GIS-BASED QUANTIFICATION OF FUTURE NUTRIENT LOADS INTO LAKE PEIPSI / CHUDSKOE USING QUALITATIVE REGIONAL DEVELOPMENT SCENARIOS

D. S. J. Mourad[1], M. Van der Perk[1], G.D. Gooch[2], E. Loigu[3], K. Piirimäe[3] and P. Stålnacke[4]

[1]*Department of Physical Geography, Utrecht University, P.O.Box 80115, 3508 TC Utrecht, the Netherlands (E-mail: d.mourad@geog.uu.nl)*
[2]*Department of Management and Economics, Linköping University, 58183 Linköping, Sweden*
[3]*Department of Environmental Engineering, Tallinn Technical University, Järvevana tee 5, 19086 Tallinn, Estonia*
[4]*Jordforsk (Norwegian Centre for Environmental Research), Frederik A. Dahls vei 20, 1432 Ås, Norway*

ABSTRACT

This study aims at the quantification of possible future nutrient loads into Lake Peipsi/Chudskoe under different economic development scenarios. This drainage basin is situated on the borders of Russia, Estonia and Latvia. The sudden disintegration of the Soviet Union in 1991 caused a collapse of agricultural economy, and consequently, a substantial decrease of diffuse and point-source nutrient emissions. For the future, uncertainties about economic development and the priorities that will be set for this region make it difficult to assess the consequences for river water quality and nutrient loads into the lake. We applied five integrated scenarios with regard to future development of this transboundary region for the next twelve to fifteen years. Each scenario consists of a qualitative story line, which was translated into quantitative changes in the input variables for a geographical information system based nutrient transport model. This model calculates nutrient emissions, as well as transport and retention and the resulting nutrient loads into the lake. The model results show that the effects of the different development scenarios on nutrient loads are relatively limited over a time span of about 15 years. In general, a further reduction of nutrient loads is expected, except for a fast economic development scenario.

Keywords: GIS, nutrients, Lake Peipsi/Chudskoe, modelling, regional development, scenarios

INTRODUCTION

The emerging of newly independent states after the fall of the Soviet Union has given an extra dimension to the management of diffuse pollution. Many transboundary river basins are now shared by countries acceding to the European Union (EU) and non-acceding countries. The integration into the EU forces acceding countries to adopt stringent environmental requirements, but this is not the case for non-acceding countries. The EU Water Framework Directive calls for an integrated catchment approach for tackling water management, also in the case of such transboundary catchments. For an adequate implementation of the EU Water Framework Directive, information on the past, present, and future water quality and riverine pollutant loads is essential, but these are generally scarce in these particular catchments. This paper describes the simulation of future nutrient loads within the catchment of Lake Peipsi/Chudskoe at the border of Estonia, an EU acceding country, and Russia, a non-acceding country, under different scenarios of regional development.

THE LAKE PEIPSI / CHUDSKOE CASE

The pilot area is the basin draining to Lake Peipsi (Estonian) / Chudskoe (Russian), shared by Russia (67 %), Estonia (26 %) and Latvia (7 %). The lake and its drainage basin (figure 1) are extensively described by Jaani (1996), Miidel and Raukas (1999) and Nõges (2001). This basin measures approximately 44000 km^2 and is a typical North-European lowland area of glacial origin, characterized by Palaeozoic bedrock, covered by unconsolidated glacial materials of variable thickness. It contains two major rivers, the Velikaya with a mainly Russian and Latvian catchment (mean discharge: 195 m^3/s), and the Emajõgi with a mainly Estonian catchment (mean discharge: 68 m^3/s). These two rivers account for nearly 65 % of the water discharge into the lake (Stålnacke *et al*., 2001), and thus are the most important when it comes to nutrient input. Lake Peipsi/Chudskoe is one of the biggest European lakes (3555 km^2), and because of its shallow character (depth does not exceed 15 m) together with activities in the river basin, it is sensitive to eutrophication problems (Nõges, 1996).

