History, development, and characteristics of lake ecological models

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Abstract: This paper provides some introductory information on the history, development, and characteristics of various lake ecosystem models. The modeling of lake ecological processes began to gain importance in the early 1960s. There are a number of models available today, with varying levels of complexity to cope with the variety of environmental problems found in lake environments, e.g., eutrophication, acidification, oxygen depletion, wetland management, heavy metal and pesticide pollution, as well as hydrodynamic problems. In particular, this paper focuses on lake eutrophication and wetland models, as well as addressing strategies appropriate for the design and development of reliable lake ecological models.

Keywords: lake ecosystem; eutrophication model; wetland model; pollution model

Introduction

Lake models and modeling have improved significantly since the 1960s. There are a number of factors behind this development. For the most part, however, the improvements have grown out of the need for sound, reliable measures to use in designing and applying lake pollution controls, the need to better understand lake ecosystems from a management perspective, and as a result of developments in computer technology. Today, there are a number of models with differing levels of complexity available to cope with the environmental problems in lakes, such as eutrophication, acidification, oxygen depletion, wetland management, heavy metal and pesticide pollution, as well as hydrodynamic problems. Several recent reviews of the various lake models have been published, including Orlob (Orlob, 1983) for one-dimension lake models, Watanabe et al. (Watanabe, 1983) for two- and three-dimension mathematical models, Jørgensen (Jørgensen, 1983; 1994b; 1995a; 1995b) and Jørgensen et al. (Jørgensen, 1995b) for various other lake models, Straskraba and Gnauck (Straskraba, 1985) for eutrophication models, Mitsch (Mitsch, 1983), Mitsch et al. (Mitsch, 1988), and Costanza & Sklar (Costanza, 1985) for various wetland models. These references provide a solid introduction to the variety of lake models in use today.

1 History, development, and characteristics of various lake models

1.1 Eutrophication models

Most lake models address the eutrophication issue. Most of the eutrophication models have been developed since the 1960s when the eutrophication of lakes around the world drew the attention of environmentalists. Since that time, the models have evolved from comparatively simple, single-layer, single-segment, single-constitute, and zero-dimension models to complex, multi-layer, multi-segment, multi-constitute, and three-dimensional models. Eutrophication models may be divided into four classes: very simple regression models; simple nutrient budget models; complex water quality-ecological-hydrodynamic models; and structural dynamic models. The characteristic features of the various lake eutrophication models are presented in Table 1.

1.1.1 Simple regression models

During the middle 1960s and early 1970s, some very simple regression models of lake eutrophication were proposed concerning the water quality and biology of lakes. They were based on large amounts of data
and tended to focus on the correlation between the phosphorous and chlorophyll-a concentrations (Sakamoto, 1966; Dillon, 1974; Jones, 1976). A few of the models were developed around the relationship between Secchi disc transparency and the chlorophyll-a concentration (Dillon, 1975). Regression models have proven fairly useful in three areas: (1) suggesting general trends in lake water quality (Charpa, 1977); (2) providing a quick assessment of water quality; and (3) introducing useful quantitative techniques to planners and decision makers who are not familiar with mathematical models and modeling concepts (Reckhow, 1979). However, because of their simplicity, they have only limited use as predictive tools when compared to models based on more accurate data and taking more processes into consideration. Their best use is in making preliminary, semi-quantitative estimates in cases supported by poor data, or as a first approximation prior to the development and application of a more complex model (Jøgensen, 1994b).

