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FUTURE PROJECTIONS OF NUTRIENT FLUXES TO LAKE MÄLAREN

Framtida projektioner av närsaltflöden till Mälaren

by RENÉ CAPELL, JONAS OLSSON
Research and Development (hydrology), Swedish Meteorological and Hydrological Institute, 601 76 Norrköping
e-mail: rene.capell@smhi.se, jonas.olsson@smhi.se

Abstract

Two climate projections are used as forcing data in a hydrological model for the Lake Mälaren catchment, in order to evaluate the expected impact on nutrient fluxes (nitrogen and phosphorus) into the lake. Lake Mälaren comprises a large lake system, discharging into the Baltic Sea through the city of Stockholm, Sweden. Being a major fresh-water source, the lake is a potentially vulnerable resource under climate change impacts on e.g. inflow of nutrients, which is a main factor for drinking water production. The two projections both point at a future increase of temperature and precipitation and a decrease of snow cover, although the level of change differs somewhat. According to the model results, these changes will increase both nutrient concentrations in the catchment and the inflow to Lake Mälaren, the latter sometimes by a significant fraction of today's inflow.

Key words – climate change, nitrogen, phosphorus, concentration, transport

Sammanfattning

Två klimatprojektioner används som indata i en hydrologisk modell för Mälarens avrinningsområde, i syfte att utvärdera den förväntade påverkan på närsaltflöden (kväve och fosfor) till sjön. Mälaren utgör ett stort sjösystem och mynnar i Stockholm ut i Östersjön. Eftersom sjön är en viktig färskvattenkälla är den potentiellt sårbar för klimatförändring och dess inverkan på t.ex. inflödet av närsalter, vilket är en huvudsaklig faktor för dricksvattenproduktion. De två klimatprojektionerna pekar båda på en framtida ökning av temperatur och nederbörd och en minskning av snötäcket, även om nivån på förändringarna är något olika. Enligt modellresultaten kommer dessa förändringar att öka både koncentrationerna av närsalter inom avrinningsområdet och inflödena till Mälaren, det senare med i vissa fall en signifikant fraktion av dagens inflöde.

1 Introduction

Projected climate changes for the current century have a potential impact on the hydrological cycle. The impacts comprise both changes in water quantity and water quality. Examples for the former are changes in flood and drought extremes through changing precipitation patterns or – namely in the mid-high latitudes as the region this report focuses on – through changes in snow accumulation-ablation cycles. Water quality changes are, in addition to the change in climate forcing, very much influenced by societal impacts through land management decisions, especially in intensively used areas with multiple pressures from e.g. urban development and agriculture. These factors increase uncertainties connected to impact assessment. However, integrated rainfall-runoff and water quality models as the one used in this study can be used to assess potential water quality impacts of climate change under current land use and nutrient source distributions.

Lake Mälaren comprises a large lake system, discharging into the Baltic Sea through the city of Stockholm, Sweden. The basin includes large fractions of agricultural and forestry areas as well as several urban centres. The lake currently provides fresh water to Stockholm city and greater metropolitan area and as such is a potentially vulnerable resource under climate change impacts, both quantitative and qualitative (e.g. Lagerblad, 2011). Inflow of nutrients is one of the main factors that directly or indirectly have an adverse effect on drinking water production.

The number of climate change impact studies on the water quality of freshwater sources in Sweden is rather small. One example is Arheimer et al. (2005), who studied the catchment of Lake Ringsjön, southern Sweden, and the results implied a future increase in nitrogen concentrations and fluxes. Another example is Darracq et al. (2005), who found climate changes to have only a small impact towards increased nitrogen and phosphorus loads at the outlet of Lake Mälaren, albeit within a comparably short time horizon of 30 years. Within HYDROIMPACTS2.0 and coupled projects, new future water-quality projections have been or are being produced for Sweden as well as surrounding regions (e.g. Arheimer et al., 2012). In this study, we extract and analyse results for the Lake Mälaren catchment, which is a study area in the ECLISE project, in order to provide an updated picture of the expected future changes in nutrient inflows to the lake in response to climate change.

2 Data and methods

Activities comprise compilation and preparation of data bases and hydrological modelling including analysis of model results.

2.1 Study area

Lake Mälaren is situated in central Sweden, draining into the Stockholm archipelago in the Western Baltic Sea (Figure 1). Large parts of the areas draining into the lake systems are forested (68 %), especially in the north-west upstream areas where hilly terrain dominates. In the low-lying eastern parts and around the large lakes Mälaren and Hjälmaren, large parts of the land are used for intensive agriculture (22 % of the total area). Small lakes are spread throughout the catchment owing to its glaciation history (5 % without Mälaren and Hjälmaren). The Mälaren outlet to the Baltic Sea is situated in central Stockholm, with surrounding areas on the lower lake shores being largely urbanized as part of the Stockholm metropolitan area. Other urban centres in the basin include the city of Uppsala in the north-eastern part of the lake system, Västerås and Eskilstuna on the northern and southern lake shores, respectively, and Örebro west of Lake Hjälmaren, upstream of the Mälaren lake system. The total (semi-)urban area accumulates to 4 %. Other, minor land cover types include fens and peat bogs.

2.2 Data bases

A database with down-scaled Regional Climate Model (RCM) simulations of precipitation and air temperatures for the Mälaren basin has been compiled and prepared (Table 1). Two General Circulation Model (GCM) projections were used; both being forced with International Panel for Climate Change (IPCC) greenhouse gas emission scenario A1B data. A1B is an intermediate emission scenario under the assumptions of continuing economic but declining population growth, and a balanced energy source distribution (Nakićenović et al., 2000).

The GCMs used were ECHAM5 (Roeckner et al., 2003) and HadCM3 (Gordon et al., 2000). In a comparison of temperature and precipitation change differences in Scandinavia between different GCMs under A1B forcing conditions, increases for both variables were shown to be comparatively low for ECHAM3 but relatively high for HadCM3 (Kjellström et al., 2011). Including both GCM projections in the analysis thus allowed for roughly estimating a projection uncertainty spread of the modelled impact on the hydrology in the Mälaren basin.

