The ecological dynamics of Barra Bonita (Tietê River, SP, Brazil) reservoir: implications for its biodiversity

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(With 17 figures)

Abstract

Barra Bonita reservoir is located in the Tietê River Basin – São Paulo state – 22° 29" to 22° 44" S and 48° 10° W and it is the first of a series of six large reservoirs in this river. Built up in 1963 with the aim to produce hydroelectricity this reservoir is utilized for several activities such as fish production, irrigation, navigation, tourism and recreation, besides hydroelectricity production. The seasonal cycle of events in this reservoir is driven by the hydrological features of the basin with consequences on the retention time and on the limnological functions of this artificial ecosystem. The reservoir is polymitic with short periods of stability. Hydrology of the basin, retention time of the reservoir and cold fronts have an impact in the vertical and horizontal structure of the system promoting rapid changes in the planktonic community and in the succession of species. Blooms of *Microcystis* sp. are common during periods of stability.
Superimposed to the climatological and hydrological forcing functions the human activities in the watershed produce considerable impact such as the discharge of untreated wastewater, the high suspended material contributions and fertilizers from the sugar cane plantations. The fish fauna of the reservoir has been changed extent due to the introduction of exotic fish species that exploit the pelagic zone of the reservoir.
Changes in the primary productivity of phytoplankton in this reservoir, in the zooplankton community in the diversity and organization of trophic structure are a consequence of eutrophication and its increase during the last 20 years. Control of eutrophication by treating wastewater from urban sources, adequate agricultural practices in order to diminish the suspended particulate matter contribution, revegetation of the watershed and riparian forests along the tributaries are some possible restoration measures. Another action that can be effective is the protection of wetlands in the main tributaries as an effort to control eutrophication and particulate material load.
Hydrology, *climatic forcing* and *retention time* are major forcing functions that promote the circulation (vertical and horizontal) in the reservoir and probably have a strong effect on dissolved and particulate material distribution. The 114 tributaries are systems that enhance spatial heterogeneity promoting diversity throughout ecological niches. Switches of control systems of this artificial ecosystem seems to be related with physical – physical forces; physical – biological forces during short periods of time, and biological – biological interactions at varying degrees during the seasonal cycle.

Keywords: reservoir, hydrology, climate, retention time, biodiversity.

A dinâmica ecológica da represa de Barra Bonita: as implicações na sua biodiversidade

Resumo

A represa de Barra Bonita localizada na bacia do médio Tietê, Estado de São Paulo (22° 29" a 22° 44" S e 48° 10" W) é o primeiro de uma série de seis reservatórios de grande porte localizados nesse rio. Construída em 1963, com a finalidade de produção de energia elétrica, esta represa é utilizada atualmente também para produção de peixes, recreação, turismo, navegação e irrigação. O ciclo estacional de eventos nesse reservatório é dirigido, em grande proporção, pelas características hidrológicas da bacia hidrográfica com conseqüências nas funções limnológicas desse ecossistema. O reservatório é polimítico com curtos períodos de estabilidade vertical. A hidrologia da bacia hidrográfica, o tempo de retenção do reservatório e as frentes frias têm um papel fundamental na estrutura horizontal e vertical do sistema, produzindo rápidas alterações na comunidade planctônica e na sucessão de espécies do fitoplâncton, zooplâncton e bacterioplâncton. Florescimentos de *Microcystis aeruginosa* são freqüentes durante períodos de estabilidade térmica vertical. Atelomixia é também um fenômeno recorrente na represa de Barra Bonita. Os 114 tributários são elementos de heterogeneidade espacial na represa.
Superpostas às funções de forças climatológicas e hidrológicas, as atividades humanas na bacia hidrográfica produzem considerável impacto, tais como a descarga de nitrogênio e fósforo de esgotos não tratados, materiais particu-

lados e dissolvidos em suspensão, e fertilizantes provenientes das extensas plantações de cana-de-açúcar na bacia hidrográfica. A fauna iíctica apresentou inúmeras alterações, principalmente, devido à introdução de espécies exóticas de peixes que exploram a zona pelágica do reservatório.
Alterações na produção primária do fitoplancton, na comunidade zooplanctônica e no bacterioplâncton, e na estrutura trófica, são uma das conseqüências da eutrofização e do seu aumento nos últimos 20 anos. Além disto, a toxicidade e a predação intrazooplanctônica podem causar alterações substanciais na biodiversidade e na sucessão de espécies do fitoplâncton, zooplâncton, bacterioplâncton e bentos. Controle da eutrofização, reflorestamento da bacia hidrográfica, proteção das áreas alagadas nos tributários e controle da carga interna do reservatório são algumas das possíveis medidas para recuperação da represa, da qualidade da água e dos serviços neste ecossistema, inclusive recuperação da biodiversidade.
Alterações nos sistemas de controle desta represa estão relacionadas com interações fisicas-fisicas; físicas-biológicas; biológicas-biológicas em várias intensidades durante o ciclo estacional.

Palavras-chave: represas, ciclo hidrológico, climatologia, tempo de retenção, biodiversidade.

1. Introduction

Barra Bonita reservoir is the first of a series of six large reservoirs in the Tietê River São Paulo state, primarily constructed for hydroelectricity production. The reservoir is located in the Middle Tietê River Basin in the central region of São Paulo state (22° 29” to 22° 44” S and 48° 10" W). The reservoir started its operation in 1963 and from that period several changes in its watershed occurred as a consequence of agricultural and industrial development and increase of population. The reservoir is situated in a region of geographical transition between tropical and subtropical climates, with a rainy season (from October and March) and a dry season (from March to October) Tundisi. et al. 1981. The reservoir is subjected to impacts of cold fronts from the Antarctic that affects the South East of Brazil (Tundisi et al., 2004).

This reservoir has the following main characteristics:

Watershed area: 32.330 km^2.

Inundated area: 324,84 km^2.

Perimeter: 525 km.

Total volume of reservoir: 3.160 x 10^6 m^3.

Mean Depth: 10.2 m.

Maximum Depth: 25 m.

Retention on time: 30 days (summer) 90 days (winter).

Figure 1 - Shows the reservoir its main characteristics and regions.

Figure 2a,b - Shows the storage variation for Barra Bonita reservoir in the 30 years from 1970 to 2000.

Figure 3 - is a satellite image of the reservoir. One of the important feature of the reservoir is the presence of wetlands at the entrance of tributaries. (Figure 4) Oliveira (1993).

In this review the authors analyse the functioning of this artificial reservoirs from an ecosystem perspective in order to understand the role of main forcing functions and interactions among components. The changes in biodiversity can be explained by changes in forcing functions such as climatological-hydrological interactions with consequences on the primary production, seasonal cycles of phytoplankton and zooplankton. As Jorgensen and Marques (2001) pointed out there are a few observed links between the various studies, laws and rules and this paper is an attempt to promote the knowledge of these links and a theoretical network in order to advance the studies on reservoir ecosystem in the neotropics. Long term changes due to the influence of external forces and eutrophication will be analyzed.

2. Material and Methods

Several research activities were developed at Barra Bonita reservoir. Many sampling stations for work with phytoplankton, zooplankton, fishes ecology, benthic organisms, studies on biogeochemical cycles and primary production of zooplankton were established.

Sampling periods varied depending on the subject of study. In general the seasonal cycle was chosen as a basis for periodic sampling but some of the research activities focused on two periods: summer (higher temperature, high rainfall) and winter (lower temperature, low rainfall).

Sampling was not only performed in the reservoir. Some studies focused on the watershed, for example sampling in rivers in order to estimate the load for nutrients (N, P, suspended material) to the reservoir (Oishi, 1996). (Figure 5).

Sampling was designed in order to give attention to the organizational morphometric features of the reservoir. Accordingly to Bini 1997 Barra Bonita has three homogeneous zones: i) riverine zone; ii) transitional zone; and iii) lacustrine zone.

3. Results

3.1. The seasonal dynamics of Barra Bonita reservoir

The seasonal dynamics of the Barra Bonita reservoir is dependent on the following forcing functions:

i) The hydrological cycle and the storage/release characteristics of the volume. The storage/discharge variation showed a pattern with accumulation during winter periods and higher discharge and less accumulation during summer.

