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Ecological carrying capacity for intensive tilapia (*Oreochromis niloticus*) cage aquaculture in a large hydroelectrical reservoir in Southeastern Brazil

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ABSTRACT

Cage culture of tilapia (*Oreochromis niloticus*) in large reservoirs is an emergent aquaculture practice in Brazil. Due to the availability of large amounts of suitable quality waters in hydroelectric dams, there is a large but still undetermined potential for cage aquaculture in the upper Paraná River basin. Sustainable aquaculture production should consider assessment of ecological carrying capacity for rational use of natural resources such as water bodies. The present survey estimates the ecological carrying capacity for tilapia cage culture in several sites on a large reservoir of "Ilha Solteira" upper Paraná River basin, Southeastern Brazil. Ecological carrying capacity was estimated based on the Dillon and Rigler (1975) mass balance model, considering limnological and farming field data to evaluate area-specific Phosphorus loads that can be assimilated in these environments. Using average farming data of feed composition, tilapia (*O. niloticus*) whole body composition and Feed Conversion Rate (FCR), the estimated emission of Phosphorus per ton of fish produced was 14.8 kg P ton^{-1}. Modeling provided evidence for the importance of feed Phosphorus content and availability for determination of total allowable production, as well as the relevance of proper inputs of limnological field data. When field data was collected, only two sites (Ponte Pensa and Dourados) had aquaculture activities; as aquaculture is expanding, limnological information provided in the present study is a registry of conditions found before the massive aquaculture development. Production estimated to the reservoir as a whole (156,000 ton) is more than fivefold the pooled production (30,000 ton) of the fifteen selected sites; if production estimated to the reservoir as a whole cluster around a few best sites, than effects on water quality is expected to be even more drastic. The limit of 1% occupancy by aquaculture posed by Brazilian government is not an effective safeguard against excessive eutrophication, and detailed limnological studies are demanded for each inlet assigned for cage aquaculture. The impact of cage fish farming on the aquatic environment by the release of nutrients that affect water quality can not only bring about conflict with multiple users, but also primarily exert a negative feedback effect in the cage operations themselves.

1. Introduction

Current population growth and increase of per capita fish consumption will demand water resources to be more efficient in terms of food production in a global scale (Tacon and Halwarth, 2007). The rising demand is pushing aquaculture expansion into new areas (Halwarth et al., 2007) and in Brazil, cage aquaculture emerged as a feasible technology for tilapia production in large hydroelectric reservoirs in the upper Paraná River basin. Fitzsimmons (2006) pointed that Brazil will likely compete with China to be the major global producer of tilapias. Relevant information for aquaculture development compiled by Lovshin (2000) about Brazilian socio-economic context are mostly still valid, except for the current development of high quality feeds and the trend of using larger cages in recent years. More details about the production systems in use in Brazil were described by Rojas and Wadsworth (2007); Scott (2013) reports that in Brazil many reservoirs, including the

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study area, Ilha Solteira reservoir, are undergoing studies for the establishment of "Aquaculture Parks", which are water bodies set by the State for development of aquaculture, which may contain several areas to be leased for cage aquaculture. Brazilian government already established limits for the maximum allowable change caused by aquaculture in these ecosystems, stating a limit of 30 mg of Total Phosphorus (TP) per m^3, and a maximum of 1% occupancy for aquaculture of the total area of each reservoir.

Overcrowding and intensive stocking involves risks of water pollution, caused by nutrient loads from uneaten feed and metabolic waste products (Pillay, 2004; Ross et al., 2013). The limited potential for treatment of the waste material produced is a key issue in the environmental concern of cage aquaculture (Cripps and Kumar, 2003), so further aquaculture development should be planned and designed in a responsible manner that minimize as much as possible negative impacts on water quality (Hambrey and Senior, 2007). Ecological carrying capacity is an important concept for management based on sustainability, resilience and best practices guidelines, which helps to set upper environmental limits for aquaculture production, and thus avoiding "unacceptable change" to natural ecosystems (Ross et al., 2013). Reservoirs have a homeostatic capability of smoothing out and depressing the effects of inputs of nutrient, and if thresholds of driving variables are crossed, strong feedbacks often induce highly non-linear responses, which may lead ecosystems to break down and collapse (DeAngelis et al., 1986; Straškraba, 1999a; Wiens, 2006). Aquaculture carrying capacity methods was presented by Beveridge (1984) and increasing scientific interest in this field started with the fish cage culture problems in Chinese reservoirs (Li et al., 1989, 1994; Xiong et al., 1993), where the development of intensive fish cage farming in reservoirs and lakes in recent years has brought prominent threats to environment (Ning and Gu, 2004; Ning et al., 2006; Sun et al., 2005). Excessive eutrophication and massive fish kills as results of surpassing the ecological carrying capacity and overcrowding into environmental unsuitable areas were reported by Costa-Pierce (2002) for Indonesian reservoirs.

Cage aquaculture uses ecosystems services for the degradation of organic matter, nutrients and provision of oxygen, but a certain level of fish biomass may exceed the system capacity to process nutrients, thus generating excessive eutrophication (White et al., 2013). Nutrient loads should be within the assimilative capacity of the local environment, without degradation of its future waste absorption capacity or other important services (Goodland and Daly, 1996). Considering that a certain amount of nutrient loads may be beneficial for the environment in oligotrophic food webs, there should be a level of production that does not cause environmental damage (Schmittou, 2006).

McKindsey et al. (2006) proposed a hierarchical structure to determine the carrying capacity of a given area, where the first stage would involve the calculation the physical carrying capacity or suitability of a site, based on the natural conditions and on the needs of the species and culture system. This is followed by the calculation the magnitude of aquaculture production that can be supported by the available area, using mass balance models without leading to significant changes to ecological processes, services, species, populations or communities in the environment (Ross et al., 2013) Ecological carrying capacity in obtained in an ecosystem perspective as a need for sustainable development, with no degradation beyond resilience capacity (Soto et al., 2008; FAO, 2010). Critical limits for ecological carrying capacity has been explored to some extent using mass balance models, and Phosphorus is assumed to be the main nutrient that trigger eutrophication in freshwaters (Reynolds, 1999). Multiple users of reservoirs, including fish farmers, should have a common concern on enhancing water quality and sustaining this condition throughout generations.

The present study used field limnological data to estimate the ecological carrying capacity of a large tropical reservoir for assimilation of nutrient loads derived from tilapia production in floating cages, focusing on consequences upon excessive eutrophication processes. This is part of an effort based on ecosystem approaches to deliver scientific based numbers for the limits of fish production as a basis for planning, decision making and integrated management of sustainable aquaculture in this reservoir. In this study is presented a prediction of the consequences of aquaculture upon water quality, based on criteria of general applicability, and a methodological reference is proposed for ecological carrying capacity estimation in other similar ecosystems.

2. Materials and methods

Data used in mass balance models resulted from field surveys on morphometry, hydrodynamics, and limnology. This section presents a description of the sequence of methods and procedures used for addressing site selection and ecological carrying capacity of the Ilha Solteira reservoir. Mass balance models were used to estimate the carrying capacity of Phosphorus assimilation of the whole reservoir and of two of the main aquaculture sites; further, other 13 selected sites suitable to cage aquaculture had its ecological carrying capacity estimated. Phosphorus assimilation capacity was converted to potential of tilapia production by considering the amount loaded per ton of fish produced separately for the main sites selected for the development of cage aquaculture.

