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Climate Change Impact on Riverine Nutrient Load and Land-Based Remedial Measures of the Baltic Sea Action Plan

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Abstract To reduce eutrophication of the Baltic Sea, all nine surrounding countries have agreed upon reduction targets in the HELCOM Baltic Sea Action Plan (BSAP). Yet, monitoring sites and model concepts for decision support are few. To provide one more tool for analysis of water and nutrient fluxes in the Baltic Sea basin, the HYPE model has been applied to the region (called Balt-HYPE). It was used here for experimenting with land-based remedial measures and future climate projections to quantify the impacts of these on water and nutrient loads to the sea. The results suggest that there is a possibility to reach the BSAP nutrient reduction targets by 2100, and that climate change may both aggravate and help in some aspects. Uncertainties in the model results are large, mainly due to the spread of the climate model projections, but also due to the hydrological model.

Keywords Nutrient modelling · Climate change · Remedial measures · Baltic Sea basin

INTRODUCTION

The implementation of the Marine Strategy Framework Directive (MSFD; 2008/56/EC) to protect Europe's oceans and seas is now underway in the EU Commission and the Member States. The Helsinki Commission (HELCOM) is the coordination platform for the MFSD implementation in the Baltic Sea region. The Baltic Sea in Northern Europe is an enclosed sea, receiving fresh-water and waterborne pollution from nine surrounding countries, and another six upstream countries in the drainage basin (Fig S1, Electronic supplementary material). A serious and difficult to mitigate challenge facing the Baltic Sea is eutrophication. The effects of eutrophication include algal blooms, dead-sea beds and reductions in fish stocks, which also are detrimental to the future economic prosperity of the Baltic Sea Region (HELCOM 2007). For this reason, HELCOM commissioned the preparation of the Baltic Sea Action Plan (BSAP), a programme to restore good ecological status of the Baltic Marine Environment by 2021. The BSAP was approved in 2007 by the countries surrounding the Baltic Sea (HELCOM 2007). An important part of this plan is the reduction of nutrient inflow from the drainage basin into the marine environment. Required nutrient reductions have been apportioned to the countries in the basin and these countries are now planning the remedial measures necessary to meet the plan's requirements (Swedish EPA 2010).

An important factor that remains to be considered, however, is how well the planned nutrient reduction measures improve nutrient inflows into the Baltic Sea in a changed future climate. Nutrient inflows from land to sea are a result of atmospheric deposition, erosion, subsurface leaching from soil, diffusion from river and lake sediments, point-source emissions from industrial and urban sources and biochemical processes in the freshwater system. With the exception of the point-source emissions these factors are weather dependent.

So far, the international strategic agreements on reduction targets for various countries and societal sectors have been based on the results from the NEST model concept (Mörth et al. 2007; Wulff et al. 2009) and the HELCOM pollution load compilations (HELCOM 2005). Recently, the HYPE model (Lindström et al. 2010) was also applied for the entire Baltic Sea basin, i.e. Balt-HYPE (Donnelly

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et al. 2010; Arheimer et al. 2012). This model simulates water and nutrient concentrations from land to the sea on a daily basis, including major sources and sinks along the flow path. As the HYPE model is process based and driven by daily temperature and precipitation, it reflects the influence of weather and climate on water and nutrient flow. Hence, it can be used for experimenting with impacts of both the remedial measures and the future climate.

Contemporary climate change analysis uses several model concepts in ensemble runs to estimate the uncertainty in the overall conclusions to decision makers (IPCC 2007). A similar ensemble approach is used for meteorological model input to hydrological forecasts (e.g. Norbert et al. 2010; Arheimer et al. 2011a, b). Ensemble means from several hydrological models have actually been found to give better performance than each single model used (Viney et al. 2005), and recently this approach has also been applied to water quality models (Exbrayat et al. 2010). The Balt-HYPE model may contribute to such a model ensemble in the future.

There have been a few previous efforts on dynamic hydrological modelling of the pan-Baltic basin. For instance, Bergström and Carlsson (1994) constructed a model partly based on observations and Graham (1999) set up the HBV hydrological model to calculate monthly inflows to the Baltic Sea. The latter model was also used to evaluate how freshwater inflows to the Baltic Sea might change in a future climate (Graham 2004), and for modelling nitrogen fluxes in the region (Pettersson et al. 2000). None of the mentioned models, however, were ever used for decision support.

The aim of this article is to show that advanced simulation models can provide useful information not only to scientists but also to decision makers who have to take into account future climate and management when considering environmental issues. Nevertheless, all models involve uncertainties and it is therefore suggested that the presented results should be part of an ensemble of predictive models, rather than be the sole basis for strategic decision making in the Baltic Sea region.

The scientific hypothesis is that climate change will affect the efficiency of suggested measures against eutrophication in the BSAP. This hypothesis was explored by using the Balt-HYPE model as a hydrological laboratory and experimenting with several 'what if' scenarios on nutrient emissions and future climate. To sum up, the objectives are to:

- demonstrate the Balt-HYPE model concept for estimating water and nutrient loads to the major Baltic Sea basins.
- quantify the impacts of climate change on land-based water and nutrient loads.
- quantify the effects of suggested remedial measures in present and future climates.

MATERIALS AND METHODS

The Balt-HYPE Model

The BALTic Sea basin HYdrological Predictions for the Environment (Balt-HYPE) model calculates water and nutrient fluxes with a relatively high resolution from land to the sea. It is based on the HYPE model code (Lindström et al. 2010), which is dynamic, semi-distributed, process-oriented, and based on well-known hydrological and nutrient transport concepts. The model simulates time series of hydrological and nutrient variables for 5128 sub-basins, which are mostly unmonitored. Observed data are used to evaluate model performance at the points in the model where these are available. Major nutrient sources and sinks are included in the concept. In the model, the landscape is divided into classes according to soil type and vegetation. The soil representation is stratified and can be divided up to three layers. Nutrients follow the same soil path as water. The flow paths include surface runoff, macropore flow, tile drainage and groundwater outflow from the individual soil layers. Rivers and lakes are described separately with routines for outlet flow, turnover, sinks and sources. Several processes in the model concept are weather dependent as precipitation and temperature force the dynamics at each time step. For example, weather affects flow paths, detention time, mineralisation, denitrification, plant uptake, erosion, water volumes and fluxes in rather complex interactions. Thus, the model results reflect the effects of climate.