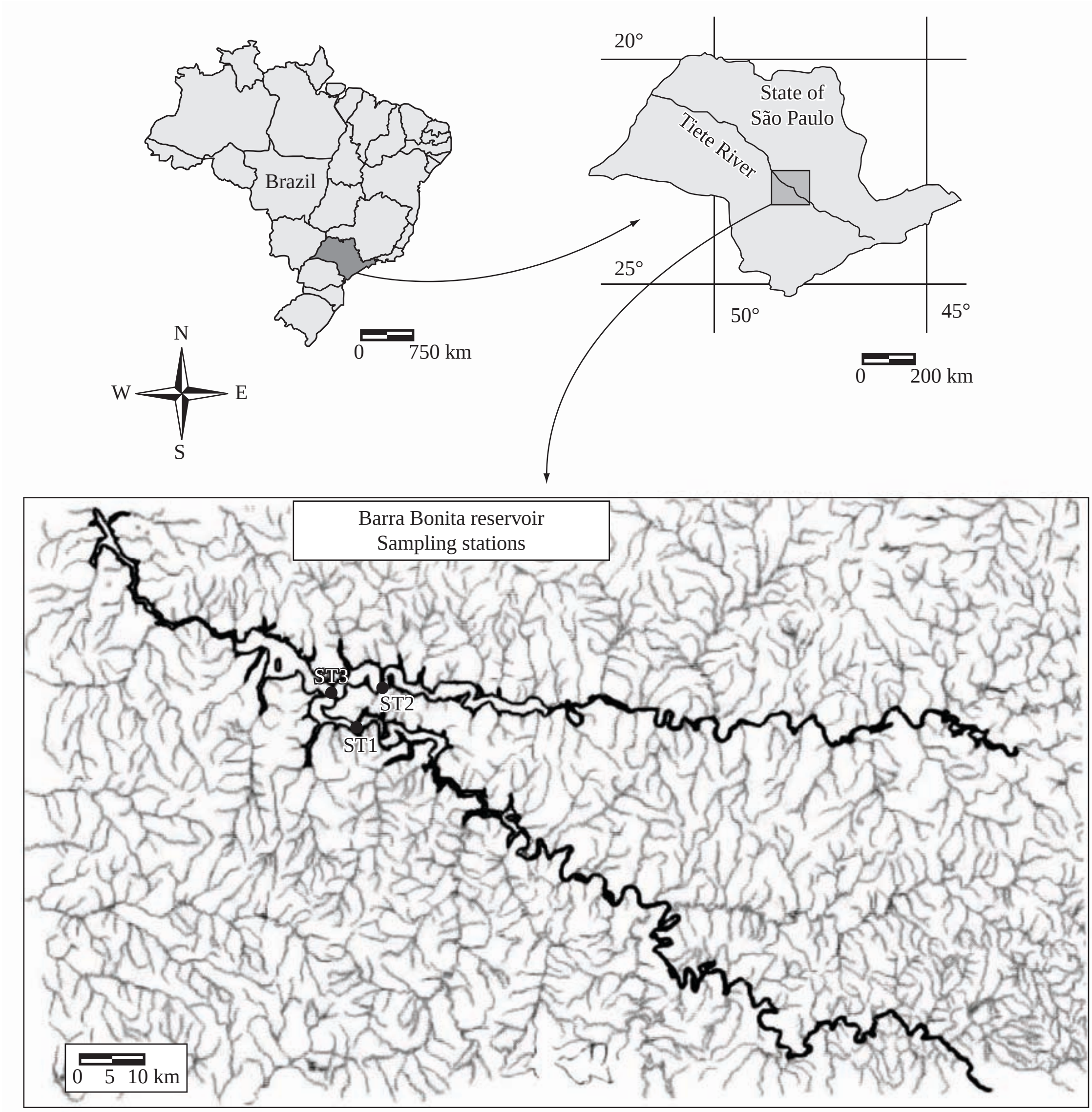

Figure 1. Barra Bonita reservoir its main characteristics and regions. Sampling stations for plankton richness studies are shown. (Matsumura Tundisi and Tundisi 2005).

ii) Superimposed to this seasonal variation of the hydrological components there is the impact of cold fronts in the reservoir. The relationship monthly occurrence of cold fronts and wind velocity shows a strong dependence. Therefore increase of wind velocity during cold fronts promotes vertical mixing. (Figure 6) This has important consequences in the vertical distribution of phytoplankton and zooplankton as shown by Tundisi et al. (2004). As shown by Dellamano-Oliveira et al. (2008) the highest proportions of Cyanophyceae (51%) occurred in the euphotic zone during the hottest months. The most representative data for the phytoplankton groups were, accordingly with these authors: *Microcystis aeruginosa* (Kützing), free cells of *Microcystis* sp. *Aphanocapsa elachista* (West and West), *Pseudoanabaena mucicola* (Naumann and Hubber Pestalozzi), *Planktotrix tropicalis* (Komarek), *Spaerocavum brasiliense* (Azevedo and Sant'Anna), *Cylindrospermopsis raciborskii* (Wolozynska Seeruya and Suba-Rao), among the Cyanophyceae, and *Aulacoseira granulata* (Ehremberg) *Cyclotella meneghiana* (Kützing) (Baccillariophyceae) *Monoraphidium* sp. *Schroederia* indica Philipose (Chorophyceae) and Cryptononas sp. (Cryptophyceae). The highest values of richness and diversity of phytoplankton occurred in the dry period, and “interannual and seasonal variability in richness and species diversity was significant” (apud Dellamano

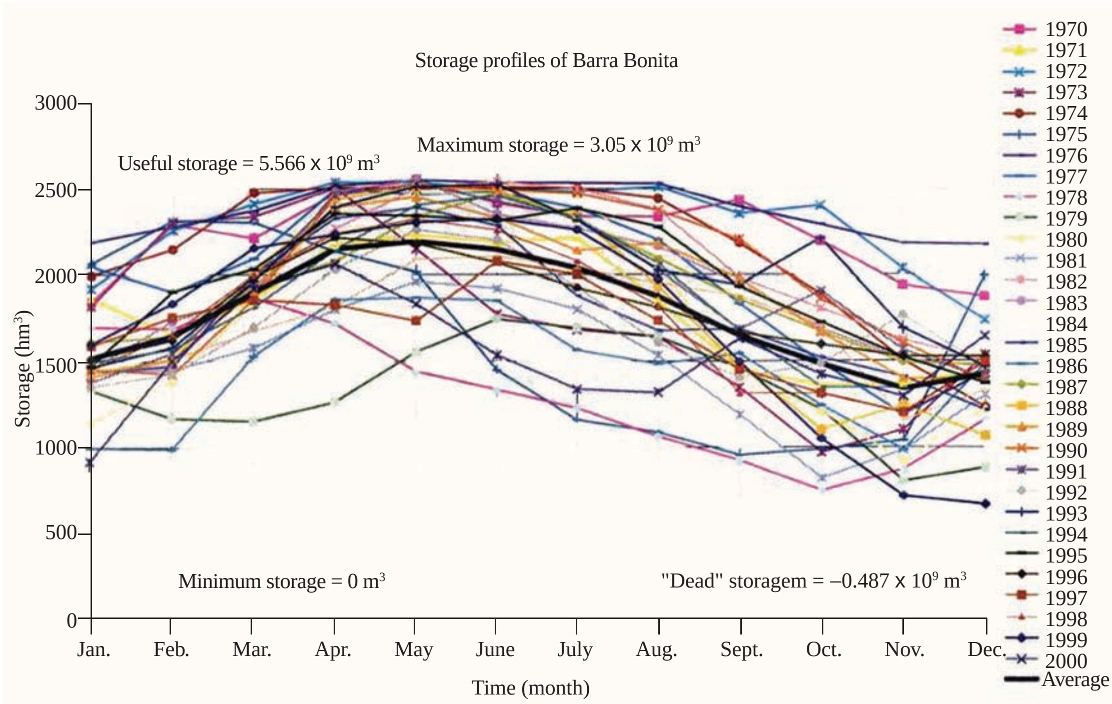

Figure 2a. Storage variation for Barra Bonita reservoir in 30 years (from 1970 to 2000). Source: (Chaves, 2002).

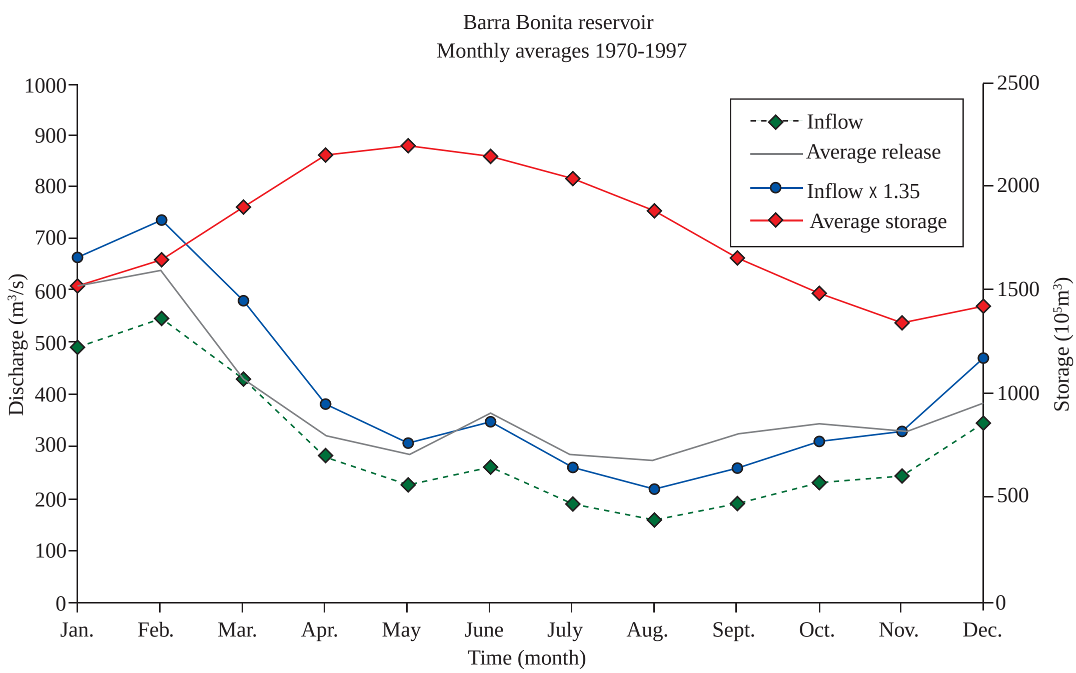

Figure 2b. Average storage variation for Barra Bonita reservoir 1970-2000. Source: (Chaves, 2002).

Oliveira et al., 2008). The vertical distribution of *Aulacoseira granulata* is influenced by the vertical mixing patterns and the frequency of *Microcystis aeruginosa* blooms was determined by short periods of thermal stratification. In some regions of the reservoir were mixing of waters of different density occurs (such as in the confluence of the Tietê and Piracicaba river inflow waters) large accumulation of *Cyclotella meneghiana* was found (Tundisi unpublished) confirming the hypothesis of "cells" in the horizontal discontinuities, as was pointed out by Matsumura-Tundisi and Tundisi (2005).

Figure 3. Satellite image of Barra Bonita reservoir.

Figure 4. Wetlands in the entrance of tributaries in Barra Bonita.

