DEVELOPMENT OF DECISION-MAKING TOOLS FOR EUTROPHIC LAKES

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Summary

Hydrodynamic, biogeochemical and water-quality (transport) numerical models to simulate processes in eutrophic lakes are described giving 1) a general introduction, including some history of development, 2) structures and equations of selected models, and 3) application of the models to hindcast and forecast dissolved oxygen deficiency under weak stratification, cyanobacterium blooms, and the effect of phosphorus control. Submodels important for shallow lake simulations such as phosphorus exchange between water and sediment and SS are also included. Finally, some topics desirable for further development of the models are summarized.

1. Introduction

Human-induced eutrophication has been studied mainly for deep lakes, which usually exhibit a remarkable year-to-year regularity in behavior, and the processes influencing this behavior are quite well known. On the contrary, the phenomenon of eutrophication is more irregular in character and less satisfactorily understood for shallow bodies of water, which are often the most common lake type in lowland countries. In deep lakes, an average chlorophyll-a (*chl-a*) concentration in summer can be estimated as a linear function of total phosphorus concentration at spring overturn in the water column. This simple relationship can be established because mineralized nutrients in the hypolimnion can only return to the epilimnion after the turnover.

In contrast, the intense sediment-water interaction in shallow lakes causes a continuous return of bottom materials into the water column, making such a simple interpretation impossible. Furthermore, a high algal biomass yield can occur even when the nutrient concentration in the water column is low, as observed for example at Lake Biwa in Japan and Lake Balaton in Hungary. In these lakes, available nutrient is rapidly uptaken by phytoplankton, leading to the low concentration of the nutrient in the water column. The nutrient supplied through rapid recycling of nutrients from the bottom sediment as well as through bacterial decomposition in the water column sustains the algal growth. After a long duration of external nutrient loading, the nutrient stocked in the bottom sediment may become the main nutrient source as observed in Lake Balaton, and as found in shallow Dutch lakes. In addition, the phytoplankton population in shallow lakes is often limited by light, not only because of self-shading of phytoplankton but also because of the re-suspension of the bottom sediment. The bottom sediment, therefore, plays a crucial role in the ecological system in shallow lakes.

As remarked by Jørgensen et al., the development of computer science has rendered it feasible to view such complex systems as ecosystems with many interacting variables and processes. This article describes the development of numerical models, which can be applied as decision-making tools, for eutrophication lakes, especially shallow lakes, through environmental fluid dynamics and ecological studies.

2. Dynamic Lake Models

Figure 1 shows wind-induced mixing in a basin and biogeochemical processes in a compartment of a shallow lake schematically. An appropriate dynamic model needs to be created to simulate such unsteady processes, which occur in response to meteorological conditions, nutrient loading, and inflow and outflow. The processes can be divided into three elements: the mixing of lake water, transport of constituents, and biogeochemical reactions of the constituents. Model components corresponding to these elements are hydrodynamic, transport, and biogeochemical models, respectively. The relationship between the components can be structured as in Figure 2. The biogeochemical model, also termed a 1-box model, is applicable to simulate phytoplankton population dynamics in water, which can be assumed to be a completely mixed tank. It can be incorporated into a transport model as sink/source and reaction terms to form a water-quality model, which has spatial resolution. Velocity fields are calculated with a single-layer model or a three-dimensional model. Since the final water-quality model output is obtained as a combined result of hydrodynamic, transport, and biochemical processes, calibration and verification of the models and model parameters should be carefully examined in each step.

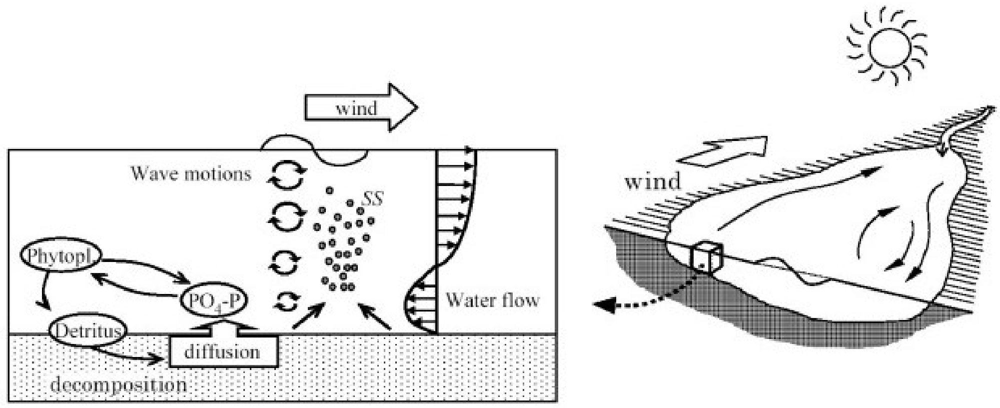

Figure 1. Schematic representation of major processes in a eutrophic shallow lake

