A MODELLING APPROACH TO ASSES ALGAL BLOOM OCCURRENCE IN YACYRETÁ RESERVOIR, SOUTHAMERICA

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ABSTRACT

A modelling approach to asses algal bloom occurrence in Yacyretá reservoir is presented. Phosphorous input is carefully evaluated; phosphorous transport is modelled, on top of an existing suspended solid transport model driven by a hydrodynamic model, and the model validated based on measured data; a chlorophyll-a transport model is built, on top of the phosphorous model, based on recorded information from algal bloom events; an algal bloom criterion, based on chlorophyll-a concentration, is established. This chain of models is used to asses the present probability of algal bloom occurrence and the trophic state of the reservoir, and to make predictions for future scenarios of water level increase, from the present one up to the design value, and nutrients input increment, due to the continuous development of the watershed. The presented modelling approach is shown to be an appropriate tool to determine trophic conditions, an essential element for reservoir and watershed management.

1. INTRODUCTION

Yacyretá dam is located on the Upper Paraná River (around 27º25´S, 56º28´W), which constitutes the limit between Argentina and Paraguay (Figure 1). The reservoir has an extension of about 100 km. Its maximum width is around 30 km, diminishing upstream. For a water level of 76 m (above mean sea level) the maximum depth is about 15 m; it will reach around 22 m when the final water level is achieved (83 m). The Paraná River starts at the confluence of Grande and Paranaíba Rivers (20ºS, 51ºW), in Brazil. Its basin (part of the Plata Basin) is about 970,000 km^2. The mean discharge at the dam location is about 15,000 m^3/s. The climate of the dam region is subtropical, with a mean annual temperature of around 20ºC. Maximum temperatures are above 30ºC in summer and minimum temperatures stay above 10ºC during winter.

The possibility for a lake or reservoir to become eutrophic depends critically from the nutrients input, as it constitutes the limiting factor for bioproductivity. The major limiting nutrients are usually nitrogen and phosphorous. For tropical lakes with N:P relations higher than 9 phosphorous is the limiting nutrient. This is the case for Yacyretá reservoir (Menéndez et al. 2005).

In the present paper, a modelling approach to asses algal bloom occurrence in Yacyretá reservoir for the present situation and future scenarios (including water level increase to attain design conditions), is presented. Phosphorous input is carefully evaluated; phosphorous transport is modelled, on top of an existing suspended solid transport model (which, in turn, is driven by a hydrodynamic model), and the model validated based on measured data; a chlorophyll-a transport model is built, on top of the phosphorous model, based on recorded information from algal bloom events; an algal bloom criterion, based on chlorophyll-a concentration, is proposed. This chain of models is used to asses the present probability of algal bloom occurrence and the trophic conditions of the reservoir, and to make predictions for future scenarios of water level increase, from the present one up to the design value, and nutrients input increment, due to the continuous development of the watershed.

Figure 1. Location of Yacyretá dam reservoir

2. MODEL IMPLEMENTATION AND VALIDATION

2.1. Hydrodynamic model

The comparison between the horizontal and vertical length scales of the reservoir, and the absence of stratification (Morillo & Tarela 2002), lead to the conclusion that the system can be described as a shallow-water, well-mixed reservoir. Hence, the hydrodynamics can be modelled through the (2D) shallow water equations, which are solved through an implicit finite difference method (Menéndez 1990).

The model domain extended upstream from the line Candelaria-Garupá, down to the dams at the main and secondary branches (Figure 2).

Figure 3 shows a comparison between some measured and calculated velocity profiles (a total of 31 profiles were taken). The agreement is considered as satisfactory. More details are presented elsewhere (Menéndez et al. 2004a).

