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LONG-TERM CHANGES OF NUTRIENT FLUXES IN THE DRAINAGE BASIN OF THE GULF OF FINLAND – APPLICATION OF THE POLFLOW MODEL

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

DOKTORITÖÖ LOODUS- JA TÄPPISTEADUSTES

TOITEELEMENTIDE TRANSPORDI PIKAAJALISED MUUTUSED SOOME LAHE VESIKONNAS – POLFLOW MUDELI RAKENDUS

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1. Introduction

1.1. Background

1.1.1. Eutrophication

Load of nutrients as the reason for eutrophication

Lakes and estuaries, but also Baltic Sea, can eutrophy naturally through their geological time due to land-derived nutrients which enter these waterbodies (Bianchi et al., 2000). However, human activities can accelerate the rate at which nutrients enter ecosystems. Agriculture, sewers, and other anthropogenic sources increase the flux of nutrients into aquatic ecosystems. Of various nutrients, nitrogen (N) and phosphorus (P) cause most often attention regarding eutrophication due to high N and P requirements of plants. Additions of N or P compounds usually stimulate primary production. If natural and human-related inputs over-saturate terrestrial ecosystems with nutrients then their leakage to groundwater and surface water increases, causing eutrophication (Hornung, *et al*., 1995).

Ecological effects

Human activities have significantly affected the global cycling of nutrients in coastal systems. Numerous ecological effects can arise where primary production is stimulated, but there are two particularly troubling ecological impacts: decreased biodiversity and toxicity effects.

Decreased biodiversity. Increase of nutrients in a waterbody enhances primary producers first, causing also algal blooms. Such blooms tend to disturb the ecosystem by limiting sunlight to bottom dwelling organisms and by causing wide swings in the amount of dissolved oxygen in the water. Oxygen is required by all respiring plants and animals in an aquatic environment and it is replenished in daylight by photosynthesizing plants and algae. Under eutrophic conditions, dissolved oxygen greatly increases during the day, but decreases during dark time due to respiration. When dissolved oxygen levels decline to hypoxic levels, fish and other marine animals suffocate. As a result, fish, shrimp, and immobile bottom dwellers may die off (Horrigan et al. 2002). In extreme cases, called ‘dead zones’, anaerobic conditions promote growth of toxic bacteria such as *Clostridium botulinum* which kill birds and mammals.

Toxicity. Some algal blooms, otherwise called "nuisance algae" or "harmful algal blooms," poison plants and animals. Toxic compounds produced by the algae can climb up the food chain, resulting in animal mortality (Anderson 1994).

Socio-economic impacts

Health impacts. Water toxicity may directly harm human health while bathing, via food web and in case water is used for drinking.

Recreational impacts. Algal blooms harm the aestetics of the waterbody with changed color, reduced transparency and odoration. Coastal macrophytes may hinder the access to waterbody.

Fishery impacts. A common side-effect of eutrophication is substitution of high-quality fish with low-quality fish. Thus, the revenue from fishery often decreases as a result of eutrophication.

Present situation

The global problem of harmful algal blooms (HAB) in estuarine and coastal waters in the end of 20th century worsened (Anderson 1989; Smayda 1990; Hallegraeff 1993). Most of coasts in the world suffer from the threat of harmful or toxic algal blooms. Since Second World War, the load of P and N to the coastal waters multiplied (Caraco 1995; Smil 2001). In densely populated coastal regions these anthropogenic inputs have increased the nutrient pool which has promoted HAB species (Anderson et al, 2002; Smayda, 1989 and 1990).

1.1.2. Catchment models

There are two ways of describing the fluxes of nutrients from sources to waterbodies: field monitoring and modelling (Shoemaker et al, 1990; Shirmohammadi and Gnisel, 1994). These two ways usually complement but can also substitute each other. Monitoring can give good information on the present load of nutrients in rivers but hardly describes the flux of nutrients from diffuse sources to surface waters. Collection of statistically sound data on soils, geology, cropping, cultural systems and climate remains limited (Shirmohammadi et al, 2001). Alternatively, computer modelling can better examine environmental fate of nutrients under different physiographic, climatic and management scenarios (Knisel, 1980; Pacenka and Steenhuis, 1984; Baker, 1985; Donigian and Carsel, 1986; Leonard et al, 1987; Shirmohammadi et al, 1992). Modelling may describe linkages between sources and loads, and, hence, analyse also future scenarios. Further on, linking process models with economic models can determine economic feasibility of different management scenarios (Hamlett et al, 1992; Searing et al, 1985).

As far as all the pollutant molecules (except these in atmospheric phase) in a river mouth originate from the catchment area, it is well justified to describe the pollution in catchment level. (Of course, there are some cross-catchment processes such as sources of atmospheric deposition of nutrients.) Thus, several models have been developed which describe transport of nutrients from sources to river outlet in catchment (river basin) scale. If point sources form the majority of loads then the model could be 0- or 1-dimensional (QUAL, Chapra et al, 2005). Globally, however, diffuse sources play more significant role (Anderson, 2002). Description of diffuse processes over the drainage basin requires 2D GIS-models which relate loads with land use and other spatial parameters storing, processing and visualising the model data in GIS (Goodchild et al, 1996). GIS have been appied to the analysis of water quality problems since the early 1980s (Logan et al, 1982). Nowadays, mainly due to potential incompatibility between GIS and the model as a result of upgrade of any individual components, several models – such as Mike Basin (Manoj and Gupta, 2003) and element surface flow model of Vieux and Gauer (1994) – have been integrated in GIS.

Diffuse load is characterised with complicated soil and groundwater processes which have a lot of uncertainties. These processes depend also on previous time periods because for example leaching of nutrients from agricultural soil depends on the nutrient pool in soil which has been formed during past decades (Whitehead et al., 2002; Cooper et al., 2002). Such kind of dependencies may require dynamic models to describe relationships between nutrient sources and their loads. Dynamic catchment models, such as PolFlow (deWit, 1999) and INCA (Whitehead et al, 1998) consider results of the previous timestep as an imput in the next timestep.

Empirical catchment models are usually not universal but applicable only to a certain geographical and temporal areas (Shirmohammadi et al, 2001). It is because the models are derived from and calibrated against measured data. Applying such model to a different site without recalibration may give unrealistic results. Talking about processes, for example, in dry climate, irrigation may significantly influence water quality (Duivenvoorden and Kasel, 2001) while in temperate and cold zone instead drainage has proved important (Heathwaite, 1991; Jin, C.-X. and Sands, G.R., 2003). Another example, groundwater fluxes in porous rocks are in principle different from these in crystalline bedrocks (Banks & Robins, 2002). Due to vast impact of lakes on water quality (Andersson et al., 2005; Al-Layla & Fathalla, 1989) lake-rich areas, such as Finland, may require special assessment compared to Central Europe. Also, the availability of data and structures of databases vary much (Winslow et al., 2001; .Gottschalk & Askew, 1987). US and Western European extensive environmental databases enable models which “eat” much specific information (such as pollutant concentrations and loads in many river reaches, precipitation time series, point source databases, agricultural inventories etc). For example, the most extensively used water quality model HSPF (Donigian et al, 1976) requires very large amounts of input data. In contrary, most of the other nations have such information in only generalised level with many data gaps. As a result, “western” models may not work in other countries or require serious adaption efforts.

The objectives of catchment models may vary. In water management the main aim of catchment models is to predict the environmental consequences (loads, concentrations etc) of human pressures (Woolhiser and Brakensiek, 1982;) and policy measures (Refsgaard et al, 1999; Wendland et al, 1998). However, some models are designed to identify the impacts of a single source while other models may quantify the total human impact in the river basin. Some models may propose concrete short-term management options while others may discuss long-term strategies. Another reason for differences is spatial scale. Models of small catchments usually require information on agricultural management practices while in large drainage basins the numbers of animals and fertilizer amounts are more important. Even more, de Wit (1999) claimed that large-scale and small-scale processes are totally different.

Most of catchment models such as AGNPS (Young et al, 1989), SWRRB (Arnold et al, 1990) and SWAT (Arnold et al, 1996) simulate daily timesteps requiring thus daily climatic data. Some catchment models, such as ANSWERS-2000 (Bouraoi and Dillaha, 1996) are event-based requiring even more detailed data such as duration and amount of each rainfall.

1.1.3. PolFlow model

PolFlow model, created by 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 N and P loads and concentrations. Originally, the model worked in Rhine, Elbe and Po basins (De Wit 1999, De Wit 2001, De Wit and Bendoricchio 2001). Mourad et al (2005, 2006) started adaption of PolFlow to the conditions of the GOF drainage basin. The pilot area was L Peipsi drainage basin which lies in the southern part of the GOF drainage basin..

PolFlow integrates environmental processes with databases and screen display. The model uses PCRaster software package (Wesseling et al. 1996) which includes the PCRaster Dynamic Modelling Language. The software requires all spatial data in Raster GIS format.

PolFlow differs from the other catchment models with its required large study area and long time periods of five years. PolFlow well suits to data-poor regions while still gives better output from more data (De Wit 2001). PolFlow comprises hydrological part, description of nutrient sources, their pathways to surface water, and transport of nutrients to the river mouth.

Hydrological part of the model describes directions and quantities of water fluxes within the river basin (De Wit 1999, De Wit et al. 2000). The input maps comprise precipitation data, hydrogeological information, soil features, slope, landcover information, temperature, map of surface waters etc. Output maps indicate evapotranspiration, runoff, groundwater recharge, residence time and other hydrological characteristics.

Nutrient sources in the model consist of direct and diffuse sources covering the drainage basin (Fig. 1). Direct emissions consist of industrial and municipal discharges as well as agricultural direct emissions. Diffuse emissions are formed of municipal waste of sparse population (not connected to canalization) and of agricultural diffuse emissions. Land cover, livestock amounts, population numbers, crop yields, fertilizer application rates, locations of point sources and other input data generate two output maps giving for each grid cell the total direct and diffuse em issions. The latter is defined as nutrient surplus at soil surface.

To model the transport of soil nutrients to surface water, the output of hydrological sub-model and the output of sources sub-model combine with several soil and groundwater parameters. Through various pathways in soil and groundwater system the model transports the nutrients to surface water. The output maps include amounts of nutrients loading to surface water, decay of nutrients in the soil and groundwater system as well as pools of nutrients in soil and groundwater. The model gives all information in kilogrammes per year in a grid cell for a 5-year time period. Each time period gives output to the next time period.

The last model part routes nutrients through surface water system starting from small ditches and springs flowing through rivers, lakes and reservoirs to the river mouth. Local drainage direction map, created from the elevation map and surface water network, indicates the drainage direction for each grid cell. Retention of material is defined by transportfraction through each cell, varying between 0 and 1. In case of streams this fraction of material, draining to the next downstream cell, depends on slope and runoff. In case of lakes and reservoirs the transport fraction is different, based on empirical information about retention of these waterbodies. As the final result the model calculates five-year annual average load of nutrients (total N and total P) in surface water flowing through each grid cell as a stream segment.