When setting up the HYPE model for a specific region, relevant input data and parameter values are needed. For the Balt-HYPE model, readily available databases covering the entire region were applied (Table S1, Electronic supplementary material). In the model, coefficients are global, or related to specific characteristics of hydrological response units (HRU), i.e. combinations of soil type and land use. The HYPE model has many rate coefficients, constants and parameters, which in theory could be adjusted. For the Balt-HYPE model-parameter values were based on the Swedish application (called S-HYPE; Strömqvist et al. 2012) and then modified using a step-wise, multi-basin calibration technique (Donnelly et al. 2009). This regional calibration included 35 daily river discharge stations and 20 water quality stations, with validation in a further 121 daily discharge stations. The model was not calibrated to individual stations but to give optimal performance across all stations. Although this may give less optimised performance for

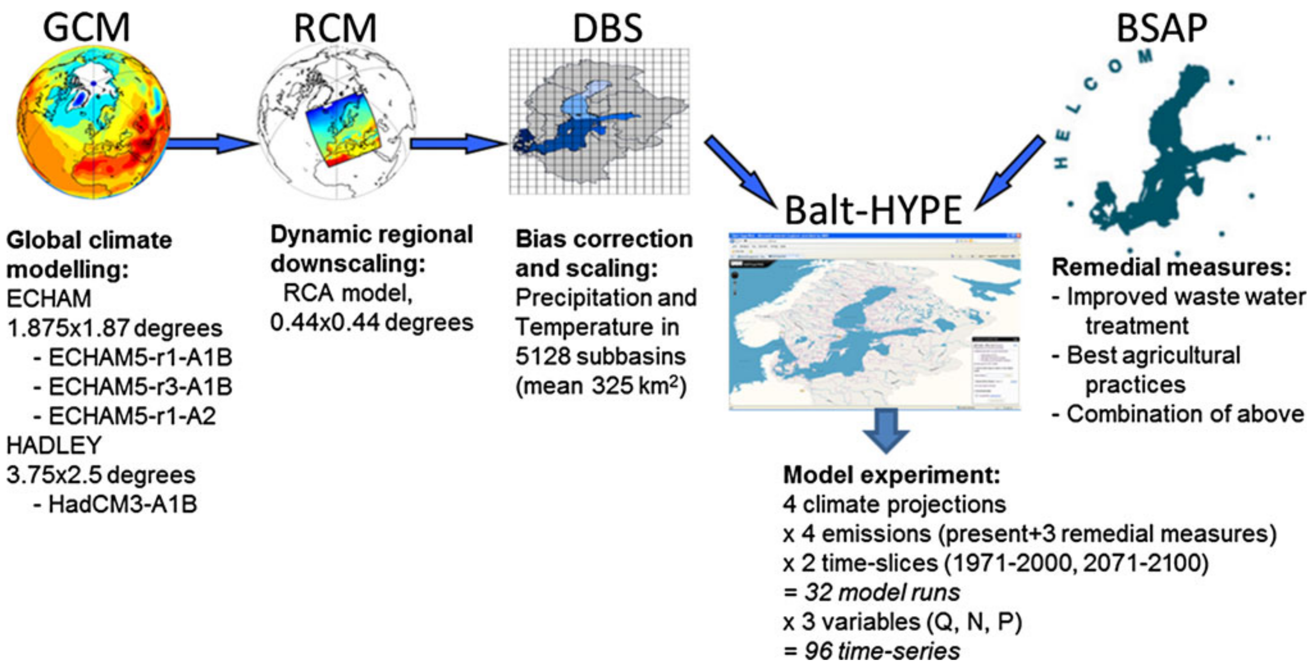

Fig. 1 Procedure of the model experiment on climate change and remedial measures impact on land-based nutrient loads to the Baltic Sea

individual sites, overall it gives a robust parameter setting for predictions in all ungauged basins. The spread of the model performance in the gauged basins may be assumed to be an estimate of the uncertainty in the predictions in the ungauged basins (e.g. Strömqvist et al. 2012). The model was run on a daily time step from 1961 to 2008 to account for variability in weather and water flow, but using nutrient emissions from the 2000's. Observed data for the period 1996–2005 was used for calibration and validation (Arheimer et al. 2012). The chosen parameter values were assumed to also be valid in the future climate.

Model Experiments

The model was used for experimenting with changes in nutrient emissions and climate (i.e. precipitation and temperature). One or a few factors were changed at a time in the predefined system and compared with original simulations to distinguish the net effect of these changes from complex interactions of water and nutrient processes in both the soil and the watercourses.

The climate-impact assessment was based on an ensemble of four future climate projections (Fig. 1), representing different general circulation models (GCM), different emission scenarios and different initial conditions in the climate modelling (Linden and Mitchell 2009; Meier et al. 2011). The ensemble is used to illustrate the uncertainty in the climate modelling, whereby each member of the ensemble is considered equally reliable. Each GCM was first dynamically downscaled, using the regional Rossby Center Atmosphere (RCA) model with ocean coupling (Döscher et al. 2002; Meier et al. 2011). Thereafter the data was bias-corrected, using the distribution-based scaling method (Yang et al. 2010) to tailor the climate projections for hydrological applications. Bias correction and scaling are made to increase the resolution of the data to the hydrological sub-basin scale and to improve the resemblance to observations, because raw data from dynamically downscaled climate models is generally of insufficient resolution and accuracy for driving hydrological models. Climate models do not have precision for specific years, only for statistical averages. Therefore, only long-term average annual loads were analyzed in the experiment. For each model projection, a future period, 2071–2100, was compared to a control period, 1971–2000, to distinguish future changes in average annual load. Simulated time slices for each 30-year period were used instead of transient modeled time series, as long-term trends were detected in the soil storage and release of nutrients in the model. Such trends may be realistic but are difficult to evaluate, so it was decided to do the experiment without this effect. The future climate change results can therefore be considered to show the effects of a future climate on present nutrient status, rather than a scenario for the end of the century.

The remedial measures for wastewater were based on the suggested treatment levels in of the BSAP (HELCOM 2007), which prescribes a treatment efficiency of 90 % for phosphorus (P) and 70–80 % for nitrogen (N) for waste water treatment plants (WWTP) larger than 100 000 person equivalents (p.e.). As for rural population (and WWTP up to 300 p.e), there is a maximum permissible load per capita of 0.65 g P and 10 g N per day prescribed by the BSAP.

