The cascading reservoir continuum concept (CRCC) and its application to the river Tietê-basin, São Paulo State, Brazil

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The Cascading Reservoir Continuum Concept (CRCC) and its Application to the River Tietê-basin, São Paulo State, Brazil

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ABSTRACT

Major changes in the water quality and basic features of phytoplankton assemblages in a series (cascade) of 7 reservoirs in the middle Tietê river, south-east Brazil were investigated in February 1998 (rainy season). The biologically non-affected variables change rapidly in the upstream reservoirs and then remain constant while biologically affected ones showed a prolonged response that can be explained only if considering the cascade as an entire system. The changes in the first reservoir in the system accords to the predictions of the serial discontinuity concept (SDC): the river continuum (RCC) is basically affected. However, changes on the downstream reservoirs become continuous again and show that the same processes remain operative throughout the entire river continuum. Therefore, a cascading reservoir continuum concept (CRCC) can be proposed for handling the ecological processes at a system level. A comparison of the present data with those recorded previously for some of the reservoirs show a fast growing eutrophication of the upper reservoirs in the cascade. On the basis of the CRCC and the present ecological status and water quality of the Tietê cascade a progressive downstream eutrophication can be forecasted thus calling attention for urgent need of restoration measures at the headwaters.

Key words: cascading reservoirs; river continuum concept; eutrophication; phytoplankton; gradients.

INTRODUCTION

Starting in the upper-middle reaches of the Tietê River and continuing to its confluence with the Paraná River (SE Brazil), the reservoirs of Barra Bonita, Bariri, Ibitinga, Promissão, Nova Avanhandava, Três Irmãos and Jupiá form a linked cascade of large (> 100 km^2; except Bariri) reservoirs built since the late 60's mainly to meet the fast-growing energy demand of this highly populated region. The Tietê basin includes 9 reservoirs, flooding *c.* 2,326 km^2 and accumulating *c.* 29,100 m^3 of water. Its headwaters drain the area of São Paulo, the highest populated and most industrialized area in the country. The reservoir construction on the one hand and the increasing sewage discharge on the other might be expected to have had a profound impact on biota and biotic processes of the original river.

Apart from obvious differences in origin and age, damned reservoirs and deep lakes show significant differences in their morphometric properties, retention time, coupling with watershed, hydrodynamics, etc. as summarized in Straškraba (1996). In turn, these features drive a series of limnological differences as, for example, higher pollution rates in reservoirs as a consequence of larger watershed, weaker thermal stability, more defined longitudinal gradients and higher capacities to retain material (Straškraba, 1998).

Some theoretical considerations as to the effects of upstream reservoirs on those downstream have been grouped by Straškraba (1990) as follows:

a. Temperature changes in the upperlaying reservoirs [1. Surface temperatures during spring are decreased, maximum temperature nearly identical; 2. Bottom temperatures increase; 3. Mixing depth increases; 4. Birgean heat budget increases; 5. Inflow stream jet depth increases; 6. Intensity of the mixing of inflow with reservoir water increases].

b. Chemical changes in the upperlaying reservoir [1. Turbidity decreases; 2. Organic load and color decreases with consequences for light conditions; 3. P-concentration decreases markedly due to turbidity decrease and phytoplankton uptake; 4. The oxygen concentration at the inflow to the lower reservoir is decreased due to decomposition in the hypolimnion of the water above].

c. Indirect effects on chemical and biological processes [1. in the vertical direction the distribution of conservative chemical substances is more uniform (due to A6) but this is not seen on biologically affected chemical variables; 2. Primary production decreases due to B3 and A3. This is not compensated by the decreased extinction coefficient of water for light (B1); 3. Phytoplankton composition tends to shift towards more oligotrophic assemblages (from the highly eutrophic with heavy blooms of blue green algae to less eutrophic with more diatoms); 4. Oxygen concentration of the deeper strata decreases].

Worldwide, numerous cascading reservoir systems have been constructed on large rivers including the Dnepr (Ukraine), Kama, Volga, Angara (Russia), Ebro, Guadiana, Tejo, Douro (Spain/Portugal), Zambezi (E-Africa), Missouri, Colorado (USA), Paranaíba, Grande, Tietê, Paranapanema (Brazil) and Paraná (Brazil/Paraguay).

