Impacts Of A Single Untreated Domestic Effluent Discharge On Water Quality In An Amazonian Urban Stream: An Integrated Assessment Using Wqi And Legal Compliance Indicators

Edinelson Saldanha
edinelsonsaldanha@ufpa.br

Universidade Federal do Pará

Vando Jose Gomes
Universidade Federal do Pará

Ana Clara Anjo
Universidade Federal do Pará

Ruan Felix
Universidade Federal do Pará

Matheus Costa
Universidade Federal do Pará

Shelda Rebbeca Corrêa
Universidade Federal do Pará

Joao Vitor Araujo
Universidade Federal do Pará

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ABSTRACT

Urban streams are highly vulnerable to localized sources of pollution, particularly untreated domestic effluent discharges, even in regions characterized by high freshwater availability. This study evaluated the impacts of a single untreated domestic wastewater discharge on water quality in an urban tropical stream located in the Amazon region, using an integrated assessment framework combining the Water Quality Index (WQI) and a Legal Compliance Index (LCI). Physicochemical and microbiological parameters were monitored at three sampling points—upstream, at the effluent discharge, and downstream—during rainy and dry seasons.

The results revealed severe degradation of water quality at points directly and indirectly influenced by effluent discharge, with recurrent exceedances of legal thresholds for dissolved oxygen, biochemical oxygen demand, total phosphorus, turbidity, and microbiological indicators. WQI values classified water quality as poor to very poor at all impacted points, with minimal variation between hydrological periods, indicating the dominance of continuous point-source pollution over seasonal effects. The LCI analysis confirmed widespread legal non-compliance, demonstrating that a single discharge point controlled the overall regulatory condition of the stream.

The combined application of WQI and LCI provided a robust and complementary diagnosis of environmental and legal water quality conditions, highlighting limitations of relying solely on natural dilution capacity in water-abundant regions. The findings emphasize the need for targeted wastewater management interventions and spatially explicit monitoring strategies to protect urban streams. The integrated assessment framework applied in this study is transferable and can support water quality monitoring and management in other urban watersheds affected by localized pollution sources, particularly in rapidly urbanizing tropical regions.

1. INTRODUCTION

Environmental degradation associated with anthropogenic activities has intensified over recent decades, particularly as a consequence of rapid urban expansion and inadequate sanitation infrastructure. Among the most affected natural resources, surface waters have experienced significant deterioration in quality, driven by increased pollutant loads and altered hydrological processes. As a result, qualitative water scarcity has emerged as a major environmental challenge of the 21st century, with direct implications for aquatic ecosystems and public health (Li et al., 2020; UN-Water, 2021).

The hydrological behavior of a watershed is strongly controlled by its natural characteristics and land use patterns, including geomorphology, vegetation cover, precipitation regime, and surface runoff dynamics. In urban environments, however, soil sealing, removal of riparian vegetation, and the discharge of untreated effluents substantially modify these processes, reducing dilution capacity and increasing the vulnerability of streams to localized pollution sources (Paul & Meyer, 2001; Walsh et al., 2005; Kaushal et al., 2014; Zhang et al., 2021).

Recent studies have consistently shown that point-source discharges of untreated domestic wastewater can rapidly and persistently degrade water quality in urban streams, even over short spatial scales and independently of seasonal hydrological variability. This pattern has been reported in cities across both developed and developing regions, indicating that natural water availability alone does not guarantee resilience to anthropogenic pressures (Carey et al., 2020; Sharma et al., 2021; Nguyen et al., 2020).

In Brazil, the debate on water resources management and basic sanitation has intensified following the enactment of the Legal Framework for Sanitation (Law No. 14,026/2020), which established ambitious targets for universal access to drinking water and wastewater services by 2033. Despite institutional advances, significant structural challenges remain, particularly in rapidly urbanizing regions where wastewater treatment infrastructure has not kept pace with population growth, leading to continuous discharges of untreated domestic effluents into urban water bodies (Brazil, 2022).

From 2022 onward, reforms in the Brazilian sanitation sector introduced regional service provision models and performance-based contracts, reshaping governance structures and reinforcing the role of the National Water and Basic Sanitation Agency (ANA) in establishing technical reference standards (ANA, 2022; IBGE, 2023). Nevertheless, the limited expansion of wastewater treatment plants continues to represent a critical bottleneck, especially in medium-sized cities, where localized effluent discharges exert disproportionate impacts on urban streams.

Although the Amazon region contains the largest volume of surface freshwater on the planet, recent evidence indicates that urban streams within Amazonian cities are highly susceptible to degradation from localized pollution sources. Studies conducted in tropical and subtropical regions demonstrate that concentrated point-source discharges can override natural dilution processes, resulting in severe and persistent water quality impairment even in water-abundant settings (Dudgeon et al., 2006; Nguyen et al., 2020; Almeida et al., 2021).

Within this context, the municipality of Santarém, located in western Pará State, represents an important urban center in the Amazon. Despite its regional relevance, wastewater treatment coverage remains below 25%, favoring the direct discharge of untreated domestic effluents into urban drainage systems and receiving water bodies. Deficiencies in sanitation services—including sewage collection, urban drainage, and solid waste management—have been associated with declining water quality and increased public health risks (Oliveira, 2018).

Water quality reflects the cumulative interaction between natural processes and anthropogenic pressures throughout the watershed. Recent research emphasizes that systematic and spatially explicit monitoring is essential to detect localized degradation patterns, support regulatory enforcement, and guide management interventions in urban watersheds, particularly in rapidly urbanizing tropical regions (Goonetilleke et al., 2005; Li et al., 2020; Souza et al., 2023).

In this context, Water Quality Indices (WQI) continue to be widely applied as integrated tools for environmental monitoring, as they synthesize multiple physicochemical and microbiological parameters into a single metric, facilitating interpretation and comparison across sites and periods. Recent advances have highlighted both the strengths and limitations of WQI approaches, particularly their inability to explicitly capture regulatory compliance and legal thresholds (Varol, 2020; Sutadian et al., 2022).

Consequently, compliance-based assessment frameworks grounded in water quality legislation have gained increasing attention as complementary tools for environmental monitoring. Integrating conventional water quality indices with legal compliance indicators enhances diagnostic capacity and provides more robust support for environmental management and decision-making (Zhang et al., 2021; Hernández-Romero et al., 2023).

