

THESIS ON NATURAL AND EXACT SCIENCES B64

**BIOCHEMICAL DEFINITION OF COASTAL
ZONE USING NUMERICAL MODELING AND
MEASUREMENT DATA**

GENNADI LESSIN

TUT
Press

TALLINN UNIVERSITY OF TECHNOLOGY
Marine Systems Institute

Dissertation was accepted for the defence of the degree of Doctor of Philosophy in Natural Sciences on June 12, 2007.

Supervisors: Ph.D Urmas Rausepp, Marine Systems Institute at Tallinn University of Technology

D.Sc Vladimir A. Ryabchenko, St.Petersburg Branch P.P. Shirshov Oceanography Institute, Russian Academy of Sciences, St.Petersburg, Russia

Opponents: Ph.D Thomas Neumann, Institute of Baltic Sea Research, Warnemünde, Germany

Ph.D Peeter Ennet, Estonian Environment Information Centre

Defence of the thesis: August 9, 2007

Declaration:

Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any degree.

Gennadi Lessin

Copyright: Gennadi Lessin, 2007

ISSN 1406-4723

ISBN 978-9985-59-709-5

Contents

List of publications	4
Introduction	5
1. Material and methods	7
1.1. Study area	7
1.2. Numerical model	7
1.3. Model set-up	9
1.4. Data for comparison and validation	9
1.4.1. Monitoring data	9
1.4.2. Biotests	10
1.4.3. Ferrybox data	10
1.4.4. Satellite images	10
1.5. Model validation	11
1.5.1. Hydrodynamic parameters	11
1.5.2. Ecological parameters	11
1.5.3. Analysis of the ecological model response to changes in parameter values	13
2. Nutrient limitation in Narva Bay	15
2.1. Nutrient limitation in MIKE 3 model	15
2.2. Nutrient limitation as seen from the combination of methods	20
3. Modeling for coastal zone definition in Narva Bay	21
3.1. Distribution of phytoplankton and <i>IN</i> in Narva Bay	21
3.2. Factors controlling coastal zone formation in Narva Bay	24
4. Generalization of the coastal zone definition for the central and eastern Gulf of Finland	26
Conclusions	28
Acknowledgements	29
References	30
Publications	Error! Bookmark not defined.
Curriculum Vitae	109
Elulookirjeldus	111
Abstract	113
Kokkuvõte	114

List of publications

This thesis is based on the following papers, which will be referred to in the text by their Roman numerals.

- I. *Lessin, G., Raudsepp, U.* 2006. Water quality assessment using integrated modeling and monitoring in Narva Bay, Gulf of Finland. *Environmental Modeling and Assessment*, 11(4), 315–332.
- II. *Lessin, G., Lips, I., Raudsepp, U.* 2007. Modelling nitrogen and phosphorus limitation on phytoplankton growth in Narva Bay, south-eastern Gulf of Finland. *Oceanologia*, 49(2), 257–274 (accepted for publication).
- III. *Lessin, G., Raudsepp, U.* 2007. Modelling the spatial distribution of phytoplankton and inorganic nitrogen in Narva Bay, southeastern Gulf of Finland, in the biologically active period. *Ecological Modelling*, 201(3–4), 348–358.
- IV. *Lessin, G., Belikova, V., Raudsepp, U., Lips, I.* 2007. Identification of coastal zone of the central and eastern Gulf of Finland by numerical modeling, measurements and remote sensing of chlorophyll *a*. *Hydrobiologia*, submitted.

Introduction

Coastal sea areas form a transition zone between land and the open sea. Intensive physical processes in the junction of coastal and open sea are responsible for enhanced material and energy exchange there. High fluxes of fresh water, nutrients and organic matter from the land together with the availability of light down to the seabed in shallow areas make coastal zones highly productive and vulnerable to eutrophication (Cedervall and Elmgren, 1980; Larsson et al., 1985; Gazeau et al., 2004; Jickells, 2005; Laane et al., 2005).

Although it is an important area in terms of bioproduction, water quality and management of living resources, a common specification of the coastal zone is missing. Instead, a wide range of definitions for the coastal zone exist. Definition of the coastal zone extent is often chosen based on arbitrary criteria, usually comprising distance lines from the coastline or baseline. Such a definition is considered adequate for management programs and plans. This approach has spread throughout the world due to its ease of operation (Vallega, 2003). For instance, the European Water Framework Directive defines the coastal zone by its geographical extent, i.e. the coastal zone is the “surface water on the landward side of a line every point of which is at a distance of one nautical mile on the seaward side from the nearest point of the baseline from which the breadth of territorial waters is measured” (European Commission, 2000). However, areas delimited according to formal boundaries very rarely coincide with the geographical extent of contiguous ecosystems (Vallega, 2003). An ecological approach to coastal zone definition has developed in recent years. For example, considering the fact that one of the main impacts on the state of coastal areas comes from pollution discharged by large rivers, a definition based on riverine influence has been proposed (Artioli et al., 2005). Gibbs et al. (2006) used remote sensing data to propose a biophysical definition of the coastal zone determining it as the area between the coast and the offshore extent of terrigenous influence.

Studying the specific hydrodynamic and biogeochemical processes taking place in the coastal zone requires implementation of special methods. Usually properties of coastal water are determined from data obtained in the frame of monitoring programs. For detailed spatial and temporal resolution of water quality information, numerical modeling can be used. However, coastal and offshore sea processes differ considerably and a model tuned for the open sea might fail to reproduce coastal sea properties adequately. Moreover, spatial resolution of the model must be appropriate to fit the scale of coastal processes. Satellite imagery also allows detailed spatial resolution of the data, but due to frequent cloud cover over the Gulf of Finland, high-quality images for this area are rather rare. For these reasons integration of numerical modeling with other

methods for coastal zone research is necessary and has increased in recent years (e.g. Gerritsen et al., 2001; Cozzi et al., 2004; Erkkilä & Kalliola, 2004).

This work aims at studying specific hydrodynamic and biogeochemical processes in the coastal zone of Narva Bay by using ecohydrodynamic modeling results and available measurement data. A scientifically-based definition of the coastal zone suitable for the tasks of marine ecology is proposed.

The goals of the work include:

- Determination of the factors that limit phytoplankton growth in the coastal zone of Narva Bay;
- Studying sources of nutrients (inorganic nitrogen) in Narva Bay;
- Proposing a new definition of the coastal zone for application to the tasks of marine ecology;
- Defining the extent and variability of the coastal zone in various areas of the Gulf of Finland based on the distribution of chlorophyll *a*.

The work consists of four chapters. Chapter 1 gives an overview of the methods applied. Results of the ecological model validation and parameter manipulations are also presented. Chapter 2 analyzes nutrient limitation for phytoplankton growth in Narva Bay. Chapter 3 is dedicated to defining the coastal zone extent in Narva Bay and identifying factors that influence coastal zone formation. Finally, Chapter 4 discusses the problem of generalization of the proposed coastal zone definition for central and eastern areas of the Gulf of Finland.

1. Material and methods

1.1. Study area

The Gulf of Finland is an elongated estuary of the Baltic Sea with a mean depth of 37 m and maximum depth of 123 m (Figure 1). The western part of the Gulf is directly connected to the Baltic Proper. The eastern part receives the largest single freshwater inflow to the Baltic Sea – the Neva River (Alenius et al., 1998). In the Gulf of Finland nutrient concentrations and algae biomasses increase towards the east and most of the pollution loads originate from the eastern part of the Gulf (Kuusisto et al., 1998).

Narva Bay is defined according to Piirsoo et al. (1992) as an area in the Gulf of Finland bounded by the coastline in the south and in the east, with its northern and western boundaries falling within the respective coordinates of 59.55°N and 26.35°E. Narva Bay is an open bay with an intensive water exchange with the main Gulf of Finland. The Narva River, which discharges into the south-eastern part of the bay, has an average annual runoff of 14.3 km³ and loads of 4010 tons of nitrate nitrogen and 290 tons of phosphate phosphorus (Stålnacke et al., 1999). These loads comprise 8.8% and 11.15% of the total nitrate and phosphate riverine input into the Gulf of Finland.

1.2. Numerical model

The model applied is a coupled three-dimensional hydrodynamic–ecological model MIKE 3 (developed by Danish Hydraulics Institute; detailed description and mathematical formulation of the model are given in paper I). The basic equations of the hydrodynamic model consist of a mass conservation equation for compressible fluid, non-linear momentum equations in the three main directions, a conservation equation for salinity and temperature, and an equation of the state of sea water (Rasmussen, 1993). The simulations were performed with hydrostatic model versions. The Smagorinsky formulation was used for horizontal eddy viscosity, while k-ε formulation was used for the vertical turbulent closure model (Burchard et al., 1998, Rasmussen et al., 1999). The main forcing factors included wind stress and heat exchange at the surface, prescribed sea level at the open boundary and freshwater inflow by rivers.