To facilitate downscaling climate projection time series to a spatial resolution which could be used to force a hydrological model, a downscaling model chain was

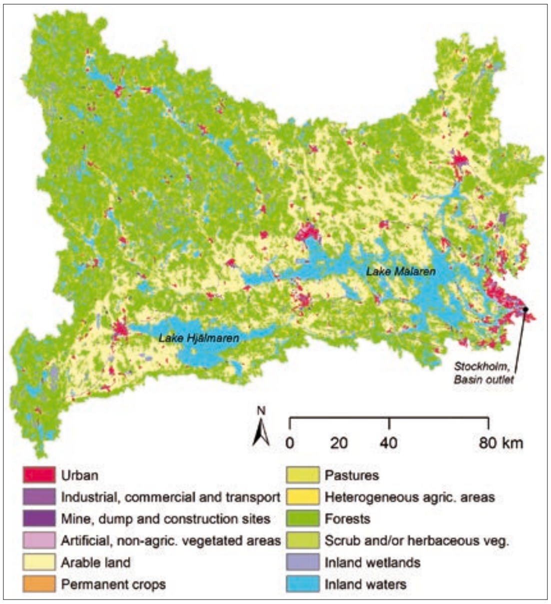

Figure 1. *Land use distribution in the Mälaren basin, derived from CORINE land cover (CLC, 2000). The main basin outlet to the Baltic Sea is located in central Stockholm in the south-eastern corner of the basin.*

Table 1. *Overview table with climate projection model details, abbreviations see text.*

ID	Echam	Hadley
Global Circulation model	ECHAM5 (member 3), 1.875° horiz. resolution	HADCM3, 3.75x2.5° horiz. resolution
Regional model	RCA3, 50 km horiz. resolution	RCA3, 50 km horiz. resolution
Bias correction	DBS to PTHBV, 4 km horiz. resolution	DBS to PTHBV, 4 km horiz. resolution
IPCC emission scenario	A1B	A1B

employed: The GCM projections were first dynamically downscaled using the RCM Rossby Center Atmospheric model (RCA3; Kjellström et al., 2005; Samuelsson et al., 2011) to a 50×50 km horizontal resolution. Subsequently these data were bias-corrected and downscaled using the Distribution-Based Scaling (DBS) method of Yang et al. (2010). Reference data consisted of gridded measurements of precipitation and temperature with a 4×4 km spatial resolution, which is also the final resolution of the processed climate projection data. The DBS method was fitted on the baseline period 1981–2010 and then applied to a mid-century (2036–2065) and an end-century (2071–2100) 30-year time slice.

2.3 Hydrological modelling and analyses

Hydrological and water quality analyses were performed using the S-HYPE2012 high-resolution hydrological model of Sweden, developed at and operationally run by the SMHI. At its core, the model is a conceptual rainfall-runoff model, solving for up to three vertically stacked storages, albeit with a range of relevant details for large-scale applications and water quality modelling, e.g. drainage pipe systems, crop types and ploughing regimes on agricultural land, and diffuse and point sources for nutrients (Figure 2). A detailed description of hydrological concepts and water quality routines together with calibration and performance results can be found in Lindström et al. (2010) and Strömqvist et al. (2012).

Sub-catchments are connected through a river channel and ground water flow network system. Each sub-catchment can include several of a total of 60 soil-land use-classes (SLC) which were derived for Sweden using mapped soil and land use data and include dedicated lake classes with conceptualized regulation regimes and specific nutrient turnover processes. Figure 2 gives an overview over the functional modules of the model. Each SLC is parameterized separately and flows and concentrations are merged at sub-catchment level before passed on downstream. Parameter sets for each SLC

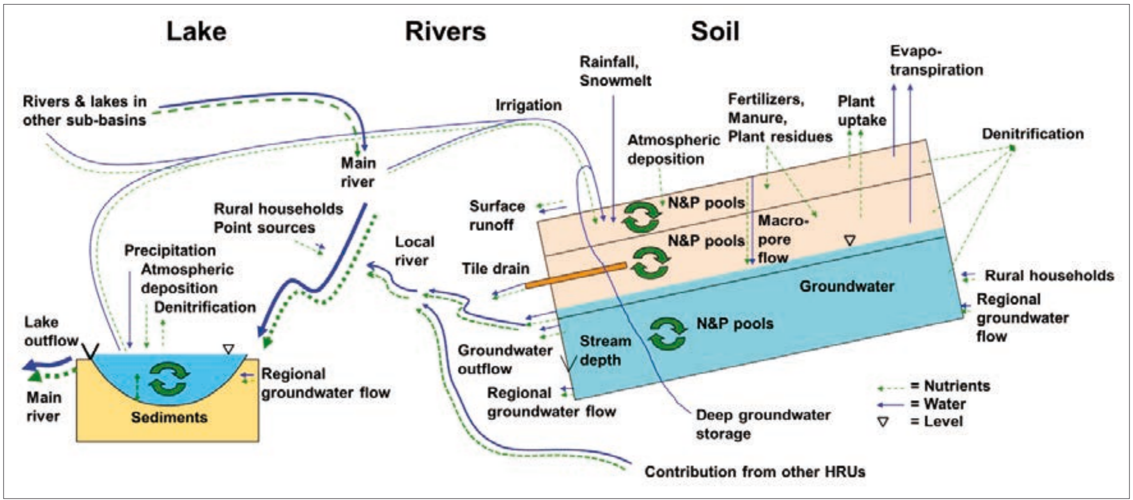

Figure 2. *HYPE mode schematic showing the functional elements of rainfall-runoff and nutrient model components together with modelled processes. The model is semi-distributed with separately parameterised but spatially lumped soil-land use groups within spatially explicit, coupled sub-catchments.*

were identified for the whole of Sweden by calibrating selected sub-catchments to observed data and using a catchment similarity approach to transfer parameter sets throughout the model domain. The model requires daily precipitation and air temperature forcing data at sub-catchment resolution.

For the analyses presented in this report, a sub-model covering the Mälaren basin was extracted from the Swedish model domain, and analyses are based on this new Mälaren model consisting of 1170 sub-catchments with a median size of 12 km^2. The model was driven with bias-corrected RCM forcing data as described above (Section 2.2) for the baseline and two projection periods. Modelled water balance and total nitrogen (TN) as well as total phosphorus (TP) concentrations were analysed and visualised by different methods:

– Long-term averages of select variables at sub-catchment resolution, and modelled changes for projection time slices.
– Amounts and projected changes in annual fluxes of TN and TP into Lake Mälaren, at sub-catchment level.

3 Results

The results cover analyses of discharge as well as TN and TP concentrations throughout the Mälaren basin and fluxes to Lake Mälaren under both historical conditions and climate change forcing.

