Re-oligotrophication as a challenge for tropical reservoir management with reference to Itaparica Reservoir, São Francisco, Brazil

G. Gunkel and M. Sobral

ABSTRACT

The process of reservoir eutrophication has been recognised as a central problem in tropical reservoir environmental quality. Effects of eutrophication are complex interactions involving a decrease in water quality, especially loss of aquatic biodiversity, occurrence of undesired species such as cyanobacteria with its cyanotoxins, mass development of macrophytes such as *Egeria densa* with its mechanical impact on turbines, and an increase in greenhouse gas emissions, mainly of methane. The eutrophication process can be described by the OECD critical load concept or related models. The phosphorus use efficiency is given by the Chl *a*–P – relationship, indicating eutrophic conditions by only 10 μg L^{-1} P in Itaparica Reservoir, Brazil. Eutrophication of the reservoir is quantified for internal phosphorus sources (inflow, mineralisation of inundated soils and vegetation, net cage aquaculture) and external ones (agriculture, emissions of natural caatinga vegetation and rural communities) The actual internal P load is calculated to be 0.40 g m^{-2} a^{-1}, and the critical P load is given with 1.20 g m^{-2} a^{-1}. The external P load amounts about 1.16 g m^{-2} a^{-1} and thus exceeds the critical export rate of 7.1 kg km^{-2} a^{-1} by 50%, thus a bundling of measurements has to be considered when attempting to promote re-oligotrophication.

Key words | carrying capacity, eutrophication, Itaparica, re-oligotrophication, reservoir

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INTRODUCTION

Reservoirs in tropical and semi-arid zones often have numerous water quality problems, because in many of them a rapid change of the aquatic ecosystem to a higher trophic level has occurred (Friedl & Wüest 2002; Gunkel *et al.* 2003; Biswas 2004). Recently this process of eutrophication has been recognised as a central problem in a reservoir's environmental quality and sustainability, and besides water quality impact due to cyanobacteria development, mass development of macrophytes, emission of methane as greenhouse gas has become a focus of interest (Giles 2006; Barros *et al.* 2011). Goals for integrated and sustainable reservoir management are reduction in water quality impact, reduction of impact on nature, mainly on biodiversity as well as of the contamination level, and in a global point of view, reduction of greenhouse gas emissions (Tundisi *et al.* 2008; White 2010).

Eutrophication of tropical reservoirs is a phenomenon often observed, but knowledge of related biological processes is still scarce (Jeppesen *et al.* 2005a). The eutrophication potential of tropical reservoirs has to be evaluated as being very high (Lewis 2010) due to high insolation and year- round production, high temperature with promotion of cyanobacteria, dendrite formation with a large shore line development, high inflow rate with short water residence time, unstable thermal stratification (polymictic water body) with high nutrient turnover, and intensive operational water level changes.

Tropical reservoirs underlie a 'natural' rapid eutrophication, the so called trophic upsurge (Gunkel 2009) as a general effect of damming up a river and an increased bioproductivity; this is based on several ecological processes, such as (a) mineralisation of inundated vegetation and soils, (b) changed hydrodynamic conditions with an increase of the potamon character, which means increased temperature, reduced physical re-aeration, and settling of suspended matter, (c) accumulation of fine organic sediments with deficits of oxygen and redox chemical re-mobilisation of phosphorus, and (d) a long-term change of land use in the watershed with increasing emissions of nutrients due to migration of people to reservoir shores, seeking better economic

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possibilities, called cultural eutrophication. Quantification of these nutrient input pathways is of high significance for eutrophication evaluation and any management of the reservoir watershed (Friedl & Wüest 2002). The aim of further reservoir management has to be a re-oligotrophication, based on a reduction of nutrient load and a limitation of primary production by phosphorus. Re-oligotrophication has been successfully carried out with lakes, even large lakes (Anderson *et al*. 2005; Jeppesen *et al*. 2005b), but for reservoirs, especially tropical reservoirs, knowledge is strictly limited. Several limnological processes have to be analysed and quantified, e.g. reduced water exchange of branches due to the dentritic form of the reservoir, the release of nutrients from periodic dessication zones (Turner & Haygarth 2001), sediment sorting by water current and wind-driven waves, mass development of submerged or floating macrophytes as pioneer plants and capacity limits for aquaculture.

