Studies of the assimilation capacity and effects of nutrient load reductions in the eastern Gulf of Finland with a biogeochemical model

Oleg P. Savchuk

State Oceanographic Institute, St. Petersburg branch, 23d line 2A, 199026, St. Petersburg, Russia, and Department of Systems Ecology, Stockholm University, SE-10691 Stockholm, Sweden

A model of the nitrogen and phosphorus biogeochemical cycles was applied to the Gulf of Finland for summer and autumn 1991 and validated with concurrent field observations. Estimates derived from modeled biogeochemical fluxes indicated that in August a relatively small easternmost area can assimilate up to 70%–100% of the nitrogen load from the St. Petersburg region. Phosphorus assimilation is equivalent to 160%–260% of the land load. In November, the nitrogen retention decreases to about 4%, while the phosphorus export exceeds the entire land input by 12% due to internal (sediment) loading. The nutrient load reduction scenarios imply that reduction of nitrogen load would result in locally reduced eutrophication and decreased nitrogen export into the open Gulf, while phosphorus reduction would increase assimilation of phosphorus imported into the easternmost area from the west.

Introduction

The Gulf of Finland is highly predisposed to anthropogenic impacts (Fig. 1 and Table 1). Indeed, the nutrient loads per unit of both sea surface area and water volume (calculated from HELCOM 1993) are among the highest within the entire Baltic Sea. As a result, the present trophic status of the Gulf is clearly elevated (Leppänen *et al.* 1997). Even more subject to human impact and more eutrophied is the easternmost part of the Gulf, where the largest Baltic metropolis St. Petersburg (ca.

5 million inhabitants) is situated at the mouth of the largest Baltic river Neva (annual discharge 79 km^3, about 70% and 16% of the total run-off to the Gulf of Finland and to the Baltic Sea, respectively). However, the freshwater residence time in the easternmost part (a few months) is much shorter than in the entire Gulf (8–10 years) and in the entire Baltic Sea (25–35 years). Hence, one can expect faster improvements in response to water protection measures. From a basin-wide perspective, the whole Gulf of Finland and especially its eastern end with pronounced salinity and nu-

Fig. 1. Location of the study areas: (A) the Gulf of Finland drainage basin (shaded) within the Baltic Sea drainage basin; (B) the Gulf of Finland: Hel = Helsinki, SPb = St. Petersburg, Tal = Tallinn; (C) local sub-areas referred to in the Eastern Gulf of Finland. Lines show approximate boundaries according to the Russian classification (*see* e.g., Silina 1997 a): Nb = the Neva Bay, Sh = shallow water area, Tz = transient zone, area westward of Tz is considered as deep waters of the Eastern Gulf of Finland. Dashed lines show approximate boundaries according to the Finnish classification (Pitkänen *et al.* 1993, Pitkänen and Tamminen 1995, Lehtoranta 1998, Heiskanen *et al.* 1999): (1) the inner Neva estuary that includes Sh and Tz areas, (2) and (2a) the outer Neva estuary (position of the western boundary slightly differs in cited papers), (3) the coastal archipelago, (4) the Narva Bay. The area within the boundaries 2 (2a), 3 and 4 is considered as the open Eastern Gulf of Finland = EOGF.
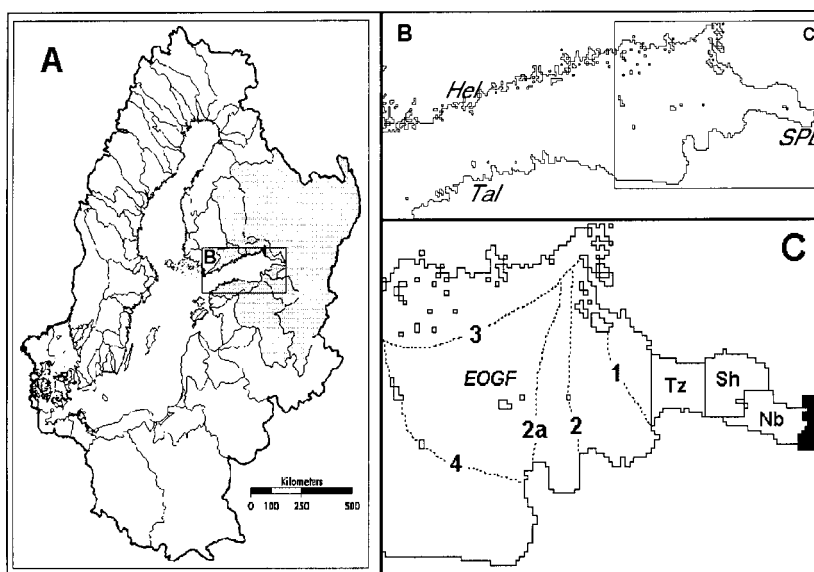
trients gradients can be regarded as a biogeochemical filter and transformer of pollutants. Such consideration makes local and regional water protection measures internationally important.

However, the development of scientifically solid recommendations for cost-effective water management decisions in this region is extremely complicated. Both field studies and some nutrient budgets imply pronounced spatial and seasonal variations of physical and biogeochemical properties (Pitkänen 1991, Pitkänen *et al.* 1993, Perttilä *et al.* 1995, Pitkänen and Tamminen 1995, HELCOM 1996, Leppänen *et al.* 1997, Heiskanen *et al.* 1999). In such a variable environment the scarce field observations allow only semi-qualitative conclusions. Consequently, one needs a tool to quantify ecosystem interactions and biogeochemical fluxes in order to understand cause-effect relationships and, eventually, to be able to forecast possible ecosystem reactions to different scenarios of nutrient load reductions.

The ultimate tool to address such complex is-

**Table 1**. Geographical characteristics of the Gulf of Finland compared to the Baltic Sea.

Characteristic	Gulf of Finland	Baltic Sea	% of Baltic
Surface area[1] (km^2)	29 600	412 560	7
Water volume[1] (km^3)	1 100	21 631	5
Drainage area[1,2] (km^2)	424 000	1 700 000	25
River runoff[2], (km^3 yr^{-1})	112	483	23
Population[3] (10^3 people)	12 671	84 941	15
People km^{-2} (land)	30	50	
People km^{-2} (sea)	428	206	

[1]HELCOM 1990.
[2]1950–1990 mean (Bergström and Carlsson 1994).
[3]population within total drainage area (Sweitzer *et al.* 1996).

Fig. 2. Horizontal box representation of the Gulf of Finland. The vertical structure coincides with that of the hydrodynamic model. Boxes are approximately related to sub-areas in Fig. 1C as follows: 1 = Nb, 2 = Sh, 3 and 4 = Tz, 5 and 6 = the outer estuary, 7 = the Narva Bay, 8 = the coastal archipelago, 9 = EOGF.
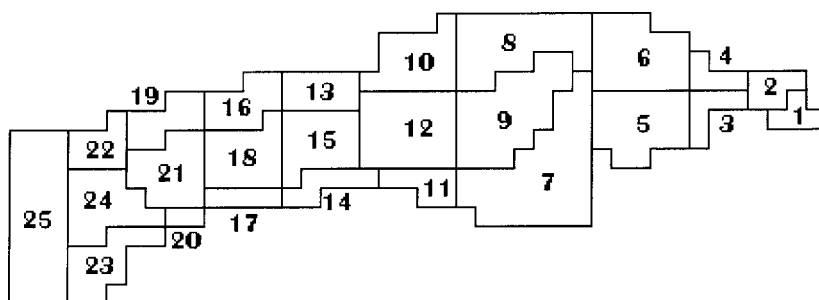
sues in a consistent way is numerical modeling (*see* for example, Kremer and Nixon 1975, Lenhart *et al.* 1997). Two models were recently implemented for the Gulf of Finland (Tamsalu and Ennet 1995, Inkala *et al.* 1997). In both cases, the results were presented and discussed only in terms of nutrient concentration and plankton biomass but not in terms of biogeochemical fluxes.