Agricultural economy in past, present and future

The collapse of the Soviet Union in 1991, and the simultaneous end of its power in Central and Eastern Europe, brought massive changes to the region's agriculture. In communist times, the landscape in this northwestern part of the Soviet Union had always been used more intensively than other regions. The collective and state farms were mainly specialised in meat and dairy production and additional growing of fodder crops. Because of inefficient use of fertiliser and the lack of proper manure handling, agriculture caused high emissions of nutrients Ntot and Ptot into rivers and lakes and subsequent eutrophication problems (Loigu & Leisk 1996). After the 1991 revolution, the Baltic States became independent, and a coincidence of developments caused the stagnation of agricultural economy in the Baltic States. Unwin (1997) gives a total overview of factors, of which the most important are: 1) the collapse of the traditionally important Russian market, especially after the introduction of import tariffs in 1994; 2) the impossibility to penetrate the EU-market due to its protectionist policies, while in the mean time import of cheap EU products is not hindered; 3) the general confusion about privatisation and land reform, in which a coherent national policy is absent. In the Russian part of the river basin, agricultural economy stagnated as well, mainly as a result of the deep economic crisis in Russia.

At present, the area has already been in a period of transition for more than a decade, and the future is still highly uncertain. Although economy will grow definitely, especially on the western side of this new EU border, it is not yet clear whether the environment will gain or loose from that. The decline of agriculture during the nineties actually caused diffuse pollution to decrease and the quality of rivers to rise. So, in the future, it is possible that water quality will decrease again, if agriculture recovers. On the other hand, water quality may benefit from EU regulation and good transboundary cooperation to agree on farm mineral balances and better public wastewater treatment. Thus, nutrient emissions and water quality are linked to future economic development in various, sometimes indirect ways.

Figure 1. *The Lake Peipsi/Chudskoe drainage basin.*

Integrated scenarios

The use of scenarios to assess the possible effect of various directions of economic development on environmental problems is generally accepted (cf. Alcamo, 2001; Alcamo and Nakicenovic, 1998). Integrated scenarios, based on both social and natural scientific knowledge, can be valuable tools for decision-making, because a vast amount of environmental information is ordered in clear storylines. Although a limited set of future development scenarios do not necessarily represent the entire range of 'what is most likely going to happen', they are at least plausible future expectations. The use of scenario calculations can help to assess the sensitivity of the natural system to a range of possible future developments.

METHODS

We applied five possible economic development scenarios for the Lake Peipsi/Chudskoe basin. Each scenario consists of a qualitative storyline that tells what main developments will occur in the next 12-15 years. These storylines were translated into changes in quantitative inputs into a geographical information system (GIS) based emission and transport model for the main nutrients total nitrogen (Ntot) and total phosphorus (Ptot). The main results of the calculation of the scenarios using this model are 1) the change in emissions (T) over the area and 2) changing loads (T/yr) into Lake Peipsi/Chudskoe.

Nutrient emissions, transport and retention model

The changes in nutrient transport under the various scenarios were calculated using a dynamic, GIS-embedded model that simulates nutrient emissions, transport and retention in drainage basins in time steps of five years. This modelling approach was originally developed for simulating past and present nutrient loads for the Rhine and Elbe rivers (De Wit, 1999, 2001). Recently, the model has been implemented for Lake Peipsi/Chudskoe drainage basin (Mourad and van der Perk, 2002) using an integrated GIS-database of this region (Langaas *et al*., 2002; Langaas *et al*., 2003).

The modelling approach consists of three main steps: 1) Compiling maps of diffuse emissions (soil surface surplus) and point sources emissions from agricultural statistics and a land cover map; 2) Modelling of long-term hydrological fluxes and residence times in the various hydrological compartments (“slow”, “medium”, and “fast” runoff component); 3) routing the emitted nutrients through the soil/groundwater system and river network in proportion to the long-term hydrological fluxes. The first two steps are static: for each model time step (five year), the procedure is repeated, using the appropriate input data. The third step is dynamic: this means that output from a previous step is used as input for the next step. In this way, the effect of temporary storage of nutrients in the soil/groundwater is accounted for. A more detailed description of the modelling procedure can be found in De Wit (1999, 2001) and in Mourad and Van der Perk (2002). Nutrient loads were calculated for the time period 1985-1999 (3 time steps) and calibrated using measured nutrient loads in rivers (EMHI, unpublished data).