Limnological investigations on particular reservoirs of such systems are not rare. However, the studies in which such cascades are considered as step-like continuous systems are uncommon (e.g. Litvinow & Roschchupko, 1994; Korneva & Solovyova, 1999) despite their obvious hydrological and suspected functional interconnectivity downstream. Such studies involve mostly the transport mechanisms of for example, natural suspended matter (Ibanez *et al.*, 1996), or of toxic substances (Iskra & Linnik, 1994; Linnik, 1995a, 1995b; Marciulioniene *et al.*, 1996; Gapeeva *et al.*, 1997). In this respect, transport of radionuclides, especially ^{137}Cs, and its biological effects along the Dnieper reservoir cascade, have been documented in particular detail (Klenus *et al.*, 1992; Sirenko *et al.*, 1992; Rogal & Dobrynskij, 1994; Shevchenko, 1995).

Recent developments in river ecology stressed the continuity of ecological functioning of entire river systems from 0^{th} to 6^{th}-7^{th} order large rivers (Vannote *et al.*, 1980). Along the successive stretches, dominance of planktonic assemblages in the overall ecosystem increases and phytoplankton forms complex interelations with other components, involving both bottom-up control by nutrients and top-down control by predators. These interactions have been incorporated to the RIVERSTRAHLER model (Billen *et al.*, 1994) and tested successfully on rivers Maine and Oise of the Seine river system.

The main purpose of this paper is to test some of the above considerations on the Tietê reservoir cascade. Since there are no historical data for the water quality of the Tietê river prior to the construction of the reservoir chain we hypothesize that the formerly existing river continuum still prevails, at least partly, in terms of connectivity of metabolic processes. Taking the continuum concept as a theoretical basis, the aim of this study is to demonstrate that despite the reservoir cascade, there still remains a "normal" trophic gradient in the Tietê river which, in this particular case, tends to decrease downstream, thus developing an "inverted gradient" due to the untreated sewage of the city of São Paulo. The depth profiles of physical and chemical parameters and the major changes in the phytoplankton composition where used to evaluate the changes along the reservoir cascade.

Description of study sites, material and methods

Starting at the upper-middle Tietê river and right before its entrance into the Paraná River (SE Brazil), the reservoirs of Barra Bonita, Bariri, Ibitinga, Promissão, Nova Avanhandava, Três Irmãos and Jupiá form a linked cascade of large (> 100 km^2; except Bariri) and mostly shallow man-made lakes (8-40 m depth) built from the late 60's to attend mainly the fast growing energy demand of this region which possesses the greatest demographic density in the country, including, alone in the State of São Paulo, 2,300 industries demanding 113 $m^3 \cdot s^{-1}$ of water, an amount further increased by irrigation to supply an ever-increasing agriculture, cattle-raising (Agostinho *et al.*, 1995), and also to meet other uses such as flood regulations, navigation, recreation, and water supply (Figure 1).

Each reservoir in the cascade is a dendritic main stem reservoir having a dam of > 15 m, and an impounded water volume of 542-14,200 $\cdot 10^6$ m^3.

