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Research Article

Spatial and temporal limnological changes of an aquaculture area in a neotropical reservoir

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Abstract – This study evaluated the spatial and temporal limnological characteristics of an aquaculture area in the Itaipu reservoir, Brazil. During a one-year period, water quality parameters were evaluated in seven collection sites using a fish culture system as the reference point. A regression analysis was performed on water transparency *versus* chlorophyll *a* and total phosphorus *versus* chlorophyll *a*. The trophic state index (TSI) was calculated using data from water transparency, chlorophyll *a*, and total phosphorus. In addition, a study of the carrying capacity was conducted in situations of high and low flow and rainfall based on 725 $m^3 s^{-1}$ and 298 mm and 34.5 $m^3 s^{-1}$ and 11 mm, respectively. No difference was observed in the parameters of water quality and the TSI in relation to the collection sites; these parameters only varied significantly throughout the seasons. The regression analysis showed that increased total phosphorus in the environment leads to increase in chlorophyll *a* concentrations and consequently decreased water transparency. Evaluation of the carrying capacity demonstrated that under conditions of high precipitation and flow it is possible to produce 623.7 tons of fish per year, which is above the total cultivated in fish farms at the study site.

Keywords: Carrying capacity / eutrophication / reservoir management / trophic status index

1 Introduction

Pisciculture in cages is considered an efficient form of fish culture and has been regarded as a good production system capable of fulfilling the increased demand for animal protein caused by population growth and an increasing interest in healthy foods (Crepaldi *et al.*, 2006; Demétrio *et al.*, 2012). The main advantage of this type of production is the fact that it can be installed in already existing environments such as seas, lakes, and mainly reservoirs. It costs less and can be quickly and easily implemented, managed, and harvested. It also produces high-density stocking and water renewal (Ono and Kubitza, 2003; Degefu *et al.*, 2011; Demétrio *et al.*, 2012).

Brazil has favorable conditions for fish farming in cages because of its five million hectares of fresh water in reservoirs found in all of the large hydrographic basins in the country (Agostinho *et al.*, 2007; Bueno *et al.*, 2008). Although the water resources present in these environments are mainly used in energy production, they can be used for irrigation as well as production of aquatic organisms (Tundisi, 2005). The Brazilian legislation allows 1% of the total area of a reservoir to be expended for aquaculture production without exceeding the limit load of 30 mg m^{-3} of total phosphorus in the environment (David *et al.*, 2015).

Although reservoirs have the capacity to balance the effects of nutrient intake, the loads generated by metabolic waste and unconsumed food from fish farming must be within the environment's capacity of assimilation in order to avoid environmental collapse through eutrophication (Degefu *et al.*, 2011; David *et al.*, 2015; Venturoti *et al.*, 2015), a situation which, in turn, also negatively affects fish production. Therefore, the spatial and temporal monitoring of the limnological characteristics at fish production sites through the investigation of water quality parameters and evaluation of trophic state index (TSI) and carrying capacity is essential in order to avoid environment overloading (Varol *et al.*, 2012; Cunha *et al.*, 2013).

Efficient aquaculture production is based on guidelines for sustainability, resilience, and good management practices. TSI and carrying capacity are effective tools for managing the use of reservoirs as they are based on parameters such as light availability and the amount of total phosphorus and chlorophyll *a* that directly and indirectly influence the development

