SOILS2SEA DELIVERABLE NO. 5.4

BONUS
SCIENCE FOR A BETTER FUTURE OF THE BALTIC SEA REGION

Projected Impacts of Climate, Anthropogenic Changes, and Remedial Measures on Nutrient Loads to the Baltic Sea

SOILS2SEA

Reducing nutrient loadings from agricultural soils to the Baltic Sea via groundwater and streams

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Projected Impacts of Climate, Anthropogenic Changes, and Remedial Measures on Nutrient Loads to the Baltic Sea

March 2018

Authors: Alena Bartosova[1], René Capell[1], Jørgen E. Olesen[2], Mohamed Jabloun[2], Chantal Donnelly[1], Gustav Strandberg[1], Johan Strömqvist[1], Ida Morén[3], and Johanna Tengdelius-Brunell[1]

[1] SMHI
[2] AU
[3] KTH

Reducing nutrient loadings from agricultural soils to the Baltic Sea via groundwater and streams

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1. Background and objectives

The Baltic Sea Action Plan and the EU Water Framework Directive both require substantial additional reductions of nutrient loads (nitrogen and phosphorus) to the marine environment. The BONUS Soils2Sea project conducts research on a widely applicable concept for spatially differentiated regulation, exploiting the fact that the removal and retention of nutrients by biogeochemical processes or sedimentation in groundwater and surface water systems shows large spatial variations. By targeting measures towards areas where the local removal is low, spatially differentiated regulation can be much more cost-effective than the traditional uniform regulation.

To design and evaluate the effectiveness of spatially differentiated regulation requires improved knowledge on the nutrient transport and removal processes at local scale. Soils2Sea therefore conducts field studies with comprehensive data collection and modelling at four sites in Denmark, Sweden, Poland and Russia. Furthermore, Soils2Sea conducts scenario analyses at the Baltic Sea region scale to assess how different regulatory measures as well as changes in land cover, agricultural practices and climate may affect the nutrient losses from the entire Baltic Sea region (BSR) to the Baltic Sea. The Baltic Sea region level analyses are a subject of this deliverable.

Evaluating the impacts of local scale spatially differentiated measures at a scale such as the 1.8 million km^2 Baltic Sea region poses a particular challenge. Multi-basin hydrological and nutrient models at this scale (e.g. Donnelly et al., 2013) are not able to simulate local scale spatially differentiated measures, because i) the models operate at a much coarser spatial resolution than the measures; ii) they often do not include local scale data but rather aggregated data which can vary in quality and resolution between countries; iii) they have a spatial resolution that is coarser than the heterogeneity of the physical system that controls the local variation in the nutrient reduction; and iv) they often have simplified process descriptions adequate for the input data complexity and model scale, but sometimes inadequate for simulating specific local scale measures such as field scale crop rotations. Such measures can be simulated by comprehensive and data demanding local scale models (Hansen et al., 2014a); however, for computational and data access reasons these models are not operational at the Baltic Sea region scale. Therefore, other methods must be applied for upscaling the results from suitable local scale models to models operating at the Baltic Sea scale. Bronstert et al. (2007) provide one of the very few examples reported in literature of this type of upscaling based on dynamic combinations of small and large scale models.

The first objective of the present deliverable report is to describe how the upscaling methodologies developed in Soils2Sea (Refsgaard et al, 2016) were implemented into E-HYPE by adjusting the model structure and process descriptions. Further, the previously revised model was used to simulate effects of climate and societal changes in the Baltic Sea region that can occur by 2050s. The second objective is to evaluate changes in inflows to the Baltic Sea due to climate and societal changes as well as mitigation potential from the spatially differentiated measures.

2. Methodology

2.1 Study Overview

The purpose of this report is to evaluate changes in nutrient loads delivered to Baltic Sea for selected scenarios. The scenarios include climate change, changes in human activities such as land use or waste water management, and two measures specifically tested in the SOILS2SEA project. The first measure focuses on spatially differentiated regulations that allocate activities with high leaching of nitrogen to areas with high natural reduction of nitrogen in soils and groundwater. The second measure focuses on increasing natural reduction of nitrogen in streams.

