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ENVIRONMENTAL PROTECTION

Searching efficient protection strategies for the eutrophied Gulf of Finland: the integrated use of experimental and modelling tools (SEGUE)

Final Report

Heikki Pitkänen and Petra Tallberg (eds.)

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PREFACE

The SEGUE Project was a part of the BIREME (Baltic Sea Research) Program coordinated by the Academy of Finland. The project was financed by the Finnish Ministry of the Environment, the Academy of Finland and the Nordic Council of Ministers, as well as by all the participating research institutes. The SEGUE-consortium consisted of four independent sub-projects as a joint venture between the following institutes: Finnish Environment Institute (SYKE), Finnish Institute of Marine Research (FIMR), University of Helsinki (UH), Agrifood Research Finland (MTT), Institute of Limnology at the Russian Academy of Sciences, North-West Administration of Federal Service of Russia for Hydrometeorology and Environmental Monitoring (NW Hydromet), Stockholm University, Linköping University and Tallinn Technical University. The project also cooperated with several other institutes and projects studying eutrophication of coastal and marine waters. The consortium was led by Heikki Pitkänen, SYKE.

- SEGUE-LOAD analysed how cost-effectiveness assessments are affected when both ecological and economic factors are considered. The project estimated the amounts of total and algal-available nutrient loading to the Gulf of Finland, as well as catchment budgets for total nitrogen and total phosphorus. The role of coastal retention was also estimated. Alternative outcomes of socio-economic development and agricultural production in Finland, Estonia and Russia and their effects on the nutrient loading of the Gulf were studied. The project was led by Petri Ekholm, SYKE and Anni Huhtala, MTT.
- SEGUE-P studied various chemical fractions of sedimentary phosphorus (P) and silicon (Si), and estimated the accumulation of settled P and Si under the varying environmental conditions prevailing in the coastal and open Gulf of Finland. The studies were conducted in cooperation with the National Environment Institute, Denmark (Si) and the Institute of Biology, University of Southern Denmark (P). The project was led by Mirja Leivuori, FIMR.
- SEGUE-N studied nitrogen removal by denitrification and anammox at the sediment-water interface and the factors controlling these processes in different kinds of benthic environments in the Gulf of Finland. Close contacts were developed with the Danish Center for Earth System Science, University of Southern Denmark. The project was led by Jorma Kuparinen, University of Helsinki.
- SEGUE-MODEL compiled the obtained results on loading and nutrient processes together with other relevant information (e.g. monitoring data, national and international protection targets) and applied ecosystem models to form long-term forecasts with enhanced spatial resolution for the Gulf of Finland, the Archipelago Sea and adjacent waters of the north-eastern Baltic Proper. The relevance of existing protection programmes were assessed in the light of the results of the project. In the modelling work close co-operation was performed with the Swedish MARE Project, the Department of Chemistry at Göteborg University, Luode Consulting, and with the Environment Impact Assessment Centre of Finland Ltd. The project was led by Heikki Pitkänen, SYKE.

The work of the Consortium was guided by the Scientific Advisory Board: Daniel Conley (NERI/Lund University), Per Hall (Göteborg University), Helinä Hartikainen

(University of Helsinki), Markku Ollikainen (University of Helsinki), Eeva-Liisa Poutanen (Ministry of the Environment/FIMR), Seppo Rekolainen (SYKE) and Fredrik Wulff (Stockholm University). Eeva-Liisa Poutanen acted as the Chair of the Board.

This report contains preliminary data and results produced during the project which will later be published in scientific publications (referred to as submitted manuscripts or manuscripts in preparation). Figures 4.3, 4.4, 5.8, 5.9 and 5.10 are published with the kind permission of AMBIO. Figures 5.1–5.4 are reprinted from Journal of Marine Systems, Vol 61, Kiirikki, M., Lehtoranta, J., Inkala, A., Pitkänen, H., Hietanen, S., Hall, P., Tengberg, A, Koponen, J. & Sarkkula, J., A simple sediment process description suitable for 3D-ecosystem modelling – Development and testing in the Gulf of Finland, Pages 55–66, Copyright (2007), with permission from Elsevier.

CONTENTS

LIST OF ABBREVIATIONS

a	year
Al	Aluminium
ANCOVA	ANalysis of COVAriance
BIREME	Baltic Sea Research Program
BOD	biological oxygen demand
BSi	biogenic Si
Ca	Calcium
CI	confidence interval
CO_2	carbon dioxide
DAS	Data Assimilation System/Stockholm University
DIN	dissolved inorganic nitrogen
DIP	dissolved inorganic phosphorus
DM	dry matter
DNRA	dissimilatory nitrate reduction to ammonium
EIA	Environment Impact Assessment Centre of Finland Ltd.
EU	European union
Fe	Iron
FIMR	Finnish Institute of Marine Research
FINNFLOW	a three-dimensional hydrodynamic model of the Gulf of Finland
HCl	hydrogen chloride
HCl-iP	apatite-P
HELCOM	Helsinki Commission – the Baltic Marine Environment Protection Commission
INTAS	The International Association for the Promotion of Co-operation with Scientists from the New Independent States of the Former Soviet Union
IPT	isotope pairing technique
MARE	Marine Research on Eutrophication – A Scientific Base for Cost-Effective Measures for the Baltic Sea
Mn	Manganese
MTT	Agrifood Research Finland
N	Nitrogen
N_2	molecular nitrogen
NaBD	sodium bicarbonate-dithionite
NaBD-iP	P bound to reducible iron and manganese
NaCl	sodium chloride
NaCl-iP	pore-water P or loosely bound P
NaOH	sodium hydroxide
NaOH-iP	P bound to oxides of non-reducible metals
NEST	Decision Support System/MARE
NH_4	ammonium
NO_2	nitrite
NO_3	nitrate

NRP	transformable organic or biogenic P
N_{tot}, total N	total nitrogen
NW Hydromet	North-West Administration of Federal Service of Russia for Hydrometeorology and Environmental Monitoring
O_2	molecular oxygen
P	Phosphorus
P_{aa}	algal-available phosphorus
PLC	Pollution Load Compilation (HELCOM)
PO_4-P	phosphate-phosphorus
P_{tot}, total P	total phosphorus
RAS	Russian Academy of Science
Res-P	residual P
SANBALTS	Simple As Necessary BAltic Long-Term large-Scale Model
SD	standard deviation
SEGUE	Searching Efficient protection strategies for the eutrophied Gulf of Finland: the integrated use of Experimental and modelling tools
Si	Silicon
SMHI	Swedish Meteorological and Hydrological Institute
SS	suspended solids
SYKE	Finnish Environment Institute
t	tonnes
TC	total carbon
TP_{extr}	total extractable P
TS	total sulphur
UH	University of Helsinki
WTP	willingness to pay
WWTP	wastewater treatment plant

1 Introduction

1.1

The Gulf of Finland: a eutrophied example case

The Gulf of Finland is an ideal case for testing and developing approaches for the abatement of eutrophication. It is the most eutrophied sub-basin of the Baltic Sea and receives direct nutrient loading from three surrounding countries: Finland, Russia and Estonia. A considerable input of nutrients comes via the atmosphere and the water exchange with the northern Baltic. In the long run, the development of the nutrient load – and eutrophication – depends on the economic progress and environmental policy in the Baltic Sea catchment area, and especially in the three countries surrounding the Gulf. In a wider perspective the plans and recommendations by HELCOM and the directives and policies of the European Union are important, as well. The Gulf of Finland case is, further, interesting because it displays the problems of a jointly managed resource. A joint project focusing on the Gulf thus provides insights that can be applied elsewhere, as well.

Nutrient inputs into the Gulf of Finland relative to its surface area amount to two to three times the average inputs of the Baltic Sea (HELCOM 2002, Pitkänen et al. 2001), which is one of the most eutrophied marine waters in Europe (Ærtebjerg et al. 2001). Two land-based sources of nutrients are of prime importance in the Gulf of Finland: the city of St Petersburg (population 4.7 million), and the River Neva drainage basin, which covers about 70% of the Gulf of Finland catchment (Kiirikki et al. 2003). These two sources drain into the eastern extension of the Gulf, the Neva Bay. On the scale of the whole Gulf of Finland, the role of small rivers and coastal municipal and industrial point sources is small. However, these sources cause local eutrophication, especially near the Finnish southern and south-western coast. There, the shallow water and complex coastal morphometry make horizontal mixing slow and the eutrophying effects of nutrient inputs are thus highlighted.

The importance of external nutrient inputs in creating and maintaining the present eutrophic state of the Gulf of Finland is significant. However, during the mid-1990s intensified salinity stratification led to poor oxygen conditions and voluminous release of nutrients, particularly phosphorus (P), from the Gulf of Finland sediments. Occasionally, the estimated annual benthic P efflux has exceeded the external input of P from the catchment several times over (Pitkänen et al. 2001, 2003, Lehtoranta 2003). Since the cycling of nitrogen (N) within, especially, the sediment surface (Chapter 4) does not include a comparable mechanism, this caused dramatic changes in the N/P ratio of the water, which triggered extensive blue-green algal blooms in the late 1990s (Kahru et al. 2000).

The cycles of N and P in the Baltic Sea are heavily interlinked via e.g. sediment processes (Vahtera et al. 2007). The vernal primary production of the study area is, for example, clearly controlled by N availability (Tamminen & Andersen 2007). This vernal plankton production is in its turn responsible for a large part of the annual sedimentation of organic matter (Heiskanen 1998), which may induce reduced conditions at the sediment surface and enhance the internal loading of P. A further twist to this problem may be caused by the future availability of silicon (Si). In contrast to for P and N, anthropogenic activities rather decrease than increase the input of bio-available Si to the Baltic Sea (e.g. Humborg et al. 2000), which in the long run weakens the competitive position of the Si-requiring diatoms within the phytoplankton community. While this may lead directly to more available P and N for other, potentially more harmful groups such as cyanobacteria, the vernal sedimentation of phytoplankton biomass is also affected by the availability of Si. The vernal bloom in the northern Baltic Sea consists almost exclusively of either diatoms or dinoflagellates. Of these, diatoms are much more prone to sediment out of the water column (Heiskanen 1998), and thus potentially cause reduced conditions at the sediment surface, which releases P. Under oxidized conditions, Si and P also compete for the same sorption sites at the sediment surface (Hingston et al. 1967, Hartikainen et al. 1996), and a surfeit of Si may enhance the release of P (Tuominen et al. 1998, Tallberg & Koski-Vähälä 2001).

The chemical and biological processes behind the benthic liberation of P under reduced conditions are not precisely known, either (Golterman 2001). It is, however, evident that benthic P retention is favoured when the sediment surface is oxidized. Denitrification is also enhanced by oxidized conditions, as it uses nitrate produced in the oxidized surface layer of the sediment (Kemp et al. 1990, Kuparinen & Tuominen 2001). In coastal marine waters the state of the sediment surface depends on both density stratification and the oxygen consuming organic load that settles out from the productive surface layer. The only way to keep the sediment surface layer oxidized is to reduce organic production, which can can be achieved by decreasing external nutrient loading. This is further stressed by the fact that compared to lake sediments, marine sediments are poor sinks for bioavailable P due to differences in elemental and mineral composition (P-binding iron (Fe) compounds, abundance of sulphur (S); Caraco et al. 1990, Sundby et al. 1992, Jensen et al.1995).

Estuaries and coastal waters can act either as sinks for or sources of nutrient load (e.g. Seitzinger 1988, Froelich 1988, Balls 1994, Nixon 1995, Prastka et al. 1998, Rozan et al. 2002). For example, the Neva Estuary, which receives ca 60 % of P and ca 40 % of the N input into the whole Gulf, strongly regulates the nutrient fluxes through it (Pitkänen & Tamminen 1995, Savchuk & Wulff 1999). When the sediment surface remains oxidised, the eastern Gulf of Finland effectively retains the external nutrient load, and thus decrease the nutrient input to the western Gulf and the Baltic Proper (Pitkänen & Tamminen 1995). The potential nutrient filtering capacity of smaller estuaries is, however, not as clear (e.g. Humborg et al. 2003).

Modelling studies suggest that it is possible to improve the present eutrophic state of both the whole Baltic Sea and the Gulf of Finland by cutting nutrient loading, but the recovery will be slow for the Baltic Proper and its open coasts (Savchuk & Wulff 1999, Kiirikki et al 2003). Regarding the Gulf of Finland and its coastal waters, a substantial recovery can take place within only a few years on the condition that major pulses of either nutrient imports from the Baltic Proper (Kahru et al. 2000, Savchuk 2005) or internal nutrient loading (Pitkänen et al. 2001) do not counteract the decreased loads. The sediment–water dynamics of nutrients are still poorly known on a whole basin scale, which weakens the reliability of the modelling scenarios. It has also been suggested that the Baltic Sea as a whole has gone through a regime shift from a less eutrophic to a more eutrophic state (SEAC 2005). According to ecological theory (e.g. Scheffer et al. 2001), returning the system to the state in which it was before the regime shift may be more complicated than simply reversing e.g. the increase in nutrient loading. This poses additional challenges to eutrophication abatement as a whole.

Results obtained by cost-efficiency studies (Gren et al. 1997, Ollikainen & Honkatukia 2001) show that it is in general more cost-effective to reduce nutrient loading from the new EU member states and Russia than from the other countries around the Baltic Sea. When the state of the coastal waters of the Gulf of Finland is regarded, the question is more complicated due to the great variability in geomorphologic conditions and in the location of loading sources. The complex southern and south-western coast of Finland, where the water exchange with the open Gulf waters is poor, is especially challenging in this respect. Furthermore, when abatement measures entail discrete investments that impose considerable sunk costs on society, the investment costs should be appropriately accounted for in policy choices. Therefore, it is important to compare the economical optimality of a significant investment in reducing nutrient loads from municipal point sources to that of reversible, small-scale abatement measures in agriculture.

1.2

The main study areas

The Gulf of Finland (total area ca 30 000 km^2, sediment accumulation area ca 12 300 km^2, average depth 37 m, maximum depth 123 m) is the most eutrophied sub-basin of the Baltic Sea (Fig. 1.1), with a drainage area of 420 990 km^2 and a volume of ca 1100 km^3 (Alenius et al. 1998 with references). This represents around 20% of the drainage area of the whole Baltic, but only 5% of the water volume (Alenius et al. 1998). The surface water salinity (PSU) varies from zero to ca 7, with the lowest values in the East and near river mouths and the highest in the West. The Gulf is, geomorphologically, an extension of the main basin of the Baltic Proper, and subject to substantial inflows of saline water, which causes a halocline to form at 60–80 m depth (Alenius et al. 1998). This phenomenon is of particular importance for the oxygen conditions in the bottom water layer.

The Paimionlahti Bay (Fig. 1.2) is a narrow estuary of the Archipelago Sea (the Baltic Sea). It covers an area of 96 km^2, has a mean depth of 11.6 m and a hydraulic detention time of about 5 years. The fresh-water inlet, River Paimionjoki (mean flow 9.6 m^3 s^{-1}), has a catchment of 1088 km^2 and is located in an intensively cultivated part of Finland. A total of 43% of the catchment of River Paimionjoki consists of fields, mainly under crop production, the remaining areas being forests (50%) and peatland (4%). Lakes are few and situated in the upper reaches, and thus their effect on hydrology and nutrient transport is negligible. The topsoil of fields is mostly clayey, and erosion of surface soil renders the river water turbid (turbidity up to 750 FNU). Most of the flow and nutrient transport occurs during the snowmelt in spring and during autumn storms; at dry periods in summer and winter, there is almost no flow in the river. The furthest sampling sites in Paimionlahti Bay also receive some loading from two other small agricultural rivers.

The Ahvenkoskenlahti Bay (Fig. 1.2) is a shallow (mean depth 4.3 m) semi-enclosed estuary (52.5 km^2, hydraulic detention time 17 d) of the western branch of the River Kymijoki (mean flow 156 m^3 s^{-1}), which drains into the eastern Gulf of Finland. The large drainage basin of the River Kymijoki (37 159 km^2) contains several lake basins, which account for 18% of the entire catchment area and efficiently remove nutrients. The field percentage is low (mean 6.6), except in the lower reaches that have 28% field land and 'only' 4.2% lakes. Since the lower reaches account for only 3.2% of the total catchment, the effect on nutrient fluxes is relatively low. River Taasianjoki (530.3 km^2) also discharges into Ahvenkoskenlahti Bay (mean flow about 5 m^3 s^{-1}). The catchment of this river has 30% field land and 0.5% lakes and thus provides a source of eroded matter into Ahvenkoskenlahti Bay. According to the chlorophyll-*a* concentrations Ahvenkoskenlahti Bay is more eutrophic than Paimionlahti Bay.

Tvärminne Storfjärden (Fig. 1.2) is a coastal basin in the northern Gulf of Finland. It represents a typical outer archipelago accumulation bottom, consisting of soft mud.

Fig. 1.1. The main basins of the Baltic Sea and its drainage area (shaded). The drainage area of the Gulf of Finland is indicated by a black line.

Water depth at the sampling station is 33 m, and the water column is usually thermally stratified from June to September. The highest bottom water temperatures, up to 13°C, are found in late autumn when thermal stratification breaks, and the lowest, below 2°C, in early spring when the water column has yet to stabilize after ice-break. Sedimentation at the station shows a typical pattern of about 80% of the sedimenting carbon reaching the bottom at the end of the spring bloom in May, with hardly any sedimentation during the rest of the year (Heiskanen & Leppänen 1995, Heiskanen & Tallberg 1999). In an intensive study in 1992, the total primary sedimentation at the station from March to October was found to be 34 g C m^{-2} (Heiskanen & Tallberg 1999), of which phytoplankton carbon contributed 8.3 g C m^{-2} (Tallberg & Heiskanen 1998). A more detailed description of the Tvärminne area is presented by Niemi (1975).

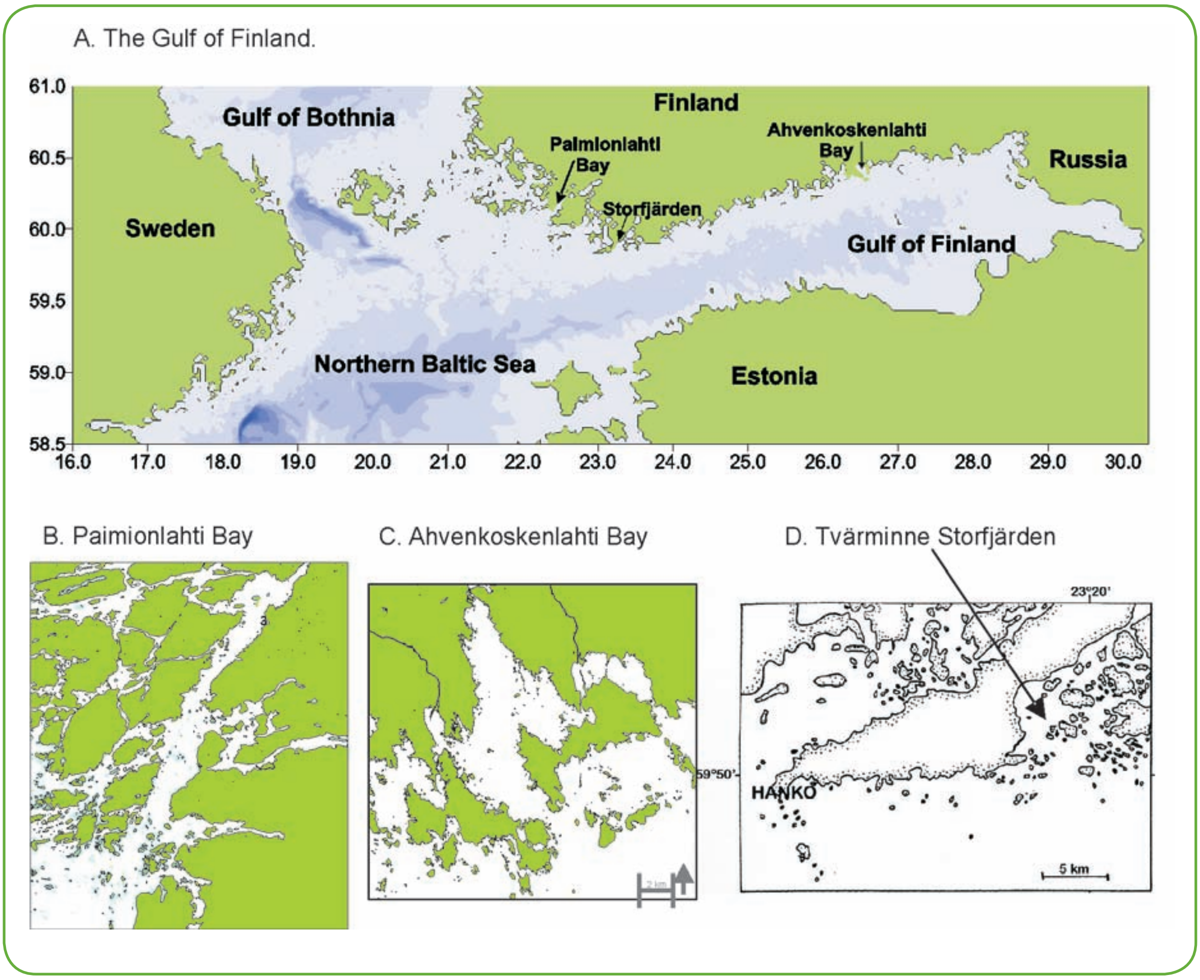

Fig. 1.2. The main study areas in the Gulf of Finland (A), Paimionlahti Bay (B), Ahvenkoskenlahti Bay (C) and Tvärminne Storfjärden (D; map by Riitta Autio, FIMR).

1.3
The objectives of SEGUE

The basic aim of SEGUE was to enhance the reliability and spatial resolution of medium and long term state scenarios for the Gulf of Finland and its adjacent waters. This was achieved by the complementary use of spatially and temporally orientated ecological models, together with experimental data produced both within SEGUE and other relevant projects dealing with the main internal nutrient flows controlling eutrophication. Further, the project aimed to study socio-economic controls on the nutrient loading of the Gulf of Finland. The project combined new information on the eutrophying effects of nutrient loads and the biogeochemical processes controlling these with an understanding of the policy processes that aim at reducing the loads. The study thus contributes to the debate on cost-effective pollution control, and also provides new knowledge that can be used in developing practical environmental policies.

The general objective of SEGUE was to assess different protection alternatives for the eutrophied Gulf of Finland (as an example case). Starting from the main external nutrient fluxes, internal processes and socio-economic controls, the relevant protection measures needed for a lower state of trophy of the open and coastal Gulf of Finland could be assessed.

The more specific targets were:

- to compile the existing nutrient loading data from the Estonian, Finnish and Russian drainage area of the Gulf of Finland and assess the role of catchment retention on this load (chapter 2)
- to improve the knowledge about the cycling of nutrients (N, P, Si) in sediments, as well as about the factors controlling this (chapters 3 and 4)
- to improve the knowledge about the role of coastal behaviour and retention of P, N and Si (chapters 2, 3 and 4)
- to develop tools for water protection management by the complementary use of two modelling approaches (EIA –SYKE and MARE/SANBALTS; chapter 5)
- to analyse optimal protection strategies for both the open Gulf and the Finnish coastal waters, with special emphasis on agricultural loading (chapter 6), and
- to compare the effectiveness of different national and multilateral water protection programmes and plans (chapters 5, 7) .

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2 Nutrient loading and coastal retention

2.1

The loads of nitrogen and phosphorus into the Gulf of Finland

Heikki Pitkänen, Grigori Frumin, Sergey Kondratyev, Antti Räike, Svetlana Basova and Natalia Ignatieva

Relative to its surface area, the Gulf of Finland is – together with the Gulf of Riga- the most loaded sub-basin of the Baltic Sea. Compared to the average for the whole Baltic Sea, the area specific nutrient loads to the Gulf of Finland are 2 to 3 times higher (Figure 2.1).

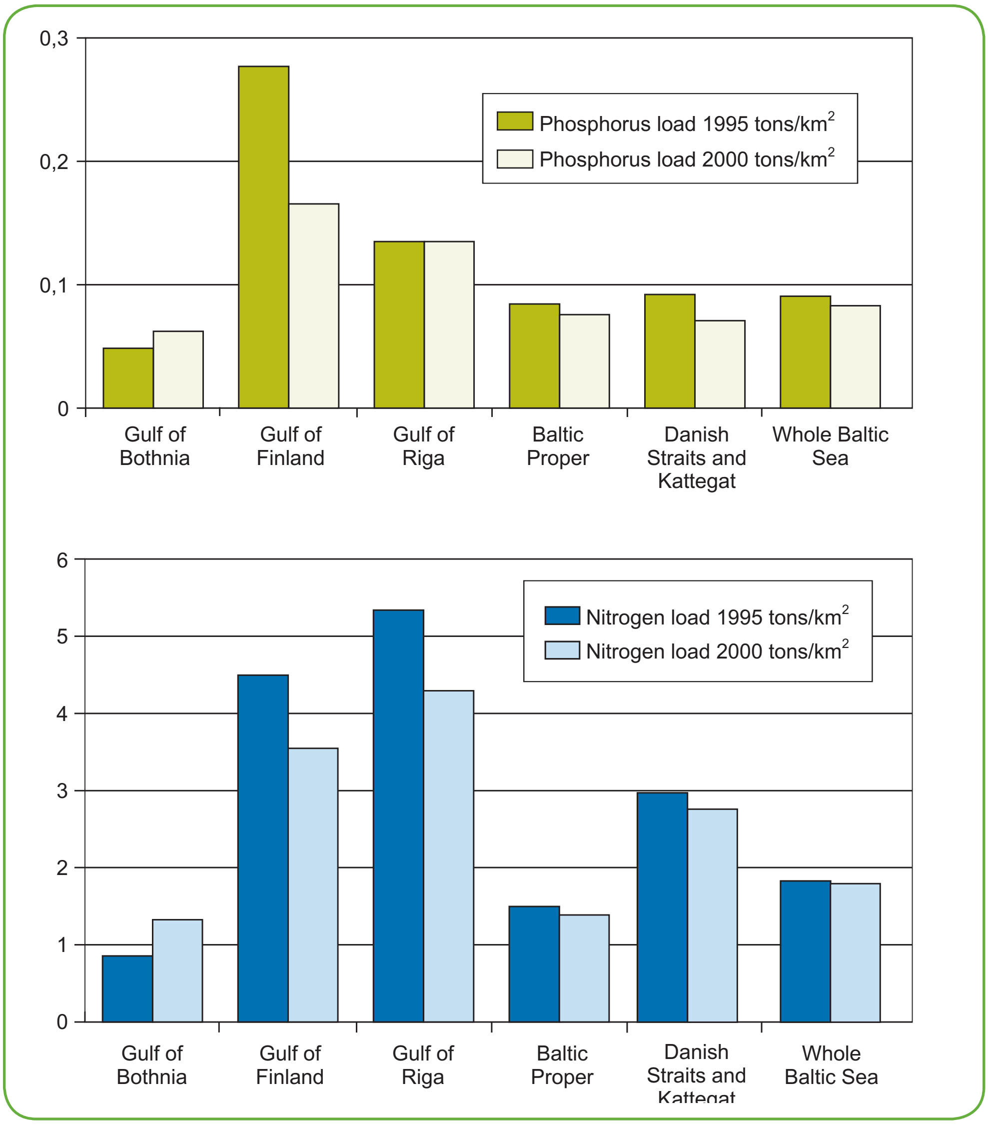


Fig. 2.1. The surface area specific loads of total nitrogen (N) and phosphorus (P) into the Baltic Sea and its sub-basins in 1995 and 2000 (recalculated from HELCOM, 1998, 2004).

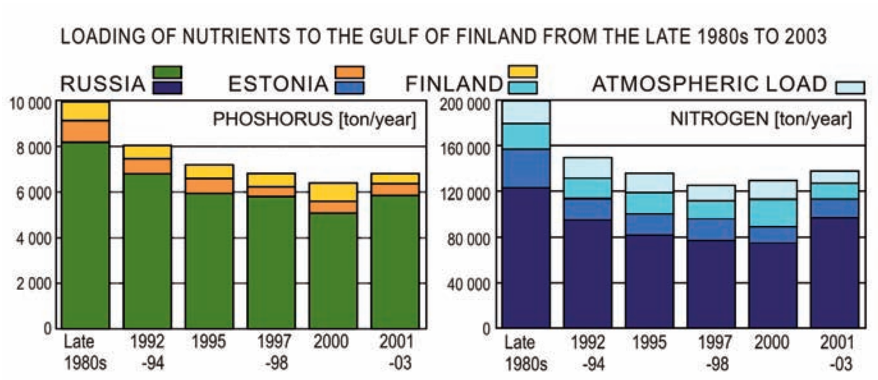


Fig. 2.2. The development of total N and total P loads into the Gulf of Finland from the late 1980s to 2001–2003 (redrawn from Kiirikki et al. (2003), data for 2001–2003 from Pekka Kotilainen, HELCOM/PLC data base). Initial sources: data bases of SYKE and Estonian Environment Information Center. The Russian data originates from various sources: from the late 1980s to 1995 from the Institute of Limnology; 2000 from Kiirikki et al. (2003); 1997–98 and 2001–2003 from NW Hydromet.

Both total N and total P loads into the Gulf were strongly reduced, by about 35%, in the early 1990s (Figure 2.2). The reductions were mainly caused by the collapse of agricultural and industrial production in the former Soviet Union (Lääne et al. 2002). The decrease has ceased in the late 1990s, and in the early 2000s a slow increase seems to have taken place.

The changes in the total annual nutrient loads into the Gulf of Finland are largely governed by the changes in the Russian national loads, and especially the changes in the loads from the River Neva. The trends presented in Fig. 2.2 from the late 1980s to 2000 are in good agreement with the results of Kondratyev and Ignatieva (Chapter 2.3) on the trends in nutrients entering River Neva from Lake Ladoga. It seems that a considerable part of the decrease in the nutrient loads entering the Gulf of Finland can be explained by the decreased inputs of total P and total N from Lake Ladoga to the River Neva. On the contrary, no major changes took place in the amounts of unpurified waste waters entering the lowest parts of the river in the St. Petersburg region in 1990–2003 (Figure 2.3).

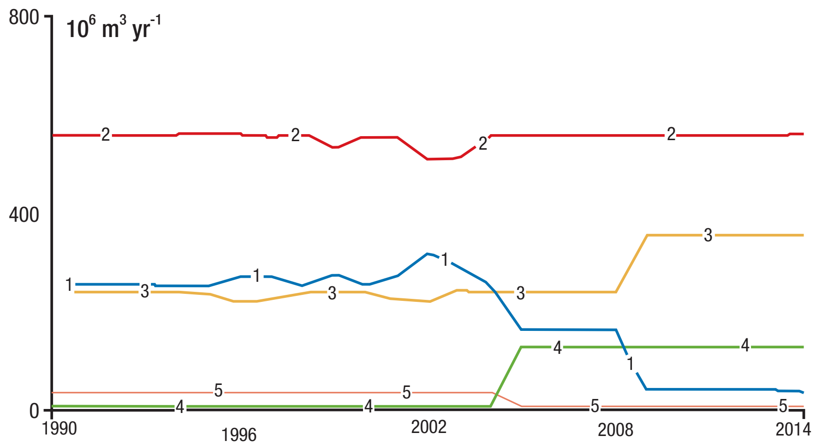


Fig. 2.3. The development of municipal wastewaters inputs into the Neva Bay based on monitoring data and according to SUE Vodokanal SPb plan of future municipal wastewaters treatment (Karmazinov 2002). 1 – untreated wastewaters, 2 – Central Waste Water Treatment Plant, 3 – Northern Waste Water Treatment Plant, 4 – South-western Waste Water Treatment Plant, 5 – Krasnoselskaya Waste Water Treatment Plant.

