Response of eutrophication in the eastern Gulf of Finland to nutrient load reduction scenarios

Oleg P. Savchuk · Tatjana R. Eremina ·
Alexey V. Isaev · Ivan A. Neelov

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Abstract The trophic status of the eastern Gulf of Finland, where the largest Baltic metropolis St. Petersburg sits at the mouth of the largest Baltic river Neva, is elevated but existing recommendations on water protection measures are controversial. In this study, the effects of nutrient load reductions on this ecosystem were estimated with the aid of a three-dimensional coupled hydrodynamic-biogeochemical model. As a reference, the contemporary seasonal dynamics were simulated with nutrient inputs corresponding to the recent estimates of point and riverine sources. In order to eliminate the effects of natural inter-annual variations, the computations were run under recurrent annual forcing for 3 years, until quasi steady-state seasonal dynamics were reached. Reasonable comparability of simulated concentrations and biogeochemical fluxes to available field estimates provides credibility to scenario simulations. These simulations show that substantial reductions of nutrient point sources in St. Petersburg would affect only the Neva Bay as the immediate receptor of treated sewage waters, where primary production could decrease by up to 20%. Eutrophication in the other parts of the Neva Estuary and in the entire eastern Gulf of Finland would change insignificantly owing to increased nutrient import from the offshore waters. Therefore, more significant changes can occur only via a reduction in nutrient pools in the open Gulf of Finland and the Baltic Proper, which would require a longer time.

Keywords Eutrophication · Numerical model · Nutrient load reduction · Gulf of Finland

Introduction

The eastern Gulf of Finland (Fig. 1) comprises only 3% of the surface area and 1% of the volume of the Baltic Sea, but receives from its watershed over 10% of the total nitrogen and phosphorus inputs from land into the entire Baltic Sea (HELCOM, 2004). Of this load that entered directly into the Neva Bay in 2000, about 12% of nitrogen and 24% of phosphorus were generated by the largest Baltic metropolis, St.

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O. P. Savchuk (✉)
Baltic Nest Institute, Stockholm University,
10691 Stockholm, Sweden
e-mail: oleg@mbox.su.se

T. R. Eremina · A. V. Isaev
Russian State Hydrometeorological University,
Malookhtinsky pr., 98, 195196 Saint-Petersburg,
Russian Federation

I. A. Neelov
Arctic and Antarctic Research Institute, Bering str. 38,
199397 Saint-Petersburg, Russian Federation

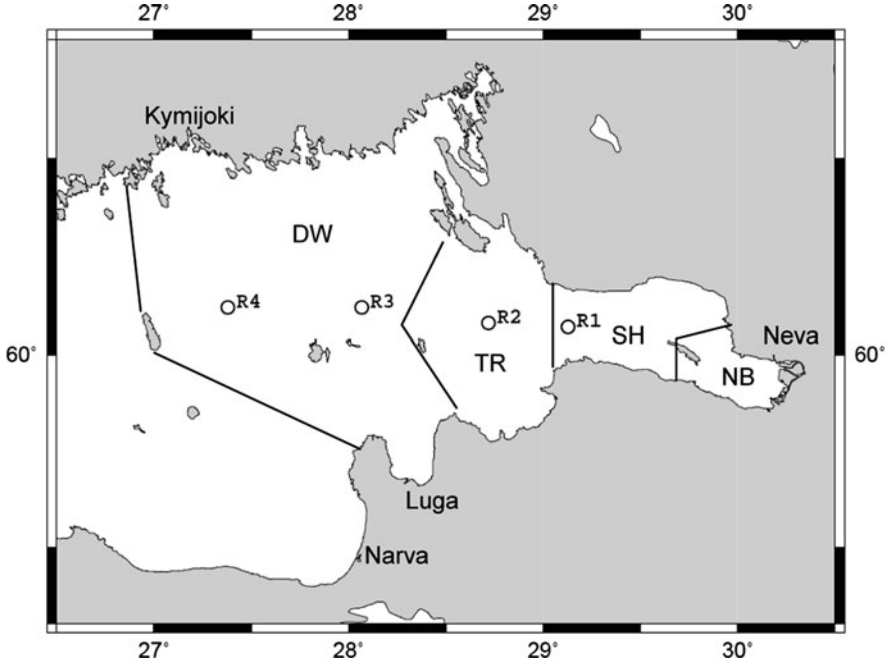


Fig. 1 Map of the eastern Gulf of Finland with locations and delineations of the Russian monitoring stations (Rs), the Neva Bay (NB), the shallow (SH), transit (TR), and deep-water (DW) areas as well as the mouths of the rivers Kymijoki, Neva, Luga, and Narva; the background map is from http://www.aquarius.geomar.de/omc. The NB, SH, and TR areas together are considered as the Neva Estuary (Pitkänen, 1991)

Petersburg (approx. 5 million inhabitants). Consequently, the trophic status of this area is elevated (Pitkänen et al., 1993; Davidan & Savchuk, 1997; Leppänen et al., 1997). However, the development of scientifically sound recommendations for nutrient load reductions in this area is complicated by variations in limiting factors and estuarine nutrient-retention processes (Pitkänen, 1991; Pitkänen & Tamminen, 1995; Savchuk, 2000; Pitkänen et al., 2001). Several models have been implemented for this purpose, but their results are controversial.

