limnological review

Article

Influence of Anthropogenic Activities on the Water Quality of an Urban River in an Unplanned Zone of the Amazonian Coast

Luci Cajueiro Carneiro Pereira [1], Natália do Socorro da Silva Sousa [1], Brenda Ribeiro Padilha da Silva [1], Ana Lucia Biondo da Costa [1], Francielle Raquel Baltazar Cavalcante [1], Laiane Maria dos Santos Rodrigues [1] and Rauquírio Marinho da Costa [2,*]

1 Laboratory of Coastal and Estuarine Oceanography, Institute of Coastal Studies, Universidade Federal do Pará, Alameda Leandro Ribeiro sn, Aldeia, Braganca-Pará 68600-000, Brazil; cajueiro@ufpa.br (L.C.C.P.); nataliasousa89@yahoo.com.br (N.d.S.d.S.S.); brenda.ribeirops@gmail.com (B.R.P.d.S.); anabiondo.costa@gmail.com (A.L.B.d.C.); franciellercavalcante@gmail.com (F.R.B.C.); laianemsrodrigues@gmail.com (L.M.d.S.R.)

2 Laboratory of Plankton and Microalge Cultivation, Institute of Coastal Studies Universidade Federal do Pará, Alameda Leandro Ribeiro sn, Aldeia, Braganca-Pará 68600-000, Brazil

* Correspondence: raucosta@ufpa.br

Abstract: The database on water quality in Amazonian rivers located in unplanned urbanized regions along the Brazilian Amazon Coast is still quite limited. This study addresses these concerns, and the tested hypothesis was that the water quality of the Cereja River has deteriorated in recent years, despite the efforts of government authorities to mitigate anthropogenic impacts. To assess changes in water quality, seven campaigns were conducted, collecting data at six fixed points during two different periods. High-resolution satellite images were used to document unplanned occupation. Unfortunately, the number of houses along the Cereja River has increased, in violation of the law. This has contributed to the river's intense trophic condition, lower dissolved oxygen concentrations, higher concentrations of pathogenic bacteria, and loss of vegetation cover. According to national water quality standards, the Cereja is unsuitable for any human use. This is in stark contrast to the scenario a few decades ago when the river was used for leisure, fishing, and other activities. The results obtained confirm the initial hypothesis and can support potential management strategies and decision-making by authorities. The observed scenario can be extrapolated to other rivers located in urban areas in the Amazon region that have similarly regrettably experienced relatively uncontrolled growth.

Keywords: sewage; population growth; pathogenic bacteria; DPSWR; Amazon coast

Citation: Pereira, L.C.C.; Sousa, N.d.S.d.S.; Silva, B.R.P.d.; Costa, A.L.B.d.; Cavalcante, F.R.B.; Rodrigues, L.M.d.S.; Costa, R.M.d. Influence of Anthropogenic Activities on the Water Quality of an Urban River in an Unplanned Zone of the Amazonian Coast. *Limnol. Rev.* **2023**, *23*, 108–125. https://doi.org/10.3390/limnolrev23020007

Academic Editor: Daniel Constantin Diaconu

Received: 3 August 2023
Revised: 29 August 2023
Accepted: 3 September 2023
Published: 6 September 2023

1. Introduction

Contamination by pathogenic bacteria is among the most frequent motives for the prohibition of access to rivers worldwide [1–3]. Adequate river management is crucial, given that high levels of bacterial contamination may represent a risk to the health of bathers, non-contact recreational users, and the consumers of raw or undercooked food that has come into contact with the river water [4,5]. These pathogenic bacteria include coliforms and enterococci, which can cause serious illnesses, such as gastroenteritis and diarrhea. The positive correlation between the density of these enteric bacteria and the occurrence of gastrointestinal diseases has been used as an indicator of the presence of pathogenic microorganisms in aquatic environments, especially in waters used for recreational purposes [6]. Unplanned urban growth may contribute to the proliferation of these microorganisms due to the absence of adequate municipal services, in particular public sanitation services and sewage treatment facilities [7]. In this context, contamination may occur through both specific sources, such as untreated sewage, and more general input from urban activities, industrial effluents, dry weather washout from storm sewers, and associated sewer overflows [1,8,9].

Understanding the use of water and its potential relationship with human activities is fundamental to the development of strategies for local water management policies [10]. Domestic effluents and other residues may cause substantial changes in the quality of the water of an aquatic environment in terms of hydrological indicators and its trophic state [11]. The analysis of pathogenic bacteria, hydrological variables, and the trophic state of the system is essential for the evaluation of water quality and the proposal of effective management measures.

Given its enormous size, Brazil presents considerable regional diversity in economic conditions and sanitation infrastructure, with only 40% of the sewage generated nationally being treated adequately [12]. The Brazilian National Environment Council (CONAMA) regulates the criteria used to classify water resources and establishes standards for the evaluation of aquatic environments and freshwater resources. In particular, the concentrations of thermotolerant coliforms and enterococci, and other hydrological variables are used as indicators of water quality, to determine the aptness of aquatic resources for different uses, including drinking water for humans and livestock, the preservation of aquatic environments and their biota, recreational activities, irrigation, aquaculture and fisheries, and navigation.

The database on water quality in Amazonian rivers located in unplanned urbanized regions along the Brazilian Amazon Coast is still quite limited. Some notable works include [13], which studied the levels of environmental degradation, including water quality, in the Caeté Hydrographic Basin; [14], which investigated the impact of anthropogenic activities by comparing water quality and fish larvae communities in two creeks that flow into the Guamá River; in [15], the authors examined the effects of the lack of sanitation and other human activities on water quality in the micro-watershed of the Ouricuri River; the authors of [16,17] studied the evolution of contamination by thermotolerant coliforms in the estuary of the Caeté River; and those of [18] conducted a review demonstrating the effects of increasing demographic, urban, and land development pressures, as well as governance issues, on basin-wide and deltaic environmental deterioration in the Amazon River Delta and the Amazon-Influenced Guianas Coast.

In order to enhance understanding of water quality in urban rivers situated within unplanned areas along the Amazon coast, the Cereja River in the city of Bragança was selected for this study. With an estimated population of 128,914 inhabitants [19], the town of Bragança, located in the North region of Brazil, lacks a proper basic sanitation system due to the lack of investments in infrastructure, municipal services, and territorial planning. Specifically, the town lacks a sewage collection system, regular garbage collection, as well as drinking water and sewage treatment plants. While the town's population grows at a rate of 2.1% per annum, the municipality does not implement any housing programs to support the underprivileged sectors of the local population. Consequently, these sectors tend to settle in environmentally protected areas through unregulated settlements [17]. As a result, local water resources, including the Cereja River (which runs through much of the more densely-populated sectors of Bragança), are being increasingly impacted [13,20].

Given these problems, this present study focuses on the Cereja River, a tributary of the Caeté estuary, and a Permanent Preservation Area (PPA) according to the Federal law number 12,651/2012 [21]. This law prohibits the occupation of river margins to ensure the "preservation of water resources, the landscape, geological stability and biodiversity, in order to guarantee the gene flow of the fauna and flora, the protection of the soil, and the welfare of local human populations" (Article 3, item II). In recent decades, however, the water of the Cereja River has been compromised profoundly by the illegal occupation of its margins and the discharge of raw sewage directly into the river [22].

The present study tested the hypothesis that the quality of the water of the Cereja River has worsened significantly over recent years, despite the efforts of government authorities to mitigate anthropogenic pressures. To achieve this, the study assessed spatial and temporal changes in the quality of the water of the Cereja River, comparing data from 2013–2014 with those available for 2018–2019. To evaluate water quality for direct or indirect use, we employed the current Brazilian legislation, used international classification criteria for water quality and examined the Master Plan of the municipality to verify the effects of unplanned urban growth. We also adopted the DPSWR (Driver-Pressure-State-Welfare-Response) socioecological framework to identify potential measures for the management of environmental and anthropogenic problems [23].

The results obtained will provide valuable insights for government authorities to take action in mitigating the identified impacts. It is hoped that the results of the study can provide important guidelines for further research in equivalent fluvial environments under similar anthropogenic pressures.

2. Study Area

The Cereja River is located in Bragança, a town in the Northeast mesoregion of the Brazilian state of Pará, which has approximately 128,914 inhabitants [19]. The source of this river is located outside the urban zone of Bragança, and it crosses the town from West to East, flowing through the neighborhoods of Vila Sinhá, Taíra, Alegre, Padre Luiz, Centro, and Aldeia. The waters of the Cereja River run through 11 of the 12 official neighborhoods that are located partially within its drainage basin, which has an area of approximately 10 km^2 (Figure 1). The principal course of the river is approximately 5 km long, with a mean depth of 1.4 m [24]. The mouth of the Cereja River is located in a mangrove area and its waters flow into the Caeté River estuary [17].

