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Water quality changes along the reservoir cascade of river Tietê (São Paulo State, Brazil)

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Eutrophication has been one of the most apparent threats to surface waters throughout the world, however especially in many tropical countries where demographic growth and social problems have created unplanned and huge cities without sanitation, and expanding industrial parks with ineffective protection laws among many other factors contributing to the degradation of almost all available fresh water.

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, Jupiá and Ilha Solteira 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 posses the greatest demographic density in the country, including, only in the State of São Paulo, 2,300 industries demanding 113 $m^3 s^{-1}$ of water, an amount further increased by irrigation to supply an ever-increasing agriculture. The reservoirs are located in one of the most impacted watersheds of SE Brazil, the Tietê river, which drains the area of São Paulo, the highest populated and industrialized area in the country. They receive considerable loads of nutrients mainly due to discharges of untreated sewage and industrial effluents, amounting to 25 $m^3 sec^{-1}$ (TUNDISI et al., 1993). The aim of this study was to assess changes in water quality (1) at level of most important nutrients and chlorophyll; (2) species composition and biodiversity; and and to assess the toxic hazard of cyanobacteria growing abundantly, even causing water blooms in the upper reservoirs. For the latter (3) toxins were identified with HPLC; (4) laboratory tests were made using different test and (5) toxicity of isolated cyanobacterial species was investigated.

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Vertically integrated samples were taken between 2-11 February 1998 and 1-10 February 1999 from each reservoirs. Dissolved oxygen, conductivity and temperature were measured by a portable profile sensor. Phytoplankton countings and chemical measurements were performed according to the widely accepted international standards. Methods of toxicity studies are described in HEINZE (1996) and KÓS et al. (1995). Morphometric parameters, average water chemical and phytoplankton data obtained in 1998 are given in Table 1.

1. Physical and chemical variables (Table 1)

In February 1998, the waters ranged between slightly acidic to alcaline (pH 6.20-8.46), average conductivity for the Tietê reservoirs between 105 and 182 $\mu S\ cm^{-1}$, much lower for Jupiá and Ilha Solteira (43-51 $\mu S\ cm^{-1}$), and oxygen levels showing a smooth decrease with depth although still present within the bottom waters in all the reservoirs.

Table 1: Morphometric parameters, average water chemical and phytoplankton data from the Tietê and Paraná basin reservoirs

Reservoir	Barra Bonita	Bariri	Ibitinga	Promissão	Nova Avanhandava	Três Irmãos	Jupiá	Ilha Solteira
Area (km^2)	310	63	114	741	210	817	330	1195
Average depth (m)	10.1	8.6	8.6	14.0	13.0	17.2	11.2	17.6
Year of completion	1964	1969	1969	1975	1985	1991	1974	1978
retention time (days)	37-137	7-24	12-43	124-458	32-119	166-615	?	?
TP, $\mu g\ l^{-1}$	51.8	48.9	63.6	27.9	23.1	22.8	21.7	27.4
PO_4-P, $\mu g\ l^{-1}$	4.7	5.8	15.2	14.7	4.3	3.0	5.6	17.0
TN, $\mu g\ l^{-1}$	3,690.0	2,750.0	1,550.0	1,250.0	760.0	930.0	210.0	280.0
NO_3-N, $\mu g\ l^{-1}$	299.4	84.6	112.3	77.7	29.6	9.3	16.8	13.2
NO_2-N, $\mu g\ l^{-1}$	194.4	96.1	23.0	17.3	7.8	2.5	2.8	2.7
NH_4-N, $\mu g\ l^{-1}$	786.4	51.2	26.4	12.5	23.7	33.8	23.0	91.0
dissolved O_2 in upper 5 m, mg 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	0-7.6
Total Suspended Solids, mg l^{-1}	18.2	7.3	4.8	4.2	5.4	6.2	3.5	3.2
Inorg. suspended solids, mg.l^{-1}	8.6	3.4	1.7	2.3	2.4	2.3	1.2	1.7
phytoplankton species number	57	65	65	95	64	51	129	81
Shannon diversity	3.18	1.88	1.78	1.64	2.53	1.09	2.53	2.53
chlorophll *a* ($\mu g\ l^{-1}$)	42.57	55.77	54.9	17.11	10.98	6.70	4.52	3.02
% 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	48

The reservoir Ilha Solteira exhibited a complete oxygen depletion within the upper layers (0 -4 m depth) with water temperatures oscillating between 29.8°C and 32.4 °C throughout the day. On the other hand, the layers in between 4 and 13 meters depth exhibited oxygen levels ranging between 7.6 and 5.5 mg $^{l-1}$ and water temperatures oscillating between 29.1 and 29.7 °C, and even near to the bottom (17 m) low level such as 0.30 mg l^{-1} was still recorded.

