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Seasonal changes and spatial variation in the water quality of a eutrophic tropical reservoir determined by the inflowing river

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Abstract

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The water quality of a eutrophic tropical reservoir was studied over a 5-year period (2000–2004), with quarterly sampling (Jan, Apr, Jul, and Oct) carried out at 3 sampling stations with one station in each of 3 zones (fluvial, transitional, and lacustrine). During the wet season, large amounts of phosphorus were introduced into the reservoir by the increased inflow of the river. Dissolved oxygen, pH, and chlorophyll *a* levels peaked in the wet season; pH, chlorophyll *a*, and total phosphorus in several cases were recorded above the recommended Brazilian guidelines. Dissolved oxygen was lower than acceptable levels in the euphotic layer and reached very low levels in the hypolimnion, indicating thermal stratification. Efficient reservoir management is necessary to restore environmental quality, and our results indicate that selective withdrawal may be an effective means of improving the quality of water in Funil Reservoir.

Key words: nutrients, physico-chemical variables, reservoirs, seasonality, sedimentation

Reservoirs built for hydroelectric purposes can induce significant ecological transformation on aquatic systems that change the water quality at spatial and temporal scales (Rice et al. 2001). The amount and quality of inflowing water into a reservoir affects nutrient loading rates, which can influence water quality (Nogueira 2001, Delazari-Barroso et al. 2009). Seasonal rainfall variation influences inflow volume in quantity and quality. These changes typically reflect the watershed geology, land use, landscape patchiness, and climate (Rybak 2000).

Spatial gradients are formed along the longitudinal axis of reservoirs and reflect 3 reservoir compartments (Thornton 1990, Nogueira et al. 1999): (a) fluvial zone, characterized by comparatively high water velocity, nutrient availability, and lower light penetration; (b) lacustrine zone, characterized by still water, higher light penetration, and lower nutrient availability for uptake by phytoplankton due to sedimentation processes that occur in the upstream zone of the reservoir; and (c) transitional zone, with intermediate characteristics.

The Funil Reservoir was built in 1969 to generate hydroelectric power and to control the Paraíba do Sul River (PSR) flow. Although a major source of drinking water for Greater Rio de Janeiro city and a number of smaller cities, the PSR watershed has been polluted by industrial discharges and untreated urban sewage because it drains a highly industrialized region with large metallurgic, petrochemical, textiles and food plants upstream from Funil Reservoir (Klapper 1998). Water quality in some years is unsuitable for uses such as human and livestock consumption or for crop irrigation.

This study analyzed the spatial and temporal changes in the water quality of Funil Reservoir to supply basic information to managers to help improve reservoir water quality, and to address whether water quality changes reflect spatial (longitudinal gradient) and temporal (dry vs. wet season) variation. The following questions were posed: Is there a decline in water quality in particular seasons and in certain parts of the

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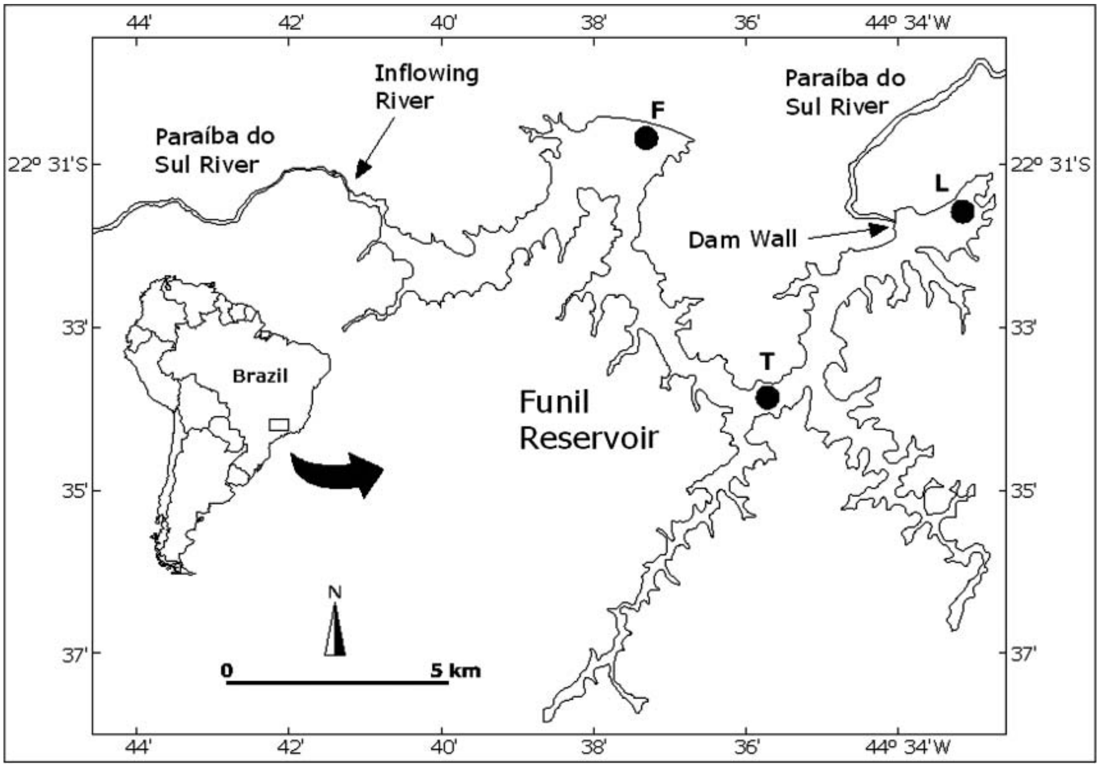

Figure 1.-Study area, Funil Reservoir, showing the 3 sampling zones: F, fluvial; T, transitional; L, Lacustrine.

reservoir? Are there trends in spatial variation and seasonal changes in eutrophication and sedimentation? Is there any temporal trend in water quality during the sampling period? Are there management options that can be implemented to minimize water quality decline?

Study area

The Funil Reservoir (approximately 22°30′S, 44°45′W; 440 m a.s.l.) is located in the middle reaches of the PSR basin, in southeastern Brazil (Fig. 1). The reservoir has a surface of 40 km^2, mean depth of 22 m, maximum depth of 70 m, and total volume of 890×10^6 m^3. Hydraulic residence time varies between 10 and 50 d, dictated by seasonal variation in precipitation. Rainfall averages 500 mm in winter and 1500–2500 mm in summer (Klapper 1998, Branco et al. 2002, Soares et al. 2008). Annual temperature averages 21 C, with means of 24 C in summer and 17 C in winter. Water level fluctuation contributes to erosion of the shoreline and sedimentation in the reservoir. There is little vegetation cover around the reservoir as a result of previous agricultural use for coffee plantation and pasture. Reforestation programs are being implemented by the power generation company responsible for the reservoir and by other industries in the adjacent areas. In the late 1990s, a reforestation program was initiated to replenish the reservoir banks. Since then, about 470,000 seedlings of native plants have been planted, contributing to the reforestation of 162 ha around the reservoir; about 47–78 species are planted every year (Coppetec Foundation 2007).

Materials and methods

Sampling program

Furnas Electric Power Company (FURNAS) provided data on rainfall, river flow (inflow), reservoir discharge (outflow), water temperature, and reservoir water level. Physical and chemical data were sampled from the euphotic and aphotic layers in 3 reservoir zones (fluvial, transitional, and lacustrine) on a quarterly basis (Jan, Apr, Jul, Oct) from 2000 to 2004. Samples from the aphotic layer were taken from water collected about 1 m from the bottom using a Van Dorn bottle. Samples from the euphotic zone were collected at 3 depths (surface, Secchi depth, and 3 times Secchi depth, the limit of the euphotic zone) and the results of the 3 measurements were averaged. Water level, temperature, and rainfall were used to characterise the 2 seasons in terms of the hydrological conditions of the reservoir (dry season: Apr and Jul; wet season: Oct and Dec). The dry season has lower river inflow rates, lower temperatures, and lower rainfall, while the opposite situation occurs in the wet season.

