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Trophic State Index (TSI) of the Reservoir of the Itaipu Binacional Hydroelectric Power Plant, Brazil

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Abstract: In order to evaluate the water quality of the reservoir of the Itaipu Binacional hydroelectric power plant, the present study classifies the Itaipu Dam using the Trophic State Index (TSI) of Carlson (1977) modified by Toledo-Jr *et al*. (1983), considering the period from 2008 to 2014. From the limnological data of analyzes carried out by the Environmental Institute of Paraná (IAP), provided by the Itaipu Environmental Monitoring Program, the TSI of the reservoir was calculated for the period 2008 to 2014, considering the quarterly averages of the sampling stations grouped according to the hydrological regime (averages of fluvial, transition and lacustrine zones). The limnological variables used in the calculation were the chlorophyll-α and total phosphorus concentrations and the depth of transparency, measured with the Secchi disk. The Itaipu Dam can be classified as ultraoligotrophic (TSI = 39.41). From the ANOVA and the Tukey test, it was verified that the lacustrine zone differs significantly from the transition and fluvial zones (and these do not differ from each other). The residuals presented normal distribution, confirmed by the Lilliefors test, whose probability value was $p = 0.873$. The reservoir is classified as ultra-lithotrophic and the quality of its waters may be considered adequate for the purposes for which they are intended.

Key words: trophic degrees, water quality, environmental monitoring, artificial environments

1. Introduction

The riverbeds are one of the oldest and most important anthropogenic interferences in natural ecosystems that alter the environment, generating a series of socioeconomic benefits, but also causing detrimental impacts to the environment due to the drastic alteration.

Reservoirs consist of structures with physical capacity to store water and change the magnitude and timing of river flows, favoring various purposes, including reducing harmful flood flows, water quality and ecosystem support. However, they interfere with ecosystems by modifying their physicochemical and thermal aspects and intercepting habitat connectivity and sediment and nutrient fluxes [1].

It is observed throughout history, and even today, the use of water bodies to launch domestic sewage, industrial and agricultural origin contaminants, polluting and negatively impacting aquatic environments. In areas of agricultural occupation there is a greater complexity regarding the pollution of water resources, given the difficulty of associating the source with the polluter, since this type of pollution occurs through important hydrological events, associated to the conditions of use and occupation of the source and soil characteristics of the river basin [2].

The pollution of water resources, whether punctual or diffuse, can cause eutrophication, defined as increasing the concentration of nutrients in aquatic ecosystems (especially phosphorus and nitrogen),

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resulting in an increase in their productivity [3]. Although it occurs naturally, it is usually associated with anthropic activity.

Classification of water bodies using trophic state index (TSI) is common in studies on the aquatic environment. Measure the trophic status of aquatic ecosystems is important because it reflects the human influence on water quality and the ecological functioning of the aquatic environment [4]. The TSI, proposed by Carlson in 1977 [5] has undergone modifications over the years due to the climatic and hydrological peculiarities of the studied water bodies, such as the adaptation made by Toledo-Jr *et al.* to water bodies of subtropical climate [6], or the modification of Lamparelli, who developed an equation for reservoirs and another for rivers [7].

Thus, this work continues precursors to evaluate the quality of the water of the reservoir of the Itaipu using the TSI of Carlson, modified to subtropical by Toledo-Jr. et al.

2. Material and Methods

2.1 Study Area

The Itaipu reservoir is located on the border between Brazil and Paraguay between the parallels 24°05' S and 25°33' S and the meridians 54°00' W and 54°' W (Grw) [8]. Formed from the damming of the Paraná River, the second largest river in South America, is the seventh largest in Brazil it has 1,350 km² of flooded area but has the best index of water use to produce energy between the large Brazilian reservoirs [9]. Its main use is the production of electricity, however other secondary uses are applied such as navigation, recreation, tourism, water supply for the population, irrigation, fishing etc. [10]. The reservoir presents dendritic characteristics, with the formation of six large arms in the left margin, its Brazilian portion [11].

2.2 Sampling Stations

The data comes from eleven sampling stations located along the reservoir (Fig. 1 and Table 1), according to the reservoir zones, determined according to a commonly accepted criterion followed by several authors [8, 10-13], considering the longitudinal sections of the reservoir, established according to their respective hydrodynamic characteristics: (i) fluvial zone — lotic region, with fluvial characteristics, that is located in the initial portion of the reservoir; (ii) lacustrine zone — lentic region, with lake aspect, where the reservoir is deeper and wider; and (iii) transition zone — intermediate region between the fluvial and lacustrine zones.

Table 1 Location of sampling stations in the Itaipu dam.