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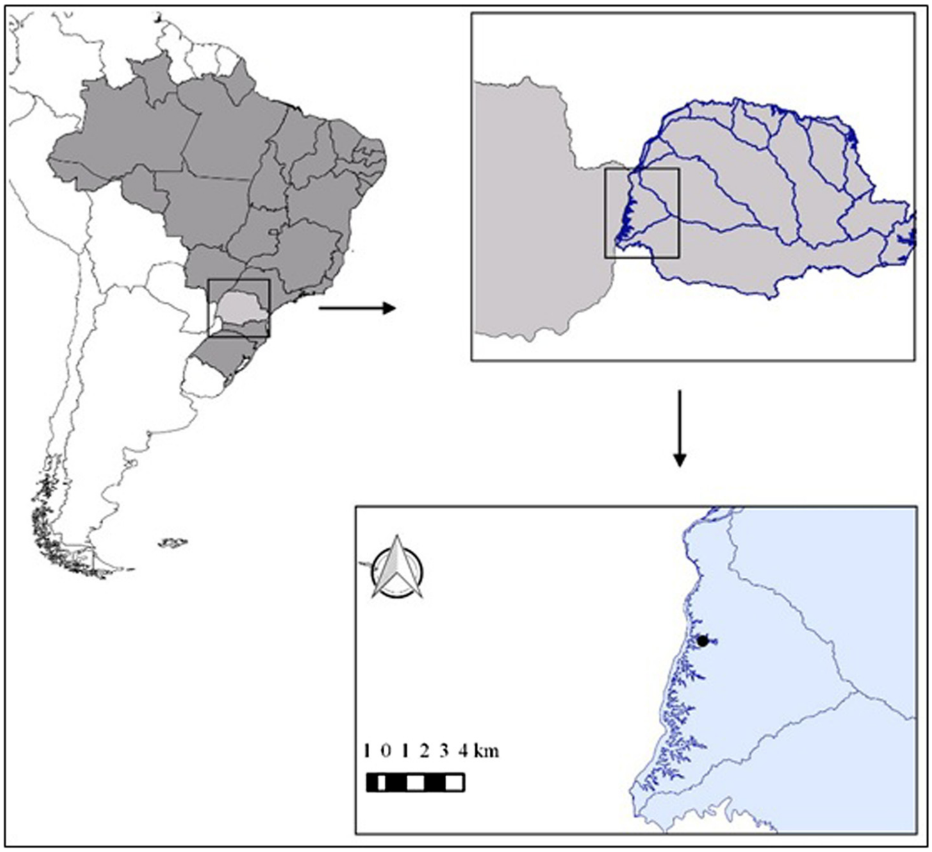

Fig. 1. Study site in the Itaipu reservoir in the city of Entre Rios do Oeste, State of Paraná, Brazil.

of algae biomass and, therefore, provide an understanding of the limnological profile. TSI and carrying capacity contribute to and indicate an increase in the enrichment condition of an aquatic system (Varol *et al.*, 2012; Cunha *et al.*, 2013; Ross *et al.*, 2013).

Hence, this study evaluated spatial and temporal parameters of water quality, calculated the TSI, and assessed the carrying capacity in two situations of flow and rainfall in an aquaculture area in the Itaipu reservoir in order to provide data for planning, decision making, and integrated aquaculture management. The Itaipu reservoir is the largest energy producing reservoir in Brazil with an area of 1 350 km^2 (Agostinho *et al.*, 2007).

2 Materials and methods

2.1 Time and study site

The study was conducted in an aquaculture area in the Itaipu Hydroelectric Power Plant artificial reservoir located in the city of Entre Rios do Oeste, in the State of Paraná, Brazil. Water samples were collected bimonthly during one year. Seven collection sites were established for the analysis of limnological parameters allowing for a temporal and spatial evaluation.

The collection sites were determined upstream and downstream from the location of a production system of Pacu (*Piaractus mesopotamicus*, Holmberg, 1887) in network tanks, used as the reference central point for the areas studied: P1 (500 m upstream), P2 (300 m upstream), P3 (100 m upstream), P4 (Pacu production system at −54.241001 longitude and −24.685842 latitude), P5 (100 m downstream), P6 (300 m downstream), and P7 (500 m downstream) (Fig. 1). In addition, total biomass data and the amount of feed supplied to the fish were recorded on collection days. The temporal evaluation was performed using seasonal averages obtained for the period studied.

2.2 Limnological parameters and TSI

The following water quality parameters were evaluated on surface water: dissolved oxygen (mg L^{-1}), temperature (°C), pH, and electrical conductivity (μS cm^{-2}). Electrical conductivity was measured with the aid of the YSI Professional Plus multiparameter equipment, while transparency (cm) was measured with a Secchi disk. In addition, water samples were collected from the epilimnion (surface layer) and hypolimnion (deep layer at the maximum onsite depth) using a Van Dorn bottle to analyze the vertical water profile.

The samples were stored in polyethylene bottles and kept refrigerated for later analysis in the Quality Control Laboratory of the Aquaculture Management Study Group at the West of Paraná State University. Biochemical oxygen demand (APHA, 1998), chlorophyll *a* (Wetzel and Likens, 1991), total phosphorus, orthophosphate (Mackereth *et al.*, 1978), and ammonia (Strickland and Parsons, 1972) were evaluated in the laboratory.

