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The effect of load reductions on algal biomass in the eastern Gulf of Finland estimated by the FINNALGA model

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Eutrophication and algal blooms are major environmental problems in the Gulf of Finland. One possible way to approach the problem is mathematical modelling. If the most important processes are successfully modelled, it is possible to calculate the effects of human activity. The application of an ecological model to the eastern Gulf of Finland is presented here. The algal model used is coupled with a 3-dimensional hydrological one. The application year used was 1994 and the validation year 1995. The load reductions used are based on the recommendation of HELCOM or a more realistic assessment. Results received indicate, that clear effects can be observed even within a short period. According to our model the reduction of phosphorus load is important near river entrances, while for the open eastern Gulf of Finland nitrogen is more important.

Introduction

Mathematical modelling is a method to gather relevant information and knowledge, but models are always simplifications of reality. At first eutrophication models were point models taking into account only one limiting nutrient and temperature as controlling factors (Lehman *et al*. 1975). Nowadays many models are 3-dimensional and the description of the dynamics is complex. These kind of models were applied for the Gulf of Finland by Savchuk (1986), Wulff *et al*. 1990, and Tamsalu and Ennet (1995).

One of the main goals of The Gulf of Finland Year 1996 Project was to improve the understanding of eutrophication mechanisms. The objective was also to give recommendations for improving the environmental state of the Gulf of Finland. Different ecological models from Estonia, Finland and Russia (Savchuk *et al*. 1997) were applied within the project. All models had different approaches for describing transportation and nutrients cycling. In this paper the application based on the FINNALGA model (Inkala 1993) is presented.

FINNALGA has been applied to seven differ-

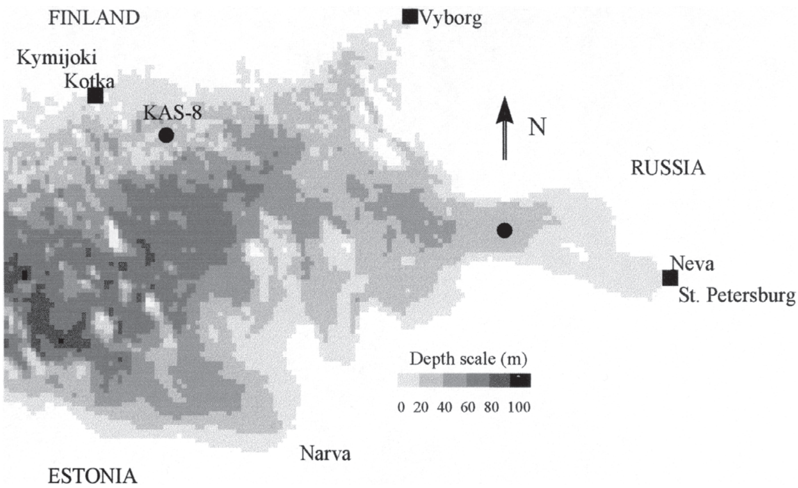

Fig. 1. Research area (the calculation grid) and time-serie points (●) KAS-8 and other in Neva estuary.

ent water areas. For instance, the effect of climate change was studied in the Gulf of Finland (Inkala *et al*. 1997) and the effects of a planned reservoir of Vuotos on the eutrophication of a downstream lake, Kemijärvi, was simulated (Inkala *et al*. 1998).

The model is 3-dimensional taking into account all relevant forces affecting the flow in the sea area. The biological submodel includes phytoplankton dynamics, where essential nitrogen and phosphorus cycles are described in a simplified way.

The ability of the model to simulate the reality is discussed and the results are compared with relevant measurements made in the eastern Gulf of Finland (Database of the Finnish Environment Institute).

The study area

The eastern Gulf of Finland (Fig. 1) is a difficult area to model, due to large variations in both hydrodynamics, water chemistry and algal biomass (Pitkänen and Tamminen 1995). There is a steep gradient in average algal biomasses from the Neva Bay to the open sea, as the major part of the nutrient loading and also the fresh water comes from the Neva River and St. Petersburg area to the Gulf of Finland (Pitkänen *et al*. 1993).

Matherials and methods

Hydrodynamics

The water currents were calculated with the 3-dimensional multilayer model (Simons 1980, Virtanen *et al*. 1986, Koponen *et al*. 1992). The water mass was treated as vertical layers. The model area was subdivided horizontally into rectangles with arbitrary mesh intervals in both directions. Explicit finite-difference schemes were used for the numerical solution of flow velocities and water level elevations.