3.1 Historical evaluation of model performance

There are 35 stations with runoff observations and 72 with TN and TP observations in the catchment. In Figure 3, an evaluation of model performance at these stations is shown. Concerning discharge, the Nash-Sutcliffe Efficiency (NSE) is generally between 0.7 and 0.8 which indicates good performance (Figure 3a). Only three stations have an NSE below 0.5. Simulated TN concentrations are generally within ±20 % of the observed (Figure 3b). There is a weak tendency of the model to underestimate TN, at one station by more than 100 %, but overall the spread is well centred around 0. The relative error of TP is generally within ±50 % of

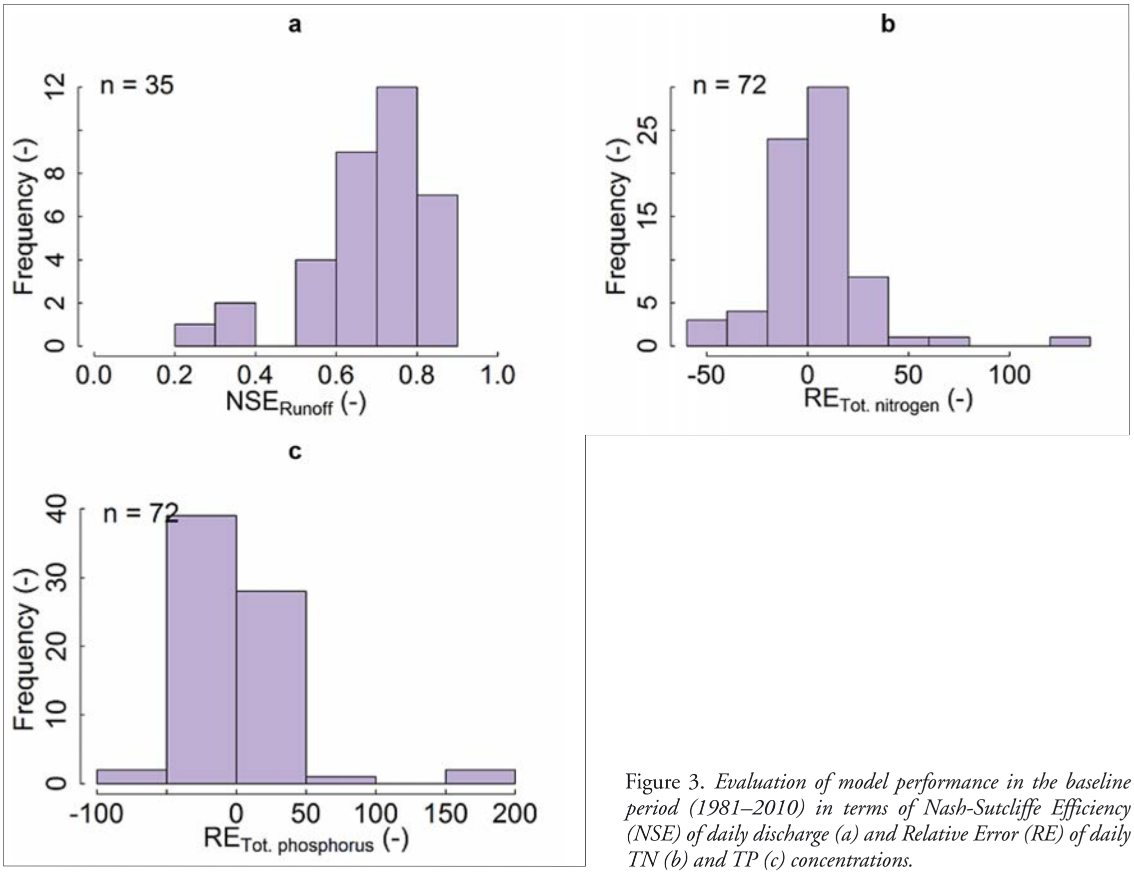

Figure 3. *Evaluation of model performance in the baseline period (1981–2010) in terms of Nash-Sutcliffe Efficiency (NSE) of daily discharge (a) and Relative Error (RE) of daily TN (b) and TP (c) concentrations.*