Ilha Solteira reservoir is located in the confluence of two large rivers, Grande and Parnaíba, at the upper Paraná River basin (Fig. 1). The drainage basin area of the reservoir is 375,460 km^2, mainly occupied by pastures in a tropical region with low population density, in a landscape where sandstones and basalts underlie very weathered hills (CESP, 2005). This large and dendritic freshwater reservoir was built in 1965 for electric power generation, with total area 1195 km^2 and mean depth 17.62 m. Total volume is $21{,}060 \times 10^6\ m^3$, and long term average flow is $5206\ m^3\ s^{-1}$, resulting in 46.7 days residence time. It is the main component of the world's sixth largest hydroelectric complex, in operation since 1973.

The first step in the process of site selection was a detailed bathymetric survey of the whole reservoir, identifying areas with suitable depth for cage farms installation, regarding at least 10 m depth at the minimum historical reservoir level. Equipment used in bathymetric field surveys included an echo-sounder RESON NaviSound 205M, connected to a GPS system CSI DGPS-MAX, with resolution of 0.1 m. Bathymetric data was also used for hydrodynamic modeling.

Field checking of availability of basic infrastructure (i.e. electric energy, roads) was performed in the whole reservoir for generation of constraints maps, which also considered limitations imposed by other uses of the reservoir, regarding power generation, protected areas, tourism, shipping lanes and sewage discharge. Massive abundance of riparian vegetation, filamentous algae, and presence flooded trees at surface also were criteria for exclusion. Areas with urban occupation were avoided, as well as inlets with water uptake for human consumption.

Criteria for site selection were also based wind exposure and maximum wave heights, regarding as a limit the exposition to waves 0.5 m high calculated from measurements wind direction, velocity and fetch. Modeling of waves generated by winds used data measured in the medial portion of the main body of the reservoir registered by a Druck pressure sensor model PDCR 1830 and anemometer Young RM05103. The wave heights were calculated using a software developed in AutoLisp language in CAD environment, named OndisaCad (Marques et al., 2007; Maciel et al., 2011). The software calculates wind fetch by the classical method of Saville

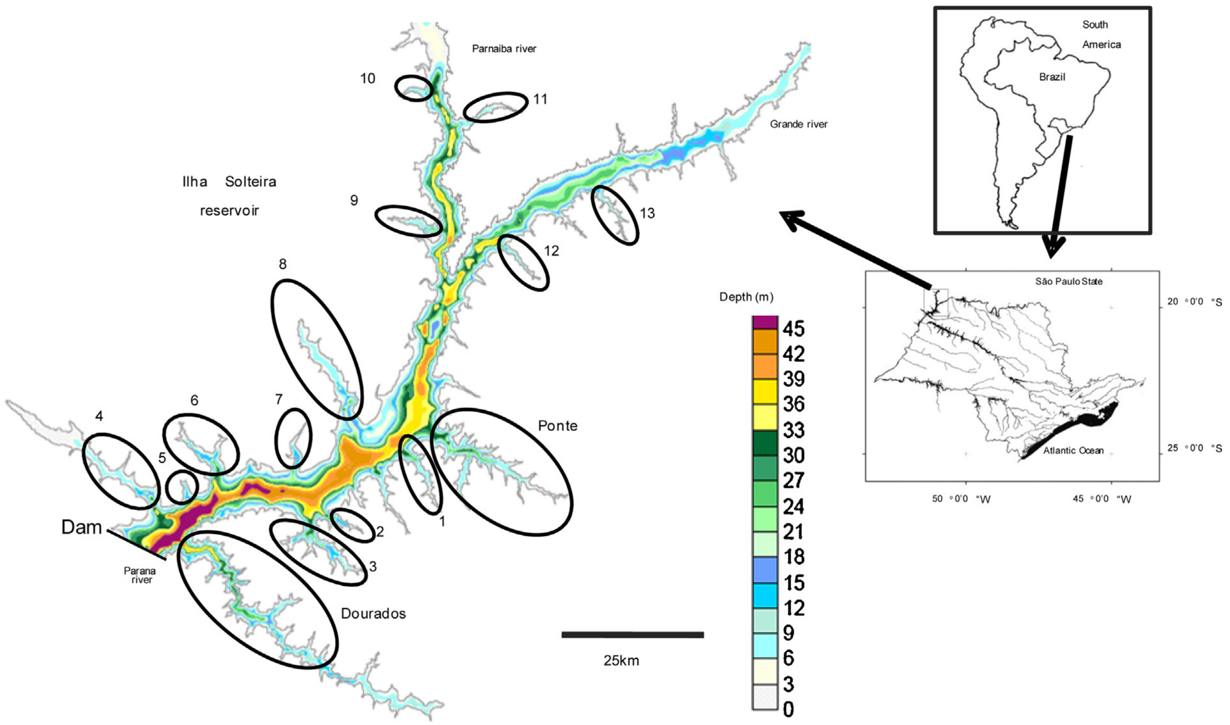

Fig. 1. Bathymetry of Ilha Solteira reservoir showing main aquaculture sites (Ponte and Dourados) and selected sites for aquaculture expansion assessed in the present study. Site numbers are coupled to Table 2 and Appendix 1 and 2.

(1954) on the nodes of a mesh with user-supplied spacing. The program calculates fetch using the lengths of 19 auxiliary lines spaced every 5°, weighted by the angle to the main wind direction. Fetch was used to calculate the wave height through JONSWAP method (Carter, 1982). The tracks were calculated assuming 8 wind directions and mesh with spacing of 250 m. About 8 tracks of each node was applied JONSWAP method, using the maximum daily wind observed in each direction. Data on wind intensity and direction was obtained from three permanent weather stations located around the reservoir, using historical data from 1996 to 2006. The largest wave from the 8 values calculated for each node was used in the construction of wave exposure map, shown in Fig. 3. Waves

Table 1
Physical and chemical parameters and respective methods used for water analysis of fifteen assessed sites at Ilha Solteira reservoir.

