



Surface water quality as a function of land use and occupation in two sub-basins in the Southern Amazon

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ABSTRACT: Water quality monitoring is essential for understanding and assessing physical, chemical, and microbiological characteristics, while accounting for spatial and temporal variations driven by climate, soil, and land use and land cover. Given this context, the study aimed to evaluate whether surface water quality is affected by land use and land cover in the Renato and Caiabi river basins, located in the southern Amazon region. The Water Quality Index (WQI) and Trophic State Index (TSI) were determined at eight sampling points on the Renato River and five on the Caiabi River across four seasonal transitions (wet, wet-to-dry, dry, and dry-to-wet), following methodologies from Standard Methods for the Examination of Water and Wastewater. The Renato River presented a water quality compliance index exceeding 90%, while the Caiabi River recorded 90.45%, considering Class 2 rivers. For both rivers, parameters such as temperature, acidic pH, low electrical conductivity, turbidity, nitrogen, and chlorophyll *a* indicated an absence of effluent discharge. Dissolved oxygen, biochemical oxygen demand, total organic carbon, thermotolerant coliforms, and total suspended and dissolved solids exhibited greater seasonal variability but remained within regulatory limits. Both the Renato and Caiabi rivers displayed a "good" WQI and an oligotrophic TSI, indicating low eutrophication potential and an absence of adverse impacts on water usage, despite significant land use and land cover changes within the basins.

Keywords: water quality index; LULC; agricultural watersheds; Cerrado-Amazon transition.

Qualidade das águas superficiais em função do uso e ocupação do solo em duas bacias hidrográficas no Sul da Amazônia

RESUMO: O monitoramento da qualidade da água é essencial para conhecer e avaliar suas características físicas, químicas e microbiológicas, considerando as variações espaciais e temporais decorrentes do clima, solo e do uso e cobertura da terra. Considerando o exposto, objetivou-se avaliar se a qualidade da água superficial é afetada pelo uso e pela cobertura da terra nas bacias hidrográficas Renato e Caiabi, na região sul da Amazônia. O índice de qualidade da água (WQI) e o índice de estado trófico (TSI) foram determinados em oito pontos no rio Renato e em cinco no rio Caiabi, nas quatro transições sazonais (chuva, chuva-seca, seca e seca-chuva), seguindo as metodologias do Standard Methods for Examination of Water and Wastewater. O rio Renato apresentou índice de conformidade da qualidade da água superior a 90%, e o Caiabi, de 90,45%, ambos classificados como rios de Classe 2. Para ambos os rios, os parâmetros de temperatura, pH ácido, baixa condutividade elétrica, turbidez, nitrogênio e clorofila-*a* indicaram a ausência de lançamento de efluentes. O oxigênio dissolvido, a demanda bioquímica de oxigênio, o carbono orgânico total, os coliformes termotolerantes, os sólidos suspensos e dissolvidos totais apresentaram maior variabilidade sazonal, sem ultrapassar os limites normativos. Os rios Renato e Caiabi apresentaram WQI bom e TSI oligotrófico, indicando baixo potencial de eutrofização e ausência de interferências indesejáveis nos usos da água, mesmo diante do expressivo uso e da cobertura do solo nas bacias.

Palavras-chave: índice de qualidade da água; LULC; bacias hidrográficas agrícolas; transição Cerrado-Amazônia.

1. INTRODUCTION

The hydrological cycle is characterized by the movement of water across the planet and encompasses the phenomena

of precipitation, infiltration, percolation, runoff, and evaporation. Due to the multiple interactions within the hydrological cycle, water becomes susceptible to disturbances

resulting from natural or anthropogenic events (BONIFÁCIO; NÓBREGA, 2021). As urban, industrial, and agricultural activities develop in a region, an inversely proportional relationship is observed between the growth of infrastructure and productive practices and the quality of water bodies (MENEZES et al., 2016; PEREIRA et al., 2023; SANAE et al., 2024).

The process of water quality degradation is generally complex and involves multiple factors. External interference in the aquatic environment causes imbalances in the physical, chemical, and microbiological parameters of the water, necessitating assessments and analyses to determine potential alterations and risks to the health of those who consume the water resource (RAMOS et al., 2019; REIS et al., 2022; RAVI et al., 2023).

Regarding sources of pollution, these can be classified as either point or diffuse sources. Point sources are characterized by easily identifiable discharges, such as the release of domestic sewage or industrial effluents, whereas diffuse pollution sources lack a specific discharge point and can occur in various ways, such as through agricultural or urban drainage (FRASCARELI et al., 2015; ALVES et al., 2022).

Water quality monitoring is essential for understanding and evaluating the physical, chemical, and microbiological characteristics of water, while accounting for spatial and temporal variations. According to Drose et al. (2020) and Bonifácio; Nóbrega (2021), note that water quality monitoring assesses the health and integrity of water resources, identifies potential contamination issues, and ensures that water is suitable for various uses, such as public supply, irrigation, recreation, and the preservation of aquatic ecosystems.

However, water quality monitoring generates large volumes of data, and interpreting the results of such qualitative assessments is not always easy or straightforward for all stakeholders involved with these water resources. Using indices or indicators can facilitate communication between technical professionals and those who utilize the water resources. On the other hand, aggregating information into indices or indicators can mask specific results, hinder the evaluation of individual parameters, or fail to effectively demonstrate changes in water quality. Consequently, the analysis of indices and indicators should always be grounded in raw water quality data or other interpretive mechanisms (RAVI et al., 2023; MARSELINA et al., 2025).

Given the importance of understanding the relationship between water quality and land use and land cover, as a foundation for water resource management, this study aimed to evaluate whether surface water quality is affected by land use and land cover within watersheds in the southern region of the Amazon.

2. MATERIALS AND METHODS

2.1. Study area and sampling sites

The two study areas are located within the Teles Pires River basin, which spans latitudes 7° 16' 47" to 14° 55' 17" S and longitudes 53° 49' 46" to 58° 7' 58" W, covering territories in the Brazilian states of Mato Grosso and Pará. The basin has a drainage area of approximately 141,278 km² and a main river channel length of 1,498 km. The predominant vegetation cover consists of the Cerrado biome (Upper Teles Pires), a Cerrado-Amazon transition zone (Upper and Middle Teles Pires), and the Amazon rainforest (Middle and Lower Teles Pires) (Figure 1). Currently, the

basin is situated within a major agribusiness hub in Mato Grosso, characterized primarily by agricultural and livestock activities, alongside hydroelectric and industrial developments.

The two sub-basins studied, those of the Renato and Caiabi rivers, are located on the right bank of the Teles Pires River (Figure 1). The region features an Aw climate (tropical, hot, and humid), with a seasonal pattern defined by two distinct hydrological periods: the rainy season (October to April) and the dry season (May to September). The average annual precipitation is 1,970 mm, with more than 1,700 mm occurring during the rainy season, while mean monthly temperatures range between 24 and 27 °C (SOUZA et al., 2013).