The evaluation was done using a simulation model, namely E-HYPE v.3.1.4 as described in Section 2.2 below. The changes were evaluated against a baseline that represents sources and processes of the 2010s. Rather than quantifying nutrient loads for one specific year, the natural variability of loads was simulated using climate data from 1981 to 2010. The model was executed for another ten-year period preceding the evaluation period to ensure stable model conditions. The thirty-year baseline was chosen to achieve a good representation of climate variability with an acceptable level of stationarity. The nutrient loads are presented as averages over the evaluation period. Effects of measures were simulated for both the current and future conditions and compared to the respective baseline model runs to determine the relative effect that these measures would have on total loads to the sea.

The new scenarios framework developed by the climate change research community over the recent years consists of two sets of pathways: Representative Concentration Pathways (RCPs) that describe the extent of climate change and Shared Socioeconomic Pathways (SSPs) that depict plausible socio-economic conditions during the 21st century. We selected RCP 8.5 together with three SSPs: SSP1 (Sustainability), SSP2 (Middle of the road), and SSP5 (Fossil-fuelled development). SSPs were interpreted within the context of the RCP 8.5 to project land use and agriculture practices as well as changes in waste water discharges to 2050s.

Future conditions were also simulated using a thirty-year period representing 2050s (from 2036 to 2065 with a ten-year spin up period from 2027). Generally, time slices are preferred over transient runs as long-term changes in nutrient storage within soils are difficult to validate and can have a large impact on scenario results. It is therefore important to communicate that these are NOT projections for the future, but scenarios simply to compare the relative effects of different variables.

2.2 Baltic HYPE description

Baltic HYPE is a part of E-HYPE, a pan-European HYPE model setup. HYPE (Hydrological Predictions for the Environment) is an integrated rainfall-runoff and nutrient transport model developed by SMHI under a Creative Commons open source licence (Lindström et al., 2010). E-HYPE v.3.1.4 was used in this study. E-HYPE v.3.1.4 is described in Deliverable 5.1 (Bartosova et al., 2017). This version was based on E-HYPE v.3.1 (Donnelly et al., 2015; Hundecha et al., 2016) and updated during the SOILS2SEA project. Only a summary description is provided here, the reader is referred to Bartosova et al (2017) for the full information.

Selected parts of the E-HYPE v.3.1 were updated. The updates included: (a) point sources, (b) crop data, and (c) deep soils with active aquifers (implemented as new soil-land use classes to make differentiation of model parameters possible). The model was then recalibrated using the stepwise, representative gauged basin approach described in Strömqvist et al. (2011) and Donnelly et al. (2016). In addition to evaluating model performance based on comparing simulated and observed concentrations at observation points, the E-HYPE model performance was also reviewed with respect to three process-based data for which maps could be provided: baseflow fraction, nitrogen leaching, and reduction of nitrogen in groundwater.

While the process descriptions were improved, the overall change in the model performance from v.3.1 was insignificant. Relative error (RE) in the recalibrated model varies among the monitoring sites, with 65% and 66% of sites having RE within 50% for total phosphorus (TP) and total nitrogen (TN) concentrations. The average RE is 42% and 14% and the median RE is 8% and -10% for TP and TN, respectively. Correlation coefficient (CC) in the recalibrated model varies with 7% and 30% of sites having CC greater than 0.5 for TP and TN, respectively. The average CC is 0.28 and 0.10 and the median CC is 008 and -0.28 for TP and TN. The details of the calibration are fully described in Bartosova et al (2017).

2.3 Climate Models

For the BONUS SOILS2SEA it was deemed feasible to run a mini-ensemble of four climate projections for each scenario. Given this limitation, it was desirable to choose four projections that would represent the potential spread in nutrient load projections to the Baltic Sea; however without actually running the full ensemble of climate projections, it is difficult to say in advance which projections would lead to the most extreme nutrient load projections. We therefore make the assumption that change in precipitation and change in temperature in the summer months are predictors for the changes in nutrients.