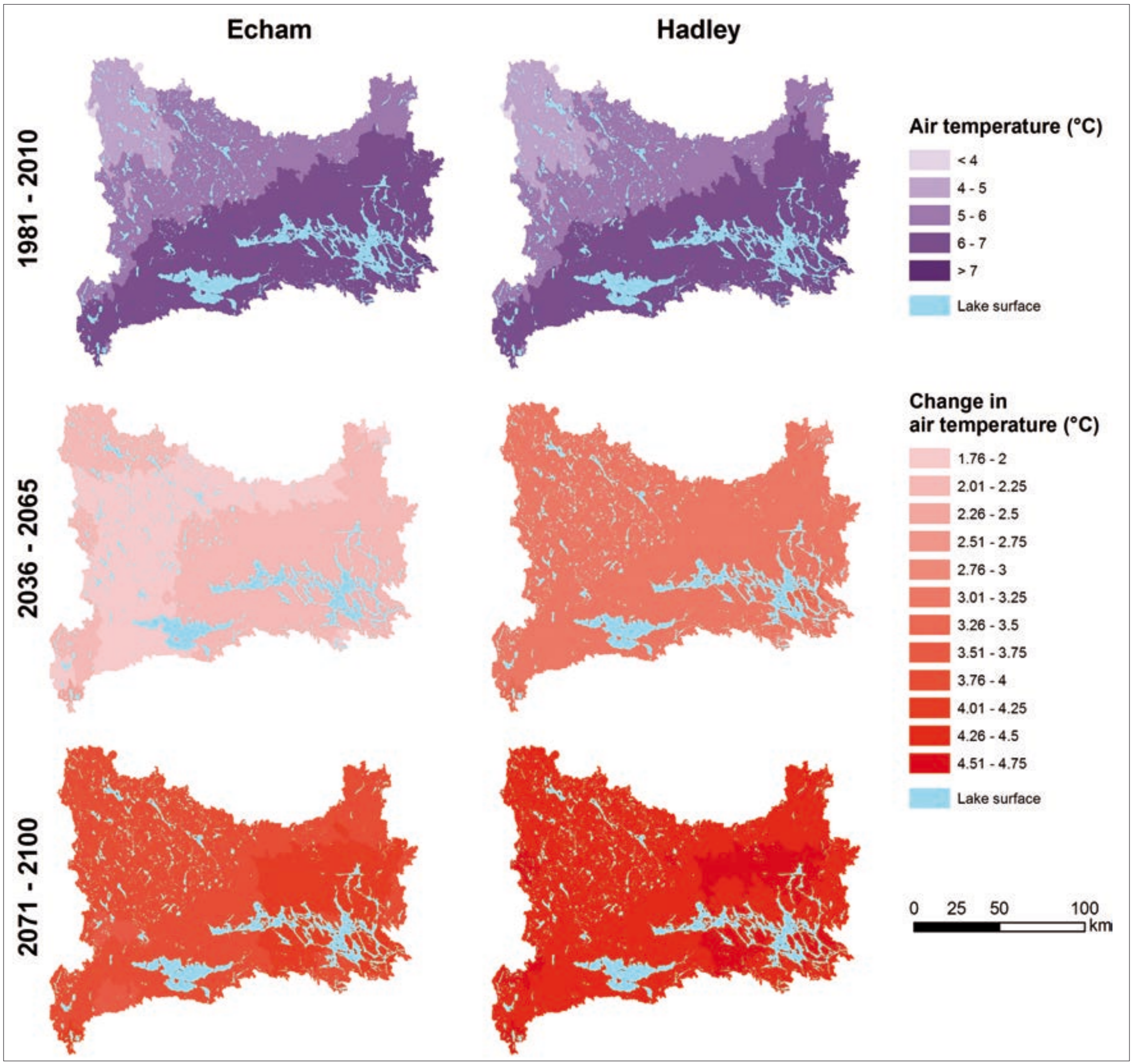

Figure 4. *Average air temperature in the Mälaren catchment in the baseline period (top row) and expected future changes until the middle (middle row) and end (bottom row) of the century in projections Echam (right) and Hadley (left).*

the observed (Figure 3c). In this case there is a weak tendency towards overestimation by the model, although the main deviations are in the form of underestimation by up to 200 % in a few stations. Overall, the results are in line with the expectations of a state-of-the-art hydrological model and we conclude that the model is acceptable for climate change assessment.

3.2 Climate change impacts on precipitation, temperature and snow cover in the Mälaren basin

In today's climate, the mean temperature in the catchment ranges from 7°C in the southern part down to 4°C in the north-western part (Figure 4). Note that because of the bias correction applied, the projections are virtually identical in the baseline period. In projection Echam the increase is about +2°C until mid-century and +3.5°C until the end of the century. Hadley indicates a stronger increase, by +1°C for both time horizons. There is a weak general tendency towards a stronger increase in the south-eastern part of the catchment.

Concerning precipitation (Figure 5), today the annual total ranges between up to 900 mm in the north-western part and down to 500 mm in the south-eastern part of the catchment. Until mid-century, projection Echam indicates only a small increase by up to 25 mm

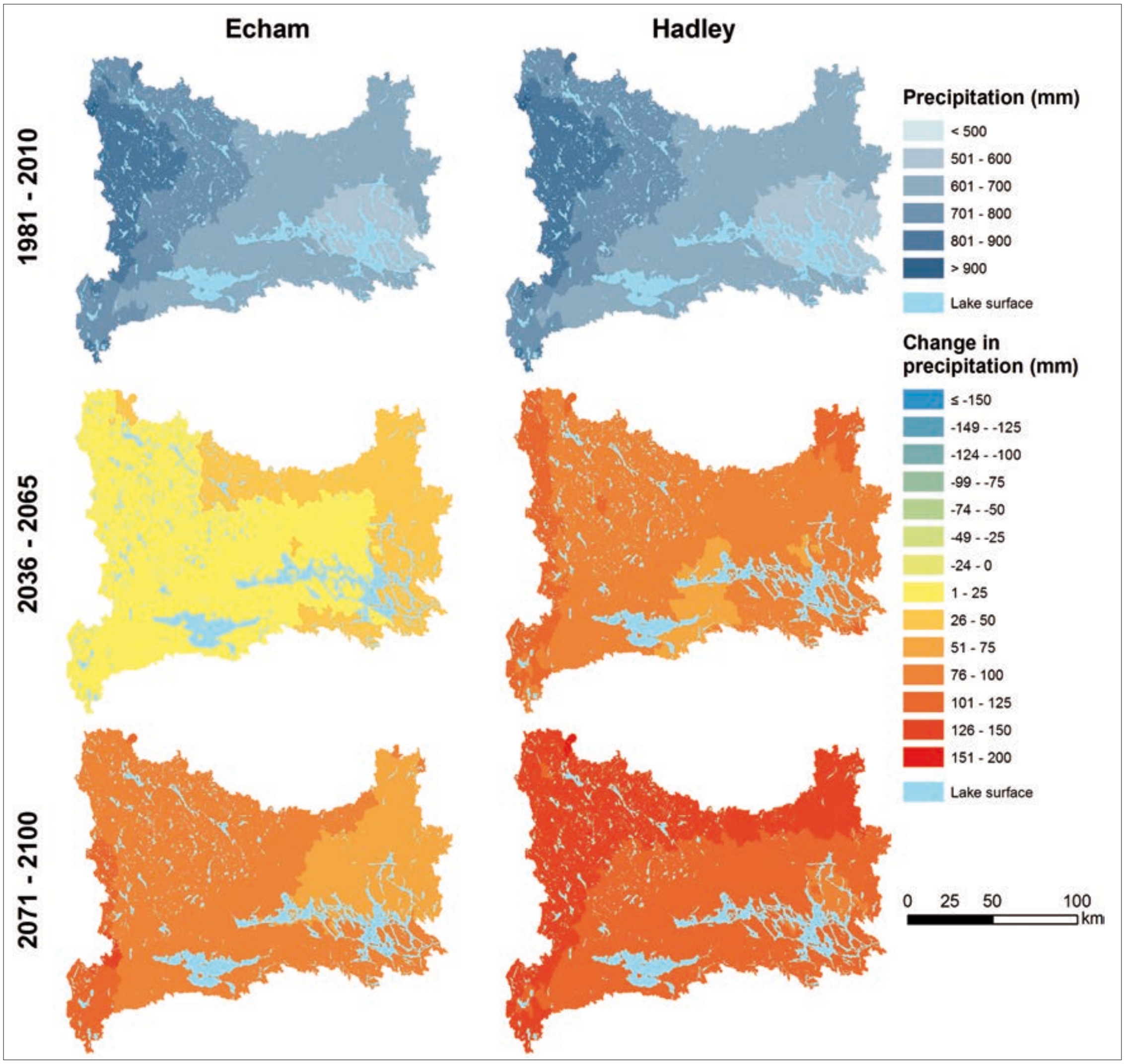

Figure 5. *Average annual precipitation in the Mälaren catchment in the baseline period (top row) and expected future changes until the middle (middle row) and end (bottom row) of the century in projections Echam (right) and Hadley (left).*

in most parts of the catchment and a somewhat higher increase in the north-eastern parts. In Hadley the increase is stronger, 75–100 mm in most parts of the catchment. A similar increase, i.e. 75–100 mm, is found until the end of the century in projection Echam. In Hadley, the corresponding increase is 100–125 mm in most parts and up to 150 mm in the north-west.