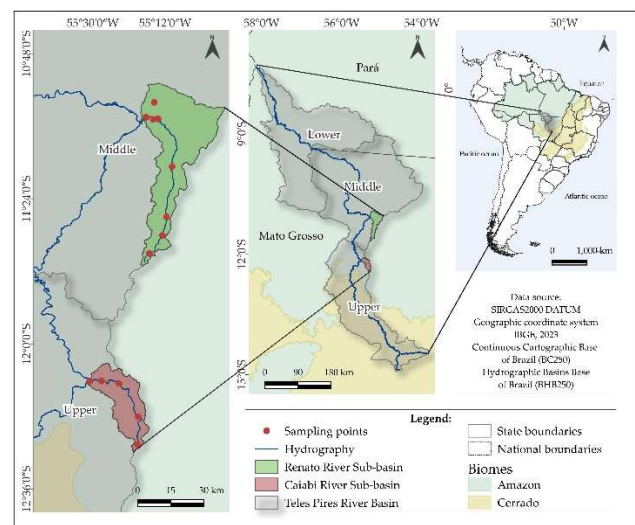


Figure 1. Location map of the Teles Pires River sub-basins within the Cerrado-Amazon transition zone in Mato Grosso, Brazil.

Figura 1. Mapa de localização das sub-bacias hidrográficas do rio Teles Pires na zona de transição Cerrado-Amazônia, em Mato Grosso, Brasil.

The Renato and Caiabi river sub-basins are predominantly rural (Figure 2). The Caiabi River sub-basin is primarily occupied by agricultural activities (approximately 60%), whereas the Renato River sub-basin is covered by natural vegetation across about 69% of its area. The main economic activities are concentrated in forest management, involving both timber and non-timber products, extensive livestock farming, and a significant expansion of agriculture.

The Renato River sub-basin has a drainage area of 1,336 km² and is located in the Middle Teles Pires region, within the southern part of the Amazon biome, a tropical forest area characterized by dense, large-stature vegetation (MARQUES et al., 2019). According to the Brazilian Institute of Geography and Statistics (IBGE), the predominant soil types in this sub-basin are Red and Red-Yellow Latosols, both of which are dystrophic, with a more clayey texture in the upper reaches (near the headwaters) and a medium texture in the lower reaches (near the mouth) (IBGE, 2009; ALVES et al., 2022).

The Caiabi River sub-basin has a drainage area of 493 km² and is situated in the Upper Teles Pires region, in a transitional zone between savanna and forest formations. This area is characterized by trees with twisted stems, some of which are partially deciduous, alongside large-stature trees with dense canopies (OLIVEIRA et al., 2017; MARQUES et

al., 2019). According to the Brazilian Institute of Geography and Statistics (IBGE), the predominant soils in this sub-basin are dystrophic Red-Yellow Latosols, with a very clayey texture in the upper reaches (headwaters) and a clayey texture near the mouth (IBGE, 2009; ALVES et al., 2022).

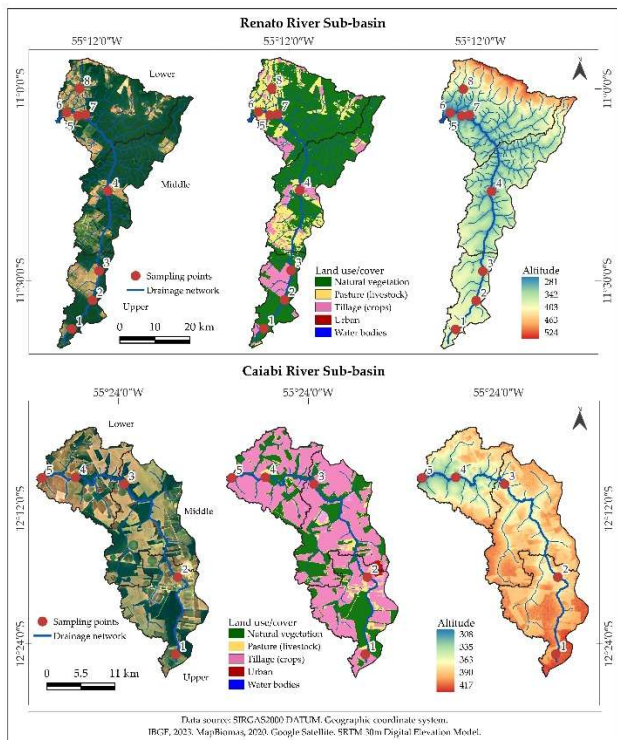


Figure 2. Location map of water sampling points and major land uses in the Teles Pires River sub-basins within the Cerrado-Amazon transition zone in Mato Grosso, Brazil.

Figura 2. Mapa de localização dos pontos de amostragem de água e dos principais usos do solo nas sub-bacias hidrográficas do rio Teles Pires, na transição Cerrado-Amazônia, em Mato Grosso, Brasil.

2.2. Analysis of collected samples

Water sampling campaigns in the Renato and Caiabi river sub-basins were conducted between February 2020 and November 2021. Sampling occurred place during the region's hydrological seasonal transitions (wet, wet-to-dry, dry, and dry-to-wet periods) at 8 locations in the Renato River sub-basin and 5 locations in the Caiabi River sub-basin (Figures 3 and 4), corresponding to different drainage areas and varying land use and land cover types (Tables 1 and 2).

For the Renato River sub-basin, 8 water sampling sites were selected: 6 along the main channel (Renato River) and 2 on tributaries. For the Caiabi River sub-basin, 5 sampling points were established along the main watercourse. The sites along the main channels were strategically chosen in areas influenced by various land uses and occupations, such as croplands, rural roads, and pastures. The sampling points on the Renato River sub-basin tributaries represent areas with low and high levels of land use, respectively.

The water quality parameters monitored to determine the Water Quality Index (WQI) and the Trophic State Index (TSI) included dissolved oxygen (DO), turbidity (Turb), pH, water temperature (TW), thermotolerant coliforms (CT), total dissolved solids (TDS), biochemical oxygen demand (BOD), nitrate (NO₃), total phosphorus (TP), and chlorophyll-*a* (*Chl-a*). Additionally, true color (TC), electrical conductivity (EC), and total organic carbon (TOC) were also determined.

