Using hydrodynamic and water quality variables to assess eutrophication in a tropical hydroelectric reservoir

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ABSTRACT

Few studies have examined the influence of reservoir hydrodynamics on the water quality of its limnological zones. In this study, the relationships between the operational phases and the water quality of the limnological zones were assessed for the Amazonian reservoir Tucuruí. Limnological zones were clustered by means of an artificial neural network technique, and inputs used were water quality variables, measured at twelve stations between 2006 and 2016. Generalized Linear Models (GLMs) were then used to identify the influence of the operational phases of the reservoir on the water quality of its limnological zones. The GLM with a gamma-distributed response variable indicated that Chlorophyll-a concentrations in the riverine and transitional zones differed notably from those observed in the lacustrine zone. Chlorophyll-a concentrations were significantly lower during the operational falling water phase than in the low water phase (p < 0.05). The GLM with an inverse Gaussian-distributed response variable indicated that Secchi depth was significantly lower in the riverine than in the lacustrine limnological zone (p < 0.05). Our results suggest that more eutrophic conditions occur during the operational rising water phase, and that the area most vulnerable to eutrophication is the transitional zone. We demonstrate that the use of GLMs is suitable for determining areas and operational phases most vulnerable to eutrophication. We envisage that this information will be useful to decision-makers when monitoring the water quality of hydroelectric reservoirs with dendritic patterns and dynamic operational phases.

1. Introduction

Reservoirs built for the purpose of hydropower generation are large scale artificial ecosystems, which are very often used for many and varied purposes affecting the water quality of their basin (Tundisi and Tundisi, 2012). These projects provide social and economic development, but also have severe ecological and social impacts that may impair the multiple uses of water (Le Moal et al., 2019).

Anthropic activities in the areas surrounding reservoirs are known to worsen the water quality of the river basins in which they are located (Wunderlin, 2018). These activities may, in some cases, also affect the water quality and volume available for electric power generation and human supply. The main factor leading to eutrophication is water enrichment with nutrients such as phosphorus and nitrogen (Glibert et al., 2018).

Eutrophication has been affecting the ecological health of many lakes and reservoirs worldwide since the 1960s (Ogashawara and Moreno-Madriñán, 2014; Padedda et al., 2017; Vinçon-Leite and Moreno-Madriñán, 2018).
that (i) operational phases with higher eutrophic conditions will be the rising and high water phases, where nutrient input is high due to the rainfall, and the second hypothesis is that (ii) the area most vulnerable to eutrophication is the riverine zone, located in a river basin that suffers from the direct impact of organic material entering the reservoir (Furnas, 2018; Quilliam et al., 2015).

In general, water in a river basin area where hydropower reservoirs are built, has many uses. These multiple uses increase the need for integrated management of the natural resources involving both land and water, which require information that can be used for water quality assessment (Tundisi and Tundisi, 2013). Therefore, acquiring knowledge on the trophic state of these water bodies as well as on spatial and temporal variations will eventually become essential in the management of the water quality issues within these ecosystems.

Several models were developed to identify the emission source of nutrients as well as to predict the consequences for aquatic ecosystems (Vinçon-Leite and Casenave, 2019). These models are mainly empirical, focusing on statistical relationships between predictor and response variables of interest in order to analyze the influence of nutrients on Chlorophyll-a (Chla) concentrations (Alves et al., 2012; Barbosa et al., 2006; Carlson, 1977; Cunha et al., 2013b; Devi Prasad, 2012; Gupta, 2014; Lamparelli, 2004b; Le Moal et al., 2019; Walker, 1979).

Approaches with new techniques have been explored to improve these empirical models based on classical regression analysis including Bayesian regressions and machine learning algorithms for eutrophication assessment in water bodies (Lobato et al., 2015a; Vinçon-Leite and Casenave, 2019).

Among many variables responding to eutrophication in aquatic ecosystems, Chla, Secchi depth and nutrients are the most used when modeling the trophic status of water bodies (Haydée, 1997; Lamparelli, 2004a; Tundisi et al., 1988; Wetzel, 2001).

However, the relationship between Chla and nutrients may be far more complicated than is currently assumed. Due to the hydrodynamic operational phases in Amazonian hydropower reservoirs, for instance, horizontal and vertical heterogeneity are frequently observed in the water quality variables (Tundisi et al., 2012).