Figure 6 shows modelled long-term snow cover averages as snow water equivalent (SWE) and projected changes in the Mälaren basin for the modelled time slices at sub-catchment resolution. For the baseline period 1981–2010, forcing data of both climate models produces similar pattern of snow distribution with maxima in the north-western hills and minima around the large lake systems. Echam forcing results in slightly higher average snow amounts and little change for the mid-century projection period (2036–2065), whereas Hadley scenarios show long-term decreases by up to 25 mm in the north-west of the basin already in this period. However, Echam projections result in stronger decreases than Hadley during the end-century time slice (2071–2100). Since snow melt is the major driver for seasonal discharge dynamics in the basin, these changes are important keys to assessing the impact of climate change on water quality here as well.

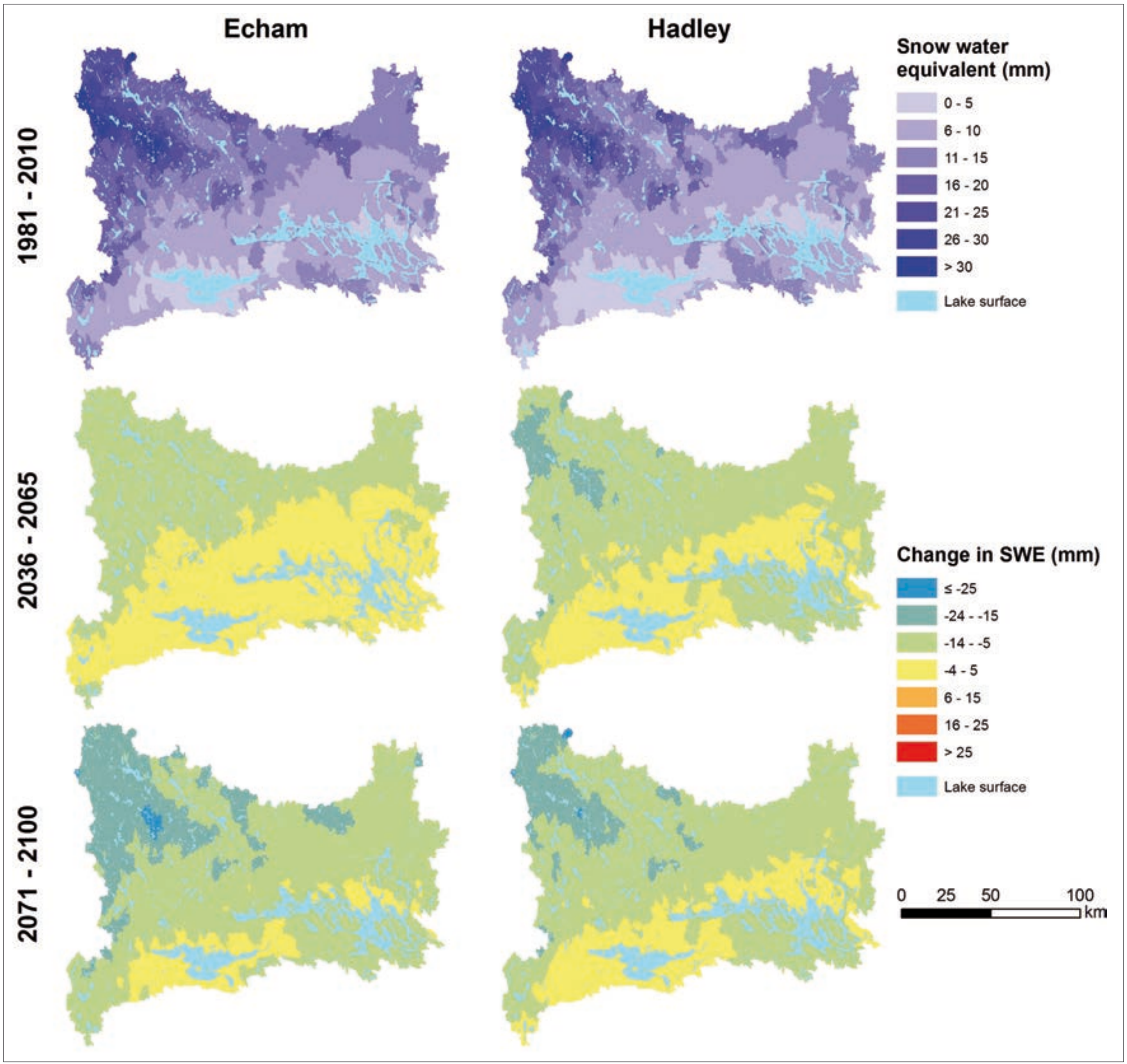

Figure 6. *HYPE-modelled snow water equivalent (SWE) in the Mälaren basin for the 1981–2010 baseline period, and projected long-term SWE changes for the mid-century and end-century projection time slices.*

3.3 Climate change impacts on nutrient concentrations and fluxes in the Mälaren basin

Looking at long-term average concentrations of modelled total nitrogen (TN) and total phosphorus (TP) released into the stream water network, the current distributions predominantly reflect the land use distribution, especially diffuse source contributions from agricultural practice and point sources relating to urban areas, i.e. sewage treatment plant and industrial releases (Figure 7 for TN and Figure 8 for TP).

