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

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Intake tower

Artificial Wetland

Fish Removal

Motivation

-**Harmful Algal Blooms**: the most severe problem associated with **eutrophication**

-Water bodies increasingly eutrophic due to antropogenic inputs of nutrients

-Rigorous water quality model for **Paso de las Piedras Reservoir** (Estrada *et al*., 2009 a, 2011; Di Maggio *et al*. 2016)

-**EPA** recommendation in 2015: **Dual Nutrient Criteria** (**N** and **P** reduction)

-Experimental **data** from a **pilot artificial wetland** with *Senecio bonariensis* as **biofilter**

-External reduction of nutrients by **artificial wetlands**: not enough due to internal nutrient recycle

-Food web manipulation (**Biomanipulation**) through zooplanktivorous fish removal: suitable **internal strategy**

-Application of restoration strategies: systematic study, **modeling** and **optimization**

Objectives

Formulation of integrated ecological models of lakes and artificial wetlands within a dynamic optimization framework

Determination and planning of optimal restoration policies for water bodies

Water Quality Mathematical Model (DAE)

Global Mass Balance

$$\rho A \frac{dh_r}{dt} = \sum_{k=1}^{NIN} Q_{IN\,k} - \sum_{m=1}^{NOUT} Q_{OUT\,m} + Q_{rain} - Q_{evap}$$

Upper Layer

$$\frac{dC_{Uj}}{dt} = \sum_{k=1}^{NIN} \frac{Q_{IN\,U,k}}{V_U} C_{IN\,Ujk} - \sum_{m=1}^{NOUT} \frac{Q_{OUT\,U,m}}{V_U} C_{OUT\,Ujm} + r_{Uj} - \frac{kdA}{\Delta h_U h_U}(C_{Uj} - C_{Lj}) - \frac{C_{Uj}}{h_U}\frac{dh_U}{dt}$$

Lower Layer

$$\frac{dC_{Lj}}{dt} = \sum_{m=1}^{NOUT} \frac{Q_{OUT_L}}{V_L} C_{Lj} + r_{Lj} + \frac{kdA}{\Delta h_L h_L}(C_{Lj} - C_{Uj})$$

Phytoplankton

$$r_{ij} = R_{ij,growth} - R_{ij,resp} - R_{ij,death} - R_{ij,\text{settling}} - R_{ij,graz}$$

$$R_{ij,growth} = k_{j,growth} f(T) f(I) f(N) C_{ij} \qquad f(N) = min\left(\frac{IP_j - IP_j^{min}}{IP_j^{max} - IP_j^{min}}, \frac{IN_j - IN_j^{min}}{IN_j^{max} - IN_j^{min}}\right)$$

$$R_{ij,graz} = k_{j,graz} \frac{C_{ij}}{C_{ij} + K_{graz}} C_{Zoo_j} \qquad R_{ij,resp} = k_{i,resp} \theta_r^{(T-20)} C_{ij}$$

$$R_{ij,\text{sedim}} = k_{j,\text{sedim}} \frac{1}{h_i} C_{ij} \qquad R_{ij,death} = k_{i,death} \theta_m^{(T-20)} C_{ij}$$

Zooplankton

$$r_{ik} = R_{ik,graz} - R_{ik,bm} - R_{ik,pred}$$

$$R_{ik,pred} = \sum_{m=S_1,S_2,S_3} Pred_{ikm} \theta_{\text{pred}_m}^{(T-20)} C_{ik} \qquad R_{ik,bmi} = k_{k,bm} \theta_{bm_k}^{(T-20)} C_{ik}$$

$$R_{ik,graz} = \left(\sum_{j=C,D,G} Graz_{kji} + Graz_{k,det\,i}\right) A_k \; f(T)_k$$

$$Graz_{ikj} = k_{k,grazing} \frac{P_{ijk} C_{ij}}{KZ_k + \sum_{j=C,D,G} P_{ijk} + P_{i,det\,k}}$$

$$Graz_{ik,det} = k_{k,grazing} \frac{P_{i,det\,k} C_{iPOC}}{KZ_k + \sum_{j=C,D,G} P_{ijk} + P_{i,det\,k}}$$

Artificial Wetland

$$V_w \frac{dC_{NO_3,w}}{dt} = Q_w C_{NO_3,Div,IN} - k_1 C_{NO_3,Div,IN} Q_w - Q_w C_{NO_3,\dot{O}}$$

$$V_w \frac{dC_{PO_4,w}}{dt} = Q_w C_{PO_4,Div,IN} - k_2 C_{PO_4,Div,IN} Q_w - Q_w C_{PO_4,\dot{O}}$$

$$V_w = A_w h_{\dot{O}}$$

Zooplanktivorous Fish

$$r_{iS_1} = R_{iS1,pred} - R_{iS1,bm} - R_{iS_3,canib} - R_{iS1,recruit} + R_{iS1,spaw}$$

$$r_{im} = R_{im,pred} - R_{im,bm} - R_{im,recruit} - R_{im,spaw}$$

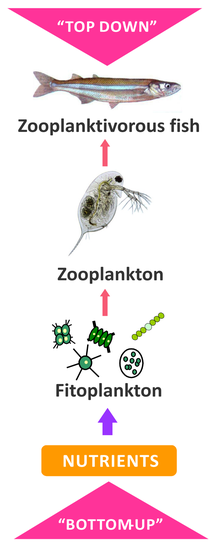
$$R_{im,pred} = \left(\sum_{j=C,D,G} Pred_{imj} + \sum_{k=Cla,Co} Pred_{imk} + Pred_{im,det}\right) A_m \theta_{pred_m}^{(T-20)}$$

$$R_{iS_1,pred} = \left(\sum_{k=Cla,Co} Pred_{imk} + Pred_{im,det} + Pred_{iS_3 S_1}\right) A_m \theta_{pred_{S_3}}^{(T-20)}$$

$$R_{im,bm} = k_{m,bm} \theta_{bm_m}^{(T-20)} C_{im} \qquad R_{iS_3,canib} = k_{S_3,canib} \theta_{m_{S_3}}^{(T-20)} C_{iS_3}$$

$$R_{im,recruit} = k_{m,recruit} C_{im} \qquad R_{im,spaw} = k_{m,reprod} C_{im} \quad m = S_2, S_3$$