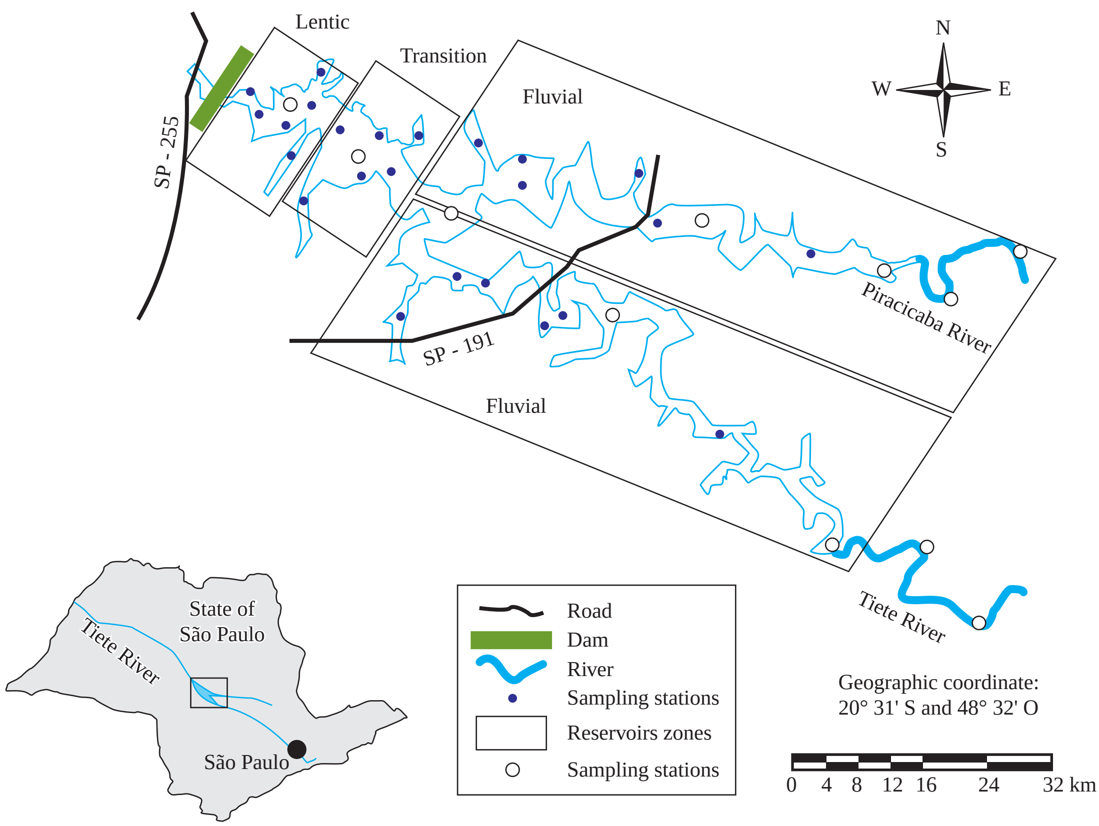

Figure 5. Sampling stations in Barra Bonita, in the last 30 years. (Modified from Petesse et al 2007).

iii) The seasonal dynamics of the reservoir is also promoted by the input of nutrients from the basin and the contribution of the two maim tributaries Tietê and Piracicaba rivers. Despite the fact that Barra Bonita is a eutrophic reservoir (Tundisi and Matsumura-Tundisi, 1990) the external input by its 114 tributaries is an important process, therefore pulses of nutrient input may be expected during rainfall periods (Oishi, 1996). (Figure 7). Figure 8 shows the seasonal cycle of phytoplankton primary production during 1983-1984. A maximum production occurred during winter period (May-June-July) and lower production occurred during the summer. Intense precipitations reduction of euphotic zone (ZEU) due to input of suspended matter are the probable cause of this lower

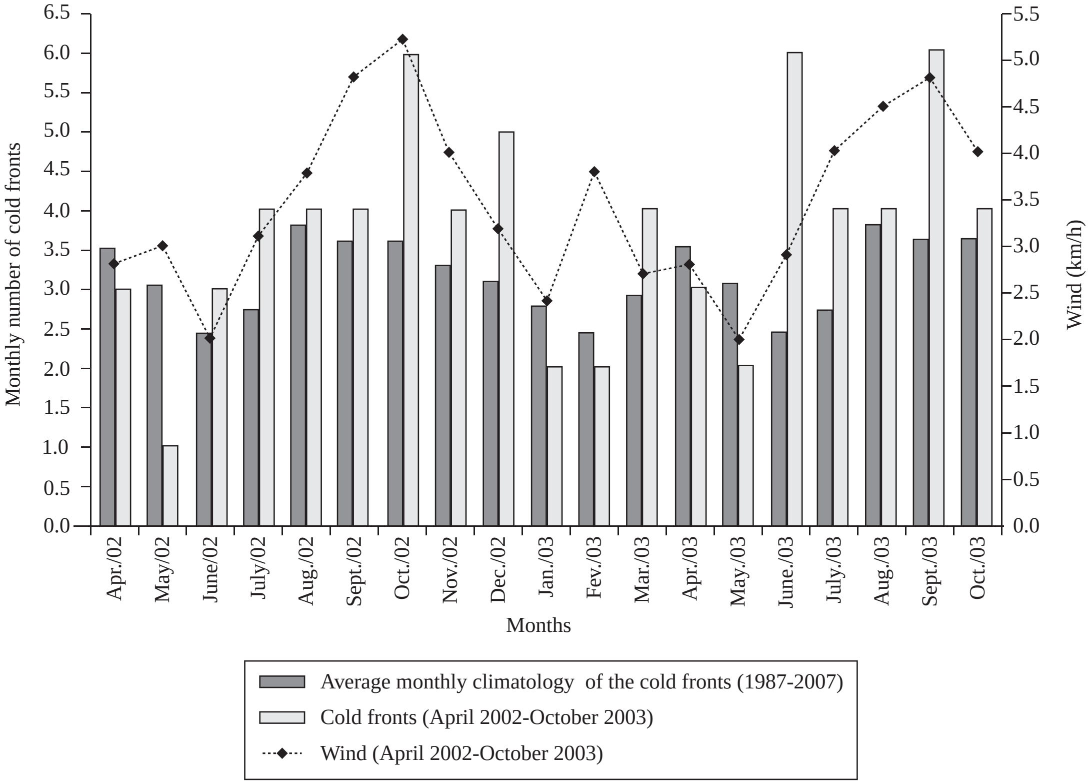

Figure 6. Wind velocity and cold fronts in Barra Bonita reservoir. Source Dellamano Oliveira et al. 2008, modified.

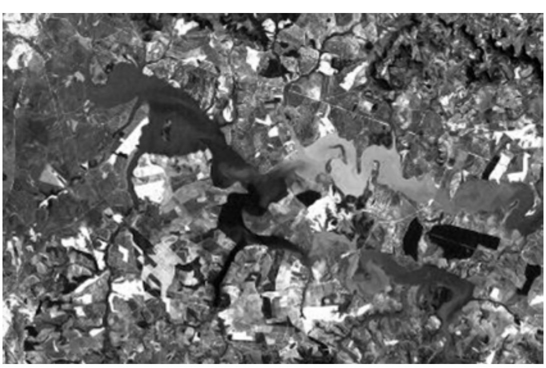

Figure 7. Satellite image of Barra Bonita during the summer showing the large contribution of suspended material to the reservoir.

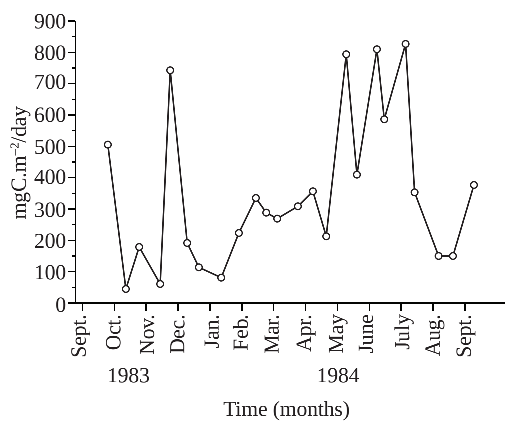

Figure 8. Seasonal cycle of primary production of phytoplankton during 1983-1984. The summer of 1984 was a period of intense El Niño phenomenon.

production in the summer. Therefore regenerated production resulting from nutrient inputs into the euphotic zone due to internal recycling is a probable cause of higher primary production during winter; also light penetration is higher during winter (Figure 9) (Matsumura Tundisi and Tundisi 1997).

Figure 10 Shows the simulated seasonal variation of phytoplankton biomass (chlorophyll) as presented by Saggio (1992). Comparative evaluations with sampling showed results in reasonable agreement with the simulation. (De Fillipo 1987, Dellamano-Oliveira, et al. (2008).

Table 1 - Shows the nutrient, chlorophyll and primary production data for a series of lakes and reservoirs. Table 2 shows the mean annual phytoplankton (cells.l) and zooplankton (ind.m^{-3}) for these ecosystems.