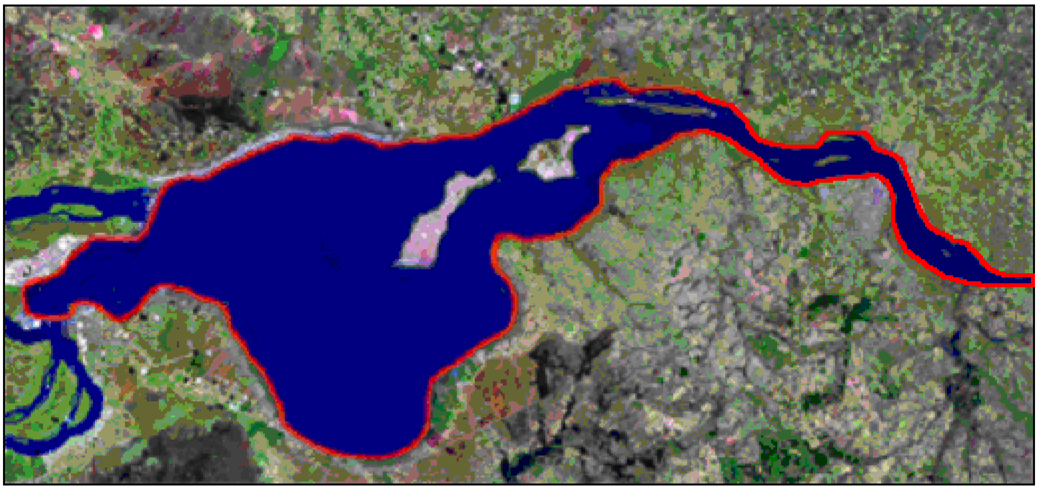
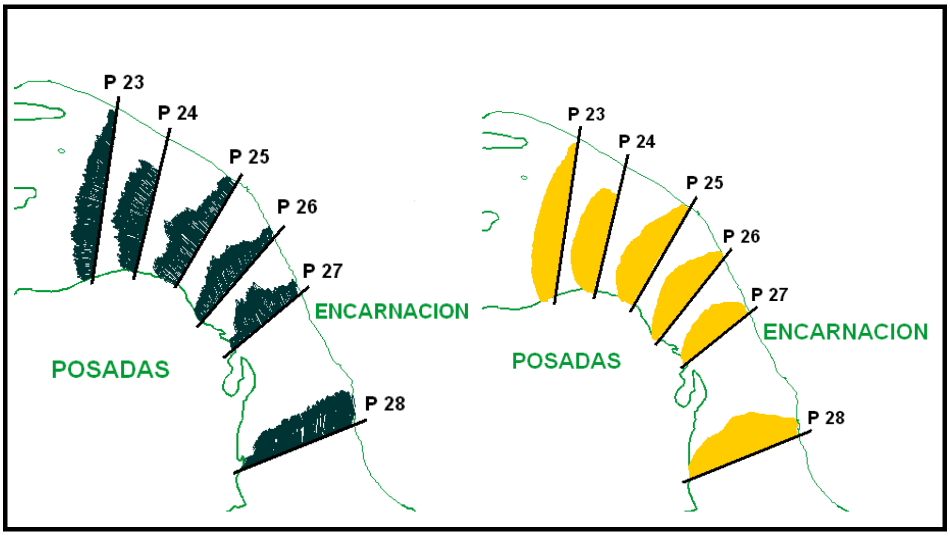


Figure 2. Model domain



a) Measurements b) Model

Figure 3. Velocity profiles

2.2. Suspended solid transport model

The transport through the reservoir of the suspended solid load carried by the river or entered through the reservoir sides, is also treated as 2D-horizontal. The advection-diffusion equation, plus a sink term representing siltation, is solved with a lagrangean technique, which involves a follow-up of small clouds with a Gaussian distribution of concentration (Carreras & Menéndez 1990). The clouds are advected by the water current, rotated and deformed under the action of the velocity gradients, diffused by the turbulence, and attenuated due to siltation. From the superposition of clouds, instantaneous spatial distributions of concentration are obtained.

Details of the suspended solid transport model for Yacyretá reservoir are presented elsewhere (Menéndez et al. 2004b). Figure 4 shows the siltation rate distribution for the present situation. It is compared with a zoning for the bottom sediments by sizes. It is observed that there is a reasonable correspondence between the zone with coarse material and the one with where the model indicates no sedimentation of fine material (blue zones).

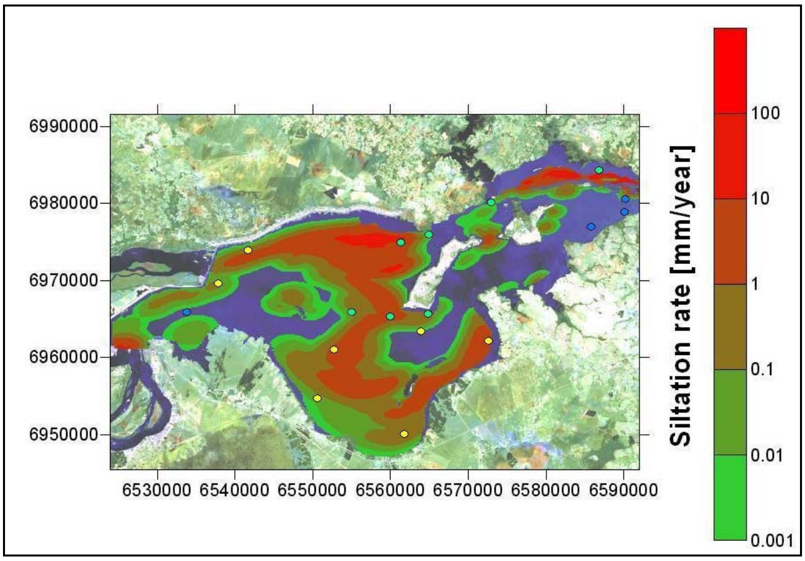


Figure 4. Siltation rate according to model, and measured bottom sediment sizes (blue: coarse; green: medium; yellow: fine)

2.3. Phosphorous input

Time series of measured phosphorous concentration, with an average sampling time step of 15 days, were available at the model upstream border. To eliminate "noise" (short time scale variations), a filtering procedure was implemented through Singular Spectral Analysis (Vautard et al., 1992), or SSA, which provides the "trends". In relation to the more classical Principal Components Analysis, this method has the advantage that the parameters that determine the form of the principal components are obtained from the data set itself, in lieu of being established beforehand. The time series was previously resampled with a daily time step.

