High resolution 3D-ecosystem model for the Neva Bay and Estuary – model validation and future scenarios*

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Abstract

We have used a simple 3D-ecosystem model to describe nutrient dynamics and biomass production in the Neva Bay off St. Petersburg. The River Neva is responsible for carrying the waste waters of St. Petersburg to the Gulf of Finland. Literature values of chlorophyll-*a* concentrations and satellite images have been used for model validation. The results indicate that our model can reproduce both the temporal and spatial variation in the phytoplankton biomass with reasonable

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accuracy. The model was used to analyse scenarios describing the ecological effects of planned water protection measures. More efficient phosphorus purification was found to be the most effective measure for improving the water quality off St. Petersburg.

1. Introduction

The state of the Gulf of Finland (GoF) has been a matter of considerable concern during the last decade. It is the most loaded part of the Baltic Sea in relation to its water volume (Pitkänen 1994). Even though the nutrient load entering the sea diminished in the 1990s, the opposite development took place with regard to phosphorus concentration. This is a consequence of large areas of oxygen-deficient bottoms in the eastern part of the open GoF. Lack of oxygen causes a flux of phosphate from the sediments, a process known as internal loading (Pitkänen & Välipakka 1997, Pitkänen et al. 2001). At the same time a decrease in nitrogen levels has been reported due to load reductions, particularly in Russia and Estonia (Kauppila & Bäck 2001, Pitkänen et al. 2001). These changes in the nutrient balance have caused intensive, at least partially toxic blue-green algal blooms. The influence of eutrophication can also be seen in the coastal areas of the GoF. The littoral filamentous algae form annoying mass occurrences on the Finnish coast of the GoF (Kauppila & Bäck 2001).

Mathematical modelling is the only method for outlining the effects of the nutrient load entering the GoF. In order to understand the process of eutrophication and to create a reasonable prevention strategy, it is essential to distinguish the effects of the loads from different sources. A large-scale evaluation of the whole GoF has already been carried out by using the 3D-ecosystem model developed by the Finnish Environment Institute and the Environment Impact Assessment Centre of Finland Ltd (Kuusisto et al. 1998, Kiirikki et al. 2001). Local high-resolution models have been linked to the GoF model in the Kotka archipelago, in the eastern GoF (Kiirikki et al. 2002) and off Helsinki (Korpinen et al. 2002). The GoF has also been in the focus of Russian water quality modellers (e.g. Savchuk & Wulff 1999); however, their results have largely been beyond the reach of western scientists.

The eastern GoF receives an extensive amount of fresh water from the River Neva. The nutrient load carried by the river is remarkable. There are 4.5 million people living in St. Petersburg and the waste waters of this area end up in the GoF. The main motivations for this work have been to develop a useful tool for evaluating eutrophication in the Neva Estuary and to concretise the effects of different measures to be carried out in the near future in the treatment of the waste waters of St. Petersburg.

2. Material and methods

2.1. Study area

The easternmost GoF acts as an estuary for the River Neva, the largest fresh water source to the Baltic Sea. The mouth of the Neva is called the Neva Bay, and this is separated from the Estuary by an incomplete flood protection barrier. Surface salinity in the Neva Bay ranges from 0 to 1 PSU and in the Neva Estuary from 1 to 4 (Pitkänen et al. 1993, Pitkänen & Tamminen 1995). The halocline is weak or totally absent and vertical mixing is almost continuous. The thermocline partly separates the nutrient-rich deeper waters from the homogenous euphotic layer in summer everywhere apart from the shallowest parts of the Neva Bay (Pitkänen & Tamminen 1995).

Primary production in the study area is much higher compared to the open GoF (Pitkänen et al. 1993, Kauppila et al. 1995). The nutrient load carried by the River Neva together with the municipal waste waters of St. Petersburg form a major part of the nutrient load to the GoF. The bioavailable nitrogen load from these two sources is 48% of the total bioavailable nitrogen load to the GoF. The share of the bioavailable phosphorus load is even higher, 69% (Kiirikki et al. 2001). Via recycling and secondary effects, the extensive nutrient loading increases the productivity of the whole GoF (Pitkänen & Tamminen 1995).