When total P fluxes of the River Neva into the Gulf of Finland are assessed (data of the North-West Administration of Federal Service of Russia for Hydrometeorology and Environmental Monitoring, NW Hydromet), there are inconsistencies between the steep decreasing trend in the late 1980s/early 1990s shown in Fig. 2.2 and the absence of a clear trend in the data of NW Hydromet (Fig. 2.4). Further, the values for 2000 (3 900 t a^{-1}) and 2002 (4 300 t a^{-1}) based on the data of NW Hydromet are 2 000 to 2 500 t a^{-1} higher compared with the values based on measurements from the main branches of the River Neva in a joint project, where analyses were made both in a Finnish (South-East Finland Regional Environment Centre, KAS) and a Russian (Water Research Control Centre, WRCC) laboratory (see chapter 2.5).

The sampling sites used in the KAS-WRCC joint study were not identical with the sites used by NW Hydromet. This explains the observed differences to some extent, because by-passes of unpurified waste waters and storm waters enter the river between the lowest bridges across the river (KAS-WRCC study sites) and the sampling locations of NW Hydromet monitoring, which are situated a few kilometers lower in the river. The amount of by-passes entering the main branch of the river between the monitoring sites, about 72 000 m^3d^{-1} (Vodokanal 2006), corresponding to a maximum of 130 t a^{-1} of the total P is, however, far too small to explain the whole observed difference between the results.

The main reason for the observed differences is most likely the high lowest detection limit of the total phosphorus analysis (40 µg l^{-1}) applied by NW Hydromet (Management directive 52.24.387-95, in Russian), while the detection limit of total P applied at the KAS Laboratory was 5 µg l^{-1} (SFS –Standard 3026,1986) in 2000–2002. According to the KAS-WRCC study, the average annual flow-weighted total P concentration of the river varied from 21 to 30 µg l^{-1} in 2000–2002 (Ekholm, P., pers. comm.).

Obviously, the present analysis method applied by the laboratory of NW Hydromet is too rough for the relatively low total phosphorus concentrations prevailing in the River Neva, even in its lowest reaches which receive direct waste water discharges from St. Petersburg. The result highlights the need to further compare and intercalibrate the results of the different laboratories monitoring the River Neva. The role of

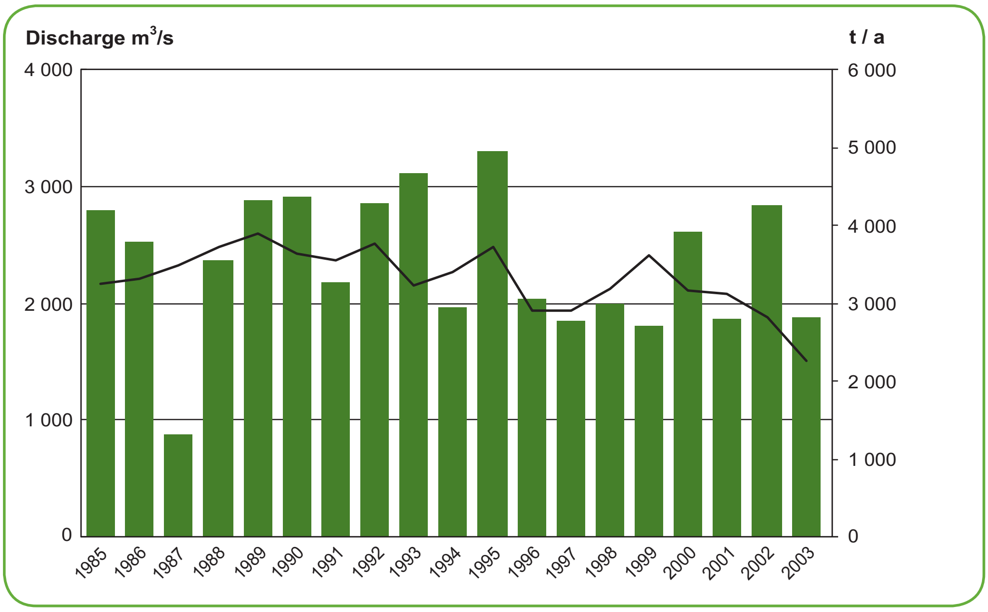


Fig. 2.4. The water discharge (black line, m^3 s^{-1}) and load of total phosphorus (green columns, t a^{-1}) from the River Neva into the Gulf of Finland in 1985–2003 according to the data of the North-West Administration of Federal Service of Russia for Hydrometeorology and Environmental Monitoring, (Frumin, G. and Basova, S., unpublished data).

the River Neva in the overall nutrient budget of the Gulf of Finland is very important, and reliable values on its nutrient discharges are needed for several purposes, e.g. state assessments and modeling scenarios.

2.2

Application of a catchment model in predicting changes in agricultural nutrient load

Kristjan Piirimäe, Petri Ekholm and Marjukka Porvari

The Gulf of Finland receives a substantial share of its nutrient loading from agricultural activities. Here, our aim was to link the long-term changes in agriculture to the nutrient loads entering the Gulf. To this end, we constructed scenarios of future agricultural development for the time period of 2020–2024. Then, we applied a catchment model, the PolFlow model, to these scenarios to approximate the corresponding past, present and future nutrient loads to the Gulf of Finland.

The PolFlow model (De Wit 1999, 2001) describes sources, transport and loads of nutrients in large drainage basins. The model, operating in raster-GIS, follows long-term changes in nitrogen (N) and phosphorus (P) loads and concentrations. It uses PCRaster software package which includes the PCRaster Dynamic Modelling Language. One time step in the model lasts five years. The PolFlow model comprises a hydrological part, description of nutrient sources (emissions), their pathways to surface waters and transport of nutrients to the river mouth.

The model makes difference between emission, gross load and net load of nutrients. These parameters differ quantitatively. While point emission obviously means discharge of wastewater, diffuse emission in PolFlow concept stands for the surplus of nutrients in soil surface. That surplus subtracts nutrients removed with crops from these added by manure, mineral fertilizers and atmospheric deposition. Gross load is the total amount of nutrients that reaches surface water while net load is the amount passing a river segment.

The drainage basin of the Gulf of Finland (Fig. 2.5.) was defined according to the MapBSR database (Digital Map of the Baltic Sea Region 2000). Here, we applied a grid cell size of 1 km^2 and examined four five-year time periods as follows:

- 1985–1989 as a period of intensive agriculture and high nutrient emissions
- 1995–1999 as a period of low agricultural activities in the Estonian and Russian parts of the basin and implementation of agri-environmental policy in Finland expected to result in low emissions and loads
- 2000–2004 representing the current situation
- 2020–2024 representing possible future alternatives.

To assess the effect of economic changes on future nutrient emissions and river loads, two plausible agricultural scenarios were developed for 2020–2024. The 'Low loading' scenario resulted from environmental friendly political and economic processes towards the Gulf of Finland in all three countries. By contrast, the 'High loading' scenario combined developments in Russia, Finland and Estonia which led to an increase in N and P loads to the Gulf (Piirimäe et al. in prep.).

We considerably modified the model to better suit the specific conditions (Piirimäe et al. in prep.). In contrast to previous model applications, the changes in agriculture were also reflected in the model land cover (e.g. in the case when abandoned field land in Estonia was re-cultivated, Fig. 2.6.). Considering the speciality of Finnish pedogeology, the Finnish soil system was modelled according to the P balance ap-

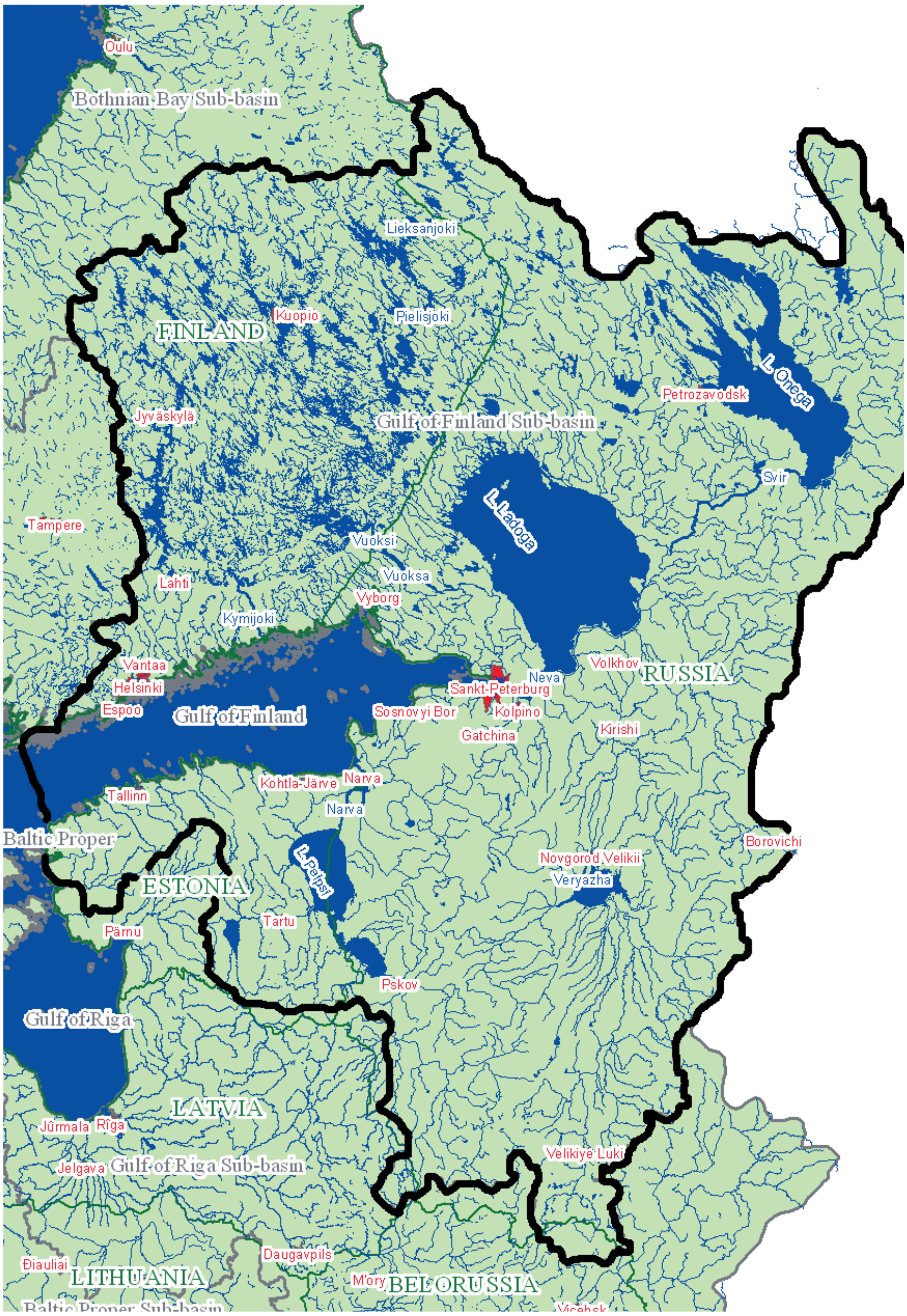


Fig. 2.5. The drainage basin of the Gulf of Finland.

proach of Ekholm et al. (2005). Owing to the high importance of lakes in the drainage area (including large lakes such as Ladoga, Peipsi, Onega, Ilmen and the numerous lakes in Finland), we paid special attention to lake retention of nutrients. The model was completely rewritten in order to be able to process such an extensive database and new knowledge on basin processes (e.g. retention of lakes, soil processes). Input data for the model were taken from various national and international databases and from literature. Because of the requirements of the PolFlow model, all data were reworked to one km^2 grids.

The tentative modelling results suggested that the emissions of N have halved since the late 1980s. In turn, the emissions of P have decreased by as much as 64%. Most of these reductions have appeared due to the reduction in agricultural diffuse

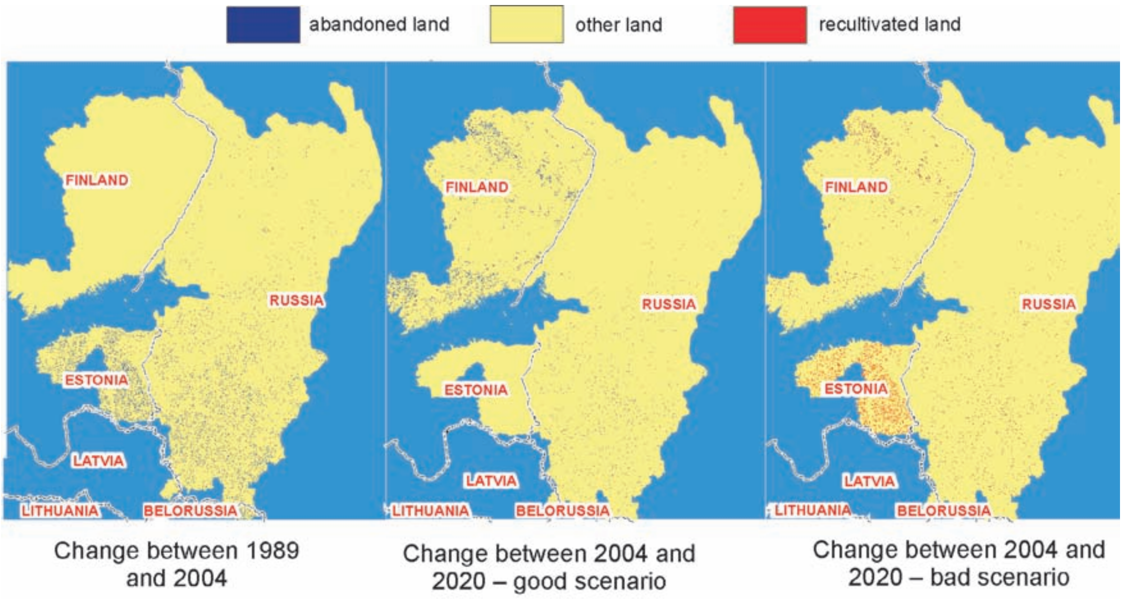


Fig. 2.6. Change in the use of agricultural land in Gulf of Finland drainage basin.

emissions (e.g. fertiliser use, manure application). However, along the different time periods and scenarios the actual diffuse load of nutrients remained on the same level. The main reason for the almost negligible effect on loads was found to be the high reserves of N and P in soil, which buffer against changes in diffuse emissions. As the rate of diffuse load is related to the content of N and P in the soil, which changes only slowly, the diffuse load can not change much within a short and medium term time frame. Of the three countries only Russia can produce significantly different agricultural loads depending on economic scenarios.

In total, 42% of N and 73% of P which reached the surface waters was retained in the network of streams and lakes without entering the Gulf of Finland (Fig. 2.7.). The impact of a pollution source thus depends on its distance from the river mouth and on the lake percentage of the catchment. Coastal pollution sources, loading more per emission unit than far inland sources, therefore require more attention.

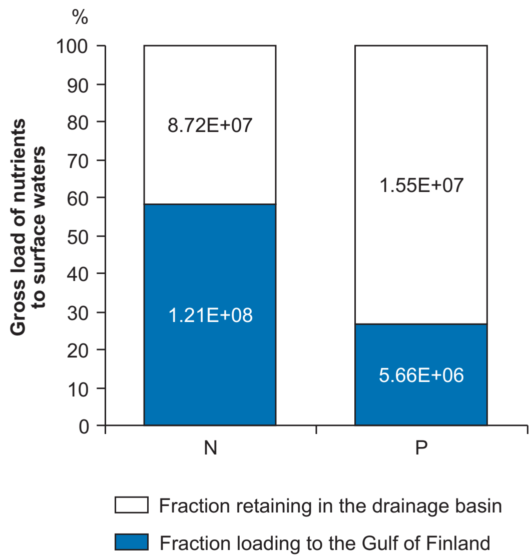


Fig. 2.7. Gross load, net load and retention of nutrients (kg) in Gulf of Finland drainage basin in 2000–2004.

We conclude that although agriculture is a large source of nutrients, the possibility to control this nutrient load is limited within relatively short time periods. For example, reduction in fertiliser use without other concomitant measures probably does not yield the required results soon.

2.3

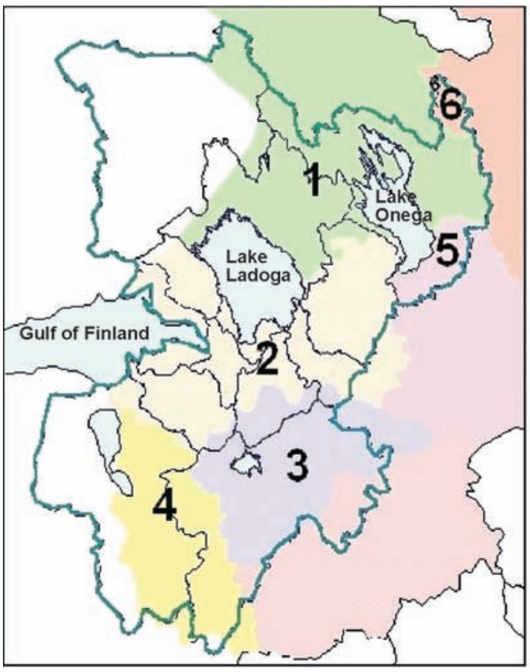
An assessment of the nutrient load on the Russian parts of the catchment of the Gulf of Finland and a nutrient budget for Lake Ladoga

Sergei Kondratyev and Natalia Ignatyeva

The catchment area of the Russian part of the Gulf of Finland is about 308 000 km^2. It includes the Lake Ladoga catchment (about 280 000 km^2; partly located in Finland), the River Neva immediate catchment (about 5 000 km^2) and the Gulf of Finland immediate catchment (23 000 km^2). The following sub-catchments were considered in this study: the catchments of Lake Ilmen and Lake Onega, the immediate catchments of the rivers Volkhov, Svir and Vuoksen, and Lake Ladoga, the catchment of the River Luga, and the Russian part of the River Narva catchment (Fig. 2.8.).

To estimate the nutrient load on the selected regions the following data were collected and calculated (time period 1995–2002, separately for each year):

1. Annual loads of nutrients (total phosphorus, P_{tot}, and total nitrogen, N_{tot}) from point sources (industrial, agricultural and municipal enterprises) on water bodies of administrative regions of the Russian Federation located in the Russian parts of the catchments of the Gulf of Finland and lakes Ladoga



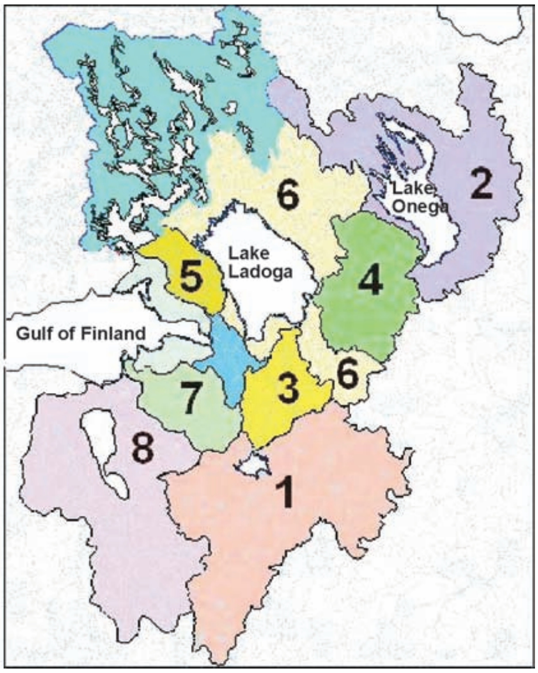


Fig. 2.8. A. Studied regions: Republic of Karelia (1), Leningrad (2), Novgorod (3), Pskov (4), Vologda (5) and Arkhangelsk (6) regions. B. Studied catchments: the catchments of lakes Ilmen (1) and Onega (2), the immediate catchments of the rivers Volkhov (3), Svir (4) and Vuoksen (5), the immediate catchment of Lake Ladoga (6), the catchment of the River Luga (7) and the Russian part of the River Narva catchment (8).

and Onega (Republic of Karelia, Leningrad, Novgorod, Pskov, Vologda and Arkhangelsk regions; Fig. 2.8.).
2. Information about field cultivation and population (scattered settlements) in the studied regions.
3. Annual nutrient loads (P_{tot}, N_{tot}) from point sources in the catchments of Lake Ilmen and Lake Onega, the immediate catchments of the rivers Volkhov, Svir, Vuoksen, and Lake Ladoga, the catchment of the River Luga and the Russian part of the River Narva catchment (Fig. 2.8.).

The information was gathered from long-term research of the Institute of Limnology RAS (Kondratyev et al., 1998, 2002, 2003 a and b) and other organizations (Anon. 2000a, Anon. 2000b), and from statistical data of the Russian State Statistic Committee (Anon. 2003) and St Petersburg Statistic Committee (Anon. 2002). The studied water bodies are subjected to different nutrient loads. The highest values of the annual phosphorus load from point sources occur in the Leningrad region and the Republic of Karelia, while the nitrogen load is highest in the Leningrad and Novgorod regions. The highest values of the annual nutrient loads occurred in the first two years of the time period under consideration (1995–1996). Thereafter they tended to decrease, and during the period 1997–2002 varied only slightly from year to year.

The population in scattered settlements within the administrative regions has been almost the same in 1995–2002. The area of field cultivation in the administrative regions shows a decreasing trend, especially in the Novgorod and Pskov regions. In all the studied catchments, agricultural enterprises represent the smallest contribution to the total nutrient load on water bodies. No common tendency in temporal changes of annual phosphorus and nitrogen loads from different point sources were revealed in 1995–2002.

The water quality and ecological state of the Neva Bay of the Gulf of Finland depend mainly on the Neva River inflow, which flows from Lake Ladoga, and on the impact of St Petersburg. Therefore, Lake Ladoga has received special attention. Lake Ladoga is the largest lake in Europe, with a surface area of about 18 000 km^2. The lake volume is 908 km^3, and its average and maximum depths are 51 and 230 m, respectively. The catchment of Lake Ladoga has an area of about 280 000 km^2 (about 65 % of the total Gulf of Finland catchment area). Twenty percent of this area is located in Finland. The aquatic system of Lake Ladoga includes the catchments of lakes Saimaa (Finland), Onega and Ilmen (Russia) which are connected by large rivers: Vuoksen, Svir and Volkhov. The case study catchment is located on the territory of 7 administrative regions of Russia and 4 provinces of Finland.

An assessment of the main elements in the total P balance of Lake Ladoga is presented in Fig. 2.9. It can be seen that the P load on Lake Ladoga has decreased during the last decades. In the 1980s the main reason for the decrease in the load was the water protection measures conducted, in particular on the Volkhov aluminium enterprise. In the 1990s the reasons were the reductions within the industry in Russia and a decrease in the load from point sources to the water bodies in the Lake Ladoga catchment area. The lake reacted correspondingly to the decrease in the load: the total phosphorus

Table 2.1. Internal nutrient load and atmospheric deposition on Lake Ladoga.

Nutrient	Internal load (ton $year^{-1}$)	Atmospheric deposition (ton $year^{-1}$)	Source of information
P_{tot}	875	34.6	Ignatyeva 1997, Kondratyev et al. 1997
N_{tot}	2100	8366	Stravinskaya & Ignatyeva 1987, Kondratyev et al., 1997

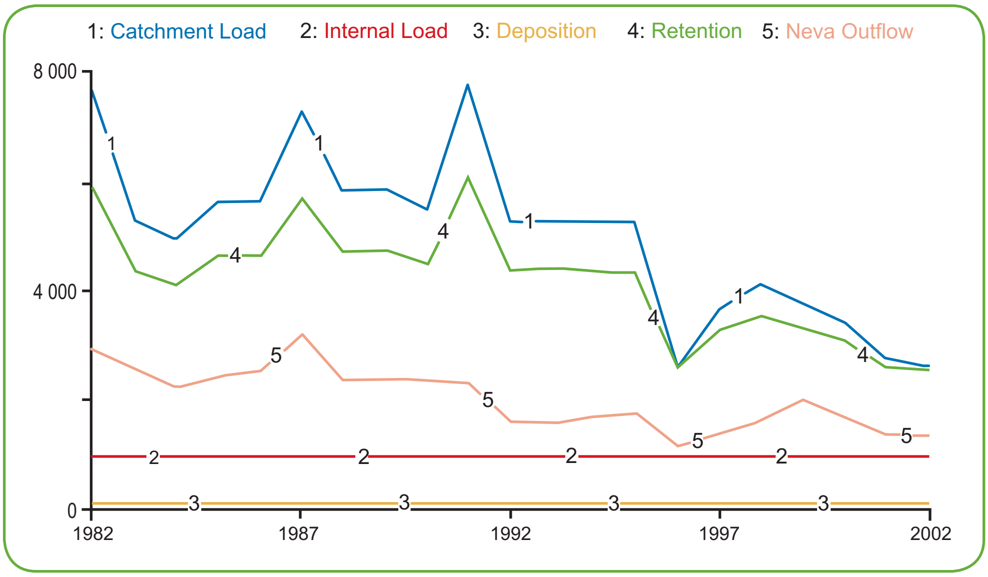


Fig. 2.9. The main components of the P balance of Lake Ladoga (ton year^{-1}) calculated using measured data: catchment load (1), internal load (2), atmospheric deposition (3), accumulation or retention (4), outflow with the Neva River (5).

concentration in the lake water decreased as well, and this resulted in a decrease in the phosphorus load on the Neva Bay through the inflow of Neva River.

An assessment of the main elements in the total N balance of Lake Ladoga is presented in Fig. 2.10. The N load on Lake Ladoga and the total N concentrations in the Lake Ladoga water have changed from year to year. There has been an overall decreasing trends since the 1980s, but not as clearly as in the case of total P.

It should be noted that the hydrochemical composition of the water at the start of the Neva River is governed mainly by Lake Ladoga. However, the mean concentrations at the start of the Neva River (Petrokrepost Bay) can be different from the corresponding mean concentrations in the Lake Ladoga water. The main reason is that part of the waters of rivers Volkhov and Syas are transported directly to Petrokrepost

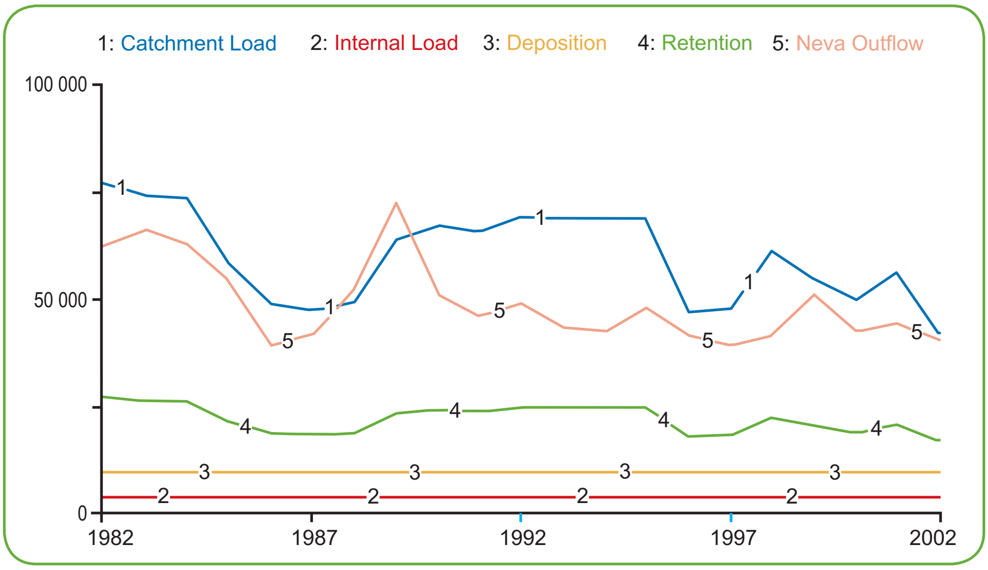


Fig. 2.10. The main components of the N balance of Lake Ladoga (ton year^{-1}) calculated using measured data: catchment load (1), internal load (2), atmospheric deposition (3), accumulation or retention (4), outflow with the Neva River (5).

Bay in winter, and from River Vuoksen in spring. When this is the case, the big water volumes of these large rivers' inflows are not included in the lake circulation. Besides, overland runoff and inflow from small rivers form part of the hydrochemical composition of Petrokrepost Bay (Kryuchkov 1982, 1987).

Lake Ladoga is very important in the retention of P originating from the upper parts of the Gulf of Finland catchment area. Calculations have shown that about 70 % of the incoming P is retained in the lake. As for nitrogen, a smaller part of it (about 30 %) is retained in Lake Ladoga, and the rest is transported to the Gulf by the River Neva waters.

2.4

Role of estuaries in retaining external phosphorus load

Jouni Lehtoranta, Petri Ekholm and Heikki Pitkänen

The transition zone between a river and the open sea is called an estuary. Estuaries are subject to land-based nutrient loading from the catchment, and may have a crucial role in modifying nutrients reaching the open sea. In Finland, the major part of the phosphorus flux transported via rivers to the Baltic Sea originates from agriculture. Phosphorus consists of dissolved and particulate fractions, and most of the phosphorus load from arable land is in particulate form, i.e. phosphorus bound to eroded soil particles (Uusitalo 2004). Phosphorus is transported from cultivated fields especially during the snowmelt in spring – occasionally in winter – and during autumn storms (Ekholm & Kallio 1996). In order to study the ability of estuaries to retain land-derived phosphorus, we focused on river water and sediment chemistry, with special emphasis on particulate phosphorus and its reactions in the bottom sediments of two Finnish estuaries: Paimionlahti Bay and Ahvenkoskenlahti Bay.

A total of 43% of the drainage basin of River Paimionjoki is agricultural land, mainly under crop production (Table 2.3). The topsoil of the agricultural land is mostly clayey: a total of 58% of the soil in the catchment consists of geologically recent lacustrine/marine sediments. Erosion of surface field soil makes the river waters turbid and rich in suspended solids (Table 2.4, Mansikkaniemi 1982, Pietiläinen & Ekholm 1992). During dry periods in summer, there is almost no flow in the river. River Paimionjoki discharges into Paimionlahti Bay, which is a long and narrow estuary in the Archipelago Sea (south-west Finland).

Table 2.3. Characteristics of the drainage basins of River Paimionjoki and River Kymijoki (data base of the Finnish Environment Institute).

River	Area (km^2)	Agricultural land %	Forests %	Peatland %	Lakes %
Paimionjoki	1 088	43	50	4	1.5
Kymijoki	37 160	9	62	11	19

River Kymijoki is clearly larger than River Paimionjoki (Table 2.4). Although 9% of the vast catchment consists of agricultural land, much of the phosphorus originating from field cultivation and animal husbandry is retained by lakes located in the upper and central reaches of the catchment. In addition, the top soil in the River Kymijoki catchment is less susceptible to erosion (only 5% of the soils being geologically recent sediments). The concentrations of suspended solids, phosphorus, iron and calcium are thus much lower in River Kymijoki than in River Paimionjoki (Table

2.4). If the retention in lakes is omitted, the proportion of phosphorus originating from agriculture in the total riverine phosphorus flux is 35% in the River Kymijoki and 80% in the River Paimionjoki (VEPS assessment system of the Finnish Environment Institute). The remaining phosphorus transported by River Kymijoki is derived from natural background (27%), atmospheric deposition (14%) and sewage and industrial effluents. However, mass-balance calculations have shown that as much as 69% of the phosphorus input is retained by the lakes (Räike et al., unpublished data). The western branch of River Kymijoki discharges into Ahvenkoskenlahti Bay, a shallow (mean depth 4.3 m) semi-enclosed estuary in the eastern Gulf of Finland. Due to the marked difference in the proportion of agricultural land in the catchments and in the riverine inputs we hereafter refer to Paimionlahti Bay as an "agricultural bay" and to Ahvenkoskenlahti Bay as a "non-agricultural bay".

Table 2.4. Average discharge and the concentrations of selected water quality variables in the rivers Paimionjoki and Kymijoki in 1990–2003.

River	Discharge $m^3\ s^{-1}$	Total suspended solids mg l^{-1}	Total iron mg l^{-1}	Total calcium mg l^{-1}	Total organic carbon mg l^{-1}	Total phosphorus mg l^{-1}	Dissolved phosphorus mg l^{-1}
Paimionjoki	9.6	192	11	9.95	12	0.280	0.054
Kymijoki	149.0	7.8	0.400	5.65	7.1	0.026	0.007

The chlorophyll *a* (Fig. 2.11) and total phosphorus concentrations were higher in the non-agricultural bay than in the agricultural bay, although the phosphorus flux per area was higher in the latter. The shallow non-agricultural bay was more stratified by salinity than the agricultural bay, which may inhibit vertical mixing of water and thus decrease the transport of oxygen to the bottom water.