This study addresses the question of whether other features, including morphometry, hydrology, climate condition, and anthropic pressures, rather than only physicochemical and biological responses are important in eutrophication assessment of hydropower reservoirs (Cunha et al., 2013a; Silvino and Barbosa, 2015; Tundisi et al., 2012; Vinçon-Leite and Casenave, 2019). The primary hypothesis herein is that (i) operational phases with higher eutrophic conditions will be the rising and high water phases, where nutrient input is high due to the higher occurrence of rains. The second hypothesis is that (ii) the area most vulnerable to eutrophication is the riverine zone, located in a river basin that suffers from the direct impact of organic material entering the system.

For a tropical hydropower reservoir, an exploratory analysis of water quality variables was performed throughout the study period to assess changes in water quality data during operational phases and in the limnological zones. Secondly, regression models with gamma- and inverse Gaussian-distributed response variables were used to evaluate Chla concentrations and Secchi depth, respectively. These models help to describe ecosystem responses to environmental changes based on robust calculations of linear and non linear datasets (Marques et al., 2019). Water quality variables usually are highly skewed, and it may be inappropriate to assume normality (Fu and Wang, 2012). Water quality variables used in this modeling were ammonium (μg L⁻¹), Chla (mg m⁻³), dissolved oxygen (mg L⁻¹), orthophosphate (μg L⁻¹), Secchi depth (m), total phosphorus (μg L⁻¹), total suspended solids (mg L⁻¹), and turbidity (NTU).

This work aims to provide valuable information for public decision-making and water management when confronted with eutrophication trends in reservoirs with dendritic areas and multiple uses. We used an approach that offers better understanding of the ecological interactions that occur between river basin, multiple reservoir uses and the preservation or deterioration of the water quality in reservoirs (Tundisi and Tundisi, 2012).

2. Materials and methods

2.1. Study area

The Tucuruí impoundment is located in the state of Pará, Brazil, between 5° 07′ 54″S, 49° 17′ 40″W and 3° 49′ 46″S, 49° 39′10″W. The dam was built in 1984 on the Tocantins River and is situated 7 km to the south from the city of Tucuruí and 300 km to the south from the city of Belem. The total flooded reservoir area varies from 1500 to 2500 km² throughout the year. The storage capacity of the reservoir is up to 45 km³ in the high water operational phase. The annual average length of the reservoir is approximately 133 km, and the annual average width is 13 km (Cartarelli et al., 2016; Espíndola et al., 2000).

The dam operates under four different operational phases: rising water (from December to February); high water (from March to May); falling water (from June to August); and low water (from September to November). The study area is influenced by two seasons: wet and dry, as shown in Fig. 1.

The impoundment is the largest hydroelectric project located in the Brazilian rainforest. The reservoir is surrounded by protected areas that were created in the beginning of the construction of the dam. These include an Environmental Protection Area (EPA), two Sustainable Development Reserves (SDRs), which encourage the sustainable use of natural resources, and two strictly protected Wildlife Conservation Zones (WCZ) (MMA, 2011). In general, riverine populations that are organized in communities and small rural properties occupy the surrounding areas of the reservoir (Araújo et al., 2016). The total estimated population is approximately 6500 inhabitants, with higher concentrations in the SDRs Alcobaça and Pucuruí-Arárao.

There are also three cities located in the area surrounding the reservoir (Fig. 2). The estimated population within these cities is approximately 105,180 inhabitants (0.049% of the total Brazilian population), and from 1995 to 2017 growth has been observed (Araújo et al., 2016). Despite the increase in population in these cities, very little has been published regarding changes in land use and occupation in the protected areas, suggesting that local communities perform activities more related to their subsistence such as extraction of natural resources and fishing. These activities have minimal impact on deforestation in the areas surrounding the reservoir as showed in Fig. 3 (INPE, 2017).

2.2. Sampling stations

The sampling stations for this study have been labelled S1 to S12, and they are distributed in three zones upstream of the Tucuruí dam (Fig. 2), where different land use and occupation has been reported (Chen et al., 2015). The maximum depth of these stations throughout the operational phases varies and is reported as depth(max) between parentheses in the next paragraphs.

The lacustrine zone includes stations S1 to S4. The station S1 (depth(max) = 70.0 m) is the most monitored area of this impoundment, and it has water quality patterns similar to those observed in the river basin prior to impoundment. The SDR Alcobaça (~306.40 km²) is located on the left margin of the reservoir, surrounding stations S2 (depth(max) = 30.0 m) and S3 (depth(max) = 21.4 m), where human land use and occupation is based on sustainable exploitation of the natural resources. The station S4 (depth(max) = 32.0 m) is located near the town of
Fig. 1. Average monthly precipitation (mm) from January 2006 to December 2016 at the study area. The wet season (on average from December to June) is above the broken line and the dry season (on average from July to November) below the broken line. Source of data: (INMET, 2017).