The following environmental variables were sampled at the site. Transparency (euphotic layer only) was measured in centimetres using a 21 cm diameter Secchi disk. Dissolved oxygen (DO, mg/L) and temperature (C), were measured using a multiprobe YSI (model YSI 556). The pH was measured using a field potentiometer Cole-Parmer model 19820–10, and conductivity (K) measurements were made with a Markson Model 10 conductivity meter with automatic temperature compensation to 25 C.

Analytical procedures

Total phosphorus as P (TP), orthophosphate as P (ortho-P), ammonia as N, nitrite (NO_2) and nitrate (NO_3) were determined according to procedures in Murphy and Riley (1962), Mackereth et al. (1978), and Strickland and Parsons (1968). Total suspended solids (TSS) were determined by filtering with a glass fiber filter and drying at 103–105 C for 1 h (APHA 2005). All these parameters were measured in both the euphotic and aphotic layers. In addition, euphotic chlorophyll *a* (Chl-*a*) was measured according to Lorenzen (1967), and euphotic dissolved reactive silica (DRSi) was determined according to Golterman et al. (1978). All water samples were preserved on ice in transit to the laboratory.

Data analysis

All environmental variables were compared among the reservoir zones (fluvial, transitional, and lacustrine), seasons (dry and wet) and years (2000, 2001, 2002, 2003, and 2004). Environmental variables were also compared between aphotic and euphotic layers. Logarithmic transformations, $\mathrm{Log}_{10}(x + 1)$, of environmental variables data were performed before all statistical tests to meet assumptions of normality and homoscedasticity for statistical tests, and to reduce the effects of extreme values. A 3-way analysis of variance (ANOVA) was used for spatial, seasonal, and among-year comparisons for each environmental variable. A posteriori Tukey test was performed when ANOVA detected significant ($P < 0.05$) differences among the tested factors. A principal component analysis (PCA) was applied to environmental variables to detect patterns. A biplot of the 2 main PCA axes was used with samples labeled by spatial, seasonal, and yearly factors.

Results

Hydrological conditions

Water temperature was higher from October to March and lower from May to August (Fig. 2). In general, higher average temperatures were recorded in summer (27 C), and lower averages were recorded in winter months (18 C). Rainfall was higher in December and January and the lower from May to September. The highest rainfall per month occurred in December 2000 (560 mm) and the lowest in June and July 2002 and August 2004 (0 mm).

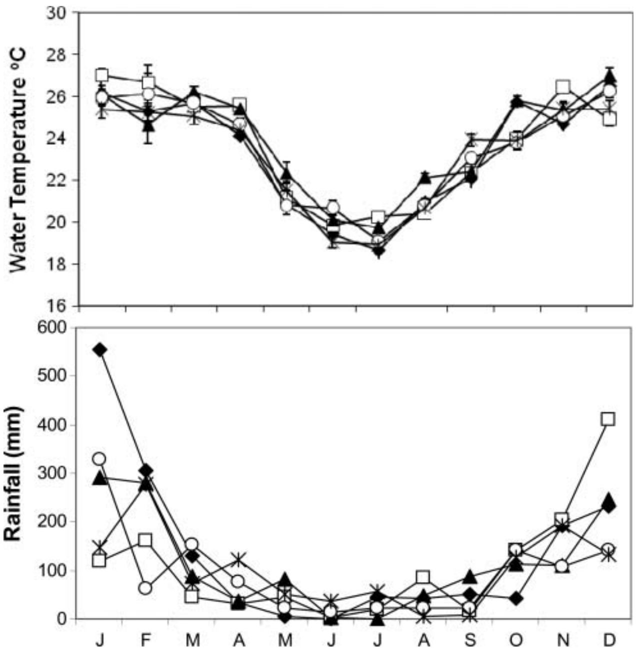

Figure 2.-Monthly average in water temperature (above) and accumulated rainfall (below) in Funil Reservoir between 2000 and 2004. ◇ = 2000; □ = 2001; ▲ = 2002 ○ = 2003; * = 2004.

Water level was highest during the rainy season and lowest during the dry season, a recurrent annual pattern between 2000 and 2003 (Fig. 3). Year 2004 was atypical, with higher levels in May and June, because discharges of the hydroelectric power operations were maintained at low rates. The lowest and the highest levels of the reservoir were 447 and 466 m a.s.l, respectively, recorded in August 2001 and June 2004. The inflow rate was highest during the summer and lowest in the winter months, which coincided with rainfall levels (Fig. 3). Overall, the outflow rate was stable throughout the study period, indicating the stable demand of the hydroelectric plant and the role the reservoir plays in stabilizing river flow downstream. Retention time was highest during the summer months when water level and inflow rate are highest.

Water quality

Mean values and significant differences of environmental variables between euphotic and aphotic zones (pooled data) and among zones of the reservoir, seasons, and years were compared (Tables 1, 2 and 3).

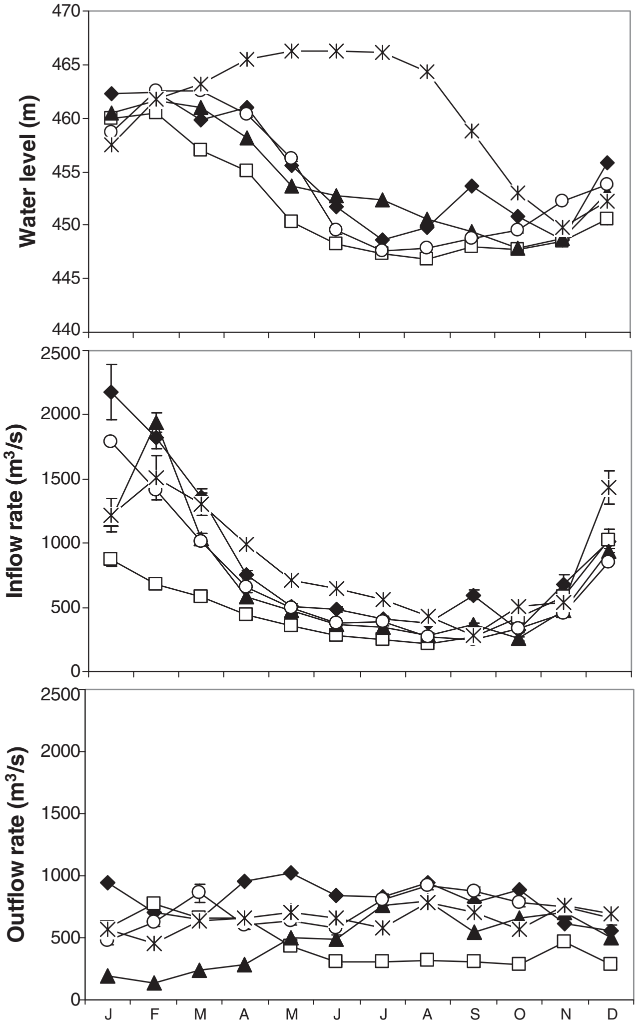

Figure 3.-Monthly average in water level, inflowing and outflowing flow rates in Funil Reservoir between 2000 and 2004. ◇ = 2000; □ = 2001; ▲ = 2002 ○ = 2003; * = 2004.

