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Modelling climate change impact on phosphorus load in Swedish rivers

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Abstract Climate change impact on phosphorus load is modelled and compared for two Swedish rivers with different characteristics. The modelling was based on the ECHAM4/OPYC3 B2 scenario, downscaled with the RCA3 model and a complementary scaling procedure. Hydrology and phosphorus concentrations were simulated for the time period 1961–2100, using the ICECREAM model for arable leaching, and HBV-NP model for integrated catchment analysis including all sources, erosion and major turnover processes at the catchment scale. The results show 10% increased load, and 25% reduced load, respectively, for the rivers. In both catchments, phosphorus leaching from crops was found to increase; however, this load was only a minor fraction in one river. For the other river, a suggested plan of measures for reducing load was found to be less effective in a future climate. Finally, the study concludes that climate change impact studies are based on a chain of assumptions and uncertainties which should be emphasised in future research.

Key words catchments; climate change impact study; phosphorus; river load; Sweden

INTRODUCTION

Phosphorus transport from land (mainly by rivers) is contributing to the eutrophication problems in Swedish lakes and the Baltic Sea. The amount of phosphorus transported is a result of point-source emissions, atmospheric deposition, erosion, subsurface leaching from soil, diffusion from river and lake sediments and biochemical processes in the freshwater system. Except for point-source emissions, all these factors are strongly influenced by weather (e.g. temperature and precipitation) and would thus be affected by a climate change. The Intergovernmental Panel on Climate Change quoted a global mean warming of 1.4–5.8°C between 1990 and 2100 (IPCC, 2001). Regional analysis indicates an increase in temperature of 3–4°C and up to 40% more precipitation for Sweden (Rummukainen *et al.*, 2004). Hydrological impact studies have shown that these new conditions will change the water balance with significant geographical variation when it comes to long-term means, seasonal cycles, and extreme conditions (Andréasson *et al.*, 2004).

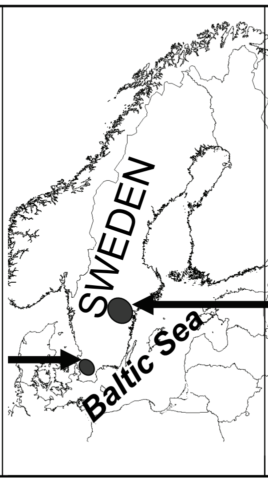
One way to evaluate possible effects of climate change on ecosystems and water quality is to use numerical models. These are applied with input data for both present climate and future climates. Several examples of simulated changes in future nutrient loads have been presented lately. They show large variations and often contradictory conclusions between catchments, cf. e.g. Kallio *et al.* (1997), Cruise *et al.* (1999), Bouraoui *et al.* (2002) and Varanou *et al.* (2002). Obviously, such differences in conclusions are related to site-specific conditions and regional differences of the changes in the climate pattern. Hence, results from climate change impact studies are not universal, and therefore each watershed must be studied separately. In this study, the climate change impact on phosphorus load is modelled and compared for two Swedish rivers with different characteristics. Moreover, the results are related to a present plan of measures for reducing riverine nutrient load to the Baltic Sea, and general difficulties when performing climate change impact studies are discussed.

MATERIAL AND METHODS

The present study is undertaken for two Swedish catchments; the Motala ström River which drains an area of 15 000 km^2 and is located in middle/southeastern Sweden, and the Rönneå River which drains an area of 2000 km^2 and is located in southwestern Sweden (Fig. 1). The two basins represent a drier and a wetter part of Sweden, and differ in soil types as well as geographical distribution of landscape elements. The modelling of climate change was based on the ECHAM4/OPYC3 global model (Roeckner *et al.*, 1999) using the emission scenario SRES B2 (Nakićenović *et al.*, 2000). Downscaling to regional conditions was undertaken using the RCA3 model (Rummukainen *et al.*, 2001) for a 50 × 50 km grid, from which local subcatchment conditions were derived by adapting a scaling procedure (Rosberg & Andréasson, 2006) to adjust results to observed data for present conditions during the control period of 1961–1990.

