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Water quality index (WQI) and bathing suitability of freshwater beaches on the Negro River, Manaus (Amazonas)

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Abstract: Many aquatic environments are affected by urbanization and inadequate sanitation, which directly deteriorates local environmental quality. This study aimed to assess the Water Quality Index (WQI) and bathing suitability of Tupé, Lua and Ponta Negra beaches along the Negro River in Manaus. Water samples were collected from the three beaches during the flood and dry seasons in 2008 and subsequently processed and analyzed. The WQI was calculated using the weighted product method based on nine parameters: water temperature, pH, dissolved oxygen, biochemical oxygen demand, thermotolerant coliforms, total nitrogen, total phosphorus, total residue and turbidity. Each parameter was assigned a fixed weight according to its impact on overall water quality. Bathing suitability was evaluated in line with Resolution No. 274/2000 issued by the National Environment Council, classified as suitable or unsuitable based on fecal coliform density. Tupé and Lua beaches were suitable for bathing in both seasons, while Ponta Negra was unsuitable during the dry season. The water quality of the beaches ranged from excellent to good, declining gradually closer to downtown Manaus. Local residents and supervisory authorities should keep informed of water bathing conditions, so as to implement measures to curb potential pollution sources.

Key words: contamination; potability; recreation; water resources

1 Introduction

Manaus lies on the left bank of the Negro River in the humid equatorial tropical forest area. Numerous streams run through the city and empty into the Negro River. The region has two distinct seasons. The rainy and flood season lasts from November to May, while the dry season spans June to October (Silva et al., 1999). Tupé, Lua and Ponta Negra beaches situated here attract crowds of visitors all year round for sports and leisure activities (Arcos et al., 2016).

The Negro River receives water from the small watersheds of Educandos, São Raimundo and Tarumã streams. Untreated domestic and industrial wastewater is discharged along the Manaus waterfront, gradually altering the natural features of this area (Pinto et al., 2009). Aquatic ecosystems have been disturbed by various human-induced environmental impacts. Rivers, streams, lakes and reservoirs are severely affected by uncontrolled human activities (McAllister et al., 1997).

The Environmental Sanitation Technology Company (CETESB) adopts the Water Quality Index (WQI), which is revised based on the standard of the United States National Sanitation Foundation (NSF), to monitor and report the quality of public water supply. Nevertheless, this index cannot replace detailed water quality assessment for a specific watershed. The evaluation parameters of WQI reflect water pollution resulting from the discharge of untreated domestic sewage

(CETESB, 2008).

Water quality for primary contact recreation refers to bathing suitability, which is assessed by objective criteria. Evaluation shall be carried out based on monitored indicators, and measured values shall be compared with established standards to judge whether the waters are suitable for bathing (CETESB, 2016).

Water bodies face diverse pollution sources. According to Braga et al. (2002), major pollutants include heavy metals, pathogenic organisms, heat, nutrients, radioactive substances, biodegradable and refractory organic contaminants. Natural water quality refers to the combination of physical, chemical and microbiological properties of aquatic environments (Coneza, 1997). Water pollution mainly stems from domestic sewage, industrial wastewater, atmospheric deposition, leaching of fertilizers and pesticides, and improper solid waste disposal (Studart & Campos, 2001; Meybeck, 2004).

In Brazil, rivers, reservoirs, beaches, and bays located near urban areas are generally polluted due to the improper disposal of sewage, using streams that run through cities to discharge effluents, causing sanitary and environmental problems (Brazil, 2000). With the increase in polluting sources, native ecological systems are replaced by urbanized ecological environments (Novotny and Olem, 1993).

Given the environmental impacts on local water resources, this study aims to assess the bathing conditions of freshwater beaches and identify potential fecal coliform contamination as well as associated ecological and public health risks. Meanwhile, the water quality index revised by CETESB was adopted to evaluate changes in raw water quality for municipal water supply. The investigation was carried out on beaches along the Negro River across two seasonal periods in Amazonas.

2 Materials and methods

2.1 Study area

Water samples were collected from three beaches on the left bank of the Rio Negro: Tupé beach (S03˚04.635' and W060˚25.422'), Lua beach (S03˚03.230' and W060˚13.874') and Ponta Negra beach (S03˚06.485' and W060˚10.668') (Figure 1). These locations are commonly frequented by residents and tourists due to the presence of long stretches of warm water beaches, which are easily accessible to bathers by boats and launches departing from the city of Manaus.