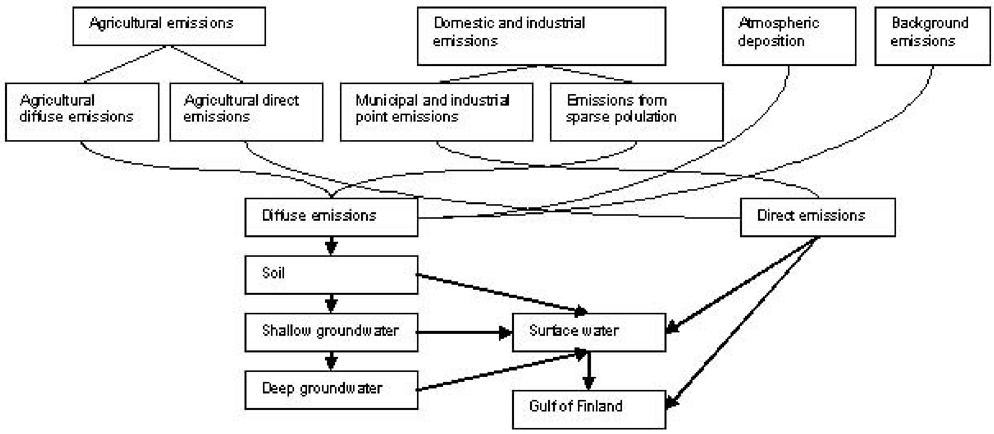


Fig. 1: Conceptual presentation of the main nutrient fluxes as the basis of PolFlow model

1.2. The goal

1.2.1. Environmental situation of GOF

The GOF reaches to Finland, Russia and Estonia. The distance of 30 km from the coast serves as home for 7.4 million people. They intensively use the water of the gulf for economy and recreation. Eutrophication still seriously deteriorates the environment of the gulf although all its coastal countries have considerably reduced nutrient emissions (Kauppila and Bäck 2001, Pitkänen *et al.* 2001). These reductions have improved water quality locally near some direct sources while eutrophication has still proceeded mostly because N and P have resuspended from sediments in the eastern part of the gulf (Pitkänen *et al.* 2001). That process works due to historical loads which have formed much nutrient-rich sediments. To decrease such internal load the external load requires long-term cutting (Kiirikki et al. 2003). Kiirikki et al (2003) recommend to prioritise load reductions to the areas of very high biomass production and oxygen deficiency. These vulnerable areas exchange water slowly: eastern GOF and the Archipelago Sea.

The GOF receives most of the nutrients from agriculturural activities. Agriculture and managed forestry constitute 51% of N and 45% of P losses in the Baltic Sea catchment area (HELCOM, 2004). Reduction of agricultural load could thus solve the eutrophication problem.

1.2.2. Knowledge gaps

Source apportionment. HELCOM (2004) has performed an inventory of sources of nutrient loads to the GOF. However, Russia, constituting 64.5% of the catchment area, has not developed source-oriented approach to quantify nutrient loads from diffuse sources. Estonia and Finland have shared their load originating from point sources, diffuse sources and natural sources. Yet, making quantitative difference between natural and anthropogenic diffuse load may be very speculative as far as diffuse load forms as a result of co-work of several historical natural and anthropogenic processes (Cooper et al., 2002). For example, leaching of nutrients to groundwater depends on the nutrient contents in soil, which, in turn, results from several decades of agricultural activities and natural processes (Whitehead et al., 2002). Thus, the way of source apportionment proposed by HELCOM (2004) can estimate only long-term (several decades) average shares while in annual scale apportioning between anthropogenic and natural diffuse loads remains inaccurate.

In the same time, HELCOM (2004) does not differentiate between diffuse and direct agricultural sources, considering the entire agricultural sector as diffuse sources. However, the input of nutrients to surface water from agricultural activities come from three different pathways (Shirmohammadi and Knisel, 1994): (1) surface runoff to surface waters, (2) lateral movement of nutrients through soil media to surface water, and (3) leaching of nutrients to groundwater. The quantities of each of these pathways depend on climate, soils, geology, land use and management practices (Shirmohammadi et al, 2001). While the pathway through soil and groundwater systems goes through big buffer systems (soil buffer, groundwater buffer), direct agricultural emissions are much more harmful to the environment causing immediate and significant increase of nutrient load. Apportionment between diffuse and direct agricultural load is still missing.

Information from the Russian side. As far as acquisition of environmental data from the Russian side (nutrient loads, wastewater discharges, agricultural statistics, climate data, background data etc.) remains problematic, the description of nutrient fluxes in the GOF drainage basin serves as a great challenge. Relatively simple questions (how much nutrients Russia emits, how much discharges to GOF etc) hold still big uncertainties.

Relationship between agricultural changes and nutrient loads. All countries around the GOF have reported high reduction of agricultural emissions of nutrients since late 1980s (Kiirikki et al., 2003; HELCOM, 2004). However, resulting load reductions to GOF remained suprisingly vague (HELCOM, 2004). Several new reports have described buffer systems which reduced environmental improvements from reduced emissions (Pitkänen et al., 2001; Whitehead et al., 2002; Ekholm et al., 2005). Still, quantitative relationships between agricultural changes and nutrient loads need clarification.

1.2.3. Bridging the knowledge gaps

This paper aims at linking long-term changes in agriculture with nutrient loads entering the GOF. In addition, we aim to specify scientific basis for management decisions to improve the environment of the eutrophied GOF. We focus on land-based loads, which comprise riverine inputs, coastal inputs and direct wastewater discharges to the GOF. To estimate future loads, we constructed scenarios of future agricultural development for the time period of 2020–2024. The PolFlow model was then linked to these scenarios to approximate the corresponding nutrient loads to the GOF.

1.3. Acknowledgements

Prof **Enn Loigu**, Tallinn University of Technology (TUT), supervised this work.. His most imprtant contribution was import and mobilisation of resources: financial resources, knowledge, labor etc. He contributed as a local expert working out agricultural scenarios, estimating data gaps, collecting data and literature. Dr Loigu participated in making conclusions from the results. He critically revised and developed the drafts of this document.

Dr **Arvo Ital**, TUT, assisted in the assessment of nutrient sources, emissions and soil processes. He contributed in determining sevral parameters such as animal excretion, background and atmospheric input, and aerial loss. He helped in interpretating agricultural statistics and other information.

Dr **Aleksander Maastik** helped estimating agricultural sources and emissions in Estonia in time period 1985-1989.

Ms **Ülle Leisk**, TUT, provided data of loads in the Estonian side. She also assisted in acquiring other Estonian data such as meteorological and environmental data.

Dr **Karin Pachel** and Ms **Maaja Narusk**, Estonian Ministry of Environment, collected and analysed data of Estonian point sources.

Dr **Heikki Pitkänen**, Finnish Environment Institue (FEI), organised financial resources for the work. He defined the environmenrtal goal and the task of this work.. Dr Pitkänen mobilised an international team of Estonian, Russian, Swedish and Finnish researchers to contribute the work. He also critically reviewed the work periodically adjusting the tasks and goals.

Dr **Pekka Härmä**, FEI, helped acquiring GIS data of Finnish side including administrative borders and soil types.

Dr **Tuoma Sarkula** and Dr **Jouni Nousiainen**, FEI, provided climatic data.

Dr **Antti Räike**, FEI, provided data of Finnish point sources and information about retention in Finnish lakes

Dr **Jussi Vuorenmaa**, FEI, provided data on atmospheric deposition of nutrients in Finland

Dr **Mikael Brännback** (Kemira Agro, Finland) provided data abot the application of mineral fertilisers in Finland.

1.4. List of publications included in the thesis

I Mourad, D.S.J.; Perk, M. van der; Gooch, G.D.; Loigu, E; **Piirimäe, K**., 2003. GIS-based quantification of future nutrient loads into Lake Peipsi/Chudskoe using qualitative regional development scenarios. Proceedings of Diffuse Pollution and Basin Management Conference (DipCon), Dublin, 17-22 Aug., 2003. , 2003, 105 - 111.

II Piirimäe, Kr., 2003. Modeling point and non-point nutrient fluxes in river systems of lake Peipsi drainage basin. Proceedings Kalmar Eco-Tech '03 "Bioremediation and Leachate Treatment", 25.-27. November 2003, Kalmar, Sweden, Hogland, W., Kuznetsova, N. (Hrsg), 389 – 398. University Kalmar.

III Mouard, D.S.J.;Van der Perk, M.;Gooch, G.D.;Loigu, Enn; **Piirimäe, K**.; Stålnacke, P., 2005. GIS-based quantification of future nutrient loads into L Peipsi/Chudskoe using qualitative regional development scenarios. Water science & technology, 355 - 363.

IV Mourad, D; van der Perk, M; Nõges, T; Stålnacke, P; Pihlak, M; Loigu, E; **Piirimäe, K**; Skakalsky, B., 2006. Quantitive scenarios and modelling. G. DDD. Gooch, P. Stålnacke (Eds.). Integrated Transboundary Water Management in Theory and Practice: Experience from the New EU EAstern Borders. 101 - 126. London: I W A Publishing.

V Mourad, D.S., van der Perk, M., **Piirimäe, Kr**., 2006. Changes in nutrient emissions, fluxes and retention in a north-eastern European lowland drainage basin. Environmental monitoring and assessment. 120: 415 - 448.

VI Piirimäe, Kr., Ekholm, P., Porvari, M., Pitkänen, H., 2007. Effect of Past and Future Agriculture to Nutrient Fluxes in the Gulf of Finland Drainage Basin – Application of the PolFlow model (Submitted to Water Research).

1.5. Abbreviations

CAP – common agricultural policy
GIS – Geographic Information Systems
GOF – Gulf of Finland
HAB – harmful algal blooms
L – lake
N – nitrogen
P – phosphorus
R – river
WTO – World Trade Organisation
WWT – wastewater treatment

2. Methodology

In this study, PolFlow model was applied as a test, on L Peipsi Drainage Basin which is a part of the GOF Drainage Basin, and, secondly, on the entire GOF drainage basin. As input we combined data from several different databases covering Estonian, Finnish and Russian part of the drainage basin. Grid cell size was one km^2.

2.1. Case study at L Peipsi Drainage Basin

Nutrient fluxes were simulated in L Peipsi drainage basin in three past five-year time periods: 1985 – 1989, 1990 – 1994, and 1995 – 1999. The first time period represented the time of high agricultural emissions in both Estonia and Russia, the second time period represented the decline of these emissions while the last period described low agricultural emissions. The model was adapted to the data-poor Russian side of the drainage basin. Point source emissions were estimated based on population statistics, wastewater connection rates, and the level of WWT. One third of the sewage from population not connected to WWT systems was considered a point source. All agricultural emissions were considered as diffuse emissions, contributing to soil surface surplus. The initial time period of the model was 1945 – 1949. Diffuse emissions were assumed zero in that time, increasing linearly until the 1985 – 1989 time period. While the retention of nutrients of other grid cells was modelled, the largest lake in the drainage basin, Võrtsjärv, got the empirical retention values.