Transient modelling of hydrology and phosphorus concentrations in each river was undertaken for the time period 1961–2100 using the ICECREAM model (Tattari *et al.*, 2001) for diffuse arable leaching and the HBV-NP model (Andersson *et al.*, 2005) for integrated catchment analysis including all sources, erosion and major turnover processes at the catchment scale. The hydrological catchment model HBV consists of routines for snow, soil moisture, groundwater, runoff response, and routing through rivers and lakes (Lindström *et al.*, 1997). The model was adapted to simulate hydrological conditions in Sweden where the groundwater water table is often shallow, follows the land surface topography, and responds quickly to rainfall and snowmelt

Rönneå River	
Catchment area	1 900 km^2
Forest	48%
Lakes	3%
Arable land	31%
Arable land with:	
<13% clay content	93%
animal farms	40%
Present climate (ann.av):	
temperature	7.4°C
precipitation	830 mm
water discharge	13 ls^{-1}km^{-2}
Population:	
inhabitants	52.5 km^{-2}
rural households	21%



Motala ström River	
Catchment area	15 500 km^2
Forest	51%
Lakes	20%
Arable land	15%
Arable land with:	
<13% clay content	1%
animal farms	10%
Present climate (ann.av):	
temperature	6.1°C
precipitation	635 mm
water discharge	6 ls^{-1}km^{-2}
Population:	
inhabitants	35.5 km^{-2}
rural households	9%

Fig. 1 Location and characteristics of the two study catchments.

events. The streamflow generation zone in the HBV model is divided into an "upper zone" with short transit times and a "lower zone" with longer transit times. The HBV-NP model was first developed by attaching a nitrogen module (Arheimer & Brandt, 1998) and later a phosphorus module (Andersson *et al.*, 2005).

The HBV-NP is a dynamic mass balance model with a daily time step, which simulates both particulate (PP) and soluble reactive (SRP) phosphorus (Andersson *et al.*, 2005). It considers residence, transformation, and transport in groundwater, rivers, and lakes in coupled subcatchments throughout the river network of a catchment. Routines for surface runoff sediment transport are based on a modification of the Curve Number Method (USDA Soil Conservation Service, 1972) combined with equivalent ICECREAM results for enrichment factors. Streambank erosion is based on the concept of the AVGWLF model (Evans *et al.*, 2003). Subsurface leaching is achieved from soil–crop–land management matrices of SRP, which yields long-term averages from simulations with the ICECREAM model; the daily values show very little temporal variability. To account for the high temporal variability of the macropore flow concentrations, which are included in ICECREAM based on the concept of Larsson *et al.* (2007), time series of monthly average macropore flow concentrations of SRP and PP are imported. In addition to the diffuse nutrient losses (from arable land, pasture, mire and forest), contributions from rural households, industries, and wastewater treatment plants are included for streams, rivers and lakes in the HBV. Atmospheric deposition is added to lake surfaces, while deposition on land is implicitly included in the diffuse losses.

The equations that account for the nutrient turnover processes are mainly based on empirical relations between physical variables, landscape characteristics, and concentration dynamics (Andersson *et al.*, 2005). For SRP, exchange with sediment may give temporary production or retention, while biological production and the adhesion to soil particles are assumed always to cause net SRP retention. Three equations determine PP turnover, biological production, and temporary sedimentation or resuspension.

In the present study, the ICECREAM model was applied using climate data from one typical location in the main agricultural district of each catchment for four different soil types combined with two crop rotations (one for animal farms and one for pure plant farms), which resulted in eight concentrations levels for subsurface leaching from arable land in each river basin. These were related to land use and soil type classification in each sub-basin and attached to water infiltration according to the more distributed calculations with the HBV model.

For the catchment modelling with the HBV model, the Motala ström River was divided into 253 subcatchments and the Rönneå River into 64 subcatchments. Calculations were made for each subcatchment, mostly for ungauged conditions, using regional parameterisation. However, monitored time series in some sites were used for calibration of concentration and water flow, respectively, and validation of P transport in the last 20 years. The models were then run for the entire time period simulating water discharge and phosphorus concentrations in a future climate. Phosphorus emissions and input data, which are not directly related to climate, were not changed in the simulation, e.g. population, traffic, and crop distribution were assumed to be similar in the 1990s and 2090s. Results are presented on an average annual basis for periods of at least 20 years, as the daily weather is not considered to be reliable in climate modelling.