Present loads from wastewater were calculated from numbers on untreated sewage discharge and the HELCOM guidelines for reporting to the 2005 pollution load compilations (HELCOM 2011). The efficiency of WWTPs (primary, secondary and tertiary) was estimated according to Mörth et al. (2007), and for each country the share of population connected to each type of treatment was taken from EEA (2010). For countries outside the EU, where data was often unavailable, the same values as for neighbouring countries were assumed. The WWTP's loads per capita were included in the Balt-HYPE model set-up together with population density (both the urban and the rural fractions), obtained from the HYDE database (Goldewijk et al. 2011). In the experiment, the present treatment levels were adjusted to BSAP prescriptions only where these were not already met.

Recommendations for best agricultural practices are less detailed in the BSAP. It is not well known that how much best agricultural practices might reduce the load from arable land, or how large the actual potential for improvements is in different regions. Analysis of the potential effects of remedial agricultural measures in southern Sweden shows that a combination of the most effective measures could at most reduce the nutrient load to water by 20 % (Arheimer et al. 2005a, b; Larsson et al. 2005). As an example of a very simple agricultural nutrient reduction scenario, best agricultural practices were thus assumed to reduce the load from all arable land across the basin by 20 % for this model experiment. This was done to relate the effect of improved point-source treatment with remedial measures of diffuse sources, which is also suggested by the BSAP. Finally, the combined effects of future climate and remedial measures were tested by changing both the forcing data according to the climate projections and including the remedial measures in the Balt-HYPE model.

RESULTS AND DISCUSSION

Balt-HYPE Model Estimation of Nutrient Load

Efforts were made to collect observed data of water flow and nutrient concentrations to be able to calibrate and validate the model; however, for several large rivers such data was not found (e.g. nutrients in the Neva River and flow from the Vistula River were not present for the simulation period in available databases). The lack of observed data emphasises the overall need for models of the region to make complete assessments. In total, only one-third of the flow to the Baltic Sea basin was covered by observations, which could be used in calibration and validation of the model, nevertheless, the model calculates the whole region. Balt-HYPE results were compared to observations at river outlets to the sea where available and are presented here accumulated for each marine basin (Fig. S2, Electronic supplementary material). A more comprehensive overview of model performance can be found in Arheimer et al. (2012), including several goodness-of-fit statistics and a sensitivity study. In general, the Balt-HYPE model overestimates nutrient discharge on an annual basis, especially in the southern part of the catchment. The model was originally set up and calibrated assuming human nutrient release based on a method proposed by Bouwman et al. (2005), whereby a country's GDP is related to protein intake and hence nutrient emission. This method has the advantage of being model based so that future populations with different lifestyles can be accounted for in future scenarios; however, it has since been shown to give unrealistic emissions from point sources. Pending further study with this method, the point sources in this study are now estimated using the emissions assumed by Mörth et al. (2007), which are more consistent with the BSAP assumptions. As the model was not recalibrated, the change in assumptions for point source loading results in the overestimation of nutrient loads from more populated regions when compared with observed concentrations in river mouths. Nevertheless, the Balt-HYPE results for entire drainage basins compare well with the annual loads reported by HELCOM (Fig. 2). Both these estimates also include unmonitored areas, and there is then no systematic bias for the Balt-HYPE model. In contrast, the Balt-HYPE model more often underestimates the load as compared to these official loads reported by the countries surrounding the basin. For the Baltic proper, the current Balt-HYPE simulations still show higher loads, especially for P. Overall, the model shows the same inter-annual dynamics as the reported loads.

Source apportionment can be provided by the Balt-HYPE model for the net load reaching the sea (Fig. 3). In these calculations, the effect of retention processes in ground- and surface water are considered, which means that the numbers may differ from other calculations based on gross load at the sources. For instance, point sources contribute less to the total load (16 % less for N and 20 % less for P) than when gross load is considered. This reflects the removal effects in rivers and lakes along the flow paths towards the sea for load from inland WWTP.

For the entire sea basin, half of the N load reaching the Baltic Sea comes from agriculture. The corresponding figure for P is one-third. The soil of arable land is probably responsible for a large portion of loading in its natural state, i.e. fertile and rich in nutrients, nevertheless the results indicate that remedial measures in the agricultural sector may have a high potential for load reductions. It