Parameter	Unit	Method	Reference
Temperature	°C	Electrometric	[a]
Conductivity	$\mu S \times cm^{-1}$	Electrometric	[a]
Dissolved Oxygen (DO)	$mg \times l^{-1}$	Electrometric	[a]
pH	–	Electrometric	[a]
Turbidity	NTU[b]	Nephelometric	[a]
CO_2	$mg \times l^{-1}$	Analytic	AOAC (1984)
Biochemical Oxygen Demand (BOD)	$mg \times l^{-1}$	Analytic	Carignan et al. (1998)
Suspended Solids	$mg \times l^{-1}$	Gravimetric	AOAC (1984)
Transparency	m	Secchi Disk	AOAC (1984)
Euphotic zone depth (EZD)	m	[c]	Cole (1994)
Alkalinity	$mg \times l^{-1}$	Analytic	AOAC (1984)
Hardness	$mg \times l^{-1}$	Analytic	AOAC (1984)
Total Nitrogen (TN)	$mg \times l^{-1}$	Analytic	Valderrama (1981)
Total Ammoniacal Nitrogen (TAN)	$mg \times l^{-1}$	Analytic	Koroleff (1976)
Nitrite	$mg \times l^{-1}$	Colorimetric	Golterman et al. (1978)
Nitrate	$mg \times l^{-1}$	Colorimetric	MacKereth et al. (1978)
Total Phosphorus (TP)	$\mu g \times l^{-1}$	Colorimetric	Valderrama (1981)
Orthophosphate	$\mu g \times l^{-1}$	Colorimetric	MacKereth et al. (1978)
Total Calcium	$\mu g \times l^{-1}$	Colorimetric	AOAC (1984)
Total Iron	$\mu g \times l^{-1}$	Colorimetric	AOAC (1984)
Total Potassium	$\mu g \times l^{-1}$	Colorimetric	AOAC (1984)
Chlorophyll *a*	$\mu g \times l^{-1}$	Colorimetric	Golterman et al. (1978)
Trophic State Index (TSI)	–		Carlson (1977) modified by Toledo (1983)
Phytoplankton	taxa		Komárek and Anagnostidis (1999)[d]
Zooplankton	taxa		Espíndola (1994)[e]

[a] Multiparametric Probe model YSI 6920, specifications at http://ysi.com/media/pdfs/069300-YSI-Series-Manual-RevH.pdf.

[b] NTU is Nephelometric Turbidity Unit.

[c] Estimated by multiplying Secchi depth by 2 and dividing the result by 3.

[d] Used for phytoplankton identification.

[e] Used for zooplankton identification.

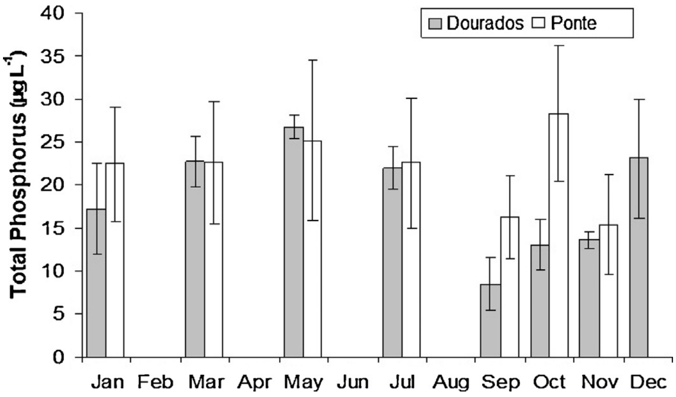

Fig. 2. Monthly variation of average Total Phosphorus level (TP) for surface waters in two sites of Ilha Solteira Reservoir, from 2000 to 2004. Error bars refers to mean ± standard deviation.

Data from CESP (2005).

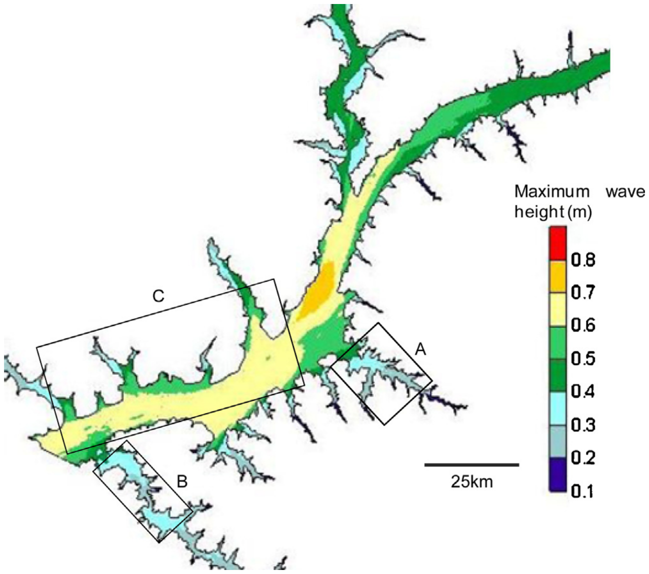

Fig. 3. Maximum wind wave heights of Ilha Solteira reservoir, selected between height values calculated with maximum observed wind speed in 8 directions. Areas indicated with letters A–C refers to details shown in Fig. 4.

were not included in the calculations of flushing time scales or resuspension. The process of wave modeling resulted in the selection of 15 areas suitable for cage aquaculture to be further investigated in a survey for collection of limnological data and water samples; limnological variables measured and methods used are listed in Table 1.

Hydrodynamic modeling considered water level of 324 m, which is flooded 95% of the year, using data from average monthly water levels of the reservoir for the period of 1988–2003 (CESP, 2005); bathymetric data were integrated to the contour of the reservoir using the software SURFER 8®.

Seasonal variation of TP content was addressed by compilation of 224 surface water analyses from years 2000 to 2003 in sites Ponte and Dourados (Fig. 2), which pointed to higher values of TP for surface waters in dry season (May–August in this region). An intensive limnological survey was performed in June 2006 in all fifteen selected sites. Water samples and limnological data were collected in the three points along the central portion of each of the fifteen selected areas. Sampling took place at the middle of the euphotic zone, as estimated based on Secchi depth, using van Dorn bottles. In situ measurements of dissolved oxygen (DO), conductivity, pH and temperature were made using a multiparametric probe YSI 6920. Water samples of 500 ml were filtered through 20 µm mesh for chlorophyll *a* determinations; TP, total Nitrogen (TN) and other parameters listed in Table 1 were measured in the laboratory. Zooplankton was collected by three midwater vertical trawls of 10 m each using 200 µm mesh nets, with opening 50 cm in diameter; for phytoplankton collections, three midwater vertical trawls of 10 m each using 60 µm nets with opening 30 cm in diameter. Sedimentation rate was calculated following Larsen and Mercier (1976) and Trophic State Index (TSI) was calculated according to Carlson (1977), modified by Toledo et al. (1983).

Hydrodynamic modeling was performed to the reservoir as a whole, and then water flow in the entry section of all the selected sites, each hour during a period of 24 h to estimate water exchange of each one of the selected sites. Data used in the modeling process included water inflow at the hydroelectric power plants of Agua Vermelha and São Simão, upstream to the reservoir at the rivers Grande and Parnaíba, respectively, and outflow from Ilha Solteira power plant (Fig. 1), considering monthly averaged data from the period of 1970–2004, from public data of the National Operator of the Hydroelectric System (ONS), available at: http://www.ons.com.br/operacao/vazoes_naturais.aspx (accessed 02.04.2015).