2.2. Ecosystem model

The ecosystem model used in the present application is built on top of a baroclinic 3D-flow and water quality model by Virtanen et al. (1986) and Koponen et al. (1992). The model takes sea level variations into account. The uncompleted flood protection barrier is taken into account in the model topography according to Russian sea charts. The model presented in this paper focuses on the Neva Bay. However, the whole GoF, east of the Hanko peninsula, is included in the model with a lower resolution. The Baltic Proper facing border of the GoF is closed and no inflow is possible. There is only an outflow from the GoF, which is equal to the inflow of the main rivers.

The horizontal resolution increases in two steps – from 5 km used in the GoF to 1 km in the Neva Estuary and 0.5 km in the Neva Bay (Fig. 1). In the vertical dimension the grid is divided into 10 layers: 0–1 m, 1–2 m, 2–3 m, 3–5 m, 5–9 m, 9–15 m, 15–25 m, 25–40 m, 40–65 m and >65 m. There is a two-way connection between the nested grids, meaning that all calculated variables can be transported from the coarse grids to the finer grids and

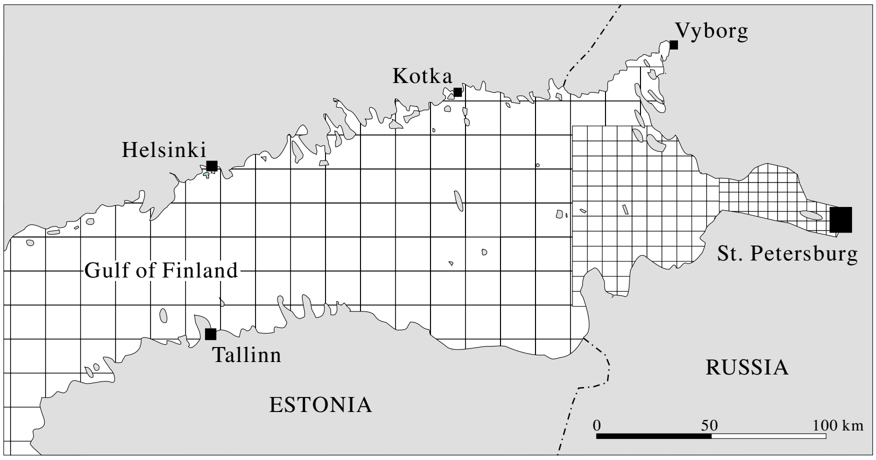


Fig. 1. Model grid used in the nested 3D-ecosystem model application focused on the Neva Bay off St. Petersburg. The horizontal resolution increases in two steps from 5 km used in the Gulf of Finland to 0.5 km in the Neva Bay