The impact of future climate change was compared to the impact of a present plan of measures, which was recently developed for the Rönneå catchment. The measures were then incorporated in the model and run with the future climate. The plan has been presented in a previous study as a cost-effective way to reach the national goal to reduce phosphorus load to the sea by 20% (Arheimer *et al.*, 2005a). The cheapest measures were allocated where they were simulated to be most effective, and included changes in farming practices (with spring crops, catch crops, fertilisation in spring and buffer zones), construction of wetlands on arable land and close to largest point sources, and upgraded rural household treatment.

RESULTS AND DISCUSSION

The HBV-NP model showed reasonable agreement with observed values when evaluating five sites in Rönneå River and eight sites in the Motala ström River for a 20-year period with present climate (Fig. 2). For the Rönneå River, the upstream sub-catchments are most poorly simulated, while the errors are largest at the outlet stations of the Motala ström River. This corresponds to the geographical locations of lakes in each catchment. Thus, phosphorus turnover in lakes seems to be the weakest part of the HBV-NP model. However, it should also be recognised that 20 years is a rather short period for present climate representation of the RCA modelling, which is the forcing data of the model simulations. Per unit area, the P transport is 40% higher in the Rönneå catchment, which can be related to relatively more arable land, more animal farms, denser population, more rural households and higher water discharge (cf. Fig. 1). The Motala ström River has higher percentage of clay content in arable soils, which result in higher leaching concentrations from crops, but the point sources and lakes close to the river outlet dominate the river transport reaching the sea.

The climate change scenario results in very different impacts on the two rivers. According to the HBV modelling, the Rönneå River shows a gradual increase in water flow up to 10% on an annual basis. In contrast, the Motala ström River shows a decrease in water flow with 25% less discharge to the sea. This is in agreement with previous studies indicating that the present hydrological pattern of Sweden will be further strengthened in a future climate, with dry regions getting drier and the wet parts wetter (e.g. Andréasson *et al.*, 2004).

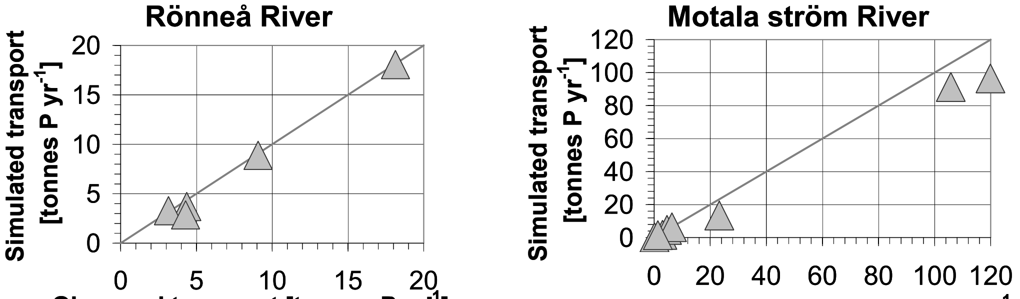


Fig. 2 Model performance at monitoring sites where monthly P concentrations and daily water discharge is measured. Values represent 20-year averages of daily modelling and daily interpolated transport, respectively.