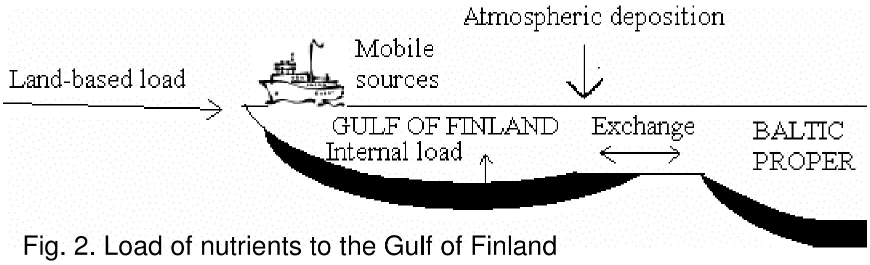


Fig. 2. Load of nutrients to the Gulf of Finland

In addition to past time periods, five future scenarios foreseeing the time period of 2015-2019 were simulated.

2.2. Study on the entire GOF Drainage Basin

Land-based loads of N and P to GOF, consisting of riverine, coastal and direct inputs, were modelled (Fig. 2). Nutrient exchange with the Baltic Proper, atmospheric deposition to the surface of the GOF, internal loading from sediments, as well as discharge from mobile sources (ferries) were left out of focus. The selected time periods include: (i) 1985 – 1989 as a period of very intensive agriculture and high nutrient emissions in the drainage basin; (ii) 1995 – 1999 as the period of very low agricultural activities in Estonian and Russian part of the basin, as well as implementation of agri-environmental policy in Finland expected to be resulted with low emissions and loads; (iii) 2000 – 2004 representing current situation in the study area. Two future scenarios were simulated for the time period 2020 – 2024.

Differently from previous applications, enormous changes in agriculture were reflected also in the model landcover. Landcover as an input parameter was made dynamic differing in each time period. The original landcover map was combined with agricultural statistics. Map items “cultivated and managed terrestrial areas” and “mosaic: crop/tree cover” were integrated and divided between “agricultural areas” and “forests” in a way the resulting land cover maps matched with agricultural statistics.

Considering the speciality of Finnish pedogeology, the Finnish soil system was modelled completely differently from previous PolFlow applications. The transport of P from Finnish soils was modelled according to Ekholm et al (2005).

Considering relatively high importance of lakes in the drainage area (large lakes such as Ladoga, Peipsi, Onega, Ilmen as well as numerous lakes in Finland), the retention of nutrients in these lakes got extra attention in the model. Empirical retention estimates were used for Peipsi, Võrtsjärv, Saimaa, Ilmen, Ladoga and Onega. For other lakes, the retention models were taken from literature (table 1) or calibrated.

The model distinguished agricultural diffuse and direct emissions. Diffuse emissions add to soil while direct emissions may refer to fertilisers which originate from arable land without joining previously soil particles. Agricultural direct emissions contributed more in the conditions of sloppy Soviet agriculture when much slurry from animal barns flew directly to waterbodies; farms applied manure often to snow and frozen soil; manure pits, granaries and silos leaked noticeably (Maastik, 1984). In the conditions of good agricultural practice, the model assumed direct agricultural emissions much lower, referring mostly to the inevitable loss of a fraction of fertiliser prior to joining pedosphere.
Differently from river basins, the GOF Drainage Basin lacks one single output to collect all loads. Instead, nutrients flow to the gulf from all its coastline. To get total load values covering the entire drainage basin we defined a fictional pit in the GOF which collected all land-based loads.

The model was calibrated and validated according to de Wit (1999) against monitored load data from Estonian and Finnish streams as well as from the R Neva (Finnish Environment Institute, various years; Tallinn University of Technology, various years; HELCOM, 2004).

3. Study area

3.1. The GOF Drainage Basin

The GOF drainage basin was defined according to MapBSR database (Digital Map… 2000).

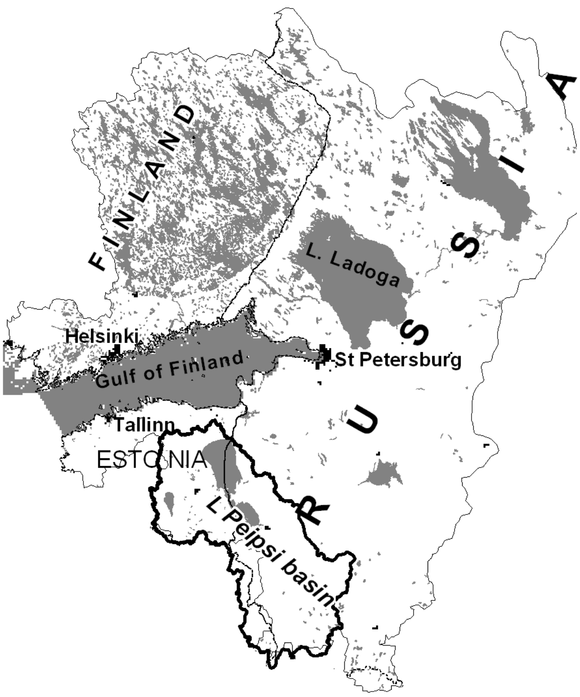


Figure 3. Drainage basin of the Gulf of Finland

General information

GOF with area of 29030 km2 (Digital map… 2000), mean and maximum depth correspondingly 37 m and 123 m (Andrejev et al, 2004)) is the north-eastern sub-basin of the Baltic Sea. The gulf works as a large estuary of R Neva and smaller rivers. The catchment area of the GOF comprises 415100 km² of which 106100 km² (26%) belongs to Finland, 267800 km² (64.5%) to Russia, 38700 km² (9%) to Estonia, 0.4% to Belarus and 0.2% to Latvia (Hannerz, 2002, Fig. 3). The largest river flowing into the Baltic Sea, the Neva, is part of the GOF catchment area, and drains from Russian territory. The population of the drainage area is ca 12.4 million (HELCOM, 2004). Drainage systems exist in most of the arable lands (Joint Research Centre, 1999). Since time period 1985-1989 until 2000-2004 in total 26% of arable lands were abandoned (Statistical Office of Estonia, various years; Goskomstat Rossii, various years; Miettinen et al., 2004). Long-term annual average precipitation in the area varies between 600 and 700 mm (Leemans et al., 1991; New et al., 1999; Digital Atlas, 1997; New et al., 2000) while evapotranspiration between 310 and 390 mm (modelled here).

About 36% of Finland belongs to the GOF drainage basin (hereinafter HELCOM, 2004). In total 2 536 330 inhabitants populate the area with an average density of 24 km^{-2}. The land is covered mainly by forests (Fig. 4). Also, lakes cover a significant area. In average 460 m^3 of water discharges to the gulf from Finland. Hydrochemical and hydrological monitoring covers ca 89% of the Finnish part of the GOF Drainage Basin.

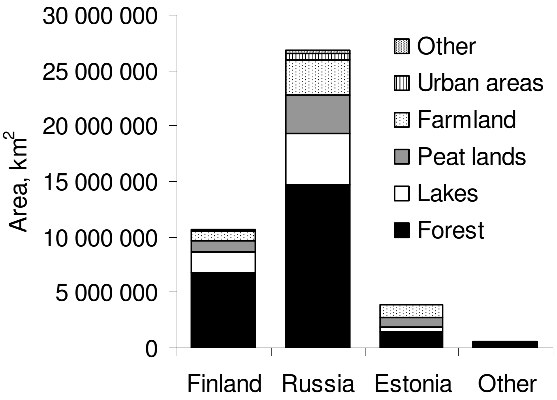


Fig.4. Landcover (%) in the Gulf of Finland Drainage Basin (HELCOM, 2004)

About 1.6% of Russia drains to the GOF . This area comprises the city of St Petersburg, most of the territory of the Leningrad District, the eastern part of the Pskov District, most of the Novgorod District, as well as parts of the Tver, Vologda, Archangelsk and Karelian Districts. R Neva basin covers ca 80% (215600 km^2) of the area. In average 2488 m^3 of water discharges from to the GOF from the Neva. Ca 8 million inhabitants populate the area with the density of ca 30 km^{-2}. Most of these people (4.6 million) live in St Petersburg. The low-lying area contains much peat land and large lakes such as Ladoga, Onega, Ilmen and Chudskoe/Peipsi. Water retains in L Ladoga 4.5 years, in L Ilmen 1.5 years, and in L Chudskoe 2.5 years. About hydrochemical and hydrological data only information about the Neva oulet was available for this study.

Ca 60% of Estonian territory locates within the the GOF drainage basin. Ca 1.3 million inhabitants populate the area with a density of 48 km^{-2}. Mostly lowland area contains many wetlands and lakes. The largest river, Narva (in average 399 m^3/s) gets most of its waters from Russia. Hydrological and hydrochemical monitoring covers over 80% of the Estonian catchment area of the GOF.

3.2. L Peipsi Drainage Basin

L Peipsi, a large shallow lowland lake (surface area: 3555 km2) formed during the most recent ice age (Weichselian) by over-deepening of meltwater valleys (Miidel *et al.*, 2001). Its drainage basin of 45541 km^2 forms ca 11% of the entire GOF drainage basin. Until 1991 the area belonged to Soviet Union, since that to Russia (59%), Estonia (33%), Latvia (8%), and Belarus (almost 0%). The population number of ca 777281 (Statistikaamet, 2004) covers the area relatively sparsely. The largest town, Pskov (Russia), has 201500 inhabitants. The mean height of that glacial lowland area reaches 91m while maximum height to 338m above sea level. Dominating land cover classes are forest (61%) and agricultural land (28%), which are spatially arranged in a patchy landscape pattern. Of the main rivers Velikaya (Russia) discharges 127 $m^3 s^{-1}$ and Emajõgi (Estonia) 55$m^3 s^{-1}$. During spring floods at the end of the snow cover period, river discharges usually multiply. L Peipsi discharges to the R Narva (mean discharge: 322 $m^3 s^{-1}$), which, in turn, to the GOF.

4. Input Scenarios

4.1. L Peipsi scenarios

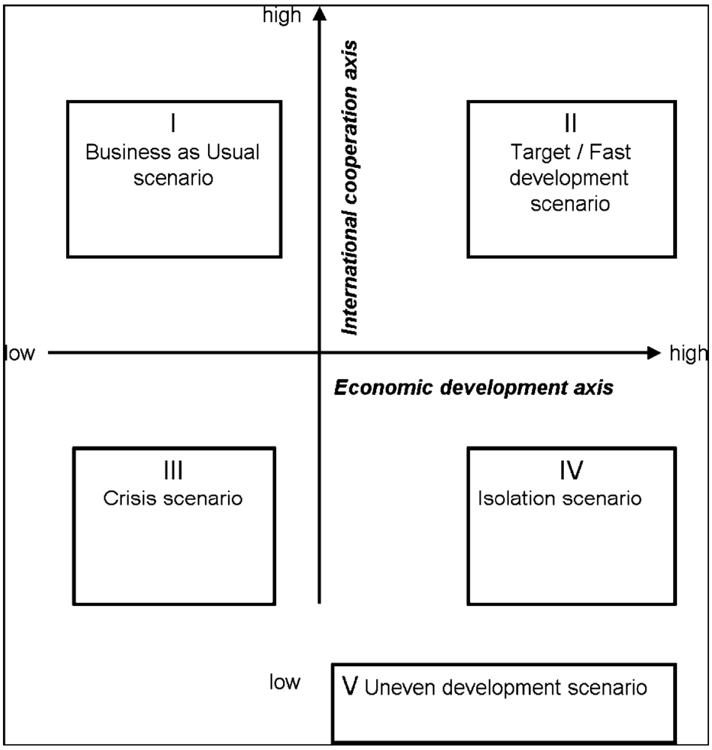


Fig.5. Five scenarios for future economic development in the Lake Peipsi/Chudskoe drainage basin.

