Mass balance estimation of nitrogen, carbon, phosphorus and total suspended solids in the urban eutrophic, Pampulha reservoir, Brazil.

TORRES[1], I.C; RESCK[1], R.P. & PINTO-COELHO[2], R.M.

[1] Pós Graduação em Ecologia Conservação e Manejo da Vida Silvestre. Lab. Gestão Ambiental de Reservatórios, Dept. Biologia Geral, ICB-UFMG, Belo Horizonte, Minas Gerais, CEP: 31270-010, Brazil. e-mail:belactorres@netscape.net

[2] Lab. Gestão Ambiental de Reservatórios, Depto. Biologia Geral, ICB-UFMG, Belo Horizonte, Minas Gerais, CEP: 31270-010, Brazil. e-mail:rmpc@.icb.ufmg.br

ABSTRACT: Mass balance estimation of nitrogen, carbon, phosphorus and total suspended solids in the urban eutrophic, Pampulha reservoir, Brazil. This article deals with the estimation of the nutrient retention capacity of a small tropical reservoir. The main objective of this study was to estimate the mass balance of water, essential nutrients (carbon, nitrogen and phosphorus) and total suspended solids and to determine which tributary have the major contribution of maintaining the poor water quality of the reservoir. Seven main streams, a central point in the reservoir and its outlet were sampled monthly from January 1998 to December 1998. Nutrient inputs were higher during the rainy season. Pampulha reservoir retained most of the incoming nutrients (nitrogen and phosphorus) and exported particulate organic carbon in the rainy season. The lower residence time found for total phosphorus and the high retention percentage found for this element suggest that it is the limiting nutrient in Pampulha. Finally, the study identified two tributaries that contribute to the bulk of nutrient input as well as organic matter, and consequently, to the water quality degradation of the reservoir: the Ressaca/Sarandi and Água Funda streams.
Key-words: Pampulha, reservoir, eutrophication, nutrients, mass balance.

RESUMO: Estimativas de balanço de massa de nitrogênio, carbono, fósforo e sólidos totais em suspensão em um reservatório urbano, reservatório da Pampulha, Brazil. Este artigo trata da estimativa de retenção de nutrientes de um pequeno reservatório tropical. O objetivo principal deste estudo foi estimar o balanço de massa da água, nutrientes essenciais (carbono, nitrogênio e fósforo) e sólidos totais em suspensão, e determinar qual tributário tem a maior contribuição na manutenção da baixa qualidade de água do reservatório. Sete tributários, um ponto central e o efluente da represa foram amostrados mensalmente de janeiro a dezembro de 1998. O reservatório recebeu as maiores quantidades de nutrientes durante a estação chuvosa (Novembro a Março), reteve a maior parte dos aportes externos de nitrogênio e fósforo e exportou carbono orgânico particulado. O menor tempo de residência encontrado para o fósforo bem como a alta taxa de retenção encontrada para esse nutriente sugere seu papel como elemento limitante para a biota do sistema. Finalmente, o estudo identificou dois tributários que seriam responsáveis pela grande parte do aporte externo de nutrientes e, conseqüentemente, pela deterioração da qualidade de água do reservatório: os ribeirões Ressaca/Sarandi e Água Funda.
Palavras-chave: Pampulha, reservatório, eutrofização, nutrientes e balanço de massa.

Introduction

In recent decades, the estimation of nutrient input through streams into lakes and reservoirs and nutrient mass balance have become an essential element in most programs aiming the recovery and preservation of these ecosystems (Carney et al., 1993; Vadenboncouer, 1994; Straskraba et al., 1995; Young et al., 1996; Holas et al., 1999). Usually, streams that have a large amount of anthropogenic activity in their basins carry a higher nutrient load. This increase of nutrient input through tributaries is frequently the major cause of several ecological disturbances in lentic water bodies (Krug, 1993; Straskraba et al., 1995; Noges et al., 1998).

Aquatic systems may have quite different roles in the cycling of nutrients, as they can act as "sources" of nutrient exportation or as "sinks" in case they absorb or retain most of the incoming nutrients, respectively (Krug, 1993; Svendsen &

Kronvang, 1993; Noges et al., 1998). In Brazil, a large number of reservoirs have been built for several purposes in the last forty years. In many cases, rapid eutrophication has been observed, and this process is usually related to the input of untreated wastewater. This rapid eutrophication may be related to the fact that these systems have a higher a capability to retain the incoming nutrients as compared to similar systems in the temperate zone.

The diversion of untreated wastewater into freshwater systems is a common practice in Brazil as well as in many other tropical areas. The large input of organic load, nutrients and industrial pollutants has been responsible for the rapid eutrophication and ecological degradation in several Brazilian reservoirs. The most cited cases are the Paranoá Reservoir (Branco & Senna, 1996; Starling et al., 2002), Billings Reservoir (Sendacz, 1984), the Lobo and Barra Bonita Reservoirs (Calijuri & Tundisi, 1990; Matsumura-Tundisi & Tundisi, 2005) and several small reservoirs in the Northeastern semi-arid region (Huszar et al., 2000, Bouvy et al., 2000).

The eutrophication of Pampulha reservoir was detected and characterized by Giani et al. (1988) in the early eighties. Pinto-Coelho (1998) provided further evidence for the increasing eutrophication of this reservoir during the 1990's. Eutrophication problems in this reservoir have their origin in its hydrographic basin and are primarily caused by the diversion of untreated wastewater in its tributaries (von Sperling, 1997; Pinto-Coelho & Greco, 1999). The assessment of the external nutrient input, and of the fate of this load in a small tropical reservoir, is essential to the better understanding of the eutrophication dynamics in this kind of system. This is a key element for the development of strategies for the recovery of the reservoir and could serve as a model to be applied in similar systems elsewhere.

The main objectives of this research were: 1) to estimate seasonal variations in the external inputs and output of nutrients and total suspended solids; 2) to estimate the annual mass balance for particulate organic carbon, inorganic nitrogen, total phosphorus, total solids and water volume in order to test whether the Pampulha reservoir is acting as a "sink" or a "source" for these nutrients and solids; 3) to measure the retention time of these nutrients in the reservoir and identify patterns of accumulation or loss; 4) identify the majors tributaries responsible of nutrients input into the reservoir.

The study area

The Pampulha reservoir is located in the northern part of Belo Horizonte city, Brazil (43°56'47"W and 19°55'09"S). It has a volume of 8.52 million m^3 and a surface area of 208 ha (CPRM, 2001). Its maximum depth is 14 m and the mean depth is 4.1 m (CPRM, 2001; von Sperling, 1999). The hydrographic basin has an area of 9,790 ha, including the lake contribution area (820 ha) (CPRM, 2001). Eight main streams flow into the reservoir: stream Mergulhão (A), Tijuco (B), Ressaca (C), Sarandi (C), Água Funda (D), Baraúna (E), Associação Atlética Banco do Brasil (AABB) (F) and Olhos D'Água (G) (Champs, 1992) (Fig. 1). These tributaries have quite different basin areas (from 71 to 6152 ha) and host different human activities. Their discharges (outflows) range from 0.003 to 1.63 m^3s^{-1}, with noticeable variations between dry and wet (rainy) seasons (Tab. I). According to SUDECAP (1997) the main environmental problems of these sub-basins are:

A) Mergulhão: The streambed and margins are covered by open concrete gallery in about 30% of the total length. There is a moderate human occupation. Riparian vegetation is partially present. This stream receives treated wastewater as point contamination.