Numerical Results



Optimal Control Problem

Fraction of tributary stream derived to wetland for nutrient removal

Removal rate for each zooplanktivorous fish size class (S1, S2 , S3)

$$\min\phi = \left[0.7\int_0^{tf}\left(\sum_{j=C,D,G} Cj(t) - 0.25\right)^2 dt + 0.3\int_0^{tf}(CP(t) - 0.02)^2 dt\right]$$

subject to

Integrated Ecological Model of Water Reservoir and Wetland (DAE)

$$r_{iS1} = R_{im,pred} - R_{im,bmetab} - R_{iS3,canib} - R_{im,recriut} + R_{im,spaw} - S_1\,Removal$$

$$r_{im} = R_{im,pred} - R_{im,bmetab} - R_{im,recriut} + R_{im,spaw} + S_m\,Removal$$

$$C(0) = C^0$$

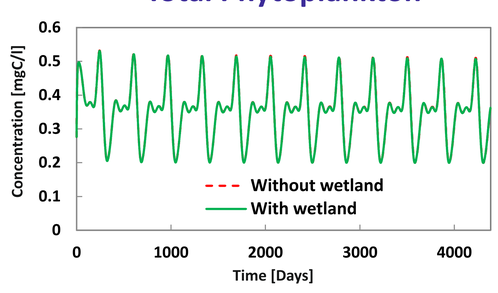
$$C^L \le C \le C^U$$

$$0 \le F_{Wetland} \le 0.5 F_{Divisorio}$$

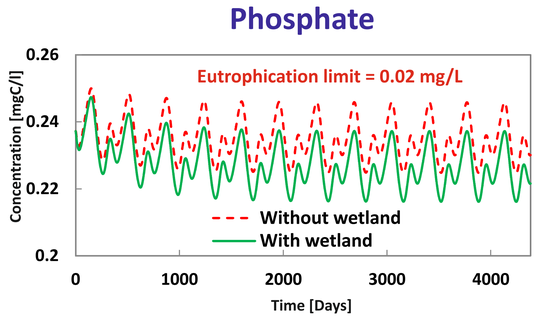
$$SR^L \le S_m\,Removal \le SR^U$$

CVP approach (gPROMS, PSEnterprise)

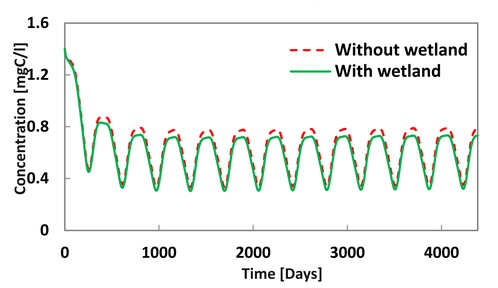
Total Phytoplankton



Phosphate

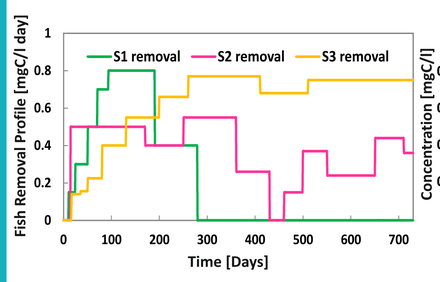


Nitrate

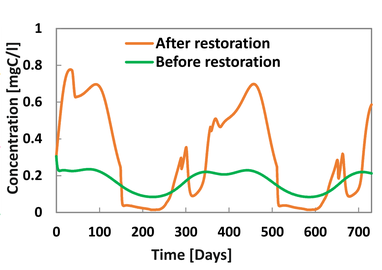


Time Horizon: 12 years

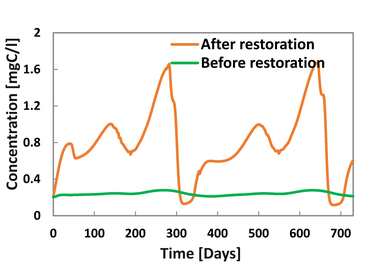
Fish Removal Rate



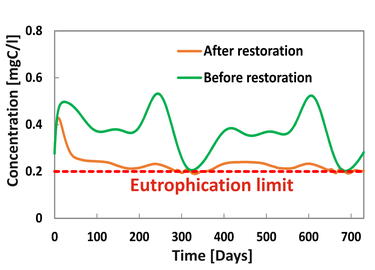
Zooplankton: Cladocera



Zooplankton: Copepoda



Total Phytoplankton



Time Horizon: 2 years

Conclusions

-**Optimal control problem to plan short/middle term restoration in a highly eutrophic reservoir with hybrid ecological water model.**

-**Need for simultaneous external nutrient loading reduction and biomanipulation.**

-**Process systems engineering approaches have proved to be effective for determination and planning of restoration strategies.**

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