Table 1 The characteristic features of various eutrophication models

<table>
<thead>
<tr>
<th>Model type</th>
<th>Very simple regression models</th>
<th>Simple nutrient budget models</th>
<th>Complex ecological- water quality- hydrodynamic models</th>
<th>Structural dynamic models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main period</td>
<td>Middle 1960 - 1970s</td>
<td>In 1970s</td>
<td>Since middle 1970</td>
<td>Since late 1980s</td>
</tr>
<tr>
<td>Modeled problems</td>
<td>Relations between Chl-a and P or SD</td>
<td>Relations between nutrient in lake and input, output</td>
<td>Ecology Water quality Hydrodynamic Ecology + hydrodynamic Water quality + ecology + hydrodynamic Water quality + ecology + hydrodynamic</td>
<td>Changes in species composition or/and properties</td>
</tr>
<tr>
<td>Biological components</td>
<td>No</td>
<td>No</td>
<td>Several No or 1 - 2 No or 1 - 2 Several No or 1 - 2</td>
<td>Several</td>
</tr>
<tr>
<td>Substance components</td>
<td>P</td>
<td>P or N</td>
<td>P,N,C Many 1-many P,N,C Many Many P,N,C Si</td>
<td>Si</td>
</tr>
<tr>
<td>Hydrodynamics</td>
<td>No</td>
<td>No</td>
<td>Yes or no Yes or no Yes Yes Yes Yes Yes Yes or no</td>
<td></td>
</tr>
<tr>
<td>Thermal layers</td>
<td>No</td>
<td>1 - 2L</td>
<td>1 - 3L 1-many 1-many 1-many 1-many 1-many 1-many 1-many</td>
<td>1-many</td>
</tr>
<tr>
<td>Dimensions</td>
<td>No</td>
<td>0</td>
<td>0 - 1 0 - 1 1 - 3 1 - 3 1 - 3 1 - 3 0 - 1 0 - 1</td>
<td>0 - 1</td>
</tr>
<tr>
<td>Segments</td>
<td>No</td>
<td>1</td>
<td>1-many 1-many 1-many 1-many 1-many 1-many 1-many 1-many</td>
<td>1-many</td>
</tr>
<tr>
<td>Goal functions</td>
<td>No</td>
<td>No</td>
<td>No No No No No No No No</td>
<td>Yes</td>
</tr>
<tr>
<td>Typical examples</td>
<td>Note 1</td>
<td>Note 2</td>
<td>Note 3a Note 3b Note 3c Note 3d Note 3e Note 3f Note 4</td>
<td></td>
</tr>
</tbody>
</table>

A: nutrient/food web models; B: water quality models; C: hydrodynamic models; D: food web-hydrodynamic models; E: water quality-hydrodynamic models; F: water quality-food web-hydrodynamic models.


1.1.2 Simple nutrient budget models

During the 1970s, lake models were developed to describe the relationships between the nutrient concentration in lakes and nutrient loading from point sources, non-point sources, and lake sedimentation processes. Three important developments in lake eutrophication modeling took place during this period. The first was the incorporation of thermal stratification and the exchange of nutrients between the hypolimnion and the epilimnion into the models (Imboden, 1974; 1979; O’el, 1974; Snodgress, 1975; Imboden, 1978). The second concerns modeling of the phosphorus exchange between a lake’s water and its sediments (Imboden, 1974; 1978; 1979; Lorenz, 1976). The third development was the description of nutrient and biomass concentrations as continuous functions of time and depth using Michaelis-Menten
kinetics in place of traditional first-order kinetics (Imboden, 1978; 1979). However, all nutrient budget models deal with eutrophication in gross terms, i.e. with only one or two layers, long time scales, and only one governing nutrient. They pay little, if any, attention to short-term hydrodynamics, ecosystem dynamics, or the spatial resolution of water quality changes within the impoundment (Jørgensen, 1983).