A linear regression analysis ($p < 0.05$) was performed with chlorophyll *a*, total phosphorus, and water transparency data to determine the correlation between phosphorus and chlorophyll *a*, and transparency and chlorophyll *a*. TSI was determined at all sampling sites and periods using equations one to four, and according to the methodology described by Carlson (1977) and modified by Toledo Jr *et al.* (1983) as follows:

$$TSI(S) = 10 * \{6 - [(0.64 + \ln(S))/\ln 2]\}$$

$$TSI(Chla) = 10 \times \{6 - [2.04 - 0.95 + \ln(Chla))/\ln 2]\}$$

$$TSI(PT) = 10 \times \{6 - [\ln(80.32/PT)/\ln 2]\}$$

$$TSI = (TSI(S) + TSI(Chla) + TSI(PT))/3$$

where S is water transparency readings according to the depth of the Secchi disk (m), Chla is surface chlorophyll concentration ($\mu g\,L^{-1}$), PT is surface total phosphorus concentration ($\mu g\,L^{-1}$) and TSI is trophic state index.

2.3 Assessment of the carrying capacity

Carrying capacity was evaluated under conditions of low and high rates of precipitation and flow. The values considered were 34.5 and 725 $m^3\,s^{-1}$ for flow and 11 and 298 mm for the accumulated average precipitation. The methodology described for fish farming in cages, developed by Dillon and Rigler (1974) and Attayde and Panosso (2011), was used.

In addition, the water quality classification was based on Brazilian legislation (Resolution 357/05 of Conama, Brazil, 2005) where waters of lentic environments available for fish farming fall into class 2 with an annual phosphorus limit of 30 $\mu g\,L^{-1}$. It was assumed that the fish farming activity could contribute up to 1/3 of the phosphorus contribution as described by Attayde and Panosso (2011). Thus, the allowable phosphorus variation in the environment was first determined as:

$$\Delta = [P] = [P]_f - [P]_i = 30 - [P]_i$$

where $\Delta[P]$ is allowable phosphorus concentration variation in the environment, $[P]_f$ is maximum allowable phosphorus concentration in the environment (30 $\mu g\,L^{-1}$) and $[P]_i$ is average annual phosphorus concentration in the ecosystem.

The amount of additional allowable phosphorus for the aquaculture enterprise was subsequently calculated as described by Beveridge (2004):

$$Lp = (\Delta[P] * Z * \Theta)/(1 - Rp)$$

where L_p is allowable phosphorus load derived from fish farming in cages ($g\,m^{-2}\,year^{-1}$), $\Delta[P]$ is allowable phosphorus concentration variation in the environment, Z is Local mean depth (m), Θ is fraction of the water column that is annually lost to downstream reservoir ($m^3\,year^{-1}$) and R_p is fraction of this load that sediments and is retained in the reservoir sediment.

The maximum phosphorus load from the Pacu (*P. mesopotamicus*) production was estimated based on the maximum allowable phosphorus load, and according to the methodology described by Beveridge (2004). For this purpose, a production system of 160 cages measuring 5 m^3, with 75 $kg\,m^{-3}$ of fish productivity, 2.49 feed conversion, and total consumption of 149 400 kg of feed (Signor *et al.*, 2011; Silva *et al.*, 2012) was considered:

$$P_e = (P_f * FCR - P_a)$$

where P_e is phosphorus contribution per ton of fish produced, P_f is phosphorus concentration in the feed provided ($kg\,ton^{-1}$) calculated according to Signor *et al.* (2011), FCR is feed conversion according to Silva *et al.* (2012), and Pa is phosphorus amount in whole fish estimated according to Signor *et al.* (2011).

The carrying capacity of the reservoir (CC) was calculated by the ratio between the maximum allowable phosphorus load for the fish farming activity and the phosphorus load released into the environment per ton of fish produced:

$$CS = Lp/Pe$$

where CS is carrying capacity ($ton\,year^{-1}$), L_p is allowable phosphorus load derived from fish farming in cages ($g \times m \times year^{-1}$) and P_e is phosphorus contribution of per ton of fish produced.