This procedure was also applied to the water discharge time series. Multiplying both trend time series, the trend for the phosphorous mass-flux input at the model upstream border was obtained, as shown in Figure 5. In the same figure, the trends for the phosphorous mass-flux output and the water discharge are also shown. It is observed that the trends for the mass-flux preserve an annual oscillation, which is considered as representative of the seasonal cycle. Note that the difference between phosphorous mass-influx and outflux, or 'net mass-influx', becomes negative some time after the start of the extraordinary 1997-98 Paraná River flood, and remains as negative practically until the end of 1999; this indicates the existence of an extraordinary phosphorous exportation from the watershed to the reservoir through the sides, and is interpreted as linked to a watershed washout caused by the same pattern of high precipitation that originated the river flood.

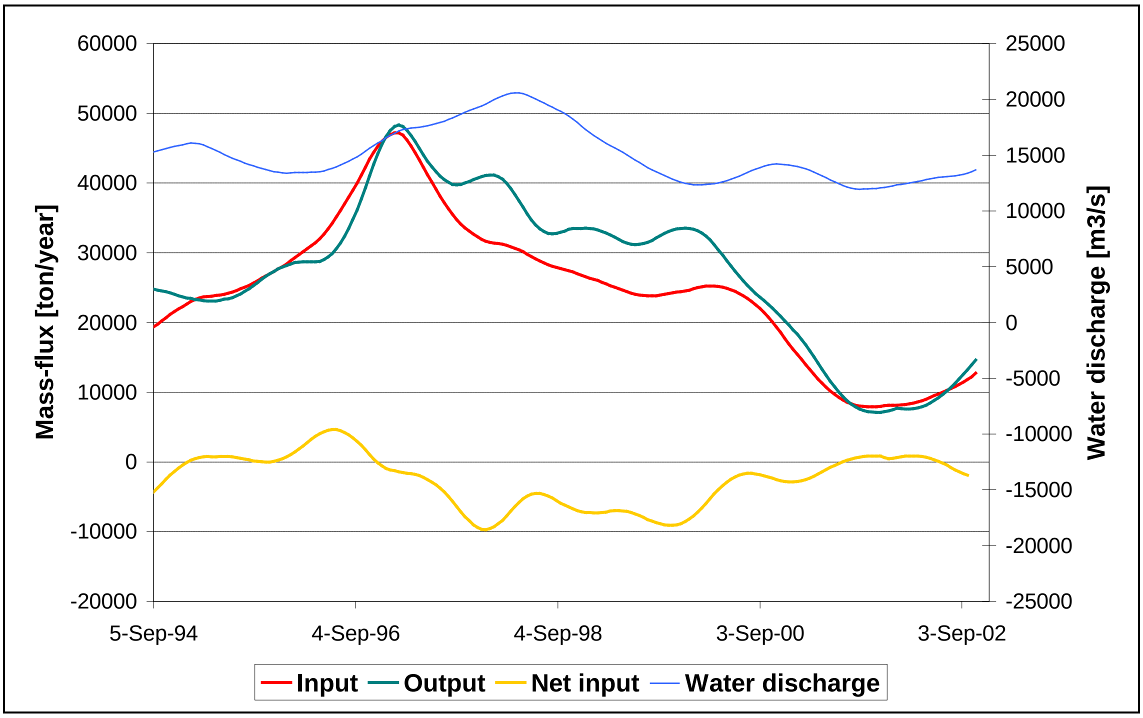


Figure 5. Trends for phosphorous mass-fluxes

Using the results from the suspended solid model, the trend for siltation was obtained for the time period March/98 to October/02, from which the associated phosphorous mass-flux towards the reservoir bottom, or 'phosphorous sedimentation', was calculated (Menéndez et al. 2004b), as shown in Figure 6 (negative, as it constitutes a loss; the positive values have to be considered as an indication of the errors involved in the methodology of estimation), where the net phosphorous mass-influx is also represented. In the same figure, the difference between the net mass-influx and the sedimentation, or 'phosphorous additional input', is shown. This constitutes the phosphorous input still to be explained, associated to the benthic and watershed phosphorous production.