METHODS

São Francisco River Basin is one of the main river basins of Brazil with a water basin of 640,000 km^2, a length of 3,160 km, stretching from the rainy southwest of Brazil to the dry northeast. Up to the present, eight reservoirs have been constructed, including Itaparica in the middle course of the river, located in the semi-arid region of Bahia and Pernambuco, 290 km from the Atlantic Ocean. Itaparica dam (Figure 1), finished in 1988, was constructed for hydroelectric power generation (1,500 MW). Itaparica Reservoir has a regulated inflow of 2,060 m^3/sec, a length of 149 km, 828 km^2 surface area and a sub-water basin of 93,040 km^2. Maximum depth is 101 m (mean depth = 13 m), the reservoir's capacity is 10.7×10^9 m^3 (CHESF 2011). Nowadays the main water use is for irrigation in agriculture, representing 51% of usage, but there is an increasing water demand for aquaculture as well as for net cage culture in the reservoir.

After 20 years of operation, a comparative evaluation between the environmental impacts foreseen in the environmental study and the environmental situation nowadays exists (Gunkel & Sobral 2007), using among others, data from regular monitoring of water quality, done by CHESF (Companhia Hidrielectrico do São Francisco) in 2004/2005. Physical, chemical and biological data were analysed every three months, using standard limnological methods such as by field probes (conductivity, pH, dissolved oxygen, turbidity), water chemical analyses (N, P, among others) by US *Standard Methods* and biological analyses of phytoplankton using the Utermöhl method, and zooplankton by net catches (CHESF