2.4 Statistical analyses

Dissolved oxygen, pH, temperature, electrical conductivity, and water transparency data were evaluated using analysis of variance (ANOVA) with a 5% probability in relation to collection sites and seasons. The other water quality parameters were evaluated using ANOVA in a factorial scheme considering "collection sites *versus* layers" and "seasons *versus* layers."

3 Results

3.1 Parameters of water quality and TSI

The values of physical-chemical variables of water differed statistically only between seasons ($p < 0.05$) and not between collection sites ($p > 0.05$) (Tab. 1). Dissolved oxygen demonstrated seasonal variations with values ranging from a low of 3.78 ± 0.59 $mg\,L^{-1}$ recorded during summer to a high of 14.61 ± 3.15 $mg\,L^{-1}$ in the autumn. The highest temperatures were recorded in the spring and summer while the lowest were recorded in the fall and winter. Temperatures were never lower than 19 °C. The values of electrical conductivity were lowest in the summer, but values in other seasons were not statistically different, remaining above 45.6 $\mu S\,cm^{-2}$. Water transparency values varied from 0.75 to 2.35 m in the annual cycle; the highest value was observed in the summer.

Values for biochemical oxygen demand, chlorophyll *a*, total phosphorus, orthophosphate, and ammonia showed no significant difference with respect to collection sites and layers (epilimnion and hypolimnion) or interactions between these two points ($p < 0.05$) (Tab. 2).

Factorial analysis for these same parameters, based on season and collection layer showed a significant seasonal

Q1 **Table 1.** Parameters of water quality measured at collection sites and at different seasons.

Variables	Seasons				Mean sites	*p*-value	
	Spring	Summer	Autumn	Winter		Seasons	Sites
pH	7.6 ± 0.5^{b}	8.2 ± 0.1^{a}	7.2 ± 0.1^{b}	8.2 ± 0.2^{a}	7.8 ± 0.2	0.0	0.9
DO ($mg\,L^{-1}$)	7.8 ± 1.5^{b}	3.8 ± 0.5^{c}	14.6 ± 3.2^{a}	8.7 ± 0.3^{b}	8.7 ± 1.4	0.0	0.9
Temperature (°C)	26.9 ± 3.2^{a}	28.5 ± 0.2^{a}	23.2 ± 0.1^{b}	19.8 ± 0.1^{b}	25.5 ± 0.8	0.0	0.9
EC ($\mu S\,cm^{-2}$)	45.2 ± 25.1^{a}	10.1 ± 0.1^{b}	63.9 ± 6.7^{a}	48.8 ± 6.3^{a}	42.6 ± 9.5	0.0	0.9
Transparency (m)	0.7 ± 0.4^{c}	2.4 ± 0.2^{a}	1.6 ± 0.1^{b}	0.7 ± 0.1^{c}	1.3 ± 0.2	0.0	0.9

Data in the same row with different letters are significantly differ ($p < 0.05$) among different seasons.
DO = Dissolved oxygen.
EC = Electrical conductivity.

Table 2. Variations in the vertical water parameters for biochemical oxygen demand (BOD), chlorophyll *a* (Chla), total phosphorus (TP), orthophosphate (Ortho), and ammonia in relation to sites and layers (epilimnion and hypolimnion).