B) Tijuco: This stream is completely covered by cellular concrete gallery. It receives a diverse array of non-point contamination sources that include: domestic sewage, garbage disposal and erosion.

C) Ressaca and Sarandi: This is an area of intense human occupation. Both tributaries suffer from point and non-point contamination sources. The most important point contamination sources are the input of sewage from the Contagem county industrial district and the input to Sarandi of the leachate from the municipal land fill of Belo Horizonte city. The non-point contamination sources come from domestic sewage, diffuse garbage disposal on stream margins and high sediment inputs caused by superficial erosion. Sand extraction occurs along its margins. Both streams join each other forming a single channel before reaching the reservoir.

Table I: Drainage areas of Pampulha's reservoir tributaries and mean outflow in wet and dry season.

Stream	Drainage Area (ha)	Mean Outflow ($m^3.s^{-1}$)	
		Wet season	Dry season
Mergulhão	340	0.041	0.029
Tijuco	180	0.029	0.021
Ressaca/Sarandi	6170	1.632	0.651
Água Funda	1680	0.539	0.058
Baraúna	190	0.035	0.026
AABB	120	0.004	0.003
Olhos D'Água	290	0.045	0.010
Total	8970	2.326	0.798

Source: SUDECAP (1997).

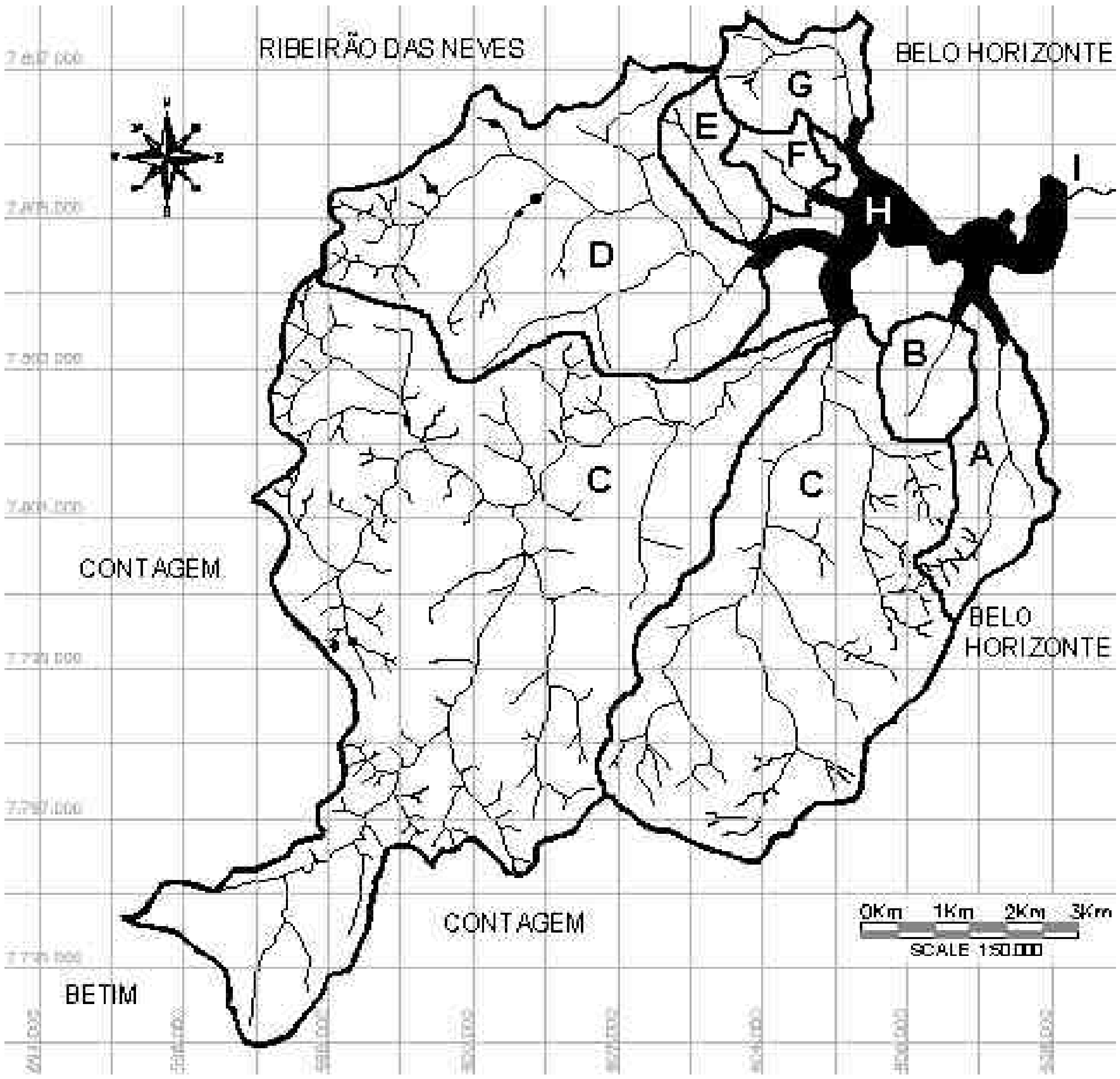

Figure 1: Map of Pampulha reservoir (H) hydrographic basin with sub-basin divisions: (A) Mergulhão stream, (B) Tijuco stream, (C) Ressaca/Sarandi streams, (D) Água Funda stream, (E) Baraúna stream, (F) Associação Atlética Banco do Brasil (AABB) stream, (G) Olhos D'Água stream and the outlet (I).

D) Água Funda: Most of riparian vegetation was recently removed. The basin is affected mostly by non-point contamination of domestic wastewater and garbage. Sand extraction is in progress along its margins.

E) Baraúna: This area has riparian vegetation and low human occupation.

F) AABB: Most contamination here is derived from non-point sources. Some sediment input as well as domestic wastewater discharges occurs within this basin.

G) Olhos D'Água: There has been the removal of all riparian vegetation. The stream is completely covered with cellular concrete galleries and receives heavy pollution from non-treated domestic sewage water.

The climate of the region is divided in two seasons: 1) a wet season from October through March and 2) a dry season from April through September. It is classified as tropical b-2 type (Ferreira, 1992). Annual mean precipitation is around 1,480.0 mm (CPRM, 2001). Monthly air temperatures usually range between 18 (May-July) and 23 °C (October-February).

Materials and methods

A monthly sampling program covered the seven main streams: Mergulhão (A), Tijuco (B), Ressaca/Sarandi (C), Água Funda (D), Baraúna (E), AABB (F) and Olhos D'Água (G), a central station in the reservoir (H) and the outlet at the dam (I). The samplings were conducted from January 1998 to December 1998 (Fig. 1). Ressaca and Sarandi streams were sampled together at the site where these two streams form a single channel that reaches the reservoir.