The average annual benthic contribution was estimated as 340 tons. The estimated phosphorous contribution from the watershed resulted much higher, 2860 tons/year (distributed as 660 and 2200 tons/year from the Argentine and Paraguayan banks, respectively) (Menéndez et a. 2005). To introduce seasonality to the watershed annual mean value, an analysis of the seasonal distribution of rain (the main agent of sediment production from the watershed) was performed. Using the R-factor definition of RUSLE (Toy et al. 2002), a 'monthly modulating function' (with a time average of 1) was built for the time period Dec/98 to Dec/03. Multiplying it by the total watershed contribution, applying a 5-month time-window moving-average, in order to preserve only the seasonal trends, and adding the benthic contribution, the curve shown in Figure 7 was obtained. It is observed that it explains rather satisfactorily the phosphorous additional input for 'normal conditions', after the effects of the high rains of 97-98 has died out.

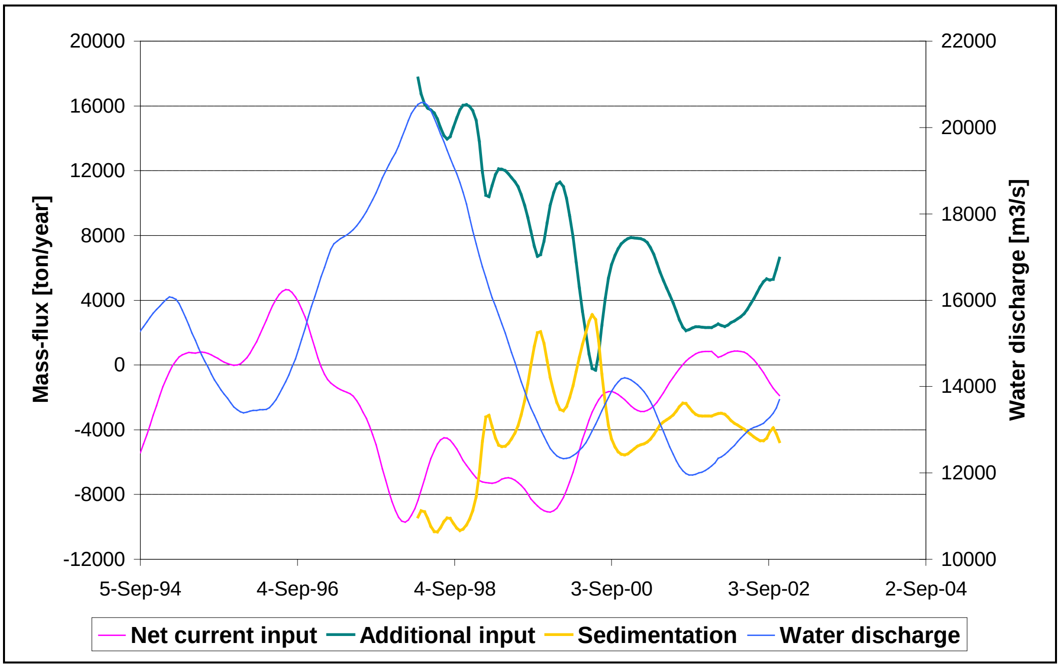


Figure 6. Trends for phosphorous sedimentation and additional input

2.4. Phosphorous transport

Phosphorous transport through the reservoir was modelled analogously to the suspended solid transport, as explained above, but the sink term associated to phosphorous sedimentation was adapted in order to distinguish between dissolved and particulated phases through a partition coefficient (Menéndez et al. 2005). Phosphorous input trends values from the river, the sides and the bottom (as shown above), corresponding to 13/Oct/01 (when the system is definitely back to normal conditions), were used as forcings.

In Table 1 and Figure 8 the model results are compared to those representing measurements. The agreement is considered as satisfactory.

