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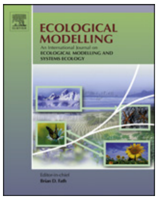

Implementation of ecological modeling as an effective management and investigation tool: Lake Kinneret as a case study

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ABSTRACT

The need for scientifically based management of lakes, as key water resources, requires the establishment of quantitative relationships between in-lake processes responsible for water quality (WQ) and the intensity of major management measures (MM, e.g. nutrient loading). In this paper, we estimate the impact of potential changes in nutrient loading on the Lake Kinneret ecosystem. Following validation of the model against a comprehensive dataset, we applied an approach that goes beyond scenario testing by linking the lake ecosystem model DYRESM–CAEDYM with a set of ecosystem variables included in a pre-assessed system of water quality indices. The emergent properties of the ecosystem predicted from the model simulations were also compared with lake data as a form of indirect validation of the model. Model output, in good agreement with lake data, indicated differential effects of nitrogen and phosphorus nutrient loading on concentrations, and major in-lake fluxes, of TN and TP, and dynamics and algal community structure. Both model output and lake data indicated a strong relationship between nitrogen loading and in-lake TN values. This relationship is not apparent for phosphorus and only a weak relationship exists between phosphorus loading and in-lake TP. The modeling results, expressed in terms of water quality, allowed establishment of critical/threshold values for the nutrient loads. Implementation of the ecological modeling supplemented with the quantified set of WQ indices allowed us to take a step towards establishment of the association between permissible ranges for water quality and major management measures, i.e. towards sustainable management.

1. Introduction

The need for management of water resources (in contrast to their passive exploitation) reflects an understanding that these resources are not infinite and have limited stability under anthropogenic forcing. The European Union, for example, charges the Union and Associated Members to establish a set of managing measures to reach "good" status of the national fresh waterbodies by 2015 and to introduce basic principles of sustainable management of water resources (Water Framework Directive, WFD, 2000).

The task of water resource management can be formulated (Kalceva et al., 1982; Straskraba and Gnauck, 1985) as optimization of an objective function:

$$Q = f(\mathrm{MM};\ \mathrm{WQ};\ \mathrm{CB}) \qquad (1)$$

where the state variable Q, representing the management goal, is a function of the management measures (MM) encompassing economical activity in the lake watershed (estimated as nutrient and pollutant loading) and intensity of water resource use such as water supply, water quality (WQ), and economic effectiveness of the management (costs versus benefits, CB). All parameters of the objective function are interconnected and therefore, for example, management measures are a function of water quality and economic effectiveness. Determining the relationships between the various parameters in Eq. (1) (MM, WQ, CB) should be a central task for establishing a scientifically based water resource management strategy. In reality, however, this is rarely performed.

Almost all potential threats to lake water quality (WQ hereafter) are associated with water resources use and management (Kira, 1983), and in this context the management measures from Eq. (1) are frequently considered as synonyms of the environmental threats. In the Framework Directive (WFD, 2000) it is assumed, implicitly, that eutrophication and toxic pollution are the key factors affecting WQ and therefore improvement efforts should focus on these two processes. In the United States, eutrophication accounts for about half of the impaired lake areas, 60% of the impaired river reaches, and is the most widespread pollution

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problem of estuaries (USEPA, 2002). The signs of WQ deterioration due to eutrophication are well known: decrease of water transparency, increase of algal biomass, shifts in algal communities to cyanobacteria, and deoxygenation of bottom layers. Eutrophication is considered a direct consequence of excessive nutrient (mostly phosphorus) loading (Dillon and Rigler, 1975; Vollenweider, 1976), and in most cases reduction of the nutrient loading due to restriction and/or modification of economical activities in a lake watershed, such as reduction in fertilizers in agricultural areas, is thought as the prime remedial solution for deteriorating WQ.

Changes to stable biogeochemical cycles are an underlying element of WQ deterioration (Gasith and Gafny, 1990; Wetzel, 1990). This becomes especially obvious when considering the ecological consequences of water over-abstraction from lakes (Kira, 1983). Changes in lake level can lead to changes in circulation and other physical processes resulting in increased water mixing, and increased resuspension of bottom sediments enriched with nutrients (Oganesian and Parparov, 1989; Hakanson et al., 2000).

Recognizing the necessity to conserve aquatic ecosystems at some desirable state, or at least preventing further WQ deterioration, led to the development of the concept of sustainable management. In this paper, we define sustainable water resource management as the utilization of water resources that allows conservation of quality of these resources within assessed permissible ranges bound by permissible limits of water quality and management measures (Parparov et al., 2006). Water quality indices and the appropriate rating values have been defined for a series of parameters for Lake Kinneret using the Delphi method (Brown et al., 1970; Hambright et al., 2000).