Transparency (Secchi depth):

Secchi depth ranged from a minimum of 0.3 m in the fluvial zone to a maximum of 3 m in the lacustrine zone. Overall, a well-defined spatial gradient was found, with lower values in the fluvial zone compared with the transitional and lacustrine zones ($P < 0.05$). Seasonally, higher values were recorded during the dry season (Apr and Jul) compared with the wet season (Oct and Dec) throughout the study ($P < 0.01$). In 2002–2003, the transparency values were significantly lower than in the other years (minimum 0.6 m; maximum 1.5 m).

Total suspended solids (TSS):

Mean TSS was higher in the aphotic layer (10.6 mg/L) than in the euphotic layer (7.3 mg/L). In the euphotic layer, TSS ranged from 0.6 to 23.9 mg/L with higher mean values in the wet season (8.5 mg/L) than in the dry season (5.2 mg/L, $P < 0.01$). There was a nonsignificant trend toward higher TSS in the fluvial and transitional zones than in the lacustrine zone. Significant differences ($P < 0.01$) were found between the years with higher mean values in 2001 and 2002 (10.6 mg/L) and a lower mean value in 2004 (2.7 mg/L). In the aphotic layer, TSS ranged from 1.2 to 36.8 mg/L with significant differences ($P < 0.01$) between 2001–2002 (17.9 mg/L) and 2004 (6.8 mg/L), but no significant differences were found between the zones or the seasons.

Chlorophyll a (Chl-a):

Concentrations of Chl-*a* ranged from 2.1 to 53.4 μg/L, with higher mean values ($P < 0.01$) during the wet season (20.59 μg/L) compared with the dry season (6.48 μg/L). No significant differences were found between zones or years.

Dissolved Reactive Silica (DRSi):

Mean reservoir DRSi concentration ranged from a minimum of 1 mg/L to a maximum of 6.9 mg/L. Concentrations of DRSi in the reservoir changed significantly between seasons ($P < 0.01$), with higher mean values during the dry season (mean = 5.45 mg/L) and lower values during the wet season (mean = 4.15 mg/L). No significant differences were found among years or zones.

Dissolved oxygen (DO):

Mean DO concentrations were higher in the euphotic layer (7.6 mg/L) than in the aphotic layer (4.1 mg/L). In the euphotic layer, DO ranged from a minimum of 3.8 mg/L to a maximum of 12.5 mg/L, and significant differences ($P < 0.01$) were found between seasons, with higher mean values during the wet season (9.2 mg/L) and lower values during the dry season (6.3 mg/L). No significant differences were found between the years or zones in the euphotic layer. In the aphotic layer, DO ranged from a minimum of 0.3 mg/L to a maximum of 7.5 mg/L, but no significant differences were found among the years, zones, or seasons.

pH:

Most pH values were above 7, indicating that the reservoir is a relatively alkaline system. The euphotic layer (overall average pH = 8.7) showed consistently higher values ($P < 0.01$) than the aphotic layer (overall average pH = 6.9) throughout all years. In the euphotic layer, pH ranged from 6.5 to 11, and significant differences in mean values were found between seasons ($P < 0.01$), with higher mean values during the wet season (8.6) and lower mean values during

Table 1.-Means ± standard error for water quality parameters in Funil Reservoir between 2000 and 2004. Zones: F = Fluvial; T = Transitional; L = Lacustrine. Concentrations in bold were above the recommended Brazilian guideline (CONAMA - Resolution n° 357/2005 from 18 Mar 2005).