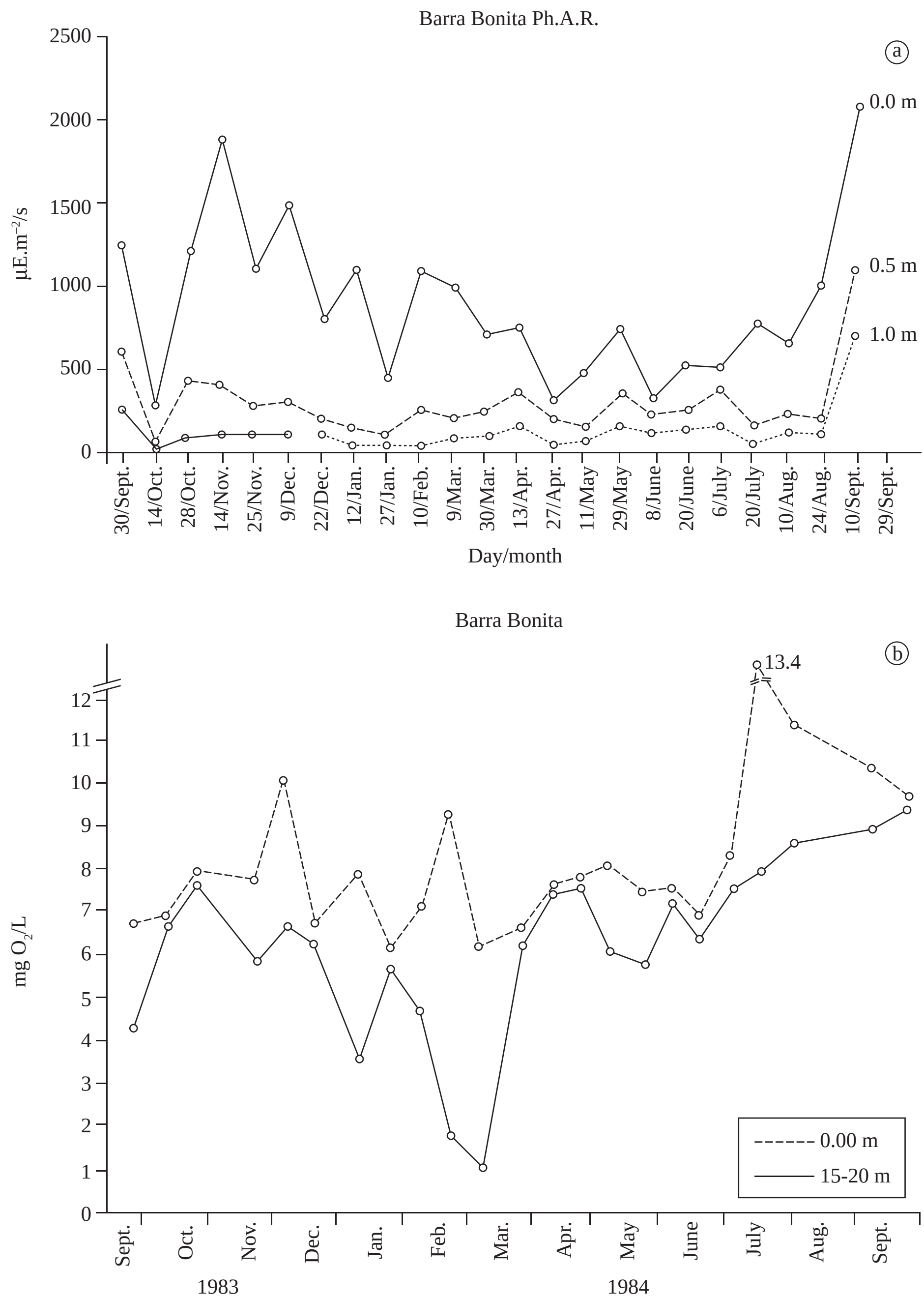

Figure 9. a) The seasonal cycle of the photosynthetic active radiation at Barra Bonita reservoir and b) The seasonal dynamics of dissolved oxygen at surface and bottom waters.

Accordingly to past work, Tundisi et al., 2002 a wind force of 6 km/h is sufficient to promote turbulence in the whole water column, or at least in a great volume of the reservoir with important mixing consequences on the vertical distribution of dissolved oxygen, turbidity, and water temperature.

The seasonal dynamics of the phytoplankton community at Barra Bonita reservoir fits well with the matrix discussed by Tundisi, 1990; Reynolds, 1984; 1997. As far back as 1987, De Filippo (1987) presented results of seasonal succession that showed the conformity of the phytoplankton succession with the known matrices

Table 1. Mean annual phytoplankton (cell.L^{-1}) and zooplankton (ind.m^{-3}) numeral density for, the selected lakes and reservoirs.

Lake	Phytoplankton Mean ± SD	Zooplankton Mean ± SD	Source authors
R. Lagoa Dourada, SP	$5.90 \times 10^4 \pm 4.80 \times 10^4$	$4.80 \times 10^5 \pm 4.20 \times 10^5$	Talamoni (1995)
R. Broa, SP	$1.90 \times 10^6 \pm 2.30 \times 10^5$	$9.90 \times 10^6 \pm 13.1 \times 10^6$	Matsumura-Tundisi and Tundisi (1976)
R. Monjolinho, SP	$1.30 \times 10^5 \pm 2.40 \times 10^5$	$4.10 \times 10^5 \pm 6.40 \times 10^5$	Nogueira (1990)
R. Pedreira, SP	$6.60 \times 10^7 \pm 1.80 \times 10^6$	$1.05 \times 10^6 \pm 3.10 \times 10^6$	Talamoni (1995)
R. Barra Bonita, SP	$1.90 \times 10^7 \pm 6.80 \times 10^6$	$8.50 \times 10^4 \pm 4.90 \times 10^4$	Thematic Project (unpubl; 1994)
R. Paranoá, SP	$4.00 \times 10^7 \pm 2.70 \times 10^7$	$4.30 \times 10^4 \pm 2.60 \times 10^4$	Branco (1991)
L. Dom Helvécio, MG	$2.60 \times 10^6 \pm 4.20 \times 10^6$	$2.90 \times 10^3 \pm 2.70 \times 10^2$	Pontes (1980), Matsamura-Tundisi and Tundisi (1986)
L. Emboaba, RS	$8.60 \times 10^6 \pm 8.60 \times 20^6$	$6.70 \times 10^5 \pm 3.80 \times 10^5$	Spohr-Bacchin (1995)
L. Caconde, RS	$1.60 \times 10^7 \pm 8.80 \times 10^6$	$1.50 \times 10^5 \pm 8.40 \times 10^4$	Güntzel (1995)
R. Jacaré-Pepira, SP	$2.50 \times 10^5 \pm 2.20 \times 10^5$	$5.30 \times 10^5 \pm 7.10 \times 10^4$	Franco (1982), Claro (1978)

Table 2. Nutrient chlorophyll and primary production data. Annual mean and standard deviation (in parenthesis). TIN = total organic nitrogen; TDP = total dissolved phosphorus.

Lake	TIN μg·L^{-1}	TDP μg·L^{-1}	Chl *a* μg·L^{-1}	Primary Production mgC·m^{-2}/h	Source authors
R. Lagoa Dourada, SP	25.25 (9.48)	2.89 (2.09)	4.22 (0.82)	2.55 (1.58)*	Talamoni (1995), Pompêo (1991)
R. Broa, SP	42.15 (10.25)	7.94(2.91)	10.05 (2.41)	13.98 (4.84)	Matheus and Tundisi (1988)
R. Monjolinho, SP	204.8 (287.68)	6.80(8.48)	8.69 (8.50)	-	Nogueira (1990)
R. Pedreira, SP	788.51 (57.24)	5.67 (4.55)	43.70 (3.85)	156.40 (19.36)**	Talamoni (1995)
R. Barra Bonita, SP	656.2 (811.50)	13.31 (3.98)	28.80 (45.92)	214.61 (150.91)	Tundisi et al. (1990)
R. Paranoá, DF	662.8 (366.01)	32.41 (7.18)	56.90 (21.10)	120.22 (77.18)	Branco (1991)
L. Dom Hevécio, MG	17.80 (18.12)	3.62 (2.97)	2.47 (1.16)	18.85 (8.67)	Okano (1980), Pontes (1980)
L. Emboada, RS	10.58 (14.93)	4.85 (4.36)	4.47 (3.60)	-	Spohr-Bacchin, M. (1995)
L. Caconde, RS	654.86 (206.64)	25.52 (4.88)	9.41 (3.91)	268.96 (222.04)	Güntzel (unpubl.)
R. Jacaré-Pepira, SP	12.4 (4.99)	1.13 (1.07)	1.71 (0.62)	4.05 (1.39)	Claro (1978), Franco (1982)

*Three month study in Lagoa Dourada reservoir. **A month study on alternate days in Pedreira reservoir. In some cases, data were obtained from the original and transformed to comparable units.

of phytoplankton seasonal changes. Lima et al. (1979) presented a model of *Melosira italica* succession at Lobo/Broa reservoir that also fits well with the of phytoplankton succession at Barra Bonita as discussed by Dellamano-Oliveira et al. 2008.

3.2. The zooplankton, community

Matsumura-Tundisi et al. (1990) studied the organization and structure of the rotifera community in Barra Bonita. Accordingly to these authors the zooplanktonic community in this reservoir is dominated by rotifers, and its diversity varies accordingly with the stations: stations I and IV (in the Tietê river) have higher richness of species (32 and 33 respectively) and station II and III (Piracicaba River) have lower richness of species (25 and 21 respectively).

This difference was attributed by Matsumura-Tundisi et al. (1990) to the more eutrophic condition in the Tietê

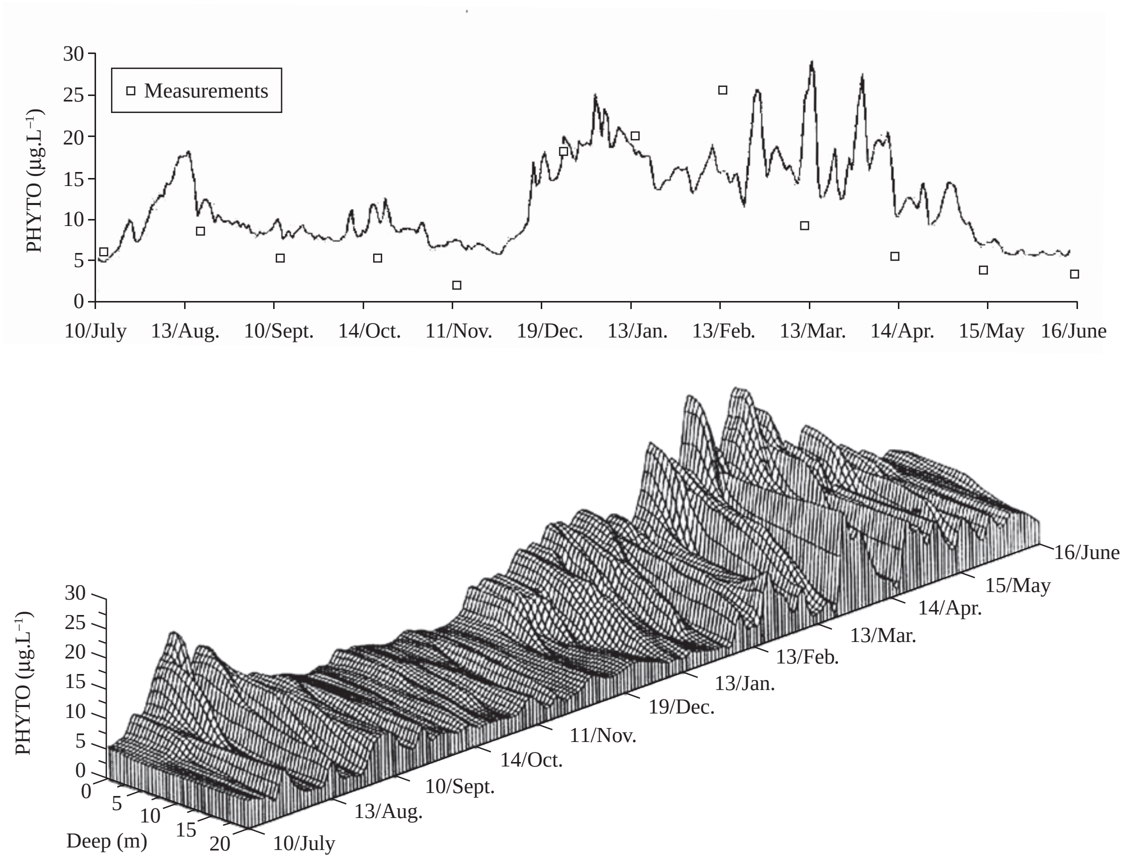

Figure 10. Simulated variation of chlorophyll (phytoplankton biomass) 1992-1993, and the measurements. Source (Saggio, 1992).

river than the Piracicaba river. The association *Conochilus unicornis* / *Keratella cochleoris* was dominant for Tietê River and the association *Polyarthra vulgaris*/ *Keratella tropica* was common in the Piracicaba River. This river has a faster water flux and a more riverine condition a fact that explains the strong seasonal fluctuation of the density of rotifers at this river.