The spread in the CORDEX downscaled CMIP5 projections can be evaluated over a region by quantifying the mean precipitation and temperature changes across the region from each model. As the focus of SOILS2SEA is on the nutrient load contribution from the agricultural portion of the Baltic Sea catchment, a square region encompassing the Baltic Sea catchment south of 60 degrees latitude was defined. Mean changes in the precipitation and temperature were calculated for each GCM and GCM/RCM combination for the summer months (June, July and August), as processes occurring in the warmer summer months were deemed to be most important for changes in nutrient concentrations over the region.

To limit the ensemble spread to the climate model uncertainty, only one emissions scenario was chosen, RPC8.5. This higher end scenario was chosen as it represents the current development in emissions. Changes are evaluated for mid-20th century (2041-2070). The changes from each GCM and GCM/RCM combination are shown in Figure 1. The regionally downscaled projections with the highest and lowest changes in temperature and precipitation were then identified (Table 1). Note that the uncertainty in the downscaled RCMs is significantly different than from the forcing GCMs and the possibility that the RCMs underestimate decreases to precipitation or increases in temperature should be taken into account when analyzing final results.

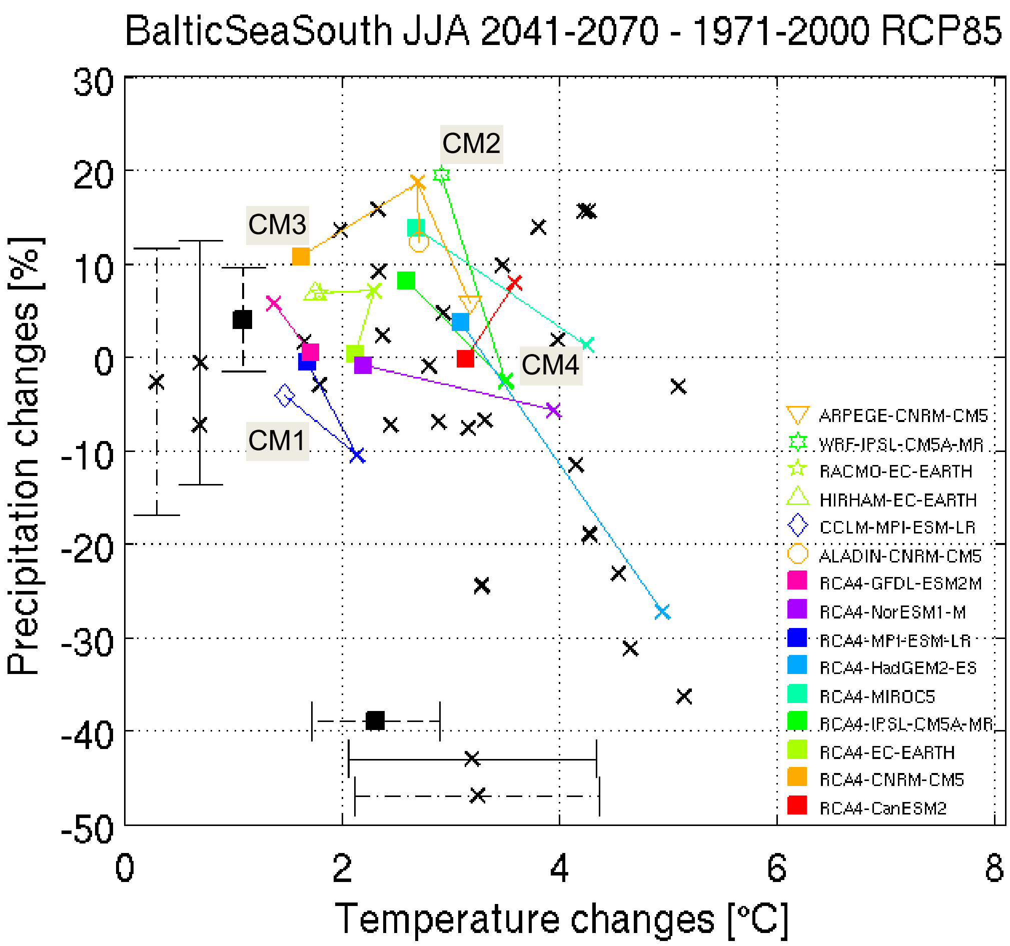

Figure 1. Temperature (°C) and precipitation (%) differences 2041-2070 compared to 1971-2000 for summer (June-August) according to scenario RCP 8.5 for a rectangle encompassing the Baltic Sea catchment south of 60 degrees. Coloured squares show the differences in the RCA4 simulations, open