Variables	Layers	Sites						
		1	2	3	4	5	6	7
BOD ($mg\,L^{-1}$)	Bottom	4.9 ± 1.2	3.7 ± 0.8	3.4 ± 2.9	6.6 ± 2.9	4.4 ± 3.2	5.2 ± 2.3	3.4 ± 2.5
	Surface	4.9 ± 1.7	4.6 ± 3.0	4.1 ± 1.7	3.4 ± 2.5	4.2 ± 1.8	5.8 ± 3.9	3.5 ± 3.0
Chla ($\mu g\,L^{-1}$)	Bottom	2.9 ± 2.3	3.9 ± 2.9	4.2 ± 4.3	3.5 ± 4.3	3.5 ± 2.1	3.7 ± 1.9	5.8 ± 2.7
	Surface	4.5 ± 2.5	3.9 ± 3.2	4.8 ± 3.5	4.3 ± 2.3	4.4 ± 3.4	4.6 ± 3.7	5.3 ± 2.1
TP ($\mu g\,L^{-1}$)	Bottom	29.8 ± 0.0	29.0 ± 0.0	29.6 ± 0.0	27.8 ± 0.0	32.4 ± 0.0	35.7 ± 0.0	28.3 ± 0.0
	Surface	32.4 ± 0.0	27.1 ± 0.0	32.4 ± 0.0	26.7 ± 0.0	25.4 ± 0.1	27.6 ± 0.0	26.2 ± 0.0
Ortho ($\mu g\,L^{-1}$)	Bottom	27.5 ± 0.0	28.9 ± 0.0	27.4 ± 0.0	27.4 ± 0.0	32.9 ± 0.0	31.6 ± 0.0	29.4 ± 0.0
	Surface	23.6 ± 0.0	25.7 ± 0.0	26.7 ± 0.0	25.9 ± 0.0	29.8 ± 0.0	26.9 ± 0.0	26.8 ± 0.0
Ammonia	Bottom	38.2 ± 0.0	39.6 ± 0.0	36.9 ± 0.0	39.2 ± 0.0	39.6 ± 0.0	41.9 ± 0.0	41.8 ± 0.0
($\mu g\,L^{-1}$)	Surface	37.2 ± 0.0	38.4 ± 0.0	38.0 ± 0.0	37.4 ± 0.0	39.7 ± 0.0	$37.4 \pm .0$	36.8 ± 0.0

Table 3. Variations in the vertical water parameters for biochemical oxygen demand (BOD), chlorophyll *a* (Chla), total phosphorus (TP), orthophosphate (Ortho), and ammonia in relation to seasons and water layers.

Variables	Layers	Seasons				*p*-value		
		Spring	Summer	Autumn	Winter	L	S	I
BOD ($mg\,L^{-1}$)	Bottom	3.7 ± 2.1^{bA}	2.6 ± 1.7^{bA}	6.4 ± 2.5^{aA}	6.3 ± 1.2^{aA}	0.59	0.00	0.01
	Surface	4.1 ± 1.6^{bA}	1.7 ± 1.4^{bA}	3.9 ± 2.2^{bB}	8.3 ± 1.5^{aA}			
Chla ($\mu g\,L^{-1}$)	Bottom	5.1 ± 2.9^{A}	1.8 ± 1.4^{bA}	1.8 ± 0.5^{bA}	4.4 ± 1.7^{abA}	0.43	0.00	0.69
	Surface	6.2 ± 2.8^{A}	1.4 ± 1.3^{bA}	2.5 ± 1.1^{bA}	4.7 ± 2.0^{abA}			
TP ($\mu g\,L^{-1}$)	Bottom	43.9 ± 0.0^{aA}	8.5 ± 0.0^{bA}	19.4 ± 0.0^{abA}	22.4 ± 0.0^{abA}	0.56	0.00	0.93
	Surface	47.7 ± 0.0^{aA}	7.6 ± 0.0^{bA}	20.8 ± 0.0^{abA}	29.8 ± 0.0^{abA}			
Ortho ($\mu g\,L^{-1}$)	Bottom	41.8 ± 0.0^{A}	22.2 ± 0.0^{bA}	8.3 ± 0.0^{dA}	15.8 ± 0.0^{cdA}	0.03	0.00	0.52
	Surface	40.2 ± 0.0^{aA}	18.9 ± 0.0^{bA}	3.8 ± 0.0^{dA}	15.4 ± 0.0^{cdA}			
Ammonia ($\mu g\,L^{-1}$)	Bottom	18.5 ± 0.0^{bA}	95.8 ± 0.0^{A}	88.8 ± 0.0^{A}	0.1 ± 0.0^{bA}	0.64	0.00	0.90
	Surface	16.8 ± 0.0^{bA}	96.3 ± 0.0^{A}	80.3 ± 0.0^{A}	0.1 ± 0.0^{bA}			

Different lowercase letters in the same row for each parameter indicate statistical difference ($p < 0.05$).
Different uppercase letters in the same column for each parameter indicate statistical difference ($p < 0.05$).
L = Layers.
S = Seasons.
I = Interaction.

difference ($p < 0.05$) for all items evaluated. The only significant difference observed in the results from collection layers was in orthophosphate; the interaction between the two factors (epilimnion and hypolimnion) was observed only for biochemical oxygen demand (Tab. 3).