Despite extensive research on urban stream degradation, quantitative assessments explicitly demonstrating how a single untreated domestic effluent discharge can dominate both environmental and regulatory conditions in water-abundant tropical regions remain limited.

Thus, this study aims to demonstrate how a single untreated domestic effluent discharge can significantly degrade water quality in an urban tropical stream, even in a region characterized by high freshwater availability. This is achieved through the analysis of physicochemical and microbiological parameters, the calculation of the Water Quality Index (WQI), and the application of a Legal Compliance Index (LCI), contributing to improved monitoring strategies and management of urban water resources in tropical environments.

2. MATERIALS AND METHODS

2.1 Study area

The study was conducted in the municipality of Santarém, located in western Pará State, in the Lower Amazon mesoregion, at the confluence of the Amazon and Tapajós rivers. The municipality represents the second largest urban center in the state and has experienced accelerated urban growth, associated with historical limitations in basic sanitation infrastructure, which has contributed to the degradation of urban water bodies (IBGE, 2016; Aquino et al., 2017).

The study area comprises the Irurá stream, located along Olavo Bilac Avenue, within the urban area of the municipality. This site was selected because it represents a preferential axis of urban drainage, receiving direct contributions from stormwater runoff and untreated domestic effluents discharged in open channels. The stream constitutes a water body highly sensitive to local anthropogenic pressures and is representative of the reality of urban streams in the Amazon region (Lima et al., 2017).

Three sampling points were defined: an upstream point (P1), representative of conditions prior to direct anthropogenic impact; a point corresponding to the discharge of raw domestic wastewater (P2), characterized by the continuous flow of untreated sewage; and a downstream point (P3), located after the effluent enters the receiving water body. Sampling campaigns were carried out during the rainy and dry seasons, as recommended for hydrological studies in tropical regions (Silva et al., 2008). The location of the sampling points is shown in Figure 1 and described in detail in Table 1.

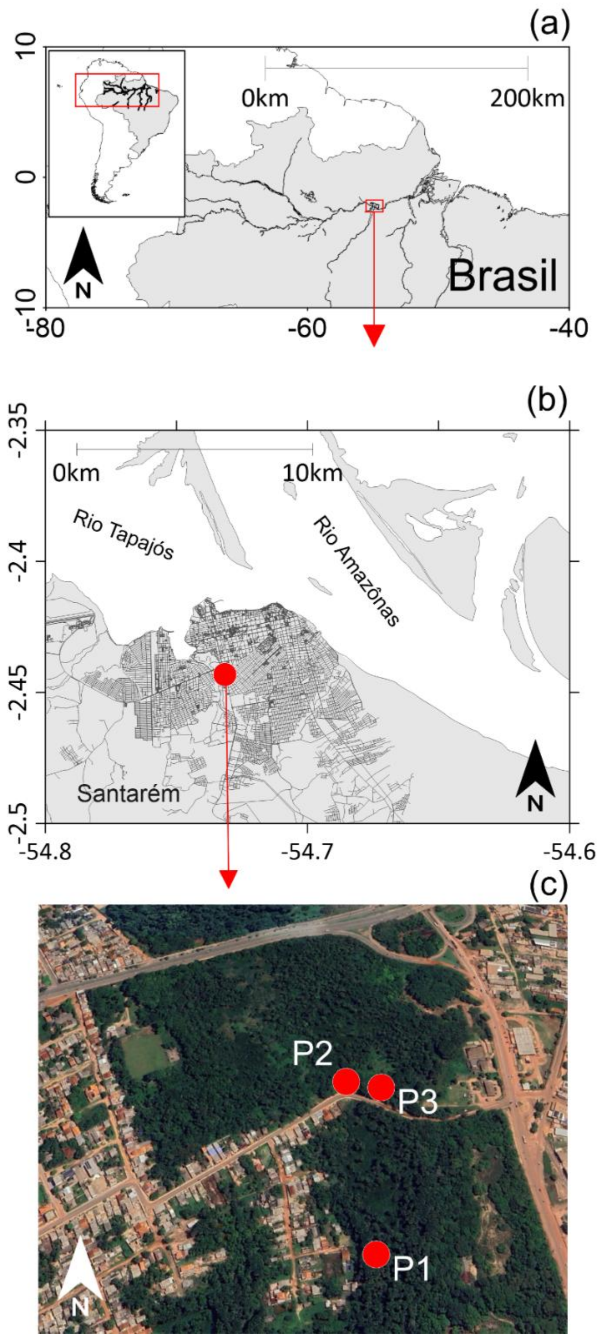

Figure 1. Location map of the sampling points: (a) South America showing the Amazon region where the city of Santarém is located; (b) location of the city of Santarém, highlighting its urban extent, the confluence of the Amazon and Tapajós rivers, and the position of the study area; and (c) detailed view of the study area showing the sampling points (P1, P2, and P3).

Table 1. Description of sampling points and photographic records

Sampling point	Description	Photo
P1	This sampling point is located downstream of the effluent discharge point. Although residential areas are present nearby, it still preserves an approximately 30 m-wide permanent preservation area along the stream margins.	
P2	This point corresponds to a public roadway presenting a water layer approximately 30 cm deep as a result of rainfall events. However, a continuous flow toward the receiving water body is observed even in the absence of precipitation.	
P3	Sampling point located upstream of point P1, where waters originating from point P2 are discharged into the receiving water body.	

Figure 2 illustrates the methodological workflow adopted in this study, summarizing the main stages from water sample collection to data processing and interpretation. The flowchart provides an overview of the procedures used for sample transportation and preservation, laboratory analyses, and the application of water quality and legal compliance assessment frameworks.

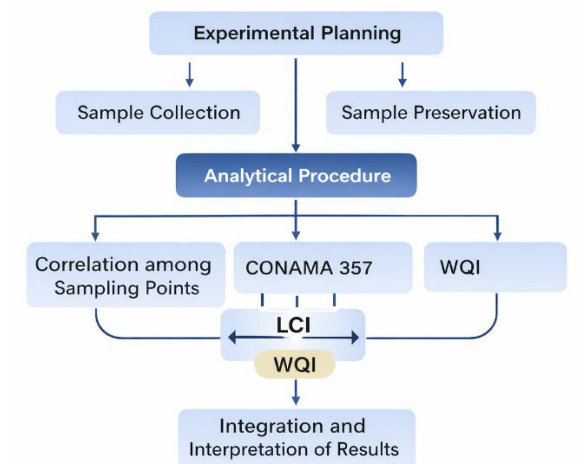

Figure 2. Flowchart of the methodological stages of the study, including sample collection, transportation and preservation of samples, and procedures adopted for data analysis and result evaluation.