Well defined stratification patterns were recorded within none of these reservoirs although the presence of secondary thermoclines were evident. Temperature differences between surface and bottom ranged between 0.5 and 3.4 °C, including even not very deep waters, since a difference of 3.4 °C was recorded for Ilha Solteira in only 17 meters.

Inrorganic nutrient concentrations showed an oveall decrease along the cascade. The chlorophyll-a concentrations (not corrected for phaeophytin-a) showed a similar pattern, with values ranging between 43 and 55 $\mu g\ l^{-1}$ in the upper reservoirs and considerable decrease in the lower ones (3-7$\mu g\ l^{-1}$).

2. Phytoplankton flora and biodiversity (Table 1)

Phytoplankton species numbers were highest in reservoirs Ilha Solteira, Jupiá and Promissão as a consequence of large number of chlorococcalean species and desmids. It has to be noted that among *Microcystis* spp. predominant in the three uppermost reservoirs 9 morphologically different forms were found, however, only *M. wesenbergii* was readily identifiable.

Shannon diversity was the highest (3.18) in Barra Bonita, the first the cascade then dropped to a low level in the three subsequent ones. An increase in compositional diversity could be observed in Nova Avanhandava then in Três Irmãos the lowest level was found. In adjacent reservoirs Ilha Solteira and Jupiá of the Paraná basin compositional diversity increased.

A marked change in dominant species can be found during the reservoir cascade.The Barra Bonita reservoir unicellular centric diatoms dominated with a considerable *Microcystis* population and with many subdominants as *Planktothrix agardhii*, *Aphanizomenon issatschenkoi*, *Cylindrospermopsis raciborskii*, *Eutetramorus tetrasporus* and *Aulacoseira granulata*. In the adjacent Bariri reservoir overwhelming dominance of *Microcystis* spp. was characteristic with some *Aulacoseira*. In the Ibitinga *Microcystis* reached the highest dominance.. Quite a marked change occurred in the Promissão reservoir where

Microcystis spp. were largely replaced by *Coelastrum reticulatum* var. *cubanum* and an unidentified *Staurastrum* sp. was subdominant. Records of the Nova Avanhandava reservoir are quite similar. Cyanobacteria became negligible in the Três Irmãos reservoir where *Coelastrum* reached an overwhelming dominance with *Eutetramorus policoccus* being subdominant. In the two reservoirs (Jupiá and Ilha Solteira) belonging to the Paraná basin also *Coelastrum* predominated in the phytoplankton, *Eutetramorus policoccus* were subdominant and contribution of different desmids (*Cosmarium reniforme*, *Staurastrum chaetoceras*, *S. planktonicum*) was also significant. Besides, *Peridinium cinctum* in Jupiá reservoir and *Aulacoseira granulata* in the Ilha Solteira reached higher amounts.

Table 2: Toxin analytical data and toxicity in different tests of freeze-dried materials deriving from different Brazilian reservoirs (n.t.: not tested, n.i.: non-inhibitory)

	Barra Bonita	Bariri	Ibitinga	Promissão
microcystin-LR ($mg\ g^{-1}$), HPLC	0.0	0.0	0.2	0.2
microcystin-RR ($mg\ g^{-1}$), HPLC	12.5	14.8	18.8	16.0
microcystin-YR ($mg\ g^{-1}$), HPLC	2.2	2.7	3.0	1.6
IC_{50} ($mg\ ml^{-1}$) in BGST test	2.0	2.0	n.t.	n.t.
LC_{50} ($mg\ ml^{-1}$) in rat hepatocyte test	0.05	0.14	0.05	0.19
Cytotoxicity in cell-line CHO-K1 in 0-1.67 $mg\ ml^{-1}$ conc. range	n. i.	n. i.	n. i.	n. i.
LC_{50} ($mg\ ml^{-1}$) in *Thamnocephalus* test	0.55	0.40	n.t.	n.t.