The MIKE 3 eutrophication (EU) module is coupled to the MIKE 3 advection–dispersion module for simultaneous simulation of transport, dispersion and biogeochemical processes.

The current model version includes 11 interdependent state variables: phytoplankton carbon (*PC*, g/m³), phytoplankton nitrogen (*PN*, g/m³), phytoplankton phosphorus (*PP*, g/m³), chlorophyll *a* (*chl a*, g/m³), zooplankton biomass (*ZC*, g/m³), detritus carbon (*DC*, g/m³), detritus nitrogen (*DN*, g/m³), detritus phosphorus (*DP*, g/m³), inorganic nitrogen (*IN*, g/m³), inorganic phosphorus (*IP*, g/m³) and dissolved oxygen (*DO*, g/m³).

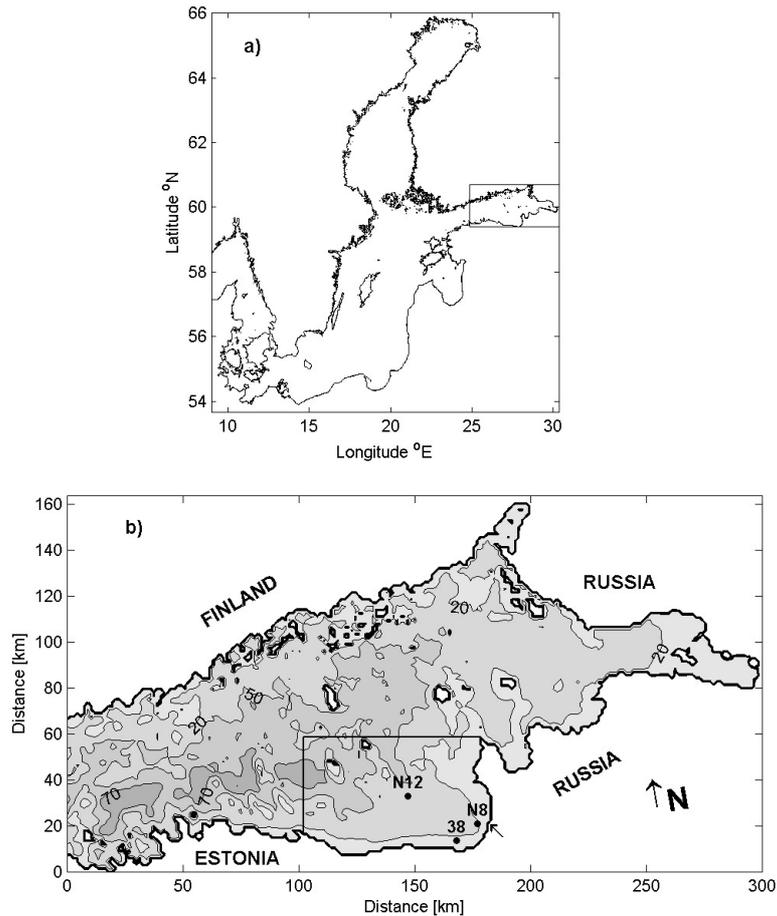


Figure 1. The Baltic Sea (a) and the model domain covering the central and eastern parts of the Gulf of Finland (b). The limits of Narva Bay and the location of monitoring stations N8, N12 and 38 are shown. The small arrow points to the mouth of the Narva River.

In addition to the state variables, a number of derived variables are calculated, e.g. primary production, total nitrogen (*TN*) and phosphorus (*TP*) concentrations, sediment oxygen demand and Secchi disc depth. The model implements two phytoplankton groups: diatoms and green algae, which appear in consecutive order in the model. The ecological model describes the relation between the available inorganic nutrients and the following phytoplankton growth. The nutrient supply depends on the land based load and the transport into the area through model open boundaries.

Further description of the ecological model can be found in DHI Water and Environment (2001).

1.3. Model set-up

The modeling domain covers the central and eastern Gulf of Finland (Figure 1b). The western open boundary of the model was set at about the longitude of Tallinn and Helsinki. The set-up applies a 1500 m × 1500 m horizontal grid based on the Universal Transverse Mercator (UTM) coordinate system. Vertical resolution of the model is 2 m, except for the upper layer which was 3 m thick. A modeling period from April 1, 2001 to October 1, 2001 was chosen, which spans the biologically active season. Model results were stored at 6 h intervals. Land-based freshwater, *IN* and *IP* sources consist of river discharge from the major rivers of the Gulf of Finland and some smaller Estonian rivers. The river input data from Russia and Finland (Neva, Koskenkylanjoki, Kemijoki, Mäntsälänjoki, Porvoonjoki, Virojoki, Vantaa and Mustionjoki) were compiled relying on the database of a monthly time resolution (Stålnacke et al., 1999). Data on Estonian rivers (Narva, Pühajõgi, Purtse, Kunda, Seljajõgi, Loobu, Valgejõgi, Puidisoo and Jägala) were compiled from the observations in 2001. The initial temperature and salinity fields for April 1, 2001 were prepared based on a limited number of TS-casts. The initial temperature distribution was assumed to be horizontally uniform while keeping vertical stratification. Longitudinal salinity drops from about 6 psu in the central Gulf of Finland to 0 psu in Neva Bay. Therefore, the initial salinity profiles were resampled to the model vertical grid. Then, the salinity values were horizontally interpolated to a model grid using a bilinear interpolation method. The prescribed sea level, temperature and salinity distributions were applied at the open boundary.

Air pressure, air temperature and wind fields were taken from HIRLAM at 3 h intervals.

The initial concentrations of *PC*, chl *a* and *ZC* were derived from measurements. A very limited amount of data only allowed the use of homogeneous concentrations for those variables. The initial concentrations of 0.2 g/m³ were taken for *PC* and 0.01 g/m³ for chl *a*. The growth rates of 0.8 day⁻¹ and 1.4 day⁻¹ were selected for diatoms and green algae, respectively. The respective temperature dependences for growth were 1.2 and 1.07. The initial concentration of *ZC* was 0.01 g/m³. The initial distribution of *IN*, *IP*, *DC*, *DN*, *DP* and *DO* were prepared based on a limited amount of measurement data. The data were interpolated onto the model grid using objective analysis. The distributions of ecological state variables were prescribed at the open boundary.

1.4. Data for comparison and validation

1.4.1. Monitoring data

Monitoring data used for ecological model validation originate from Estonian coastal sea monitoring program of the year 2001 (TÜ Eesti Mereinstituut, 2002). Three sampling stations were analyzed throughout the study (Figure 1). Station N8 (17 m deep), is located in the vicinity of the Narva River mouth (59°28.6 N,

27°58.5 E). Station 38 (depth 7 m) in the south-eastern part of the bay (59°24.4 N, 27°47.0 E) is away from the direct influence of the Narva River. However, a local wastewater outlet is situated in the proximity to the station. Station N12 (depth 40 m) is situated offshore, more or less in the center of the bay (59°38.0 N, 27°26.9 E).

1.4.2. Biotests

In 2001 measurements and biotests (nutrient addition experiments) were carried out in the Narva Bay area. Water samplings at two coastal stations, N8 and 38, and at the offshore station N12 were carried out once in May and September and every week from June, 27 to August, 27. The precise methodology of nutrient addition experiments is described in paper II.

1.4.3. Ferrybox data

Measurement data from an automatic ferrybox system operating between Tallinn and Helsinki (Kanoshina et al., 2003) were used for studying the coastal zone extent. The water intake and sampling was located at 4–5 m depth and data were collected once per week from April to November 2001. Fluorescence was recorded every 10 seconds (corresponding to a horizontal resolution of approximately 200 m) during the crossing between Tallinn and Helsinki. During each crossing, water samples were collected from 9 sampling locations for laboratory analyses of chl *a*. The fluorescence values were converted to chl *a* for each crossing separately using a linear regression relationship.

1.4.4. Satellite images

Moderate resolution (1 km/pixel) MODIS/Aqua Level 2 images of chl *a* were obtained from OceanColor website (<http://oceancolor.gsfc.nasa.gov/>). The OC3 algorithm used for MODIS/Aqua image processing usually tends to overestimate the chl *a* concentration in the Baltic Sea, especially during heavy cyanobacterial blooms (Reinart & Kutser, 2006). Due to frequent cloud cover over the Gulf of Finland good quality satellite images are rare. Images from May 10, 2003, July 13 and September 12, 2002, which cover different seasons, were selected. The data were normalized prior to the analysis. Some pixels showing very high chl *a* concentrations may be erroneous. These pixels were replaced by a value of 50 g/m³ in every image. Then all pixels of the image were divided by the maximum value.