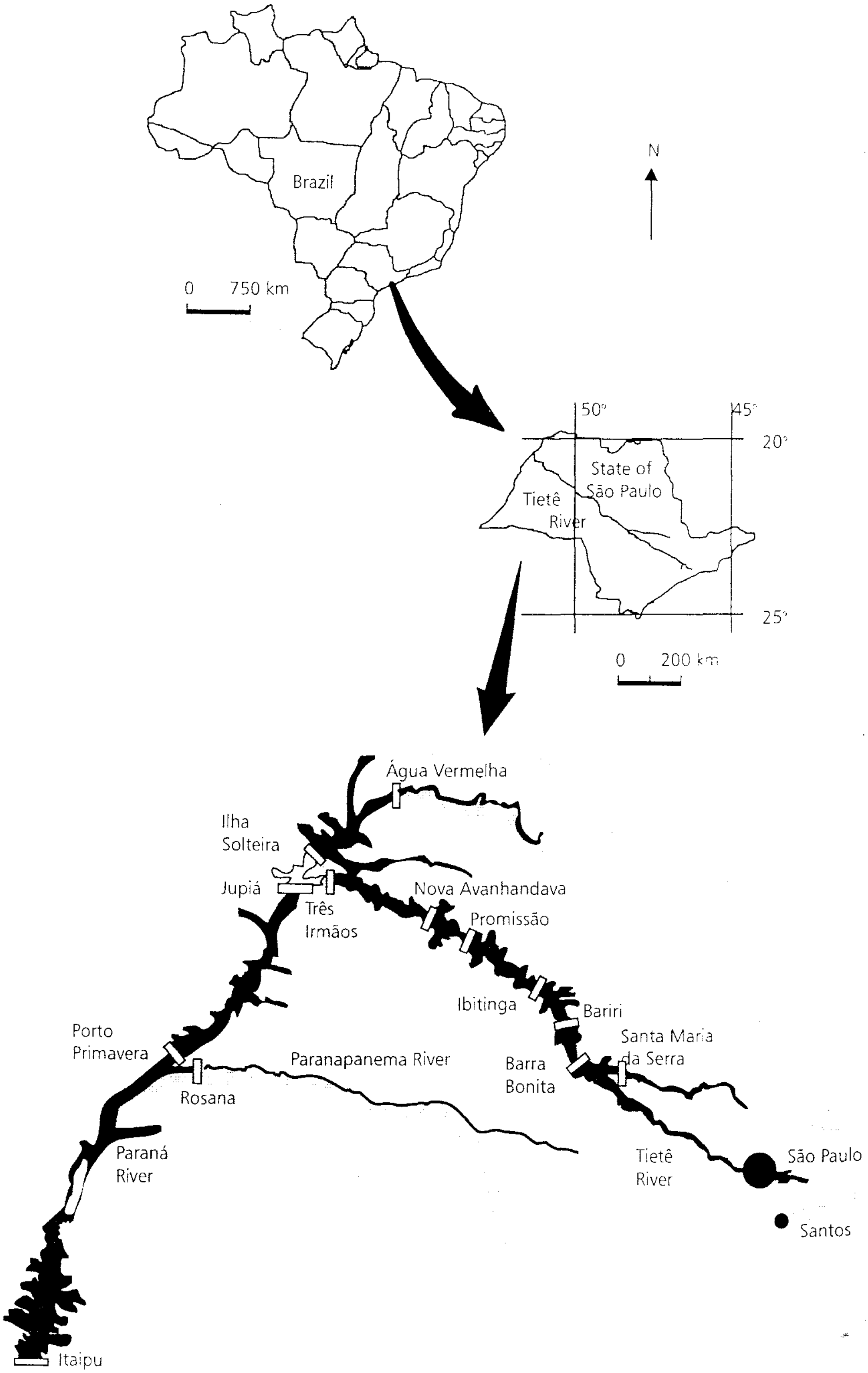

Figure 1 The Tietê River reservoir cascade.

Between 2 and 11 February, 1998 vertically integrated (whole water column) samples were taken from 4-8 sampling stations in each of the reservoirs. Dissolved oxygen, conductivity and temperature were measured with a portable profile sensor. Averages of records for each reservoir are used in this paper. Phytoplankton (both for quantitative and qualitative analyses) samples were preserved in 3%-4% formaldehyde. Samples for chlorophyll *a* analyses were filtered through GF/F glass fiber filters and frozen until subsequent laboratory analysis. Phytoplankton was counted under an inverted microscope. A minimum of 400 settling units were counted in each sample giving a counting accuracy of ± 10%. *Microcystis* spp. were counted in separate sedimentation chambers after 15 sec ultrasonication.

RESULTS

Mixing, water column stability, vertical gradients

At the time of the investigations the first reservoir, Barra Bonita, was strongly stratified with a steep thermocline between 6.5 and 11 meters depth (1.6°C difference). The presence of secondary thermoclines was evident in most of these reservoirs in February 1997 (summer = rainy period) and temperature difference of 3.4 °C between surface and bottom was recorded (Figure 2a).

Some chemical stratification of the reservoirs is suggested by the recorded depth profiles of dissolved oxygen, pH, and electrical conductivity (Figure 2 b, c, d). The depth profile of dissolved oxygen in this reservoir is characteristically of the clynograde type with concentrations decreasing from 5.0 mg · L at the surface to nearly 0.0 mg · L at 8 m depth, indicating a completely anoxic hypolimnion. Matching the pattern thermal stratification, recorded in February 1998, pH levels ranged between 7.14-6.59 within the upper layers to slightly acidic conditions (6.46-6.37) within the bottom ones. Furthermore, the existence of some "inverted profiles" (e.g. maximum conductivity at surface layers) suggests an instability of the water column mainly caused by the combined effects of the wind action and the operational routines (flushing out) of the reservoirs.

With regard to temperature (Figure 4), a continuous increase of surface temperature in the upper five reservoirs occurred while bottom temperatures seemed to depend more on the depths of the particular reservoirs ($r = -0.63$, non-significant).

Major changes along the reservoir cascade

The most characteristic feature of the upper part of the Tietê Reservoir cascade was the high suspended matter and nutrient content (Table I). Expressing the data relative to those of the Tietê river upstream of the cascade, the highest reduction of total and inorganic matter content occurs in the Barra Bonita reservoir, while the concentration of organic suspended matter continues at a similar rate in the Bariri reservoir (Figure 3a).

Of the most important inorganic nutrients, soluble reactive silica increase slightly down the cascade (Table I) but the recorded values well exceed the levels that are considered as limiting for diatom growth.