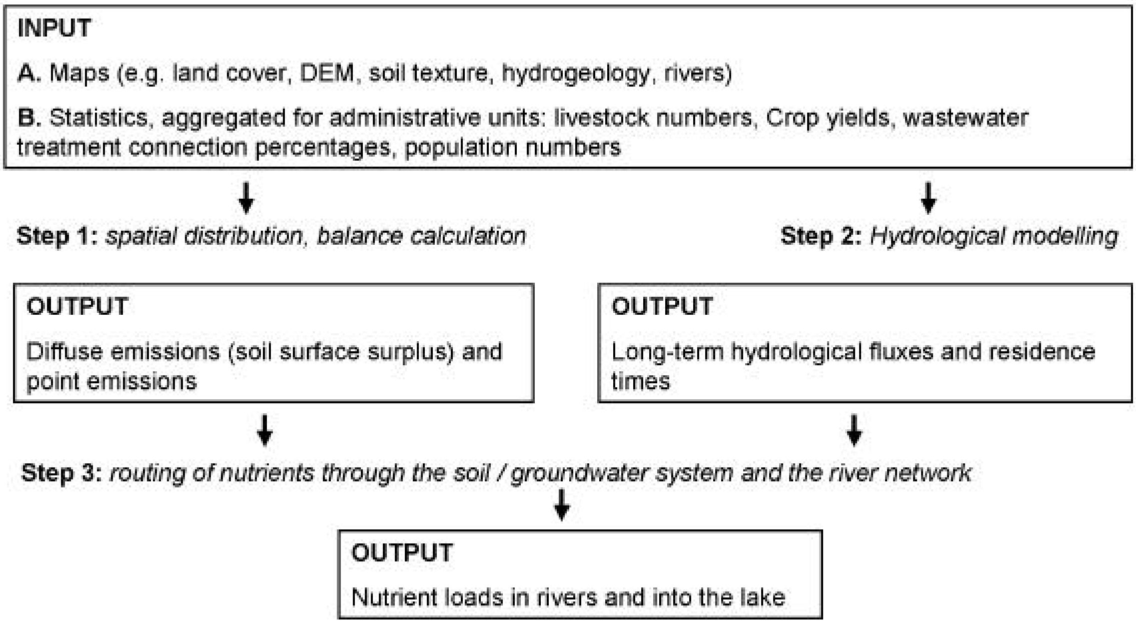

Figure 2. *Overview of the nutrient modelling approach. The model output results for the different scenarios are obtained by adjusting the model input at B.*

Definition of scenarios

For the definition plausible scenarios (see Gooch, 2003) for the next twelve to fifteen years, two key variables were identified that influence the possible economic future development of the region: economic development and transboundary cooperation. If those key factors are plotted as two axis (figure 3), and the extremes of both factors are considered, four possible scenarios for future economic development on the Baltic-Russian border emerge, each defined as a combination of a low or a high score on the axis of the two key factors: I) *Business as Usual*; II) *Target / Fast Development*; III) *Crisis*; IV) *Isolation*. Because it is plausible that development will be unevenly at each side of the border, another scenario is added: V) *Uneven Development*, which is a combination of the *Fast Development* scenario in Estonia / Lativia and *Crisis* in Russia. A detailed description of the storylines of the scenarios is given in Gooch (2003).

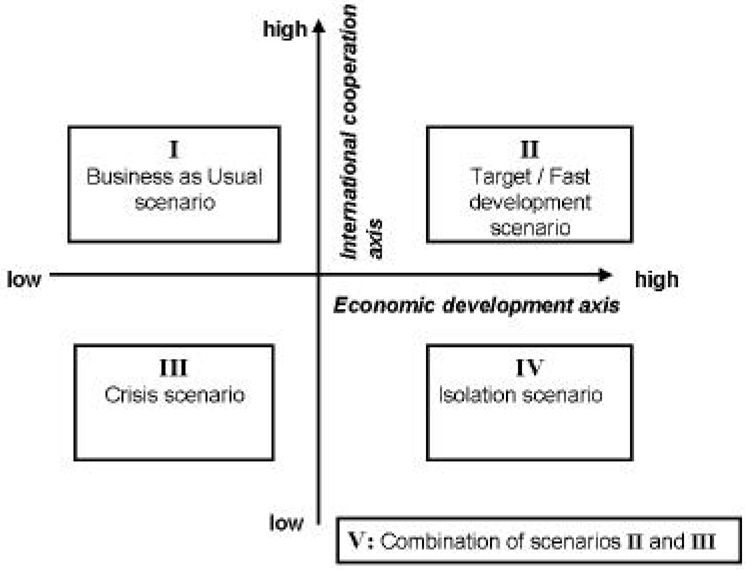

Figure 3. *Rationale of defining the five scenarios*

These qualitative storylines were translated into changes in a number of input driving forces of the nutrient emission, transport and retention model between 1995-1999 and 2015-2019. These driving forces include *population*, *wastewater treatment connection rate*, *fertiliser use*, *livestock amount*, *crop yields*, *atmospheric deposition* and *amount of agricultural land*. Table 1is an overview of the changes in these driving forces of the model for the five scenarios considered.