Five plausible scenarios assessed the effects of economic changes on future nutrient emissions and river loads for 2015–2019 (Mourad *et al*., 2003; Mourad *et al*., 2005). Two key variables influenced possible future nutrient load in the region: economic development and transboundary cooperation (Fig. 5). Plotting those key factors to two axes, and considering extremes of them both, four possible future scenarios on the Baltic-Russian border emerged: (I) ‘Business as usual’; (II) ‘Target/fast development’; (III) ‘Crisis’; (IV) ‘Isolation’. Another scenario, (V) ‘Uneven development’, combined Target/fast development scenario in Estonia/Latvia and the

Table 1. Changes in driving forces of nutrient emissions under five scenarios from 1995-1999 to 2015-2019 (after Mourad et al, 2005)

Scenario	**Region**	**Population**	**WWT plant connection rate and treatment level**	**Fertiliser use (kg ha-1 y-1**	**Livestock amounts**	**Crop yields**	**Atmospheric deposition (kg ha-1 y-1**	**Amount agricultural land in comparison with 1980s**
I Business as usual	Estonia and Latvia	Tartu: No change Rural: -8%	No change	N: 50 P: 2	+10%	+25%	No change	Tartu county: -15% Rest: -40%
	Russia	Pskov: no change Rural: -5%	No change	No change	No cghange	No change	No change	-40%
II target/fast development	Estonia and Latvia	Settlements: treatment will improve one level	N: 130 P: 15	N: 130 P: 15	100%	+40% Industrial crops: +70%	N: 15 P: 0.08	No change
	Russia	Pskov: +10% Rural: +5%	Settlements > 10 000 inh: treatment will improve one level	N: 130 P: 15	+100%	No change	N: 15 P: 0.08	No change
III. Crisis	Estonia and Latvia	Tartu: -5% Rural: -25%	No change	No change	-50%	-50%	No change	-50%
	Russia	Pskov: - -5% Rural: -30%	Collapse of current systems	N: 2.8 P: 0.22	-75% Milk cows: +100%	-50%	No change	-80%

Table 1. (Continued)

Scenario	Region	Population	WWT plant connection rate and treatment level	Fertiliser use (kg ha-1 y-1	Livestock amounts	Crop yields	Atmospheric deposition (kg ha-1 y-1	Amount agricultural land in comparison with 1980s
IV. Isolation	Estonia and Latvia	No change	Settlements: treatment will improve one level	N: 21 P: 165	+30%	+40%	N:15 P: 0.08	-10%
	Russia	No change	No change	No change	No change	No change	N:15 P: 0.08	-60%
V. Uneven development	Estonia and Latvia	Tartu: +10% Rural: +5%	Settlements: treatment will improve one level	N: 130 P: 15	+100%	+40% Industrial crops: +70%	N:15 P: 0.08	No change
	Russia	Pskov: -5% Rural: -30%	Collapse of current systems	N: 2.8 P: 0.22	-75% Milk cows: +100%	-50%	No change	-80%

Crisis scenario in Russia. Local experts helped to develop for each of these five scenarios qualitative storylines (Mourad *et al*., 2005). Then, these storylines got quantitative numbers of input driving forces determing the emissions in 2015–2019. These driving forces included population, WWT connection rate, fertiliser use, livestock amount, crop yields, atmospheric deposition and amount of agricultural land (Mourad *et al*., 2005, Table 1). The model changed the driving forces linearly between the 1995–1999 and the 2015–2019 periods. Climatic input data of 2015 – 2019 remained in the long-term average level of 1960 – 1999.

4.2. GOF scenarios

Qualitative scenarios

To assess the effect of economic changes on future nutrient emissions and river loads, two plausible scenarios were developed for 2020-2024 describing the load of nutrients in GOF drainage basin as effects of different agricultural scenarios. In Finnish side the scenarios were based on Miettinen et al., 2004. In Estonian side the scenarios were based on Mourad et al 2005 and Mourad et al 2003. In Russian side the scenarios were worked out within this study, supported by Mourad et al 2005.

'Low loading' scenario. 'Low loading' scenario creates relatively little load. In Russia the main identified factors determing diffuse load of nutrients include international and national trade policies (which are included in one driving force, "globalization") and agricultural policies. Low loading scenario in Russia means 'Backyard agriculture'. In this scenario, Russia becomes a member of the WTO, and therefore must decrease its agricultural subsidies and remove border controls. Moreover, at the same time agricultural policies implemented by the central government are mixed and non-uniform, and agricultural and food production chains can't be reconstructed. Therefore Russian food producers purchase their raw materials mainly from abroad and meat imports substitute domestic products in the westernmost Russian regions. This applies especially to dairy, beef and pork production. Poultry is produced in small amounts. Agricultural production in the North-Western Russia continues mainly in household plots and small private farms. Main products are potatoes and vegetables, which are consumed locally. Livestock is held in small numbers in household plots, and animal manure is used for fertilization. Use of commercial fertilizers remains in low levels. Until 2020, the amount of agricultural land in the region will continue logarithmic decreasing trend.

In Estonia, 'low loading' scenario is based on the assumption that the EU agricultural funds (EAGGF) are not able to significantly enhance Estonian agriculture. The market situation will not improve: Estonia will fail in EU market competition. In the same time, economic partnership with Russia will neither improve. It means that Estonian agriculture will stagnate and will remain in the level of 2000-2004. l.

In Finland, ‘low loading’ scenario relates to the liberalisation of agricultural trade. Global trade liberalisation will lead to the following drastic adjustments and reforms in agricultural policy. From 2010 onwards all agricultural support, including national, LFA and agri-environmental support, will be decoupled from production and transformed on area-based flat-rate support. Direct area payments will thus be equal for all crops and set-aside. Receiving support includes a requirement of maintaining land in good agricultural condition. The total sum of agricultural support will be reduced by 15% by year 2014. The prices of agricultural products in the EU will fall to world market price levels. EU cereal prices will decrease by 8% whereas beef and poultry meat prices will decrease by 20% and pork prices by 10% from the 2002 level until 2010.

‘High loading’ scenario. ‘High loading’ scenario gives much load of nutrients to GOF. In this scenario, Russia does not become a member of the WTO, partly due to protectionist regional policies in Russia and partly due to stricter WTO regulations. On a regional and also federal level, protectionist lobby groups increase their power. At the same time, active agricultural policy is directed towards self-sufficiency and increased domestic subsidies. Thus, imports and exports are limited through various mechanisms, including regional export restrictions, and on the other hand, norms and technical standards for imported agricultural products. Domestic meat production chains are partly reconstructed by active policy measures, and food producers can purchase raw materials from domestic producers. In the North-West Russia, especially pig and poultry production increase rapidly, but also beef production increases from current low levels. As land privatization proceeds, meat production is centralized into larger and more effective production units. Pskov and Leningrad oblats will produce 10% of the EU beef and pigmeat import. Vegetables and potatoes are produced in household plots. As large scale crop and vegetable cultivation is largely situated in other locations, animal manure overproduction becomes a problem. Some manure is used in crop cultivation, which increases nutrient runoff from fields.

In Estonia, ‘high loading’ scenario will be a result of fast agricultural development in Estonia. Strong farms will need much land to support their growth. Land deficit will force more intensive farming. Estonia will successfully export its food products to EU and Russian market.

In Finland, the ‘high loading’ scenario goes along with CAP reform according to which most direct CAP subsidies will be decoupled from production and paid in a single, lump-sum farm payment based on 2000-2002 historical production levels. Also decoupled CAP animal support, based on 2000-2002 production, will be paid for individual farms. However, 75% of bull premia and 100% of suckler cow premium will remain coupled to production.

Quantitative scenarios

The above described qualitative scenarios for 2020-2024 were transfromed to model input data such as changes in land cover map, animal numbers, animal excretion coefficients, fertilisation rates and crop production rates (Table 2). Time period 2000 – 2004 was chosen for the reference period for changes. Finnish quantitative scenarios were taken from Miettinen at al, 2004. Changes in landcover were located stochastically within administrative units transforming the rate of abandoned agricultural land to the probability of such event in each agricultural grid cell. In Finland, fertiliser application and crop yields were assumed linearly correlating with cultivated areas. In Russia, as several parameters (crop yields, animal numbers) have decreased logarithmically between 1985 – 2004, such trend was mathematically elongated to 2020-2024 in case of grain production in Pskov and Novgorod as well as in case of cattle and pig numbers of low loading scenario. The EU import of beef and pigmeat was assumed standing in the level of 2000 – 2004 (in total 1 470 000 tons of beef in 2002 and 71 700 tons of pigmeat in 2003). Five per cent of that was assigned to Pskov oblast and another five per cent to Leningrad oblast. The annual production of meet per animal was assumed 211 kg for cattle and 114 kg for pigs. The number of diary cows and the number of beef cows per capita for own consumption in Russia was assumed equal (0.093). The number of pigs per capita for own consumption in Russia was assumed 0.38. Fertiliser areal application rates and animal excretion coefficients of Russia in case of high loading scenario were assumed the same as the rates of the Netherlands in 1985-1989 (deWit, 1999).

Table 2. Two quantitative future agricultural scenarios of time period 2020-2024 in GOF drainage basin. Changes refer to time period 2000-2004.