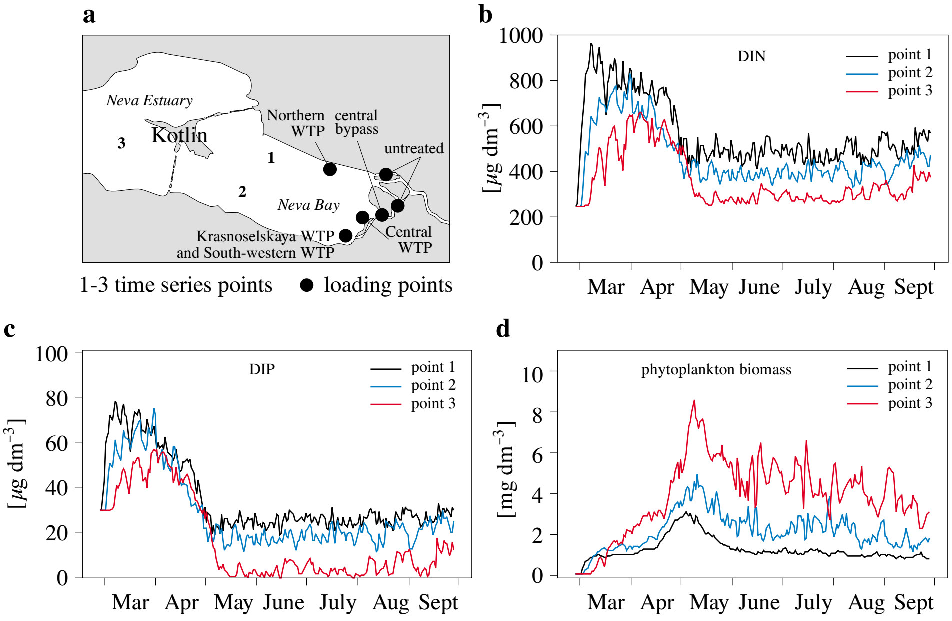


Fig. 2. Nutrient loading points and time series points in the 3D-Ecosystem model off St. Petersburg (a). Modelled dissolved inorganic nitrogen time series for points 1–3 (b). Modelled dissolved inorganic phosphorus time series for points 1–3 (c). Modelled phytoplankton biomass wet weight time series for points 1–3 (d)

vice versa. The loading and time series points used in the application are presented in Fig. 2.

The model calculates the load and transport of soluble nutrients, growth of phytoplankton as well as settling, sedimentation and regeneration of detritus nutrients (Fig. 3). There are neither oxygen-calculation-nor oxygen-concentration-dependent sediment processes in the Neva Bay and Estuary application. The oxygen situation in the Estuary is generally good and the closest areas with regularly detected oxygen deficiency are located in the open GoF. The ecosystem model has been tested by Kiirikki et al. (2001). In the present work no modifications were made to the parameters used previously in the local model applications in Kotka and Helsinki (Kiirikki et al. 2002, Korpinen et al. 2002).

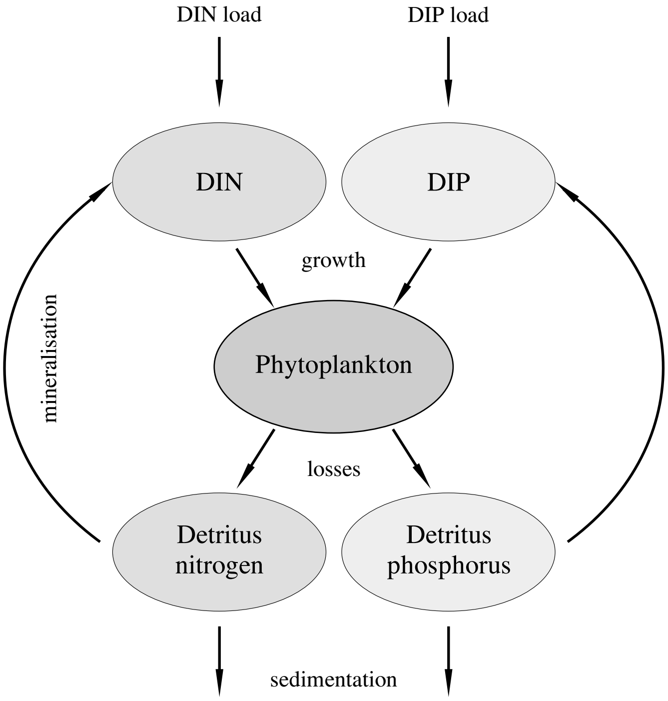


Fig. 3. Variables and main processes of the 3D-ecosystem model

The model uses linear combinations of precalculated steady state flow fields for transport calculations (Virtanen & Koponen 1985). The mass conservation of the ecosystem model variables is verified in the model simulations. The model is run by using synoptic meteorological observations of coastal weather stations by the Finnish Meteorological Institute. Water temperature data is collected from the intensive monitoring sites of the

Finnish Environment Administration, and the light intensity in the form of total radiation data at the Helsinki weather station by the Finnish Meteorological Institute. Data on ice cover is provided by the Finnish Institute of Marine Research. Finnish data representing adjacent areas is used in view of the lack of current Russian data.

