Review

A review of recent developments in lake modelling

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ABSTRACT

This paper reviews the lake models published the last five years, mainly in Ecological Modelling. The review shows that structurally dynamic modelling and coupling between hydrodynamic and ecological models are applied increasingly. A number of processes that have not been included in lake models before have been proposed. It has been shown that these additional processes in specific case studies are significant, for instance the competition between phytoplankton and macrophytes or cyanobacteria growth and growth of mussels. It is recommended to study these models for the development of models for case studies where these processes are relevant.

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1. Introduction

Lake models, that describe eutrophication processes were developed for environmental management already in the seventies. Models with a wide spectrum of complexity were applied for environmental management during the eighties and nineties; see for instance the overview of eutrophication models in Jørgensen and Bendoricchio (2001). From the beginning of the eighties, it has been possible to find a suitable eutrophication models applicable to almost any lake with an available data set. This does not imply that better and other additional lake models should or could not be developed and applied in environmental management context. Recently, lake models have focused on expanding the disciplinary domain by coupling hydrodynamic and the ecological processes. Models of particular food webs, that have not been applied before in lake modelling, have been developed. Structurally dynamic models that consider adaptation and shifts in species composition have been applied in a number of case studies.

A number of lake model case studies can be found on Internet. They represent mostly new applications of an already developed and published lake model from the seventies, eighties or nineties.

This paper reviews, however, only the new lake models that have been published the last five years. Ecological Modelling has for more than a decade had the policy not to publish "old" models applied on new case studies, but only new models. The review is therefore mainly based on papers published the last five years in Ecological Modelling in our attempt to answer the following three questions:

- What have we learnt in lake modelling the last five years?
- Which progress has recently been made in lake modelling?
- What can lake modelling offer environmental management today?

2. Review of important lake modelling papers published the last five years

Zhang et al. (2008) published an interesting two-dimensional eutrophication model of Lake Erie, characterized by

(1) a two-dimensional coupling between hydrodynamics and the ecological processes,
(2) detailed submodels of zooplankton and
(3) inclusion of the impact of zebra and quagga mussels.

The model has 18 state variables and was acceptably validated. The model study shows the importance of having a detailed zoo- plankton model and how to include the impacts of mussels. If the

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points (2) and (3) are of importance for the eutrophication, it can be recommended to apply the equations from this model study.

Bartleson et al. (2005) have developed a model that supported data from microcosm data. The model focuses on the competition between epiphytic algae and submerged plants in the presence of grazers. The model results show that the initial concentration of submerged plants is very important for the final state of eutrophication. The results fit with the general experience of recovering shallow lakes by planting submerged vegetation and with the use of structurally dynamic models to describe the competition between phytoplankton and macrophytes (Zhang et al., 2003a,b). The competition between submerged plants and algae is important for the improvement of the water quality in shallow lakes. The model is recommended and applied if a shallow lake is going to be restored by planting submerged plants. The model could probably be improved further by making it structurally dynamic by use of exergy as goal function, as shown in Zhang et al. (2003a,b).

Roth et al. (2007) have developed a model that looks into the role of woody habitat in lake food web. Trees fall into lakes from riparian forest and become habitat for aquatic organisms. The entire food web may thereby be changed. The production of benthic invertebrates prey is promoted and the fallen trees are refuge for prey fishes, which are consumed by piscivorous fishes. The presented model includes external processes, for instance input of allochthonous energy sources that may lead to large shifts in the lake fish communities. The paper demonstrates how these processes can be included in a model, if it is relevant for a lake case study.

It has previously been shown that terrestrial ecosystems develop energetically according to a Michaelis–Menten like equation relating exergy destroyed versus exergy stored; see Jørgensen (2000). Jørgensen (2007) has shown that it is also the case for aquatic ecosystems, although different aquatic ecosystems have a different carrying capacity. Lakes have a carrying capacity of about 6 kg detritus/m² y or 112 MJ/m² y.