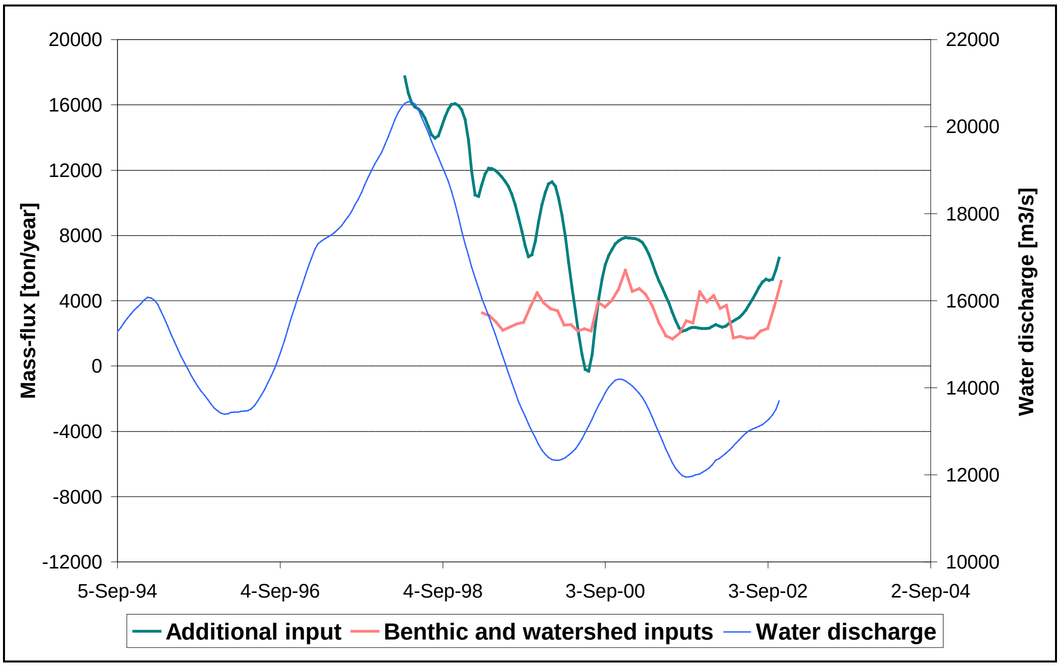


Figure 7. Trends for benthic and watershed phosphorous production.

Table 1. Phosphorous mass-fluxes [ton/year].

13/Oct/01	**Input**	**Output main branch**	**Output secondary branch]**	**Sedimentation**
Measured	10762	6108	1042	3612
Modeled	10762	5625	1228	3909
Difference	0%	-7,9%	+18%	+8,2%

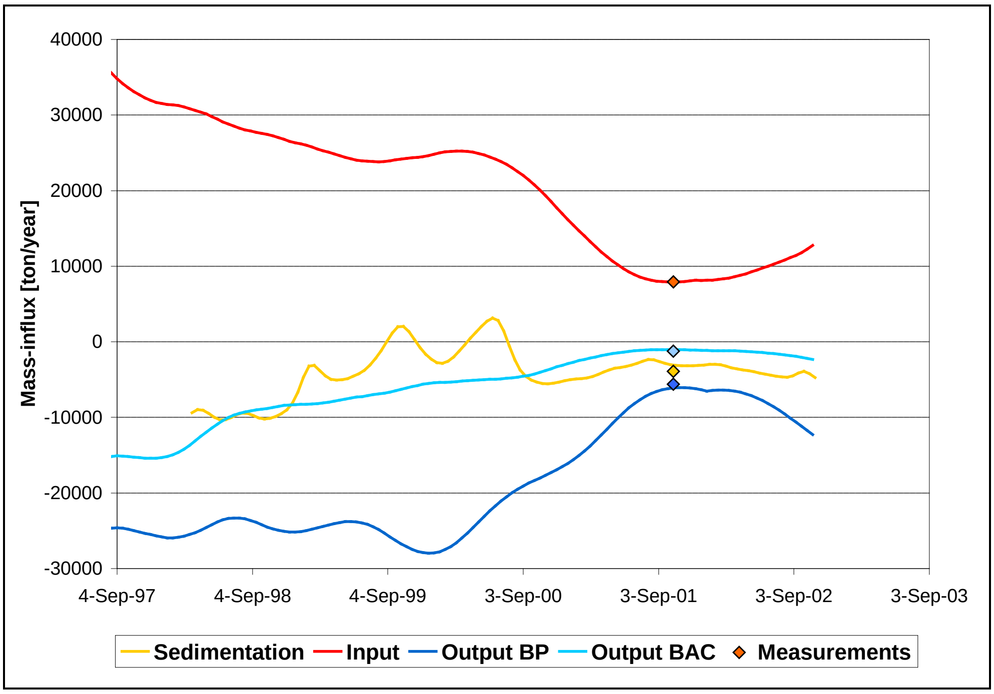


Figure 8. Validation of phosphorous transport model.

2.5. Chlorophyll-a transport

Chlorophyll-a is a measure of the density of phytoplankton and, hence, an index for the trophic state of the system.

Figure 9 presents a dispersion graph for the measured chlorophyll-a and phosphorous concentrations for all of the sampling stations of Yacyretá reservoir. In the same figure, correlation curves between these concentrations for temperate lakes (Toman & Mueller 1987) and tropical lakes (Salas & Martino 1990) are shown. It is observed that the measured points lie consistently below the correlation curves. This is interpreted as an indication that the system is not behaving strictly as a lentic body, in which the contact time for phytoplankton is enough to be in equilibrium with the available nutrients load.

