Proceedings of the Modelling, Identification & Control 19–22 Feb. 2001, Innsbruck, Austria

BUILDING AND VALIDATING MODELS OF FRESHWATER ECOSYSTEMS

MAGNUS DAHL DAVID WILSON LARS HÅKANSON*

Modelling & Simulation Group
Department of Chemical Engineering
Karlstad University, SE - 651 88 Sweden

Abstract

The development of water quality models face some unique challenges. Poorly understood fundamental relations, coupled with a chronic scarcity of measured data, often driving a model with ill-defined or multiple goals all combine to require careful planning if the model is to be useful.

Despite the challenge many important aquatic ecosystem models have been developed spanning a large variety of ecosystems and modelling philosophies. This paper presents a short review of some of these modelling techniques, and argues that a relatively simple ODE type model is adequate and stands some chance to be validated.

A preliminary model, adapted from a previous eutrophication model has been applied to Lake Vänern. The modifications and the new demands on validation are highlighted.

Keywords: Lake modelling, environmental, LEEDS, Phosphorus, SPM.

1 Introduction

Lake Vänern is the largest freshwater body in Sweden, containing one third of Sweden's fresh water, and the third largest lake in Europe after the Russian lakes Ladoga and Onega. Lake Vänern is situated in the south west part of Sweden, (refer Fig. 1), adjacent to the city of Karlstad and this close proximity means that the lake plays an important tourist, commercial and recreational role. For this reason Karlstad university in collaboration with various industrial and local municipal bodies are currently developing a model of the lake. This paper first outlines the unique issues associated with ecological modelling, reviews some general techniques and software, and finally presents some preliminary results for a model of Lake Vänern.

*Department of Sedimentology, Uppsala University, Sweden

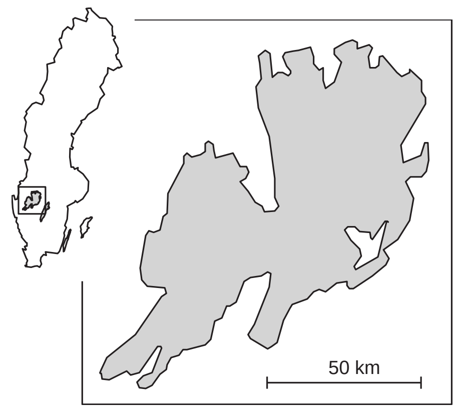


Figure 1: Map of Lake Vänern, Sweden.

2 Freshwater ecosystem models

The modelling of freshwater ecosystems has some unique characteristics which complicate the development compared with modelling in other disciplines in science and engineering such as the modelling of chemical plants, or fluid flow through turbines, [1]. Firstly, there is the enormous variety of models serving an equally disperse audience, [2]. Simple dynamic flow models suitable for river control, may be totally inadequate for simulating the steady-state of a lake's ecosystem. Models based on computational fluid dynamics, while well understood, are always difficult to validate, and when coupled with the ecology, which is rarely well understood, often leads to overly unwieldy models.

One key characteristic is that the system is best described by a large, interconnected system of algebraic and differential equations, often requiring an interdisciplinary approach at least between the two crucial dominating phenomena, hydrodynamics and ecology. The physical transport is well characterised, but biochemical relations are not, and it is comparatively expensive to collect the raw data over the necessary time scales, say decades, to resolve this dichotomy. Furthermore some states such as temperature and inorganic concentrations are adequately described using continuum mechanics, while other states such as fish populations are discrete, mobile and less amenable to standard modelling techniques.

Finally, large volumes of disparate information (time series of concentrations, weather records, fishing extents, geographical information) are required to build and validate models before any meaningful results are possible.

2.1 Model types and software tools

Despite the diverse demands, freshwater ecosystem models tend to have the following components in common: physical transport (circulation and temperature patterns), chemical reactions (pH, heavy metals, oxygen balances, phosphorus), the latter leading to eutrophication and the ecology of the phytoplankton, zooplankton, and fish.