The concentrations of phosphorus in the sediment pore water were lower in the agricultural bay than in the non-agricultural bay, whereas the opposite applied to

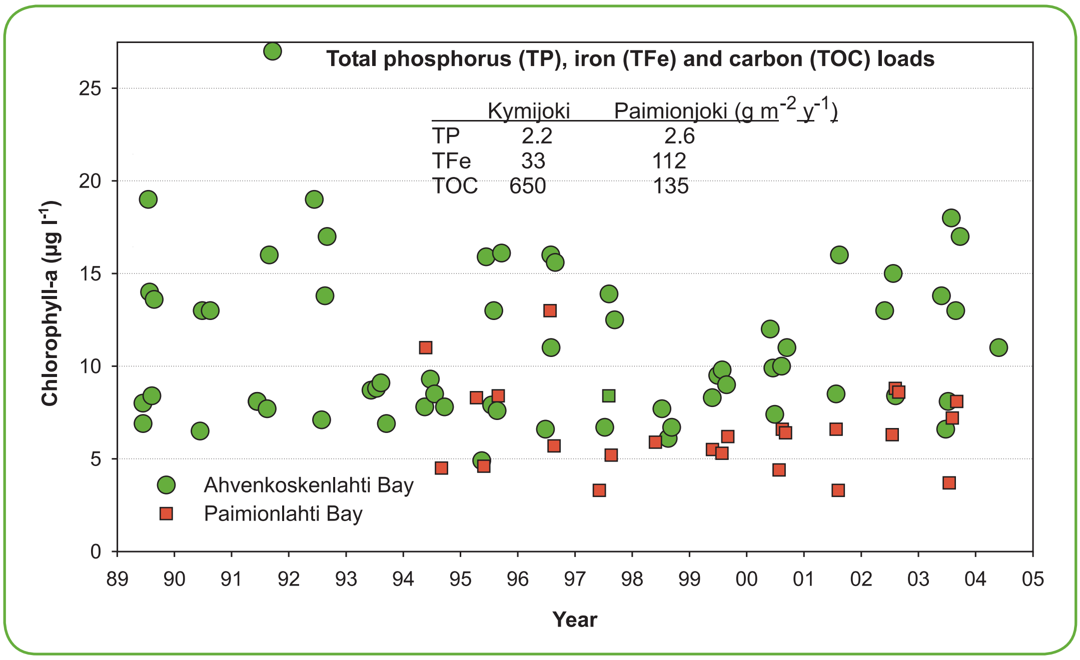


Fig. 2.11. Chlorophyll *a* in the 'agricultural' Paimionlahti Bay and the 'non-agricultural' Ahvenkoskenlahti Bay.

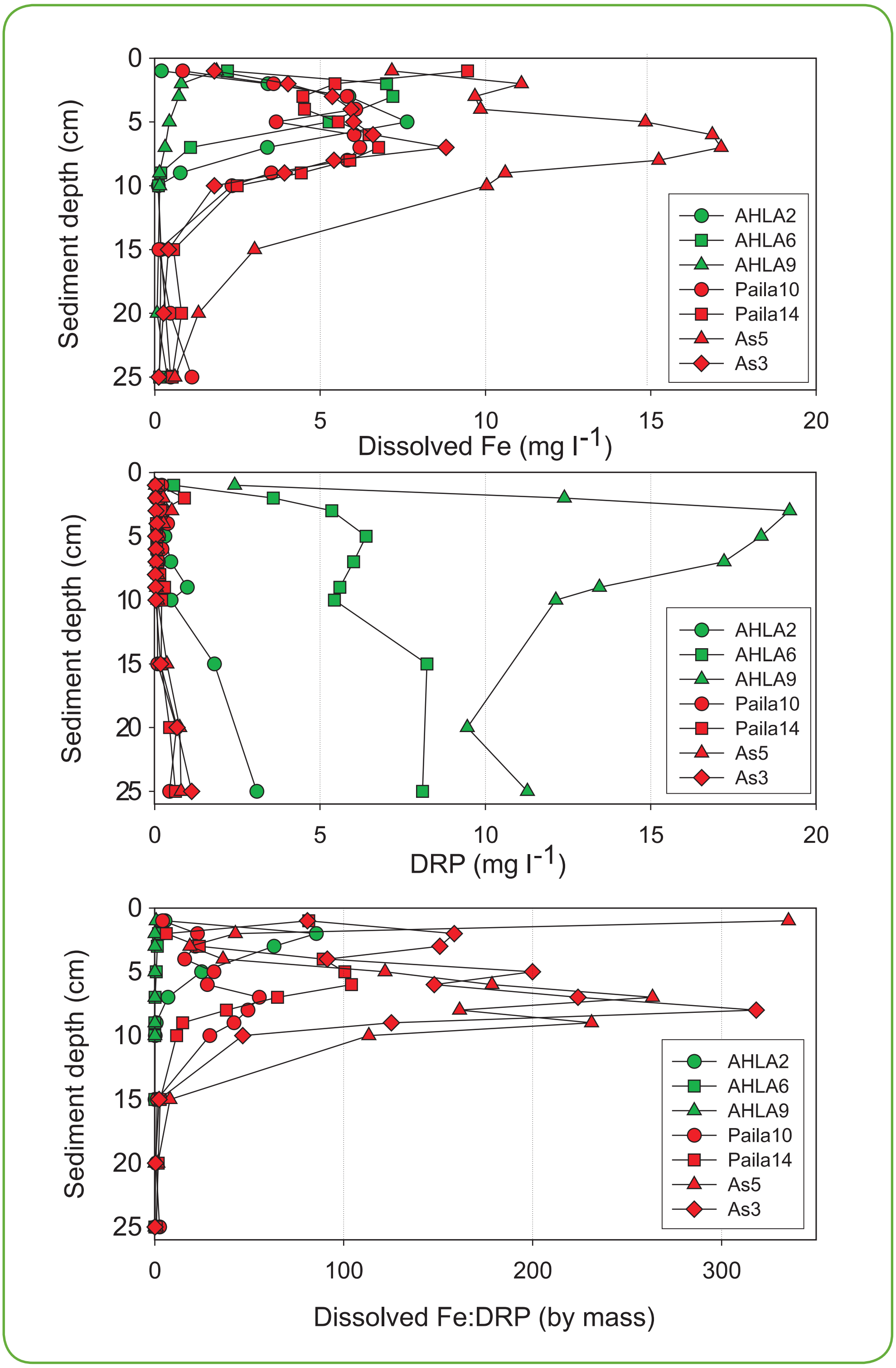


Fig. 2.12. Concentrations of dissolved iron (Fe) and dissolved phosphorus (DRP) in the sediment profile of the 'agricultural' Paimionlahti Bay (sites Paila 10, 14, As5, 3) and the 'non-agricultural' Ahvenkoskenlahti Bay (sites AHLA2–AHLA6), see Fig. 3.1.

the pore water concentrations of iron (Fig. 2.12). This observation suggests that the sediments of the agricultural bay were in a state where microbial iron reduction dominates in the mineralization of organic matter, whereas in the non-agricultural bay sulphate reduction was more likely. This was supported by the smell of hydrogen sulphide and by black-coloured sulphides at the sediment surface, as well as by the pore water results (Lehtoranta et al. in prep. a, b). In sediments where microbial iron reduction dominates in the recently deposited sediments layers, the fraction of Fe(III) oxides that is dissolved to Fe(II) upon reduction will ultimately be transported to the oxic layer, where it will be re-oxidized. Phosphorus, which is released from Fe(III) oxides and decomposing organic matter from deep layers of the sediment, will be largely trapped by this newly formed Fe(III) oxide layer. In such a system the benthic efflux of phosphorus is low and there are low concentrations of phosphorus in near-bottom water, too. In contrast, in surface sediments where sulphate reduction dominates, Fe(III) oxides are reduced by sulphides. This chemical reduction leads to the formation and permanent burial of solid iron sulphides that are unable to capture phosphorus. As a result, the cycling of iron is blocked, and phosphorus is released to the overlying water.

The differences in sediments between the two estuaries may be related to the higher flux of eroded soil matter transported to and settled within the agricultural bay, which may have a strong impact on bottom sediment processes controlling phosphorus retention (Lehtoranta et al. 2005). Suspended sediments contain iron oxides that promote iron reduction. In addition, they also include clay particles, which may lower microbial activity in the sediments (Keil et al. 1994). Thus, in addition to nutrient loading, the state of estuaries may be affected by the riverine flux of suspended sediments (Fig. 2.13). If so, this finding may have implications for the agri-environmental measures applied to abate eutrophication in coastal areas. Further research is urgently needed in order to assess to which extent erosion control may be practised in the catchment without risk of increased release of phosphorus from the sediments in the receiving estuaries. Note that erosion control is practiced not only to mitigate eutrophication, but e.g. to improve soil quality, reduce siltation of water bodies, improve aquatic habitats and reduce the flux of harmful substances to receiving waters.

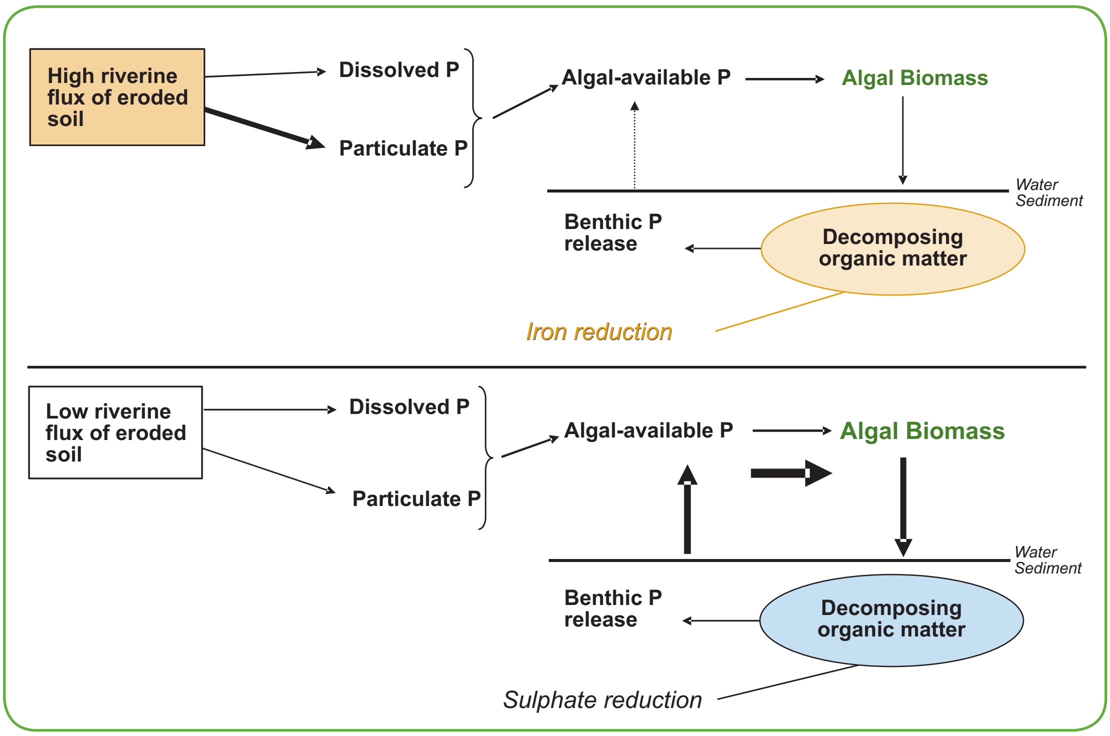


Fig. 2.13. Schematic representation of the hypothesized effect of riverine flux of eroded soil on algal biomass in an estuary.

2.5

Algal-available phosphorus discharged into the eastern Gulf of Finland

Petri Ekholm, Heikki Pitkänen, Pirjo Rantanen and Hannu Rita

Reducing the total load of phosphorus to aquatic systems is a widely applied measure to abate eutrophication of surface waters. All forms of phosphorus are, however, not available to algae and thus do not contribute to increased algal biomass (DePinto et al. 1981, Ekholm 1994, Ellison & Brett 2006). The proportion of potentially algal-available phosphorus in total phosphorus has been studied by different kinds of bioassays and chemical methods (Nakajima et al. 2006), but the wide range in the results complicates their use in eutrophication assessment and management. In addition to natural variation in phosphorus availability, for example due to loading patterns and hydrology (Ellison & Brett 2006), methodological issues cause major variations in the results.

The management of eutrophication is a topical issue when the Gulf of Finland is concerned. The land-based load of total phosphorus to this sea area was estimated to be 6400 tons in 2000 (Kiirikki et al. 2003). Most of this load enters the eastern Gulf, transported by large rivers and discharged by the City of St Petersburg (Kiirikki et al. 2003). Previously, Ekholm & Krogerus (2003) estimated potential availability of phosphorus in various loading sources by employing a fresh-water assay with a green alga as the test organism. In the 13 samples collected from large rivers entering the eastern Gulf of Finland the mean percent of potentially algal-available phosphorus in total phosphorus was 20%, whereas in the 10 samples from the purified wastewaters of the Central and Northern Wastewater Treatment Plants of St Petersburg it was 83% (Ekholm & Krogerus 2003). Using such mean percentages for major loading sources, it has been estimated that 2800 tons of potentially algal-available phosphorus entered the Gulf of Finland in the year 2000 (Kiirikki et al. 2003). This value has been used as an input load when predicting the effect of alternative water protection strategies on the algal biomasses in the Gulf by a 3-D ecosystem model (Kiirikki et al. 2003, Pitkänen et al. 2007). However, in a box model approach applied to the Baltic Sea, including the Gulf of Finland, as much as 90% of total phosphorus load was assumed to consist of bioavailable phosphorus (Savchuk, O., personal communication).

The report on prioritising the investments in the wastewater sector of St Petersburg (Anon. 2006) will be used as one of the bases for financing decisions in the future. According to the report, which utilised e.g. the bioassay results of Ekholm and Krogerus (1998, 2003), the load of algal-available phosphorus for several future scenarios of water protection investments were calculated with the following coefficients from total phosphorus: 0.65 for untreated, 0.8 for biologically treated, and 0.5 for chemically (iron, Fe, as the active ingredient) treated wastewater.

With the aim of getting more pertinent results for the brackish Gulf of Finland, we recently modified the algal assay so that it had a brackish-water medium and a diatom as the test alga (Ekholm et al. 2005). The first results suggested that the brackish-water assay appeared to give higher estimates for the potentially algal-available phosphorus than the fresh-water assay (Ekholm et al. 2005). If so, the obvious implication for the Gulf of Finland case would be that the eutrophying phosphorus load to this sea area is higher than believed earlier. In addition, the relative share of different loading sources, and thus the cost-efficient management strategies, could change, too.

In this study, we expanded an existing data set (Ekholm & Krogerus 2003) with additional samples collected from the major incoming rivers to the Gulf of Finland (R. Neva, R. Kymijoki, R. Narva) and from untreated and treated urban wastewaters of St Petersburg, and analysed these for potentially algal-available phosphorus (Tables 2.5

Table 2.5. Concentration of different forms of phosphorus in the river water samples analysed for algal-available phosphorus and in a larger set of samples taken from the sites. The latter results are given in green colour (R. Neva, years 2000–2002, Ekholm unpubl.; R. Kymijoki, years 2000–2004 (western branch), Data Base of the Finnish Environment Institute).

	n	Total phosphorus	Dissolved reactive phosphorus	Dissolved unreactive phosphorus	Particulate phosphorus
		µg l^{-1} Mean (range) [SD]			
R. Neva, Outflow of Lake Ladoga (Kirovsk bridge)	1 18	14 18 (10–70) [14] [A]	<1 3.1 (1–13) [3.7]	6 3.9 (2–5) [1.1]	8 7.3 (5–10) [2.3]
R. Neva, Outer St Petersburg (Volodarskiy Bridge)	4 19	18 (13–24) [5.4] 17 (12–30) [4.6]	1.4 (1–3) [1.1] 3.5 (1–9) [3.2]	4.1 (4–5) [0.6] 3.6 (2–5) [0.9]	13 (8–18) [4.8] 10 (3–23) [5.1]
R. Neva, Bolshaya Neva, St Petersburg (Bridge Leytenanta Shmidta)	13 20	26 (17–41) [7.0] 24 (16–41) [7.4]	5.1 (1–12) [4.2] 5.9 (1–13) [4.9]	4.6 (3–6) [1.0] 4.4 (3–7) [1.0]	17.1 (9–31) [6.5] 14 (5–31) [6.1]
R. Neva, Bolshaya Nevka, St Petersburg (3rd Elagin bridge)	8 20	44 (40–56) [5.0] 43 (23–56) [8.8]	15 (9–24) [5.1] 12 (1–24) [7.3]	5.8 (4–8) [1.4] 5.8 (4–8) [1.2]	23 (13–29) [5.7] 17 (10–22) [5.0]
R. Kymijoki, Eastern or western branch (Ahvenkoski, Kokonkoski)	6 65–129	21 (10–39) [11] 21 (9–51) [9.5]	2.0 (1–6) [2.0] 1.8 (1–6) [1.3]	4.0 (3–5) [0.9] 3.9 (1–8) [1.3]	15 (4–28) [9.1] 15 (2–44) [8.5]
All	41	27.5 (10–56) [11]	6.2 (<1–24) [6.0]	4.9 (3.0-9.0) [1.4]	17 (3.0–31) [7.9]

[A] Includes an exceptionally high value (second highest value 29 µg l^{-1})

and 2.6). Some of the samples were tested using the fresh-water assay, some using the brackish-water assay and a subset of samples using both assays. A focal part of this study consisted of the statistical analysis of whether the results obtained using the brackish-water assay were indeed higher than those given by the fresh-water assay as suggested by the tentative results of Ekholm et al. (2005). Since bioassays cannot be used in routine monitoring, we also related the results to those obtained with a simple operational phosphorus fractionation, based on Murphy & Riley (1962) and in use in standard water analysis and monitoring. It distinguishes between particulate phosphorus, total dissolved phosphorus, dissolved reactive phosphorus and dissolved unreactive phosphorus. Here, our aim was to find 'a good enough' surrogate for laborious and costly algal assays. The data, methods and results are detailed in Ekholm et al. (in prep.).

The performance (random and systematic error, detection limit) of the two algal assays was similar. For the river waters samples, the brackish-water assay gave higher results for the potentially algal-available phosphorus than the fresh-water assay, but for the wastewater samples the results did not differ. Total dissolved phosphorus in river waters best approximated algal-available phosphorus as estimated by the brackish-water assay. Based on the relationship between total dissolved phosphorus and algal-available phosphorus (derived from an analysis of covariance) the flux of potentially algal-available phosphorus transported by the River Neva and River Kymijoki was estimated to be about 650 t a^{-1} and 70.4 t a^{-1} (Table 2.7.), respectively. These values are higher than those formerly used in the loading and modelling assessments. In turn, the Central Wastewater Treatment Plant in St Petersburg discharged 639 t a^{-1}and the northern plant 211 t a^{-1} algal-available phosphorus. The wastewater discharged untreated to the River Neva and the Neva Bay contained about 409 t a^{-1} algal-available phosphorus.

Table 2.6. Concentrations of total phosphorus in the wastewater samples from the central and northern wastewater treatment plant analysed for algal-available phosphorus and in a larger set of samples taken from the sites (Ekholm, unpubl.). The latter data are given in green colour (for inflow and outflow years 2000–2001, for raw sewage 2001–2002, Ekholm unpubl.).

	Central plant		Northern plant	
	n	mg l^{-1} Mean (range) [SD]	n	mg l^{-1} Mean (range) [SD]
Pumping station	4 8	2.9 (1.6–4.2) [1.1] 3.3 (1.9–4.4) [0.73]	4 8	3.6 (1.6–4.2) [1.1 4.2 (2.2–5.2) [0.95]
Inflow	2 11	3.2 (2.1–4.3) 3.7 (2.8–4.6) [0.58]	2 11	7.5 (5.4–9.6) 6.2 (3.7–10) [2.1]
Outflow	10 12	1.3 (0.63–3.3) [0.75] 1.2 (0.71–1.9) [0.28]	9 12	0.66 (0.32–1.7) [0.46] 0.52 (0.1–1.7) [0.46]

It is probable that the fluxes above are somewhat underestimated, but the degree of underestimation is unknown. The role of the rivers Neva and Kymijoki as sources of algal-available phosphorus is larger than previously estimated in modeling studies. It is extremely important that the phosphorus load from the River Neva is reliably estimated. Note that algal assays give potentially algal-available phosphorus under oxidized conditions. Under reduced conditions, iron-bound phosphorus may be released and thereby increase the pool of ultimately available phosphorus.

The difference in the two assays could not be explicitly explained here. At least in part it was due to the very high affinity for phosphorus by the diatom used as a test organism in the brackish-water assay. The use of such an alga in phosphorus availability studies can be justified by the fact that the indigenous algae in the Gulf of Finland are accustomed to very low ambient phosphorus concentrations.

Of the chemical phosphorus forms, total dissolved phosphorus best described algal-available phosphorus as tested with the brackish-water assay, underestimating it by on average 32%. This underestimation revealed that part of the particulate phosphorus must have been transformed into an available form. On the other hand,

Table 2.7. Flux of algal-available phosphorus to the eastern Gulf of Finland from the major sources based on a statistical model (ANCOVA) between total dissolved phosphorus (TDP, rivers) or total phosphorus (wastewaters) and potentially algal-available phosphorus. The values for the mean concentrations and flow are derived from Ekholm (unpublished data), the data base of the Finnish Environment Institute and Anon. (2006). CI = the 95% confidence interval of the estimate.

Source	Year	Algal-available phosphorus	
		10^3 kg a^{-1}	
		Mean	CI
Neva at Volodarskiy	2000	660	460–850
	2001	680	490–870
	2002	620	450–790
	Mean	650	
Kymijoki	2000–2005	70.4	45.8–95.0
Central plant	2004	639	536–742
Northern plant	2004	211	173–249
Untreated[1]	2004	339	13.2–665
Storm water[2]	2004	70	2.7–137

1 Based on several calculation methods for total phosphorus load (Anon. 2006)
2 Also contains untreated wastewaters, the concentration of total phosphorus assumed to be half of that in untreated wastewaters

it was dissolved reactive phosphorus that best described algal-available phosphorus as tested with the fresh-water assay. No clear difference was found between algal-available phosphorus in purified wastewaters as tested with these two assays. The lack of difference may partly be attributed to the fact that a high proportion of the phosphorus in purified wastewater was already in the form of readily available dissolved reactive phosphorus at the start of the assay.

2.6 Conclusions

- Comparison of different Finnish and Russian phosphorus data sets from the River Neva revealed large differences, which cannot be explained by the differences in sampling locations, relatively low sampling frequencies or by hydrological conditions. The main reason for the differences is evidently the high detection limit of the total phosphorus analysis used in the chemical monitoring of the River Neva. Analytical quality control in the laboratories responsible for the chemical monitoring of the River Neva should be evaluated and improved.
- Future economic development may increase the nutrient load originating from agriculture that enters the Gulf of Finland.
- Lake Ladoga retains a large proportion (about 70 %) of the land-based phosphorus entering the lake. The retention rate for nitrogen (about 30 %) is lower and therefore abatement measures are also needed upstream of Lake Ladoga.
- Estuaries modify the land-derived nutrient load that enters the open sea. An agriculturally loaded estuary appeared to have a higher ability to retain phosphorus than an estuary less impacted by eroded soil transported from cultivated fields. This observation was hypothesized to be due to differences in the benthic mineralization pathway, iron reduction resulting in a low benthic efflux of phosphorus and sulphate reduction leading to a high phosphorus efflux. The effect of erosion control measures directed at agricultural soils on coastal eutrophication abatement should be comprehensively clarified.
- The measurement technique affects the obtained level of potentially algal-available phosphorus. For river water samples, a brackish-water algal assay gave higher results for algal-available phosphorus than the fresh-water assay mainly used so far in Finnish bioavailabilty studies. Algal-available phosphorus in river waters can be approximated with a simple phosphorus analysis, the determination of total dissolved phosphorus. The flux of algal-available phosphorus entering the eastern Gulf of Finland appears to be higher than previously thought.

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3 Phosphorus and silicon dynamics in sediments

Mirja Leivuori, Kaarina Lukkari, Antti Räike and Petra Tallberg

The nutrient dynamics in the sediment of the Baltic Sea depend on the composition of the sediment particles and on the chemical environment in the surface sediment and bottom waters. Phosphorus (P) exchange across the sediment-water interface and the role of retention and release of P has been recognized as important for the nutrient metabolism of lake sediments (e.g. Einsele 1938, Mortimer 1941, 1942). However, the extent and consequences of decreased P retention capacity of marine sediments has been recognized later, partly due to the fact that marine eutrophication is a younger environmental problem than lake eutrophication (Jonsson 2001). The processes regulating the P release and retention at the sediment-water interface in the Gulf of Finland have, however, been studied during recent years (Conley et al. 1997, Lehtoranta 1998, Carman et al. 2000, Edlund & Carman 2001, Mäkelä & Tuominen 2003, Lehtoranta & Heiskanen 2003, Lehtoranta & Pitkänen 2003). It is evident that release of sediment P and the processes governing the release and binding of P at the sediment surface, which are mainly oxygen controlled, are of great importance for the trophic state of the Gulf.

Further, silicon (Si) and P can both be adsorbed to specific ligand exchange sites at particle surfaces (Hingston et al. 1967, Hartikainen et al. 1996), and it has been shown that large amounts of Si in fact may enhance the release of P from the sediment to the water column. Silicon may also, like P, be released from the sediment under both oxic and anoxic conditions, but both the distribution of potentially bio-available forms of Si in the sediments and the effects of different levels of oxygen concentration on the benthic mobility of Si are very poorly known. Also, the external loading of Si into the Baltic Sea has been shown to decrease, not increase (Rahm et al. 1996), emphasising the potential role of internal loading of Si.

The main objective of SEGUE-P was to investigate the effects of varying environmental conditions and sediment variables on the spatial sediment accumulation of for settled P and Si in the Gulf of Finland. We quantified the potentially mobile versus the permanently buried P and Si pools in the sediments using sequential extraction (fractionation). Sediment samples were taken in 2002–2004 from Paimionlahti Bay (Archipelago Sea), Ahvenkoskenlahti Bay and the open Gulf (Fig. 3.1).

3.1 Development and comparison of phosphorus fractionation methods

Kaarina Lukkari and Mirja Leivuori

Chemical fractionation is a common method for studying different binding and solubility forms of sediment P. However, there are several schemes that use different extraction solutions and the results thus depend on the method. The method chosen for investigating the sediment P sources in the Archipelago Sea, in the Gulf of Finland, and in two estuaries is described in Jensen & Thamdrup (1993). The method separates six P forms (Table 3.1): pore-water P or loosely bound P (referred to as NaCl-iP), P bound to reducible iron (Fe) (and manganese (Mn); NaBD-iP), transformable organic or biogenic P (NRP), P bound to oxides of non-reducible metals (e.g. aluminium; NaOH-iP), apatite-P (HCl-iP), and residual P (Res-P) which is mainly recalcitrant organic P. The method is a modification of that presented by Psenner et al. (1984) and it was slightly modified further and tested for our studies. Testing the method with commercial reference material proved its good reproducibility (Lukkari et al. submitted a) and sampling and storing practices that were tested with fresh sediment samples using shielding with nitrogen atmosphere were found to be appropriate (Lukkari et al. submitted b). The main failing of the fractionation method used seemed to be its inability to accurately discriminate between P bound to Al and Fe oxides. However, elemental analysis of the extracts gave indirect evidence of the importance of both metal oxides in the binding of P in the estuary sediments that received eroded clayish material from fields (Lukkari et al. submitted c). The biogeochemistry behind the fractionation method and the relevancy of the extraction scheme is discussed further in Lukkari et al. (submitted a, b, and c).

Ruttenberg (1992) presented a fractionation scheme that has been widely used for investigating P in marine sediments, also in the Baltic Sea (the Archipelago Sea, Virtasalo et al. 2005). It was compared with the Jensen & Thamdrup (1993) method (Lukkari et al. in prep. a) to find out which of the methods was better for investigating the non-calcareous, humic rich sediments in the Gulf of Finland and whether the methods gave identical results. The two fractionation methods yielded rather similar results in total contents of extractable P (TP_{extr}) and organic P, but the Ruttenberg (1992) method resulted in slightly higher content for Fe-bound P. Generally, the results were promising, as it seems that despite the differences in these extraction schemes, at least the concentrations of TP_{extr} and organic P (to some extent also Fe-bound P) are comparable. The effect of freeze-drying, the common storing method used with sediments, on different P fractions was also studied and seemed to cause a slight overestimation in the share of Fe-bound P, mainly at the expense of organic P forms (Lukkari et al. in prep. a).

In addition to testing the fractionation method, two laboratory experiments were carried out in co-operation with SEGUE-N and another BIREME project, BITIS. Shortly, the first experiment showed the fast response of the pore-water (loosely bound) P and redox sensitive P to fluctuating O_2 conditions (Hietanen and Lukkari submitted). The second experiment demonstrated the effects of bioturbation on sediment P forms: an initial release of pore-water P, and later, an improvement in the ability of the sediment surface to trap released P (Hietanen et al. submitted).