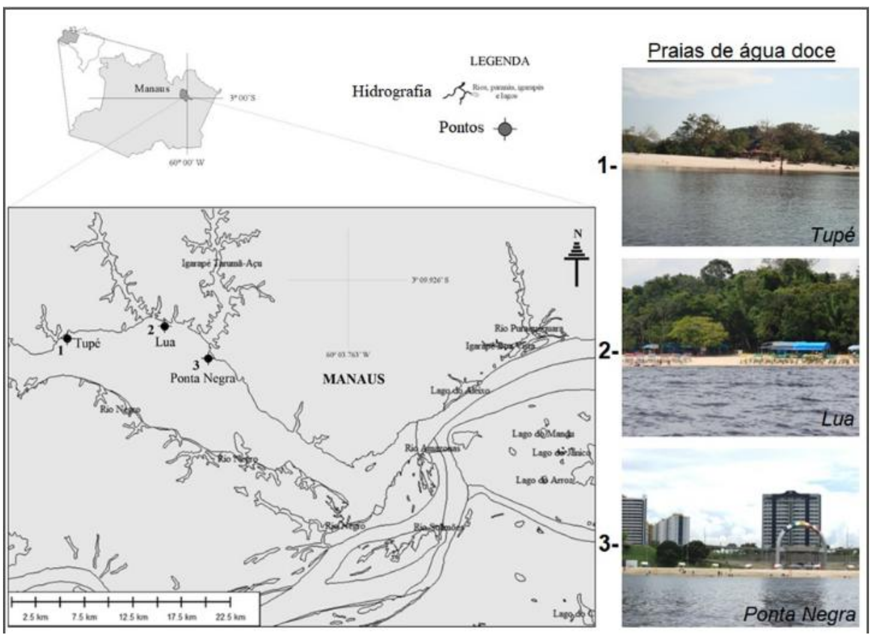

Figure 1. Distribution of beaches along the Negro River.

Source: IBGE (2010), Authors.

2.2 Limnological sampling and analysis

Sampling was conducted in May and June (flood season), September and October (dry season) 2008. Samples were taken once a week for five consecutive weeks in compliance with CONAMA Resolution No. 274. Surface water was collected using 250 mL glass bottles at each sampling point.

The multiple-tube technique was adopted to determine the Most Probable Number (MPN) of total and fecal coliforms in samples. Calculations referred to the Hoskins table (1933), as specified in CONAMA Resolution No. 274/2000. The method was based on *Standard Methods for the Examination of Water and Wastewater* (APHA, 1985), see Figure 2 and Table 1.

This multiple-tube method consists of two tests: presumptive test for coliform growth and confirmatory test for fecal coliform growth. It includes three procedures for coliform detection and enumeration. Finally, positive tubes in each dilution series are counted, and the results are compared against the Hoskins table (Arcos et al., 2020).

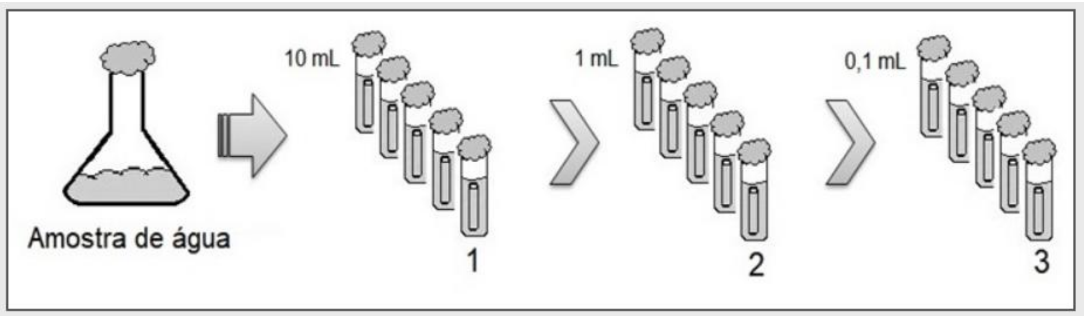

Figure 2. Diagram of the multiple tube technique for the growth of fecal coliforms in water samples.

Source: Arcos et al. (2020).

Table 1. Classification category for bathing suitability according to Conama Environmental Resolution No. 274/2000.

	Standard Category	Fecal coliform limits (*MPN/100mL)
Suitable	Excellent	Max. 250 fecal coliforms in 80% or more of the samples.
	Very Good	Max. 500 fecal coliforms in 80% or more of the samples.
	Satisfactory	Max. 1000 fecal coliforms in 80% or more of the samples.
Unsuitable		More than 1000 fecal coliforms in 20% or more of the samples

Source: Arcos e Cunha (2021).