In 2007 Mulderij and coworkers also developed a model focusing on the competition between submerged aquatic macrophytes and phytoplankton. In their competition description they include shading effect, sediment resuspension, competition for nutrients and allelopathy. Their study concludes that S. aloides that is floating on the water surface has a major shading effect and has a high allelopathic potential, while the relative contribution of allelopathy and shading is low or negligible for charophytes. If a shallow lake study has floating species of macrophytes, then it is recommended to include in the description of the competition between submerged aquatic macrophytes and phytoplankton the equations as presented in this paper.

Thapanand et al. (2007) use Ecopath to develop a model for the management of multi-species fishery. The model is useful for optimization of multi-species fishery, as well as showing the potential importance of the preservations of littoral zones for the fishery.

Also in 2007 Bergamo and coworkers combined extensive satellite-based measurements with a modelling approach that considers both spatial and temporal dynamics of Lake Tanganyika. Empirical orthogonal function analysis was used to find regions with similar temporal co-variation of phytoplankton biomass. The study made it possible to link phytoplankton dynamics to climatic changes. The found shifts confirm the high sensitivity of the lake to climate change. The model study offers new approaches to developing of large lake models under changing climatic conditions.

Zhao et al. (2008) have examined a number of improvements for eutrophication models:

(1) use of multiple nutrients cycles (P, N, Si, C and O);
(2) multiple functional phytoplankton (diatoms, green algae and cyanobacteria);
(3) inclusion of two zooplankton groups: copepods and cladocerans;
(4) the use of the recent advances in stoichiometric nutrient recycling theory, which allows one to examine the effect of food quality.

The model results indicate that all the four points offer significant model improvements, provided that the parameterization particularly of the zooplankton processes is reliable and robust.

Mukherjee et al. (2008) have developed a pond model, focusing on the carbon cycle. The carbon cycle is usually not included in detail in eutrophication models, but this model study shows that the nutrients processes are dependent of a proper and detailed description of the carbon cycle. This approach could have wide application in the general development of eutrophication models.

Villanueva et al. (2008) have developed an Ecopath model for Lake Kivu to quantify the impact of invasive fish species. This model could be used to quantify the impact on phytoplankton, zooplankton, other fish species and the fishery, whenever fish species are introduced to a lake.

Petahi and Mengistou used Ecopath in 2007 to develop a model for Lake Awassa in Ethiopia. The quality of lake model predictions is highly dependent on the quality of the data used for calibration and validation. This model study demonstrates how it is possible to develop an Ecopath model on even a relatively poor data set by using existing literature and the Ecopath facilities to estimate several of the most crucial parameters. The limited amount of data in developing countries often makes it difficult to construct reliable lake models in spite of the urgent need for good lake models to aid in environmental management. This paper indicates a good solution to this problem.

Mieleitner and Reichert (2008) have modelled the functional groups of phytoplankton in three lakes of different trophic state. They consider four functional groups with different parameters in the model: F1 consists of small flagellates, small diatoms and small green algae. F2 encompasses large diatoms, while F3 are large green algae, blue green algae, large chrysophyceae and dinoflagellates. The last group, F4, consists of Planktothrix rubescens. The model results demonstrate that functional group modelling is useful for our understanding of the lake ecosystems and the characteristics that are decisive for the response to different nutrient impacts. The predictability of the model is, however, poor at the functional group level, which is in accordance with the discussion of structurally dynamic modelling in Jørgensen (2002).

Mieleitner and Reichert (2006) have examined the transferability of biogeochemical lake models and have shown that it is possible to transfer their model with the functional phytoplankton groups from one lake study to another by changing only three parameters based on a careful calibration using a good data set. The authors conclude that the attempt to make models more general seems to be achievable to some degree for biogeochemical models.

