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Towards the development of a biogeochemical model for addressing the eutrophication problems in the shallow hypertrophic lagoon of Albufera de Valencia, Spain

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ABSTRACT

Our study presents a biogeochemical model that aims to reproduce the ecological processes shaping phytoplankton dynamics in the shallow hypertrophic lagoon of Albufera de Valencia (Spain). The model simulates two elemental cycles (N and P), two phytoplankton groups (cyanobacteria and non-cyanobacteria), and heterotrophic bacteria. First, we examine the capacity to reproduce the observed plankton patterns, while accommodating the uncertainty related to the external forcing factors of our model (hydraulic and nutrient loading, zooplankton grazing). Sensitivity analysis is also performed to identify the most influential parameters and therefore to shed light on the knowledge needed to solidify the model parameter specification. We subsequently utilize the calibrated model to assess the phytoplankton response to potential restoration actions; namely, the interplay between external nutrient loading reductions and variant flushing rates. The model successfully simulates a number of relevant water quality variables in the system, including total chlorophyll *a*, nitrate, ammonia, total nitrogen and total phosphorus. According to our sensitivity analysis, the credibility of the model as a management tool is primarily dependent upon the characterization of the phytoplankton growth strategies and associated settling rates. External P and N loadings are identified as the predominant driver of the system dynamics and their control should remain the main priority of local management efforts. Finally, we pinpoint future research directions that could advance our understanding of the ecosystem functioning, including an improved quantitative description of the seasonal variability of the hydraulic regime in the studied lagoon.

1. Introduction

Shallow lakes are the most abundant lake type at the global scale (Wetzel, 1990). The lack of stratification during extended periods in the summer and the tight water column-sediment coupling are predominant features of this type of water bodies (Scheffer et al., 1993). Many of these systems support significant economical and recreational activities, such as agriculture, fishing, bird watching, boating or tourism (McNeary and Erickson, 2013; Postel and Carpenter, 1997). However, an increasing number of shallow lakes worldwide has been subject to a variety of degradation processes, with the most profound being the cultural eutrophication (Dodds et al., 2008; Smith, 2003). The ramifications of shallow lake eutrophication usually comprise a wide range of detrimental changes in the food web structure and water biogeochemistry, but possibly the most conspicuous effects are the reduction in water transparency, the excessive increase in primary productivity, and the increased frequency of algal blooms, usually dominated by cyanobacteria that may be toxic or inedible (Carpenter et al., 1998; Smith et al., 2006).

The control of phosphorus (P) and nitrogen (N) exogenous loading has been shown to effectively alleviate the severity of eutrophication (Jeppesen et al., 2005; Schindler, 2006). In shallow lakes though, where the sediment surface to water volume ratio is high, the intense sediment-water column interplay aggravates the eutrophication problem and (most importantly) results in a considerable time lag in their response to the reduction of external nutrient loading (Søndergaard et al., 2003). Sediment resuspension, driven by both wind action and bioturbation, is responsible for a sizable reflux of nutrients into the water column. Likewise, the elevated amount of P retained in the sediments is subject to diagenesis processes and gets mobilized to the interstitial waters as phosphate, subsequently returning into the water column through Fickian diffusive transport (Søndergaard et al., 2003). Many of the associated sediment processes (e.g., bacteria-mediated mineralization) display seasonal variation, with their maximal rates typically observed during the summer period when the highest water temperatures occur (Søndergaard et al., 2003). Alongside with the P control, recent studies have also emphasized the importance of reducing N loading in temperate shallow lakes. For example, high N ambient levels can prevent the establishment of a clear-water state in shallow temperate lakes at moderately high ambient TP, but may play a lesser

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role at very low TP concentrations (González Sagrario et al., 2005). Likewise, low nitrogen availability has been identified as a critical condition for the maintenance of macrophyte dominance at intermediate to high TP levels in the shallow Mediterranean Lake Eymir, Turkey (Beklioglu et al., 2003). Thus, recognizing the uncertainty of restoration efforts that solely focus on external nutrient loading reductions, the contemporary eutrophication management paradigm has evolved to include biological or hydrological manipulations as complementary strategies to accelerate system restoration (Gulati and van Donk, 2002). For example, early work highlighted the importance of the causal linkage between water residence time and phytoplankton productivity or other eutrophication symptoms (Dickman, 1969; Dillon, 1975). Since then, numerous studies have described a negative relationship between flushing rates and phytoplankton biomass in eutrophic shallow lakes, pinpointing the reduction of water residence time by flushing as a potentially effective restoration action (Jagtman et al., 1992; Moustaka-Gouni et al., 2006; Padisák et al., 1999).

According to the alternative stable states theory, shallow eutrophic lakes can oscillate between two alternative equilibria: a clear water state characterized by high water transparency and submerged macrophyte vegetation, and a turbid state dominated by phytoplankton with little or absent macrophyte cover (Scheffer et al., 1993). Albufera de Valencia, a warm-temperate shallow oligohaline lagoon, was populated by rich submerged vegetation during the first half of the 20th century (Pardo, 1942). Following intense eutrophication processes throughout the 1960s, the system shifted from a clear into a turbid stable state which was consolidated by the virtual disappearance of macrophytes in the early 1970s (Vicente and Miracle, 1992). The latter turbid state has prevailed since then, although short-term clear-water events, with chlorophyll *a* concentrations below 5 μg L^{-1}, intermittently offer a different perspective of the dynamics of this shallow coastal lagoon (Miracle and Sahuquillo, 2002; Romo et al., 2005). These events are largely dependent upon the hydrological regime and are characterized by a drastic increase in water transparency which lasts for a short period (up to five weeks), reduction of phytoplankton biomass, and change in the plankton community composition, with decline of cyanobacteria and increase of chlorophyte and diatom abundance, concomitant to large cladocera (*Daphnia magna*) abundance increase (Onandia et al., 2014b; Sahuquillo et al., 2007).