2.2 Sample collection, preservation, and transportation

Water samples were collected using previously cleaned and sterilized polyethylene bottles with a capacity of 1 L. Sample collection, preservation, storage, and transportation procedures followed the guidelines established in the *Manual for the Preservation and Analysis of Water Samples* published by the São Paulo State Environmental Agency (CETESB) (CETESB, 2011; CETESB, 2023).

Field parameters, including water temperature, hydrogen potential (pH), dissolved oxygen (DO), and electrical conductivity, were measured *in situ* immediately after sample collection in order to minimize physicochemical changes during transportation. The remaining samples were preserved under refrigeration (≈4 °C) and transported to the laboratory, respecting the maximum holding times and specific preservation conditions recommended by CETESB (2011) for each analyzed parameter.

2.3 Analytical procedures

Water quality assessment was based on the determination of physicochemical and microbiological parameters widely used in environmental monitoring studies, legal compliance assessments, and the calculation of water quality indices (ANA, 2023; CETESB, 2023).

The following parameters were analyzed: temperature, pH, turbidity, electrical conductivity, dissolved oxygen (DO), five-day biochemical oxygen demand (BOD_5), total alkalinity, total dissolved solids (TDS), total nitrogen, ammoniacal nitrogen, nitrite, nitrate, total phosphorus, total coliforms, and thermotolerant coliforms.

In situ analyses were performed using properly calibrated portable instruments, following the procedures described in *Standard Methods for the Examination of Water and Wastewater* (APHA, 2023). Turbidity was determined in the laboratory using a digital benchtop turbidimeter.

BOD_5 was determined using the incubation method at 20 °C for five days, according to standardized procedures described by APHA (2023). Nutrient concentrations (total nitrogen, ammonia, nitrite, nitrate, and total phosphorus) were determined by colorimetric methods using spectrophotometry. Total alkalinity was quantified by acid–base titration.

2.4 Legal classification of water quality

The legal classification of water quality was evaluated through direct comparison of the measured results with the standards established by CONAMA Resolution No. 357/2005, considering water bodies classified as Class II (Brazil, 2005).

Results obtained at the impacted sampling points (P2 and P3) were compared with those observed at the upstream point (P1), adopted as a reference condition, allowing assessment of the degree of water quality alteration associated with the discharge of untreated domestic effluents (ANA, 2023).

2.5 Water Quality Index (WQI)

The Water Quality Index (WQI) was used as a synthetic indicator for the integrated assessment of water quality at the sampling points. The index was originally developed by the National Sanitation Foundation (NSF) in the United States and later adapted and widely disseminated in Brazil by the São

Paulo State Environmental Agency (CETESB). It is currently one of the main tools employed in surface water quality monitoring programs (Libânio, 2005; CETESB, 2023).

The WQI is based on the integration of nine physicochemical and microbiological parameters considered representative of the sanitary and environmental conditions of surface water bodies. The parameters used in this study were: dissolved oxygen (DO), thermotolerant coliforms, hydrogen potential (pH), five-day biochemical oxygen demand (BOD_5), temperature variation, total nitrogen, total phosphorus, turbidity, and total dissolved solids (TDS).

Each parameter has an average quality variation curve, from which the measured value is converted into a partial quality index (q_i), ranging from 0 to 100. These values represent the individual contribution of each parameter to the overall water quality. In addition, each parameter is assigned a relative weight (w_i) that reflects its importance in the calculation of the final index, according to the methodology established by CETESB.

The WQI was calculated using the weighted geometric mean of the partial quality values, as expressed in Equation (1):

$$\boldsymbol{WQI = \prod_{i=1}^{n} q_i^{w_i}} \quad (1)$$

where:

$\boldsymbol{q_i}$ is the quality value associated with the i-th parameter, obtained from the quality curves; $\boldsymbol{w_i}$ is the weight assigned to the i-th parameter, with the sum of all weights equal to 1.

The weights adopted in the WQI calculation followed the values recommended by CETESB, with greater importance attributed to dissolved oxygen, thermotolerant coliforms, and biochemical oxygen demand, due to their direct relationship with organic pollution and public health risks.

Interpretation of the WQI values was based on the qualitative classification presented in Table 2, originally proposed by CETESB, which categorizes water quality into five classes: excellent, good, regular, poor, and very poor. This classification allows spatial and temporal comparison of water quality and the identification of the most critical stretches along the analyzed water body.

All WQI calculations, as well as the generation of corresponding graphs and tables, were performed using computational routines developed in the Python programming language, ensuring data standardization, reproducibility, and analytical accuracy.

Table 2. Water Quality Index (WQI) classification according to CETESB

Category	WQI range
Excellent	$79 < WQI \leq 100$
Good	$51 < WQI \leq 79$
Regular	$36 < WQI \leq 51$
Poor	$19 < WQI \leq 36$
Very poor	$WQI \leq 19$

Source: CETESB (2004)

2.6 Legal Compliance Index (LCI)

The Legal Compliance Index (LCI) was applied to provide an integrated and quantitative assessment of the degree of compliance of water quality with legally established standards, considering Class II water bodies defined by CONAMA Resolution No. 357/2005. Compliance-based water quality assessments have been widely used in environmental monitoring studies as complementary tools to conventional water quality indices, allowing direct verification of conformity with regulatory thresholds (CCME, 2001; Varol, 2020; Hernández-Romero et al., 2023).

Unlike synthetic environmental indices, such as the Water Quality Index (WQI), compliance-based indices focus on normative thresholds rather than relative environmental condition, enabling a direct interpretation of results from a regulatory perspective. Similar compliance-oriented approaches have been applied in different geographical contexts to support water quality management and regulatory enforcement (Sutadian et al., 2022; Zhang et al., 2021).