The currents in the model were determined by the same forces and factors, which affect the currents in reality; wind force (or ice friction), atmospheric pressure (plus ice and snow) at the surface, conservation and incompressibility of water, internal friction (viscosity), transport of velocity differences with water currents (advection), the Coriolis force, density differences and water level gradients (hydrostatic pressure) and bottom friction.

The calculation of water currents is detached from that of the material transport and water quality by Virtanen and Koponen (1985), Halfon (1990), Koponen *et al*. (1992).

FINNALGA

The complexity of the algal model was kept on a low level, because of two main reasons. There is no such ingertated monitoring program in the Gulf of Finland, where all important variables (physical conditions, nutriens, their fractions, minerals, bacteria-, algal- and zooplankton biomasses and species) are measured frequently enough during the whole year. Another important fact is that in the 3D model calibration runs takes a lot of computer time (one simulation used in the calibrations takes about 7.9 hours with a computer equipped with a Pentium Pro 200 MHz processor).

The following simplifications were included in the model: (1) algal biomass is only one calculation variable, (2) grazing by zooplankton is included in the mortality rate of phytoplankton, (3) the limiting nutrient for phytoplankton growth is either nitrogen or phosphorus or both, and (4) the reason for the termination of the phytoplankton spring bloom is the depletion of nutrients, not grazing. The exact description of equations and parameters of the model are presented in Inkala *et al.* (1997).

A flowdiagram of nutrients modelled with the FINNALGA is given in Fig. 2. The dissolved nitrogen is fixed by algae. The nitrogen in detritus originates from dead algae or from zooplankton grazing. The detritus is settled and sedimented on the bottom or remineralized to ammonium by bacteria in the water column. Finally, ammonium can be nitrified to nitrite or fixed again by algae. In the FINNALGA model denitrification can occur in the whole water column or more intensively in the water-sediment interface. The cycle of bioavailable phosphorus is modelled with phosphate concentration, algal uptake and detritus phosphorus which sedimentates and remineralizes.

The external factors and interactions coupled with the presented nutrient cycles are: point and riverine nutrient loads, dry and wet atmospheric deposition and the release of ammonium and phosphate from the bottom sediment.

Application to the eastern Gulf of Finland

In the calculations the horizontal resolution was 1.5 km. Vertically ten layers with boundary surfaces at the depths of 1, 2, 3, 5, 8, 12, 20, 30, 50 m and the bottom were used. Due to steep gradients

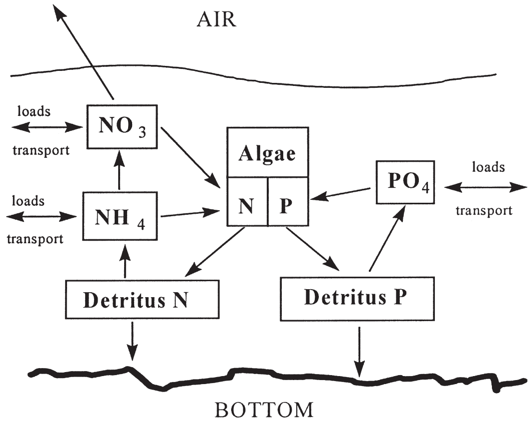

Fig. 2. Flowdiagram of nutrients modelled by FINNALGA.

of variables (algal biomass and nutrients), the resolution was more dense towards the surface.

The bathymetric data were obtained from the sea chart no. 901 (Merenkulkuhallitus 1992) with the digitizing table Mutoh xl-1824. The final grid was made with the help of the grid generation Aigrid (Fig. 1). The generator was developed during this project.

Measurements

The chemical and biological data for calibrations were obtained from the Finnish intensive station KAS-8 in the Gulf of Finland (Fig. 1). The calibration year was 1994 when the station was visited 17 times. The samples were taken and analyzed by South-east Finland Regional Environment Center according to the standard methods recommended by HELCOM (1988a, 1988b).

