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Water Resources Management with Dynamic Optimization Strategies and Integrated Models of Lakes and Artificial Wetlands

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Abstract

In this work, we propose an integrated mechanistic model for a freshwater eutrophic reservoir and an artificial wetland and within a dynamic optimization framework. A partial differential equation system results from dynamic mass balances for the main phytoplankton groups; two zooplankton groups and two size classes of zooplanktivorous fish in the reservoir, as well as dissolved oxygen and main nutrients in both the reservoir and wetland. Algebraic equations stand for forcing functions profiles, such as temperature, solar radiation, river inflows and concentrations, etc. The model is formulated as an optimal control problem within a control vector parameterization approach in gPROMS. Optimization variables are the fraction of nutrient rich water stream that is derived through the wetland and fish removal rates from the reservoir. The objective function is the minimization of a weighted sum of integrals along the entire time horizon: the quadratic difference between phytoplankton concentration and a desired value below eutrophication limits and the quadratic difference between phosphate concentration in the wetland outflows and a desired value. Numerical results provide optimal profiles for restoration actions and their effects on the studied ecosystem.

Keywords: Optimal Control Problem, Eutrophication, Restoration, Biomanipulation

1. Introduction

Eutrophication, associated to high nutrient concentrations and recurrent algae blooms, is the most important environmental problem in many lakes and reservoirs. An issue of concern associated with algal blooms is the potential production of toxins by different phytoplankton species within the blooms, which are dangerous for human health (Paerl and Otten, 2013). The implementation of short and long term restoration strategies that contribute to health recovery of water bodies requires deep knowledge of the aquatic system, as well as detailed modelling and optimization (Estrada et al., 2011).

Water resources management must include restoration of water bodies not only affected by point sources (which has been intensively addressed by the construction of water treatment plants), but also those affected by nonpoint nutrient sources (Jeppesen *et al*., 2012). One approach applied to address the problem of nonpoint nutrient sources for water bodies is the use of artificial wetlands. They are portions of land, covered with macrophytes, through which a water stream is derived, to reduce its nutrient concentration (nitrogen and phosphorus) before being discharged into the water body under study. Many physicochemical processes are involved in the reduction of nutrient concentration within wetlands, such as retention and assimilation by macrophytes, plankton and other microorganisms; sedimentation, adsorption from the sediments, among others (Langergraber et al., 2009). During the last decades, artificial wetlands have become an attractive alternative for water treatment since they have low maintenance cost, have a high efficiency and productivity and present ecological benefits (Reddy et al., 1999). Many lakes and water reservoirs have a positive response to reduced nutrient discharge, while others present a great resistance to improve their trophic condition due to nutrients discharge from sediments, internal recycle of nutrients and, in some cases, the presence of zooplanktivorus fish that cause a reduction on zooplankton population, which can no longer control phytoplankton growth by grazing. In this case, it may become necessary to implement inlake restoration strategies like sediment dreadging, hypolimnetic oxygenation and biomanipulation.

Experimental analysis of restoration actions is time-consuming and monitoring for long periods has large associated costs to implement. The development of ecological water models integrated to optimization strategies can help to propose and evaluate management strategies in both the short and long term (Estrada et al., 2011).

In this work, we propose an integrated mechanistic model for an eutrophic reservoir and artificial wetland within a dynamic optimization framework. Dynamic mass balances have been formulated for the main phytoplankton groups, two zooplankton groups and two size classes of zooplanktivorous fish in the reservoir, as well as dissolved oxygen and main nutrients. A simplified model has been considered for the artificial wetland. Algebraic equations stand for forcing functions profiles, such as temperature, solar radiation, river inflows and concentrations, etc. The complete model is formulated as an optimal control problem with a control vector parameterization approach (gPROMS, PSEnterprise 2014). Optimization variables characterize external reduction of nutrients (fraction of nutrient rich water stream that is derived through an artificial wetland) and biomanipulation strategies (fish removal rate). Numerical results provide optimal profiles for restoration actions. The present study has been carried out on Paso de las Piedras Reservoir, which is the drinking water source for two cities in Argentina.