In this study, the LCI represents an application and adaptation of previously established compliance-based assessment frameworks, structured to reflect national water quality legislation while remaining conceptually consistent with internationally recognized regulatory approaches, such as those proposed by the Canadian Council of Ministers of the Environment (CCME) and other regulatory-based assessment methods (CCME, 2001; Varol, 2020). This approach does not constitute the development of a new index, but rather the operationalization of an existing methodological concept within a specific legal and environmental context. Therefore, the LCI applied here should be interpreted as an operational compliance indicator rather than a newly proposed index.

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2.6.1 Selection of legal parameters

Parameters included in the LCI calculation comprised physicochemical and microbiological variables with explicit legal limits defined by CONAMA Resolution No. 357/2005 for Class II water bodies and that were effectively analyzed in this study. These parameters included hydrogen potential (pH), dissolved oxygen (DO), biochemical oxygen demand (BOD_5), turbidity, total phosphorus, ammoniacal nitrogen, thermotolerant coliforms, and total dissolved solids, among others applicable to legal classification.

The selection of parameters followed procedures commonly adopted in compliance-based water quality assessments, in which only variables with clearly defined regulatory thresholds are considered, ensuring legal consistency and methodological robustness (CCME, 2001; Varol, 2020).

2.6.2 Legal compliance criterion

For each selected parameter, observed values were directly compared with the maximum allowable limits or permissible ranges established by CONAMA Resolution No. 357/2005. Compliance assessment followed a binary criterion, widely adopted in regulatory water quality evaluations (Zhang et al., 2021; Hernández-Romero et al., 2023), as described below: Compliant (C): when the observed value fully met the established legal limit; Non-compliant (NC): when the observed value exceeded the maximum allowable limit or fell outside the permissible range.

For parameters whose limits are expressed as intervals, such as pH, only values within the legally established range were considered compliant.

2.6.3 Calculation of the Legal Compliance Index

The Legal Compliance Index (LCI) was calculated as the ratio between the number of parameters in legal compliance and the total number of evaluated parameters, expressed as a percentage, according to Equation (2):

$$LCI(\%) = \left(\frac{N_C}{N_T}\right) \times 100 \qquad (2)$$

where:

N_C corresponds to the number of parameters that met the established legal standards; N_T represents the total number of parameters considered in the index calculation.

This formulation is consistent with compliance-based indices previously applied in water quality assessment studies and allows direct comparison between monitoring sites and periods (CCME, 2001; Varol, 2020; Sutadian et al., 2022).

The ICL ranges from 0 to 100%, with higher values indicating a greater degree of legal compliance of water quality with current legislation.

2.6.4 Classification of the Legal Compliance Index

For interpretation and spatial and temporal comparison purposes, LCI values were classified into qualitative categories adapted from normative water quality assessment approaches reported in the literature (Varol, 2020; Hernández-Romero et al., 2023), as presented in Table 3.

Table 3. Classification criteria for the Legal Compliance Index (LCI)

ICL range (%)	**Classification**	**Interpretation**
≥ 95	Excellent	Water body in full compliance with legal standards, with no or minimal regulatory violations
80 – < 95	Good	High legal compliance, with few non-compliances and low violation severity
60 – < 80	Regular	Intermediate compliance, indicating the need for attention and monitoring
40 – < 60	Marginal	Threshold condition of legal compliance, with multiple parameters out of compliance
< 40	Poor	Critical condition, with severe legal non-compliance and high violation magnitude

This classification allows the objective identification of the most legally compromised stretches of the water body, supporting control actions, mitigation measures, and environmental planning.

2.6.7 Data processing and reproducibility

The calculation of the Legal Compliance Index (LCI) was performed using computational routines developed in the Python programming language, which automated the verification of legal compliance for each parameter, the calculation of the index, and the generation of analytical graphs and tables. Similar computational approaches have been recommended in recent environmental monitoring studies to enhance analytical transparency and reproducibility (Sutadian et al., 2022; Zhang et al., 2021).

All computational routines were designed to ensure full reproducibility of the analyses, allowing the same workflow to be applied to other datasets and study areas, in accordance with best practices for quantitative environmental monitoring.

3. RESULTS AND DISCUSSION

Figures 3–13 present the physicochemical and microbiological parameters measured at the three sampling points (P1, P2, and P3) during the Amazonian rainy and dry seasons, including dissolved oxygen, pH, biochemical oxygen demand (BOD_5), total phosphorus, turbidity, apparent color, nitrogen compounds, total dissolved solids, settleable solids, and coliform indicators. The figures also indicate compliance with the legal thresholds established by CONAMA Resolution No. 357/2005 for Class II rivers. The Water Quality Index (WQI) values are summarized in Table 5.

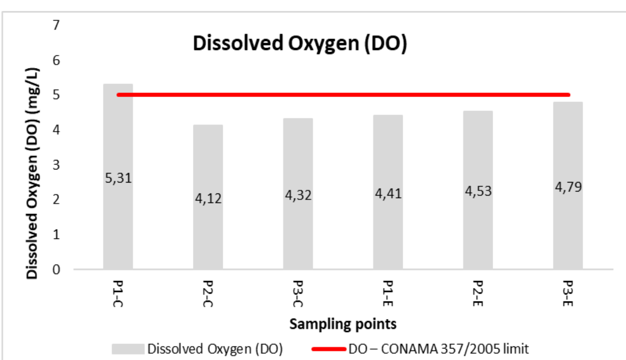


Figure 3. Dissolved oxygen (DO) concentrations at the sampling points (P1, P2, and P3) during the rainy and dry seasons. The dashed line indicates the minimum limit established by CONAMA Resolution Nº. 357/2005 for Class II water bodies.

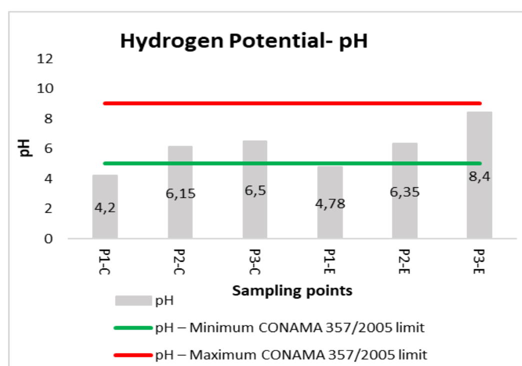


Figure 4. pH values measured at the sampling points (P1, P2, and P3) during the rainy and dry seasons. The shaded area represents the permissible range (5.0–9.0) established by CONAMA Resolution Nº. 357/2005 for Class II waters.

