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Mass balance of nutrients during the filling phase of two reservoirs of Sistema Produtor Alto Tietê (SPAT)

Valéria Cope[1*], Cacilda Thais Janson Mercante[2], Clovis Ferreira do Carmo[2], Suzana Sendacz[2] and Adalberto José Monteiro Júnior[2]

*[1]Programa de Pós-graduação em Aquicultura e Pesca, Instituto de Pesca, Av. Francisco Matarazzo, 455, 05001-900, São Paulo, São Paulo, Brazil. [2]Centro de Pesquisa e Desenvolvimento em Recursos Hídricos, Instituto de Pesca, São Paulo, São Paulo, Brazil. *Author for correspondence. E-mail: valeria_cope@yahoo.com.br*

ABSTRACT. Paraitinga and Biritiba reservoirs are part of Sistema Produtor Alto Tietê and they play an important role at the public water supply. The purpose of this study is to understand the mass balance of nitrogen and phosphorus that can influence the eutrophication process in reservoirs during the filling phase, and provide information for the implementation of mechanisms to manage water quality. Water samples were collected from August 2005 until May 2006. Concentrations of total phosphorus (PT) and total nitrogen (NT) were measured and the mass balance and loads were estimated. Paraitinga reservoir presented retention of NT and PT during the dry season and export during the rainy season; whilst at Biritiba reservoir we evidenced retention of NT and PT for both dry and rainy seasons. The annual balance demonstrated that during the reservoirs filling process, the systems retain NT and PT. The retention of nutrients into the system indicates that the environments have been modified leading to eutrophication and its consequences, and that it is necessary to outline strategies in order to mitigate the problem and suggest implementation of techniques to reduce the diffuse load.

Key words: water supply, nitrogen, phosphorus.

RESUMO. Balanço de massa de nutrientes na fase de enchimento de dois reservatórios do Sistema Produtor Alto Tietê (SPAT). Os reservatórios Paraitinga e Biritiba estão inseridos no Sistema Produtor Alto Tietê, com elevada importância para o abastecimento público. O objetivo do trabalho foi compreender o balanço de massa do nitrogênio e fósforo os quais podem influenciar o processo de eutrofização em reservatórios durante o enchimento e subsidiar informações para implantação de mecanismos de gerenciamento da qualidade de água. Coletas trimestrais de água foram realizadas no período de um ano de agosto/2005 a maio/2006. As concentrações de fósforo total (PT) e nitrogênio total (NT) foram medidas, e estimadas as cargas e o balanço de massa. O reservatório Paraitinga indicou retenção de NT e PT no período seco, e exportação no chuvoso, e retenção de NT e PT para o período seco e chuvoso em Biritiba. O balanço anual demonstrou que durante o processo de enchimento dos reservatórios, os sistemas funcionaram armazenando NT e PT. A característica de retenção de nutrientes no sistema sinaliza para os gestores que os ambientes sofrem um processo em direção à eutrofização e suas consequências, necessitando, de estratégias para mitigar o problema, sugerindo-se implantação de técnicas para redução da carga difusa.

Palavras-chave: abastecimento, nitrogênio, fósforo.

Introduction

The fast growth of population in many regions of Brazil has required an increasing generation of electricity and water supply for the urban centers. By interrupting a river water flow, the dams play the role of 'event gatherers', thus providing significant information about the hydrographical basins. Therefore, the water quality reflects mostly the human activities in the air, the ground, and in the straining water itself (BICUDO et al., 1999). According to Dionne and Thérien (1997), during the reservoirs filling process, important green areas and large ground areas are waterlogged. Organic and inorganic compounds, dispersed and dissolved are released into the water column during this stage, and the top concentration of such materials is reached by the end of the filling process. At that moment, the rate of release into the water decreases, thus promoting the system stabilization. The mass balance (or material balance) is a quantitative description of all materials entering, leaving and accumulating in a system with delimited borders (SALAH et al., 2005). Therefore, it is an important tool for management of operational procedures in reservoirs, besides permitting to evaluate how the hydrographic basin influences water quality. Mass balance has been taken as a pattern in several studies to quantify the entrance, retention and export of nutrients as well as to evaluate the reservoir eutrophication potential (BRIGAULT; RUBAN, 2000; MATZINGER et al., 2007; JOSSETTE et al., 1999). According to Nürnberg (1984), the balance can contribute with the handling of these ecosystems, making it possible to predict events. According to Reckhow et al. (1980), the patterns that describe the phosphorus load and the lacustrine trophic reaction can be very useful for planning the hydrographic basin management. The simple and empiric model named input/output or 'black box' adds information about the system inflow and outflow, but it does not explicitly include any chemical or biological reactions associated with the water environment. According to Sendacz et al. (2005), with the operational start-up of Biritiba and Paraitinga reservoirs up to 20 $m^3 s^{-1}$ of water will be available for the metropolitan area of São Paulo, thus guaranteeing the water supply for the coming years. Therefore it is evident that understanding the mass balance of chemical elements that influence the eutrophication process during the filling period of reservoirs, especially those dedicated to water supply, is an important tool for the implementation of mechanisms to manage the water quality.