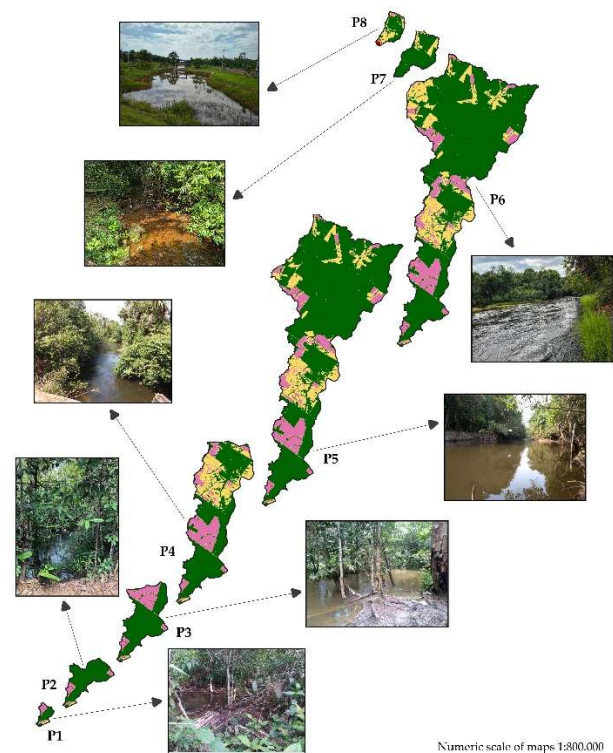


Figure 3. Location map of water sampling points and their relationship to the drainage area and land use in the Renato sub-basin in Mato Grosso, Brazil. As setas apenas indicam a área de contribuição (não representam a localização do ponto amostral).

Figura 3. Mapa de localização dos pontos de amostragem de água e suas relações com a área de drenagem e o uso do solo na sub-bacia hidrográfica do rio Renato, em Mato Grosso, Brasil.

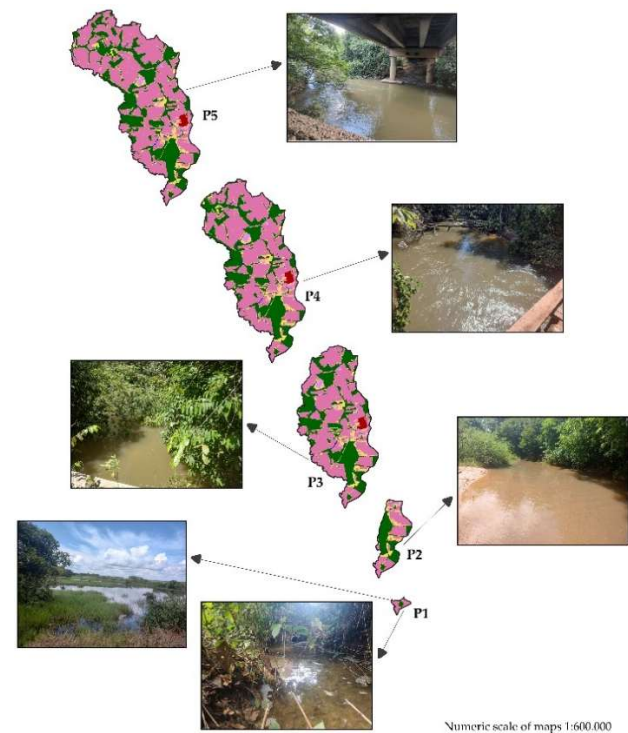


Figure 4. Location map of water sampling points and their relationship with the drainage area and land use in the Caiabi sub-basin in Mato Grosso, Brazil.

Figura 4. Mapa de localização dos pontos de amostragem de água e suas relações com a área de drenagem e o uso do solo na sub-bacia hidrográfica do rio Caiabi, em Mato Grosso, Brasil.

Table 1. Principal land use/cover of water sampling points' contribution areas of the Renato sub-basin in the Amazon biome, Mato Grosso, Brazil.

Tabela 1. Principal uso/cobertura da terra nas áreas de contribuição amostradas em pontos de água da sub-bacia do rio Renato, no bioma Amazônia, Mato Grosso, Brasil.

Land use/cover	Area P1	Area P2	Area P3	Area P4	Area P5	Area P6	Area P7	Area P8
	km ² (%)							
Natural vegetation	10.97 (62.58)	71.76 (87.84)	114.36 (72.12)	251.32 (57.90)	869.7 (73.66)	881.01 (72.09)	67.92 (82.99)	23.84 (60.55)
Pasture (livestock)	1.27 (7.24)	1.44 (1.76)	3.38 (2.13)	94.43 (21.75)	169.24 (14.33)	197.68 (16.18)	11.71 (14.31)	12.85 (32.64)
Tillage (crops)	5.29 (30.18)	8.50 (10.40)	40.82 (25.85)	88.27 (20.34)	141.32 (11.97)	142.89 (11.69)	2.21 (2.70)	2.45 (6.22)
Urban	0	0	0	0	0	0.04 (0.003)	0	0.15 (0.38)
Water bodies	0	0	0	0.05 (0.01)	0.37 (0.04)	0.39 (0.03)	0	0.08 (0.20)

Table 2. Principal land use/cover of water sampling points' contribution areas of the Caiabi sub-basin in the Cerrado biome, Mato Grosso, Brazil.

Tabela 2. Principal uso/cobertura da terra nas áreas de contribuição amostradas em pontos de água da sub-bacia do rio Caiabi, no bioma Cerrado, Mato Grosso, Brasil.

Land use/cover	Area P1	Area P2	Area P3	Area P4	Area P5
	km ² (%)				
Natural vegetation	1.00 (15.60)	26.13 (39.54)	110.06 (33.07)	136.23 (32.07)	152.30 (30.80)
Pasture (livestock)	0.32 (4.99)	9.77 (14.79)	30.90 (9.30)	36.65 (8.63)	40.26 (8.14)
Tillage (crops)	5.07 (79.10)	29.95 (45.32)	186.89 (56.16)	246.84 (58.11)	296.88 (60.04)
Urban	0	0	3.74 (1.12)	3.80 (0.89)	3.80 (0.77)
Water bodies	0.02 (0.31)	0.23 (0.35)	1.17 (0.35)	1.27 (0.30)	1.27 (0.25)

Water temperature (TW) and dissolved oxygen (DO) were measured *in situ* at the time of collection (Digimed DM40P oximeter), while the remaining parameters were analyzed in the laboratory. Turbidity and pH were determined using a turbidimeter (Policontrol AP 2000) and a pH meter (Lojalab mPA-210), respectively. Thermotolerant coliform (TC) analyses were performed using the multiple-tube fermentation technique (presumptive test: 35 °C, SP Labor SP-101/42 incubator; confirmatory test: 44.5 °C, Mylabor SSDc-30L water bath).

Total dissolved solids (TDS) were determined gravimetrically by subtracting suspended solids from total solids (drying oven: 103–105 °C, Caltech ES 1.5). Biochemical oxygen demand (BOD) was determined after a 5-day incubation at 20 °C (Solar SL-200/300 incubator).

Nitrate (NO₃⁻) was measured using the cadmium reduction method (Hach Method 8039, NitraVer pillows, 0.03–30 mg L⁻¹; Hach DR900). Total phosphorus (TP) was determined through hot acid digestion followed by the ascorbic acid method (BioEng A75 autoclave; Global Equipamentos GTA-96 spectrophotometer).

For chlorophyll-*a* (*Chl-a*) determination, samples were filtered through glass-fiber filters, followed by extraction with methanol (PA-ACS grade) and analysed using a spectrophotometer (Global Equipamentos GTA-96). True color was measured using a colorimeter (Hach Method 8025, DR900) on water samples filtered through a 0.45 µm pore-size membrane.