*MPN (Most Probable Number): is the estimate of the density of fecal coliforms in a 100mL sample, calculated from the combination of positive and negative results.

The physical-chemical and chemical analyses are described in APHA (1985). Table 2 lists the parameters and methodologies used.

Table 2. Parameters used and their methodologies.

Parameters	Methods
Temperature	Thermometry
Turbidity	Nephelometric method
Total Suspended Solids	Gravimetric method
pH (Hydrogen Potential)	Potentiometry
Dissolved Oxygen - DO	Potentiometry
Biochemical Oxygen Demand (BOD)	Winkler method
Phosphorus	Spectrophotometry - Flow Injection Analysis (FIA)
Nitrate	Ion Chromatography - DIONEX

Source: Author's own elaboration.

The Water Quality Index (WQI), standardized by the Environmental Sanitation Technology Company of São Paulo State (CETESB), was adopted to assess the current water condition of this system. Among the initially proposed 35 water quality indicators, nine relevant parameters were selected based on public water supply demand: dissolved oxygen, fecal coliforms, pH, biochemical oxygen demand, nitrate, phosphorus, water temperature, turbidity and total solids. Average water quality variation curves corresponding to substance concentrations were plotted for each parameter, as shown in Table 3.

Table 3. Weight assigned to each evaluated parameter.

Evaluated Parameters	Weight - wi
Dissolved Oxygen - DO % sat	0.17
Fecal Coliforms - MPN/100 mL	0.15
Hydrogen Potential - pH	0.12
Biochemical Oxygen Demand - BOD mg/L	0.10
Nitrates mg/L	0.10
Phosphates mg/L	0.10
Temperature Variation °C	0.10
Turbidity - NTU	0.08
Total Solids mg/L	0.08

Source: Author's own elaboration

The WQI at each point was calculated by the weighted product of the corresponding water qualities of the nine parameters mentioned, using the following formula:

$$\text{IQA} = \prod_{i=1}^{n} q_i^{w_i}$$

Where:

IQA: Water Quality Index, a value ranging from 0 to 100;

qi: quality value of parameter i, obtained from its specific average quality curve;

wi: weight assigned to each parameter, therefore:

$$\sum_{i=1}^{n} w_i = 1$$

Where:

n: number of parameters included in the WQI calculation.

Based on the calculations performed, the quality of the raw water was determined, which is indicated by the WQI (Water Quality Index), on a scale of 0 to 100, as shown in Table 4.

Table 4. Water quality classification.

Category	Weighting (IQA Range)
Excellent	80<WQI≤100
Good	52<WQI≤79
Fair	37<WQI≤51
Poor	20<WQI≤36
Very Poor	0≤WQI≤19

Source: Authors.

All analyses were performed at the Environmental Chemistry Laboratory (LQA) of the Coordination of Environmental Dynamics (CODAM), National Institute for Amazonian Research (INPA), in accordance with the standardized protocols of LQA and the techniques specified in *Standard Methods for the Examination of Water and Wastewater* (1985).

The water level of the Rio Negro (elevation in meters) was sourced from the database of the Port of Manaus (Port of

Manaus, 2022). A normality test was conducted, followed by the Kruskal-Wallis test to compare coliform density across beaches and seasonal periods. The significance level was set at $p \leq 0.05$, and analyses were performed using PAST version 4.02 (Hammer et al., 2001).

3 Results and discussion

The coliform density at Tupé Beach remained below 1,000 MPN of fecal coliforms during the five consecutive weeks of sampling, ranging from 1 to 36 MPN/100mL during the high-water season and from 1 to 230 MPN/100mL during the low-water season, with a significant difference between the seasonal periods (p=0.05). This result indicates that the beach is suitable for bathing and direct body contact throughout the Negro River's dry and flood seasons. Lua Beach exhibited a significant difference between the seasonal periods (p=0.04), with a variation in fecal coliform density between the two periods. This site presented higher densities during the low-water season (36 to 960 MPN/100mL) and lower densities during the high-water season (1 to 93 MPN/100mL), being classified as suitable for bathing during both sampling periods (Figure 3).

Ponta Negra Beach recorded high fecal coliform density in the dry season, ranging from 36 to 2300 MPN/100mL. In the flood season, the density fluctuated from 1 to 4,300 MPN/100mL. No significant seasonal difference was detected (p=0.11). Nevertheless, the beach was classified as unsuitable for bathing in the dry season. Over five consecutive weeks of sampling, more than 20% of samples exceeded the fecal coliform threshold of 1000 MPN. Significant differences were also found among the three beaches (p=0.01), as illustrated in Figure 3.