Material and methods

Study area

The hydrographic basin Tietê Cabeceiras (Figure 1) occupies a draining area of 1.694 km^2 and comprises the Sistema Produtor Alto Tietê (SPAT), a set of 5 reservoirs (Ponte Nova, Paraitinga, Biritiba, Jundiaí and Taiaçupeba), which objective is to get multiple use of the water resources such as public water supply, flood control and prevention, regularization of watercourse, recovery and drainage of floodplains for agriculture, increase of outflows to dissolve urban and industrial wastewater, irrigation of the green belt at São Paulo Metropolitan Area, and water supply for industrial purposes (FUSP, 2007; CCN, 1997). In 2005 the gates of rivers Biritiba-Mirim (Biritiba dam) and Paraitinga (Paraitinga dam) were closed (Table I).

Table 1. General aspects of Paraitinga and Biritiba reservoirs.

Reservoir	Paraitinga	Biritiba
river	Paraitinga	Biritiba-Mirim
city	Salesópolis	Mogi das Cruzes and Biritiba-Mirim border line
sub-basin	Paraitinga	Biritiba and Biritiba Açu Cabeceiras
Maximum Volume (million m^3)	37	60.2
Available Volume (million m^3)	35	35
area (km^2)	6.43	9.24
Shape	Extended	Sub-dendritic
Draining area (km^2)	184	75
Retention time (year)	0.48	0.95
draining ($m^3 s^{-1}$)	2.00	1.75
Filling start-up	10 Jan/2005	13 May/2005
date (% filling)	6 May/2006 (95)	21 Apr/2006 (100)
Days spent	175	383

Source: CCN (1997). Eng. Ernesto Nobuo Mory and Eng. Luiz Carlos da Silva, personal communication.

Experimental outline

Water samples were collected every three months for a year, from August 2005 until May 2006. Samples were taken from the sub-surface of the main affluent rivers and from the effluents of the reservoirs, downstream and upstream of each analyzed reservoir. Concentrations of total phosphorus and total nitrogen were simultaneously identified in laboratory with the digestion method described by Valderrama (1981) and then the analysis was performed with Strickland and Parsons (1960) methods for phosphate ions and Mackeret et al. (1978) for nitrogen ions. Information about Paraitinga e Biritiba reservoirs outflow was provided by Departamento de Águas e Energia Elétrica. The inflow was calculated considering the result of water velocity and average area of the channel transverse section, determined by the bathymetry in two points (upstream and downstream). In order to determine the water velocity, obtained with the floating method, it was chosen a section where the watercourse was as straight and uniform as possible concerning its width and depth, so that it could be obtained a regular flow. The floater was launched into the chosen section of the watercourse and the time spent in the route was registered. The operation was repeated three times and the average of the observed data was used for calculation. Velocity was adjusted according to the adjustment factors that take into consideration the nature of the lake bed as proposed by Marques and Argento (1988).

Daily pluviometric level about the reservoirs was supplied by Departamento de Águas e Energia Elétrica. Daily pluviometric level about the reservoirs was supplied by Departamento de Águas e Energia. Elétrica The load values obtained in each collection were extrapolated and estimated for one day.