2.3. Validation

The limited availability of both flow and water quality measurements was a major problem for validating the model. However, integrated information about chlorophyll-*a* concentrations on the northern and southern sides of the Neva Bay as well as outside the flood protection barrier can be found in the Russian literature (Basova et al. 2000). Satellite image interpretations describing turbidity variations can be used in the semi-quantitative validation of the phytoplankton biomass, because the load of suspended solids from the River Neva is rather low. The best areal resolution can be obtained from MODIS image interpretations by the Laboratory of Space Technology, Helsinki University of Technology (Koponen et al. 2002). The image is calibrated by using data provided by the Finnish Environment Institute.

2.4. Current situation of sewage treatment in St. Petersburg

There are currently three major wastewater treatment plants (WTP) in the city of St. Petersburg: Central, Northern and Krasnoselskaya WTPs. Outside St. Petersburg but under the auspices of the St. Petersburg waterworks, SUE Vodokanal, there are 16 smaller treatment plants. The total amount of treated wastewater is c. 2 460 000 m^3 d^{-1}.

The treatment plants are conventional activated sludge treatment plants with mechanical screening, sand removal, primary sedimentation, aeration and secondary sedimentation. No chemicals are added to remove phosphorus. However, the inflowing water has a rather high concentration of iron, which partially precipitates phosphorus. At the Central and Northern WTPs nitrogen is removed by nitrification and denitrification. Nitrification is enabled by sufficient aeration and sludge age. No special denitrification compartment exists, since the activated sludge basin is aerated throughout its length. Obviously, this aeration is not always sufficient, so anoxic conditions and denitrification do occur. In addition to the treated wastewater, 960 000 m^3 d^{-1} of wastewater (28% of the total flow) was discharged without treatment directly into the Gulf of Finland or the Neva River in the year 2000. Industrial enterprises are responsible for c. 300 000 m^3 d^{-1} of untreated wastewater. However, the nutrient concentrations of the industrial wastewaters were so low that if the concentrations are reliable, it is questionable whether some of them should be treated as wastewater at all. Generally, the treatment results of the two largest WTPs in St. Petersburg are good, especially as no specific nutrient removal process exists. They already comply with the HELCOM recommendations of 1.5 mg dm^{-1} phosphorus concentration in effluent.

2.5. Load reduction scenarios

Model calculation of the scenarios

The model was run over one growing season to illustrate the direct impacts of the scenarios on water quality and algal biomass. The calculation was started at the beginning of March and was stopped at the end of September. One growing season is time enough for demonstrating the direct effects of local measures in a river estuary where the water residence time is very short. The load of the River Neva (kg d^{-1}) was calculated from monthly average concentrations of soluble nutrients and average monthly flows. The three major WTPs of St. Petersburg were included in the model. The estimated untreated waste waters were added to the model as two point loads upstream on branches of the River Neva. The present and reduced loads used in the St. Petersburg model are shown in Table 1. The estimates of loads and load reductions may change in the future when more detailed data about the nutrient concentrations in influent and effluent waters is obtained in St. Petersburg. Winter measurements of soluble nutrients by the Finnish Environment Administration were used as starting values for the open GoF. The simulations of the scenarios were first run with the present load and then with reduced loads according to the scenarios. The meteorological data used in the scenarios represents the year 1998. In the model validation, meteorological data for 1997–2000 was used. The average biomass of the phytoplankton was recorded for the growing season. The biomass of each scenario was then compared with the biomass calculated by using the present load. The results are presented as relative change of biomass. We have classified the results into five categories: $<5\%$, 5–10%, 10–15%, 15–20% and $>25\%$ biomass decrease. Changes lower than 2% were regarded as no change.

South-western wastewater treatment plant

The first calculated scenario illustrates the load reductions following the construction of the South-western wastewater treatment plant. Construction of the WTP started in 1987, but work has ceased since the collapse of the Soviet Union. The most likely year of completion is now 2005. In particular, the WTP will diminish by-passes from the South-western

Table 1. The present and reduced biologically available nutrient loads [t yr^{-1}] from the municipal wasterwaters of St. Petersburg

	DIN load [t yr^{-1}]	Reduction [%]	DIP load [t yr^{-1}]	Reduction [%]
Present load	11 900	–	1 310	–
1. South-western WTP	11 000	8	1 190	9
2. Northern collector sewer	11 600	11	1 210	8
3. Chemical P-removal in northern and central WTPs	11 900	0	800	39
All measures (1., 2. and 3.)	9 700	18	580	56

DIN = dissolved inorganic nitrogen.
DIP = dissolved inorganic phosphorus.

and Central sewerage areas. The nutrient load reduction to be achieved is estimated at 900 t yr^{-1} of biologically available nitrogen and 120 t yr^{-1} of biologically available phosphorus.