Year	Season	Zone	Transparency (m)	Chlorophyll *a* (µg/L)	Dissolved Reactive Silica (mg/L)	pH		Conductivity (µS/cm)		Total Suspended Solids (mg/L)		Dissolved oxygen (mg/L)	
						Euphotic	Aphotic	Euphotic	Aphotic	Euphotic	Aphotic	Euphotic	Aphotic
2000/01	Dry	F	1.0 ± 0.4	7.5 ± 1.0	4.0 ± 1.1	6.8 ± 0.1	6.6 ± 0.2	53 ± 6.2	59 ± 4.2	3.3 ± 0.0	6.6 ± 0.0	6.8 ± 0.0	6.4 ± 0.0
		T	2.3 ± 0.2	6.0 ± 0.1	4.1 ± 0.8	6.9 ± 0.2	6.5 ± 0.2	66 ± 3.3	65 ± 3.2	2.1 ± 0.0	10.4 ± 0.0	6.3 ± 0.0	4.5 ± 0.0
		L	2.3 ± 0.5	5.1 ± 0.7	4.0 ± 0.7	6.8 ± 0.2	6.5 ± 0.2	67 ± 3.3	66 ± 2.6	2.8 ± 0.0	8.9 ± 0.0	5.7 ± 0.0	2.7 ± 0.0
	Wet	F	0.7 ± 0.1	**40.8 ± 0.0**	6.1 ± 0.0	**9.4 ± 0.1**	7.6 ± 0.3	72 ± 1.1	66 ± 0.2	11.4 ± 0.3	13.0 ± 1.1	10.6 ± 0.0	5.6 ± 0.0
		T	0.8 ± 0.2	**34.5 ± 0.0**	5.7 ± 0.0	**9.8 ± 0.0**	7.2 ± 0.3	83 ± 3.5	72 ± 2.9	10.2 ± 0.6	12.8 ± 2.8	11.4 ± 0.0	1.0 ± 0.0
		L	0.9 ± 0.1	**38.6 ± 0.0**	5.9 ± 0.1	**9.4 ± 0.1**	7.3 ± 0.4	74 ± 2.9	70 ± 0.3	8.8 ± 0.2	9.3 ± 1.4	11.6 ± 0.0	3.1 ± 0.0
2001/02	Dry	F	1.0 ± 0.2	9.1 ± 3.8	4.1 ± 0.6	7.8 ± 0.4	7.7 ± 0.7	68 ± 3.9	68 ± 2.2	10.7 ± 0.9	25.8 ± 4.4	6.8 ± 1.4	6.2 ± 0.8
		T	1.8 ± 0.2	6.3 ± 0.9	4.3 ± 0.4	7.5 ± 0.3	7.2 ± 0.1	71 ± 1.4	69 ± 0.1	6.9 ± 2.9	18.2 ± 8	6.8 ± 1.7	5.7 ± 0.9
		L	2.1 ± 0.3	3.8 ± 0.6	3.2 ± 0.4	7.4 ± 0.2	7.3 ± 0.3	71 ± 1.4	68 ± 1.0	6.1 ± 3.9	22.3 ± 10	5.8 ± 2.0	5.6 ± 1.1
	Wet	F	0.4 ± 0.1	**11.0 ± 3.0**	4.2 ± 0.0	6.9 ± 0.1	6.7 ± 0.1	72 ± 1.8	72 ± 10	14.1 ± 3.6	18.7 ± 0.6	6.7 ± 0.7	5.4 ± 1.6
		T	0.6 ± 0.1	**34.7 ± 12**	4.5 ± 0.0	7.9 ± 0.9	6.4 ± 0.1	69 ± 0.3	64 ± 6.8	19.2 ± 3.4	7.1 ± 2.7	8 ± 0.6	4.5 ± 1.5
		L	0.9 ± 0.1	**12.5 ± 1.3**	5.5 ± 0.0	7.6 ± 0.0	6.7 ± 0.0	71 ± 1.9	70 ± 4.4	6.5 ± 0.6	15.5 ± 2.5	7.9 ± 0.6	4.2 ± 1.4
2002/03	Dry	F	1.0 ± 0.0	6.7 ± 0.0	3.9 ± 0.0	7.4 ± 0.0	7.1 ± 0.0	80 ± 0.0	89 ± 0.0	3.5 ± 0.0	14.6 ± 0.0	7.2 ± 0.0	7.2 ± 0.0
		T	1.3 ± 0.0	7.4 ± 0.0	4.5 ± 0.0	7.5 ± 0.0	7.0 ± 0.0	76 ± 0.0	71 ± 0.0	3.8 ± 0.0	7.6 ± 0.0	6.8 ± 0.0	3.5 ± 0.0
		L	1.5 ± 0.0	5.2 ± 0.0	3.5 ± 0.0	7.3 ± 0.0	6.9 ± 0.0	76 ± 0.0	80 ± 0.0	3.2 ± 0.0	5.2 ± 0.0	5.9 ± 0.0	0.3 ± 0.0
	Wet	F	0.9 ± 0.1	**17.5 ± 7.2**	5.9 ± 0.5	8.0 ± 0.6	6.8 ± 0.2	86 ± 5.4	86 ± 6.5	8.1 ± 2.3	11.3 ± 5.0	9.2 ± 1.8	5.3 ± 0.3
		T	0.7 ± 0.1	**22.7 ± 9.0**	6.9 ± 0.0	8.8 ± 0.7	7.0 ± 0.2	91 ± 0.3	80 ± 4.3	12.2 ± 3.3	5.3 ± 2.1	10.0 ± 2.2	4.4 ± 1.9
		L	0.8 ± 0.1	**31.0 ± 15.0**	6.8 ± 0.1	**9.3 ± 0.5**	6.8 ± 0.1	93 ± 4.1	80 ± 3.1	8.2 ± 0.6	4.6 ± 2.1	10.5 ± 2.0	3.4 ± 2.6
2003/04	Dry	F	1.8 ± 0.2	9.6 ± 1.3	5.2 ± 0.7	7.5 ± 0.2	7.2 ± 0.2	98 ± 3.3	88 ± 13.3	12.7 ± 2.2	15.0 ± 0.4	6.9 ± 1.3	6.5 ± 1.1
		T	2.4 ± 0.1	4.3 ± 0.7	3.6 ± 1.8	6.9 ± 0.0	6.9 ± 0.0	97 ± 0.2	93 ± 6.9	6.0 ± 1.1	8.9 ± 0.6	5.6 ± 1.2	4.6 ± 1.8
		L	2.3 ± 0.2	3.2 ± 0.7	3.7 ± 1.1	6.9 ± 0.0	6.7 ± 0.1	98 ± 0.6	96 ± 5.3	8.4 ± 0.5	2.7 ± 1.1	5.7 ± 1.6	4.3 ± 1.7
	Wet	F	0.8 ± 0.2	**21.2 ± 9.0**	5.0 ± 0.1	7.5 ± 0.2	7.7 ± 0.7	102 ± 2.0	94 ± 5.2	9.2 ± 1.9	9.8 ± 0.1	6.6 ± 0.9	1.5 ± 0.8
		T	1.1 ± 0.1	**16.8 ± 1.5**	5.6 ± 0.5	**9.9 ± 0.7**	8.3 ± 1.1	104 ± 7.0	97 ± 7.4	6.8 ± 0.1	8.7 ± 3.1	9.2 ± 2.2	3.7 ± 0.7
		L	1.5 ± 0.1	**10.8 ± 3.6**	3.6 ± 1.6	**9.2 ± 1.0**	8.6 ± 0.7	100 ± 1.0	92 ± 3.4	4.1 ± 0.4	3.6 ± 0.8	8.3 ± 2.9	1.5 ± 0.2
2004	Dry	F	1.8 ± 0.2	8.1 ± 3.0	4.9 ± 0.3	8.0 ± 0.7	7.5 ± 0.5	99 ± 12.0	93 ± 7.4	3.4 ± 0.5	9.8 ± 2.2	6.5 ± 0.0	5.8 ± 0.0
		T	2.4 ± 0.4	7.2 ± 3.1	4.7 ± 0.5	8.3 ± 0.3	8.0 ± 0.8	90 ± 6.5	96 ± 9.8	2.4 ± 0.7	6.0 ± 0.5	5.9 ± 0.0	4.2 ± 0.0
		L	2.0 ± 0.0	7.8 ± 4.0	4.8 ± 1.5	8.0 ± 0.6	7.0 ± 0.0	90 ± 5.8	92 ± 5.8	2.3 ± 0.8	4.6 ± 1.8	5.6 ± 0.0	0.5 ± 0.0