2. Model description

We have formulated a water quality model as a differential algebraic system that describes temporal and spatial profiles of three phytoplankton groups (cyanobacteria, diatomea, chlorophyta), two zooplankton groups (cladocera, copepoda) and two size classes of zooplanktivorous fish (Odontesthes bonariensis), dissolved oxygen and main nutrients in the reservoir. Algebraic equations stand for forcing functions profiles, such as temperature, solar radiation, river inflows and their associated nutrient concentrations. The model takes into account concentration gradients along the water column (two horizontal layers) and horizontal averaged concentrations, constant water density and constant lake transversal area. Equations (1) to (6) correspond to main equations in the wetland and the reservoir, respectively. Equations (1) and (2) are phosphate mass balance and retention equation in the wetland:

$$V_w \frac{dC_{PO_4,w}}{dt} = Q_w c_{PO_4,DIV,IN} - kC_{PO_4,DIV,IN} Q_w - Q_w c_{PO_4,w} \quad (1)$$

where $\boldsymbol{C_{PO4,w}}$ is phosphate concentration at wetland output; $\boldsymbol{Q_w}$, and $\boldsymbol{V_w}$ correspond to inlet flowrate and wetland volume, respectively; $\boldsymbol{C_{PO4,DIV,IN}}$ is phosphate concentration in wetland inlet stream and the nutrient retention rate ***k*** has been obtained from a pilot plant scale artificial wetland in the site. Equations (2) to (4) are component mass balances for the upper and lower layer in the reservoir and total mass balance, as follows:

$$\frac{dC_{Uj}}{dt} = \sum_k \frac{Q_{IN,Uk}}{V_U} c_{IN,Ujk} - \frac{Q_{OUT,U}}{V_U} c_{Uj} + r_{Uj} - \frac{k_d A}{\Delta h V_U}\left(c_{Uj} - c_{Lj}\right) - \frac{c_{Uj}}{h_U}\frac{dh_U}{dt} \quad (2)$$

$$\frac{dC_{Lj}}{dt} = -\frac{Q_{OUT,L}}{V_L} c_{Lj} + r_{Lj} - \frac{k_d A}{\Delta h V_L}\left(c_{Uj} - c_{Lj}\right) \quad (3)$$

j = NO_3,NH_4, ON, PO_4, OP, BDO, DO, Cyanobacteria, Diatomea, Chlorophyta, Cladocera, Copepoda, Odontesthes (2 size classes)

$$\frac{dh_T}{dt} = \frac{1}{A}\left[Q_{rain} - Q_{evap} + \sum_k Q_{IN,k} - \sum_m Q_{OUT,m}\right] \quad (4)$$

where $\boldsymbol{C_{IN,Ujk}}$ is component *j* concentration in the upper layer for tributary *k* (Sauce Grande River and El Divisorio Stream, in our case study); $\boldsymbol{C_{U,j}}$ and $\boldsymbol{C_{L,j}}$ are component concentrations within the water body in the upper and lower layer, respectively; $\boldsymbol{r_{U,j}}$ and $\boldsymbol{r_{L,j}}$ stand for generation/consumption terms; $\boldsymbol{Q_{IN,U}}$ refers to tributaries inputs (Sauce Grande River and El Divisorio Stream), $\boldsymbol{Q_{OUT,U}}$ is the Sauce Grande River output, ***A*** and h_T are the lake transversal area and depth, respectively, and $\boldsymbol{Q_{OUT,L}}$ refers to outputs for drinking water and industrial activities. Model parameters have been estimated based on collected data during 2004-2005 for Paso de las Piedras Reservoir (Estrada et al., 2009). For a more detailed description of the generation/consumption rate terms, see Estrada et al. (2011). The entire model has 42 differential and 110 algebraic equations.

3. Optimal Control Problem

In this work, we formulate a model including two restoration strategies: the reduction of external loading of nutrients as an optimal control problem along a long term time horizon of twelve years, and an internal lake strategy, biomanipulation, that is based on the food chain theory and is supported on top-down control on phytoplankton growth (Søndergaard *et al*., 2013). The basic idea is to perform zooplanktivorous fish removal to keep a high grazing pressure on the phytoplankton community by the herbivore zooplankton. In this work, we have considered the application of biomanipulation by fish removal, considering fish removal rate as control variable, which are included as negative terms ($S_{1.,Removal}$ and $S_{2,Removal}$) in the rate equations of fish biomass (Eqs. 5 and 6) for both size classes of *O. bonariensis* (S_1 and S_2).

$$r_{iS_1} = R_{im,pred} - R_{im,bmetab} - R_{iS_3,canib} - R_{im,recruit} + R_{im,spaw} - S_{1,Removal} \quad (5)$$

$$r_{iS_2} = R_{im,pred} - R_{im,bmetab} - R_{im,recruit} + R_{im,spaw} - S_{2,Removal} \quad (6)$$

The objective function is the minimization of a weighted sum of two integral terms. The first integral corresponds to the square difference between phytoplankton concentration in the upper layer of the lake and a tight desired value of 0.25 mg/l. The second integral is the square difference between phosphate concentration in the wetland outlet stream and a desired value of 0.02 mg/l. Both desired values are below eutrophication limits. The dynamic optimization problem is formulated as:`

$$min\ \emptyset = \left[\int_0^{tf}\left(\sum_{j=C,D,G} C_{U,j}(t) - 0.25\right)^2 dt + \int_0^{tf}\left(C_{PO_4,w}(t) - 0.02\right)^2 dt\right] \quad (7)$$

subject to

DAE Integrated Model for Wetland and Reservoir

$0 \leq Q_w \leq 0.5\ Q_{DIV,IN}$ (L/ day)

