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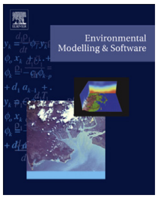

Defining limits to multiple and simultaneous anthropogenic stressors in a lake ecosystem – Lake Kinneret as a case study[☆]

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ABSTRACT

In this study we expanded a recently developed approach for defining acceptable levels of management policy that will allow sustainable management of water quality in a lake ecosystem. A three dimensional solution space was created to define all acceptable scenarios of N loads, P loads and lake water level (WL) thus providing an integrated tool for defining the extent of measures that will allow lake ecosystem sustainability. The approach included use of a lake ecosystem model, a quantitative system of composite water quality indices (CWQIs) and defined sustainability criteria for the ecosystem. The approach was tested on the Lake Kinneret (Sea of Galilee) ecosystem and succeeded in defining the range of acceptable management policy through the use of long term simulations of different scenarios. Using the results of the scenarios, a number of polygons were created, defined as relative solution domain area (RSDA), which denote the permissible ranges of nutrient loads at different water levels. The polygon, and hence RSDA, boundaries represent critical values of nutrient loads allowing conservation of the lake water quality at each WL. By integrating all RSDA, a three dimensional solution space was created which defines all acceptable ranges of N loads, P loads and WL thus providing lake managers with an integrated tool for defining the extent of measures that will allow sustainability of the lake ecosystem. This novel approach is unique, and presents an example of implementation of a management tool that integrates an ecosystem model, multiple stressors and quantified water quality indices to determine limits of management actions. This approach may well be implemented to other lakes around the world suffering from water quality deterioration as a result of changes in water level and nutrients loads.

1. Introduction

Deterioration in lake water quality as a result of anthropogenic activities is a worldwide concern (Wang, 2001). Anthropogenic activities in watersheds leads to the appearance of various point and non-point sources of agricultural, industrial, and sewage pollutants, especially nutrient loading (Berman, 1998; Wang, 2001). In addition, different regimes of water extraction for water supply can result in large changes in the morphometric parameters of the lake (e.g. the ratio of the epilimnion depth to the hypolimnion thickness) caused by drastic changes to the lake water level. Fig. 1, depicts over 100 lakes around the world suffering from deterioration in water quality as a result of these two types of anthropogenic activities: changes in water level and increased nutrient loads. This stresses the need to further explore the issue.

As water is more intensively used and as water quality deteriorates, there is an increasing need for improved decision-making processes to manage water quality and quantity, from both an ecological and economic point of view (Priazhinskaya, 2002; DeJong et al., 1996). In addition, the implementation of the EU Water Framework Directive (WFD) entails the development of appropriate tools to improve water quality and declares the need for introduction of basic principles of sustainable management of water resources (WFD 2000).

The concept of sustainable management was developed from recognizing the necessity to conserve aquatic ecosystems at some desirable state, or at least preventing further water quality (WQ) deterioration (e.g. Parparov and Gal, 2012). Loucks and Gladwell (1999) defined sustainable water resource systems as systems that will be able to satisfy the changing demands, that will inevitably be placed on them, without significant system degradation.

Abbreviations: CWQI, combined water quality index; RSDA, relative solution domain area; WFD, water framework directive; WL, water level; WQ, water quality; WQI, Water quality index.

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Parparov et al. (2006) claimed that sustainable water resource management is the utilization of water resources that allows conservation of quality of these resources within assessed permissible ranges bound by permissible limits of WQ and management policy.

Sustainable management requires establishment of relationships between WQ and activities that are a result of lake and watershed management actions such as nutrient loading and pumping of water from the lake (Gal et al., 2009). Quantitative assessment of WQ is an essential aspect of efficient water resource management (Banerjee and Srivastava, 2009). The concept of a water quality indices (WQI), which express water quality by aggregating the measurements of water quality parameters, has been developed in many countries and found to be effective in evaluating composite water pollution levels (Lumb et al., 2011). Pescem and Wunderlin (2000) developed two WQIs using 3 and 20 parameters for evaluating spatial and seasonal changes in the water quality from the river in Coardoba City, Argentina, and nearby locations. They mentioned that the use of the WQI is a simple practice which allows the public and decision makers to receive water quality information, and in addition it permits assessment of changes in the water quality and to identify water trends. Since 1990 a WQI system has been used by several water authorities in New Zealand as a planning tool and as a simple means of disseminating water quality information (Smith, 1990). Bordalo et al. (2006) modified a nine-parameter Scottish WQI to assess the monthly water quality of the Douro River Spain–Portugal during a 10-year period (1992–2001). The authors noted the need for developing ecological sound management strategies as stated in the WFD (WFD 2000).

Hambright et al. (2000) developed a system of water quality indices for Lake Kinneret (Sea of Galilee, Israel) based on various chemical, physical and biological parameters that are monitored routinely in the lake. The parameters selected for the WQI system provide an overall picture of many of the ecosystem's processes. In this system, WQ, which is mainly impacted by human activities, is expressed by metrics that allow analytical expression of relationships between WQ and various management policy measures, and in relation to a reference state. As the acceptable ranges of the WQI were determined to ensure lake conditions similar to those found during the reference period, the WQI system's measurable parameters express *sustainability criteria* for the lake. The water quality indices were later aggregated into a composite water quality index (CWQI, Parparov and Hambright, 2007), which is a weighted sum of the individual parameters ratings. Hence, through the use of the CWQI it is possible to determine the limits of management actions that will allow sustainable use of the lake and its ecosystem. Recently, Parparov and Gal (2012) suggested a methodological framework for sustainable lake management based on ecological monitoring, a quantified system of WQ indices, and a lake ecosystem model, DYRESM-CAEDYM (DYCD). Combining the quantified WQ system and DYCD provided a means for establishing and verifying the quantitative relationships between WQ and major management policy measures, with data obtained from the ecological and WQ monitoring. This allowed Parparov and Gal (2012) to establish direct correspondence between desired ranges for WQ and permissible ranges for the management measures and thus to outline the sustainable management policy for Lake Kinneret based on N and P loads.