In the reservoir, samples were collected in a central station, at the depth of 1 m. In all other sites, samples were taken from the surface. Unfiltered samples for total phosphorus analysis were also frozen upon reaching at the laboratory. All the analyses were done with replicates.

At the laboratory, 0.5 L aliquots were vacuum filtered using pre-weighed Schleicher & Schüll GF-50 filters (47mm of diameter). The filtrate was frozen for later chemical analysis. The filters were used for the determination of suspended solids. Samples for particulate carbon analysis were filtered on a 1 mm pre-combusted filtrated "Kieselguhr" (infusory earth) layer on a GF filter. This pre-combusted silica layer can retain all sestonic particles, including as many as 90% of all free living bacteria (Simon & Tilzer, 1987). The dried samples were hot digested to measure chemical oxygen demand (COD). Estimation of particulate organic carbon (POC) was determined by measuring COD as described by Torres et al. (1998), using the open reflux method (Greenberg et al., 1992).

Total suspended solids were measured gravimetrically, using methodology presented in APHA (Greenberg et al., 1992). Total phosphorus was determined by spectrophotometer method (Murphy & Riley, 1962).

Ammonium was measured according to Chaney & Marbach (1962) and nitrite and nitrate followed Mackereth et al. (1978). The inorganic nitrogen was estimated by the sum of ammonium, nitrate and nitrite concentrations.

All the following calculations for the estimative of water and nutrients mass balances were conducted using flow rate data collected on tributaries and outflow in 1985 by a City Administration Office named SUDECAP (SUDECAP, 1997).

Monthly estimates of input and output (I/O, kg.month^{-1}) were obtained by multiplying tributary outflows (F.R., m^3.s^{-1}) by the nutrient concentrations (N.C., g.m^{-3}) at each collection site, as follows:

$$I/O = \frac{FR * NC * 86400 * days.month}{10^3} \quad \text{(Eq1)}$$

The annual input of each tributary (AIT, ton.year^{-1}) was estimated as the sum of monthly inputs (kg.month^{-1}) from the tributaries (January/98 to December/ 98) and the results were converted to tons:

$$AIT = \sum_1^{12} MI \quad \text{(Eq2)}$$

The year was divided into two main seasons called: "wet season" and "dry season". Months with rainfall higher than 100 mm were considered the "wet season" (January, February, March, October, November, and December) (CPRM, 2001). Averages of wet months and dry months were determined to estimate the inputs in the "wet season" and in the "dry season" as follows:

$$IPW = \frac{\sum_1^6 WMI}{6} \quad (Eq3)$$

where: IPW= average of wet season (kg.month^{-1})WMI= monthly inpt in wet season (from October to March) in kg.month^{-1}

$$IPD = \frac{\sum_1^6 DMI}{6} \quad (Eq4)$$

where: IPW= average of wet season (kg.month^{-1})WMI= monthly inpt in wet season (from October to March) in kg.month^{-1}

The mass balance (MB,ton.year^{-1}) was estimated by the difference between the total input (IT, kg.month^{-1}) and the dam output (OT kg.month^{-1}). Nutrients and solids input due to the contribution of subterranean waters, superficial runoff, and their loss to the biota and/or sediment were not considered.

$$MB = \frac{\sum_1^{12} IT - \sum_1^6 OT}{10^3} \quad (Eq5)$$

Partial water balance (WMB, m^3.year^{-1}) was estimated by the difference between the sum of tributary input (m^3.month^{-1}) plus the direct precipitation into the reservoir surface (RR, m^3.month^{-1}) and the outflow.

$$WMB = \sum_1^{12} (trib. + RR) - \sum_1^{12} OT \quad (Eq6)$$

Estimation of direct precipitation into the reservoir (R.R., m^3.year^{-1}) was made by multiplying the reservoir area (R.A., m^3) by the total annual rainfall (mm.month^{-1}). Water input through subterranean waters, superficial runoff, and its loss through evaporation were not included.

$$RR = RA * \frac{\sum_1^{12} \text{monthly rainfall}}{10^3} \quad (Eq7)$$

Water, nutrients and solids retention times were measured as follows: step 1: The pool of nutrient availability in the reservoir (RP, kg) was estimated by multiplying reservoir water volume (WV, m^3) by the nutrient concentration (NC, g.l^{-1}).

$$RP = NC * WV \quad (Eq8)$$

Step 2: the annual input from all tributaries for a given nutrient (AIT, kg.day^{-1}) was estimated by adding the input of nutrients from different seasons (IPW and IPD, kg.day^{-1}) for each tributary and expressing the final result in kilograms per day:

$$AIT = \sum_1^7 (IPW + IPD) \quad (Eq9)$$

Retention time (RT, days) was determined by the ratio of the reservoir nutrient availability (RP, kg) to the input from tributaries (AIT, kg.day^{-1}).

$$RT = \frac{RP}{AIT} \quad (Eq10)$$

All the results were later converted to tons.

Results

Seasonal Mass Balance

The Pampulha reservoir had different seasonal patterns for export and retention according to the variable (nutrient) considered (Tab. II). These patterns were strongly influenced by rainfall. The reservoir retained total suspended solids, total phosphorus and inorganic nitrogen in both wet and dry seasons. However, these retention values were usually higher during the rainy season. Export rates occurred only for particulate carbon (Tab. II) during the rainy season.

The tributaries Ressaca/Sarandi and the Água Funda always contributed with the highest values of the external load of total suspended solids (wet, 96.3 %; dry, 94.2 %), particulate organic carbon (wet, 97.3 %; dry, 94.8 %), total phosphorus (wet, 99.2 %; 98.5 dry, %) and inorganic nitrogen (wet, 99.2 %; dry, 97.9 %) (Tab. II).

Some streams suffered large variations in the nutrient loads when contrasted the wet and dry seasons while others have small seasonal variations in their contributions (Tab. II). The Água Funda stream presented the largest variation in water flow (Tab. I) and consequently the highest discrepancy in monthly export rates of nutrients. The amount exported by this stream during wet season increased 9.5 times for POC and 12.0 times for suspended solids, respectively.

Table II: Total solids and nutrient exports (particulate organic carbon, total phosphorus and dissolved inorganic nitrogen) of tributaries and mass balance (ton.month^{-1}) estimation during wet and dry season, in Pampulha reservoir, 1998.

Input	Total Suspended Solids		Particulate Organic Carbon		Total Phosphorus		Dissolved Inorganic Nitrogen	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Mergulhão	2.99	2.15	0.39	0.50	0.02	0.03	0.240	0.32
Tijuco	1.62	0.67	0.18	0.11	0.004	0.006	0.045	0.04
Ressaca/Sarandi	183.08	58.78	39.47	13.26	5.79	2.63	41.06	18.41
Água Funda	42.09	3.47	4.93	0.51	0.55	0.01	6.104	1.04
Baraúna	1.27	0.52	0.27	0.06	0.005	0.002	0.008	0.009
AABB	0.41	0.10	0.05	0.03	0.003	0.002	0.011	0.005
Olhos D'Água	2.13	0.33	0.31	0.05	0.01	0.003	0.076	0.02
Total Input	233.59	66.03	45.60	14.51	6.38	2.76	47.54	19.85
Outlet (Output)	159.27	29.76	52.72	9.41	1.37	0.37	16.11	7.68
Balance (input - output)	74.32	36.27	7.12*	5.11	5.01	2.39	31.43	12.17

*Italic values indicate export of particulate carbon during rainy season (see equation 5).