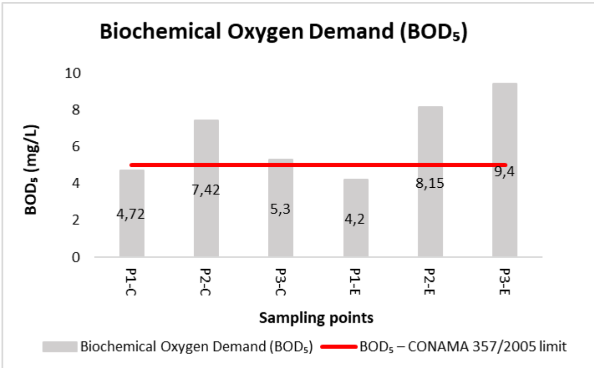


Figure 5. Five-day biochemical oxygen demand (BOD_5) at the sampling points (P1, P2, and P3) during the rainy and dry seasons. The dashed line indicates the maximum limit established by CONAMA Resolution Nº. 357/2005 for Class II water bodies.

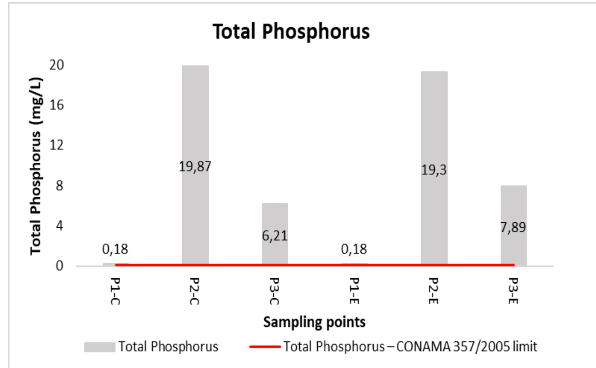


Figure 6. Total phosphorus concentrations at the sampling points (P1, P2, and P3) during the rainy and dry seasons. The dashed line indicates the maximum limit established by CONAMA Resolution Nº. 357/2005 for Class II waters.

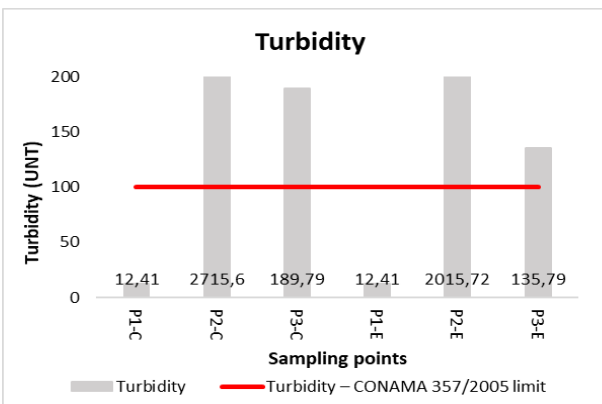


Figure 7. Turbidity values at the sampling points (P1, P2, and P3) during the rainy and dry seasons. The dashed line indicates the maximum permissible limit according to CONAMA Resolution Nº. 357/2005 for Class II waters.

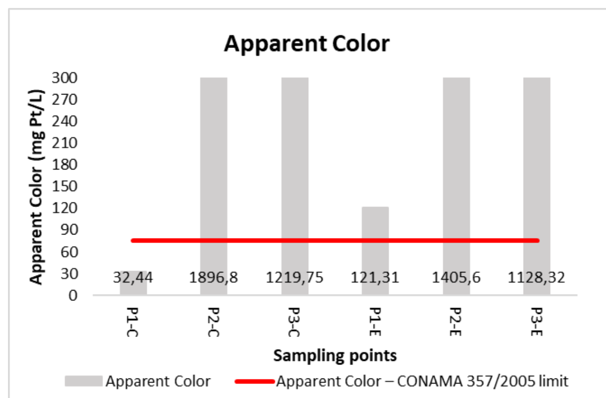
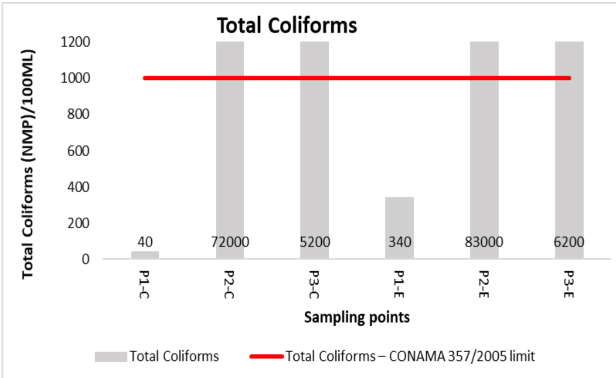


Figure 8. Apparent color values measured at the sampling points (P1, P2, and P3) during the rainy and dry seasons, indicating the influence of organic matter and effluent discharges on water quality.



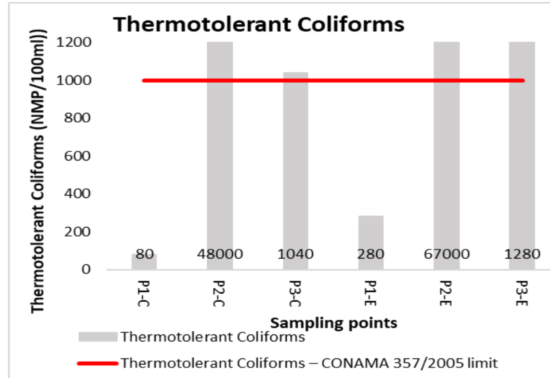
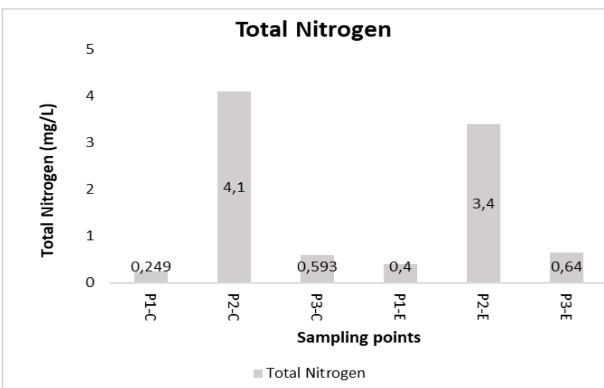


Figure 9. Total coliform concentrations at the sampling points (P1, P2, and P3) during the rainy and dry seasons. The dashed line indicates the legal limit established by CONAMA Resolution Nº. 357/2005 for Class II water bodies.