EC was measured using a conductivity meter (Edulec, DDS-12DW), and TOC was determined by the closed-vessel hot digestion method (Hach, method 10129, TOC LR 0.3–20 mg L⁻¹; Hanna HI839800-02 reactor).

Sampling, preservation, and laboratory analyses followed the protocols described in Standard Methods for the Examination of Water and Wastewater (APHA, 2012).

2.3. Calculation of the Water Quality Index (WQI)

The calculated WQI value was obtained by multiplying the nine quality parameters, each raised to its respective weight based on its importance (Equation 1) (<https://www.ana.gov.br/portalanqa/indicadores-indice-aguas.aspx>).

$$WQI = \prod_{i=1}^n q_i^{w_i} \quad (01)$$

where: q_i is the quality value of the i th parameter, a number between 0 and 100, obtained from the respective average quality variation curve (National Water and Basic Sanitation Agency), depending on its concentration or measurement; w_i is the weight corresponding to the i th parameter, fixed according to its importance for the global conformation of quality, that is, a number between 0 and 1. Each parameter has a determined weight (Table 3), relative to its contribution to water quality (source: <https://www.ana.gov.br/portalanqa/indicadores-indice-aguas.aspx>).

Table 3. Weights corresponding to water quality parameters (in the present study, the total nitrogen parameter was replaced by nitrate). Tabela 3. Pesos correspondentes aos parâmetros de qualidade da água (no presente estudo, o parâmetro de nitrogênio total foi substituído por nitrato).

Parameter	Weight w
Dissolved Oxygen (DO)	0.17
Thermotolerant Coliforms (TC)	0.15
Hydrogen ion Potential (pH)	0.12
Biochemical Oxygen Demand (BOD)	0.10
Water Temperature (TW)	0.10
Total Nitrogen (TN)	0.10
Total Phosphorus (TP)	0.10
Turbidity (NTU)	0.08
Total Suspended Solids (TSs)	0.08

Based on the values obtained for each parameter, the monitored points were categorized according to the weighting presented in Table 4.

Table 4. Surface water category based on WQI-based weighting (National Water and Basic Sanitation Agency).

Tabela 4. Categoria da água superficial de acordo com a ponderação do WQI (Agência Nacional de Águas e Saneamento Básico).

Category	Weighting (WQI Range)
Excellent	91 < IQA ≤ 100
Good	71 < IQA ≤ 90
Regular	51 < IQA ≤ 70
Poor	26 < IQA ≤ 50
Very Poor	IQA ≤ 25

Source: <https://www.ana.gov.br/portaltpnqa/indicadores-indice-aguas.aspx>
 Fonte: <https://www.ana.gov.br/portaltpnqa/indicadores-indice-aguas.aspx>

2.4. Calculation of the Trophic State Index (TSI)

Following the analysis of chlorophyll-a and phosphorus parameters, TSI values were determined using Equations 2, 3, and 4 (ALVES et al., 2012). With the TSI values calculated, it is possible to define six trophic classes for the water in the water body, as shown in Table 5.

$$TSI = (TSI(Chl a) + TSI(TP))/2 \quad (02)$$

$$TSI(Chl a) = 10 * \left[6 - \left((-0.7 - 0.6 * (\ln Chl a)) \div \ln 2 \right) \right] - 20 \quad (03)$$

$$TSI(TP) = 10 * \left[6 - \left((-0.42 - 0.36 * (\ln PT)) \div \ln 2 \right) \right] - 20 \quad (04)$$

where: TSI is the trophic state index of the water; *Chl a* is the concentration of chlorophyll a measured at the water surface, in $\mu\text{g L}^{-1}$; TP is the concentration of total phosphorus measured at the water surface, in $\mu\text{g L}^{-1}$; $\ln$ is the natural logarithm.

Table 5. Trophic classes according to the water trophic state index.
 Tabela 5. Classes de trofia de acordo com o índice de estado trófico da água.

Class	TSI
Ultraoligotrophic	≤ 47
Oligotrophic	47 < TSI ≤ 52
Mesotrophic	52 < TSI ≤ 59
Eutrophic	59 < TSI ≤ 63
Supereutrophic	63 < TSI ≤ 67
Hipereutrophic	TSI > 67

Source: Alves et al. (2012).

Fonte: Alves et al. (2012).

2.4. Data analysis

Data on water quality parameters were analyzed using descriptive methods and presented in boxplots, created in Microsoft Excel (Microsoft 365). The results were discussed with reference to Class 2 standards as defined by CONAMA Resolution No. 357 of 2005 (BRAZIL, 2005), the Brazilian benchmark for the classification of surface water quality.

Water Quality Index (WQI) results are presented in tabular format, broken down by sampling event and location, while Trophic State Index (TSI) results are shown in correlation plots that compare dry and rainy seasons for each sub-watershed and sampling site.

3. RESULTS

3.1. Renato River sub-basin

Water quality parameter values measured during sampling in the Renato River are presented in Figures 5 and 6. Water

temperature values (Figure 5A) were consistent with the regional climate and followed the air temperature trend, ranging from 20 to 26 °C at point 1 and from 25 to 39 °C at point 8 throughout the years studied. The sampling sequence followed the order of the points, with point 1 sampled around 7:00 AM and point 8 around 1:00 PM. The difference in water temperature between the points was primarily due to the rise in air temperature during the sampling period.

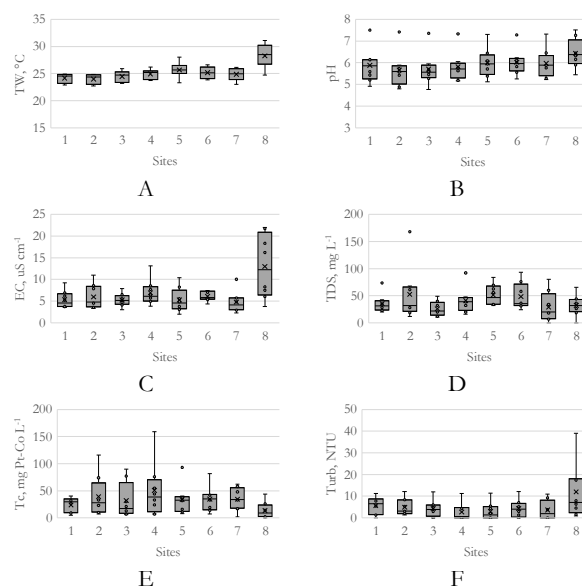


Figure 5. Measured values of water temperature, Tw (A), pH (B), electrical conductivity, EC (C), total dissolved solids, TDS (D), true color, TC (E), and turbidity, NTU (F) at sampling points in the Renato River sub-basin.