The simplest models are steady-state regressions such as those presented in [3] (e.g. bacteria as a function of total phosphorus and benthic biomass as a function of total phosphorus) and used subsequently in the model described in §3.1.

However to track the development of an ecosystem over time, one really needs differential, or at least discrete-time models. The latter form is commonly used in fish population balances such as that for pike reported in [4] where the number of of fry one year form the basis for the number of juveniles the next year, the number of juveniles form the basis for the number of adult fish, and adult fish form the basis for the number of eggs, deciding how much fry there will be.

The logical extension to the discrete-time model is the collection of continuous ordinary differential equations (ODEs). Oxygen balance models (DO/BOD) initially used in river modelling, (which treated the river as a series of linked stirred tank reactors), soon incorporated phosphorus and nitrogen. Typical examples are the set of models that culminated in the software package Qual2e, [5], or the Leeds model, further developed in §3.1.

Tracking components in two, or even three dimensional space requires the solution of partial differential equations (PDEs). This added complexity is rarely justified but is used for example to model flow profiles when constructing civil engineering works (such as the Öresund bridge, [6]) or river flood control. The modelling of the hydrodynamics and inerts is generally acceptable, but the results for nutrients (N, P, Si) and dissolved oxygen is often less convincing. [7] indicate how the predictive quality of the model deteriorates for the elements higher up the food chain.

2.2 Validation

Validation of any scientific model is a crucial requirement, but the high demands to validate a sophisticated ecosystem model mean that it is rarely done. In many scenarios (such as spills, catastrophes, etc.) it may not be possible, or even desirable, to validate the model at all.

Both the survey paper, [8], and [3] devote some attention to the difficulties of validating ecosystem models. By introducing the term 'operational validity', [8] deftly avoids the more stringent demands of a scientific proof, so only tests if the model output is sufficiently close to the measured data within the accuracy specified when formulating the modelling objectives. This is an engineering-type of validation, concerned with the practical use of the model and directly assess the predictive potential of the model.

Conversely conceptual validation aims to find out whether the model structure and underlying assumptions are reasonable for the intended use of the model. As conceptual validation is concerned with the model structure and assumptions and not with the accuracy of the predictions. A successful conceptual validation, justifying the scientific content of the model, does not guarantee accurate predictions, but hopefully gives a basis from which to extrapolate predictions into areas not validated previously.

3 Modelling Lake Vänern

Lake Vänern's catchment consist mainly of forests (50%), lakes (20%) and farmland (12%) with the remaining predominantly bogs and mountains. The local industry is dominated by pulp and paper with six pulp and paper mills on the lake shore, with a yearly production of approximately 1400 dry metric tons, and six further mills in the catchment area with a yearly production of 400 dry metric tons.

Historically the pulp and paper industry have dominated the effluents to the lake starting around 1930 when the industrial emissions of organic matter exceeded the natural inflow. The peak occurred in 1965 when 75% of the supplied organic matter had industrial origin although currently it has decreased to 17%. Since that period the use of elementary chlorine bleaching of pulp, resulting in large emissions of chlorinated organic matter coupled with large emissions of mercury from a chlor-alkali factory, have stopped (see Fig. 2), and emissions of zinc from manufacturing of rayon fiber occurred are now 10% of their previous maximum.

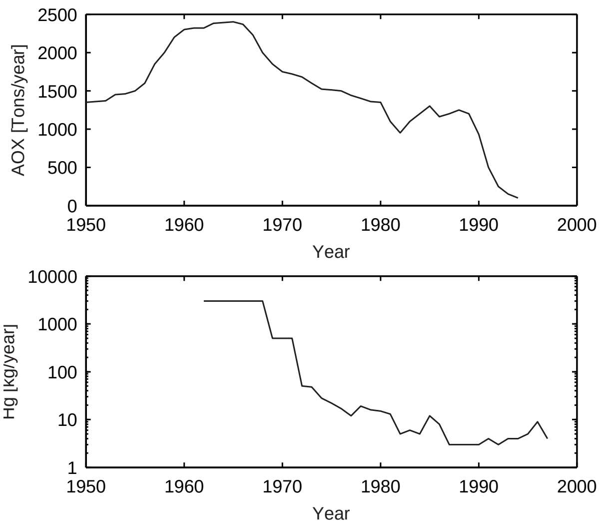


Figure 2: Emissions of AOX and mercury into Lake Vänern from pulp and paper industry. (Data from [9].)