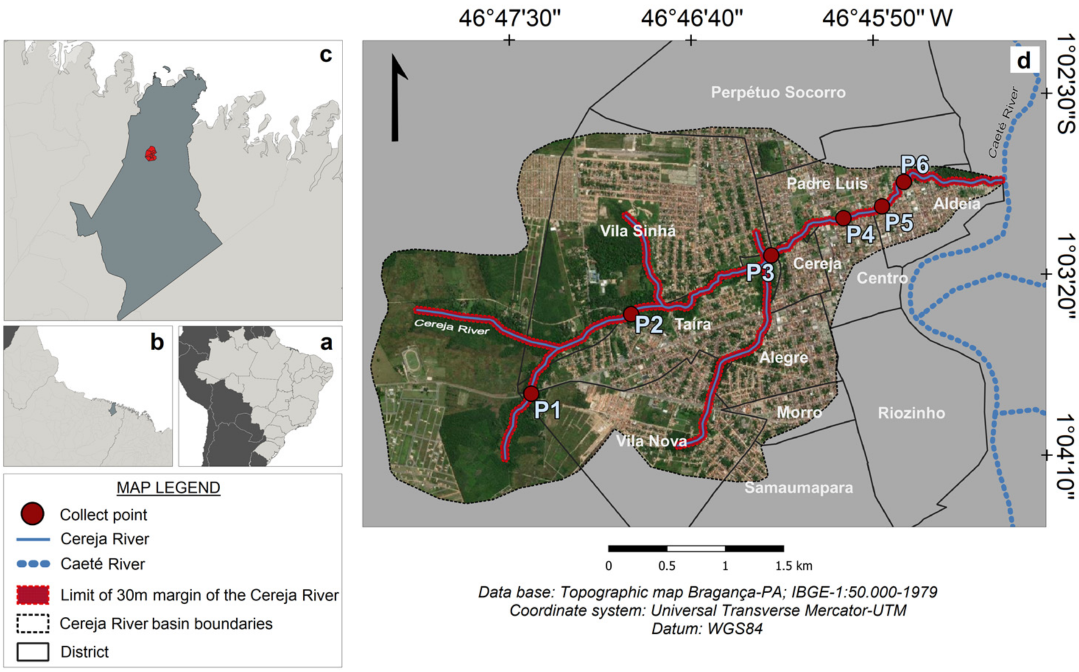

Figure 1. Map of the study area, showing (**a**) Brazil, (**b**) the coast of the state of Pará, (**c**) the municipality of Bragança and (**d**) the microbasin of the Cereja River.

The study region has a humid equatorial climate, characterized by high levels of rainfall, with annual rainfall of over 2000 mm marked by two well-defined seasons: the dry season and the rainy season [25]. Approximately 85% of the rainfall occurs during the rainy season, which typically corresponds to the first semester [26]. In addition, there are no data available on the discharge of this small river. However, data obtained by the National Water Agency [27] show a marked seasonal pattern of river discharge in the neighboring Caeté River estuary, with a 65% higher river discharge in the first half of the year. During the rainy season, the level of the Cereja River rises to 1.5 m above the mean levels of its bed, which often causes flooding and other impacts [28].

Uncontrolled urban growth and the unplanned occupation of the margins of the Cereja River have led to the widespread and uncontrolled discharge of domestic effluents and solid waste into the river [24–29]. According to the data provided by the Brazilian Institute of Geography and Statistics [19], the population of the municipality of Bragança is currently growing at a rate of approximately 2.1% per annum. This exacerbates the long-standing socio-environmental problems associated with the lack of basic sanitation. Figure 2 shows the loss of vegetation associated with erosion on the banks (A–C), unplanned occupation (C–E), the presence of aquatic plants indicating high trophic status (E) and the presence of solid waste (D,F). Each photo represents a collection point, from P1 (A) to P6 (F).

Figure 2. (**A**) sampling at P1, near the source of the Cereja River; (**B**) P2; (**C**) P3; (**D**) P4; (**E**) P5; (**F**) P6, near the mouth of the Cereja River.

3. Methods

Data on rainfall and population growth were obtained from public institutions, while hydrological and microbiological data were collected during fieldwork. A total of six sampling points were selected in the different neighborhoods of Bragança city, where samples were gathered during the rainy and dry seasons of 2013–2014 and 2018–2019. High-resolution satellite images from GoogleEarth (2012 and 2019) were used to verify unplanned occupation of land.

3.1. Rainfall Data

Rainfall data were obtained from (INMET—National Institute of Meteorology, Tracuateua meteorological station) for the study period, and for 1982–2019 (historical means). The Tracuateua station is 17 km west of Bragança, at 36 m above sea level. The monitoring of rainfall patterns is essential for the understanding of natural oscillations in hydrological variables and their possible influence on water quality and microbiological contamination.

3.2. Field Survey

The samples were collected during two distinct periods (2013–2014 and 2018–2019) to assess changes in the quality of the water of the Cereja River over time. Seven campaigns were undertaken, four during the dry season (November 2013; August 2014; November

2018; July 2019) and three during the rainy season (April 2014; June 2018; April 2019), with data being collected at six fixed points (Supplementary Materials—Table S1). A total of 126 samples were collected (42 samples for the measurement of pH, turbidity, and chlorophyll-a, 42 samples for the measurement of dissolved oxygen concentrations, and 42 samples for the evaluation of microbiological variables). Surface water samples were collected near the margin of the river at six points using a Niskin bottle. Once collected, the samples were stored in 250 mL polyethylene containers or glass flasks for laboratory analysis, following the APHA (American Public Health Association) protocol [30].

3.3. Laboratory Procedures

The water samples were vacuum-filtered through glass-fiber filters (Millipore GF/F 0.7 mm, 47 mm) and freeze-dried for the analysis of chlorophyll-a. The pH was determined by a HANNA pH meter (HI2211), and a HANNA turbidimeter (HI 93703) was used to measure turbidity. The concentrations of dissolved oxygen (DO) were obtained, according to the method described by Winkler, as modified by [31]. The chlorophyll-a was extracted from the filters with 90% acetone *v.v.* and the concentration was determined by spectrophotometry, following [32,33].

The TSI (Trophic State Index) was used to calculate the level of eutrophication of the Cereja River based on its biological productivity. This index was developed by [34] and modified by [35]. The used formula was $TSI (Chla) = 10 \times \{6 - [-0.7 - 0.6 \times (\ln Chla)/\ln 2]\} - 20$, where, ln Chla is the Napierian logarithm of the concentration of chlorophyll a. The water quality was classified in six categories: ultraoligotrophic ($TSI \leq 47$), oligotrophic ($TSI = 47 < TSI \leq 52$), mesotrophic ($52 < TSI \leq 59$), eutrophic ($59 < TSI \leq 63$), supereutrophic ($63 < TSI \leq 67$), and hypertrophic ($TSI > 67$).

The method used to determine thermotolerant coliform levels was based on the inoculation of samples in both sodium lauryl sulphate (presumptive test) and brilliant green broths (confirmatory test) with posterior incubation for 48 h at 35 ± 2 °C. The positive samples were then inoculated in *Escherichia coli* (EC) selective broth for 24–48 h at 45 ± 0.2 °C. In both procedures, the presence of bacteria was confirmed by the cloudiness of the water and the formation of gas in the Durham tubes [30]. The *Enterococcus* sp. levels were analyzed by membrane filtration using the membrane-*Enterococcus* Indoxyl-ß-D-Glucoside Agar (mEI) method [36]. This consists of the direct counting of the bacteria in a selective medium (mEI agar). All the detected colonies greater than or equal to 0.5 mm in diameter were counted for further enumeration.

The quality of the water was evaluated based on the CONAMA resolutions [37,38], [35] and [39]. Freshwater is classified according to the type of use by CONAMA resolutions as shown in the Supplementary Materials (Supplementary Materials—Table S2).

3.4. Unplanned Occupation

The mapping of areas of unplanned occupation on the margins of the Cereja River basin consisted of four phases: (i) the capture of high-resolution satellite images from Google Earth; (ii) the assemblage of image mosaics for 2012 and 2019; (iii) creation of the interpretation key for the visual classification of the images, and (iv) formulation of the database and geoprocessing using the software QGIS 3.16.0 © (Figure S1). When necessary, in loco verification was also conducted to validate the data from satellite images.

The total population of the Cereja River basin area was estimated by multiplying the number of properties by the size (individuals) of the mean household in the North region of Brazil, i.e., 4.3 people per household, following IBGE data from 2020 [19]. "Unplanned" occupation was defined as any property located within the 30-m buffer surrounding the margins of the Cereja River, which is considered to be a Permanent Protection Area (PPA) under the Federal law 12,651/2012 [21].

3.5. Sewage Production per Capita

The production of sewage by the inhabitants of each neighborhood bordering the Cereja River was estimated for 2012 and 2019 following the method of [40]. Each individual produces 150 L of sewage per day in urban areas and is responsible for releasing 100–400 billion thermotolerant coliforms into the environment.

3.6. Statistical Analysis

For the statistical analyses, the data were first evaluated for normality using the Anderson–Darling test [41], which has a strong statistical power to determine whether a sample was extracted from a population with a specific distribution [42]. Levene's F test [43] with a 95% Bonferroni confidence interval was applied to verify the homogeneity of variances. The parametric one-way Analysis of Variance (ANOVA) and paired t-test were applied to the variables that complied with the assumptions of normality and homogeneity of variances. Otherwise, the nonparametric Welch ANOVA [44] was used. The paired t-test was used to compare mean values between years [45]. Spearman correlation coefficients were calculated to examine the influence of rainfall levels on the variables under analysis. All statistical tests were conducted using IBM SPSS software v. 25.

Principal Component Analyses (PCAs) were run in R Studio v 1.2.5, based on a correlation matrix generated by the FactorMineR package. The plots were subsequently created and edited using the Factoextra package [46]. To enhance data visualization, three sectors were established for the spatial PCA, based on the number of households present in 2019 (see Results): sector I (<30 households, sampling points P1 and P2), sector II (30–50 households, P3), and sector III (>50 households, P4–P6).