Figure 10. Thermotolerant coliform concentrations at the sampling points (P1, P2, and P3) during the rainy and dry seasons. The dashed line indicates the maximum permissible limit established by CONAMA Resolution Nº. 357/2005 for Class II waters.



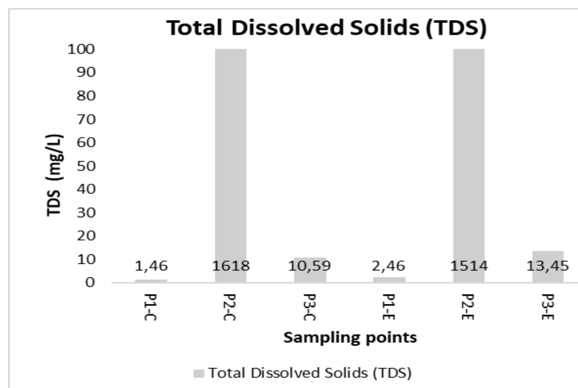


Figure 11. Total nitrogen concentrations at the sampling points (P1, P2, and P3) during the rainy and dry seasons, indicating nutrient enrichment associated with domestic effluent discharges.

Figure 12. Total dissolved solids (TDS) at the sampling points (P1, P2, and P3) during the rainy and dry seasons, reflecting the degree of anthropogenic influence along the urban drainage system.

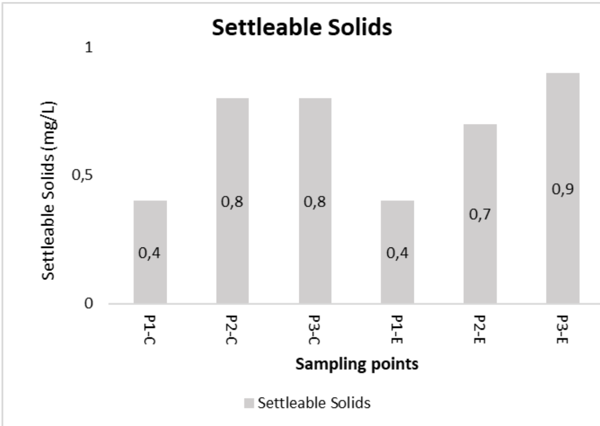


Figure 13. Settleable solids measured at the sampling points (P1, P2, and P3) during the rainy and dry seasons, indicating physical degradation processes and sediment input into the water body.

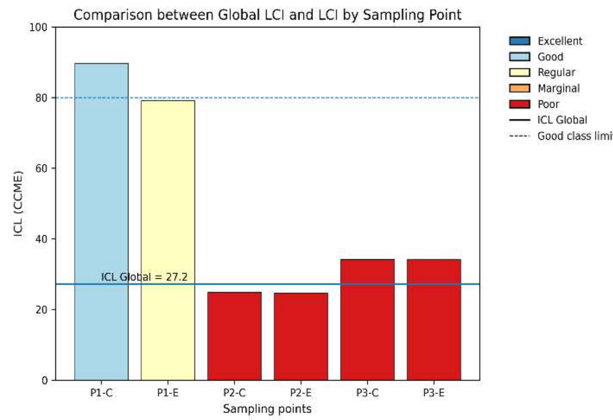


Figure 14. Legal Compliance Index (LCI) values by sampling point and hydrological period, highlighting spatial differences in legal compliance with CONAMA Resolution Nº. 357/2005.

3.1 Dissolved oxygen (DO)

Dissolved oxygen (DO) concentrations (Figure 3) clearly demonstrate the influence of untreated domestic effluent discharge on the water quality of the Irurá stream. At the upstream reference point (P1-C), DO values remained slightly above the legal minimum of 5 mg L^{-1}. In contrast, DO concentrations at points P2 and P3 consistently fell below this threshold during both the rainy and dry seasons.

The observed DO depletion at impacted points reflects intensified oxygen consumption associated with microbial degradation of organic matter derived from untreated domestic wastewater. Similar patterns have been widely reported in urban streams affected by point-source pollution, where localized effluent inputs are sufficient to disrupt oxygen dynamics regardless of seasonal hydrological variability (Carey et al., 2020; Zhang et al., 2021). The persistence of low DO values across both sampling campaigns indicates a continuous pollution source, rather than episodic or rainfall-driven impacts.

3.2 Hydrogen potential (pH)

pH values (Figure 4) ranged from acidic to slightly alkaline conditions across sampling points and seasons. At the upstream point (P1), pH values below the minimum legal limit were observed in both hydrological periods, a condition commonly associated with natural characteristics of Amazonian streams, such as acidic soils and high concentrations of dissolved organic matter.

Conversely, pH values at points P2 and P3 generally fell within the legal range, with an increase observed downstream of the effluent discharge. Elevated pH values at impacted sites may be linked to the presence of nitrogenous compounds, particularly ammonia from domestic wastewater, as well as enhanced eutrophication processes that alter the carbonate equilibrium of the water column. Similar shifts in pH have been reported in urban tropical streams receiving untreated sewage inputs (Nguyen et al., 2020; Almeida et al., 2021).

3.3 Biochemical oxygen demand (BOD_5)

BOD_5 values (Figure 5) further corroborate the strong influence of domestic effluents on the Irurá stream. While concentrations at P1 remained below the legal limit of 5 mg L^{-1} in both seasons, points P2 and P3 exhibited values exceeding this threshold, reaching up to 9.4 mg L^{-1} at P3-E.

Elevated BOD_5 indicates a high load of biodegradable organic matter, a hallmark of untreated domestic sewage inputs. The strong inverse relationship observed between BOD_5 and dissolved oxygen highlights the coupled nature of organic pollution and oxygen depletion in urban streams. Comparable responses have been documented in studies addressing point-source impacts on surface waters in developing regions (Sharma et al., 2021; Li et al., 2020).