From simulations with the EIA-SYKE three-dimensional ecosystem model, one modeling team anticipates that the better removal of nitrogen and, especially, phosphorus at the St. Petersburg wastewater treatment plants would result in about a 15–25% reduction in the annual average algal biomass in the Neva Estuary (Kiirikki et al., 2003; Pitkänen et al., 2007). However, results from the box version of our model have indicated that the easternmost Gulf of Finland acts as a purification facility and imports phosphorus from the open Gulf. Consequently, a reduction of the phosphorus load from St. Petersburg would increase this import, hardly improving the trophic status of the area (Davidan & Savchuk, 1997; Savchuk & Wulff, 1999; Savchuk, 2000).

Subsequently, the same biogeochemical module as in our box model was implemented within a fully three-dimensional model (Neelov et al., 2003). A six-year simulation made with a relatively high spatial resolution but under climatic boundary conditions was compared to the available data. The comparison showed that the model adequately reproduced typical seasonal dynamics in the surface layers but failed to simulate chronologically correctly the inter-annual variations in the deep layers caused by exact succession of year-to-year changes in the driving forces. The simulated biogeochemical dynamics are determined by continuous interactions of natural and anthropogenic drivers, effects that are extremely difficult to separate. In order to eliminate the effects of natural variations, the numerical experiments in this study have been run under recurrent boundary conditions until the quasi steady-state seasonal dynamics were reached.

Materials and methods

Details of the hydrodynamic and biogeochemical modules of the St. Petersburg Eutrophication Model (SPBEM) with all the necessary references are given by Savchuk & Wulff (1996, 2001), Neelov et al. (2003), and Bashmachnikov et al. (2005). Here the authors briefly introduce the variables and processes accounted for in SPBEM.

In the hydrodynamic module, the ocean model is coupled to the sea ice model. The ocean model simulates the dynamics of three-dimensional fields of water velocity, temperature, and salinity as well as two-dimensional sea level variations. The intensity of vertical mixing is calculated from a local balance of the turbulent energy generated by the breaking of wind waves and the shear of the current velocity and damping by water stratification. The ice model describes seasonal evolution of the ice thickness and compactness. In this study, SPBEM is implemented for the entire Gulf of Finland with a horizontal grid step of 2 n.m., and a vertical resolution of 2 m in the layer of upper 30 m and 5 m below.

The biogeochemical module describes nitrogen and phosphorus cycling in the coupled pelagic and sediment sub-systems. The module contains eight pelagic (phytoplankton, zooplankton, detritus nitrogen and phosphorus, ammonium, nitrate, phosphate, and oxygen) and two sediment (bioavailable nitrogen and phosphorus) state variables. The variables interact by the following fluxes: nutrient utilization by phytoplankton including nitrogen fixation, zooplankton feeding and excretion, plankton mortality and sedimentation, mineralization of organic matter in the water column and by the sediments including denitrification and burial, photosynthetic aeration, and oxygen consumption.

Quasi steady-state seasonal dynamics intended to describe the contemporary trophic state of the Gulf of Finland were calculated with the following boundary conditions. Atmospheric forcing corresponding to 1999 was the same as that used in a previous experiment (Neelov et al., 2003). The boundary conditions at the entrance to the Gulf of Finland obtained from the simulation of the entire Baltic Sea were also taken from that experiment. Atmospheric depositions of ammonium (0.70 mg N m^{-2} d^{-1}) and nitrate (0.76 mg N m^{-2} d^{-1}) were the prescribed constants for the entire year except for June, when these fluxes were increased to 1.17 and 1.76 mg N m^{-2} d^{-1}, respectively (Bartnicki et al., 2005). Atmospheric deposition of phosphorus was given as 0.045 mg P m^{-2} d^{-1} throught the year (Savchuk, 2005 and references therein).

The entire Baltic Sea simulation used to generate boundary conditions was made with terrestrial nutrient loads given as monthly averages for 1986–1990 (Neelov et al., 2003). In the present Gulf of Finland simulation, all the nutrient inputs (Fig. 2) were assumed to be concentrated into four sources with locations corresponding to the mouths of the largest rivers, that is, Neva, Narva, Kymijoki, and Luga, all of which are situated in the eastern Gulf of Finland (see Fig. 1). Monthly mean (1996–2000) riverine loads were taken from the Baltic Environment Database (BED) that has recently been updated using data from the North-West Administration of Roshydromet (NW RHM) responsible for environmental monitoring. Organic fractions were calculated as the difference between total amounts and inorganic fractions. Loads from point sources corresponding to the year 2000 were given according to HELCOM (2004) data on total nitrogen and phosphorus, and further dividing these fluxes equally between organic and inorganic fractions. Finally, only 30% of organic nitrogen from every source and 65% of organic phosphorus from the St. Petersburg area were assumed to be bioavailable (e.g., Seitzinger et al., 2002; Stepanauskas et al., 2002). Thus, the annual terrestrial loads of bioavailable nitrogen and phosphorus inputs into the Gulf of Finland were prescribed as 66834 t and 5603 t, respectively, with 63% and 67% of these coming from the St. Petersburg area into the Neva Bay.

In order to approximate the trophic status typical for the end of the last century, the initial conditions for temperature, salinity, oxygen, and dissolved inorganic nutrients have been given as average winter (January–March 1998–2001) three-dimensional fields reconstructed by the Data Assimilation System (DAS) from observations in the Baltic Environment Database (Sokolov et al., 1997). Initial homogeneous fields for plankton and detritus variables were filled in with typical season-specific values.