Figure 11 - Shows the fluctuation of the density of Rotifera in the Tietê and Piracicaba river during the period of study 1985-1986.

Figure 12 - Shows the abundance of Calanoida/ Cyclopoida at one station in the main reservoir (lacustrine zone) during 1992-1993, and Figure 13 shows seasonal fluctuation of *Thermocyclops decipiens* and *Thermocyclops minutus* during 1983-1984 (Silva and Matsumura-Tundisi, 2005). Figure 14 - shows temporal changes of the populations of Calanoida in the period 19 83-1984 and 1985-1986.

The seasonal fluctuations of the zooplankton population is attributed to several factors, such as: phytoplankton availability as food (or particulate organic matter as food); mixing patterns and flushing rates; intrazooplankton predation and fish predation (Espindola, 1994) (Rietzler, 1995) (Tundisi and Matsumura-Tundisi, 2008); water temperature changes during the seasonal cycle. Figure 15 - shows the intrazooplanktonic predation at the Barra Bonita reservoir between *Mesocyclops* spp. (predator) and *Brachionus caliciflorus* (prey), (Tundisi and Matsumura-Tundisi, 2008). Short term variability of the zooplanktonic community is attributed to spatial heterogeneity and short-term changes in the physical organization of the ecosystem (Panarelli et al., 2001). Other papers that corroborate the zooplankton successional patterns at Barra Bonita reservoir are Matsumura-Tundisi (1986), Pinto Coelho, 1987; Pinto Coelho et al., 2005. Gonzalez et al. (2008) showed a relationship between the zooplankton biomass and the trophic state of the reservoirs. Eutrophic reservoirs support high abundance of zooplankton and structure, size and biomass of the zooplankton community (Pinto Coelho et al., 2005).

3.3. Vertical and horizontal circulation

Barra Bonita reservoir is a polymitic ecosystem with fluctuations promoted by rainfall and wind. The external forces that influence the mixing processes in the horizontal and vertical scales in this reservoir are: wind, intrusion of water from tributaries, low retention time during summer months (December to March); density currents

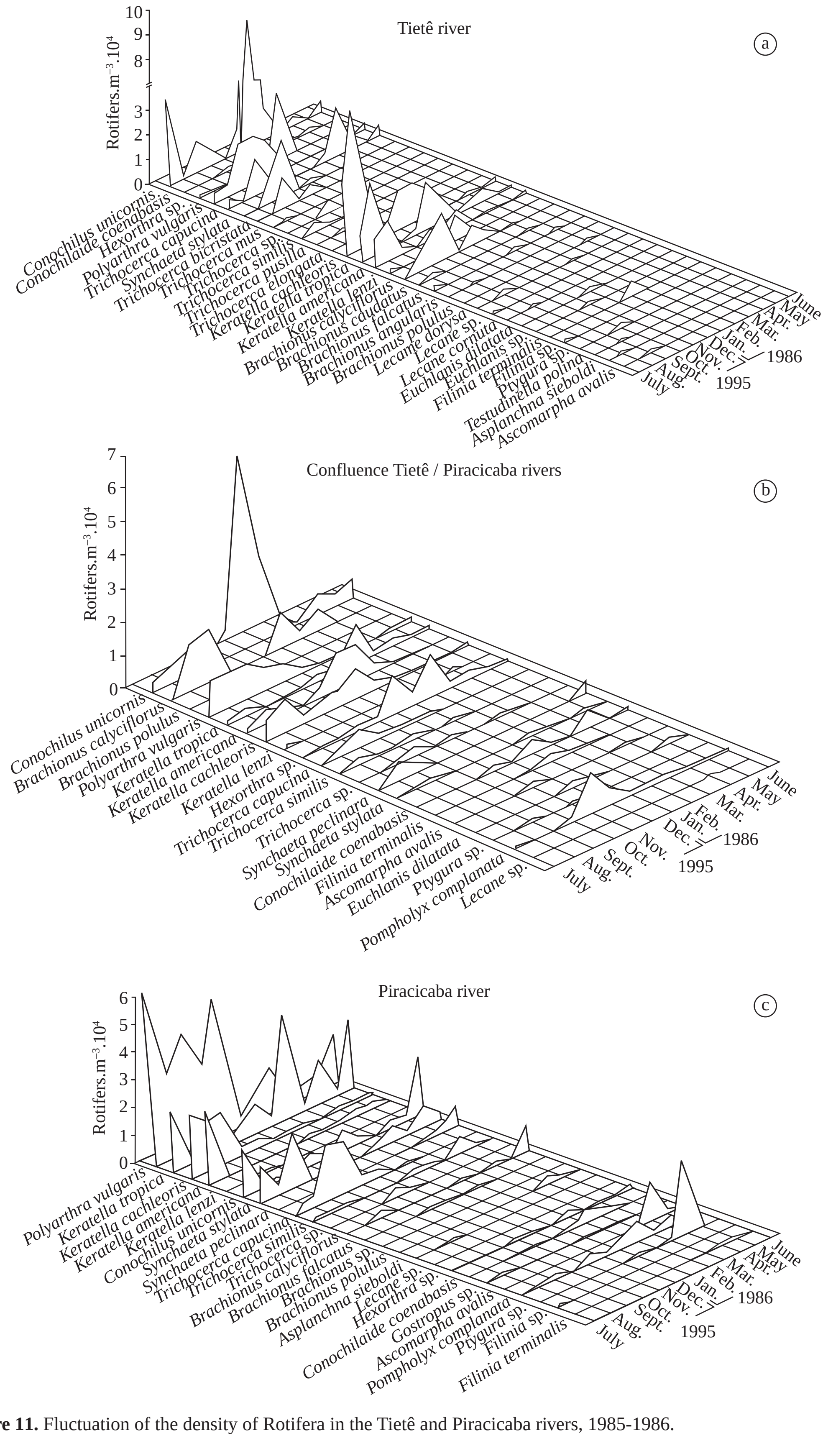

Figure 11. Fluctuation of the density of Rotifera in the Tietê and Piracicaba rivers, 1985-1986.

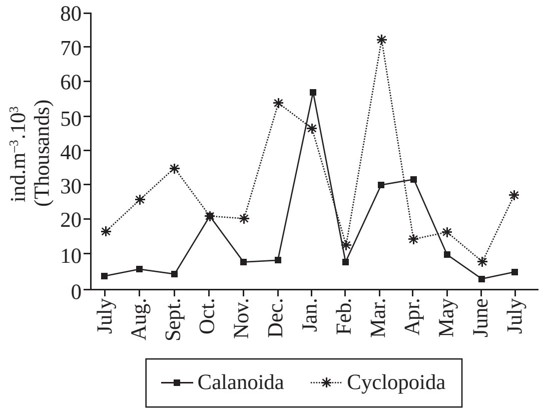

Figure 12. Abundance of Calanoida / Cyclopoida – seasonal fluctuation at a station in the main reservoir (1992-1993).

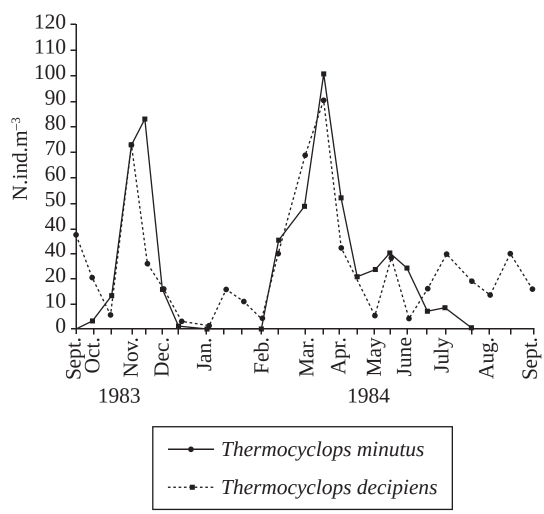

Figure 13. Seasonal fluctuations of *Thermocyclops decipiens* and *Thermocyclops minutus* 1983-1984.

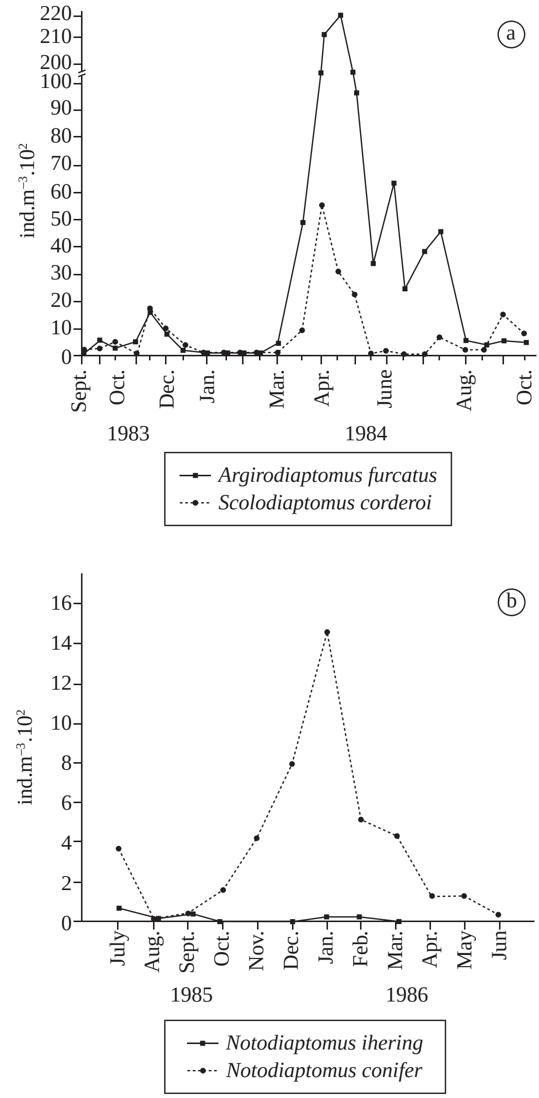

Figure 14. Temporal changes of the populations of Calanoida in the period a) 1983-1984 and b) 1985-1986.

as a result of the contribution of the two main tributaries Tietê river and Piracicaba river (Barbosa et al. 1999).