Sampling stations	Location	Dam area
E1	Right channel of the Paraná River, upstream of the dam, Guaíra City, Brazil	Fluvial zone
E2	Right channel of the Paraná River, upstream of the dam, Guaíra City, Brazil	Fluvial zone
E3	Body of the central reservoir, Guaíra City, Brazil	Fluvial zone
E5	Body of the central reservoir 15 Km upstream of the dam, Foz do Iguaçu City, Brazil	Lacustrine zone
E7	Arm of the reservoir formed by Arroio Guaçu River	Fluvial zone
E8	Arm of the reservoir formed by São Francisco Verdadeiro River	Transition zone
E11	Arm of reservoir formed by Passo Cue River	Lacustrine zone
E12	Arm of reservoir formed by São Francisco Falso River	Transition zone
E13	Arm of reservoir formed by Ocoí River	Lacustrine zone
E14	Arm of reservoir formed by Passo Cue River	Lacustrine zone
E20	Arm of reservoir formed by Ocoí River	Lacustrine zone

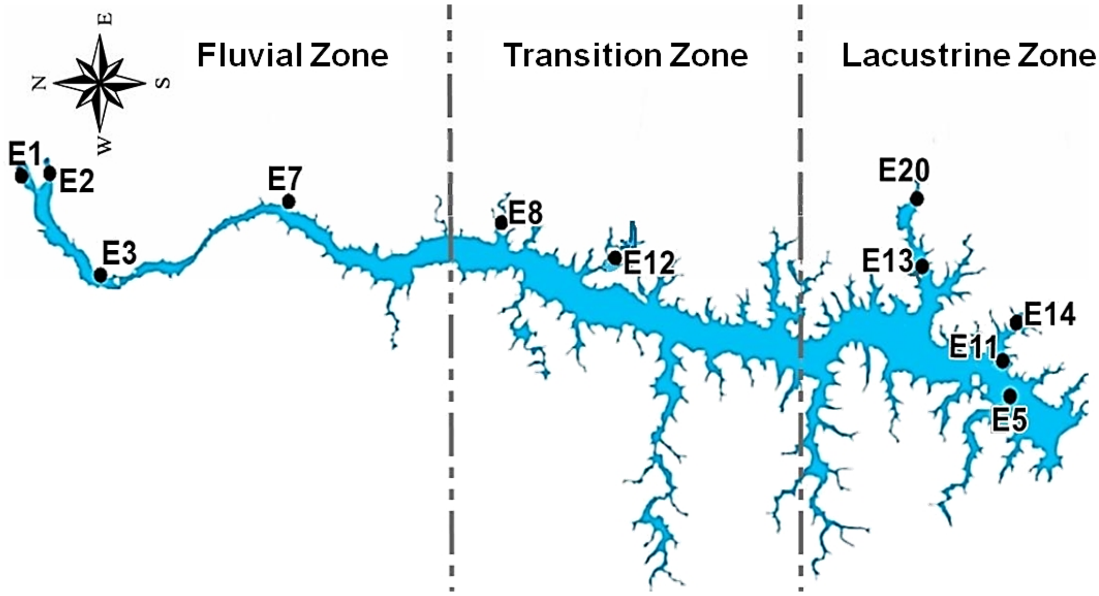

Fig. 1 Location of sampling stations in the Itaipu reservoir

2.3 Data Acquisition

The limnological data were provided by Itaipu Binacional and the analyzes were conducted by the Environmental Institute of Paraná water samples collected in the water surface using Van Dorn bottle. They comprise values of chlorophyll-α, total phosphorus, total Kjeldahl nitrogen (TKN) and transparency (measured with Secchi disc), analyzed according to the methodology described in Table 2. The analyzed data comprise a total of twenty-one quarterly samplings conducted between February 2008 and August 2014.

2.3 Data Analysis

The averages of the limnological variables were calculated by grouping the quarterly values by sampling stations, according to the zone of the reservoir (fluvial, transition and lacustrine).

For the means of limnologic variables, the measured quarterly values were grouped by each quarter sampling station and also according to the area of the reservoir in which each sampling point belongs.

The differences at company level as well as in the single consumption sectors are.

Table 2 Analytical methods of each limnological variable.

Limnological variable	Unit	Analytical method
Chlorophyll-α	$mg.m^{-3}$	Spectrophotometer, brand DMS 100, at wavelengths 750 nm and 665 nm [14]
Total phosphorus	$mg.L^{-1}$	Ascorbic acid method [15]
Nitrogen Kjeldahl total	$mg.L^{-1}$	Phenate method [15]
Transparency	m	Secchi disc [16]

In order to evaluate the trophic degree of the waters of the Itaipu dam, the Trophic State Index (TSI) of Carlson [5], adapted for subtropical climate [6] where the TSI for transparency (S), total phosphorus (Ptotal) and chlorophyll-α (C) is calculated, and, finally, the mean TSI, by means of a weighted average, assigning weight 2 to concentrations of chlorophyll-α and total phosphorus and weight 1 to water transparency.