The relation ($R^2 = 0.80$) between algal biomass and chlorophyll *a* was calculated from all simultaneous measurements made in the Gulf of Finland since 1990. Both are in mg m^{-3} and algal biomass in wet weight.

$$c_A = 149 c_{chl}^{1.211} \quad (1)$$

where c_A = algal biomass wet weight (mg m^{-3}) and c_{chl} = chlorophyll *a* concentration (mg m^{-3})

The data of nutrient loading were gathered by the Estonia-Finnish-Russian WG during the Gulf

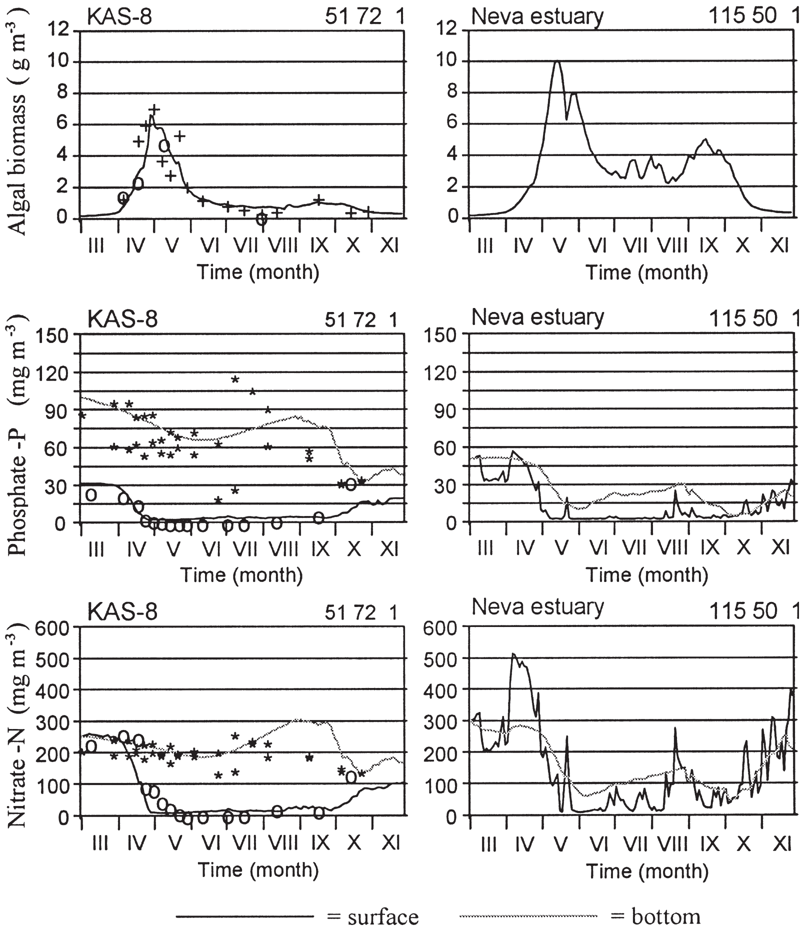

Fig. 3. The calibration results 1994. Numbers in the up right corner are the points x, y and z coordinates in grid system. Symbols: o = surface measurements, * = bottom (30–50 m) measurements and + = calculated biomass from chlorophyll *a*. KAS-8 = measurement point.

of Finland Project (Pitkänen *et al.* 1997). Mean values from the different sources in 1992–94 were used in the calculations. Wind velocities from Kotka-Rankki meteorological station were used.

Scenarios

Two kinds of load reduction scenarios were used in predictions. In the first one, based on the recommendation of HELCOM, loading from all sources is cut by 50%. There are calculated combinations of 50% N and P reduction, for all nutrient sources and also for St. Petersburg alone. The second scenario is based on more realistic and detailed load reductions.

Results

Calibration

Initial conditions were assessed from the nutrient measurements in winter 1993–1994. Three basic levels were given for dissolved nitrogen: 250 mg m^{-3} Finnish coastal waters, 170 mg m^{-3} Estonian coastal waters and 300 mg m^{-3} the Neva Estuary. There were also three levels for phosphate-P: 30 mg m^{-3} surface layer (–30 m), 100 mg m^{-3} bottom layer (30– m) and 50 mg m^{-3} the Neva Estuary.