Flow rates of the smaller tributaries that inflows to the studied inlets (eight in the right margin, seven in the right margin, as shown in Fig. 1) were estimated considering its watershed drainage area and the average area contribution of the basin of Ilha Solteira reservoir (0.007 $m^3 s^{-1} km^{-2}$), obtained specifically for the region of Ilha Solteira reservoir and considered uniform to the whole area of approximately 6000 km^2, available at www.sigrh.sp.gov.br (accessed 02.04.2015). Modeling was performed using SisBAHIA® (System Base Environmental Hydrodynamics); Triangle software was used for the pre-processing, editing and generation of two-dimensional finite element meshes, resulting in 3101 nodes and 1178 triangular elements. The size of the total domain is 807 km^2 and the average size of elements was 865,000 square meters, although it was not uniform, with smaller elements in the studied inlets and larger in the main channel of the reservoir. These were exported to SisBAHIA for two dimensional numerical modeling and Surfer8® for map edition. Water circulation pattern in the reservoir was initially considered to be driven by three main forces: wind currents, inflow by the main rivers and tributaries, and outflow release through the Ilha Solteira hydroelectric plant. Simulations of water circulation were also performed using SisBAHIA® to estimate the magnitude of water exchange between the main body of the reservoir and each of the 15 selected sites. The model supplied hourly values of the average speeds in the output sections of each inlet considered during 24 h simulation. Considering the area of each section of water output, provided by the bathymetry, speeds of water circulation was used to calculate flows and volumes of water exchange between the main channel of the reservoir and the inlets. The general pattern of water circulation velocity in the reservoir was simulated starting with a uniform water level, over a period of three days, with time step of 60 s, until a steady circulation pattern was achieved. The simulated scenario aimed to repeat approximately the typical daily pattern level float in the reservoir due to the demand for power generation, which is more relevant than the yearly variation for this reservoir. From the steady state with the historical average flow, the simulation considered a period of 12 h with lower flows than average, followed by 12 h with above average flows, representing the peak hours of electricity generation. The roughness on the bottom was set as 0.001. Specifically for site Dourados an inflow of 200 $m^3 s^{-1}$ was adopted, respective to historical daily average value of water transposition (informed by CESP, the company which operates the system) from the neighboring Tietê river by an artificial channel, sited upstream to the aquaculture areas.

A mass balance model was used to estimate ecological carrying capacity of the whole reservoir and of each of the 15 selected sites separately (Pulatsü, 2003; Beveridge, 2004). This is a modification of the Dillon and Rigler (1975) model, and was used to estimate the maximum P load each site could receive *per* year before excessive eutrophication process is triggered. This model was adopted using data of average depth (from bathymetric survey), seasonal TP maximum (from field data), water exchange rates (from hydrodynamic modeling) and sedimentation rates, and assumes that TP level limits phytoplankton growth and therefore excessive eutrophication.

The maximum allowable production of the studied sites was estimated considering the field farming technologies regionally used, that consisted in tilapia (*Oreochromis niloticus*) grow-out systems, intensive cultivation in 6 m^3 floating cages, and manual feeding using pelleted, floating compound feeds. Fish production was calculated by dividing the TP loads respective to the capacity of TP assimilation of each site by average TP load *per* ton of fish produced. The area needed to achieve the estimated carrying capacity was also calculated according to Brazilian government environmental requirements that establish the use a dilution area of tenfold that effectively occupied by the cages.

As an overview of the procedures adopted, we can make explicit that wave modeling was used only for site selection purposes; hydrodynamic modeling supplied water exchange rates for mass balance model, which was used to estimate the capacity of Phosphorus assimilation of the whole reservoir and for each of the studied sites. Results of mass balance model was used to calculate the respective fish production in each area per year, based on estimates of Phosphorus emission per weight of fish produced. Maximum allowable fish production was used to estimate what would be the area needed to exploit the maximum potential of aquaculture in the reservoir.

2.1. Calculations

The capacity of TP assimilation was estimated by using the following equation (Beveridge, 2004):

$$L = \frac{\Delta TP \times Z \times \theta}{1 - R}$$

where L is the yearly, area-specific capacity of P ($g\,m^{-2}\,year^{-1}$); ΔP is TP measured in the field (in each studied site) subtracted from 30 mg/m^{-3}, the limit concentration of TP set by the Brazilian government; Z is the mean depth (m, from bathymetric survey); θ is the water exchange rate ($years^{-1}$), calculated separately for each of the fifteen sites studied using the volume of the inlet, and the water flow, composed by the inflow of water by each tributary and the water exchange between the inlet and the reservoir, derived from hydrodynamic modeling; and R is the sedimentation rate of each site, derived from the formulae (Larsen and Mercier, 1974, in Beveridge, 2004):

$$R = \frac{1}{1 + 0.614 \times \theta^{0.491}}$$

The total amount of Phosphorus each area would be able to assimilate was obtained by multiplying L by the area of each selected site. Phosphorus loads per ton of fish (Pe) produced was estimated following Beveridge (2004). Using the following equation:

$$\mathrm{Pe} = (\mathrm{Pf} \times \mathrm{FCR}) - \mathrm{Pa}$$

where Pf is the P concentration in fish feed, in kg ton^{-1}; FCR is the Feed Conversion Rate, calculated using data from Mallasen et al. (2012); and Pa is the P content of whole, adult fish estimated by Dantas and Attayde (2007).

3. Results

Site selection process resulted in the identification of 15 sites, i.e. the two sites where there are currently tilapia cage farms operating (Ponte and Dourados, Fig. 1) and other 13 sites considered suitable for intensive tilapia grow out systems in cages. All selected sites are former tributaries of the main rivers, flooded since the formation of the reservoir. Three sites were selected in the portion respective to River Parnaiba (referred as 9–11 in Fig. 1), two in the area respective River Grande (referred as 12 and 13 in Fig. 1) and all other (referred by numbers 1–8) are in the river Parana, downstream to the confluence of rivers Parnaiba and Grande. This numeration is used in tables and in figures to report specific features of each area.

Northern winds were most frequent, above 1.5 $m\,s^{-1}$ in 30.4% of time; Northeast and South winds were also common, accounting for approximately 16% each. Maximum waves heights registered were 0.8 m, with maximum period of about 3 s in the main channel of the reservoir. Although winds were found to be relevant in wave generation, simulations with extreme winds showed no effect in water circulation, resulting in non-significant level changes and thus indicating that inflow and outflow should be the main forces to be considered. Hydrodynamic modeling showed that unidirectional transport occurs in the shallow, narrow inlets (Fig. 4A and B), but also showed that transport in the main body of the reservoir does not flows straight in downstream direction, and large vortex can develop in the widest portions (Fig. 4C), probably due to bottom shape, and the main flow direction following the main channel of the reservoir. Although water flow velocities were frequently lower than 3 $cm\,s^{-1}$ in the main channel of the reservoir, maximum velocities can reach up to 8 $cm\,s^{-1}$.

Fig. 2 shows the seasonal variation of TP in the sites Ponte and Dourados, which already have tilapia farms operating. For precautionary purposes, maximum seasonal P levels were considered for mass balance models. At Ponte, maximum values of TP was found in May and September, which did not differed significantly each other (T test, $p = 0.05$). For Dourados, September resulted in significantly lower P levels, while maximum TP was found in May. Based on these results, July (early winter) was chosen to perform detailed limnological assessments in all selected sites.