1.5. Model validation

1.5.1. Hydrodynamic parameters

Hydrodynamic factors essentially affect the spatio-temporal distribution of biochemical fields mainly through transport and mixing processes. Therefore, the performance of the hydrodynamic model was checked first. Modeled currents were compared with current meter measurement data at the offshore location. The model has reproduced amplitude reasonably well. Also, low-frequency currents compare rather well, which is essential for horizontal transport of biochemical parameters. On average, the modeled transport is to the east and slightly onshore, while measured currents are to the east and offshore.

Temperature and salinity profiles were measured close to the mooring station. In general, the stratification is weaker in the model than measured. The upper mixed layer is thicker, salinity higher and temperature lower in the model than in the measurements. Underestimated vertical stratification might cause overestimated vertical heat, salt and nutrient flux in the model. Simulated lower layer salinity and temperature match better with the measurements. Detailed validation of the hydrodynamic model is given in paper I.

1.5.2. Ecological parameters

Performance of the ecological model was validated at two points in Narva Bay: near the coast in the vicinity of Narva River mouth (station N8) and offshore (station N12). The time series of *IN*, *IP*, *DO*, *TN* and *TP* concentrations at the surface, 5 m, 10 m and the near-bottom layer and *PC* and chl *a* concentrations integrated over the upper 1–10 m layer were compared with available measurement data. Detailed ecological model validation is given in Lessin (2004) and papers I and III.

Modeled phytoplankton showed reasonable seasonal behavior at station N12 (Figure 2a). The spring bloom started in early April and reached its peak at the end of the month, when concentrations were slightly higher than 0.8 gC/m^3 . Biomass decreased to minimum in summer with concentrations less than 0.2 gC/m^3 . There is evidence of a small increase of biomass in September. Measurements of phytoplankton biomass with reasonable temporal resolution are lacking, especially during spring. The only measurement does not match the modeled values, possibly due to ice cover in Narva Bay. Modeled summer values and measurements compare reasonably well.

Near the Narva River mouth a strong phytoplankton spring bloom started to develop in late April (Figure 2b). The concentration exceeded the limit of 1.2 gC/m^3 during the bloom peak. The spring bloom was missed by measurements. The only measurement in spring was on April 24, just before the initialization of the bloom. In the model the bloom started to cease in the middle of May and vanished by the end of June. The biomass in July–September is slightly overestimated by the model.

The strong temporal variability of the surface *IN* concentration observed at station N8 in both model results and measurements clearly indicates the effect of nitrogen supplied by the river (Figure 2c). Most of *IN* is already consumed by the beginning of May. According to the single measurement occasion in April, the model might underestimate the *IN* concentration during this period. The modeled *IN* for summer and autumn in general follows the measurement data.

The surface *IP* at station N8 was highly variable in the summer period in both the measured and modeled data, which is evidence of an increased river phosphates discharge (Figure 2d). The modeled spring values match the measurement data rather well.

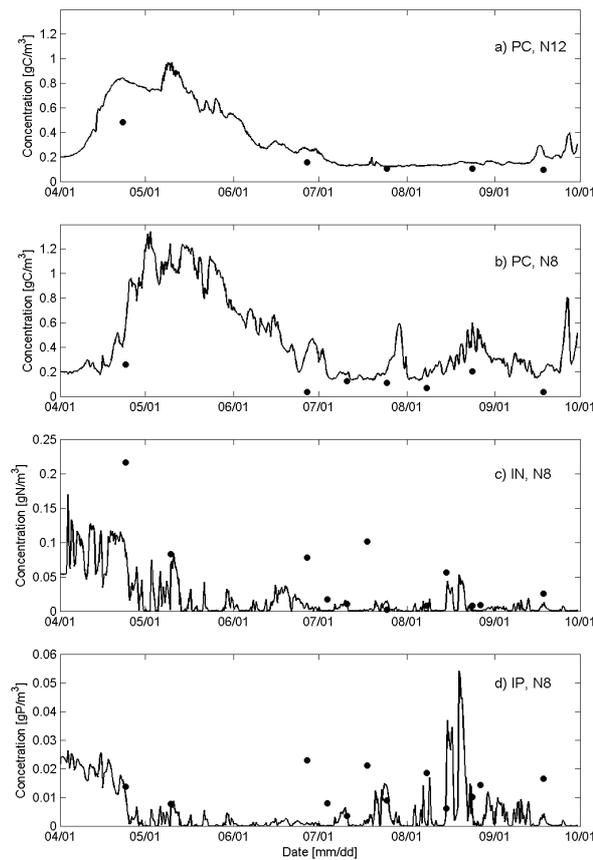


Figure 2. Model validation results for Narva Bay: a) *PC* at N12, b) *PC* at N8, c) surface inorganic nitrogen at N8 and d) inorganic phosphorus at N8. Lines – model results, dots – observed data.

1.5.3. Analysis of the ecological model response to changes in parameter values

Modeling results for the surface layer agreed satisfactorily with measurement data, but concordance in some variables was less good for deeper layers. Analysis of model response to changes in the values of different parameters was performed to improve model performance in the near-bottom layer. Changes in the near-bottom *IP* and *DO* at station N12 were checked, whereas parameters were altered separately or in combinations. Model equations are given in paper I.

In the control run the near-bottom *DO* concentrations were strongly overestimated (Figure 3a) and *IP* underestimated (Figure 3b) in comparison to the measurement data. Increasing proportionality factor for phosphorus mineralization in sediments (2 compared to 1 in the initial run) increased *IP* concentration only slightly but had no effect on *DO*. Increasing proportionality factor for respiration in sediments (2 comparing to 1 in the initial run) allowed to a decrease in *DO*, which now followed the measurement data rather well. However, the effect on *IP* was negligible. The only treatment that led to a considerable increase in the near-bottom *IP* included combined effect of the increased proportionality factor for phosphorus mineralization in sediments (2 compared to 1 in the initial run), higher detritus settling rate (0.4 m/d compared to 0.2 m/d in the initial run), smaller half-saturation concentration for *DO* consumption in sediments (0.5 g/m³ compared to 2 g/m³ in the initial run) and higher proportionality factor for respiration in sediments (2 compared to 1 in the initial run). The average *IP* concentration increased only slightly, but several high peaks reaching measured concentration values emerged occasionally. The previous manipulation also led to a lowering in the near-bottom *DO*, which now was more variable. Since the measurement data are too scarce, a straightforward conclusion on which run fits *DO* data best is rather difficult to draw.

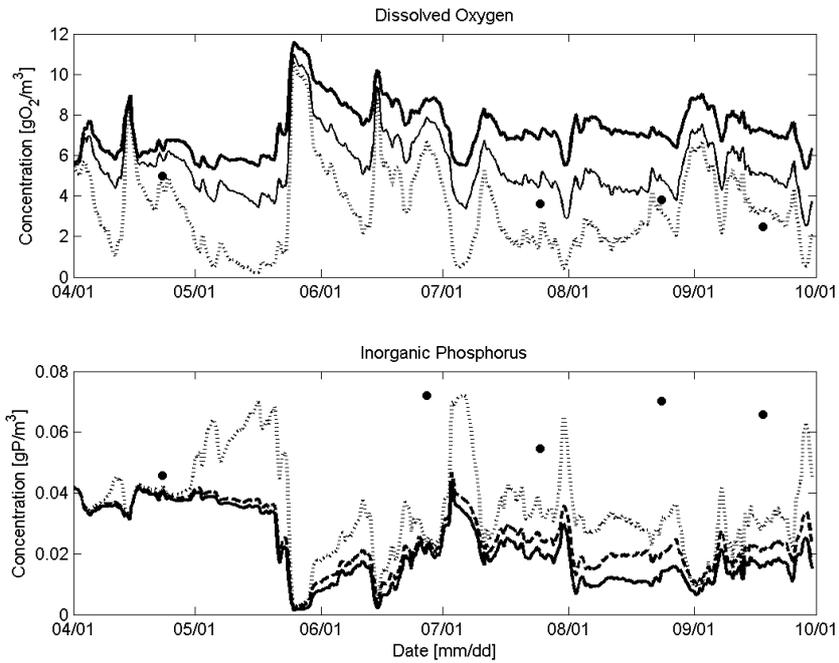


Figure 3. Analysis of model performance in the near-bottom layer. Thick line – control run, thin line – increased proportionality factor for respiration in sediments, dotted line – combined effect of the change of several parameters (see description in text), dashed line – increased proportionality factor for phosphorus mineralization in sediments, filled circles – observed data.

2. Nutrient limitation in Narva Bay

2.1. Nutrient limitation in MIKE 3 model

In MIKE 3 model phytoplankton growth depends on internal nutrient pools, and nutrient limitation for growth is calculated from the relative saturation of phytoplankton cells with nutrients expressed by nutrient function as

$$f(N, P) = \frac{2}{\frac{1}{NF} + \frac{1}{PF}} \quad (1)$$

where $f(N, P)$ is nutrient function, NF is nitrogen function and PF is phosphorus function.