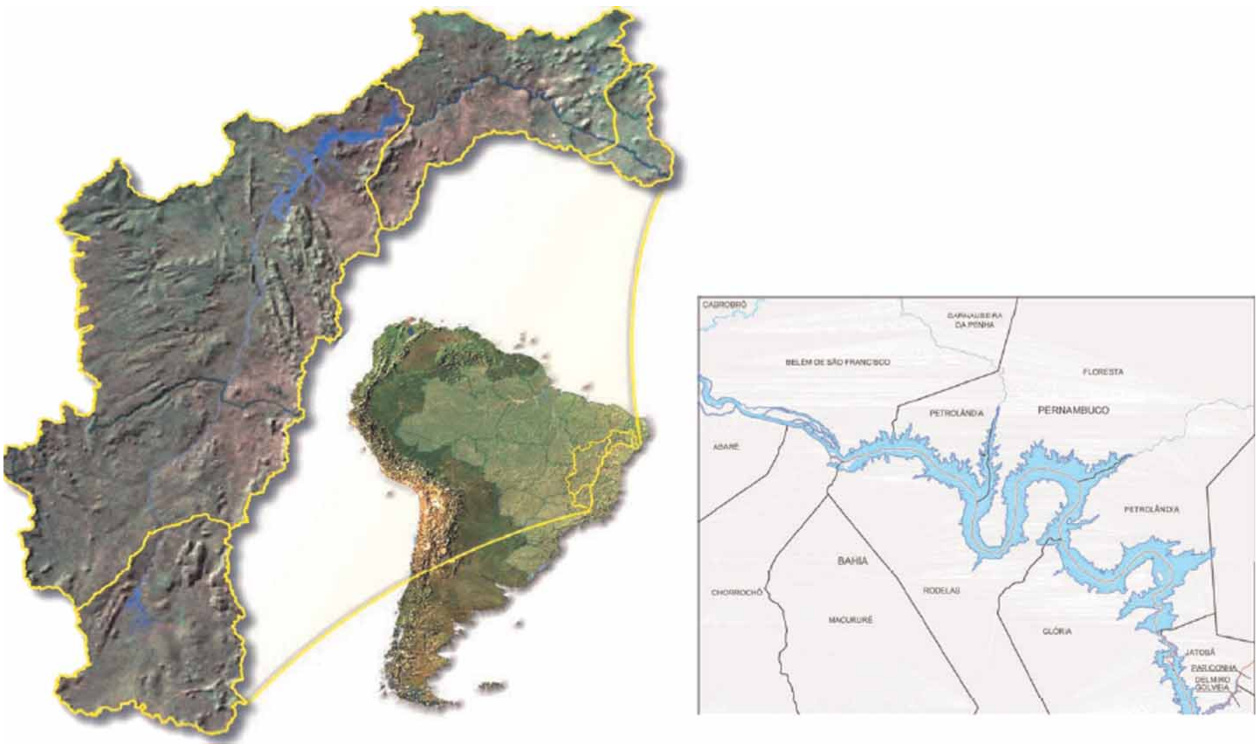

Figure 1 | Itaparica Reservoir, Brazil.

2005). Further studies concerning water and sediment quality were carried out on aquaculture systems.

RESULTS AND DISCUSSION

Itaparica Reservoir's eutrophication process

Water quality

Water temperature in the Itaparica Reservoir is very high and reaches 32 °C. Water chemistry is characterised by poor buffering capacity (mean alkalinity = 31 mg L^{-1} $CaCO_3$) and low ionic content (mean conductivity = 65–132 μS cm^{-1}). In the rainy season (April to July) high concentrations of suspended minerals (clay, silt) are observed (up to 425 mg L^{-1} in 2005). Precipitation leads to a significant change in water chemistry, and low values of conductivity with high values of P (51 μg L^{-1}, $n = 23$) and N (647 μg L^{-1}, $n = 23$) are representative of the rainy period. The phosphorus concentration is moderate during the dry period (13 μg L^{-1} P-total, $n = 46$).

Oxygen concentrations vary from 5.3 mg L^{-1} (68% saturation) to 12.0 mg L^{-1} (150% saturation). Primary production is dominated by periodical mass developments of algae, as well as of cyanobacteria and the submerged macrophyte *Egeria densa*. Primary production is limited by phosphorus, $N/P_{\text{mass ratio}}$ factor amounts all over the year = 17–20 (mean of the months, 2004–2005).

Phosphorus use efficiency

The phosphorus loading concept by OECD, developed in the northern hemisphere (Vollenweider 1975) and by analogous studies for Latin American water bodies by CEPIS (Salas & Martino 1991) as well as for reservoirs (Huszar *et al.* 2006; Gikas *et al.* 2009) use a phosphorus-chlorophyll relationship as bioproductivity efficiency, for Itaparica Reservoir a correlation is given by

$$\log \text{Chl}a = -0.07 + 0.714 \log P_{\text{tot}},\ r^2 = 0.202,\ n = 46 \qquad (1)$$

which gives quite a good fit to the OECD and CEPIS bioproduction equations (Figure 2). The variation of the P use efficiency is mainly given by seasonal conditions (dry and rainy period) as well as by local algae development being the focus of recent investigations.

P load

The Chl a – P_{total} correlation (Figure 2) can be used to identify a critical P_{total} concentration in the reservoir of 10 μg L^{-1} P_{total}, representing phytoplankton biomass of <5 μg L^{-1} Chl a, that means mesotrophic conditions by the OECD (1982) classification system. This P use efficiency has to be classified as very high, compared with 27 μg L^{-1} P_{total} given by OECD (1982) and 16 μg L^{-1} P_{total} from Huszar *et al.* (2006).

The critical load (L_{crit}) was determined by the Vollenweider model (OECD 1982; Equation (2))

$$L_{\text{crit}} = P_{\text{crit}} q_s \left(1 + \frac{\sqrt{z_m}}{q_s}\right) [\text{g m}^{-2}\,\text{a}^{-1}] \qquad (2)$$

P_{crit} = critical phosphorus concentration in water, q_s = hydraulic load ($= Q/A = z_m/\tau_w$; Q = annual discharge [m^3 a^{-1}], A = lake surface [km^2], z_m = mean depth [m], τ_w = theoretical water residence time [a]).