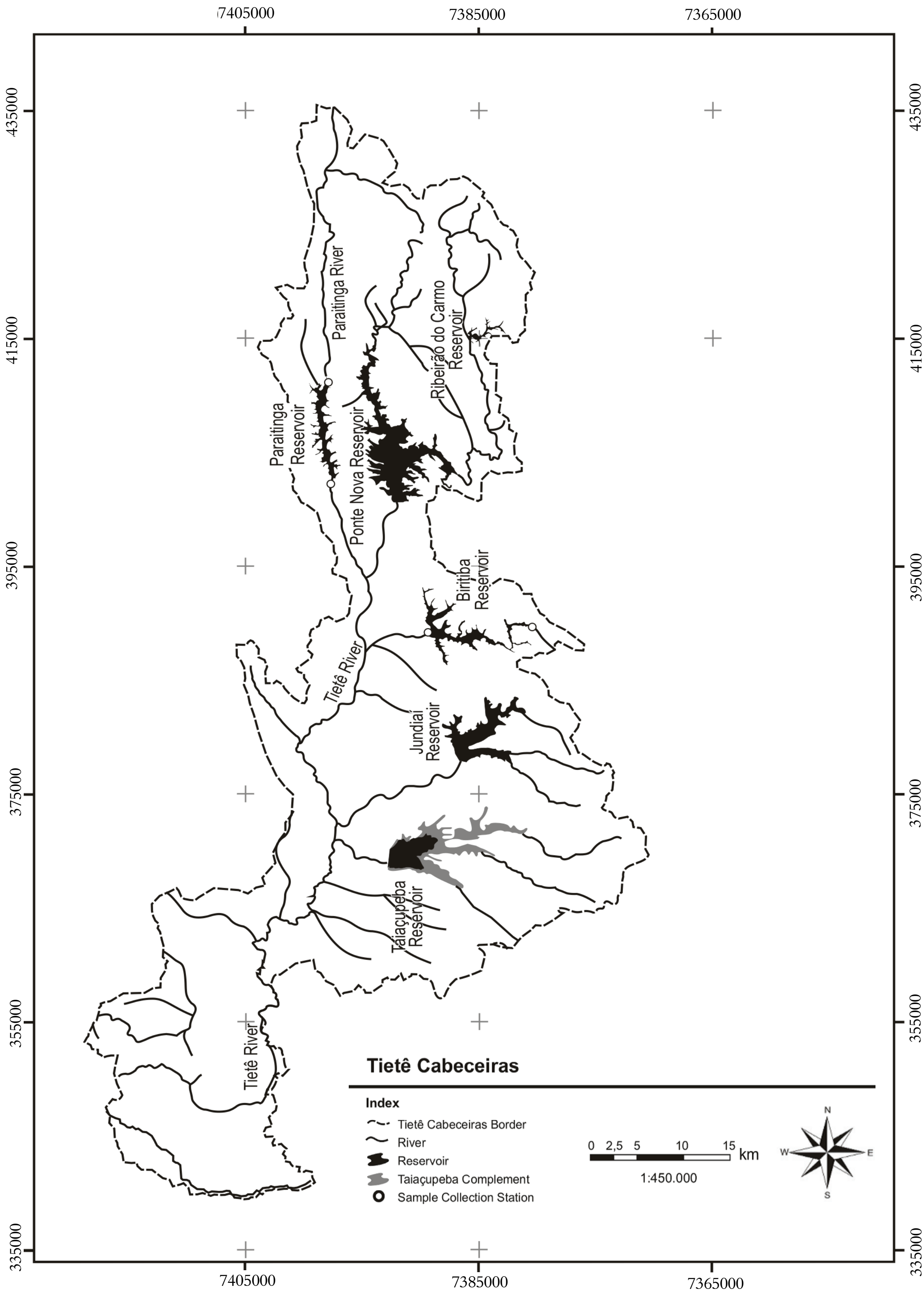

Figure 1. Tietê Cabeceiras hydrographic basin. Modified from: Sendacz et al. (2005).