Nitrogen and phosphorus functions describe the saturation of phytoplankton cells with the respective nutrient. Saturation is calculated in respect to the minimum and maximum nutrient-to-carbon ratio in phytoplankton. Phosphorus function also depends on the half-saturation constant.

Hence, the nitrogen function is formulated as

$$NF = \frac{PN/PC - PN_{\min}}{PN_{\max} - PN_{\min}} \quad (2)$$

where PN is phytoplankton intracellular nitrogen content, PC is phytoplankton carbon concentration, PN_{\min} is the minimum and PN_{\max} is the maximum nitrogen-to-carbon ratio in phytoplankton.

The phosphorus function is calculated as

$$PF = \frac{(PP/PC - PP_{\min})}{(KC + PP/PC - PP_{\min})} \bigg/ \frac{(PP_{\max} - PP_{\min})}{(KC + PP_{\max} - PP_{\min})} \quad (3)$$

where PP is phytoplankton intracellular phosphorus content, PP_{\min} is the minimum and PP_{\max} is the maximum phosphorus-to-carbon ratio in phytoplankton and KC is the half-saturation constant for phosphorus in phytoplankton.

The NF/PF ratio may be used to estimate the relative roles of limiting nutrients. The NF/PF ratio close to 1 ± 0.2 can mean either weak or no nutrient limitation (both nutrients are high) or co-limitation (both nutrients are low).

Three points, one offshore station N12 (Figure 4) and two coastal stations, N8 (Figure 5) and 38 (Figure 6), were selected for detailed analyses of temporal variations of nutrient functions. Model results showed maximum values of NF and PF during April (~0.8–0.9 at all three stations). Near-shore stations retained high function values until the end of April, while at the offshore station N12 function values dropped rapidly in the middle of the month. The very fast increase of NF and PF and corresponding phosphorus limitation (NF/PF ratio up to 1.8) during the first week of April could be attributed to the short-term

adjustment of initial fields to model dynamics. After the spring bloom station N12 retained low NF values compared to the stations near the coast and did not show any strong fluctuations, which was the case at coastal stations. Generally, values at station N8 were slightly higher and more variable than at station 38. The PF values showed a steady decline from the beginning of May until mid-June. At the offshore station N12 the function stabilized at values of 0.3–0.4. Station N8 showed high variability but the general trend showed an increase until the third week of August, when the function reached the maximum value of 1, and a consequent decrease. Fluctuations were less frequent, but more variable, at station 38, e.g. function values reached ~0.9 in late August and ~0.94 in mid-September.

In general, after the spring bloom the NF/PF ratio was below one at all stations, indicating nitrogen limitation of phytoplankton growth. At station N12 the value was mostly below 0.4. The same average level of NF/PF ratio characterizes station 38 except two short events at the end of June and in mid-September. During the first event, the NF/PF ratio exceeded 1.2, indicating a sporadic shift to phosphorus limitation. During the second event, the NF/PF ratio rose to 0.9, which may be interpreted as neither nutrient limited phytoplankton growth.

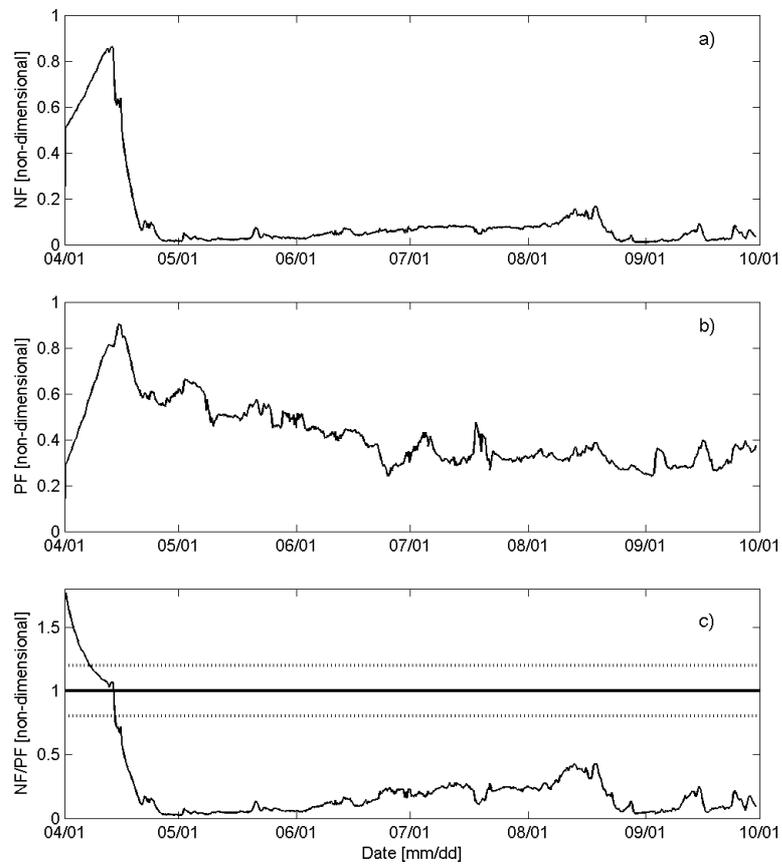


Figure 4. Modeled time-series of nitrogen (a) and phosphorus (b) functions and their ratio (c) at station N12 in Narva Bay.

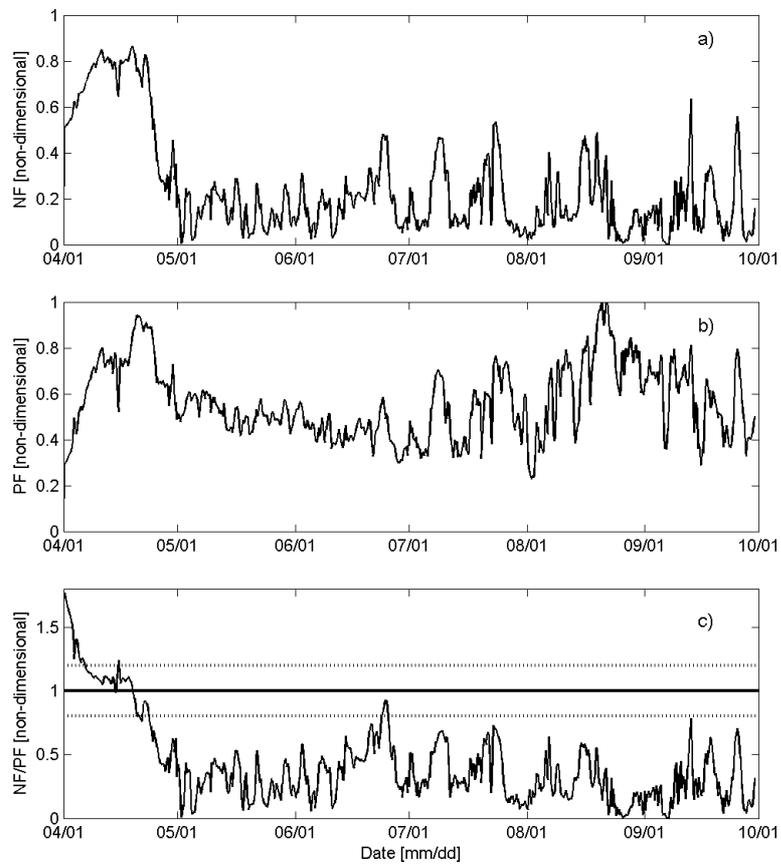


Figure 5. Modeled time-series of nitrogen (a) and phosphorus (b) functions and their ratio (c) at station N8 in Narva Bay.

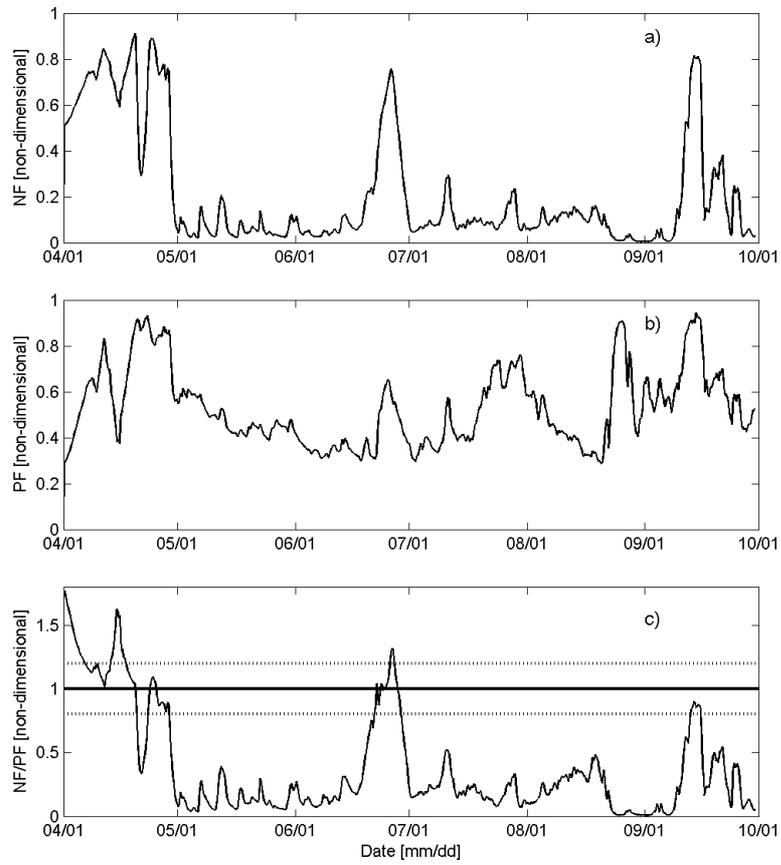


Figure 6. Modeled time-series of nitrogen (a) and phosphorus (b) functions and their ratio (c) at station 38 in Narva Bay.

