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Investigation of factors affecting the trophic state of a shallow Mediterranean reconstructed lake

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ABSTRACT

In this article, we focus on shallow sub-tropical lakes and study the factors that determine their trophic state and food web structure. We use the model PCLake to simulate lake nutrient dynamics and investigate key factors causing eutrophication, such as in-lake nutrient cycling, long residence time and low depths. Modeling results are validated in a reconstructed lake that is also used as a reservoir located in central Greece. Various operational scenarios and their effect on lake trophic state are explored. A climate change scenario is also presented, showcasing its influence on lake nutrient dynamics and food web structure. Our results confirm that lake residence time, lake depth and nutrient inflows are the factors that determine the lake trophic state, while climate change seems to slightly intensify the mechanisms that establish lake eutrophic conditions.

1. Introduction

Mediterranean shallow lakes exhibit specific hydrological, chemical and biological patterns (Beklioglu et al., 2007) that concern hydrological regimes, nutrient cycling and meteorological conditions that, in turn, define its food web and trophic state through multiple complex interrelations. A typical Mediterranean climate, characterized by cool but mild winters and arid and hot summers has relatively low annual precipitation that is unequally distributed throughout the year—with 65% or more of the annual precipitation confined to the winter season (Aschmann, 1973). Especially when the lake is used as a reservoir to meet seasonal local water demand, the annual variability in precipitation causes intense water level fluctuations and changes in lake hydrology (Naselli-Flores and Barone, 2003). Such changes affect, among others, macrophyte (Coops et al., 2003; Beklioglu et al., 2006, 2007) and phytoplankton growth (Naselli-Flores, 2003), invertebrate and fish community structure and abundance (Leira and Cantonati, 2008; Özen et al., 2010; Bucak et al., 2012), as well as photosynthesis, respiration and mineralization rates (Beklioglu et al., 2007). The year-around intense sun light in the Mediterranean region may enhance macrophyte growth (Romo et al., 2004; Meerhoff et al., 2003), which can play a key role in the stabilization of a clear-water state (Scheffer, 1998; Jeppesen et al., 1997), while on the other hand, low water level in shallow lakes activates wind-driven sediment resuspension, a mechanism working against clear-water state stabilization.

The trophic structures of warm lakes vary markedly, depending on meteorological conditions, such as precipitation and temperature, as well as lake age and continental or coastal location (Jeppesen et al., 2007). High temperature affects both the growth and grazing rates of zooplanktivorous fish (Bachmann et al., 1996), while the latter tend to be more selective in the size of zooplankton they are consuming (Lazzaro, 1997). Large-sized zooplankton species tend to decrease, weakening the control of phytoplankton (Lazzaro, 1997; Fernando, 1994), especially when the competitive role of macrophytes on nutrient uptake is counteracted. Lastly, among phytoplankton species, potentially toxic cyanobacteria are more likely to prevail in subtropical lakes (Romo et al., 2004). This trophic cascade effect would naturally—and in addition to the climate and nutrient cycling regimes—function as a stabilizing mechanism to the turbid state of the lake. Indeed, a Mediterranean shallow lake demands a significantly greater drop in nutrient loading, compared to a temperate shallow lake, in order to alter from a turbid to a clear and macrophyte-dominant state (Romo et al., 2005).

Recently, Jeppesen et al. (2015) investigated the impact of climate change on the function and biodiversity of lakes and concluded that the increase in salinity and drop in water level that

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results from global warming will ultimately make lake ecosystems less resilient, or even lead to a shift in a turbid water state. These impacts are expected to be exaggerated for the water scarce and arid Mediterranean region (Sánchez et al., 2004). Decrease in precipitation and run-off and increase in temperature and, as a consequence, in water abstraction to cover agricultural needs are highly correlated to the reinforcement of eutrophic conditions (Moss et al., 2011). Low water levels and high retention times in shallow lakes lead to high nutrient concentration and high salinity, thus to more frequent or intense algal blooms, that are often harmful (Papadimitriou et al., 2013). This kind of climatic and anthropogenic phenomena already occur and are expected to occur even more intensely in the Mediterranean (Erol and Randyr, 2012; IPCC, 2007, 2014).

Lake ecosystem modeling is of critical importance for identifying and understanding the principles of a lake, as it provides a coarser quantification of the major drivers, namely, nutrient loading, hydrology, climate and the interrelations between biotic and abiotic components. Throughout the past decades, extensive work on different modeling approaches provides a great variety of adequate tools, at least on the purpose of defining basic lake processes. A 2010 review of several lake ecosystem models (Mooij et al., 2010) classifies different types of models based on their structure, while evaluating their ability to capture biotic or abiotic processes, such as the ones related to phytoplankton, zooplankton, benthic, fish, macrophytes, stratification, sediment, hydrodynamics, temperature dynamics, nutrient loading, internal nutrient recycling and other.