In order to estimate the monthly load values it was applied the linear interpolation, also known as two-point interpolation. Interpolation is used for obtaining intermediate values among given points (date of collection in this case). After obtaining the intermediate points, the load values of each station were grouped two by two and the monthly load value was forecasted applying planimetrics, considering a gap of 30 days between the subsequent periods. As to estimate the load during the dry and rainy seasons, the maximum theoretical value for the estimated daily load per period in each station was multiplied by the number of days referring to the rainy and dry periods. The number of days related to dry and rainy seasons was estimated based on data from Minuzzi et al. (2007). The authors studied the behavior of the rainy season at the Southeast Brazil (which comprises the area of study) and observed that it begins between September 23 and October 2 at the reservoirs area and ends up about 192 and 210 days later. In order to estimate the annual load, the load values estimated for the dry season were added to the load values for the rainy one per station. Loads of total nitrogen and total phosphorus via non-punctual sources were estimated according to coefficients proposed by Jørgensen (1988), considering rainfall, geological classification, use and occupation of soil and of the influence area in the hydrographic basin; and by Castagnino, apud Salas and Martino (1991) for urban exportation. Data about use and occupation of soil was extracted from maps prepared in 2004 comprising part of alto Tietê basin (Emplasa, 2006). These maps were vectored and then delimited by the reservoirs direct influence area such as geographical relief characteristics, obtaining areas smaller than their respective sub-basins. For estimates about of via terrestrial and via rainfall, the lower values of the export coefficients were applied as proposed for the terrestrial and rainfall loads equations. The sum of punctual (main tributary) and diffuse loads resulted in the estimate of total load for both reservoirs. Nitrogen and phosphorus mass balance was calculated as from the difference between inflow and outflow estimated load values per nutrient at each reservoir.

Results and discussion

It was observed an increase of nutrients concentration (total nitrogen and total phosphorus) from upstream towards downstream (Table 2).

At this study Paraitinga and Biritiba upstream were considered class 1 (SÃO PAULO, 1977), and downstream, class 2 (BRASIL, 2005). As per total phosphorus concentration, all results were within the limits established by Resolution Conama no. 357 about water quality, below 100 μg L^{-1}, for freshwater class 1 at lotic environments and for tributary at intermediate environments. According to Diniz (1998), the phenomenon El Niño changes the weather pattern in South America, thus provoking alterations in the rainfall pattern. According to Trenberth and Shea (2006) and Logan et al. (2008), this phenomenon occurred in 2005 and 2006, the collection period. In November, possibly influenced by El Niño, little rain fell over Biritiba reservoir area, 45.1 mm, and Paraitinga, 35.1 mm (Figure 2).

Operational procedures of Paraitinga and Biritiba reservoirs are conditioned to the requirements of water supply from sistema produtor alto Tietê, which main purpose is to accumulate water to supply occasional needs. For this reason the retention time can vary a lot, but according to CCN (1997) in the description of the environmental impact study average values of 0.48 year are expected, equivalent to 175 days for Paraitinga and 0.95 year, equivalent to 347 days for Biritiba. According to Straškraba (1999), reservoirs presenting such characteristics are classified as class B, retention time intermediate, between 2 weeks and 1 year.

Table 2. Values for total nitrogen (NT) and total phosphorus (PT) at sample stations from August 2005 to May 2006.

reservoir	station	date	NT mg L^{-1}	PT g L^{-1}	reservoir	station	date	NT mg L^{-1}	PT g L^{-1}
Paraitinga	affluent	8/25/2005	0.44	25.67	Biritiba	affluent	8/25/2005	0.41	23.88
		11/16/2005	0.53	27.33			11/16/2005	0.45	25.67
		2/22/2006	0.44	13.56			2/22/2006	0.41	25.90
		5/25/2006	0.42	24.56			25/05/2006	0.37	20.08
	effluent	8/25/2005	0.53	34.96		effluent	8/25/2005	0.56	38.65
		11/16/2005	0.60	37.25			11/16/2005	0.63	40.23
		2/22/2006	0.54	26.72			2/22/2006	0.49	34.44
		5/25/2006	0.54	32.00			5/25/2006	0.56	37.20