The extraordinarily high nitrogen content of the upper Tietê falls considerably in the first reservoirs. Reduction of NH_3-N, the most readily consumable form, is the quickest and that of NO_2-N is most prolonged (Figure 3b). Reduction of inorganic-P (Figure 3b) was even faster than that of NH_3-N, however, in the middle-stretch reservoirs an increase and again a subsequent decrease occurred. TN and TP (Figure 3c) also decrease through the system. TP declined faster than TN which reduced at a rather constant rate through the cascade. The differences in reduction rates of N and P compounds (both dissolved and total) resulted in a sharp increase of N/P ratios (Figure 3d) in the Barra Bonita Reservoir followed by a roughly gradual decrease along the subsequent ones. The chlorophyll content rose steeply in the first two reservoirs, did not change in the third then fell sharply in the fourth followed by only slow gradual in the rest of the system (Figure 3e).

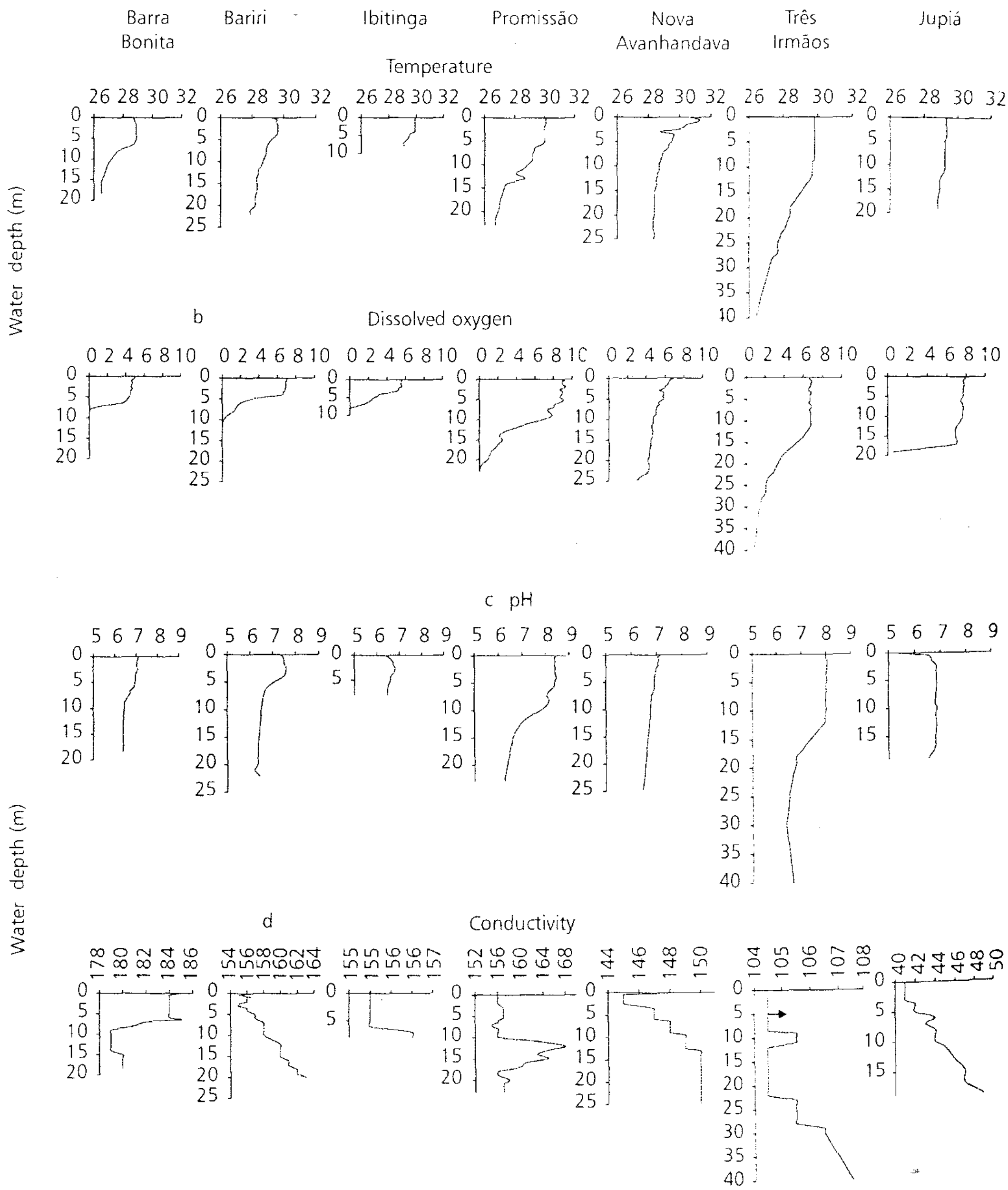

Figure 2 Depth profiles of water temperature (a), dissolved oxygen (b), pH (c), and electrical conductivity (d) recorded for the reservoirs along the cascade in the middle Tietê River, in February 1998 (average values).