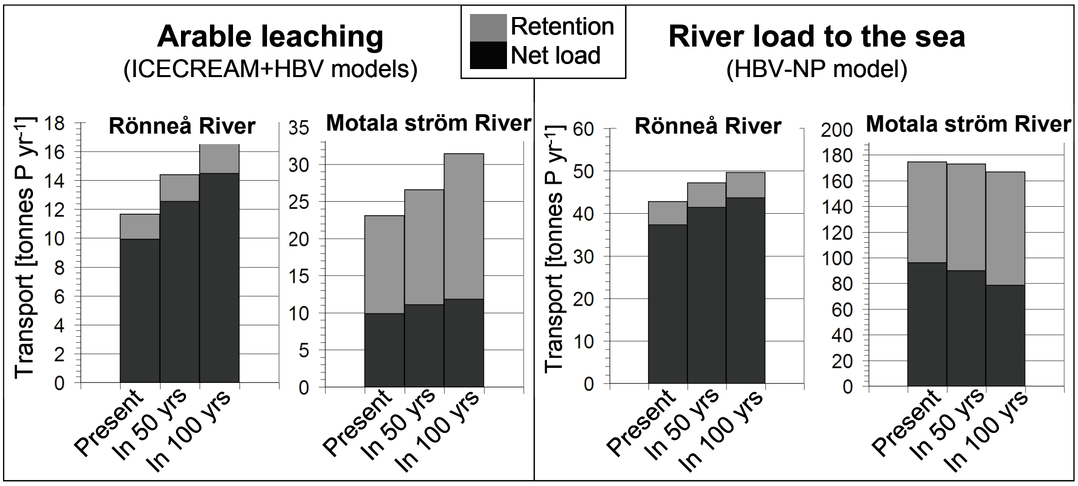


Fig. 3 Modelled phosphorus load in the two catchments, using ICECREAM concentrations for arable leaching combined with HBV water from various combinations of crops and soils according to their distribution. River load includes contribution from all sources. Full bars represent gross load in the catchment, the grey part is removed in the river network during the transport, while the black part eventually reaches the sea. Average values for climate periods are shown: Present = 1991–2010, in 50 years = 2031–2050, in 100 years = 2071–2100.

Phosphorus leaching from arable land will increase according to the modelling using ICECREAM and HBV (Fig. 3). It is likely that higher temperature will increase the mineralization rate. However, the effect is most pronounced for crops, such as cereals, and is probably related to less snow cover and increased soil moisture, intensive rains and water throughflow in the soil profile during the winter. The fields at that time are bare without nutrient up-take by vegetation and the soil is sensitive to surface erosion. Animal farms with pasture and ley in the crop rotation are less affected, and in the Motala ström catchment there is no significant change in leaching from animal farms at all, due to lower water discharge in a future climate.

As there is no direct modelling of leaching processes for other soil types than those related to agriculture in the model concept used, the results for forest and other land only reflect changed water flow. Thus, there is a slight increase in load from these land covers in the Rönneå River, and a decrease in Motala ström River. However, the HBV-NP model simulates natural internal processes in lakes and watercourses, which resulted in increased retention (e.g. sedimentation, adsorption, up-take by biota) in both catchments. This may be explained by higher temperature and higher concentrations in the future climate, which increase biological growth and change redox potentials in river and lake sediments. The effect on retention was most significant in Motala ström River (>10 tonnes P more on an annual basis), where it may also reflect increased residence time and reduced water flow. Internal loading from lakes increased in the Rönneå River, which is in agreement with a previous analysis using a more detailed biogeochemical model for Lake Ringsjön in the Rönneå catchment (Arheimer *et al.*, 2005b). However, this internal loading decreased in the Motala ström River, which may reflect the different shift in hydrological regimes between the catchments or may just be a matter of calibration. It can be questioned whether this rather empirical model is describing the new ecological lake conditions of a future climate in a realistic way.

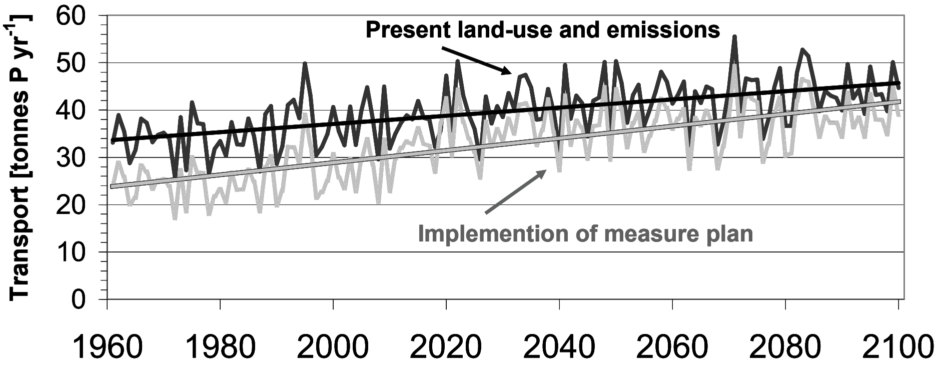


Fig. 4 Simulated phosphorus load in the Rönneå River in a changed climate based on present land use and emissions, and the cost-effective plan of measures, respectively. Trend lines are given.