The importance of fluxes as driving forces responsible for changes of biomass had been recognized already in a pioneer modeling study by Riley (1946) and later it was stressed by Platt *et al.* (1981): "For understanding biological oceanographic systems, it is necessary to have at least as much information on the fluxes as on the biomasses". Today, the study of biogeochemical fluxes is a focal point of many climatological and environmental research programs (e.g., Wollast *et al.* 1993, Pernetta and Milliman 1995).

Estimates of biogeochemical fluxes and budgets explicitly show the fate of eutrophying substances entering the water body, especially how much is recycled and accumulated in the system and how much is lost from the system due to biogeochemical processes. The alterations of fluxes indicate the integral system reactions to imposed perturbations. Simulation results presented in this way are easily comprehended by both the scientific community and the decision-makers as a clear demonstration of possible consequences of different management scenarios.

The model implemented in this study allows tracking of the biogeochemical fluxes between the ecosystem variables. Some results of the model implementation have already been discussed briefly within the "Gulf of Finland Year 1996" (Savchuk *et al.* 1997b) and at ECSA Conference (Savchuk and Wulff 1999) as well as published in

Russian (Savchuk *et al.* 1997 a). Here a more extended analysis of the results with further validation using new data and recent publications is presented.

Method

Model description

The model is based on a system of three nested models (Andrejev and Sokolov 1992, Sokolov *et al.* 1997). A two-dimensional ("shallow water") hydrodynamic model of the whole Baltic Sea is used to compute the sea level variations at the entrance to the Gulf of Finland. With these boundary conditions, a three-dimensional hydrodynamic model simulates the water dynamics within the Gulf. In this study, the hydrodynamics were computed with a time step of three hours and a horizontal resolution of five nautical miles. The vertical structure in the Gulf of Finland was approximated by nine layers with upper boundaries situated at 0, 3, 5, 10, 15, 20, 30, 50, and 60 m depths. The horizontal and vertical transport flows were daily integrated and used in a three-dimensional box model, which simulates physical transports between and biogeochemical transformations within large homogeneous boxes (Fig. 2).

The coupling of both 2D to 3D hydrodynamic models (Rasmussen 1989) and hydrodynamic to ecosystem box models (Chen and Smith 1979, Barreta *et al.* 1995, Pätsch and Radach 1997) has been primarily intended to reduce computational efforts. Other considerations behind a box approach include both a deficiency of knowledge necessary to explicitly describe small-scale processes and a paucity of data needed to run and vali-
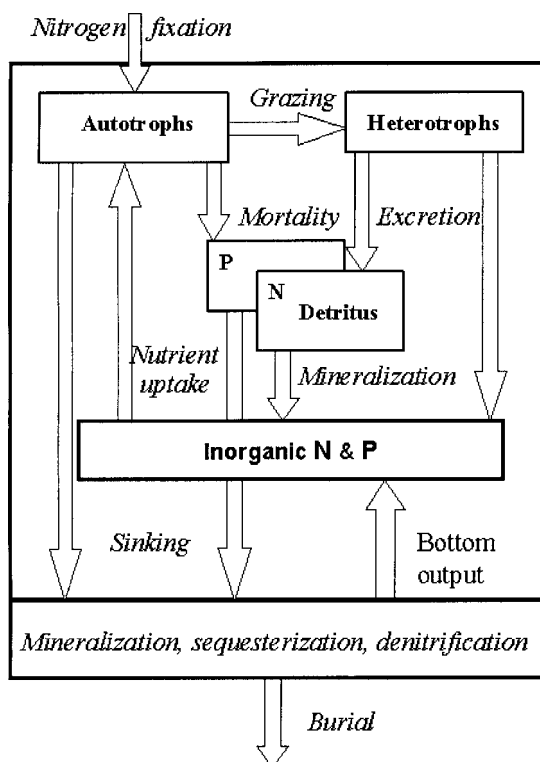
Nitrogen *fixation*

Fig. 3. Generalized scheme of the biogeochemical interactions in the model.

date models with fine resolution. Fully three-dimensional ecosystem models, in which both water dynamics and biogeochemical interactions are modeled at the same fine grid (e.g., Delhez 1998, Grégoire *et al.* 1998), are demanding too much data and computational resources to permit multiple runs necessary for both model calibration and sensitivity analysis.

Algorithmically, the box model is a shell that can be filled in with different biogeochemical formulations. The general principles of such formulations have been used in modeling of marine systems for several decades (*see* for example, Patten 1968, Nihoul 1975, Goldberg *et al.* 1977, Platt *et al.* 1981, Evans and Fasham 1993). The specific parameterizations, gradually developed within these principles (Savchuk 1980, 1986, Stigebrandt and Wulff 1987) and implemented in this study, are described in detail by Savchuk and Wulff (1996).

In this model, each box contains eight state variables: autotrophs, heterotrophs, detritus nitro-

gen and phosphorus, ammonium, nitrate and phosphate, as well as dissolved oxygen. The deepest boxes include also the nitrogen and phosphorus pools in the top active layer of sediments. The model describes coupled nitrogen and phosphorus biogeochemical cycles that are driven by relevant interactions within pelagic and sediment sub-systems (Fig. 3).

Model implementation

The initial fields were constructed using data collected by the standard methods (HELCOM 1988) in special multi-ship surveys (Davidan and Savchuk 1992) in August and November 1991 (Fig. 4).

Hydrodynamic boundary conditions at the sea surface for 13–25 August 1991 and 9–29 November 1991 were obtained from meteorological synoptic maps. At the open boundary between the Northern Baltic and the Gulf of Finland, the lateral water temperature and salinity gradients were set to zero, while vertical distributions of the biogeochemical variables were kept constant in the boundary box 25 (*see* Fig. 2). Climatic river runoff values for August and November (Bergström and Carlsson 1994) were "concentrated" into three main sources: Kymijoki, Neva, and Luga+Narva. The annual estimates of nitrogen and phosphorus inputs to the Gulf of Finland from the land in the late 1980s–early 1990s were compiled from HELCOM (1993) and Perttilä *et al.* (1995) and recalculated into daily loads of bioavailable nutrients from "Kymijoki", "Neva", and "Luga+Narva" sources (Table 2) directed into surface boxes 10, 1, and 7, respectively (Fig. 2). The resulting ratios of bioavailable fraction to total amount prescribed for "Kymijoki" are nearly the same as estimated by Pitkänen (1994) for nutrient inputs to the Finnish coastal waters under different and more elaborated assumptions.