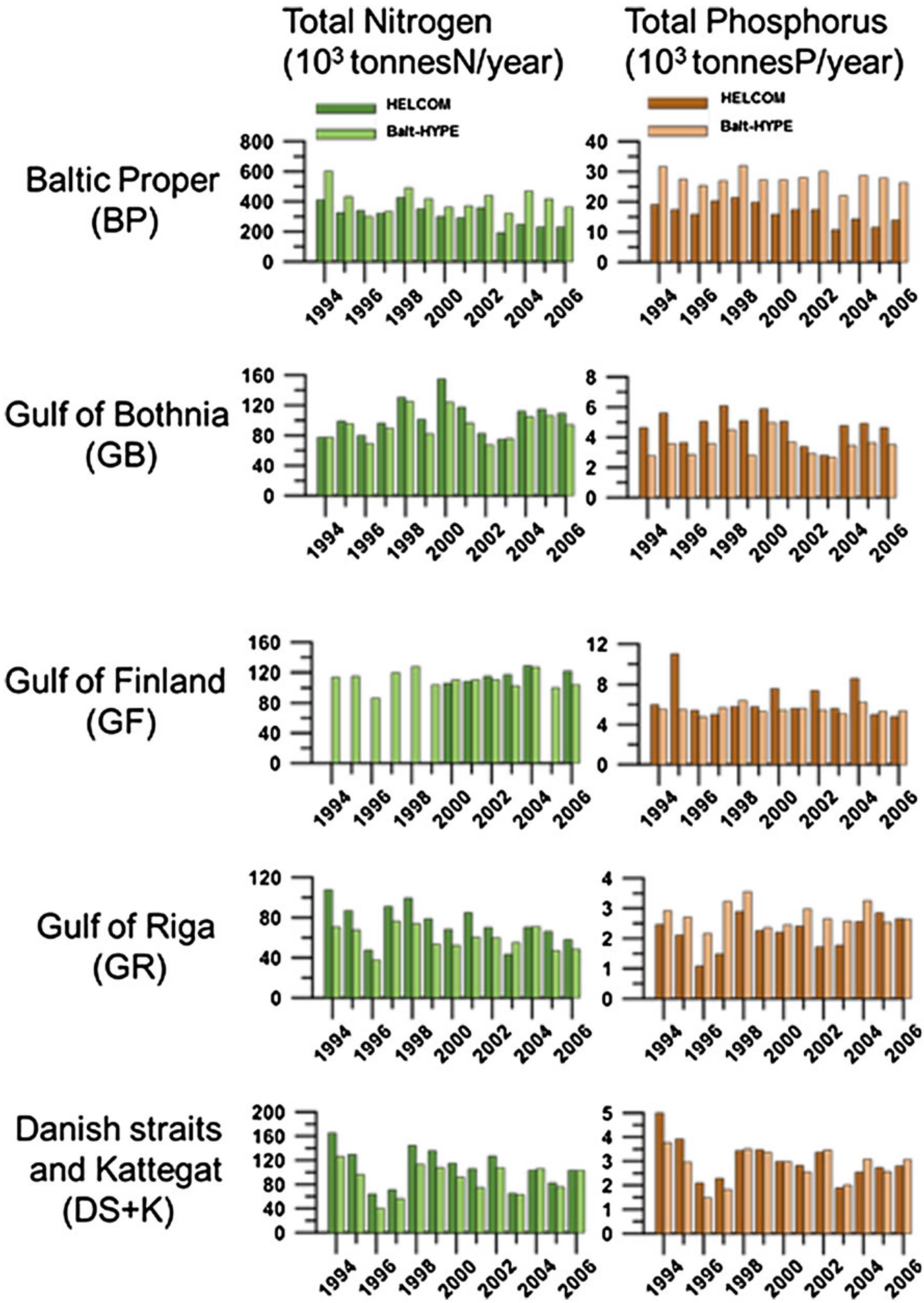

Fig. 2 Annual nutrient load from land-based sources to each marine basin of the Baltic Sea, estimated according to the HELCOM pollution load compilation (Swedish EPA 2008), and simulated using the Balt-HYPE model

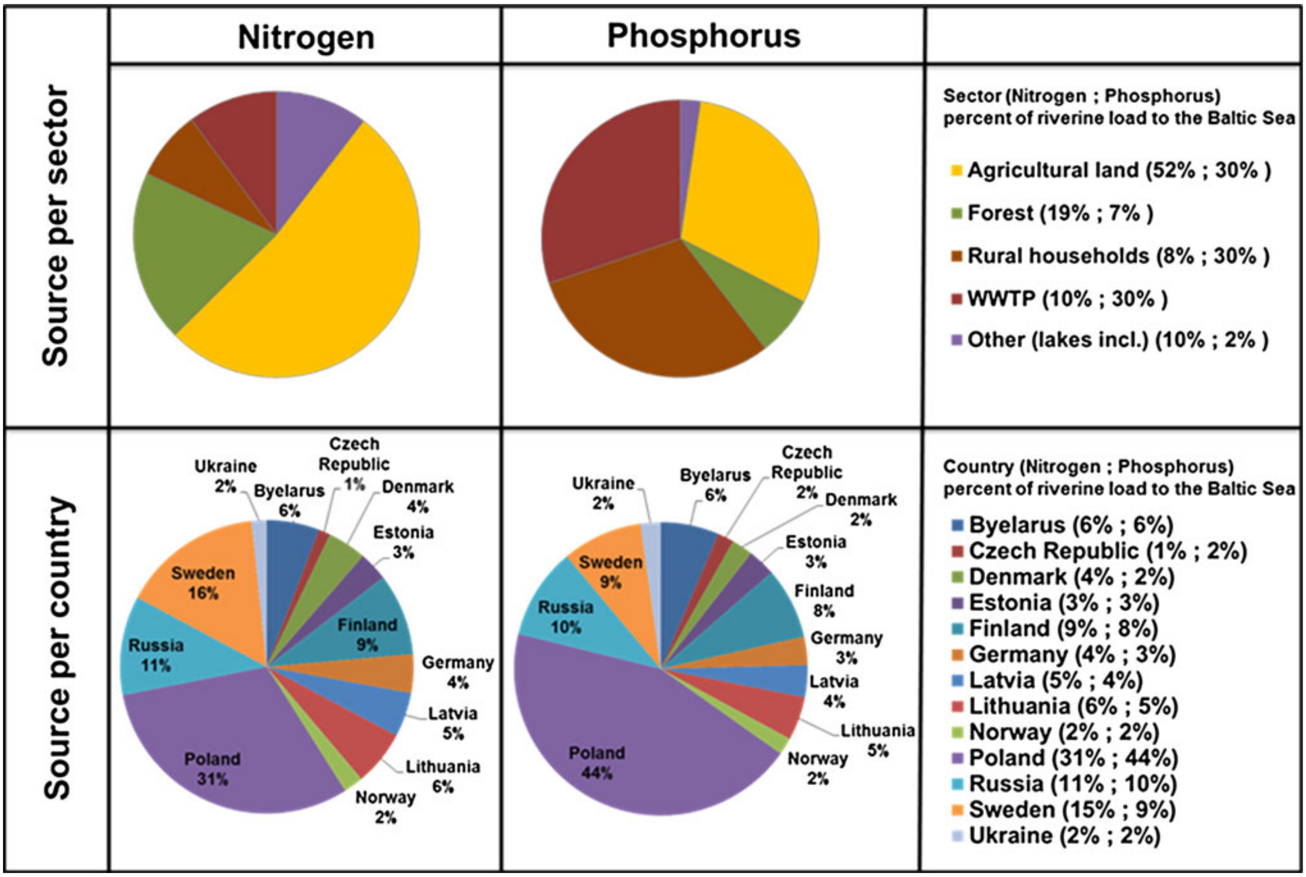

Fig. 3 Source apportionment based on societal sector and country, using the Balt-HYPE model

should be noted that these calculations do not include leakage from the enormous manure storages directly on the soil in the eastern part of the basin, which have been recently discovered. Nor does it include direct emissions from industries to water. In this model version, manure is only included as a fertilizer on arable land with 100 % use efficiency, and the leakage from the storage of this manure is not explicitly accounted for.

Figure 3 shows that the Balt-HYPE model is capable of providing nutrient loads also for more remote upstream countries, such as Czech Republic, Ukraine and Belarus. Such figures are rarely found elsewhere and it should be noted that the Belarus contribution is 6 %, which is more than each of the coastal Baltic states, Estonia, Latvia and Lithuania. Belarus is not yet included in HELCOM but these results indicate that it should not be neglected in future international agreements. For most countries, Balt-HYPE estimated about the same contribution as HELCOM (2010). Russia and Latvia, however, show lower relative contributions which is explained by the separate inclusion of Ukraine and Belarus in the Balt-HYPE source apportionment. HELCOM fully apportions the load from the river Neman to the countries at the river's outlet.

