Helsinki University of Technology

Systems Analysis Laboratory Research Reports A82, October 2001

# MODELLING OF WATER CIRCULATION AND THE DYNAMICS OF PHYTOPLANKTON FOR THE ANALYSIS OF EUTROPHICATION

**Arto Inkala**

TEKNILLINEN KORKEAKOULU
TEKNISKA HÖGSKOLAN
HELSINKI UNIVERSITY OF TECHNOLOGY
TECHNISCHE UNIVERSITÄT HELSINKI
UNIVERSITE DE TECHNOLOGIE D'HELSINKI

Helsinki University of Technology
Systems Analysis Laboratory Research Reports A82, October 2001

# MODELLING OF WATER CIRCULATION AND THE DYNAMICS OF PHYTOPLANKTON FOR THE ANALYSIS OF EUTROPHICATION

**Arto Inkala**

Dissertation for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and debate in Auditorium E at Helsinki University of Technology (Espoo, Finland) on the 26th of October at 12 o'clock noon.

Helsinki University of Technology
Department of Engineering Physics and Mathematics
Systems Analysis Laboratory

Distribution:
Systems Analysis Laboratory
Helsinki University of Technology
P.O. Box 1100
FIN-02015 HUT, FINLAND
Tel. +358-9-451 3056
Fax. +358-9-451 3096
systems.analysis@hut.fi

This report is downloadable at
www.sal.hut.fi/Publications/r-index.html

ISBN 951-22-5664-9
ISSN 0782-2030

**Title:** Modelling of Water Circulation and the Dynamics of Phytoplankton for the Analysis of Eutrophication

**Author:** Arto Inkala
Environmental Impact Assessment Center of Finland (EIA ltd.)
Tekniikantie 21 B, 02150 Espoo, FINLAND
arto.inkala@iki.fi

**Date:** October, 2001

**Status:** Systems Analysis Laboratory Research Reports A82 October 2001

**Abstract:** The eutrophication and algal blooms are problems in many Finnish lakes and sea areas. One possible way to approach the problem is mathematical modelling. If the most important processes have been successfully modelled, it is easy to calculate the effects of nutrient load changes. This thesis presents experiences on developing and applying eutrophication models.

The pre-calculated flow fields are the most important input to the water quality model, so the applications of the flow model are examined in two papers. The results indicate that the flow model can produce typical flows caused by wind. The simulations of the timing of upwelling were also successful. The excessive vertical diffusion can cause problems in eutrophication model applications.

The results of simulations indicate that the greenhouse effect will advance and enlarge the spring bloom of phytoplankton. However, the average phytoplankton biomass in the Gulf of Finland will be near current level, defined in these scenarios by the available amount of nutrients almost unchanged due to the insignificant changes in the external nutrient inputs.

The more significant nutrient load reductions from the major loading points have a clearly decreasing effect on the total algal biomasses even in one year long simulations. When the nitrogen fixing cyanobacteria was taken into account in the simulation, the results indicated that the phosphorus removal from St. Petersburg would decrease both average cyanobacteria and other algae biomasses. The biomass of other algae might increase in the zone where additional nitrogen is transported from the east. The Finnish national agenda, which is nitrogen dominated, does not seem to be an effective way to fight against accumulations of cyanobacteria. However, the total phytoplankton biomass will decrease near the Finnish coast.

**Keywords:** phytoplankton dynamics, hydrodynamics, load reductions, eutrophication, nutrients, Gulf of Finland

**Academic dissertation**

Systems Analysis Laboratory
Helsinki University of Technology

**Modelling of Water Circulation and the Dynamics of Phytoplankton for the Analysis of Eutrophication**


| | |
|---|---|
| Author: | Arto Inkala |
| Supervising professor: | Dr. Raimo P. Hämäläinen |
| Supervisor: | Dr. Mikko Kiirikki, Finnish environment institute |
| Preliminary examiners: | Dr. Erkki Alasaarela, University of Oulu, FI<br>Dr. Oleg Savchuk, University of St. Petersburg, RU |
| Official opponent: | Dr. Peeter Ennet, Estonian Marine Institute, Tallinn, EE |


Publications:

The dissertation consists of the present summary article and the following papers:

[I] Inkala A., Myrberg K. 2001 Comparison of hydrodynamical models of the Gulf of Finland in 1995 -a case study, Systems Analysis Laboratory Research Reports E9, September 2001, Helsinki University of Technology, (submitted also to Environmental Modelling & Software)

[II] Inkala A.,Kuusisto M., Sarkkula J., Koponen J. 1999, Currents and transport of sewage water in the coastal area of Vaasa, Northern Baltic Sea - a study with current measurements and modelling, Proceedings of the 3rd International Marine Environmental Modelling Seminar '99, 12-14.4.1999, Lillehammer, Norway

[III] Inkala A., Hellsten S., Heikkinen M. 1998, Integrated 3D Modelling of Water Circulation and the Dynamics of Phytoplankton; the Effects of New Reservoir Internat. Rev. Hydrobiol. 83:681-688; Copyright Wiley-VCH Verlag Berlin GmbH

[IV] Inkala A., Bilaletdin Ä., Podsetchine V., 1997, Modelling the effect of climate change on nutrient loading, temperature regime, and algal biomass in the Gulf of Finland, Boreal Environment Research 2:287-301

[V] Inkala A., Pitkänen H. 1999, The effect of load reductions on algal biomass in the eastern Gulf of Finland - modelling point of view, Boreal Environment Research 4:357-366

[VI] Kiirikki M., Inkala A., Kuosa H., Pitkänen H., Kuusisto M., Sarkkula J. 2001, Evaluating the effects of nutrient load reductions on the biomass of toxic nitrogen-fixing cyanobacteria in the Gulf of Finland, Boreal Environment Research 6:131-146

The author has served as leading author in papers **I-V** and participated in writing paper **VI**. In paper **I**, the author carried out the numerical calculations of the FINNFLOW model and compared the results to the measurements of salinity, temperature, water level and flows. Results were also compared to the simulated time-series of FinEst model.

In paper **II**, the author applied the FINNFLOW and FINNQUAL models to the coastal area of Vaasa city. The simulated currents were compared to the measured ones and the transportation of wastewater from alternative outlet positions was calculated.

In paper **III**, the author applied the model to the lake Kemijärvi. The current situation was compared to the measurements and the effects of the new Vuotos reservoir was estimated.

In paper **IV**, the author's contribution was to formulate relations, and design and carry out the numerical calculations of the FINNALGA model. The model was applied to the Gulf of Finland and several scenarios were simulated to estimate the effects of climate change.

In paper **V**, the author applied models to the eastern Gulf of Finland. Differently stratified flow fields were calculated for calibration and validation years, according to the observations. The effects of load reductions were simulated. The simulation grid has a fine (1.5 km) resolution, which was made by a new grid generation program developed by the author.