Northern collector sewer

The construction work of the 12 km long Northern collector sewer was started in 1987. At present, Vodokanal is carrying out the construction work with local funds. The first tunnel should reach completion in 2006–07. Completion of the first tunnel of the Northern collector sewer will bring c. 450 000 m^3 d^{-1} from the Central and Northern sewerage areas to the Northern WTP. Sludge handling at the Northern WTP has to be upgraded before more wastewater can be fed into the plant. It is uncertain whether the second line required by legislation will ever be built. The expected nutrient load reduction will be around 1 300 t yr^{-1} of biologically available nitrogen and 100 t yr^{-1} of biologically available phosphorus.

Chemical removal of phosphorus in the Central and Northern WTPs

At present, chemicals are not used to precipitate phosphorus at the WTPs in St. Petersburg. Chemical precipitation is a well-known and reliable way of enhancing phosphorus removal. Simultaneous precipitation is the most widely used method in Finland. Most often it is done with ferrous sulphate ($FeSO_4 \cdot 7H_2O$), which is dosed partly before the pre-sedimentation basin and partly in the stream entering the secondary sedimentation basin. Ferrous iron is oxidised to ferric iron in the aeration basin, where the main precipitation effect occurs. The use of simultaneous precipitation with ferrous sulphate requires tanks to dissolve the solid chemical and store the solution, a dosing pump or pumps and piping. The amount of total solids produced will increase somewhat. On the other hand the dewaterability of chemical-biological sludge may be better than that of purely biological sludge. These antagonistic effects may compensate each other and no extra capacity in the sludge treatment will be needed. The nutrient load reduction to be achieved is c. 510 t yr^{-1} of biologically available phosphorus.

3. Results and discussion

3.1. Validation

Figs. 4 and 5 are redrawn from data by Basova et al. (2000). Fig. 4 presents average August chlorophyll-*a* concentrations in the Neva Bay and in the Neva Estuary outside the flood protection barrier. Higher chl-*a* concentrations have been measured in the Neva Estuary than in the Neva Bay. This was the case throughout the 1990s. Fig. 2 (B-D) shows the modelled phytoplankton biomass for one calculation period (March 1st – September 30th). In the model, the phytoplankton grows most effectively just outside the flood protection barrier, just as in reality.

Fig. 5 shows chl-*a* concentrations from 1992 to 1999 on opposite sides of the Bay. August chl-*a* concentrations in the southern part of the Neva Bay are much higher than in the northern part of the Bay. Modelled average values for the months of August 1997–1999 are presented in the same figure.