The vertical mixing promoted by the wind, changes the mixing layer in the layer of 1-2 m with a consequence of destroying the stable water column consisting of a thermal microstructure as defined by Imberger and Patterson (1990). The dynamics of the surface layer has repeated influences on the vertical distribution of dissolved gases as CO_2 and O_2, on the light penetration and on the permanence of blooms of *Microcystis aeruginosa* (Figure 16).

The overall dynamics of this mixing layer was determined by the magnitude of the Wedderburn number as shown by Saggio (1992), Tundisi et al. (2002) (Figure 17). For W 0.001-10 the layer deepening is uncoupled from internal seiches as determined. The turbulence promoted by the wind at this layer is generated thus by wind force, transporting and redistributing organisms and dissolved substances throught TKE (Turbulent Kinetic Energy). Therefore athelomixis as defined by Lewis (1983) is a common phenomenon in Barra Bonita reservoir during the whole year. Small patches of turbulence and slow motion breaks the regularity of the system also in the horizontal scale, decomposing the system into horizontally heterogeneous units, responsible for heterogeneous distribution of planktonic organisms (phyto, zooplankton and bacteria) as well as neustonic organisms dissolved and particulate organic matter. The bottom layer circulation is defined by the intrusion of waters of Tietê River more dense than the Piracicaba river producing therefore a vertical gradient of density in the deeper layers (Calijuri and Tundisi, 1990).

Considering therefore all the processes of water circulation, density layers, intrusion in Barra Bonita reservoir it can be considered that this ecosystem is composed of several patches of water of various conditions of surface circulation at the surface layer the vertical spatial variability due to differential density and intrusions, and the effect of outflows that changes the velocity and promotes density currents in the bottom layer at the 20-25 m depth. Gavilan Diaz 1990 (Straskraba, 1999; Matsumura-Tundisi and Tundisi, 2005).

3.4. Long term changes

As shown by Neiff et al. (2000) ENSO floods (El Niño southern Oscillation) have an impact on the whole Parana basin, therefore Barra Bonita reservoir is affected by these changes due to high precipitation and drainage and input of suspended material on the reservoir. Low concentration of dissolved oxygen (from 0.0 mg.L^{-1} to 3 mg.L^{-1}) was found during extreme events, in 1994. (Tundisi, unpublished results)

Barra Bonita is a reservoir subjected to a extense eutrophication process process resulting from the input of nitrogen and phosphorus from the two main tributaries Tietê and Piracicaba rivers and the non point sources as contributions from its watershed.

This long term eutrophication process resulted in the following main changes of the reservoir:

i) A continuous increase in the frequency of cyanobacteria blooms, particularly *Microcystis aeruginosa*;
ii) An increase in several eutrophication indicators (Table 3). For example phytoplanktonic primary production increased 15 times in 20 years; and
iii) Changes in the zooplanktonic community particularly the copepod composition. Table 4 shows the changes in Calanoida species dominance from 1979 to 2002.

Changes in the ionic composition may affect the calanoida species. Conductivity values of water from Barra

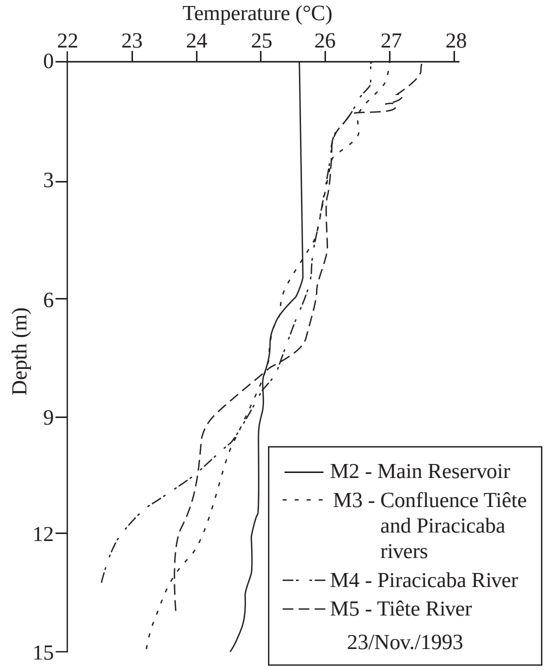

Figure 16. Dynamics of the surface layear demonstrated by vertical distribution of water temperature at Barra Bonita in a station in the main reservoir. Intrazooplankton predation at Barra Bonita reservoir.

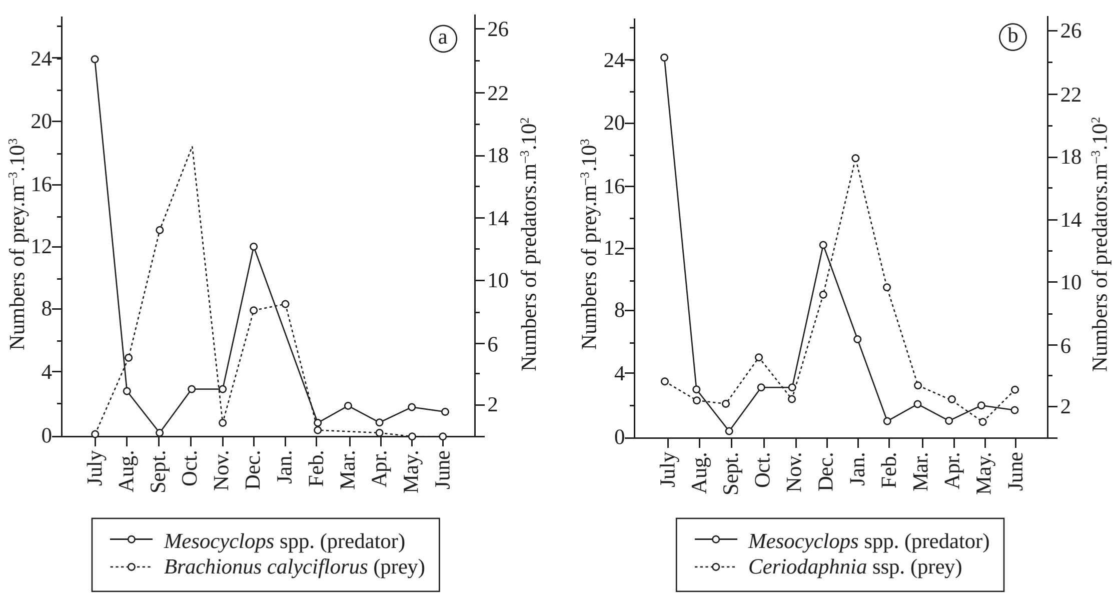

Figure 15. Intrazooplankton predation at Barra Bonita.

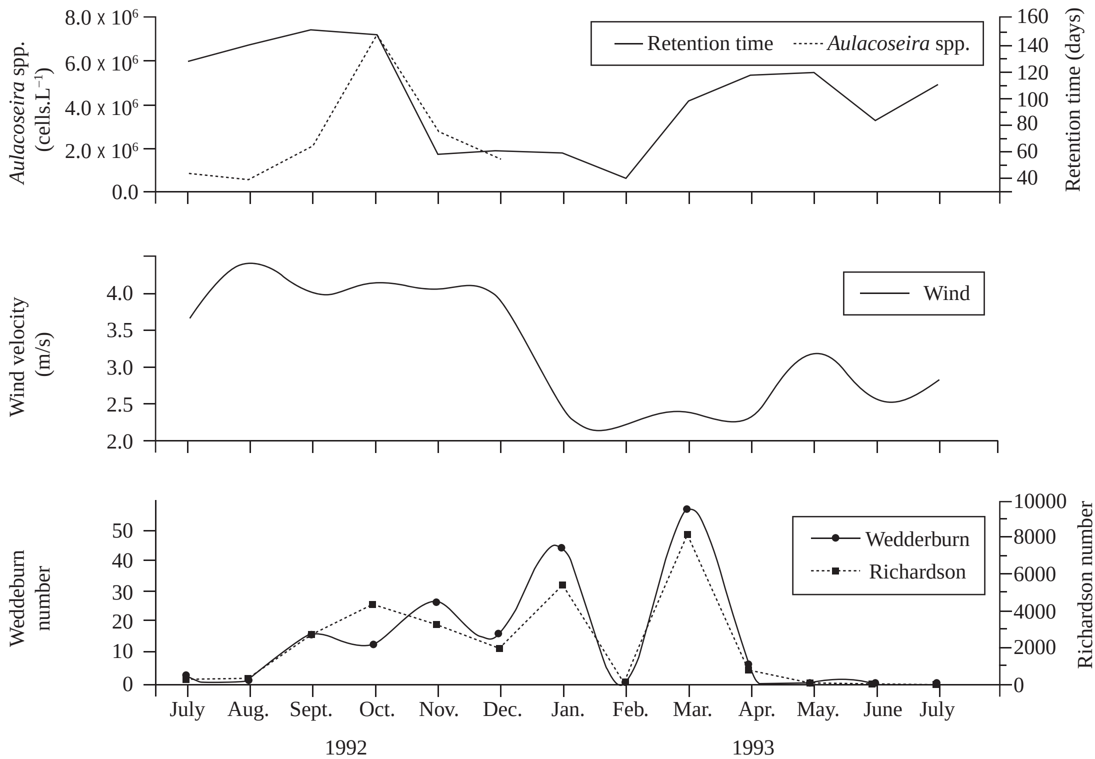

Figure 17. The seasonal variation of Wedderburn number, wind velocity retention time. (Tundisi et al. 2002).

Table 3. Changes in some factors in the Barra Bonita reservoir from 1979 to 2002 (annual average values).