L_{crit} of Itaparica is 1.2 g P m^{-2} a^{-1} using 10 μg L^{-1} as critical P concentration.

For Itaparica Reservoir, P inputs are given by internal sources:

- inflow (2,154 m^3 sec^{-1}) with a mean P concentration of 19.6 μg L^{-1} (CHESF 2005), but occasional increased concentration up to 77 μg L^{-1}, observed in the rainy season;
- an internal load by mineralisation of the remaining vegetation of about 74 t ha^{-1} biomass and a P content of 40 kg ha^{-1} (Kaufman *et al.* 1993) with a P loss over a period of 20 years;
- net cage aquaculture of Tilapia with a productivity of 20.000 t a^{-1} (planning target), release of 260 t P (feed conversion factor of 1.3, P content of feed of 0.6%, P release of 80%), the actual fish production is about 4.000 t a^{-1}; increased P concentration in water (up to 60 μg L^{-1} P) and in sediment below net cages with up to 0.3 g kg^{-1} P (background concentration <0.1 g kg^{-1} P) were observed;
- internal P load by redox chemical release, no data available;
- rainfall to the lake surface with about 1 kg km^{-2} a^{-1} P (Resende *et al.* 2011).

External sources are:

- export from irrigation in agriculture (surface runoff, drainage, erosion) of about 4,700 ha with a P release of 100 kg km^{-2} a^{-1}, this value is in good accordance with Brazilian watersheds with an export of 73 respectively 86 kg km^{-2} a^{-1} (Sperling & Behrendt 2007; Barros *et al.* 2008) and in the lower range of European export rates