	High loading scenario			Low loading scenario		
	Finland	Russia	Estonia	Finland	Russia	Estonia
Landcover	23% of agricultural land forested	Ratio between agricultural land and forest derived from the areal needs of different crops (see following 3 cells below)	All agricultural land abandoned (forested) in 1990s will be re-cultivated	46% of agricultural land forested	Ratio between agricultural land and forest derived from the areal needs of different crops (see following 3 cells below)	No change
Grain production	A strong decrease	Pskov and Novgorod oblasts: A logarithmic decrease in area under grains. Leningrad oblast: no change	Restoration of the level of 1985-–1989	A strong decrease	Pskov and Novgorod oblasts: A logarithmic decrease of area under grains. Leningrad oblast: no change	No change
Potatoes, vegetables, industrial crops	A slight decrease	No change	Restoration of the level of 1985–1989	A strong decrease	No change	No change
Fodder	A strong decrease	Correlates with change in cattle numbers	Restoration of the level of 1985–1989	A strong decrease	Correlates with change in cattle numbers	No change
Cattle numbers	Decrease. Southern Finland: from 187 000 to 139 000. Central Finland: from 162 000 to 118 000.	Increase. 1. For own meet consumption: 0.093 animals per capita 2. For own milk consumption: 0.093 animals per capita 3. For export: 350000 animals in Pskov	No change	Decrease. Southern Finland: from 187 000 to 149 000. Central Finland: from 162 000 to 62 000.	Logarithmic decrease	No change

		Oblast and 350000 animals in Leningrad Oblast				
Pigs numbers	Southern Finland: Increase from 501 000 to 580 000. Central Finland: Decrease from 72 000 to 39 000.	Increase: 1. For own consumption: 0.38 animals per capita 2. For export: 31 000 animals in Pskov oblast and 31000 animals in Leningrad	No change	Decrease. Southern Finland: from 501 000 to 495 000. Central Finland: from 72 000 to 48 000.	Decrease logarithmically	No change
Poultry numbers	Southern Finland: Increase from 13.7 million to 22.9 million. Central Finland: Decrease from 0.14 million to 0.03 million	Multiplied by 1.5	No change	Southern Finland: Increase from 13.7 million to 21 million Central Finland: Decrease from 0.14 million to 0.06 million	No change	No change
Animal excretion coefficients	No change	Average level of the Netherlands in 1985-1989	No change	No change	No change	No change
Application of mineral fertilisers	No change	Average level of the Netherlands in 1985–1989: 245 kg /ha N 18 kg /ha P	Increases to 150 kg /ha N 15 kg /ha P	No change	Doubles	No change

5. Nutrient sources

5.1. Sources in L Peipsi drainage basin

Pressure data

L Peipsi/Narva basin GIS database (Hannerz *et al*., 2002), developed for large-scale environmental assessment and modelling, gave the basic input maps. These maps converted to PCRaster format for modelling. Several national databases provided agricultural, hydrometeorological and wastewater data. The model distinguished five levels of WWT: not connected, connected without treatment, mechanical treatment, biological treatment, and tertiary treatment (additional P removal). Failure to obtain complete data from Russian and Latvian side for each time period forced to extrapolate the gaps from other periods or regions based on expert judgment.

Results - emissions

Between the 1985–1989 and the 1995–1999 period, net diffuse N emissions decreased by 47% in the Russian part of the L Peipsi/Chudskoe drainage basin, and by 82% in the Estonian part and 81% in the Latvian part (Table 3). Simulated net diffuse emissions well conformed with the estimates by Loigu (1990) for the end of the 1980s as well as the estimates by Stålnacke *et al*. (2001) and Piirimäe (2003) for the end of the 1990s. For P, the development of diffuse emissions is similar, although the soil surface surplus became negative in Estonia and Latvia in the 1995–1999 period which means that the soil P export due to agricultural yields exceeded the agricultural P inputs into soil. For the 2015–2019 period, none of the scenarios results in N emissions to be at the same level as in the 1980s, except for scenario II in Russia and scenario II and V in Latvia. Scenario III will result in the lowest emissions. For P, future emissions will also be highest under scenario II and lowest under scenario III. None of the scenarios will result in emissions comparable with the 1980s levels, except for scenario II in Russia. The point source N emissions decreased by 20% and the point source P emissions decreased by 10% between the 1985–1989 and 1995–1999 period. The N and P point source emissions generally continue to decrease under scenarios I 'Business as usual' and II 'Target/fast development'. Under scenario III 'Crisis', the point source emissions only continue to decrease in Estonia, whereas the emissions will increase in Russia due to the collapse of current WWT systems (see Table 3). Under scenario IV 'Isolation', the point source emissions will slightly decrease further due to slow improvement of treatment levels.

Table 3. Simulated soil surface surplus (103 kg yr^{-1}) aggregated per country (Belarus excluded)

	Past periods			Future senarios (2015-2019				
	1985-1989	1990-1994	1995-1999	I. Business as usual	II. Target / fast development	III. Crisis	IV. Isolation	V. Uneven development
N								
Russia	253930	185852	134116	134117	335550	71203	153294	71203
Estonia	143 209	5709	25294	32699	130715	32687	37255	130715
Latvia	26 567	10532	4921	6496	26941	6879	7572	26941
Total	424812	253 466	164 314	173291	493472	110920	198195	229124
P								
Russia	48831	33759	20324	20585	51871	4265	20444	4265
Estonia	26253	7545	–1478	–2932	10291	–661	–2866	10291
Latvia	4574	883	–937	–1353	1112	–454	–1438	1112
Total	79651	42154	17866	16256	63253	3128	16196	15647

5.2. Sources in the entire GOF drainage basin

Data

Input data for the model were interpreted from various national and international databases as well as from literature sources (Table 4). Because of PolFlow requirements, all data were reworked to 1 km2 grids. Point data of precipitation and atmospheric deposition were interpolated to raster in Inverse Distance Weighted (ESRI ArcMap 8.3).

Table 4. Description, resolution and sources of input data for modelling nutrient loads in the GOF drainage basin

Data	Spatial resolution	Sources
Catchment boundaries	Entire drainage basin	Digital Map of the Baltic Sea Region (2000)
Five-year average annual precipitation for each time period	1 km^2	Estonian Hydrological and Meteorological Institute (various years) ; Finnish Environment Institute (various years); All-Russian Research Institute of Hydrometeorological Information (2002); Northern Water Problems Institute of Russian Academy of Science (2005)
Long-term annual precipitation	Various resolutions, remapped to 1km^2	Leemans et al. (1991); New et al. (1999); Digital Atlas (1997), New et al. (2000)
Average annual temperature	25 x 25 km^2	New et al. (1999)
Average January temperature	25 x 25 km^2	New et al. (1999)
Dominant parent material	1: 1 000 000	Joint Research Centre (1999)
Digital elevation model	1: 2 000 000	Digital Map of the Baltic Sea Region (2000)
Land cover	200m x 200m, resampled to 1 km^2	Digital Map of the Baltic Sea Region (2000)
Soil data: types, texture	1: 1 000 000, reworked to 10 x 10 km^2	Joint Research Centre (1999)
Aquifer thickness	Country level	European Environmental Agency (2004); Yanovski (1983)
Population	200 x 200 m^2, reworked to 1km^2	Digital Map of the Baltic Sea Region (2000)

Point emissions	Each discharge localised	Estonian Environmental Information Centre (2005); Finnish Environment Institute (2005), In Russia modelled according to population numbers, their wastewater production, their connection rates with WWT and treatment efficiency.
Connection with various WWT systems in Russia	Oblast and city level	Water management… (2004); Sillfors (2007); Vodokanal…(1997)
Removal of nutrients by various WWT systems in Russia	Country level	Water management… (2004)
Agricultural statistics (fertiliser application, livestock numbers, crop yields)	Province level	Statistical Office of Estonia (various years), Maatilatilastollinen vuosikirja (various years), Goskomstat Rossii (various years)
Excretion coefficients for various animals, giving nutrient export per animal	Country level	Brouwer et al. (1995), Plan Upravlenija …(2004), Antikainen et al. (2005)
Crop coefficients for various crops, giving nutrient export per mass yield	Country level	de Wit (1999), Frede and Bach (1995), Antikainen et al. (2005)
Background emission of nutrients	Entire drainage basin	de Wit (1999)
Atmospheric deposition of nutrients	1 km^2	Finnish Environment Institute (various years)
Initial nutrient content in the soil in 1945	Entire drainage basin	de Wit (1999), Kivinen (1934); Kaila (1948).
Initial value of Soil Test P in 1940-1944	Entire drainage basin	Grönroos & Seppälä (2000); Mäntylahti (1999)
Initial content of P (kg/km^2) in ploughed layer	Entire drainage basin	Ekholm et al. (2005)
Initial P erosion rate ($kg/km^2/yr$)	Entire drainage basin	Ekholm et al. (2005)
Soil mass	Entire drainage basin	Wendland (1992)
Maximum storage of nutrients in the soil	Entire drainage basin	calibrated by de Wit (1999)

Surface runoff of nutrients in forest	1 km^2	Vuorenmaa et al. (2002); Mattsson et al. (2003); Rossolimo et al. (1975)
Retention of nutrients in lakes	Lake level	De Wit (1999), Tomaszek & Koszelnik (2003), Lepistö et al, 2006; Kondratyev (2005), Ekholm et al (1997), Nõges et al (2003), Arheimer & Brandt (1998).
Location of surface waters	1:1 000 000	Digital Map of the Baltic Sea Region (2000)
Data	Spatial resolution	Sources
Catchment boundaries	Entire drainage basin	Digital Map of the Baltic Sea Region (2000)
Five-year average annual precipitation for each time period	1 km2	Estonian Hydrological and Meteorological Institute (various years) ; Finnish Environment Institute (various years); All-Russian Research Institute of Hydrometeorological Information (2002); Northern Water Problems Institute of Russian Academy of Science (2005)
Long-term annual precipitation	Various resolutions, remapped to 1km2	Leemans et al (1991); New at al (1999); Digital Atlas (1997), New at al (2000)
Average annual temperature	25 x 25 km2	New at al (1999)
Average january temperature	25 x 25 km2	New at al (1999)
Dominant parent material	1: 1 000 000	Joint Research Centre (1999)
Digital elevation model	1: 2 000 000	Digital Map of the Baltic Sea Region (2000)
Landcover	200m x 200m, resampled to 1 km2	Digital Map of the Baltic Sea Region (2000)
Soil data: types, texture	1: 1 000 000, reworked to 10 x 10 km2	Joint Research Centre (1999)
Aquifer thickness	Country level	European Environmental Agency (2004); Yanovski (1983)
Population	200 x 200 m2, reworked to 1km2	Digital Map of the Baltic Sea Region (2000)
Point emissions	Each discharge localised	Estonian Environmental Information Centre (2005); Finnish Environment Institute (2005)
Connection with various WWT systems in Russia	Oblast and city level	Plan upravlenija (2004); Sillfors (?); Vodokanal…(1997)

Removal of nutrients by various WWT systems in Russia	Country level	Plan upravlenija (2004)
Agricultural statistics (fertiliser application, livestock numbers, crop yields)	Province level	Statistical Office of Estonia (various years), Maatilatilastollinen vuosikirja (various years), Bank of Finland (various years)
Excretion coefficients for various animals, giving nutrient export per animal	Country level	Brouwer et al. (1995), Plan Upravlenija …(2004), Antikainen et al (2005)
Crop coefficients for various crops, giving nutrient export per mass yield	Country level	de Wit (1999), Frede and Bach (1995), Antikainen et al, 2005
Background emission of nutrients	Entire drainage basin	de Wit (1999)
Atmospheric deposition of nutrients	1 km2	de Wit (1999), Finnish Environment Institute (various years)
Initial nutrient content in the soil in 1945	Entire drainage basin	de Wit (1999)
Initial value of Soil Test P in 1940-1944	Entire drainage basin	Grönroos & Seppälä,2000; Mäntylahti, 1999
Initial content of P (kg/km2) in ploughed layer	Entire drainage basin	Ekholm et al, 2005
Initial P erosion rate (kg/km2/yr)	Entire drainage basin	Ekholm et al, 2005
Soil mass	Entire drainage basin	Wendland (1992)
Maximum storage of nutrients in the soil	Entire drainage basin	calibrated by de Wit 1999
Retention of nutrients in lakes	Lake level	De Wit (1999), Tomaszek & Koszelnik (2003), Lepistö et al, 2006; Kondratyev (2005), Ekholm et al (1997), Nõges et al (2003), Arheimer & Brandt (1998).
Location of surface waters	1:1 000 000	Digital Map of the Baltic Sea Region (2000)

Modelling of emissions

Difference was made between direct and diffuse agricultural emissions. Estonian and Finnish municipal and industrial point sources were taken from the relevant point source databases while Russian point sources were modelled according to population numbers and, connection per centages with WWT, production of nutrients per capita, and effectiveness of WWT. Direct emissions from Russia were estimated according to population map. Map showing the location of population in the entire area was used. Data were collected about percentage of the population whose waste water is treated. Combining the average nutrient content of human waste, the fraction of nutrients removed by WWTPs, nutrient emissions of connected people were localized equally with the population map. Then, pollution was routed to the nearest modeled river. One third of the emissions of the people not-connected was assumed to be direct source. The remaining two third of not-connected people were considered as indirect or diffuse sources, to be dealt with in the chapter of indirect emissions.