In this paper, an approach for defining an acceptable management policy based on sustainability criteria is demonstrated by studying the combined effect of changes to nutrient loads and water levels on WQ and the ranges that allow sustainability of the ecosystem in question. In doing so, we expand on the application of this approach from a two-factor issue that included nitrogen and phosphorus loading (Parparov and Gal, 2012), to a three-factor issue that includes also lake level. This approach is tested on the Lake Kinneret ecosystem and defines the range of acceptable management policy measures through the use of long term simulations of different scenarios. In addition, we attempt to study the system sensitivity to increasing intensity of the management actions by extending the range of scenarios beyond the acceptable management policy.

Though this study focuses on Lake Kinneret, the management approach shown here is not lake specific. Therefore the approach we demonstrate here could be implemented to other lakes around the world suffering from deterioration in water quality as a result of anthropogenic activities such as changes in water level and nutrients loads.

2. Materials and methods

2.1. Lake Kinneret

Lake Kinneret is a warm-monomictic lake located at an elevation of about −210 m (i.e. 210 m below mean sea level) in the northern part of the Dead Sea Rift Valley (part of the Afro-Syrian Rift Series). The limnology of the lake is well documented (Serruya, 1978 and others). The lake is 22 km long and 12 km at maximum width; maximum and mean depths are 44 and 24 m, respectively, and its surface area is 170 km^2. Lake Kinneret is meso-eutrophic with a mean annual primary production of 650 g C m^{-2} (Berman et al., 1995). Since the mid-1990s the lake ecosystem has undergone a number of significant changes that are most likely linked to lake, or watershed, management (Zohary, 2004; Gal and Williamson, 2010; Zohary and Ostrovsky, 2011). Further details on the basic ecology of the lake, prior to these changes, can be found in Berman et al. (1995).

2.2. Models description

2.2.1. Water quality approach

The determination of the acceptable management policy for Lake Kinneret, was based on sustainability criteria represented by the water quality indices (WQI) and composite water quality index (CWQI) developed specifically for Lake Kinneret (Hambright et al., 2000; Parparov and Hambright, 2007). Ten parameters that are monitored routinely in the lake were chosen by a panel of experts to be those by which water quality will be evaluated (Table 1). The parameters selected for the WQI provide an overall picture of many of the ecosystem processes.

At the initial stage, the correspondence between the WQI value (e.g. total suspended solids concentration) and a numeric Rating (R) was established in the form of a rating curve, by standardizing water quality parameters to a 0–100 scale ($0 < R < 100$), assuming conservation is the prime objective for the management of Lake Kinneret. The rating curves were then presented in the analytical form using linear approximations. Acceptable ranges for the separate water quality indices were restricted to the range 60–100. The WQI system was designed based on a basic understanding that proper management of Lake Kinneret implies preserving an ecosystem that conforms to a predefined reference state, corresponding to conditions when all major uses were satisfied. The reference state was defined as the condition of the lake during the period of 1969–1991 (Hambright et al., 2000). Individual water quality indices were aggregated into a composite water quality index (CWQI), which is a weighted sum of the individual parameters ratings (Parparov and Hambright, 2007). The CWQI was weighted by assuming that the lower a rating value the higher is its relative weight.

2.2.2. DYCD model and setup

The one-dimensional hydrodynamic-ecological coupled models DYRESM-CAEDYM (DYCD) were developed at the Centre for Water Research, University of Western Australia (Hipsey et al., 2006; Bruce et al., 2006). DYRESM is a 1-D hydrodynamic model for predicting the vertical distribution of temperature, salinity and density in lakes and reservoirs (Imberger and Patterson, 1981; Gal et al., 2003). In DYRESM, the lake is represented as a series of homogenous horizontal Lagrangian layers of variable thickness; as inflows and outflows enter or leave the lake, the affected layers expand or contract, respectively, and those above move up or down to accommodate any volume change (Bruce et al., 2006). Mass, including that of the ecological state variables, is adjusted conservatively each time layers merge or are affected by inflows and outflows. The main processes modeled in DYRESM are surface heat, mass and momentum transfers between the layers, mixed layer dynamics, hypolimnetic mixing, benthic boundary layer mixing and inflows and outflows. Local meteorological data are used to determine penetrative heating due to short-wave radiation and surface heat fluxes due to evaporation, sensible heat flux, long-wave radiation and wind stress. The model provides the means for simulating the daily behavior of the surface layer and the seasonal and inter-annual variability of the lake as a whole. DYRESM requires only minimal calibration to a specific lake or reservoir to which it is being applied.

The ecological model, CAEDYM, explicitly models the inorganic, organic, phytoplankton and zooplankton components of carbon, nitrogen and phosphorus; it

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