Table 2 shows limnological characterization of the sites Ponte and Dourados, while data the other 13 selected sites are presented in Appendix 1. Physical and chemical water parameters points to an oligotrophic environment. Conductivity was rather low in most areas, among 40 and 50 $mS\,cm^{-1}$, except in Dourados, that registered values above 100 $mS\,cm^{-1}$. Secchi depths was between 2.1 and 5.5 m, and winter temperatures were between 23.1 °C and 26.6 °C, while DO was above 6.0 $mg\,l^{-1}$ and pH was close to neutrality in all sites. Considering that TP was always below 20 $mg\,m^{-3}$, and chlorophyll-*a* values were mostly below 5 $\mu g\,l^{-1}$, Trophic State Index (TSI) of all sites indicated oligotrophic conditions. A maximum of eight phytoplankton families were found at site 13 (Jacu), with 27 species represented there. Cyanobacteria were numerically responsible to more than 80% of total phytoplankton abundance in 12 sites. Zooplankton density had a wide variation, from a minimum of 16 to a maximum 149 individuals per ml, ranging from five to thirteen species. Cladocera, Rotifera and Copepoda were the main zooplankton groups (Appendix 1).

Morphometric data of area, mean depth and volume of the studied sites considered in modeling are listed in Table 4. The area of nine sites is less than 1 km^2, four are among 1 km^2 and 32 km^2 and Dourados site area is 69.5 km^2. Mean depth presented wide variation from 3.43 to 15.07 m, and sites which receives larger rivers

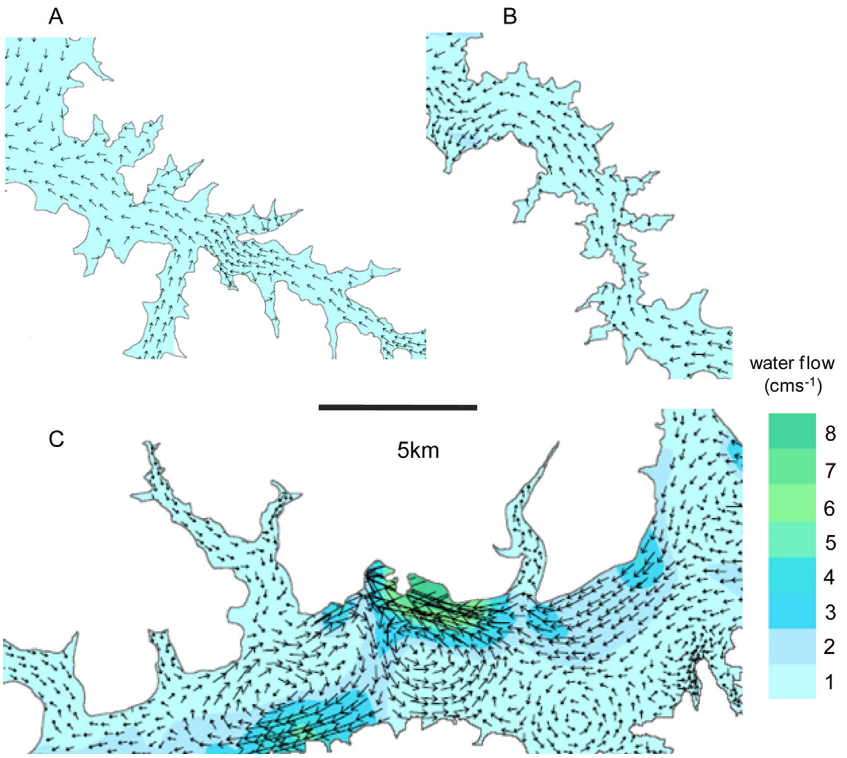

Fig. 4. Water circulation pattern of Ilha Solteira reservoir, in the areas indicated by letters A–C in Fig. 3, as resulted from hydrodynamic modeling using SISBahia Software. Arrows indicates current direction and colors refers to velocity.

registered higher water exchange rate, such as Dourados and Ponte (Table 4), as well as sites 3 (Anta), 4 (Pantano), and 6 (Grandinho, Appendix 1).

Specific capacity of Phosphorus assimilation (L) varied from 1016.3 to 5294.0 mg of Phosphorus per square meter per year, reflecting the heterogeneity of sites within this reservoir. Total allowable Phosphorus loads for each site ranged from 4.15 to 125.03×10^3 kg of Phosphorus per year. The calculations for conversion of Phosphorus assimilation capacity of each area into total fish allowable production is strongly affected by the efficiency of fish to assimilate Phosphorus (Fig. 5). If current field farming practices are used, i.e. FCR is 1.7 and feed TP content is 1.4%, than aggregated values for all sites pooled would be 32,542 MT per year, around one tenth of the value obtained for the reservoir as a whole, 155.686 metric tons (Table 4). The ecological carrying capacity of the sites Ponte and Dourados (5800 MT year^{-1} and 6950 MT year^{-1}, respectively), where aquaculture was already installed when this study was carried out, were the highest among all sites studied (Table 4; Appendix 2). Three other sites showed intermediate potential for cage aquaculture, namely Pantano (2990 MT year^{-1}), Grandinho (2920 MT year^{-1}) and Anta (2690 MT year^{-1}). Quiteria had a estimated carrying capacity of (1440 MT year^{-1}) and the other sites were below 1000 MT year^{-1}.

4. Discussion

The main bottlenecks to implementing broad scale analyses are lack of data of appropriate resolution and variety of input data for models (Bermudez, 2013). Even when simple mass balance models are used, the bulk of data needed to estimate the ecological carrying capacity of a reservoir is complex and demands a multidisciplinary effort that makes it laborious and expensive, but necessary given the strategic importance of freshwater resources. In this sense, aquaculture parks (Scott, 2013) represent a positive approach to aquaculture development planning, but needs to be managed carefully with carrying capacity estimation and restriction of licenses (White et al., 2013). Best site selection must take into consideration optimal flushing and dispersal of nutrients, and could actually promote and increase local and total productivity, especially in oligotrophic and mesotrophic systems, particularly when additional substrate heterogeneity is provided (Ferreira et al., 2013). Size and distribution of cage farms could be dimensioned by considering local, site by site criteria. Sitting

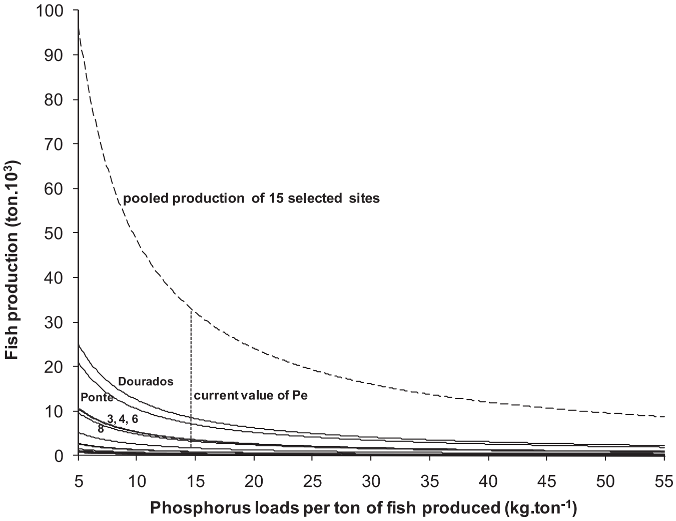

Fig. 5. Relationship of Phosphorus loads per metric ton of fish produced (estimated based on Food Conversion Rate and feed TP content) and total allowable production for the 15 assessed sites of Ilha Solteira reservoir (respective to the total amount of TP that each area can assimilate in one year, listed in Table 3), calculated for maximum ecological carrying capacity of each site in the present study. Dotted line refers to the pooled production of all 15 assessed sites, numbers are coupled to Fig. 1 and Table 2. Sites 2, 4, 6, 7, 8, 11, 12, 14 and 15 are represented by to be lower lines and its numbers are not identified in the figure.