Based on the mean TSI values calculated for the Itaipu Dam areas, one of the trophic status classes was assigned: ultraoligotrophic (TSI ≤ 47), oligotrophic (47 < TSI ≤ 52), mesotrophic (52 < TSI ≤ 59), eutrophic

(59 < TSI ≤ 63), supereutrophic (63 < TSI ≤ 67), hypereutrophic (TSI ≥ 67) [7].

An analysis of variance (ANOVA) was applied to compare the TSI values between the reservoir zones and between the dry and rainy periods. In addition to the calculation of the TSI, the physicochemical variables of water were compared to the limits established by the National Environmental Council [17], to verify the classification of reservoir waters in class 2 — attributed due to the uses that are intended.

3. Results and Discussion

3.1 Trophic State Index (TSI)

As can be seen in Fig. 2, in the fluvial zone the mean and maximum TSI values calculated were, respectively, 49.67 (in February 2010) and 6.22 (in February 2008), and the mean value for this zone was 40.43. In the transition zone the maximum and minimum values of the average TSI were, respectively, 56.54 (in August 2014) and 34.60 (in March 2012); and the mean value for this zone was 43.54. In the lake area, the maximum and minimum values of the average TSI were, respectively, 48.14 (in August 2014) and 25.17 (in May 2013); and the mean value for this zone was 34.25.

Of the sixty-three mean TSI values recorded in the twenty-one sampling campaigns (three values per campaign, respective to each of the reservoir zones), the three TSI values classified the reservoir as ultraoligotrophic, seven values classified it as oligotrophic, and three values classified it as mesotrophic (in November 2009 and August 2009 and 2014).