In paper **VI**, the author took part in the development of a new ecological model which includes cyanobacteria. The new formulations were coupled to the 3D water quality model.

## Preface

This thesis has been made for the Systems Analysis Laboratory, Helsinki University of Technology and the practical work has been carried out in the Environmental Impact Assessment Center of Finland. I wish to thank Professor Raimo P. Hämäläinen, the Head of the Laboratory, for his positive attitude towards my work. I am indebted to my supervisor, Dr. Mikko Kiirikki, for familiarizing me with the problems of measurements and many enlightening discussions concerning the development of environmental modelling. Dr. Oleg Savchuk and Dr. Erkki Alasaarela kindly reviewed and professionally commented my thesis.

The staff of the Environmental Impact Assessment Center of Finland has created a nice working atmosphere for scientific research. Mr. Markku Virtanen and Mr. Jorma Koponen have familiarized me with the hydrodynamic equations, the practical solution to them and the ways to do environmental modelling. The discussions with Dr. Boping Han have given me deeper understanding on the research of theoretical biology. I especially value the discussions and the interesting moments I have shared with Mr. Tero Kokkila, Mr. Hannu Lauri and Mr. Hannu Peltoniemi. The great Z, craft, and heptatlon sessions and days are definitely worth a special mention.

I also wish to thank the personnel of the Finnish Environment Institute, especially Mrs. Minna Torsner, Dr. Heikki Pitkänen and Dr. Juha Sarkkula and the whole Environment Impact Unit. The personnel in the Regional Environment Agencies of Pirkanmaa, Länsi-Suomi, Pohjois-Pohjanmaa, Lappi and Uusimaa have been helpful in the projects related to the thesis.

The discussions with the staff of the Finnish Institute of Marine Research have been rewarding. Dr. Kai Myrberg and Dr. Harri Kuosa have been very co-operative in the common projects.

All my dear friends and relatives, who have been very enthusiastic during the work, deserve a special thank you. My warmest thanks are due to my parents Raimo and Annikki as also to my brother Pasi, cousin Kirsi and grandmother Selma. My friends Mirja and Tuija have helped much with practical arrangements and corrected the language in the drafts. The encouragement of all of these people has been a great inspiration.

The financial support from the Academy of Finland, Finnish Environment Institute, Ministry of Environment, Kemijoki ltd. and the city of Vaasa in the single projects is gratefully acknowledged.

Espoo, October 2001

Arto Inkala

## 1. Introduction

Mathematical modeling is a method to gather all the relevant information and knowledge together, but models are always simplifications of reality. At first, eutrophication models were point models and they took into account only one limiting nutrient and temperature as controlling factors (Lehman *et al*. 1975). Nowadays, many models are 3-dimensional (Tamsalu and Ennet 1995, Neumann 2000). The descriptions of equations in the ecological models vary much both in variables and functions (Los 1993, Savchuk 1986, Wulff *et al*. 1990). The purpose of the applications determines the variables used in the model. However, the equations can vary. Several different models have been used to estimate the effects of nutrient load in the Gulf of Finland (Kuusisto 1997, Savchuk et al. 1997, Tamsalu et al. 1997, **V**, **VI**)

The results of the hydrodynamic modelling are important input information for ecosystem modelling; salinity and temperature have variations which play directly or indirectly important roles in ecosystems. An accurately simulated salinity field is to some extent a proof that the transport of passive biochemical tracers can also be simulated correctly. Biological processes are often functions of sea temperature, which has to be predicted accurately with the hydrodynamic model. For these reasons, the model studies here and the verification of the model results concentrate on investigating the salinity and temperature variations and structures, but the model results (**I**, **II**) are also verified against current and water level measurements.

The aim of this study is to summarize experiences and present typical problems and results in practical applications of the ecological models. The second chapter describes the practical work that has to be done before applications. The third chapter presents the results and the special demands of ecological models on the hydrological input, and in the fourth chapter, the results from simulations are discussed.

## 2. Procedure for Eutrophication Model Applications

In practice, it is impossible to take into account all the phenomena observed in the nature. The food chain has to be simplified and the number of species in each level is usually one or two. The aim of the study (**V**, **VI**) is to define the minimum number of calculation variables needed in the model.

In the simplest cases, the transportation of a nutrient from the loading point gives an estimate of the effects of the loading point to the ecosystem. This is the case when the calculated nutrient is the limiting nutrient for the growth of algae and the load is relatively small compared to the back round concentrations.
The first ecological models (Lehman et al. 1975) calculate the algal biomass from one limiting nutrient. However, since different areas in the Baltic Sea are limited by different nutrients and limitation may change in a future, it is necessary to calculate at least nitrogen and phosphorus in the dissolved inorganic and detritus forms. Different algae species have to be taken into account in the model simulations, if the rations between algae groups in the area vary much.
The Redfield ratio (Redfield 1958) can be used as the first approximation of internal N:P ratio of phytoplankton. The luxury uptake of a less limiting nutrient (Glibert *et al*.1995, Istvanovics *et al*. 1994) is the next development (Jörgensen 1988).

The zooplankton has to be taken into account, if it is the main limiting factor for the growth of algae. In some cases, it is not necessary to calculate zooplankton as a separate state variable, but its effects should be indirectly accounted for as the higher respiration or mortality of phytoplankton. Then seasonal variation can be taken into account with the temperature limitation functions.

Next practical matter is the availability and comprehensiveness of data. The parameters in aggregated model equations cannot be measured exactly and they vary between application areas, which means that the parameters have to be calibrated to reach plausible behavior of the model. The calibration process needs the direct (nutrient concentrations) or indirect (chlorophyll a) measurements of simulated variables. The measurements of bacteria and zooplankton biomasses are often missing, thus the correctness of simulation results of these variables can be only speculated. The food chain in the eutrophication models is often cut to the primary production.

All processes in the water systems are also not well known, so the most relevant processes have to be included in the model, but the rest should be described in the simplest way or ignored, or the effect of these processes should be given manually. The calibration of the application will also be faster and easier, if the number of model parameters is kept low (**V**).

The resolution of the model grid will be defined by the demands of the model application and the application area. If the application area is isolated, the resolution used can be constant. However, in practical problems, the area of interest is quite small, but the flows inside it cannot be simulated, if the surrounding area is ignored. In these cases, it is sensible to use a nested grid, where the resolution is highest in the most relevant area and lower depending on the distance. The grid used in paper **II** is presented as an example of this (fig. 1).