4. Results

4.1. Rainfall Levels

The historical mean annual rainfall (1982–2019) was 2330 mm (Figure 3). The driest year of the present study was 2013 (1612 mm), while the rainiest was 2019 (3512 mm), which was 151% higher than the historical mean (T = 2.36; $p = 0.015$, Table 1). The rainy season corresponds to the first half of the year; however, rainfall levels in the first half of 2013 were nearly 50% lower than in 2019. Furthermore, in 2013, the rainfall period was shorter and concentrated mainly between March and May (~300 mm per month), whereas in 2019, the rainiest months were from February to June (440–660 mm per month). Two distinct seasons (rainy and dry) were identified (F = 80.51; $p = 0.000$, Table 1), with April 2014 (total rainfall = 432 mm), April 2018 (410 mm), June 2018 (115 mm), and July 2019 (182 mm) corresponding to the rainy season, and November 2013 (1 mm), August 2014 (50 mm), and November 2018 (1 mm) to the dry season (Figure 3).

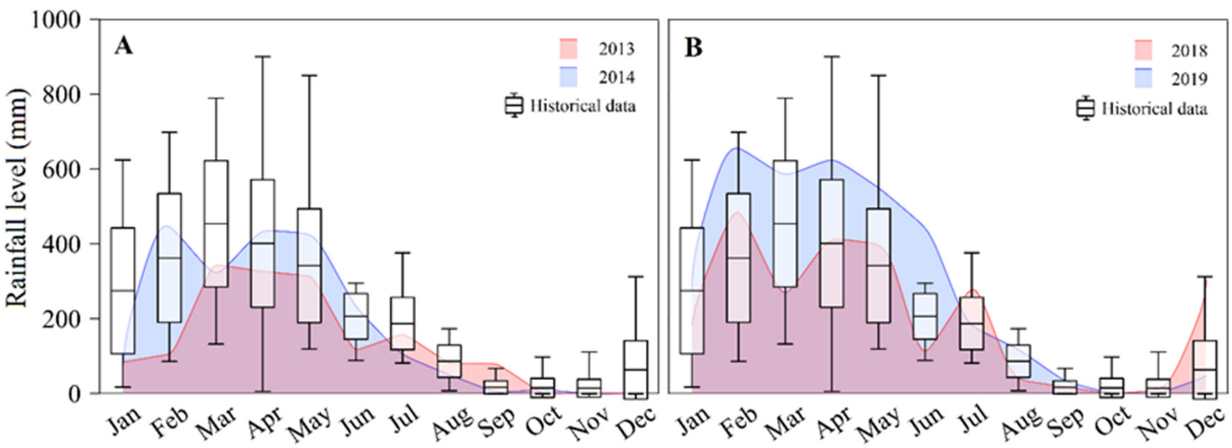

Figure 3. Historical mean and standard deviation of monthly rainfall (1982–2019), and monthly rainfall values recorded in 2013–2014 (**A**) and 2018–2019 (**B**). Source: [26].

Table 1. Significant effects (*p*-values) of physical, chemical, and biological parameters in the Cereja River, interannually (2013–2014 and 2018–2019), seasonally (rainy and dry), and spatially (P1–P6). In the interannual analysis, June/2018 and July/2019 were merged in the dataset to assure monthly row equivalence after similarity tests. Values of $p < 0.05$ mean significant differences.

Variables	Interannual (N = 36)	Seasonal (N = 42)	Spatial (N = 42)
Rainfall	$t = 2.36$ $p = 0.015$	$F = 8.051$ ** $p = 0.000$	---
Ph	$t = -4.73$ $p = 0.000$	$F = 0.30$ ** $p = 0.589$	$F = 1.13$ * $p = 0.360$
Turbidity	$t = 1.60$ $p = 0.063$	$F = 4.72$ ** $p = 0.040$	$F = 9.34$ ** $p = 0.000$
Dissolved oxygen	$t = 4.59$ $p = 0.001$	$F = 22.75$ * $p = 0.000$	$F = 10.54$ ** $p = 0.000$
Chlorophyll-a	$t = 2.68$ $p = 0.008$	$F = 4.37$ ** $p = 0.043$	$F = 0.93$ * $p = 0.471$
Coliforms	$t = 1.32$ $p = 0.102$	$F = 1.79$ * $p = 0.188$	---
Effluents	$t = 5.17$ $p = 0.000$	---	---

--- Not applicable; * ANOVA One-Way; ** ANOVA Welch.

4.2. Hydrological Variables

The mean pH (Figure 4A) was significantly higher in 2013–2014 in comparison with 2018–2019 ($T = -4.73$; $p = 0.000$, Table 1) with a peak mean of 6.8 ± 0.3 at P5, and lower values at P1 (5.8 ± 0.8). Seasonally, the highest mean pH was recorded during the dry season (P6, 6.8 ± 0.2) and the lowest in the rainy season (P1, 6.0 ± 1.3; Figure 5A). Overall, 88% of the samples complied with CONAMA standards (Supplementary Materials—Table S3).

The waters of the Cereja River were more turbid in 2018–2019 (Figure 4B), with the peak mean turbidity being recorded at P6 (47.8 ± 51.8 NTU), while the least turbid water was recorded in 2013–2014, with the minimum value being obtained at P1 (0.6 ± 0.5 NTU). Seasonally, the most turbid water was recorded in the rainy season ($F = 4.72$; $p = 0.04$, Table 1) with a peak mean being recorded at P6 (55.3 ± 59.6 NTU, $F = 9.34$; $p = 0.000$, Table 1), while the least turbid water was recorded in the dry season, with the lowest values being recorded at P1 (0.7 ± 0.6 NTU, Figure 5B). Overall, 98% of the samples complied with CONAMA standards on turbidity (Table S3).

The lowest mean dissolved oxygen concentrations (Figure 4C) were recorded in 2013–2014 ($T = 4.59$; $p = 0.001$, Table 1), with the lowest value being recorded at P1 (1.8 ± 0.0 mg L^{-1}). The highest values were recorded in 2018–2019, in particular at P3 (4.8 ± 1.0 mg L^{-1}). Seasonally (Figure 5C), the most oxygenated water was recorded during the rainy season ($F = 22.75$; $p = 0.000$, Table 1), with a peak at P3 (4.8 ± 0.7 mg L^{-1}, $F = 10.54$; $p = 0.000$), while the lowest concentration was recorded in the dry season at P1 (2.0 ± 0.2 mg L^{-1}). Only 17% of the water samples had dissolved oxygen concentrations consistent with CONAMA's water use class 2, while 21% were considered hypoxic and 60% indicative of conditions of oxygen stress in the biological community (Table S3).

The mean chlorophyll-a concentrations peaked at 18.8 ± 9.3 mg m^{-3} (at P6) in 2018–2019 ($T = 2.68$; $p = 0.008$, Table 1), and were the lowest in 2013–2014, reaching 5.1 ± 3.8 mg m^{-3} at P1 (Figure 4D). The water was significantly richer in chlorophyll-a during the rainy season ($F = 4.37$; $p = 0.043$, Table 1), primarily at P6 (18.2 ± 12.1 mg m^{-3}; Figure 5D), while the lowest values were recorded in the dry season, reaching 6.9 ± 3.8 mg m^{-3} at P5. Just over half (57%) of the samples had chlorophyll-a concentrations consistent with CONAMA's water use class 1 (Table S3).