Annual Mass Balance

Annual water balance showed that Pampulha reservoir receives more water than it exports, with a difference of 19.4 x 10^3 m^3.year^{-1} (5.8% of retention). The tributaries responsible for the highest inflow were Ressaca/Sarandi (70.01 %), followed by Água Funda (16.81 %) (Fig. 2).

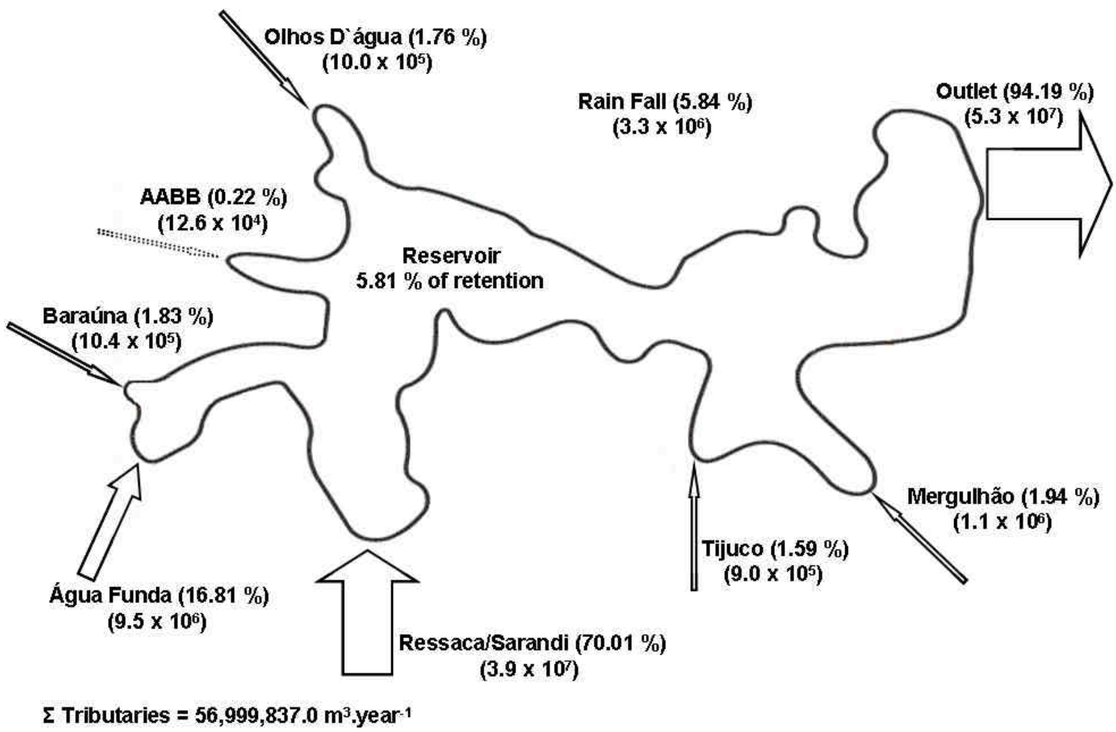

Figure 2: Annual water balance (m^3.year^{-1}) schematic drawing of Pampulha reservoir, 1985.

The retention capacity of the reservoir for total suspended solids and essential nutrients was confirmed on an annual basis (Figs. 3, 4, 5 and 6). For total suspended solids, the reservoir retained 36.9 % of the incoming total solids, totalizing 1.8 x 10^3 ton.year^{-1} (Fig. 3).

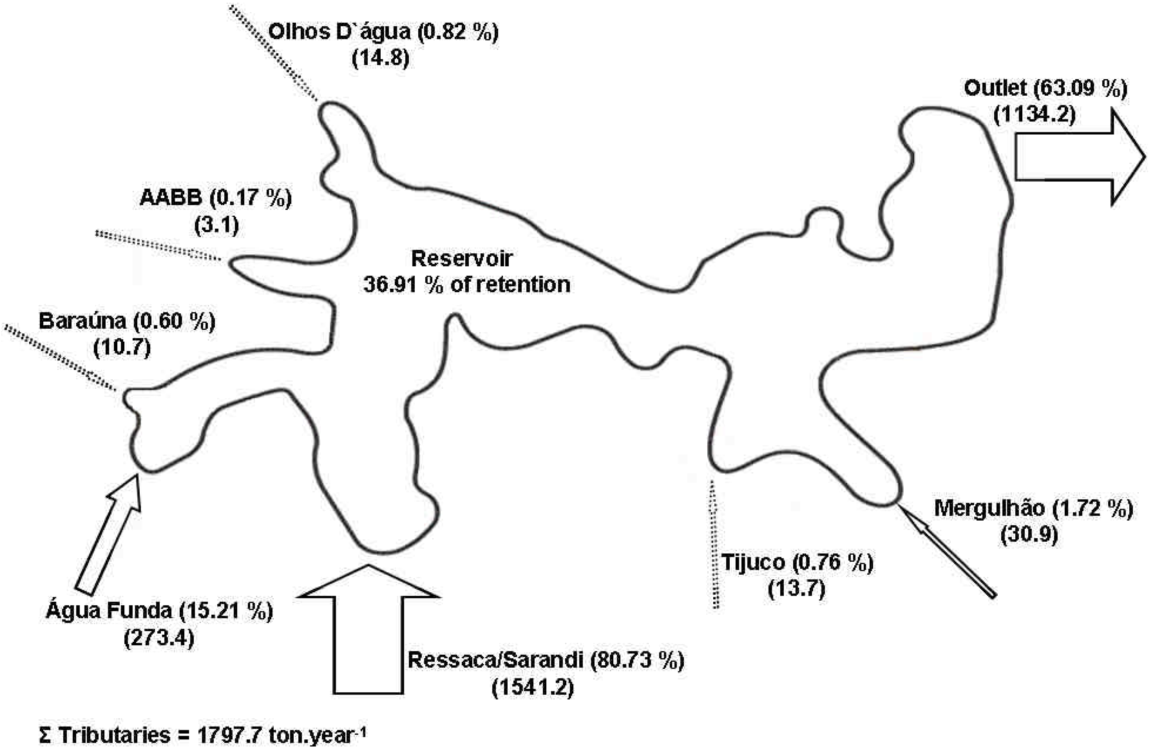

Figure 3: Annual total suspended solids mass balance (ton.year^{-1}) schematic drawing of Pampulha reservoir, 1998.