Figura 3. Valores aferidos de temperatura da água, Tw (A), potencial hidrogeniônico, Ph (B), condutividade elétrica, EC (C), sólidos totais dissolvidos, TDS (D), cor verdadeira, TC (E) e turbidez, NTU (F), nos pontos de amostragem na sub-bacia hidrográfica do rio Renato.

Regarding pH values, they were predominantly acidic (Figure 5B). Electrical conductivity (EC) values were generally low ($<100 \mu\text{S cm}^{-1}$) (Figure 5C), as expected for waters that do not receive significant quantities of effluents. In fact, no effluent discharge points were observed along the Renato River. However, point 8, a tributary of the Renato River located within an area under urban influence, exhibited higher EC values, suggesting a potential contribution of sewage to the surface waters.

The dispersion of total dissolved solids (TDS) values (Figure 5D) indicated variability in the generation and transport of these solids within the Renato River. Nevertheless, the observed values were generally quite low ($<100 \text{ mg L}^{-1}$), well below the maximum limit established by Brazilian regulations ($<500 \text{ mg L}^{-1}$). Similarly, true color (TC), which is associated with TDS, also showed some variability across the basin (Figure 5E). Unlike the TDS, however, the true color values in some instances exceeded the limits for Class 2 rivers (i.e., they were greater than $75 \text{ mg Pt-Co L}^{-1}$). These measurements, which surpassed the regulatory limit, occurred at points 2 through 6 and were associated with the rainy season, indicating the transport of substances that impart color to the water, such as soil and organic matter. As for turbidity, the values observed were low ($<20 \text{ NTU}$; Figure 5F) and remained below the applicable regulatory limit ($<100 \text{ NTU}$). Turbidity is related to the

presence of suspended solids that impede the passage of light. Such suspended solids enter the water from both diffuse and point sources, as well as through the resuspension of solids from the riverbed. Point 8 exhibits the greatest dispersion in turbidity values, again suggesting the potential contribution of sewage to the surface water.

Dissolved oxygen (DO) values showed significant variability, with most falling above the minimum recommended level for Class 2 rivers (5 mg L^{-1}) (Figure 6A). Low DO values can be associated with high concentrations of organic matter; however, the measured biochemical oxygen demand ($< 3 \text{ mg L}^{-1}$) and total organic carbon ($< 10 \text{ mg L}^{-1}$) values were not particularly high (Figures 6B and 6C). Therefore, the low DO values recorded are likely related to the river's hydraulic conditions, which may not be conducive to the reoxygenation of the water.

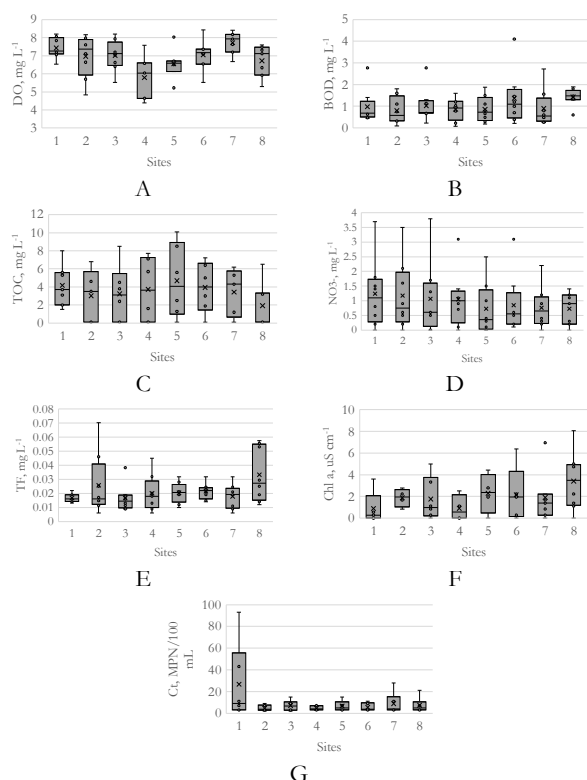


Figure 6. Measured values of dissolved oxygen, DO (A), biochemical oxygen demand, BOD (B), total organic carbon, TOC (C), nitrate (NO_3^- (D), total phosphorus, TP (E), chlorophyll-*a*, *Chl-a* (F), and thermotolerant coliforms (Ct (G), at sampling points in the Renato River sub-basin.

Figura 4. Valores aferidos de oxigênio dissolvido, DO (A), demanda bioquímica de oxigênio, BOD (B), carbono orgânico total, TOC (C), nitrato, NO_3^- (D), fósforo total, TP (E), clorofila-*a*, *Chl-a* (F) e coliformes termotolerantes (Ct (G), nos pontos de amostragem na sub-bacia do rio Renato.

Regarding nutrients and primary production, low nitrate levels were observed (Figure 6D) (below 4 mg L^{-1}) when compared to the regulatory limit (10 mg L^{-1}). Low total phosphorus levels were also recorded, remaining below 0.1 mg L^{-1} (the maximum regulatory limit for Class 2 rivers) (Figure 6E). Furthermore, chlorophyll-*a* concentrations were low ($< 10 \mu\text{g L}^{-1}$; the regulatory limit is $< 30 \mu\text{g L}^{-1}$) (Figure 6F), likely due to the low concentrations of nitrogen and phosphorus.

For thermotolerant coliforms, low values ($< 100 \text{ MPN}/100 \text{ mL}$) were recorded, well below the $1000 \text{ MPN}/100 \text{ mL}$ limit (Figure 6G). This is primarily due to the absence of point-source effluent discharges within the basin. However, higher coliform levels were observed at the sampling point representing the headwater area. The low water volume at the headwaters, combined with the presence of wild animals that visit the streams to drink, accounts for the higher values observed in these locations.

3.2. Caiabi River sub-basin

The data collected for the Caiabi River are presented in Figures 7 and 8. The behavior of water temperature (TW) (Figure 7A), much like that described for the Renato River, follows the air temperature; however, no pronounced increase in TW is observed between the sampling points. This pattern may be due to the fact that the samples were collected within a relatively short time frame, between 9:00 AM (P1) and 11:00 AM (P5). The pH values show an increase at point 1 compared to the other points (P2, P3, P4, and P5). Nevertheless, the recorded values indicate acidic to slightly acidic water (Figure 7B). This result is similar to that observed for the Renato River, which also exhibited acidic water. Regarding the electrical conductivity (EC) parameter, the values were found to be low ($< 100 \mu\text{S cm}^{-1}$) (Figure 7C), which is consistent with water that does not receive effluent discharges.