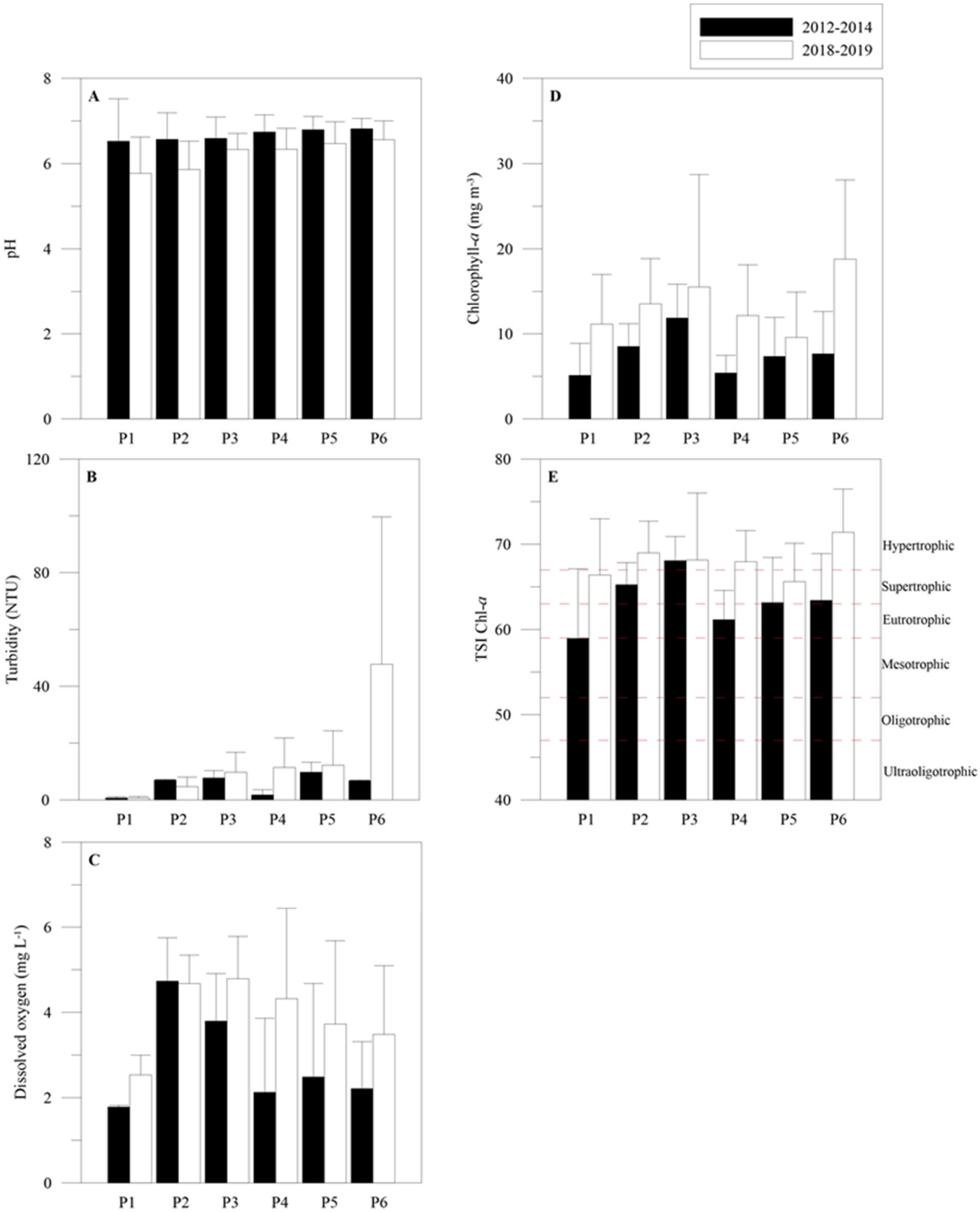

Figure 4. Interannual (mean and standard deviation) of pH (**A**), turbidity (**B**), dissolved oxygen (**C**), chlorophyll-a (**D**) and TSI (**E**) variables per sample point (P1–P6) on the Cereja River. The dashed line represents the upper limit of each TSI classification.

4.3. Microbiological Analysis

Over 90% of the water samples presented thermotolerant coliform levels of 1100 MPN 100 mL^{-1} or more, which is the threshold recommended by CONAMA for most types of water use (Supplementary Materials—Tables S4 and S5). Site P1 was the only sector with appropriate conditions for most types of water use during the dry season, when values did not exceed 240 MPN 100 mL^{-1}. The other sectors were impacted intensely by sewage outfalls, however, with up to 90.5% of the samples from the most contaminated points having coliform concentrations of 1100 MPN 100 mL^{-1} or more.

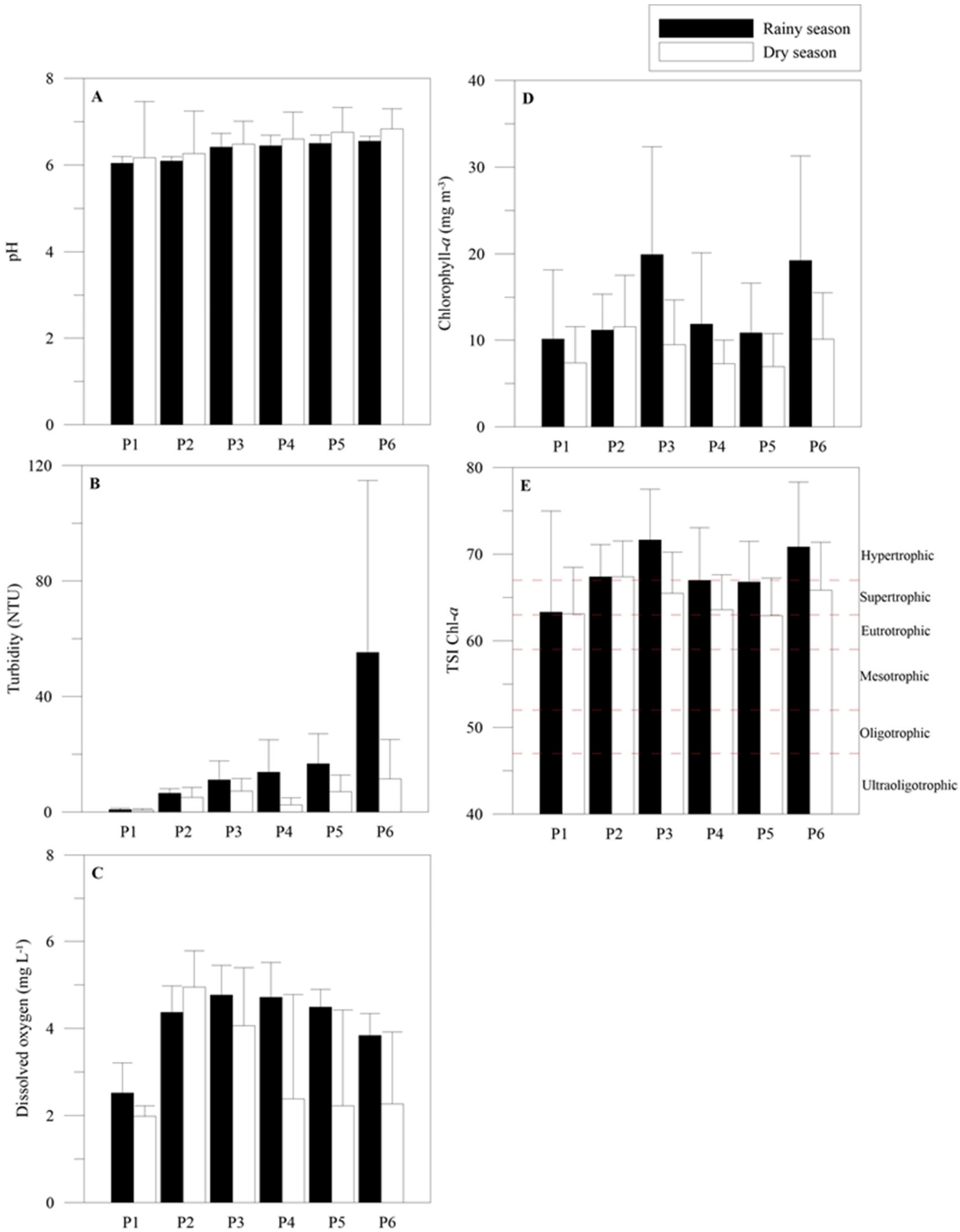

Figure 5. Seasonal (mean and standard deviation) of pH (**A**), turbidity (**B**), dissolved oxygen (**C**), chlorophyll-a (**D**) and TSI (**E**) variables per sample point (P1–P6) on the Cereja River. The dashed line represents the upper limit of each TSI classification.

As the *Enterococcus* levels were only analyzed in 2018–2019, it was not possible to compare years (Table S4). However, the findings did show that the quality of the water at P1 was relatively good (0–101 MPN 100 mL^{-1}) in comparison with the other points, peaking at P5 and P6 (generally ~500 MPN 100 mL^{-1}). As CONAMA does not provide a value for this bacterium, the bacterial water quality criteria were adopted in line with USEPA [47]. According to these criteria, 93% of the water samples analyzed were inappropriate for recreational contact (Table S5), and water use would only be permitted at P1 during the periods with the lowest rainfall levels.

4.4. Trophic State Index (TSI)

The water of the Cereja River had a significantly higher trophic level in 2018–2019 (T = 5.17; p = 0.000), peaking at 71.4 ± 5.1 (hypertrophic) at P6 (Figure 4E). In 2013–2014, the lowest values were recorded at P1 (59.0 ± 8.2—eutrophic), and the highest at P3 (68.1 ± 2.8—hypertrophic). The highest mean values were recorded during the rainy season (Figure 5E), peaking at P6 (70.8 ± 6.1—hypertrophic) and reaching their lowest level at P1 (63.3 ± 11.7—super-eutrophic). During the dry season, the highest values were recorded at P2 (67.4 ± 4.1). Overall, 78% of the samples were classified as eutrophic, super-eutrophic or hypertrophic (Table S3).

4.5. Unplanned Occupation

The number of unplanned constructions identified within the PPA increased 18% between 2012 and 2019, with the highest growth rates being recorded in Vila Nova (P1, 54%) and Vila Sinhá (P2, 37%), while the most populous sectors were Padre Luiz (P4) and Aldeia (P5, P6). In 2019, a total of 318 constructions were recorded on the margins of the Cereja River within the PPA, with an estimated 1369 inhabitants (Table S6). The vegetation cover in the PPA was 0.37 km^2 in 2012 and 0.34 km^2 in 2019, with approximately 4% of this area being lost due to unplanned occupation (Table S7).

Within the Cereja River PPA, in 2019, the greatest volume of domestic effluents was estimated in Padre Luiz (P4, 60.6 m^3 day^{-1}), Aldeia (P5, P6, 35.5 m^3 day^{-1}), Cereja (27.1 m^3 day^{-1}), and Taíra (P3, 25.8 m^3 day^{-1}), with a total of 151.6 m^3 day^{-1}. The quantity of effluent estimated in 2019 was 18% greater than in 2012. This resulted in the highest thermotolerant coliform concentrations being esimated in these neighborhoods in 2019 (Table S6), that is, 1.62 MPN 100 mL^{-1} ($\times 10^{14}$) in Padre Luiz, 0.95 MPN 100 mL^{-1} ($\times 10^{14}$) in Aldeia, 0.79 MPN 100 mL^{-1} ($\times 10^{14}$) in Cereja, and 0.69 MPN 100 mL^{-1} ($\times 10^{14}$) in Taíra. Given the increase in unplanned occupation in Vila Nova (P1), an increase of 54% was estimated in the volume of domestic effluents at this point in 2019.