In many cases, present effluents have been shown not to cause environmental damage near the effluent source. While negative effects in the main lake are considered improbable, there is at present no method to quantify them. In a political climate driving towards tighter demands on emissions, the local industries and even environmental consultants, [10], are starting to question the wisdom of the 'best available technology' (BAT) policy. It could be argued that some of the proposed technologies consume financial resources and energy attributing to increased emissions at power plants for example, while contributing little to the improvement of water quality. A model of the lake would provide a quantitative method to determine the long term effects of these proposals, thereby giving a basis to finding the optimum level of cleanup.

A project initiated in the 1970s with the then ambitious aim to construct a large scale ecosystem model of lake Vänern is summarised in [11]. A few circulation models were subsequently developed, [12, 13], and one model to predict ice-cover, [14], but lack of knowledge and sparse data prevented the completion of an ecosystem model. A lasting legacy of the program was the creation of a continual monitoring program, of which this modelling project uses the data.

3.1 Leeds model

The Lake Eutrophication, Effect, Dose, Sensitivity, (Leeds), model described in [15] is a suitable framework to model Lake Vänern. The original model consisted of only one basin and was primarily concerned with the dynamics of phosphorus. As phosphorus is the limiting nutrient in freshwater it is indicative of of many other biotic variables in the lake, [3], so it is crucial for predictive modelling.

However Lake Vänern is arguably more complex than the lakes used to validate the original Leeds model so the 7 phosphorous dynamic states were augmented with 5 suspended particulate matter (SPM) states to adequately quantify the state of the lake as shown in Table 1. To account for the distributed nature of the lake, we used five basins as opposed to just one used in the original development. In total the model comprises of 55 states, around 250 derived variables (outputs), 5 basin specific inputs (flows), and 3 global inputs (wind, light and rain).

Fig. 3 illustrates just part of the interplay of the phosphorus states in a single basin. The models for different basins and the models for suspended particulate matter are similar in structure.

Table 1: The states in the Leeds model. All units are ton dry weight.

State	*Explanation*
	Suspended particulate matter (SPM)
S_a	In deep lake sediments
S_{awl}	Due to lake surface lowering (not used)
S_s, S_b	Epilimnion, hypolimnion
S_{et}	In shallow sediments
	Phosphorus
P_a	In deep lake sediments
P_{de}, P_{dh}	Dissolved in epilimnion, hypolimnion
P_{et}	In shallow sediments
P_{pe}, P_{ph}	Particulate in epilimnion, hypolimnion
P_{pp}	In phytoplankton

The advantages of this structure is that the model is a system of ODEs describing the transport of various phases of phosphorus and suspended particulate matter in the lake and sediment. By reducing the spatial modelling requirement, one can use software tools such as iThink[1] and this has the added benefit of simplifying the model validation step.

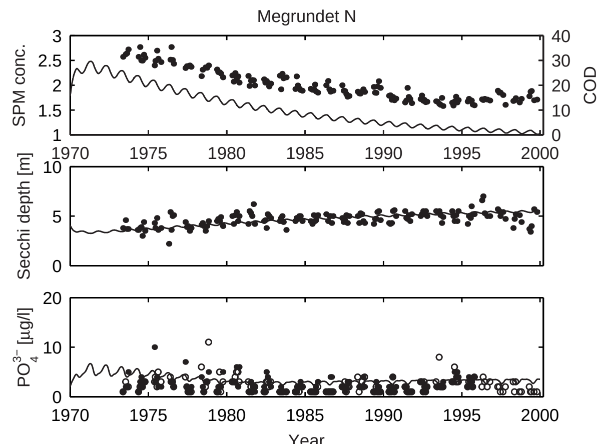
The multiple basin nature of the Vänern model, and the lack of vectorisation and information hiding in tools such as iThink meant that the model became increasingly unwieldy. For this reason, we decided to port the model to Matlab/Simulink as shown in Fig. 4 taking advantage of robust numerical routines such as adaptive integration routines as opposed to the constant one month stepsize used previously.