Fig. 2. Study area and sampling stations (S1 to S12) located throughout the reservoir and delimitation of protected areas. The satellite scene is from the S2A/MSI (20-07-2017) in natural color (R = 665 nm, G = 560 nm, B = 490 nm). Source of data: Natural Earth (free vector and raster map data @naturalearthdata.com) and INPE (2017) (protected area vectors). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
Breu Branco, on the right bank of the reservoir, where anthropic activities as well as some areas of primary forest are observed.

The transitional zone includes stations SS to S8. Stations SS (depth\textsubscript{max} = 32.2 m) and S6 (depth\textsubscript{max} = 22.8 m) are located in the SDR Pucuruí-Araçoi and 1502.93 km\textsuperscript{2} in the EPA Tucuruí. Source of data: INPE (2017).

The riverine zone includes stations S9 to S12. Station S9 (depth\textsubscript{max} = 22.2 m) is located near the indigenous land Parakanã (~3379.30 km\textsuperscript{2}), which is a protected area delimited after the filling phase of the reservoir. Two fishing harbor facilities surround station S10 (depth\textsubscript{max} = 22.0 m). Station S11 (depth\textsubscript{max} = 42.0 m) is situated 130 km from the dam. Finally, station S12 (depth\textsubscript{max} = 11.5 m) is located in front of the city of Itupiranga, in the Tocantins River.

2.3. Water quality measurements

A total of 570 samples from the water surface of the twelve stations (S1 to S12) located in the reservoir were used in this analysis. The samples were taken in the period from 2006 to 2016 and were mainly collected on a bimonthly basis. The dataset was provided by the “Centrais Elétricas do Norte do Brasil S.A.” (Eletronorte), the company that monitors the reservoir. Variables were determined using Standard Methods (SMs) for water examination (APHA, 2005) and included total suspended solids (TSS), dissolved oxygen (DO), orthophosphate (orthPO\textsubscript{4}), ammonium, and water temperature (WT). Total phosphorus was determined by the ascorbic acid method. Chl\textsubscript{a} was estimated using the acetone-extraction method described in Gotterman et al. (1978).

Secci depth was determined using a Secchi disk, turbidity by the ascorbic acid method. Chl\textsubscript{a} and water temperature using a digital thermometer (SM 2550).

2.4. Methods and techniques to separate hydrodynamic from water quality variables

Several statistical techniques were used to summarize and organize the dataset used in this study. Firstly, the reservoir was divided into lacustrine, transitional, and riverine zones, according to Chapman (1996). Secondly, several combinations of techniques were performed to evaluate the division in zones. Best results from these combinations were obtained through an artificial neural network (ANN) analysis, in which the training dataset included hydrodynamic conditions of the reservoir (operational phase and local depth) as well as water quality variables (ammonium, Chl\textsubscript{a}, DO, orthoP, WT, SD, TP, TSS, and turbidity). The 570 samples were randomly divided into 60% for training (342 samples), 30% for testing (171 samples) and 10% for validation (57 samples). Output variables were the limnological zones, characterizing the spatial variation.

Thirdly, an exploratory data analysis (EDA) was performed to determine summary statistics (mean, standard deviation and coefficient of variation), trends (performed through time series analysis with the Mann-Kendall trend test), correlation and tests of mean and variance. A correlation analysis between the measured variables was performed to test for multicollinearity. A Student’s t-test with the Levene’s test for different variances was performed to assess whether mean values of water quality variables were significantly different across limnological zones and operational phases. A significance level of \( p < 0.05 \) was adopted, and these analyses were performed using the R software and the Hmisc (version 4.2) and the tidyverse (version 1.2.1) libraries (R Team, 2016).

Generalized linear models (GLMs) were used to identify the key environmental factors driving eutrophication trends in the Tucuruí reservoir. Analyses were also performed using the R software. The MASS (version 7.3) library was used for GLM analyses and the ggplot2 (version 3.1.1), cowplot (version 0.9.4) and easyGgplot2 (version 1.0) libraries for data visualization. After an EDA, a GLM with gamma-distributed response variable was adopted to investigate the response of Chl\textsubscript{a} to ammonium, local depth, limnological zone, operational phase, DO, orthoP, and TSS.