4.6. Integration of the Water Quality Indicators

The first two axes of the Principal Components Analysis (PC1 and PC2) explained 49.1% of the variability in the dataset, with 31.4% and 17.7%, respectively (Figure 6). Axis PC1 was positively related with turbidity (0.67), dissolved oxygen (0.62), chlorophyll-a (0.64), and coliform concentrations (0.64). Effluents (0.50) and pH (0.81) also presented a strong positive correlation with all of these variables in quadrant I. By contrast, PC2 presented a strong correlation with dissolved oxygen concentrations (−0.55) and rainfall (−0.69), clustering in quadrant II.

Seasonally, the variables were grouped with the rainy season (Figure 6A), indicating a slightly acidic water, which was relatively turbid, well-oxygenated, and rich in chlorophyll-a. A similar pattern was recorded between years, with all the variables grouped with the 2018–2019 period (Figure 6B) due to a longer rainy season. Coliform levels and effluent production were also higher in the second study period, due to population growth over time. Spatially (Figure 6C), the most urbanized area (sector III, P4-P6) clustered with the highest values of pH, turbidity, chlorophyll-a, coliforms, and effluents. This indicates that these neighborhoods maintain the highest values of these variables between seasons and among years.

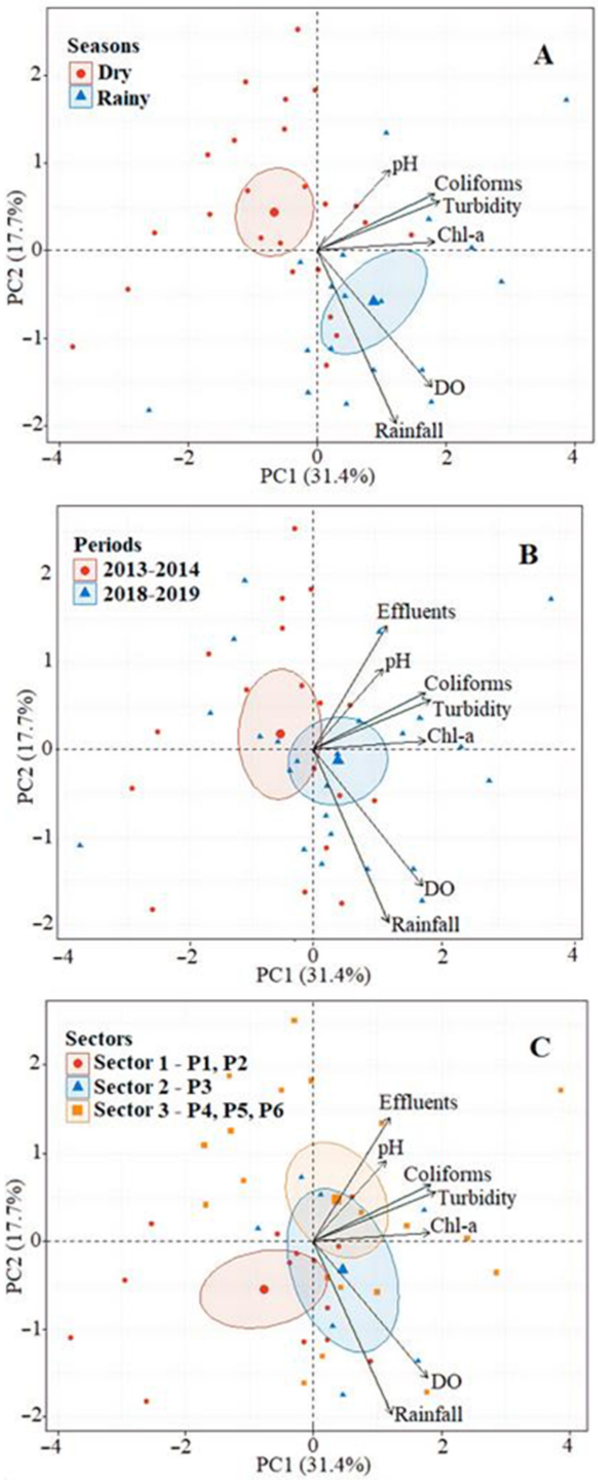

Figure 6. Seasonal correlation observed in the Principal Component Analysis (axes PC1 vs. PC2) among the abiotic variables of the water of the Cereja River. The ellipses represent the seasonal (**B**), interannual (**A**), and sector (**C**) clusters.

5. Discussion

5.1. Natural Conditions, Anthropogenic Activities, and Management Concerns

Oscillations in rainfall levels are one of the principal factors that determine seasonal shifts in the physicochemical and hydrobiological parameters of riverine systems [48]. The PCA analysis confirmed that rainfall plays a significant role in driving changes in the studied parameters. It resulted in the grouping of all variables with the rainy season (for seasonal analysis) and with the period of 2018–2019 (for the analysis of the interannual period), primarily due to an extended rainy season (Figure 6). However, anthropogenic activities were responsible for deteriorating water quality in the Cereja River, and several indicators were used to demonstrate this. The variables studied will be discussed below, taking into account both natural and anthropogenic conditions.

Among the studied variables, the pH is one of the most important for the evaluation of water quality, because it indicates specific conditions and alterations [49,50]. In the present study, the water was slightly acidic with lower pH values being recorded during the second period (2018–2019), as a consequence of the more prolonged rainy season, which resulted in a major increase in the input of freshwater in comparison with 2013–2014. The discharge of sewage into a river also tends to reduce its pH [50,51], and the increased production of effluents recorded in 2019 (18% greater than 2012) may also have contributed to the decrease in pH values during the 2018–2019 period. The presence of an area of better-preserved habitats at the headwaters of the Cereja River may also have favored the lower pH values recorded in sector 1 (P1 and P2), due to the higher concentration of plant-based organic matter in the water, derived from the riparian vegetation and forest fragments upstream of P1, which contributes higher concentrations of humic acid, as reported by [49,52] in other Amazonian rivers.

Turbidity typically depends on the amount of particulate material suspended in the water and it is also considered to be an important indicator of water quality [53–55]. The turbidity of river water depends on natural conditions (e.g., rainfall patterns, river flow levels) and anthropogenic activities (e.g., effluent discharge, deforestation, mining). In the present study area, the water was relatively more turbid during the first half of the year, in particular in 2018–2019, due to the prolonged rainy season, although no systematic correlation was found between turbidity and precipitation. Even so, in Amazonian river systems, the increase in the water level during the rainy season and the related growth in fluvial discharge is known to intensify the re-suspension of sediments from the bottom into the water column [56,57]. Changes in land use associated with urbanization may also contribute to an increase in turbidity [58], and in the most urbanized sectors of the study area (sectors 2 and 3), the unregulated occupation of the margins of the river have resulted in shifts in the riparian vegetation, which has contributed to the erosion of the margins of the Cereja River, and a further increase in turbidity value in these sectors. Turbidity may also be influenced by urban runoff [59]. In the present study, the high levels of effluent discharge into the most urbanized sector of the river contributed to the highest turbidity being recorded in this sector, supported by their positive correlation ($r_s = 0.404$, $p < 0.008$, $n = 56$). In fact, excessive turbidity, in terms of the CONAMA criterion, was only recorded in sector P6. Meanwhile, the input of the turbid waters from the Caeté estuary may also have contributed to these high values, given the role of the extensive local mangroves and precipitation patterns in the sedimentary dynamics of an estuary controlled by meso-macrotides [57].

Dissolved oxygen is also considered to be a good indicator of water quality [59,60]. Under natural conditions, the waters of Amazonian rivers are well oxygenated, due to their high hydrodynamic energy, in particular during the rainy season [61]. This results in a combination of high water levels and more intense river flow, which increases the efficiency of the exchange between the atmosphere and surface waters. In the Cereja River, the highest values were recorded during the rainy season, when the water level was at its highest and the river flow was most intense, with a positive correlation being recorded between dissolved oxygen concentrations and precipitation ($r_s = 0.489$, $p < 0.001$, $n = 56$). Additionally, the local municipal authorities often dredge the river to clean it up during the raining, a process that contributes to an increase in fluvial discharge due to the greater depth of the river, which further enhances the interaction between the water and the atmosphere.

Unfortunately, the intense discharge of sewage into the river contributed to a reduction in the dissolved oxygen concentrations, which resulted in conditions of hypoxia

(0–2 mg L^{-1}) or oxygen stress for the biological community (2–5 mg L^{-1}). This is the result of the consumption of oxygen by bacterial decomposition, which is a response to the high concentrations of organic matter present in the environment [39,62,63]. While no correlation was found between dissolved oxygen concentration and the production of effluents, there was a significant correlation between dissolved oxygen and thermotolerant coliform concentrations (r_s = 0.338, p < 0.028, n = 56).

The discharge of untreated sewage contributes to eutrophication [11,64,65] and the density of phytoplankton is considered to be an important indicator of eutrophic environments [66]. In the study area, the discharge of sewage into the Cereja River appears to have contributed to an increase in the chlorophyll-a concentrations in the most urbanized sector through the proliferation of microalgae, which was reflected in a longitudinal gradient, with the lowest chlorophyll-a values being recorded in sector P1 and the highest in P6 (15% higher than P1, on average). The TSI, which is based on biological productivity, once again indicates that the highest trophic levels were recorded in the most urbanized sector in 2018–2019, reflecting the negative influence of population growth and the related increase in effluent discharge on the quality of the water of the Cereja River.