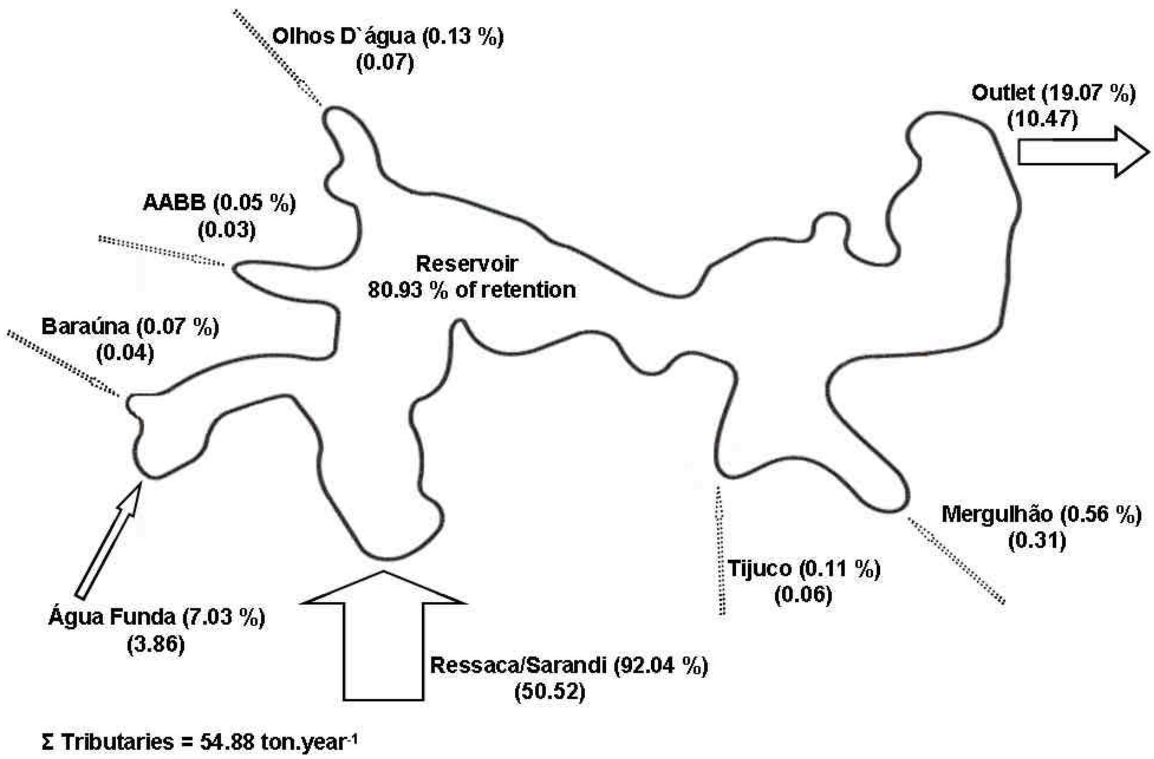

Figure 4: Annual total phosphorus mass balance (ton.year^{-1}) schematic drawing of Pampulha reservoir, 1998.

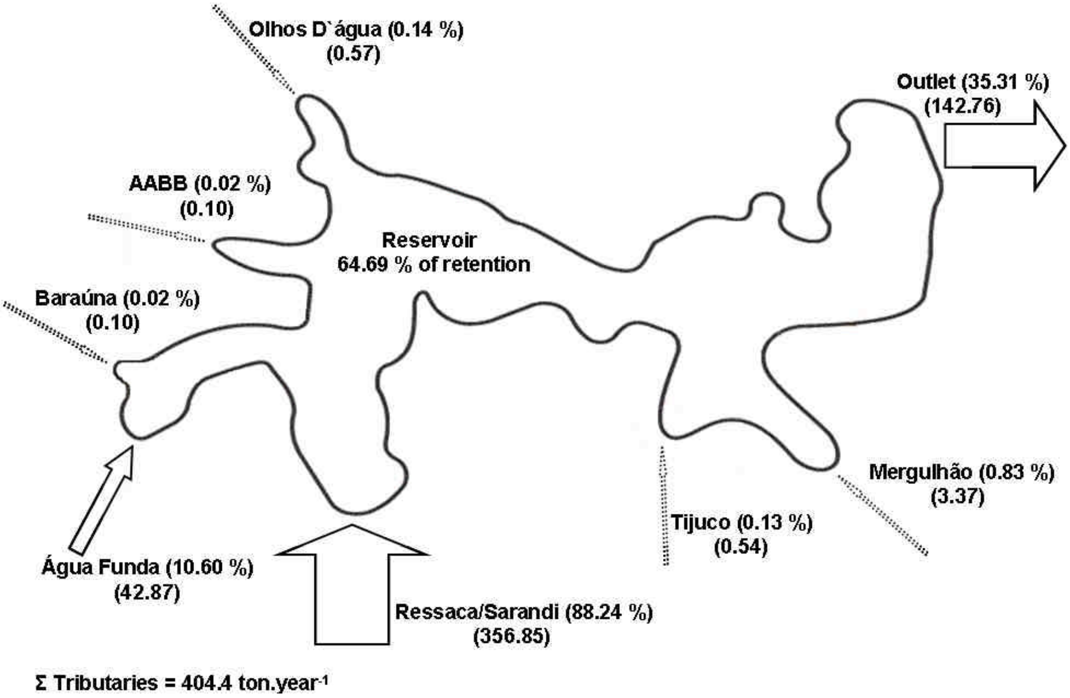

Figure 5: Annual dissolved inorganic nitrogen mass balance (ton.year^{-1}) schematic drawing of Pampulha reservoir, 1998.

Even higher retention proportions were found for nitrogen and phosphorus. The relative amounts of retained nutrients were 64.7 % and 80.9 % for inorganic nitrogen and total phosphorus, respectively (Figs. 4 and 5). The external load of total phosphorus and inorganic nitrogen to the lake were 54.9 and 404.4 ton.year^{-1}, respectively.

Conversely, the reservoir exported organic matter as attested by the annual mass balance of particulate organic carbon. The output of particulate organic carbon was 372.8 ton.year^{-1} (Fig. 6).