3.2 Scenario testing

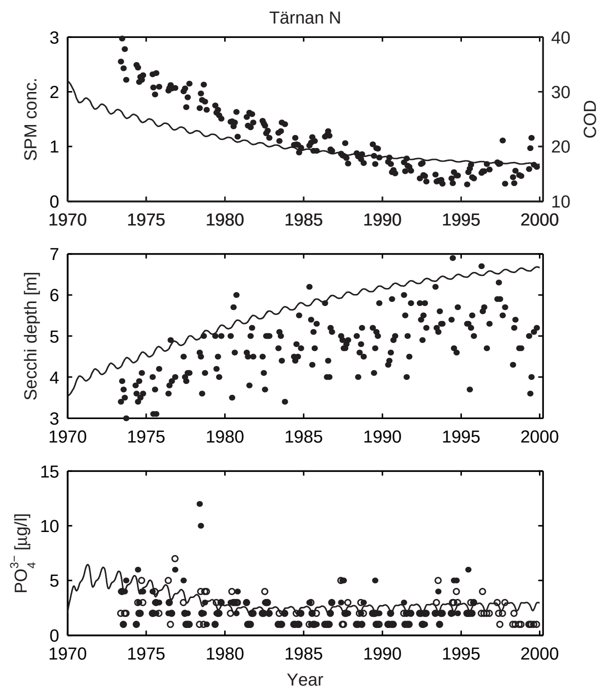
Fig. 5 shows some preliminary results of the 5 basin Leeds model for Lake Vänern. The inputs driving the model (weather, wind, river flows etc.) are from the Swedish Meteorological and Hydrological Institute[2] and validation data are taken from the database available at `http://info1.ma.slu.se`. The validation data consists of Secchi depth which is strongly related to SPM, COD, (measured as the amount of $KMnO_4$ consumed, mg/l), and dissolved phosphorus (μg/l of PO_4^{3-}) sampled near the middle of the two large basins: Tärnan in the east basin, (Värmlandssjön), and Megrundet N in the west basin, (Dalbosjön).

The decreasing trend of COD coupled with the increasing Secchi depth indicates that the water quality of Lake Vänern is improving over the last 2 decades, although the model seems to suggest that it is now approaching a steady-state. This is attributed to better municipal waste-water treatment, and the the reduction of fiber emissions form the pulp and paper industry. The 'bane of ecologists' is also evident in the validation data. The Secchi depth readings are noisy, and the dissolved phosphorus is both noisy and heavily quantisied. The spread in the sampled COD readings is less, but we can only compare this data indirectly to the concentration of suspended particulate matter.

It was interesting to note that if we ran the dynamic simulation using a fixed stepsize of 1 month, as opposed to the adaptive stepsize integrator used by default, the simulated trends deteriorated due to numerical instabilities. These are, in part, due to the algebraic coupling between the various basins which when implemented with dummy dynamics introduce excessive stiffness into the problem.



(a) Trends of Secchi depth, COD, and phosphorus, (○ epilimnion, • hypolimnion), in the west basin, Megrundet N.



(b) Trends of Secchi depth, COD, and phosphorus, (○ epilimnion, • hypolimnion), in the east basin, Tärnan.

Figure 5: State and derived variable trends (—) from the Leeds model for Lake Vänern compared to validation data (•).