coloured shapes show the differences in the other regionally downscaled simulations. Each regionally downscaled projection is connected by a line to the corresponding GCM, indicated by a coloured cross. Black crosses indicate CMIP5 GCMs not used for downscaling in this study.

Table 1. Regionally downscaled projections with the highest and lowest changes in temperature and precipitation for RCP8.5 in Baltic Sea Region and a final selection that represents the range of changes. P is precipitation, T is temperature.

	P change		T change	
	lowest	highest	Lowest	Highest
RCP8.5	CM1	CM2	CM3	CM4
Actual	CCLM-MPI-ESM-LR	WRF-JPSL-CM5A-MR	CCLM-MPI-ESM-LR	ARPEGE-CNRM-CM5
Selected	CCLM-MPI-ESM-LR	WRF-JPSL-CM5A-MR	RCA4-CNRM-CM5	RCA4-CanESM2

Because the GCM/RCM combination CCLM-MPI-ESM-LR represented both the lowest precipitation change and lowest temperature change, a fourth GCM/RCM combination showing the 2nd lowest temperature change (RCA4-CNRM-CM5) was chosen so that four different models can be used. Also, three models have very similar change in temperature but with different changes in precipitation. Thus, we choose RCA4-CanESM2 instead of Arpege-CNRM-CM5 to further diversity the GCMs in the chosen ensemble. The final four chosen projections for RCP8.5 are therefore:

CM	RCM	GCM	Symbol
1.	CCLM	MPI-ESM-LR	Empty blue rhombus
2.	WRF-JPSL	CM5A-MR	Empty dark green star
3.	RCA4	CNRM-CM5	Full orange square
4.	RCA4	CanESM2	Full red square

These four alternatives also help encapsulate the range of changes seen in the annual changes. Figure 2 shows similar diagrams as Figure 1 for RCP4.5 and 8.5 for both summer and an annual mean. It can be seen that for other periods and emissions scenarios the choices of models would have been different.