Table 3.1. Outline of the P fractionation procedure (table from Lukkari et al. submitted b)

Step	Extractant	Separated P fraction
I	Sodium chloride, NaCl	Porewater P, loosely sorbed P (NaCl-iP)
II	Sodium dithionite + sodium bicarbonate, NaBD	P bound to oxides of redox sensitive metals, Fe and Mn (NaBD-iP)
III	Sodium hydroxide, NaOH	P from oxides of non-reducible metals, mainly aluminium (Al) (NaOH-iP) and transformable organic/biogenic P (NRP)
IV	Hydrochloric acid, HCl	Apatite-P (HCl-iP)
Ignition of the sediment residue: 2 h at 550 °C		
V	Hydrochloric acid, HCl	Residual P, mainly refractory organic P (Res-P)

3.2

Sediment phosphorus forms in the study area

Kaarina Lukkari and Mirja Leivuori

Jensen et al. (1995) coarsely divided the six P fractions described above into mobile and immobile P. The pore-water P (loosely sorbed P), P released with chemical reductant (NaBD), and the transformable organic or biogenic P were considered "mobile" P forms. However, only the dissolved PO_4-P and P in some other small molecules are directly available for marine primary producers and bacteria. The redox-sensitive P needs to be released as PO_4-P from the Fe-compounds by reduction of Fe(III), and the transformable organic P compounds need to be degraded to liberate PO_4-P. Furthermore, a substantial amount of such "mobile" P forms were also found in the deepest sediment layers studied. This is partly a consequence of the unspecificity of the extractants, but also a consequence of biogeochemical processes occurring in the sediment. Thus, the term "transformable" is preferred instead of "mobile". The "immobile" P forms include P bound to non-reducible metal oxides, apatite-P, and

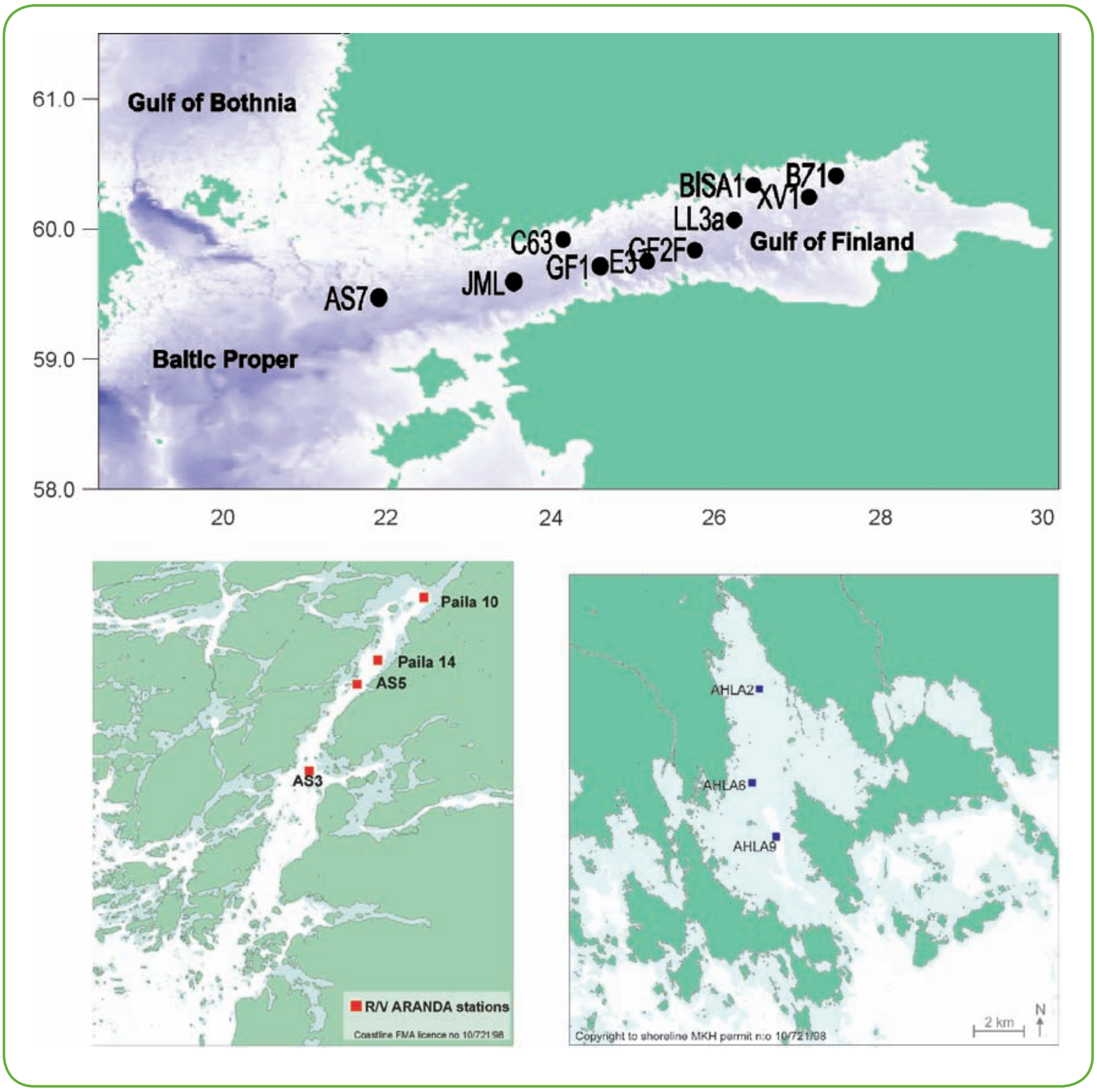

Fig. 3.1. Map of the sampling sites in sediment P fractionation studies.

P in recalcitrant organic material. Accordingly, the transformable part of sediment P can, under favorable circumstances, be transformed into P that is available for marine primary producers and bacteria, while the immobile P is buried with the sediment and removed from the nutrient cycle.

The composition of sediment P at the studied sites (Fig 3.1) showed considerable spatial and vertical variation (Lukkari et al. submitted c, Lukkari et al. in prep. b, c). The concentration of TP_{extr} was up to 2.1 mg g^{-1} dry matter (DM) in the oxidized estuary sediment in Paimionlahti Bay and up to 3.5 mg g^{-1} DM in Ahvenkoskenlahti Bay. In the central Gulf of Finland, TP_{extr} was up to 1.5 mg g^{-1} DM in reduced and 2.8 mg g^{-1} DM in oxidized open sea sediment. In the organic rich sediments of the eastern Gulf, TP_{extr} was up to 3.8 mg g^{-1} DM. At most sites, about half of the TP_{extr} consisted of transformable P and the total amount of organic P was considerable. Of the *immobile forms*, HCl-iP and NaOH-iP were almost stable and Res-P was stable or decreased slightly with sediment depth. Despite their similar concentrations among the sites, the share of Res-P and HCl-iP of TP_{extr} in the sediment increased towards the open sea. Spatial and vertical differences were more apparent in the *transformable P*, in NaBD-iP and NRP, while NaCl-iP was small. NRP usually decreased slightly with sediment depth, suggesting slow degradation of some organic P compounds. It clearly increased eastwards in the Gulf, coinciding with the high content of organic matter in the sediment. NaBD-iP generally decreased sharply in the depth profile with decreasing redox-potential in the subsurface layers and was higher in the coastal area, diminishing towards the open sea with decreasing oxygen concentration in the near-bottom water.

When evaluating the share of sediment P that will be permanently buried, the minimum concentration of transformable P buried in the studied depth profile at each site was taken into account to make the calculations more accurate (Lukkari et al. submitted c). Figure 3.2 represents these corrected concentrations, termed as potentially mobile P, in the sediment surface in different areas in the Archipelago Sea and in the Gulf of Finland. In other words, depending on prevailing conditions, the areas with the biggest spots in the map can be the most sensitive for release of P from the sediment. Phosphorus can be released slowly as a result of degradation of P-containing organic compounds or rather quickly from Fe-compounds, if formerly oxidized sediments turn reduced. Transformable P was highest near the NE coast of the Gulf, i.e. in the area with sediments rich in organic matter. On the other hand, some sites in the central Gulf showed high transformable P in the surface (high NaBD-iP)

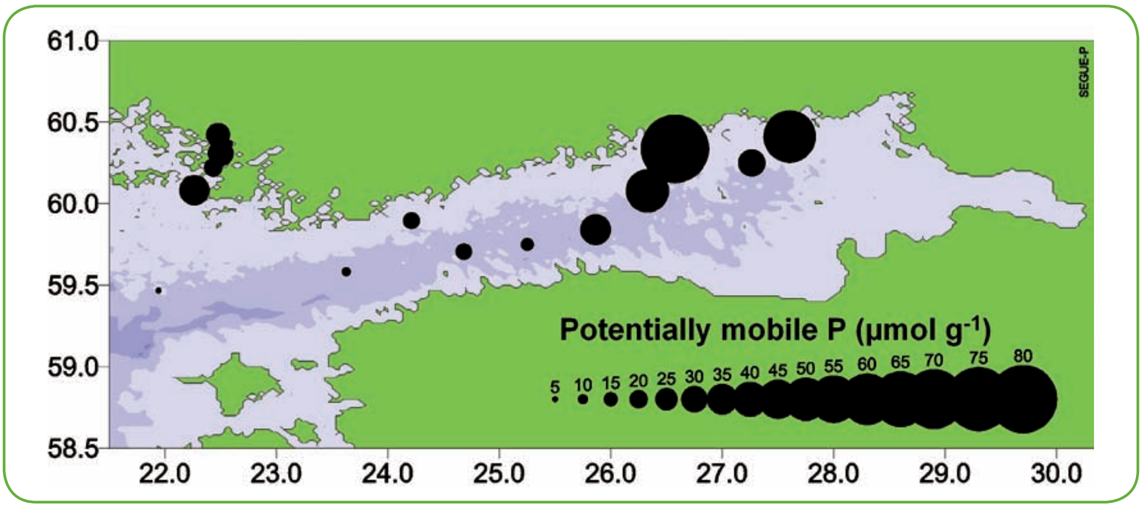

Fig. 3.2. Concentrations (µmol g^{-1} dry sediment) of potentially mobile P in surface sediment layers in the study area (Lukkari et al. submitted c, Lukkari et al. in prep. b, c). 1 mol = 30.97 g P.

despite reduced conditions during sampling. This may have partly resulted from dissolution of easily hydrolysable organic P compounds.

When the concentration of potentially immobile P in the surface sediment layer is used as an approximate share of the permanently buried part of the annually deposited P at each site, the burial fluxes of P in the whole study area range from 155 to 6474 mg P $m^{-2}y^{-1}$ (Lukkari et al. submitted c, Lukkari et al. in prep. b, c). Burial fluxes of P were highest in the coastal areas and estuaries with high sedimentation rates, although those sediments were rich in transformable P. In these areas, transformable P in the surface sediment was mostly Fe-bound P. Under the conditions that prevailed during sampling they were able to retain P, but they are the most vulnerable areas for release of sediment P if conditions turn from oxidized into reduced. Some coastal areas of the Gulf have been subject to reduced conditions (Vallius 2006). During our sampling cruises, the deepest open sea areas, especially in the western Gulf, were reduced and showed no Fe-bound P in the sediment, probably due to lack of active sorption components. The burial flux of P was high in these open sea areas since they were rich in immobile P and had low sedimentation rates.

The areas rich in organic matter and organic and biogenic P, i.e. the sediments in the NE Gulf, were those with the lowest burial fluxes of P. These sediments also contained some Fe-bound P sensitive to oxygen depletion, but most of the transformable P in the surface layer was organic or biogenic P that can be partly degraded. Microbiological degradation of organic matter containing P can occur either under oxidized or reduced conditions and sediments may consequently slowly release substantial amounts of P. It has been evaluated that in brackish water sediments, the half lives of some organic and biogenic P compounds may vary from a few years to a couple of decades (e.g. Ahlgren et al. 2005). Released PO_4-P may be incorporated into algal and bacterial cells or trapped into oxidized Fe compounds in the surface sediment, but part of it may end up in the water column, driven e.g. by bioturbation (Hietanen et al. submitted). Our results showed that the share of organic P in the Gulf of Finland sediments is considerable (Lukkari et al. in prep. b, c), which may partly explain the high release of sediment P in the Gulf and the slow response of the system to decreases in the external P loading. Organic P in the sediments originates from the autochthonic production in the Gulf of Finland, but also partly from the terrestrial environment (Stepanauskas et al. 2002). It is thus important to diminish external P loading and loading of organic matter and to prevent further expanding the reduced sea areas.

3.3

Applicability of a sequential phosphorus fractionation procedure to silicon

Petra Tallberg, Kaarina Lukkari and Antti Räike

Biogenic Si bound into live or empty diatom shells is normally the main pool of potentially bio-available Si in water ecosystems. Some potentially bio-available Si is, however, also found (ad)sorbed to particle surfaces or in relatively easily dissolved mineral Si fractions. In this study, we examined different potential analytical methods for BSi. We also tested whether a P fractionation procedure (Jensen & Thamdrup 1993) could be applied to study potentially mobile (=bio-available) forms of Si as well. Silicon and P can both be adsorbed to specific ligand exchange sites at particle surfaces (Hingston et al. 1967, Hartikainen et al. 1996). It has also been shown that large amounts of Si may in fact enhance the release of P from the sediment to the water column. A method which explores the binding mechanisms of both elements simultaneously would facilitate the study of this phenomenon. Also, any process which increases the release of P from the sediment into the water column is, naturally, of supreme importance in the eutrophication of e.g. the Gulf of Finland. Due to the extremely laborious nature of sediment fractionation procedures, it would, further, be cost-effective to be able to use the same procedure for two elements.

The P fractionation procedure used in this study is described in detail by Lukkari et al. (submitted a, section 3.1.). The analysis of biogenic Si follows DeMaster (1981) and Conley (1998; for more data, see Tallberg et al. submitted). The reliability of the BSi protocol for Gulf of Finland sediments was verified by calibrations with the SIBER project (National Environment Research Institute, Denmark, and Institute of Aquatic Ecology, Latvia). The same sediment samples (Gulf of Finland samples) were used as in the P part of the study (section 3.2.); in addition, some samples of either very high or low BSi content were used (Tallberg et al. submitted).

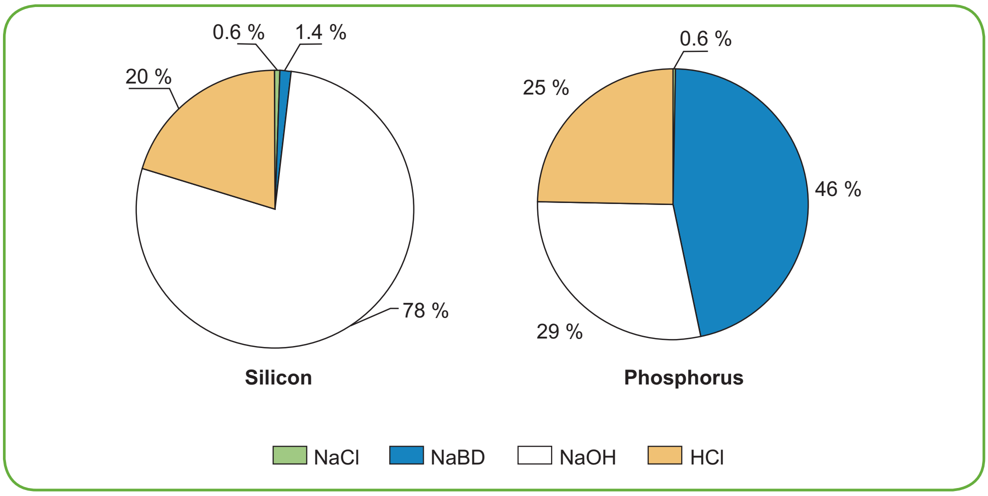

Fig. 3.3. The relative distribution of total dissolved P and Si between the pools extracted by the fractionation procedure (Tallberg et al. submitted). The values are averages from sediment samples from the estuarine Gulf of Finland (n=76).

The distribution of Si and P between the respective potentially mobile pools did, unfortunately, not follow the same pattern (Fig. 3.3, Tallberg et al. submitted). As the results from sediment samples of high respectively low biogenic Si content showed, the P fractionation procedure could not reliably separate biogenic Si and adsorbed Si fractions (Fig. 3.4). Most, but not all, of the biogenic Si in the samples was extracted by NaOH (see section 3.1.), but all Si extracted by NaOH was not found in the biogenic Si pool. The study showed, however, that the HCl-extractable, predominantly minerogenically bound and not easily mobilized pools were of similar relative size for both elements. Silicon is normally a much more abundant element is sediments, and the absolute amount of Si was thus higher.

The study also showed that the amount of Si released under strongly reducing circumstances simulated by the NaBD-extraction is low. This strongly contrasts with what is found for P, and shows that anoxic conditions in e.g. the bottom waters of the Gulf of Finland are not likely to release high amounts of Si from the sediments into the water column. Consequently, increased eutrophication in the Gulf does not include any switch-back mechanism at the sediment surface which would drastically increase the internal loading of Si from the sediment to compensate for observed decreases in external loading (e.g. Rahm et al. 1996).

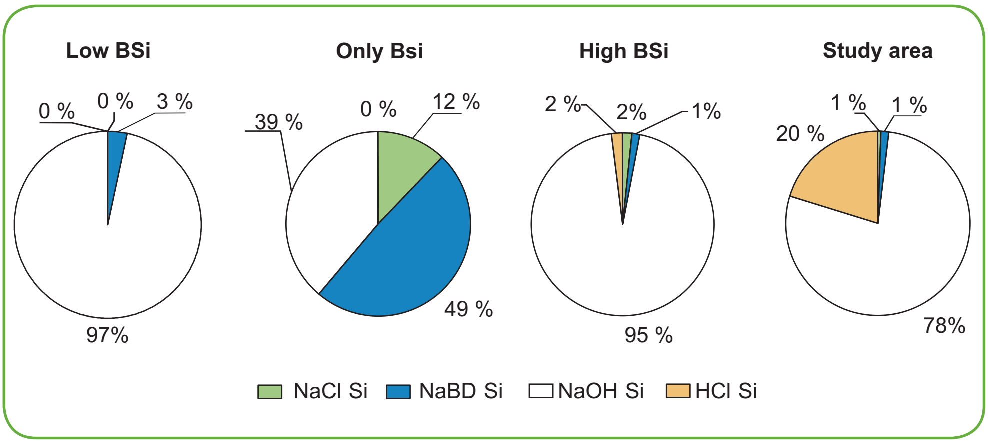

Fig. 3.4. The distribution of Si between four sequentially extracted sediment pools, NaCl-, NaBD-, NaOH- and HCl-extractable Si, in a sand sample (Low BSi), a sample of fresh diatom material (Only BSi), a sample of surface sediment from the Southern Ocean (High BSi) and sediment samples from the Gulf of Finland (samples from study area, see Fig. 3.1). Data from Tallberg et al. (submitted).

3.4

Potentially mobile silicon pools in the Gulf of Finland: implications for retention and burial

Petra Tallberg, Antti Räike and Kaarina Lukkari

Biogenic Si was overwhelmingly the most important potentially mobile Si pool in the entire study area (Fig. 3.5). The vertical differences were small. Only in the profundal zone, where the sedimentation rates are lower and the studied period covered somewhat longer, lower concentrations of BSi were found below 15 cm sediment depth. This phenomenon has been attributed to the increased eutrophication and, consequently, production and sedimentation of diatoms in the Baltic Sea during the past century (http://siber.ecology.su.se). BSi does, however, also undergo diagenetic changes within the sediment, and this is responsible for some "loss" of BSi with burial time and sediment depth (e.g. Gallinari et al. 2002 with references). The loosely bound, very easily mobile pool of Si represented by NaCl-Si was, for similar reasons, slightly higher in the very surface sediment layer, as was also the potentially anoxia-sensitive NaBD-Si.

The concentration of BSi in the sediment was clearly higher in the Eastern than in the Western Gulf and in the deep-sea area compared to in the estuaries. The concentrations in Paimionlahti Bay were i.e. also clearly lower than in Ahvenkoskenlahti Bay (Fig. 3.5, Tallberg et al. in prep.). High concentrations of (B)Si were accompanied by high concentrations of TC and TN in the sediment (data not shown), and it seems probable that the reason for the higher BSi content is closely related to the more eutrophic state of the eastern Gulf.

Despite the higher concentration of mobile Si in the sediments in Ahvenkoskenlahti Bay, more Si was retained by the sediment in Paimionlahti Bay (ca 36 g m^{-2} d^{-1}) than in Ahvenkoskenlahti (16 g m^{-2} d^{-1}; Tallberg et al. in prep.), primarily due to the higher sedimentation rate in Paimionlahti. Since the external load of Si to Ahvenkoskenlahti Bay (ca 7000 t a^{-1}) is much higher than for Paimionlahti (ca 1500 t a^{-1}), Paimionlahti Bay retained Si efficiently while Ahvenkoskenlahti Bay did not.

On a Gulf of Finland scale, our preliminary results indicate that BSi is buried in the sedimentation area in the profundal sediment at a yearly rate of ca 210 kt a^{-1} of

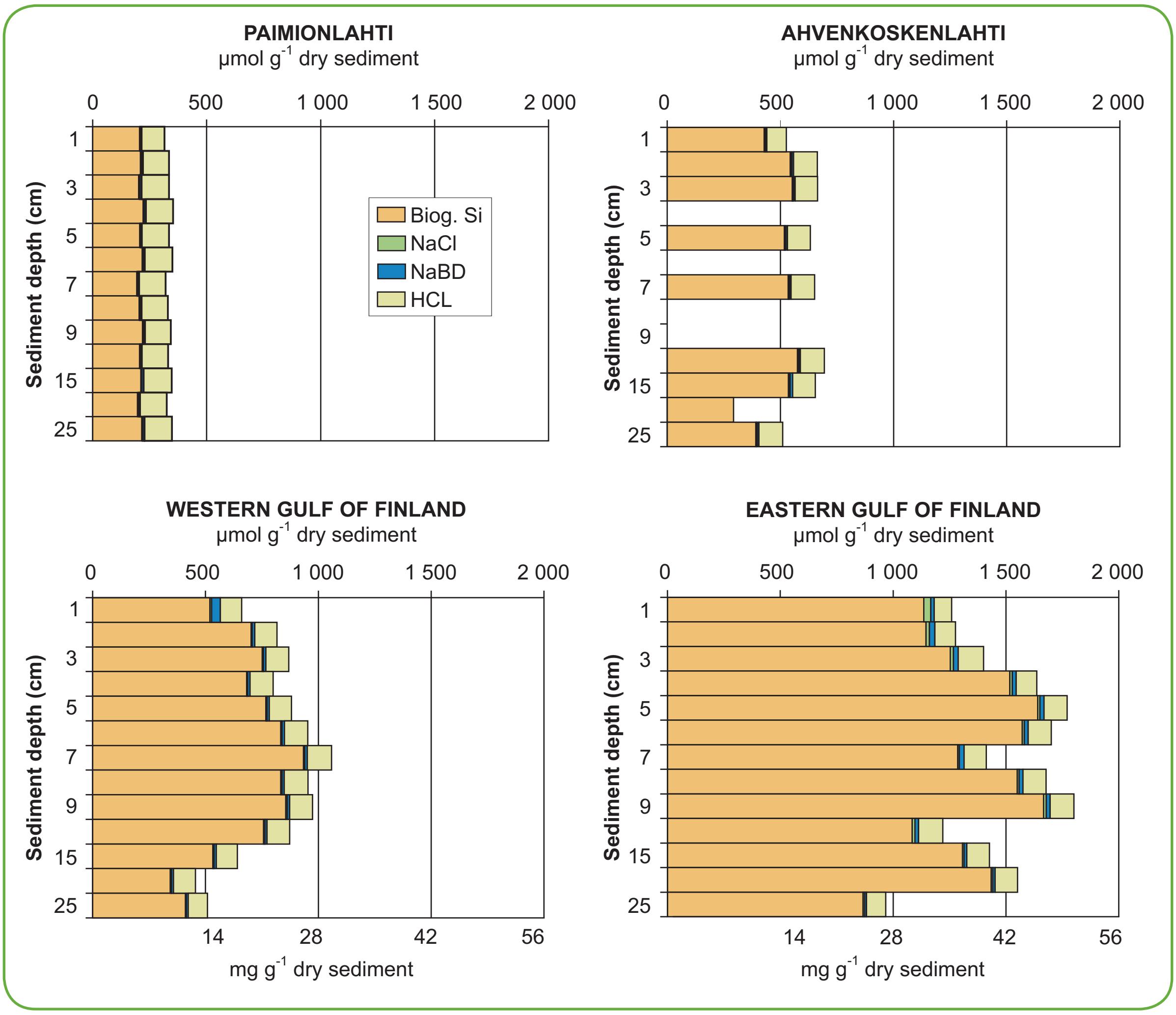

Fig. 3.5. The vertical distribution of biogenic Si (BSi) and three fractionation pools, NaCl-Si, NaBD-Si and HCl-Si, in sediment samples from different parts of the Gulf of Finland. 1 mol = 28.09 g Si. Data from Tallberg et al. (in prep.).

Si (range 90–440 kt a^{-1} Si, Tallberg et al. in prep.). Compared to the total riverine load of Si into the Gulf (ca 60 kt a^{-1}, http://siber.ecology.su.se/) this is a very high value. Although some potential sources of Si are not included in this estimate (e.g. diffuse and internal loading and the water exchange with the Baltic Proper), the Gulf of Finland sediment seems to be a significant sink for Si. Since the external loading of Si to the Baltic Sea shows a decreasing trend (Sandén et al. 1991, Rahm et al. 1996) while the burial rate is likely to increase if eutrophication proceeds (e.g. Conley et al. 1993), the burial of BSi may in the future be a pivotal contributing factor to decreasing Si concentrations in the water column. This may, in turn, lead to Si-limitation of the diatom community and, ultimately, favour other, potentially more harmful algal species. Decreased availability of Si in spring may, however, also lead to decreasing sedimentation of organic material and concomitantly diminish the risk of reduced conditions at the sediment surface and redox-sensitive release of P. The vernal phytoplankton bloom, which is responsible for most of the annual biomass production in the Northern Baltic Sea, consists almost exclusively of either diatoms or dinoflagellates. Of these, diatoms are much more prone to sediment out of the water column (Heiskanen 1998).

3.5
Conclusions

- Chemical characterization of sediment phosphorus in the Gulf of Finland and in the Archipelago Sea showed spatial and vertical variability of different phosphorus forms. Iron-bound phosphorus sensitive to oxygen depletion was most abundant in the oxidized surface sediments in the estuaries and in the coastal areas of the Archipelago Sea and the northern Gulf. Under the environmental conditions that prevailed during sampling, these sediments were able to retain phosphorus, but if conditions turn reduced, they can release phosphorus from the sediment to the overlying water.
- The fractionation studies of sediment phosphorus revealed relatively high amounts of organic or biogenic phosphorus, especially near the north-east coast of the Gulf of Finland. The organic or biogenic phosphorus pool can slowly release phosphorus from the sediment as a result of degradation of organic matter occurring both under oxidized and reduced conditions. This may, in addition to the poor oxygen conditions in the Gulf, partly explain the high release of P from sediment and the slow response of the Gulf of Finland to the decline in anthropogenic loading of phosphorus.
- Sea areas where sediments are rich in either iron-bound phosphorus or organic or biogenic phosphorus are the most sensitive for release of sediment phosphorus, especially under declining oxygen conditions. It is thus important to diminish the external phosphorus loading and prevent further accumulation of organic matter. It is also important to try to prevent further expanding the reduced sea areas in the Gulf of Finland.
- The studied sediments bind silicon efficiently under reduced circumstances, which contrasts strongly with what is found for phosphorus. Accordingly, no switch-back mechanism at the sediment surface which would drastically increase the internal loading of silicon from the sediment to compensate for the observed decreases in external loading is apparent.
- The concentration of potentially mobile silicon in the Gulf of Finland sediments is determined by the content of biogenic silica, and the highest concentrations are found in profundal sediments in the open, eastern Gulf. These differences in sedimentary, potentially mobile silicon content are driven by eutrophication, which increases the sedimentation of organic material and biogenic silica.
- Although the concentration of potentially mobile silicon in the sediment was lower in the west than in the east, more silicon was retained by Paimionjoki estuary, where the overall sedimentation rate was high, than by Ahvenkoskenlahti Bay in the Kymijoki estuary, where runoff is high.
- The burial rate of biogenic silica in the profundal Gulf of Finland is high compared to the external loading of silicon.

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4 Benthic nitrogen removal in the Gulf of Finland

Susanna Hietanen

Nitrogen (N) entering the bottom ecosystem flows through different mineralisation pathways, all of which are microbially mediated (Fig. 4.1). **Denitrification**, the sequential reduction of nitrate to nitrogen gas, is a process that removes N from the water ecosystem. Mass balance calculations (Perttilä et al. 1995) and ecosystem models (Kiirikki et al. 2006) indicate that about 70 000 t N is denitrified in the Gulf of Finland annually. Denitrification has been extensively measured on open sea accumulation bottoms (Tuominen et al. 1998). However, the rates measured were lower than predicted, and denitrification was calculated to remove only 45 000 t of N from the Gulf of Finland annually. This estimate was based solely on measurements done on open sea accumulation bottoms, assuming that denitrification proceeds at the same rate throughout the whole basin. The shallower, coastal areas were hypothesized to be sites of more intense denitrification due to the differences in e.g. temperature and nitrate and carbon input, but no data had so far been published concerning coastal denitrification in the Gulf of Finland, except from the inner Neva estuary, where it was found to be very low (Gran & Pitkänen, 1999).

Another process which removes fixed N from the water ecosystem, anaerobic ammonium oxidation (anammox), has recently been shown to be active in marine sediments (Dalsgaard & Thamdrup 2002, Thamdrup & Dalsgaard 2002, Trimmer et al. 2003). No information about the importance of this process, in which ammonium is oxidized with nitrite to form gaseous N, was available from the Baltic Sea.

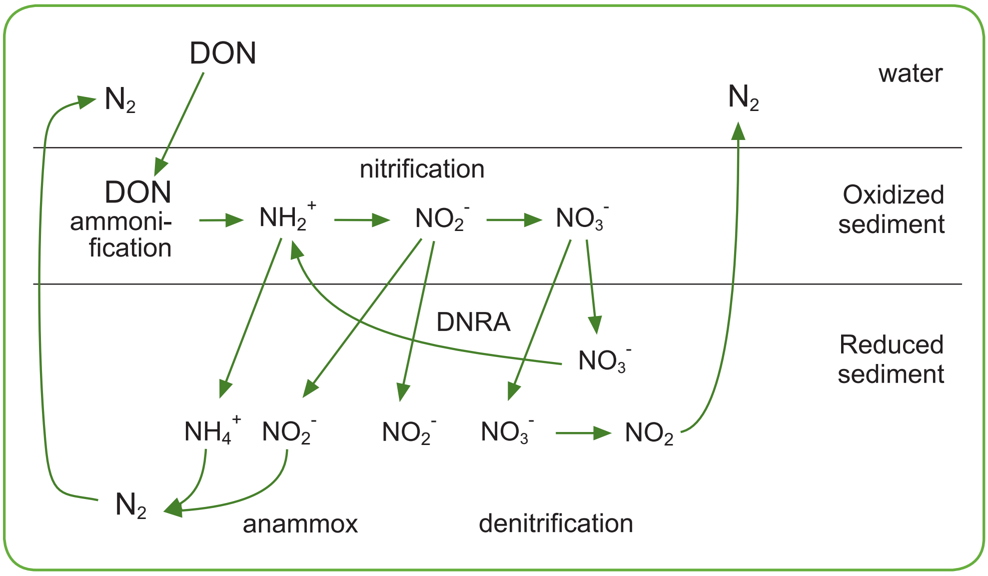

Fig. 4.1. Nitrogen pathways in the sediment. DNRA: dissimilatory nitrate reduction to ammonium, anammox: anaerobic ammonium oxidation. NO_2^-: nitrite, NO_3^-: nitrate, NH_4^+: ammonium, DON: dissolved organic nitrogen, N_2: molecular nitrogen.

We studied the seasonal and short term variation of N removal at a coastal station in the northern Gulf of Finland (Storfjärden). Denitrification was measured in May, August, October and December 2003 and in April 2004. The contribution of anammox to total N reduction was estimated in May and August. In addition, experiments were made to study the factors controlling the processes.

4.1

Seasonal variation of and controlling factors for coastal nitrogen removal

Susanna Hietanen, Jorma Kuparinen, Ari Laine and Kaarina Lukkari

The N_2 production rates, which were 1.3–5.6 mg N m^{-2} d^{-1} at the studied coastal accumulation bottom (Storfjärden), were slightly lower than the rates measured in the central Gulf of Finland (1.4–9.1 mg N m^{-2} d^{-1}, Tuominen et al. 1998). The N_2 production, of which **denitrification** contributed 85-90%, followed an annual cycle similar to that in the open sea areas, with low spring values and higher late summer, early winter rates (Fig. 4.2). In addition to the **temperature**, which explained ca 40% of the annual variability in the denitrification rates, the variation was strongly related to mineralisation of the settled spring diatom bloom, the main **carbon** source to the sediment in the basin studied. The availability of **nitrate** in the bottom water had only minor effects on the denitrification rate. While the uncoupled denitrification was enhanced by higher nitrate concentrations, the amount of total denitrification was closely connected to the nitrate formed by nitrification in the sediment. Nitrification, in turn, is largely regulated by **O_2 availability** in the sediment, and therefore the anoxic denitrification process does not simply increase with a decreasing O_2 concentration. However, in Storfjärden, the oxygen deficiency in August (3.0 mg l^{-1}, 23% of saturation) did not block nitrification, as the denitrification values were high in August. (Hietanen & Kuparinen 2007).

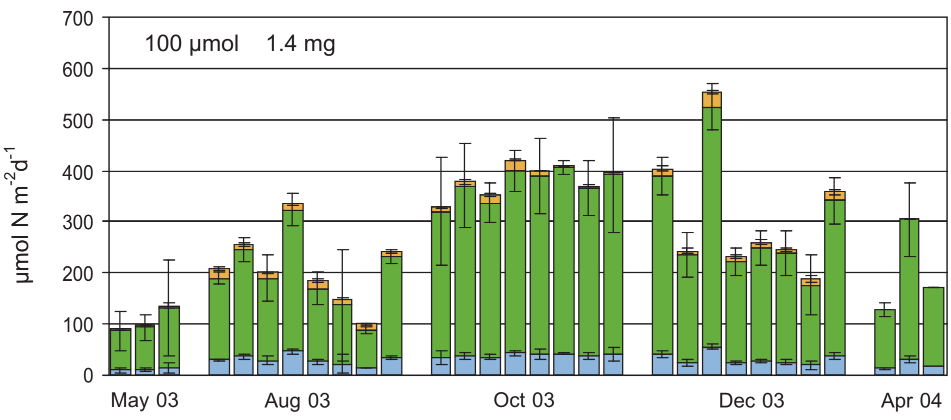

Fig. 4.2. Seasonal and daily variation in the N_2 production rate (µmol N m^{-2} d^{-1}) in a coastal accumulation basin (Storfjärden). Orange columns: anammox, green columns: coupled nitrification-denitrification, blue columns: denitrification based on water column nitrate. Figure modified from Hietanen & Kuparinen (2007).