Results and discussion

Model validation

Pelagic variables

Examples of spatial distributions of the model variables from August and November standard

runs are presented in Figs. 5 and 6 together with some field estimates. When comparing simulated to "observed" distributions, several points should be kept in mind:

1. An analysis of simulated dynamics shows that any significant changes had occurred within first two-three days, mainly due to a mutual adaptation of the initial fields according to the model parameterizations. Afterwards the variations were small enough to consider the system as being at quasi-steady state. That consideration justifies a comparison between model outputs in the end of simulations with the measurements composed for the entire months, August and November 1991.

2. The Baltic Environmental Database (BED) at Stockholm University was recently updated with nutrient measurements made in the Gulf of Finland by Finnish Marine Research Institute and Finnish Environmental Institute. Consequently, the "observed" fields constructed with the Data Assimilation System (DAS) (Sokolov *et al.* 1997) are based on more extensive data coverage than was used for both initialization and calibration of the model. In that sense, the model validation with these data can be considered as a real post-simulation exercise.

3. Even with all the available observations used (Fig. 4), there are far less data than necessary to construct 3D fields similar in coverage and resolution to model outputs. Therefore, we have to compare simulated concentrations of aggregated model variables homogeneously distributed within boxes covering hundreds of square kilometers with the fields constructed from sparse measurements of real ecosystem
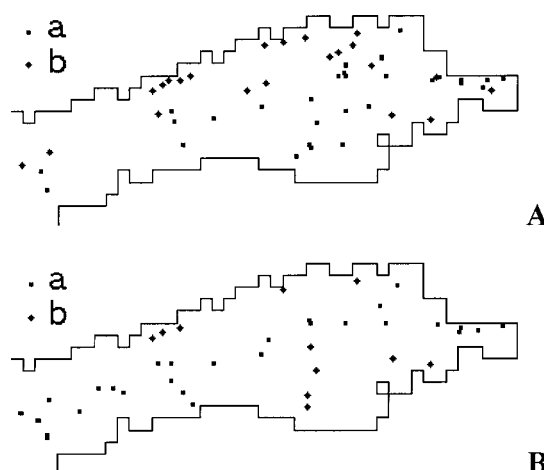

Fig. 4. Oceanographic stations sampled in August (A) and November (B) 1991: a = observations made within the "Baltica" project and used for initialization and calibration of the model, b = observations from BED additionally used in validation.

components made at specific sites in concrete moments. The form of data presentation in Fig. 6 illustrates this controversy.

In general, simulated nutrients distributions match the observations reasonably well. Some discrepancies in ammonium distribution (Fig. 5A) can be related to both underestimated initial fields and the lesser reliability of ammonium measurements in the field compared, for instance, to nitrate and phosphate. Simulated concentrations are higher than measured in November (Fig. 6) due to slightly overestimated vertical mixing that redistributed an excessive amount of nutrients from the deep layers toward the surface.

A comparison of biotic model variables with observations is even less straightforward due to

Table 2. The model inputs of the nitrogen and phosphorus variables (tonnes d^{-1}).

Source	Org.-N	NH_4-N	NO_3-N	Org.-P	PO_4-P
Kymijoki	2.2	25.9	7.0	0.4	0.9
Neva	22.9	108.0	43.2	3.0	6.5
Luga+Narva	8.8	16.0	6.0	0.8	1.8

The inputs were re-calculated from (HELCOM 1993, Perttilä *et al.* 1995) assuming that: (1) 30% of total phosphorus load is inorganic, (2) the inorganic fraction of nitrogen constitute 60%, 40%, and 20% of total nitrogen amount in the rivers of Finland, Russia, and Estonia, respectively, (3) only 10% of organic nitrogen and 20% of organic phosphorus are labile fractions and included into the model.
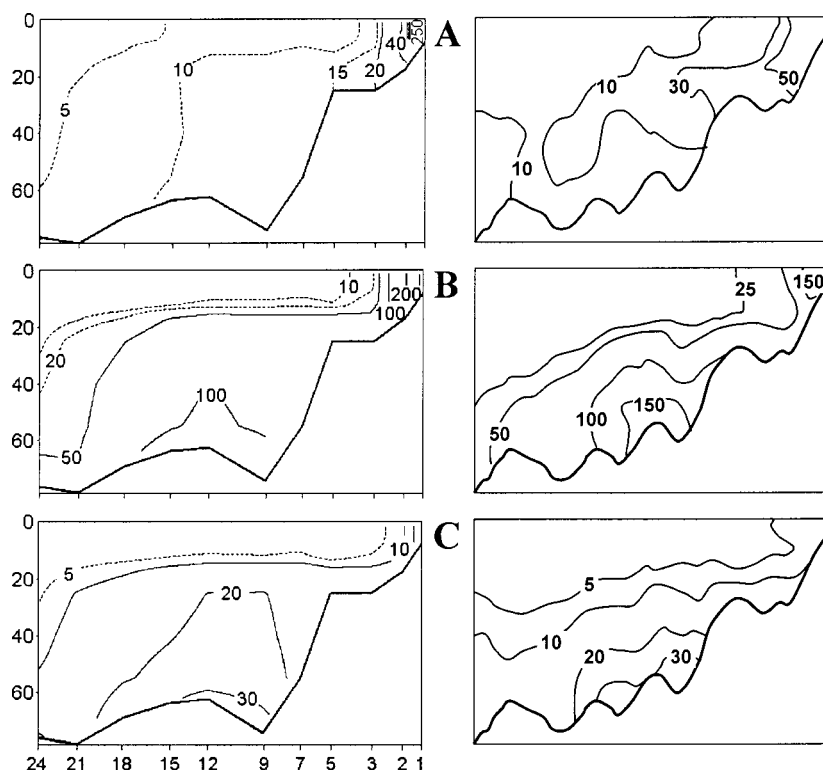
Fig. 5. A comparison of simulated (left, x-axis shows position of the boxes according to Fig. 2) and observed (right) nutrient distributions at the cross-section along the Gulf of Finland axis in August 1991: — A: ammonium (mg N m^{-3}), — B: nitrate (mg N m^{-3}), — C: phosphate (mg P m^{-3}).

both an aggregation problem and different units used to describe biomass in the model (nitrogen) and in observations (chlorophyll *a*, wet or dry weight, carbon). Assuming a nitrogen content of 0.5%–1% in the heterotroph biomass, simulated 4–8 mg N m^{-3} correspond well to a biomass 0.5–2.0 g m^{-3} reported by Pitkänen *et al.* (1993), with highest values found in the transient zone (cf. Fig. 1C) and lowest in the westernmost Gulf. A similar gradient is also found in the phytoplankton distributions, both modeled and observed (Fig. 7).

The good correspondence of modeled to observed distributions of variables could appear to be pre-determined by the short duration of numerical experiments that does not allow simulated three-dimensional fields to diverge too far from the given initial fields. However, the simulated fields are formed as a balance of all biogeochemical and transport fluxes. The amount of material transferred daily by each of these fluxes between variables and in space is comparable to and often several times higher than the amount of material contained in the variables, especially in August (cf. for example, Figs. 5, 7 and 9). Therefore, the

capability to maintain concentration gradients during several weeks should be considered as a validation of the whole model at system scale.