$LB \leq C_m \leq UB$ (mgC/L day) $m = S_1, S_2$

4. Results and Discussion

The optimization problem was implemented within a control vector parameterization framework in gPROMS (gPROMS, PSEnterprise, 2014), considering a time horizon of two years. Numerical results for the case study are shown in Figures 1 and 2. Optimization control variables are the fraction of tributary stream that is derived through the wetland and removal rates for the two fish size classes. Based on experimental results, obtained in a pilot scale artificial wetland, phosphorus retention of 50% and nitrogen retention of 60% are considered.

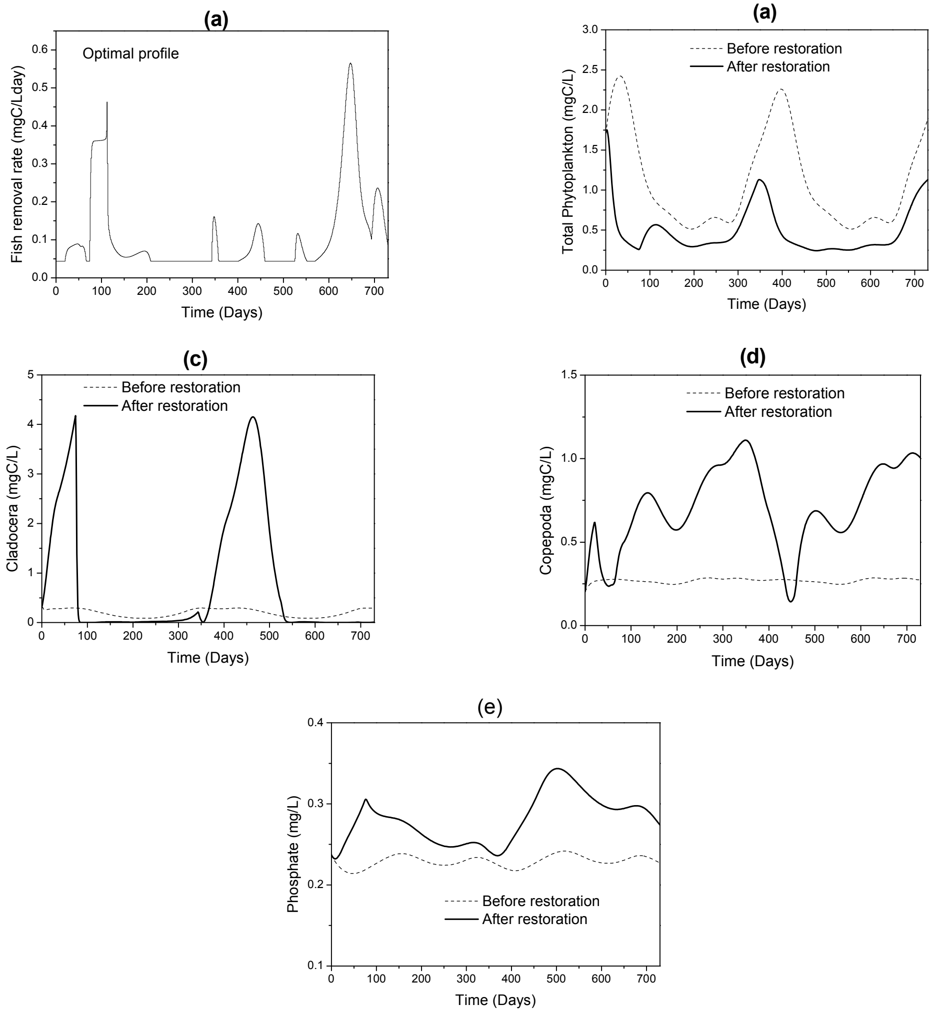

Figure 1. Optimal profiles for restoration along two years for fish removal rate (a); total phytoplankton concentration before (dashed line) and after restoration (solid line) (b), Cladocera concentration (c), Copepoda concentration (d) and phosphate concentration (e)

Figure 1(a) shows zooplanktivorous fish removal rate profile along the time horizon of two years. It can be seen that the obtained removal profile allows an important increase on zooplankton concentration (Figs. 1(c) and 1(d)), which increases its grazing pressure on phytoplankton. Figure 1(b) shows total phytoplankton biomass profile before and after restoration, it can be seen that phytoplankton biomass peaks are reduced after restoration actions due to the increase of zooplankton biomass. Figure 1(e) shows phosphate concentration profile before and after restoration actions, it is observed that its concentration increases after fish removal, even though the fraction of tributary stream deviated through the wetland (control variable) is at its upper bound. This can be attributed to a decrease in phosphate consumption due to the decrease in phytoplankton biomass, and also to the internal recycle of nutrients within the water reservoir.