Effluent discharge also may affect human health due to presence of microorganisms [67–69]. The microbiological data indicate that the quality of the water of the Cereja River was already compromised in 2013–2014, and only worsened in 2018–2019. With the exception of sector P1, all the water samples exceeded the recommended limits for thermotolerant coliforms, whether measured or estimated, and *Enterococcus* sp. due to the large number of sewage outfalls within the study area. The discharge of untreated sewage into aquatic environments is strictly prohibited in Brazil by CONAMA [38] and in Pará by state law number 5887/1995 [70]. However, based on the CONAMA [37,38] and USEPA [47] criteria, the water of the Cereja River is inadequate for any type of human use, given that more than 90% of the water samples tested were contaminated with pathogenic bacteria. Previous studies have also shown that Cereja River is responsible for a considerable proportion of the sewage discharged into the Caeté estuary, given that the concentrations of thermotolerant coliforms at the confluence of these two bodies of water exceed 1100 MPN per 100 mL^{-1} [16,17,20]. Unfortunately, this is a common scenario in many rivers located in the vicinity of urban areas that have inadequate public sanitation or completely lack any infrastructure, resulting in an increase in the levels of human pathogens [67,71].

5.2. Application of the DPSWR, Management Actions, and Recommendations

The DPSWR was used to explain how human activities (Drivers) lead to environmental pressures (Pressure) that affect water quality (State) and how this has implications for the health and well-being of the local population (Welfare). In addition, response strategies were employed to address these environmental problems. Each component of this conceptual model was discussed below, and a schematic can be found in Supplementary Materials—Figure S2.

Rapid population growth associated with a lack of urban planning and inadequate investment in public sanitation are considered to be the principal drivers responsible for the discharge of large amounts of untreated sewage into urban rivers and the illegal occupation of their margins (Pressure). Considering the eight neighborhoods located on the margins of the Cereja River, the number of residences located illegally within the PPA increased by 18% between 2012 (261 households) and 2019 (318 households), while the discharge of effluents grew from 168 m^3 day^{-1} to 205 m^3 day^{-1}, an increase of about 18.1%.

Spatially, with the exception of sector P1, all the water samples exceeded the recommended limits for thermotolerant coliforms and Enterococcus sp. (State). These pathogenic bacteria can cause serious illnesses such as gastroenteritis and diarrhea (Welfare) through contact with water polluted by untreated sewage [4,5]. In fact, the number of cases of gastroenteritis and diarrhea in the neighborhoods bordering the Cereja River was high (>14,000 cases between 2010 and 2020), according to data provided by the Pará State Health Department (SESPA).

Rainfall is responsible for natural changes in hydrological variables, as discussed above, but when at a higher level it tends to exacerbate this situation, affecting both the State (water quality) and Welfare (human and environmental health). During the rainy season, for example, the Cereja River floods, and its water reaches the level of the sewage outfalls located on higher ground, while also lixiviating other substances into the soil, which leads to a further increase in the concentration of pathogenic bacteria (State). This reinforces the negative effects of the illegal occupation of river margins (Pressure), and increases the discharge of sewage (Pressure), which reached 205 m^3 per day in 2019.

Unplanned urbanization and urban growth (Drives) also affect land use and cover and lead to the erosion of the river margins (State), for example, which results in the siltation of the riverbed (State), as recorded in the present study, where illegal occupation (Pressure) is also associated with the loss of vegetation (State) [72,73]. While the urban development of river margins is strictly prohibited in Brazil by federal law 12,651/2012 (Response), failures to enforce this legislation were obvious, and 57 new residences were added to the PPA between 2012 and 2019.

In the most urbanized sectors of the study area, population growth was relatively low because the margins are already almost completely occupied, whereas in the least urbanized sectors, there was a considerable increase in the number of residences—53.8% in sector P1 and 36.4% in P2—which contributed to a decline in the quality of the water at the source of the Cereja River (State), based on all the different indices, in 2018–2019 in comparison with 2013–2014.

Despite being an area protected by Federal law, preservation measures on the Cereja River are limited to annual, but irregular dredging (Response), and warning signs on the margins of the river (Response), announcing the prohibition of unplanned occupation of the river margins. These measures are clearly inadequate, however, and some level of protection could be achieved if the measures proposed initially in the 2006–2016 municipal master plan (and transferred to the 2016–2026 master plan) were implemented systematically.

The findings of the present study lead us to recommend the following measures (responses)—the establishment of an effective public sanitation system that prevents the disposal of solid waste, including plastics, paper, and metal, leftover food, and human and animal excrement, directly into the rivers that traverse the urban sector of the town of Bragança, to inhibit the possible spread of disease, and prevent the risk of injuries, visual pollution, and the migration of floating debris on the Cereja River and Caeté Estuary.

In addition to this recommendation, education programs and more effective monitoring will be essential to prevent the unplanned occupation of the river margins. Appropriate planning of land use will also be essential to improve the local landscape and avoid potential conflicts.

6. Conclusions

Rapid population growth without adequate urban planning and insufficient investment in infrastructure have placed immense pressure on the Cereja River in recent years. The increase in riverside households has led to severe trophic conditions, low dissolved oxygen levels, high concentrations of pathogenic bacteria, and loss of vegetation cover. Oscillations in rainfall levels caused shifts in the physicochemical and hydrobiological parameters.

Unfortunately, the water quality of the Cereja River, even near its source, already exceeds sanitary standards. Our study findings clearly indicated that contamination from pathogenic bacteria has worsened over the past decade, potentially affecting public health. At this moment, responses from local authorities to address these issues have been limited.

Overall, the results obtained confirmed the initial hypothesis and can also support possible management strategies and decision-making by authorities. It is hoped that the results of the study can provide important guidelines for further research in equivalent fluvial environments under similar anthropogenic pressures.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/limnolrev23020007/s1, Figure S1: Interpretation key for the evaluation of the basin of the Cereja River; Figure S2: Summary of the DPSWR management model for the Cereja River; Table S1: Localization of the sample stations; Table S2: Types of freshwater use, according to Brazilian National Environment Council (CONAMA); Table S3: Percentage of limits of hydrological variables, considering national resolution and international classification; Table S4: Temporal and spatial *Enterococcus* sp and thermotolerant coliform data in Cereja River; Table S5: Limits of thermotolerant coliforms and *Enterococcus* sp per type of uses and the unappropriated samples (%), according to national and international classification; Table S6: Number of inhabitants, growth rate, effluents and thermotolerant coliform levels within the Cereja River PPA; Table S7: Land cover area in PPA of Cereja River in 2012 and 2019.

Author Contributions: Conceptualization, L.C.C.P., N.d.S.d.S.S. and B.R.P.d.S.; methodology, N.d.S.d.S.S., B.R.P.d.S., F.R.B.C., L.M.d.S.R. and A.L.B.d.C.; formal analysis, L.C.C.P., N.d.S.d.S.S., B.R.P.d.S., F.R.B.C., L.M.d.S.R. and A.L.B.d.C.; methodology, L.C.C.P., N.d.S.d.S.S., B.R.P.d.S., F.R.B.C., L.M.d.S.R. and A.L.B.d.C.; investigation, L.C.C.P., N.d.S.d.S.S., B.R.P.d.S., F.R.B.C., L.M.d.S.R., A.L.B.d.C. and RMC; resources, L.C.C.P. and RMC; data curation, L.C.C.P. and RMC; writing—original draft preparation, L.C.C.P., N.d.S.d.S.S., B.R.P.d.S., F.R.B.C., L.M.d.S.R. and A.L.B.d.C. and R.M.d.C.; writing—review and editing, L.C.C.P., N.d.S.d.S.S., B.R.P.d.S., F.R.B.C., L.M.d.S.R. and A.L.B.d.C. and R.M.d.C.; visualization, L.C.C.P. and R.M.d.C.; supervision, L.C.C.P. and R.M.d.C.; project administration, L.C.C.P. and R.M.d.C.; funding acquisition, L.C.C.P. and R.M.d.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Conselho Nacional de Desenvolvimento Científico (483913/2012-0, 431295/2016-6, 314037/2021-7 and 314040/2021-8) and Coordenaçao de Aperfeiçoamento de pessoal de nível superior (88881.736742/2022-01).

Data Availability Statement: Data will be available on request.