Hense and Beckmann (2006) have modelled the life stages of cyanobacteria. They consider four life stages: vegetative cells, vegetative cells with heterocysts, akinetes and recruiting cells including germinates. The model assumes that the life cycle is governed by the internal energy and nitrogen quotas of the cells. The study indicates that prediction of cyanobacteria blooms has to be based on a detailed knowledge of all stages of the life cycle. It is for instance insufficient only to take temperature and P/N ratio into account. A relatively complex equation is applied for the temperature dependence of the main cell processes of cyanobacteria. The model study is an important step toward an improved understanding and a reliable prediction of cyanobacteria blooms. As prediction and occurrence of harmful cyanobacteria bloom is an important task of environmental management, it is recommendable to pursue the ideas presented in this paper.
Reid and Crout (2008) have developed an interesting model of freshwater Antarctic lake ice. Freshwater lake ice is affected more by air temperature than any other variable and is therefore a useful indicator of climate changes. The model performs well and can obviously be used to follow the climate changes and compare different climate change scenarios.

Brynh and Blencker (2007) have focus on the nitrogen fixation in Lake Erken and conclude that nitrogen fixation is unlikely ever to be limited by the nitrogen concentration in the lake water. Elliott et al. (2007) have developed a model for Lake Erken based on a coupling of a hydrophysical model and an ecological model. The main conclusion of their model study is that a coupling of a model focusing on the hydrology with a model focusing on the ecological processes shows a successful validation and can generally be recommended.

Rivera et al. (2006) have published an energy system language model of Broa Reservoir. The model study demonstrates how the energy system language developed by H.T. Odum can be used advantageously to obtain a more detailed overview of the state variables and their interactions in lake modelling.

Bruce et al. (2006) have demonstrated the importance of a good description of zooplankton processes to achieve a reliable lake eutrophication model. Both the grazing rate and the nutrients excretion rates were important parameters that should be determined on the basis of good primary data, literature and estimates of the nutrients cycling.

Hu et al. (2006) have developed a three-dimensional model for Lake Taihu in China, that is prepared for the use of the structurally dynamic approach.

Malmaeus et al. (2006) have developed a mechanistic phosphorus model, which has been applied on three sites. The model results have shown that the lakes have different sensitivity to climate changes, which is explained by the different water residence time.

Vladusic et al. (2006) have used what is called Q2 learning (Qualitatively faithful Quantitative prediction) to interpret lake eutrophication data and they claim that their approach is comparable to competing methods in terms of numerical accuracy and give good insight into domain phenomena.

Zhang et al. (2003a,b) have developed a structurally dynamic model, that is able to explain the hysteresis in vegetation shifts for shallow lakes between phytoplankton dominated lakes and lakes dominated by the submerged vegetation. Such shifts are obviously particular challenge for the structurally dynamic approach. The hysteresis in shifts between a zooplankton dominated structure and a structure dominated by phytoplankton and planktivorous fish was previously explained by the use of structurally dynamic models (Jørgensen and de Bernardi, 1998). The model was in this case able to predict the shifts from submerged vegetation to phytoplankton at about 250 mg P/m^3 and again from phytoplankton at about 100 mg P/m^3 which is in agreement with the observations by Scheffer et al. (2001). The structurally dynamic approach was in this case also applied to improve the calibration, because a shift in species composition usually take place in lakes from spring to summer to autumn.

Zhang et al. (2004) have also examined the validation results that can be obtained by eutrophication models that were tailored from case to case and general models that were offered as ready-to-go-software on the one side and between general biogeochemical eutrophication and structurally dynamic models on the other side. They concluded, that the structurally dynamic approach offers slightly better validation mainly due to the possibilities to consider seasonal changes in the calibration. They could on the other hand also concluded that the tailored model offers better validation results than the ready-to-go-software models, although the difference was minor if the two models were using the same data bases.