A GLM with an inverse Gaussian-distributed response variable was adopted to investigate the response of water transparency (Secchi depth) to ammonium, limnological zone, operational phase, local depth, Chl\textsubscript{a}, DO, orthoP, and TSS.

The gamma-distributed and the inverse Gaussian-distributed models were used because of the non-negative and continuous nature of the dataset. When performing the gamma-distributed model it is important to consider that independent random variables are likely to present a correlation analysis between the measured variables was performed to test for multicollinearity. A Student’s t-test with the Levene’s test for different variances was performed to assess whether mean values of water quality variables were significantly different across limnological zones and operational phases. A significance level of \( p < 0.05 \) was adopted, and these analyses were performed using the R software and the Hmisc (version 4.2) and the tidyverse (version 1.2.1) libraries (R Team, 2016).

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reciprocal. Diagnostic analysis of the residuals and the Akaike’s Information Criteria (AIC) score were calculated to choose the best model for each link function (Paula, 2013). Diagnostic analysis included visualization of graphic parameters such as Cook’s distance, leverage, and linear prediction. 

3. Results and discussion

3.1. Separation of hydrodynamic and water quality variables

Sampling stations were categorized into three limnological zones using an ANN (Table 1). Results of the separation of zones using the multilayer perceptron method obtained from a training dataset, test, and validation were equal to 73%, 70%, and 76%, respectively. The ANN had two hidden layers (containing 8 and 6 nodes) trained using the backpropagation algorithm and the hyperbolic tangent sigmoid transfer function. The training was applied to all nodes of the network. Hydrodynamic and water quality variables that were most important in the classification of limnological zones were local depth (92%) and Secchi depth (100%), TSS (94%), TP (76%), and Chl (62%), respectively.

The water temperature was essentially similar in all three limnological zones. In the lacustrine zone, a deep basin with high values of Secchi depth, mean water temperatures of 29.93 ± 0.74 °C were observed. In the transitional zone, shallower than the lacustrine basin, mean water temperatures were 30.28 ± 0.97 °C. In the riverine zone, a more channelized basin, mean water temperatures were 29.97 ± 0.97 °C, similar to those registered in the lacustrine zone. In multipurpose water reservoirs, little difference is observed in water temperatures, resulting in similar patterns for this variable across the limnological zones (USGS, 2018). Heterogeneity in the water quality variables is mainly observed in the chemical and biological characteristics. These temporal and seasonal changes are dependent on water entering the reservoir during different operational phases (Tundisi and Tundisi, 2012).

3.2. Water quality variables per operational phase

Table 2 shows summary statistics of the water quality variables in the different operational phases of the Tucuruí reservoir from 2006 to 2016. A decrease in Chl concentrations was observed from 2006 to 2016, with mean values per operational phase lower than those established in Brazilian legislation for class 2 waters (<30 mg m⁻³) (Conama, 2005). There were significant differences in the means of Chl concentrations when comparing some of the operational phases, i.e. low and rising water (t = −2.41, p < 0.02), low and falling water (t = 4.40, p < 0.01), rising and high water (t = 4.25, p < 0.01), rising and falling water (t = 6.38, p < 0.01), and high and falling water (t = 3.13, p < 0.01). Pairwise comparison tests revealed multiple statistically significant comparisons between operational phases (p < 0.05) and the water quality variables Chl, ammonium, orthoP, Secchi depth, TP, TSS, and turbidity. As expected, mean of DO concentrations did not show significant differences per operational phases. However, when pairwise compared, DO saturation (%) was significantly (p < 0.01) different between the operational high and rising water phase. Seasonal similarity of DO in the water surface of hydroelectric reservoirs and variation in nutrients (ammonium, orthoP, TP) have been attributed to the consumption of DO in oxidation of organic matter loadings, indicative of organic pollution (Dorgham, 2010; Persic et al., 2010; Teytel et al., 1996).

Increasing nutrients (TP and ammonium) in the operational rising water phase are likely to be accompanied by an increase in Chl (8.61 ± 0.52 mg m⁻³) and turbidity (14.63 ± 1.61 NTU) and consequent decrease in Secchi depth (1.72 ± 0.08 m). The availability of nutrients and the increase in Chl concentrations in the water surface of the operational rising water phase seems to be linked to rainfall events in the region bringing organic matter and dissolved nutrients from surrounding areas into the reservoir (Tundisi et al., 2014).