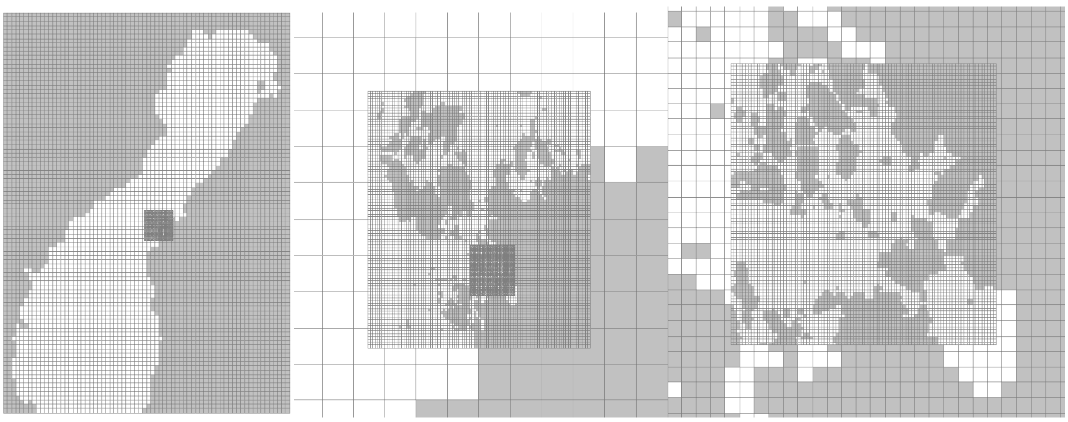


Figure 1. The example of a nested grid from the application of Vaasa (**II**).

The memory of the computer used limits the maximum number of grid boxes in the applications. The FINNALGA model can be used with about 200,000 grid boxes in a PC with 256 MB RAM (**V**). If only flows and the transport of one calculation variable are simulated, the number of grid boxes can be tripled (Inkala et al. 1999).

The toughest issue in the model applications is the accurate simulation of the current situation. Simplifications have been made in the model equations, parameters are unknown, and input and measurement data is inaccurate. The simulations presented in the papers take time from dozens of minutes to hours, which limits the use of the optimization algorithms for parameters.

The area can be selected so that there is enough data for validation in the applications which have scientific aims. The situation is different in the practical applications. The measurement data is not available for all simulation variables. A two-year-long measurement program can give data for model calibration and validation, but it is also possible that a model cannot produce the measured dynamics. In these cases, the model results can be only demonstrative or indicative (Sarkkula et al. 2000).

The strength of the mathematical models is the ability to produce plenty of different scenarios for the possible changes (**V**). In the case of eutrophication models, most scenarios are linked to changes in the nutrient loads. The level of changes is usually so small that the calibrated model can be used. However, in many cases we are interested in long-term changes. This demands that the model must be able to produce long-term dynamics (**VI**).

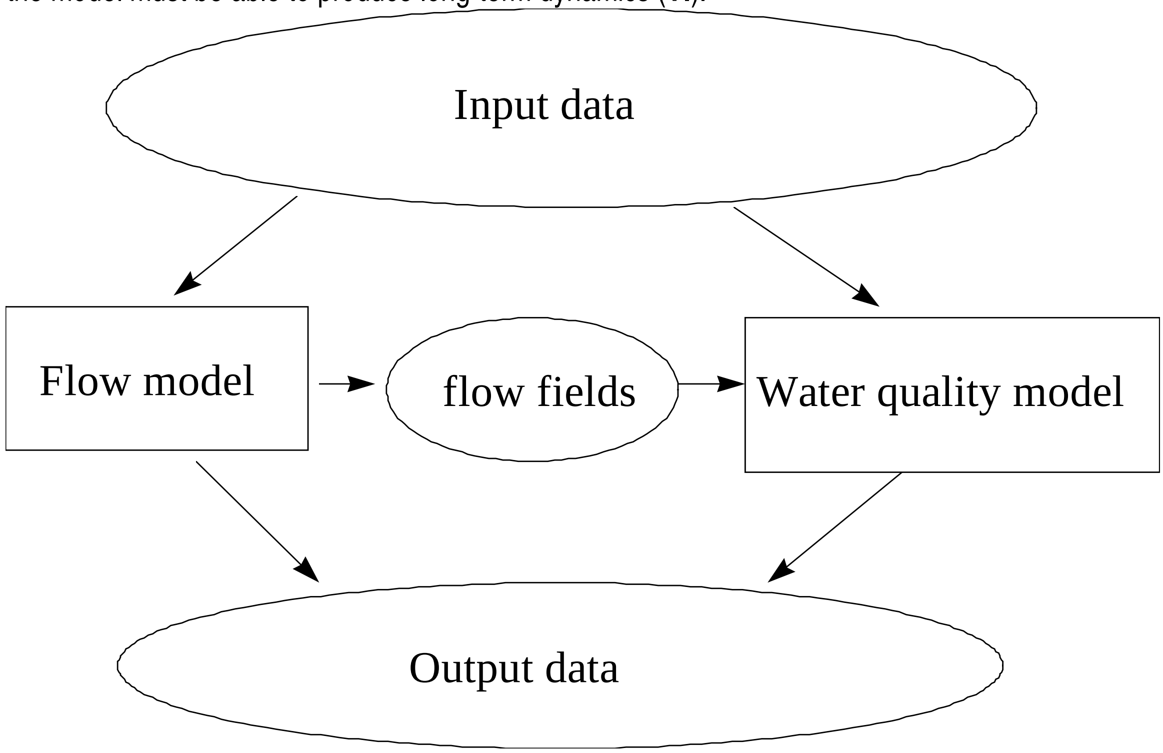



Figure 2. The flow diagram of the model system.

Figure 2 presents the simplified flow diagram of the model system used. Only the flow section is used in papers **I** and **II**, whereas the whole system is used in the other applications. The input data includes data about wind, temperature, ice, river flows, water levels, radiation, boundary concentrations, initial concentrations and loads.

The flows are pre-calculated for water quality models. Usually, in this model system, two stable wind fields are calculated and the linear combination of these fields is used to produce all other wind situations. The river flows are also taken from a stable flow field in the same way (Virtanen & Koponen 1985). It is also possible to use a dynamic field saved with relevant time steps. The output data includes time series, animation and concentration fields.

## 3. Flow Model

### 3.1 The FINNFLOW Model Used

The model used is a 3-dimensional baroclinic multilayer model (Simons, 1980, Virtanen et al, 1986, Koponen et al, 1992). The water mass is treated as vertical layers similarly to the z-level models. Horizontally, the model area is subdivided into rectangles with arbitrary mesh intervals in both directions. The grid system is E according Arakawa's classification (Arakawa 1972), which means that u- and v-components are calculated in the center of the grid cell while the pressure, concentrations and w-components are calculated in the corners of the grid points. U- and v-components are calculated to diagonal directions.