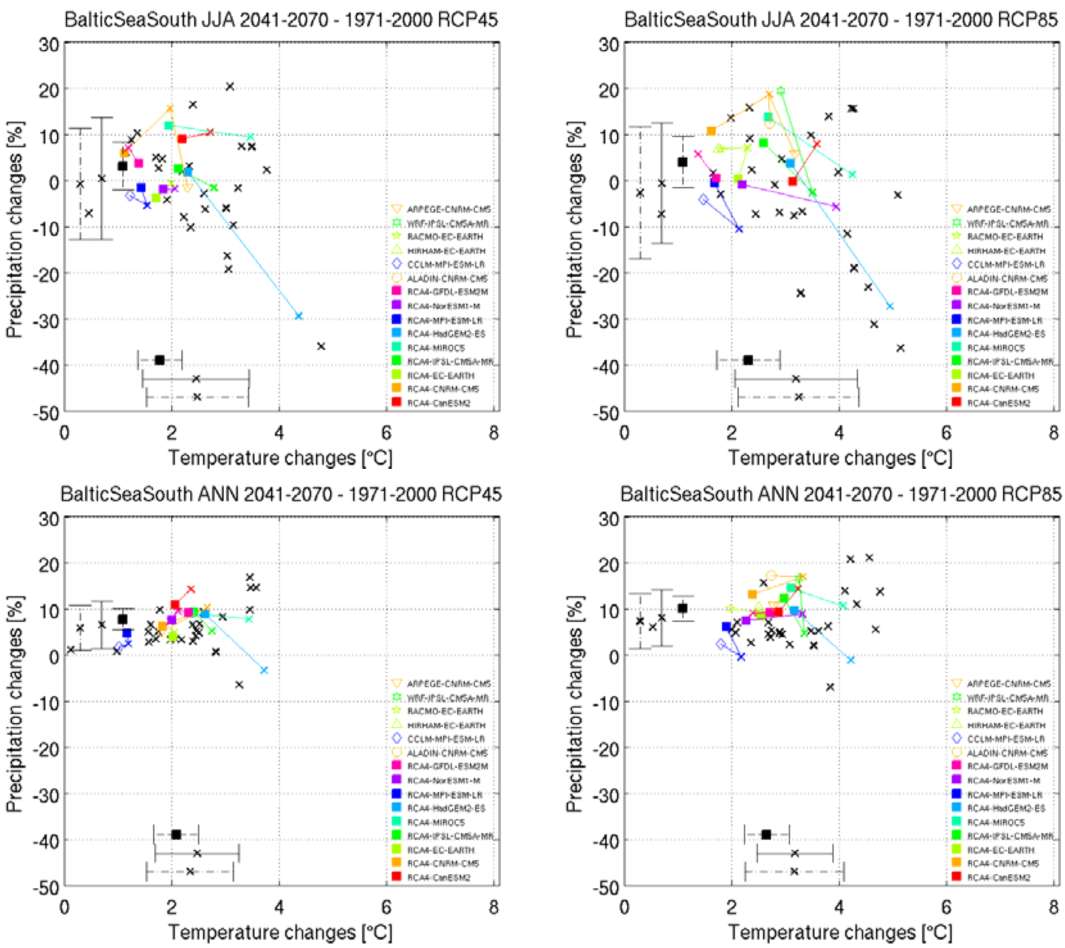

Figure 2. Temperature (°C) and precipitation (%) differences 2041-2070 compared to 1971-2000 for summer (JJA=June-August, top) and the whole year (ANN = Jan to Dec, bottom) according to scenario RCP 4.5 (left) and 8.5 (right) for a rectangle encompassing the Baltic Sea catchment south of 60 degrees. Coloured squares show the differences in the RCA4 simulations, open coloured shapes show the differences in the other regionally downscaled simulations. Each regionally downscaled projection is connected by a line to the corresponding GCM, indicated by a coloured cross. Black crosses indicate CMIP5 GCMs not used for downscaling in this study.

When analyzing final results, the efficiency of this method for representing spread in concentration or load scenarios could be partly analysed by comparing whether those scenarios that give the largest precipitation and temperature changes also give the largest nutrient changes, although this can be difficult given the smaller number of simulations.

The selected climate projections were bias-adjusted using DBS method (Yang et al., 2010). DBS is a parametric quantile-mapping method and adjusts the full quantile distribution of climate models output towards the reference data's quantile distribution. Here, we applied DBS to daily precipitation and temperature using Watch ERA-Interim Forcing Data (WFDEI, Weedon et al., 2011) as a reference dataset. The reference period for the calibration of the bias-adjustment parameters was set to 1991-2010.

2.4 SSPs

Climate represents only one aspect of changes we can expect to occur by 2050s. Land use, agriculture, population, life style, legislation, and economic development are also important drivers that change over time and can significantly affect generation and transport of nutrients to the Baltic Sea. The possible changes simulated with E-HYPE that can occur by 2050s were driven by two aspects: changes in the climate forcing data as described in Section 2.3 Climate Models (p. 6) and changes in socio-economic variables.