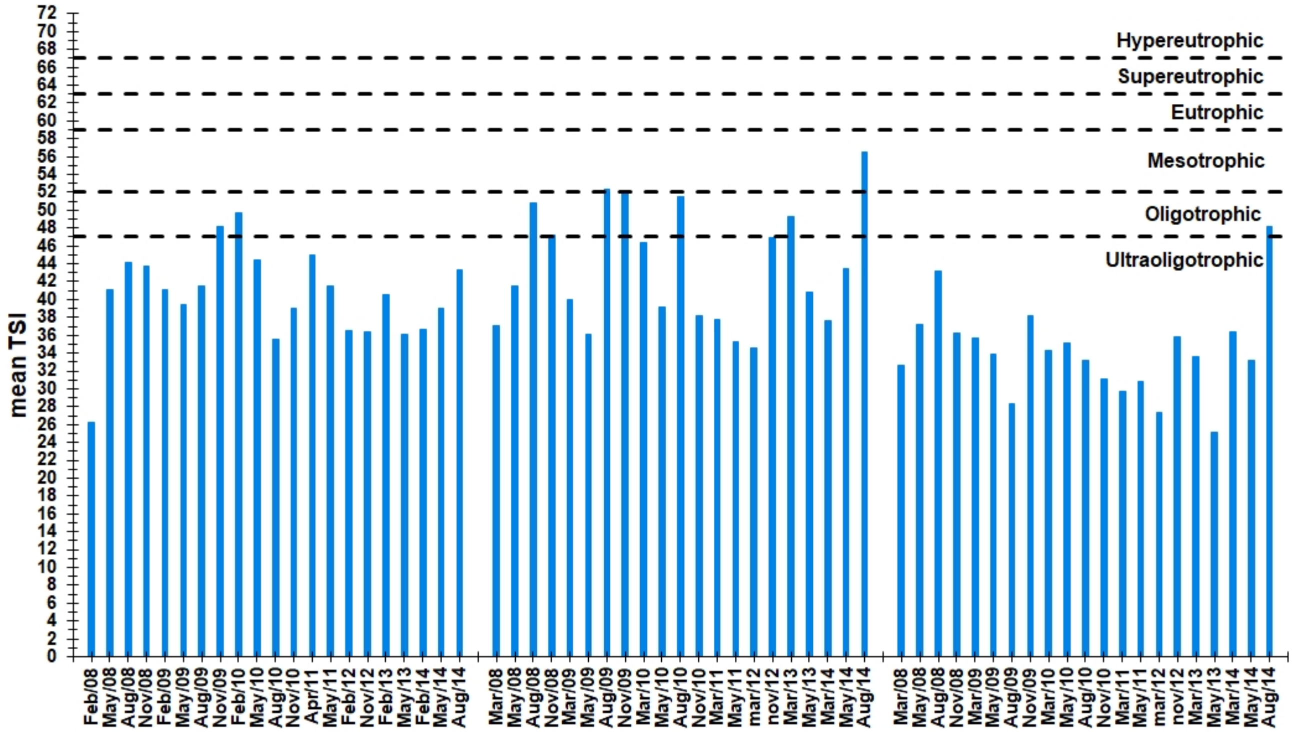

Fig. 2 Average trophic state index by reservoir zone from 2008 to 2014

The reservoir can be classified as ultra-lithotrophic, both by the average value of the TSI of 39.41 and by the majority of the average values of TSI that classify the waters as ultraligotrophic (84.13% of the means), as verified in a precursor study to this one (TSI = 45.50), for the entire reservoir [13], and the TSI of 28.41 for the area of the reservoir with fish tank-net activity [18]. Differences in nomenclature between the present work and the authors mentioned above are due to the updating of the classification [7].

The Itaipu Dam showed lower trophic level than reservoirs Hubian, Shidou, Bantou and Tingxi located in an urbanized region of southeast Chinese, also under subtropical — the four reservoirs presented TSI values varying in the bands of 50 to 70 [19]. It is important to note that differences of this type, in the case of a similar climate, are potentially related to the occupation of the basin and the measures adopted to mitigate the anthropic impacts on water quality.

The analysis of variance showed a significant difference between the means of TSI of the reservoir zones. The subsequent comparison showed that the lacustrine zone differs significantly from the transition and fluvial zones — and these do not differentiate between them (Fig. 3). The residuals presented normal distribution, confirmed by the Lilliefors test (p = 0.873).

The significant variation of the trophic state between the reservoir zones, evidenced in periods prior to this study [13] remained, unlike that observed for the Barra Bonita reservoir (São Paulo, Brazil) where the rainfall regime influences the variation of the average TSI and the zones did not present significant differences among them [19]. It is also different from the Porto Primavera reservoir, where the rainfall and temperature regime shows a significant variation in the average TSI [21].

While the TSI of the reservoir in its entirety did not have significant variation depending on the different seasons of the year and rainfall regime, varied in the area intended for aquaculture the TSI varied significantly throughout the seasons and did not spatially varied. It is important to emphasize that the aquaculture area corresponds to a small portion of the reservoir and metabolic activities involved in the distinct aquatic environment given the pressure exerted by pisciculture.

The mean TSI for Itaipu also differed from that calculated for the Ekbatan Dam reservoir in Iran, whose eutrophication status in the wet hydrological season may be higher than during the dry season [22], which corresponds better to the observed behavior in the Poções Dam, in the Brazilian northeast [23] possibly due to climate similarity. In these examples,

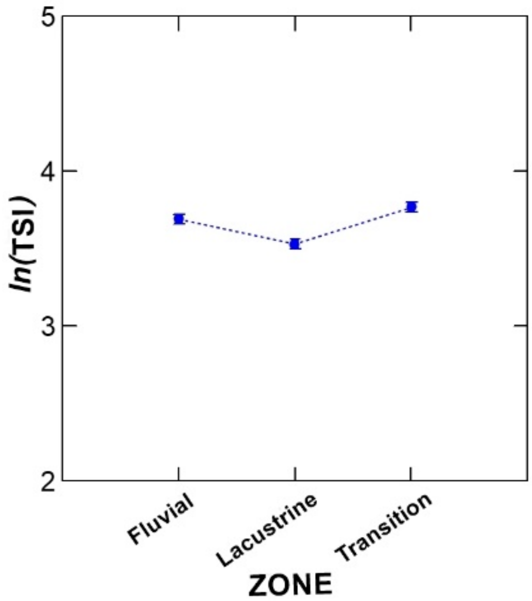

Fig. 3 Adjusted means of the natural logarithm of the average TSI (*lnTSI*) for the zones of the reservoir.

the increase of the trophic degree can be associated to the nutrient supply by the precipitation flow.

3.2 Limnological Vvariables

The Itaipu reservoir presents strong relationships between the lotic, intermediate and lentic regions, which suggest the explanation of the seasonal oscillations by the hydrodynamic process, in particular by the discharges suffered by the Paraná River, culminating in a floating dynamics for the limnological variables. Different variations related to the zones were registered for the Itaipu reservoir, as well as the influence of the transport and deposition of particles in the ecological processes [13, 24].

3.2.1 Chlorophyll-α

The average concentrations of chlorophyll-α (Fig. 4) of the three zones of the reservoir throughout the analysis period were below the limit of 30.0 $\mu g.L^{-1}$ established by CONAMA for water to class 2 [17], unlike most concentration recorded for the lake Barigui (Curitiba, PR, Brazil) [2] and high chlorophyll concentrations recorded for Barra Bonita Dam (Barra Bonita, SP, Brazil) [20].