3.4 Total phosphorus

Total phosphorus concentrations (Figure 6) exceeded the legal limit of 0.1 mg L^{-1} at nearly all sampling points and during both campaigns, with extremely high values recorded at the effluent discharge point (P2). These concentrations are characteristic of direct inputs of domestic wastewater rich in detergents and organic matter.

Phosphorus enrichment is a key driver of eutrophication, promoting excessive primary productivity and altering oxygen dynamics in aquatic systems. Recent studies emphasize that phosphorus loading from point sources can rapidly compromise water quality in urban streams, particularly when dilution capacity is limited (Carey et al., 2020; Zhang et al., 2021).

3.5 Turbidity

Turbidity values (Figure 7) showed pronounced contrasts between the reference and impacted points. While P1 remained below the legal threshold, extremely high turbidity values were observed at P2 and P3, exceeding 2000 NTU during both seasons.

Such elevated turbidity reflects intense inputs of suspended solids, organic debris, and urban waste, which reduce light penetration and impair photosynthetic processes. Similar turbidity responses have been reported in urban drainage systems subjected to untreated sewage and stormwater runoff, indicating severe physical degradation of the aquatic environment (Li et al., 2020; Goonetilleke et al., 2005).

3.6 Apparent color

Apparent color values (Figure 8) were markedly elevated at impacted points, exceeding recommended limits by more than an order of magnitude. High apparent color is commonly associated with dissolved organic matter and humic substances, originating from both domestic effluents and surface runoff.

This parameter reinforces the combined chemical and visual degradation of the water body, limiting its suitability for multiple uses. Comparable findings have been reported in tropical urban streams affected by untreated wastewater inputs (Nguyen et al., 2020; Almeida et al., 2021).

3.7 Microbiological parameters

Total and thermotolerant coliform concentrations (Figures 9 and 10) exceeded legal limits by several orders of magnitude at points P2 and P3, unequivocally indicating fecal contamination. These results confirm the direct influence of untreated domestic sewage and represent a significant public health concern.

Persistent microbiological contamination across hydrological periods underscores the dominance of point-source pollution over seasonal variability, a pattern widely reported in urban streams lacking adequate sanitation infrastructure (Sharma et al., 2021; UN-Water, 2021).

3.8 Total nitrogen

Total nitrogen concentrations (Figure 11) were substantially higher at impacted points compared to the reference site. Although no specific legal limit is defined for this parameter, elevated nitrogen levels contribute to eutrophication processes and may exacerbate oxygen depletion and pH alterations.

Recent studies highlight that nitrogen enrichment from domestic wastewater remains a major driver of water quality degradation in urban tropical watersheds (Li et al., 2020; Nguyen et al., 2020).

3.9 Total dissolved solids (TDS)

TDS values (Figure 12) increased markedly at points P2 and P3, reflecting the accumulation of dissolved salts and compounds associated with wastewater discharges. Elevated TDS concentrations are indicative of sustained anthropogenic pressure along the urban drainage system and have been reported as a common feature of urban streams impacted by domestic effluents (Zhang et al., 2021).

3.10 Settleable solids

Settleable solids (Figure 13) further highlight the physical degradation of the Irurá stream. While low and stable values were observed at the reference point, higher concentrations at impacted points indicate enhanced sediment inputs driven by effluent discharge and urban runoff.

The strong correspondence between settleable solids, turbidity, and apparent color suggests a coupled process of physical, chemical, and microbiological degradation. Similar interactions have been documented in urban streams worldwide, reinforcing the vulnerability of small watercourses to localized pollution sources (Walsh et al., 2005; Li et al., 2020).

3.11 Water Quality Index (WQI)

Water Quality Index (WQI) values, presented in Table 4, provide an integrated synthesis of the physicochemical and microbiological alterations observed along the Irurá stream. At the upstream reference point (P1), WQI values were classified as *poor* during both the dry (25.71) and rainy (22.40) seasons, indicating that water quality is already compromised before the direct discharge of domestic effluents. This condition suggests the influence of diffuse anthropogenic pressures within the watershed, a pattern commonly reported for urban streams subjected to cumulative land-use impacts (Li et al., 2020; Varol, 2020).

Table 4. Water Quality Index (WQI) values and classification by sampling point

Sampling point	**WQI**	**Classification**
P1-S	25.71	Poor
P2-S	8.36	Very poor
P3-S	13.25	Very poor
P1-C	22.40	Poor
P2-C	8.69	Very poor
P3-C	14.05	Very poor

Source: Autors

At points P2 and P3, WQI values were consistently classified as *very poor* during both sampling campaigns. At point P2, which directly receives untreated domestic effluent, WQI values of 8.36 (dry season) and 8.69 (rainy season) indicate severe degradation of water quality. Downstream at point P3, WQI values of 13.25 (dry season) and 14.05 (rainy season) demonstrate that the impacts generated at the discharge point propagate along the stream, affecting downstream sections.

The limited variation in WQI values between hydrological periods indicates that water quality degradation is not driven primarily by seasonal hydrological conditions, but rather by a persistent point-source pollution input. Similar patterns have been observed in urban streams worldwide, where untreated domestic wastewater discharges dominate water quality dynamics regardless of seasonal flow variability (Nguyen et al., 2020; Sharma et al., 2021; Zhang et al., 2021).

The low WQI values observed in this study are primarily associated with elevated concentrations of thermotolerant coliforms, total phosphorus, turbidity, and BOD_5, combined with reduced dissolved oxygen levels at impacted sites. Recent studies emphasize that these parameters exert a disproportionate influence on WQI outcomes in urban environments, particularly in regions lacking adequate wastewater treatment infrastructure (Carey et al., 2020; Sutadian et al., 2022).

Overall, the integrated assessment provided by the WQI confirms that the water quality of the Irurá stream is incompatible with the multiple uses intended for Class II water bodies. These findings reinforce the diagnosis of environmental degradation previously identified through individual parameter analysis and highlight the limitations of relying solely on dilution capacity in water-abundant regions. The complementary evaluation provided by the Legal Compliance Index (LCI), discussed in the following section, further substantiates this diagnosis from a regulatory perspective.

3.12 Legal Compliance Index (ICL)

The results of the Legal Compliance Index (LCI), presented in Figure 14 and Table 5, provide an objective assessment of water quality compliance with the legal thresholds established by CONAMA Resolution No. 357/2005. The application of the index enabled the evaluation of both the overall regulatory condition of the stream and the spatial variability among sampling points and hydrological periods.