On average, TN concentrations are projected to increase, with a focus on areas with high percentages of agriculture (Figure 7). Both Echam and Hadley show this trend, with Hadley projections showing a slightly more intensive response, likely relating to the stronger projected increases in temperatures and precipitation with this model (Figures 4 and 5) and subsequent intensified flushing and release of nitrogen from the soil storages. The increase is generally 100–500 µg/l, larger in the eastern part of the catchment and only marginally larger until end- than mid-century. One side effect visible in the results is the projected decrease around Lake Hjälmaren in the south, which is largely surrounded by headwater areas without upstream contributions. Here, the discharge generated is already low today because of the limited contributing area and low slope gradients, and projected lower summer precipitation in combination with higher temperatures results in intermittent cessation of discharge generation and subsequent non-linear feedbacks on nutrient transport. However, such long projection feedback chains accumulate uncertainty of every step of the projection chain, and must be evaluated with adequate cautiousness.

For TP, the picture is generally similar but much more restricted to the agricultural areas in the east (Figure 8), owing to lack of phosphorus in forested areas in general as well as to the predominant transport of phosphorus as particulate in surface(-near) runoff from non-vegetated, i.e. agricultural areas. Nonetheless, the projection patterns correspond to TN, with larger increases for Hadley forcing compared to Echam, and a continued trend through to the end-century projections, where the increase in the agricultural areas geneally amount to 30–100 μg/l.

The modelled nutrient concentrations as shown in Figure 7 and 8 inherently also reflect the change in flow volumes as a result of climate change forcing. In order to examine the accumulated effects of modelled upstream climate change impacts on the Mälaren lake system,

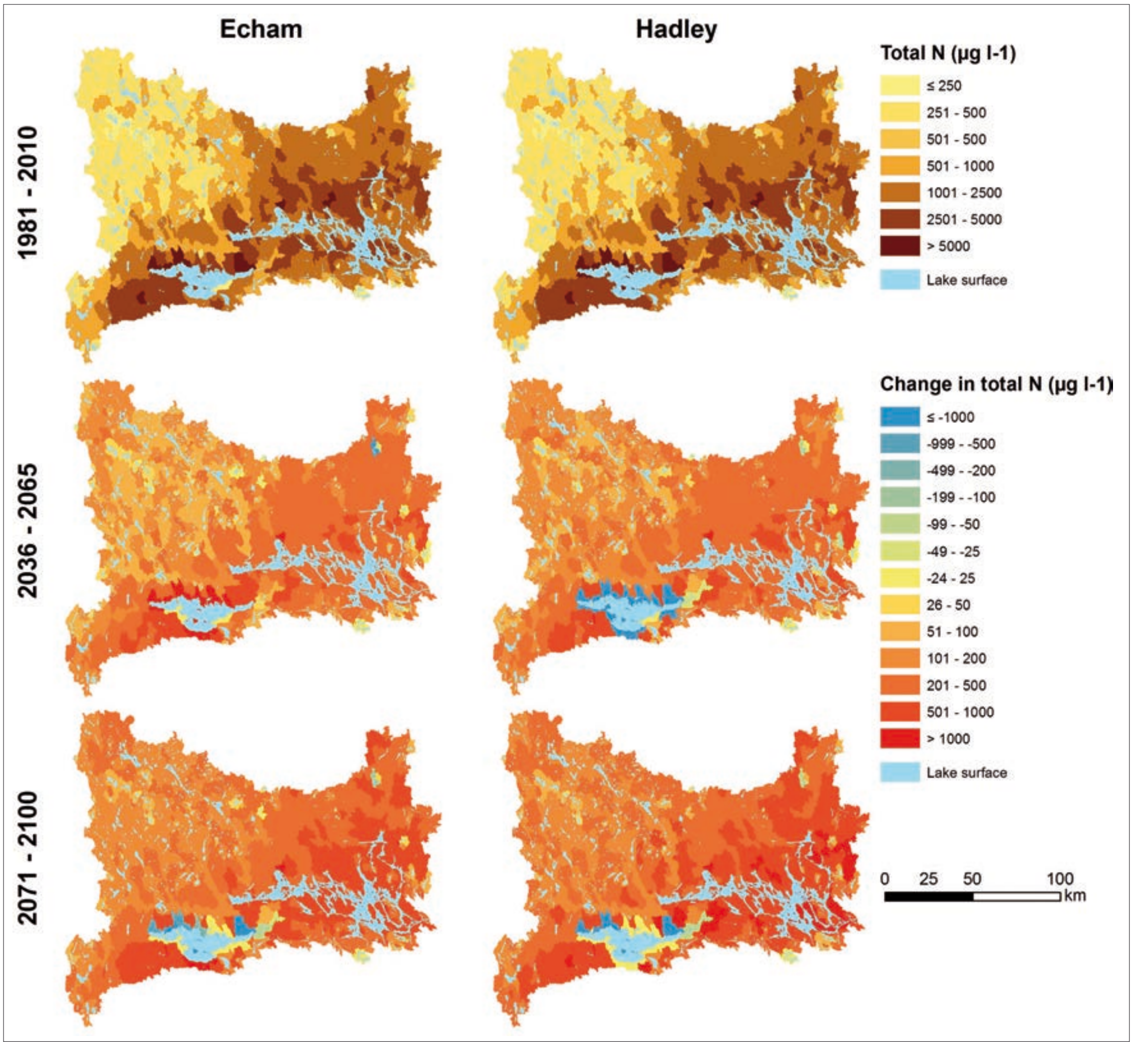

Figure 7. *HYPE-modelled total nitrogen concentrations in sub-catchment discharges of the Mälaren basin for the 1981–2010 baseline period, and concentration changes for the projection periods.*

Figure 9 and 10 show average annual fluxes of TN and TP into the lake, as well as projected changes for the future time slices as a result of climate change forcing. Again, both modelled fluxes of TN and TP are very similar for Echam and Hadley during the baseline period. Amounts reflect upstream areas of lake coastal sub-catchments as well as upstream land use.

For TN, the model projections diverge until mid-century, however, with Echam showing little change to a small net flux decrease from most areas, but Hadley showing mostly increasing fluxes (Figure 9). These diverging trends relate to diverging precipitation and temperature changes, and are somewhat resolved for the later projection period where both projection impacts result in increased TN fluxes, even if the projected signal remains stronger for Hadley with >100 ton/y in some areas.