2.2. Nutrient limitation as seen from the combination of methods

Biotests showed that at stations N12 and 38, phytoplankton always responded with enhanced growth during combined addition of nutrients. The growth was also usually high due to nitrate additions only. This is in accordance with the modeling study. There were two exceptions that are not consistent with modeling results. At station N12, separate treatment experiments showed a faster phytoplankton growth response to phosphate addition than to nitrate addition on two occasions in midsummer. The other exception is station 38 in August 15, when in separate treatments phytoplankton also responded to phosphorus addition with increased growth. At station N8 biotests showed weak response to nutrient additions until mid-July. Thereafter phytoplankton growth was strongest due to combined addition of nutrients. In a separate treatment nitrogen addition resulted in stronger phytoplankton growth.

Experimental results showed that at the offshore station N12 N-fixing cyanobacteria prevailed during summer. This fact explains a higher response in phytoplankton growth in July at the offshore station after addition of phosphates compared with nitrate addition. The somewhat weaker response to the nutrient addition than expected can be explained by closed incubation bottles. In late August the community structure became more heterogeneous and this also caused a higher growth response in the nutrient addition experiments. The model does not implement the process of atmospheric nitrogen fixation, showing strong nitrogen limitation during this period. Taking into account the higher *PF* relative to *NF* in the model, conditions favorable for N-fixing cyanobacteria growth were established in the open bay (Kahru et al., 2000; Stal et al., 2003).

Both method results showed that although the growth of phytoplankton was mainly limited by nitrogen at coastal station 38, in July–August the additions of nitrates did not give a very strong response in the phytoplankton growth and obviously both nutrients were needed. The rapid response to the phosphorus addition in mid-August might be due to the nitrogen leakage from a local outlet in the vicinity of the station. Model results showed that upwelling events along the southern coast of the bay were able to bring a considerable amount of *IN* to the surface layers (see paper III). This led to several high peaks of *NF* shifting to sporadic *P*- or co-limitation at the station. Shifts in nutrient limitation of phytoplankton growth due to physical processes were previously found in the Gulf of Riga where thin or moderate mixed layers favored nitrogen limitation and deep mixing led to phosphorus limitation (Tamminen and Seppälä, 1999).

Generally, both modeling and experiment results have shown that *IN* is the primary limiting nutrient in Narva Bay, while *IP* limitation may occur sporadically near the river mouth and elsewhere in the coastal zone. These results are in accordance with previous studies in the Gulf of Finland (Kivi et al., 1993; Pitkänen and Tamminen, 1995) and Gulf of Riga (Seppälä et al., 1999, Tamminen and Seppälä, 1999).

3. Modeling for coastal zone definition in Narva Bay

3.1. Distribution of phytoplankton and *IN* in Narva Bay

The extent of the coastal zone in Narva Bay was assessed by analyzing spatial distributions of *IN* and phytoplankton averaged over the entire modeling period. *IN* is the main limiting nutrient in Narva Bay, which was confirmed by an integrated modeling and biotest study (see paper II).

The river plume extending about 2 km offshore and about 5 km along both coasts with *IN* concentrations from 0.015 to about 0.03 gN/m³ is clearly visible in the vicinity of the river mouth (Figure 7a). The *IN* concentration drops rapidly within the plume and coastal waters become more diluted. Consequently, calculated mean spatial gradient of *IN* concentrations was high in the vicinity of the river mouth (Figure 7b). Another area of elevated *IN* concentration can be found at the southern coast of Narva Bay some 30 km to the west of the river mouth. The core of *IN* concentration is a couple of kilometers offshore. The concentration drops rapidly in the direction of the open bay, therefore a significant gradient can be found along the southern coast of the bay. In general, coastal waters enriched with inorganic nitrogen ($IN > 0.006$ gN/m³) formed a narrow belt of about 5 km width that extends along the entire southern coast of the bay up to the middle of the eastern coast. The open Narva Bay had a uniform mean concentration of less than 0.006 gN/m³ without any noteworthy gradients.

Similarly to *IN*, the mean phytoplankton concentrations were higher in the coastal sea than in the open part of the bay (Figure 8a). The coastal waters can be characterized with phytoplankton concentrations exceeding 0.45 gC/m³. The phytoplankton concentration and gradient (Figure 8b) are relatively low adjacent to the river mouth, where a strong *IN* plume was observed. Phytoplankton concentrations increase in both directions alongshore right off the *IN* plume. Higher phytoplankton concentrations and steep gradients were found all along the eastern coast of the bay, while elevated *IN* concentrations extended only about 10 km from the river mouth. Phytoplankton concentrations were slightly lower in the coastal waters along the southern coast of the bay, being highest in its westernmost area. The gradient of phytoplankton concentration is very sharp along the southern bay adjacent to the coastline and less so in a belt of approximately 10 km width. In general, the phytoplankton concentration decreases offshore more regularly than *IN* concentration. In the offshore areas of Narva Bay uniform concentrations of 0.3–0.4 gC/m³ could be found. Taking into account the difference between coastal areas and the open bay, the coastal zone in Narva Bay can be defined as an area of strong transversal gradients of ecological parameters in contrast to the more homogeneous offshore area.

In order to eliminate the effect of the spring bloom, the spatial distributions of *IN* and phytoplankton for the period June 15, 2001 to October 1, 2001 were averaged. Although showing lower concentrations, no significant differences in spatial distribution of variables comparing to the entire period were noticed.

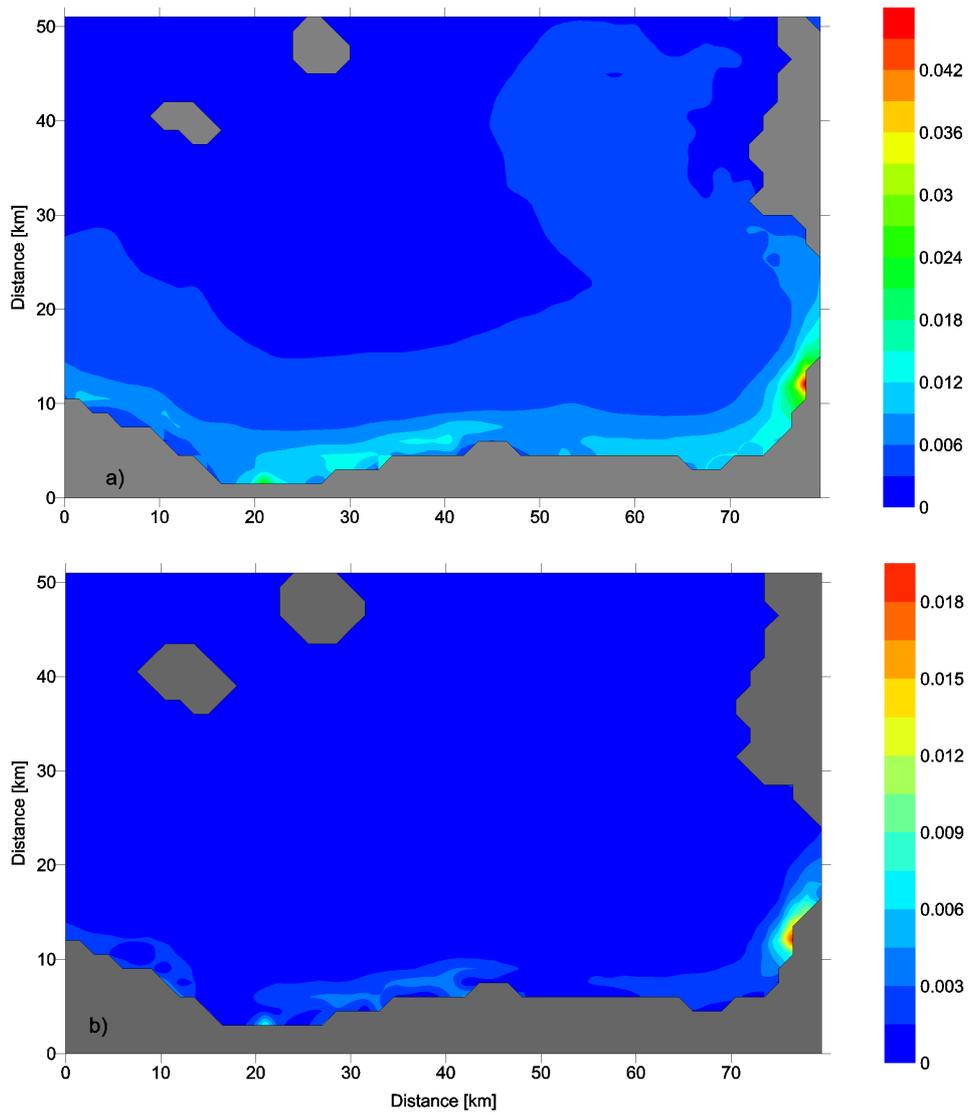


Figure 7. Modeled mean spatial distribution (a) and gradient (b) of the upper 10 m inorganic nitrogen concentration (gN/m^3) in Narva Bay.