Variables	1979	1983-1984	1985-1986	1992-1993	2002
Conductivity (µS.cm–1)	103.3	-	190	203	370
Phosphorus content (µg.L–1)	15.0	14.4	16.3	22.2	40.1
Nitrate content (µg.L–1)	200.0	960.0	1,214.2	1,088.8	3,479.6
Ammonium content (µg.L–1)	-	16.8	38.8	28.5	232.0

Table 4. Succesion of Calanoida species dominance in Barra Bonita Reservoir.

	1979	1983	1984	1985	1986	1992	1993	2002
Notodiaptomus conifer	-	-	-	*	*	*	*	-
Agyrodiaptomus furcatus	-	****	****	-	-	*	*	-
Scolodiaptomus corderoi	-	***	***	-	-	-	-	-
Notodiaptomus iheringi	-	-	-	****	****	****	****	***
Notodiaptomus cearensis	-	-	-	-	-	***	***	***
Notodiaptomus nsp.	-	-	-	-	-	**	**	***

****Abundant and dominant; ***abundant but not dominant; **scarce; *very scarce.

Bonita reservoir showed increase from approximately 100 µS.cm–1 (1979) to 400 µS.cm–1 (2002).

As Rietzler et al. (2002) showed for Lobo Broa reservoir shifts from a *Argyrodiaptomus furcatus* dominance to a *Notodiaptomus iheringi* dominance occurred as a consequence of increasing conductivity and suspended material in that reservoir, confirming the succession at Barra Bonita.

iv) An increase in the toxicity of the ecosystem. Sotero-Santos et al. (2006) demonstrated that toxins released from cyanobacterial blooms from Barra Bonita were potentially capable of toxicity for cladocerans. Mortality rates of *Ceriodaphnia silvestris* in acute toxicity tests (24 hours) showed high mortality for this species a native cladoceran occurring in Barra Bonita reservoir. This experiment raises the question: to what extent the changes in the zooplankton composition of the Barra Bonita reservoir can be attributed to an increase in the overall toxicity of this ecosystem? The high density of cyanobacteria in Barra Bonita reservoir, the frequency of blooms and the large pool of DOM and DOC in this reservoir (Panhota et al., 2007) indicate several alternative routes for distribution and dynamics of this DOM in the reservoir with consequence on the food chain and heterotrophic activity and toxicity.

3.5. Short term changes

Short term mixing and stability periods in Barra Bonita reservoir (hours to days) are important controlling mechanisms for the primary productivity of phytoplankton, the zooplankton succession and the nutrient availability. Stratification depends upon the wind velocity and the mixing promoted by wind stress is regulated by the pattern of cold fronts.

Variations in the outflow during summer also control the cyanobacteria blooms that are washed out by the spill water defluent current. Matsumura Tundisi and Tundisi (1997) demonstrated that phytoplantonic primary production is higher in the winter rather than in the summer as a consequence of high rainfall and suspended matter with a strong reduction in the euphotic zone. The extent of the vertical mixing measured by Brunt Vaisulla frequency showed values in the scale of 10^1 to 10^3 seconds thus producing effects on the nutrient supply to phytoplankton by vertical mixing in small scale patches.

Composition of phytoplankton, photosynthetic responses and growth rates are controlled and regulated by fluctuations in discharge specially in the summer, by the athelomixis processes governing the response of the phytoplanktonic and zooplanktonic community its diversity and their successional patterns, in short periods. (Calijuri and Dos Santos, 2001). Short time fluctuations in nutrient availability are also due to physical disturbances. Santos, 1995 has shown that phosphorus availability is related to short periods of changes in the redox potential thus complexing ferric phosphate to the sediment or reducing ferric phosphate to ferrous phosphate and liberating phosphorous to the water (short periods = hours).

3.6. The fish community at Barra Bonita reservoir

Reservoir construction produces several impacts on fish diversity as demonstrated by Agostinho et al., 1999; 2007. In Barra Bonita several changes from the riverine to the reservoir ecosystem were registered and production and development of fisheries was studied by Petrere 1996; Petrere et al., (2002). Accordingly to Petesse et al. (2007) from the 35 species of fishes collected in the study and adaptation of the RFAI (Reservoir fish assemblage index), 3 were introduced species. *Plagioscion squamossissinus* was introduced and exploited the pelagic zone with great success Leal Castro (1994). Petesse et al. (2007) emphasized the structural and functional importance of macrophyte stands that occur in the reservoir, near the entrance of tributaries, and the riparian forest in the tributaries and the reservoir. These characteristics are fundamental for the maintenance and development of the fish assemblage, and its evolution in the ageing process of reservoirs. This was also considered by Straskraba, Tundisi and Duncan (1993) as a spatial and functional re-organization of the reservoir influencing strongly its biodiversity. Accordingly to Leal-Castro (1994) exploitation of resources by the fish fauna was efficient and diversified.

As pointed out by Agostinho et al., 1999, reservoirs are dominated by opportunistic species with high compensatory reproductive strategies and high resilience (r-strategists) (Petrere et al., 2002). Stands of aquatic macrophytes play a fundamental role in the dynamics of Barra Bonita reservoir as pointed out by Bini et al., 2001; for other reservoirs, in the Paraná River system.

3.7. Biogeochemical cycles

The cycle of nutrients and chemical elements and substances in Barra Bonita reservoir is influenced by the following factors:

a) Precipitation and drainage from the watershed producing a high input of nitrogen and phosphorus from non point sources;
b) Discharge of point sources of untreated waste water from the upstream human populations around the reservoir (approximately 1,500,000 inhabitants in the watershed);
c) Internal load of stored N. P. and metals in the sediment; and
d) Contribution of decomposing biomass of phytoplankton, zooplankton and fishes, as well as macrophytes to the pool of elements and substances in the water and sediments.

Petracco (1997) showed that *Polygnun spectabile* had a reserve of 308 $kgN.ha^{-1}$ in Tietê and Piracicaba rivers and *Paspalum repens* reserve was 194 $kgN.ha^{-1}$ in the Piracicaba river and 72 $kgN.ha^{-1}$ in the Tietê river. This indicates high storage capacity of these plants and their importance in the total nutrient budget of the reservoir.

The wetlands play an extensive role in the biogeochemical cycles at Barra Bonita reservoir, storing N, P and metals, release carbon phosphorus and nitrogen and promoting changes in the concentration of nitrogen, phosphorus , carbon and metals in the water. Storage-release processes depend on the seasonal cycle of inundation and dry periods, and on the dynamics of growth, reproduction and decomposition of macrophytes during this cycle. Pedro et al. (2006).

Eutrophication processes at Barra Bonita reservoir accelerates the emission of CH_4; CO_2 and N_2O as demonstrated by Abe et al. 2008 (in press).

3.8. Greenhouse gas emissions in Barra Bonita reservoir

Classic organic pollution, eutrophication and hypolimnetic anoxia are some of the common water quality problems in reservoirs (Straskraba and Tundisi, 1999). In Brazil these problems are related mainly to the loading of untreated sewage to the water bodies, as most of the sewage produced has no treatment. Besides the known consequences, like hygienic problems, formation of potentially toxic cyanobacterial blooms and fish mortalities, these impacts may also contribute to greenhouse gas production in the reservoirs and emission to the atmosphere. Untreated sewage loading promotes high dissolved carbon, phosphorus and nitrogen input, which result in increased autochtonous biomass in the water column. The sinking of the organic particles (dead organisms, fecal pellets), on the other hand, results in increased accumulation of organic matter in the sediments. Precipitation also has an important contribution to the input of allochtonous dissolved and particulate organic matter from the watershed to the reservoirs. As the accumulated organic matter in the sediments is decomposed by microorganisms, increased gas production in the sediments and in the anoxic hypolimnion might occur.

In a study carried out in Barra Bonita reservoir, Abe et al. (2008) showed that the highest CH_4, CO_2 and N_2O concentrations in the sediments and their diffusive fluxes across the water-air interface were observed at the upstream site in the dry season (Table 1). A decreasing trend in CH_4 and N_2O concentrations was observed along the reservoir from the upstream to downstream. The same pattern was also observed for TP, TN, nitrite, nitrate and DOC in this period (Table 2). In the rainy season the concentrations of CH_4, CO_2 and N_2O in the sediments were higher than in the dry season. CH_4 and N_2O diffusion flux across the water-air interface were also higher during the dry season if compared to the rainy season, and showed a good correlation to TP and TN. These results show that both trophic conditions of the reservoirs and seasonality have a strong influence on the diffusive flux of gases across the water-air interface. The higher was the trophic status, higher was the emission of greenhouse gases to the atmosphere. The high N_2O emission in Barra Bonita reservoir was related to the high concentrations of nitrite and nitrate in the water, as these ions are the precursors of denitrification. The higher gas concentrations observed in the rainy season was probably related to the input of allochtonous organic matter from the watershed into the reservoir that accumulated mainly near the dam. TP and TN concentrations, on the other hand, were higher in the dry season than in the rainy season. In this case, precipitation resulted in phosphorus and nitrogen dilution during the rainy season, decreasing their concentration in the water.

Table 5 - CH_4, CO_2 and N_2O concentrations and lost on ignition (LOI) integrated in the sediment (0 to 4 cm) and diffusion fluxes across the water-air interface along the reservoirs of the middle Tietê River. SD: standard deviation.

Table 6 - Average concentrations of temperature, pH, nitrite, nitrate, DOC, TN and TP in the water column along the Barra Bonita reservoir.

In a previus study carried out by Abe et al. (2003) in Barra Bonita reservoir, the authors showed that the maximum in situ denitrification integrated in the water column ranged from 1.36 and 3.79 mmol-N_2O m^{-2}

Table 5. CH_4, CO_2 and N_2O concentrations and lost on ignition (LOI) integrated in the sediment (0 to 4 cm) and diffusion fluxes across the water-air interface along the reservoirs of the middle Tietê River. SD: standard deviation.

