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Dealing with uncertainty in ecosystem model scenarios: Application of the single-model ensemble approach[☆]

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ABSTRACT

Complex ecosystem models are often used as a tool for resource managers in the application of ecosystem based management. The uncertainty associated with these models is a major stumbling block in their acceptance as a management tool. Yet, conducting a rigorous uncertainty analysis of complex models is often not feasible. We present an alternative approach to assessing the impact of parameter uncertainty on the outcome of management scenarios on a lake ecosystem. We applied the single-model ensemble approach to the ecosystem model DYRESM–CAEDYM and Lake Kinneret, Israel. We introduced uncertainty to parameters and conducted an ensemble of simulations for three scenarios. Despite the large degree of uncertainty in parameter values the trends in ecosystem response were consistent with those observed based on calibrated parameter values. The variation in results allowed us to estimate the consequences of parameter uncertainty on lake resource management without the need for a comprehensive uncertainty analysis.

1. Introduction

Ecosystem-based management (EBM) is not a new concept and its value and importance has long been recognized, however, its implementation has been slow (Slocombe, 1993). EBM is required in order to sustain the ecosystem over time while securing the services humans want and need (Link, 2010). One of the challenges in applying EBM is the lack of confidence surrounding our understanding of the functioning of the ecosystem in question and the likely response given various management measures. Ecosystem models have been used to reduce this limitation and to provide insight into ecosystem functioning and relationships between internal processes and external forcing (Link et al., 2012; Rose et al., 2010). They provide resource managers with the ability to examine the ecological and economic efficiency of the measures planned to achieve a predefined objective such as the Water Framework Directive “good status” (Bärlund et al., 2007; Plagányi, 2007; Volk et al., 2009). Ecosystem model output and predictions are, however, perceived as uncertain suffering from variable degrees of error thus limiting their wider application as a key tool in the development and application of EBM (Link, 2010).

Aquatic ecosystem models tend to be complex models comprising of tens of state variables and hundreds of parameters. This is because of the belief that complex models parameterize numerous processes and theoretically have the potential to be a more accurate representation of the natural ecosystem. This is due in part to the large number of tunable parameters and higher degree of freedom when calibrating the model. A large number of state variables does not, however, necessarily ensure a higher degree of accuracy (Arhonditsis and Brett, 2004) and may lead to model over-parameterization which can result in misinterpretation and poor prediction performance (Jakeman et al., 2006).

The results of complex models, for example lake ecosystem models, often suffer from limitations due to various sources of error and uncertainty such as the initial conditions, input data, model structure, model parameters, validation data, etc. (Beck, 1987). Numerous studies have suggested approaches and frameworks to confronting uncertainty in models (Refsgaard et al., 2007) especially those serving as decision-support tools (Halpern et al., 2006; Regan et al., 2005; Walker et al., 2003). Refsgaard et al., (2007), for example, list 14 different methods for assessing the various sources of uncertainty associated with water resource models and Halpern et al. (2006) review several approaches to incorporating uncertainty into modeling marine reserve design. In complex models,

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however, it is extremely difficult to independently quantify each of these sources of uncertainty and error, let alone their combined effect (Tebaldi et al., 2005). A large source of model uncertainty is associated with the calibrated parameter values (Beck, 1987). Parameter uncertainty results in increased uncertainty in model predictions, the degree of uncertainty of a particular prediction depending to a large extent on the uncertainty of the parameters to which it is most sensitive (Gallagher and Doherty, 2007). By recognizing the existence of parameter uncertainty, we explicitly accept that the search for a single set of parameter values that reproduces the observations of a dynamic ecosystem is not a reasonable expectation (Reichert and Omlin, 1997). Furthermore, as a consequence of the parameter uncertainty, ecosystem models are often perceived as not sufficiently reliable as a management tool.

It is therefore crucial that an uncertainty analysis is conducted for natural resource management applications (Jakeman et al., 2006). However, quantifying parameter uncertainty and the resulting predictive error is not trivial especially with complex ecosystem models. With large complex models, uncertainty analyses are often prohibitively computationally intensive, and/or require a high level of quantitative skills that are not always readily available. Nevertheless, uncertainty analysis of mechanistic models has received substantial attention in aquatic ecosystem research in recent years including attempts to rigorously address parameter uncertainty (Arhonditsis et al., 2007; Brun et al., 2001; Omlin and Reichert, 1999; Rigosi and Rueda, 2012; Spear and Hornberger, 1980).