Looking at the spatial distribution of the load from various sources (Fig. S3, Electronic supplementary material), it is clear that the nutrient load to the entire Baltic Sea mainly originates from arable land, WWTP and rural households in the southern part of the drainage basin. More than half of both the N and the P load enters the Baltic proper. Contributions from forest and to the northern marine basins are small. Nevertheless, these marine waters may be more sensitive to nutrient loads as they are naturally nutrient poor and the ecosystem is adapted to that. This is also reflected in the differences among nutrient targets that HELCOM has setup for the marine basins (HELCOM 2007).

Climate Change Impact on Water and Nutrient Load to the Baltic Sea

The results from the model experiment did not show any dramatic trends in annual discharge or nutrient loads to the entire Baltic Sea as a result of a future climate (Fig. 4, upper graph). The variations between years were found to be much larger than an eventual long-term trend for each climate projection. On the other hand, the seasonal variation during an average year was found to change

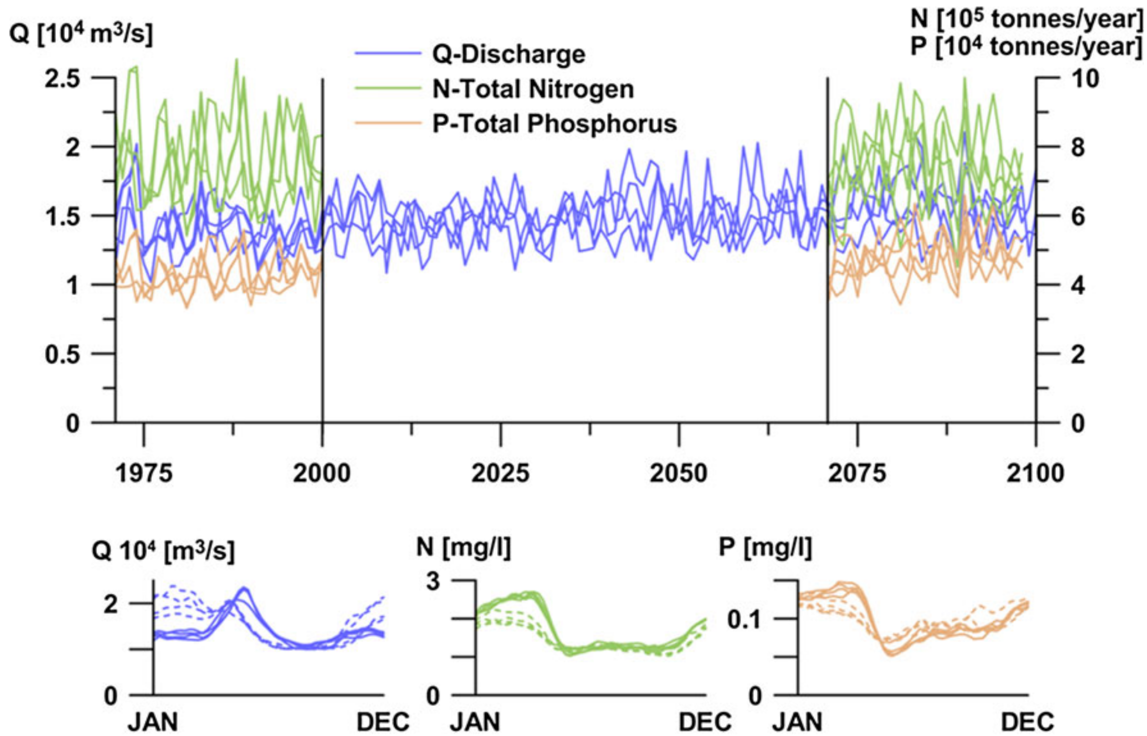

Fig. 4 Simulated dynamics of annual water and nutrient loads, when experimenting with the four climate projections in the Balt-HYPE model. The time slices used in the estimation of future changes of average loads are marked in the *upper graph*. The *lower graphs* show dynamics in water flow and nutrient concentrations during an average year; *solid lines* for the period 1971–2000, *dotted lines* for the period 2071–2100. Each *line* represents one climate projection

significantly when comparing results from the various time slices (Fig. 4, lower graphs). This could be of major importance for the biological response to the land-based load as the ecosystem will react differently depending on season and the biological activity at the time when the water and nutrients reach the sea. The change in dynamics of water discharge indicates that less snow is accumulated during winter and the snow-melt peak will be less distinct. This is consistent with results from previous climate change impact studies by Graham (2004) and Andréasson et al. (2004). The simulated results of future dynamics in nutrient concentrations show a decrease in winter concentrations, which may be a dilution effect of the higher water flow. P shows a slightly increased peakiness, which can be an effect caused by increased erosion due to more intensive rains. This is not a very prominent process in the most contributing southern parts of the region today; however, the results indicate that these processes may be more dominant in the future. The figures represent the entire inflow to the Baltic Sea and aggregated model results must be carefully evaluated on a catchment specific level to better understand the dominant processes involved (Arheimer et al. 2005a, b; Rosberg and Arheimer 2007).

When looking at the average annual change in water and nutrient load to specific marine basins (Fig. 5), the largest changes in water discharge were found for the northern part of the Baltic Sea basin, while the nutrient load was most affected in the south. For the Bothnian Bay and the Bothnian Sea, the average water inflows to the sea were increased by 16 and 14 %, respectively. In fact, the precipitation is increasing in the south but so is the evapotranspiration and the net effect is a drier condition (Donnelly et al. 2011). This assumed change in evapotranspiration has yet to be validated in the model.

The spread in results for change from the various climate projections was of the same magnitude as the ensemble mean. The uncertainty is thus large. For the southeast region, the Hadley GCM-driven simulations indicate drier conditions than those driven by the Echam GCM. It is also interesting to note that the difference in results caused by the climate models is sometimes larger than the difference caused by using various emission rates and initial conditions in the same GCM. It is thus very important to include several model concepts in an ensemble to account for model uncertainty in climate change impact assessments.