In the final model, all Estonian and Finnish point sources and their annual emissions were localized to the map according to environmental data.

The content of nutrients in municipal and industrial wastewater in Russia was assumed to be 12 g N and 2 g P per individual per day (Water management…, 2004). In Estonia, municipal and industrial point emission of all time periods were assumed equal with the emissions in 2004. Total application of mineral fertilisers in time period 1985–1989 in Estonia was assumed according to Carlson and Loigu (1993). In Russia, mineral fertiliser was assumed to contain 0.72% of N and 0.057% of P. These ratios correspond to the average mineral fertiliser chemical composition in Estonia in 1995–1997 (Statistical Office of Estonia, various years). In case of missing agricultural data for the time period 1985–1989, the amounts per hectare were assumed equal with time period 1995–1999, or equal with Estonian data of 1985–1989.

The ratio of both nutrients between solid manure and liquid slurry was assumed 50% (Maastik, 1984; Keskkonnaministeerium et al., 2005). The rate of application of solid manure to snow or frozen soil in Estonia and Russia in 1985–1989 was assumed 50% (Maastik, 1984). In later time periods, that rate was assumed 0%. In Finland in all time periods, we assumed that no manure was applied to snow or frozen soil. The rate of direct emission of N and P from such manure was assumed 50% (Maastik, 1984). In addition, 5% of manure N and 10% of N from mineral fertilisers was assumed leaking directly to water bodies in the entire area, covering all time periods. The rate of direct discharge of slurry in Estonia and Russia was assumed 15% while in Finland 0% (Maastik, 1984). However, Estonia is expected to reduce the rate to 0% by 2020–2024.

Results

Total surplus of N in soil surface varied roughly between -3000 (crops removed more N than fertilisers and other sources added) and +16 000 kg km^{-2} yr^{-1}. Surplus of P varied between -300 and +4000 kg km^{-2} yr^{-1}.

The emissions of N halved from late 1980s to 2000–2004 and those of P decreased by 64% (Fig. 6). Most of these reductions took place due to the reduction in agricultural diffuse emissions (88% reduction in N and 80% reduction in P emissions). Also, agricultural direct emissions decreased substantially (N emissions by 80% and P emissions by 79%). However, agricultural direct emissions constituted only 11–18% of the total N and 5–6% of the total P emissions of agriculture. Of future scenarios ‘low load’ would maintain approximately current emission levels while ‘high load’ scenario would increase N emissions by 138% and P emissions by 124%. In the 'high load' scenario, N emissions thus would be on a higher level than they were in the late 1980s, but P emissions would be clearly lower.

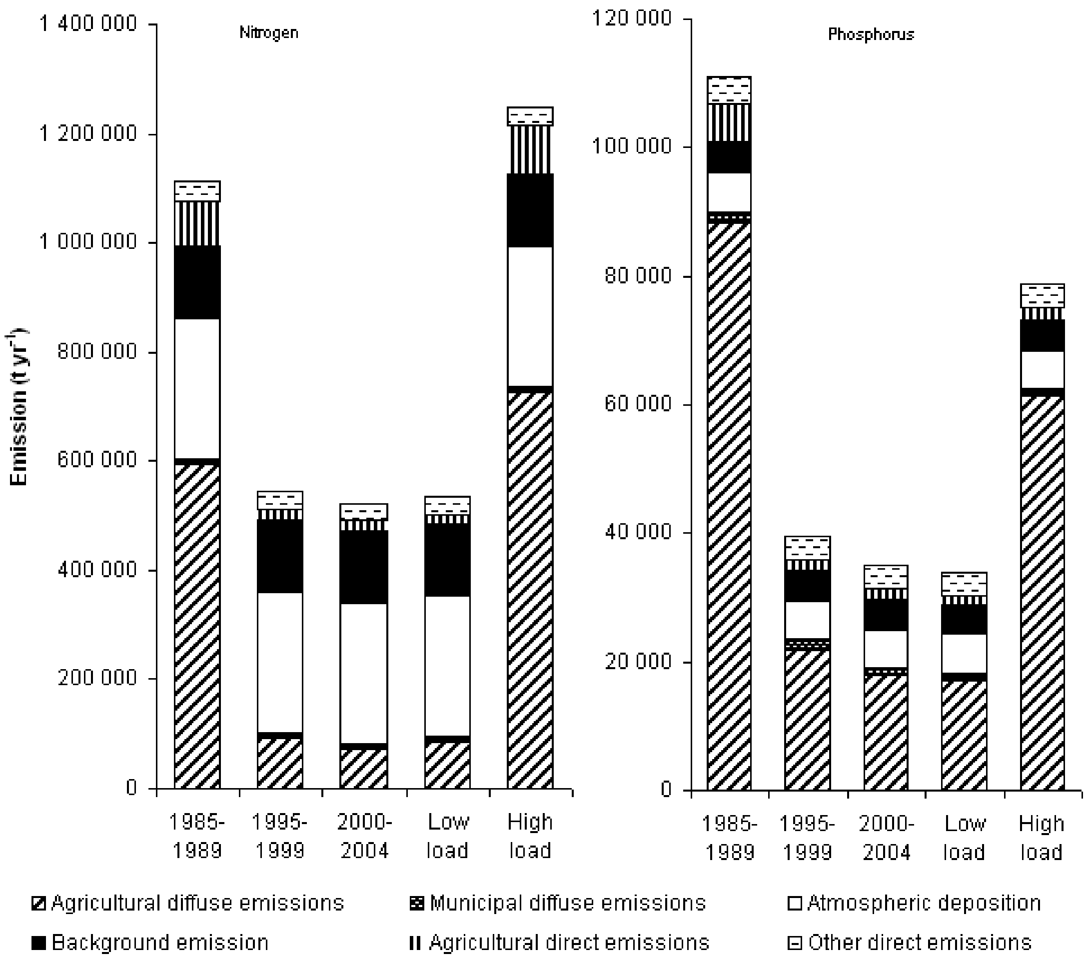
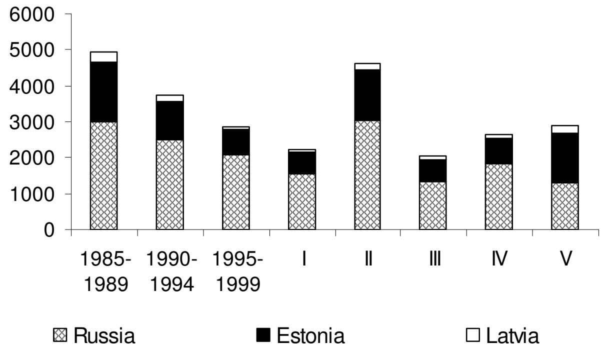


Fig. 6. Emission of nutrients to the Gulf of Finland from various sources in different time periods and in low and high load scenarios at 2020-2024.

6. Nutrient fluxes

6.1. Nutrient fluxes in L Peipsi drainage basin

For the entire lake system, N loads were reduced by 42% from the 1985–1989 to the 1995–1999 period, and the P loads by 21% (Fig. 7). These reductions in loads were smaller than the reduction of the respective emissions for N and P between these periods. For N, Scenario II is the only future scenario in which total loads will be similar to the 1980s. In all other scenarios, N loads will be about the same or less as in the 1990s. P loads under scenario II are likely to be the same as in the 1990s, but decrease under all other scenarios.



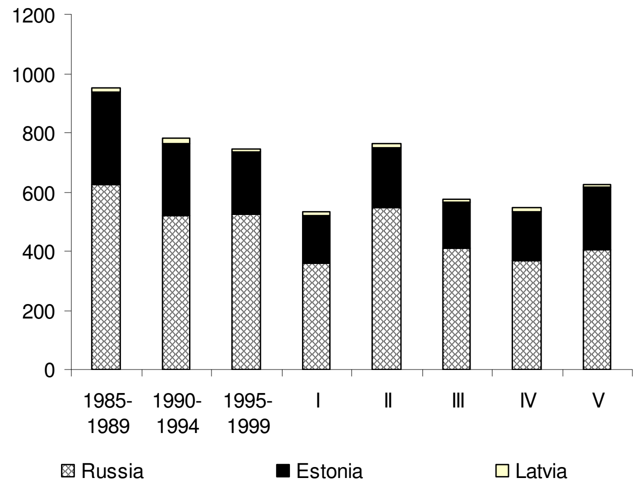


Fig.7. Load of N and P in L Peipsi drainage basin in past time periods and in various future scenarios (t yr^{-1}): I – Business as Usual, II – Target / Fast development, III – Crisis, IV – Isolation, V – Uneven development

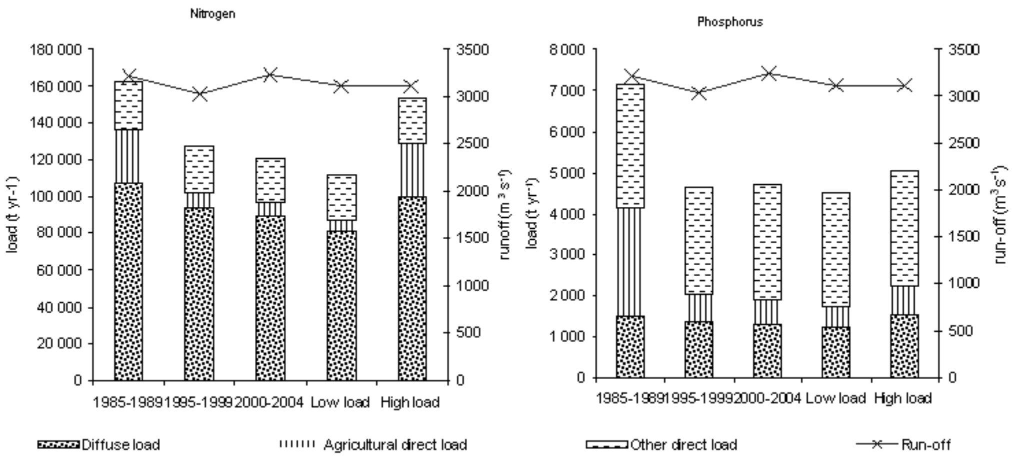


Fig. 8. Annual load of nutrients to the Gulf of Finland (t y^{r-1}) by various sources in different time periods and in low and high load scenarios at 2020-2024.