Model simulations

The calibrated nutrient transport model for the period 1985-1999 (three 5-year time steps) was extended with four more time steps for the period 2000-2019. The model input for the five scenarios was defined for the last time step, i.e. the period 2015-2019. For the intermediate period 2000-2014, the spatially disaggregated diffuse and point source emissions were linearly interpolated in time. Subsequently, the accordingly calculated emissions served as input for the nutrient transport module that calculated the spatially distributed riverine loads of Ntot and Ptot. The model results were reported as the average annual loads from the main Velikaya (Russia) and Emajõgi (Estonia) rivers and the total average annual load into Lake Peipsi/Chudskoe.

Table 1. Changes in model driving forces under different scenarios

SCENARIO	Population	WWTP connection	Fertiliser use	Livestock amounts	Crop yields	Atmospheric deposition	Amount of Agricultural land
I Business as Usual	Constant in Tartu and Pskov EST/LAT: Rural: 8 % decrease RUS: 5 % decrease	No changes	EST/LAT: Increasing from 14 kg/ha/yr N and 1.1 kg/ha P to 50 kg/ha/yr N and 2 kg/ha/yr RUS: no change	EST/LAT: 10 % increase RUS: no change	EST/LAT: 25 % increase RUS: no change	No change	Tartu and Pskov counties: only 85 % left from 1980ies land Other counties: only 60 % left
II Target/Fast Development	Tartu and Pskov: growth of 10 %. Rural: growth of 5 %	EST/LAT: only in settlements, treatment will improve one step RUS: only in settlements > 10000 inhabitants	Increasing from 14 kg/ha/yr N and 1.1 kg/ha/yr P to 130 kg/ha/yr N and 15 kg/ha/yr	100 % increase	EST/LAT: 40 % growth. Industrial crops: 70 % increase RUS: no change	Changes from 7.7 kg/ha/yr to 15 kg/ha/yr (N) and from 0.05 kg/ha/yr to 0.08 kg/ha/yr (P)	Same amount as in 1980ies
III Crisis	Tartu and Pskov: decrease of 5 % EST/LAT: Rural: decrease of 25 % RUS: 30 %	EST/LAT: no change RUS : Collapse of current systems	EST/LAT: no change (14 kg/ha/yr N and 1.1 kg/ha/yr P) RUS: decrease with 80 % to 2.8 kg/ha/yr N and 0.22 kg/ha/yr P	EST/LAT: 50 % decrease RUS: 75 % decrease, except for milk cows: 100 % increase	50 % decrease	No change	EST/LAT: 50 % decrease RUS: 80 % decrease
IV Isolation	No change	EST/LAT: only in settlements, treatment will improve one step. RUS: no change	EST/LAT: 50 % increase (to 21 kg/ha/yr N and 1.65 kg/ha/yr P). RUS: no change	EST/LAT: 30 % increase RUS: no change	EST/LAT: 40 % increase RUS: no change	Changes from 7.7 kg/ha/yr to 15 kg/ha/yr (N) and from 0.05 kg/ha/yr to 0.08 kg/ha/yr (P)	EST/LAT: 10 % decrease RUS: 60 % decrease
V Target/Fast Development in Estonia/Latvia, Crisis in Russia	Pskov: decrease of 5 % Tartu increase of 10 % EST/LAT: Rural 5 % increase. RUS: Rural 30 % decrease	EST/LAT: only in settlements, treatment will improve one step. RUS: Collapse of current systems	EST/LAT: increasing from 14 kg/ha N and 1.1 kg/ha P to 130 kg/ha N and 15 kg/ha RUS: decrease with 80 % to 2.8 kg/ha/yr N and 0.22 kg/ha/yr P	EST/LAT: 100 % increase RUS: 75 % decrease, except for milk cows: 100 % increase	EST/LAT: 40 % growth. Industrial crops: 70 % increase RUS: 50 % decrease	EST/LAT: Changes from 7.7 kg/ha/yr to 15 kg/ha/yr (N) and from 0.05 kg/ha/yr to 0.08 kg/ha/yr (P) RUS: no change	EST/LAT: Same amount as in 1980ies RUS: 80 % decrease

RESULTS AND DISCUSSION

Nutrient emissions

In table 2, the diffuse and point sources emissions for the past modelling periods and the future scenario period are given, aggregated over three countries sharing the drainage basin. Because in the intermediate period between 1989 and 2015 the emissions were assumed to change linearly, emissions for this period are not given.