The regression analysis between transparency and chlorophyll *a* showed a negative correlation with the R^2 value of 0.8792, whereas that analysis between phosphorus and chlorophyll *a* showed a positive correlation with an R^2 value of 0.8374 (Figs. 2 and 3). However, these correlations were not

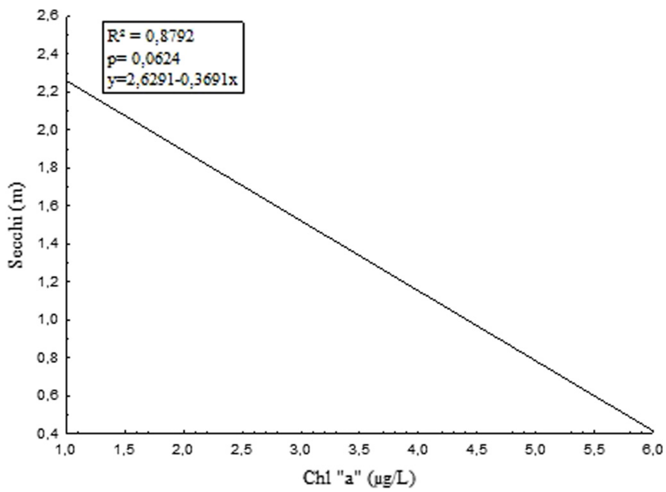

Fig. 2. Regression between values of transparency (Secchi) and chlorophyll *a* (Chl "a") in relation to seasons.

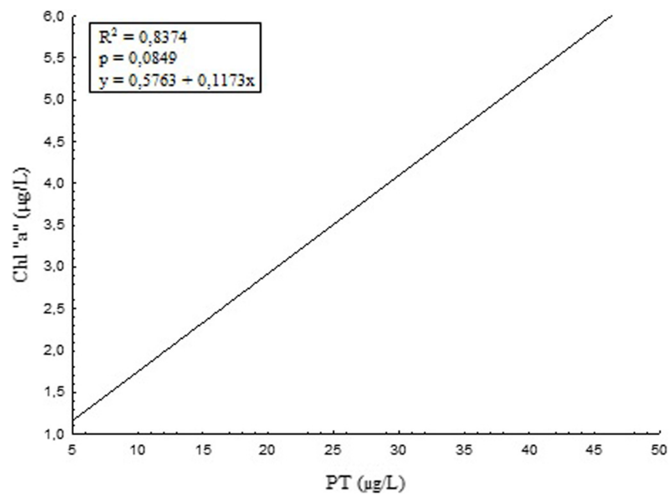

Fig. 3. Regression between the values of chlorophyll *a* (Chl "a") and total phosphorus (PT) in relation to seasons.

Table 4. Mean of trophic state index in relation to seasons and collection sites in the studied aquaculture area in the Itaipu Reservoir.

Parameters	TSI (Chla)	TSI (TP)	TSI (S)	TSI	Trophic classification
Seasons					
Spring	57.9	52.5	54.7	55.1	Eutrophic
Summer	42.6	26.1	38.4	35.7	Oligotrophic
Autumn	48.8	40.5	44.2	44.5	Mesotrophic
Winter	55.2	45.7	57.1	52.6	Eutrophic
Points					
1	52.8	46.9	49.4	49.7	Mesotrophic
2	53.3	44.3	48.9	48.8	Mesotrophic
3	54.6	50.4	48.7	51.3	Mesotrophic
4	53.3	44.1	48.7	48.7	Mesotrophic
5	53.3	54.2	48.9	52.2	Mesotrophic
6	53.9	44.5	48.9	49.2	Mesotrophic
7	56.3	43.7	48.8	49.6	Mesotrophic

Table 5. Carrying capacity in different flow and rainfall conditions in an aquaculture area of the Itaipu reservoir, located in the city of Entre Rios do Oeste, Paraná, Brazil.