6.2. Nutrient fluxes in GOF drainage basin

Load from various sources

In different time periods and future scenarios, the annual load of nutrients from diffuse sources (from soil and groundwater system and from precipitation) was permanently around 90 thousand tons of N and 2 thousand tons of P (Fig. 8). Enormous changes in fertiliser amounts and crop yields did not affect significantly the diffuse load of nutrients. Instead, agricultural practices made difference. The dynamics of nutrient loads came from changes in agricultural direct load which in this model consisted of (1) direct discharges due to application of manure to snow or frozen soil and (2) direct discharge of slurry to waterbodies. Between 1985-1989 and 1995-1999 the annual direct agricultural load decreased from 15 800 tons of N to 2800 tons of N and from 1800 tons of P to 460 tons of P. Of future scenarios even 'low loading' scenario would reduce the total load of both nutrients only one per cent. 'High loading' scenario would increase the load of N by 7.4% and the load of P by 5.1%.

Load by countries.

Since 1985-1989 load of both N and P decreased significantly in all three countries (Fig. 9). Load of N from Finland would decrease in 'low load' scenarios by 20% and in 'high load' scenario by 9%. Load of P from Finland would decrease in 'low load' scenario by 5.0% and in 'high load' scenario by 3.3%. Load of N from Estonia in case of 'low load' scenario would decrease 6.3% and load of P by 23%. In case of ‘high load’ scenario, Estonia would increase N load by 39% and P load by 2.8%. ‘Low load’ scenario would reduce N load from Russia by 1.8% and P load by 1% while ‘high load’ scenario would increase N load from Russia by 43% and P load by 11%.

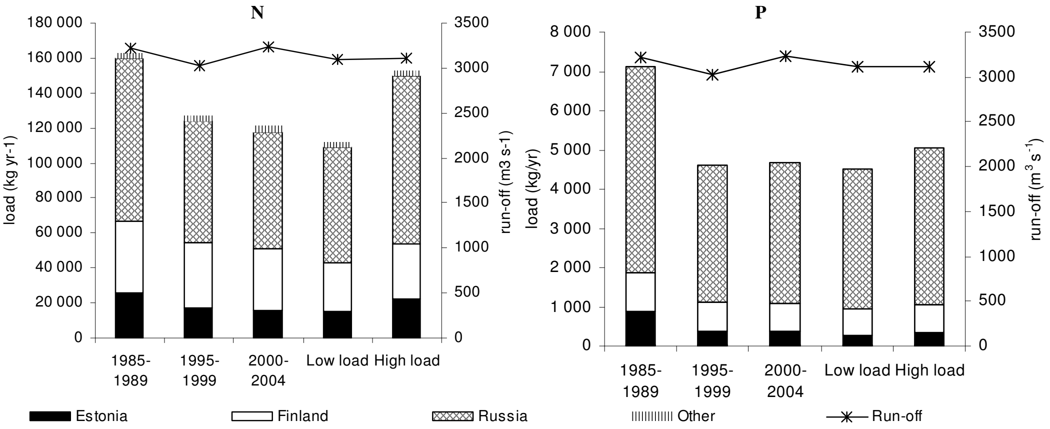


Fig. 9. Annual load of nutrients to the Gulf of Finland (t yr^{-1}) by countries in different time periods and in low and high load scenarios at 2020-2024. N – total nitrogen. P – total phosphorus

Retention of nutrients.

Total annual input of nutrients to surface waters in the GOF drainage basin was 332 000 tons of N and 9930 tons of P. Of these amounts 211 000 tons of N (64%) and 5230 tons of P (53%) was retained in surface water network (Fig. 10). As ca 60% of the inhabitants (including St Petersburg, Helsinki and Tallinn) of the drainage basin live less than 30 km from the coast, most of municipal and industrial emissions reach to the gulf almost unretained. In contrary, a large part of agricultural emissions, originating far from river mouths, retains in lakes and streams.

N

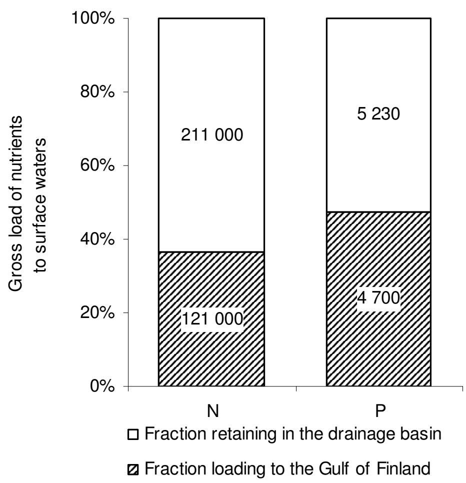


Figure 10. Gross load, net load and retention of nutrients in Gulf of Finland Drainage Basin in 2000 - 2004

7. Conclusions

7.1. Interpretation of the model results

In spite of enormous changes in agricultural emissions, along time periods and scenarios diffuse load of nutrients remained stabile. Diffuse load of nutrients depends greatly on their storage in soil (Goodchild et al., 1996; Piirimäe *et al.*, 2007). That storage varies roughly between 300 000 and 4 000 000 kg N km^{-2} as well as 120 000 and 500 000 kg P km^{-2} (hereinafter modelled information). Large storage of nutrients in soil may feed pollutant load for many years, even if emissions stop. Such soils with high nutrient content also cover much of the GOF drainage basin. In most agricultural areas the ratio between diffuse input of N to surface water and storage of N in topsoil ranged between 0.23% and 0.57%. For P, the ratio was even lower – between 0.01% and 0.07%. In ten years, the storage of N and P may therefore reduce only up to 6% and 0.7%, respectively. In the perspective of a few years, the reduction of fertiliser application thus gives no significant decrease in diffuse load, especially for P. (Fig. 11). In a 20-year perspective, reduction of direct pollution - either from industrial, municipal or agricultural sources – gives much more effect.

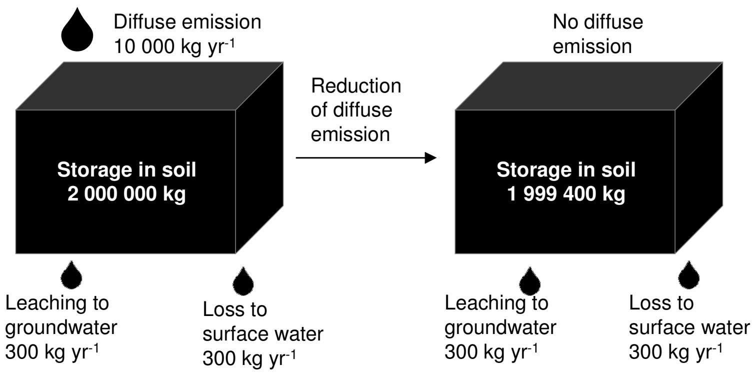


Figure 11. Reduction of diffuse emissions may fail to significantly reduce loss of nutrients from soil

In the same time, land cover type alters diffuse load significantly. While forest gives roughly 300 kg of N and 1 kg of P per km^2 annually, agricultural areas in most cases load many times more. Thus land use changes play a crucial role in governing nutrient losses.

In total 64% of N and 53% of P which reached to surface waters retained in the network of streams and lakes without entering the GOF. The impact of a pollution source thus depends much on its distance from river mouth. Coastal pollution sources, loading more per emission unit than far inland sources, require more attention.

7.2. Modelling approach

The results show that besides water fluxes, the most sensitive variable controlling diffuse loads is land use. Diffuse load is regulated by a complicated soil and groundwater processes which involve a lot of uncertainties. These processes also depend on previous time periods because, as discussed above, leaching of nutrients from agricultural soil depends on the nutrient pool in soil which has been formed during past decades (Whitehead et al., 2002; Cooper et al., 2002). Diffuse emissions control loads only indirectly. Adding emission data to the model also requires dynamic, cumulative inventory of soil nutrient content. That requirement was fulfilled in this study – results of the previous time step worked as inputs to the next time step.

US and Western European extensive environmental databases enable models which can assimilate much specific information (such as pollutant concentrations and loads in many river reaches, precipitation time series, point source databases, agricultural inventories etc). For example, the most extensively used water quality model HSPF (Donigian et al, 1976) requires very large amounts of input data. In contrast, many nations have such information in only generalised level with many data gaps. As a consequence, "western" models may fail to work in such countries or require serious adaption. The modelling approach of this study originates from large river basins, including data-poor regions..

Unlike previously modelled areas with PolFlow, nutrient loads in the GOF drainage basin depend on three specific features. First, in the marine boreal climate with high soil humidity, arable areas are mostly drained. In addition to leaching to groundwater, soil water and dissolved nutrients drain via pipes and ditches directly to surface water. Second, lakes, covering 14% of the studied area, retain a large proportion of nutrients, reducing load downstream. Third, due to the collapse of Soviet agriculture in 1990s, land cover changed significantly in the GOF drainage basin. Forestation of arable lands decreased significantly nutrient loads. We modified PolFlow model, considering all these three aspects. The model now well works in the conditions of extensive drainage systems, many lakes, and changing land cover.

7.3. Major uncertainties

Data-poor regions require many rough estimations based on best available information. For instance, having no information about agricultural practices in Russia we applied Estonian information for Russia, too. Although the reliability of such assumptions remains questionable, these enabled seamless coverage of the entire area. However, the model still misses much information about catchment processes and geographical features.

The past and present rates of agricultural direct emissions remain largely uncertain. These emissions include loss due to application of manure to snow or frozen soil and direct discharge of slurry to surface waters. Since such emissions are mostly illegal, the polluters hardly give reliable information about them. Direct agricultural emissions, adding a significant amount to the load of nutrients to the GOF, require thus further investigations.

Retention of nutrients in lakes also remains uncertain. For instance, L Peipsi, although being a well studied body of water, still lacks a model describing in-lake retention of N and P. Retention of N has fluctuated in different five-year periods between 39% and 70%, retention of P between 47% and 70% (as calculated from monitoring data). However, current mathematical models lack the description of impact of climate change, weather conditions and other factors to the retention of nutrients. Lakes cover 14% of the GOF drainage basin reducing much of the load of nutrients to the gulf (see e.g. Kondratyev et al. 2007). Unfortunately, simple map characteristics such as lake area or runoff do not correlate with retention of nutrients (Lepistö et al., 2006; Søndergaard et al., 2001). A global model predicting nutrient retention in lakes remains missing.

Areal loss of nutrients from diffuse sources also requires clarification. Numerous studies relating these losses with hydrological variables, land cover types, soil and geological features as well as management practices appear inapplicable due to the lack of geographical data. For instance, loss from forests depends greatly on the forestry operations such as draining, scarification, fertilisation, cutting (Vuorenmaa et al., 2002). However, GIS data of these practices remain insufficient.