Pelagic fluxes

The model, intended primarily to simulate biogeochemical cycles, has also to be validated against measured rates of biogeochemical processes. Unfortunately, rate measurements are performed far more seldom than measurements of concentration and biomass. In addition to the aggregation problem, the diversity of measurement methods and possible uncertainties with interpretation of resulting values further complicate a comparison of simulated versus measured rates.

A good example is the rate of primary production, one of the most frequently measured parameters. Two sources of data for August 1991 were available for comparison (Fig. 8). Daily values of potential photosynthesis were obtained with the oxygen method in a desk incubator and combined for the shallow waters, transient zone and
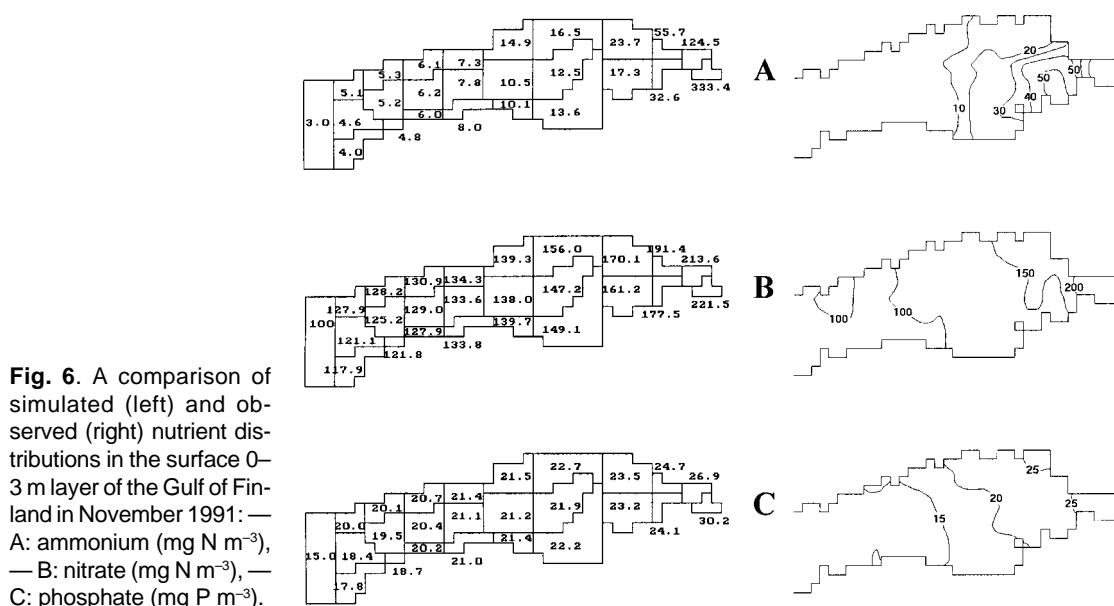
Fig. 6. A comparison of simulated (left) and observed (right) nutrient distributions in the surface 0–3 m layer of the Gulf of Finland in November 1991: — A: ammonium (mg N m⁻³), — B: nitrate (mg N m⁻³), — C: phosphate (mg P m⁻³).

deep-water region of the Eastern Gulf of Finland (Fig. 1C) by Silina (1997a). Particulate primary productivity *in vitro* was measured with the ^{14}C-method from samples incubated at constant temperature and illumination by Pitkänen *et al.* (1993). A comparison shows that the model reproduces well the east-west gradient found in measurements. As expected, the modeled net primary production, which simulates *in situ* conditions, is lower than measured "potential" primary production. The integral values calculated for the whole water column (Silina 1997a) in the transient zone Tz (0.67 g C m⁻² d⁻¹) and in the deep-water area (0.63 g C m⁻² d⁻¹) are very close to simulated values in boxes 4 (0.74 g C m⁻² d⁻¹) and 9 (0.65 g C m⁻² d⁻¹). But we have no good explanation for two-fold difference in shallow area Sh (0.61 g C m⁻² d⁻¹) vs. box 2 (1.36 g C m⁻² d⁻¹).

Nutrient utilisation by the phytoplankton community during nutrient depletion experiments performed in the eastern Gulf of Finland in August 1990–1992 (Pitkänen and Tamminen 1995) is not directly comparable to simulated fluxes (Fig. 9). In the experiments, the surface water samples were highly and separately enriched (10 mg P m⁻³, 40 mg N m⁻³) with different nutrients (ammonium, nitrate, and phosphate) and incubated on deck. In the model, the nutrient uptake rates are defined by *in situ* illumination and ambient nutrient con-

centrations according to Liebig's "minimum law", the nitrate uptake being inhibited at high ammonium concentrations. By qualitative comparison, the experimental nitrogen depletion rates clearly indicate decrease from the easternmost area towards the open eastern Gulf (from 3–8 to 0.2–3 mg N m⁻³ h⁻¹ in different years), as does the simulated nitrogen uptake (from 46 to 10 mg N m⁻³ d⁻¹, note different time units). The phosphate uptake was nearly invariable in space in the experiments (0.4 to 1.0 mg P m⁻³ h⁻¹), while in the model it is strictly proportional to nitrogen uptake according to the Redfield N:P ratio of 7 (by weight).

The long-term average integral respiration of the zooplankton community in different areas of the Eastern Gulf of Finland during May–October was estimated as 5.36–3.30 g C m⁻³ period⁻¹ with the same east-west gradient (Silina 1997b). Assuming temporal invariability during 180 days and C:N weight ratio of 6, this range would correspond to zooplankton excretion rates of 5–3 mg N m⁻³ d⁻¹, which is expectedly lower than the simulated 12–6 mg N m⁻³ d⁻¹ (Fig. 9) excreted by the highly developed heterotroph community under maximal water temperature in August.