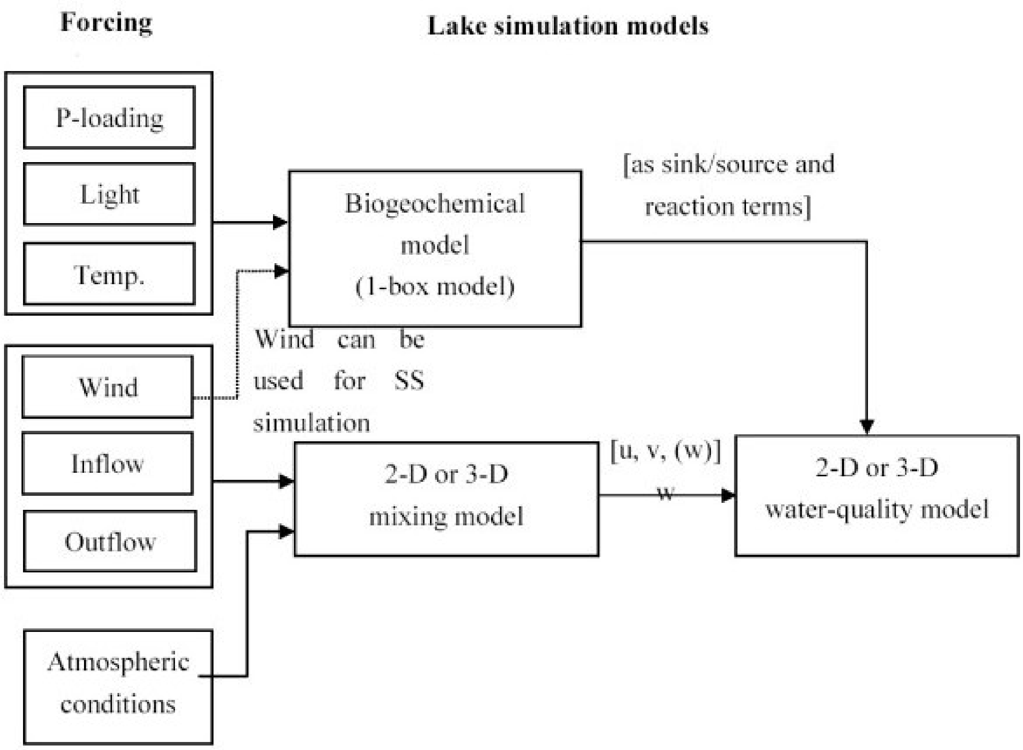

Figure 2. Lake simulation models and corresponding forcing terms

Development of the hydrodynamic models can be achieved deterministically based on the Navier-Stokes equation. Model parameters necessary to calibrate are limited to bottom friction coefficients and a wind drag coefficient (possibly plus some turbulence parameters). On the other hand, modeling the biogeochemical processes, including phytoplankton dynamics, requires an especially rigorous effort in a trial-and error process for finalizing the model as well as its calibration. In biogeochemical modeling, a more detailed model does not guarantee more accurate results. This is because biogeochemical modeling requires simplification of a complex system by aggregating similar processes and neglecting unimportant ones in a lake ecosystem. In the following sections, the hydrodynamics, biogeochemical, and water-quality models are described, giving for each a brief overview, formulation of a selected model, and application to a shallow eutrophic lake.

3. Mixing Models

3.1. Overview of the Mixing Models

Wind-driven lake mixing models, which can be linked to the water-quality models, may be categorized in three classes: single-layer models, multi-layer models, and three-dimensional models. Horizontal variation of constituents is essential information for water-quality management so that the single-layer model is still useful with much smaller computational cost than three-dimensional models. However, total volumetric transport does not provide information on vertical velocity profiles, and its application should be limited to an unstratified shallow basin where a water column can be assumed to be homogeneous.

Multi-layer models use hydrostatic assumptions simplifying a vertical momentum equation that results in much less computation time than for three-dimensional models. Multi-layer models can be divided into two types. The first type of models are a simple extension of the single-layer model, using a vertical grid dividing a lake into layers of constant density. The grid then follows the density layers, which move vertically in response to internal waves, seiches (rhythmic oscillation of lake water), and set up. Application of the models is limited to a lake that is strongly stratified and with no mass transport through the thermocline. The other type of model has been called a multilevel model; the positions of multiple layers are fixed in the vertical, and density is calculated at vertical grid-points, free to vary within each layer. This type of model has been extensively applied in Lake Ontario in Canada by Simons. Recent work using this kind of model was done by the University of Western Australia's Centre for Water Research (*http://www.cwr.uwa.edu.au/~hodges/elcom.html*).

The multilevel model has been further developed by incorporating a turbulence closure model, such as a k-epsilon model or Mellor and Yamada's model, to reproduce more realistic vertical turbulent mixing. Sigma-coordinate was also introduced to the layer models, where vertical grid positions vary according to changes of total depth according to surface elevation. The merit of this model is that fitting of the bottom grids to the bottom boundary can be automatically achieved because of its relative coordinate system. This model was originally applied to atmospheric simulations and oceanic currents by Blumberg and Mellor and the latest information on this model is available at http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/; it was later applied to Lake Kasumigaura in Japan as will be shown in the following section.

Application of three-dimensional models to solve lake hydrodynamics is not widespread, since the multilevel models are in most cases accurate enough with much less computer power requirement. However, the three-dimensional models should be applied when magnitude of vertical and horizontal velocity are comparable (e.g. fast current on steep bottom and a vertical jet, where hydrostatic assumption cannot be made). Their application may include simultaneous simulation of atmosphere and water, which can reduce errors arising from wind field generation based on data taken at a limited number of wind stations.

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Biographical Sketch

A. Hirayama The author took a B.Eng. in civil engineering from Kagoshima University, an M.S. in applied oceanography from the University of California, San Diego, and a D.Eng. from Saitama University. He has been working for Shimizu Corporation since 1982, while his main research topics are wave-structure interaction, hydrodynamic and water-quality problems of natural surface waters. He was involved in collaborative research projects for Lake Biwa and Lake Balaton.