The simulations of nutrient loads indicate that a future climate may reduce the inflow of N but slightly raise the inflow of P to the marine basins; however, some of the climate projections indicated the opposite. If the HadleyA1B projection were to eventuate, the Balt-HYPE model suggests that the HELCOM target for N reduction

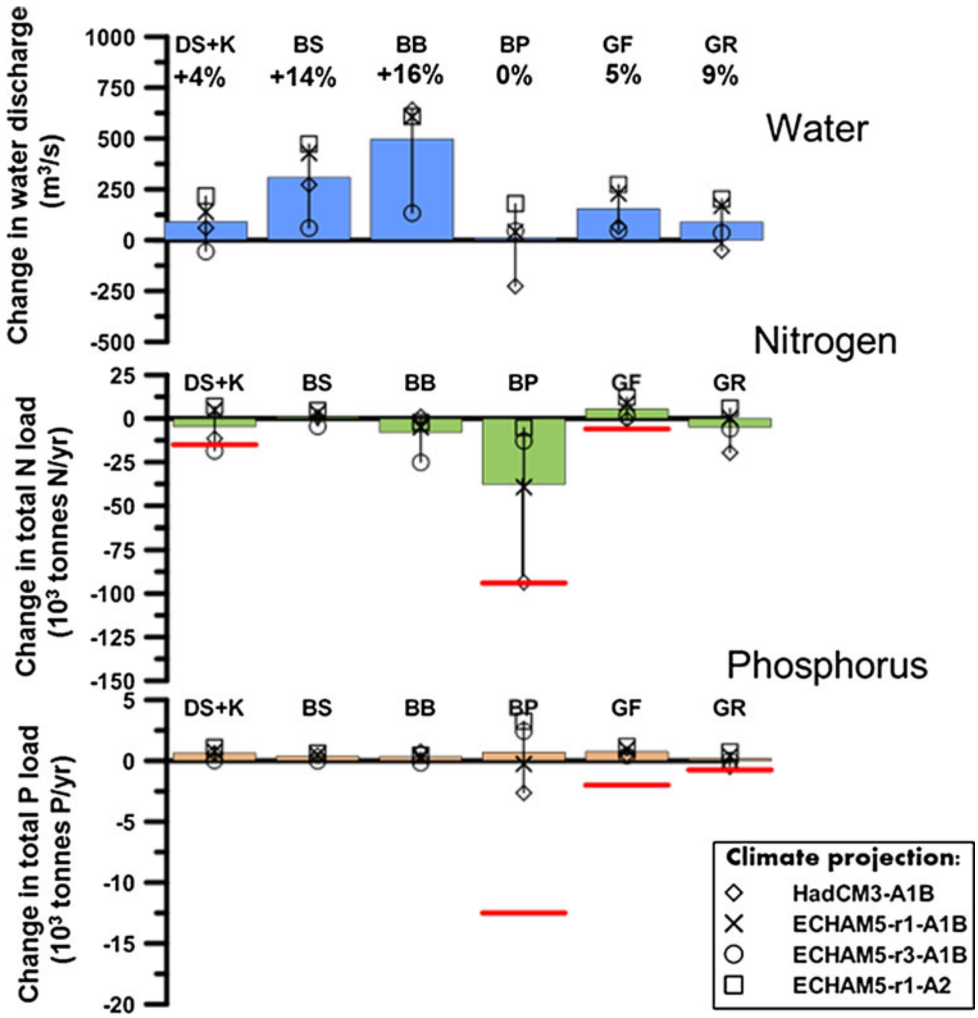

Fig. 5 Simulated future change in annual averages (2071–2100 vs 1971–2000) of water, nitrogen and phosphorus loads to each marine basin of the Baltic Sea. *Bars* The ensemble mean while the results from each climate projection are marked with a *symbol*. For water flow, the change in relation to the total volume is given as percentage above each bar. *Red lines* BSAP targets for load reductions

would be fulfilled for the Baltic proper by the impact of climate change alone by 2100. Nevertheless, the spatial variation is large within countries and within river basins (Donnelly et al. 2011) and on the local scale increases in N concentrations are also seen. The processes responsible for the reduced load in a future climate are mainly reduced water flow, increased detention times and elevated temperature, which are factors that increase denitrification and nutrient availability in the soil in the model. N is thus removed naturally during the storage in water compartments along the water flow paths towards the sea. The increase of P is probably caused by increased mineralisation, due to higher temperatures in the model.

Impacts of Remedial Measures

The model experiment on the inclusion of remedial measures in the Balt-HYPE model during present climate indicates that these may be sufficient to fulfill the BSAP targets for P in each of the Baltic Sea's basins (Fig. 6). For the N targets, the results indicate that the N measures may not be sufficient for the target reductions to the Baltic Proper and the Danish Straights/Kattegat. Actually, the model suggests that only about half of the target will be achieved for N load to the Baltic Proper. The BSAP targets are based on desired nutrient concentrations in the sea, combined with load estimates from a single model concept (HELCOM 2007; Wulff et al. 2009). Using a model ensemble for estimating water and nutrient load may thus have resulted in other targets for receiving desired marine conditions.

The model results clearly show that remedial measures of WWTP are most efficient for reducing the P loads, while N load must be combated by also reducing the non-point source pollution, especially from arable land. Similar results have been reported from previous integrated catchment studies in the region (Arheimer et al. 2005a, b). However, the assumption of 20 % reduction of agricultural leaching may be very optimistic for arable land all over the Baltic Sea basin. Presumable impact of best practices in agriculture must thus be examined much more in detail using local information for trustworthy impact analysis.