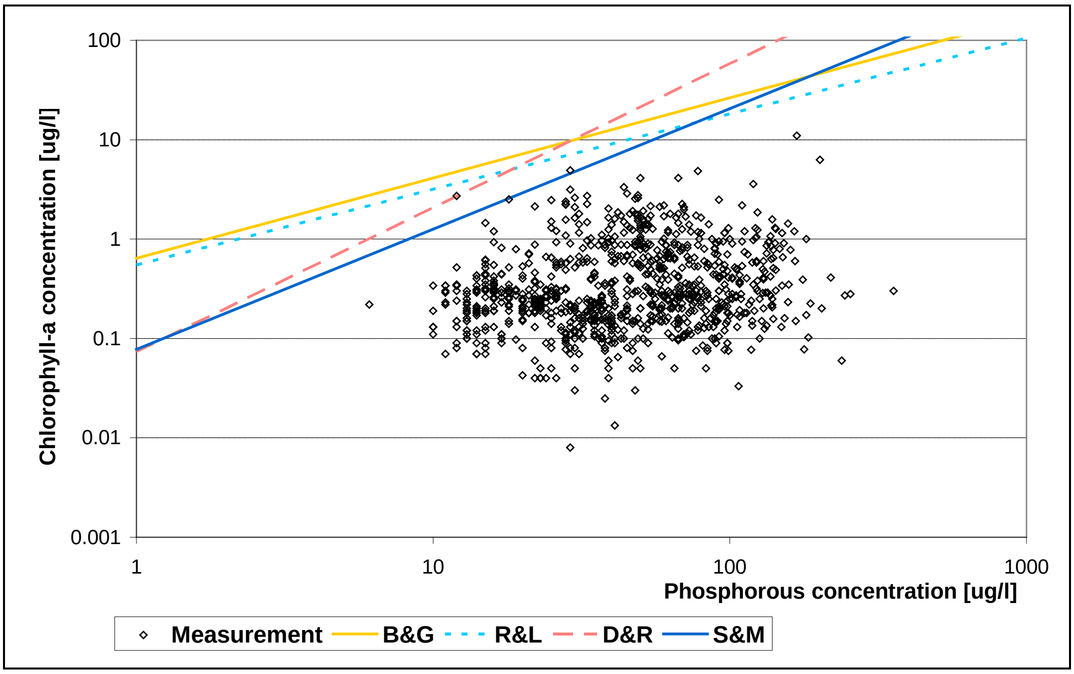


Figure 9. Relation between chlorophyll-a and phosphorous concentrations.
B&G: Bartsch & Gakstatter; R&L: Rast & Lee; D&R: Dillon & Rigler; S&M: Salas & Martino.

Based on this interpretation, the following lagrangian model for chlorophyll-a concentration, [*Chl*], was proposed:

$$\frac{dD}{dt} = -\frac{D}{\tau} \Rightarrow D(t) = D_o e^{-t/\tau}, \qquad D(t) \equiv [Chl]_{eq} - [Chl]$$

where D is the 'chlorophyll-a deficit', $[Chl]_{eq}$ the equilibrium value of [*Chl*] (Salas & Martino correlation curve was chosen, see Figure 9), D_o the chlorophyll-a deficit at the reservoir entrance, t the flying time along each (2D) fluid particle, and τ a parameter representing a time scale for phytoplankton adjustment to local conditions. The feasibility of the proposed model can be established if, based on available data, it can be demonstrated that: (a) the chlorophyll-a concentration gets closer to the local equilibrium value when a fluid particle moves along the reservoir; (b) a calibration law can be found for the adjustment time τ. Property (a) was verified for water discharges below 16,000 m^3/s; for higher discharges, estimation errors are too high due to a too short total flying time along the reservoir. This did not constitute a limitation because trend water discharges are below that limit for normal conditions (see above). Regarding property (b), calibration values for the adjustment time were obtained differentiating among a right (130 days), a central (30 days) and a left (330 days) flow corridors. This difference might be due to the different phosphorous concentration levels associated to each corridor (non linear effect), which would mean that the adjustment time gets lower when the phosphorous concentrations gets higher.

2.6. Algal bloom criterion

The following criterion by CEPIS (Salas & Martino 1990) for tropical lakes was used as an indication of the trophic state: (a) [*Chl*] < 30 μg/l: oligotrophic; (b) 30 < [*Chl*] < 70 μg/l: mesotrophic; (c) [*Chl*] > 70 μg/l: eutrophic. Based on it, measurements (Figure 9) would indicate that the Yacyretá dam reservoir is in an oligotrophic state.

However, algal blooms events have been recorded in the reservoir during February, 2004. They were associated to a peak concentration value for chlorophyll-a of around 4.2 μg/l at the reservoir inlet, as shown in Figure 10. Similar peak concentrations occur on December, 1994, and March/May, 1996, but no significant blooms were observed. An additional observation was that the three situations with high peaks of chlorophyll-a concentration correlated with high ambient temperatures (greater than 25ºC), but the one with algal blooms also correlated with low turbidity, below 4 NTU (Figure 10). Based on these observations, the following criterion for algal blooms was established: ambient temperature > 25ºC; water turbidity < 4 NTU; chlorophyll-a concentration: (i) [*Chl*] ≈ 2.7 μg/l: threshold for algal bloom events; (ii) [*Chl*] > 9.0 μg/l: very high concentration of algae; these limits are taken from Chapra & Tarapchak criterion for the trophic state of temperate lakes (Toman & Mueller 1987).