Acknowledgments: This study was financed by Conselho Nacional de Desenvolvimento Científico e Tecnológico-CNPq, through a Universal projects (483913/2012-0, 431295/2016-6). Pereira LCC (314037/2021-7) and Costa RM (314040/2021-8) would like to thank CNPq for research grants, and Costa RM (88881.736742/2022-01) would also like to thank CAPES for research grants. We are also indebted to Stephen Ferrari for his careful revision of the English text.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Garcia-Armisen, T.; Servais, P. Respective contributions of point and non-point sources of E. coli and Enterococci in a large urbanized watershed (the Seine River, France). *J. Environ. Manag.* **2007**, *82*, 512–518. [CrossRef] [PubMed]
2. Mitch, A.A.; Gasner, K.C.; Mitch, W.A. Fecal coliform accumulation within a river subject to seasonally-disinfected wastewater discharges water research. *Water Res.* **2010**, *44*, 4776–4782. [CrossRef]
3. Muniz, J.N.; Duarte, K.G.; Braga, F.H.R.; Lima, N.S.; Silva, D.F.; Firmo, W.C.A.; Batista, M.R.V.; Silva, F.M.A.M.; Miranda, R.C.M.; Silva, M.R.C. Limnological Quality: Seasonality Assessment and Potential for Contamination of the Pindaré River Watershed, Pre-Amazon Region, Brazil. *Water* **2020**, *12*, 851. [CrossRef]
4. Lee, H.J.; Park, H.K.; Lee, J.H.; Park, A.R.; Cheon, S.U. Coliform pollution status of Nakdong River and tributaries. *J. Korean Soc. Water Environ.* **2016**, *32*, 271–280. [CrossRef]
5. Seo, M.; Lee, L.; Kim, Y. Relationship between coliform bacteria and water quality factors at weir stations in the Nakdong River, South Korea. *Water* **2019**, *11*, 1171. [CrossRef]
6. WHO—World Health Organization. *Guidelines for Safe Recreational Water Environments—Coastal and Fresh Waters*; WHO: Geneva, Switzerland, 2003; 253p.
7. Bek, M.A.; Azmy, N.; Elkafrawy, S. The effect of unplanned growth of urban areas on heat island phenomena. *Ain Shams Eng. J.* **2018**, *9*, 3169–3177. [CrossRef]
8. Bohra, D.L.; Modasiya, V.B.; Kumar, C. The distribution of coliform bacteria in wastewater. *Microbiol. Res.* **2012**, *3*, 5–7. [CrossRef]
9. Kindiki, S.; Kollenberg, M.; Siamba, D.; Sifuna, A.; Wekesa, C. Analysis of fecal coliform levels at watering points along the upper reaches of River Isiukhu in Kakamega Country. *Kenya J. Adv. Microbiol.* **2018**, *10*, 1–7. [CrossRef]
10. Petrucio, M.M.; Medeiros, A.O.; Rosa, C.A.; Barbosa, F.A.R. Trophic state and microorganisms community of major sub-basins of the middle Rio Doce Basin, Southeast Brazil. *Braz. Arch. Biol. Technol.* **2005**, *48*, 625–633. [CrossRef]
11. Dodds, W.K. Eutrophication and trophic state in rivers and streams. *Limnol. Ocean.* **2006**, *51*, 671–680. [CrossRef]

12. von Sperling, M. *Urban Wastewater Treatment in Brazil*; Technical Note No IDB-TN-970; Department of Sanitary and Environmental Engineering Federal University of Minas Gerais, Brazil, Inter-American Development Bank Felipe Herrera Library: Minas Gerais, Brazi, 2016; 102p.
13. Gorayeb, A.; Lombardo, M.A.; Pereira, L.C.C. Environmental conditions in urban area of the Caeté River Hydrographic Basin in Oriental Brazilian Amazon. *J. Integr. Coast. Zone Manag.* **2009**, *9*, 59–70.
14. Souza, C.L.R.; Costa, V.B.; Pereira, S.F.P.; Silva, D.C.M.; Sarpedonti, V. Impacts of urban life on water quality and fish larvae communities in two creeks of the Brazilian Amazon. *Rev. Ambient. Água* **2016**, *11*, 13–23.
15. Junior, P.M.D.S.; Miranda, J.; Pereira, S.P.; Dinis, A.C.; Nunes, L.S.; Paula, F.S.; Dias, A.R.; Silva, M.L.S.; Teixeira, O.M.M.; Silva Gonçalves, A. Integration of environmental assessment models: A study of the impact on urban micro-watersheds in the Amazon-Brazil. *Rev. Bras. Geogr. Fís.* **2022**, *15*, 2194–2199. [CrossRef]
16. Monteiro, M.C.; Jiménez, J.A.; Pereira, L.C.C. Natural and human controls of water quality of an Amazon estuary (Caeté-PA, Brazil). *Ocean. Coast. Manag.* **2016**, *124*, 42–52. [CrossRef]
17. Pereira, L.C.C.; Sousa, N.S.S.; Rodrigues, L.M.S.; Monteiro, M.C.; Silva, S.R.S.; Oliveira, A.R.G.; Dias, A.B.B.; Costa, R.M. Effects of the lack of basic public sanitation on the water quality of the Caeté River estuary in northern Brazil. *Ecohydrol. Hydrobiol.* **2021**, *21*, 299–314. [CrossRef]
18. Anthony, E.J.; Brondizio, E.S.; Santos, V.F.; Gardel, A.; Besset, M. Sustainable Management, Conservation, and Restoration of the Amazon River Delta and Amazon-Influenced Guianas Coast: A Review. *Water* **2021**, *13*, 1371. [CrossRef]
19. IBGE—Brazilian Institute of Geography and Statistics. Bragança-Pará Census. Available online: https://wwwibgegovbr/cidades-e-estados/pa/bragancahtml? (accessed on 15 November 2022).
20. Guimarães, D.O.; Pereira, L.C.C.; Monteiro, M.C.; Gorayeb, A.; Costa, R.M. Effects of urban development on the Cereja River and Caeté estuary (Amazon coast, Brazil). *J. Coast. Res.* **2009**, *SI56*, 1219–1223.
21. Brazil. *Law No 12651 on the Protection of Native Forests*; United Nations Environment Programme: Nairobi, Kenya, 2012.
22. Sousa, S.S.N. Influence of Domestic Sewage Disposal on the Water Quality of the Caeté River and the Cereja River (Bragança-Pará). Master's Thesis, Universidade Federal do Pará, Belém, Brazil, 2015.
23. Cooper, P. Socio-ecological accounting: DPSWR, a modified DPSIR framework, and its application to marine ecosystems. *Ecol. Econ.* **2013**, *94*, 106–115. [CrossRef]
24. Santos, M.R.S.; Moreira, A.M.; Santos, M.N.S. Socio-environmental analysis of the residents of the urban PPA of Rio Cereja, Bragança-Pará. In Proceedings of the 3rd National Seminar on Treatment of Permanent Preservation Areas in Urban Areas and Environmental Restrictions on Land Installment, Experiences of Interventions in Urban APPs: Technologies, Urban Regulation, Intervention Plans and Projects, Belém, Brazil, 10–13 September 2014.
25. Moraes, B.C.; Costa, J.M.N.; Costa, A.C.L.; Costa, M.H. Spatial and temporal variation of precipitation in the state of Pará. *Acta Amaz.* **2005**, *5*, 207–214. [CrossRef]
26. INMET—National Institute of Meteorology. Monitoring of Automatic Stations. Available online: http://wwwinmetgovbr/sonabra/maps/automaticasphp (accessed on 15 November 2022).
27. ANA—Agência Nacional de Águas. Região Hidrográfica Atlântico Nordeste Ocidental. Available online: https://www.ana.gov.br/as-12-regioes-hidrograficas-brasileiras/atlantico-ne-ocidental. (accessed on 15 November 2022).
28. Silva Filho, C.P.; Nunes, Z.M.P. Environmental integrity index of the Cereja River—Bragança—PA. In Proceedings of the 8th International Solid Waste Forum Venturini Institute, Curitiba, Brazil, 12–14 June 2017; pp. 1–10.
29. Gorayeb, A.; Lomabardo, M.A.; Pereira, L.C.C. Natural conditions and environmental impacts in a coastal Hydrographic Basin in the Brazilian Amazon. *J. Coast. Res.* **2011**, *SI64*, 1340–1344.
30. APHA—American Public Health Association. *Standard Methods for Examination of Water and Wastewater*; APHA: Washington, DC, USA, 2004.
31. Grasshoff, K.; Emrhardt, M.; Kremling, K. *Methods of Seawater Analysis*; Verlag Chemie: New York, NY, USA, 1983.
32. Parsons, T.R.; Strickland, J.D.H. Discussion of spectrophotometric determination of marine plant pigments with revised equations of ascertaining chlorophyll-a and carotenoids. *J. Mar. Res.* **1963**, *21*, 155–163.
33. UNESCO. *Monograph on Oceanographic Methodology I Determination of Photosynthetic Pigments in Sea Water United Nations Education, Science, and Culture Organization*; UNESCO: Paris, France, 1996.
34. Carlson, R.E. A trophic state index for lakes 1. *Limnol. Ocean.* **1977**, *22*, 361–369. [CrossRef]
35. Lamparelli, M.C. Degree of trophy in water bodies in the state of São Paulo: Evaluation of Monitoring methods. Ph.D. Thesis, Universidade de São Paulo, São Paulo, Brazil, 2004.
36. EPA—Environmental Protection Agency. *Method. 1600: Enterococci in Water by Membrane Filtration Using Membrane-Enterococcus indoxyl-Beta-D-Glucoside Agar (mEI)*; EPA: Washington, DC, USA, 2006.
37. CONAMA—National Council of the Environment. Resolution 274/2000. Available online: http://www2mmagovbr/port/conama/legiabrecfm?codlegi=272 (accessed on 15 November 2022).
38. CONAMA—Conselho Nacional do Meio Ambiente. Resolution 357/2005. Available online: http://www2mmagovbr/port/conama/legiabrecfm?codlegi=459 (accessed on 15 November 2022).
39. Bricker, S.B.; Ferreira, J.G.; Simas, T. An integrated methodology for assessment of estuarine trophic status. *Ecol. Model.* **2003**, *169*, 39–60. [CrossRef]
40. von Sperling, M. *Wastwater Characteristics, Treatment and Disposal*; IWA Publishing London: London, UK, 2007.