Furthermore, lower Chl concentrations in the falling water phase compared with the low water operational phase seem to be explained by the water residence time. In the operational falling water phase, water is flushed out from the reservoir upstream, decreasing nutrient concentrations (TP, ammonium) and phytoplankton biomass (Chl). Meanwhile, in the low water phase, favorable conditions occur due to the release of nutrients from the sediments to the upper water layers, thus increasing Chl concentrations (Damanik-Ambarita et al., 2016; Wang et al., 2019).

In addition, results of the TSI (based on Chla and TP concentrations) were 54.64 ± 0.23, 54.47 ± 0.18, 52.37 ± 0.17 and 53.16 ± 0.22 for rising, high, falling and low water operational phases, respectively. These results classify the reservoir as mesotrophic (52 ≤ TSI < 59) throughout all of its operational phases. Similar results were reported by Lobato et al. (2015b) studying the same reservoir. It is worth emphasizing that this reservoir seems to be reaching its stabilization phase, where eutrophication conditions can be easily managed in the drainage basin. However, large fluctuations of the hydrodynamic conditions are known to modulate biogeochemical processes with consequent acceleration of eutrophic conditions (Wang et al., 2019; Zhao et al., 2013).

3.3. Water quality variables per limnological zone

Table 3 shows summary statistics of the water quality variables in the different limnological zones from 2006 to 2016. Chl concentrations and DO levels did not present any significant increase between different limnological zones from 2006 to 2016. There were significant differences in the means of Chl when comparing transitional with lacustrine (t = 3.79, p < 0.01), and riverine with lacustrine (t = 2.61, p < 0.02) limnological zones. There was also a significant overall difference in the means of DO between riverine and lacustrine (t = 3.94, p < 0.01), as well as between riverine and transitional (t = 4.52, p < 0.01) zones. Pairwise comparison tests revealed multiple statistically significant differences between zones (p < 0.05) and the water quality variables Chla, orthoP, Secchi depth, TP, TSS, and turbidity.

The differences in the means of ammonium were not significant for the different limnological zones. An increase in nutrient (TP and orthoP) concentrations was observed from riverine towards the lacustrine zone. Highest Chla concentrations were observed in the transitional zone, where ammonium was highest as well. A possible explanation is that the ion ammonium is the inorganic nitrogen form, which is assimilated more easily than orthoP and TP by phytoplankton in this reservoir (Rückert and Giani, 2004).

Chla seemed not be the only variable influencing Secchi depth and turbidity variables in the lacustrine zone. The decrease in Secchi depth from the lacustrine to the riverine zone may be related to the increase of nutrients and suspended matter, which follows the same pattern in these zones. Many factors influence spatial and temporal turbidity patterns. In reservoir systems, variation in turbidity is mainly due to hydrodynamic processes and meteorological events. For instance, during precipitation periods, turbidity increases due to the intense rainfall, which increases
the input of allochthonous material into the reservoir (Dai et al., 2013; means in a row without a common superscript letter differ (p < 0.05) as analyzed by the Student-test with the Levene’s test for different variances.

Means in a row without a common superscript letter differ (p < 0.05) as analyzed by the Student-test with the Levene’s test for different variances.

Table 3
Summary statistics of the water quality variables per limnological zones. Mean, standard deviation (SD) and coefficient of variation (CV).

| Limnological zones/Variables | Lacustrine | | | | Transi- | | | | Riverine | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature (°C) | Mean | SD | CV | Mean | SD | CV | Mean | SD | CV | Mean | SD | CV |
| Ammonium (µg L⁻¹) | 35.23 | 35.76 | 88.82 | 46.31 | 57.93 | 126.9 | 40.33 | 40.8 | 100.3 |
| DOC (mg L⁻¹) | 2.76 | 1.02 | 36.90 | 2.32 | 36.70 | 1.43 | 0.73 | 51.10 |
| TP (µg L⁻¹) | 17.86 | 10.04 | 57.25 | 23.78 | 31.67 | 19.12 | 12.59 | 53.59 |
| TSS (mg L⁻¹) | 5.45 | 4.90 | 86.30 | 7.49 | 5.34 | 71.30 | 6.97 | 3.87 | 55.60 |
| Turbidity (NTU) | 14.65 | 19.88 | 133.51 | 11.52 | 16.62 | 144.26 | 3.58 | 3.72 | 105.05 | 4.63 | 4.99 | 104.13 |

Means in a row without a common superscript letter differ (p < 0.05) as analyzed by the Student-test with the Levene’s test for different variances.