Table 5. Legal Compliance Index (LCI) results by sampling point

Sampling point	**ICL**	**Classification**	**F1 – Scope (%)**	**F2 – Frequency (%)**	**F3 – Amplitude (%)**
P1-C	89.71	Good	12.50	12.50	2.33
P1-E	79.11	Regular	25.00	25.00	7.66
P2-C	24.88	Poor	62.50	62.50	95.48
P2-E	24.72	Poor	62.50	62.50	95.87
P3-C	34.22	Poor	62.50	62.50	71.89
P3-E	34.11	Poor	62.50	62.50	72.19

Source: Autors

The global LCI value was 27.25, classified as *poor*, indicating severe legal non-compliance of water quality along the studied reach. This result reflects the extensive scope of non-compliances (F1 = 75.00%), the high frequency of exceedances relative to legal limits (F2 = 47.92%), and, most critically, the high magnitude of violations (F3 = 89.20%). Together, these components indicate that a large proportion of the evaluated parameters systematically exceeded regulatory thresholds, characterizing a critical legal and environmental condition. Similar regulatory non-compliance patterns have been reported for urban streams subjected to untreated wastewater discharges in developing regions (Zhang et al., 2021; Hernández-Romero et al., 2023).

Spatial analysis of the LCI revealed pronounced heterogeneity among sampling points. At the upstream reference point (P1-C), the index reached 89.71, classified as *good*, indicating high compliance with legal standards. This condition is associated with low scope (F1 = 12.50%) and frequency (F2 = 12.50%) of non-compliances, as well as minimal violation magnitude (F3 = 2.33%), suggesting limited influence of point-source pollution at this location.

At P1-E, also located upstream, the LCI decreased to 79.11 (*regular*). Although this classification still indicates moderate compliance, the increase in scope and frequency of non-compliances (F1 = F2 = 25.00%) suggests reduced resilience during the dry season, likely associated with lower streamflow and diminished dilution capacity. Similar seasonal sensitivity of regulatory compliance has been reported in urban streams affected by continuous pollutant inputs (Varol, 2020; Sutadian et al., 2022).

In contrast, sampling points directly influenced by domestic effluent discharges exhibited the poorest legal performance. At point P2, both during the rainy (P2-C = 24.88) and dry (P2-E = 24.72) seasons, the LCI was classified as *poor*, reflecting severe and persistent legal non-compliance. These results were driven by the combined effects of high scope and frequency of failures (F1 = F2 = 62.50%) and, notably, extremely high violation magnitudes (F3 > 95%), clearly evidencing the dominant impact of untreated domestic sewage on water quality.

Downstream points (P3-C = 34.22 and P3-E = 34.11) also remained classified as *poor*, demonstrating that the pollutant load introduced at P2 propagates along the stream course. Although LCI values at P3 were slightly higher than those observed at P2, they still indicate widespread regulatory non-compliance, particularly for dissolved oxygen, BOD_5, total phosphorus, turbidity, and thermotolerant coliforms. This spatial persistence of legal violations highlights the limited self-purification capacity of the stream when subjected to continuous point-source inputs.

Comparison between the global LCI and point-specific values (Figure 14) indicates that, despite the presence of upstream sections with relatively better legal performance, the overall regulatory condition of the stream is governed by critical points where untreated effluents are discharged. This finding underscores the importance of spatially explicit compliance assessments, as aggregated indices may obscure severe local violations, a limitation previously highlighted in regulatory water quality studies (Hernández-Romero et al., 2023).

Overall, the LCI analysis complements the findings obtained from individual parameters and from the Water Quality Index (WQI). While the WQI reflects environmental degradation from an integrated ecological perspective, the LCI explicitly demonstrates the legal incompatibility of the Irurá stream with the intended uses for Class II waters. Together, these indices provide a robust and convergent diagnosis, reinforcing the conclusion that even a single untreated domestic effluent discharge can dominate both environmental and regulatory conditions in urban tropical streams.

4. Conclusions

This study demonstrated that a single point discharge of untreated domestic effluent is sufficient to cause severe and persistent degradation of water quality in an urban tropical stream, even in a region characterized by high freshwater availability such as the Amazon. The results clearly show that localized pollution sources can override natural dilution capacity, leading to widespread physicochemical, microbiological, and regulatory impairment of urban water bodies.

The analysis of individual parameters revealed critical exceedances of legal thresholds for dissolved oxygen, biochemical oxygen demand, total phosphorus, turbidity, and microbiological indicators at sampling points directly and indirectly influenced by effluent discharge. These impacts were observed consistently during both rainy and dry seasons, indicating that water quality degradation is driven primarily by continuous point-source inputs rather than by seasonal hydrological variability.

The integrated application of the Water Quality Index (WQI) and the Legal Compliance Index (LCI) proved to be an effective and complementary framework for assessing urban water quality. While the WQI provided a synthetic evaluation of environmental degradation, the LCI offered a direct measure of regulatory compliance, allowing a more comprehensive diagnosis of water quality conditions and legal suitability for intended uses. The convergence of both indices strengthened the robustness of the assessment and highlighted the limitations of relying solely on conventional water quality indicators.

Spatial analysis revealed that although upstream sections exhibited relatively better conditions, the overall environmental and regulatory status of the stream was dominated by critical points associated with untreated effluent discharge. This finding underscores the importance of spatially explicit monitoring approaches, as aggregated assessments may mask severe local impacts that control system behavior.

From a management perspective, the findings emphasize the urgent need for targeted sanitation interventions, particularly the control and treatment of domestic wastewater discharges in urban drainage systems. Even in water-abundant regions, such as the Amazon, effective wastewater management remains essential to protect urban streams, safeguard public health, and ensure compliance with environmental legislation.

Finally, this study contributes to the broader understanding of urban stream vulnerability in tropical environments and demonstrates the applicability of integrated monitoring frameworks combining environmental and regulatory indicators. The approach adopted here can support water quality management and decision-making in other urban watersheds affected by localized pollution sources, especially in rapidly urbanizing regions of the developing world. The integrated framework applied in this study can be readily adapted to other urban watersheds where localized pollution sources control environmental and regulatory conditions.

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