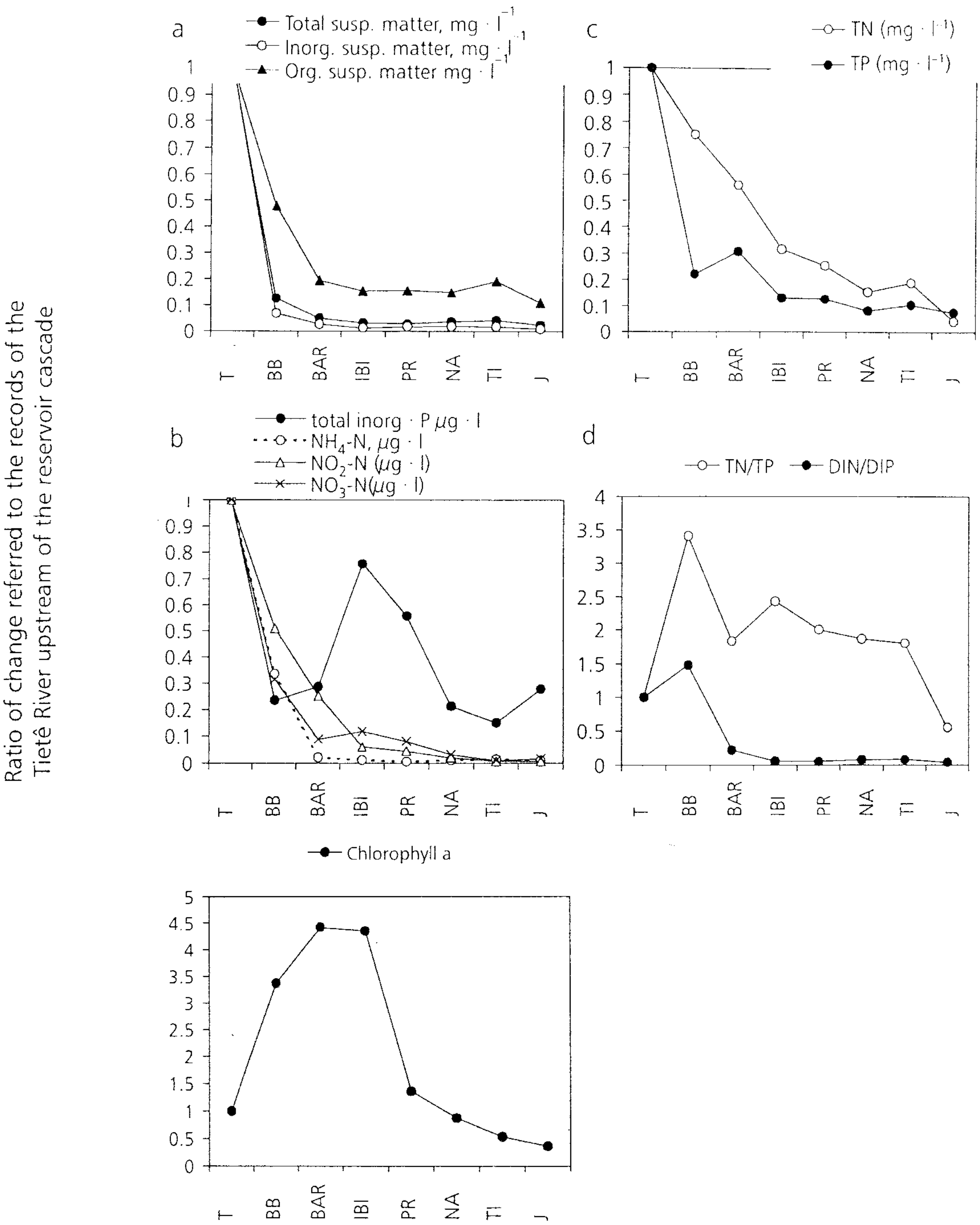

Figure 3 Change ratios for the studied chemical variables along the reservoir cascade of the middle Tietê River in February 1998.