An earlier exposure to low oxygen concentrations or even anoxia has been found to cause adaptations in nitrifying communities so that bacteria repeatedly experiencing such conditions have higher affinity towards O_2 than bacteria from permanently oxic environments (Bodelier et al. 1996). That this was also the case in the Storfjärden area was confirmed in experiments in which anoxia was imposed on sediments for 2.5 weeks. The denitrification rates were found to be less sensitive to oxygen deficiency than expected. Nitrification did not cease totally during a 17 day nearly anoxic incubation, but the layer of activity probably narrowed towards the more suitable conditions at the surface sediment, indicating that the nitrifying communities of the muddy accumulation bottoms are well adapted to seasonal anoxia. The pulses of oxygen, first in the beginning of the experiment and then on day 12, were efficiently used, and after a shift from anoxic to oxic conditions the coupled nitrification-denitrification rate was restored to the same level as in the permanently oxic aquariums in only a few days. In our experiments, the switch from oxic conditions to anoxia in the water column was very sudden, only a matter of minutes, whereas in nature the oxygen concentration decreases slowly in the course of several weeks, leaving the microbes time to adjust to changing conditions. In contrast, the re-oxidizing of the bottom waters in the study area happens relatively fast as a result of the autumn turnover, and the response in the processes is probably as fast in nature as it was in the experiments reported here. According to these results, the nitrification-denitrification system in the study area is highly flexible, and denitrification proceeds unaffected at least two weeks after the beginning of anoxia (Hietanen & Lukkari 2007).

Bioturbation enhances nitrification activity by increasing surfaces with access to both ammonium and oxygen (Pelegri and Blackburn 1994, Svensson et al. 2001, Tuominen et al. 1999). Due to enhanced nitrification, the denitrification rate generally increases in the presence of benthic animals, too (Svensson & Leonardson 1996, Pelegri & Blackburn 1994, Hansen & Kristensen 1998, Bartoli et al. 2000, Svensson et al. 2001), although this effect is not always clear (Tuominen et al. 1999). We studied the effect of the polychaete *Marenzelleria* spp. (Polychaeta, Spionidae), a non-indigenous species rapidly increasing in the Baltic Sea, on denitrification rates. At a population density corresponding to about half of the highest measured in the northern Baltic Sea, no effect of *Marenzelleria* spp. on denitrification could be recorded. As the earlier dominant species of the area, *Monoporeia affinis*, has been shown to enhance denitrification (Tuominen et al. 1999), the replacement of *M. affinis* with *Marenzelleria* spp. might lead to decreased denitrification, increasing the ammonium flux to the water column. However, in the long run, the sediment reworking by the *Marenzelleria* spp. also oxidizes the surface sediment, improving its ability to support nitrification. Therefore, the impact of *Marenzelleria* spp. on sediment nitrogen cycling may not be as drastic as the initial reactions seen in our experiments suggest (Hietanen et al. 2007).

4.2 Anammox in the Gulf of Finland

Susanna Hietanen and Jorma Kuparinen

In this project, the existence of anaerobic ammonium oxidation, anammox, was explored for the first time in the Gulf of Finland. Anammox was found to produce 10–15% of the total N_2 production at our coastal intensive study station. The calculated contribution of 10–15% caused a dramatic 80–150% overestimate in the N_2 production when using the classical isotope pairing technique (IPT) due to the high labelled nitrate concentration used. Coastal anammox was also studied in the Ahvenkoskenlahti Bay estuary sediment where no anammox could be detected, indicating spatial variability of the process. In the open sea, anammox was found at both of the stations studied, one at the entrance to the Gulf of Finland and the other in the middle of the Gulf. There, anammox contributed up to 20% of the total N_2 production (Hietanen 2007).

However, in addition to denitrification and anammox, DNRA, dissimilatory nitrate reduction to ammonium, was also found to be active in the Gulf of Finland, further complicating the calculations and possibly causing bias in the N_2 production rate estimates. DNRA is usually considered to be of minor importance in natural sediments, and to occur mainly in organically enriched environments, such as fish farm sediments (Hattori 1983, Christensen et al. 2000). However, Karlson et al. (2005) found that DNRA represented a major pathway of nitrate removal in laboratory experiments in which reduced Baltic Sea sediments were used. As DNRA was not directly measured in our experiments, the extent of the bias in the measured rates cannot be calculated.

The low contribution of anammox to the total N_2 production in the study area may result from its low nitrate/nitrite concentration, which usually never exceeds 0.14 mg l^{-1}; in the eastern end of the Gulf of Finland higher nitrate/nitrite concentrations are common. The slow-growing anammox bacteria compete for nitrate/nitrite with heterotrophic nitrate/nitrite reducers (e.g. denitrifiers). At low nitrate/nitrite concentration (below 0.14 mg l^{-1}), not only the relative contribution, but also the absolute rate of anammox diminishes (Trimmer et al. 2005). In the coastal accumulation area, the increase in both the relative contribution and the absolute rate of anammox from May to August was possibly related to a small increase in nitrate/nitrite concentration (from 4.2–19.6 µg l^{-1}), an increase in the temperature (from 2 to 3 °C), or to the coincident drop in the oxygen concentration (from 10.6 to 3.0 mg l^{-1}). In the open sea sediments of the Gulf of Finland, temperature is rather stable year round. Both the nitrate/nitrite and oxygen concentrations fluctuate, however, and show remarkable year-to-year variation due to the complicated hydrodynamic nature of the area. This environmental instability may also have an impact on the anammox activity by keeping the populations of the slow-growing anammox bacteria low, while the faster growing heterotrophic denitrifiers can seize the opportunity when it arises (Rysgaard et al. 2004, Dalsgaard et al. 2005).

The discovery of anammox in the Gulf of Finland has larger ramifications for our view of the nitrogen budget of the Gulf than one would expect from the low activity detected. The coexistence of anammox and denitrification compromises the central assumptions behind the IPT, and leads to overestimates of the N_2 production. This overestimation is positively related to the concentration of the label added to the system (Risgaard-Petersen et al. 2003). Since the mid-1990's, denitrification has been measured *in situ* as well as in laboratory experiments from sediments of the northern Baltic Sea using the IPT (Tuominen et al. 1998, Gran & Pitkänen 1999, Tuominen et al. 1999, Autio et al. 2003, Hietanen and Kuparinen submitted). In all these measurements, high concentrations of label have been used, based on a paper published in 1998 (Tuominen et al. 1998). There, it was stated that denitrification was saturated at 100 µM of label in the water above the sediment, and that using such an admittedly high concentration did not change the first-order kinetics of denitrification. The measured coupled nitrification-denitrification was plotted against the incubation concentration, but not statistically analysed, and the deviations from the line were either explained by the lack of oxygen or simply omitted as technical problems, due to the lack of theoretical explanation. The discovery of anammox in the Gulf of Finland sediments finally gives a plausible explanation to these unexpected results.

4.3

Nitrogen removal in river estuaries

Susanna Hietanen and Jorma Kuparinen

Estuaries have been suggested to be effective sinks for land-based nitrogen loading, reducing the load transported to the sea (Seitzinger 1988, Ogilvie et al 1997, Savage et al 2004). The few estimates of the filtering capacity published from the northern Baltic Sea seemed to challenge this view (Gran & Pitkänen 1999, Humborg et al 2003), and more data was needed to understand the capacity of these ecosystems to reduce the nitrogen load entering the sea. We measured denitrification rates in two estuary bays, Paimionlahti Bay in the Archipelago Sea (southern Gulf of Bothnia) and Ahvenkoskenlahti Bay in the Gulf of Finland. The rates measured were compared to the local nitrogen loading in order to estimate the filtering capacity of the estuaries.

Paimionlahti Bay is an estuary of the river Paimionjoki. The discharges of both freshwater and nitrogen compounds to the bay are remarkably pulsed, with half of the nitrogen loading reaching the estuary in April–May, and most of the other half late in

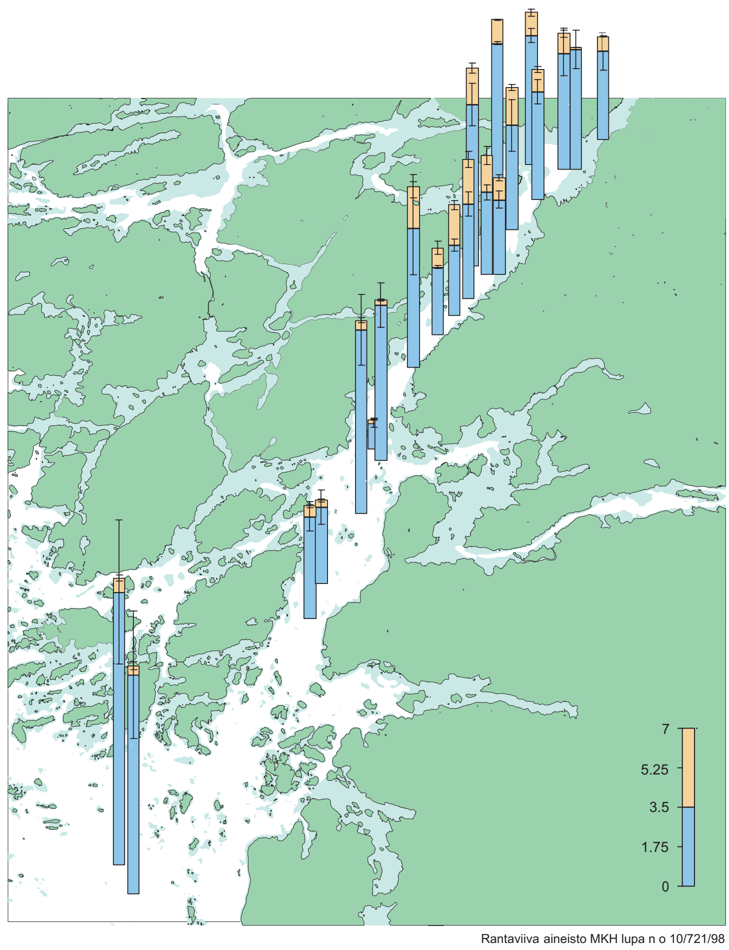

Fig. 4.3. Denitrification rates (mg N m^{-2} d^{-1}) in Paimionlahti Bay in August 2003. Blue columns: coupled nitrification-denitrification, orange columns: denitrification based on water column nitrate. Figure modified from Silvennoinen et al (2007).

the autumn. The flow is low in the summer months. In 2004, 1200 t N entered the bay, and nitrite/nitrate formed on average 75% of the total N loading. Ahvenkoskenlahti Bay is a semi-enclosed estuary receiving loading from a large river, Kymijoki, and a smaller river, Taasianjoki. The discharge, as well as the nitrogen loading, fluctuate only modestly from season to season, and are usually highest in April–May. The N loading was 4200 t in 2004, and on average 36% of the total N was in the form of nitrite/nitrate.

In Paimionlahti Bay, the denitrification rate varied tenfold within the estuary, from 1.3 mg N m^{-2} d^{-1} at one station in the middle to 12.7 mg N m^{-2} d^{-1} at the outer end of the estuary (Fig. 4.3). The denitrification rate in Ahvenkoskenlahti Bay varied from 3.2–4.5 mg N m^{-2} d^{-1} (Fig. 4.4). The two estuaries studied differed greatly from each other in their capacity to remove nitrogen entering the bay. In Ahvenkoskenlahti Bay denitrification removed only 1.4 % of the total nitrogen loading reaching the bay. In Paimionlahti Bay denitrification removed 19 % of nitrogen loading from the water.

According to our results, the estuary sediments are inefficient filters of the nitrogen load. This emphasizes the need for reduction of anthropogenic nitrogen loading to high latitude rivers and estuaries in order to avoid further eutrophication of susceptible sea areas (Silvennoinen et al. 2007).

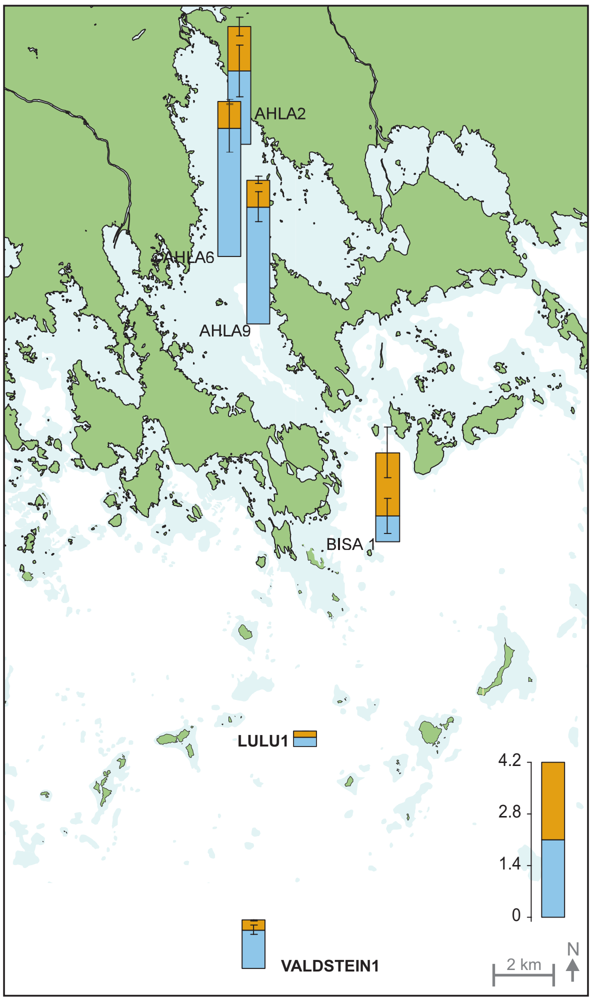

Fig. 4.4. Denitrification rates (mg N m^{-2} d^{-1}) in Ahvenkoskenlahti Bay in August 2004. Blue columns: coupled nitrification-denitrification, orange columns: denitrification based on water column nitrate. Figure modified from Silvennoinen et al. (2007).

4.4
Nitrogen balance of the Gulf of Finland

Susanna Hietanen and Jorma Kuparinen

As no data about the seasonal and spatial variability of anammox rates from the Gulf of Finland are yet available, the true N_2 production rates cannot be reliably estimated. Both N budgets and models, however, indicate that some 70 000–86 000 t N are removed from the Gulf of Finland annually (Perttilä et al. 1995, Savchuk 2005, Kiirikki et al. 2006). The N_2 production rates measured in this project give release to 39 100 t N annually, leaving 30 900–46 900 t N to be removed by other processes, or by more efficient N_2 production in some areas. As some of the highest N_2 production values have been measured from coastal and river estuarine basins, these seem likely places to start looking for the "mysteriously disappearing nitrogen". The high spatial and temporal variability in the sediment processes, caused by heterogeneity in the bottom topography, flow rates, environmental conditions and inter-annual changes in these, leave room for speculations. Obviously, there are still large gaps in our understanding of the nitrogen dynamics of the Gulf of Finland. Future research should include at least measurements from transportation and erosion sediments, as well as seasonal dynamics of the river estuary N_2 production. These may yet prove to be sites of more active N_2 production than the accumulation basins studied so far have been.

4.5
Conclusions

- Nitrogen removal from accumulation sediments near the coast and in the open Gulf of Finland are of similar magnitude – neither more efficient nor weaker near the coast.
- Seasonal variation in nitrogen removal is significant, with the lowest values recorded during early spring and the highest during late autumn. This variability is linked to the sedimentation and decomposition of organic matter. In the coastal areas, temperature has a large impact on the process rates.
- Spatial variability of nitrogen removal is high, even on a small scale.
- Estuary sediments are inefficient filters of the nitrogen load.
- In addition to denitrification, another nitrogen removing process, anaerobic ammonium oxidation (anammox) was recorded in the Gulf of Finland, and it challenges the earlier measurements made in the area. The extent of the bias remains to be estimated, but it may be remarkable (up to more than 100%).
- About 70 000–86 000 t N is removed from the Gulf of Finland annually. Denitrification and anammox give release to 39 100 t N annually, leaving 30 900–46 900 t N to be removed by other processes, the most important of which is probably burial in the sediments. The high spatial and temporal variability in the sediment processes, caused by heterogeneity in the bottom topography, flow rates, environmental conditions and inter-annual changes in these, leave room for speculations. Obviously, there are still large gaps in our understanding of the nitrogen dynamics of the Gulf of Finland.

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5 Ecosystem modelling as a tool for state forecasts

The basic objective of the modelling sub-project was to use the knowledge on nutrient processes produced in the other SEGUE projects, as well as other available and relevant data from the Gulf of Finland, in the testing and developing of the existing EIA-SYKE 3-dimensional (3D) model. Further, medium and long-term eutrophication forecasts were made for the case study area (the Gulf of Finland, the Archipelago Sea and the north-eastern Baltic Proper) with this model alone, as well as in combination with the SANBALTS 1D box-model developed under the Swedish MARE Project.

Four separate modelling experiments were done:

- Calibration and validation of a sediment-water nutrient flux sub-model suitable for 3D model simulations
- Testing the calculation of nutrient (nitrogen, N, and phosphorus, P) fluxes between the Baltic Proper and the Gulf of Finland with the 3D model
- Testing the 3D model with a hind-cast case of strongly decreased nutrient loads into the Gulf of Finland
- Testing the integrated use the SANBALTS box-model with the 3D model in order to produce long term (> 30 y) state scenarios with high spatial resolution.

5.1

EIA-SYKE 3D and SANBALTS ecosystem models

Heikki Pitkänen, Mikko Kiirikki, Oleg Savchuk and Fredrik Wulff

The main modelling tool of the present study, the EIA-SYKE 3D ecosystem model, is a combined hydrodynamic-biogeochemical model that has been developed for the Gulf of Finland (Kiirikki et al. 2001, 2003, 2006). To avoid boundary conditions close to the main target area, the model grid area covers the entire Baltic Sea, except for the southernmost Baltic and the Danish Straits. The horizontal resolution of the model is 5 km and it has 17 vertical layers.

In medium-term simulations the 3D-flows are first simulated for a 5-year calculation period (1995–1999) with the FINNFLOW model equipped with K-epsilon turbulence calculation (Virtanen et al. 1986, Koponen et al. 1992). FINNFLOW is a full baroclinic Simmons-type model applied in an Arakawa-E type grid. The ecosystem part (Kiirikki et al. 2001, 2006) is a Tyrrell-type approach with two algal groups, ”nitrogen fixers” and ”other phytoplankton” (Tyrrell 1999). In the model the carbon: nitrogen: phosphorus-ratio of both algal biomass and detritus follows the Redfield ratio 41:7.2:1 (by weight). The model includes a sediment module describing the exchange of nitrogen and phosphorus at the sediment-water interface under oxidized and reduced conditions. The ecosystem model has been calibrated using coastal and open sea monitoring data on nutrients and phytoplankton biomass from SYKE and FIMR.

For meteorological forcing of the FINNFLOW-model SMHI real analysis fields were used. The initial 3D fields for salinity, temperature and nutrients for the whole Baltic Sea were reconstructed with the Data Assimilation System (DAS) from observations found in the Baltic Environment Database (BED) at Stockholm University (Sokolov et al. 1997). The nutrient loads follow the Pollution Load Compilation (PLC) data of HELCOM (2002). In the case of the Gulf of Finland more precise information about the biologically available load was used (Kiirikki et al. 2003, Pitkänen et al. 2007). Depth-dependent sediment nutrient concentrations were obtained from the MARE Project. Before actual simulations, these sediment values were subjected to a 5-year spin-up run to produce more stable and reliable concentration fields for the final calculations. The 3D ecosystem simulations were forced by measured water temperatures instead of simulated temperatures to avoid cumulative errors. Sediment resuspension takes place in the model simulation when the near bottom velocity exceeds 10 cm s^{-1} (Huttula 1992).

In the Decision Support System NEST developed within the MARE Project, the trophic status of the Baltic Sea is quantitatively described by a fairly aggregated biogeochemical box-model, SANBALTS (Savchuk & Wulff 2007, Wulff et al. 2007). This model simulates the coupled N and P cycles in the seven major sub-basins, considered as homogeneous boxes, on an annual scale. In these boxes, the dynamics of the N and P pools are driven by interactions between external nutrient inputs, inter-basin physical transports and internal biogeochemical fluxes. The external inputs comprise the basin-wise land-based nutrient loads and deposition from the atmosphere, as well as the nutrient import from the Skagerrak into the Kattegat. The physical transports are carried on by the water exchange between the basins, mixing between surface and deep layers in the Baltic Proper, and outflow from the Kattegat to the Skagerrak. The internal nutrient cycling in each sub-basin is driven by nutrient utilization for primary production, including nitrogen fixation by cyanobacteria, pelagic and benthic recycling, sedimentation, denitrification, and sediment burial.

In the present study the SANBALTS model was implemented in its steady state mode, where the model was run under constant external inputs and water flow until a steady state was reached (Savchuk & Wulff 2007, Wulff et al. 2007). Basin-wise concentrations and biogeochemical fluxes simulated by SANBALTS under contemporary nutrient loads corresponded well to observed concentrations and estimated fluxes (Savchuk & Wulff 2007). Moreover, a simulation made for the conditions assumed to occur a century ago matched historical data on water transparency and oxygen conditions quite well. This was also the case for existing estimates of the historical primary production and sediment processes (Savchuk, O. et al., personal communication).

5.2

Development of 3D ecosystem modelling for the Gulf of Finland: calibration and validation of the sediment-water interaction sub-model

Mikko Kiirikki, Jouni Lehtoranta, Arto Inkala, Heikki Pitkänen, Susanna Hietanen, Per O.J. Hall, Anders Tengberg, Jorma Koponen and Juha Sarkkula

The ecosystem of the Gulf of Finland is strongly dominated by benthic nutrient fluxes (Tuominen et al. 1998, 1999, Pitkänen et al. 2001, Lehtoranta 2003). These fluxes are highly sensitive to stratification conditions and the redox state of the sediment surface, and their successful modelling on a basin-wide scale requires a description in the model. On time scales of a few years, changes in benthic fluxes can be much higher than changes in the external loading (Conley et al. 2002). The present approach published in Kiirikki et al. (2006) shows that complex benthic nutrient processes can be simplified and included in a 3D model without a vast number of uncertain parameters.

In our relatively simple approach, sediment-water exchanges of nitrogen and phosphorus are directly linked to the fluxes and decomposition of sedimented carbon, instead of to the oxygen concentration in the near-bottom water (Kiirikki et al. 2006). Mineralisation of organic carbon is known to be the major factor controlling sediment nutrient cycling, including denitrification and Fe(III) oxide reduction, which is responsible for high phosphorus fluxes from reduced sediment surface layers.

Experimental results from the western coastal Gulf (Hietanen, submitted) suggest that neither temperature alone nor oxygen, nitrate or total organic carbon concentrations can explain the seasonal variation in measured denitrification. Instead, its activity was dependent on organic matter decomposition in the sediment. Recently, anaerobic ammonium oxidation (anammox), has been shown to be active in marine sediments (Thamdrup & Dalsgaard 2002, Dalsgaard and Thamdrup 2002, Trimmer et al. 2003, Rysgaard et al. 2004). The first measurements from both the open Baltic and coastal sediments show that anammox also occurs in this brackish water basin, and obviously explains part of the nitrogen removal in the Gulf of Finland (Hietanen, submitted).

In the sediment sub-model (Fig. 5.1), the description of sediment processes is based on four main parameters, which are identified by using in situ CO_2, dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) flux measurements carried out in 2003 in the Gulf of Finland by lander measurements (Tengberg et al. 2003). The model parameters and their critical values are:

- Critical point of organic carbon sedimentation/carbon dioxide (CO_2)- flux triggering "internal loading": 240 mg C m^{-2} d^{-1}
- Percentage of denitrified N from sedimented N in aerobic mineralisation: 70 %
- Percentage of chemical P-binding from sedimented P in aerobic mineralisation: 70 %
- Ratio of mineralised detritus P to P-flux from Fe(III) oxide-bound compounds under reduced conditions at the sediment surface: 3.75 w/w

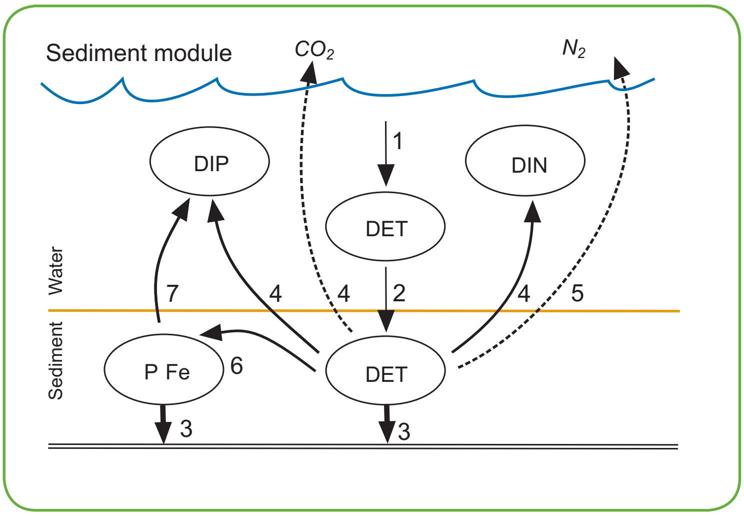

Fig. 5.1. Structure of the sediment module as a part of the EIA-SYKE 3D ecosystem model (Kiirikki et al. 2006). Main processes: 1 - settling, 2 - sedimentation, 3 - burial, 4- mineralisation, 5 - denitrification, 6 P - binding, 7 - internal P release.

The sub-model was tested as a part of the EIA-SYKE 3D model with monitoring data from both the eastern and western Gulf of Finland, and with the aid of time series data on denitrification and sediment DIP flux rates measured in the western Gulf of Finland (Kiirikki et al. 2006). The simulation period (1995–1999) covers two episodes of intensive internal DIP loading, in 1996 and 1998, with abundant blooms of nitrogen-fixing cyanobacteria in the preceding years, especially in 1997 (Pitkänen et al. 2001, 2003).

The modelled DIN and DIP concentrations of near-bottom waters were generally close to the observed ones, but the model had difficulties in reproducing the short-term dynamics correctly (Kiirikki et al. 2006). The sediment-water processes at depths of 40–60 m, i.e. just above the halocline, are very sensitive to changes in physical conditions. According to surveys made in the eastern Gulf of Finland and along the northern coast of Finland, bottom water nutrient concentrations vary considerably, depending on physical and geomorphological conditions (Lehtoranta 2003, Pitkänen et al. 2003), which is difficult to precisely follow with the applied basin-scale 3D model.

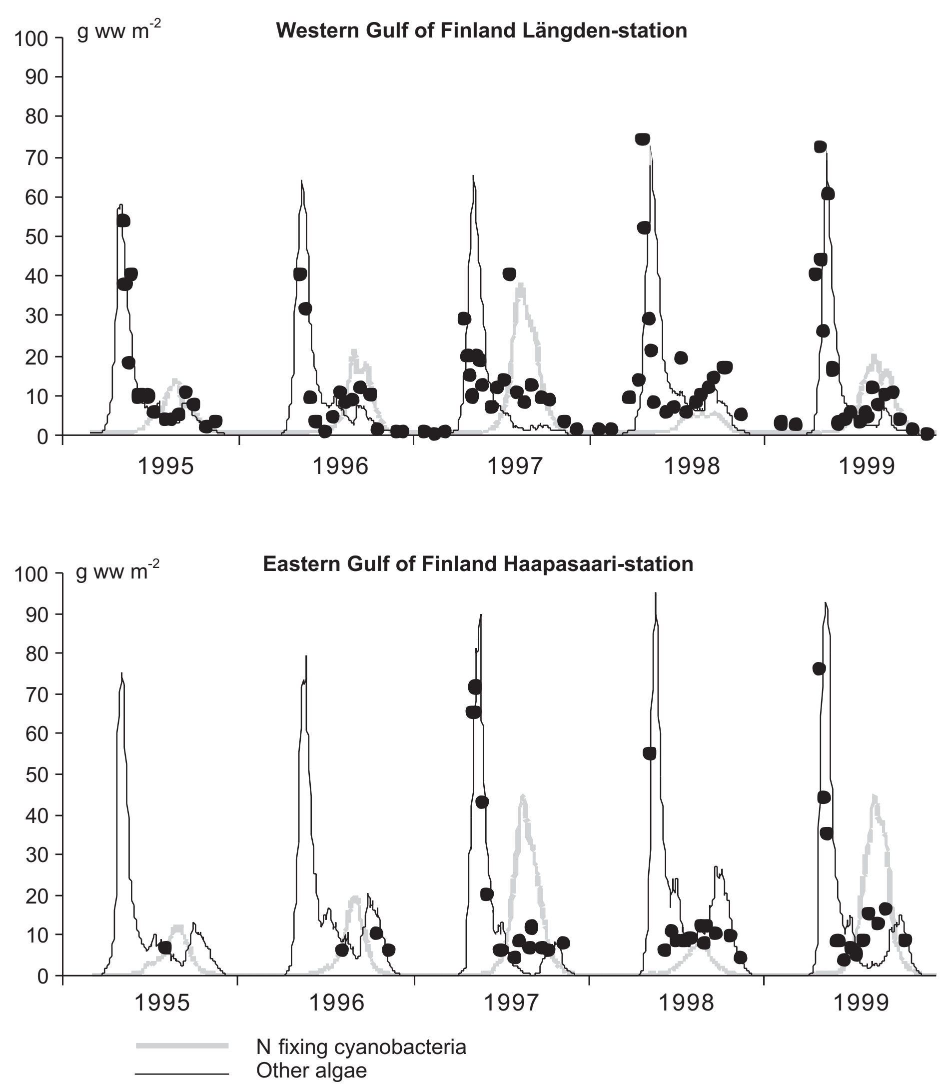

Fig. 5.2. Modelled and measured vertically integrated phytoplankton biomass in the western and eastern Gulf of Finland (Kiirikki et al. 2006).

In the western Gulf of Finland, the near-bottom DIN level was reasonably well simulated by the model, while in the eastern Gulf, the modelled near-bottom level of DIN was in general about 20% higher than measured values. In the surface layer the model reproduced well the annual dynamics both in the western and eastern Gulf. Ecologically, the most important deviation between model and measurements concerned summer DIP concentrations, which in the eastern Gulf are slightly higher than the measured values. As a result of this deviation, primary production in the eastern Gulf of Finland is more strictly nitrogen limited in the model than in reality (Kiirikki et al. 2006).

The modelled vertically integrated algal biomass closely followed the simulated values (Fig. 5.2, Kiirikki et al. 2006). In the western Gulf of Finland, the algal biomass values were consistent with the measured data. The spring bloom peaks were in accordance with the measurements, and even the record-setting cyanobacteria bloom in summer 1997 was reproduced by the model. In the eastern Gulf, the spring bloom biomass level was reasonably well aligned with the measurements. However, the modelled summertime cyanobacteria biomass value was clearly higher than the measured level. The high cyanobacteria biomass value is a direct consequence of the elevated modelled DIP concentrations.

The model simulations suggest that the average net annual ecosystem production entering the sediment surface from the euphotic layer was 49 g C m^{-2} a^{-1} (135 mg C m^{-2} d^{-1}), which is in a relatively good accordance with the values on average primary sedimentation (160–268 mg C m^{-2} d^{-1}) given for the coastal western Gulf of Finland by Heiskanen (1998). This organic load induced an average denitrification rate of 2.5 g m^{-2} a^{-1} of N and a DIP efflux of 0.67 g m^{-2} a^{-1} of P, corresponding to 75 000 t a^{-1} of N and 20 200 t a^{-1} of P for the whole Gulf of Finland, respectively. These estimated value for denitrification is almost twice the basin-wise estimates based on experimental measurements by Hietanen and Kuparinen (submitted) for summarized denitrification and anammox, while the estimate on DIP efflux is quite close the estimated upper limit of basin-wise DIP efflux of 18 000 t a^{-1} under poor oxygen conditions given by Lehtoranta (2003) . The model is able to describe the seasonality of denitrification and sediment DIP efflux with relatively good precision compared to the measurements from the coastal western Gulf (Figs. 5.3 and 5.4).