Monitoring of inland aquatic environments has been expanding alongside advancing urbanization, which has brought about various environmental issues such as water contamination caused by fecal coliforms and heavy metals (Tundisi, 2008; Souza & Gastaldini, 2014). In the Amazon region, studies adopting microbial indicators are carried out to assess recreational water quality, aiming to explore potential causes and impacts. These researches also classify water bodies as suitable or unsuitable for public recreational activities (Campos & Cunha, 2015; Arcos et al., 2016; Queiroz & Rubim, 2016; Arcos & Cunha, 2021; Falcão et al., 2021).

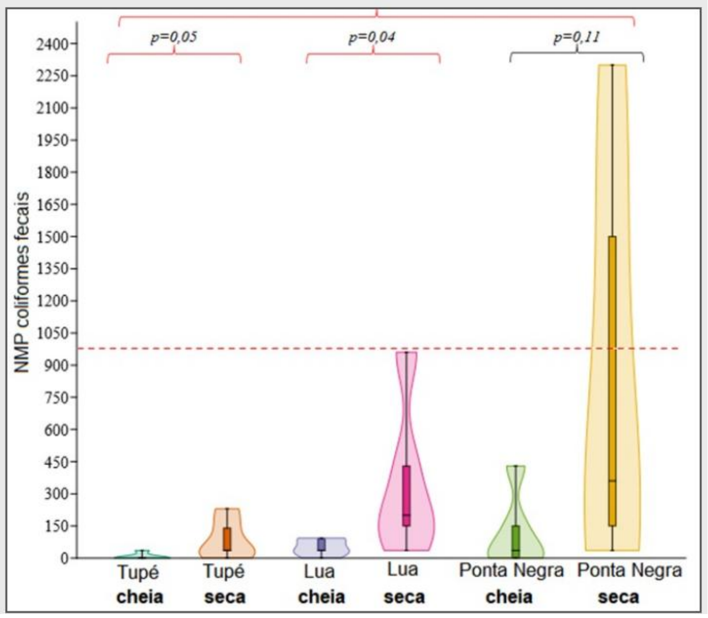

Figure 3. Density of fecal coliforms (MPN) present on the three beaches during five consecutive weeks in the flood and dry season in the Rio Negro, Amazonas. The dashed red line indicates the limit stipulated by Conama Resolution No. 274/2000 (1000 MPN fecal coliforms), and the symbols indicate the p-value. (Source: Author's own elaboration.)

When comparing the three main beaches of the Rio Negro (Tupé, Lua, and Ponta Negra), we identified a relationship between the distance of the beaches from the city and the water quality present in them. Tupé and Lua beaches are further from the Manaus region, presenting the lowest density of fecal coliforms compared to Ponta Negra (Figure 3). Arcos et al. (2020), in a study conducted at Tupé beach, identified that water quality is related to seasonal periods in the region and the presence of boats and bathers at the study site. Furthermore, according to the authors, the same beach is suitable for sports and leisure activities, with direct contact with the water for recreational purposes. This variation in coliforms between seasonal periods was also observed in the present study, since the high water period of the Rio Negro provides an improvement in water quality, making it suitable for bathing.

The coastal region of the city of Manaus has been impacted by the discharge of untreated sewage, causing changes in water quality and potentially affecting the chemical and biological dynamics of this water body, the health of aquatic organisms, and the population that depends on it (Lages et al., 2007; Pinto et al., 2009; Santos et al., 2016). This diagnosis reflects the water quality of Ponta Negra beach, which, being the most frequented location compared to other beaches and being within the urban area, becomes a target for environmental problems related to basic sanitation. According to Alves (2018), the discharge of pollutants into water resources contributes to the deterioration of the environment. Furthermore, these anthropogenic alterations to the environment lead to the biological impoverishment of the environment (Piedade et al., 2014) and expose the population to waterborne diseases, especially bathers who frequent these environments.

The water level of the Negro River ranged from 28 to 28.6 meters in the flood season and from 19 to 23.3 meters in the dry season, indicating a larger water volume during flooding (Figure 4). River water level and volume directly affect environmental parameters and accordingly water quality. According to Pinto et al. (2009) and Falcão et al. (2021), abundant water dilutes pollutants in flood periods, which is also confirmed in this study of the three beaches.