In the fluvial zone the maximum concentration of chlorophyll-α was 6.8 $\mu g.L^{-1}$ (average of November

2009), in February 2008 there was no detection of this variable and the mean value for the region was 1.8 μg.L^{-1}. In the transition zone was observed maximum value of chlorophyll-α (both to this zone, as the reservoir for the entire sample period) of 17.7 μg.L^{-1} in August 2014, the minimum concentration was 0.9 μg.L^{-1}, in May 2011 and the mean concentration for this zone over the analyzed period was 5.8 μg.L^{-1}. In the lacustrine zone, the minimum (May 2013) and maximum (August 2008) values were respectively 0.2 and 5.6 μg.L^{-1}. The mean concentration for this zone over the analyzed period was 2.0 μg.L^{-1}.

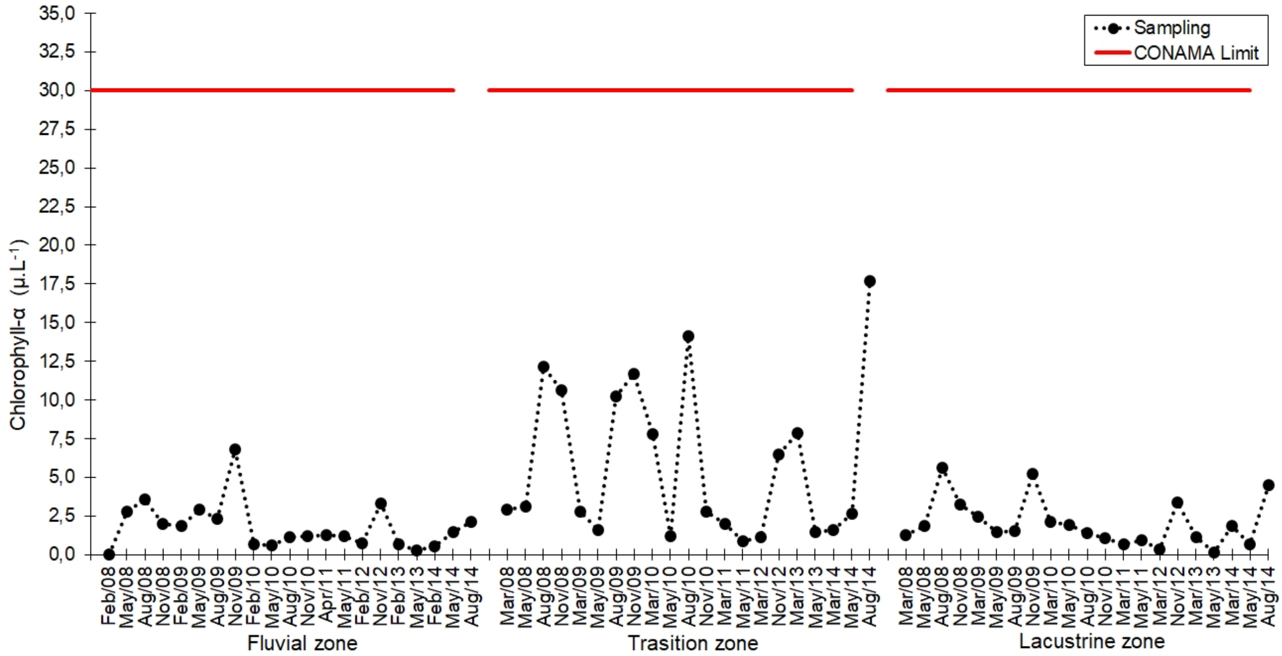

Fig. 4 Concentrations of chlorophyll-α per reservoir zone from 2008 to 2014.

In the fluvial zone, there were lower chlorophyll-a concentrations, with an increase in the transition zone (region whose watershed section has intensive agricultural activities implemented) and fall in the lacustrine zone, like that observed anteriorly for the Itaipu Dam [25]. It is also possible to observe differences in the chlorophyll-α behavior due to the climate, when comparing, for example, to the Ekbatan Dam in Iran, in a semi-arid hot climate region, where the concentration of chlorophyll-α at the entrance to the reservoir is higher than in the intermediate region and near the dike [22].

The ANOVA indicated a difference between the zones of the reservoir. As for the rainfall regime, there was no difference. The subsequent comparison showed that the average chlorophyll transition zone differs statistically from the averages river and lake areas (which showed no significant difference between them) (Fig. 5). The residuals presented normal distribution, confirmed by the Lilliefors test, whose probability value was p = 0.744.