Table 3: IC_{50} of cyanobacterial strains isolated from Rio Tietê region in BGST tests on the base of chlorophyll a content

Isolated species	Origin of isolate	Strain N°	IC_{50} ($\mu g\ ml^{-1}$)
Microcystis sp.	Ibitinga	BGSD 300	100
Microcystis sp.	Promissão	BGSD 301	40
Microcystis sp.	Nova Avanhandava	BGSD 302	30
Cylindrospermopsis raciborskii	Nova Avanhandava	BGSD 303	15
C. raciborskii	Promissão	BGSD 304	20
Aphanizomenon aphanizomenoides	Bariri	BGSD 305	30
A. issatchenkoii	Bariri	BGSD 306	60

3. Toxin content of freeze-dried filed samples (Table 2)

In the four freeze-dried materials from the four uppermost reservoirs with large or relatively large fraction of cyanoprokaryota microcystin-RR was found in the largest concentration (12.5-18.8 $mg\ g^{-1}$), concentrations of microcystin- LR (0.0-0.2 $mg\ g^{-1}$) and microcystin- YR (1.6-3.0 $mg\ g^{-1}$) were considerably lower according to HPLC analyses.

4. Toxicity tests (Table 2)

The freeze-dried material had a definite toxic effect for rat hepatocyte-, *Thamnocephalus*- and mustard (BGST)-tests and no cytotoxicity on CHO-K1 cell line was registered.

5. Toxicity of isolated cyanobacterial strains (Table 3)

For the isolated cyanobacterial strains the IC_{50}s in BGST-test were calculated on the base of chlorophyll-a and according to the data all strains had inhibitory effect.

Phytoplankton floras of rivers are usually dominated by diatoms and chlorococcalean green algae and South American rivers often support a rich planktonic desmid flora. Cyanobacteria, outside Australia, are not characteristic elements of river phytoplankton. Dominance of different species of the genus

Aulacoseira has been repeatedly reported from turbid South American rivers and river impoundments Almost none of these characteristics were observed along the cascade of reservoirs in the basin of the Tietê river where at the upper parts a cyanobacteria (in this case *Microcystis* spp.) dominated assemblage occurs as a consequence of combined effect of slowered water flow, increased sedimentation of inorganic turbidity therefore a better light climate and nutrient rich headwaters. Proliferation of cyanobacteria becomes even more prominent in the two subsequent reservoirs (Bariri and Ibitinga). A transition occurs in the two middle-stretch reservoirs (Promissão and Nova Avanhandava) where *Microcystis* spp. become outcompeted by the tropical, chlorocococcalean green alga, *Coelastrum reticulatum* var. *cubanum*. Compositional diversities indicate two monospecific equilibrium stages with minimal diversities: one is dominated by *Microcystis* spp: the other by *Coelastrum reticulatum* var. *cubanum*.

Comparing TP of different reservoirs to the OECD scale, the first three (Barra Bonita, Bariri and Ibitinga) can be qualified as eutrophic, the others as mesotrophic. These TP data do not indicate very eutrophic conditions, thus suggesting the occurrence of nutrient losses, probably precipitation to the sediments. However, there was only a 3-fold difference between the lowest and highest TP data while the difference increases to 18-fold in terms of chlorophyll-a. These data allow to conclude that the major part of TP is found either as dissolved or bound to algal cells in the upper reservoirs and that in the lower ones a richer and more complex trophic structure is supported by primary producers.

Apart of different kinds of difficulties that eutrophication in itself implies, presence of dense cyanobacterial populations imply danger of cyanotoxicity with its consequences.

In natural samples different combinations of microcystins can be found. For example, in a *Microcystis* bloom from Homer Lake USA 19 different microcystins were characterized (NAMIKOSHI et al., 1992,1995). Microcystin-LR is often mentioned as the most frequently occuring microcystin and frequently co-occuring with microcystin-RR and -YR in Japan (WATANABE et al., 1988, 1989). In Hungary the situation is similar to Japan where microcystin-LR are accompanied by microcystin-RR and – YR. Comparing the toxicity of other *Microcystis* containing samples collected from different Hungarian ponds and lakes the Brazilian samples seem to be similar or more toxic than the Hungarian ones. All of the isolates of Brazilian origin were toxic in plant tests. For *Microcystis* and *Cylindrospermopis* strains (BGSD 300-304) IC_{50} data are comparable to those isolated from different waters in Central Europe. In rat hepatocyte tests the toxicity was very high in relation to many samples from Germany and indicates a high microcystin content.

This reservoir cascade play an important role not only in providing the services referred to previously but they also function as effective „storing agents" of considerable loads of nutrients, particularly at the upper-middle Tietê stretch, thus contributing to a better water quality of the waters downstream the cascade, as demonstrated by total phosphorus decrease recorded for Promissão, as compared to the levels recorded for Barra Bonita, Bariri and Ibitinga, upstream. However, water quality of upstream reservoirs including prevalent blooms of toxic cyanobacteria must not be disregarded.

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