1.1.3 Complex ecological-water quality-hydrodynamic models

Lake eutrophication models have seen rapid development since the middle 1970s. Many complex models with multi-constitute, multi-layer, and multi-segment components have been proposed based on the principle of mass conservation. Nearly all lake processes, including the physical, chemical, biological, ecological, and hydrodynamic, have been modeled. At present, there is no universal model detailed enough to describe the overall behavior of lakes. Based on certain behavioral categories, however, complex models may be classified into six groups that account for most of the modeling efforts. From these six groups there is a further concentration of effort devoted to nutrient cycling in the food web (nutrient/food web models) (Table 1 for examples). The GlumS® model developed by Jørgensen (Jørgensen, 1976) is typical of the ecological models addressing shallow, very eutrophic lakes. The GlumS® model, with 17 state variables, describes the cycling of nutrients (P, N, C, Si) within the entire food chain. It has two characteristic features: (1) a two-stage algal growth process instead of the simple Menten kinetic process, and (2) a more complex sub-model for the exchange of nutrients between the sediments and the water that distinguishes between exchangeable and non-exchangeable phosphorus. The phosphorus release process incorporated in the Jørgensen model consists of two-steps: (exchangeable phosphorus → interstitial phosphorus orthophosphorus in the water phase). The model has been applied in numerous case studies with slight modifications depending on site-specific needs (Jørgensen 1994b; 1995a for details).

The development of lake eutrophication models since the middle 1970s was summarized by Jørgensen as follows: (1) 3-D hydrodynamic models are available but are not necessarily the right answer to a given modeling problem (dependent on data availability); (2) models with a wide spectrum of complexities are available which make it possible to select a model type appropriate to the available data; and (3) models with general applicability (Jørgensen, 1983; 1995a). In nearly every case, however, it has been necessary to make slight modifications to account for variation in local conditions and data. For example, the GlumS® CLEANER, Luvsoe, LAKECO, and 3DWFGAS models all have been used with varying degrees of modification.

1.1.4 Structural dynamic models

Structural dynamic models have developed since the late 1980s. Ecosystems have the ability to adapt to changing environmental conditions (forcing functions) through modifications in their biological structure or through the adaptive ranges of tolerance in species characteristics. It is important for the models used in research and environmental management to reflect and account for the changes in property capabilities of ecosystems. Our present models, however, tend to be based on a given structure and fixed set of parameters. They do not possess the flexibility or adaptability present in real ecosystems. Constructing models that account for all species for the entire time period a study addresses is extremely difficult. The models quickly become complex, since they contain numerous state variables for each trophic level, and a large number of parameters all of which must be calibrated and validated (Jørgensen, 1994b; 1995b). As such, complex models will produce outcomes having high levels of uncertainty (Nielsen, 1992). Also, they may not accurately account for the continuously changing properties of a lake ecosystem (Fontaine, 1981).

In the future, models with a dynamic structure (structural dynamic models) may be able to more accurately address and hopefully solve such problems.

Structural dynamic models are able to account for changes in species composition as well as the ability of a species to adapt to changes in prevailing conditions, i.e. the degree to which the biological
components of our models can change their properties (Jørgensen, 1986). Their characteristic feature is the
use of goal functions to determine how to change the current parameters in a model to more accurately
express the adaptations and/or changes in species. Several goal functions have been proposed. Only a few
models, however, have been developed that account for changes in species composition or the ability of a
species to change its properties within some limits. Straskraba (Straskraba, 1979), for instance, used the
maximization of biomass as the governing principle in his model to describe changes in the properties of
phytoplankton species. Exergy has been widely used as a goal function in many ecological models. It has
also been used in a number of case studies, including seven lake studies, two population dynamic case
marine ecosystems studies (Bocci, 1997; Coffaro, 1997a; 1997b).

A summary of results from the various case studies indicates that: (1) it is possible to use models with
dynamic structure to describe changes in properties and structure; (2) these models require adequate data
and it is difficult to find such data that have recorded the changes in structure and property which are
necessary to validate the models properly, at least until more general experience have been achieved; and
(3) greater experience is needed in order to be able to offer more general conclusions about the approach.
The results look promising, but wider experience with several of the more practical applications of these
models is needed (Jørgensen, 1997).