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Summary: Long-term changes of nutrient fluxes in the drainage basin of the Gulf of Finland – application of the PolFlow model

Eutrophication is the most serious environmental problem in freshwaters and coastal seas, including Gulf of Finland (GOF). Agriculture changed largely in 1990s in all countries bordering the gulf: Finland, Estonia and Russia. Fertilizer application and animal production decreased significantly. Grassland and later forested land substituted large areas of arable land. Depending on future economic development these changes could either reverse or freeze. The study examined the effects of such economic changes on P and N load in the drainage basin to determine potential load dynamics in future. Such coupling could help designing management strategies for the eutrophied GOF, and other eutrophied waterbodies.

A raster-GIS based PolFlow model, designated for large river basins and long time periods, was modified for that purpose. The model described nutrient loads in (1) L Peipsi drainage basin (a part of the GOF drainage basin) as a pilot study, and (2) entire GOF drainage basin. Two extreme future agricultural scenarios were constructed based on economic development in the study area. 'Low load' scenario was based on the assumptions that Russia will become a member of WTO, EU structural funds fail in Estonia, and agricultural trade will liberalize in Finland. 'High load' scenario assumed that Russia will not join WTO, success of structural funds in Estonia, and domination of ongoing CAP reform in Finland.

'Low loading' scenario, along with weak agriculture, would reduce the loads of N and P by 7% and 4%, respectively. 'High loading' scenario – including recultivation of forested lands – would increase the load of N by 26% and the load of P by 7.5%. The results highlight the considerable time lag between the changes in agricultural intensity and the nutrient load to surface waters.

The model results drew the following conclusions:

1. Due to high buffering capacity of soils, in the perspective of few years, the reduction of fertiliser application gives no significant decrease of diffuse load. Especially, load of P depends little on fertilisation dynamics.
2. Proper land use management may give the most efficient reduction of diffuse nutrient loads.
3. Due to high retention ratio of both nutrients in surface waters, the impact of a pollution source depends much on its distance from river mouth.
4. Nutrient load in water depends only indirectly on diffuse emission. Diffuse emission adds nutrients to soil while soil, in turn, loses a fraction of its storage to water. Thus, considering emission data in a model requires also dynamic, cumulative inventory of soil nutrient content.
5. Several catchment models which prove well-working in western countries may fail to work in data-poor countries or require serious adaption efforts. PolFlow model well suits to large data-poor catchments such as GOF drainage basin.

6. The modified PolFlow model, presented in this paper, now well works in the conditions of extensive drainage systems, many lakes, and changing land cover.
7. For more reliable predictions the model requires more information on direct agricultural emissions, retention of nutrients in lakes and geographic data on land use management.

Kokkuvõte: Toiteelementide transpordi pikaajalised muutused Soome lahe vesikonnas – PolFlow mudeli rakendus

Eutrofeerumine on tõsiseim keskkonnaprobleem magevetes ja rannikumeredes, sealhulgas Soome lahes. Üheksakümnendail aastail põllumajandus kõigis Soome lahe äärsetes maades – Soomes, Eestis ja Venemaal – muutus väga palju. Väetiste kasutamine ja loomakasvatus vähenes oluliselt. Rohumaad ja hiljem metsamaad vahetasid välja suuri põllumaaterritooriume. Sõltuvalt tuleviku majandusarengutest võivad need muutused kas pöörduda või põlistuda. Käesolev töö uuris niisuguste majandusmuutuste mõju P ja N koormustele antud valglal, et hinnata võimalikke koormuste dünaamikaid tulevikus. Niisugune seostamine võiks aidata eutrofeerunud Soome lahe – aga ka muude eutrofeerunud veekogude – jaoks keskkonnakorralduslike strateegiate loomisel.

Eesmärgi tarvis kohaldati raster-GIS mudelit PolFlow, mis on välja töötatud spetsiaalselt suurte valglate ja pikkade ajaperioodide jaoks. Mudel kirjeldab toiteelementide koormusi (1) pilootuuringuna Peipsi järve valglal (mis moodustab osa Soome lahe valglast) ja (2) tervel Soome lahe valglal. Uuritaval alal konstrueeriti kaks äärmuslikku tulevikkuvaatavat põllumajandusstsenaariumit, mis põhinesid erinevatel majandusarengutel. ‚Madala koormuse' stsenaarium põhines eeldustel, et Venemaa saab Maailma Kaubandusorganisatsiooni liikmeks, EL sturktuurifondide programmid Eesti majanduse arendamisel ebaõnnestuvad ning Soome liberaliseerib põllumajandustoodete kaubanduse. ‚Suure koormuse' stsenaarium eeldas, et Venemaa ei ühine Maailma Kaubandusorganisatsiooniga, EL struktuurifondid osutuvad Eestis edukaks ning Soome põllumajandus hakkab sõltuma eelkõige käimasolevast EL Ühise Põllumajanduspoliitika reformist.

'Madala koormuse' stsenaarium, mis kaasneks kiratseva põllumajandusega, vähendaks lämmastiku ja fosfori koormust vastavalt 7% ja 4%. ‚Suure koormuse' stsenaarium – sealhulgas metsastunud maade taasharimine – suurendaks lämmastiku koormust 26% ja fosfori koormust 7.5%. Tulemused näitavad olulist viibeaega, mis jääb põllumajanduse intensiivsuse muutumise ja toitainete koormuse pinnavetesse vahele.

Mudeli tulemustest järeldub:

1. Seoses muldade suure puhverdusvõimega, mõne aasta perspektiivis ei anna väetamise vähendamine olulist hajukoormuse vähenemist. Eriti fosfori koormus sõltub väetamise dünaamikast vähe.
2. Sobiva maakasutuskorraldusega võib efektiivselt hajukoormust vähendada.
3. Seoses mõlema toiteelemendi suure peetuse osakaaluga pinnavetes sõltub saasteallika mõju oluliselt selle kaugusest jõe suudmest.
4. Toiteelementide koormus vees sõltub hajuheitest ainult kaudselt. Hajuheide lisab toiteelemente mulda, samas kui muld omakorda kaotab osa nende

sisaldusest vette. Seetõttu nõuab heiteandmete kasutamine mudelis ka dünaamilist, kumulatiivset mulla toiteelementide sisalduse inventuuri.

5. Paljud valglamudelid, mis töötavad hästi lääneriikides, võivad andmevaestes maades ebaõnnestuda või nõuda tõsiseid kohaldamispingutusi. PolFlow mudel sobib hästi suurtele ja andmevaestele valglatele nagu näiteks Soome lahe vesikond.

6. Modifitseeritud PolFlow mudel, mida selles aruandes esitletakse, töötab nüüd hästi ekstensiivsete dreenisüsteemide, paljude järvede ja muutliku maakatte tingimustes.

7. Et saada usaldusväärsemaid ennustusi, vajab mudel rohkem infot põllumajandusheite kohta, peetuse kohta järvedes ja geograafilisi andmeid maakasutuse kohta.

Annex 1. Curriculum Vitae

In English

Name: Kristjan Piirimäe
Date of birth: June 13th 1975
Place of birth: Tartu
Citizenship: Estonian
Marital status: married, one child
Address: Ramma k., Järva-Jaani v., Järvamaa, Estonia
Phone: (37 2) 5116916
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Education
2000 MSc, hydrobiology, University of Tartu, Estonia
1997 BSc, microbiology, University of Tartu, Estonia
1993 Graduated, Tartu Secondary School No 16. Estonia

Language skills (1-excellent; 5-basic)

Language	Reading	Speaking	Writing
Estonian	1	1	1
English	1	1	1
Russian	3	3	3

Special courses
2006 School pedagogy, University of Tallinn
1998 course (40 credit points): perspectives on environment and sustainable development in Baltic Sea Area. University of Kalmar, Sweden
1995 World Youth Leadership Training Summit, United Nations, New York

Professional Employment
2007 - ... Tallinn University of Technology , Faculty of Civil Engineering, Department of Environmental Engineering , Chair of Environmental Protection; Extraordinary Researcher
2001 - 2006 Tallinn University of Technology , Faculty of Civil Engineering, Department of Environmental Engineering , Chair of Environmental Protection; Researcher
1997 - 2001 Estonian University of Life Sciences, Institute of Agricultural and Environmental Sciences, Võrtsjärve Limnological Station;
1995 - 1997 Estonian Academy of Sciences;

Publications
Piirimäe, Kr. (2003). Modeling point and non-point nutrient fluxes in river systems of lake Peipsi drainage basin. Proceedings Kalmar Eco-Tech '03 "Bioremediation

and Leachate Treatment", 25.-27. November 2003, Kalmar, Sweden, Hogland, W., Kuznetsova, N. (Hrsg), 389 – 398. University Kalmar.

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Mourad, D.S.J.; Van der Perk, M.; Gooch, G.D.; Loigu, E.; Piirimäe, K.; Stålnacke, P. (2004). River nutrient transport under various economic development scenarios - the transboundary lake
Peipsi/Chudskoe drainage basin. Douben, K-J.; van Os, A. G. (Eds.). Proceedings NCR-days 2003 : Dealing with Floods within Constraints : November 6 – 8 (71 - 73). Delft, Holland: Netherlands Centre for river studies

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Lokk, S.; Kisand, V.; Piirimäe, K. (2001). Bacterioplankton. Ervin Pihu; Juta Haberman (Eds.). Lake Peipsi. Flora and Fauna (23 - 28). Tartu: Sulemees

Curriculum vitae
Eesti keeles

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Haridus
2000 MSc, hüdrobioloogia, Tartu Ülikool
1997 BSc, mikrobioloogia, Tartu Ülikool
1993, lõpetatud, Tartu 16s Keskkool

Keeleoskus (1 – suurepärane, 5 – algtase)

Keel	Lugemine	Kõne	Kirjutamine
Estonian	1	1	1
English	1	1	1
Russian	3	3	3

Täiendõpe
2006 Koolipedagoogika, Tallinna Ülikool
1998 Kursus (40 ainepunkti): keskkonna ja säästva arengu perspektiivid Läänemere regioonis. Kalmari Ülikool, Rootsi
1995 Maailma Noorte Liidrite Õppekonverents, ÜRO, New York

Teenistuskäik
2007 - ... Tallinna Tehnikaülikool, Ehitusteaduskond, Keskkonnatehnika instituut, Keskkonnakaitse aluste õppetool; Erakorraline teadur

2001 - 2006 Tallinna Tehnikaülikool, Ehitusteaduskond, Keskkonnatehnika instituut, Keskkonnakaitse aluste õppetool; Teadur

1997 - 2001 Eesti Maaülikool, põllumajandus- ja keskkonnainstituut, limnoloogiakeskus; vanemlaborant

1995 - 1997 Eesti Teaduste Akadeemia; laborant

Artiklite loetelu
Piirimäe, Kr. (2003). Modeling point and non-point nutrient fluxes in river systems of lake Peipsi drainage basin. Proceedings Kalmar Eco-Tech '03 "Bioremediation

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