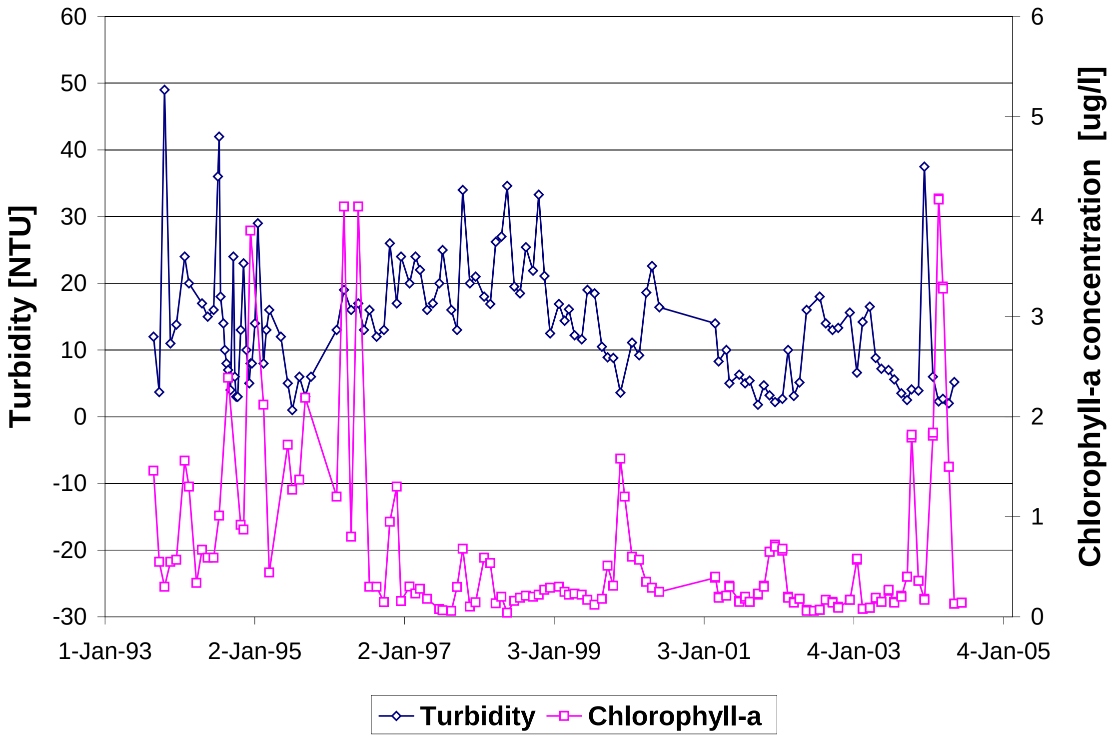


Figure 10. Records of chlorophyll-a concentration at the reservoir inlet.

3. MODEL APPLICATION

3.1. Present conditions

Summer scenarios were defined to undertake numerical experiments. Water discharge was fixed at 12,000 m^3/s. Two phosphorous mass-influx scenarios were established: a 'mean' scenario (EMN), with average input values, and an 'extreme' scenario (EEN), with a factor 3 applied to the average input values (as arises from the monthly modulating function). On the other hand, three initial chlorophyll-a deficit scenarios were considered: (a) a 'zero deficit' scenario (EDC), $D_o = 0$, representing the most critical condition; (b) a 'maximum deficit' scenario (EDM), $D_o = [Chl]_{eq}$, representing the least critical condition; (c) a 'most probable deficit' scenario (EDP), $D_o = 0.9[Chl]_{eq}$, representing the most probable condition, as arises from a regression line for chlorophyll-a and phosphorous concentrations (see Figure 9).

An analysis of the three situations with high peaks of chlorophyll-a concentration (Figure 10), lead to the conclusion that the following associations can be made: (I) *Nov-99:* scenario EEN- EDM ; (II) *Oct-03:* scenario EMN- EDC ; (III) *Feb-04:* scenario EMN- EDC.

For scenario EMN-EDC (mean phosphorous input, zero deficit of chlorophyll-a concentration), the model shows that the incoming algal biomass is preserved along extended 'tongues', reaching maximum values closer to the Paraguayan side (Figure 11). For the maximum deficit scenario, EMN-EDM, no algal bloom is produced, while for the most probable deficit scenario, EMN-EDP, only a quite localized zone, close to the Paraguayan side, could produce some algal bloom.