Unfortunately, only few feasible measurements were available for the open sea area. Only at the station KAS-8 measurements were made

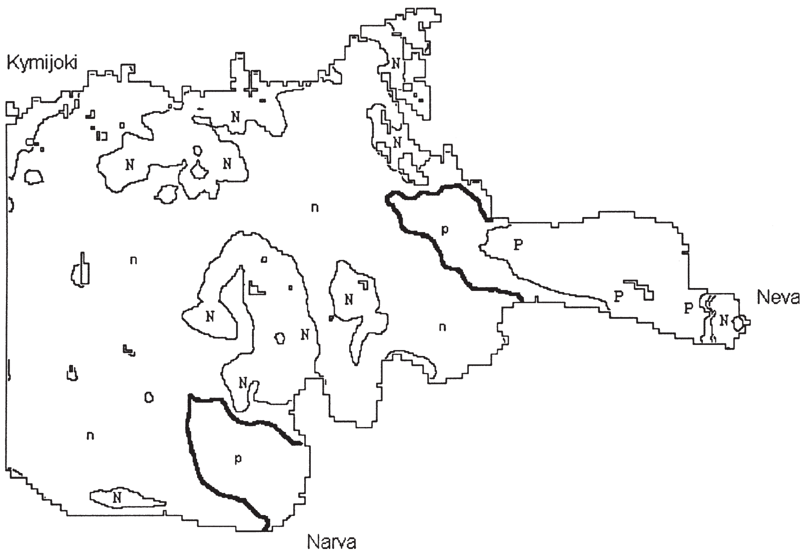

Fig. 4. Calculation of limiting nutrient. Nitrogen is limiting clearly in the areas marked by letter N and slightly in the n-letter areas. Phosphorus limiting areas are marked analogously by P- and p-letters. In the bold line nitrogen is as limiting as phosphorus.

frequently enough. The peak of the spring bloom (Fig. 3) was observed in late April in the open sea and about two weeks later in the Neva Estuary. Simulated algal biomass was much higher in the Neva estuary (2–5 g m^{-3}) than in the open sea (0.3–1.5 g m^{-3}) during the summer months.

In the early June dissolved nutrients were depleted in the surface layer by phytoplankton to concentrations near zero. The concentrations in the deep waters were high until autumn, when the water mass were mixed.

In the Neva Estuary calculated concentrations of nutrients near the bottom were rather low (100 mg N m^{-3}, 15 mg P m^{-3}), because the area is relatively shallow and vertical mixing is stronger than in the open sea. Higher concentrations of nutrients in the surface waters occur, when the wind is from the east. The wind can spread high concentrations from the Neva Bay to the open sea. Especially high concentrations (300 mg m^{-3}) were calculated for nitrate.

The importance of nitrogen compared to phosphorus as a limiting nutrient can be calculated from functions ($f_N(c_A, c_{NA})$ and $f_P(c_A, c_{PA})$) which are defided by the algal biomass concentration (c_A) and the intracellular nitrogen (c_{NA}) and intracellular phosphorus (c_{PA}) concentrations.

$$\mathrm{NUTL} = \frac{f_N(c_A, c_{NA})}{f_P(c_A, c_{PA})} = \frac{\left(\frac{c_{NA}}{c_A}\right) - \left(\frac{c_{NA}}{c_A}\right)_{\min}}{\left(\frac{c_{NA}}{c_A}\right)_{\max} - \left(\frac{c_{NA}}{c_A}\right)_{\min}} \frac{\left(\frac{c_{PA}}{c_A}\right)_{\max} - \left(\frac{c_{PA}}{c_A}\right)_{\min}}{\left(\frac{c_{PA}}{c_A}\right) - \left(\frac{c_{PA}}{c_A}\right)_{\min}} \quad (2)$$

Intracellular nutrients and algal biomass are the calculation variables of the model. Low values mean that nitrogen is more significant than phosphorus. The areal distribution of limiting nutrients during summer (1.6–30.8) is presented in Fig 4.

A study by Pitkänen and Tamminen (1995) indicates that, phosphorus regulate primary production in the Neva Estuary, because the dissolved N:P ration (by weight) in the nutrient load from the Neva River is 25–30 compared to the Redfields ratio of 7. In the outer estuary the ratio rapidly decrease due to internal processes.