Parameters/conditions	Flow 34.5 $m^3 s^{-1}$ Rainfall 11 mm	Flow 725 $m^3 s^{-1}$ Rainfall 298 mm
Rp	21.91	21.91
Δ[P] (µg L^{-1})	10	10
Evaluated area (m^2)	2 219 110 000	2 219 110 000
Average depth (m)	12	12
Lp (g × m^2 × $year^{-1}$)	0.5	11.36
Carrying capacity (ton $year^{-1}$)	27.80	632.70

Rp = Sedimentation rate.
Δ[P] = Allowable variation of phosphorus concentration in the environment.
Lp = Allowable phosphorus load derived from fish farming in cages.

significant ($p < 0.05$). Resulting equations were $y = 2.6291 - 0.3691x$ for transparency and chlorophyll *a* and $y = 0.5763 + 0.1173x$ for phosphorus and chlorophyll *a*.

There was no variation in the TSI in relation to the sites evaluated; however there was seasonal variation; the aquatic environment was classified as eutrophic in the winter and spring and as oligotrophic and mesotrophic in the summer and autumn, respectively (Tab. 4).

3.2 Carrying capacity study

The study demonstrated that the cumulative average rainfall of 298 mm and flow rate of 725 $m^3 s^{-1}$ resulted in a higher production capacity of 632.7 tons per year of Pacu (*P. mesopotamicus*), which is 22 times higher than Pacu production under conditions of low flow and rainfall (27.8 tons) (Tab. 5).

4 Discussion

According to Varol and Sen (2009), an inverse relationship occurs between temperature and dissolved oxygen because hot water easily becomes saturated and may contain less dissolved oxygen, a relationship consistent with our observations. In addition, high temperature is associated with increased metabolism of organisms, which consequently consume more oxygen to maintain their biological processes (Esteves, 1998).

Temperature variation was observed between the seasons, which not only are well defined in the south of Brazil but also oscillate between spring, autumn, summer, and winter (Feiden *et al.*, 2015). In tropical regions, conductivity values in aquatic environments are related to the local geochemical characteristics and to climatic conditions (dry and rainy seasons) rather than to trophic state (Esteves, 1998).

Meteorological data of the city of Entre Rios do Oeste noted lower precipitation levels in the summer than in the other seasons (Tab. 6). According to Diemer *et al.* (2010), electrical conductivity is a tool to evaluate the availability of nutrients in an aquatic ecosystem because it increases linearly with the concentration of salts in the environment. The allochthonous contribution of nutrients to an environment occurs during periods of high precipitation, leading to a high concentration of ions coming from suspended particles. Lowest rainfall is recorded in the summer; therefore, suspended particles are at a minimum concentration and water is clearer. This observation is consistent with Tundisi (2005), who states that rain plays an important role in water transparency.

The lack of significant difference in the water quality parameters between collection sites demonstrates that the fish farming system used as a reference is not changing the limnological profile of this environment since water samples were collected upstream and downstream of that aquaculture enterprise. Water flow is very important in choosing a location for the implementation of a fish farming system in cages because constant water movement and exchange allows greater oxygenation and prevents adverse effects caused by parameters such as phosphorus and ammonia.

The interaction between the layers and the seasons in relation to BOD is explained by the occurrence of stratification. The water on the surface by being warmer and receiving greater luminosity increases the metabolism and favors the photosynthesis of the primary organisms, resulting in a greater amount of oxygen. In addition, the water is less dense, remaining on the surface with little mass transfer, causing the oxygen produced in it, does not pass to lower layers, increasing the BOD in that region. With the decrease of the temperature in winter, the surface water cools, becoming less dense than the bottom water. In this way, mass transfer occurs between the upper and lower layers, causing the available oxygen on the surface to descend. This process causes that the BOD of the surface increase, but by the transfer of oxygen in the vertical profile of the water, there is no statistical variation regarding the demand between the layers (surface and bottom), as verified in the present study.

According to Silva *et al.* (2014), the growth of phytoplankton is mainly regulated by light and nutrient resources. The excess of nutrients in the aquatic environment, together with favorable light conditions, causes the excessive increase of algae populations, resulting in ecosystem eutrophication. Chlorophyll *a* is a pigment used to perform the first stage of the photosynthetic process; it is found in all plants that perform oxygenic photosynthesis (Streit *et al.*, 2005) and is considered a parameter in the determination of phytoplankton biomass (Kasprzak *et al.*, 2008).

Table 6. Rainfall index of the city of Entre Rios do Oeste, Paraná, Brazil, from December of 2013 to December of 2014, according to the Instituto das Águas do Paraná.