The variation in land use and loadings from rural and urban sources is represented through three selected Shared Socioeconomic Pathways (SSPs). SSPs are used in the climate research community to explore uncertainty in mitigation, adaptation and impacts associated with alternative climate and socioeconomic futures and can be viewed as boundary conditions that provide the framing for more complex assumptions for regions and/or sectors. They are quantitative and qualitative narratives of possible socio-economic futures up to the end of the century. These SSPs were developed for the Baltic Sea region by Zandersen et al. (2018) in order to cover aspects related to nutrient loadings to the Baltic Sea. The three SSPs used here include:

SSP1 (sustainability) describes a world making relatively good progress towards sustainability, with sustained efforts to achieve development goals, while reducing resource intensity and fossil fuel dependency. For the Baltic Region it is assumed that there is a 10% reduction in agricultural land use and most of this is converted to forest. In agriculture, management plans to achieve goals of the EU Water Framework Directive (WFD) and all other plans are fully implemented. Consumption trends change towards less demand for meat. For sewage more sophisticated and comprehensive treatments are implemented. Air pollution is reduced through cleaner energy production and use of electric vehicles.

SSP2 (middle of the road) describes a world, where trends typical of recent decades continue with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependency. For the Baltic Region there is no change in agricultural land use. Trends in agriculture are towards larger farms, intensive farming, and industrialized and more effective agriculture. Management plans for reducing nutrient loadings from agriculture (WFD) are only partly implemented. For sewage, technology development and increased urbanisation means reduced nutrient loadings from sewage. For air pollution NOx-emissions decrease. Hybrid and electric cars will be more common and therefore urban emissions will decrease.

SSP5 (fossil-fuelled development) is a world that stresses conventional development oriented toward economic growth as the solution to social and economic problems through the pursuit of enlightened self-interest. The preference for rapid conventional development leads to a high energy demand, most of which is met with carbon based fuels. For the Baltic Region it is assumed that there is a 10% increase in agricultural land use and most of this taken from forest. The increasing agricultural land use is associated with higher livestock production within a global market. There will be fewer regulations of agricultural nutrient loadings, but improvements in production technologies. For sewage, there will be a higher amount of waste water because of the increased urbanization. Technologies to improve sewage treatments will increase in efficiency. For air pollution, technologies to reduce NOx pollution will continue but with a reduced rate compared to SSP1 and SSP2.

2.4.1 Land Use

The Land Cover-CCI (LC-CCI) global land cover map was used as baseline to generate the map projections for the three SSPs and the four different climate models. The land use map has a resolution of 300 m and represents the year 2010. The land-use (LU) classes had been reclassified and regrouped into seven land-use/cover classes (i.e. forest, grassland, cropland, wetland, urban/built up area, bare/spare vegetation, and water bodies).

A stratified random sample of 10.000 points for each LU class with points separated by >1000 m were selected. Only forest, grassland, cropland and bare/sparse vegetation LU classes were considered. For each point, we extracted values for the LU class and all the explanatory variables available including coordinates, soil characteristics, topographical information, climate indices and an enrichment factor.

The slope and altitude were based on a 25 by 25 m grid cell Digital Elevation Model. The soil related parameters (i.e. water storage capacity, soil depth, the clay, silt and gravel fraction, bulk density and obstacle to root depth) were derived from the Harmonized World Soil Database (HWSD) version 1.2. The gridded climate indices representing different aspects of climate, based on the recommendation by the CLIMDEX project, were generated for the baseline (1991-2010) as well as for the future (2041-2060) periods. In total 10 climate indices maps were generated and averaged for each period including annual total precipitation, number of consecutive dry and wet days, cold and hot frequency during day and night, the warm and cold spell and the growing season length. To characterize the neighbourhood of a grid (pixel) in the land use map we used the defined enrichment factor (F) introduced by Verburg et al., (2004) which is a measure based on the over- or under representation of different land use types in the neighbourhood of a grid. F is defined by the occurrence of a land use type in the neighbourhood of a grid relative to the occurrence of this land use type in the whole Baltic Sea catchment. The shape of the neighbourhood was a 3x3 design with the distance of the neighbourhood from the central grid-cell being equal to one grid with eight neighbouring grids in total.