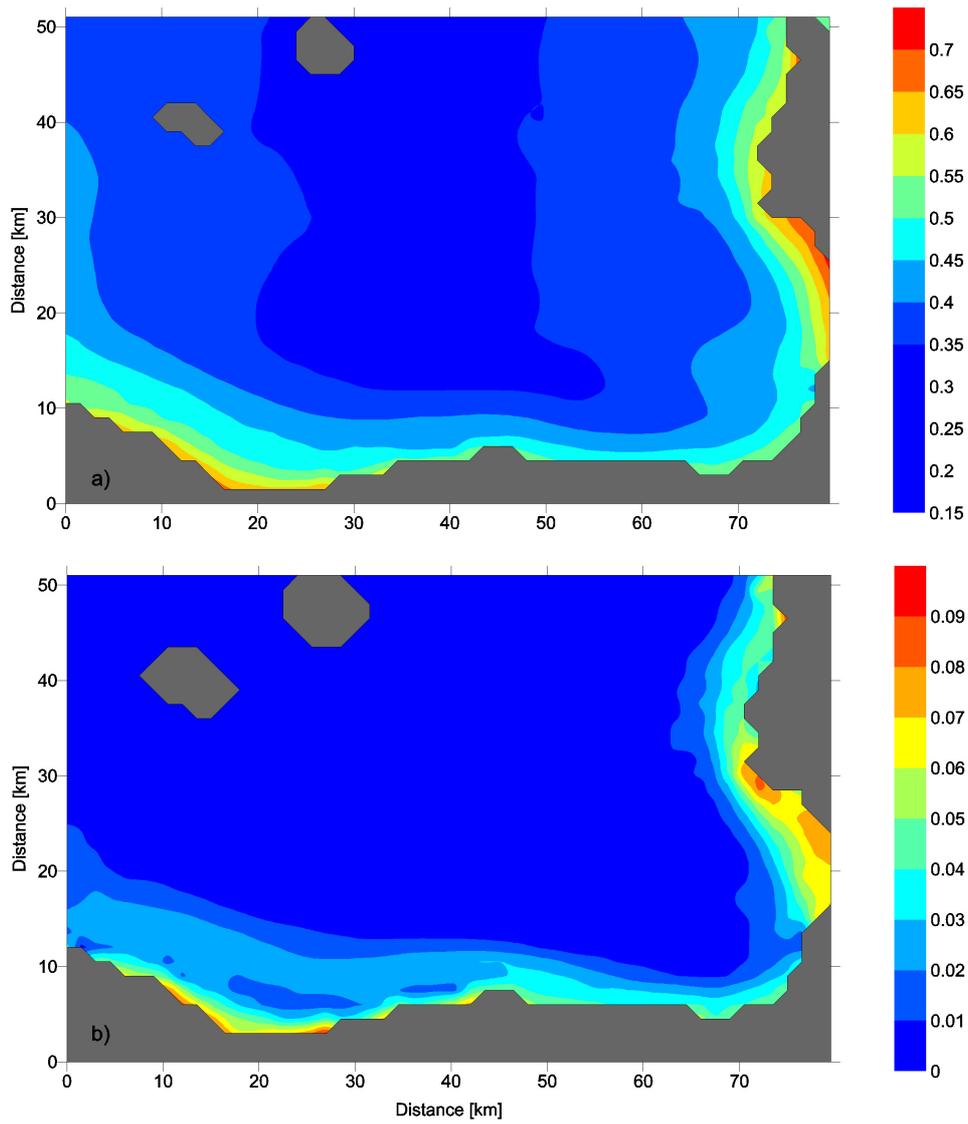


Figure 8. Modeled mean spatial distribution (a) and gradient (b) of the upper 10 m phytoplankton concentration (gC/m^3) in Narva Bay.

3.2. Factors controlling coastal zone formation in Narva Bay

The Narva River *IN* discharge is about four times higher in April ($\sim 16 \times 10^4$ g/s) than during the summer months ($\sim 4 \times 10^4$ g/s). As the mean distribution shows, most of the *IN* is trapped in the vicinity of the river mouth. However, phytoplankton biomass is low near the river mouth relative to adjacent coastal sea areas. Similar results showing high nutrients and relatively low chl *a* concentrations were obtained at the Daugava River mouth in the Gulf of Riga (Müller-Karulis, 1999) and the Santa Clara River mouth in the Santa Barbara Channel (Warrick et al., 2005).

The average distribution of surface currents in Narva Bay showed the presence of anticyclonic water circulation. This circulation occurred at a distance of 3–10 km from the coast, except for the southeastern part of the bay, where the current passed immediately along the coast. The influence of the Narva River inflow was similar in both alongshore directions. However, the riverine water flowing northward (in the opposite direction to the main circulation flow) entered the near-coast area, which acts as a trap for nutrients as well as phytoplankton in that part of the bay. In the southern direction the riverine flow was in the same direction as the main current flow, which caused a spreading and dilution of *IN* along the southeastern part of the coastal area. The southwestern part of the bay was not affected by the main water circulation. However, model results showed a high concentration of mean *IN* along the southern coast of Narva Bay. Analysis of vertical fluxes of nutrients at intermediate depths revealed that large areas in Narva Bay had an average upward flux of *IN*, which was strongest along the southern coast of the bay. This caused an increased *IN* content in the upper layers, which was able to maintain a considerable phytoplankton concentration in the surface waters during summer. Coastal upwelling is an important phenomenon that brings inorganic nutrients to the surface layers (Vahtera et al., 2005).

Although distributions of both *IN* and phytoplankton in the coastal areas were quite uniform, based on the factors described, several sub-regions could be separated in the coastal zone of Narva Bay (Figure 9). These sub-regions include: (1) the river mouth area with a high *IN* and low phytoplankton concentration due to intensive hydrodynamic processes, (2) the area to the right of the river mouth with a high phytoplankton concentration due to the river *IN* discharge, (3) the upwelling area near the southern coast of Narva Bay where the high phytoplankton concentration is caused by *IN* of non-riverine origin, and (4) the area between the upwelling zone and river mouth influenced partly by upwelling and river discharge.

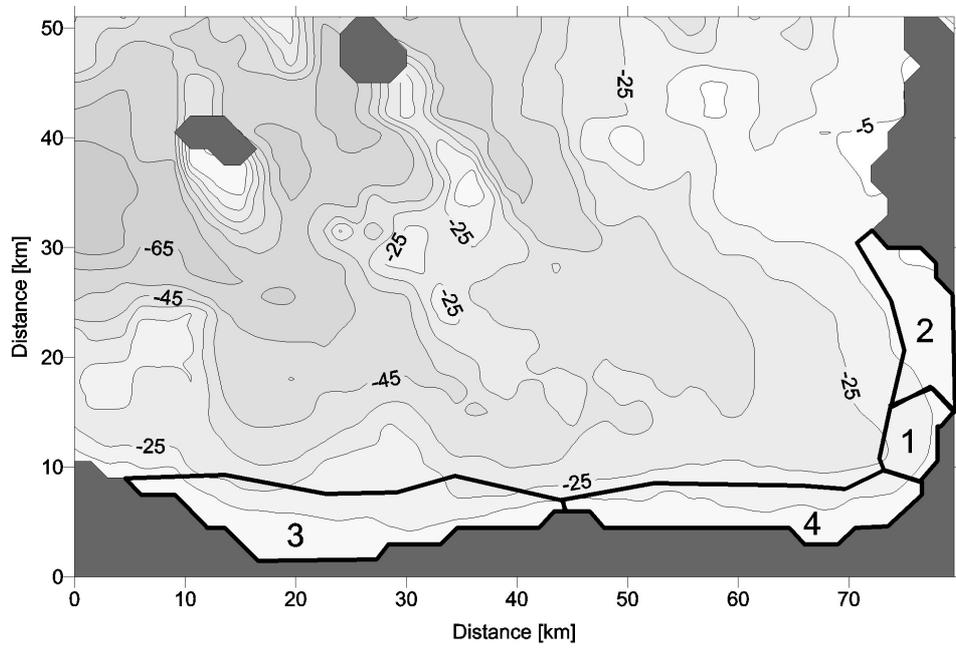


Figure 9. Narva Bay coastal zone and topography. Narva river mouth area (1), area of riverine influence (2), upwelling zone (3) and area of mixed upwelling and riverine influence (4) are shown.