Simulated rates of sedimentation in offshore areas of 15–30 mg N m⁻² d⁻¹ are almost the same as those measured in summer 1983 at the entrance
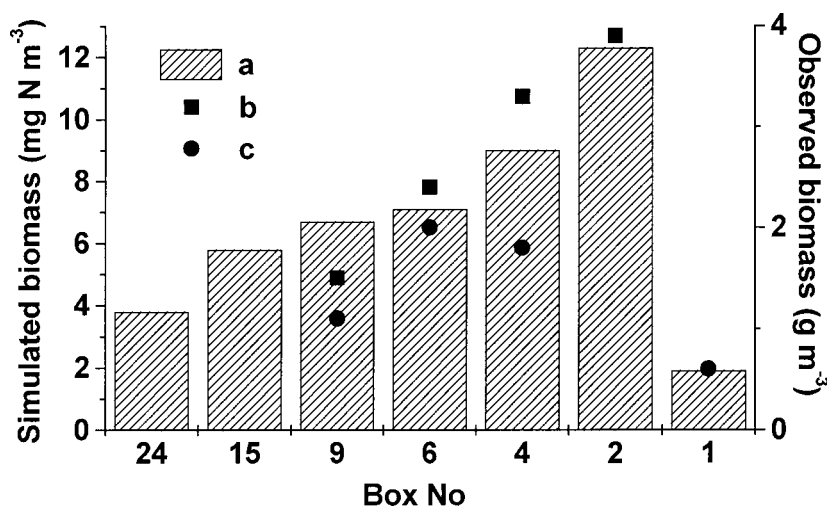
Fig. 7. A comparison of simulated phytoplankton biomass in August 1991 in the surface layer along the Gulf of Finland axis with aggregated estimates from field data (a: model results, b: Makarova 1997, c: Pitkänen *et al.* 1993 and Kauppila *et al.* 1995). Note the different units of y-axes.
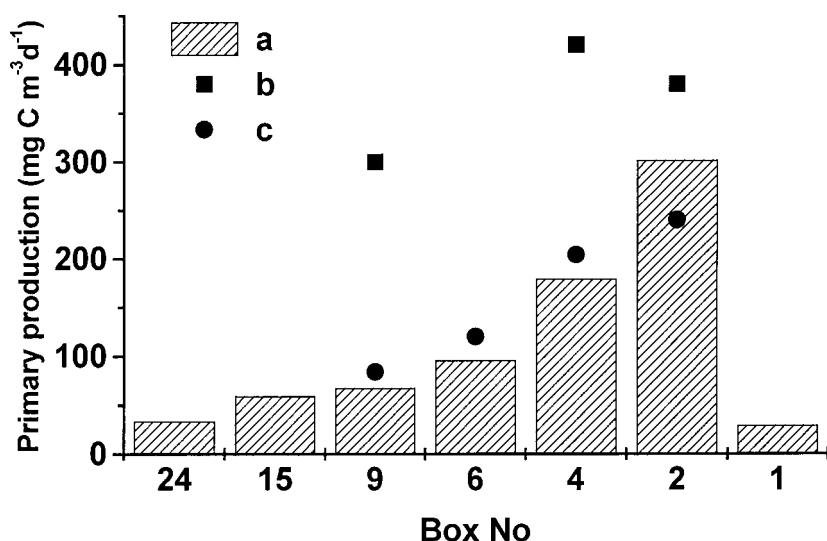

Fig. 8. A comparison of simulated primary production in August 1991 in the surface layer along the Gulf of Finland axis with aggregated estimates from field measurements (a: model results, b: Silina 1997a, c: hourly values from Pitkänen *et al.* 1993 multiplied by 12). Simulated nitrogen values are expressed in carbon units using C:N weight ratio 6.

to the Gulf of Finland (Heiskanen and Leppänen 1995). The significantly higher range of 90–40 mg N m^{-2} d^{-1} was simulated for the eastern boxes 1–6, which are strongly influenced by the River Neva discharge. Heiskanen and Tallberg (1999) described similar differences between archipelago and offshore waters, where total sedimentation estimated for the whole summer (early June–August 1992) was 5.9 and 3.2 g N m^{-2} period^{-1}, respectively. Assuming temporal invariability during 80 days, these values would correspond to 74 and 40 mg N m^{-2} d^{-1}. Recent generalization of sedimentation measurements in the Eastern Gulf of Finland from August 1992 and 1995 (Heiskanen

et al. 1999) allows even more detailed comparison (Table 3), which shows a good fit between simulated and measured values. In the easternmost shallow area simulated sedimentation is lower than measured one due to a neglect of resuspension effect in the model.

Sediment variables

Due to the lack of field data at the time of simulation the initial distributions of nitrogen and phosphorus in sediments were assumed from experience with the Baltic Proper modeling (Savchuk

Fig. 9. Simulated nitrogen fluxes in the surface layer and the N:P ratio along the Gulf of Finland axis. a = ammonium uptake, b = nitrate uptake, c = heterotroph excretion, d = nitrification, e and f = inorganic N:P ratio (weight) in the surface and 15 to 20 m layers, respectively.
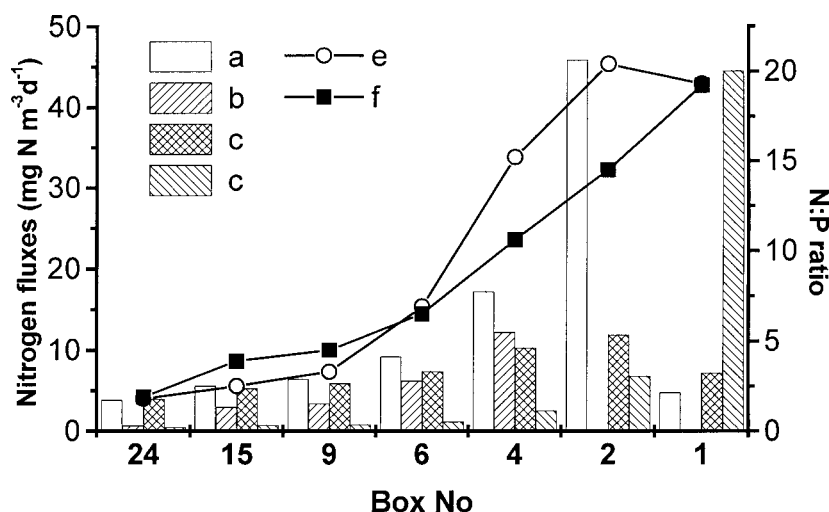
and Wulff 1996) as spatially homogeneous areal concentrations 20 g N m^{-2} and 5 g P m^{-2}, respectively. These estimates correspond well to total nitrogen 20 g N m^{-2} (6.75 to 31.5 g N m^{-2}) and total phosphorus 7.25 g P m^{-2} (2.75 to 11 g P m^{-2}) concentrations at the surface of sediments measured in the Eastern Gulf of Finland during field surveys in 1992–1997 (Lehtoranta *et al.* 1997). The conversion to areal units from gram per gram units presented by Lehtoranta *et al.* (1997) was made assuming average porosity of 90% and density of the solid matter of 2.5 g cm^{-3}. Note also, that the model sediment variables are considered as the "labile" fractions of total amounts of nutrients. In contrast to nitrogen, which is present in sediments mainly in organic form, a large proportion of phosphorus is contained in the insoluble inorganic minerals. Therefore, the concentra-

tion of modeled phosphorus must be smaller than the measured total phosphorus. Indeed, Lehtoranta (1998) found by P-fractionation that only 50% to 60% of the total sediment phosphorus were extracted by NH_4Cl (labile, loosely adsorbed phosphates) and NaOH (Fe phosphates).

Sediment fluxes

Since sediment fluxes in the model are proportional to areal concentrations, the homogeneous distribution of sediment nutrients results in smaller spatial variations of simulated fluxes in comparison to field estimates (Table 4). The four to five-fold range of measured sediment concentrations is one of the reasons of large variations of "natural" fluxes estimated within an area covered by a

Table 3. Simulated and observed sedimentation fluxes (mean ± standard deviation) of nitrogen and phosphorus in the Eastern Gulf of Finland in summer.