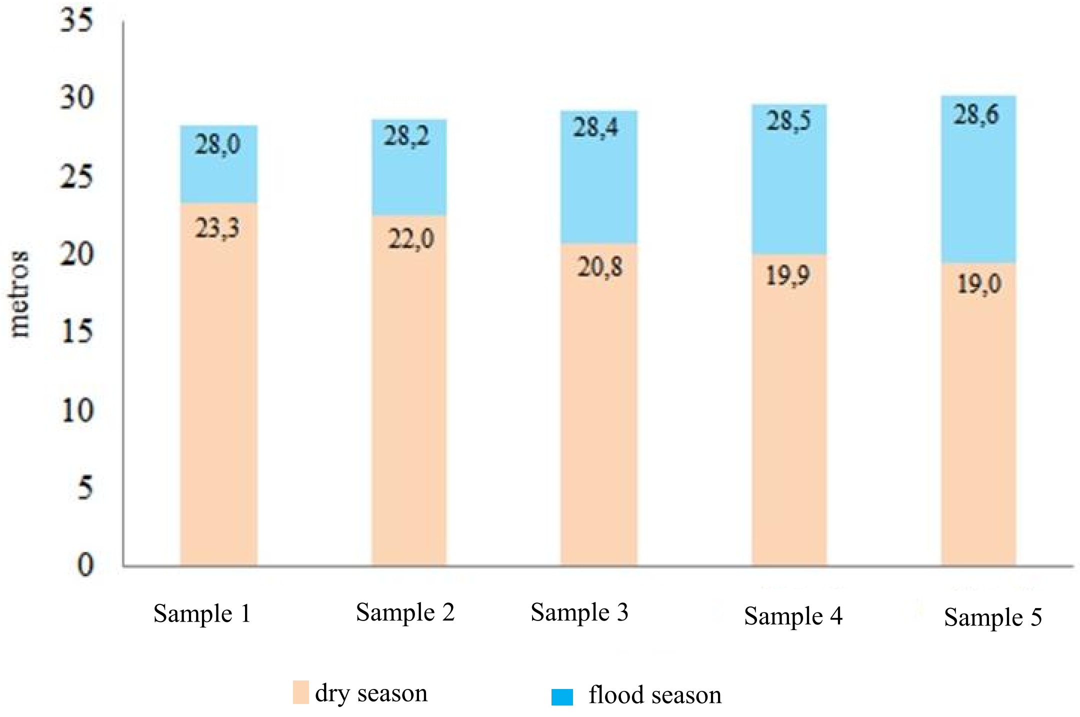

Figure 4. Level of the Negro River in the two seasonal periods.

Source: Authors.

The results of the Water Quality Index (WQI) revealed a gradient of decreasing water quality with proximity to the city of Manaus. Furthermore, water quality also varied across the local seasonal periods (flood and dry seasons). At Tupé

Beach, the WQI reached 83 during the flood season, classified as excellent, and dropped to 74 during the dry season, classified as good. At Lua Beach, the WQI was 80 during the flood season (classified as excellent) and 72 during the dry season (classified as good). Finally, Ponta Negra Beach presented a WQI of 81 during the flood season and 70 during the dry season, classified as excellent and good, respectively (Table 5; Figure 5).

The Water Quality Index has been increasingly applied in continental aquatic environment studies, as it effectively reflects the pollution level of water bodies used by local residents (Benetti & Bidone, 2001). WQI assessment of the studied beaches indicates the water suitability for public water supply. By comparing the findings with CONAMA Resolution No. 357/2005, water body classification and corresponding water treatment requirements can be determined.

Table 5. Water Quality Index (WQI) classification of Tupé, Lua, and Ponta Negra beaches during the two seasonal periods in the region.

Beaches	WQI (Water Quality Index)-Flood Season	
Tupé Beach	83	Excellent
Lua Beach	80	Excellent
Ponta Negra Beach	81	Excellent
Beaches	**WQI (Water Quality Index)-Dry Season**	
Tupé Beach	74	Good
Lua Beach	72	Good
Ponta Negra Beach	70	Good

Source: Authors.