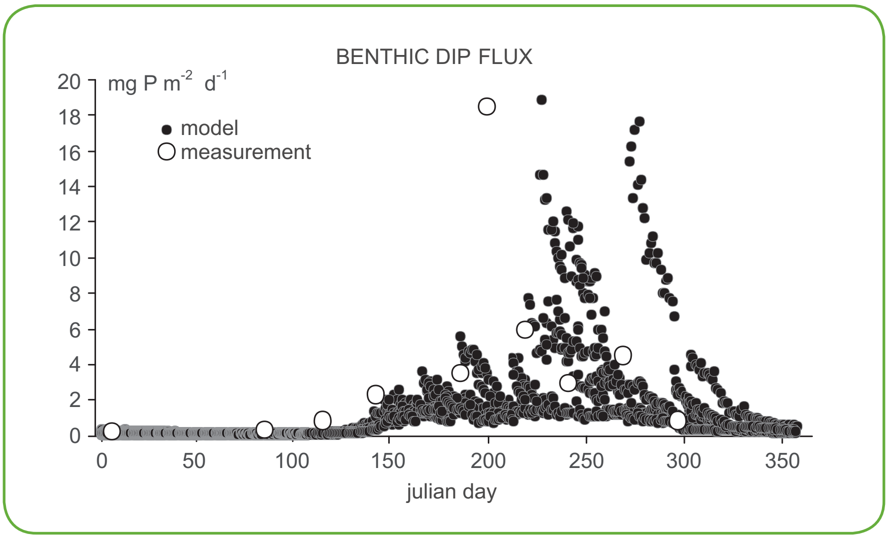

Fig. 5.3. Modelled and measured seasonality of sediment DIP efflux (Kiirikki et al. 2006). Measured values are from the coastal western Gulf.

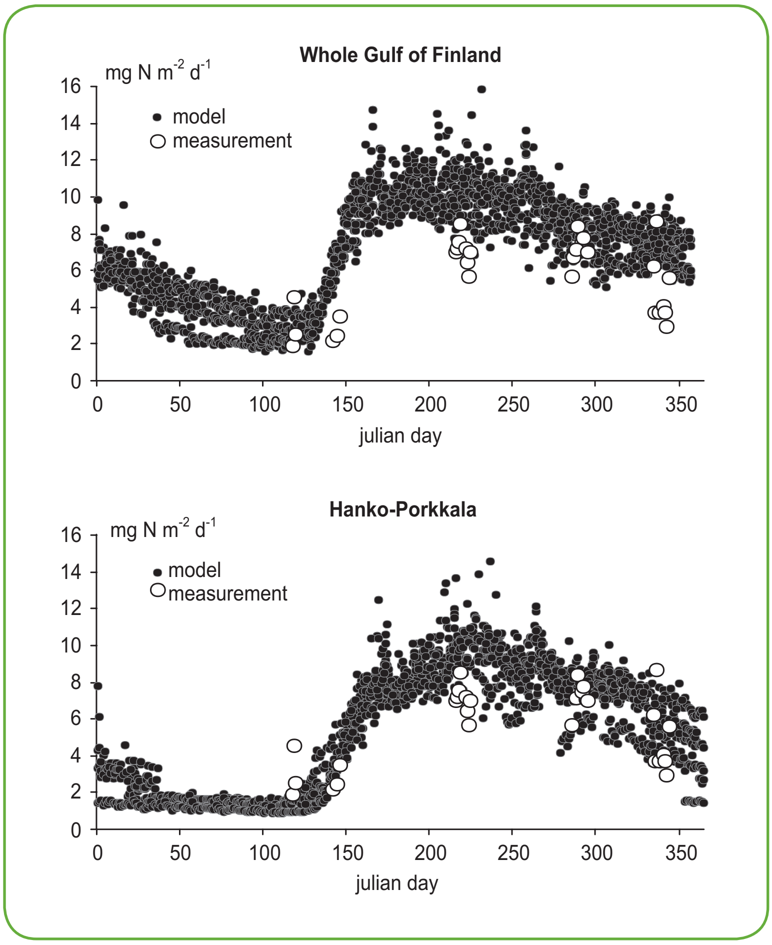

Fig. 5.4. Modelled and measured seasonality of denitrification in the whole Gulf of Finland (upper figure) and in the western Gulf of Finalnd (lower figure) (Kiirikki et al. 2006). All the measured values are from the coastal western Gulf.

It was clearly more difficult to reproduce the nutrient and phytoplankton dynamics in the eastern than in the western Gulf of Finland. The main reason for this is probably the highly dynamic nature of the eastern Gulf, which already poses a challenge for the physical part of the model. The easternmost Gulf is relatively shallow and its density stratification is labile (Alenius et al. 1998). Nutrients are thus vertically transported from deeper waters to the euphotic layer more easily than in the western Gulf, and the changes are more difficult to reproduce with the model (Kiirikki et al. 2006).

The model results and the available measurement data both indicate that the amount of settling fresh organic matter and its decomposition, described or measured as CO_2 flux, are dominant factors in predicting benthic nutrient fluxes. Furthermore, the benthic fluxes could be reduced by reducing the input of labile organic matter – the settling algal biomass. The relatively good fit of the model to the measured benthic DIP flux and N_2 production rates indicate that the factors controlling these processes are, even when not fully understood, anyhow adequately described in the model. At the moment, the main problem for water protection in the Gulf of Finland is the strong benthic phosphorus release caused by reduced conditions at the sediment-water interface. The present model enables tentative predictions to be calculated in order to study the effects of the external load on the production and decomposition of organic matter, and on the subsequent benthic nutrient fluxes.

5.3

Testing the calculation of nutrient fluxes between the Baltic Proper and the Gulf of Finland with the 3D ecosystem model

Mikko Kiirikki and Heikki Pitkänen

Reliable knowledge on the exchange of nutrients between the Gulf of Finland and the Baltic Proper is crucial for the estimation of the Gulf of Finland nutrient balances. In traditional budget studies (Perttilä et al. 1995, Savchuk 2005), the exchange has been based on water flows calculated from Knudsen's equations which use the average salinities of the inflowing deep and outflowing surface layers, and monitored nutrient concentrations at the entrance of the Gulf. The results of this approach are rough due to the very dynamic nature of the flows near to the Gulf of Finland-Baltic Proper transect. In the present study an effort was made to calculate total bioavailable N and P exchange at the mouth of the Gulf with the EIA-SYKE 3D model, and to produce a sub-routine where the calculation procedure is available in the user interface of the model (Kiirikki 2005a).

The nutrient exchange book-keeping allows the user of the 3D ecosystem model to define any transect where water inflow and outflow are calculated on a daily basis together with corresponding nutrient, plankton biomass and detritus concentrations in the water mass. The produced logfile allows the user to calculate the daily nutrient exchange across the defined transect, and daily changes in the nutrient reserve of the whole Gulf of Finland. In this report the calculation results by the EIA-SYKE 3D ecosystem model describing the nutrient exchange at the entrance of the Gulf of Finland during a 5-year simulation period (1995–1999) are presented. The model operates with bioavailable nutrients, and in the following calculations particulate inorganic and dissolved organic fractions are thus not included in the figures of total N and P.

The modelled average daily water flow varied between an outflow of 73 000 $m^3 s^{-1}$ and an inflow of 41 000 $m^3 s^{-1}$ within the 5-year simulation period. The frequency of days with an inflow of over 10 000 $m^3 s^{-1}$ was 4% and the frequency of days with an outflow of over 10 000 $m^3 s^{-1}$ was 13%. The average outflow of the whole simulation period was 3 530 $m^3 s^{-1}$, a value very close to the average river inflow into the Gulf of Finland (e.g. Savchuk 2005).

According to the calculations, the Gulf of Finland exports nitrogen during winter (Fig. 5.5). This export is facilitated by the high DIN concentration in the outflowing surface layer, especially along the Finnish coast, where the predominant flow direction is westwards. In summer, there is practically no DIN available in the euphotic surface layer because primary production is nitrogen limited. The export consists mostly of organic nitrogen contained in algal biomass, while DIN is imported by the inflow of deeper water masses. The model probably overestimates late spring/early summertime nitrogen import, because it overestimates DIN concentrations below the euphotic layer in the western Gulf (Kiirikki et al. 2006).

The calculated average net import of total bioavailable nitrogen for the whole simulation period was 5 200 t a^{-1}, which is a small value compared with the land based nitrogen load of both bioavailable (77 000 t a^{-1}) and total N (120 000 t a^{-1}) (Kiirikki et al. 2003). It is also low compared with the estimated combined denitrification and anammox of 39 000 t N a^{-1} (Hietanen & Kuparinen, submitted), and with the simulated nitrogen reserve in the water mass of ca. 140 000 t. It thus seems likely that during the simulation period (1995–99) the net annual exchange of total bioavailable N between the Gulf of Finland and the Baltic Proper was small compared with other internal and external factors in the budget.

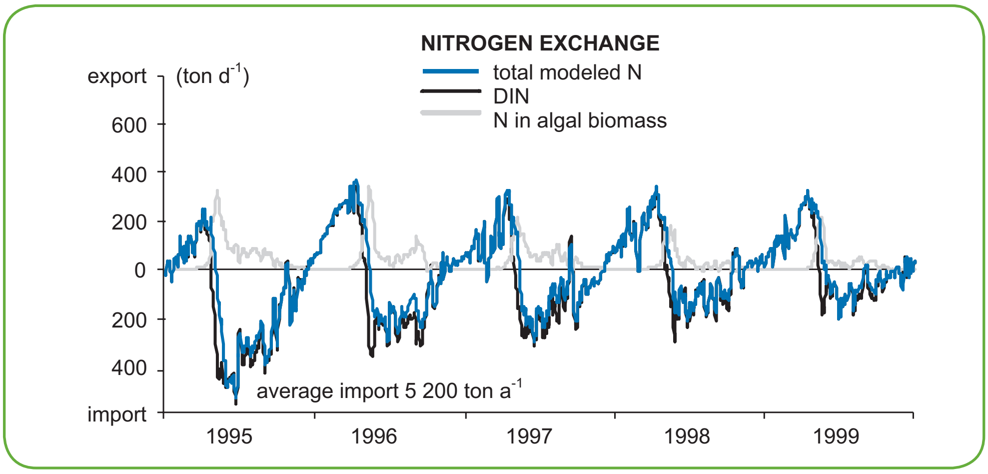

Fig. 5.5. Simulated nitrogen exchange at the entrance of the Gulf of Finland (Kiirikki 2005a).

The phosphorus exchange basically followed the same pattern as nitrogen showing winter export and summer import (Fig. 5.6). Import strongly dominated the beginning of the simulation period, turning into net export towards the end of the simulation. In 1995 the net import was 11 500 t a^{-1} and in 1999 the net export was 3 600 t a^{-1}. The average import for the whole 5-year simulation was 1 000 t a^{-1}. The simulated years 1995–1999 represent a transition period, when the P retention capacity of the Gulf of Finland worsened dramatically (Pitkänen et al. 2001, 2003). In the beginning of the 1990s, the deep sediment bottoms were well oxidized around the year, retaining nutrients, especially phosphorus, from the settled detritus. In 1996 the density stratification strengthened, and large bottom areas went into a reduced state, releasing massive amounts of sediment-bound phosphorus to the water mass (Lehtoranta 2003). The simulated winter phosphorus reserve in the water mass increased by 7 000 t, from 28 000 in 1995 to 35 000 t in 1996, thereafter decreasing gradually to 32 000 in 1999.

The calculated net import of bioavailable total P during good oxygen conditions in 1995 of 11 500 t a^{-1} is close the estimate of 8 000 t a^{-1} by Perttilä et al. (1995) calculated for total P in 1990. The year 1990 also represented good deep water oxygen conditions, and evidently low benthic P release. In the 1990s the annual land-based input of total P

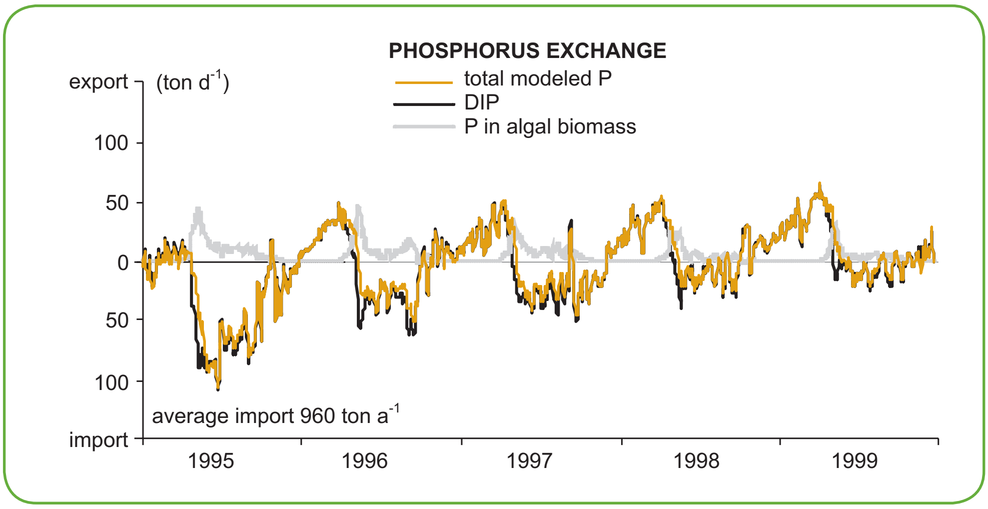

Fig. 5.6. Simulated phosphorus exchange at the entrance of the Gulf of Finland (Kiirikki 2005a).

ranged from 7 000 to 10 000 a^{-1} (Pitkänen et al. 2001). Thus, under good oxygen conditions the land-based input of P and net input of P from the Baltic Proper were almost equal and totalled approximately 20 000 ta^{-1}. When no particular changes took place in the P concentrations of the Gulf of Finland in the late 1980s/early 1990s (Perttilä et al. 1995, Pitkänen et al. 2001), the annual P retention of the Gulf of Finland was apparently close to this estimate. Experimental studies by Lehtoranta (2003) suggest that P amounts up to 18 000 t a^{-1} can be released under poor oxygen conditions when extensive sediment areas are reduced.

5.4

Back in the USSR: Testing the 3D model with strongly decreased nutrient loads

Mikko Kiirikki and Heikki Pitkänen

One of the major reasons for developing ecosystem models for the Baltic Sea, and particularly for the eutrophied Gulf of Finland, has been the urgent need to test the effects of planned or imaginary nutrient load reduction on the biomass production (Kiirikki et al. 2003, Pitkänen 2004). So far, the only way to evaluate the present models has been their ability to hindcast the past nutrient and biomass concentration levels. Good hindcast results have been interpreted as "permission" to use the model also for evaluating the effects of altered nutrient loading, often meaning planned investments in waste water treatment or changes in agricultural politics. It has been difficult to find a well documented test case where nutrient loadings would have changed so much that the effects could be measured on a whole basin scale.

In the beginning of the 1990s the Soviet Union collapsed. This led the country into a deep economic depression. Industrial and livestock production, as well as field cultivation were retarded in the Russian and Estonian parts of the Gulf of Finland drainage area (Lääne et al. 2002, Kiirikki et al. 2003). This had a dramatic effect on the nutrient load entering the Gulf of Finland. The net decrease in the total nutrient load entering the Gulf was estimated to be 39% for phosphorus and 36% for nitrogen between the years 1987 and 2000 (including natural background discharges; Pitkänen & Räike 2004). Despite possible uncertainties in the load estimates (see Chapter 2.1), a nutrient load reduction of about one third of the total load should have caused visible and measurable effects in the Gulf of Finland.

The EIA-SYKE 3D ecosystem model (Kiirikki et al. 2001, 2006) was used to estimate the scale of the ecosystem level changes and their location in the Gulf of Finland (Kiirikki 2005b). The model results were compared with reported water quality changes. The 5-year simulation was first carried out with present algal-available nutrient load representing the year 2000 for the Gulf of Finland (Kiirikki et al. 2003). The second simulation was carried out by using the same nutrient load data, multiplied with factors presented in Table 5.1. The factors are based on changes in the total nutrient loads between the years 1987 and 2000 in Russia, Estonia and Finland (Pitkänen & Räike 2004). Relative changes in total and algal available nutrient loads were estimated to be equal. This assumption probably underestimates the true change, because the algal availability of the anthropogenic load is generally higher than that of the natural background load. However, there is no reliable information available on the algal-available loads for the year 1987. The average algal biomasses and nutrient concentrations of the 5th calculation year were stored as average fields during both simulations, and relative changes were calculated based on these fields.

Table 5.1. Total nutrient loads for years 1987 and 2000 by countries according to Pitkänen and Räike (2004). N and P factors were used to calculate the algal available loads for the year 1987.

Source	Ptot 2000 (ton)	Ptot 1987 (ton)	P Factor	Ntot 2000 (ton)	Ntot 1987 (ton)	N Factor
Finland	770	850	1.1	20400	20700	1.0
Russia	5000	8200	1.6	73200	123000	1.7
Estonia	500	1000	2.0	12400	30000	2.4
Atmospheric	-	-	-	17000	20000	1.2
Total	6270	10059	1.6	123000	193700	1.6

The most striking effect in the model results is the increase in nitrogen fixing cyanobacteria biomass compared with the reference run (Fig. 5.7). An increase of over 200% took place in the eastern Gulf of Finland between Helsinki and Vyborg. In the Gulf of Finland, the major source of nitrogen is the load from the drainage area and via the atmosphere, whereas during the simulation period (1995–99), the major part of phosphorus came from the bottom sediments as so called "internal loading" (see chapter 5.2). Thus, even without this phenomenon, the cutting of both external N and P loads by about one third would have reduced N/P ratio input into the open Gulf ecosystem of the nutrient, and created a competitive advantage for N-fixing cyanobacteria there.

The period from the mid 1980s to the early 1990s is known as a period with only few cyanobacterial blooms in the Gulf of Finland (Kahru et al. 1994). In the mid-1990s the blooms became a common phenomenon, and the area of dense surface accumulations spread towards the east, first reaching the Gogland Island and later on even the easternmost Gulf of Finland (Kahru et al. 2000). The pulse of saline water into the Baltic Sea in the winter of 1993 is commonly considered as the major trigger for the massive blooms in the summers of 1997 and 1999. The pulse pushed near-bottom waters with

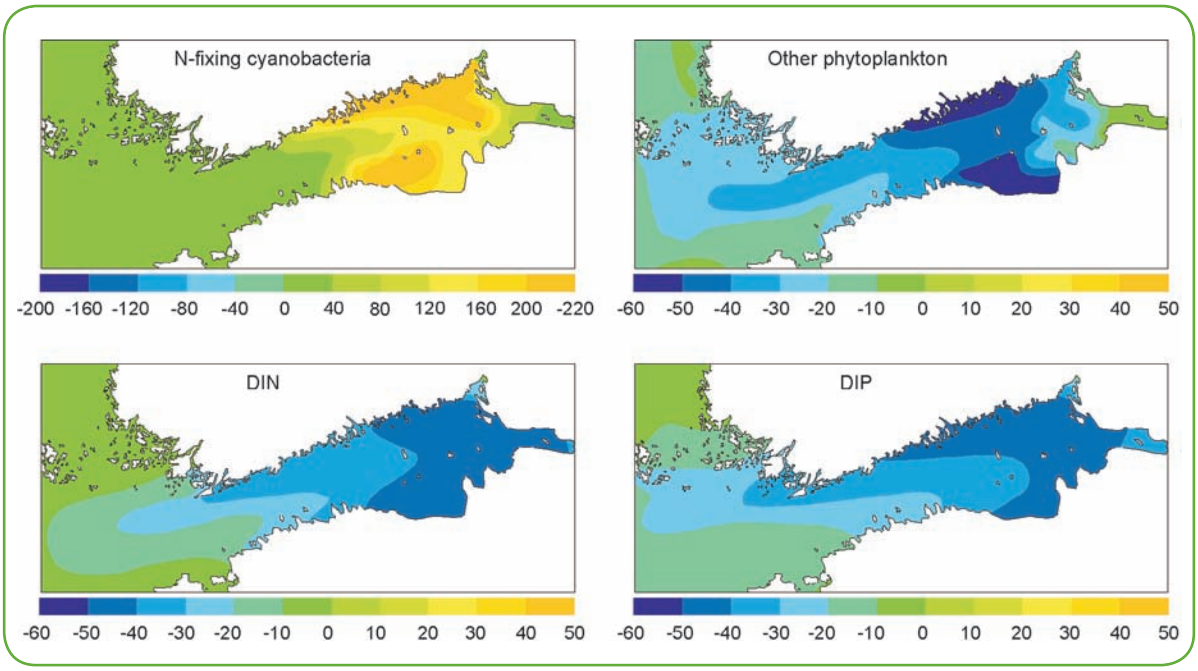

Fig. 5.7. Model simulated relative biomass and nutrient concentration changes (%) caused by the collapse of the Soviet Union (Kiirikki 2005b).

already high phosphate concentration towards the Gulf of Finland, strengthening the salinity stratification, lowering the oxygen concentration and subsequently increasing the benthic release of phosphorus (Pitkänen et al. 2001).

As a result of the load reductions in the early 1990s, those phytoplankton species not able to utilize molecular nitrogen had clearly less nutrients available. In the model simulation, the most pronounced biomass decrease of the modelled group "other phytoplankton" took place in the central parts of the Gulf, where the maximum decrease was 50–60% (Fig. 5.7). Decreases of 20–40% were reached all over the Gulf, except in the Neva Estuary. The influenced area was larger along the northern coast of the Gulf of Finland where the general flow pattern pushes the waters from the eastern Gulf towards the west (Alenius et al. 1998). Raateoja et al. (2005) suggest that the spring bloom chlorophyll-a concentration has decreased by about 30 % between the late 1980s and the 2000s in the coastal western Gulf. This supports the modelled result, because most of the biomass of the group "other phytoplankton" is formed by vernal species.

The levels of the algal-available nutrients DIN ($NO_{2,3}$, NH_4) and DIP (PO_4) both decreased in the model simulation. DIN decreased by 20–40% in the western Gulf and by up to 40–50% in the eastern Gulf. The DIP simulation gave almost the same pattern. According to available monitoring data, DIN levels in reality decreased by 20–30% along the Finnish coastline, as well as in the western and middle open Gulf (Pitkänen et al. 2001, 2007), which is close to the simulated reductions. There is not enough data available from the eastern Gulf to validate the 40–50% decrease there. However, the available concentration data of DIN from the Neva Bay in 1990–92 and from the lowest parts of the Neva River in 2000–2002 (Pitkänen & Tamminen 1995, chapter 2.5) suggest that summertime DIN concentrations at the mouth of the river have deceased from 300–500 mg m^{-3} to about 200 mg m^{-3}, which evidently supports the simulated result.

According to monitoring data the concentration of DIP has on the contrary increased by 30–50%, i.e. opposite to the model results, which indicates a decrease of the same size. The strongly intensified internal phosphorus loading explains the increase in the observed values. It is very possible that the present DIP level would be even higher, and consequently cyanobacterial blooms would be even stronger than those measured in recent years, if the external nutrient loading had remained on the high level of the late 1980s.

5.5

Medium and long term state forecasts based on the integrated use of 1D and 3D models

Heikki Pitkänen, Mikko Kiirikki, Oleg Savchuk, Antti Räike, Päivi Korpinen and Fredrik Wulff

Modelling studies suggest that it is possible to improve the present eutrophic status of the Baltic Sea, but the overall recovery will be slow. For the open Gulf of Finland, a recovery seems to be possible within five years from the implemented measures, if the reductions are high enough (Kiirikki et al. 2003). In the present study the EIA-SYKE 3D ecosystem model was chosen as a tool to study the effects of different loading scenarios for the Gulf of Finland. In the Swedish MARE project the box-model SANBALTS (Savchuk & Wulff 2007, Wulff et al. 2007) was developed to analyse the effects of different measures to reduce nutrient loads into the different Baltic Sea basins.

An experiment combining the use of these two ecosystem models was made to produce long-term state scenarios with high spatial resolution, and to search for effective protection strategies for the Gulf of Finland and the adjacent waters of the northern Baltic Sea (Pitkänen et al. 2007). Reference and scenario simulations were first run with the SANBALTS box model for the seven main basins of the entire Baltic Sea until steady state was achieved (Fig. 5.8). The obtained basin-wise distributions of inorganic N and P, as well as of sediment labile P, were then used as initial values for 5-year simulations with the 3D ecosystem model.

Three basic load scenarios were used in the calculations:

1. "Finland": Water Protection Policy Outlines to 2015: the most stringent alternative presented in the draft background report on eutrophication (Rekolainen et al. 2006). The reductions from the total loads from Finland, Estonia and Russia and via the atmosphere into the Gulf of Finland and the Archipelago Sea correspond to –7% for both total N and total P.
2. "St Petersburg": All waste waters of the City region are purified with 80% efficiency regarding P, and with 75% efficiency regarding N. The reductions correspond to –5% and –17% of the total N and P loads into the study area, respectively .
3. "Poland": Reductions of –21% for N and –25% for P from the reference Polish loads into the Baltic Proper, corresponding to the 50% target reduction set by the 1988/98 Ministerial Declaration.

The runs were in addition made with a scenario which combined all the basic scenarios (1+2+3).

The relatively small local load reductions (the "Finland" scenario, Fig. 5.9) would significantly improve only the state of the adjacent coastal waters. This would be the case even for runs covering several decades, which clearly exceeds the residence time of nutrients in the Gulf of Finland. A significant decrease in a substantial loading source to the Gulf (the "St Petersburg" scenario, Fig. 5.10) would decrease cyanobacterial biomasses in the entire Gulf of Finland and immediately outside it. A reduction in the current Polish nutrient loads would improve the situation in the whole Baltic Proper, and cause an extensive decline in cyanobacterial biomasses in the Gulf of Finland, as well (Fig. 5.11). However, it would take several decades until the improvement caused by reducing loads in the "Poland" scenario is seen, while in the "St Petersburg" scenario the corresponding time lag would be only a few years.

According to the combined scenario (1+2+3), total phytoplankton biomasses of the case area would decrease by 5–35% in the medium-term run, and by 25–45% in the long-term run (Fig. 5.12). The differences between the scenarios are mainly due to the fact that in the long-term run reductions in Poland also affect the state of the study area. The results clearly suggest that the common water protection policy in the Baltic Sea region should have the largest nutrient sources as its primary target, regardless of their location and country. On the other hand, it seems that even if the most stringent combined scenario and the long-term simulation is combined, the state of the Gulf of Finland will probably not reach the preliminary target values of the Good Ecological Status presumed by EC's Water Framework Directive.

On a basin-wise scale the relatively small nutrient load reductions from Finland cannot cause any considerable whole-basin reduction in the present eutrophic status of the Gulf of Finland, even when the time-scale is several decades. Near the loading sources, locally large nutrient load reductions improve the state of the coastal waters, however. On the other hand, significant reductions even at far-away sources in the Baltic Proper can have considerable lowering effects on both coastal and off-shore planktonic biomasses, especially on cyanobacteria.

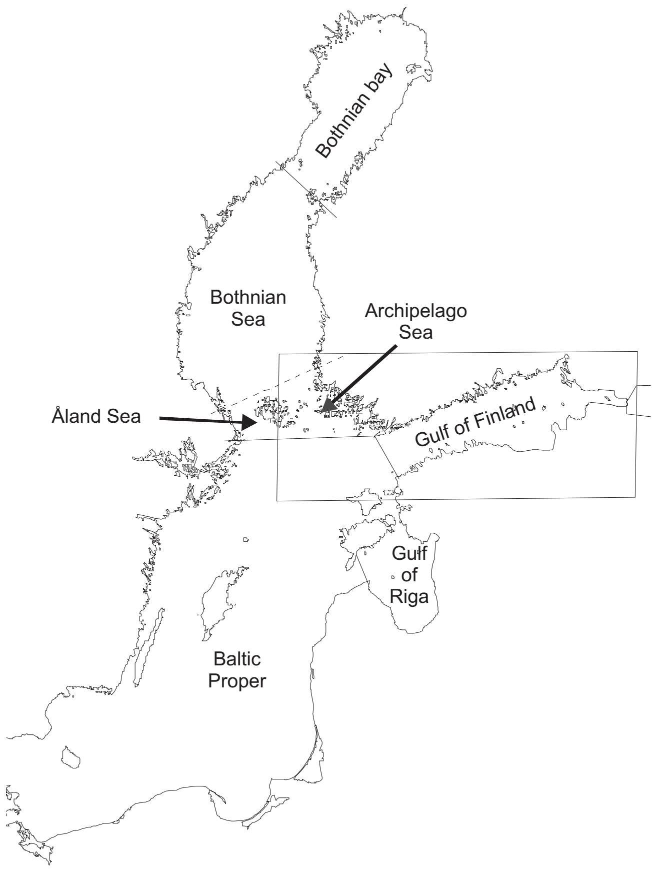

Fig. 5.8. The study area of the 1D-3D runs (box) and the basin division of the MARE 1D model (Pitkänen et al. 2007).

In coastal water areas, such as the Archipelago Sea, a considerable decrease in loading from local sources, comparable to the reductions of the background report on eutrophying nutrient loading of the Finnish Water Protection Policy outlines to 2015 (Rekolainen et al. 2006), and corresponding 40 to 50 % reductions in anthropogenic nutrient loads entering the Finnish coastal waters, would clearly improve the local trophic status. However, this improvement will cease when the water quality of the adjacent open sea waters is reached, and this is primarily affected by large, often more far-away sources. Thus, the coastal areas clearly benefit from both local small-scale and more distant large-scale load reductions.

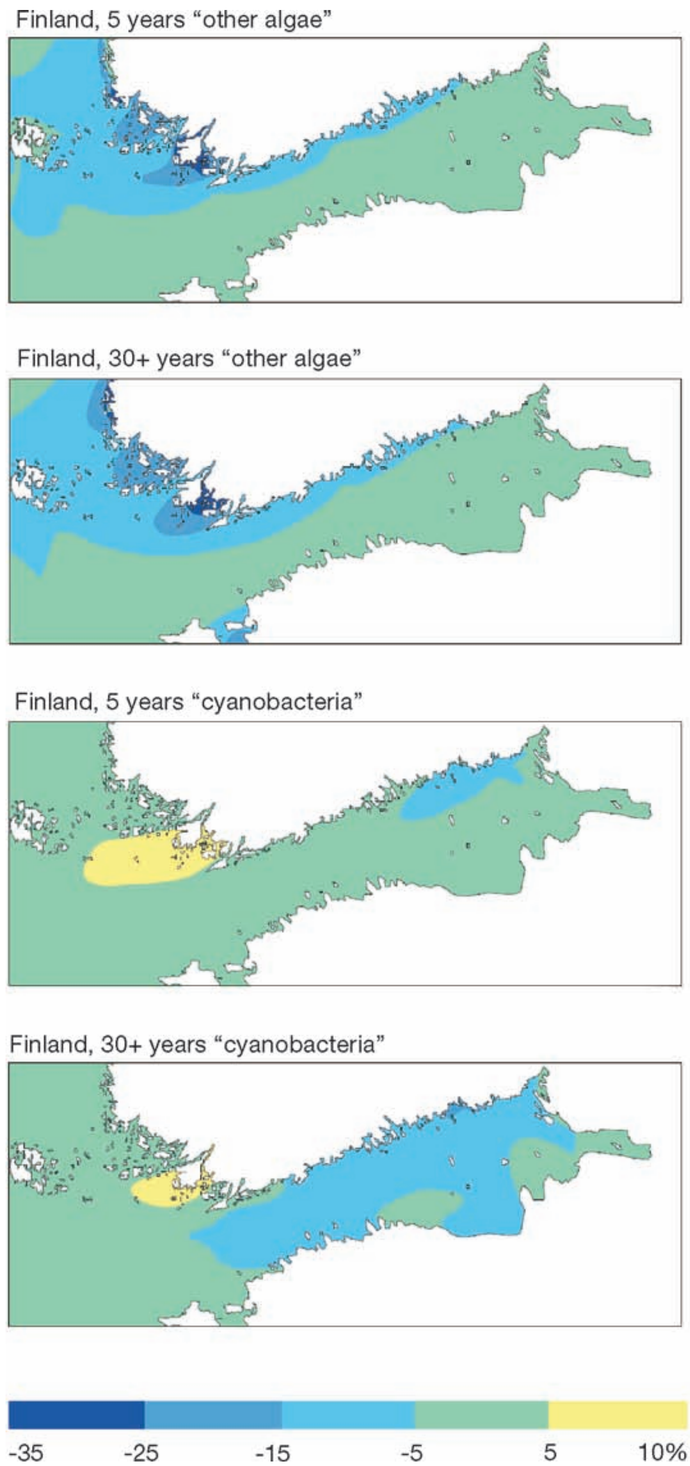

Fig. 5.9. The modelled 5 year 3D and 30+ year 1D–3D scenarios of other algae and N-fixing cyanobacteria according to the "Finland" scenario. a) 5 year scenario of other algae; b) 30+ year scenario of other algae; c) 5 year scenario of N-fixing cyanobacteria d) 30+ year scenario of N-fixing cyanobacteria (Pitkänen et al. 2007).