Table 2.-Means ± standard error for compounds from nitrogen and phosphorus in Funil Reservoir, between 2000 and 2004. Zones: F = Fluvial; T = Transitional; L = Lacustrine. Concentrations in bold were above the recommended Brazilian guideline (CONAMA - Resolution n° 357/2005 from 18 Mar 2005).

			Ammonia-N (μg/L)		Nitrite-N (μg/L)		Nitrate-N (μg/L)		Orthophosphate-P (μg/L)		Total phosphorus-P (μg/L)	
Year	**Season**	**Zone**	**Euphotic**	**Aphotic**	**Euphotic**	**Aphotic**	**Euphotic**	**Aphotic**	**Euphotic**	**Aphotic**	**Euphotic**	**Aphotic**
2000/01	Dry	F	56.5 ± 37.1	99.0 ± 26.9	10.5 ± 3.9	15.5 ± 2.5	154.0 ± 13	177.0 ± 13	10.5 ± 3.9	18.0 ± 3.5	**39 ± 5.7**	28 ± 1.8
		T	14.0 ± 5.7	64.5 ± 3.9	3.5 ± 1.1	14.5 ± 3.2	160 ± 34	161.5 ± 16	5.5 ± 1.8	11.5 ± 0.4	20 ± 0.7	**46 ± 0.4**
		L	11.5 ± 6.7	79.5 ± 19	2.5 ± 1.1	26.0 ± 11.0	195.5 ± 25	206.0 ± 22	5.5 ± 1.8	14.0 ± 0.0	17 ± 2.1	**39 ± 2.5**
	Wet	F	11.5 ± 1.8	63.5 ± 1.8	3.5 ± 1.1	15.5 ± 3.2	193 ± 129	360.5 ± 60	9.5 ± 1.1	17.5 ± 1.8	**65 ± 10.0**	**45 ± 10.0**
		T	5.0 ± 3.5	36.5 ± 5.3	3.0 ± 0.7	6.5 ± 0.4	108.5 ± 70	566.0 ± 7	6.0 ± 1.4	16.5 ± 1.8	**48 ± 8.5**	**39 ± 6.0**
		L	6.5 ± 4.6	33.5 ± 1.8	2.5 ± 0.4	3.5 ± 1.1	155.5 ± 97	500.5 ± 50	10.5 ± 5.3	21.0 ± 4.9	**31 ± 2.5**	27 ± 3.5
2001/02	Dry	F	34.5 ± 17.3	97.5 ± 1.8	5.0 ± 1.4	10.0 ± 0.0	400.5 ± 11	415.5 ± 14	10.5 ± 6.0	19.0 ± 0.0	**42 ± 2.5**	**44 ± 7.8**
		T	17.0 ± 7.1	78.0 ± 10	2.0 ± 0.7	5.5 ± 0.4	462.0 ± 19	462.0 ± 2	3.0 ± 0.0	11.5 ± 3.2	17 ± 1.8	**33 ± 6.0**
		L	12.5 ± 8.8	108.5 ± 10	0.5 ± 0.4	9.0 ± 2.8	474.0 ± 3	414.5 ± 41	4.0 ± 0.7	16.0 ± 0.7	17 ± 1.4	**41 ± 5.3**
	Wet	F	95.0 ± 0.0	96.0 ± 0.0	14.5 ± 1.1	17.5 ± 1.1	381.0 ± 0	338.0 ± 0	25.0 ± 9.2	29.0 ± 1.4	**58 ± 0.0**	**53 ± 0.0**
		T	64.0 ± 0.0	39.0 ± 0.0	13.0 ± 2.8	21.0 ± 2.8	355.0 ± 0	478.0 ± 0	18.0 ± 8.5	25.5 ± 1.8	**42 ± 0.0**	**43 ± 0.0**
		L	20.0 ± 0.0	29.0 ± 0.0	9.0 ± 2.1	8.5 ± 3.9	338.0 ± 0	421.0 ± 0	8.0 ± 4.9	16.5 ± 1.1	**71 ± 0.0**	20 ± 0.0
2002/03	Dry	F	15.0 ± 0.0	72.0 ± 0.0	7.0 ± 0.0	18.0 ± 0.0	342.0 ± 0	672.0 ± 0	12.0 ± 0.0	21.0 ± 0.0	**58 ± 0.0**	**61 ± 0.0**
		T	17.0 ± 0.0	6.0 ± 0.0	7.0 ± 0.0	5.0 ± 0.0	264.0 ± 0	372.0 ± 0	6.0 ± 0.0	29.0 ± 0.0	29 ± 0.0	**61 ± 0.0**
		L	3.0 ± 0.0	–	6.0 ± 0.0	6.0 ± 0.0	340.0 ± 0	359.0 ± 0	11.0 ± 0.0	19.0 ± 0.0	**38 ± 0.0**	**48 ± 0.0**
	Wet	F	6.0 ± 2.8	99 ± 13.4	12.5 ± 1.1	8.0 ± 0.0	535.0 ± 50	723.5 ± 62	22.5 ± 1.1	70.0 ± 31.0	**70 ± 15**	**99 ± 29.0**
		T	8.0 ± 0.7	20.5 ± 13.0	10.5 ± 0.4	17.0 ± 9.2	241 ± 135	705.0 ± 127	11.5 ± 0.4	25.5 ± 2.5	**87 ± 14**	**50 ± 0.4**
		L	1.0 ± 0.7	25.5 ± 14.0	7.5 ± 0.4	4.5 ± 0.4	135.0 ± 62	658.0 ± 78	8.5 ± 0.4	22.0 ± 1.4	**42 ± 12**	**44 ± 0.7**
2003/04	Dry	F	8.0 ± 3.5	58.0 ± 4.2	6.0 ± 1.4	9.5 ± 2.5	582.5 ± 97	631.5 ± 175	6.5 ± 0.4	16.0 ± 4.2	**32 ± 0.4**	**44 ± 0.7**
		T	2.5 ± 0.4	59.5 ± 1.8	4.0 ± 0.7	4.5 ± 1.1	599.5 ± 66	730.0 ± 138	6.5 ± 0.4	15.5 ± 3.2	21 ± 1.4	**40 ± 2.1**
		L	12.5 ± 6.0	54.5 ± 11.0	4.5 ± 1.8	5.0 ± 2.1	633.5 ± 56	731.0 ± 137	12.5 ± 3.2	17.0 ± 3.5	26 ± 1.8	**34 ± 7.8**
	Wet	F	36.5 ± 7.4	59.5 ± 30.0	8.0 ± 0.0	14.5 ± 7.4	730 ± 138	906.0 ± 237	34.5 ± 3.2	32.0 ± 2.1	**62 ± 13.4**	**48 ± 0.0**
		T	15.5 ± 4.6	35.0 ± 2.8	5.0 ± 0.0	11.0 ± 5.7	196.5 ± 49	831.0 ± 94	21.5 ± 8.1	30.5 ± 4.6	**54 ± 17**	**42 ± 10.0**
		L	13.0 ± 0.0	47.5 ± 30.0	11.0 ± 5.7	17.5 ± 7.4	448.0 ± 52	867.5 ± 27	16.0 ± 4.9	27.0 ± 0.0	**37 ± 9.9**	**42 ± 1.8**
2004	Dry	F	9.0 ± 2.1	11.0 ± 3.5	2.5 ± 0.4	3.0 ± 0.7	545.0 ± 293	462.0 ± 248	8.0 ± 1.4	18.0 ± 7.1	**34 ± 7.4**	**39 ± 8.0**
		T	3.0 ± 0.0	32.0 ± 17.7	2.5 ± 0.4	2.5 ± 0.4	491.5 ± 269	647.0 ± 409	10.5 ± 3.2	16.5 ± 6.0	29 ± 8.1	**44 ± 15.9**
		L	3, 0 ± 0.0	91.0 ± 0.0	3.0 ± 0.7	3.5 ± 1.1	457.5 ± 236	704.0 ± 199	8.0 ± 2.1	13.0 ± 0.7	**35 ± 1.1**	40 ± 0.7

Table 3.-Significant differences ($P < 0.01$) among environmental variables between layers, years, seasons, and zone of Funil Reservoir, between 2000 and 2004; Layers: Eu = Euphotic; Ap = Aphotic. Zones: F = fluvial; T = transitional; L = lacustrine. n.s. = nonsignificant.

Variables	Layer		Year	Season	Zone
Transparency	–		2002/03 < other years	Dry > Wet	F < T, L
Chlorophyill *a*	–		n.s	Wet > dry	n.s
Silicate	–		n.s	Wet > dry	n.s
Conductivity	ns	Eu	2003/04 > 2000/01	n.s	n.s
		Ap	2003/04 > 2000/01	n.s	n.s
TSS	Ap > Eu	Eu	2001/02 > other years	Wet > dry	n.s
		Ap	2001/02 > other years	n.s	n.s
pH	Eu > Ap	Eu	n.s	Wet > dry	n.s
		Ap	n.s	n.s	n.s
Dissolved oxygen	Eu > Ap	Eu	n.s	Wet > dry	n.s
		Ap	n.s	n.s	n.s
Ammonia-N	Ap > Eu	Eu	n.s	n.s	n.s
		Ap	n.s	n.s	n.s
Nitrite-N	Ap > Eu	Eu	n.s	n.s	n.s
		Ap	n.s	n.s	n.s
Nitrate-N	Ap > Eu	Eu	2003/04 > 2000/01	n.s	n.s
		Ap	2003/04 > 2000/01	n.s	n.s
Total-P	n.s	Eu	n.s	Wet > dry	F > T,L
		Ap	n.s	n.s	F > T,L
Ortho-P	Ap > Eu	Eu	n.s	Wet > dry	F > T,L
		Ap	n.s	n.s	n.s

the dry season (7.2), except for 2001–2002, when no significant seasonal pH differences were found. No difference was found between zones or years in the euphotic layer. In the aphotic layer, the pH ranged from 6.1 to 9.8, but no significant differences were found between zones, seasons, or years.

Conductivity:

Conductivity did not differ between the euphotic and aphotic layers ($P > 0.05$). Values in the euphotic layer ranged from 45 to 116 μS/cm, and highly significant differences were found between years ($P < 0.01$), with higher mean values in 2002–2003 (84 μS/cm) and 2003–2004 (100 μS/cm) and lower mean values in 2000–2001 (69 μS/cm) and 2001–2002 (70 μS/cm). In the aphotic layer, conductivity ranged from 53 to 110 μS/cm and, similar to the euphotic layer, significant differences ($P < 0.01$) were found between the years, with higher mean values in 2002–2003 (81 μS/cm) and 2003–2004 (93 μS/cm) and lower values in 2000–2001 (66 μS/cm) and 2001–2002 (69 μS/cm). No significant differences in conductivity were found between zones or seasons for either the euphotic or aphotic layers.

Total Ammonia Nitrogen (TAN):

TAN levels in the euphotic layer ranged from less than detection limit (DL) to 109 μg/L, while in the aphotic layer TAN ranged from 2 to 137 μg/L. Significant differences were found ($P < 0.01$) between the higher values of the aphotic layer (overall average = 57.5 μg/L) and the lower values of the euphotic layer (overall average = 18.6 μg/L), with a consistent difference throughout all study years. No significant differences were found for ammonia values between the seasons, zones, or years in either the aphotic or euphotic layers.