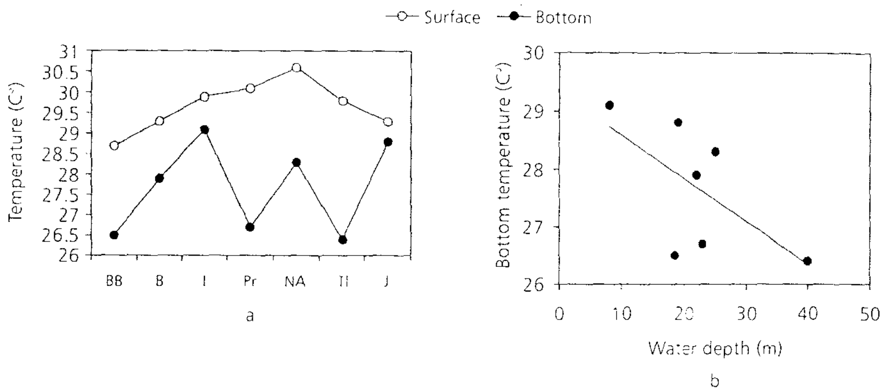

Figure 4 Water temperature variation within the upper and bottom layers (a) and its relation to depth (b) along the reservoir cascade in the middle Tietê River in February 1998.

Table I Morphometric parameters, major chemical and phytoplankton data on the middle Tietê River and the reservoirs along the cascade recorded in February 1998 (average values).

Reservoir	Tietê River upstream	Barra Bonita	Bariri	Ibitinga	Promissão	Nova Avanhandava	Três Irmãos	Jupiá
Area (km^2)		310	63	114	741	210	817	330
Average depth (m)		10.1	8.6	8.6	14.0	13.0	17.2	11.2
Year of completion		1964	1969	1969	1975	1985	1991	1974
retention time (days)		37-137	7-24	12-43	124-458	32-119	166-615	?
TP, $\mu g \cdot l^{-1}$	284.2	62.6	87.0	36.9	34.1	23.6	29.9	21.8
Total inorganic-P, $\mu g \cdot l^{-1}$	20	4.73	5.77	15.16	14.72	4.27	3.03	5.59
TN, $\mu g \cdot l^{-1}$	4,910	3,690	2,750	1,550	1,250	760	930	210
NO_3-N, $\mu g \cdot l^{-1}$	947.5	299.4	84.6	112.3	77.7	29.6	9.3	16.8
NO_2-N, $\mu g \cdot l^{-1}$	380.8	194.4	96.1	23	17.3	7.8	2.5	2.8
NH_4-N, $\mu g \cdot l^{-1}$	2,334.8	786.4	51.2	26.4	12.5	23.7	33.8	23.0
Total inorganic-N, $\mu g \cdot l^{-1}$	3,663.10	1,280.19	231.95	161.79	107.52	61.12	45.50	42.63
Soluble reactive silica mg $\cdot l^{-1}$	5.0	3.91	5.97	5.90	5.44	5.73	6.12	6.74
Dissolved O_2 in upper 5 m, mg $\cdot l^{-1}$		4.4-5.0	3.3-7.0	2.6-5.6	9.0-9.3	5.9-6.8	6.8-6.9	7.6-8.0
Total Suspended Solids, mg $\cdot l^{-1}$	144.2	18.2	7.3	4.8	4.2	5.4	6.2	3.5
Inorg. Suspended solids, mg $\cdot l^{-1}$	123.4	8.6	3.4	1.7	2.3	2.4	2.3	1.2
Organic suspended matter, mg $\cdot l^{-1}$	20.0	9.58	3.88	3.1	3.13	2.97	3.83	2.2
Dissolved N/P	183.16	270.65	40.20	10.67	9.66	14.31	15.02	7.63
TN/TP	17.27	58.97	31.61	41.98	34.61	32.24	31.12	9.66
Phytoplankton species number		57	65	65	95	64	51	129
Shannon diversity		3.18	1.88	1.78	1.64	2.53	1.09	2.53
chlorophll *a* ($\mu g \cdot l^{-1}$)	12.6	42.57	55.77	54.9	17.11	10.98	6.70	4.52
% contribution of unicellular centric diatoms to total biomass		38						
% contribution of *Microcystis* spp. to total biomass		34	75	78	12	9		
% contribution of *Coelastrum reticulatum* var. *cubanum* to total biomass					73	67	86	61

Changes within the phytoplankton community

As demonstrated previously (Padisák *et al.*, in press) a marked change in dominant species was recorded along the reservoir cascade; in Barra Bonita, the uppermost reservoir, unicellular centric diatoms dominated (38% of total biomass); among the blue-greens *Microcystis* spp. represented 34%, followed by many subdominant species. In Bariri, the subsequent reservoir, *Microcystis* spp. accounted for 75% of total biomass, reaching their highest dominance (78%) in Ibitinga, just downstream. A marked change occurred in the Promissão reservoir, where *Microcystis* spp. (12%) were replaced by *Coelastrum reticulatum* var. *cubanum* (73%) and an unidentified *Staurastrum* sp. (6%) was the subdominant species. Nova Avanhandava showed similar results, with *Coelastrum* reaching 86% of total biomass, *Microcystis* spp. 9%, *Cylindrospermopsis* 4% and *Staurastrum* sp. 7%. From Três Irmãos reservoir downstream Cyanobacteria became negligible and apart from the contribution of different desmids (*Cosmarium reniforme* in Jupiá), the reservoirs were dominated by *Coelastrum* (61%).