The projected TP flux changes into Lake Mälaren show a similar impact in terms of Echam/Hadley differences, but also show the importance of specific source areas for occurrence of in-stream phosphorus (Figure 10). The highest increases in TP fluxes are projected in inflows from the northern lake shores where large fractions of agricultural areas exist in the upstream sub-catchments. Another focus is the fluxes from Lake Hjälmaren and contributing areas into the western end of

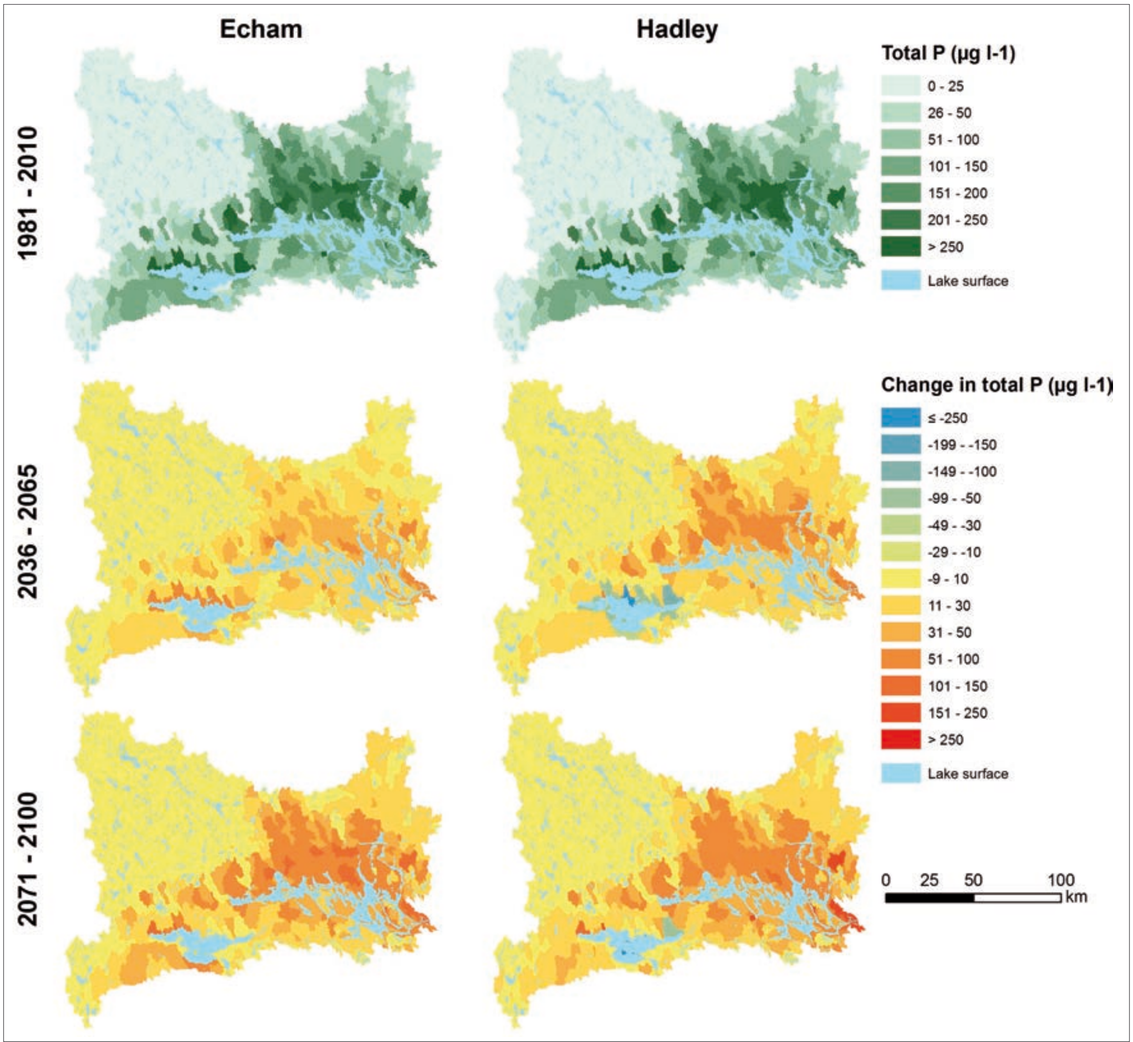

Figure 8. *HYPE-modelled total phosphorus concentrations in sub-catchment discharges of the Mälaren basin for the 1981–2010 baseline period, and concentration changes for the projection periods.*