[1] Stella clone, http://www.hpc-inc.com
[2] www.smhi.se

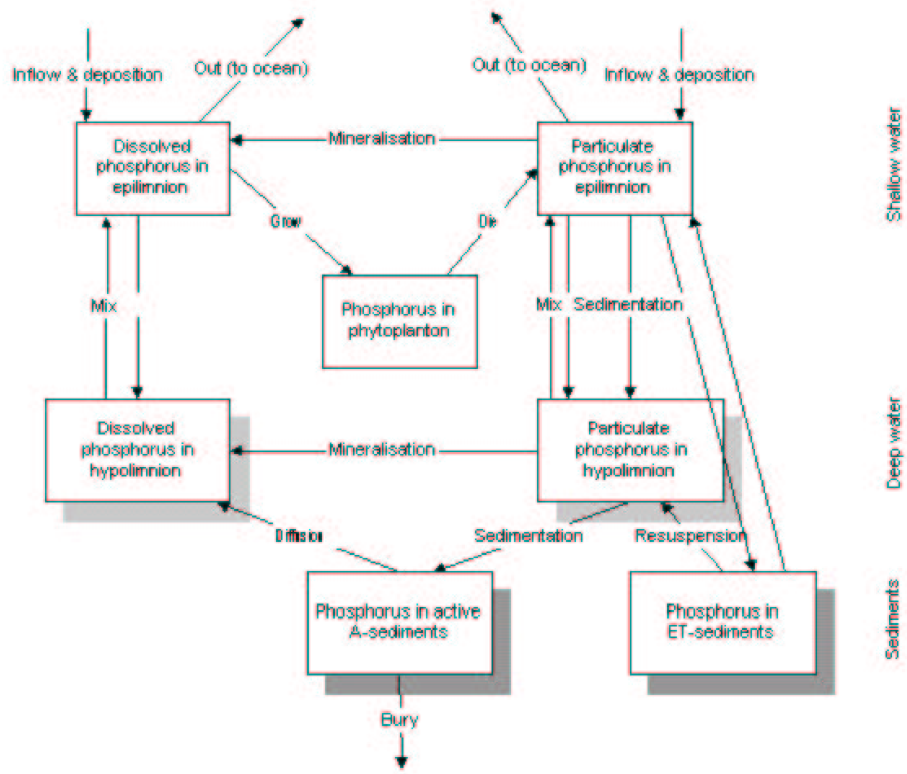


Figure 3: States and flows of phosphorus in the LEEDS Model

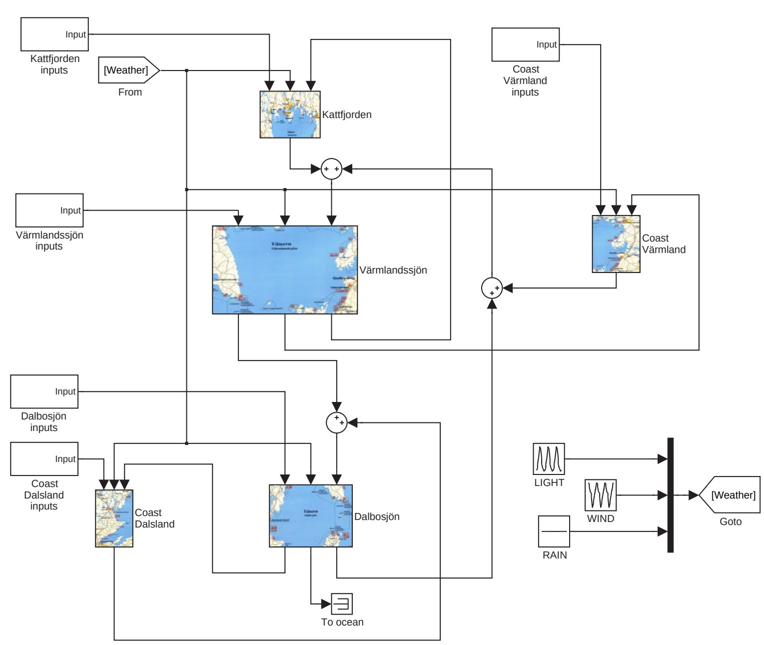


Figure 4: A 5 basin LEEDS model of Lake Vänern implemented in SIMULINK. The internals of each of the five boxes contain the 12 state differential equations and numerous algebraic equations for each of the five basins in Lake Vänern.