DISCUSSION

Characterized as polymictic (Tundisi, 1990), some of the reservoirs do stratify during short periods as was the case in the time of these studies, in accordance with Straškraba (1998) prediction for reservoirs of similar depths and residence times. Despite exhibiting secondary thermoclines and potentially being able to stratify during summers as judged by their depth, a permanent stratification, however, is unlikely to establish mainly due to their operational routines (flushing out) associated with wind action, facilitated by their relative shallowness and lack of better sheltering on their shores (since considerable forested areas had been clear-cut in the past for coffee plantations nowadays substituted by extensive areas planted with sugar-cane). Moreover, it seems reasonable to infer a prevailing instability of the water column.

The existence of vertical gradients depends basically on the above mentioned driving forces and also the contributions of allochtonous material to the reservoirs. These largely changeable contributions are the primary factors affecting water quality within the reservoirs. The untreated sewage from the city of São Paulo is, certainly the major source of organic loads to the reservoirs and Barra Bonita, the uppermost reservoir, which has been cited as a clear example of fast developing eutrophication in the Tietê basin. A comparison of the present data and those of Tundisi *et al.* (1991) show some marked differences in water quality, suggesting a rapid eutrophication. Thus for instance, the total nitrogen levels (average values) have increased *c.* 2.7 times in Barra Bonita, doubled in Bariri, increased *c.* 25% in Ibitinga, and 50% in Promissão, decreasing *c.* 10% in Nova Avanhandava. Total phosphorus concentrations doubled in Barra Bonita and Bariri, remained the same in Ibitinga, increased 58% and 73% in Promissão and Nova Avanhandava, respectively. Furthermore, the chlorophyll-a values increased 3-fold in Barra Bonita (32.6 to 97,0 $\mu g \cdot l^{-1}$) and *c.* of 12% in Bariri, the two uppermost reservoirs, and an increase of *c.* 11% in the total suspended matter was also recorded for Barra Bonita. These changes have occurred in no more than 5 years and strongly suggest the onset of a fast growing eutrophication, particularly within the upper reservoirs of the cascade and should be taken into consideration in future restoration and conservation programs.

With regard to predictions about the effect of upstream reservoirs on downstream and in comparison to Straškraba's (1990) predictions, we can conclude that:

A) Surface temperatures show a continuous increase in the cascade until the Três Irmãos reservoir which is the deepest in the cascade. The predicted increase in bottom temperature was not observable, bottom temperature were inversely dependent upon water depths of individual reservoirs.

B) Turbidity (especially inorganic fraction) decreases rapidly right in the first reservoir; but subsequent changes are minor. The response of organic turbidity is delayed and masked by autochtonous biotic processes (development of blue-green algal blooms), but it clearly accords to predictions. P-concentrations also decrease rapidly.

C) Phytoplankton biomass and chlorophyll-a content is increasing in the first reservoirs and only lower down the cascade does a marked decrease occurs. Because of high inorganic and organic load from the upper Tietê, this feature may be unique for this cascade. A shift towards more diverse and more oligotrophic phytoplankton assemblages can be clearly demonstrated (Padisák *et al.*, in press), however, not diatoms but green algae (Chlorococcales and Desmidiales) become dominant. Oxygen concentration in the deeper strata increases: only within the last three reservoirs of the cascade anoxic conditions near the bottom were not registered.

A remarkable feature of the reservoir cascade is the immediate response in some of the variables and the apparent delay to others. Inorganic turbidity (with consequences on light climate) changes most rapidly in the first reservoir, as does inorganic *P*, the latter primarily because of uptake by phytoplankton. In the downstream reservoirs, heavy algal blooms reduce light penetration, therefore an increase in inorganic *P* level occurs which again diminishes in the downstream reservoirs. Such a dynamic is not observable on inorganic *N* compounds because they are in a great surplus as compared to *P*. *N/P* ratios and low inorganic *P* concentrations suggest *P* limitation in the first reservoirs, while both ratios and concentrations suggest combined *N* and *P* limitation or even *N* limitation in the last four reservoirs in the cascade. In general, biotic or biologically-affected variables show more pronounced response than non-effected ones and their changes can be understood only by handling the cascade at a system level.