Nonetheless, the short duration of these events, together with the lack of macrophyte resurgence, represent fundamental differences relative to the clear-water alternative stable states typically characterizing shallow lakes (Scheffer et al., 1993). Further, the timing and causes of clear-water events in Albufera de Valencia appear to differ from most descriptions in the limnological literature. In the majority of shallow eutrophic lakes, clear-water phases typically occur in spring and are triggered by zooplankton grazing (Dröscher et al., 2008; Lampert et al., 1986; Tõnno et al., 2003), although other factors such as climatic forcing could be relevant (Dröscher et al., 2009; Tirok and Gaedke, 2006). In Albufera de Valencia, clear-water phases are experienced in the winter and are mainly driven by a suite of factors, such as: i) the intense "flushing" induced by the draining of the rice paddies in the surrounding watershed, leading to the reduction of phytoplankton biomass by its direct export from the lagoon into the sea; *ii*) the mild water temperatures that enhance the net growth of *Daphnia magna*; and *iii*) a decrease in fish predation on zooplankton, stemming from the annual maximum catch rates by local fishermen during the same period (Romo et al., 2005). These factors, along with the low light availability and suboptimal water temperatures for algal growth, magnify the top-down control of phytoplankton biomass by herbivorous zooplankton. However, these favorable conditions do not last for long, very likely because of the intense fish predation on zooplankton exerted by *Liza aurata* Risso and *Cyprinus carpio* L. during the spring, which is a recurring pattern in subtropical and southern temperate shallow lakes and lagoons (Blanco et al., 2003; Romo et al., 2005 and references therein). Of equal importance is that the water flow through the lake is drastically reduced after the rice paddies are drained, favoring the re-establishment of cyanobacteria dominance.

In an attempt to improve the water quality of the lagoon, a sewage purification plan was implemented during the 1990s, resulting in a significant nutrient input reduction; namely, 77% in TP and 24% in TN (Romo et al., 2005). This improvement was translated into a notable reduction in chlorophyll *a* levels (from 270 to 180 μg L^{-1}), but cyanobacteria dominance still remains a thorny issue (Romo et al., 2005, 2008). More recently, several surface constructed wetlands have been developed (Tancat de la Pipa, Tancat de Mília and Estany de la Plana), but their current functioning does not necessarily maximize the removal of phytoplankton, phosphorus and nitrogen (Martín et al., 2013). Thus, in spite of all the management actions, the system arguably remains hypertrophic. According to the Ecoframe scheme (Moss et al., 2003), Albufera de Valencia is still in a bad ecological status and additional actions should be undertaken to ameliorate ecosystem recovery.

In this regard, the goal of the present modeling study is to reproduce the interplay among the ecological processes that shape the planktonic patterns in the coastal shallow lagoon of Albufera de Valencia. Ecological modeling represents a useful tool to elucidate the physical and biogeochemical processes underlying the local eutrophication problems and to design management plans that effectively balance between environmental concerns and local socioeconomic values (Usaquén Perilla et al., 2012). The N and P cycles as well as the dynamics of two phytoplankton groups (cyanobacteria and non-cyanobacteria) and heterotrophic bacteria are simulated by the model. We present the results of the calibration and validation exercise and examine the ability of the model to reproduce the observed plankton patterns in Albufera de Valencia, while accommodating the uncertainty of the external forcing factors. Sensitivity analysis is performed to identify the most influential parameters for the phytoplankton simulations. We conclude by pinpointing knowledge gaps and recommending future research directions.

2. Materials and Methods

2.1. Study Site-Data Collection

Albufera de Valencia is an oligohaline (salinity ≈ 1 ‰) lagoon located at the Mediterranean coast, 15 km south of the city of Valencia (Spain). It has a mean depth of ≈ 1 m and covers an area of approximately 24 km^2. This shallow system is currently characterized as hypertrophic, with average annual chlorophyll *a* levels of 167 μg L^{-1} (4 – 322 μg L^{-1}), Secchi disk depth of 0.34 m (0.18 – 1 m), total phosphorus (TP) of 155 μg L^{-1} (41 – 247 μg L^{-1}), and total nitrogen (TN) of 3.9 mg L^{-1} (1.8 – 6.6 mg L^{-1}). Similarly, the primary productivity is remarkably high, varying between 1 – 12 mg C m^{-2} d^{-1} (Onandia et al., 2014b). The lagoon is surrounded by a 223 km^2 area primarily used for rice cultivation. Numerous irrigation ditches cross the rice paddies and flow into the system, discharging nutrient and organic matter loadings. Three outlet channels or "golas" with sluices connect the lagoon with the Mediterranean Sea, separated only by a 500 − 1000 m wide sand bar, thereby allowing water level regulations. Thus, the water requirements of the rice culture predominantly shape the hydrological cycle of the lagoon. In mid-autumn, the rice paddies are flooded without culture. In the winter, there is a major period of high water renewal rate driven by the draining of the flooded paddies. During the spring period, the dry paddies are prepared for rice sowing in May; at that point, the paddies are flooded again, defining the beginning of a period of low water renewal rate that lasts throughout the rice growing season. Rice is harvested in late summer (mid-September) and thereafter, a secondary period (end of September - October) of moderately high water flow takes place until the paddies are flooded again. The lagoon, the surrounding paddies, and the sand bar, characterized by two parallel dunes covered by Mediterranean vegetation, form the "L'Albufera de Valencia Natural Park", which has been included in the Ramsar List of