As expected, low Chla and nutrient concentrations resulted in low TSI in the range of 52 < TSI < 59, results that were also reported by Lobato et al. (2015b). Overall, limnological zones were categorized as mesotrophic showing TSI values of 52.43 ± 0.18, 53.92 ± 0.19, and 54.99 ± 0.16 for lacustrine, transitional, and riverine zones, respectively.

3.4. GLM results

Fig. 4 shows a time series plot of the variables used in the GLMs, namely Chla and Secchi depth. Results of the time series analysis using the Mann-Kendall trend test revealed a significant decrease trend in Chla concentrations in the lacustrine zone (p < 0.05) from 2006 to 2016, while no significant trends were observed in the transitional (p = 0.06) and riverine (p = 0.25) zones. The Secchi depth did not present a significant trend in either the lacustrine (p = 0.44), the transitional (p = 0.65) or the riverine (p = 0.39) limnological zone.

Correlation analysis was performed between hydrodynamic (local depth) and water quality variables (Chla, TP, DOC, orthoP, ammonium, TSS and turbidity) considering their response to eutrophication and their level of multicollinearity. Results showed that Chla was significantly correlated with TP (r = 0.55, n = 570, p < 0.01) and turbidity (r = 0.65, n = 569, p < 0.01), and had a very slight significant correlation with DO (r = 0.08, n = 570, p = 0.05), orthoP (r = 0.09, n = 550, p = 0.03), ammonium (r = 0.08, n = 579, p = 0.05), local depth (r = -0.39, n = 570, p < 0.01), and TSS (r = 0.09, n = 570, p = 0.02). The least correlated variables were chosen as explanatory variables as is required in the assumptions of the models, and these were ammonium, local depth, DO, TSS and orthoP.

In both models, limnological zones and operational phases were
3.4.1. Gamma-distributed model with logarithmic (log) link function applied to Chla

The asymmetric behavior of the Chla concentration in Fig. 5C suggests that a gamma distribution is appropriate to explain the mean concentration of this variable per limnological zone and operational phase. Several outliers can be observed in Fig. 5A and B which are also reported in Tables 2 and 3 as high coefficients of variation values. Different land use and occupation in the area surrounding the Tucuruí reservoir might be contributing to this great variability between sampling stations of the same category.

Results of the maximum likelihood estimates of the eutrophication model considering Chla response to ammonium, DO, orthoP, TSS and local depth are given in Table 4.

The results in Table 4 indicate that Chla concentrations were significantly influenced by hydrodynamic conditions of the Tucuruí reservoir such as local depth, rising and falling water operational phases, and transitional and riverine limnological zones. It has been well established that complex hydrodynamics affect Chla concentrations in hydroelectric reservoirs (Mac Donagh et al., 2009; Straskraba and Tundisi, 2013). Water quality variables that significantly influenced Chla response to these hydrodynamic conditions were TSS and orthoP.

Chla concentrations differed significantly (p < 0.05) among operational phases and limnological zones (Fig. 5A and B). During the operational falling water phase, these concentrations are significantly lower (p < 0.05) than in the low water phase (the reference phase used by the model), whilst in the operational rising water phase these concentrations were highest (8.61 ± 52 mg m⁻³). High concentrations of Chla in the operational rising water phase are associated with nutrient loading from surrounding areas into the reservoir, thus favoring eutrophication (Tang et al., 2018). While in the operational falling water phase low Chla concentrations may be related to shortened water residence time, as in this phase the water flow is higher compared with that of other operational phases. Hydroelectric reservoirs with short residence time are expected to present better water quality than those with longer residence time (Straskraba and Tundisi, 1999).

Regarding limnological zones, highest mean values of Chla concentrations were observed in the transitional zone (7.45 ± 0.39 mg m⁻³), accompanied by the highest values of ammonium (46.31 ± 4.38 μg L⁻¹). In this zone, the S6 station (near a city and recreational fishing) presented the highest overall Chla concentration (10.45 ± 1.12 mg m⁻³), which seems to be linked to the high values of total phosphorus (37.20 ± 5.08 μg L⁻¹) and orthoP (11.81 ± 1.64 mg L⁻¹) recorded for this station.

In the riverine zone, mean values of Chla were 6.97 ± 0.30 mg m⁻³, with the highest values observed at station S10 (area surrounded by fishing harbor facilities), with a mean of 8.20 ± 0.61 mg m⁻³. Correspondingly, high mean concentrations of total phosphorus (28.18 ± 1.93 μgL⁻¹) and orthoP (12.21 ± 1.25 mg L⁻¹) were observed.