There are diverse approaches for estimating and quantifying uncertainty of the various model components affecting model outcome (Walker et al., 2003; Helton et al., 2006). In general it is possible to define the various approaches into two categories: the frequentist and Bayesian approaches (Gallagher and Doherty, 2007). The latter assumes some knowledge about the parameters is available to the modeler prior to calibration and regards model parameters (or at least knowledge of them) as random and thus possessing probability distributions (Arhonditsis et al., 2008). The frequentist approach, on the other hand, sees unknown parameters as fixed and attempts to estimate them through the calibration data-set. Regardless of the approach and methodology used the methods become extremely challenging when applied to complex models that include hundreds of parameters and dozens of state variables (Smith, 2002). We therefore attempt to circumvent this issue by taking a different approach in assessing the impact of parameter uncertainty of a complex lake ecosystem model on the outcome of management scenarios.

A multi-model ensemble approach in which a given scenario is simulated with a series of models is popular among the climate change community (IPCC, 2007). The use of a multi-model ensemble can help quantify initial conditions, parameter and structural uncertainties in the model design (Tebaldi et al., 2005). While the use of the ensemble approach will not provide a unique answer or response (e.g. how much warmer will the lake be in 50 years?) it will increase the reliability of the results (Velázquez et al., 2011). The use of an ensemble approach requires, however, multiple models. In practice, the existence of multiple models is rarely found for a given lake ecosystem. In cases, however, where a single model is not available for a given ecosystem, a single-model ensemble approach can be used (Palmer et al., 2004; Taylor, 2001). The application of an ensemble approach using a single model can provide resource managers with an assessment of the reliability of model management scenarios given parameter uncertainty. In this approach multiple simulations are conducted with the same model, for a given scenario, while parameter values are varied between simulations. As the ensemble approach can be computationally taxing it is important to carefully select the simulations to be conducted. The ensemble of simulations allows determination of a range of results for each scenario. This range of results will reflect the variation in parameter space. It is then possible to establish whether the management scenario outcome is consistent across all simulations regardless of the possible errors in parameter values. A consistent ecosystem response over a large parameter space, in relation to a particular management action (i.e. scenario), will increase model reliability and strengthen the conclusions derived from the model results.

We examine this approach by applying a calibrated ecosystem model to Lake Kinneret, Israel, which due to its importance is intensively managed. The lake provides approximately 30% of the country's freshwater needs, thus maintaining water quality is of prime importance. The EBM of the lake includes an intensive monitoring and research program, advanced modeling, and active management measures. Lake management measures include nutrient loading reduction, water level manipulation, saline springs diversion, fisheries regulation and stocking and shore-line development regulation (Markel and Shamir, 2002). Over two million tourists visiting the lake and its basin annually along with a population increase of 1–2.5% per year in the cities and communities around the lake, result in a significant pollution load reaching the lake. Furthermore, the watershed is primarily used for agriculture including orchards, field crops, fishponds, cowsheds, and cattle-grazing areas. This determines the main watershed pollutants: nutrients, pesticides, and pathogenic bacteria (Parparov et al., 2013). One of the two prime concerns facing the resource managers is the increasingly frequent nuisance cyanobacteria blooms (Zohary et al., 2012). Cyanobacteria blooms are indicators of an eutrophication process where nutrient loading (mainly nitrogen and phosphorus) is traditionally considered to be responsible for this process. And indeed the Israeli Water Authority, the body in charge of managing the lake and its' watershed, has worked towards controlling and reducing loading into the lake. The reduction in nutrient loading was expected to affect nuisance algae such as cyanobacteria that are usually phosphorus limited (Sukenik et al., 2012). Due to the importance and popular use of manipulation of nutrient loading as a prime management measure, we focus our scenarios on the impact of changes to nutrient loading on the ecosystem.

In this paper, we use the single-model ensemble approach to study the impact of model parameter uncertainty in a complex lake ecosystem model (DYRESM–CAEDYM) on the results of management scenarios using the calibrated model for Lake Kinneret, Israel. Thus, we are implicitly assuming the calibrated version represents the best possible reflection of reality attainable with the model. The underlying assumption in our work is that consistent trends in the response of the simulated ecosystem to the management scenarios across a wide range of parameter values (the ensemble of simulations in this study) indicate robust model output. Furthermore, consistency between the simulated trends based on the calibrated parameter values and the trends resulting from a wide range of parameter values suggests that parameter uncertainty has only a minor impact on model outcome. And as a consequence, the model can be used as a reliable management tool.

2. Methods

2.1. Model

We use the 1-D hydrodynamic-ecological model, DYRESM–CAEDYM (DYCD), developed at the Centre for Water Research, University of Western Australia, to study a series of management scenarios for Lake Kinneret, Israel. DYCD simulates the hydrodynamic and the biogeochemical dynamics of aquatic