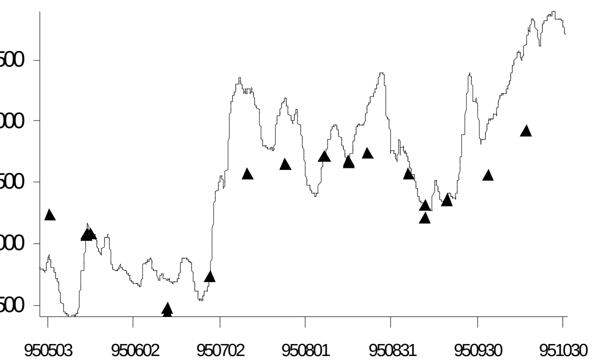
Control volume approach is used in numerical solution. The division of the calculation of 3D currents is made by mode splitting, integrated 2D external mode (surface heights, depth integrated currents) and to 1D internal mode (layer velocity differences). Fractional steps are used (different time steps for different physical processes). Forward-backward Euler method is used in external mode with trapezoidal approximation for Coriolis term and forward Euler in other modules. The first order explicit upwind method is used for advection of concentration (and momentum). The density of the water is calculated linearly from salinity and squarily from temperature.

Eddy viscosity approximation of turbulence is used with constant coefficients. In addition, hydrostatic assumption, Boussinesq approximation and incompressibility of water are used in the model. The advection of momentum has only minor effects on flows, when the flow velocities are small, so it is not usually calculated in the model.

### 3.2 Problems and Results in Applications

The comparison of the measured flow velocities to the simulated ones has some special features which are usually not present in concentration comparisons. The real flow velocity varies more than the concentrations within the calculation cell, so the measured point flow velocity and the simulated one do not describe the same thing (**I**). The measurements of the flow over a large cross-section would be useful for model validation, but this kind of measurements have not been taken much.

There is also a lack of direct measurements of vertical velocities. The point measurements cannot be used and there is no good way to measure average vertical velocity between layers, when the area extends to several square kilometers. However, the transport from the deeper layers can be estimated from the temperature and salinity measurements (**I**), if the water in the application area is stratified. The figure 3 presents one upwelling situation.



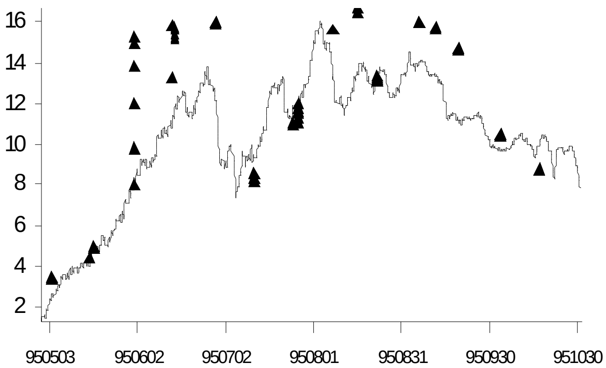




Figure 3. Simulated and measured salinity (ppm) and temperature ($^{O}$C) from point HKVV Gulf of Finland (**I**).

The timing of upwelling can be simulated quite accurately (**I**). The upwind scheme used in the transport algorithm of the model is diffusive, which increases the transport from deeper layers. It is important to take this phenomenon into account in model applications connected to eutrophication, where the vertical gradient of nutrient concentrations is strong.

The horizontal flow velocities are easier to measure, and the measurements and model results are usually compatible in the areas where flow velocity has strong correlation with wind velocity or river flow. The figure 4 presents one comparison of measurements and simulations (**II**).

The results of a regression model and the simulation are compatible, but regression models always have better correlation to the real measurements, because constant term is zero in the combinated fields. The strength of calculated flow fields is that the field is conservative and thus more usable in the transport calculations.

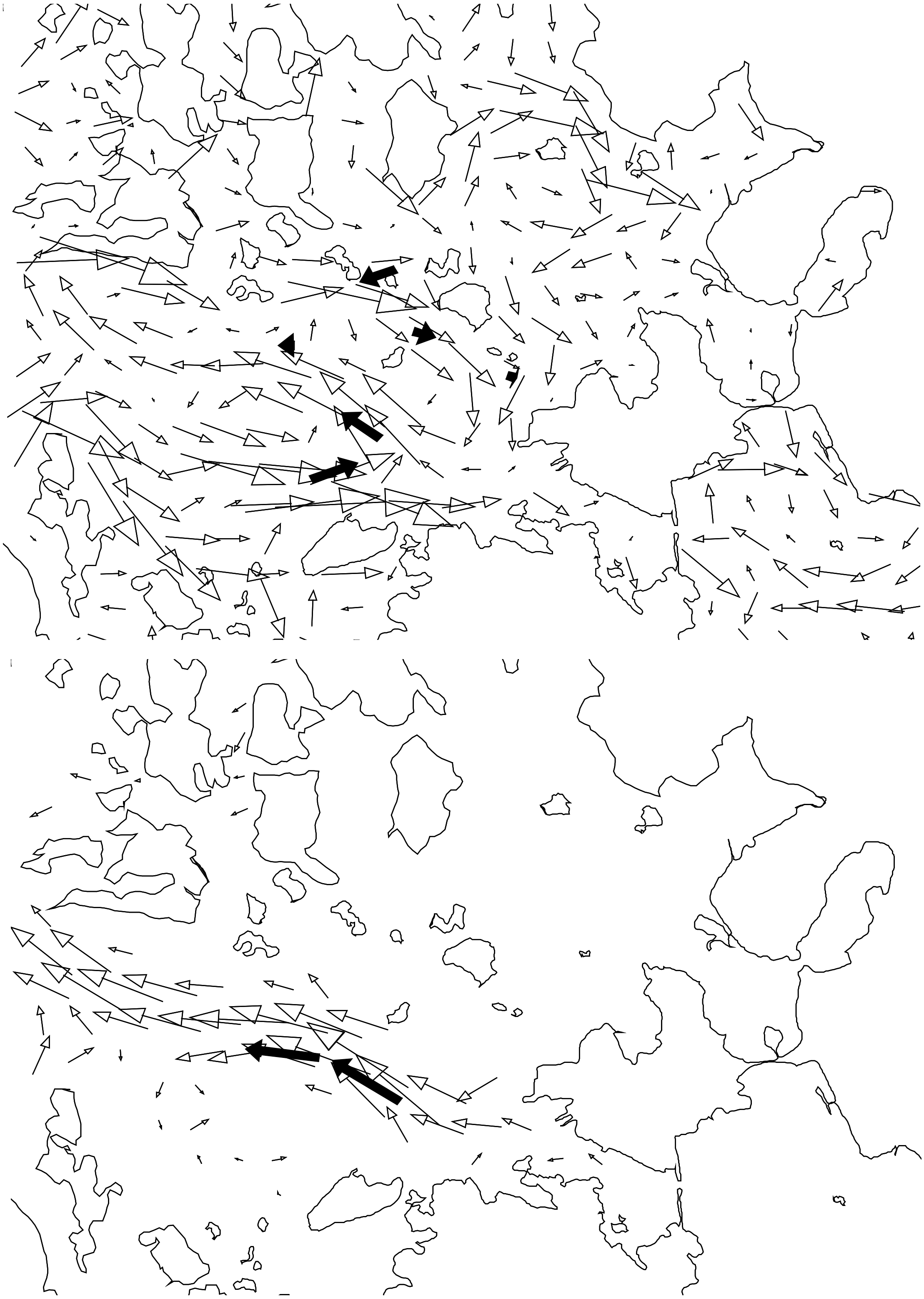


Figure 4. Calculated flow field compared to the results of regression model. Upper field is from layer 0-2 m and downer from 6-8 m depth. Wind is 5 m/s from west. (**II**)

The use of dynamic flow fields in the water quality model makes it possible to use a wind field as input data, which clearly improves the correlation between the simulated and the measured flows (OPCOM 1999). One limitation in the use of a dynamic field had been the large file size. One year's dynamic flow field takes approximately 0.2-1GB in the applications used in the papers.