Sub-area[1]	Nitrogen (mg N m^{-2} d^{-1})		Phosphorus (mg P m^{-2} d^{-1})	
	Simulated [2]	Observed [3]	Simulated[2]	Observed[3]
Boxes 3, 4 & Inner estuary	52 ± 15	67 ± 33	7.3 ± 2.1	12.0 ± 8.3
Boxes 5, 6 & Outer estuary	29 ± 3	34 ± 15	4.0 ± 0.4	3.7 ± 1.5
Box 9 & EOGF	17 ± 3	17 ± 13	2.4 ± 0.4	2.0 ± 1.6

[1]Location of sub-areas is shown in Figs. 1 and 2.
[2]Model outputs from the depth ranges corresponding to mooring depths of the traps.
[3]Observed values for summer by personal communication from A.-S. Heiskanen.

certain box (e.g., box 6). Therefore, when comparing simulated fluxes within vast homogeneous boxes representing "average" sediments in August 1991 to field estimates obtained in different years with various techniques mostly from muddy sediments, our approach is to look for an order-of-magnitude correspondence rather than for the smaller inevitable differences.

From that perspective, both simulated and "observed" nitrogen and phosphorus outputs as well as oxygen consumption are comparable within reasonable limits, especially in the easternmost Gulf of Finland. Simulated rates of denitrification are well inside the range reported for similar marine environments (*see* e.g., Seitzinger 1988, Enoksson *et al.* 1990). However, in general they are higher than those recently estimated in the Gulf of Finland. All reported denitrification rates rep-

resent accumulation bottoms that cover a relatively small fraction of the total area and consist of silty sediments, where coupled nitrification-denitrification is limited by a very thin oxidized surface layer. Typically, the denitrification rates were higher at stations with abundant benthic population and thicker oxidized layer (Tuominen *et al.* 1998, Gran and Pitkänen 1999). In the model, denitrification fluxes represent the whole bottom area including much better oxidized and populated sandy sediments, where denitrification can be higher than in muddy sediments (Kähler 1991). Therefore, the overestimation of simulated denitrification might not be as large as it appears from Table 4.

In contrast to denitrification, simulated burial fluxes of 0.2 mg N m^{-2} d^{-1} and 0.05 mg P m^{-2} d^{-1} are likely underestimated. Lehtoranta (1998) cal-

Table 4. Simulated and estimated sediment fluxes in the Gulf of Finland.

Box no.	N output (mg N m^{-2} d^{-1})		P output (mg P m^{-2} d^{-1})		O_2 consumption (mg O_2 m^{-2} d^{-1})		Denitrification (mg N m^{-2} d^{-1})	
	Model	Estimate	Model	Estimate	Model	Estimate	Model	Estimate
2	18.9	24.6[2]	5.3	7.0[2]			19.2	0.1–0.2[3]
3	15.2	8.6–10.2[2]	4.2	1.2–7.2[2]			13.7	0.7–1.3[3]
6	12.4	0.0–18.4[2] / 16.0[1]	3.3	0.0–12.0[2] / 21.3[1]	403	398[1]	10.6	0.6–15.7[3] / 3.5[1] / 4.0[4]
7	12.1	7.1[1]	3.1	1.1[1]	387	359[1]	9.8	3.9[1]
8	15.4	29.8[2]	3.2	17.4[1]			12.3	0.2–1.1[3]
9	11.8	3.0[2]	3.0	0.2[2]			9.2	5.8–17.6[3]
12							9.2	4.0–5.0[4]
18	11.8	5.7[1]	3.1	5.6[1]	371	356[1]	9.3	5.5–7.5[4] / 2.6[1]

[1]Conley *et al.* (1997) in July 1993 measured fluxes of ammonium, nitrite, nitrate, and phosphate from incubated core samples, calculated oxygen consumption from sediment micro-profiles and calculated denitrification from oxygen consumption rates and water column concentrations of oxygen and nitrate.
[2]Lehtoranta (1998) calculated diffusive fluxes with Fick's first law from vertical profiles in pore waters measured in August 1995. Only ammonium fluxes were calculated, while the total nitrogen output can be by 25%–50% composed of nitrate flux (Conley *et al.* 1997).
[3]Gran and Pitkänen (1999) in August 1995 measured denitrification by nitrogen isotope pairing technique.
[4]Tuominen *et al.* (1998) measured denitrification by nitrogen isotope pairing technique, only measurements for summers 1994–1995 are included, i.e. those made before the recent occurrence of oxygen deficit in the deep waters of the Gulf of Finland, when measured denitrification became higher.

culated mean annual accumulation rates of 6.9 g N m^{-2} yr^{-1} and 2.0 g P m^{-2} yr^{-1} for the accumulation areas in the eastern Gulf of Finland using mean sediment nutrient concentrations in the anoxic layer from 9 to 10 cm and mean sedimentation rate of 11 mm yr^{-1} based on ^{137}Cs dating. Assuming that the proportion of accumulation areas is 17% (2 227 km^2 of 13 000 km^2, Lehtoranta 1998), these rates would correspond to daily burial fluxes of 3.2 mg N m^{-2} d^{-1} and 0.9 mg P m^{-2} d^{-1}, evenly distributed over the whole area according to the model parameterization. Thus, possible overestimation of the nitrogen "sink" due to denitrification is to some degree compensated by underestimated burial flux. However, on the daily basis both the overestimation of sediment nitrogen sink and the underestimation of sediment phosphorus sink are by several orders of magnitude lower than the sediment pools of nutrients. Therefore, this discrepancy will not affect other daily fluxes derived from short-term simulations.

Considering the results of model validation in general, it appears that the model is capable to reproduce key features of seasonal dynamics and spatial distribution of both state variables and fluxes, especially in the easternmost part of the Gulf of Finland, an area subjected to more detailed analysis below. Consequently, the results of numerical experiments can be used to study effects of eutrophication, especially the pathways of nutrients.

Model application

Limitation and sources of primary production

In the model, the limitation of primary production is in general agreement with the conclusions derived from fieldwork (Pitkänen 1991, Pitkänen and Tamminen 1995). Both in the Neva Bay and in the easternmost shallow area, where nutrients are in excess, the simulated integral primary production is limited by light due to low water transparency (Secchi depth of 0.5 and 1.0–2.0 m, respectively). As nutrient concentrations decrease and water transparency increases towards the west, the light limitation is replaced by phosphorus limitation in the transient zone and by nitrogen limitation in the open Gulf of Finland (Fig. 9).

A similar gradient of limiting nutrients, albeit created by diverse and still discussed mechanisms, is often found in the vicinity of nutrient inputs both in the Baltic Sea (Brattberg 1986, Elmgren and Larsson 1997) and elsewhere (*see* for example, Neilson and Cronin 1981, Woodward and Owens 1989, Nixon *et al.* 1995, Malone *et al.* 1996, De Vries *et al.* 1998). In the model, the high N:P ratio found in land-derived input decreases westward over the easternmost area due to an interaction of biogeochemical and transport processes. The present parameterization does not account for an active phosphate adsorption/desorption on particles either in the water column (Froelich 1988) or onto sediments (Santschi *et al.* 1990, Sundby *et al.* 1992). However, it does allow for the partial release of mineralized phosphorus from sediments even under oxic conditions (Caraco *et al.* 1990, Gunnars and Blomquist 1997). The N:P ratio of nutrient fluxes from sediments is lower than the N:P ratio of both sinking detritus and phytoplankton (cf. also Fig. 10) and outflowing waters become relatively enriched with phosphorus. This biogeochemical effect is further augmented by dilution with nitrogen-depleted waters transported from the open Gulf, as was also suggested by the analysis of field data (Pitkänen 1994, Pitkänen and Tamminen 1995). The water dynamics is responsible for both lower N:P ratios in the deeper layers (Fig. 9) and their significant south-north differences in the easternmost area. The general water circulation pattern (Alenius *et al.* 1998) reproduced by the model causes the westward transport along the northern coast, while the eastward flow occurs along the southern coast (*see* Fig. 6). Consequently, the N:P weight ratios in the surface/deep layers of "southern" (Fig. 2) boxes 5 (4.7/5.6) and 3 (9.4/7.5) are lower than in their "northern counterparts" — boxes 6 (6.9/6.5) and 4 (15.2/10.6).