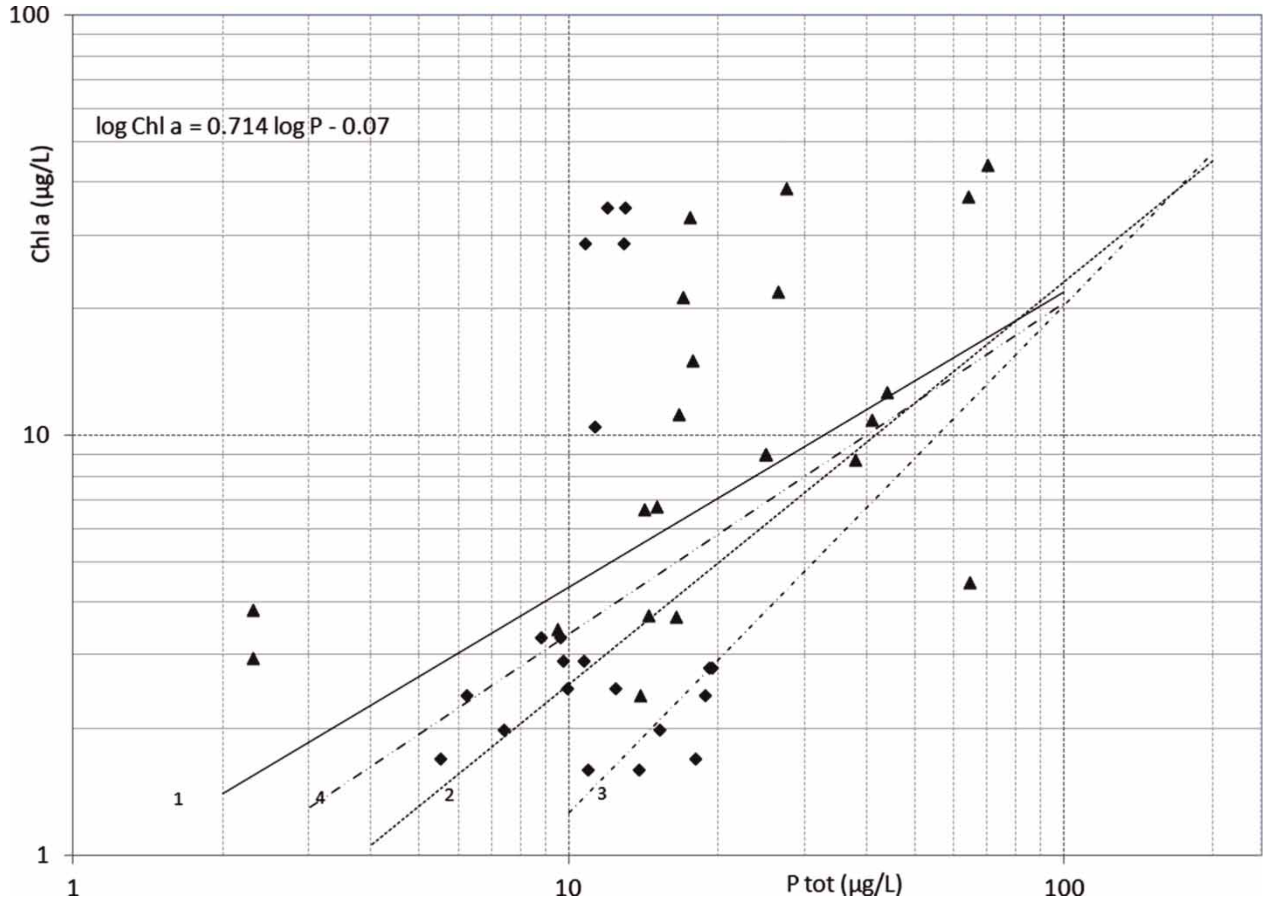

Figure 2 | Chl *a* correlation with the total P in Itaparica Reservoir: 1 = this study (■ = rainy period, ▲ = dry period), 2 = OECD (1982), 3 = CEPIS by Salas & Martino (1991), 4 = Huszar *et al*. (2006).

from 100 to 1,000 kg km^{-2} a^{-1} (10 and 90 percentile, $n = 17$; Kronvang *et al*. 2007);

- export from the natural caatinga area (93,040 km^2) with about 0.01–0.3 kg ha^{-1} a^{-1} (Bruijnzell 1991);
- sewage input by about 50,000 people living on the margins of the reservoir without or with insufficient sewage treatment (facultative ponds), assuming emission of 50% of the inhabitant equivalent of about 3 g d^{-1} P.

Re-oligotrophication potential of the Itaparica Reservoir

Re-oligotrophication by restoration and sanitation measures has already been applied over the last few decades in the management of eutrophied lakes (Sas 1989; Jeppesen *et al*. 2005a), and has even been successfully carried out with large lakes, e.g. Lake Constance (Häse *et al*. 1998) and Lake Maggiore (Ruggiu *et al*. 1998). But still some deficits exist for oligotrophication of tropical lakes as well as of reservoirs, e.g. nutrient use efficiency (Huszar *et al*. 2006), the significance of top-down control (Jeppesen *et al*. 2005b), and the severe water level decreases during droughts (Naselli-Flores 2003).

Re-oligotrophication of a reservoir is a multi-factor process, that includes sanitation (watershed measurements) and restoration (*in situ* measurements) strategies, hydropower operational conditions, and an adapted use of the water body (e.g. by aquaculture).

Sanitation means pollution control in the watershed, and a critical export rate (ER_{crit}) in kg ha^{-1} a^{-1} (Wolfram *et al*. 2009) can be calculated on the basis of the critical P concentration (P_{crit}) in a reservoir.