In this article, we investigate factors related to the trophic state and food web structure of a shallow Mediterranean lake. As a case study, we use a shallow lake in central Greece (Lake Karla), which is a reconstructed lake and is classified as a heavily modified water body used as a reservoir with an operational regime that affects its trophic state. Ecological modeling is conducted with the PCLake model and its suitability in capturing the peculiarities of the ecosystem is assessed. Moreover, the influence of climate change on the ecosystem is explored. The objective of this study is to identify and quantify the most important factors affecting the lake trophic state, to evaluate how various operational schemes affect lake water quality, food web structure and trophic state and to investigate what the effect of climate change is on the lake.

2. Methods

2.1. Study Site: Lake Karla, a shallow Mediterranean lake and reservoir

Lake Karla is a reconstructed lake in the Thessaly plain (Fig. 1), one of the most productive agricultural regions in central Greece and crucial for the Greek economy. Lake Karla and the adjacent areas are considered of high ecological importance, which is reflected by their designation as a Natura 2000. Before its drainage, it has always been a shallow lake that was rich in fish and a habitat for hundreds of birds (Gerakis and Koutrakis, 1996). The lake had a surface area fluctuating from 45 to 180 km^2; the recorded lake depth in 1956 was about 2.5 m (Ananiadis, 1956), while in the 1930s the depth varied from 4 to 6 m. It was acting as a natural reservoir recharging the underground aquifer and the lake is suggested to have been important for regulating the local microclimate (Gialis and Laspidou, 2014). Following the general trend in the 60s, lake Karla was drained and converted to agricultural land; however, a series of negative consequences would later prove that the drainage was a major ecological, financial and cultural misstep (Gialis and Laspidou, 2014). The lake was finally refilled in 2010 in an attempt to mitigate the negative impacts of its drainage.

The drainage of Lake Karla resulted in a series of negative consequences for the region of Thessaly. These include the change of local microclimate, reduction of aquifer water level, sea water intrusion in the aquifer resulting in groundwater salinization, lack of drinking and irrigation water, flooding of farmed areas, surface erosion, pollution of the adjacent Pagasitikos gulf, loss of habitat for endangered European birds and overall reduction in the number of farmers in the area (Gialis and Laspidou, 2014). The reconstructed reservoir would have a limited surface area of approximately 38 km^2, as defined by the Greek Ministry of Environment, Physical Planning and Public Works (YPEHODE, 1999). The study included plans for works that would allow the lake to both function as reservoir for irrigation and as an ecosystem. The works included: 1) two ditches with a pump that transfers water from Pinios River and an agricultural run-off to the lake, 2) a run-off collector network that would divert run-offs from surrounding mountains into the reservoir, 3) an irrigation network and 4) an artificial wetland adjacent to the lake that would partially retain inflow nutrients. Today, the works are still not completed with obvious consequences for ecology and hydrology: the construction of run-off collectors is incomplete; as a result, there is limited water inflow to the lake from the catchment area. Inflows to the lake—namely, Pinios river water and agricultural run-off—are loaded with nutrients since the artificial wetland is not operational yet.

According to the original plans, the main outflow from the lake would be water pumped out for irrigation purposes; irrigation works remain incomplete and the only outflows from the lake are infiltration and evaporation, which means a practically infinite retention time, leading to a progressive increase in salt content of lake water (Meybeck, 1995). Increases in lake salinity often significantly alter the community composition of phytoplankton, zooplankton, macrophytes and fish and often result in reduced biomass and lake biodiversity (Jeppesen et al., 2015). Due to the aforementioned mismanagement practices, which reflect the complex socio-political situation in Greece, the lake faces both a vital water shortage, with its average level falling down to 1 m or even lower and a phenomenal boost in primary production resulting in a hyper-eutrophic lake. These hypertrophic conditions, followed by extensive and persistent toxic cyanobacterial blooms prevailing in the lake, coincided with two consecutive massive fish kills in March and April of 2010 (Oikonomou et al., 2012; Papadimitriou et al., 2013). Lake Karla has no macrophytes and this fact, along with its very low depth that enforces the wind-induced sediment resuspension mechanism, enhances the establishment of a stable turbid state. In Table 1, the specific biotic characteristics, regarding fish biomass, phytoplankton biomass, and breeding bird abundance are presented.

To better comprehend the peculiarities of Lake Karla, one needs to recognize the factors that affect its hydrology, ecology and trophic state, such as climate, water level and water management regime. Being both highly affected by anthropogenic pressures and being a key-player for the region in terms of local economy, environment, culture and politics, Lake Karla has a strong societal influence that has made the need to understand its natural mechanisms imperative. Several massive fish kill incidents and ephemeral detection of high concentrations of microcystins through the period 2010- 2014 (Papadimitriou et al., 2013), have reinforced the demand to clarify the factors related to the eutrophication conditions prevailing in the lake and the aforementioned incidents.