In the present study the calculation of limiting nutrients near the mouth of the Neva River is not relevant, as high concentrations of both nutrients exist there due to the huge riverine nutrient load (Pitkänen *et al.* 1997). In the open Gulf of Finland the limiting nutrient was nitrogen according to the calculations. Near the Finnish coast the importance of nitrogen was also high, whereas near the Estonian coast the role of phosphorus increased. Near the river mouths phosphorus always showed a higher impact on algal growth. The re-

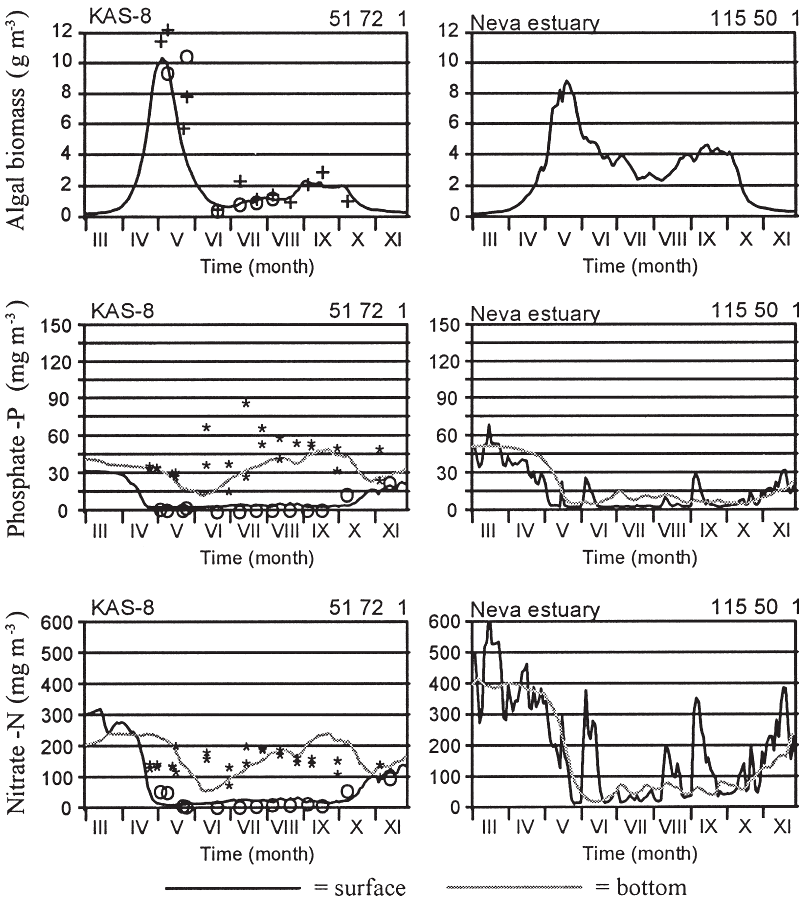

Fig. 5. The validation results 1995. Numbers in the up right corner are the points x, y and z coordinates in grid system. Marks: o = surface measurements, * = bottom (30–50 m) measurements and + = calculated biomass from chlorophyll *a*. KAS-8 = measurement point.

sults of the model are in good agreement with the concentration and experimental data of Pitkänen and Tamminen (1995).

Table 1. Initial concentrations of nutriens in the different areas.

	1994		1995	
	0–30 m	30– m	0–30 m	30– m
Finnish coastal N	250	250	300	200
Estonian coastal N	170	170	200	150
Neva estuary N	300	300	500	400
Finnish coastal P	30	100	30	40
Estonian coastal P	30	100	30	50
Neva estuary P	50	50	50	50

Validation

The validation of the model was made using the conditions of 1995. This year was hydrologically very different compared with 1994. There existed a strong stratification during 1994, while in 1995 stratification was weak, which made deep water nutrients more easily available for algae. Also initial concentrations of nutrients were different (Table 1).

The model was able to simulate the measured dynamics well (Fig. 5). All dissolved nutrients were used from the surface layers. However, in the deep water the concentrations were high. The measured phosphate concentrations were clearly higher than given initial concentrations, due to the processes not included in the model (especially internal load from the sediment). Simulated algal biomass concentrations followed well the measured ones.

Load reduction scenarios

The first scenarios are based on the assumption that all point and non-point loads to the Gulf would be reduced by 50%. The major part of loading comes from the St. Petersburg region, so calculations were made also to forecast the effects of the reductions of the nutrient load from St. Petersburg and the Neva River alone.

However, because the 50% overall reduction level is unrealistically high for many of the sources and on the other hand for some sources also higher reduction levels will be evident, a second scenario was simulated using more realistic load reductions (Table 2).