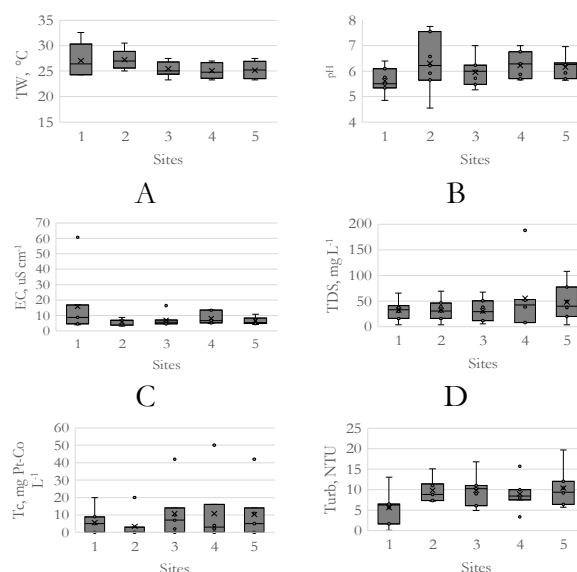


Figure 7. Measured values of water temperature, TW (A), pH (B), electrical conductivity, EC (C), total dissolved solids, TDS (D), true color, TC (E), and turbidity, NTU (F) at sampling points in the Caiabi River sub-basin.

Figura 7. Valores aferidos de temperatura da água, TW (A), potencial hidrogeniônico, pH (B), condutividade elétrica, EC (C), sólidos dissolvidos totais, TDS (D), turbidez, NTU (E), cor verdadeira, TC (F) e coliformes termotolerantes, Ct, nos pontos de amostragem na sub-bacia do rio Caiabi.

TDS values showed significant variability, particularly at point 4 (Figure 7D). Most values were below 50 mg L^{-1} , which is low compared to the regulatory limit of 500 mg L^{-1} . Regarding color (Figure 7E) and turbidity (Figure 7F), no values exceeded the regulatory limits of $75 \text{ mg Pt-Co L}^{-1}$ and 100 NTU , respectively.

For dissolved oxygen (DO), a concerning situation was observed in the section represented by point 1, with low measurements recorded, reaching a minimum of 2.79 mg L^{-1} (Figure 8A). The regulatory standard sets a limit of 5.0 mg L^{-1} for DO; values above this threshold are essential for maintaining the diversity of biological life forms in the water. As for organic matter (biochemical oxygen demand and total organic carbon; Figures 8B and 8C), the measured values indicate low levels of organic matter, a characteristic of lotic (flowing-water) environments that receive little to no effluent discharge.

Nutrient levels in the Caiabi River indicate low concentrations of nitrate and total phosphorus (Figures 8D and 8E). This low nutrient availability is reflected in primary production, with chlorophyll-*a* concentrations well below the regulatory limit ($<30 \mu\text{S cm}^{-1}$) (Figure 8F).

The results for thermotolerant coliforms in the Caiabi River comply with the standards for Class 2 rivers. However, the recorded values are high for a river that ostensibly receives no effluent discharge, particularly in the section near the headwaters. The combination of low water flow and the presence of wild animals is likely the main factor behind the higher concentration of coliforms in this stretch of the river.

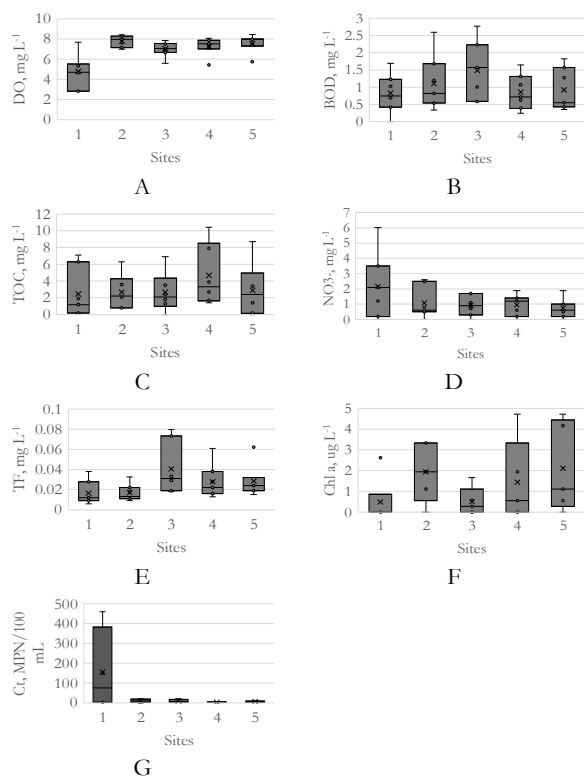


Figure 8. Measured values of dissolved oxygen, DO (A), biochemical oxygen demand, BOD (B), total organic carbon, TOC (C), nitrate, NO_3^- (D), total phosphorus, TP (E), chlorophyll-*a*, *Chl-a* (F), and thermotolerant coliforms (Ct (G)), at sampling points in the Caiabi River sub-basin.

Figura 8. Valores aferidos de oxigênio dissolvido, DO (A), demanda bioquímica de oxigênio, BOD (B), carbono orgânico total, TOC (C), nitrato, NO_3^- (D), fósforo total, TP (E), clorofila-*a*, *Chl-a* (F) e coliformes termotolerantes (Ct (G)), nos pontos de amostragem na sub-bacia do rio Caiabi.

Among the parameters evaluated, the Renato River showed a high compliance rate ($>90\%$) for Class 2 standards. The results for the Caiabi River were similar, with 90.45% compliance within the same class.

During the sampling process, certain point sources of pollution were observed, such as the sediment runoff from roads into the river and the presence of inadequate housing (Figure 9). Several secondary roads are located near the course of the Renato River throughout the entire extent of its watershed, as well as within the watersheds of the Caiabi River and other rivers. Regarding housing, a structure was identified near P1 (indicated by a red arrow in the figure), a sampling point on the Renato River. This dwelling was built to house nut gatherers who reside there for a few months each year.



Figure 9. Sediment transport due to surface runoff facilitated by unpaved roads (A) and the presence of dwellings (B).

Figura 9. Carreamento de sedimentos devido ao escoamento superficial favorecido pelas estradas não pavimentadas (A) e pela presença de moradias (B).

3.3. Water quality index (WQI)

The WQI results for the Renato river and its tributaries are presented in Tables 6 and 7. The values obtained indicate that the river water was of good ($71 < \text{WQI} \leq 90$) to excellent ($\text{WQI} > 90$) quality throughout the monitoring period. For the sections along the main stem of the Renato River basin (sampling points P1 through P6), the highest WQI value recorded was 90.4 (at point P6, in February 2020), while the lowest was 64.58 (at point P1, in June 2021). The sections of the tributaries studied, sampling points P7 and P8, yielded values similar to those observed along the main river.

It was not possible to determine dissolved oxygen (DO) levels for some sampling events, nor thermotolerant coliform counts for two sampling events, due to issues with the DO-measuring equipment and the condition of the samples upon their arrival at the laboratory.

The parameters used to calculate the WQI primarily reflect characteristics related to organic matter, nutrients, solids, and microorganisms, elements generated mainly in areas used for agriculture and livestock, as well as through the discharge of effluents.

Table 6. WQI values determined for the Renato river sampling points. (NC – not calculated due to the DO parameter not being determined) [values in blue – excellent quality; values in green – good quality; values in yellow – fair quality].