4 Conclusions

The results presented are the preliminary findings based on a model of Lake Vänern, Sweden. The model tracks phosphorus and suspended particulate matter as states from which numerous dependent components can be derived. The model, which has been previously validated in a simpler form, is validated against measured data.

This the first time the LEEDS model has been used for either large lakes, or multiple basins. Adapting the model to multiple basins is only possible because the model is based on a fundamental equations. This could not be achieved so easily starting from a black-box model. Ideally both the equation structures, and key regressed parameters should be the same in all the basins, and the degree of fine tuning of these parameters gives an indication of where perhaps the model needs improvement.

Acknowledgements

Financial support from the Karlstad University, Skogsindustriellt Centrum, Sweden is gratefully acknowledged. Thanks are due to Jonas Wirén without whose support and help this project would not have been possible.

References

[1] Magnus Dahl and David Wilson. Current status of freshwater quality models. Technical report, Karlstad University, May 2000.

[2] S.E. Jørgensen, B. Halling-Sørensen, and S. N. Nielsen. *Handbook of Environmental and Ecological Modeling*. CRC Press, 1996.

[3] Robert Henry Peters. The role of prediction in limnology. *Limnology and Oceanography*, 31:1143–1159, 1986.

[4] Charles K. Minns, Robert G. Randall, James E. Moore, and Victor W. Cairns. A model simulating the impact of habitat supply limits on northern pike, *Esox lucius*, in Hamilton Harbour, Lake Ontario. *Can. J. Fish. Aquat. Sci.*, 53:20–34, 1996.

[5] A. Drolc and J. Zagorc Kon An. Calibration of QUAL2E model for the Sava River (Slovenia). *Water Science and Technology*, 40:111, 1999. QUAL2E available free from `http://www.epa.gov/ORD/WebPubs/QUAL2E/`.

[6] Gunnar Omstedt. Miljökonsekvensbeskrivning för öresundsförbindelsen : underlagsrapport – nr 26 : Öresund, med eller utan bro : spridningsmeteorologiska beräkningar för olika alternativ. Technical report, Öresundskonsortiet, Malmö, 1992. (In Swedish with English summary).

[7] M-J Salençon and J-M Thébault. Simulation model of a mesotrophic reservior (Lac de Pareloup, France): MELODIA, an ecosystem reservoir management model. *Ecological Modelling*, 84:163–187, 1996.

[8] E.J. Rykiel. Testing ecological models: the meaning of validation. *Ecological Modelling*, 90:229–244, 1996.

[9] L. Lindeström. Metaller och stabila organiska ämnen i vänern : tillstånd, utveckling, källfördelning, risker. Rapport 2, Åtgärdsgrupp Vänern, 1995. (In Swedish).

[10] Olle Grahn. Private communication, ÅF-Miljöforskargruppen AB Fryksta Sjöleden 9, SE-665 91, Sweden.

[11] Statens Naturvårdsverk. Vänern en naturresurs. Rapport, Solna, 1978. (In Swedish with English summary).

[12] Hans Kvarnäs. *Den geostrofiska strömningen i Värmlandssjön (Vänern)*. SNV PM 561, Solna, 1975. (In Swedish).

[13] T.J. Simons, L. Funkquist, and J. Svensson. *Application of a numerical model to Lake Vänern*. SMHI rapporter, Hydrologi och Oceanografi, nr RHO 9, 1977.

[14] A. Omstedt. *A Forecast Model for Water Cooling in the Gulf of Bothnia and Lake Vänern*. SMHI Reports, Hydrology and Oceanography, RHO 36, 1984.

[15] Lars Håkanson. *Water Pollution – methods and criteria to rank, model and remediate chemical threats to aquatic ecosystems*. Backhuys Publishers, Leiden, 1999.