Depth-dependent initial distributions of bioavailable nitrogen and phosphorus in the bottom sediments were given similar to the distributions obtained in simulations of the Baltic Proper (Savchuk & Wulff, 1996). Because the resuspension of sediments is not yet accounted for in SPBEM, simulated sediment nutrients are accumulating at the shallow depths, especially close to the river mouths, and are depleting slightly in the deepest grid cells. In order to avoid artificial changes in the bottom-water nutrient fluxes and

Fig. 2 Monthly inputs of bioavailable nitrogen (*left*) and phosphorus (*right*) into the Gulf of Finland from Finland, Russia, and Estonia used in SPBEM simulations

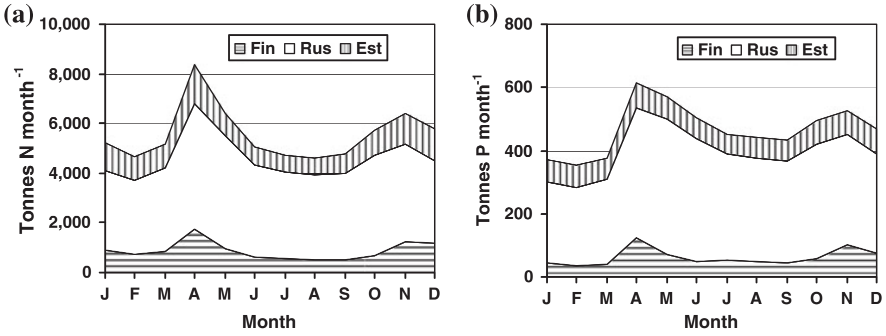
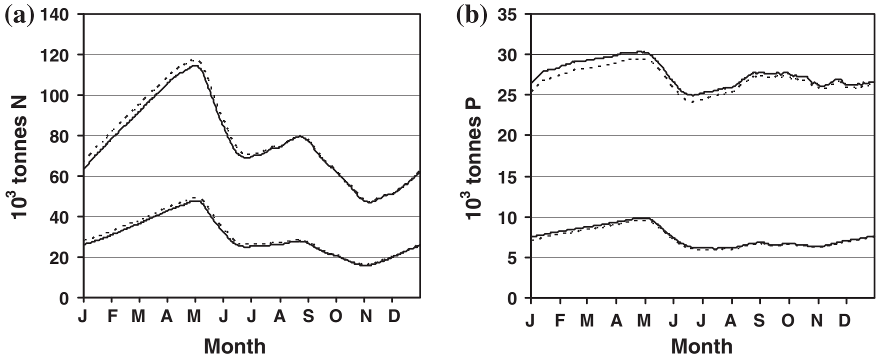


Fig. 3 Simulated seasonal dynamics of the integral water pools of nitrogen (*left*) and phosphorus (*right*) in the entire Gulf of Finland (*upper curves*) and its eastern part (*lower curves*) over the second (*dashed line*) and third (*solid line*) years of computation



maintain the sediment feedback at an approximately similar level in all the numerical experiments, the sediment nutrient distribution in the beginning of each consecutive year of simulation was restored to its initial state.

Results

Seasonal dynamics of nitrogen and phosphorus pools simulated during the third year of computations differ from the dynamics simulated during the second year by only a few percent in both the reference (Fig. 3) and scenario (not shown) experiments. In the reference run, further simulations over the fourth and fifth years make these differences even smaller and were deemed unnecessary considering the long time required for computations. Therefore, the following analysis was made on the results of the third year of both reference and scenario runs.

The reference run and model validation

Validation of the model by data from BED for the central offshore and north-eastern coastal areas (Neelov et al., 2003) has shown that SPBEM realistically reproduced seasonal dynamics of nutrients and plankton in the surface layers. However, in the deep layers, simulated oxygen and phosphate concentrations were over- and underestimated, respectively. In this study, aimed mainly at the eastern Gulf of Finland, that analysis is supplemented by a comparison with data obtained in the Russian monitoring programme run by the NW RHM and collected in summer cruises of the Baltic Floating University. Unfortunately, all the observations were made only during the ice-free period and even after the spring phytoplankton bloom. Therefore, these data cannot directly serve for an explicit assessment of the nutrient pools as a target of nutrient reductions similar, for example, to the "winter nutrient concentrations" that are normally used to characterize accumulated nutrient reserves. As a proxy for such characteristics, the authors have used the near-bottom concentrations averaged over all the measurements made during summer and autumn (Table 1). A comparison of these averages to similarly processed modeled variables shows that the model realistically reproduces the phosphate levels observed in the deep layers of the eastern Gulf of Finland, while it

Table 1 Mean observed and simulated oxygen (ml l^{-1}), phosphate (mg P m^{-3}), and inorganic nitrogen (mg N m^{-3}) concentrations, and resulting inorganic N:P ratio (based on mass) in the eastern Gulf of Finland

	R4 (50 m)		R3 (40 m)		R2 (30 m)		R1 (20 m)		Neva Bay	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
O_2	4.1	5.4	4.2	5.5	4.8	6.4	6.2	6.9	7.1	7.9
PO_4	48	43	47	46	36	35	22	26	9.9	10
DIN	100	110	137	138	108	134	80	132	297	336
N:P	2.1	2.6	2.9	3.0	3.0	3.9	3.7	5.0	30.0	33.6

Note: Averaging was made for the indicated depths (in the shallow Neva Bay for the entire water body) over June–November of the third year of simulation and over measurements made at monitoring stations in June–November 1996–2002

overestimates the oxygen concentration, apparently because of insufficient vertical resolution. Simulated concentrations of dissolved inorganic nitrogen (DIN) are comparable to the concentrations observed in the deep area but are higher than those observed in the transit area and, especially, the shallow area. However, even these somewhat overestimated DIN reserves in the near-bottom layers cannot prevent the summer expansion of strong phosphorus limitation of the primary production westward, as shown by changes in the simulated spatial distribution of inorganic nutrients and the N:P ratio (Fig. 4). Although such annual persistence of estuarine phosphorus limitation differs from the seasonal changes of limiting nutrient (Conley, 2000), it is not unusual either in the Neva Estuary (Pitkänen & Tamminen, 1995) and other Baltic coastal areas (e.g., Meeuwig et al., 2000) or elsewhere (e.g., Nedwell et al., 1999; Howarth & Marino, 2006).