The critical export rate from the watershed is given by Equation (3):

$$ER_{crit} = L_{crit} \cdot A \cdot 10 - (P_{load} - ER)[kg\,ha^{-1}a^{-1}] \quad (3)$$

where ER_{crit} = critical export rate from the watershed in kg ha^{-1} a^{-1}, L_{crit} = critical P load in g m^{-2} a^{-1}, calculated

Table 1 | Calculation of P loading of Itaparica Reservoir

P source	Calculation base	P concentration	P load g m^{-2} a^{-1}
Internal sources:			
Inflow São Francisco	2,154 m^3 sec^{-1}	P in water: 19.6 μg L^{-1}	0.14
Mineralisation of inundated vegetation and soils	Biomass = 74 t ha^{-1}	P release ≈ 40 kg ha^{-1}	0.2
Aquaculture	Actual production: 4.000 t a^{-1} Planned production: 20,000 t a^{-1}	P release: 52 t P release: 260 t	0.06 0.32
Internal load from deposited sediments	No information available		–
Atmospheric deposition by rain to the lake surface	1.1 kg^{-1} a^{-1}		0.001
Sub sum (actual)			*0.40*
External sources:			
Agriculture (70% irrigation area)	6,700 ha	P release ≈ 100 kg km^{-2} a^{-1}	0.01
Sub-basin (caatinga)	93.040 km^2	P release ≈ 10 kg km^{-2} a^{-1}	1.12
Rural communities	50,000 inhabitants	P release ≈ 1.5 g inh^{-1} d^{-1}	0.03
Sub sum			*1.16*

by OECD (1982) eutrophication model, A = surrounding factor (lake surface/watershed), P_{load} = P input into the reservoir in g m^{-2} a^{-1} and ER = export rate from the watershed (g m^{-2} a^{-1}).

For the Itaparica Reservoir the actual ER is given by 10 kg km^{-2} a^{-1} P, while ER_{crit} amounts to 7.1 kg km^{-2} a^{-1} P (without intensive aquaculture) and 4.3 kg km^{-2} a^{-1} P with intensive aquaculture. The effect of the insufficient sewage treatment is small (Table 1), but most P export is given by wash out and erosion in the watershed, and established technologies such as water infiltration, rainwater harvesting, erosion control and vegetation strips along rivulets and reservoir margins are needed.

An internal P source of high significance and with the possibility of its regulation is aquaculture, and for ponds and raceway systems water re-use for irrigation is a simple but effective method to reduce the P load of the reservoir.

Besides determination of carrying capacity of a reservoir respectively of a distinct reservoir branch this is a promising new approach in reservoir management, a key factor, and has been applied for aquaculture cage culture systems for Tilapia in Moxotó Reservoir. The capacity limits for aquaculture are given by oxygen budget with oxygen consumption by fish and nitrification (of ammonium excretion of fish), and point out only a small amount of available oxygen of 1–2 mg L^{-1} (28–24 °C; postulate no water current in the net cages). Under consideration of over-saturation during daytime and oxygen depletion at night, the amount of available oxygen is more restricted and gives an explanation of why mass fish kills have already been observed in the net cages in reservoirs of the São Francisco River.

New technologies such as low P fish feed, abstraction of feed residue under net cages by pumping (and re-use in agriculture) and cultivation of fish species with higher economic value but with lower intensity must be taken into account.

CONCLUSION

Reservoirs are central elements of flood control and energy production, but in many cases environmental impacts on nature have been significant and actual research indicates the severe greenhouse gas emission potential of tropical reservoirs, due to eutrophication processes, as well as the occurrence of undesired species such as cyanobacteria and submerged macrophytes.

The phosphorus use efficiency denoted by Chl *a*–P relationships indicates a very effective use of the nutrient and only 10 μg L^{-1} lead to a high Chl *a* concentration of up to 30 μg L^{-1} and exceed other correlations such as the OECD relationship.

The application of the OECD load concept points to internal P sources of 0.40 g m^{-2} a^{-1}, while external P sources amount about 1.16 g m^{-2} a^{-1}. The critical export rate is given by only 7.1 kg km^{-2} a^{-1}, thus a bundling of measurements has to be applied to reduce P contamination level to an acceptable level. The critical load of the reservoir and the critical export rate of the watershed enable an evaluation of different P sources and fluxes.