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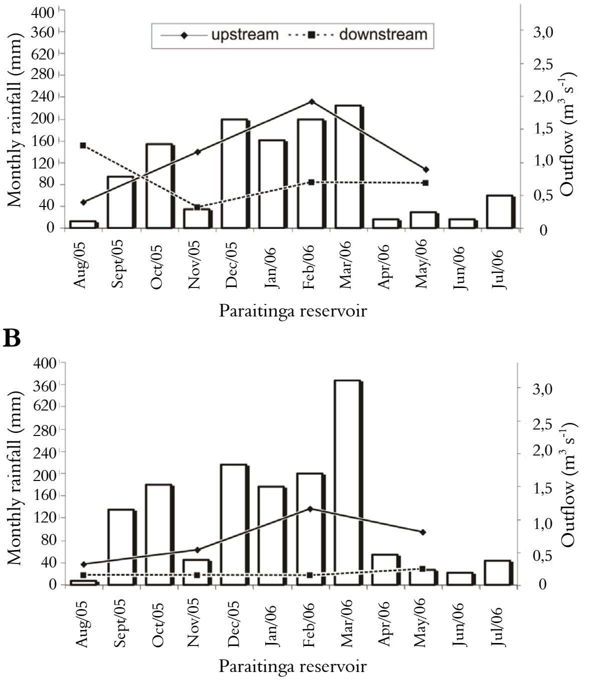

Figure 2. Rainfall in the reservoirs area, August 2005 to July 2006, and respective upstream and downstream drainage at Paraitinga (A) and Biritiba (B) reservoirs from August 2005 to May 2006.

According to Rodgher et al. (2005), a cascade reservoir system can improve water quality downstream, because part of the organic and inorganic compounds is retained in the watercourse upstream. According to Sendacz et al. (2005), Sistema Produtor alto Tietê works as a cascade, however in an opposite way compared to the description above. It means that along the system there is a progressive increase of the eutrophication effects, presenting high transportation of total nitrogen and total phosphorus to the subsequent reservoirs. According to Tundisi (1999), the position of the reservoir is relevant, because of the effects caused upstream and downstream from one reservoir to the other. Alto Tietê Cabeceiras reservoirs as well as cascade reservoirs, as observed by Tundisi (1999), can also cause a cumulative impact, however this impact is felt less intensively by the systems downstream. During the dry season Paraitinga presented a nitrogen inflow load via tributary of 23.64 kg day^{-1}, against 63.18 kg day^{-1} during the rainy season. Such values are above those observed at Biritiba: 18.61 and 31.22 kg day^{-1}, for dry and rainy seasons respectively. Nevertheless, these results are far beyond the ones estimated by Barbosa et al. (1998) at Lagoa da Pampulha, that is affected by local and industrial effluents and presents lower retained volume (12 million m^3) in a smaller area (2.4 km^2), though presenting a drainage basin of 95.19 km^2, and an inflow similar to the analyzed reservoirs, 0.86 m^3 s^{-1}, reaching values of 454 kg day^{-1} during the rainy season and 406 kg day^{-1} during the dry one. During the dry season Paraitinga presented a phosphorus inflow load via tributary of 1.38 kg day^{-1} against 2.50 kg day^{-1} during the rainy one. Such values are above those observed at Biritiba: 1.03 and 1.91 kg day^{-1}, for dry and rainy season respectively.

Both reservoirs presented higher loads of total phosphorus during the rainy season (Figure 3). Barbosa et al. (1998) also observed higher values of