Spatial and temporal dynamics of concentration and biomass are governed by interactions between the physical water transports and the biogeochemical translocations of nutrients among the ecosystem variables. Because the model is driven by the recurrent water circulation, the ecosystem's response to perturbations in external impacts is determined by the changes in biogeochemical processes. Unfortunately, there are only a few field studies of these processes in the eastern Gulf of Finland, and the available information is even more fragmented than measurements of concentrations.

Simulated dynamics of the most important biogeochemical fluxes in the eastern Gulf of Finland are exemplified in Fig. 5 and summed up in Table 2. The net primary production, equivalent to the phytoplankton nitrogen uptake, increases sharply in the last week of April and reaches its peak level of 1.5–2.5 g C m^{-2} d^{-1} at the beginning of May, a few days before the culmination of the spring phytoplankton bloom. Later, the production drops abruptly due to nutrient limitation but increases again along with the development of the heterotrophic community that intensively recycles nutrients in the water column. At the western edges of the deep area, such nutrient recycling in June–August is supplemented by nitrogen fixation and the production stabilizes at 0.2–1.2 g C m^{-2} d^{-1}. In September, the production decreases owing to both the cessation of nitrogen fixation and the reduction of nutrient excretion by heterotrophs, but increases again in October to 0.5–0.9 g C m^{-2} d^{-1} because of the increased admixing of nutrients from the deep layers. The plankton dynamics also determine the seasonal development of nutrient sedimentation with its spring and autumn maxima divided by a summer minimum. As a result, about half the nutrients—transformed from the dissolved to the particulate fraction by phytoplankton—eventually end up in the sediments (see Table 2).

Both seasonal variations and annual integrals of simulated primary production compare well with existing estimates based on scattered measurements (Davidan & Savchuk, 1997; Telesh et al., 1999; Golubkov et al., 2005), including a doubling of summer rates in the shallow area compared to the deep area (Pitkänen et al., 1993). Simulated nitrogen fixation also appears to be rather realistic both in comparison to measurements in the open Baltic Proper of 11–158 mg N m^{-2} d^{-1} (Wasmund et al., 2001) and by its limited eastward extension (Kahru et al., 2000). Ranges of simulated sedimentation rates of 20–40 mg N m^{-2} d^{-1} and 3–7 mg P m^{-2} d^{-1} are fully comparable to the ranges estimated from