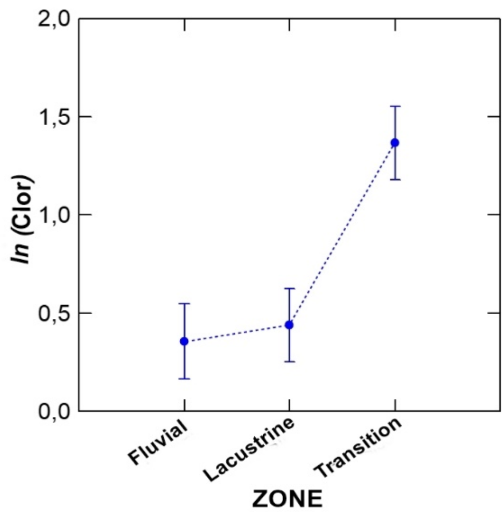

Fig. 5 Adjusted means of the natural logarithm of the concentration of chlorophyll (*ln* chlor) to the zones of the reservoir.

The longitudinal distribution pattern of chlorophyll-α observer in previous studies was maintained [25]: fluvial and lacustrine zones were similar, while the transition zone was different from the two above-mentioned ones.

The minimum values and the overall chlorophyll-α, of 3.2 $\mu g.L^{-1}$ observed in the present study were lower than those observed for the period from 1999 to 2004 (overall average concentration of 9.2 $\mu g.L^{-1}$ and the lowest average concentrations in the reservoir river and lake areas, respectively, 6.1 and 8.9 $\mu g.L^{-1}$) [25], indicating a possible fall in the primary productivity of the Itaipu reservoir.

3.2.2 Total Phosphorus

All concentrations of total phosphorus to the fluvial zone (Fig. 6) were below the maximum limit established by CONAMA Resolution No. 357/05 for the quality of class 2 waters in a lotic environment (0.100 mg.L-1) [17], different that observed during the period from 1999 to 2004, which corresponds to the highest average concentration of total phosphorus of 0.324 mg.L-1 in the fluvial zone [25]; and different from the concentrations above the environmental standard found in Lake Barigui (Curitiba, PR, Brazil) [2]. The maximum and minimum concentrations were, respectively, 0.039 mg.L-1 in February 2010 and 0.015 mg.L-1 in August of the same year. The mean concentration of phosphorus was 0.026 mg.L-1.

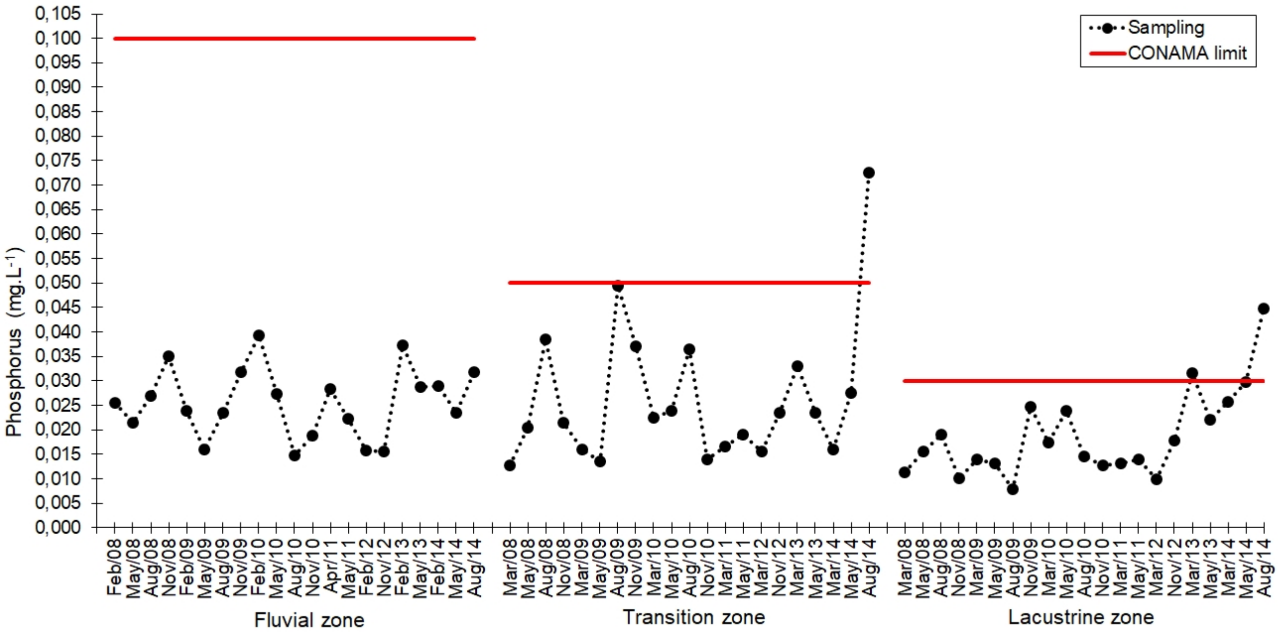

Fig. 6 Concentrations of phosphorus per reservoir zone from 2008 to 2014.