4. Generalization of the coastal zone definition for the central and eastern Gulf of Finland

The extent of the coastal zone during the biologically active period in the central and eastern Gulf of Finland was assessed by using combination of numerical modeling results, measurement data and satellite imagery on chl *a* (detailed treatment in paper IV). The definition of the coastal zone from spatial distribution of biotic parameters proposed in the Narva Bay case study (paper III) is thus generalized over the entire area covered by the model domain. It was hypothesized that chl *a* concentrations are higher in the coastal sea compared to the open sea and this pattern persists over a prolonged period.

The modeled surface chl *a* distribution averaged over the entire period showed relatively high chl *a* concentrations both close to the coast and offshore in the western part of the model domain (central Gulf of Finland). Ferrybox data measured on Tallinn–Helsinki line showed an increased chl *a* content close to both coasts. The mean chl *a* concentration was about 0.012–0.013 g/m³ close to the coast and dropped to 0.01 g/m³ within 2–3 km from the coast. Comparison of modeled and measured mean chl *a* concentrations in the central Gulf of Finland indicates that modeled values were underestimated approximately two times.

The modeled mean chl *a* showed that in the central part of the model domain (eastern Gulf of Finland) a belt of high chl *a* concentration was formed along the southern coast. Chl *a* concentrations decreased rapidly towards offshore, where a vast area of low chl *a* existed. Along the northern coast an increased chl *a* concentration is seen only during the spring bloom period. Generally, the width of the coastal zone in the eastern Gulf of Finland could be estimated at about 5–8 km.

The highest chl *a* concentrations existed in the Neva estuary. Following the outflow pattern of the Neva River, concentrations were higher in the northern part than in the southern part. Concentrations were highest offshore, about 12 km from the northern coast with a local minimum in the central part.

Instantaneous chl *a* distribution during different seasons was assessed with the help of satellite images. Although the modeled year is 2001, using images from 2002 and 2003 allows generalizing the results of numerical modeling. All images showed increased chl *a* concentrations along the coastline of the Gulf of Finland. Increased chl *a* concentrations were also present offshore in the central Gulf of Finland area, which could be attributed to spring phytoplankton or summer cyanobacterial blooms (Reinart & Kutser, 2006). The eastern Gulf of Finland was relatively poor in chl *a*. Neva Bay was rich in chl *a*, except for the late spring image, which was somehow unexpected.

Temporal variability of modeled normalized surface chl *a* concentrations was analyzed on four transects across the Gulf of Finland. In general, temporal variations of surface chl *a* were rather different in different parts of the Gulf of Finland. In the central Gulf, a relatively high chl *a* content was present in spring

and the first half of summer in a 5–15 km belt adjacent to the Finnish coast. Later on, the concentrations were usually higher offshore than close to the coast. A broad area of elevated chl *a* concentration formed near the Estonian coast in September. Further to the east, chl *a* concentrations were rather uniform across the Gulf until May. A broad area (about 20–30 km) of increased chl *a* concentrations formed at the Finnish coast and existed until the end of August disappearing occasionally. At the Estonian coast, a narrow zone of high chl *a* concentrations could be identified since the beginning of July. The width of this zone was generally about 5–10 km except when it broadened up to ~45 km. Close to Neva Bay the concentrations of chl *a* were higher in the northern part of the Gulf at some distance from the shore.

Temporal variations of chl *a* concentrations emphasize the dynamic nature of the coastal zone. During heavy blooms the coastal zone may appear occasionally depending on the spatial distribution of the bloom. Chl *a* concentrations vary in a broad range over the biologically active season. In the Gulf of Finland, high chl *a* values are present during the spring diatom bloom and summer cyanobacterial bloom. The latter has considerable inter-annual variations (Kahru et al., 1995; Laanemets et al., 2006). According to the chl *a* distribution, a coastal zone could be identified in the eastern Gulf of Finland, but not in the central gulf since the water and matter exchange between the coastal and the open sea is rather intensive there. During upwelling events filaments may extend far offshore (Vahtera et al. 2005). The coastal zone became more discernible and narrower at the southern coast from longitude 26°E towards the east. At the northern coast, the coastal zone could be defined as a broader area of up to 20 km that does not persist after the spring bloom. This distribution pattern can be explained by the mean surface water circulation to some extent. The mean currents between 4 cm/s and 10 cm/s are to the east along the southern shore, and mainly less than 4 cm/s and offshore near the northern coast (Andrejev et al., 2004). In the easternmost region of the Gulf of Finland chl *a* concentrations were permanently high affected by the Neva River. The coastal zone could be defined there as the region of about 100 km from the Neva River mouth, following the definition of Artioli et al. (2005).

Conclusions

Integrated implementation of different methods (numerical modeling, measurements, biotest and ferrybox data and satellite imagery) was performed to study the extent of the coastal zone in Narva Bay and factors controlling it.

It was confirmed that nitrogen is the main limiting nutrient in Narva Bay, which is concordant with the previous studies in the Gulf of Finland (Kivi, 1993; Pitkänen and Tamminen, 1995) and the Gulf of Riga (Seppälä et al., 1999; Tamminen and Seppälä, 1999). Phosphorus limitation can emerge sporadically near the Narva River mouth and in other areas of the coastal zone. Inorganic nitrogen and phytoplankton distributions showed a 3–8 km wide belt of higher concentrations ($>0.006 \text{ gN/m}^3$ and $>0.45 \text{ gC/m}^3$, respectively) along the coast in Narva Bay. The distributions of phytoplankton and *IN* showed strong transversal gradients within the belt. The open area of the bay is characterized by lower and more uniform concentration of modeled ecological parameters than the coastal zone and negligible gradients.

This allowed defining the coastal zone in Narva Bay as an area of strong gradients of ecological parameters. This definition is based solely on the distribution of ecological parameters and the magnitude of their gradients regardless of geomorphological features of the area or any particular sources of influence, and it is suitable for the tasks of marine ecology. Such tasks include e.g. water quality assessment, resources management or pollution control in the coastal zone.

The model allowed analysis of the different sources of *IN* existing in the area. According to these the coastal zone of Narva Bay could be divided into several sub-regions: (1) the river mouth area characterized by high *IN* and low phytoplankton concentrations; (2) area to the right of the river mouth, where the high phytoplankton concentration was fueled by river *IN* discharge; (3) the southwestern near-shore area of the bay receiving nutrients from upwelling and (4) the area between the upwelling zone and the river mouth influenced by both upwelling and river discharge.

Generalizing the proposed coastal zone definition over the entire model domain, the extent and variability of the coastal zone was analyzed through the distribution of chl *a*. It was shown that the coastal zone is dynamic and varies in time and space. Analysis of the results on chl *a* distribution allowed dividing the study area into several distinct parts. Defining the coastal zone for the central Gulf of Finland is complicated due to intensive exchange processes and heavy algal blooms causing high chl *a* concentrations both close to the coast and offshore. Still, as seen from measurement data, a narrow along-shore zone of increased chl *a* can be seen there even during algal blooms. The extent of the coastal zone can be clearly defined for the eastern Gulf of Finland, where sharp gradients from the chlorophyll-rich coastal area towards the chlorophyll-poor

offshore region existed. In Neva Bay it is more appropriate to define the coastal zone by the area of direct river influence.

Peculiarities of coastal zone ecosystems require application of specific methods for their research. High-frequency in situ measurements are valuable but costly. The problem can be partly solved by using automatic sampler data. Satellite images of high quality are rare for the Baltic and usually overestimate chl *a* concentrations, but give relatively good qualitative data on distribution. Ecohydrodynamic models used for coastal zone research must differ from the open sea models: detailed description of benthic and sediment processes, dispersion of suspended matter with riverine inflow, different properties of coastal and offshore phytoplankton communities must be considered. Combining all available data from different methods can maximize our information on coastal zone processes and dynamics.

Acknowledgements

I am very grateful to my supervisor Urmas Raudsepp for guiding my scientific career and for the immense support during my work on this thesis. I am also grateful to my supervisor Vladimir Ryabchenko for his help and lots of valuable advices.