Tabela 6. Valores de WQI determinados nos pontos do rio Renato. (NC – não calculado pela não determinação do parâmetro DO) [valores em azul – ótima qualidade; valores em verde – boa qualidade; valores em amarelo – qualidade regular].

Sampling period/season	P1	P2	P3	P4	P5	P6
Feb/2020 – rain	90.4	77.5	86.2	82.9	87.1	90.5
Nov/2020 – rain	86.6	82.5	80.6	75.4	85.2	84.1
Mar/2021 – rain	73.0	68.4	70.3	71.1	73.6	75.1
May/2020 – dry	78.2	83.1	82.5	83.0	84.3	86.1
Sep/2020 – dry	80.2	79.5	78.7	NC	NC	NC
Jun/2021 – dry	64.6	74.8	77.3	78.0	76.5	80.7

Points 7 and 8 correspond to the waters of tributaries representing distinct areas within the Renato River watershed. Point 7 corresponds to a river segment in an area with native vegetation, showing little to no human intervention. The segment at point 8 is located on a tributary impacted by the urban area of the municipality of Itaúba, Mato Grosso (MT). In both cases, the WQI yielded high values, with little difference between the two points. These results indicate that, despite human occupation, the quality parameters assessed in the WQI were not significantly affected when compared to those in less impacted areas.

Table 7. WQI values determined for the tributaries of the Renato River. (NC – not calculated due to the DO parameter not being determined) [values in blue – excellent quality; values in green – good quality].

Tabela 7. Valores de WQI determinados para os afluentes do rio Renato. (NC – não calculado pela não determinação do parâmetro OD) [valores em azul – ótima qualidade; valores em verde – boa qualidade].

Sampling period/season	P7	P8
Feb/2020 – rain	91.6	88.3
Nov/2020 – rain	84.1	82.8
Mar/2021 – rain	75.3	74.2
May/2020 – dry	90.3	88.0
Sep/2020 – dry	NC	NC
Jun/2021 – dry	76.2	83.3

The WQI values for the Caiabi River are presented in Table 8. The results show that WQI values varied along the river, from the headwaters (P1) to the mouth (P5), with an overall increasing trend. Variations in the WQI are also noticeable between sampling events at each individual point. The highest WQI value was recorded at point 2 during the November 2020 sampling (WQI = 87.35), while the lowest was recorded at point 1 during the June 2021 sampling (WQI = 51.85). In general, the assessed river segments were classified as having "excellent" or "good" quality, with the exception of the segment represented by P1 during the June 2021 sampling, which was classified as "acceptable." The parameters that contributed most negatively to the lower WQI value were pH (4.86) and dissolved oxygen (DO) (2.79 mg L⁻¹).

Table 8. WQI values determined for the Caiabi River sampling points. [values in green – good quality; values in yellow – fair quality].

Tabela 8. Valores de WQI determinados nos pontos do rio Caiabi. [valores em verde – boa qualidade; valores em amarelo – qualidade regular].

Sampling period/season	P1	P2	P3	P4	P5
Sep/2020 – dry	72.6	83.3	83.8	87	87
Jun/2021 – dry	51.8	67.8	72.3	82.6	80.5
Nov/2020 – rain	86.3	87.3	80.4	85.8	86.2
Mar/2021 – rain	63.4	77.8	76.4	77.8	76.8

During the June 2020 sampling, it was not possible to measure the number of thermotolerant coliforms in the Caiabi River; therefore, the WQI could only be calculated starting from the September 2020 sampling.

The WQI values reported by Andrietti et al. (2016), who also studied the Caiabi River, ranged from 63 to 91. The authors also recorded the lowest WQI value (63) in the

section near the source of the Caiabi River (P1). The persistence of low values at the source indicates a need for greater attention to this location.

3.4. Trophic State Index (TSI)

The calculated Trophic State Index (TSI) values indicate that the waters of the Renato and Caiabi rivers were classified as ultra-oligotrophic ($TSI \leq 47$) and oligotrophic ($47 < TSI \leq 52$). The highest TSI values were observed during the rainy season (Figure 10A). For the Renato River, TSI values based on chlorophyll-*a* were independent of the rainfall regime across months (Figure 10A). For total phosphorus, the highest frequency of TSI values occurred during months with higher humidity (below the $Y = X$ line). For the Caiabi River (Figure 10B), the data showed that the highest number of TSI values for both chlorophyll-*a* and total phosphorus occurred during the rainy season.

Although the TSI indicated a low risk of eutrophication (ultra-oligotrophic and oligotrophic), it is important to note that the TSI was calculated as an average of the chlorophyll-*a* and total phosphorus (TP) components. Furthermore, the TSI values for total phosphorus (Figures 10B and C) all fell within the 47–52 range, suggesting that, with respect to the total phosphorus parameter, the risk of eutrophication is slightly shifted toward a moderate risk (mesotrophic) level (blue points).

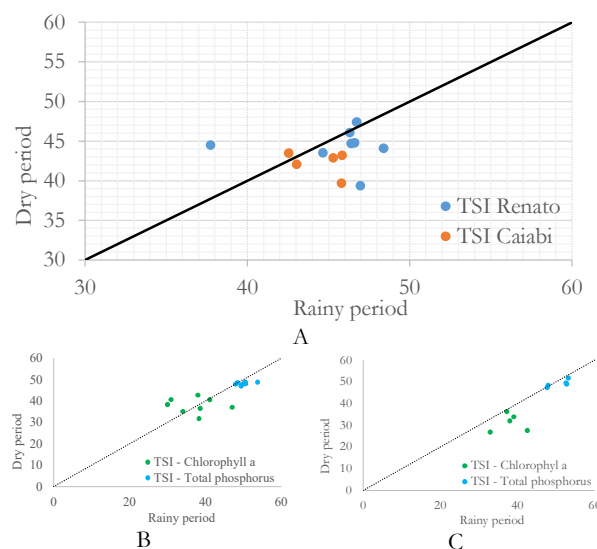


Figure 10. Mean values of TSI (A), TSIChl, and TSITP for the rivers in the Renato (B) and Caiabi (C) sub-basins during the dry and rainy seasons (each point on the graph represents the mean value for each sampling site during the dry (Y) and rainy (X) periods).

Figura 10. Valores médios de IET (A), IETChl e IETTP para os rios das sub-bacias hidrográficas Renato (B) e Caiabi (C), nas estações seca e chuvosa (cada ponto no gráfico representa o valor médio de cada ponto de coleta nos períodos de seca (Y) e de chuva (X)).

4. DISCUSSION

Changes in water quality are a reflection of various factors present within a watershed. Climate is the most significant factor, as it governs precipitation, which in turn contributes to groundwater recharge and surface runoff. Furthermore, geology, vegetation, and changes in land use and land cover, combined with climatic factors, induce substantial alterations in the hydrological cycle, such as the acceleration of water runoff. Increased water velocity enhances the potential energy available for the erosion and transport of soil and

contaminants. Additionally, the discharge of effluents increases the presence of undesirable elements in surface waters (HAMMOUMI et al., 2021; VIDALETI et al., 2021).