In the transition zone, whose recommended phosphorus limit concentration for adequate water quality is 0.050 $mg.L^{-1}$ [17], the highest concentration was 0.073 $mg.L^{-1}$ in August 2014. The lowest concentration was 0.013 $mg.L^{-1}$ in March 2008, and the mean concentration was 0.026 $mg.L^{-1}$.

In lacustrine zone were observed two peaks of total phosphorus concentrations above the limit of 0.03 mg L^{-1} for lentic environment: 0.045 mg L^{-1} in August 2014 and 0.032 mg L^{-1} in March 2013. The lowest concentration observed was 0.008 $mg.L^{-1}$ in August 2009. The mean for this zone was 0.019 $mg.L^{-1}$.

The overall average total phosphorus into the reservoir during the study period was 0.024 mg L^{-1} value below the average of 0.031 mg L^{-1} for previous work ascertained [25].

From the ANOVA, it was observed a difference between the zones of the reservoir, corroborating the one observed for the period from 2008 to 2014 [25]. Regarding the rainfall regime, there was no difference for this limnological variable.

The posterior comparison showed that the average concentrations of total phosphorus of the fluvial and transition zones showed no significant difference between them but are differ of the lacustrine zone having means of total phosphorus higher in this region (Fig. 7). The residuals presented normal distribution, confirmed by the Lilliefors test, whose probability value was p = 0.232.

3.2.3 Total Kjeldahl Nitrogen (TKN)

Fig. 8 represent graphically the averages the of total Kjeldahl nitrogen (TKN) concentrations recorded at the monitoring stations in each sampling campaign (grouped by zone of the reservoir).

The biggest mean TKN concentration observed was 0.93 mg.L^{-1} at the transition zone in August 2014 and the minor was 0.12 mg.L^{-1}, occurring twice: in May 2009 at lacustrine zone and in May 2010 at fluvial zone, whereas a previous study recorded the highest concentration of TKN (1.20 mg.L^{-1}) in the lacustrine zone, the lower concentration (0.04 mg.L-1) in the transition zone and [25]. The concentration average of TKN on the reservoir was 0.26 mg.L^{-1} (ten milligrams below that recorded for the previous historical series [25]).

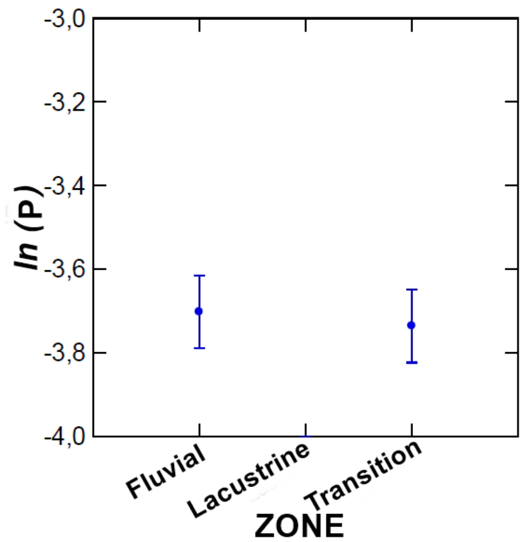

Fig. 7 Adjusted means of the natural logarithm of the concentration of phosphorus (*ln* P) to the zones of the reservoir.

