoid outbreaks were reported by 50% and 43% of upstream and downstream communities, respectively, while schistosomiasis prevalence (14.3%) downstream of the Limbe River correlated with nutrient-enriched, stagnant waters favoring intermediate snail hosts (James, 2021). Economic impacts included increased healthcare costs (reported by 35–60% of households) and reduced agricultural productivity, consistent with the socioeconomic consequences of unmanaged pollution described by the (World Bank, 2019).

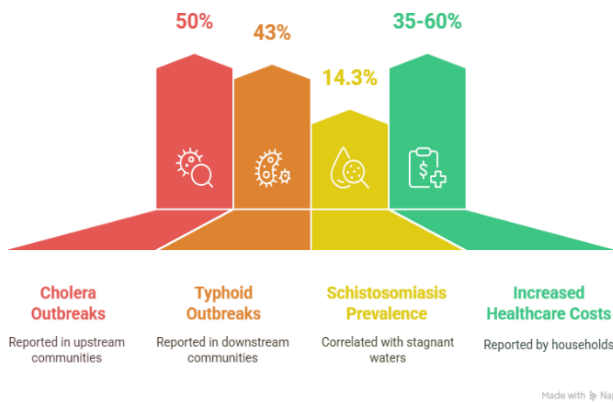


Figure 7: Health and economic impacts of waster quality decline in the study area

4.4 Spatiotemporal Patterns and Urbanization Pressures

The results of this study confirm that spatiotemporal variability in water quality is strongly influenced by both seasonal hydrology and anthropogenic activities, echoing patterns documented in other rapidly urbanizing tropical catchments (Baba et al., 2020; Zhong et al., 2022). The pronounced dry-season spikes in electrical conductivity (EC), total dissolved solids (TDS), nitrate, and coliform counts in the Macocar River reflect the concentration of pollutants during periods of low flow, as described by (Mohini et al., 2013; Giuoce et al., 2019). This seasonal effect underscores the vulnerability of smaller, less-buffered rivers to pollution pulses, particularly in regions where environmental flows are not maintained.

In contrast, the Limbe River’s muted seasonal variation but strong spatial gradients suggest persistent, year-round anthropogenic inputs-likely from continuous waste disposal and urban runoff. This aligns, who found that informal settlements and inadequate sanitation infrastructure drive chronic microbial contamination in urban rivers (Sounyoun et al., 2021). The downstream increase in temperature, EC, and TDS in both rivers is consistent with urban heat island effects, riparian vegetation loss, and cumulative pollutant loading (Isonfu and Bariweni, 2001; Sounyoun et al., 2021).

4.5 Anthropogenic Drivers: Land Use, Waste, and Erosion

The statistical association between water quality degradation and human activities-farming, construction, waste disposal, and bushfires-reinforces the critical role of land use in shaping riverine health (Anita and Sangwan, 2009; Arran et al., 2020). Seasonal farming during the rainy season was the dominant source of nitrate and phosphate, as fertilizer runoff entered waterways, corroborating findings by (Jozef et al., 2019; Giuoce et al., 2019). Construction and bushfires, particularly in the dry season, increased sediment and nutrient loads, raising TDS and turbidity, in line with observations by (Kristin, 2019; Annie and Naito, 2019).

Waste disposal emerged as the most pervasive, year-round driver of microbial contamination, with coliform counts peaking downstream and in densely populated areas. This supports the argument that unregulated

solid waste and sewage disposal are primary contributors to waterborne pathogens in low-income urban environments (Erin et al., 2001; Ritesh, 2018). The data also highlight the limitations of current waste management strategies in Limbe, emphasizing the need for improved infrastructure and regulatory enforcement (Din, 2016; Baba et al., 2020).

4.6 Health and Socioeconomic Implications

The direct link between declining water quality and increased health risks is evident in the high prevalence of cholera, typhoid, and schistosomiasis reported by local communities. These findings are consistent, who have documented the burden of waterborne diseases in regions lacking safe drinking water and effective sanitation (James, 2021; World Health Organization, 2004). The economic impacts, including increased healthcare expenditures and reduced agricultural productivity, mirror global trends described, where pollution undermines both public health and livelihoods (World Bank, 2019).

The spatial alignment of health risks with pollution hotspots-particularly downstream of informal settlements and agricultural zones-underscores the need for targeted interventions. Community perceptions, as captured in this study, reinforce the importance of participatory approaches to water management, as advocated by (UN Water, 2014; Kristin, 2019).