Table 2. Simulated Ntot and Ptot diffuse and point emissions for the three (calibrated) past modelling periods and for the five scenarios (see table 1 for a description of the scenarios).

	Simulated emissions (past)			**Simulated emissions for 2015-2019 (scenarios)**				
	1985-1989	**1990-1994**	**1995-1999**	**I**	**II**	**III**	**IV**	**V**
Ntot (kT/yr)								
Diffuse emissions								
Russia	250	183	133	133	332	70	84	49
Estonia	141	56	25	32	129	32	37	129
Latvia	26	10	5	6	27	7	7	27
Total	*417*	*249*	*163*	*171*	*488*	*109*	*128*	*205*
Point emissions								
Russia	2.41	2.27	2.12	2.06	1.72	2.48	2.21	2.46
Estonia	1.47	1.30	1.10	1.01	0.87	0.87	1.33	0.89
Latvia	0.21	0.21	0.21	0.19	0.22	0.15	0.21	0.21
Total	*4.09*	*3.78*	*3.41*	*3.26*	*2.81*	*3.50*	*3.75*	*3.56*
Ptot (kT/yr)								
Diffuse emissions								
Russia	48	33	20	20	51	4	20	18
Estonia	26	7	-1	-3	10	-1	-3	10
Latvia	5	1	-1	-1	1	0	-1	-1
Total	*79*	*41*	*18*	*16*	*62*	*-3*	*16*	*27*
Point emissions								
Russia	0.75	0.60	0.60	0.43	0.50	0.73	0.44	0.60
Estonia	0.32	0.29	0.26	0.23	0.24	0.20	0.32	0.25
Latvia	0.06	0.06	0.06	0.04	0.06	0.05	0.06	0.06
Total	*1.13*	*0.95*	*0.92*	*0.70*	*0.80*	*0.98*	*0.82*	*0.91*

Table 2 shows that the total emissions of Ntot period decreased considerably in the 1985-1999, especially the diffuse emissions (59 %). The decrease was largest in Estonia and Latvia. For point emissions, the decrease was less pronounced, because the improvement of wastewater treatment plants proceeded slowly. Table 2 also shows that the changes in simulated diffuse emissions for the 2015-2019 vary widely for the three countries for all scenarios.

The same decrease in diffuse emissions during 1985-1999 is visible for Ptot. For Estonia and Latvia, emissions are even negative: extraction of Ptot from arable land is larger than the input. Regarding the scenarios, none of the economic development scenarios will result in Ptot emissions exceeding communist period emissions. Ptot emissions from point sources did not decrease rapidly during 1985-1999. No substantial changes are expected under the future scenarios.

Nutrient loads

Figure 4 shows the simulated Ntot and Ptot loads into Lake Peipsi for the 1985-1999 period and the 2015-2019 period. Both Ntot and Ptot loads into the lake have decreased during the nineties, in particular the Ntot loads. This decrease is spread evenly over the Russian/Latvian (river Velikaya) and the Estonian (Emajõgi) part of the drainage basin. Ntot loads are expected to decrease in all scenarios, except for scenario II (*Target/Fast Development*), mainly influenced by an increase in the Velikaya river load (Russia/Latvia).

Ptot loads will be reduced under all scenarios. In general, the direction in which nutrient loads into the lake change depends on the riverine loads of the Russian rivers, in particular the river Velikaya. This is caused by the relative large part of the entire drainage basin that is situated in Russia (67 %), as well as a high sensitivity of emissions to economic developments in the Russian part.

A remarkable feature is the occurrence of the largest expected Ntot load under scenario II (*Target/Fast Development*), while the largest expected Ptot load will be reached under scenario III (*Crisis*). The main explanation for this discrepancy is the relative importance of point source emissions for the Ptot loads. Under scenario III (*Crisis*), Russian wastewater treatment is assumed to collapse and the removal of Ptot from public wastewater in Russia is assumed to be zero.

The increase in the Ntot loads under scenario II (Target/Fast Development) shows the importance of changes in the amount of arable land in use. Under this scenario, wastewater treatment generally improves, but the effect of this on Ntot loads can be neglected in comparison with the increase of diffuse runoff from agriculture.