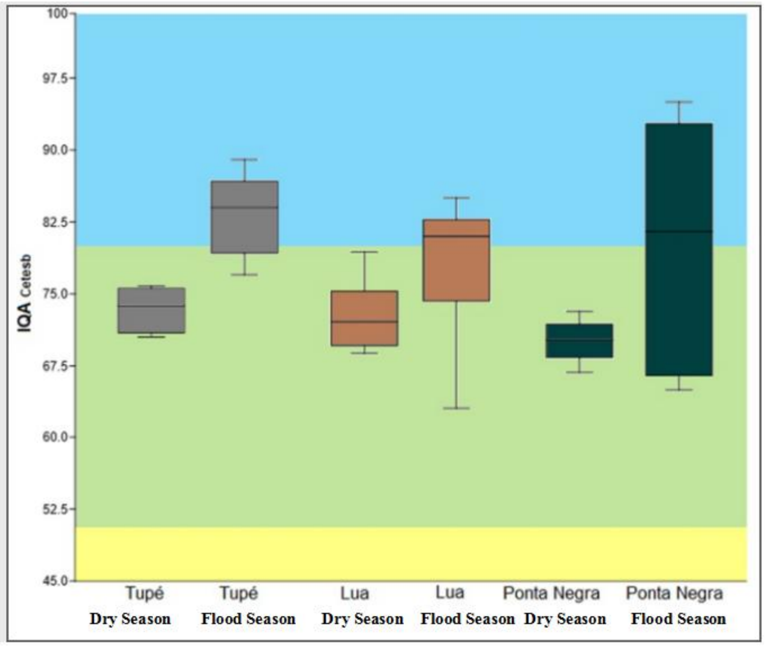

Figure 5. Boxplot of the water quality index (WQI) of the three beaches during the dry and flood seasons of the Negro River, Manaus, Amazonas.

Source: Authors.

WQI alone is insufficient to fully characterize water quality. Additional analyses are required, including, for example, assessments of heavy metals and pesticides. These parameters are not included in the WQI calculation, yet they can significantly impact river water quality, posing risks to both environmental and public health (Arcos et al., 2009). Efforts to develop regionally adapted water quality indices have already been underway in Amazonas, specifically for the Negro River. One study adjusted the pH parameter in the index equation, as the characteristic pH range of blackwater rivers in the Amazon varies between 3.5 and 5.5 (Bolson et al., 2008). That study reported excellent water quality for beaches distant from the city and good quality for those close to Manaus. These findings corroborate the WQI results of the present study for Tupé, Lua, and Ponta Negra beaches, which confirm the decline in water quality with increasing proximity to the city.

On the other hand, the revised WQI proposed by Bastos et al. (2016) yielded promising results along the waterfront of Manaus. The research indicated that the river can no longer withstand untreated solid waste and domestic sewage discharged from urban areas, leading to degradation of natural water conditions along the riverside. The Negro River has natural self-purification capacity, which enables it to dilute large amounts of pollutants. Nevertheless, continuous discharge of untreated sewage overloads this natural purification system, making it unable to restore water quality, particularly during the dry season. According to Palma-Silva et al. (2007), river self-purification facilitates nutrient cycling and pollutant dilution. It helps recover aquatic ecosystem balance after human interference and maintains recreational water suitability of local waters.

Rapid urbanization has placed immense pressure on water resources. Environmental monitoring systems are therefore essential for environmental assessment, pollution control and the development of targeted solutions. In addition, strategies for the restoration and remediation of degraded areas are required to improve ecological and public health. According to Guedes (2011), the misconception that water is an abundant and inexhaustible resource discourages conservation efforts and rational water use. Furthermore, numerous studies have documented low, moderate and high levels of contamination in groundwater, lakes, streams and the Rio Negro along the banks of Manaus (Costa et al., 2004; Arcos et al., 2018; Falcão et al., 2021; Souza Filho et al., 2020; Lages et al., 2022).

4 Conclusion

Tupé Beach and Lua Beach maintain suitable bathing conditions year-round, regardless of high or low water levels, posing no health or safety risks to swimmers. In contrast, Ponta Negra Beach recorded high levels of faecal coliforms during the low-water season of the Rio Negro, rendering it unfit for bathing at that time. Overall, water quality is largely governed by the water level fluctuations of the Rio Negro, which dilute potential pollutants and act as a natural regulating factor.

The Water Quality Index (WQI) for the three beaches was rated excellent and good, though water quality declined during the dry season. Furthermore, the closer the beaches are to the city, the more pronounced the impacts on water quality, which in turn lowers WQI values and downgrades their classification. Both the public and regulatory authorities must be informed of the bathing suitability conditions at these beaches. This knowledge is critical to implementing measures that block potential pollution sources, as well as pressing the responsible agencies to establish a continuous monitoring system. The general population should also be educated on the potential health risks associated with using these beaches for recreation and direct water contact.

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Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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