Sampling period	Reservoir	Site	Gas concentrations in the sediment (means ± SD)		
			CH_4 (mmol.m^{-2})	CO_2 (mmol.m^{-2})	N_2O (μmol.m^{-2})
Dry season	Barra Bonita	BB-UPS	54.54 ± 6.68	58.23 ± 14.70	25.78 ± 3.35
		BB-MID	20.23 ± 3.05	32.59 ± 1.42	0.30 ± 0.16
		BB-DAM	23.06 ± 0.44	39.36 ± 1.48	0.35 ± 0.11
Rainy season	Barra Bonita	BB-UPS	95.17 ± 24.75	85.59 ± 1.52	0.67 ± 0.22
		BB-MID	73.27 ± 7.69	58.97 ± 4.57	1.13 ± 0.11
		BB-DAM	75.98 ± 2.05	79.35 ± 3.54	1.49 ± 0.03
Sampling period	**Reservoir**	**Sediment LOI (g.m^{-2})**	**Diffusive fluxes across the water-air interface (means ± SD)**		
			CH_4 (mmol m^{-2} d^{-1})	CO_2 (mmol m^{-2} d^{-1})	N_2O (mmol m^{-2} d^{-1})
Dry season	Barra Bonita	5867,79	1.394 ± 0.2970	–0.037 ± 0.007	1.020 ± 0.337
		5216,57	0.585 ± 0.107	0.035 ± 0.008	0.463 ± 0.051
		4718,21	0.402 ± 0.063	0.043 ± 0.023	0.373 ± 0.045
Rainy season	Barra Bonita	6313,68	1.170 ± 0.140	0.131 ± 0.016	0.519 ± 0.057
		7090,11	0.259 ± 0.078	0.178 ± 0.050	0.298 ± 0.036
		6537,48	1.319 ± 0.185	0.191 ± 0.040	0.240 ± 0.029

Table 6. Average concentrations of temperature, pH, nitrite, nitrate, DOC, TN and TP in the water column along the Barra Bonita Reservoir.

Sampling period	Reservoir	Site	Temp. (°C)	pH	Nitrite (μg-N.L^{-1})	Nitrate (μg-N.L^{-1})	DOC (mg.L^{-1})	Total N (mg.L^{-1})	Total P (mg.L^{-1})
Dry season	Barra Bonita	BB-UPS	21.62	7.3	470.94	8198.14	6.15	11419.13	486.59
		BB-MID	21.42	7.84	92.41	5226.50	4.06	6621.64	164.18
		BB-DAM	21.96	7.33	100.18	5147.46	4.05	6550.37	123.18
Rainy season	Barra Bonita	BB-UPS	27.5	7.96	41.34	2772.68	7.58	4766.16	141.91
		BB-MID	25.77	7.62	64.72	2932.01	7.72	4291.18	56.94
		BB-DAM	26.01	7.23	127.85	2236.99	8.23	4579.37	87.16

Table 7. The probable shifts in the control systems of Barra Bonita reservoir and their influence in the ecological dynamics of this artificial ecosystem and its biodiversity.

I) Physical-physical interactions and responses
1) Climate and hydrology → water circulation → transport of organisms, particulate and dissolved organic matter → physical boundaries (vertical and horizontal).
II) Physical-biological responses
1) Climate/hydrology/retention time → phytoplankton succession → zooplankton succession → spatial and temporal succession of organisms.
III) Biological-biological responses
1) Fish predation → zooplankton succession → phytoplankton succession.
2) Phytoplankton blooms (cyanobacteria) → zooplankton succession → bacterial succession.
3) Intrazooplankton predation → zooplankton succession → phytoplankton succession.
4) Phytoplankton excretion → particulate and dissolved matter accumulation and transport.

per day in the rainy and in the dry season, respectively. Considering that the daily denitrification in 1 year period lies within this range, and that the mean annual activity is 2.58 mmol-N_2O m^{-2} per day, the annual denitrification contribution to N_2O emission into the atmosphere was estimated to 1,383.8 tons of N-N_2O per km^2/year. These data confirm the importance of denitrification as a nitrogen sink when environmental conditions are suitable.

CO_2 diffusion flux across the water-air interface was very low in Barra Bonita reservoir if compared to CH_4 and N_2O diffusion fluxes, which show that this system is not an important source of CO_2 to the atmosphere.

Although high greenhouse gas emissions were observed in the reservoirs of the Tietê River, it is important to stress that according to IPCC (2006), these emissions should not be reported in the Flooded Land category, including reservoirs, as most of the carbon, phosphorus and nitrogen input are a result of anthropogenic activities in the watershed, in order to avoid double-counting of greenhouse gas emissions already considered in the budget of these anthropogenic sources. Nevertheless, this study showed that bad management of the water resources, particularly concerning untreated sewage loading to the reservoirs, results in greenhouse gas emissions to the atmosphere, probably much higher if compared to the emissions in controlled conditions of sewage treatment plants, although they are not related to the reservoir creation.

4. Discussion and Conclusions

From the existing information on the research developed at Barra Bonita reservoir in the last 30 years, some relevant aspects of pattern of the ecological dynamics of this ecosystem emerge. First the climatological / hydrological control that is predominant in the summer (December to March). A high flushing rate at this period and low retention time complete this envelope of physical forcing in the system during this period. During most of the year stratification is weak as shown by Tundisi and Matsumura-Tundisi, 1990. The fact that the reservoir is polymictic has several consequences: first it forces phosphorus to the sediment due to the high oxygen content in the water column specially near the sediment, second, prevents cyanobacteria blooms that need stability and higher temperature in order to prevail. As soon as mixing stops and stability arises the blooms of *Microcystis aeruginosa* start to develop.

High instability is also important in the succession of and dominance zooplankton groups. Accordingly to Matsumura-Tundisi et al., 1990 the dominance of rotifers in the zooplankton during certain periods of the year is due to this instability process.

But physical forcing is not the only driving force in Barra Bonita reservoir. Fish predation on zooplankton, intrazooplankton predation and the predominance of cyanobacteria blooms are also drivers of fluctuation in the zooplankton population a well as in the bacterial population. Lial Sandes (1998) showed that bacteria are living in the organic matter in decomposition or in the mass cell of cyanobacteria growing in the reservoir. Excretion of organic matter by phytoplankton, bacterial growth and succession are also important drivers of biodiversity Vieira et al., 2008.

In a study of six reservoirs in São Paulo state, Rocha et al. (2006) compared species richness of macrophytes, zooplankton, benthos (oligochaeta), fishes and aquatic birds, and their conclusion for Barra Bonita reservoir is that eutrophication did not decreased significantly the total richness of species, of macrophytes, zooplankton fishes and aquatic birds. On the contrary this reservoir holds the highest richness for this communities. The probable cause accordingly with these authors is the frequent intermediate disturbances throughout the seasonal cycle, promoting more feeding niches and spatial variability that enhances biodiversity.

Similar conclusions was presented by Matsumura-Tundisi and Tundisi (2005). These authors in a comparative study of Barra Bonita reservoir and lake D. Helvecio a stable monomictic lake in Rio Doce Valley lakes District concluded that Barra Bonita reservoir has a greater number of limnetic zooplankton species (20 rotifera; 8 cladocera; 9 copepoda) than does lake D. Helvecio (6 rotifera; 5 cladocera; 5 copepoda). The probable cause was the high stability of tropical monomictic lake D. Helvecio and the polymitic character of Barra Bonita reservoir enhancing zooplanktonic diversity. The 114 tributaries probably contributed with spatial heterogeneity of the system.

All this information reinforces the basic assumption that to some extent physical forcing functions control the dynamics of Barra Bonita reservoir and consequently its biodiversity Tundisi, Matsumura Tundisi and Rocha, 1999.

On the other hand spatial heterogeneity of the reservoir and the fluctuating physical, chemical and biological conditions throughout the year, may offer more resource niche partitioning therefore enhancing biodiversity with increasing resource exploitation by species-niche communities (Finke and Snyder, 2008). This was also considered a fundamental factor for the diversity of the rotifera community by Matsumura-Tundisi et al. (1990).

The horizontal and vertical distribution of organisms of phytoplankton and zooplankton is also influenced by the 114 tributaries of this reservoir. As Straskraba 1997 and Straskraba and Tundisi 1999 pointed out reservoirs are generally more complex than natural lakes because of their interaction with the watershed and the influx of tributaries.

Barra Bonita is a eutrophic reservoir and the degree, extent and progression of eutrophication in the last 20 years has promoted several changes in the trophic chain and also in the biodiversity of the reservoir as well as the phytoplanktonic and macrophyte primary production. The shift in species composition of Calanoida can be attributed to these changes as demonstrated in past and recent papers.

Superimposed to the Climatological / Hydrological factors and the biological control promoted by the eutrophication, there are large scale changes derived from long term climatic flutuations at continental and subcontinental levels. Neiff et al. (2000), Depetris (2007). Table 7 summarizes the changes in control mechanisms at Barra Bonita reservoir and the shifts throughout the year.

These shifts are distributed in periods of climatological/hydrological/operation system of the reservoir. Main predominance of *physical control*: summer (October to March); main predominance of *physical-biological control* and *biological-biological* interactions and control: winter and spring (May to September).

Therefore the ecological dynamics of Barra Bonita reservoir have very high implications in the biodiversity of the reservoir as a consequence of physical-physical interactions and responses, physical-biological interactions and responses and biological-biological interactions responses and feedback controls at the level, for example of predator/prey relationships (Straskraba, 1955). The relative importance of these interactions, responses and controls varies spatially and temporarily as demonstrated by studies so far developed in this artificial ecosystem. Barra Bonita reservoir shifts, therefore between an **open**, **externally driven**, **dissipative system** and one with **structural changes**, changes in the parameters of the system with adaptability represented by alterations in species richness, and feedbacks. Hierarchical control shifts during the climatological year (Allen and Starr 1982).

5. Challenges

Management of reservoirs is a complex process due to their extense interactions with the watershed (Straskraba et al., 1993; Tundisi and Straskraba, 1999) and the temporal and spatial dynamics of these ecosystems. However main recommendations derived from the scientific knowledge thus far developed are:

i) Maintaining and conserving the wetlands in the entrance of main tributaries. These wetlants can have an important role in the reduction of point sources from the watershed (Zalewski, 2002), and enhancing biodiversity; and
ii) Maintaining the Area of Environmental Protection (AEP) around the reservoir, consisting of riparian forests along the tributaries and the reservoir. This will reduce the non point sources, of nutrients, suspended and dissolved organic matter input, promotes organic matter as food for fishes and invertebrates.

The most difficult management problem is the decreasing of internal load that is high, due to several years of eutrophication of the reservoir, and accumulation of organic matter in the bottom sediment. Another difficult task is to reduce the overall level of toxicity that may have a strong effect on the succession of biological communities.

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