Gurkan et al. (2006) have applied the structurally dynamic model on the restoration of a lake (Lake Fure, Denmark) by biomanipulation and aeration of the sediment—an obvious case for a structurally dynamic model, because of major shifts in phytoplankton. Zooplankton and planktivorous fish could be foreseen.

Fragoso et al. (2008) have developed a model that by coupling of hydrodynamics with the ecological processes is able to describe the spatial heterogeneity in a large shallow subtropical lake in Brazil. The model represents the advantages that are achieved by a better integration of the hydrodynamic and ecological components in lake modelling. The model was able to identify zones with a higher potential for eutrophication, which of course is crucial in environmental management.

Generally, it is more common to see models that integrate hydrodynamics and ecological processes today than a decade or two ago. Moreover, there has been a tendency to integrate a watershed model with a lake model to be able to coordinate environmental strategies for the lake with environmental management for the entire watershed. Zhang and Jørgensen (2005) have for instance for the UNEP lake modelling software Pamolare included a watershed model, that is able to work together with a simple lake model or a structurally dynamic lake model with a medium to high complexity. They found it easy to apply the results from the watershed model to assess the nutrient loadings (the most crucial forcing functions) in the lake model.

### 3. Discussion and conclusions

Four papers present lake models using a structurally dynamic modelling approach. All papers conclude that this model type offers the possibilities to consider the structurally changes—adaptation and shifts in species composition. The model type can be recommended to improve calibration, validation and prognoses, when it is known that structurally dynamic changes take place. One of the models combined a three-dimensional model with a structurally dynamic model. Generally, three-dimensional lake models are more widely applied today than a few years ago.

A paper is showing that the use of artificial intelligence – in this case Q2 learning (Qualitatively faithful Quantitative prediction) – offers a good additional insight.

A number of changes from the more classic eutrophication models have been tested to account for a number of processes, that in some case studies may be of importance. It is recommended to use these changes whenever tailored models are developed for case studies where the processes have relevance. The following processes have been tested in modelling context:

1. Use of multiple nutrients cycles (P, N, Si, C and O).
2. Multiple functional phytoplankton (diatoms, green algae and cyanobacteria), although in many cases it is probably giving better results to use structurally dynamic modelling; see for instance the discussion in Jørgensen (2002).
3. Inclusion of more zooplankton groups for instance: copepods and cladocerans and other more complex zooplankton models.
4. The use of the recent advances in stoichiometric nutrient recycling theory, which allows to examine the effect of food quality.
5. Competition between phytoplankton and macrophytes. Structurally dynamic modelling offers also in this case a good alternative as it is able to consider the hysteresis response of competition to changed conditions.
6. Woody habitats in lakes where fallen trees are important.
7. Cyanobacteria is a serious problem in many lakes and it is therefore not surprising that there has been an increased
interest in modelling this problem. It is recommended to use the detailed model of this problem proposed by Hense and Beckmann (2006). It would be beneficial for modelling this crucial problem to get a wider test of their model as it seems that it offers a good modelling solution.

(8) Nitrogen fixation has been modelled differently from the approach applied in classic eutrophication models, where it was considered a first order reaction governed by the lack of nitrogen by nitrogen fixing species.

(9) Mussels as important filter feeders in the lakes.

(10) Use of 3D models and coupling between hydrodynamic models and ecological models or between watershed models and lake models.

Multi-species fishery models are increasingly applied. The experience with these models is generally good and points toward a wider application in the future, which is promising for the management of fishery.

The overall conclusion from the review of the lake models papers published the last five years is that the integration of hydrodynamic models and ecological models has continued. Furthermore, the latest published structurally dynamic models confirm that this model type offers a good solution to cases where adaptation and shifts in species composition are important. Moreover, there has been an increasing interest for modelling the impact of climate changes on lakes. The review confirms also that the general trend in modelling, that a wider experience in incorporating more and more different details, that are often useful in specific cases, is continuing. It is therefore recommendable whenever a new model problem emerges to examine and to study carefully the relevant modelling experience.

References