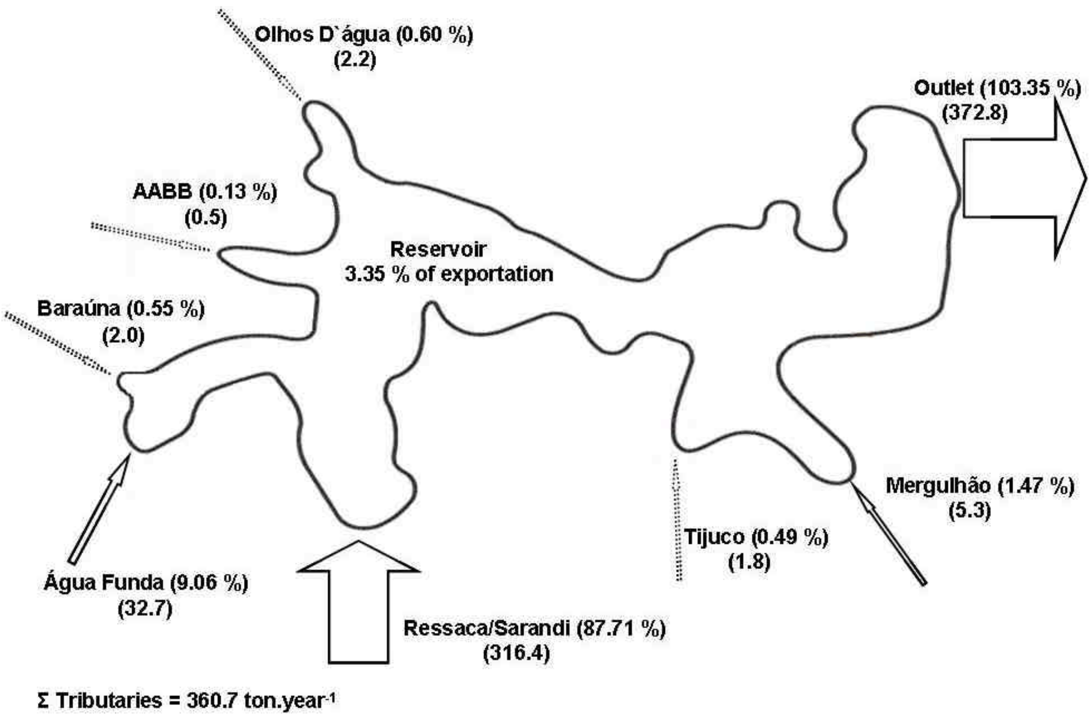

Figure 6: Annual particulate organic carbon mass balance (ton.year^{-1}) schematic drawing of Pampulha reservoir, 1998.

The key role of the streams Ressaca-Sarandi for the external loading of suspended matter and nutrients was confirmed by the mass balance considering the annual basis. Despite the contribution of 70% of the total volume of the incoming water from all tributaries, these two streams are responsible for more than 85% of the total external load of particulate organic carbon, total phosphorus and inorganic nitrogen. (Fig. 4, 5 and 6).

Residence Times

The turnover times for most nutrients and suspended matter were lower than the retention time of the water in the reservoir, estimated in 76.8 days (Tab. III). Total phosphorus had the lowest residence time (15.6 days), followed by inorganic nitrogen (29.5 days). The highest residence time for nutrients was found for particulate organic carbon (65.1 days).

Table III: Nutrients, solids and water retention time estimation in Pampulha reservoir, 1998.

Parameters	Reservoir (ton)	Tributaries (ton.day^{-1})	Retention Time (days)
Dissolved Inorganic Nitrogen	33.25	1.13	29.5
Total Phosphorus	2.37	0.15	15.6
Particulate Organic Carbon	64.76	0.99	65.1
Total Suspended Solids	220.05	4.96	44.4
Water	11.3×10^6	14.7×10^4	76.7

Discussion and conclusion

Nutrients are introduced into lakes and reservoirs through tributary discharges, superficial and subterranean runoff and atmospheric deposition (Krugg, 1993). In a study of phosphorus cycling in 16 lakes of Ireland and along the Scottish border, Gibson et al. (1996) reported that in all cases the main phosphorus sources for lakes were tributary input and rainfall. Considering small and shallow reservoirs with lower residence times, such as the Pampulha reservoir, the contribution of river discharges is usually higher than other sources.

The nutrient load from rivers usually depends on two main factors: flow rate and geology of the drainage basin (Wetzel, 2001). However, many other factors such as rainfall, river management as well as anthropogenic activities in the watershed such as agriculture, industry and housing also play an important role in establishing the nutrient load of a river (Wetzel, 2001). Additionally, the nutrient input from rivers is influenced by the river's own nutrient retention capability which is higher under low flow conditions or in areas where there is an abundance of aquatic plants (Svendsen & Kronvang, 1993). Retention has an important influence in the nutrient dynamics in aquatic systems (Svendsen & Kronvang, 1993).

Waters flowing from lakes and reservoirs will have different nutrient concentrations comparing to the incoming tributaries due to the biological, chemical and physical properties of those ecosystems (Straskraba et al., 1995). The nature and proportion of production and consumption processes are essentially different in lakes and reservoirs (Wetzel, 2001). The importance of metabolic processes occurring in the water column in the pelagic region of a lake, such as the production of phytoplankton or nutrient excretion from invertebrates, is usually much higher than similar processes occurring in rivers (Wetzel, 1996).

The Pampulha reservoir showed a pattern of accumulation of inorganic nutrients and exportation of organic particulate carbon (wet season). This is probably the result of metabolic activities occurring in the lake. The accumulation and subsequent exportation of particulate carbon can be partially explained by the high primary production rate in this reservoir. In a recent survey, Araújo & Pinto-Coelho (1998) measured a maximum value of 206 mg C.m^{-2}.day^{-1} for the primary production of phytoplankton in this reservoir. Furthermore, the reservoir usually has dense populations of the macrophyte Eichhornia crassipes. The primary production of this macrophyte in the reservoir reached a maximum of 22.17 $g.dw.m^{-2}.day^{-1}$ (Greco, 1996; Pinto-Coelho & Greco, 1999). Nevertheless, the high figures found for primary production of phytoplankton and macrophytes are not the only factors responsible for the accumulation of organic matter in the reservoir.

Other source of carbon in this lake may be the superficial runoff (garbage accumulation). Nevertheless, there is still no information about the carbon origin (autochthonous versus alochthonous) as well as there are no precise determinations about the biochemical nature of the sestonic components present in the water column of this reservoir. Only with those data, it will be possible to know the real origin of the exported carbon from this system.

This study showed that the tributaries also bring considerable amounts of inorganic nutrients to the lake. This allows a significant development of the microbial community. Torres et al. (1998) compared the contributions of primary producers and non pigmented seston for the availability of particulate carbon in the water column of the reservoir. They found that the contribution of non pigmented sestonic carbon for the overall availability of particulate carbon in the water column was higher than 70% for most occasions. Araújo & Pinto-Coelho (1998) have also shown that, despite having high values of primary production, the phytoplankton alone does not support the energetic requirements of zooplankton in the reservoir. They estimated the assimilation of the zooplankton to reach levels as high as 486 mg $C.m^{2}$ day^{-1}, a value that could not be supported by primary production of phytoplankton alone. As a consequence, the accumulation of organic matter in Pampulha reservoir is probably not only a result of high primary production of phytoplankton and macrophytes but also a result of the production due to the microbial food chain.

Lakes and reservoirs often act as "traps" for inorganic nutrients. This study showed that Pampulha reservoir clearly acts as a "trap" for nitrogen and phosphorus. Studying lakes in the Czech Republic, Straskraba et al. (1995) found a phosphorus retention time varying between 7 to 604 days. According to authors stratified and deep reservoirs are very effective traps for phosphorus. Apparently, shallow and eutrophic tropical reservoirs have similar properties as well. Cordeiro Netto & Dutra Filho (1981), in a study of phosphorus mass balance in the eutrophic lake Paranoá (Brazil), found a phosphorus input of approximately 115 $ton.year^{-1}$ with a retention of 80% of this amount in the reservoir. This percentage is very similar to the retention value found in the present study, 81% (Fig. 7). In another study in Lago das Garças (Brazil), an urban reservoir that as well as the Pampulha reservoir possesses high eutrophication indexes, Henry et al. (2004) found phosphorus retention of approximately 3.96 $ton.year^{-1}$, around 61% of the total input, corroborating the tendency of high retention of these nutrient in eutrophic urban reservoirs.