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REFERENCES

Anderson, N. J., Jeppesen, E. & Søndergaard, M. 2005 Ecological effects of reduced nutrient loading (oligotrophication) on lakes: an introduction. *Freshwater Biology* **50** (10), 1589–1593.

Barros, A. M. L., Behrendt, H. & Sobral, M. C. 2008 Application of the nutrient emission model MONERIS to the Ipojuca River Basin, Brazil. In: *Proceedings of 11th Int. Spec. conf. Watershed & River Basin Management*. IWA Budapest, 4 pp.

Barros, N., Cole, J. J., Tranvik, L. J., Prairie, Y. T., Bastviken, D., Huszar, V. L. M., Giorgio, P. & Roland, F. 2011 Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. *Nature Geoscience* **4**, 593–596.

Biswas, A. K. 2004 Dams: Cornucopia or disaster? *Water Resources Development* **20** (1), 3–14.

Bruijnzell, L. A. 1991 Nutrient input-output budgets of tropical forest ecosystems: a review. *Journal of Tropical Ecology* **7**, 1–24.

CHESF 2005 Programa de monitoramento limnológico e avaliação da qualidade da água do Reservatório Itaparica. – 1°–7° Relatório Anual. Companhia Hidro Elétrica do São Francisco. Recife.

CHESF 2011 Descrição do Aproveitamento de Luíz Gonzaga. Available from: http://www.chesf.gov.br/portal/page/portal/chesf_portal/paginas/sistema_chesf/sistema_chesf_geracao/conteiner_geracao?p_name=8A2EEABD3BE1D002E0430A803301D002.

Friedl, G. & Wüest, A. 2002 Disrupting biogeochemical cycles – consequences of damming. *Aquatic Science* **64**, 55–65.

Gikas, G. D., Tsihrintzis, V. A., Akratos, C. S. & Haralambidis, G. 2009 Water quality trends in Polyphytos reservoir, Aliakmon River, Greece. *Environmental Monitoring and Assessment* **149** (1–4), 163–181.

Giles, J. 2006 Methane quashes green credentials of hydropower. *Nature* **444**, 524–525.

Gunkel, G. 2009 Hydropower – A green energy? Tropical reservoirs and greenhouse gas emissions. *Clean* **37**, 726–734.

Gunkel, G. & Sobral, M. 2007 *Reservoirs and River Basins Management: Exchange of Experience from Brazil, Portugal and Germany*. Universitätsverlag der TU Berlin, 279 pp.

Gunkel, G., Lange, U., Walde, D. & Rosa, J. W. C. 2003 Environmental and operation impacts of Curuá-Una, a reservoir in the Amazon region of Pará/Brazil. *Lakes and Reservoirs: Research and Management* **8**, 202–216.

Häse, C., Gaedke, U., Seifried, A., Beese, B. & Tilzer, M. M. 1998 Phytoplankton response to re-oligotrophication in large and deep Lake Constance: photosynthetic rates and chlorophyll concentrations. *Archiv für Hydrobiologie* **53**, 159–178.

Huszar, V. L. M., Caraco, N. F., Roland, F. & Cole, J. 2006 Nutrient-chlorophyll relationships in tropical-subtropical lakes: do temperate models fit? *Biogeochemistry* **79**, 239–250.

Jeppesen, E., Søndergaard, M., Mazzeo, N., Mariana Meerhoff, M., Christina, C., Branco, Ch. C., Huszar, V. & Scasso, F. 2005a Lake restoration and biomanipulation in temperate lakes: relevance for subtropical and tropical lakes. In: *Restoration and Management of Tropical Eutrophic Lakes* (M. V. Reddy, ed.). Oxford & IBH Publishing, New Dehli, pp. 331–349.