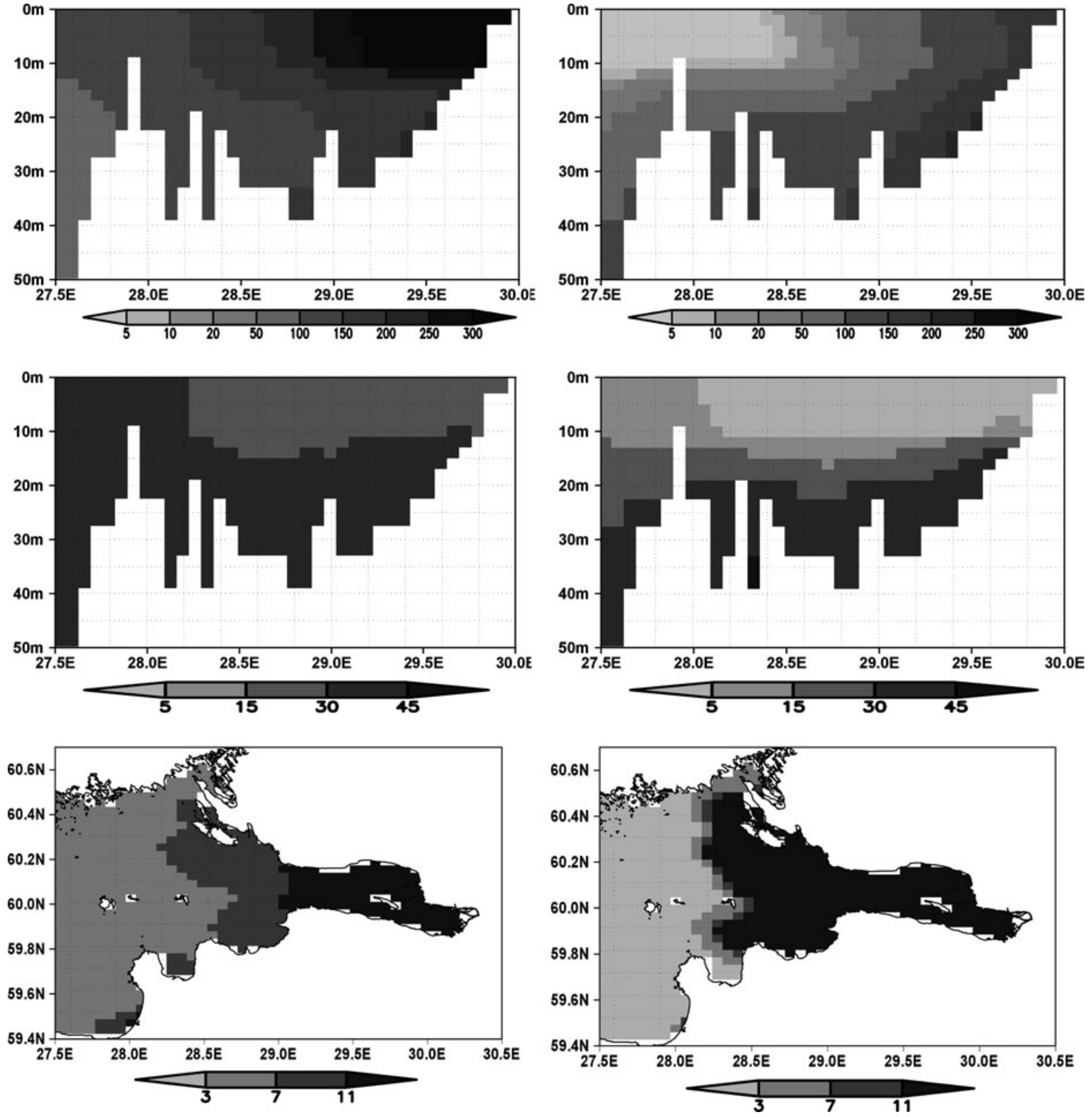


Fig. 4 Simulated distributions of inorganic nitrogen (mg N m^{-3}, *top*) and phosphorus (mg P m^{-3}, *middle*) at the cross section along 60°05′N, and the corresponding N:P ratio (based on mass, *bottom*) in the surface layer before the spring bloom (on April, 1 *left*) and in the summer (on June, 30 *right*)

sediment traps deployed in the eastern Gulf of Finland in August 1992 and 1995 (Lehtoranta et al., 2004).

Simulated nitrogen and phosphorus release from the bottom sediments into the water column varies within a range of 10–20 mg N m^{-2} d^{-1} and 2–5 mg P m^{-2} d^{-1} (see Fig. 5); these ranges are in a good agreement with the rates measured at the aerobic sediment surface (Lehtoranta, 1998; Pitkänen et al., 2001; Kiirikki et al., 2006). The biochemical oxygen consumption by the model sediments does not exceed 600–700 mg O_2 m^{-2} d^{-1}, i.e., assuming a respiratory quotient equal to 3.5 mg O_2 mg^{-1} CO_2, it is well below 240 mg C m^{-2} d^{-1}, which was suggested by

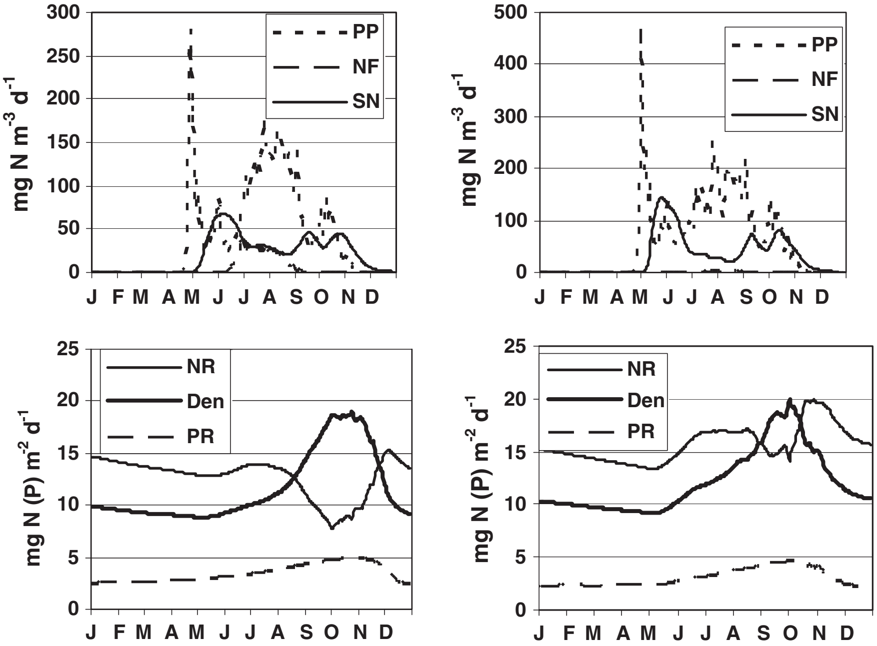


Fig. 5 Simulated seasonal dynamics of biogeochemical fluxes in the deep (St. R4, *left*) and transit (St. R2, *right*) areas of the eastern Gulf of Finland. *Top panels*: *PP* Primary production, *NF* nitrogen fixation, and *SN* sedimentation; *bottom panels*: *Den* sediment denitrification, and *NR* release of nitrogen, and *PR* phosphorus from the sediments into the water column. Note the different scales

Table 2 Annual integrals of simulated biogeochemical fluxes in the eastern Gulf of Finland

Fluxes	R4	R3	R2	R1	Neva Bay
Food assimilation (g C m^{-2})	55	50	76	82	25
Primary production (g C m^{-2})	95	103	136	162	161
Nitrogen fixation (g N m^{-2})	1.75	0.59	0.11	0.12	0.04
N recycling (g N m^{-2})	9.0	8.1	12.2	13.2	4.9
P recycling (g P m^{-2})	1.3	1.2	1.8	1.9	0.96
N sedimentation (g N m^{-2})	7.5	8.7	11.3	13.0	57
P sedimentation (g P m^{-2})	1.1	1.2	1.6	1.8	12
N release from the bottom (g N m^{-2})	4.6	5.2	5.7	5.7	10
P release from the bottom (g P m^{-2})	1.3	1.2	1.1	1.0	1.6
Oxygen demand (g O_2 m^{-2})	265	331	325	419	438
Sediment denitrification (g N m^{-2})	4.3	4.2	4.4	4.4	7.1