There is additional evidence suggesting the high affinity for phosphorus by the planktonic community of Pampulha reservoir. Pinto-Coelho (1994) found a spatial pattern in the distribution of N:P ratios of sestonic material of the reservoir that increased from regions near to the Ressaca/Sarandi stream (N:P= 41) to the dam region (N:P= 53). These spatial differences in N:P ratios and the lower retention time for this element found in the present study indicate that phosphorus is more rapidly assimilated than nitrogen and that this should be an indication of the limiting potential of this nutrient to the productivity in the reservoir.

An earlier study has also demonstrated the key role of free-living heterotrophic bacteria in the internal cycling of phosphorus in Pampulha reservoir (Pinto-Coelho et al., 1997). In this study, the high affinity of bacterioplankton for the P excreted by zooplankton was found, indicating that the microbial community is able to promptly absorb the soluble phosphorus recycled by consumers. In this sense, the free-living bacteria of the reservoir together with primary producers are very effective in removing the phosphorus from the inorganic pool, trapping it in the food chain.

The fate of nitrogen in Pampulha reservoir is the subject of some controversy. In a preliminary study, based on two samplings conducted in January and May of 1997, Barbosa et al. (1998) found evidence that this reservoir retains organic nitrogen and exports inorganic nitrogen. In contrast, our study clearly showed that the reservoir is retaining inorganic nitrogen. Possibly, the difference between previous studies in the reservoir and ours is related to the fact that our study is based on a complete seasonal cycle, permitting to identify more clearly the fate of the inorganic nitrogen in this reservoir.

The metabolic pathways for nitrogen in the water column of Pampulha reservoir should be fundamentally different from those observed for phosphorus. The cycling of nitrogen is much more dynamic since it involves the gaseous phase, N_2 (Pinto-Coelho, 2000). It is well known that several free-living microorganisms play an important role in this cycle. Examples of these organisms would be the aerobic bacteria responsible for oxidation of ammonium to nitrate and the N_2 fixing cyanobacteria and denitrifying bacteria (Wetzel, 2001). Denitrification, with the production of N_2 should be an important process explaining the mass balance for nitrogen aquatic ecosystems (Duff & Triska, 1990).

Henry et al. (1999) found evidence for total nitrogen export in the Jurumirim reservoir probably due to the nitrogen fixing cyanobacteria. The differences in the nitrogen budget in these reservoirs may be explained by the specific composition of the existing communities such as the phytoplankton (e.g: the relative importance of nitrogen fixing organisms in this community). In case of Pampulha reservoir further investigation is required to test the importance of nitrogen fixing organisms as well as the importance of denitrification on the mass balance of nitrogen.

In agreement with the study of Barbosa et al. (1998), the present investigation confirmed the importance of the streams Ressaca/Sarandi and Água Funda as the major sources of external nutrient input for the Pampulha reservoir. These streams have larger sub-basin areas, higher flow rates and suffer from intense human interference.

A recent investigation provided an update on hydrological data of Pampulha drainage basin (CPRM, 2001). However, these data were not used in the present work since it contains new estimations of flow rates only for the Ressaca and Sarandi streams. These flow rates suffered some increment, probably caused by the increase of soil impermeabilization due the large amount of anthropogenic activity in the drainage basin. Therefore, it is quite possible that the mass balance here presented may have been somewhat underestimated for the above mentioned streams. This new information, however, do not change the most important findings of the present work (see below).

The study demonstrated that the Pampulha reservoir acts as a “sink” for total phosphorus and inorganic nitrogen. Additionally, a clear seasonal effect was identified on the external input of nutrients, with higher inputs during the rainy season. Nevertheless, the reservoir is retaining suspended solids and essential nutrients (nitrogen and phosphorus) during all seasons.

The reservoir exported particulate organic carbon during the wet season. In this sense, the rainfall is an important factor for the improvement of the water quality of the reservoir since it contributes to the dilution of biomass of organic suspended material in the water column. The low residence time found for total phosphorus (15.6 days) indicates that the reservoir has a high turnover rate for this element. This can be interpreted as a signal for the limiting potential of this element for the biotic production in the reservoir.

The Ressaca/Sarandi and Água Funda is by far the most important sources of nutrients and suspended solids into this reservoir and, as a consequence, every measure concerning the management and recovery of Pampulha reservoir should incorporate strategies focused on the immediate and sustainable recovery of these streams.

Acknowledgments

This study was supported by PADI Foundation (California-USA) (Grant 59/1998) and by the city of Belo Horizonte (Grant 3581 FUNDEP-UFMG/SMMA-PBH). We also thank the biologist Cid Antônio de Morais Júnior for support in the nitrogen analysis and Dr. J. P. Prenger and Dr. J. Leader for reviewing the manuscript.

References

Araújo, M.A.R. & Pinto-Coelho, R.M. 1998. Produção e consumo de carbono orgânico na comunidade planctônica da represa da Pampulha - Belo Horizonte - MG. Rev. Bras. Biol., 58:405-416.

Barbosa, F., Garcia, F.C., Marques, M.G.S.M & Nascimento, F.A. 1998. Nitrogen and phosphorus balance in a eutrophic reservoir in Minas Gerais: a first approach. Rev. Bras. Biol., 58:233-239.

Bouvy, M., Falcão, D., Marinho, M., Pagano, M. & Moura, A. 2000. Occurrence of Cylindrospermopsis (Cyanobacteria) in 39 Brazilian tropical reservoirs during the 1998 drought. Aquat. Microb. Ecol., 23:13 27.

Branco, C.W.C. & Senna, P.A.C. 1996. Relations among heterotrophic bacteria, chlorophyll-a, total phytoplankton, total zooplankton and physical and chemical features in the Paranoa reservoir, Brasília, Brazil. Hydrobiologia, 337:171-181.

Calijuri, M.D.C. & Tundisi, J.G. 1990. Comparative limnology of Lobo, Broa and Barra Bonita reservoirs, São Paulo state, Brazil: mechanisms of functioning and bases for management. Rev. Bras. Biol., 50:893-914.

Carney, H.J., Binford, M.W., Marin, R.R & Goldman, C.R. 1993. Nitrogen and phosphorus dynamics and retention in ecotones of Lake Titicaca, Bolivia/Peru. Hydrobiologia, 251:39-47.

Champs, J.R.B. 1992. Algumas considerações sobre a situação sanitária da bacia da Pampulha. In: Anais do Seminário da Bacia Hidrográfica da Pampulha. Belo Horizonte, p.134-142.

Chaney, A.L. & Marbach, E.P. 1962. Modified reagents for the determination of urea and ammonia. Clin. Chem., 8:130-132.

Cordeiro Netto, O.M. & Dutra Filho, D. 1981. O aporte de fósforo ao Lago Paranoá. In: Anais do XI Congresso Brasileiro de Engenharia Sanitária e Ambiental. Fortaleza, p.1-19.

CPRM - Companhia de Pesquisa de Recursos Minerais. 2001. Projeto Pampulha: estudo hidrogeológico da Bacia da Pampulha. CPRM, Belo Horizonte. 151p.