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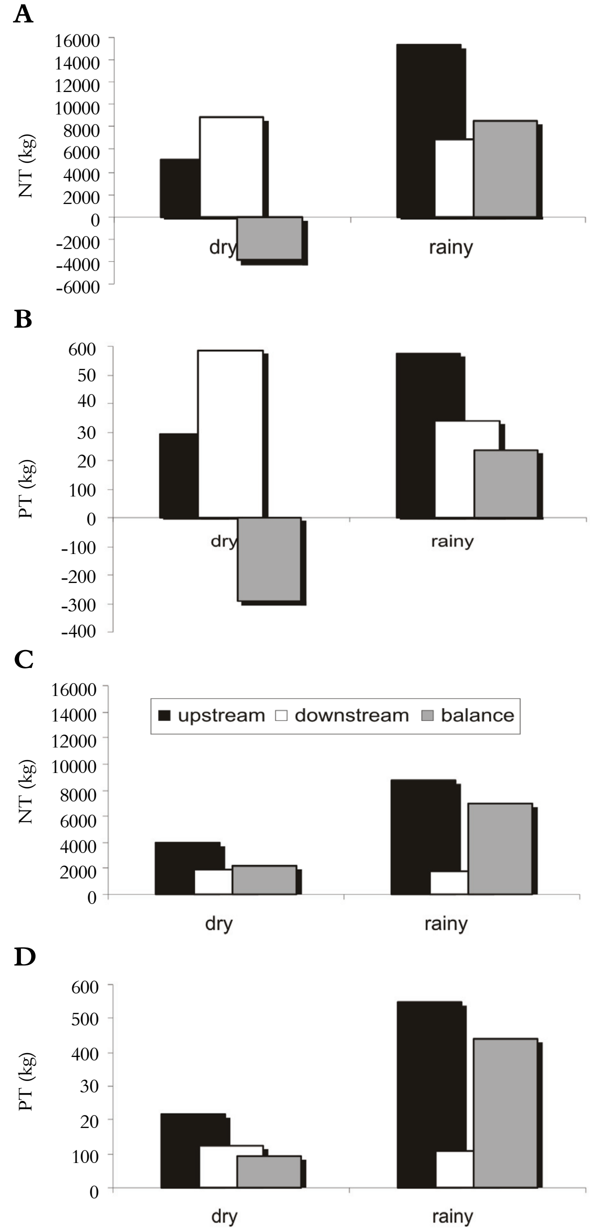

Figure 3. Total nitrogen (NT) and total phosphorus (PT) load and balance during dry and rainy seasons at Paraitinga (A) (B) and Biritiba (C) (D) reservoirs, regarding inflow via tributary. As per balance data, negative values are related to export while positive ones refer to retention.

total phosphorus load at Lagoa da Pampulha during the rainy season (45 kg day^{-1}) compared to the dry one (44 kg day^{-1}). According to Leite and Espíndola (2004) at Salto Grande reservoir, Atibaia river is responsible for the higher loads during the rainy season (3.68 t day^{-1}) rather than during the dry one (0.29 t day^{-1}).

Total nitrogen and total phosphorus load of the main tributary at Paraitinga and Biritiba reservoirs presented higher values during the rainy season compared to the dry one, thus indicating that diffuse origin material (non-punctual load) from surface flow may influence the results. Applying the pattern proposed by Jørgensen (1988) it was possible to notice that within the influence area of Paraitinga and Biritiba reservoirs the major contribution of diffuse pollution occurred via surface water flow (Figure 4).

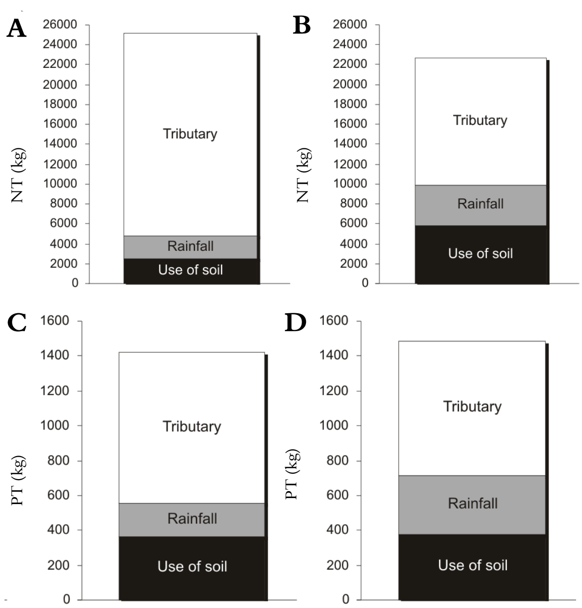

Figure 4. Total nitrogen (NT) and total phosphorus (PT) estimated upstream load during dry and rainy seasons at Paraitinga (A) (C) and Biritiba (B) (D) reservoirs.