The generated stratified random points were used to build a land use model. The Random Forest (RF) classification tree was used to fit the land use model. RF is an ensemble model which uses bagging (bootstrap aggregated sampling) to build many individual classification trees to generate a final classification. The algorithm uses a random subset of predictor variables to split observation data into homogenous subsets. The performance of the fitted RF model was assessed using the Kappa statistic, which expresses the agreement between two categorical datasets corrected for the expected agreement. The Kappa scores obtained for the RF model was 0.73 suggesting that the generated land use map for the baseline using the RF model was close to the observed baseline map. Therefore, the RF land use model was used to generate the probability maps of each of the LU classes under the different climate projections.

These probability maps were then used to generate the different future land use maps for the different SSP story lines that were defined for the Baltic Sea catchment (Figure 3). It was assumed that only forest, agricultural, and urban/built up areas are subject to changes under the different SSPs.

The application of changes in land use under the different SSPs followed a sequence of priority land uses, where these land uses follow the storylines of the SSPs (Zandersen et al., 2018):

1. Urban area
    - SSP1: total urban area unchanged
    - SSP2 & SSP5: urban area per person unchanged
2. Peri-urban area for recreation
    - SSP1: doubling of forest in 10 km city buffer
    - SSP2: 50% increase in 5 km city buffer
    - SSP5: no change
3. Agricultural area (convert to and from forest)
    - SSP1: 10% decrease in agricultural area (50% reduction in animal-based food)
    - SSP2: No change
    - SSP5: 10% increase in agricultural area due to increased global demand

The changes related to urban/built up area were modelled separately using current data on distributed total population within the Baltic Sea catchment in 2005. The projected future population for 2050 under the different SSPs obtained from IIASA at a country level were disaggregated to each grid within the Baltic Sea catchment. For SSP1 it was assumed that the urban area did not change while the urban area per person remains the same for SSP2 and SSP5, which means that the urban area was assumed to be proportional to total population. Hence, given the projected total population per grid, a new urban area was calculated.

Where urban area increased, it was assumed to occur through an expansion of existing urban areas. The agricultural pixels in the neighbouring cells of the existing urban areas were converted into urban class to represent the calculated urban sprawl. Depending on SSP, a peri-urban area was defined and agricultural land within this area was converted to forest. These changes reflect different priorities in the storylines for different SSPs (Zandersen et al., 2018).