It is observed that in the riverine zone algal growth (Chla) is controlled by the hydrologic (operational phases and local water depth) and environmental conditions in the reservoir. Although high nutrient (orthoP = 11.23 ± 0.63 mg L⁻¹ and TP = 31.60 ± 1.29 mg L⁻¹) concentrations were observed, they did not lead to algae growth (Chla), which is likely due to the high water flow in this limnological zone (Jiang et al., 2010).

Total suspended solids were significantly different among operational phases (p < 0.05) and limnological zones (p < 0.05). Higher and lower values of TSS were observed during the rising (6.98 ± 0.82 mg L⁻¹) and falling (2.01 ± 0.24 mg L⁻¹) water operational phases, respectively. Within limnological zones, higher and lower values of TSS were observed in the riverine (8.65 ± 0.77 mg L⁻¹) and lacustrine (1.68 ± 0.12 mg L⁻¹) zones, respectively. It seems that TSS is reducing the Secchi depth in the limnological zones, partly due to the input of inorganic matter from the watershed (Rangel et al., 2012).

Graphs of the residuals of leverage and Cook’s distance are depicted in Fig. 6. This figure shows that the maximum likelihood estimation between the linear prediction and the Z-variable indicates an adequate fit (pseudo-R²(McFadden) = 0.28) of the logarithmic link function for Chla.

| Table 4 |
| Coefficients Estimate Standard Error t value p-value |
| Intercept | 1.75 | 0.19 | 9.19 | 0.000 |
| Local Depth | -0.01 | 0.00 | -7.25 | 0.000 |
| C1-Rising water | 0.15 | 0.07 | 2.31 | 0.020 |
| C2-High water | 0.08 | 0.07 | 1.21 | 0.228 |
| C3-Falling water | -0.19 | 0.07 | -2.75 | 0.006 |
| Z1-Transitional | 0.29 | 0.08 | 3.58 | 0.000 |
| Z2-Riverine | 0.96 | 0.09 | 4.33 | 0.000 |
| Ammonium | <0.00 | 0.00 | -0.73 | 0.468 |
| DO | 0.03 | 0.03 | 0.92 | 0.356 |
| OrthoP | -0.01 | 0.00 | -2.25 | 0.025 |
| TSS | 0.11 | 0.03 | 4.70 | 0.000 |
| Z1-TSS | -0.08 | 0.03 | -3.13 | 0.001 |
| Z2-TSS | -0.13 | 0.03 | -5.00 | 0.000 |

Fig. 5. Boxplots of Chla concentration in limnological zones (A) and operational phases (B); histogram rug marks along x-axis indicating raw data of Chla (C). Lac = Lacustrine; Tran = Transitional; Riv = Riverine; L = Low water; R = Rising water; H = High water; F = Falling water.
as a predictor of eutrophication.

3.4.2. Inverse Gaussian-distributed model with logarithmic (log) link function applied to Secchi depth

The histogram of Secchi depth in Fig. 7C shows that this variable is less asymmetric than Chl (Fig. 5C). In addition, standard deviations were relatively similar between the means of the operational phases and limnological zones (as shown in Tables 2 and 3). Therefore, an inverse Gaussian-distributed model with a logarithmic link function was more appropriate for investigating the response of Secchi depth to the hydrodynamic conditions and water quality variables of the Tucurui reservoir water surface.

The maximum likelihood estimates of the eutrophication model considering Secchi depth response to ammonium, DO, orthoP, TSS, and local depth were obtained through Equation (2), with logarithmic link function. Results are presented in Table 5.

Results in Table 5 reveal that the operational rising, high and falling water phases significantly influenced Secchi depth. Variables that significantly influenced Secchi depth response were TSS, orthoP, and Chl. Secchi depth values differed significantly (p < 0.05) among operational phases and limnological zones (Fig. 7A and B). During the operational rising and high water phases, Secchi depth is significantly lower (p < 0.05) than that observed during the operational low water phase (the reference phase used by the model).