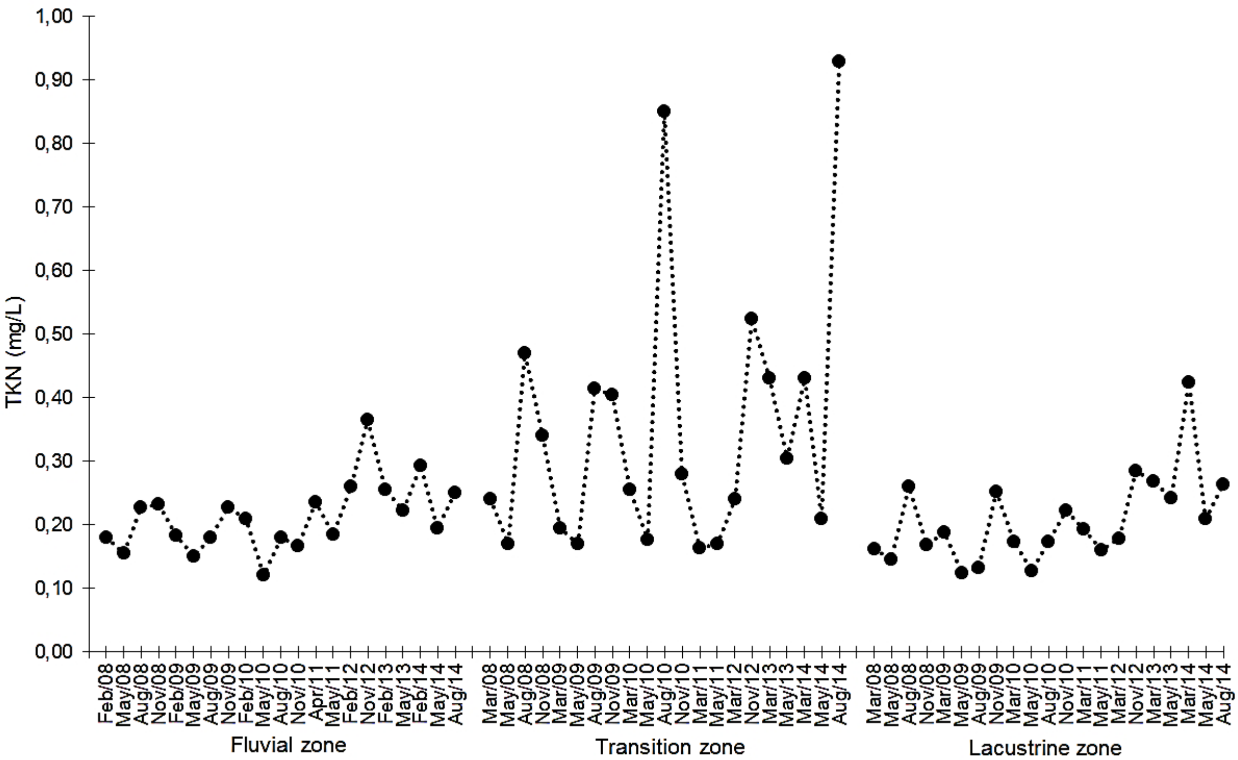

Fig. 8 Concentrations of TKN per reservoir zone from 2008 to 2014.

The majors concentrations of TKN for the fluvial zone and lacustrine zone was, respectively, 0.37 (in March 2014) and 0.42 mg L^{-1} (in November 2012), as well as the minimum TKN value of 0.16 mg.L^{-1} for the transition zone — at the samplings of March 2008 and May 2011. At the transition zone of the reservoir the minor mean TKN concentration registered was 0.16 mg.L^{-1}, occurring twice: in first time at March 2008 e again in May 2011.

The ANOVA evidenced the difference between the means of the reservoir zones corroborating a anterior study [25]. However, between the rainy and dry seasons there was no significantly difference. The subsequent comparison showed that the mean concentration of TKN in transition zone differs significantly from the mean values of the fluvial and lacustrine zones (which did not show significant difference between them) (Fig. 9). The residuals presented normal distribution, confirmed by the Lilliefors test, whose probability value was p = 0.276.

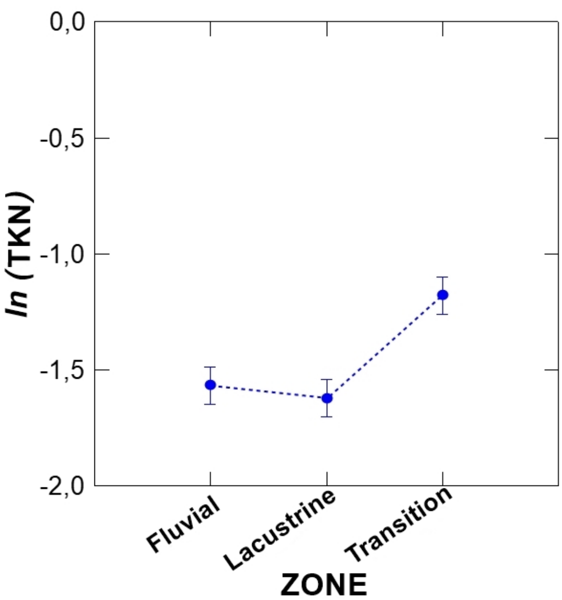

Fig. 9 Adjusted means of the natural logarithm of the concentration of total Kjeldahl nitrogen (*ln* TKN) to the zones of the reservoir.

4. Conclusion

The reservoir can be classified as ultraoligotrophic and the quality of water can be considered suitable for the purposes for which they are intended, based on the parameters analyzed. The improvements verified over time, from the comparison of the present study with precursor works, can be attributed to the good environmental management resulting from the Itaipu environmental monitoring program and adjustments in the management of basin catchment resulting from education and environmental awareness. Improving the water quality of an aquatic environment throughout the historical series does not dispense with the continuous need and importance of periodic monitoring and the combined actions of environmental management in order to preserve water resources for the future.

Acknowledgements

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