It is important to bring out that inflow via main tributary was quite relevant for both Paraitinga (61.1 and 80.8%) and Biritiba (51.7 and 56.2%). Inflow via tributary also reflects the use and occupation of the basin. According to Henry et al. (1998), the outer loads of nutrients brought by tributaries work like an additional system to enrich the reservoir. We observed a high participation of surface flow during the load of nutrients to Biritiba reservoir in its influence area, signaling that diffuse loads were the main source of total nitrogen and total phosphorus. According to Ferrareze et al. (2005), a fact that contributes directly to the retention/export of sediments and nutrients at the reservoirs is the sedimentation of the carried material. In 1998 at Pampulha reservoir, an urban reservoir situated in the State of Minas Gerais, Brazil, Torres et al. (2007), by means of estimates about water mass balance, essential nutrients and total solids in suspension, observed nitrogen and phosphorus retention and could assure that the reservoir presented the highest levels of these nutrients during the rainy season. Studies developed by Sendacz et al. (2005) at alto Tietê Cabeceiras basin demonstrated that Taiaçupeba reservoir presented retention of phosphorus and export of nitrogen, while Jundiaí reservoir exported both nutrients. Considering punctual and non-punctual sources, the annual balance (Figure 5) demonstrated that the analyzed systems played the role of deposits of total nitrogen and total phosphorus. According to the mass balance monthly estimated, the main tributary contributed to the exception recorded in the first month of analysis at Paraitinga reservoir, when a pulse of total phosphorus export was observed (Figure 6). On the other hand, the system was impacted by an overload of these nutrients during the subsequent months.

During the filling period, the mass balance of the herein analyzed reservoirs was influenced by seasonal variation, by the difference of inflow during dry and rainy seasons, by the operational procedures at the reservoirs, and by the outflow variation caused by the water demand.

Due to their characteristics, lakes and reservoirs present an absorption ability to support certain loads of nutrients. However, the system retention capacity may vary from year to year, depending on the hydrologic conditions and on the inflow. Assimilation capacity is limited and problems may occur in a relative short period as a consequence of the input of pollutants that may last a long time, depending on the use and occupation of the soil at the contribution basin (FRIEDL; WÜEST, 2002; JØRGENSEN; VOLLENWEIDER, 1989). The reservoirs response to nutrients exportation or retention is due to the hydrodynamic characteristics of the environment (water residence time and morphometrical aspects) associated to the presence or absence of submerse vegetation and to the transport of chemical compounds. Dionne and Thérien (1997) in a hydroelectric complex of James Bay territory, Quebec, Canada, demonstrated with a mass balance model that the filling and, later on, the draining of a reservoir reduces around 40 and 50% the concentration of material released to the water column from the inundated vegetation and from the soil. This procedure could be considered mainly when the reservoir is used for water supply purpose, due to the need of maintaining the water quality and of extending the reservoir lifecycle. The results of this study indicate that at Paraitinga and Biritiba reservoirs basins, the recovery of the riparian vegetation would be an important strategy in the reduction of diffuse load of the systems, mainly those originated from the use of fertilizers and defensives. This tendency of retaining nutrients is signaling to the management of water supply system that the environment could enter an accelerated process towards eutrophication and its consequences, therefore requiring strategies to mitigate the problem.