Duff, J.H. & Triska, F.J. 1990. Denitrification in sediments from hyporheic zone adjacent to a small forest stream. Can. J. Fish Aquat. Sci., 47:1140-1147.

Ferreira, W.P. 1992. Atlas Nacional do Brasil. Instituto Brasileiro de Geografia e Estatística-IBGE, Rio de Janeiro. 42p.

Giani, A., Pinto-Coelho, R.M., Oliveira, S.J.M. & Pelli, A. 1988. Ciclo sazonal de parâmetros físico-químicos da água e distribuição horizontal de nitrogênio e fósforo no reservatório da Pampulha (Belo Horizonte, M.G., Brasil). Cienc. Cult., 40:69-77.

Gibson, C.E., Foy, R.H. & Bailey-Watts, A.E. 1996. An analysis of the total phosphorus cycle in some temperate lakes: the response to enrichment. Freshwater Biol., 35:525-532.

Greenberg, A.E., Clesceri, L.S.E. & Eaton, A.D. 1992. Standard methods for the examination of water and waste water. 18th ed. APHA, Washington. 1268p.

Greco, M.K.B. 1996. Produção de Eichhornia crassipes no reservatório da Pampulha. Belo Horizonte, UFMG, 72p (Master Thesis).

Henry, R., Santos, A.A.N. & Camargo, Y.R. 1999. Transporte de sólidos suspensos, N e P Total pelos Rios Paranapanema e Taquari e uma avaliação de sua exportação na Represa de Jurumirim (São Paulo, Brasil). In: Henry, R. (ed.) Ecologia de reservatórios: estrutura, função e aspectos sociais. FAPESP, FUNDIBIO, Botucatu. p.687-710.

Henry, R., Carmo, C.F. & Bicudo, D.C. 2004. Trophic status of a Brazilian urban reservoir and prognosis about the recovery of water quality. Acta Limnol. Bras., 13(3):251-262.

Holas, J., Holas, M. & Chour, V. 1999. Pollution by phosphorus and nitrogen in water streams feeding the Zelivka drinking water reservoir. Water Sci. Technol., 39:207-214.

Huszar, V.L.M., Silva, L.H., Marinho, M., Domingos, P. & Sant'Anna, C.L. 2000. Cyanoprokaryote assemblages in eight productive tropical Brazilian waters. Hydrobiologia, 424:67 77.

Krug, A. 1993. Drainage history and land use pattern of a Swedish river system-their importance for understanding nitrogen and phosphorus load. Hydrobiologia, 251:285-296.

Mackereth, F.J.H., Heron, J. & Talling, J.F. 1978. Water analysis: some revised methods for limnologists. Freshwater Biological Associations Scientific, Washington. 120p.

Matsumura-Tundisi, T. & Tundisi, J.G. 2005. Plankton richness in a eutrophic reservoir (Barra Bonita Reservoir, SP, Brazil). Hydrobiologia, 542:367-378.

Murphy, J. & Riley, J.P. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta, 27:31-36.

Noges, P., Jarvert, A., Tuvikene, L. & Noges, T. 1998. The budgets of nitrogen and phosphorus in a shallow eutrophic Lake Vortsjarv (Estonia). Hydrobiologia, 363:219-227.

Pinto-Coelho, R.M. 1994. Limnological perspectives for the control of eutrophication in large tropical reservoirs. In: Pinto-Coelho, R.M., Von Sperling, E. &

Giani, A. (eds.) Ecology and human impact on lakes and reservoirs in Minas Gerais. SEGRAC, Belo Horizonte. p.11-26.

Pinto-Coelho, R.M. 1998. Effects of eutrophication on seasonal patterns of mesozooplankton in a tropical reservoir: a 4-year study in Pampulha Lake, Brazil. Freshwater Biol., 39:101-115.

Pinto-Coelho, R.M. 2000. Fundamentos em Ecologia. Artes Médicas, Porto Alegre. 252p.

Pinto-Coelho, R.M., De Moura, R.T. & Moreira, A. 1997. Zooplankton and bacteria contribution to phosphorus and nitrogen internal cycling in a tropical and eutrophic reservoir: Pampulha Lake, Brazil. Int. Rev. Gesamten Hydrobiol., 82:185-200.

Pinto-Coelho, R.M. & Greco, M.K.B. 1999. The contribution of water hyacinth (Eichhornia crassipes) and zooplankton to the internal cycling of phosphorus in the eutrophic Pampulha reservoir, Brazil. Hydrobiologia, 411:115-127.

Sendacz, S. 1984. A study of the zooplankton community of Billings reservoir - São Paulo. Hydrobiologia, 13:121-127.

Simon, M. & Tilzer, M. 1987. Bacterial response to seasonal changes in primary production and phytoplankton biomass in Lake Constance. J. Plankton Res., 9:535-552.

Starling, F., Lazzaro, X., Cavalcanti. C. & Moreira, R. 2002. Contribution of omnivorous tilapia to eutrophication of a shallow tropical reservoir: evidence from a fish kill. Freshwater Biol., 47:2443-2452.

Straskraba, M., Dostalkova, I., Heijzlar, J. & Vyhnalek, V. 1995. The effect of reservoirs on phosphorus concentration. Int. Rev. Gesamten Hydrobiol., 80:403-413.

SUDECAP - Superintendência de Desenvolvimento da Capital. 1997. Estudo de impacto ambiental do programa de recuperação e desenvolvimento ambiental da Bacia da Pampulha. SUDECAP, Belo Horizonte. 80p.

Svendsen, L.M. & Kronvang, B. 1993. Retention of nitrogen and phosphorus in a Danish lowland river system: implications for the export from the watershed. Hydrobiologia, 251:123-135.

Torres, I.C., Araújo, M.A. & Pinto-Coelho, R.M. 1998. Variação temporal de carbono pigmentado, carbono orgânico dissolvido e particulado na represa da Pampulha, Belo Horizonte/M.G. Rev. Bras. Biol., 58:131-141.

Vadenboncouer, Y. 1994. Longitudinal dynamics of seston and composition in lake outlet stream. J. Norht Am. Benthol. Soc., 13:181-189.

Von Sperling, E. 1997. The process of biomass formation as the key point in the restoration of tropical eutrophic lakes. Hydrobiologia, 342/343:351-354.

Von Sperling, E. 1999. Morfologia de lagos e represas. Departamento de Engenharia Sanitária e Ambiental da UFMG, Belo Horizonte. v.1, 137p.

Wetzel, R.G. 1996. Benthic algae and nutrient cycling in lentic freshwater ecosystems. In: Stevenson, R.J., Bothwell, M.L. & Lowe, R.L. (eds.) Algal ecology: freshwater benthic ecosystems. Academic Press, New York. p.641-667.

Wetzel, R.G. 2001. Limnology. Saunders College Publishing, New York. 1006p.

Young, W.J., Marston, F.M. & Davis, J.R. 1996. Nutrient exports and land use in Australian catchments. J. Environ. Manage., 47:165-183.

Received: 10 September 2003
Accepted: 19 April 2007