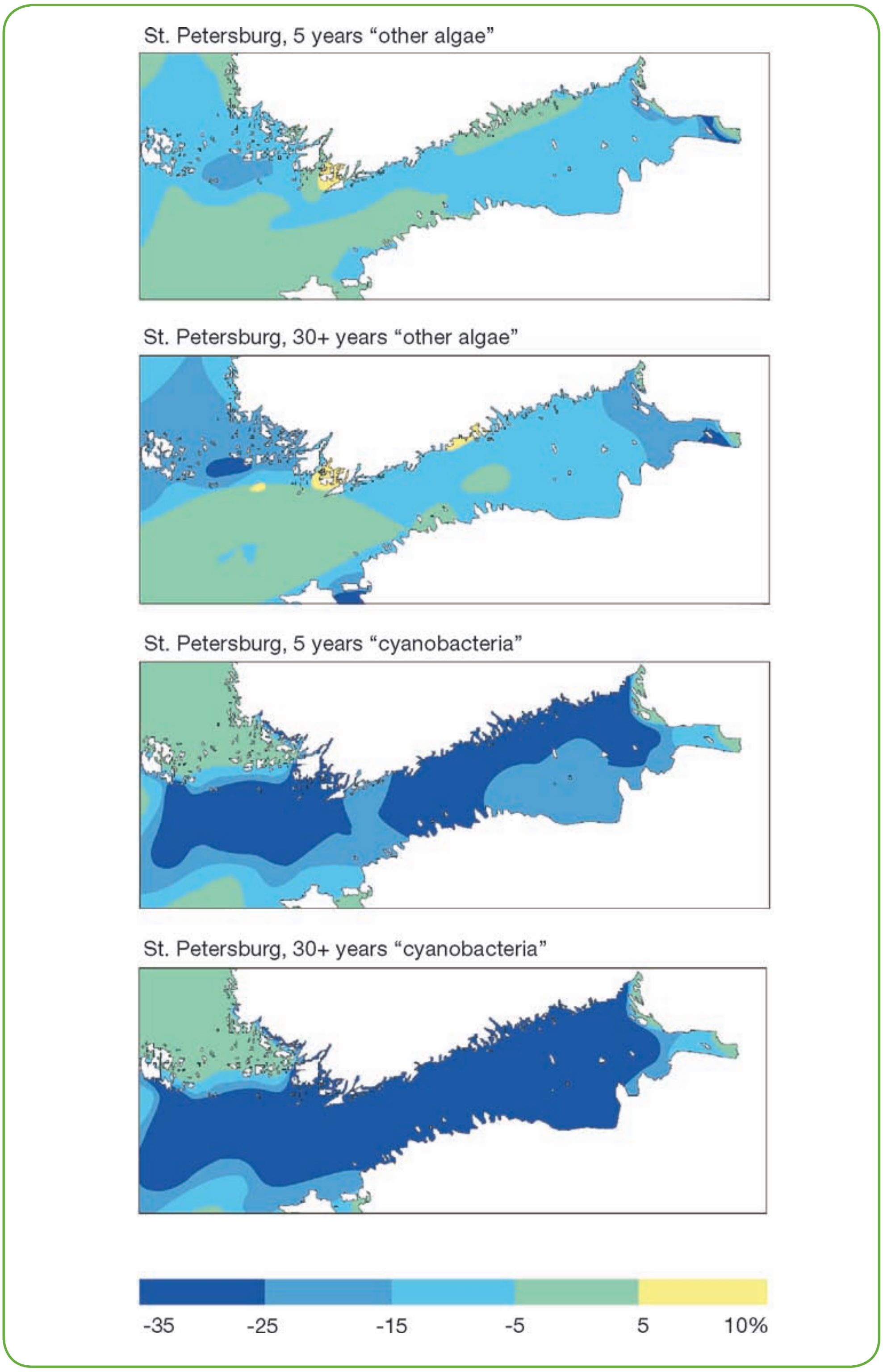

Fig. 5.10. The modelled 5 year 3D and 30+ year 1D–3D scenarios of other algae and N-fixing cyanobacteria according to the “St Petersburg” scenario. a) 5 year scenario of other algae; b) 30+ year scenario of other algae; c) 5 year scenario of N-fixing cyanobacteria d) 30+ year scenario of N-fixing cyanobacteria (Pitkänen et al. 2007).

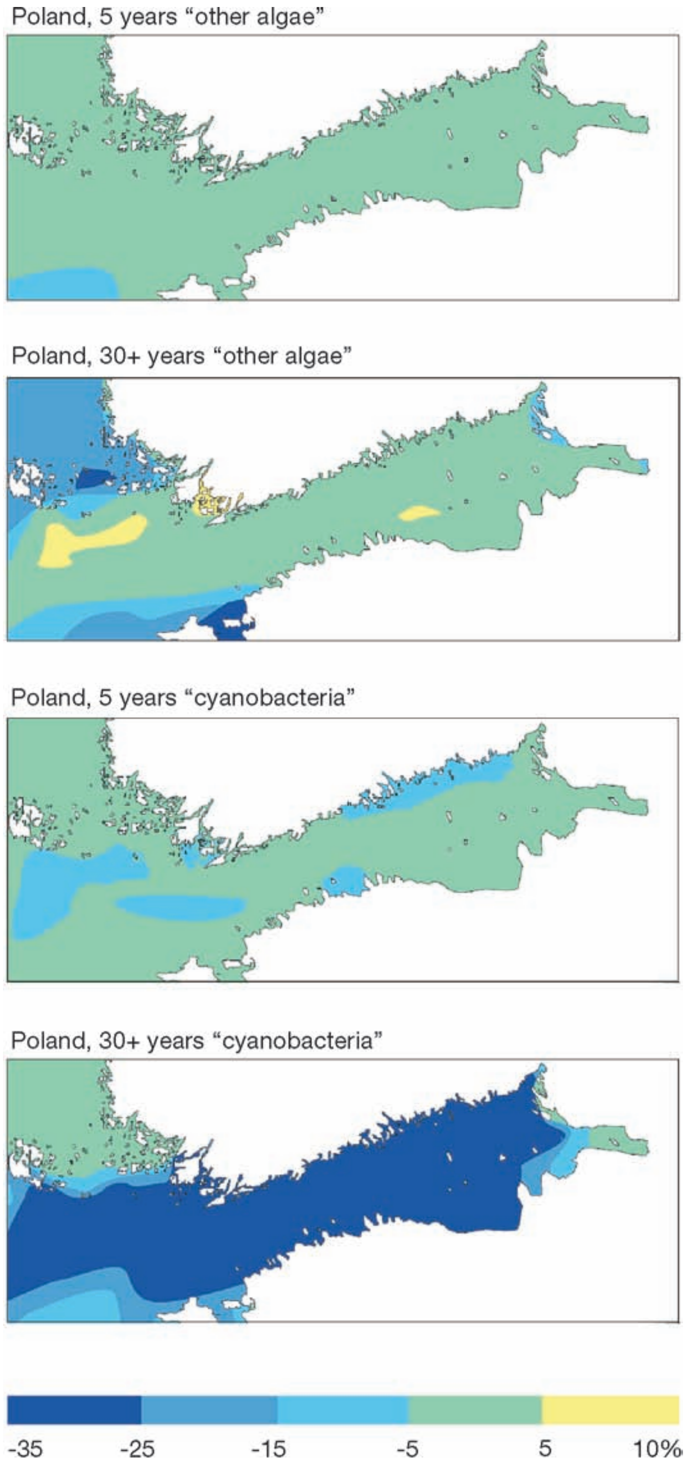

Fig. 5.11. The modelled 5 year 3D and 30+ year 1D–3D scenarios of other algae and N-fixing cyanobacteria according to the "Poland" scenario. a) 5 year scenario of other algae; b) 30+ year scenario of other algae; c) 5 year scenario of N-fixing cyanobacteria d) 30+ year scenario of N-fixing cyanobacteria (Pitkänen et al. 2007).

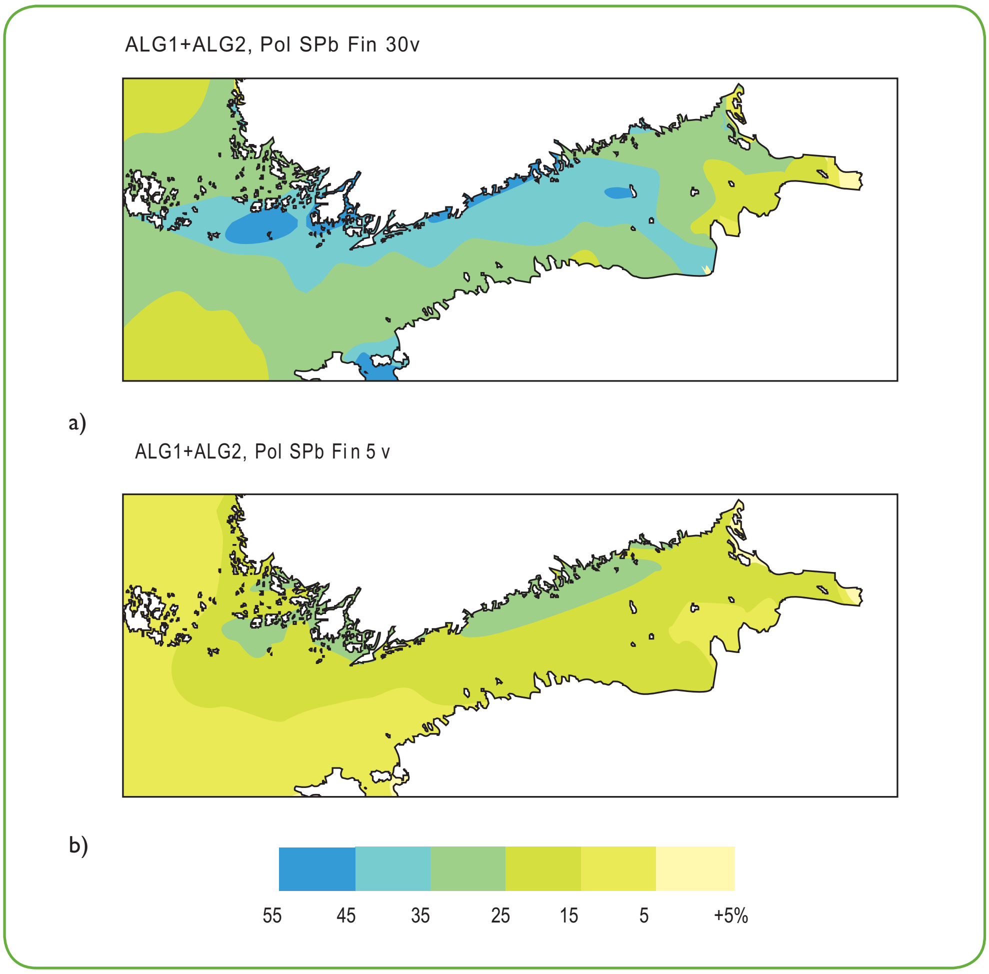

Fig. 5.12. The modelled 30+ year 1D–3D (a) and 5 year 3D (b) combined scenarios for total phytoplankton (cyanobacteria + other algae) (Pitkänen et al., unpublished).

5.6
Conclusions

The main results and conclusions of the modelling experiments and scenarios were:

- On the scales important for large-scale coastal and open sea conditions, the sediment sub-model is a clear improvement in the 3D ecosystem model. It will aid in assessing the effects of external load on the production and decomposition of organic matter and on subsequent benthic nutrient fluxes. Although functioning well in the western and middle Gulf, the applied threshold value for organic carbon sedimentation is probably too low for the easternmost Gulf. There, the halocline is usually weak, and the sediment surface probably tolerates a higher sedimentation rate of oxygen consuming organic matter before turning into a reduced state than in the areas where a stronger stratification prevails.
- Both the modelling and the earlier budget studies indicate that under good oxygen conditions the sediments of the Gulf of Finland can retain up to 20 000 t a^{-1} of phosphorus annually, corresponding to about six times the external load

of algal available phosphorus into the Gulf. On the other hand, up to similar amounts can be released when really large sediment surface areas of the Gulf are reduced, and this also contribute to the eutrophication in the southern Archipelago Sea and in the north-eastern Baltic Proper. The nitrogen balance between the Gulf of Finland and the Baltic Proper can vary dramatically from year to year, the net annual exchange always being, however, clearly smaller than the total land-based and atmospheric nitrogen input into the Gulf.

- The EIA–SYKE model was able to reproduce part of the observed changes in nutrient concentrations and algal biomasses in the Gulf of Finland caused by the strongly reduced nutrient loading from the former Soviet Union in the early 1990s. However, this load reduction took place during a period of strong physical changes, caused by an inflow of saline water into the Baltic Sea and further into the Gulf of Finland. The mechanism controlling sediment P release in the Gulf has possibly changed non-linearly since the 1980s. The applied 3D model is calibrated and validated with data from after 1995, and is thus in its present form incapable of taking into account such non-linear changes (regime shifts).
- Applications of the developed 1D-3D modeling tool suggest that strong reductions in major nutrient sources within the entire Baltic Sea catchment area are needed to effectively combat eutrophication of the Gulf of Finland and the neighboring sea areas. This concerns big cities with missing or poor waste water treatment, and large rivers with extensive agriculture in their catchments. The time-lag between purification measures and actual effects varies in different parts of the Baltic Sea. In the Gulf of Finland, improvements in water quality due to reductions in regional nutrient sources can be expected to occur more rapidly than in the Baltic Proper. Similarly, load reductions to the Baltic Proper will affect other basins like the Gulf of Finland, but much more slowly.
- According to studies on ecological economics it is more cost-effective to reduce nutrient loading in the new EU countries and Russia than in the old EU countries, where purification of point-loads, especially that of phosphorus, is already efficient. At present, most of the big point-load sources where large and rapid load reductions could be reached are located in the new EU countries and in Russia. Thus, the conclusion of the present study on "the large-scale combating of eutrophication" is obviously valid both from ecological and cost-efficiency viewpoints. At the same time, measures against agricultural loads of nitrogen and phosphorus should be continued, even if effects of abatement measures on diffuse loads will take much longer than for point-loads.
- It seems that even with the most stringent load reduction scenarios of the present study, phytoplankton biomasses in the Gulf of Finland will stay above the preliminary target value representing Good Ecological Status presumed by EC's Water Framework Directive.
- Finally, it must be emphasized that the ecosystem models applied in the present study include many simplifications, assumptions and uncertainties. The presented scenario results must be considered as tentative, not exact, values. There are still large gaps in the quantitative knowledge on the main nutrient and carbon fluxes of the Baltic Sea ecosystem, and large-scale ecosystem modelling must be developed in close and continuous interaction with experimental ecosystem studies. Modelling can help to analyse the importance of the different processes, while all new measured information on the essential processes will help to develop the models.

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6 Ecological-economic modelling of optimal abatement measures

Anni Huhtala and Marita Laukkanen

Economics studies how the actions of economic agents (consumers, firms) affect society as a whole and how to efficiently use society's scarce resources. A variety of tools have been developed to aid public policy making. One type of policy appraisal is *cost-effectiveness analysis* which considers social costs and benefits and aims at finding the least expensive way of meeting a pre-determined target: for example, a target of reducing nutrient loading by 50% from the current baseline over the next twenty years. In other words, cost-effectiveness is defined as reaching a pre-specified objective at the least cost, and a policy is cost-effective if it maximizes abatement for a given budget. Cost-effectiveness was the goal of the study by Kiirikki et al. (2003), for instance, who surveyed alternative water protection measures in the Gulf of Finland.

In this project, we have taken a step further by investigating the social optimality of alternative abatement measures by means of a *cost-benefit analysis*. Accordingly, not only the total expected costs, but also the total expected benefits of abatement measures have been estimated in order to choose the best abatement strategy. Furthermore, when abatement measures entail investments that impose considerable irreversible costs on society, the investment costs should be appropriately accounted for in policy choices. For a comprehensive analysis, we have developed a dynamic model that includes the following components: (i) the dynamics of the nutrient stocks in the receiving body of water over time, (ii) the cost of agricultural nutrient abatement, (iii) the operating cost of municipal wastewater treatment, (iv) the investment cost and the uncertainty pertaining to the duration and cost of constructing underground sewage tunnels and wastewater treatment facilities, and (v) the environmental benefits of abatement (see Laukkanen & Huhtala 2006 for details of modeling and parameterization.) The strength of our modeling is that the dynamics of nutrient stocks are truly integrated in the economic optimization framework, in contrast to some previous modeling applications which have not reached full dialog between the economic and ecological model components. Within this model structure, we investigate the optimal timing of investment in waste water treatment capacity, and address the following issues: Under what conditions should investment in wastewater treatment facilities be undertaken? What determines the optimal time to invest? How are agricultural and municipal nutrient abatement balanced where investment is undertaken? and How does the optimal agricultural abatement policy change once wastewater treatment facilities are operational?

The model has been calibrated for ecological and economic data representing waters of the Gulf of Finland along the Finnish coast, where comparison of abatement measures in agriculture and municipal wastewater treatment facilities is highly relevant. All municipal wastewater from Finland is treated before it enters the sea, but agriculture remains a significant nutrient source, comprising 42% of the load from Finland to the Gulf of Finland (Kauppila et al., 2001). In contrast, sewage infrastructure is partly lacking in the city of St. Petersburg; these wastewaters represent about 40% of the total P and about 15% of the total N loads to the Gulf of Finland (Pitkänen & Räike 2004). Significant investments will be required to enable the removal of nutrients from all municipal discharges.

Even though there are considerable challenges in estimating the total benefits of reduced eutrophication in monetary terms, the empirical literature on valuation of water quality improvements is extensive (see e.g. Freeman 1995, Wilson & Carpenter 1999). In our application, we have relied on benefit estimates available from a previous contingent valuation study by Söderqvist (1996), who carried out a valuation project of the Baltic drainage basin as part of an EU Environmental Research Program (see also Turner et al. 1999). The study indicated that inhabitants in the region place a significant value on the benefits: willingness to pay for reducing eutrophication in 20 years from its current level to a level that the Baltic Sea can sustain resulted in a basin wide estimate for total benefits of about 55 000 million Euro. As the environmental problem is caused by the accumulated stocks of nutrients (i.e. nutrient mass = concentration times volume) rather than immediate flows, we seek to relate the willingness to pay measure for avoiding eutrophication to a specific reduction in the nutrient stocks. This is consistent with many other situations where ecosystems are altered by the release of long-lived pollutants. In our model, the benefits are attributed to the state of the water ecosystem as measured by nutrient mass.

6.1 Modeling

While marine scientists use complex ecosystem simulation models to study the effects of anthropogenic nutrient loading on nutrient stocks, previous economic studies of the Baltic Sea region have produced satisfactory results for the distribution of eutrophying nutrients using simple nutrient turnover models (see e.g. Gren et al. 1997, Turner et al. 1999, Hart & Brady 2002). We followed this approach and adopted a simple parametric model to describe the fundamental characteristics of nutrient accumulation. Our ecological model and cost estimates reflect the circumstances in the Finnish coastal waters of the Gulf of Finland (see Laukkanen & Huhtala (2006) for details of the model calibration). The optimization problem was solved for numerically; the solution was implemented using the CompEcon Toolbox for Matlab.

The costs of agricultural nutrient abatement were assessed in a study that was part of this project (Helin et al. 2006). Agricultural runoff to the Finnish coastal waters of the Gulf of Finland originates primarily from the provinces of Uusimaa and Varsinais-Suomi, which cover approximately 21% of the Finnish arable lands. Compared to previous studies the analysis considered an extensive selection of crops and farming technologies and described them by nonlinear functional forms estimated from a large set of empirical data. The loads of two nutrients, N and P, were modeled simultaneously, where many studies have focused on a single nutrient and neglected the effect of reduction measures on the other. The model produced a quadratic abatement cost function for the region and was also applied to evaluate the effect of the Common Agricultural Policy reform on nutrient abatement costs. It is worth noting that the study ascertained abatement costs based on deterministic economic and biophysical models of agricultural production. The estimated cost function thus has to be interpreted as a mapping of the expected costs of agricultural abatement.

The special features of wastewater treatment costs were also modeled as realistically as possible. The building of wastewater treatment facilities is characterized by high set-up costs but the unit operating costs are constant, whereas in agriculture they increase as nutrient reduction targets are tightened. Our cost estimates on improved wastewater treatment and sewage systems are based on the investment outlay that would enable the construction of a tunnel sewer and an enhancement of nutrient removal at two major wastewater treatment plants in St Petersburg (Vodokanal 2005).

6.2
Results

The results suggest that in the case of the Gulf of Finland, the investment required to process the currently untreated wastewaters should be undertaken immediately. While the economically optimal abatement policy reduces the loads of both N and P, the measures only decrease the P stock but allow the N stock to increase. The study area was estimated to receive substantial N loading from sources other than Finnish agriculture and wastewater from St. Petersburg, i.e. natural background leaching and river discharge of N, which explains why economically viable agricultural and municipal abatement measures do not suffice to reduce the N stock. The damage specification also emphasizes P as a damage agent: To capture the joint effect of N and P on the environmental damage, we used a weighted sum of the two nutrients, nitrogen equivalents, as an indicator of eutrophication (see Anon. 2004, Kiirikki et al. 2003 and Lankoski et al. 2006 for a similar approach). When an N:P ratio of 7.2 is employed to convert P into N equivalents, P receives considerable weight in the damage function.

Figure 6.1 shows the optimal agricultural N abatement policy with and without wastewater treatment facilities and the associated agricultural P reduction. With no investment in wastewater treatment, the optimal policy cuts the agricultural N load in half relative to the load produced in the absence of any agricultural abatement measures, which equals 7760 t (Helin et al. 2006). With wastewater treatment, agricultural N abatement becomes minor while N removal from wastewater is at the maximum level allowed by the proposed technology. The role of agricultural abatement jointly with wastewater treatment would become more significant if the shorelines were considered as a separate pool or inland waters were included in the objective function. In our model the coastal region was considered as one pool and the state of inland waters was not included.

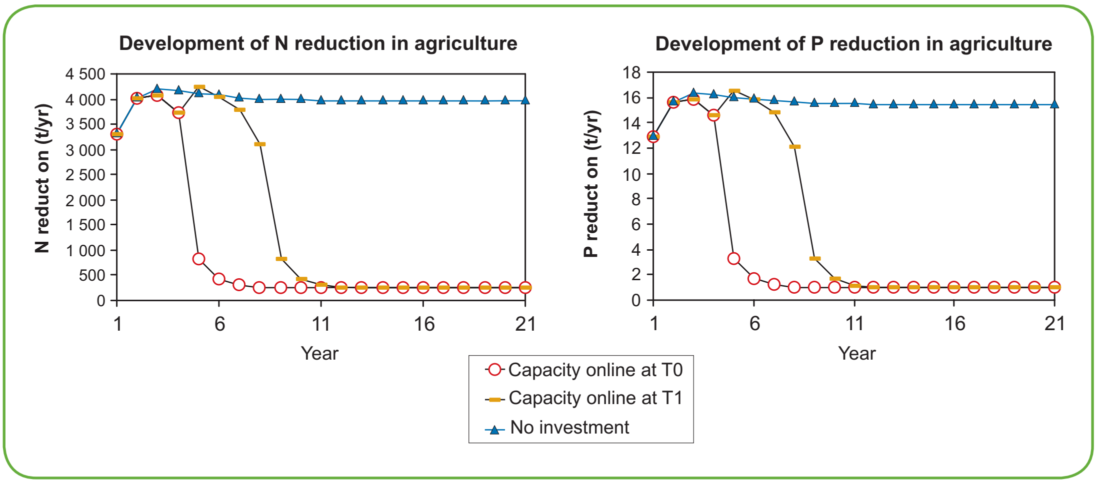

Figure 6.1. N and P reduction in agriculture in t/a, relative to the N and P loads produced by agriculture in the absence of abatement measures (7760 t/a and 522 t/a, Helin et al. 2006). P reduction is modelled at a fixed ratio to N reduction (ratio of P reduction to N reduction is 0.0039).

Figure 6.2 presents the optimal wastewater treatment policy. N removal first occurs at the projected maximum capacity of 2285 t/yr for fours years, and then falls to approximately 90% of the maximum rate. Figure 6.3 displays the socially optimal development of N and P stocks for a twenty-year time span, starting from the cur-

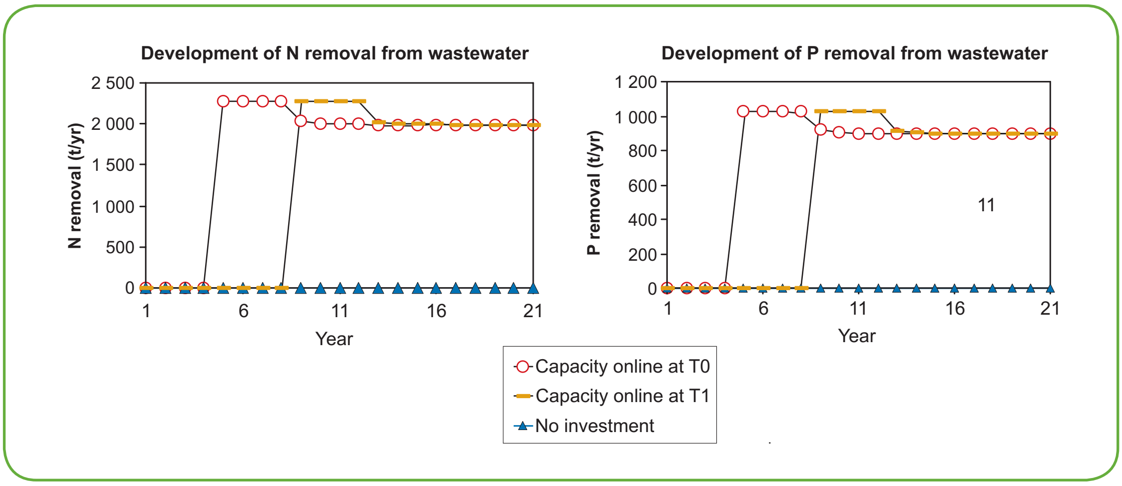

Figure 6.2. Optimal N and P removal through wastewater treatment. P removal is modeled at a fixed ratio to N removal (ratio of P removal to N removal is 0.45).

rent state. The development of the stocks in the case of no investment in wastewater treatment is depicted for comparison. Capacity is assumed to be online 4 years after the initial investment outlay if no delays occur, and 8 years after the investment if construction is delayed. Once investment has been undertaken, the N stock is allowed to increase slightly more than in the case of no investment, in anticipation of commencing wastewater treatment after 4 years. When the joint effect of N and P is measured by nitrogen equivalents, the increase in N stock is compensated for by the marked reduction in P stock afforded by wastewater treatment. However, as only modest phosphorus abatement can be achieved through agricultural measures in the present model, the investment does not affect the path of P until the time when wastewater treatment capacity is online. If a delay becomes evident after 4 years, agricultural abatement increases, and the nitrogen stock is brought back into line with the path that is optimal without investment. After 8 years, wastewater treatment commences even if construction was delayed; agricultural abatement declines, and the N stock is allowed to increase.

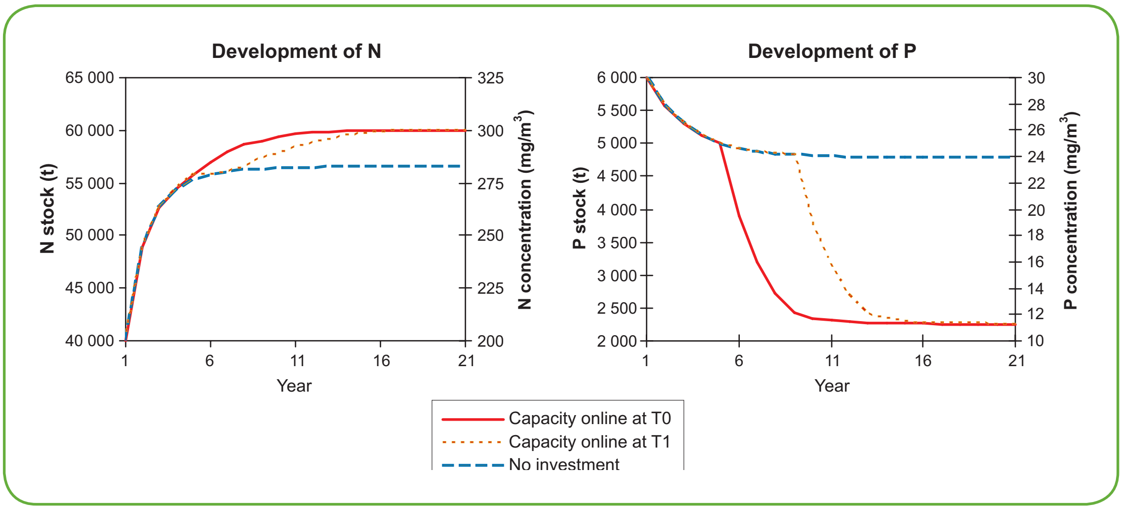

Figure 6.3. The development of N and P stocks under the optimal policy.

For any stock level the optimal agricultural abatement rate is substantially smaller when wastewater treatment facilities are online than when wastewater processing is not an option. The result is explained by the cost differences in agricultural abatement and wastewater treatment. Helin et al. (2006) found that an efficiently designed policy aimed at a 50% reduction in agricultural nitrogen load, relative to the level without abatement measures, would cost € 48 to € 35 million. The average costs would be € 7.2 to € 9.4 per kg of nitrogen abatement, whereas the operational costs of wastewater treatment used in this study were € 4.5 per kg of nitrogen removal.

To evaluate the reliability of our model, we carried out a number of sensitivity analyses. While immediate investment is optimal in the baseline case discussed above, the result is sensitive to the model parameterization. A 10% decrease in all nutrient loads in the absence of abatement, in the annual carry-over of phosphorus, or in the agricultural abatement costs render it optimal to refrain from investment. It is worth noting here that the abatement cost estimate derived from Helin et al. (2006) does not account for information asymmetries and costs of monitoring and enforcement, which is likely to cause the abatement costs to be underestimated rather than overestimated. By contrast, the decision to invest was robust to the willingness to pay measure: immediate investment was also optimal when the willingness to pay was reduced by 50%. The same holds for a 10% increase in the operating costs of wastewater treatment facilities.