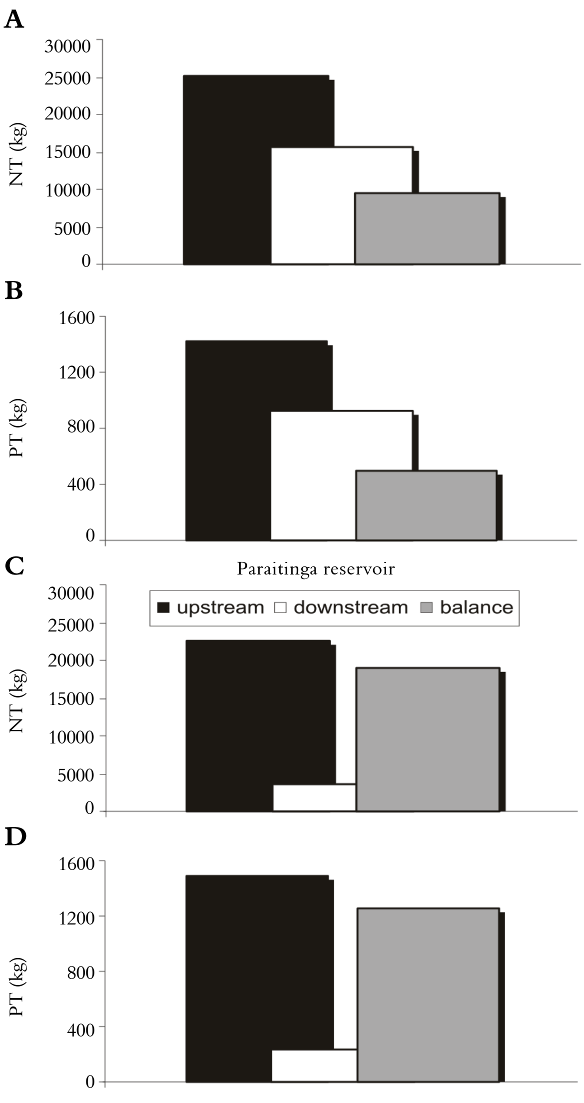

Figure 5. Total nitrogen (NT) and total phosphorus (PT) load and annual balance at Paraitinga (A) (B) and Biritiba (C) (D) reservoirs, sum of punctual and non-punctual load.

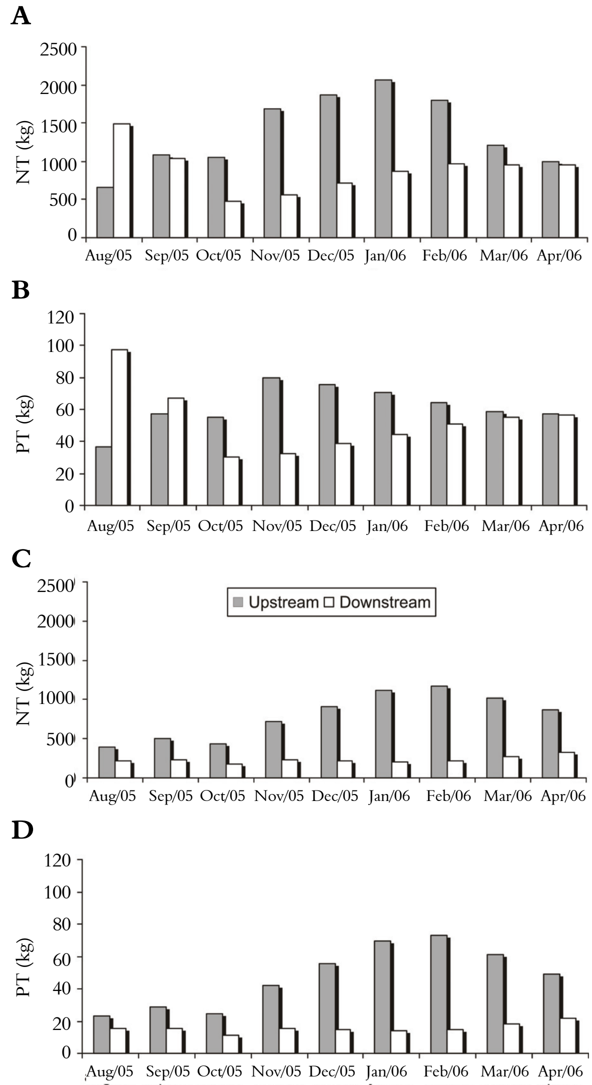

Figure 6. Total nitrogen (NT) and total phosphorus (PT) monthly load at Paraitinga (A) (B) and Biritiba (C) (D) reservoirs, inflow via tributary.

Conclusion

The seasonal effect observed at high loads of total nitrogen and phosphorus in the rainy season indicated that the material comes from diffuse sources via runoff had a direct influence on the input of these nutrients. Through the mass balance of nitrogen and phosphorus, showed that the seasonal and operational rules of the reservoirs had a strong influence on the retention mechanism and or export. The reservoirs Paraitinga and Biritiba showed high retention of nutrients, thereby the stakeholders, in relation to management and recovery proposals, should consider a program to reduce nutrients input and also the demand for water use.

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