1.2 Wetland models

Lake wetland models emerged in the middle 1970s and have developed rapidly since the early 1980s.
A wide spectrum of wetland models are available today, including energy/nutrient models, hydrological
models, spatial ecosystem models, process models, and causal models. A wide range of processes have
been modeled ranging from individual processes and the cycling of energy/nutrients in a wetland to
transformations and exchanges of water, pollutants, and energy in large regional ecosystems. The
characteristic features of various lake wetland models are presented in Table 2. Details from specific case
studies are available in Mitsch (Mitsch, 1983), Mitsch et al. (Mitsch, 1988), Costanza & Gruauk
(Costanza, 1985), and Jørgensen (Jørgensen, 1995a).

1.3 Other lake models

There are also a number of other models available that deal with lake acidification and toxic substance
pollution. Lake acidification models were developed to study the relationship between lake water pH and
the sulfur load (Henriksen, 1980; Reuss, 1983; Bobba, 1990), to understand adjustments in biological
behavior (Brown, 1981; Muniz, 1982), and to explore the hydrological and geochemical responses of and
within watersheds (Nikolaidis, 1994).

Workable ecotoxicological models have also been created for a few pesticides (e.g., DDT, methoxychlor,
PCB), as well as some heavy metals (mercury, lead, copper, zinc, and chromium). For further details of
the development, application, and results of lake acidification and ecotoxicological models, the reader should

2 Conclusions and discussions

The history, development, and characteristics of the various lake models illustrate the present
shortcomings in generalized lake modeling. As yet, there are no generalized models capable of coping with
multiple environmental problems, such as eutrophication, acidification, oxygen depletion, wetland
management, heavy metal and pesticide pollution, and hydrodynamic problems. We are able to prescribe,
however, detailed guidelines on modeling ecological processes in lakes. Papers detailing these modeling
procedures can be found in the literature and should be investigated for a more through understanding of their
advantages, disadvantages and limits (Jørgensen, 1980; 1994b).
<table>
<thead>
<tr>
<th>Model type</th>
<th>Main state variables</th>
<th>Main problems modeled</th>
<th>Typical examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Nutrients, plant biomass, detritus and peats, and so on</td>
<td>Cycling of energy/nutrient among biotic &amp; abiotic components of wetland, and exchange with surrounding</td>
<td>Note 1</td>
</tr>
<tr>
<td>II -1</td>
<td>Water storage in the wetland</td>
<td>Water budget for a homogenous individual wetland</td>
<td>Note 2a</td>
</tr>
<tr>
<td>II -2</td>
<td>Water storage in the wetland, adjacent groundwater and surface water</td>
<td>Overall gains and losses for large scale regions or watersheds</td>
<td>Note 2b</td>
</tr>
<tr>
<td>II -3</td>
<td>Stream flow, runoff, pollutants</td>
<td>Wetland hydrology and pollutant transport over short periods and large areas</td>
<td>Note 2c</td>
</tr>
<tr>
<td>II</td>
<td>Water, nutrient, pollutants, plant biomass, detritus, and so on</td>
<td>Problems in model I and II: the entire ecosystem is divided into discrete blocks with each block having the features of an ecosystem model; and the blocks are connected by hydrodynamic process</td>
<td>Note 3</td>
</tr>
<tr>
<td>IV</td>
<td>The factors that effect the processes (e.g. sunlight, CO₂, nutrients) and the processes itself (e.g. photosynthesis)</td>
<td>Individual processes, such as photosynthesis, respiration</td>
<td>Note 4</td>
</tr>
<tr>
<td>V</td>
<td>Display cause and positive and negative effect using flow diagrams (rather than the flow of energy and materials), or interactions between components. They are generally conceptual in nature</td>
<td></td>
<td>Note 5</td>
</tr>
</tbody>
</table>

I: energy/nutrient models; II: hydrology models (II -1: ecosystem hydrology models; II -2: regional hydrology models; II -3: hydrodynamic transport models); III: spatial ecosystem models; IV: process models; V: causal models.