## 4. Eutrophication Models

The history of eutrophication modeling is short compared to the history of developing mathematical descriptions of physical flows. The issue is also more complex, which leads to a situation where there are several different ways to describe the details of the model. For example, the temperature limitations of biological processes have been described in dozens of ways (Regier *et al.* 1996 ). Moreover, the calculation variables and the processes included in the model vary. The processes and the variables included in the model depend on the aims and the area of the application.

### 4.1 The Models Used

There are two different models used in the applications of this thesis. The flow diagram of the FINNALGA model is presented in figure 5 (**III-V**). The dissolved nitrogen will be fixed by algae. The detritus nitrogen is formed by dead algae or zooplankton grazing. The detritus is settled and sedimented in the bottom or mineralized to ammonium by bacteria. Ammonium can be nitrified to nitrite or fixed again by algae. The cycle is complete. In the model, denitrification can occur in the whole water mass or, with a stronger intensity, in the water-sediment interface. The cycle of bioavailable phosphorus is modelled by phosphate, the uptake of it by algae, the formation of detritus phosphorus and its sedimentation and mineralization.

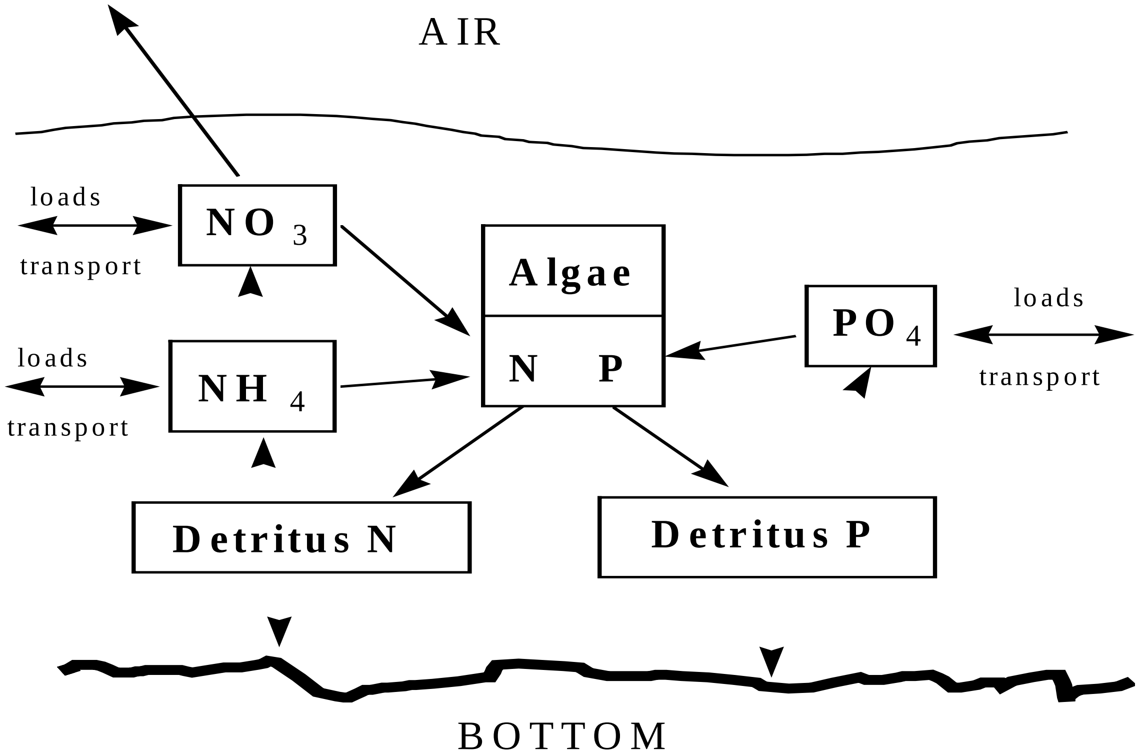



Figure 5. The flowdiagrams of FINNALGA model (**III-V**).

The external factors and interactions related to the presented cycles are point and riverine loads, dry and wet deposition and the release of ammonium from the bottom sediment.

All simulated variables in the FINNALGA model are defined in the 3-dimensional grid, while the approach used in the other model (FINN2DALGAE) is different (**VI**). In this case, the algae (cyanobacteria and other) are defined in 2 dimensions, but all other variables in 3 dimensions. In practice, this means the same as if the algae were mixed vertically at every time step. Two other simplifications have also been made: ammonium and nitrate are combined into the single variable – dissolved inorganic nitrogen. Constants (Redfield rations Redfield 1958) are used in the internal nutrient concentrations of algae.

### 4.2 Problems and Results in Applications

The eutrophication models applied to the real water systems are always strongly simplified compared to the nature. This also makes it easier to understand the dynamics of the model and faster to simulate it by computer. However, the simplification also reduces the models' ability to describe more complex phenomena. If a new phenomenon is added to the model, new problems might appear. For example, taking luxury uptake to the FINNALGA model causes errors in averaging the internal nutrients within the grid box.

The nutrient limitation is described by simple formulation:

$$Nut_{\lim} = P_{\lim} N_{\lim} \qquad (1)$$

Where $P_{lim}$ is phosphorus limitation, $N_{lim}$ nitrogen limitation and $Nut_{lim}$ total nutrient limitation. The average values of internal nutrients are used in the grid box to calculate the nutrient limitation. However, the algae cells do not share their internal nutrients equally in the grid box. If the P and N limitation in the incoming algae cells differs from the limitations in the original cells, the use of averages differs from the sum of individual cells. The difference of nutrient limitations between adjacent grid boxes is usually small. The preliminary test runs made with the grid used in paper **V** indicate that the average error is less than 0.5% and momentary maximum does not exceed 3 percent. The sensitivity analysis (Inkala 1993) shows that changes of 10% in the growth rate reduce correlation coefficient from 0.82 to approximately 0.76; thus the averaging of internal nutrients in the grid box does not cause significant errors.