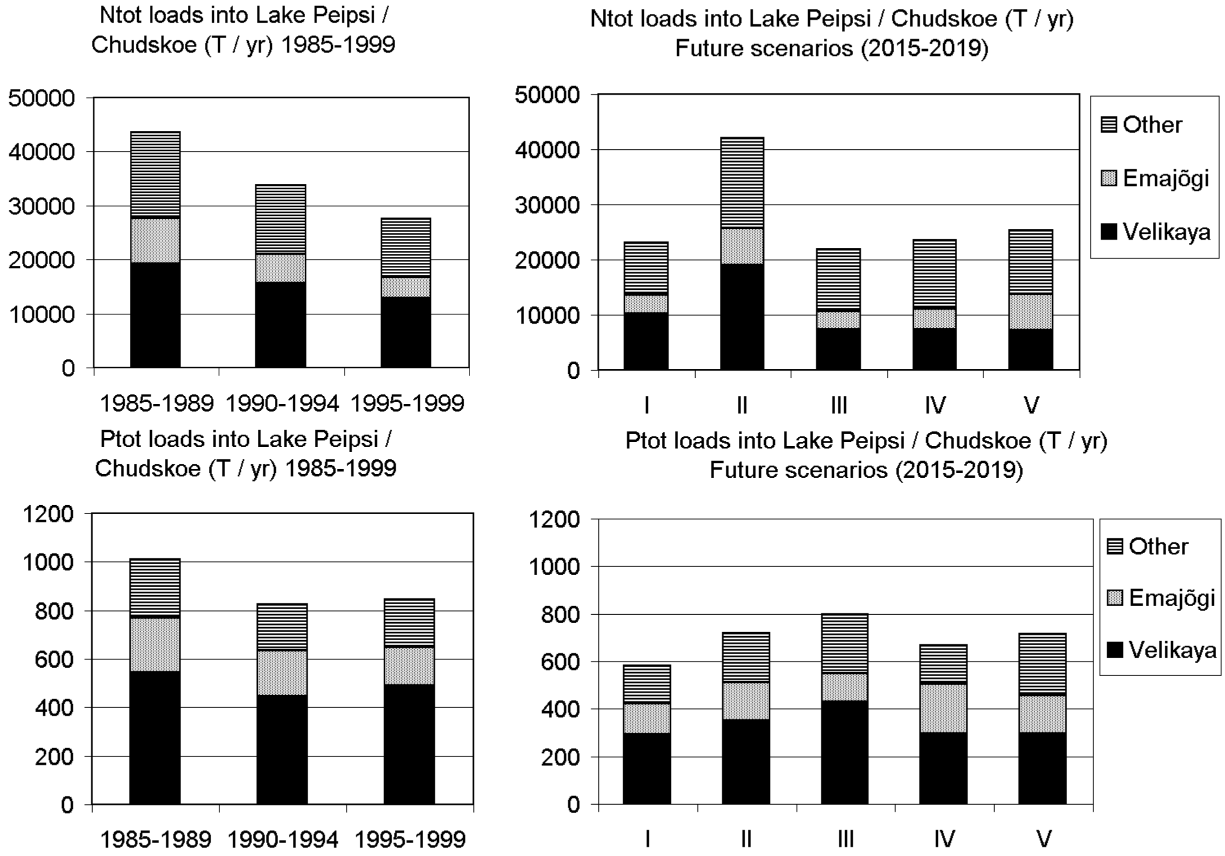

Figure 4. *Loads into Lake Peipsi / Chudskoe for three past time periods and for the five scenarios for the time period 2015-2019.*

CONCLUSIONS

The GIS-embedded nutrient emissions, retention and transport model has proved to be a useful tool for the simulation of nutrient loads in past, present and future in transboundary drainage basins. With a minimum of large-scale maps and calibration of the model using data from a relatively data-rich part (Estonia), plausible nutrient emission estimations and load simulations can be obtained for an entire basin, including data-poor parts (Russia/Latvia). The modelling of nutrient emissions and loads for future scenarios enables decision makers to identify priorities for water management, and evaluate the effect of various developments.

For the Lake Peipsi/Chudskoe case, it can be concluded that under the five scenarios of future regional development in Estonia, Latvia and northwest Russia, nutrient loads into the lake will generally decrease. Only scenario II (Target/fast Development) results in a substantial larger Ntot input to the lake. The *Crisis* scenario (III) yields the largest Ptot load. No scenario predicts larger nutrient loads than in the communist period.

The model results suggest that change of the amount of arable land is a major factor controlling nutrient loads to Lake Peipsi. Although connection to wastewater treatment plants and larger removal efficiencies for these installations can solve hygienic problems locally, strategies for nutrient load reduction should mainly focus on agricultural nutrient runoff, especially in the Russian part of the drainage basin.

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