The river continuum concept (RCC) argued for the maintenance of the main ecological processes along the rivers from 0^{th} order stretches to the 7^{th}-8^{th} (or higher) order mouths of large rivers.

The existence of dams and impoundments basin wide was argued by Vannote *et al.* (1980) to be likely to disrupt the continuum along the rivers, thus altering the basic criteria of the river continuum concept. Complementarily, the potential changes due to such impoundments were recognized by Ward & Stanford (1983), in their serial discontinuity concept (SDC). Accordingly, dams cause a discontinuity in the physical and biological characteristics, dislocating the forecasts of the continuum depending on location of the dam, number of dams in a series, operation of dams (e.g. superficial or deep out-flow, and specific characteristics of the river). According to the RCC, a dam in a mid size river (3^{rd}-6^{th} order) should stabilize temperature variations and water flow downwards thus reducing biological diversity through reduction in available habitats. In large rivers (> 6[th] order), dams must reduced downward turbidity, thus allowing higher abundance of aquatic vegetation and shifting the characteristics of the system towards those forecasted for mid size rivers.

The investigated section of the Tietê River can be considered as a 4[th] or 5[th] order river completely occupied by the reservoir cascade. The predicted discontinuity can be clearly traced in the ratio of change between the true river section and the Barra Bonita Reservoir and the changes correspond to those forecasted for > 6[th] order rivers. However, starting with the Barra Bonita Reservoir another continuum arises within the system: biological processes within any of the particular reservoirs are consequent upon the changes in the preceding reservoir, the best example being the increase of N_2-fixing cyanobacteria (*Cylindrospermopsis raciborskii*; Padisák *et al.*, in press) in the Nova Avanhandava Reservoir as a response of *N* scarcity in the upperlaying ones.

This way, instead of the SDC, another continuum concept, the Cascading Reservoir Continuum Concept (CRCC) can be proposed as a theoretical basis for dealing with interconnected ecological processes in cascading reservoir systems.

More recently, Ward & Stanford (1983, 1995) reviewing their original SDC model called attention to the fact that the original conceptual model was based mainly on the assumption that streams/rivers are single-thread channels flowing through more or less constrained reaches, having almost no further interactions with the surrounding environments and accepted that a holistic perspective of river ecosystems, must include the majority of the interactions with the surrounding environments. Furthermore river systems are interactive along three dimensions (Ward, 1989): lateral (channel-floodplain), vertical (channel-aquifer) and longitudinal (channel-channel). It is particularly important to include the lateral dimension in any analysis of cascading reservoir functioning, since, as a consequence of slowered flow, dead-zones along the lateral sides may allow a more intense habitat diversification. These habitats become an integral part of the cascade system, contributing to the whole dynamics through the allochtonous material and depositional areas thus enhancing the potential for the maintenance of the ongoing processes. Similarly important is to consider the diversified socio-economic activities and their outcomings within the watershed which may interfere with the continuity of the processes along the cascade.

The presence of the reservoir cascade certainly caused significant changes in the original continuum of the river altering aspects such as thermal heterogeneity, connectivity, and course/fine particulate organic matter ratios, affecting very likely the original biodiversity. The recorded changes in this study show clearly the effects of human influences within each reservoir's watershed thus explaining the differences along the cascade, due to hydrological, morphological and mainly chemical inputs to each one. These differences do not however impede the maintenance of the basic processes which are kept operative throughout the continuum.

In conclusion, the presence of a reservoir cascade in the middle Tietê River, influences considerable changes in the water quality and the composition and structure of phytoplankon communities, especially in the first reservoir. Furthermore, the reservoirs probably altered the original biodiversity existing in the area, particularly through the isolation of the floodplains, thus affecting and even reducing the regional biodiversity. These changes are mainly due to morphological, hydrological and chemical inputs, together resulting in the observed differences among the reservoirs. However, despite the reservoir cascade and its impacts, the recorded results allow us to point out that the same processes are operative throughout the entire river continuum, thus conforming with the basic hypothesis of RCC and the RIVERSTRAHLER model as discussed by Billen *et al.* (1994).

The present results also demonstrated a growing eutrophication of the uppermost reservoirs which as pointed out previously (Padisák *et al.*, in press) among providing several services also function as effective "storing agents" of considerable loads of nutrients, thus contributing to a better water quality of the waters downstream the cascade. However, on the basis of the CRCC and the present ecological status and water quality of the Tietê cascade a proliferation of downstream eutrophication can be forecasted thus calling attention for urgent need of restoration measures at the headwaters.

These aspects are of paramount importance in the future restoration and management plans for the area and shall be considered as important tools in maintaining and even enhance the present biodiversity and water quality for future generations.

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