Table 2
Limnological characterization of the main inlets used for cage aquaculture in Ilha Solteira reservoir. Average values refers to nine water samples taken along the central axis of each inlet, in the middle portion of the euphotic zone and local depth $\geq$10 m.

	Unit	Ponte	Dourados
Latitude (S)		20°15′	20°24′
Longitude (W)		51°01′	51°16′
Temperature	°C	25.2	24.9
Conductivity	$\mu S \times cm^{-1}$	43.0	101.0
DO	$mg \times l^{-1}$	7.6	7.2
pH	–	7.1	7.2
Turbidity	NTU[a]	3.0	5.7
CO_2	$mg \times l^{-1}$	0.5	0.7
BOD	$mg \times l^{-1}$	0.2	0.7
Suspended solids	$mg \times l^{-1}$	13.3	2.0
Transparency	m	3.1	2.1
EZD	m	4.6	3.2
Alkalinity	$mg \times l^{-1}$	21.4	24.0
Hardness	$mg \times l^{-1}$	17.0	40.0
TN	$mg \times l^{-1}$	1.0	0.7
TAN	$10 \times mg \times l^{-1}$	0.3	0.5
Nitrite	$10 \times mg \times l^{-1}$	0.7	0.2
Nitrate	$mg \times l^{-1}$	0.5	0.6
TP	$\mu g \times l^{-1}$	16.1	18.8
Orthophosphate	$\mu g \times l^{-1}$	5.5	7.8
Total Calcium	$10^2 \times \mu g \times l^{-1}$	5.6	66.0
Total Iron	$10 \times \mu g.l^{-1}$	1.0	0.8
Total Potassium	$\mu g \times l^{-1}$	1.1	1.9
Chlorophyll *a*	$\mu g \times l^{-1}$	1.7	1.9
TSI	–	33.4	34.0
Phytoplankton taxa	Species	8	9
Cyanobacteria[a]	%	98.9	94.4
Zooplankton taxa	Species	8	13
Dominant zooplankton family		ROT	CLA
Zooplankton density	ind/ml	9.5	30.0

DO is Dissolved Oxygen, BOD is Biochemical Oxygen Demand, EZD is Euphotic Zone Depth, TN is Total Nitrogen, TAN is Total Ammoniacal Nitrogen, TP is Total Phosphorus, TSI is Trophic State Index. TSI classification is: $\leq$44 – Oligotrophic; 44 < TSI < 54 – Mesotrophic; $\geq$54 – Eutrophic.

[a] Percentage of Cyanobacteria families.

CYC refers to Cyclopoideae, ROT to Rotifera, CLA to Cladocera. Data collected in July 2007.

criteria are better if managed through region-wide planning and based upon regulations appropriately aimed to address cumulative impacts. Identification of aquaculture areas should not be moved by their low value for alternative uses or for political reasons linked to broader agendas of decision makers (Leschen et al., 2005). Locations with access to high quality water resources are preferred, and in areas with weak law enforcement, locations more defendable may be of great interest for aquaculture (Little et al., 2013). Aquaculture development tends to be concentrated in clusters, which endurance in Asia suggests the benefits of such physical association outweigh the disadvantages of proximity, e.g. self-pollution and pathogen dissemination. Fragmentation of farm areas is desirable, because overcrowding of the best sites can make the whole enterprise environmentally unsustainable (Costa-Pierce, 2002). While individually cage farms create little environmental impact, the cumulative effects of large numbers of farms in clusters can be significant (White et al., 2013) (Table 5).

From a social carrying capacity perspective, the region is sparsely populated and the skilled labor availability is low. Farms near to urban centers attract the best human resources, mainly by the availability of health and education systems, more structured on the left margins of the reservoir. In addition, the sites with highest environmental carrying capacities are in this area, favoring concentration. The places in the Northern portion of the reservoir, respective to Parnaíba River have poorer urban and transport infrastructure, and lower potential output. Thus, several areas north remain unoccupied, mainly by the difficulty of operation of farms in these areas.

Table 3
Field measured data of Phosphorus loads and sedimentation rate in the site referred as Ponte, Ilha Solteira reservoir.

Total fish production	$ton \times year^{-1}$	85
TP loads	$kg \times year^{-1}$	1258
Farm area	m^2	4500
TP load per area	$10^3 \times mg \times m^2 \times year^{-1}$	0.2796
TP sedimentation	$mg \times m^2 \times year^{-1}$	0.0928

Data from Mallasen et al. (2012). *R* is the sedimentation rate, TP is Total Phosphorus.

Table 4
Morphometric and hydrodynamic data of selected sites (local depth $\geq$10 m) at Ilha Solteira reservoir used for calculation of ecological carrying capacity for assimilation of Phosphorus loads derived from fish farming in floating cages.

	Unit	Ilha Solteira reservoir	Ponte	Dourados
Area	km^2	1195.4	18.1	69.5
Mean depth	m	16.9	30.88	11.11
Inflow[a]	$10^6 \times m^3$	5186.01	10.40	233.02
Residence time[b]	days	45.07	21.61	38.35
Flushing rate[c]	$year^{-1}$	7.99	16.66	9.39
TP	$mg \times m^{-3}$	13.1	16.09	18.81
Sedimentation rate[d]	–	0.37	0.29	0.35
P assimilation per area[e]	$g \times m^{-2} \times year^{-1}$	1.93	2.20	1.80
Ecological carrying capacity[f]	$10^3 \times ton \times year^{-1}$	155.69	4.59	8.49
Occupation	%	0.47	0.53	0.43

[a] The volume of water discharged by the inlet to the main channel of the reservoir.

[b] The average amount of time water spends in the site.

[c] How many times water is totally renewed in one year.

[d] The fraction of Total Phosphorus (TP) retained by sediments, estimated according to the method proposed by Larsen and Mercier (1976).

[e] The area-specific capacity to assimilate Phosphorus per year estimated following Beveridge (2004).

[f] The fish production limit for each assessed site.