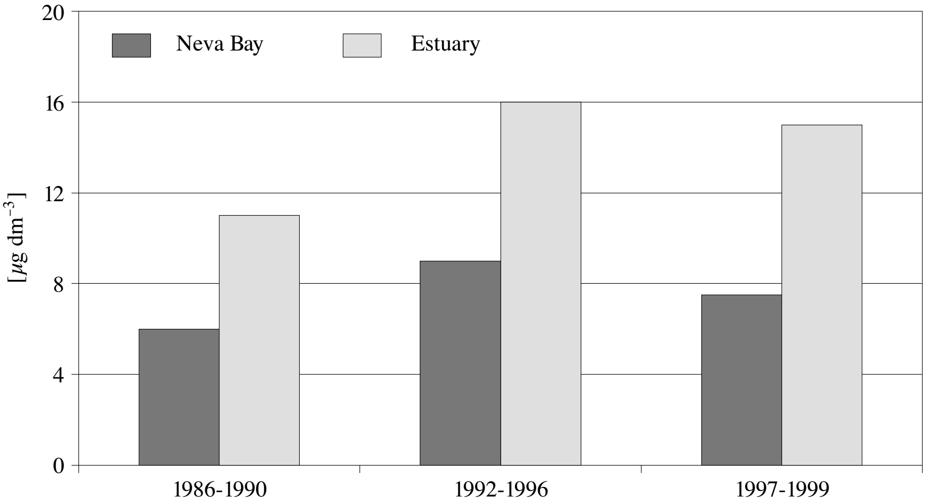


Fig. 4. Redrawn data of Basova et al. (2000) presents average August chlorophyll-*a* concentrations in the Neva Bay and beyond the flood protection barrier in the Neva Estuary

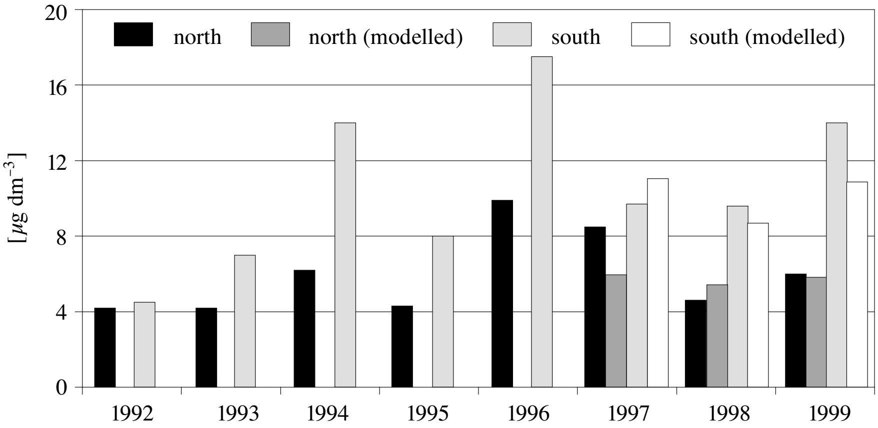


Fig. 5. Redrawn data of Basova et al. (2000) presents average August chlorophyll-*a* concentrations on the southern and northern sides of the Neva Bay. The modelled average values of comparable areas are included in the figure