Nitrite (NO_2):

NO_2 values were higher in the aphotic layer than in the euphotic layer ($P < 0.01$). In the euphotic layer, NO_2 ranged from <DL to 20 μg/L, while in the aphotic layer NO_2 ranged from 2 to 42 μg/L, but no significant differences were found between zones, seasons, or years.

Nitrate (NO_3):

The aphotic layer had higher NO_3 values ($P < 0.01$; overall average = 537.1 μg/L) than the euphotic layer (overall average = 367.4 μg/L). In the euphotic layer, NO_3 values ranged from a minimum of 9 μg/L to a maximum of 959 μg/L, and significant differences were found between years ($P < 0.01$), with higher mean values in 2003–2004 (531 μg/L) and lower mean values in 2000–2001 (161.2 μg/L). In the aphotic layer, NO_3 ranged from 69 to 1242 μg/L, and significant differences were found between years ($P <$

0.01), with higher mean values in 2003–2004 (782. μg/L) and lower values in 2000–2001 (328.6 μg/L). No significant differences in NO_3 were found between zones or seasons for either the euphotic or aphotic layers.

Total phosphorus (TP):

No differences were detected in TP between the euphotic and aphotic layers. TP in the euphotic layer ranged from 14 to 108 μg/L, and highly significant differences were recorded between the wet season (mean of 53 μg/L) and dry season (30 μg/L), but no significant differences were found among years. Overall, the fluvial zone had significantly higher means of TP (51 μg/L; $P < 0.01$) than the transitional (38 μg/L) and lacustrine zones (35 μg/L) in the euphotic layer. In the aphotic layer, TP ranged from 20 to 140 μg/L, and significant differences were found between zones with higher means in the fluvial zone (46 μg/L) than in the transitional (44 μg/L) or lacustrine zones (37 μg/L), but no significant differences were found among seasons or years.

Orthophosphate (ortho-P):

Aphotic ortho-P (average = 29.8 μg/L) showed significantly ($P < 0.01$) higher values than the euphotic layer (overall average = 15.6 μg/L) in every year of the study. In the euphotic layer, ortho-P levels ranged from 1 to 39 μg/L, with a significant difference ($P < 0.01$) between the seasons and zones. Higher mean values were detected during the wet season (14.8 μg/L) compared with the dry season (8.0 μg/L), and the fluvial zone (15.4 μg/L) had higher ortho-P mean concentrations than the transitional (9.8 μg/L) and lacustrine zones (9.3 μg/L) in the euphotic layer. No significant differences were found among years. In the aphotic layer, ortho-P levels ranged from 7 to 114 μg/L, and no significant differences ($P > 0.05$) were found among zones, seasons, or years.

Patterns of environmental variables

Two PCA components explained 57.4% of the total variance (Table 4). Component 1 had a significant negative correlation with pH, TP, DRSi, Chl-*a*, TSS, and DO, and a positive correlation with transparency. Component 2 had significant positive correlation with ammonia, NO_2, NO_3, and ortho-P.

Table 4.-Factor loadings from principal component analysis on environmental variables in Funil Reservoir, in between 2000 and 2004. Loadings >0.50 in bold.

Environmental variables	Axis 1	Axis 2
Transparency	**0.83**	−0.26
pH	**−0.66**	−0.49
Conductivity	−0.07	0.11
Ammonia	−0.17	**0.62**
Nitrite	**−0.53**	**0.65**
Nitrate	0.45	**0.57**
Orthophosphate	−0.43	**0.60**
Total phosphorus	**−0.76**	0.32
Silicate	**−0.58**	−0.30
Chlorophyll *a*	**−0.85**	−0.31
Total suspended solids	**−0.62**	0.16
Dissolved oxygen	**−0.82**	−0.33
Eigenvalues	4.60	2.28
% of explained variance	38.37	19.03

The ordination diagram (Fig. 4) separated along axis 1 samples from the wet and dry seasons. Wet season was characterized by lower transparency and higher pH, TSS, TP, DRSi, NO_2, and Chl-*a*, whereas samples from the dry season were characterised by the opposite situation for these environmental parameters (Table 4). There was not a clear trend among the reservoir zones or years; however, most samples from the lacustrine zones were located on the right part of the diagram, characterised by higher transparency and lower TP, DO, and Chl-*a* (Fig. 4).

Discussion

Funil Reservoir could be considered eutrophic over most of the sampling period as indicated by high levels of TP and Chl-*a*. Chl-*a* was above the recommended Brazilian guideline (10 μg/L) in every wet season during the study period. Furthermore, DRSi was apparently not a limiting factor for diatom growth. DRSi is a limiting factor for diatom growth when concentrations are lower than 0.5 mg/L (Agbeti et al. 1997); therefore, the reservoir has high nutrient concentrations, typical of eutrophic conditions where algae and cyanobacterial blooms can develop, resulting in poor water quality and an excess of organic matter (Tundisi et al. 1993).

A strong relationship was found between inflow rates and phosphorus (P), implying that inflow rate had a strong influence on TP and ortho-P levels. TP was highest during the wet season when it was above the maximum concentration (30 μg/L) allowed by Brazilian law (Resolution number 357, 17 March 2005). Short residence time and the “linear” shape of Funil Reservoir probably contributed to similar TP concentrations in the euphotic and aphotic layers. In comparison, ortho-P was highest in the aphotic layer compared with euphotic layer, likely a result of internal release from the sediment. Funil Reservoir has enlarged cross-section areas where the speed of the current decreases, creating conditions for sediment deposition. Thus, a reservoir of P can accumulate in the bed sediments and be released into the water column of the aphotic zone.

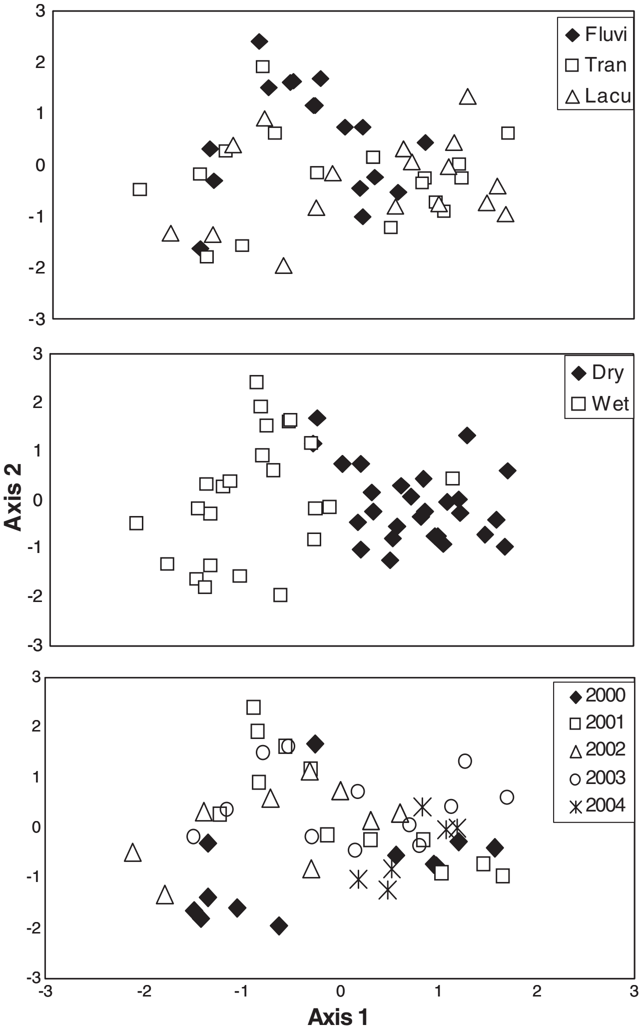

Figure 4.-Ordination diagram of the 2 first axes from principal component analysis on environmental variables in the euphotic layer from 2000 to 2004. Analyses labeled by zones (above), seasons (middle), and years (below). Zones: Fluv, fluvial; Tran, transitional, Lacu, lacustrine.