Notes: Locations are shown in Fig. 1; conversion from nitrogen to carbon units was made using a factor of 6; primary production represents the sum of DIN uptake and nitrogen fixation; recycling represents the sum of zooplankton excretion and mineralization of detritus; sedimentation represents the sum of phytoplankton and detritus deposited from the bottom layer on the sediment surface; oxygen demand comprises consumption both in the water column and by the sediments

Kiirikki et al. (2006) as a critical point for the redox alteration of the biogeochemical fluxes. The simulated rates of sediment denitrification (10–20 mg N m^{-2} d^{-1}) are higher than the rates reported from most measurements in muddy sediments of the Gulf of Finland (2–9 mg N m^{-2} d^{-1}, Tuominen et al., 1998; Kiirikki et al., 2006), but are comparable to the upper limits reported from the eastern Gulf of Finland (15–18 mg N m^{-2} d^{-1}, Gran & Pitkänen, 1999), as well as to rates up to 25 mg N m^{-2} d^{-1} measured in sandy sediments of the Kiel Bight (Kähler, 1991). The sensitivity analysis has shown that a reduction in simulated sediment denitrification would result in an elevated water nitrogen pool that already now seems overestimated in the easternmost areas compared to available observations (see Table 1).

Nutrient reduction scenarios

Three rather radical scenarios of reduction in the anthropogenic nutrient load have been studied. In a "P-scenario", the phosphorus load from St. Petersburg point sources was reduced by 90%, i.e., the total annual input to the Neva Bay was decreased by 25%, from 3751 t to 2851 t. In an "N-scenario", considering that all the nitrogen coming in from the point sources is bioavailable, the input was reduced by 75%, i.e., the annual input of bioavailable nitrogen to the Neva Bay was decreased by 15%, from 42 360 t to 36 006 t. In an "N&P-scenario", both nitrogen and phosphorus inputs were simultaneously reduced by the amounts indicated above.

A comparison of the annual and area integrals of biogeochemical fluxes simulated over the third year of reference and scenario runs shows a rather insignificant response of the eutrophication in the eastern Gulf of Finland to these substantial reductions of nutrient inputs (Table 3). Relative changes in the primary production, often considered as the essential indicator of eutrophication (Nixon, 1995), are readily explained by spatial gradients of limiting factors but do not exceed a few percent anywhere except in the Neva Bay. The nutrient sedimentation and regeneration rates are tightly related to the primary production and also change little outside the Neva Bay. In fact, in the offshore waters these changes are so minuscule that they would hardly be detected by an analysis of the irregular rate measurements and infrequent monitoring observations made in the region.

The rates of nitrogen fixation are the most susceptible to alterations in the nutrient loads, although these changes are quantitatively important only in the deep area, because eastward of this area the rates themselves are negligibly small (see Table 2). In the deep area, the nitrogen fixation increases by 24% in the N-scenario and decreases by 12% in the P-scenario, while combined nitrogen and phosphorus reductions result in a 12% increase of nitrogen fixation, similar to scenario simulations for other regions of the Baltic Sea (Savchuk & Wulff, 1999; Savchuk, 2002). Thus, the benefits of reduced primary production in the transit area should be weighed against the disadvantages of increased nitrogen fixation as a proxy of cyanobacteria blooms in the deep area.

Discussion

There are several important features of the Gulf of Finland eutrophication revealed and/or highlighted by our study.

The relatively short time period of the model adaptation to recurrent boundary conditions is consistent with the relevant temporal characteristics of the Gulf of Finland that are determined by its intensive exchange with the Baltic Proper across the wide and deep entrance (Perttilä et al., 1995; Perttilä & Savchuk, 1996; Alenius et al., 1998). The highest water ages of 2 years estimated with a different three-dimensional hydrodynamic model were found in the southeastern part of the Gulf, while the water-age distribution after a 5-year simulation was almost the same as that already achieved in 3 years (Andrejev et al., 2004). Residence times of 2.0, 1.4, and 1.3 years were estimated from the long-term empirical budgets for water, total nitrogen, and total phosphorus, respectively (Savchuk, 2005). On the other hand, a short spin-up time found also in the scenario computations can partly be explained by the

Table 3 Relative differences (%) of annual-area integrals of primary production, nitrogen fixation, nitrogen sedimentation, and nitrogen recycling between scenario and reference simulations in different areas of the eastern Gulf of Finland

	Deep			Transit			Shallow			Neva Bay		
	P	N	P&N	P	N	P&N	P	N	P&N	P	N	P&N
PP	0.3	−0.5	−1.3	−0.2	−5.4	−3.6	−4.3	0.8	−3.4	−20	0	−21
NF	−12	24	12	−23	108	38	−18	18	0	–	–	–
SN	0.4	−1.7	−1.7	0.3	−4.3	−3.4	−4.4	−0.1	−4.4	−7.8	−9.2	−17
RN	−0.1	0.6	−1.0	−0.9	−5.6	−3.7	−5.6	1.2	−4.6	−20	−3.6	−24

PP Primary production, *NF* nitrogen fixation, *SN* nitrogen sedimentation, *RN* nitrogen recycling basic set-up of numerical experiments, where the long-term changes both in the waters of the Baltic Proper and in the sediments of the Gulf of Finland have been disregarded.