The effects of the reductions of the nutrient loads are presented as the relative decrease from the summer average of algal biomass (Fig. 5 and 6). The comparison was made between the average summer (June–August) concentrations.

According to the calculations, clear effects will take place even in a short (months) time period. However, in the short run the effects of the reductions (Fig. 6b, d and f) only in the area of St. Petersburg will actuate in a quite limited area of the Neva Estuary. The effects of the load reductions of nitrogen are more extensive than those of phosphorus. The same conclusion can be drawn also from the calculations of limiting nutrients (Fig. 4).

The algal biomasses will decrease considerably, if also the initial winter concentrations will be halved (Fig. 6d and h). This presumes, that the reductions of nutrient loads would have been continued for several years.

The area distribution of the effects of the realistic reduction (Fig. 7) scenario of loads are quite similar to those of the overall 50% reduction scheme for both nutrients. The mean total load reduction in the realistic reduction scenario was only 36% for DIP and 23% for DIN. Thus also the reducing effect on planktonic biomass is weaker than in the overall 50% reduction scenario.

Discussion

We were able to calculate the measured levels of dissolved nutrients in both the surface layer and in the deep water. Both the calculated dynamics and the average concentrations of algal biomass indicate similarities with measured values for the

Table 2. Assessed realistic load (t/a) and reductions (%) for dissolved phosphorus (DIP) and dissolved nitrogen (DIN).

Area	DIP	%	DIN	%	Measurements needed
Neva River	1 053	20	29 000	20	Decreased agricultural loading
St. Petersburg	2 107	50	20 000	30	P removal, partial N removal
Luga bay	45	20	1 580	20	Decreased agricultural loading
Koporskaja bay	55	0	372	0	
Viaborg bay	58	80	377	30	P removal, partial N removal
Narva River	430	30	2 800	30	Decreased agricultural loading
Narva area	45	80	516	50	P removal, partial N removal
Kohtla Järve area from industrial waters	30	50	2 088	90	P removal, effective N removal
Diffuse load	49	0	1 151	0	
Kotka-Hamina	33	50	314	70	P removal, N removal
Kymijoki	64	20	2400	20	Decreased agricultural loading
Diffuse load	20	30	543	40	Decreased agricultural loading
Airborne load	240	0	12 000	0	