Jeppesen, E., Søndergaard, M., Jensen, J. P., Havens, K. E., Anneville, O., Carvalho, L., Coveny, M. F., Deneke, R., Dokulil, M. T., Foy, B., Gerdeaux, D., Hampton, St. E., Hilt, S., Kangur, K., Köhler, J., Lammens, E. H. H. R., Lauridsen, T. L., Manca, M., Miracle, M., Moss, B., Nõges, P., Persson, G., Phillips, G., Portielje, R., Romo, S., Schelske, C. L., Straile, D., Tatrai, I., Willén, E. & Winder, M. 2005b Lake responses to reduced nutrient loading – an analysis of contemporary long-term data from 35 case studies. *Freshwater Biology* **50**, 1747–1771.

Kaufman, J. B., Sanford Jr., R. L., Cummings, D. L., Salcedo, I. H. & Sampaio, E. V. S. B. 1993 Biomass and nutrient dynamics associated with slash fires in neotropical dry forests. *Ecology* **74**, 140–151.

Kronvang, B., Vagstad, N., Behrendt, H., Bøgestrand, J. & Larsen, S. E. 2007 Phosphorus losses at the catchment scale within Europe: an overview. *British Society of Soil Science* **23** (Suppl. 1), 104–116.

Lewis Jr., W. M. 2010 Biogeochemistry of tropical lakes. *Verhandlungen des Internationalen Verein Limnologie* **30** (10), 1595–1603.

Naselli-Flores, L. 2003 Man-made lakes in Mediterranean semi-arid climate: the strange case of Dr Deep Lake and Mr Shallow Lake. *Hydrobiologia* **506–509**, 13–21.

OECD 1982 *Eutrophication of Waters – Monitoring, Assessment and Control*. Organisation for Economic Co-operation and Development, Paris, 154 pp.

Resende, J. C. F., Markewitz, D., Klink, C. A., Bustamante, M. M. da C. & Davidson, E. A. 2011 Phosphorus cycling in a small watershed in the Brazilian Cerrado: impacts of frequent burning. *Biogeochemistry* **105**, 105–118.

Ruggiu, D., Morabito, G., Panzani, P. & Pugnetti, A. 1998 Trends and relations among basic phytoplankton characteristics in the course of the long term oligotrophication of Lake Maggiore (Italy). *Hydrobiologia* **369/370**, 243–257.

Salas, H. J. & Martino, P. 1991 A simplified phosphorus trophic state model for warm-water tropical lakes. *Water Research* **25**, 341–350.

Sas, H. (ed.) 1989 *Lake Restoration by Reduction of Nutrient Loading: expectations, experiences, extrapolatio*. Academia Verlag, St. Augustin, 497 pp.

Sperling, D. L. v. & Behrendt, H. 2007 Application of the nutrient emission model MONERIS to the upper Velhas River Basin, Brazil. In: *Reservoirs and River Basins Management: Exchange of Experience from Brazil, Portugal and Germany* (G. Gunkel & M. Sobral, eds). Universitätsverlag der Technischen Universität Berlin, pp. 265–279.

Tundisi, J. G., Matsumura-Tundisi, T. & Tundisi, J. E. M. 2008 Reservoirs and human well being: new challenges for evaluating impacts and benefits in the neotropics. *Brazilian Journal of Biology* **68**, 1133–1135.

Turner, B. L. & Haygarth, P. M. 2001 Phosphorus solubilization in rewetted soils. *Nature* **411**, 258.

Vollenweider, R. A. 1975 Input-output models, with special reference to the phosphorous loading concept in limnology. *Schweiz. Z. Hydrology* **37**, 53–84.

White, W. R. 2010 *World water: Resources, Usage and the Role of Man-Made Reservoirs*. Foundation for Water Research, Marlow, UK, 60 pp.

Wolfram, G., Argrillier, C., de Bortoli, J., Buzzi, F., Dalmiglio, A., Dokulil, M. T., Hoehn, E., Marchetto, A., Martinez, P.-J., Morabito, G., Reichmann, M., Remec-Rekar, Š., Riedmüller, U., Rioury, C., Schaumberg, J., Schulz, L. & Urbanič, G. 2009 Reference conditions and WFD compliant class boundaries for phytoplankton biomass and chlorophyll-*a* in Alpine lakes. *Hydrobiologia* **633**, 45–68.

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