As appears from the comparisons of simulated to estimated biogeochemical fluxes, the seasonal dynamics of major biogeochemical fluxes are reproduced by SPBEM well enough for a confident consideration of the annual integrals of simulated fluxes. For example, simulated sediment retention of nitrogen and phosphorus (Fig. 6) nicely demonstrates the phenomenon of estuarine nutrient removal known for this and other areas from empirical and modeling studies (e.g., Pitkänen & Tamminen, 1995; Perttilä &Savchuk, 1996; Davidan & Savchuk, 1997; Prastka et al., 1998; Nedwell et al., 1999; Savchuk, 2000; Witek et al., 2003; Lehtoranta et al., 2004). Further integration of such fluxes and water flows over selected areas and boundary cross sections (see Fig. 1) allows localizing and quantifying the nutrient retention capacity of the easternmost Gulf of Finland (Fig. 7).

In the model, the Neva Estuary retains about three-quarters of the bioavailable nitrogen coming in from the St. Petersburg region, with a quarter retained in the Neva Bay and a third in the transit area. In the case of phosphorus, total retention exceeds the terrestrial load by 25%; the “deficit” is covered by the phosphorus import from the offshore waters, mainly during the algal growth season. Almost half of this retention occurs in the shallow Neva Bay (average depth less than 4 m) due to massive sedimentation of particulate phosphorus; this is mostly allochthonus (see Table 2) because phosphorus detritus constitutes about two-thirds of the total prescribed input. Although such a high fraction of particulate phosphorus correspond to observations both in the Neva River and the Neva Bay (Davidan & Savchuk, 1997), the integral phosphorus retention in this area can be somewhat exaggerated because neither the transport of resuspended particles nor the exchange between particulate and dissolved fractions are accounted for in this model. Qualitatively, these results fully agree with earlier conclusions, although the estimates of nutrient retention are quantitatively slightly different from the previous estimates (Savchuk & Wulff, 1999; Savchuk, 2000). The very existence of the net phosphorus import into the Gulf of Finland from the Baltic Proper had been implied earlier (Perttilä et al., 1995; Kahru et al., 2000; Pitkänen et al., 2001) and its annual integral of 2934 t simulated in this study is well within the range of 1000–11 500 t yr^{-1} estimated from empirical budgets and mathematical model (Perttilä et al., 1995; Savchuk, 2005; Kiirikki & Pitkänen, 2007).

Qualitatively, a weak response of the eutrophication indicators to considerable nutrient reductions can be explained by the high buffer capacity of the eastern Gulf of Finland owing to the geographical openness of this area to compensatory transports. The

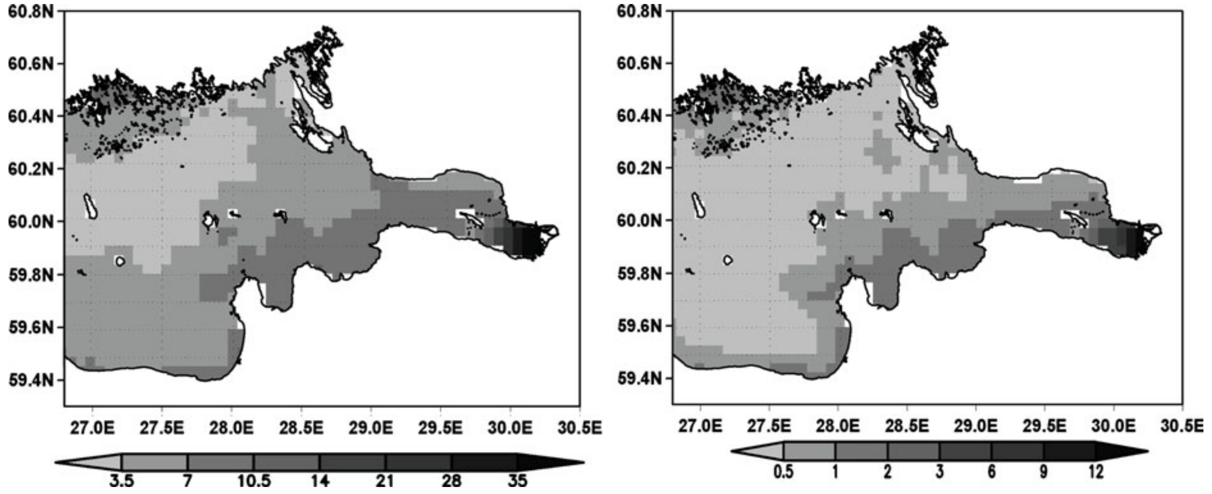


Fig. 6 Simulated sediment retention of nitrogen (g N m^{-2} yr^{-1}, *left*) and phosphorus (g P m^{-2} yr^{-1}, *right*) in the eastern Gulf of Finland calculated as the difference between the sedimentation of nutrients and their release from the bottom