The influence of the PSR on Funil Reservoir was reflected in the low water transparency and high P loads, not only in the fluvial zone but also in the entire reservoir. The driving forces for Funil Reservoir (e.g., short water retention time, high nutrient input) were responsible for a dynamic system, with high temporal variability and a typical zonation pattern with the PSR influencing not only the longitudinal pattern observed in the reservoir, but also the nutrient inputs and consequent phytoplankton biomass. Soares et al. (2008) reported that despite the high algal biomass observed in Funil Reservoir, competition among the main species and light limitation can interfere with the maximum expected Chl-*a* concentrations for this system. Therefore, limited phytoplankton growth and/or lack of nutrient uptake by phytoplankton are more likely to be caused by lack of light due to low water transparency or especially short residence times that do not allow phytoplankton to reach the maximum concentration permitted by the available nutrients.

Reduction of external P loading is necessary for the restoration of this eutrophic reservoir. Cullen and Forsberg (1988) have demonstrated that eutrophication can be reversed and that P is most often the nutrient that should be controlled. They suggested that reductions of TP in lakes can lead to a reduction in Chl-*a* sufficient to change the trophic category, making the reservoir "less eutrophic." According to Spears et al. (2007), regulating water level to increase flushing during P sediment release has the potential to significantly enhance the recovery of shallow reservoirs. This could be applicable to Funil, and if deemed an appropriate option, increased flushing (discharges) should occur during the wet season, when TP and ortho-P are highest. In turn, this should reduce excess algal growth that contributes to poor water quality during this period.

Unlike P, no relationship was found between the river flow and N-derived nutrients (ammonia, NO_2, and NO_3). These interrelated forms of N enter Funil Reservoir, probably from surface runoff, and are removed either by algal uptake and sedimentation or through denitrification. Additionally, N-fixing cyanobacteria can also play an important role in this process. The aphotic layer had more N-derived nutrients than the euphotic layer, and NO_3 is the only N compound to increase during the study period in both euphotic and aphotic layers. The source causing the build-up of NO_3 or other N-derived nutrients in the reservoir is not known. Because the reservoir suffers impact from agriculture activities, inputs from cattle farming, sewage, and soil erosion are the most likely causes of increases in N-derived compounds in Funil Reservoir. In addition, the PSR likely contributes to N-derived compounds because it is used as waste disposal for a large number of industries along its course (Carvalho et al. 2002) and for domestic discharges (Linde-Arias et al. 2008).

During the wet season in 2002 and 2003, pH was above the maximum allowed level (9.0). The pH is influenced by the metabolism of aquatic organisms and may oscillate due to metabolic processes associated with photosynthetic activity that capture CO_2 from the water. Funil Reservoir is alkaline, and pH ranged almost 2 pH units between seasons. This suggests the Funil Reservoir system is not as well-buffered chemically as some African lakes that experience limited shifts in pH, such as Lake Naivasha (Litterick et al. 1979), Lake Chilwa (Kalk et al. 1979), or Lake Baringo (Patterson and Wilson 1995).

Dissolved oxygen ranged from acceptable levels in the euphotic layer (seasonal means = 5.6–11.6 mg/L) to low levels in the aphotic layer (seasonal means = 0.5–6.4 mg/L), indicating thermal stratification. In the surface layers, increases in DO occurred in the wet season coinciding with increases in P, pH, DRSi, and Chl-*a*. Although DO was typically poor in the aphotic layers, the extent and duration of low DO has varied in response to the timing and amount of rainfall, especially in a system with low residence time such as Funil Reservoir. The fluvial zone of the reservoir receives incoming water from the main river, which affects the distribution and concentration of DO within all zones. If the inflowing water has sufficient density because of low temperature, it will enter the reservoir as an underflow and may remain on the bottom over the length of the reservoir. This seems to occur especially during some dry seasons. Outlet location also influences DO distribution within a reservoir (Cole and Hannan 1990). The highest records of DO in Funil Reservoir aphotic layer may be associated with the underflow of water currents, which is favored by longitudinal reservoir morphology. Because Funil Reservoir has a spillway at a depth of 57.5 m, discharges of low oxygenated waters from the aphotic zone could be a measure to improve water quality. Precautions should be taken to not impact the receiving waters downstream of the reservoir.

The 3 reservoir zones proposed by Thornton (1990) for discerning longitudinal gradients were examined for Funil Reservoir. A spatial gradient of transparency increases from the fluvial zone to the lacustrine zone. Nogueira et al. (1999) observed that low transparency in the fluvial zone of Jurumirim Reservoir was directly associated with high TSS carried into the system by the main river during the wet season. A slight decrease in nutrient concentrations along Funil Reservoir as determined by PCA was observed, with the seasonal variation being much more distinct. As expected, P concentrations were effectively reduced, and transparency increased along the longitudinal axis from the upper to the lower reservoir.

Levels of conductivity higher than 100 μS/cm are typical of impacted systems in the Neotropical region. In Funil Reservoir, such levels were only reached in the wet season of 2003–2004. Conductivity in Turkwell Gorge Reservoir (Kenya) ranged from 160 to 200 μS/cm (Kotut et al. 1999), well above the values recorded for Funil Reservoir. Overall, those differences were expected because Neotropical waters have low conductivity compared with other regions.

Increased erosion took place in the PSR watershed in the last century, particularly at the margins of Funil Reservoir, due to deforestation and intense coffee cultivation that impoverished the soil. Additionally, water-level oscillation contributes to marginal erosion and sedimentation in the reservoir (Branco et al. 2002). Control of erosion in the basin brings several benefits, but the most effective are difficult for reservoir managers to apply. Support is needed from other entities to manage the basin, including management practices such as reforestation, maintenance of vegetation belts, fire control, soil fertilization, drainage channels, and periodically removal of trapped sediment.

As shown for Funil Reservoir, wet and dry hydrologic periods can have profound effects on reservoir water quality. Wet periods tend to bring in higher nutrient loadings, which can fuel algal blooms and degrade water quality. However, higher flows also tend to increase flushing and decrease stratification, potentially improving water quality. A definitive statement cannot be made about the net effects of wet years because the effects can depend on the timing of high flows and watershed and reservoir characteristics. Reduction in residence time and selective drainage during periods of high water volume could be a measure to diminish eutrophication during the wet season. Retention time influences not only the longitudinal but also the vertical patterns observed in the reservoir. Retention time also seems to be a useful variable for *a priori* prediction of stratification (Tundisi et al. 2008).

Hosper (1998) lists measures that could be fundamental forces in the change of a reservoir from a stable eutrophic status to another less eutrophic status. Among them, he highlights the washout or hydraulic drainage or flushing. A major flushing event in Lake Paranoá in Central Brazil may have resulted in a new level of equilibrium between nutrients and phytoplankton biomass, which has altered the course of eutrophication in this reservoir (Padovesi-Fonseca et al. 2009). According to Dortch (1986), there are basically only 3 types of human intervention that can impact water quality in reservoirs: (1) pretreatment or control of reservoir inflows; (2) in-pool management or treatment techniques; and (3) management of reservoir outflows. The nonpoint source pollution (diffuse pollution) upriver of Funil Reservoir makes the success of pretreatment or control of inflow very unlikely. In-pool treatment should also be difficult because of the short residence time and the unknown extent of nutrient cycling in the reservoir. We speculate that selective withdrawal might be more effective for controlling water quality in Funil Reservoir (Dortch 1986). Selective withdrawal uses stratified flow to pull out water from selected depths of the pool. Thus, density stratification is required for this technique to be effective, and it was recorded for Funil Reservoir mainly during the wet season when eutrophication is highest. Additionally, multilevel intakes are desirable to provide flexibility in the choice of release elevation. Selective withdrawal is such a common and important phenomenon in reservoir mechanics that most reservoir water quality models include algorithms for predicting the outflow profile and release water quality. There have been numerous studies and reports on selective withdrawal research and its use, most of which are cited and discussed by Davis et al. (1987) and Smith et al. (1987). Control of eutrophication by treating wastewater from urban sources, adequate agricultural practices to diminish the suspended particulate matter contribution, and revegetation of the watershed and riparian forests along the tributaries are some possible restoration measures; however, they are difficult to implement because of the high costs. Furthermore, water managers are more willing today to consider reservoir management trade-offs to improve water quality to avoid costly conflict resolution.