The agricultural load is only a minor part of the total load at the outlet of the Motala ström River, due not only to a low percentage of arable land, but also because the arable land is located upstream in the catchment and load from these areas is retained in downstream lakes. Moreover, two large towns (not affected by the climate impact modelling) are situated close to the outlet and strongly influence the transport. Figure 3 illustrates that in the model the overall phosphorus transport to the sea is mainly affected by reduced water discharge in a future climate. Nevertheless, it should be remembered that changed leaching concentrations from forests have not been considered, and that the lake routine is the weakest part of HBV-NP. Modelling results for the Motala ström River can thus be considered as rather uncertain.

The increased phosphorus transport in the Rönneå River will significantly reduce the effects of the present plan of measures (Fig. 4). When incorporating the measures in the model, the total transport is reduced by 28%, but as climate change impact evolves, the effect of the measures is significantly reduced. In 2090, only 12% of the reducing effect remains, and it can be concluded that the chosen measures are thus rather climate dependent. Modelled time series show that the shift in load is not linear over time, but there is a more dramatic increase the first two decades when measures would be implemented. After 2020, the gap between scenarios is more constant. It seems to be important to include climate change analysis in plans of environmental measure in order to optimise the effect to last over several decades. Thus, climate change must be considered when establishing such measure plans in 2009 within the Water Framework Directive in Europe.

FINAL REMARKS

The paper presents a rather sophisticated climate change impact study, which is possible today thanks to numerical modelling and computer capacities. However, it should be admitted that the results are based on a chain of assumptions and uncertainties. First, and perhaps most crucial, is that the spatial resolution of the global circulation models is not sufficient to capture the main climate features of importance for Sweden, e.g. cyclone tracks and blocking situations. Decadal variations, for example, linked to the North Atlantic Oscillation are also poorly represented in the global models. Ensemble modelling is normally used to capture differences among climate models, but the models are to a large degree built on the same equations and resolution. Second, adequate downscaling procedures are still under development and the main driving data for hydrology, such as precipitation and evapotranspiration, also are among the most poorly simulated variables in regional climate models. Hence, modelled climate data is tuned to fit observed data for the control period, leading to a bias of present climate features in the scenario. Third, many of the processes linked to nutrient leaching cannot be described properly without very good knowledge of site-specific conditions. The weakest points in the presented hydrochemical model concept are probably leaching from forests, particulate phosphorus transport from arable land, exchange between water and sediments, and behaviour of lake ecosystems. The lake routine is very sensitive to calibration. Major uncertainties related to input data are soil and sediments properties, treatment and pathways of rural household emissions, and the delivery factor of soil surface erosion. More detailed monitoring would have reduced some of these uncertainties significantly. Hydrochemical modelling would also have gained from being performed within the same model frame, i.e. one single model should handle both the soil and the water system. Thus, a more homogenous model concept for water quality scenario analysis is under development at the SMHI. Finally, climate change will probably impact on agricultural practices, types of crops, population size, land cover and industrial activities in the future. Such holistic scenarios are not yet developed for these catchments. Nevertheless, this kind of impact study identifies where to put efforts for more certain analysis of a very important and complex issue.

CONCLUSIONS

- Climate change impact on riverine phosphorus load in Sweden depends on local hydroclimatological conditions combined with the geographical location of landscape elements and emissions. The two rivers studied show a 10% increased load, and a 25% reduced load, respectively. Hence, no general conclusions on climate change impact on phosphorus transport can be made, but each river and catchment must be studied separately.
- Phosphorus leaching from crops will increase and so will retention in the surface water system, according to the climate change impact modelling.
- The impact of a suggested plan of measures for present conditions will be radically reduced in a future climate, especially during the coming two decades. Hence, climate change impact assessment should be undertaken to optimise measures to last over time.
- Climate change impact studies are based on a chain of assumptions and uncertainties. The most crucial in the present study of riverine phosphorus load are spatial resolution and uncertainties of global circulation models, hydroclimatological downscaling procedures, knowledge of site-specific soil/water conditions and emissions, and finally, coupling procedures between different model concepts at the catchment scale.

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