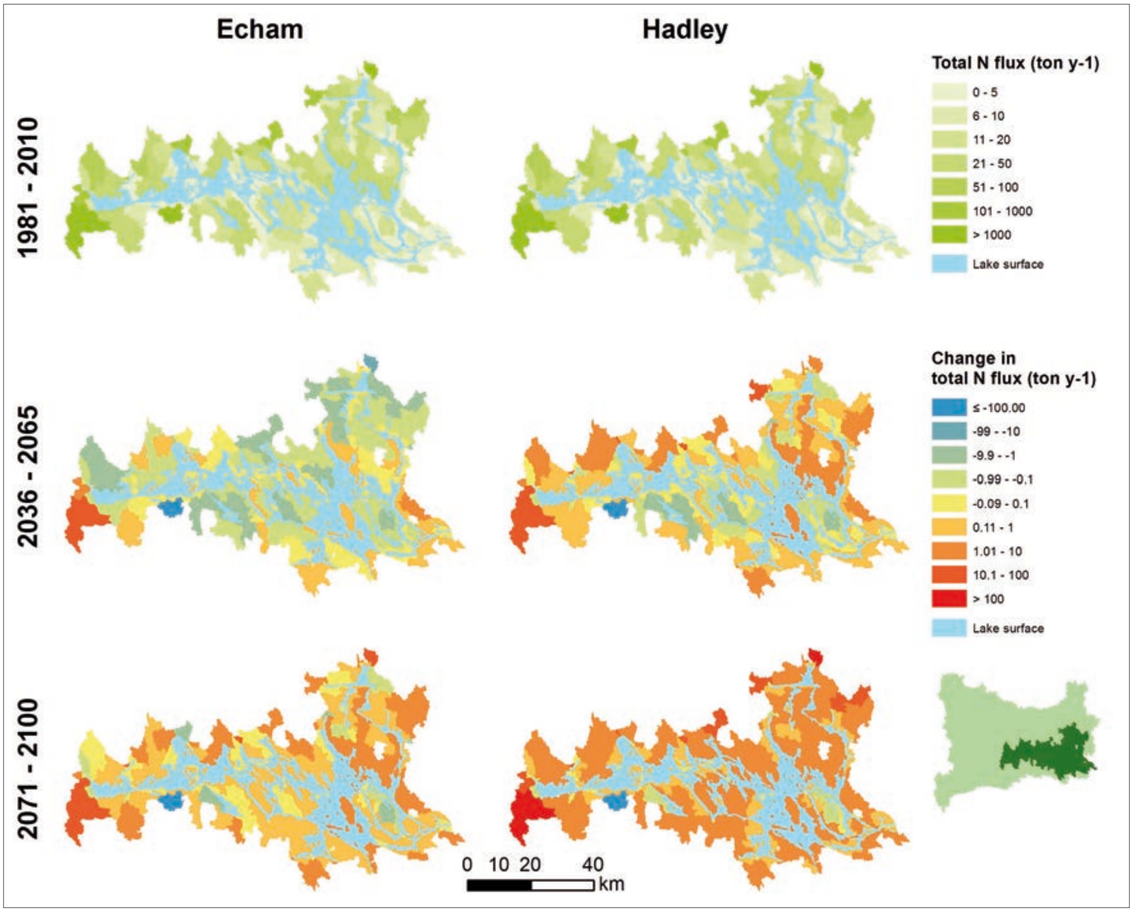

Figure 9. *Average annual total nitrogen fluxes into Lake Mälaren for the baseline period, and projected changes in average fluxes for the projection period. Location of the Mälaren coastal sub-catchments in the inset basin map.*

the lake. The picture until end-century is overall similar in both projections, with an increased flux of >1 ton/y locally.

4 Concluding remarks

Based on different levels of future increases in temperature and precipitation in two climate projections, and a resulting rather similar response in terms of decreasing snow cover, future changes in nutrient concentrations and fluxes in the Lake Mälaren catchment were estimated. Both concentrations and fluxes were projected to increase until the middle and end of the 21st century, generally more pronounced in the Hadley projection. In some sub-cathments the total nitrogen flux increases by >100 ton/y and the phosphorus flux by >1 ton/y, which may be a significant fraction of today's inflow.

It must be clear, not only from the results but also from looking at the length of the modelling chain involved, that regional to local climate change impact modelling exercises like these always carry a large portion of uncertainty accumulated from the emission scenario, GCM, down-scaling chain, and down to the hydrological model uncertainty. Not included in an approach like the one chosen are adaptive changes of land and lake management, either as direct mitigation response to regional climate change or due to other economical or societal decision chains. Nonetheless, results as the ones presented above can give a glimpse into the expectable range of impacts as a result of changing climate characteristics. This is of special importance in areas like the Mälaren basin, where extensive use (i) already puts multiple stressors on a water system that require management (e.g. for drinking water quality assurance), and (ii) climate change impacts have the po-

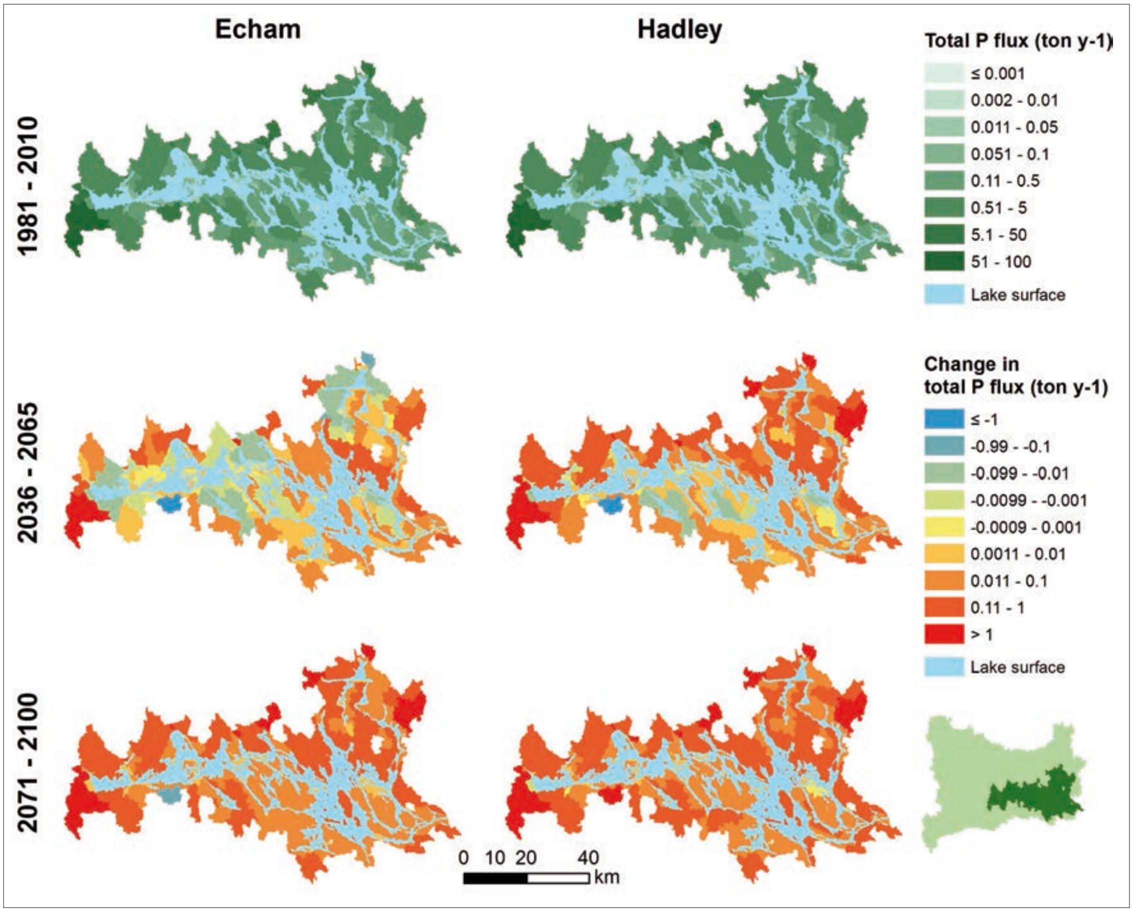

Figure 10. *Average annual total phosphorus fluxes into Lake Mälaren for the baseline period, and projected changes in average fluxes for the projection period. Location of the Mälaren coastal sub-catchments in the inset basin map.*

tential to push current (managed) states out of balance, thus creating the need for management adaptations.

Impact model approaches here have the potential to identify risk zones, i.e. agricultural areas as diffuse sources of riverine nutrients, and thus can serve as strategic support tool for land management adaptation decisions. However, further investigation is clearly needed, e.g. to analyse a wider range of projections, to quantify the lake response to the increased nutrient influx and to assess the impact of also other future changes than climate.

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