The model also shows the spatial pattern of nutrient sources fuelling primary production (Fig. 9). In the Neva Bay and in the shallow area, the autotrophs use only ammonium, the high concentration of which suppresses nitrate uptake. Abundant ammonium input both from the Neva River and the sewage treatment plants causes high nitrification in the Neva Bay. Rapid decline of ammonium concentration towards the west due to both utilization and nitrification increases the
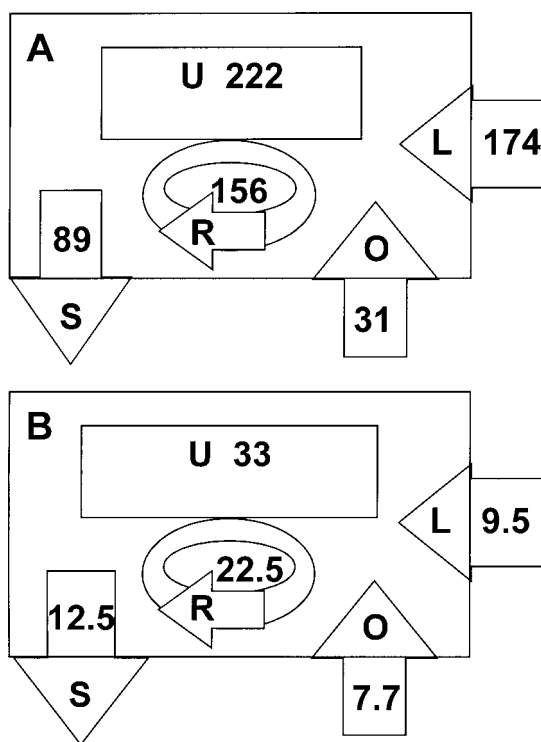
Fig. 10. Nitrogen (A) and phosphorus (B) integrated fluxes (tonnes N (P) d⁻¹) in the easternmost Gulf of Finland simulated with the biogeochemical model for August 1991 conditions. *L* = land loads, *U* = uptake by autotrophs, *R* = regeneration (heterotroph excretion + mineralization), *O* = output from sediments, *S* = sedimentation.

significance of nitrate uptake in the transient zone and the outer estuary. Farther out in the open Gulf, the proportion of ammonium vs. nitrate uptake is increased again due to heterotrophic excretion. The contribution of nitrogen fixation to the nitrogen utilization by autotrophs is increased from a few percent in the easternmost area to 13%–19% in the central and western Gulf. Thus, the external, terrigenous sources of primary production are replaced by the internal nutrient regeneration within a rather short distance from the land inputs. Since the general level of primary production decreases in the same direction, these gradients indicate a high nutrient retention potential of the easternmost end of the Gulf of Finland.

Assimilation capacity

Nutrient retention is often estimated from long-term nutrient budgets of a selected area. In the present short-term dynamic simulations, the day-to-day variations of export and import fluxes across the western boundary of easternmost area are comparable to the land-derived nutrient inputs. Consequently, the daily estimates of nutrient retention calculated as a difference between external inputs and outputs are highly variable. However, since the variations of transport fluxes are only a few percent of the total amounts of nutrients, they do not affect much the spatial distributions of state variables and biogeochemical fluxes. Such robustness of the biogeochemical fluxes makes them more reliable to address a particular question, i.e. how much of the nutrient load from the land can be assimilated within a specified area.

The nitrogen and phosphorus pathways (Fig. 10) show to which degree the total system demand in nutrients, *D*, is balanced by external land loads, *L*, and internal supply, *I*. Let us define *D* as the sum of nutrient uptake by autotrophs and sedimentation, $D = U + S$, and *I* as the sum of output from sediments and nutrient regeneration due to heterotrophic excretion and mineralization, $I = O + R$. Then the difference between nutrient demand and internal supply $D - I$ shows which fraction of the land-originated input can be assimilated within the system. Correspondingly, the relative assimilation capacity *A* in percent can be defined as $A = 100(D - I)/L$. Thus, the assimilation capacity is explicitly related to the land load, irrespectively both of the actual origin (land input vs. sea import) and the further short-term fate (accumulation vs. export) of cycling nutrients. Note, that the nitrogen fixation is excluded from these balance calculations, since the same value must be added to both nitrogen uptake and internal source. Calculations are made for the area restricted to boxes 1–4 (Fig. 2), where the most pronounced changes take place (Fig. 7–9, Tables 2 and 3).

In August, the easternmost Gulf of Finland can

assimilate about 70% of the bioavailable nitrogen land input, while the rest would be left unutilized, accumulating in the system and/or being exported to the open Gulf. However, the bioavailable phosphorus input from the land is by far not enough to satisfy the system's phosphorus demand and an amount equivalent to about 60% of land load is covered by phosphorus imported from the west and/or previously accumulated in the system. These are minimum estimates, since both regeneration and output from the sediments were integrated over the whole water volume and bottom area, respectively. The maximum estimates can be obtained assuming that a sharp pycnocline totally prevents vertical transport and integrating regeneration and output fluxes only over the water volume and bottom area situated above 10 m depth. In this case the nitrogen assimilation capacity increases to 100%, while the unsatisfied phosphorus demand increases to 160% of land loads.

In November, the integral sedimentation onto the area is reduced to less than a third due to negligible primary production. The sediment output is also decreased due to lower water temperature, but only to a half. Consequently, nitrogen assimilation capacity is reduced to about 4%, while phosphorus output from the sediments even exceeds sedimentation by about 12% of the land input, thus forming an internal, secondary pollution source.

It is highly speculative to deduce some annual estimates from the calculations made above, since such a temporal interpolation would imply too many assumptions about relative significance of different fluxes, each of them changing non-linearly during the year. Nevertheless, assuming August estimate as representative for May–October and November estimate for the other half year, we would get the annual nitrogen retention in the easternmost area to be 35%–50% and the assimilation of imported phosphorus to be 50%–150% of the land load. A similar nitrogen-export and phosphorus-import situation is also found in Chesapeake Bay and several other estuaries (Boyton *et al.* 1995).

Qualitatively, these results are in a good agreement with other studies showing high filtration capacity of the Eastern Gulf of Finland (Pitkänen 1994, Pitkänen and Tamminen 1995). However, the present study suggests that the most efficient assimilation is confined to the smaller area (inner Neva Estuary according to Finnish classification in Fig. 1).