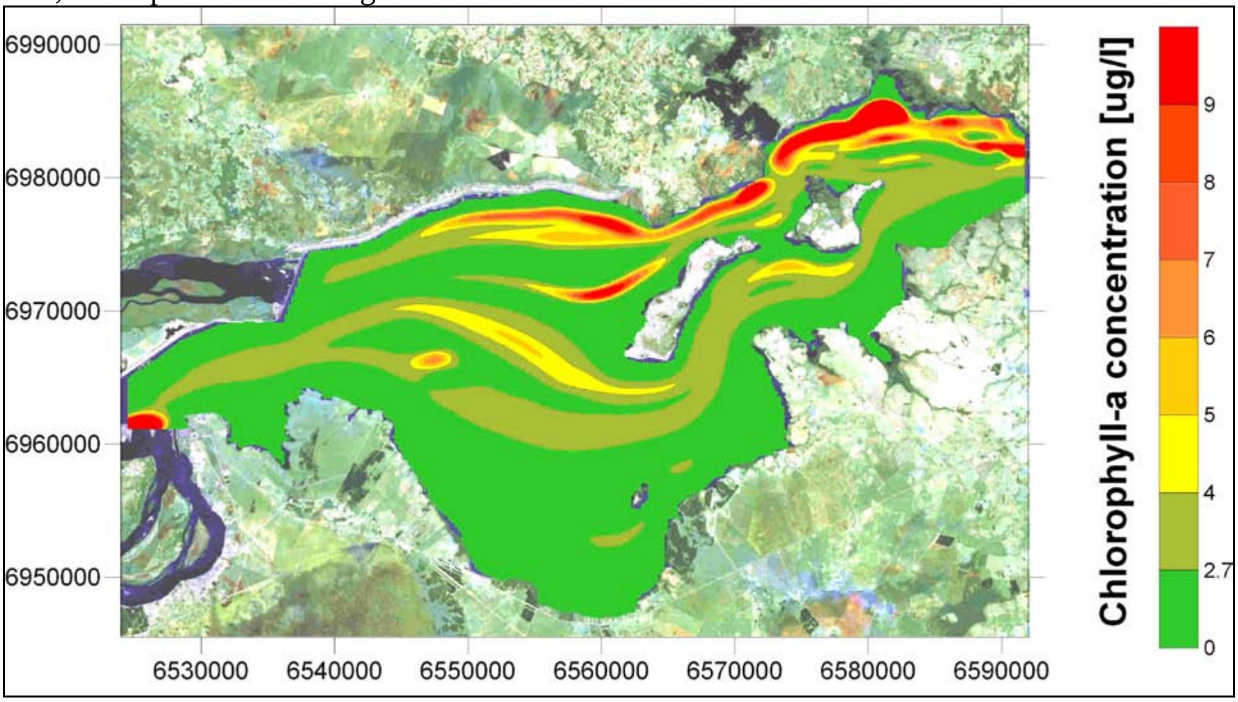


Figure 11. Chlorophyll-a concentration distribution for scenario EMN-EDC.

In the case of extreme phosphorous input, zero deficit conditions (EEN-EDC) would lead to generalized algal blooms throughout the reservoir. For maximum deficit conditions (EEN-EDM) no algal bloom would still be produced, and for the most probable deficit conditions (EEN-EDP) new and more extended zones with possible algal blooms would appear.

These results are considered as consistent with observations, then constituting a sort of validation check.

The model then indicates that the possibility of an eventual generalized algal bloom throughout the reservoir depends critically on the upstream phytoplankton input. Essentially, the reservoir transports and contributes to the development of imported algae, but it does not show a significant capacity for generating algal bloom events by itself.

Additionally, if scenario EMN-EDP is considered as representative of mean summer conditions, the model shows that the present state of the reservoir is uniformly oligotrophic, consistent with the previous observation based on data records.

3.2. Future scenarios

In addition to the present, 'low water level' scenario (76 m), an 'intermediate water level' (78 m), and a 'high water level' (83 m) scenarios were considered. Also, different phosphorous mass-influx scenarios were established: (1) 'present' scenario, representing conditions at the time of the study; (2) 'deforestation' scenario, representing conversion of non-exploited zones to agricultural and livestock use; and (3) 'intensive' scenario, representing an increment of 10% in livestock density, in addition to 'deforestation' conditions.

Model results indicate that no significant change should be expected when rising the water level from 76 to 78 m, but for 83 m recurrent algal blooms could be expected, mainly close to the Paraguayan side. The increment in phosphorous mass-influx would not produce any significant qualitative change to the previous picture, but only minor quantitative changes.

If, again, scenario EMN-EDP is considered as representative of mean summer conditions, the model shows that the reservoir would remain as uniformly oligotrophic for 78 msnm, but some mesotrophic zones could appear on the Paraguayan side for 83 m.

4. CONCLUSIONS

The presented modelling approach, a combination of sound physical theories and criteria based on observations, has proven to be an appropriate tool to asses a reservoir trophic state and the probability of occurrence of algal blooms. In particular, it constitutes a way to predict with a reasonable level of certainty the future behaviour of the reservoir when rising the water level up to its design value.

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