Figure 2 shows numerical results for the application of the use of wetland as a sole restoration strategy throughout a 12-year horizon (three times the residence time of Paso de las Piedras reservoir), for phosphate (a) and total phytoplankton concentration (b). Figure 2(a) shows a small reduction of phosphate concentration within the water body, from 0.237 mg/L at t=0 to 0.211 mg/L at t=4380 (days). Phytoplankton concentration presents a slow reduction along the time horizon (Fig. 2(b)). These results show that reduction on nutrients discharge is not enough to improve water quality for the short and medium term.

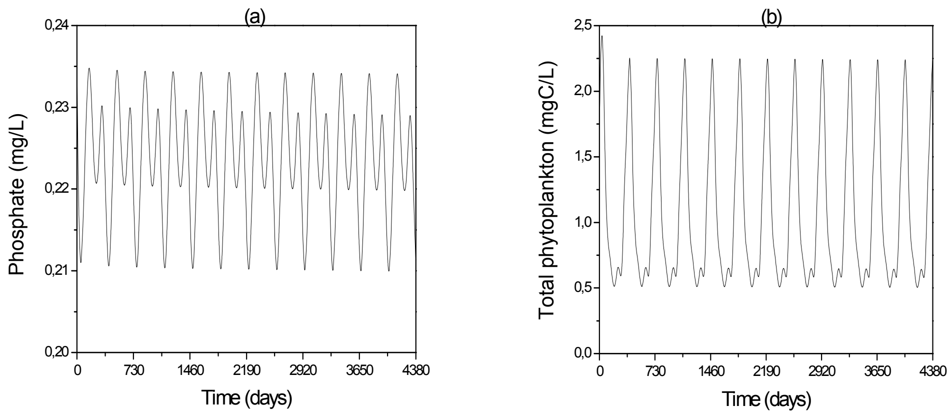

Figure 2. Temporal profiles for phosphate (a) and total phytoplankton biomass for long term restoration through an artificial wetland.

Figure 3 shows optimal profiles for total phytoplankton concentration (a) and phosphate concentration (b). Numerical results shown in Fig. 3 are obtained considering 0.21 mg/L (concentration of phosphate at t=4380 days in Fig. 2(a)) as initial concentration of phosphate within the reservoir. The comparison between Fig. 1(b) and Fig. 3(b) shows that the second peak of phytoplankton biomass can be reduced when a lower initial concentration of phosphate is considered.

Currently, the wetland model is being extended to include additional complex processes that take place within wetlands, such as nutrient (carbon, phosphorus, nitrogen) dynamics and macrophyte growth (Langergraber et al., 2009). This will allow formulating new optimal control problems to improve the wetland performance.

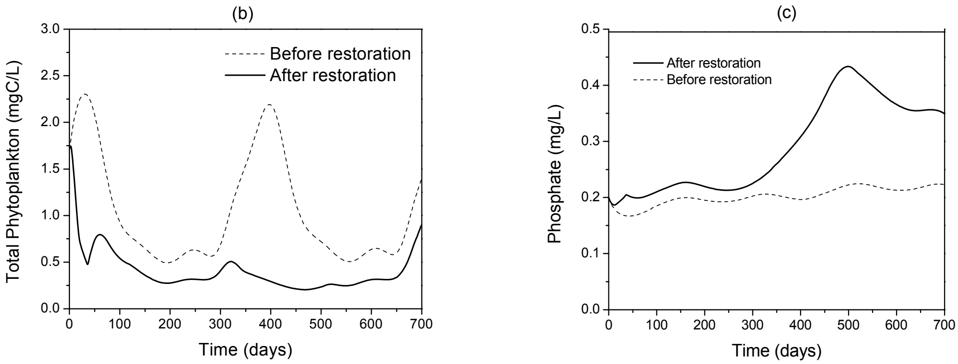

Figure 3. Optimal profile before (dashed line) and after (solid line) restoration for total phytoplankton (a) and phosphate (b), considering initial concentration of phosphate after 12 years wetland restoration

5. Conclusions

We have formulated an optimal control problem to plan short and medium time restoration in a eutrophic reservoir with a detailed ecological water model. Medium term restoration (12 years) through an artificial wetland has been explored as the sole restoration strategy. Numerical results show that both external and inlake restoration strategies must be applied simultaneously. Process systems engineering approaches have proved to be effective for the determination and planning of restoration strategies.

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