The use of carrying capacity approaches is important to assist evaluation of the effect of the cages throughout the whole system (Rojas and Wadsworth, 2007) and setting limits for cage culture expansion is one of the conditions to ensure environmental sustainability of cage aquaculture in tropical reservoirs (Costa-Pierce, 2002). Carrying capacity should be considered as a logical step in order to establish a sustainable legal framework for aquaculture, concerning regional and cumulative impacts (Bermudez, 2013). The definition of critical limits for ecological carrying capacity in freshwater reservoirs has been explored to some extent, regarding level of Phosphorus as the main driving force that will trigger excessive eutrophication (Ross et al., 2013). Organic synthesis is limited by the supply rate of essential nutrients (Sterner and Elser, 2002) and the main cause of environmental damage by nutrient loading is excessive eutrophication, which results on enhanced primary production, affecting water quality and decreasing amenities value of water bodies (Kelday et al., 2009). Once ecological thresholds are exceeded, small changes in an environmental driver produce large responses in the ecosystem, causing abrupt changes in water quality (Groffman et al., 2006). Episodic runoff peaks can be rather dangerous by inducing algal blooms or thermal inversions that can lead to massive fish mortalities (Costa-Pierce, 2002). Limnological changes resulting from external factors are more common in reservoirs than in natural lakes, which differ in specific features

Table 5
Data used for calculations of Phosphorus Loads per metric ton of tilapia produced in floating cages.

Phosphorus concentration of fish feed (Pf)	$kg \times ton^{-1}$	14.0
Feed Conversion Rate (FCR)	–	1.7
Phosphorus concentration of adult tilapia[a]	$kg \times ton^{-1}$	9.0
Phosphorus loads per ton of fish production (Pe)	$kg \times ton^{-1}$	14.8

[a] Dantas and Attayde (2007).

that stem from their peculiar hydrology and biota, reflecting the shortage of time for long term succession and evolutionary adjustments in reservoirs (Gliwicz, 1999). A main challenge related to planning and management is to limit the density of farms; if the total estimated fish production for the whole reservoir would be concentrated in few sites, excessive eutrophication is very likely to occur.

Site selection performed in the present study identified sheltered bays connected to tributaries, not exposed to strong winds and damaging waves, as excellent for cage aquaculture, a common situation in other tropical reservoirs (Costa-Pierce, 1998, 2002). Farming technologies currently in use in Southeastern Brazil for tilapia cage culture prevents expansion into deeper areas with more water circulation in the main channel of the reservoir, which would probably improve processes of nutrient assimilation and be more resilient to excessive eutrophication and development of bottom anoxia (Straškraba, 1999b; Costa-Pierce, 2002). Limnological conditions found in the studied sites indicate a generalized situation of high quality waters, but with relevant differences among them. As most hydroelectrical reservoirs from Upper Paraná river basin, limnological features at Ilha Solteira reservoir presents slight seasonal oscillations (Tundisi et al., 1993), which were considered in planning present field surveys. Inserted in a cascade system built for hydropower generation as a water accumulation basin, this reservoir reaches its maximum level in autumn, despite of a dry season in late autumn and winter. Residence time (i.e. the time required for water to leave the basin) and flushing time or turnover time (i.e. time needed to replace the volume of a basin) vary greatly for different currents forcing conditions and thus was assumed a space-dependent distribution for the same system (Valle-Levinson, 2013). In winter, the reservoir stores water to be slowly released along several months until the next spring/summer rainy season. Data used for ecological carrying capacity estimations was collected in early fall, when TP levels reach its maximum, probably due to lower rates of water exchange in this season, a procedure considered precautionary in relation to yearly averaged values. Temperatures were above 23 °C in winter in all studied sites, whereas maximum temperatures of well above 30 °C can be found in summer, outside the optimal temperature range for tilapias (Schmittou, 2006). Neutral or slightly alkaline waters where most common, were found in most of the studied sites, with no major limitations for tilapia culture (Shelton and Popma, 2006). Data on sedimentation was reported by Mallasen et al. (2012) and allows sedimentation rate to be estimated 0.3318 at Ponte; for this same site, when estimated by modeling, sedimentation rate would be 0.2904, thus used in ecological carrying capacity estimation. Feed Conversion Rates FCR is under effects of several factors. The quality of dry compounded feeds is influenced by the ingredients, digestibility, the suitability of the formulation to nutritional needs of individual species, and stability of the pellets. Feeding strategy relies on dietary feed manufacture, feeding regime, species, fish size, water temperatures and oxygen, which will strongly affect FCR (White et al., 2013). Careful feed management is an important economic consideration for aquaculturists, as well as a key aspect in limiting environmental impacts of aquaculture (Cripps and Kumar, 2003), and the better economic return should be associated with reduction of wastage and environmental pollution (Poxton, 2003). Production potential of any area is constrained by the efficiency of field farming practices, which would determine the fish production related to the amount of Phosphorus loaded (Beveridge, 2004).

In 2006, when field data was collected, only two sites (Ponte Pensa and Dourados) had aquaculture activities, but in a limited scale. In the last years the activity expanded to about 30 fish farms are operating there. Limnological and water quality information provided in the present study is a registry of conditions found before aquaculture development. Production estimated to the reservoir as a whole (156,000 ton) is over fivefold higher than the pooled productions (30,000 ton) of the fifteen sites selected as most feasible for tilapia cage aquaculture. If the first estimate is the criterion for licensing farms, the best sites for aquaculture is to receive Phosphorus loads much higher than estimated as a safe level by mass balance models; if production is clustered around a few best sites, than effects on water quality would be even more drastic. It means that the limit of 1% occupancy by aquaculture posed by Brazilian government (Scott, 2013) is not necessarily an effective safeguard against excessive eutrophication. Our results points that a careful, detailed study of limnological conditions in each aquaculture site must be performed, avoiding estimates that takes into consideration the whole reservoir.

Ecosystems are driven by complex interactions of large number of variables, with delicate balances with abrupt changes in state driven by comparatively minor inputs. The impact of cage fish farming on the aquatic environment by the release of nutrients that affect water quality can not only bring about conflict with multiple users, but primarily exert a negative feedback effect in the cage operations themselves.

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Appendix 1.

Limnological and morphological characterization of 15 selected sites at Ilha Solteira reservoir for fish farming in cages. Values presented refers to average values for six water samples taken along the central axis of each inlet, in the middle portion of the euphotic zone and local depth ≥10 m.