#### 4.2.1 Experimental and Demonstrative Applications

The algae models can be applied quickly and easily in the experimental or demonstrative level. In this approach, the model can be applied to a virtual area or time period. The input data can be demonstrative or a rough estimate. The comparison with the actual measurement can be made superficially and the averages can be used. This kind of approach is used in the study of the effects of the climate change (**IV**) and in demonstrating the effects of nutrient reductions in the whole Baltic Sea (Sarkkula et al. 2000). However, the input data used was as accurate as possible.

The study of the effects of the climate change in the Gulf of Finland indicates that the spring bloom will grow faster and the peak of phytoplankton concentration will be higher if the air temperature increases. However, the nutrients will be used during spring bloom as currently, so the biomasses after spring bloom will not change much because the nutrient loads change only little. The effects studied by other models (Frisk et al. 1997, Ennet *et al*. 1998) indicate the same kind of change.

The effects of the climate change might affect some long term processes which may change the nutrient concentrations. These are not taken into account. The increased water temperature is beneficial for cyanobacteria, which can fix nitrogen from atmosphere. The changes in the spring bloom and the temperature of the bottom water might have an effect on internal nutrient load. Changes in the physical conditions (stratification) may also indirectly change the nutrient input and the availability of nutrients.

### 4.2.2 Validated Applications

In the cases where a more scientific approach is needed, model results have to be compared with the actual measurements and the actual data is needed as input. Models were also validated with the data not used in the model parametrization or calibration. This method is used in calculating the effects of the changes of load simulations in Kemijärvi and the Gulf of Finland (**III**).

The two year long measurement program was carried out at the lake Kemijärvi before model application. Model was applied to both growing seasons and it was able to simulate measured dynamics. The FINNALGA model has originally been developed on a sea area (Haapamäki 1993, Inkala 1993), but this application indicates that the same processes are also important in lakes. Several load scenarios were simulated with the other model (Virtanen *et al*. 1994) applied to the planned Vuotos reservoir. The effects of these changes on the algal biomass were simulated. As a result, the average algal biomass increases 20–60% depending on the scenario.

The eutrophication and algal blooms are major problems in the Gulf of Finland. The Gulf of Finland is a challenging area from the modeling point of view. The salinity and temperature stratification change much during seasons and between years. The gradient of nutrient concentration changes between the Neva estuary and the open Gulf, and the N:P ratio also changes. The changes in the N:P ratio cause changes in the phytoplankton species during late summer. The nitrogen fixing cyanobacteria benefit from a lower N:P ratio and are more common in the western part of the Gulf of Finland.

The figure 6 demonstrates the importance of stratification in the algal model applications (**V**). The nutrients will be used from the upper layers where there is enough light for the growth of algae while the nutrient concentrations are high under stratification. The upwelling situations bring nutrients to the surface and cause peaks in the biomasses. Systematically underestimated phosphate concentrations indicate the lack of proper sediment feedback, which will be the main topic in the future development of the model.

The simulated areas for the limiting nutrient are in good accordance with the field studies. Even if the nitrogen is clearly a limiting nutrient in the western part of the model area, there is no additional phosphate for the cyanobacteria during the simulation year.

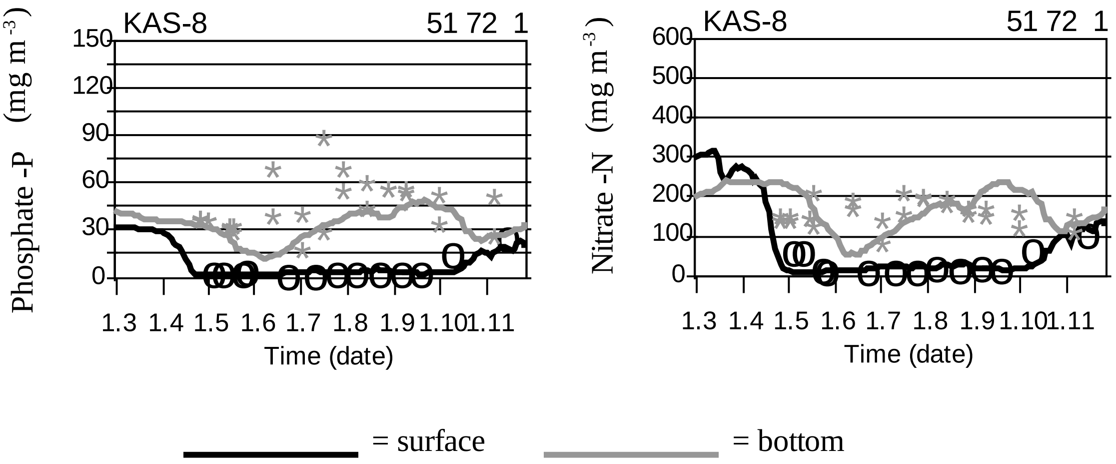



Figure 6. Simulated and measured nutrient concentrations from K8a Gulf of Finland (**V**).

According to the load reduction calculations, clear influences can be seen even in a short time period (months). However, in the short run, the reductions in the area of St. Petersburg will only influence quite a limited area in the Neva Estuary. The affected areas of the load reductions of nitrogen are more extensive than those of phosphorus. During the Gulf of Finland Year 1996, loading scenarios were calculated also with other models (Savchuk *et al.* 1996, Kuusisto 1997). These models have a different description of transport or ecosystem, but nevertheless the effects of load reductions were similar.