41. Stephens, M.A. EDF statistics for goodness-of-fit and some comparisons. *J. Am. Stat. Assoc.* **1974**, *69*, 730–737. [CrossRef]
42. Pettitt, A. Testing the Normality of Several Independent Samples Using the Anderson-Darling Statistic. *J. R. Stat. Soc. Ser. C (Appl. Stat.)* **1977**, *26*, 156–161. [CrossRef]
43. Levene, H. *Robust Tests for the Equality of variance In Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling*; Olkin, I., Ed.; Stanford University Press: Palo Alto, CA, USA, 1960; pp. 278–292.
44. Field, A. *Discovering Statistics Using SPSS*, 3rd ed.; Sage Publications Ltd.: London, UK, 2009.
45. Ross, A.; Willson, V.L. Paired Samples T-Test. In *Basic and Advanced Statistical Tests*; Sense Publishers, Rotterdam Advance Online Publication: Rotterdam, The Netherlands, 2017. [CrossRef]
46. Kassambara, A.; Mundt, F. *Factoextra: Extract and Visualize the Results of Multivariate Data Analyses Advance Online Publication*. 2020. Available online: https://rdrrio/cran/factoextra/ (accessed on 15 November 2022).
47. USEPA—US Environmental Protection Agency. *Bacteriological Ambient Water Quality Criteria for Marine and Fresh Recreational Waters EPA440/5-84-002*; USEPA: Washington, DC, USA, 1986; 24p.
48. Zeiringer, B.; Seliger, C.; Greimel, F.; Schmutz, S. River Hydrology, Flow Alteration, and Environmental Flow. In *Riverine Ecosystem Management*; Schmutz, S., Sendzimir, J., Eds.; Aquatic Ecology Series; Springer: Cham, Switzerland, 2018; Volume 8. [CrossRef]
49. Ríos-Villamizar, E.A.; Piedade, M.T.F.; Costa, J.G.; Adeney, J.M.; Junk, W.J. Chemistry of different Amazonian water types for river classification: A preliminary review. *WIT Trans. Ecol. Environ.* **2013**, *178*, 17–28.
50. Feng, Z.; Su, B.; Xiao, D.-D.; Ye, L.-Y. Study on pH value and its variation characteristics of the main rivers into Dianchi lake under the anthropogenic and natural processes, Yunnan, China. *J. Inf. Optim. Sci.* **2017**, *38*, 1197–1210. [CrossRef]
51. Barakat, A.; El Baghdadi, M.; Rais, J.; Aghezzaf, B.; Slassi, M. Assessment of spatial and seasonal water quality variation of Oum Er Rbia River (Morocco) using multivariate statistical techniques. *Int. Soil. Water Conserv. Res.* **2016**, *4*, 284–292. [CrossRef]
52. Duncan, W.P.; Fernandes, M.N. Physicochemical characterization of the white, black, and clearwater rivers of the Amazon Basin and its implications on the distribution of freshwater stingrays (Chondrichthyes, Potamotrygonidae). *Pan-Am. J. Aquat. Sci.* **2010**, *5*, 454–464.
53. Alcântara, E.; Novo, E.; Stech, J.; Lorenzzetti, J.; Barbosa, C.; Assireu, A.; Souza, A. The turbidity behavior in an Amazon floodplain. *Hydrol. Earth Syst. Sci. Discuss.* **2009**, *6*, 3947–3992.
54. Marinho, R.R.; Harmel, T.; Martinez, J.-M.; Filizola Junior, N.P. Spatiotemporal Dynamics of Suspended Sediments in the Negro River, Amazon Basin, from In Situ and Sentinel-2 Remote Sensing Data ISPRS. *Int. J. Geo-Inf.* **2021**, *10*, 86. [CrossRef]
55. Nittrouer, C.A.; DeMaster, D.J.; Kuehl, S.A.; Figueiredo, A.G., Jr.; Sternberg, R.W.; Ercilio, C.F.; Silveira, O.M.; Allison, M.A.; Kineke, G.C.; Ogston, A.S.; et al. Amazon Sediment Transport and Accumulation Along the Continuum of Mixed Fluvial and Marine Processes. *Ann. Rev. Mar. Sci.* **2021**, *13*, 501–536. [CrossRef]
56. Nittrouer, C.A.; DeMaster, D.J. The Amazon shelf setting tropical, energetic, and influenced by a large river. *Cont. Shelf Res.* **1996**, *16*, 553–574. [CrossRef]
57. Asp, N.E.; Gomes, V.J.C.; Schettini, C.A.F.; Souza-Filho, P.W.M.; Siegle, E.; Ogston, A.S.; Nittrouer, C.A.; Silva, J.N.S.; Nascimento, W.R.; Souza, S.R.; et al. Sediment dynamics of a tropical tide-dominated estuary: Turbidity maximum, mangroves and the role of the Amazon River sediment load. *Estuar. Coast. Shelf Sci.* **2018**, *214*, 10–24. [CrossRef]
58. Arnold, E.; Toran, L. Effects of Bank Vegetation and Incision on Erosion Rates in an Urban Stream. *Water* **2018**, *10*, 482. [CrossRef]
59. Díaz-Torres, O.; Anda, J.; Lugo-Melchor, O.Y.; Pacheco, A.; Orozco-Nunnelly, D.A.; Shear, H.; Senés-Guerrero, C.; Gradilla-Hernández, M.S. Rapid Changes in the Phytoplankton Community of a Subtropical, Shallow, Hypereutrophic Lake During the Rainy Season. *Front. Microbiol.* **2021**, *12*, 617151. [CrossRef]
60. Rabalais, N.N.; Harper, D.E., Jr. Studies of benthic biota in area affected by moderate and severe hypoxia. In *National Oceanic and Atmospheric Administration, Coastal Ocean Program Office, Nutrient Enhanced Coastal Ocean Productivity, Proceedings of a Workshop Louisiana Universities Marine Consortium, October 1991 Sea Grant Program*; Texas A&M University: Galveston, TX, USA, 1992; pp. 150–153.
61. Gagne-Maynard, W.C.; Ward, N.D.; Keil, R.G.; Sawakuchi, H.O.; Cunha, A.C.; Neu, V.; Brito, D.C.; Silva, L.D.F.; Diniz, J.E.M.; Matos, V.A.; et al. Evaluation of Primary Production in the Lower Amazon River Based on a Dissolved Oxygen Stable Isotopic Mass Balance. *Front. Mar. Sci.* **2017**, *4*, 26. [CrossRef]
62. Sanchez, E.; Colmenarejo, M.F.; Vicente, J.; Rubio, A.; Garcia, M.G.; Travieso, L.; Borja, R. Use of the water quality index and dissolved oxygen deficit as simple indicators of watersheds pollution. *Ecol. Indic.* **2007**, *7*, 315–328. [CrossRef]
63. Mocuba, J. Dissolved Oxygen and Biochemical Oxygen Demand in the Waters Close to the Quelimane Sewage Discharge. Master's Thesis, University of Bergen, Bergen, Norway, 2010.
64. Wu, N.; Dong, X.; Liu, Y.; Wang, C.; Baattrup-Pedersen, A.; Riis, T. Using river microalgae as indicators for freshwater biomonitoring: Review of published research and future directions. *Ecol. Indic.* **2017**, *81*, 124–131. [CrossRef]
65. Tang, X.; Li, R.; Han, D.; Scholz, M. Response of Eutrophication Development to Variations in Nutrients and Hydrological Regime: A Case Study in the Changjiang River (Yangtze) Basin. *Water* **2020**, *12*, 1634. [CrossRef]
66. Yusuf, Z.H. Phytoplankton as bioindicators of water quality in Nasarawa reservoir, Katsina State Nigeria. *Acta Limnol. Bras.* **2020**, *32*, e4. [CrossRef]
67. Tryland, I.; Myrmel, M.; Østensvik, Ø.; Wennberg, A.C.; Robertson, L.J. Impact of rainfall on the hygienic quality of blue mussels and water in urban areas in the Inner Oslofjord, Norway. *Mar. Pollut. Bull.* **2014**, *85*, 42–49. [CrossRef]

68. Nishiyama, M.; Iguchi, A.; Suzuki, Y. Identification of Enterococcus faecium and Enterococcus faecalis as vanC-type Vancomycin-Resistant Enterococci (VRE) from sewage and river water in the provincial city of Miyazaki, Japan. *J. Environ. Sci. Health* **2015**, *50*, 16–25. [CrossRef]
69. Medeiros, A.C.; Faial, K.R.F.; Faial, K.C.F.; Lopes, I.D.S.; Lima, M.O.; Guimarães, R.M.; Mendonça, N.M. Quality index of the surface water of Amazonian rivers in industrial areas in Pará, Brazil. *Mar. Pollut. Bull.* **2017**, *123*, 156–164. [CrossRef] [PubMed]
70. Pará. Law no 5,887 on the State Environmental Policy, Belém 9-05-1995. 1995. Available online: https://www.semas.pa.gov.br/legislacao/normas/view/424. (accessed on 15 November 2022).
71. Agbogu, V.N.; Umoh, V.J.; Okuofu, C.A.; Smith, S.I.; Ameh, J.B. Study of the bacteriological and physicochemical indicators of pollution of surface waters in Zaria, Nigeria. *Afr. J. Biotechnol.* **2006**, *5*, 732–737.
72. Kuhlmann, M.L.; Imbimbo, H.R.V.; Ogura, L.L.; Villani, J.P.; Starzynski, R.; Robim, M.J. Effects of human activities on rivers located in protected areas of the Atlantic Forest. *Acta Limnol. Bras.* **2014**, *26*, 60–72. [CrossRef]
73. Das, S.; Paul, S. Estimation of land surface temperature of Cooch Behar Municipality to study urban Heat Island using Landsat 8 Image. *Indian J. Spat. Sci.* **2020**, *11*, 69–75.