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References

Agbeti MD, Kingston JC, Smol JP, Watters C. 1997. Comparisons of phytoplankton succession in two lakes of different mixing regimes. Arch Hydrobiol. 140;37–69.

[APHA] American Public Health Association. 2005. Standard methods for the examination of water and wastewater. 21th ed. Washington (DC): American Public Association, AWWA, WEF.

Branco CWC, Rocha MIA, Pinto GFS, Gômara GA, Filippo R. 2002. Limnological features of Funil Reservoir (RJ, Brazil) and indicator properties of rotifers and cladocerans of the zooplankton community. Lakes Reserv Res Manage. 7:87–92.

Carvalho CEV, Salomão MSMB, Molisani MM, Rezende CE, Lacerda LD.2002. Contribution of a medium-sized tropical river to the particulate heavy-metal load for the South Atlantic Ocean. Sci Total Environ. 284:85–93.

Cole TM, Hannan HH. 1990. Dissolved oxygen dynamics. In: Thornton KW, Payne FE, Kimmel BL, editors. Reservoir Limnology – ecological perspectives. New York (NY): John Wiley & Sons. p.71–108.

Coppetec Foundation. 2007. Paraíba do Sul River – Final Report PSR-009-R1. Laboratory of hidrology and enviromental studies. 32 p.

Cullen P, Forsberg C. 1988. Experiences with reducing point sources of phosphorus to lakes. Hydrobiologia. 170(1):321–336.

Davis JE, Holland JP, Schneider ML, Wilhelms SC. 1987. “SELECT: a numerical, onedimensional model for selective withdrawal,” Vicksburg (MS): US Army Engineer Waterways Experiment Station; Instruction Report E-87–2.

Delazari-Barroso A, Barroso GF, Huszar VLM, Oliveira SMFA. 2009. Physical regimes and nutrient limitation affecting phytoplankton growth in a meso-eutrophic water supply reservoir in southeastern Brazil. Lakes Reserv Res Manage. 14:269–278.

Dortch MS. 1986. Water quality considerations in reservoir management. Vicksburg (MS): US Army Engineer Waterways Experiment Station; Technical Report. pp. 32–42.

Golterman HL, Clymo RS, Ohnstad MAM. 1978. Methods for physical and chemical analysis of freshwaters. IBP Handbook. Oxford (UK): Blackwell Scientific Publications.

Hosper SH. 1998. Stable states, buffers and switches: an ecosystem approach to the restoration and management of shallow lakes in the Netherlands. Water Sci Technol. 37:151–164.

Kalk M, McLachlan AJ, Howard-Williams C. 1979. Lake Chilwa: studies of change in a tropical ecosystem. Monogr Biol. 35:1–462.

Klapper H. 1998. Water quality problems in reservoirs of Rio de Janeiro, Minas Gerais and São Paulo. Int Rev Hydrobiol. 83(Special Issue):93–102.

Kotut K, Stephen G, Muthari M, Krienitz L. 1999. The physico-chemical conditions of Turkwell Gorge Reservoir, a new man made lake in North Kenya. Limnologica. 29:377–392.

Linde-Arias AR, Inácio AF, Novo LA, Alburquerque C, Moreira JC. 2008. Multibiomarker approach in fish to assess the impact of pollution in a large Brazilian river, Paraiba do Sul. Environ Pollut. 56:974–979.

Litterick MR, Gaudet JJ, Kalff J, Melack JM. 1979. The limnology of an African Lake Naivasha, Kenya. Unpublished edition. Technical Report, Inland Waters: Their Ecology and Utilization. Nairobi (Kenya): SLP–UNEP workshop on African Limnology.

Lorenzen CJ. 1967. Determination of chlorophyll and pheopigments: spectrophotometric equations. Limnol Oceanogr. 12:343–346.

Mackereth FYH, Heron JG, Talling JJ. 1978. Water analysis some revised methods for limnologist. Ambleside: Freshwater Biological Association. Oxford (UK): Blackwell Scientific Publication.

Murphy J, Riley JP. 1962. A modified single solution method for phosphate in natural waters. Anal Chim Acta. 27:31–36.

Nogueira MG. 2001. Zooplankton composition, dominance and abundance as indicator of environmental compartmentalization in Jurumirim Reservoir (Paranapanema River), São Paulo, Brazil. Hydrobiologia. 455:1–18.

Nogueira MG, Henry R, Maricatto FE. 1999. Spatial and temporal heterogeneity in the Jurumirim Reservoir, São Paulo, Brazil. Lakes Reserv Res Manage. 4:107–120.

Padovesi-Fonseca C, Philomeno MG, Andreoni-Batista C. 2009. Limnological features after a flushing event in Paranoá Reservoir, central Brazil. Acta Limnol Bras. 21:277–285.

Patterson G, Wilson KK. 1995. The influence of the diel climatic cycle on the depth-time distribution of phytoplankton and photosynthesis in a shallow equatorial lake (Lake Baringo, Kenya). Hydrobiologia. 304:1–8.

Rice SP, Greenwood MT, Joyce CB. 2001. Tributaries, sediment sources, and the longitudinal organisation of macroinvertebrates fauna along river systems. Can J Fish Aquat Sci. 58:824–840.

Rybak J. 2000. Long-term and seasonal dynamics of nutrient export rates from lake watersheds of diversified land cover pattern. Verh Internat Verein Limnol. 27:3132–3136.

Smith DR, Wilhelms SC, Holland JP, Dortch MS, Davis JE. 1987. Improved description of selective withdrawal through point sinks. Vicksburg (MS): US Army Engineer Waterways Experiment Station; Technical Report E-87–2.

Soares MCS, Marinho MM, Huszar VLM, Branco CWC, Azevedo SMFO. 2008. The effects of water retention time and watershed featureson the limnology of two tropical reservoirs in Brazil. Lakes Reserv Res Manage. 13;257–269.

Spears BM, Carvalho L, Paterson DM. 2007. Phosphorus partitioning in a shallow lake: implications for water quality management. Water Environ J. 21:47–53.

Strickland JDH, Parsons TR. 1968. A practical handbook of the sea water analysis. Fish Res Bd Can. 167:49–80.

Thornton KW. 1990. Perspectives on reservoir limnology. In: Thornton KW, Payne FE, Kimmel BL, editors. *Reservoir limnology: ecological perspectives*. New York (NY): Wiley-InterScience. p. 1–14.

Tundisi JG, Matsumura-Tundisi T, Calijuri MC. 1993. Limnology and management of reservoirs in Brazil. In: Straskraba M., Tundisi. JG, Duncan A, editors. *Comparative reservoir limnology and water quality management*. Dordrecht (Netherlands): Kluwer. p. 25–55.

Tundisi JG, Matsumura-Tundisi T, Abe DS. 2008. The ecological dynamics of Barra Bonita (Tietê River, SP, Brazil) reservoir: implications for its biodiversity. Braz J Biol. 68:1079–1098.