Residence times

The nutrient residence times in the easternmost area, defined here as the ratio between the total amount in the water and daily land load, are shorter than the freshwater residence time of 96 days due to sediment–water exchange. However, the net effect of the exchange is different for the different nutrient pools: phosphorus is replenished more effectively than nitrogen. In August, the sediments return back into the water almost two-thirds of the deposited phosphorus, but only one-third of the deposited nitrogen (Fig. 10). In addition, the phosphorus pool is maintained by the eastward import, while the nitrogen pool is drained by the westbound export. In result, the nitrogen residence time of 20 days is shorter than the phosphorus residence time of 30 days. In November, the total amount of nutrients is about twice of that in August, and the deposition decreases to a larger degree than output from sediment as indicated above. Consequently, the residence times in autumn are longer than in summer, 34 and 58 days for nitrogen and phosphorus, respectively.

These seasonal variations in the residence times show that the common rule-of-thumb "the longer the residence time, the higher the retention capacity" should not be taken for granted without proper consideration of the time scales.

Effects of nutrient reductions

To study the possible effects of nutrient load reductions, numerical experiments were run with the hydrography identical to that of the standard
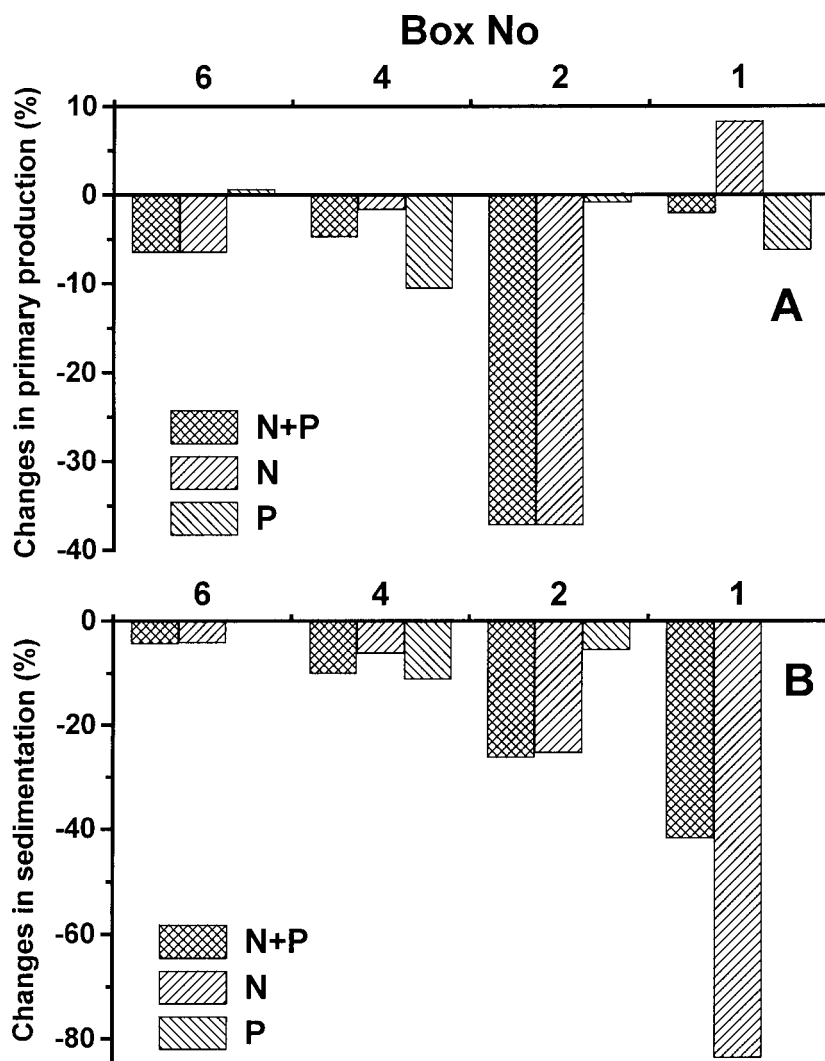
Fig. 11. The relative differences of primary production (A) and sedimentation (B) between the standard run and nutrient reduction scenarios on the 13th day of simulation.

August run but the nutrient load from St. Petersburg region being reduced by 50%. The reductions were imposed with three scenarios: only nitrogen input reduced, only phosphorus input reduced, and both N and P inputs reduced simultaneously.

As it was expected from the short nutrient residence times, the effects of reduced inputs in the easternmost part of the Gulf of Finland are quite clear already after two weeks (Fig. 11). The differences between the scenarios correspond well to the spatial differences in limiting factors discussed above. Under reduced nitrogen load light limitation in the shallow area (Box 2) is replaced by ammonium limitation and the productivity de-

creases despite of rather high nitrate and phosphate concentration. The phosphate limitation in the transient zone (Box 4) does not change much with the reduction of nitrogen load and becomes even more severe under the phosphorus load reduction. Farther westward (Box 6) the nitrogen reduction just sharpens the existing nitrogen limitation.

It may appear that the westward decrease in effect is caused by the short duration of the simulations: the larger the distance from the source of perturbation, the lesser should be the effect. However, additional simulations made with the same recurrent hydrodynamics for periods up to 78 days show that in the easternmost boxes the effect re-

mained nearly the same. To the contrary, the off-shore system, being driven by internal nutrient cycling rather than by external inputs (*see* Fig. 9 and related discussion above), even started to flourish due to artificial prolongation of the favorable August conditions.

The evaluation of the nutrient assimilation capacity implies that the phosphorus load reduction will simply increase assimilation of phosphorus imported from the west and will not affect the nitrogen retention. The nitrogen load reduction will slightly reduce the phosphorus demand.

Thus, the reduction of nitrogen load would reduce eutrophication of the easternmost Gulf of Finland, simultaneously decreasing the nitrogen export to the open Gulf and farther on to the Northern Baltic. Therefore it appears that for the St. Petersburg area nitrogen rather than phosphorus load reduction is more beneficial, both locally and re-motely. A similar opinion was expressed, albeit in a less strong form, by Pitkänen and Tamminen (1995). However, this conclusion is valid only under the assumption that the offshore nutrient pools would remain unchanged. The changes in the state of the open Gulf that can eventually occur due to the load reductions and/or climatic variations would also affect future export-import relationships.

Conclusions

A model of the nitrogen and phosphorus biogeochemical cycles has been applied to the Gulf of Finland for concrete conditions of August and November 1991 when abundant field data were available for both initialization and validation of the model. A comparison of simulations to field estimates of both concentrations and rates of biochemical processes shows that the model describes all the major nitrogen and phosphorus biogeochemical fluxes in a plausible way.

Simulated fluxes were used to evaluate the assimilation capacity of the easternmost Gulf of Finland. The estimates imply that under August conditions this relatively small area can assimilate an amount equivalent to 70%–100% of the nitrogen load from the St. Petersburg region, while phosphorus assimilation is equivalent to 160%–

260% of the land load. Under November conditions the nitrogen assimilation decreases to only about 4%, while the phosphorus export comprises the entire land load augmented by about 12% due to internal pollution from sediments.

The numerical experiments made with the nutrient load reduction scenarios indicate that nitrogen reduction yields both local effects of reduced eutrophication and long-range consequences of decreased nitrogen export into the open Gulf. The phosphorus reduction is to a large extent compensated by increased assimilation of phosphorus imported into the easternmost area from the west.

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