Lake ecological models are designed to examine the relationships between natural and man-made perturbations (e.g. the discharge of nutrients into a shallow lake) and the resulting changes taking place in the lake’s ecological environment (e.g. the degree of eutrophication). This approach implies that the models must be biogeochemical in nature. It also assumes that the model’s framework can be conceptualized and addressed through flow diagrams of the cycling of crucial elements. The key steps, then, necessary in creating workable lake models that provide acceptable results include: the comprehensive analysis of the lake ecosystem; selection of the model’s degree of complexity; estimation of the model’s parameters; and calibration of model’s results.

One of the most important lessons learned from the last few decades of modeling lake ecological processes is the absolute necessity of knowing the features of the ecosystem before beginning the modeling procedure. A comprehensive list of questions including the main sources of pollutants, retention time, various ecological processes (e.g. photosynthesis, settling, respiration, grazing, predation, sedimentation and re-suspension), relative amounts of biomass and mass flows in the different trophic levels, and the relative dominance of various species, etc., must be addressed (Jørgensen, 1994b for details).

The predictive power of a model is strongly dependent on the quantity and quality of the data. If good data are not available or cannot be provided, it will be necessary to use models with complexity levels corresponding to the quality of the data. In the absence of high quality data there is little choice but to reduce the complexity of the model—a consequence that is clearly reflected in the latest eutrophication models. In most cases, increasing the level of complexity will not improve a model’s applicability; provided, of course, that the modeler has already considered the crucial processes and state variables. On
the other hand, it is always important to try to include as much detail as possible in a model and note the corresponding changes in modeled results. The modeler, through this exercise, is thus able to record the sensitivity of the model to increasing levels of complexity (see also the discussion and method published in Jørgensen, 1991).

Reliable parameters are crucial to a good and workable ecological model. The parameters must be estimated through field observations, laboratory experiments, or through calibration. The conventional method of parameter estimation is through calibration, i.e., adjusting the most sensitive parameters using ranges obtained from the literature until the best agreement between observations and model predictions for the most important state variables and process rates is obtained. The need to make these minor adjustments to specific models makes it difficult to apply them from one case to another. Several new methods have been proposed in an attempt to overcome this issue, e.g., the fuzzy method, the artificial intelligence method, and the goal function method. The first two methods may be useful if a sufficient number of available values for parameters can be found in the literature. Fuzzy analysis, or the establishment of expert systems, can be used to determine particular parameter sets. Regardless of which of these two approaches is chosen, it is still not possible to determine whether or not one parameter value, or an entire set of parameter values, is better than another (Jørgensen, 1994).

The goal function method seems to be the most promising approach. Goal functions, such as maximum power (Oдум, 1960), biomass (Straskraba, 1980), emergy (Oдум, 1982), exergy (Jørgensen, 1982), and ascendancy (Ulanowicz, 1986), have been applied in numerous models. Exergy is the most widely used goal function in the models (Jørgensen 1986; 1992a; 1992b; 1992c; 1994; 1997; Nielsen, 1990; 1992; 1994; 1995; Boss, 1997; Coffaro, 1997; Xu, 1997).

Model calibration is an extremely important step in all ecological modeling (Jørgensen, 1994b). During model calibration, it is necessary to compare the modeled with the observed rates of processes; except for the comparisons of modeled values with measured state-variable values. Models can produce concentrations of ecosystem variables. However, they can also produce both under- and over-estimate ratios of important material flows. For instance, phytoplankton dynamics are controlled by growth and loss processes. It is easy to imagine situations where both the algal growth and loss rates are either too low or too high, yet the resulting rates for the algal biomass are still be in accordance with the field observations. In such instances, we would be getting the right results (state-variable concentration) for all the wrong reasons (compensating rate processes; refer to Xu, 1999 for an example).

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