Deriving a single ecological indicator linking nutrients and the degree of eutrophication poses a challenge. In particular, the weights that should be given to the two nutrients are difficult to assess definitively. As an alternative mapping from the nutrient levels to damage from eutrophication, we considered one where nitrogen and phosphorus have equal weights in the damage function. The decision to invest was robust to the alternative damage specification: it remained optimal to invest immediately. As could be expected, the target nitrogen stock was notably below the baseline level, and agricultural abatement had a more important role than in the baseline scenario. With nitrogen receiving a higher relative weight, nutrient abatement yields greater benefits than in the baseline case. In summary, not only the costs of abatement of the two nutrients but how their contribution to the environmental damage is taken into account affect the optimal policies.

6.3
Conclusions

- Under the base case calibration, it would be optimal to invest immediately in construction of additional wastewater treatment capacity in St. Petersburg. Wastewater treatment would then become the principal abatement measure.
- The result that the investment should be undertaken immediately is not self-evident. While the willingness to pay for reducing eutrophication is high enough to justify active measures, the optimal policy was found to hinge on the ecological modelling.
- The finding underlines the need to reconcile economic and ecological models to provide guidelines for nutrient abatement policies that are sound in both areas.
- The model identifies the key features determining how to optimally balance wastewater treatment and agricultural abatement. However, to date there is still considerable uncertainty about the specific values of many model variables and parameters, in particular those pertaining to loads and abatement costs.

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7 Extended summary, conclusions and recommendations

The Gulf of Finland is an ideal case for testing and developing approaches for the abatement of eutrophication. It is the most eutrophied sub-basin of the Baltic Sea and receives direct nutrient loading from three surrounding countries: Finland, Russia and Estonia. The SEGUE Consortium combined and analysed new scientific information on the eutrophying effects of nutrient loads and the biogeochemical processes controlling eutrophication of the Gulf, in combination with an evaluation of the policy processes that aim at reducing the loads within the Baltic Sea area. The study also contributed to the research on optimal pollution control, and provided new information that can be used in developing environmental policies in practise.

Nutrient loading and coastal retention

The external nutrient load relative to the surface area of the Gulf of Finland is two to three times that of the corresponding average for the whole Baltic Sea. It could in fact be even larger without considerable lake retention in the catchment area. The largest lake in Europe, Lake Ladoga, retains about 70% of the total phosphorus and about 30 % of the nitrogen load from its catchment. The River Neva, which receives its waters from the lake, is the largest single source of total nitrogen into the Gulf of Finland and is responsible for about 30% of the total external N load. Regarding phosphorus, the city of St Petersburg is the largest source, discharging about 40% of the total external load.

A number of processes affect the eventual fate of the external nutrient load, however, and all of it is not immediately available to primary producers in the receiving water body. Algal availability tests using a brackish water algal species suggested that about 50% of the total P load of the rivers Neva and Kymijoki is bioavailable. These new values, which are higher than those earlier obtained with a freshwater test algae, were used in SEGUE's model scenarios. Part of the riverine loads may also be retained in estuaries. The nitrogen removal efficiency of the studied estuaries (Paimionlahti and Ahvenkoskenlahti) was low, however. Paimionlahti Bay, where the sedimentation rate was high, seemed to retain silicon quite efficiently, while the retention in Ahvenkoskenlahti Bay was lower. Phosphorus accumulated in the sediments of both the studied estuaries. The estuarine phosphorus retention capacity may, further, be affected by the amount of iron-rich riverine eroded soil matter which is transported to estuaries from the catchment areas. This hypothesis should be comprehensively tested as it would have immense implications for the agri-environmental measures applied to abate eutrophication in coastal areas.

Sediment-water nutrient dynamics

Although the external load into the Gulf of Finland decreased by about one third during the 1990s, the eutrophication of the Gulf has continued. This has been connected to a strong increase in the benthic release of nutrients, especially that of phosphorus, while nitrogen concentrations of the sea have diminished along with the decreased external load.

Nitrogen removal (reduction to molecular nitrogen, N_2) from accumulation sediments near the coast and in the open Gulf of Finland are of similar magnitude. The results show that the main process removing nitrogen from the system, denitrification, is also able to remove nitrogen during short periods of anoxia, and that another nitrogen-removing process, anammox, that combines ammonium with nitrite to nitrogen gas, is responsible for 10–17% of the total N_2 reduction. Together denitrification and anammox seem to be able to remove an amount of nitrogen that is about half of the annual external load of algal available nitrogen into the Gulf of Finland. There are, however, large gaps in the present quantitative knowledge of these processes.

Sediments in the estuaries and along the north-eastern coast of the Gulf of Finland contained relatively high concentrations of iron-bound phosphorus during sampling. To maintain the ability of the sediments to retain phosphorus in these areas, the sediments should stay in oxidized condition. The coastal and open sea sediments in the north-eastern Gulf contained large amounts of organic phosphorus, part of which is slowly degraded in mineralization processes. The areas with high concentrations of both iron-bound and degradable organic phosphorus form a large pool of potentially bioavailable phosphorus for the Gulf. On the contrary, the open sea sediments in the middle and western Gulf had low concentrations of iron-bound and organic phosphorus, and thus low reserves of potentially bioavailable phosphorus. Under the environmental conditions that prevailed during sampling, the sediments of the eastern Gulf of Finland thus contained higher concentrations of phosphorus that may potentially be released compared to the open sea sediments of the middle and western Gulf.

Studies on the third nutrient affecting the planktonic dynamics of the Baltic Sea, silicon, show that sediment in the Gulf of Finland can bind silicon efficiently under both reduced and oxidized circumstances, which contrasts strongly with the corresponding behaviour of phosphorus. Accordingly, no such switch-back mechanism at the sediment surface is apparent that would drastically increase the sediment release of silicon, and thus compensate for observed decreases in external loading. Decreased availability of silicon in spring may lead to decreasing sedimentation of organic material and concomitantly diminish the risk of reduced conditions at the sediment surface and redox-sensitive release of phosphorus. The lack of silicon may, however, also affect the structure of the plankton community and favour other, potentially more harmful groups. The burial rate of biogenic silica in the sediments of the Gulf of Finland is high compared to the external loading of silicon, indicating that a large part of it enters the Gulf via the deep inflow from the Baltic Proper.

Modelling and state scenarios

Test results of the main modeling tool of the present study, the EIA-SYKE 3D ecosystem model, suggest that the model is able to describe the key internal nutrient fluxes of the Gulf of Finland, as well as the exchange between the Gulf and the Baltic Proper, relatively reliably. The model works better in the western than in the eastern Gulf, where the vertical mixing of water, as well the transfer of nutrients into the productive surface layer, is somewhat overestimated by the model.

A combined modeling tool was developed in the project by integrating the EIA-SYKE model with the SANBALTS box-model developed in the Swedish MARE Project, which allowed the creation of long-term state scenarios with high spatial resolution. According to scenario runs with this tool, combating eutrophication on the scale of the Gulf of Finland and its adjacent waters requires strong reductions especially in large nutrient loading sources within the entire Baltic Sea catchment area. This concerns big cities with missing or poor waste water treatment and large rivers with extensive agricultural loading in their catchments. The time-lag between purification measures and actual effects varies in different parts of the Baltic Sea, mostly due to the high variation in water residence times between the different basins. In the Gulf of Finland, improvements in water quality due to reductions in regional nutrient sources can be expected to occur more rapidly than in the Baltic Proper. Similarly, load reductions to the Baltic Proper will affect other basins like the Gulf of Finland, but slowly. Even in the long run, local Finnish load reductions mainly affect the coastal waters near the loading sources.

It seems that even with the most stringent load reduction scenarios of the present study, phytoplankton biomasses in the Gulf of Finland will stay above the preliminary target value representing Good Ecological Status presumed by EC's Water Framework Directive.

Economically optimal policies for the abatement of eutrophication

According to the integrated economic-ecosystem optimization model developed in the project, it would be optimal to invest immediately in construction of additional wastewater treatment capacity in the city of St Petersburg, instead of aiming at major reductions in Finnish agricultural nutrient loads. However, the result that the investment to St Petersburg should be undertaken immediately is not self-evident. A sensitivity analysis showed that relatively small changes in the ecological components of the model can reverse the outcome, and to date there is still considerable uncertainty about the specific values of many model variables and parameters, in particular those pertaining to loads and abatement costs. In contrast, the decision to invest in wastewater treatment capacity was found robust to changes in the parameters describing the damage, which are the most uncertain economic parameters. These findings underline the need to reconcile economic and ecological models to provide guidelines for nutrient abatement policies that are sound in both areas.

Recommendations

The results of the present study suggest that it is not possible to combat eutrophication of the Baltic Sea without considerable reductions at all the major nutrient sources both by the coastline and also at more far-away sources in the catchment. This result seems to be valid both from the viewpoints of ecological effects and cost-benefit analysis. Regarding the Baltic waters around Finland the fastest results can be reached via effective purification of all the waste waters of St Petersburg. From a longer time perspective (decades) effective load reductions at the major sources entering the Baltic Proper will also improve the state of the northern parts of the Baltic Sea in addition to the Baltic Proper itself. At present, most of the large point-load sources where extensive and rapid load reductions could be reached are located in the new EU countries and in Russia.

In Finland, decreasing nutrient loads particularly from the largest source, agriculture, by 40–50 % from the current loads – as presented in the background report of the Guidelines for Water Protection to 2015 and in the Finland's Programme for the Protection of the Baltic Sea – would improve the state of the coastal waters, especially in the Archipelago Sea. However, this will require much more effective measures against nutrient losses from field cultivation than those that have been taken in recent decades. The outer parts of the Archipelago Sea seem to benefit strongly from load cuttings at large, far-away sources.

The diffuse loading from Russia and Estonia into the Gulf strongly decreased in the early 1990s, due to the collapse of the Soviet Union and the strong accompanying decrease in both animal husbandry and field cultivation. It is possible that the recovery of agricultural production in these countries will increase the nutrient loading into the surface waters anew, and precautionary measures should, if possible, be taken to avoid this.

There are still large gaps in the understanding of nutrient dynamics in both the coastal and open Gulf of Finland as well as in the whole Baltic Sea. Even such very basic information as the size of the nutrient loads into the Baltic Sea is in some cases inadequately known and requires higher monitoring frequencies and more careful quality assurance in laboratories. This should be performed under HELCOM and, for the Gulf of Finland, also under the Estonian-Finnish-Russian Trilateral Co-operation. Further experimental research is also urgently needed to assess the role of riverine eroded matter in estuaries and coastal waters and the potential bioavailability of organic P in the coastal and open sea sediments of the Gulf of Finland.

Especially the role of sediment processes, which recently have been more important than the external loading in controlling the state of the Baltic Sea, should be much more thoroughly investigated. This concerns e.g. the role and control of nitrogen removal, as well as the role of the different potentially bioavailable pools of nitrogen, phosphorus and silicon in sediment and water.

Ecosystem modeling should be developed in direct communication with process studies and economic modelling. This would produce better tools for scientists and decision makers to evaluate the effects of the different protection strategies, and to test the sensitivity of the Baltic Sea ecosystem to external perpetuations.

Yhteenveto, johtopäätökset ja suositukset

Suomenlahti on Itämeren rehevin osa-allas. Siihen kohdistuu suoraa ravinnekuormitusta kolmesta maasta: Suomesta, Venäjältä ja Virosta, ja siten se soveltuu erinomaisesti rehevöitymisen torjuntaan tähtäävien kansallisten ja kansainvälisten toimenpiteiden testaukseen ja kehittämiseen. SEGUE-hanke kokosi ja analysoi tietoa ravinnekuormituksen rehevöittävistä vaikutuksista sekä biogeokemiallisista prosesseista Suomenlahdella. Projektissa tutkittiin, miten vesiensuojelun päätökset ja tavoiteohjelmat vaikuttavat merialueen tilaan, ja kehitettiin käytännön ympäristöpoliittisten toimien toteutuksen arviointiin ekologisen ja taloustieteellisen mallinnuksen yhdistävää optimointimallia.

Ravinnekuormitus ja rannikon pidätyskyky

Suomenlahden ulkoinen ravinnekuormitus on pinta-alaan suhteutettuna huomattavasti suurempi kuin Itämerellä keskimäärin. Ilman valuma-alueen järvien pidätystä se olisi vieläkin suurempi, ja erityisesti Laatokan suurella ravinteiden pidättämiskyvyllä (noin 70 % tulevasta fosforista ja 30 % typestä) on huomattava merkitys Suomenlahden tilalle. Laatokasta Suomenlahteen laskeva Nevajoki on Suomenlahden suurin yksittäinen typpikuormituslähde (n. 30 % koko ulkoisesta kuormasta) ja Pietarin kaupunki suurin fosforinlähde (40 % ulkoisesta kuormasta).

Levätestien avulla arvioitiin, että noin 50 % Nevan ja Kymijoen kokonaisfosforikuormituksesta oli leville käyttökelpoista. Ravinteiden käyttökelpoisuus yhdessä rannikon prosessien kanssa vaikuttaa siihen, miten paljon ulkoisesta ravinnekuormituksesta päätyy ulompana merellä levien käyttöön. Jokivesien mukana tulevaa fosforia ja piitä pidättyi kohtalaisen tehokkaasti tutkittuihin jokisuualueisiin (Paimionlahti ja Ahvenkoskenlahti), mutta typen pidättyminen oli vähäistä. Tutkimuksissa tuli ilmi, että jokikuorman mukana tulevan eroosioaineen koostumus, erityisesti korkea rautapitoisuus, saattaa tehostaa jokisuualueen fosforinpidätyskykyä. Hypoteesi vaatii perusteellista lisätarkastelua, koska sillä voi olla vaikutuksia rannikkoalueilla harjoitetun maatalouden vesiensuojelutoimiin.

Ravinnevirrat sedimentin ja veden välillä

Vaikka ulkoinen ravinnekuormitus Suomenlahteen väheni noin kolmanneksella 1990-luvun aikana, merialueen rehevöityminen on jatkunut. Ravinteiden, erityisesti fosforin, vapautuminen sedimentistä on vaikuttanut voimakkaasti tähän. Typpipitoisuus sen sijaan aleni 1990-luvulla samalla kun merialueen ulkoinen typpikuorma pieneni.

Typenpoistoprosessit eli denitrifikaatio, anammox ja hautautuminen sedimenttiin poistavat Suomenlahdesta karkeasti yhtä paljon biologisesti käyttökelpoista typpeä kun ulkoisen kuormituksen mukana tulee. Anammox-prosessi vastasi tutkimustulosten mukaan 10–17 % ja denitrifikaatio 83–90 % mikrobiologisesta typen poistumasta typpikaasuna. Denitrifikaatio kykenee poistamaan typpeä myös lyhyiden täysin hapettomien kausien aikana. Kvantitatiivinen tietämys Itämeren typpitaseesta ja typenpoistoon vaikuttavista prosesseista on edelleen monilta osiltaan puutteellinen.

Tutkittujen jokisuualueiden ja Suomenlahden pohjoisen rannikkovesialueen sedimenteissä oli tutkimusajankohtana runsaasti rautaan sitoutunutta fosforia. Jotta fosfori säilyisi sedimenttiin sitoutuneena, näiden alueiden pintasedimenttien pysyminen hapettuneina on tärkeää. Itäisen Suomenlahden Suomen puoleisen rannikon ja ulappa-alueen sedimenteistä löytyi myös runsaasti orgaanista, hitaasti käyttökelpoiseen muotoon hajoavaa fosforia. Suomenlahden keski- ja länsiosien sedimenteissä sen sijaan mitattiin vain vähän vapautumiskelpoista fosforia. Suomenlahden itäosa, jossa sekä rautaan sitoutunutta että helposti hajoavaa orgaanista fosforia on runsaasti, muodostaa suuren potentiaalisen rehevöittävän fosforin varaston. Vastaavasti Suomenlahden keski- ja länsiosassa varastot olivat näytteenottoajankohtana pienet, koska näiden alueiden sedimentteihin ei huonojen happiolojen vuoksi ollut sitoutunut merkittäviä fosforimääriä.

Suomenlahden sedimentteihin hautautuu piitä sekä hapellisissa että hapettomissa oloissa. Yhdistettynä todettuun ulkoisen piikuormituksen pienentymiseen tämä saattaa tulevaisuudessa heikentää piilevien kilpailukykyä, ja vastaavasti vahvistaa esimerkiksi potentiaalisesti haitallisten panssarisiimalevien tai sinilevien kilpailuasemaa pintavedessä. Piilevien kevätkukinnan pieneneminen tosin myös vähentäisi orgaanisen aineksen sedimentaatiota, mikä saattaisi parantaa pohjanläheisen vesikerroksen ja sedimentin pinnan happitilannetta, ja siten vähentää fosforin sisäistä kuormitusta. Näyttää siltä, että Suomenlahden jokien tuoma piimäärä ei yksin riitä pitämään yllä alueen piilevien tuotantoa, vaan merkittävä osa Suomenlahden piistä on peräisin Itämeren pääaltaasta.

Mallinnus ja skenaariot

Tutkimuksessa sovellettu kolmiulotteinen ekosysteemimalli (EIA-SYKE) kuvaa verrattain hyvin Suomenlahden sisäisiä ravinnevirtoja sekä Suomenlahden ja Itämeren pääaltaan välistä ravinteiden vaihtoa. Malli toimii paremmin läntisellä kuin itäisellä Suomenlahdella, jossa malli yliarvioi vertikaalista sekoittumista ja samalla ravinteiden pääsyä tuottavaan pintakerrokseen.

Hankkeessa kehiteltiin mallinnustyökalu, jossa EIA-SYKE-mallin ja ruotsalaisen MARE-projektin kehittämä yksiulotteinen mallin käyttö yhdistettiin. Näin pystyttiin simuloimaan Suomenlahdelle yli 30 vuoden pituisia tilaennusteita, joiden alueellinen erottelukyky on 5 km. Malliajojen perusteella Suomenlahden tilan parantamiseksi on tärkeää, että erityisesti isojen päästölähteiden (suuret kaupungit, isot maatalouden kuormittamat joet) ravinnekuormitusta vähennettäisiin voimakkaasti koko Itämeren valuma-alueella. Suomenlahden valuma-alueella tehtävien kuormitusleikkausten vaikutus merialueen vedenlaatuun näkyisi kuitenkin paljon nopeammin kuin Itämeren pääaltaan valuma-alueella tapahtuvien leikkausten vaikutus. Kotimaisilla päästöleikkauksilla on lähinnä paikallinen vaikutus omissa rannikkovesissämme ja vaikutukset ilmenisivät nopeasti päästöleikkausten jälkeen.

Mallinnustulosten mukaan EU:n vesipuitedirektiivin mukainen hyvä ekologinen tila tulee olemaan hyvin vaikea saavuttaa Suomenlahdella siinäkin tapauksessa, että myös Itämeren pääaltaan valuma-alueella tehdään tuntivia ravinnepäästöjen leikkauksia.

Miten rehevöitymistä voidaan torjuta taloudellisesti optimaalisella tavalla?

Projektissa kehitetyn yhdistetyn ekologisen ja taloustieteellisen mallin mukaan olisi kannattavampaa investoida välittömästi Pietarin puhdistamattomien jätevesien käsittelyyn (pohjoinen kokoomatunneli) kuin Suomen maatalouskuorman vähentämiseen Suomenlahden rannikkovaluma-alueella. Mallin tulokset ovat kuitenkin varsin herkkiä pienillekin muutoksille ekologisissa tekijöissä. Myös mm. kuormitusmääriä ja puhdistustoimenpiteiden kustannuksia kuvaavat muuttujat kaipaavat vielä tarkennusta. Toisaalta mallin antaman tuloksen herkkyys rehevöitymisestä aiheutuvalle taloudelliselle haitalle (taloudellisen mallin epävarmin osa) oli varsin vähäinen. Tulokset osoittavat selkeästi, että ekologisten ja taloudellisten mallien yhteensovittamisen jatkaminen on tärkeää, jotta rehevöitymisen torjuntaan tähtäävät suositukset olisivat kummassakin suhteessa vakaalla pohjalla.

Suositukset

SEGUE-hankkeen tulosten mukaan Itämeren rehevyyden torjuminen ei ole mahdollista ilman merkittävimpiin ravinnelähteisiin kohdistuvia huomattavia leikkauksia. Tulos on sopusoinnussa myös Itämeren piirissä tehtyjen kustannustehokkuustarkastelujen kanssa. Nopein tapa parantaa Suomen lähivesien tilaa olisi kaikkien Pietarin yhdyskuntajätevesien saattaminen tehokkaan puhdistuksen piiriin, mutta vuosikymmenien aikaskaalassa kaikki riittävän suuret leikkaukset ravinnekuormituksessa koko Itämeren valuma-alueella vaikuttaisivat myönteisesti myös Suomea ympäröivän Itämeren tilaan. Tällä hetkellä tällaiset kohteet sijaitsevat etupäässä Venäjällä ja uusissa EU-maissa.

Suomen rannikkovedet hyötyisivät merkittävästi suurimman kotimaisen kuormittajan, maatalouden, ravinnepäästöjen leikkaamisesta. Vähennyksen tulisi olla luokkaa 40-50 % nykykuormista Suomen Itämeren suojeluohjelman ja Vesiensuojelun suuntaviivat 2015 taustaselvityksen tiukimman SOVA-vaihtoehdon mukaisesti. Tämä vaatii kuitenkin huomattavasti viime vuosina toteutettuja toimia tehokkaampia menetelmiä erityisesti pelloilta vesistöihin ja rannikkovesiin kulkeutuvien ravinnemäärien pienentämiseksi. Suomen rannikkovesialueista erityisesti Saaristomeri hyötyisi sekä kotimaisista että kauempana toteutetuista ravinteiden kuormitusleikkauksista.

Venäjältä ja Virosta peräisin oleva ravinnekuorma pieneni voimakkaasti 1990-luvun alussa Neuvostoliiton hajoamisen seurauksena, jolloin sekä karjankasvatuksen että peltoviljelyn intensiteetti romahti. On mahdollista, että hajakuormitus on kääntymässä uudestaan nousuun taloudellisen tilanteen parantuessa Virossa ja Venäjällä. Tähän olisi syytä varautua mm. edelleen tehostamalla maatalouden kuormituksen seurantaan ja vähentämiseen tähtäävää kansainvälistä yhteistyötä. Venäjän Itämereen laskevien jokien ravinnekuormitustiedoissa on huomattavia epätarkkuuksia ja kuormituksen seuranta tulisi saattaa Itämerikomission (HELCOM) suositusten mukaiseksi.

Sekä rannikkovesien että avoimen Itämeren ravinnedynamiikka on vielä monilta osiltaan puutteellisesti tunnettu. Kokeellista tutkimusta tulisi lisätä mm. siten, että keskeisten ravinneprosessien alueellinen ja ajallinen vaihtelu hallittaisiin kvantitatiivisesti koko Itämeren piirissä. Maalta peräisin olevan eroosioaineen vaikutuksia jokisuualueiden ravinteiden pidätyskykyyn sekä Itämeren sedimenttien orgaanisen fosforivaraston merkitystä rehevöitymisessä tulisi selvittää. Myös luonnolliseen typenpoistoon vaikuttavat tekijät ja eri ravinteiden potentiaalisesti käyttökelpoiset varannot vedessä ja sedimentissä vaativat lisää tutkimusta. Ekosysteemimallinnusta tulisi kehittää läheisessä yhteistyössä prosessitutkimuksen ja taloudellisen mallintamisen kanssa. Tämä tuottaisi entistä parempia työkaluja, joiden avulla tutkijat ja poliittiset päättäjät voisivat arvioida eri vesiensuojelustrategioita ja Itämeren ekosysteemin tilaa.

DOCUMENTATION PAGE

Publisher	Finnish Environment Institute			*Date* May 2007
Authors	Heikki Pitkänen and Petra Tallberg (eds)			
Title of publication	**Searching efficient protection strategies for the eutrophied Gulf of Finland: the integrated use of experimental and modelling tools (SEGUE)**			
Publication series and number	Finnish Environment 15/2007			
Theme of publication	Environmental protection			
Parts of publication/ other project publications	The publication is available on the internet: www.environment.fi/publications			
Abstract	The SEGUE-project assembled and analysed new information about the eutrophying effects of nutrient loading and the biogeochemical processes which affect nutrient cycling in the Gulf of Finland and the Archipelago Sea. The project also studied how political decisions and policies concerning water protection affect the state of the Gulf. In addition, modelling tools were developed to evaluate the effects of practical environmental policy implementation. Lake Ladoga is of prime importance for the state of the Gulf of Finland: it retains 75 % of the phosphorus and 30 % of the nitrogen it receives. About half of the bioavailable nitrogen load that ends up in the Gulf of Finland is removed by nitrogen removal processes (denitrification and anammox). In the western and middle areas of the Gulf the sediments retain very little phosphorus due to the poor oxygen conditions. In the eastern part, where the oxygen conditions usually are better, large amounts of potentially eutrophying phosphorus are stored in the sediments. Significant amounts of silicon are buried in the Gulf of Finland sediments under both reduced and oxidized conditions. Effective purification of all the waste waters of St Petersburg would be the quickest way to improve the state of the Baltic waters around southern Finland. From a longer time perspective, all effective load reductions at the major sources entering the Baltic Proper would also improve the state of the Gulf of Finland and adjacent waters. In Finland, the state of the coastal waters, especially in the Archipelago Sea, would also clearly improve from cuts in the nutrient loads from the largest domestic source, agriculture. According to the integrated economic-ecosystem optimization model it would be optimal to invest immediately in construction of additional wastewater treatment capacity in the city of St Petersburg, instead of aiming at major reductions in Finnish agricultural nutrient loads.			
Keywords	Gulf of Finland, Archipelago Sea, eutrophication, loading, water protection, 3D-model, phosphorus, silicon, nitrogen, sediments, Baltic Sea, drainage area, nutrients, economic models, agriculture, ecology, modelling			
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KUVAILULEHTI

Julkaisija	Suomen ympäristökeskus	*Julkaisuaika* Toukokuu 2007
Tekijä(t)	Heikki Pitkänen and Petra Tallberg (toim.)	
Julkaisun nimi	**Kokeellisen tutkimuksen ja mallinnuksen yhteiskäyttö Suomenlahden tehokkaan suojelun välineenä (SEGUE)**	
Julkaisusarjan nimi ja numero	Suomen ympäristö 15/2007	
Julkaisun teema	Ympäristönsuojelu	
Julkaisun osat/ muut saman projektin tuottamat julkaisut	Julkaisu on saatavana myös intenetissä: www.environment.fi/publications	
Tiivistelmä	SEGUE-hanke kokosi ja analysoi uutta tietoa ravinnekuormituksen rehevöittävistä vaikutuksista sekä ravinnekiertoon vaikuttavista biogeokemiallisista prosesseista Suomenlahdella ja Saaristomerellä. Projektissa tutkittiin vesiensuojelun päätösten ja tavoitteiden vaikuttavuutta Suomenlahden tilaan, sekä kehitettiin mallinnustyökaluja käytännön ympäristöpoliittisten toimien toteutuksen arviointiin. Laatokalla on suuri merkitys Suomenlahden tilalle: se pidättää 75 % vastaanottamastaan fosforista ja 30 % typestä. Suomenlahteen kuormituksen mukana päätyvästä leville käyttökelpoisesta typestä noin puolet poistuu typenpoistoprosessien eli denitrifikaation ja anammoxin vaikutuksesta. Suomenlahden länsi- ja keskiosan sedimentit pidättävät rehevöittävää fosforia hyvin huonosti alueiden huonojen happiolojen vuoksi. Sen sijaan itäosassa, jossa happilot yleensä ovat kohtuullisen hyvät, pohjasedimenteissä on varastoituneena suuri määrä potentiaalisesti rehevöittävää fosforia. Huomattavia määriä kevään planktontuotannolle tärkeää piitä hautautuu Suomenlahden sedimentteihin sekä hapellisissa että hapettomissa oloissa. Malliskenaarioiden mukaan tehokkain ja nopein tapa parantaa Suomen lähivesien tilaa olisi Pietarin yhdyskuntajätevesien tehokas puhdistus. Pitkällä aikavälillä kaikki isot leikkaukset Itämeren valuma-alueelta tulevaan ravinnekuormaan vaikuttaisivat myönteisesti myös Suomenlahden ja sen lähivesien tilaan. Suomen rannikon läheiset vedet, erityisesti Saaristomeri, hyötyisivät selkeästi myös suurimman kotimaisen kuormittajan, maatalouden, päästöjen leikkaamisesta. Ekologis-taloudellisen mallinnustar-kastelun mukaan Pietarin käsittelemättömien jätevesien puhdistaminen on välittömänä investointikohteena kannattavampi kuin Suomen maatalouskuorman vähentäminen.	
Asiasanat	Suomenlahti, rehevöityminen, kuormitus, vesiensuojelu, maatalous, 3D-malli, fosfori, pii, typpi, Itämeri, valuma-alue, ravinteet, taloudelliset mallit, maatalous, ekologia, mallinnus	
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Painopaikka ja -aika	Vammalan Kirjapaino Oy, 2007

PRESENTATIONSBLAD

Utgivare	Finlands miljöcentral	*Datum* Maj 2007
Författare	Heikki Pitkänen and Petra Tallberg (red)	
Publikations titel	**Kombinerad experimentell och modellbaserad forskning som bas för effektivt skydd av Finska viken (SEGUE)**	
Publikationsserie och nummer	Finlands miljö 15/2007	
Publikationens tema	Miljövård	
Publikationens delar/ andra publikationer inom samma projekt	Publikationen finns tillgänglig på internet: www.environmet.fi/publications	
Sammandrag	SEGUE-projektet sammanställde och analyserade ny information om de eutrofierande verkningarna av den yttre belastningen av näringssalter samt om de biogeokemiska processer som påverkar cirkulationen av näringssalter i Finska viken och Skärgårdshavet. Projektet studerade också hur beslut och program inom vattenskyddet påverkar Finska vikens tillstånd. Modeller för att utvärdera verkställandet av miljöpolitiska åtgärder i praktiken utvecklades också. Ladoga är av stor betydelse för Finska vikens tillstånd: sjön kvarhåller 75 % av det fosfor och 30 % av det kväve den tillförs. Cirka hälften av det kväve som tillförs Finska viken via belastningen bortförs av kväveborttagningsprocesserna denitrifikation och anammox. Sedimenten i Finska vikens västra och mellersta delar kvarhåller eutrofierande fosfor mycket dåligt på grund av de dåliga syreförhållandena där. Å andra sidan finns stora mängder potentiellt eutrofierande fosfor lagrade i sedimenten i östra Finska viken, där syreförhållandena i regel är bättre. Relativt stora mängder kisel begravs i Finska vikens bottensediment under såväl syrerika som syrefattiga förhållanden. Enligt modellscenaria skulle det snabbaste sättet att förbättra Finlands närvattenområdens tillstånd vara att effektivt rengöra samhällsavloppsvattnet från St Petersburg. I ett längre tidsperspektiv påverkar dock alla större nedskärningar i näringsämnesbelastningen inom hela Östersjöns avrinningsområde också Finska vikens och dess närliggande vattens tillstånd i positiv riktning. Vattnen nära den finska kusten, speciellt i Skärgårdshavet, skulle också klart dra nytta av nedskärningar som rör den största inhemska belastningskällan, lantbrukets, utsläpp. Enligt den ekologiska-ekonomiska modellen skulle det vara lön-sammare att omedelbart investera i rening av St Petersburgs avloppsvatten än i nedskärningar av belast-ningen från Finlands lantbruk.	
Nyckelord	Finska Viken, Skärgårdshavet, eutrofiering, belastning, vattenskydd, 3D-modell, fosfor, kisel, kväve, sediment, Östersjön, avrinningsområde, näringssalter, ekonomiska modeller, lantbruk, ekologi, modellering	
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Effective purification of all the waste waters of St Petersburg would be the quickest way to improve the state of the open Baltic waters around southern Finland. From a longer time perspective, all effective load reductions at the major sources entering the Baltic Proper would also improve the state of the Gulf of Finland and adjacent waters. In Finland, the state of the coastal waters would clearly improve from cuts in the nutrient loads, especially from the largest domestic source, agriculture. According to the integrated economic-ecosystem optimization model it would be optimal to invest immediately in construction of additional wastewater treatment capacity in the city of St Petersburg, instead of aiming at major reductions in Finnish agricultural nutrient loads.

THE EUTRIPHIED GULF OF FINLAND (SEGUE)

SEGUE

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