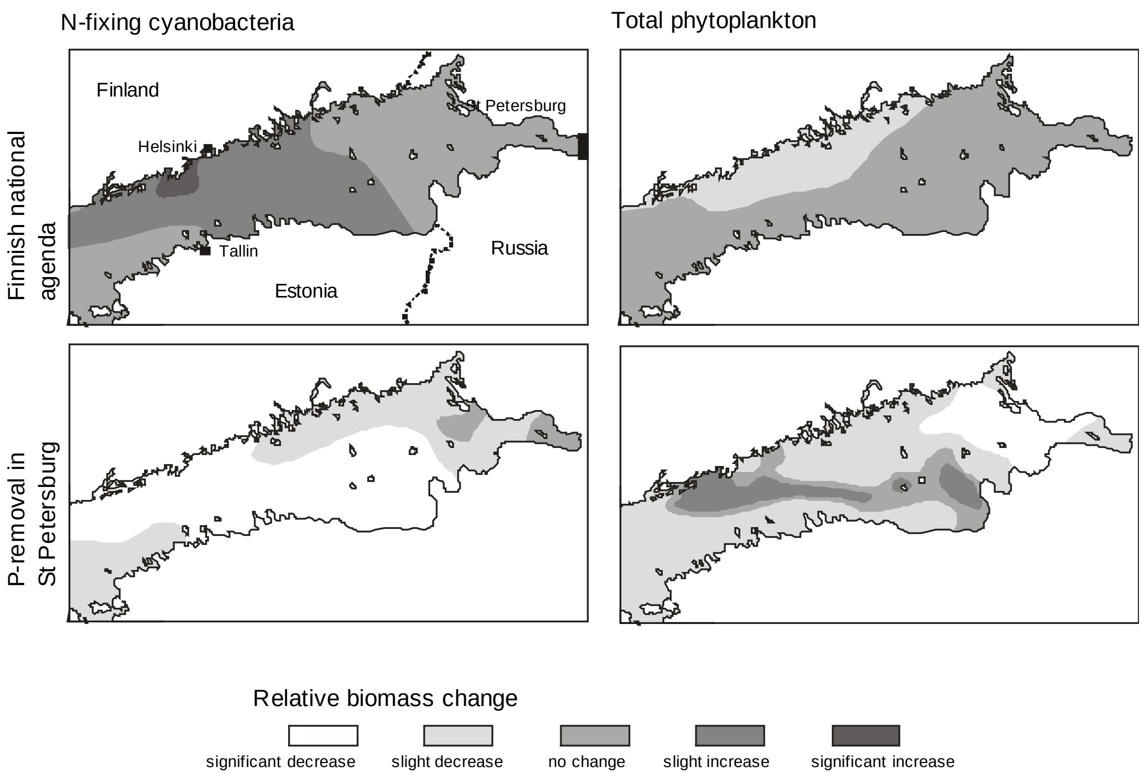



Figure 7. The effects of load reductions on the average total and cyanobacteria biomass (**VI**).

For simulating the effects of nutrient load reductions, one year is not long enough a period to demonstrate the effects in the scale of the whole Gulf of Finland (GOF), where the theoretical residence time of water is close to 3 years (e.g. Alenius *et al.*, 1998). In July 1997, the Gulf of Finland was covered with floating accumulations of cyanobacteria. Two main genera responsible for the bloom were *Nodularia* and *Aphanizomenon*, which are both capable of fixing atmospheric nitrogen. The *Nodularia* species are found to be commonly toxic in the GOF (Sivonen *et al.*, 1989). Due to these reasons, a new model (cyanobacteria included) was developed and the effects of load reductions recalculated.

The model results indicate that N-dominated nutrient load reductions, such as the Finnish national agenda, cannot decrease the biomass of N-fixing toxic cyanobacteria, but they can even have a slight increasing effect. Some experiments (Elmgren & Larsson, 1997) and model simulations (Tyrrell 1999, Savchuk and Wulff 1999) support this result. According to the model, the possible increase will occur mainly in the coastal area where the biomass of N-fixing cyanobacteria is generally lower than on the open sea.

The reduction of phosphorus load from St. Petersburg will decrease nitrogen retention in the phosphorus limited Neva estuary during the growing season and thus promote the westward export of nitrogen in summer. This process has been documented in a smaller scale in the Stockholm archipelago (Brattberg, 1986). Simulations indicate that the zone of increased total phytoplankton biomass shown in figure 7 is formed when this nitrogen load from the Neva estuary meets the nitrogen-limited parts of the GOF.

## 5. Discussion

This thesis presents research on developing and applying 3-dimensional eutrophication models. New results include the programming of two different algae models (**V**,**VI**), verifying flow model results with constant (**I**) and nested grid systems (**II**) and comparing algae model simulations with measurements (**III**-**VI**). New scenario simulations were calculated to estimate the effects of climate change (**IV**) and the nutrient reductions mainly to the Gulf of Finland (**V**-**VI**). The problems faced in the applications give a good basis to the future development of the models.

The flows and the transportation of nutrients and the biomass have important roles in the application areas where strong gradients appear. The studies concentrated on the flow calculation (**I**-**II**) show that the FINNFLOW model was able to maintain stratification, upwelling situations, water level dynamics and flow velocities, when velocities are strongly correlated with wind.

The application area where the main development of the eutrophication models was done is the Gulf of Finland (**IV**-**VI**), while the FINNALGA model was also successfully applied to a lake environment (**III**). The main target of the Gulf of Finland applications was to assess the effects of nutrient load reductions on the algal biomass. The simulation results of the current situation were in reasonable accordance with the measurements.

Due to the problems faced during the model simulations and the recent studies made in the Gulf of Finland, the development of eutrophication models is continued. The diffusive upwind method is changed to a less diffusive TVD scheme in the transportation calculations. The next step to improve transport calculations in the Gulf of Finland will be enlarging the simulation area to the whole Baltic Sea.

The calculation of the internal load is important in the long term simulations. The interaction between sediment and the bottom water will be included in the model during the ongoing research program. The target is to describe the denitrification and the phosphate release using the calculated nutrient, the carbon and the oxygen concentrations in the active and passive sediment.

The interactions of bacteria and DIP have to be estimated, because they might reduce N-fixing cyanobacteria significantly in the scenarios. Bacteria are superior competitors with regard to DIP uptake and they are often P-limited in the coastal waters, so they may alter the P dynamics considerably (Heinänen & Kuparinen 1992).

Even as the models have to be developed, some scenarios can be simulated. If it is assumed that the presented limitations do not have a major influence on the scenario results, the following indications can be found.

The importance of the load reductions of St. Petersburg was presented clearly in the scenario simulations (**V**, **VI**). The model results indicate that phosphorus removal in St. Petersburg would decrease the total phytoplankton biomass in the whole open GOF except for a narrow zone of slight increase across the eastern GOF. At the same time, a significant decrease on the biomass of N-fixing cyanobacteria will be seen practically in the whole GOF. The biomass will decrease mainly in the central parts of GOF, but the positive effects might be detectable even at the western border of the calculation area. The effect will be negligible in front of St. Petersburg, because this area is mainly phosphorus limited and thus outside the distribution of N-fixers.

The Finnish national agenda, which is nitrogen dominated, does not seem to be an effective way to fight the accumulation of cyanobacteria. The results indicate that there may be a risk of slight biomass increase in the N-fixing cyanobacteria along the densely populated part of the Finnish coastline. However, the national agenda will decrease the total phytoplankton biomass in the vicinity of the Finnish coastline, but its effect on the whole GOF is practically negligible.

## References

Alenius, P., Myrberg, K. & Nekrasov, A. 1998 The physical oceanography of the Gulf of Finland: a review. *Boreal Environment Research* 3, 97–125.

Arakawa A. 1972, Design of the ULCA general circulation model. *Numerical Simulations of Weather and Climate* 7, Depth. Of Meterology, Univ. of Calicofnia, Los Angles. 116 p.

Brattberg, G. 1986 Decreased phosphorus loading changes phytoplankton composition and biomass in the Stockholm archipelago. *Vatten* 42, 141-153.