I wish to express my acknowledgements to Anja Friis-Christensen and Anders Erichsen from DHI for their assistance with ecosystem modeling.

I am thankful to everyone at Marine Systems Institute at TUT for always being ready to support. I would like to thank personally Inga Lips for providing measurement and biotest data, Urmas Lips for constructive comments on this work, Aina Leeben for lots of support and scientific discussions, and especially Prof. Jüri Elken who invited me to work on my master thesis in Marine Systems Institute.

I also wish to thank my family, especially my wife Julija, for always supporting and understanding me.

Finally, I would like to thank Estonian escrima group for teaching me to constantly move forward.

References

- Alenius, P., Myrberg, K., Nekrasov, A. 1998. The physical oceanography of the Gulf of Finland: a review. *Boreal Environment Research*, 3, 97–125.
- Andrejev, O., Myrberg, K., Alenius, P., Lundberg, P. A. 2004. Mean circulation and water exchange in the Gulf of Finland – a study based on three-dimensional modelling. *Boreal Environment Research*, 9, 1–16.
- Artioli, Y., Bendoricchio, G., Palmeri, L. 2005. Defining and modelling the coastal zone affected by the Po river (Italy). *Ecological Modelling*, 184 (1), 55–68.
- Burchard, H., Petersen, O., Rippeth, T.P. 1998. Comparing the performance of the Mellor-Yamada and the k- ϵ two-equation turbulence models. *Journal of Geophysical Research*, 103 (C5), 10.543–10.554.
- Cedervall, H., Elmgren, R. 1980. Biomass increase of benthic macrofauna demonstrates eutrophication of the Baltic Sea. *Ophelia* (Suppl. 1), 287–304.
- Cozzi, S., Adami, G., Barbieri, P., Cantoni, C., Catalano G., Crisciani F., Fiorotto, V., Olivo, P., Purini, R., Raicich, F., Reisenhofer, E. 2004. Matching monitoring and modelling in the Gulf of Trieste. *Marine Pollution Bulletin*, 48, 587–592.
- DHI Water and Environment. 2001. MIKE 3: environmental hydraulics. DHI Software User Guide, Documentation and Reference Manual.
- Erkkilä, A., Kalliola, R. 2004. Patterns and dynamics of coastal waters in multi-temporal satellite images: support to water quality monitoring in the Archipelago Sea, Finland. *Estuarine, Coastal and Shelf Science*, 60, 165–177.
- European Commission, 2000. European Commission, Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for community action in the field of water policy. *Official Journal of the European Communities*, L327 (2000), 1–73.
- Gazeau, F., Smith, S.V., Gentili, B., Frankignoulle, M., Gattuso, J.-P. 2004. The European coastal zone: characterization and first assessment of ecosystem metabolism. *Estuarine, Coastal and Shelf Science*, 60 (4), 673–694.
- Gerritsen, H., Boon, J.G., van der Kaaij, T., Vos, R.J. 2001. Integrated modelling of suspended matter in the North Sea. *Estuarine, Coastal and Shelf Science*, 53, 581–594.
- Gibbs, M.T., Hobday, A.J., Sanderson, B., Hewitt, C.L. 2006. Defining the seaward extent of New Zealand's coastal zone. *Estuarine, Coastal and Shelf Science*, 66 (1–2), 240–254.

- Jickells, T., 2005. External inputs as a contributor to eutrophication problems. *Journal of Sea Research*, 54 (1), 58–69.
- Kahru, M., Leppänen, J.-M., Rud, O., Savchuk, O.P. 2000. Cyanobacteria blooms in the Gulf of Finland triggered by saltwater inflow into the Baltic Sea. *Marine Ecology Progress Series*, 207, 13–18.
- Kanoshina, I., Lips, U., Leppanen, J.-M. 2003. The influence of weather conditions (temperature and wind) on cyanobacterial bloom development in the Gulf of Finland (Baltic Sea). *Harmful Algae* 2 (1), 29–41.
- Kivi, K., Kaitala, S., Kuosa, H., Kuparinen, J., Leskinen, E., Lignell, R., Marcussen, B., Tamminen, T. 1993. Nutrient limitation and grazing control of Baltic plankton community during annual succession. *Limnology and Oceanography*, 38, 893–905.
- Kuusisto, M., Koponen, J., Sarkkula, J. 1998. Modelled phytoplankton dynamics in the Gulf of Finland. *Environmental Modeling and Software*, 13 (5–6), 461–470.
- Laane, R.W.P.M., Brockmann, U., van Liere, L., Bovelandt, R. 2005. Immission targets for nutrients (N and P) in catchments and coastal zones: a North sea assessment. *Estuarine, Coastal and Shelf Science*, 62 (3), 495–505.
- Laanemets, J., Lilover, M.-J., Raudsepp, U., Autio, R., Vahtera, E., Lips, I., Lips, U. 2006. A fuzzy logic model to describe the cyanobacteria *Nodularia spumigena* blooms in the Gulf of Finland, Baltic Sea. *Hydrobiologia*, 554, 31–45.
- Larsson, U., Elmgren, R., Wulff, F. 1985. Eutrophication and the Baltic sea: causes and consequences. *Ambio*, 14, 9–14.
- Lessin, G. 2004. Ecological modelling of Narva Bay. Master thesis in geology. Tallinn Pedagogical University, Estonia.
- Müller-Karulis, B. 1999. Transformations of riverine nutrients in the Daugava river plume (Gulf of Riga). *ICES Journal of Marine Science*, 56 (Supplement 1), 180–186.
- Piirsoo, K., Porgasaar, V., Viik, M. 1992. Environmental conditions, phytoplankton and chlorophyll *a* in the Narva Bay (the southern part of the Gulf of Finland). *Proceedings of the Estonian Academy of Science. Biology*, 41, 149–161.
- Pitkänen, H., Tamminen, T. 1995. Nitrogen and phosphorus as production limiting factors in the estuarine waters of the eastern Gulf of Finland. *Marine Ecology Progress Series*, 129, 283–294.
- Rasmussen, E.B. 1993. Three-dimensional hydrodynamic models. Section 3.1 hydrodynamic models. In: Abbot, M.B., Price, N.A. (Eds.), *Coastal, Estuarine and Harbour Engineer's Reference Book*. Chapman and Hall, 109–116.

- Rasmussen, E.B., Pietrzak, J., Brandt, R. 1999. A coupled ice-ocean model for the Greenland, Iceland and Norwegian seas. *Deep-Sea Research Part II*, 46, 1169–1198.
- Reinart, A., Kutser, T. 2006. Comparison of different satellite sensors in detecting cyanobacterial bloom events in the Baltic Sea. *Remote Sensing of Environment*, 102, 74–85.
- Seppälä, J., Tamminen, T., Kaitala, S. 1999. Experimental evaluation of nutrient limitation of phytoplankton communities in the Gulf of Riga. *Journal of Marine Systems*, 23, 107–126.
- Stal, L.J., Albertano, P., Bergman, B., von Bröckel, K., Gallon, J.R., Hayes, P.K., Sivonen, K., Walsby, A.E. 2003. BASIC: Baltic Sea cyanobacteria. An investigation of the structure and dynamics of water blooms of cyanobacteria in the Baltic Sea - responses to a changing environment. *Continental Shelf Research*, 23 (17-19), 1695–1714.
- Stålnacke, P., Grimvall, A., Sundblad, K., Tonderski, A. 1999. Estimation of riverine loads of nitrogen and phosphorus to the Baltic sea, 1970–1993. *Environmental Monitoring and Assessment*, 58, 173–200.
- Tamminen, T., Seppälä, J. 1999. Nutrient pools, transformations, ratios, and limitation in the Gulf of Riga, the Baltic Sea, during four successional stages. *Journal of Marine Systems*, 23, 83–106.
- Telesh, I.V. 2004. Plankton of the Baltic estuarine ecosystems with emphasis on Neva Estuary: a review of present knowledge and research perspectives. *Marine Pollution Bulletin*, 49, 206–219.
- TÜ Eesti Mereinstituut. 2002. Riiklik keskkonnaseire programm. Rannikumere seire allprogrammi “Eutrofeerumine” 2001. a. koondaruanne.
- Vahtera, E., Laanemets, J., Pavelson, J., Huttunen, M., Kononen, K. 2005. Effect of upwelling on the pelagic environment and bloom-forming cyanobacteria in the western Gulf of Finland, Baltic Sea. *Journal of Marine Systems*, 58, 67–82.
- Vallega, A. 2003. The coastal cultural heritage facing coastal management. *Journal of Cultural Heritage*, 4, 5–24.
- Warrick, J.A., Washburn, L., Brzezinski, M.A., Siegel, D.A. 2005. Nutrient contributions to the Santa Barbara Channel, California, from the ephemeral Santa Clara River. *Estuarine, Coastal and Shelf Science*, 62 (4), 559–574.