Assessment of a sustainable management policy requires establishment of the relationships between WQ and MM such as nutrient loading and pumping of water from the lake. There are two ways to establish such relationships: statistical analysis of existing long-term databases, and ecological modeling of the interactions between MM and lake ecosystem functioning. Unfortunately, only a limited number of sufficiently long-term and detailed databases exist. In addition, the available information in the existing databases cover, in most cases, a relatively narrow range of observed variability of the variables measured in the lake and watershed. In contrast to this, process-based ecological models allow simulation of practically an unlimited range of variability of MM and the ecosystem variables. Existing databases and the observed relationships between various variables can play an important role in validation of the modeling results. In this context, ecological models and limnological studies are interconnected with feedbacks, and form the best self-improving tool for investigation and management of water resources (Parparov and Hambright, 1996).

Water quality modeling is a tool applied to the management of lakes as they provide a means to study and understand physical, biological and chemical processes in highly complex ecosystems. The use of models in planning, designing and testing management strategies has become increasingly common since the 1980s (Friedman et al., 1984). The use of such models allows the manager to study, for example, the causes and consequences of lake eutrophication and potential remedial actions (Tufford and McKellar, 1999). Models can, therefore, play both a role in enhancing the ecological understanding of a lake and as a management tool (Straskraba, 1994). The effectiveness of such models, however, are dependent on the accuracy of the model in simulating the ecosystem in question and its ability to accommodate the observed variability at a scale of interest to the scientist or manager (Beck et al., 1997; Arhonditsis and Brett, 2004). It is essential that the model, applied to the ecosystem in question, captures the variability in the biological and chemical properties over the time scales of interest (Jorgensen, 1999).

A model that simulates key ecological state variables (e.g. phytoplankton biomass) in response to a wide range of environmental factors in a lake, will inevitably require a large number of rate parameters, as well as information on the boundary forcing to the system (e.g. meteorology, inflows and outflows). This information is often not readily available for most lakes. Lake Kinneret, however, has been the subject of intensive studies over the past 40 years (e.g. Serruya, 1978; Berman et al., 1992; Shlichter, 1996; Nishri et al., 1998) and these studies have provided a wealth of information on the lake, including a long-term database from a routine monitoring program, with a focus on variations in major biological and chemical variables.

While the available information for Lake Kinneret is comprehensive, it is not necessarily sufficient to study the interactions between MM and WQ empirically, as the observed natural variability is limited in its range. In this paper, we first apply and validate a coupled one-dimensional (1D) ecosystem model, DYRESM–CAEDYM, to a historical dataset, and secondly, use the model to evaluate the impact of changes in watershed activity on the water quality of Lake Kinneret. In particular, we explore how changes to nutrient export from the watershed result in modification of the nutrient cycling dynamics in the lake. This is assessed by varying the loads into the lake of phosphorus (P), nitrogen (N) and the two of them in tandem (N&P) over the course of a 10-year period. In addition, scenario results were linked to water quality indices developed for Lake Kinneret as a tool for evaluating management measures.

2. Methods

2.1. DYRESM–CAEDYM (DYCD)

For simulation of hydrodynamics the study employs the Dynamic Reservoir Simulation Model (DYRESM), which is a one-dimensional Lagrangian model able to simulate vertical stratification dynamics and which also parameterizes inflows and outflows and other mixing processes (see Yeates and Imberger, 2004) and has previously been applied to Lake Kinneret (Gal et al., 2003). DYRESM couples dynamically with the Computational Aquatic Ecosystem Dynamics Model (CAEDYM), which has been described previously for freshwater lakes (Romero et al., 2004; Bruce et al., 2006; Burger et al., 2007; Trolle et al., 2008). An earlier version of DYCD with a simplified configuration was applied to Lake Kinneret in order to evaluate the role of nutrient recycling by zooplankton in the lake (Bruce et al., 2006). The present CAEDYM configuration however is more sophisticated than these earlier studies and it has been extended to simulate the carbon, nitrogen, phosphorus, and oxygen cycles along with several phytoplankton, zooplankton and bacteria groups (Fig. 1).

In this application, five phytoplankton groups were simulated: *Peridinium gatunense* (*Peridinium* hereafter), the filamentous freshwater diatom *Aulacoseira granulata* (*Aulacoseira* hereafter), a N-fixing cyanobacterial group (e.g. *Aphanizomenon* sp.), a non-N-fixing cyanobacterial group (e.g. *Microcystis* sp.), and a general group, termed nanoplankton, considered to represent a multi-taxon group of nanoplanktonic species. The model also simulated three zooplankton functional groups (predators, grazers, and micro-zooplankton) and a single heterotrophic bacterial group. This ecological configuration was considered to resolve most of the observed seasonal biogeochemical variability. The C, N and P contents of phytoplankton were dynamic in the model, and each phytoplankton group was modeled by 3 state variables (internal C, N and P, denoted A, AIN, and AIP), thus requiring 15 state variables to model the phytoplankton assemblage, while the homeostatic zooplankton and bacteria required a single state variable per group. In addition to those, four dissolved inorganic nutrients (FRP, NO_3, NH_4, DIC), three dissolved organic matter (DOC, DON, DOP) and