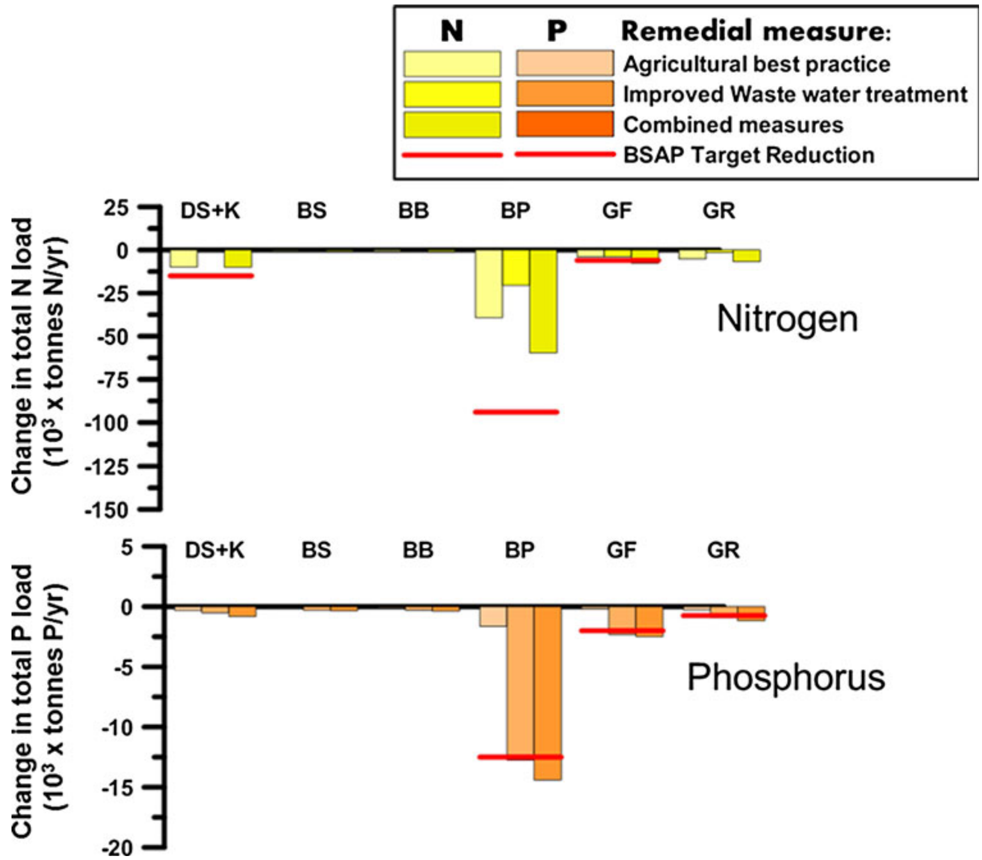

Fig. 6 Simulated reductions in average annual nutrient loads to each marine basin of the Baltic Sea achieved by remedial land-based measures, when using the Balt-HYPE model for the present climate (1971–2000) and BSAP targets for 2021

When the BSAP has been implemented on a country-wise level, this experiment can be redone using more correct estimates. The total maximum effects of the simulated remedial measures in the experiment were quantified to 86 000 tonnes N and 19 000 tonnes P reductions from the entire Baltic basin load. Hence, this is probably based on an overestimation of the reduction potential for diffuse sources.

Combined Effect of Climate Change and Remedial Measures

The experiments with combinations of remedial measures and climate change in the Balt-HYPE model indicate that there is a possibility to reach all the BSAP targets in the future for most marine basins (Fig. 7), given a longer time-scale than defined by the BSAP. The BSAP calls for reductions already by 2021 and the climate change analysis presented here considers the efficiency of those measures using the climate projections for 2071–2100. Combined reductions of load from WWTPs and agriculture, as well as the changes in climate that are predicted will probably be necessary to reach the targets. In a future climate, the Gulf of Finland was the only marine basin for which the N target was not reached by the ensemble mean of the various climate projections. This was surprising as it was the only basin for which the N target was reached during the present climate according to the Balt-HYPE simulations (cf. Fig. 6). Figure 5 shows that this basin could expect a higher N load in the future, which is different from the other basins. This is due to a higher subsurface water flow in the model, caused by higher precipitation and smaller increases in evapotranspiration in this region.

Finally, it should be noted again that there is a large spread in model results depending on which climate projection that is used. The effects of remedial measures may either be strengthened or reduced in future climate, depending on which of the four climate projections that are assumed. Each climate projection is considered equally reliable, so this shows that there is a large overall uncertainty involved in the impact assessments of future nutrient load to the Baltic Sea. As for the present climate, the probabilities to reach P targets were in general higher also in a changed climate. For N, the impact of climate change is of the same order as the expected reduction from remedial measures, according to the results of the model experiment. Thus, climate effects need to be accounted for when estimating the long-term effects of the BSAP.

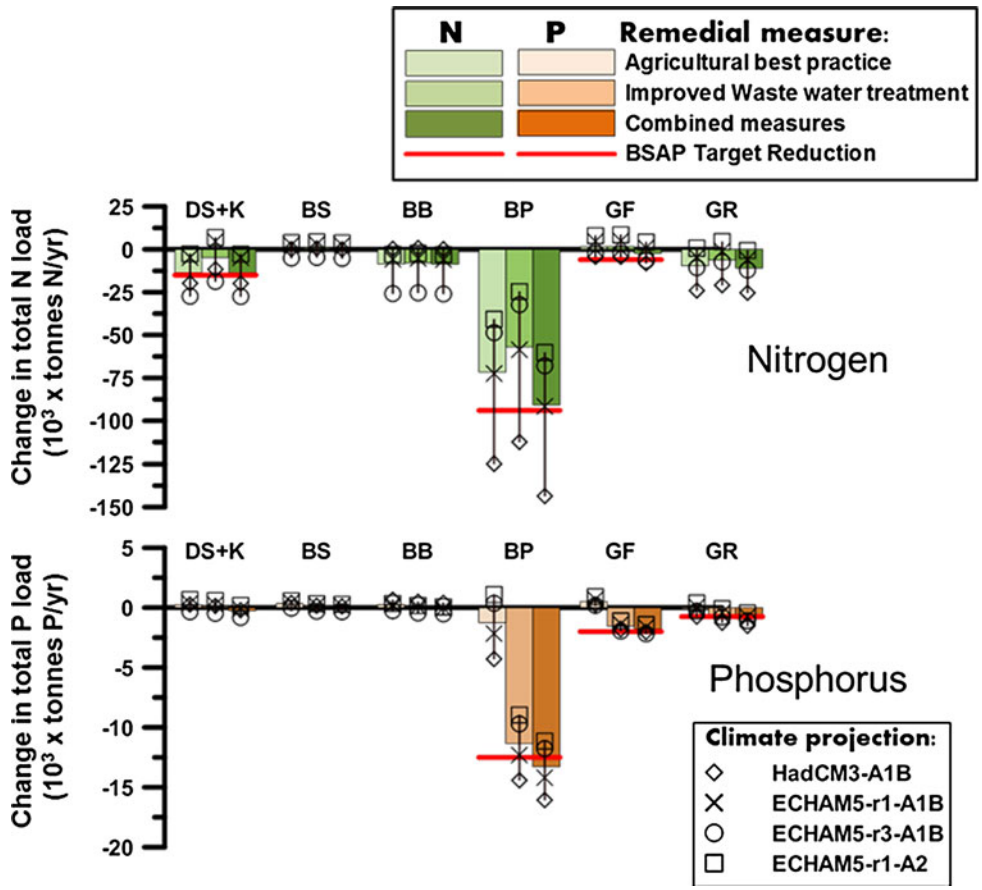

Fig. 7 Combined effect of remedial measures and future climate change impact. *Bars* Simulated change in average annual nutrient loads to each marine basin of the Baltic Sea, when using the Balt-HYPE model for the future climate projections (2071–2100 vs 1971–2000). *Bars* The ensemble mean while the results from each climate projection are marked with a *symbol*