4.7 Water Quality Index (WQI)

Water quality index is commonly used for the detection and evaluation of water pollution and may be defined as a reflection of the composite influence of different quality parameters on the overall quality of water (Horton, 1965). It is a summary of all water quality parameters into a single value index, which expresses the overall water quality at a certain location and time based on several water quality parameters. This assessment was done based on the summarization of the physiochemical and biological parameters tested. Suitability for drinking was drawn based on the score generated from the calculation ranging between 0 and 100. The lower the score the suitable the water is for drinking. From the calculations, the following results were obtained (Table 2).

Table 3: Water Quality Index Table				
Streams	Seasons	Sampling Points	WQI	Status
Limbe River	Dry Season	Source	28.91	Good
		Upstream	37.47	Good
		Downstream	44.29	Good
	Rainy Season	Source	20.05	Excellent
		Upstream	27.43	Good
		Downstream	53.67	Fair
Macocar River	Dry Season	Source	48.75	Good
		Upstream	73.52	Fair
		Downstream	81.50	Poor
	Rainy Season	Source	51.34	Fair
		Upstream	42.42	Good
		Downstream	54.03	Fair

From the results presented, WQI assessment showed significant changes in states from the source points within the Macocar and Limbe river during the dry and rainy seasons. Progressive rise in the calculated WQI values from the source indicated alterations in water quality parameters as water flows through areas of human habitations up and down stream widely attributed to increase human interactions along these rivers. During the dry season, WQI in both rivers varied significantly from the source, upstream and downstream. WQI status has been rated good, fair and poor from source to downstream respectively especially within the Macocar River.

4.8 Implications for Management and Policy

The divergent seasonal and spatial pollution signatures in the Limbe and Macocar rivers demonstrate that a one-size-fits-all approach to water quality management is unlikely to succeed. Instead, interventions must be tailored to the unique hydrological and land-use context of each river. For the Macocar River, maintaining environmental flows during the dry

season and controlling upstream pollutant sources could mitigate concentration effects. In the Limbe River, year-round source control and continuous treatment are essential to address persistent anthropogenic pressures.

The application of the weighted arithmetic Water Quality Index (WQI) in this study, building on framework and, proved effective in identifying pollution hotspots and linking water quality to health outcomes (Horton's, 1965; Chatterjee et al., 2002). However, as highlighted in the literature, the success of such tools depends on their integration with local governance structures and community engagement (James, 2021; Kristin, 2019).

5. CONCLUSION

This study demonstrates that water quality in the Limbe and Macocar rivers is shaped by a complex interplay of spatiotemporal variability and anthropogenic pressures, consistent with patterns observed in other rapidly urbanizing tropical watersheds. Seasonal fluctuations-especially the dry-season concentration of pollutants in the Macocar River-highlight the vulnerability of smaller catchments to reduced dilution, while the Limbe River's persistent spatial degradation underscores the impact of continuous urban and peri-urban pressures. The downstream rise in temperature, electrical conductivity, total dissolved solids, and nitrate, coupled with elevated coliform counts, points to the cumulative effects of urban runoff, agricultural effluents, waste disposal, and riparian habitat loss. These water quality declines translate directly into public health risks-evidenced by high rates of cholera, typhoid, and schistosomiasis-as well as economic burdens for local communities, including increased healthcare costs and reduced agricultural productivity. The findings reinforce the urgent need for context-specific, integrated watershed management that addresses both the sources and pathways of pollution in data-scarce, rapidly urbanizing regions. The following measures should be implemented.

a) Strengthen Waste Management and Sanitation

- Implement year-round solid and liquid waste management programs, prioritizing downstream and densely populated areas where coliform contamination and microbial risks are highest.
- Upgrade sanitation facilities in informal settlements to reduce direct sewage discharge into rivers, following best practices highlighted.

b) Promote Sustainable Land Use and Erosion Control

- Enforce land-use zoning and buffer zones along riverbanks to limit construction and agricultural encroachment, thereby reducing sediment and nutrient runoff.
- Restore riparian vegetation and implement erosion control measures, especially in areas affected by bushfires and construction, to stabilize riverbanks and moderate temperature increases.

c) Tailor Pollution Mitigation to Seasonal and Spatial Patterns

- For the Macocar River, prioritize maintaining environmental flows in the dry season and controlling upstream pollutant sources to reduce concentration effects.
- For the Limbe River, focus on continuous source control and year-round monitoring, given the persistent anthropogenic pressures and muted seasonal variability.

d) Enhance Water Quality Monitoring and Community Engagement

- Expand participatory water quality monitoring using tools like the weighted arithmetic Water Quality Index (WQI) to identify hotspots and track trends.
- Engage local communities in pollution prevention, health education, and reporting, leveraging their perceptions to guide interventions and build stewardship.

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