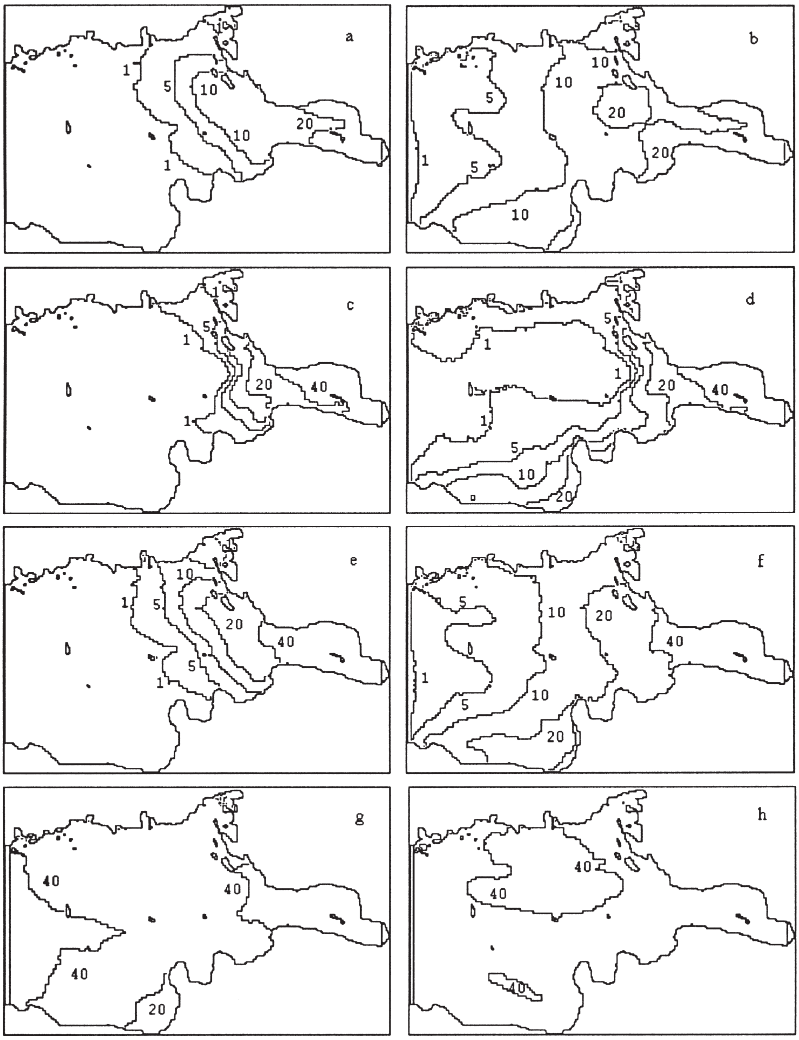

Fig. 6. The effects of the load proposal reductions on the average algal biomass concetrations (reduction%); Scenarios are: 50% N-reduction in St. Petersburg (a) and everywhere (b), 50% P-reduction in St. Petersburg (c) and everywhere (d), 50% P- and N-reduction in St. Petersburg (e) and everywhere (f), 50% reduction in the initial concentrations and 50% P- and N-reduction with in St. Petersburg (g) and everywhere (h).

eastern Gulf of Finland. In the Neva Estuary simulated concentrations of nutrients and algal biomass were also in accordance with the concentrations measured in the area (Pitkänen *et al.* 1993). The geographical distribution of areas where nitrogen or phosphorus is limiting primary production were in accordance with the results of Pitkänen and Tamminen (1995).

In eutrophication models many variables and processes can be defined in different ways, which is affecting parameter values. On the other hand the model output of a single process can be quite similar even if very different parameters are used. These kind of interactive parameters are for example the maximal nutrient uptake rate and the half saturation coefficient, the maximal growth rate and the parameters of limiting factors as well as the mineralization rate and the sinking speed of detritus.

During the Gulf of Finland Year 1996 loading scenarios were calculated also using other models (Savchuk *et al.* 1996, Kuusisto 1997). These models describe the transport or the ecosystem behavior differently, but in spite of that the effects of load reductions were quite similar in all three models. The FINNALGA model describes all algal groups as a one state variable, so the model is unable to simulate the blooms of nitrogen fixing cyanobacteria. However, in the eastern Gulf of Finland the nitrogen fixing cyanobac-

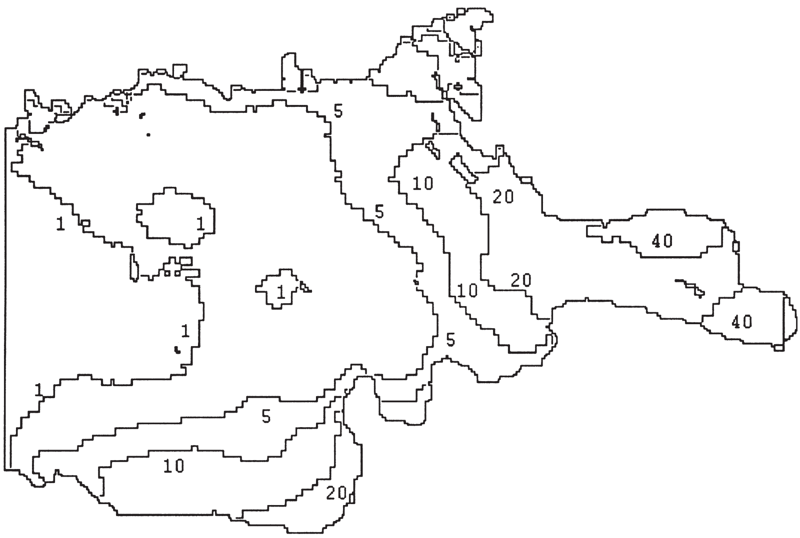

Fig. 7. The average decrease of algal biomass (%) caused by a more realistic (Table 2) nutrient reduction during summer period.

teria blooms have had rather small biomass compared to total algal biomass due to the high inorganic N:P ratio of the terrestrial inputs and large storage of DIN in the deep waters (Pitkänen and Tamminen 1995).

Even with the very simple description of the planktonic system and nutrient dynamics the FINNALGA model could simulate measured dynamics of nutrients and algal biomass satisfactorily. This suggests, that assessments can be made by simple models. If we want to simulate more detailed processes of a complex ecosystem, the model used has to be more complete. The targets of the application will detail the complexity required from the model and the reasonable simulation period.

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