Elmgren, R. & Larsson, U. 1997 Himmerfjärden. Changes in a nutrient enriched coastal ecosystem. *Naturvårdsverket Rapport* 4565, 1-197. (in Swedish with English summary)

Ennet P., Keto K., Kuosa H. & Tamsalu R. 1998. The influence of the climate change on the blue-green algal bloom of the Gulf of Finland and of the Gulf of Riga, The Second International Conference on Climate And Water Espoo, Finland 17 - 20 August 1998

Frisk T., Bilaletdin Ä. Kallio, K. & Saura, M. 1997. Modelling the effects of climate change on lake eutrophication. Boreal Env. Res. 2(1): 53–67.

Glibert, P.M., Conley, D.J., Fischer, T.R., Harding, L.W.Jr. & Malone, T.C. 1995 Dynamics of the 1990 winter/spring bloom in Chesapeake Bay. *Marine Ecology Progress Series* 122, 27-43.

Haapamäki J. 1993. Malli hiilen kierrosta avovesisysteemin ravintoverkossa (The model of carbon cycle in the foodweb of open watersystem), loppuraportti, Kasvititeen laitos, Oulun yliopisto, 41 p.

Heinänen A. & Kuparinen J. 1992 Response of bacterial thymidine and leucine incorporation to nutrient ($NH_4$ ,$PO_4$) and carbon (sucrose) enrichment. *Archiv für Hydrobiologie* 37:241-251

Inkala A 1993. Vesistöjen ravintoverkoston 3-dimensioinen laskenta –typen kierto (The 3-dimensional calculation of the foodweb of water system –the cycle of nitrogen; in Finnish), Master thesis, Helsinki University of Technology, Helsinki. 62 pp.

Inkala A., Patrakka L., Sarkkula J., Väänänen P., 1999, (In: Finnish) Grobbfjärdenin virtausmittaukset ja vesistövaikutslaskelmat, Suomen Ympäristövaikutusten Arviointikeskus, Espoo, 30 s.

Istvanovics, V., Padisak, J., Petterson, K. & Pierson, D.C. 1994 Growth and phosphorus uptake of summer phytoplankton in Lake Erken (Sweden). *Journal of Plankton Research* 16, 1167-1196.

Jörgensen S. E. 1988. Fundamentals of Ecological Modelling. Elsevier. Amsterdam. 391 p.

Koponen J., Alasaarela E., Lehtinen K., Sarkkula J., Simbierowicz P., Vepsä H., Virtanen M., 1992. Modelling the dynamics of a large sea area, Publications of water and environment research institute no. 7, Helsinki, 91 pp.

Kuusisto M., 1997. Suomenlahden kasviplankton- ja ravinnedynamiikka -vedenlaatumallisovellus, (The dynamics of phytoplankton and nutrient concentrations in the Gulf of Finland - an application of a water quality model), *Diplomityö*, Espoo, 97 pp. (In Finnish)

Legovic T. 1987, Determination of parameters for food web modes from field observations. *J. theor. Biol.* 129:211-218

Legovic T. 1989, Predation in food webs, *Ecol. Modelling* 48:267-276

Lehman J., Botkin D., Likes G., 1975. The assumptions and rationales of a computer model of phytoplankoton population dynamics. *Limnology and Oceanograph* 20: 343-364

Los F. J. 1993 Technish rapport DBS. T542, Waterloopkunding Laboratorium Delft, The Netherlands (in Dutch)

Mesinger, F., 1981. Horizontal advection schemes of a staggered grid -a enstrophy and energy conserving model. Mon. Wea. Rew., 109: 467-478.

Neumann T. 2000. Towards a 3D-ecosystem model of the Baltic Sea. *Journal of Marine Systems* 25: 405-419.

OPCOM 1999, deliverables, Task A6: Minimum User Requirements, Version 1.1, http://www.hydromod.de/projects/OPCOM/documents/deliverables/Task_A6.zip

Redfield, A.C. 1958 The biological control of chemical factors in the environment. *American Scientist* 46, 205-221.

Regier H.A., Lin P., Ing K.K. & Wichert G.A. 1996. Likely responses to climate change of fish associations in the Laurentian Great Lakes Basin: concepts, methods and findings. Boreal Env. Res. 1: 1–15.

Sarkkula J., Koponen J., Inkala A., Kuusisto M. 2000, Demonstarative modelling on nutrient load impacts to the Baltic Sea, *Baltic Sea 2008, Technical report* No 2

Savchuk O. P., 1986. The study of the Baltic Sea eutrophication problems with the aid of simulation models, *Baltic Sea Environment Proceedings. No. 19,* 52-61 pp.

Savchuk O., Andrejev O. & Sokolov A. 1997. Nitrogen and phosphorus biogeochemical fluxes in the Gulf of Finland simulated with the system of nested grids model Proceedings of the Final Seminar of the Gulf of Finland Year 1996, March 17-18, 1997 Helsinki, *Suomen ympäristökeskuksen moniste* 105:97-100,

Savchuk, O. and F. Wulff. 1999. Modelling regional and large-scale response of Baltic Sea ecosystems to nutrient load reductions. Hydrobiologia, 393: 35-43.

Simons T.J., 1980. Circulation Models of Lakes and Inland Seas, *Can. Bull. Fish. Aquat. Sci., No. 203*, 145 pp.

Sivonen, K., Kononen, K., Esala, A.-L. & Niemelä, S.I. 1989 Toxicity and isolation of the cyanobacterium *Nodularia spumigena* from the southern Baltic Sea. *Hydrobiology* 185, 3-8.

Tyrrell, T. 1999 The relative influence of nitrogen and phosphorus on the oceanic primary production. *Nature* 400, 525-531.

Tamsalu R., Ennet P., 1995. Ecosystem modelling in the Gulf of Finland II The Aquatic Ecosystem Model FINEST, *Estuarine, Coastal and Shelf Science* 41, 429-458

Tamsalu R., Ennet P., Kullas T. & Myrberg K. 1997. The marine system model FinEst and its application to the Gulf of Finland,Proceedings of the Final Seminar of the Gulf of Finland Year 1996, March 17-18, 1997 Helsinki, *Suomen ympäristökeskuksen moniste* 105:90-92

Virtanen M. & Koponen J. 1985. Simulation of transport under irregular flow conditions, *Aqua Fennica* 15,1:65-75

Virtanen M., Koponen J., Dahlbo K., Sarkkula J., 1986. Three-dimensional water-quality-transport model compared with field observations, *Ecological Modelling* 31:185-199.

Virtanen M., Koponen J., Hellsten S., Nenonen O. & Kinnunen K. 1994. Prinsiples for calculations and water quality in strong regulated reservoirs. *Ecological Modelling* 74:103-123

Wulff F., Stigebrandt A., Rahm L. 1990. Nutrient Dynamics of the Baltic sea, *Ambio* 19:126-133