Uncertainties in the Results from the Model Experiments

There are many uncertainties involved in such a complex chain of data transfer among different analysis tools as presented in this experiment. Some uncertainties were recognized during the process, for instance the climate models gave different loads for the control period for each projection, although statistical bias corrections had been applied. The Balt-HYPE model also includes uncertainties, for instance it overestimated nutrient loads to the sea, compared to the few observation sites available, and thus probably underestimated removal processes in rivers and lakes. This version of the HYPE model had a rather simplified routine for N removal in surface waters (Lindström et al. 2010), using the same parameter setting for all kind of water bodies. This was changed in later versions while working on a new setup for Sweden (S-HYPE_2010[1]) as small streams and lakes have higher removal than rivers, which for instance can be seen in the national monitoring data for Sweden. The present Balt-HYPE model thus probably underestimates removal in lakes and creeks in upstream parts of the catchment and overestimates denitrification in large river channels. This error evolves in a changed climate as the removal routine is based on temperature. For the southern parts of the basin, this effect is further enhanced by increased water residence times, which increase the removal efficiency. As such natural reduction of N in the flow paths reduces the effect of measures, this means that the effects of upstream land-based measures are probably overestimated in the model experiment and direct reductions to river channels are underestimated for the future climate. This is one example of uncertainties in the model concept.

Another uncertainty arises from trends in the nutrient storage in soil, which is difficult to validate. Here, the effect was neglected by simulating time slices, but a transient run could also be made to partly quantify the uncertainties arising from this process. A slight change in the soil storage capacity may have a very large effect on the overall transport to the sea, so there is an urgent need for future research on the long-term trends of nutrient storage in the soil, and how these are affected by climate and land use management change. More empirical data are needed to calibrate and validate the model properly, including specific validation of the model to changes in management where this has been monitored. In fact, there is an urgent overall need for validating the ability of various models to

[1] http://vattenweb.smhi.se/.

reproduce *changes* in forcing, for example whether or not a model can reproduce long-term trends in nutrient concentrations, observed following a change in agricultural practices. The assumption about model parameters being valid for another climate also needs clarification, although they were robust enough to cover such a large model domain representing various climates at present. There are few publications regarding this sort of validation of internal process descriptions, which would be valuable to complement the more classical evaluation of the model's ability to reproduce discharge and concentration variations in time and space. It is important to validate models according to their purpose, therefore more field studies and empirical data are necessary.

When applying the same model code for 17 000 subbasins covering the country of Sweden, it was possible to evaluate model predictions also for ungauged basins, as 90 % of available monitoring sites were not used for calibration (Strömqvist et al. 2012). The Swedish application (S-HYPE) has also been evaluated against independent internal model variables such as snow pack, lake water level and groundwater fluctuation (Arheimer et al. 2011a, b), which also makes that model application more trustworthy. Arheimer et al. (2012) thus compared model results for Sweden using both the S-HYPE and the Balt-HYPE and, in short, that study showed that especially water discharge was much better simulated using the S-HYPE, with most relative errors are <10 % for S-HYPE and <25 % for Balt-HYPE. Both the applications normally reproduced mean concentration for N within 25 % of the observed mean values, while P showed a larger scatter. Differences in model set-up were reflected in the simulation of both the spatial and the temporal dynamics, and the most sensitive data causing this was found to be precipitation/temperature, agriculture and model-parameter values. Hence, the lack of observations (e.g. for the large Vistula River) probably do influence the overall model performance of Balt-HYPE. How this would have affected the outcome of this specific experiment on climate change and remedial measures is yet unknown. To make the results of the experiment presented a bit more robust, only relative figures are given for future changes in this article (Figs. 5, 6, 7). Even though results are uncertain, it cannot be rejected that the outcomes from the present experiment indicate important considerations for managers to be aware of.

It has been questioned whether the largest sources of uncertainty in climate change impact studies originate from the climate models or the impact models, and several ongoing EU projects are addressing this issue (e.g. ECLISE, IMPACT2C). A recent uncertainty study using the HBV model in a changing climate for Sweden (Andréasson et al. 2011) showed that the model-parameter values did introduce uncertainties in the results, but not as much as the climate models. It has been argued that it may not even be worth using climate model data in impact assessments as the climate model results are so uncertain (Beven 2011). The spread in results from the different climate projections in this study could support this argument. Nevertheless, new knowledge about the system behaviour was achieved from experimenting with the Balt-HYPE model. It would have been difficult to figure out all possible process interactions and the net effect of such a complex system without applying a numerical model. The model is based on available knowledge and the results gave second thoughts on credibility and process descriptions. Errors and less stable assumptions were identified in the model set-up and parameter values, which increased the overall understanding of water and nutrient fluxes in the region.

The HYPE model introduces the ability to model detailed hydrological processes at high resolution simultaneously and homogenously across many river basins. It is an advantage that the methods and data used are homogenous across political boundaries. Yet, large-scale models are always difficult to validate, for climate, hydrology and chemistry. Ensemble modelling is a way to handle this problem (e.g. Viney et al. 2005; Exbrayat et al. 2010). By including more models in the analysis it is more likely that the dominant processes and initial states (e.g. of soil storages) are accounted for. More water and nutrient models and more climate projections are thus another way to quantify the uncertainty ranges of the results. The Balt-HYPE model should be considered as one such member in a larger model ensemble for strategic decision making in the Baltic Sea region.

CONCLUSIONS

- In the Baltic Sea basin, there is a large demand for more water quality data and homogeneous input data for more reliable assessments, nutrient modelling and analysis of uncertainties in results.
- Climate effects need to be accounted for when estimating the long-term effects of remedial measures. The model results suggest that the total load to the Baltic Sea may decrease for nitrogen and increase for phosphorus in the future. The experiment indicates that impact of climate change may be of the same order of magnitude as the expected nitrogen reductions from the measures simulated.
- For the Baltic Sea, the results of the experiment show that both the improved wastewater treatment and the agricultural measures are needed to reach the BSAP target reductions by 2100. Yet, for half of the climate projections, the targets were not reached, and the

variation in the quantified impact is large between different climate projections.

- Model experiments are useful to analyze complex process interactions and large databases and to merge knowledge from different disciplines. Experimenting with models also increases the system knowledge as errors and less stable assumptions may be identified in the model set-up and parameter values.
- Ensemble modelling, which includes several water/nutrient and climate models are recommended to include uncertainties in the decision support, when combating eutrophication in the Baltic region.

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