	Unit	(1) Taissu	(2) Parobi	(3) Anta	(4) Pantano	(5) Badim	(6) Grandinho	(7) Brejo	(8) Quiteria	(9) Formoso	(10) Formiga	(11) Cupim	(12) Cancan	(13) Jacu
Latitude (S)		20°16′	20°20′	20°21′	20°19′	20°18′	20°16′	20°17′	20°13′	20°01′	19°53′	19°51′	20°02′	19°59′
Longitude (W)		51°03′	51°08′	51°09′	51°21′	51°19′	51°18′	51°11′	51°07′	51°01′	50°59′	51°02′	50°55′	50°48′
Temperature	°C	25.1	25.2	25.0	26.6	23.5	26.4	23.5	23.5	23.8	24.9	23.1	24.0	24.0
Conductivity	$\mu S \times cm^{-1}$	43.0	43.0	43.0	43.0	43.0	43.0	42.0	42.0	39.0	39.0	39.0	49.6	50.0
DO	$mg \times l^{-1}$	7.5	7.8	7.7	7.4	7.5	7.6	7.1	7.3	7.3	7.0	6.9	7.5	7.4
pH	–	7.1	7.2	7.0	7.0	7.1	7.1	7.0	7.0	6.9	7.0	6.7	7.0	6.8
Turbidity	NTU[a]	3.0	3.0	3.3	4.0	4.2	4.2	3.0	3.4	2.4	3.9	3.6	2.0	2.5
CO_2	$mg \times l^{-1}$	1.3	0.7	0.8	1.0	0.7	0.7	2.0	2.0	0.7	1.3	1.0	1.0	1.0
BOD	$mg \times l^{-1}$	0.3	2.6	0.2	0.2	0.8	0.2	0.1	0.2	0.4	0.1	0.1	1.1	0.9
Suspended solids	$mg \times l^{-1}$	6.0	0.7	0.4	1.8	4.4	1.9	2.3	1.9	2.8	3.3	2.1	1.1	4.4
Transparency	m	3.4	4.0	4.0	3.0	5.5	3.0	3.6	2.8	3.5	3.0	3.0	3.0	2.3
EZD	m	5.1	6.0	6.0	4.5	8.3	4.5	5.4	4.2	5.3	4.5	4.5	4.5	3.5
Alkalinity	$mg \times l^{-1}$	22.7	21.3	22.7	21.7	21.0	20.7	23.5	22.3	21.7	18.3	21.7	23.6	23.0
Hardness	$mg \times l^{-1}$	17.6	17.3	17.3	24.0	17.3	19.3	17.0	17.0	15.7	15.3	16.0	18.3	18.2
TN	$mg \times l^{-1}$	0.6	1.1	1.0	0.6	0.2	0.6	0.7	0.6	0.5	0.6	0.6	0.3	0.6
TAN	$10 \times mg \times l^{-1}$	0.4	0.1	0.4	0.5	0.2	0.3	0.2	0.2	0.2	0.5	0.5	0.4	0.4
Nitrite	$10 \times mg \times l^{-1}$	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.2
Nitrate	$mg \times l^{-1}$	0.8	1.0	0.9	0.5	0.2	0.6	0.4	0.5	0.4	0.4	0.4	0.2	0.4
TP	$\mu g \times l^{-1}$	12.7	13.5	16.0	12.7	13.5	13.3	15.9	13.6	12.7	19.2	13.5	19.5	17.4
Orthophosphate	$\mu g \times l^{-1}$	8.7	6.9	7.8	8.0	8.7	4.7	9.4	12.4	7.8	10.0	9.8	11.5	6.2
Total Calcium	$10^2 \times \mu g \times l^{-1}$	3.2	0.9	3.6	7.4	9.7	53.0	1.2	0.9	6.2	6.5	0.9	4.2	13.4
Total Iron	$10 \times \mu g \times l^{-1}$	0.3	0.8	0.2	1.2	0.3	2.4	2.1	0.3	<0.1	<0.1	<0.1	0.2	0.1
Total Potassium	$\mu g \times l^{-1}$	0.1	0.1	1.1	1.3	0.2	1.1	1.2	0.6	0.4	0.4	1.1	1.1	0.9
Chlorophyll *a*	$\mu g \times l^{-1}$	2.1	2.6	2.8	3.5	2.6	4.9	2.8	2.9	2.5	2.0	3.6	2.3	6.4
TSI	–	34.5	35.5	35.9	37.0	35.5	38.6	35.8	36.0	35.4	34.1	37.0	35.0	39.9
Phytoplankton taxa	Species	14	10	6	15	7	10	11	10	15	6	7	19	27
Cyanobacteria[a]	%	97.5	94.7	22.2	97.5	87.7	97.2	95.7	99.3	5.3	18.2	80.0	95.8	96.9
Zooplankton taxa	Species	6	*8*	8	10	7	9	8	6	6	5	6	9	13
Dominant zooplankton family		CYC	*CYC*	ROT	CYC	ROT	CYC	ROT	CYC	ROT	ROT	CYC	CYC	CYC
Zooplankton density	ind/ml	17.0	23.5	13.5	29.0	8.0	29.5	22.5	16.5	18.0	20.0	22.0	29.5	74.5

Numbers in parenthesis refers to sites plotted in Fig. 1.

[a] Percentage of Cyanobacteria families.

DO is Dissolved Oxygen, BOD is Biochemical Oxygen Demand, EZD is Euphotic Zone Depth, TN is Total Nitrogen, TAN is Total Ammoniacal Nitrogen, TP is Total Phosphorus, TSI is Trophic State Index. TSI classification is: ≤44 – Oligotrophic; 44 < TSI < 54 – Mesotrophic; ≥54 – Eutrophic. CYC refers to Cyclopoideae, ROT to Rotifera, CLA to Cladocera. Data collected in one survey performed in July 2007.

Appendix 2.

Morphometric and hydrodynamic data of selected sites (local depth ≥10 m) at Ilha Solteira reservoir used for calculation of ecological carrying capacity for assimilation of Phosphorus loads derived from fish farming in floating cages.

		1	2	3	4	5	6	7	8	9	10	11	12	13
Area	km^2	7.3	13.35	3.99	31.61	2.45	9.62	3.72	25.56	4.58	1.47	3.87	2.36	2.5
Mean depth	m	10.25	9.35	4.92	6	11.72	8	6.03	10.21	15.07	3.54	3.43	7.09	4.93
Inflow[a]	$10^6 \times m^3$	15.50	81.00	8.00	66.50	5.00	78.00	12.50	26.40	15.00	9.50	6.50	9.00	28.00
Residence time[b]	days	55.87	17.84	28.40	33.01	66.47	11.42	20.77	114.43	53.26	6.34	23.64	21.52	5.09
Flushing rate[c]	$year^{-1}$	6.44	20.18	12.68	10.91	5.42	31.52	17.33	3.15	6.76	56.78	15.23	16.73	70.66
TP	$mg \times m^{-3}$	12.73	16.00	13.51	12.72	13.52	13.32	15.89	13.59	12.72	19.21	13.52	19.47	17.35
Sedimentation rate[d]	–	0.39	0.27	0.32	0.34	0.42	0.23	0.29	0.48	0.39	0.18	0.30	0.29	0.17
P assimilation per area[e]	$g \times m^{-2} \times year^{-1}$	1.88	3.63	1.51	1.70	1.79	5.46	2.07	1.02	2.88	2.66	1.23	1.76	5.29
Ecological carrying capacity[f]	$10^3 \times ton \times year^{-1}$	0.93	3.27	0.41	3.63	0.30	3.55	0.52	1.76	0.89	0.26	0.32	0.28	0.89
Occupation	%	0.45	0.87	0.36	0.41	0.43	1.32	0.50	0.25	0.70	0.64	0.30	0.42	1.28

Numbers in parenthesis refers to sites plotted in Fig. 1.

[a] The volume of water discharged by the inlet to the main channel of the reservoir.

[b] The average amount of time water spends in the site.

[c] How many times water is totally renewed in one year.

[d] The fraction of Total Phosphorus retained by sediments, estimated according to the method proposed by Larsen and Mercier (1976).

[e] The area-specific capacity to assimilate Phosphorus per year estimated following Beveridge (2004).

[f] The ecological carrying capacity expressed as the maximum fish production for each site.

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