Data	Precipitation (mm)
December/2013	221.6
January/2014	156.6
February/2014	64.8
March /2014	172.0
April/2014	187.0
May/2014	215.0
June/2014	478.0
July/2014	139.0
August/2014	11.5
September/2014	413.9
October/2014	63.9
November/2014	146.9
December/2014	97.2

In the present study, water transparency is directly related to the concentration of phosphorus and chlorophyll *a*. This is demonstrated by the high value of R^2 found in the regression analysis which indicates that the combination of low transparency and high content of total phosphorus causes an increase in the amount of chlorophyll *a* in the aquatic environment. Nitrogen and phosphorus are limiting the nutrients in the development of phytoplankton (Silva *et al.*, 2014). However, nitrogen plays a less important role from the point of view of reservoir management when compared to phosphorus (Schindler *et al.*, 2008; Cunha *et al.*, 2013). Thus, the values of the Secchi disk and total phosphorus were only considered for the regression analysis (Cunha *et al.*, 2013).

Because temperature is always above the limiting values for growth in tropical lakes, it does not significantly affect temporal variation of phytoplankton (Esteves, 1998; Darchambeau *et al.*, 2014), allowing algae to also bloom in the winter. Furthermore, in tropical conditions, excessive light can stress plants by inhibiting photosynthesis through photo-inhibition and photo-oxidation (Streit *et al.*, 2005; Brighenti *et al.*, 2015).

Varol *et al.* (2012) state that the inflow of streams and surface runoff carry a large amount of nutrients in the medium during rainy periods (Brighenti *et al.*, 2015). The factors that influence algae metabolism and development are interconnected. Therefore, this fact explains that despite the high luminosity in the summer, which is essential to the flowering of plants in conditions of low nutrient supply during the rainfall season, demonstrated by total phosphorus and electrical conductivity values, these influencing factors control the concentrations of chlorophyll *a* and consequently algal biomass growth in the summer.

The aquatic environment classified as eutrophic indicates high nutrients enrichment and high planktonic growth while an oligotrophic environment represents clear waters with low nutrient enrichment and the presence of few aquatic plants. TSI results in this study suggest that the main alterations observed are due to environmental and non-fish farming issues because the trophic classification of the evaluated sites did not differ and remained within the mesotrophic classification. Moreover, seasonal TSI results corroborate the data obtained in the limiting limnological parameters for algal bloom previously discussed, and thus, demonstrate the synchronization of these parameters with the TSI in this aquatic environment.

The study of the carrying capacity in reservoirs is essential to allow planning and maximize productivity in aquaculture enterprises while minimizing adverse environmental effects that could result from assimilating and metabolizing nutrients generated by aquaculture (Bueno *et al.*, 2015). Animal excreta and unconsumed food result in increased phosphorus concentrations in the aquatic environment (Diemer *et al.*, 2010; Bueno *et al.*, 2015). Excess phosphorus can lead to eutrophication and impair the quality of water in fish farms, not only resulting in damages to the aquatic environment, but also causing a negative effect on the fish activity itself.

In addition to phosphorus concentration, the carrying capacity is strongly influenced by rainfall and water flow (Konar *et al.*, 2013). Water flow is one of the main aspects to be considered when installing an aquaculture enterprise in cages because flow removes nutrients and phytoplankton populations, and allows a constant water exchange (Rangel *et al.*, 2012). Moreover, according to a study conducted by Xenopoulos *et al.* (2005), species richness in aquatic environments increases according to the river flow, which is directly related to the precipitation index (Poff *et al.*, 1997).

At the location studied, the average annual yield of Pacu (*P. mesopotamicus*) was 38.7 tons, resulting in approximately 5.98 kg of P to the environment per ton of fish produced. Fish production is below the maximum limit obtained under conditions of high precipitation and flow. Therefore, the existing fish production was not above the environment carrying capacity because the pluviometric average during the study period was 182.10 mm.

5 Conclusions

The main alterations in the limnological profile of an aquaculture area, in which fish farming in cages is performed in conditions below the carrying capacity of that area, happen due to precipitation. Rainfall exerts a great influence on the dynamics of aquatic environments; the observation of local precipitation data is necessary when performing the calculation of carrying capacity.

The seasons cause variation in the limnological dynamics of tropical regions; the factors related to water eutrophication are interrelated and largely influenced by seasonal climatic conditions.

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