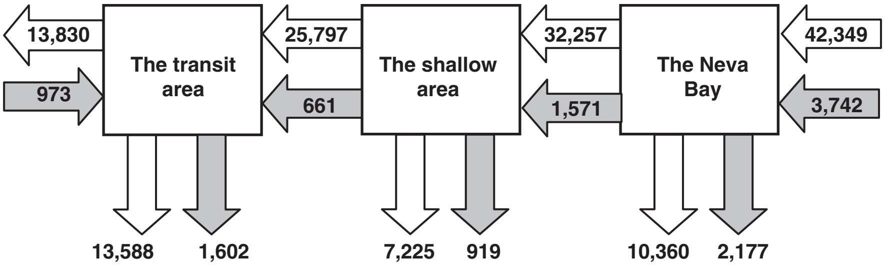


Fig. 7 Simulated annual transport and sediment retention of nitrogen (*clear*) and phosphorus (*shaded*) in the different areas of the Neva Estuary (t yr^{-1}). Areawide nutrient retentions were obtained by integration over the distributions presented in Fig. 6 within the boundaries shown in Fig. 1

reduced 6354 t of bioavailable nitrogen and 900 t of phosphorus would constitute only 8% of the nitrogen pool and 3% of the phosphorus pool in the waters of the entire Gulf of Finland (see Fig. 3). Accounting for nutrient pools in the sediments that actively participate in biogeochemical cycling (see Table 2), these ratios between the reductions and the stocks decrease down to 1% and 0.6% for nitrogen and phosphorus, respectively. The significance of reductions is more important for the eastern Gulf of Finland, where nutrient stocks are smaller and the total ratios increase up to 2.5% for nitrogen and 1.6% for phosphorus. However, in the open system local changes of concentrations create spatial gradients and induce compensatory transports that emerged in simulations and practically counteracted the reductions (Table 4). Accordingly, the response is expectedly more pronounced only in the shallow Neva Bay with predominating westward transports, where all the annual load reductions were applied and amounting up to 57% and 42% of nitrogen and phosphorus average stocks, respectively.

Quantitatively, these estimates are less reliable owing to certain shortcomings in the settings of the numerical experiments reported here. Because of the invariable boundary conditions at the entrance to the Gulf of Finland and yearly restoration of the sediment pools to their initial state, the model predicts only immediate, short-term effects of the load reductions. The long-term effects would be more substantial due to the overall reduction in the nutrient reserves both in the water column and in the sediments. For example, the basin-scale SANBALTS model (Savchuk & Wulff, 2007) predicted that under similar nutrient reductions (see Pitkänen et al., 2007) the inorganic nitrogen and phosphorus pools in the Baltic Proper would eventually change by +0.5% and –2%, respectively, while both the sediment pools and the annual primary production in the Gulf of Finland would decrease by 11%. The phosphorus

Table 4 Net transport (export minus import, t yr^{-1}) across the boundaries of different areas in the eastern Gulf of Finland in the reference and scenario simulations

	Boundary between:			
Scenarios	Deep area and the rest of Gulf of Finland	Transit and deep area	Shallow and transit area	Neva Bay and shallow area
Net nitrogen transport				
Reference	5,912	13,830	25,797	32,257
P	6,109	15,064	27,173	33,173
N	4,485	9,828	20,544	26,980
P&N	4,523	10,730	21,864	27,865
Net phosphorus transport				
Reference	−2,847	−973	661	1,571
P	−3,173	−1,264	380	1,213
N	−2,577	−835	661	1,576
P&N	−2,901	−1,155	374	1,212

concentration in the deep layers of the Baltic Proper in the late 1990s to early 2000s was clearly elevated (Conley et al., 2002; Savchuk & Wulff, this issue) and its possible decrease due to load reductions and climatic fluctuations could result in a lower import to the Gulf of Finland. Also, improved parameterization of sediment dynamics, including redistribution of resuspended particles, may result in either higher or lower overall nutrient retention, thus increasing or decreasing nutrient imports. Some quantitative changes in predictions may also occur from a more realistic spatial distribution and estimates of external nutrient sources that, in the experiments presented here, were all concentrated in the eastern Gulf of Finland.

Although such speculations can be continued further, experience with the sometimes counter-intuitive behavior of models prompts an evaluation of these and similar hypotheses in numerical experiments with the holistic models, rather than through verbal speculation about realistic but isolated cause–effect relationships.

Conclusion

In order to eliminate the effects of natural inter-annual variability in driving forces, a coupled three-dimensional hydrodynamic–biogeochemical model SPBEM has been run for the Gulf of Finland under recurrent seasonal forcing, including the use of invariable boundary conditions at the entrance to the Gulf and yearly restoration of sediment variables. In simulations with these settings, quasi-steady-state seasonal dynamics were reached in 3 years. The comparability of model results to observed concentrations and estimated biogeochemical fluxes was found to be reasonable enough to allow the use of the simulated values typical for the end of the last century as a reference in an analysis of nutrient reduction scenarios.

These scenarios resulted in rather small (<6%) reductions in the major biogeochemical fluxes determining eutrophication of the eastern Gulf of Finland, which would be difficult to detect in standard monitoring measurements. More significant changes were predicted for nitrogen fixation that, in offshore waters of the eastern Gulf of Finland, decreased by 12% in response to the reduction of the phosphorus load and increased by 24% in response to the reduction of the nitrogen load. Only in the shallow Neva Bay, first subjected to scenario impacts, did the improvement in the trophic conditions amounted up to 20%.

This weak short-term ecosystem reaction to substantial load reductions is explained by a high nutrient demand (=retention capacity) of the eastern Gulf of Finland that in response to reduced input from the east induces compensatory nutrient import from the west. In other words, the reduction of nutrient loads from the St. Petersburg region would not quickly improve the local conditions outside the Neva Bay but would be useful in an eventual reduction of the nutrient pools in the waters and sediments of the Gulf of Finland and the Baltic Sea. Only lower concentrations westward of the eastern Gulf of Finland would in the long term decrease compensatory transports into the easternmost area.

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