The Secchi depth of the riverine zone is significantly less (1.43 ± 0.06 m; p < 0.01) than that observed in the lacustrine zone (2.76 ± 0.07 m), while the opposite is true for TP, orthoP, TSS, and turbidity. This
inversion suggests that Secchi depth within this zone is driven mainly by dissolved substances and other inorganic materials. TSS concentrations decrease from the riverine (8.65 ± 0.77 mg L⁻¹) towards the lacustrine zone (1.68 ± 0.12 mg L⁻¹) with positive results on Secchi depth which, correspondingly, increases from the riverine (1.43 ± 0.06 m; p < 0.01) towards the lacustrine zone (2.76 ± 0.07 m). This confirms that nutrients (P and orthoP) are being transported from the catchment throughout the main body of the reservoir (Straskraba and Tundisi, 2013). Similarly, Dai et al. (2013) found that water clarity increased from riverine to lacustrine zones when investigating limnological zones of the Three Gorges reservoir.

Graphs of residuals of the leverage and Cook’s distance are depicted in Fig. 8. This figure shows that the maximum likelihood estimation between the linear prediction and the Z-variable indicates an adequate fit (pseudo-R²(McFadden) = 0.32) of the logarithmic link function for Secchi depth as predictor of eutrophication.

3.4.3. Performance of the GLM applied to Chla and Secchi depth

After analyzing several models with different functions, the most appropriate models for Chla concentrations and Secchi depth were those that considered factors and variables as main effects without interaction. Results were assessed through a normal probability plot and smallest AIC score. Fig. 9 shows envelope plots performed with 100 simulations for both the Chla and Secchi depth variables.

These probability plots further support the conclusion that the gamma-distributed model was adequate to explain Chla and that the inverse Gaussian-distributed model was adequate to explain Secchi depth patterns as a function of hydrodynamic conditions and water quality variables of the Tucuruí reservoir.

4. Conclusions

This study examined the influences of reservoir hydrodynamics on the water quality of its limnological zones. It was observed that Chla concentrations decreased from 2006 to 2016 and, as expected, the Secchi depth increased with a decrease in Chla concentration. However, an increase in nutrient (TP and orthoP) concentrations was observed across the entire reservoir during this study. Nevertheless, the reservoir showed improved water quality in terms of DO concentrations. Levels of DO were in the acceptable range of the Brazilian legislation (CONAMA 357/05) for water classes 1 and 2, considering multiple uses.

The gamma-distributed model was applied to assess eutrophication through Chla concentrations. In this model, Chla was adopted as a response variable. Results showed that the concentrations of Chla in the riverine and transitional zones were significantly different to those in the lacustrine zone. During the operational falling water phase, Chla levels were significantly lower than those during the low water phase.

Secchi depth was chosen as response variable in the inverse Gaussian-distributed model. Results showed that during the operational rising and high water phases the Secchi depth is significantly lower than that of the low water phase. As expected, the Secchi depth is significantly lower in the riverine zone than in the lacustrine zone. The riverine zone is where the primary input of organic matter into the reservoir occurs due to human activities such as deforestation, mining and fish
farming. 

Contrary to the hypothesis, the riverine zone was not the limnological zone most susceptible to the eutrophication process, as algae growth (Chla concentration) is not only influenced by nutrients but also by other conditions such as light availability and calm waters, which are better in the transitional zone. Thus, high Chla concentrations, which may be indicative of algal bloom occurrence, are strongly connected to the hydromorphological dynamics of the Tucurui reservoir, and affect the transitional zone.

The use of GLMs was proven useful for determining limnological zones of the reservoir and operational phases most susceptible to eutrophication, providing crucial information that can aid in monitoring the water quality of hydroelectric reservoirs with dendritic characteristics and dynamic hydrological cycles, as these factors known to influence water quality in these systems. In addition, these models also provide information on temporal and spatial scales and can be used in integrated approaches of ecosystem management in the areas surrounding reservoirs.

Despite the achievements made using these models to identify areas and operational phases most susceptible to eutrophication in hydroelectric reservoirs, further research is required to provide a more accurate and integrated assessment. Other variables should be included, such as land use, human activities and land degradation in the surrounding areas, which are known to promote eutrophication.

Author contributions

Terezinha Ferreira de Oliveira wrote the article and processed the data analysis. Isabel Brandão and Terezinha, developed the project idea and analysis methods, and also verified the hydraulic and water quality analysis and contributed to manuscript editing. Chris M. Manha and Rachel Ann Hauser-Davis analyzed the data and contributed to the discussion section. Antonio Oliveira and Augusto César Fonseca Saraiva gave ideas and reviewed the article. Michele Oliveira and Junior Ishihara helped to process the dataset and contributed to the discussion section.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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Declaration of competing interest

None declared.

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