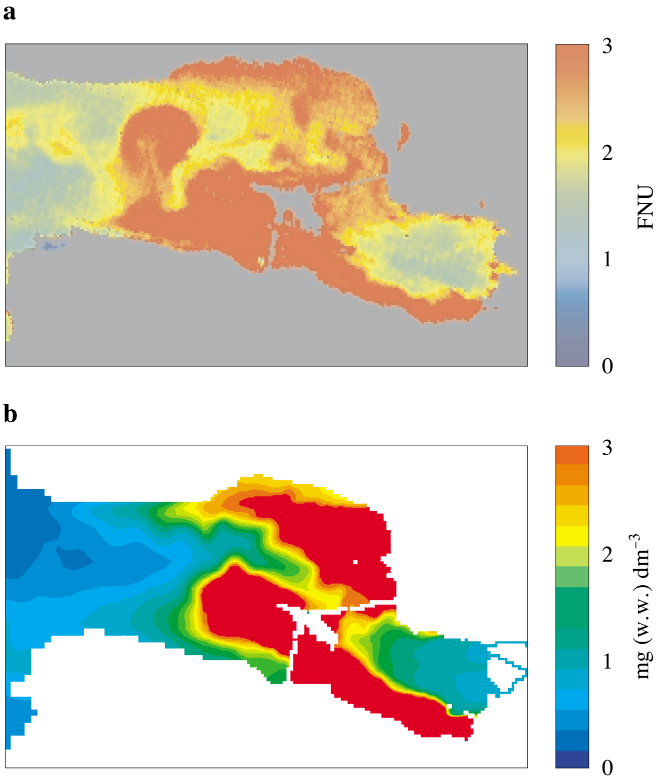


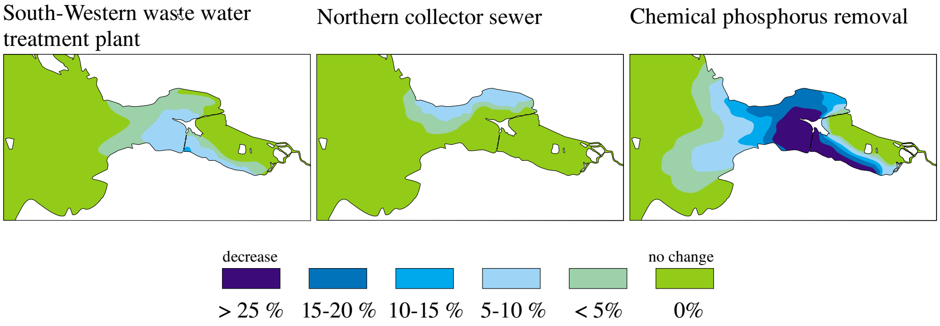
Fig. 6. Turbidity interpretation (FNU – Formazine Nephelometric Unit) derived from MODIS satellite images off St. Petersburg on August 27th, 2000 (a). Modelled phytoplankton biomass wet weight [mg dm^{-3}] for the same day (b)

The model seems able to reproduce the differences between the northern and southern parts of the Bay as well as the interannual variation. The semi-quantitative comparison with the MODIS satellite image interpretation also supports this view. Satellite image interpretation (Fig. 6) shows a high turbidity in the southern part of the Neva Bay and also in the Neva Estuary beyond the flood protection barrier. The chl-*a* measurements also clearly indicate this pattern between opposite sides of the Bay (Telesh et al. 1999, Basova et al. 2000). The model results are in accordance with this and the description of the current situation is good. The phytoplankton biomasses in the model are highest just outside the flood protection barrier. In addition, the modelled phytoplankton biomass is much higher in the southern than in the northern part of the Neva Bay.

One possible explanation for this phenomenon could be the short residence time of the water in the river mouth. The growing phytoplankton is effectively carried out of the Bay before the formation of significant biomasses can occur. The nutrients do not limit growth, since the nitrogen and phosphorus concentrations increase strongly towards the innermost Neva Estuary (Pitkänen & Tamminen 1995). Turbidity has been suggested as limiting phytoplankton growth in the northern part of the Bay. However, the load of suspended solids carried by the River Neva is relatively low.

3.2. Effects of the load reduction scenarios

According to the model, the effects of the load reductions following the construction of the South-western WTP would be most intensive outside the flood protection barrier (Fig. 7). The area influenced is quite large, and covers the northern shore of the Neva Estuary. There is a decrease in total phytoplankton biomass of up to 15%. In the Neva Bay the effects are concentrated on the southern shore.


South-Western waste water treatment plant

Northern collector sewer

Chemical phosphorus removal

Fig. 7. The modelled ecological effects of load reduction scenarios off St. Petersburg. The effects are presented as a relative change in the yearly average phytoplankton wet weight

The effects of the completion of the first tunnel of the Northern collector sewer are concentrated on the sandy northern shore of the estuary, an important recreational area in summer. The decrease in phytoplankton biomass is c. 10%. Hardly any effects can be seen in the Neva Bay itself.

The chemical removal of phosphorus from the central and northern WTPs also affects the Neva Bay. There is a decrease in the phytoplankton biomass in the southern part of the Bay, where the primary production is higher. The impacts of this measure also affect a large area of the Estuary, where there is a reduction in biomass of over 25%.

4. Conclusions

From the point of view of the recreational areas of St. Petersburg, the most effective way to improve the quality of the environment seems to be the chemical removal of phosphorus from municipal wastewaters. It is also the most economic scenario, since no major construction work is needed. Phosphorus reduction in St Petersburg may also decrease significantly the potentially toxic N-fixing cyanobacteria blooms in the central parts of the Gulf of Finland (Kiirikki et al. 2001). However, cutting down the nitrogen load is the most effective way to reduce eutrophication in the mainly nitrogen-limited GoF outside the Neva Estuary. Therefore, it is also important to implement the other planned measures affecting both nitrogen and phosphorus loads.

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