Water bodies unaffected by human activity generally exhibit higher quality than those in environments with more intensive land use and occupation (SCHNEIDER et al., 2011). Wang et al. (2023) demonstrated that the impact of land use varies by season, with agriculture and point sources of pollution serving as the primary anthropogenic sources of contamination.

Surface water quality tends to exhibit high variability because the variables involved in such environments cannot be controlled. Moreover, this variability is typically greater during rainy periods than during dry spells, a phenomenon linked to the spatial dynamics of rainfall (PASSOS et al., 2021).

Soil type, location, and land use, for instance, can all alter the physical and chemical characteristics of water. The predominance of acidic waters in the Renato and Caiabi river sub-basins is a natural condition (Andrietti et al., 2016), as the soils in the region are ancient and virtually all soil bases have already been leached (PRADO et al., 2021). Consequently, the aquatic fauna and flora are adapted to this lower pH.

The transport of organic waste and solids into water bodies leads to an increase in organic matter, solids, and turbidity, alongside a decrease in dissolved oxygen (DO) levels in surface waters (PIASENTIN et al., 2009; BASSO et al., 2011; SILVA et al., 2021).

In general, surface waters in areas with little or no human impact exhibit high DO levels, which vary according to temperature, salinity, turbulence, and atmospheric conditions. The dissolved oxygen balance in a water body is significantly affected by the discharge of effluents (Effendi et al., 2015) or by the presence of water with a high load of natural organic matter (DUVOISIN et al., 2025). Conversely, studies indicate that low DO concentrations can also occur in natural environments. Springs or small channels with low turbulence do not provide favorable conditions for water oxygenation; in such cases, measured DO values may be low ($< 5 \text{ mg L}^{-1}$) without necessarily indicating the presence of large quantities of organic matter (BARROS et al., 2018; OLIVEIRA et al., 2022). Changes in water color are linked to the presence of dissolved elements; in cases where no direct discharges are observed, the source of these elements is likely the decomposition of natural vegetation (O'NEILL, 1995). During rainy periods, an increase in the influx of solids into the system may occur due to surface runoff, which subsequently leads to a change in water color (WANG; YANG, 2019).

The presence of thermotolerant coliforms is a potential indicator of pathogenic organisms. Coliform concentrations tend to be higher in river sections under urban influence, as these areas are often subject to the discharge of effluents, primarily sewage, though rural areas may also experience the release of waste or surface runoff from locations where animals are present (QUEIROZ et al., 2019; QIAN et al., 2024).

In the Setubal River (MG, Brazil), Martins et al. (2017) classified the lotic environment as having "medium" quality, with Water Quality Index (WQI) values ranging from 47.20 to 61.10. The WQI was influenced by coliform concentrations, a result of altered water dynamics (due to river damming) and the receipt of sewage from the town of Jenipapo de Minas.

Islam et al. (2025) reported that the poor water quality and its unsuitability for consumption in the Kangsabati River (India), as assessed via a water quality index, are due to the river's interaction with various types of effluents and human activities, including the disposal of sewage and other effluents, as well as surface runoff from agricultural areas.

Regarding nutrients present in surface waters, both agricultural and urban areas contribute to the nitrogen and phosphorus load. In a study on the temporal assessment of the lower São Francisco River in the state of Sergipe, Marques et al. (2011) observed total phosphorus (TP) levels ranging from 0.054 to 0.920 mg L^{-1} . According to the authors, these high TP values were due to the discharge of domestic sewage into the river. Santos et al. (2016) identified disturbances in total phosphorus levels in the Sapucaia coastal basin (Sergipe). The use of agricultural fertilizers with high phosphorus concentrations was identified as a factor, as these substances are easily transported by rainfall into rivers.

Chlorophyll-*a* is one of the most important parameters for assessing primary production, serving as an indicator of nutrient availability, specifically phosphorus and nitrogen (DUARTE et al., 2021). Consequently, low chlorophyll-*a* values indicate low productivity, resulting from low nutrient concentrations.

According to Santos et al. (2014), phytoplankton quality depends on surface light and nutrient availability; generally, higher chlorophyll-*a* values are observed during periods of lower precipitation, which indicates optimal light and nutrient conditions for increased concentrations. Conversely, higher values during the rainy season may be linked to the contribution of rainfall to surface runoff, which can be beneficial as it delivers nutrients and sediments to the respective water bodies.

Alemayehu et al. (2016), in a study conducted at Kaw Lake (Oklahoma, USA), indicated that anthropogenic activities, including agriculture, industry, and sewage treatment, can accelerate the eutrophication process, although algal growth may also stabilize over time. Furthermore, Duarte et al. (2021) point out that the risk of eutrophication is also determined by differences in hydraulic conditions. Lentic (still-water) environments present a higher risk of eutrophication than lotic (flowing-water) ones.

An assessment of the nitrogen, phosphorus, and chlorophyll-*a* concentrations measured in the rivers in this study indicates environments with low to moderate nutrient levels and biological production. This suggests that the phosphorus supply, water turbulence, and limited sunlight, the latter due to the preservation of riparian vegetation, do not significantly favor algal growth.

Although most of the water quality parameters measured fell within regulatory limits, some river stretches show signs of disturbance. This makes ongoing water quality monitoring essential to track changes over time and, if necessary, to progressively implement strategies and goals to prevent further deterioration or to facilitate recovery.

In this context, it is worth noting that both rivers are tributaries of the Teles Pires River, which has undergone drastic changes in recent years due to the construction and operation of hydroelectric power plants. These developments have altered the river's hydraulic regime, shifting it from lotic to lentic in certain sections.

In a lotic environment, primary production is generally not a concern; however, given the shift in the hydraulic regime, nutrient enrichment could be an ongoing process that

may eventually become a significant environmental problem. Cunha (2013), in an analysis of the temporal trends of non-compliance in rivers and reservoirs in the state of São Paulo, observed a reduction in such instances over time and highlighted the importance of using CONAMA Resolution No. 357/2005 as a legal instrument for establishing progressive goals for the qualitative improvement of water resources, with a focus on the highest-value intended uses of the water and with a view toward long-term sustainability.

5. CONCLUSIONS

The water quality of the Renato and Caiabi river sub-basins is influenced by climate and land use and occupation, although only some parameters showed non-conformities in relation to the legal limits established by Conama Resolution No. 357, of 2005. The values of the water quality indices (WQI) and trophic status (TSI) indicated variable quality depending on the sampling points and times, as well as a low to medium risk of eutrophication. Most of the points evaluated had average water quality.

The results presented in this study contribute to the construction of knowledge about water quality in the Amazon-Cerrado ecotone region. However, this study does not yet bring to light some aspects related to potentially toxic elements (such as heavy metals, agricultural pesticides, pharmaceuticals, hormones, among others).

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