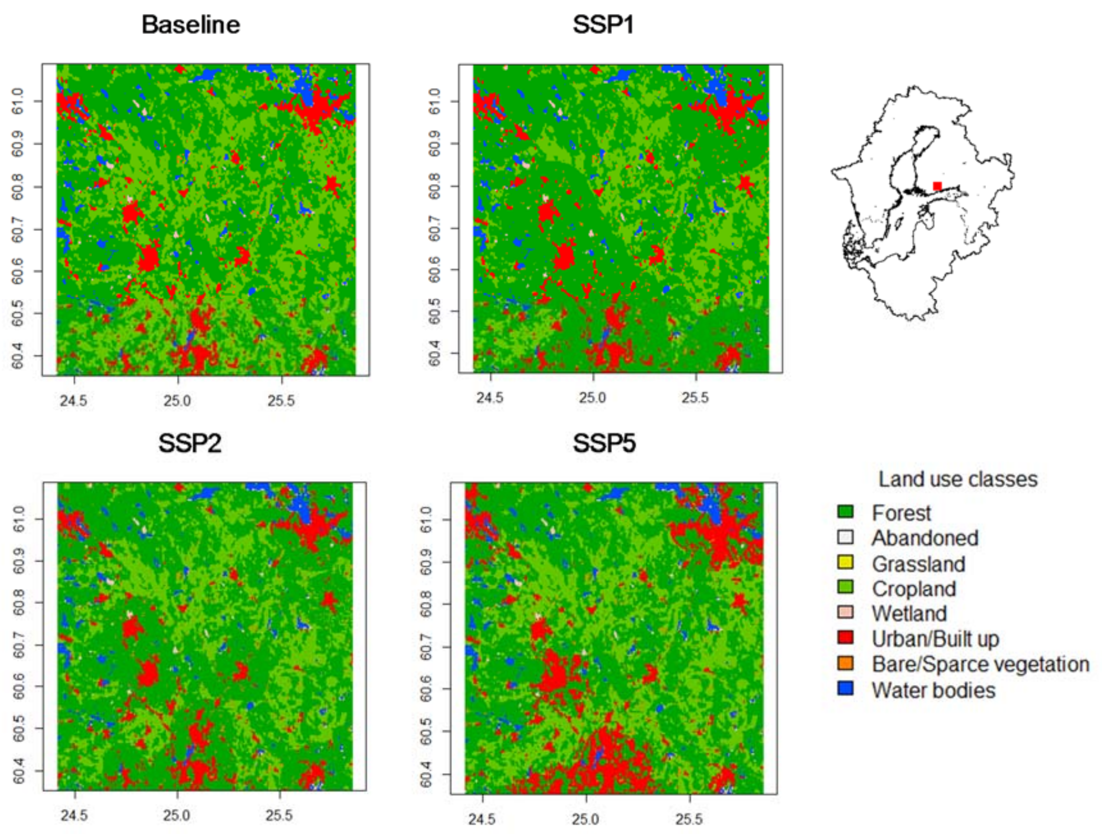

Figure 3. Example of Future Land Use for the baseline and the different SSPs generated for the CanESM2_RCA4 climate model. Longitude is shown on x-axis and latitude on y-axis.

2.4.2 Agricultural Practices

2.4.2.1 Fertilization

The fertilisation in the different SSP scenarios covers nitrogen (N) in both mineral fertiliser and manure. The effective N (Neff, kg N/ha) is calculated as a weighted value from N in mineral fertiliser and manure as:

$$\mathrm{Neff} = \mathrm{Nfer} + \mathrm{Nrep} * \mathrm{Nman} \qquad \text{Equation 1}$$

where Nfer is N in mineral fertiliser (kg N/ha), Nman is N in manure (kg N/ha), and Nrep is replacement value of N in manure. Nrep is set to 0.65 in the baseline situation corresponding to the current value for other types of manure in Denmark (Dalgaard et al., 2014).

In all scenarios the current fertiliser and manure rates in the catchments are taken as the baseline. The rates are then changed by changing the amount of manure (Nman), the N replacement value in manure (Nrep), and the amount of N effectively applied (Neff). Based on these changes, the mineral fertiliser rate is calculated for each SSP.

SSP1. Sustainability. This scenario involves a 50% reduction in meat production in the Baltic Sea region, and this is implemented as a 50 % reduction in manure N, i.e. Nman is reduced by 50%. The N replacement value in manure is increased to Nrep = 0.75 through implementation of biogas, acidification and other measures to reduce emissions and increase manure value. The effective N amount applied is reduced to 5 % below current level. If this results in Nfer < 0 then Nfer is set to 0.

SSP2. Middle of the road. Livestock and manure production is maintained at current level. The N replacement value in manure is increased to Nrep = 0.70. The effective N amount applied is maintained at current level.

SSP5. Fossil-fueled development. This scenario involves a 50% increase in meat consumption in the Baltic States, and this is implemented as a 50 % increase in manure N, i.e. Nman is increased by 50%. The N replacement value in manure is decreased to Nrep = 0.60, since new livestock production facilities will not prioritize reductions in ammonia losses. The effective N amount applied is increased to 5 % above current level. If this results in Nfer < 0 then Nfer is set to 0.

2.4.2.2 Seasonal Crops

The HYPE model distinguishes between autumn and spring sown crops. The choice of crops will depend on climatic conditions (Elsgaard et al., 2012). A model was therefore developed for the baseline proportion of autumn sown crops using predefined climatic indices as predictors. The model used is based on the M5 regression tree approach. The main advantage of this model is that at each node it tries to fit a regression model instead of simply assigning a value like the normal regression tree. This was combined with changes in climate indices to calculate the change in future proportion of autumn sown crops obtained using the M5 regression model. This change was then applied to the baseline situation to obtain the future projections of autumn sown crops (Figure 4).

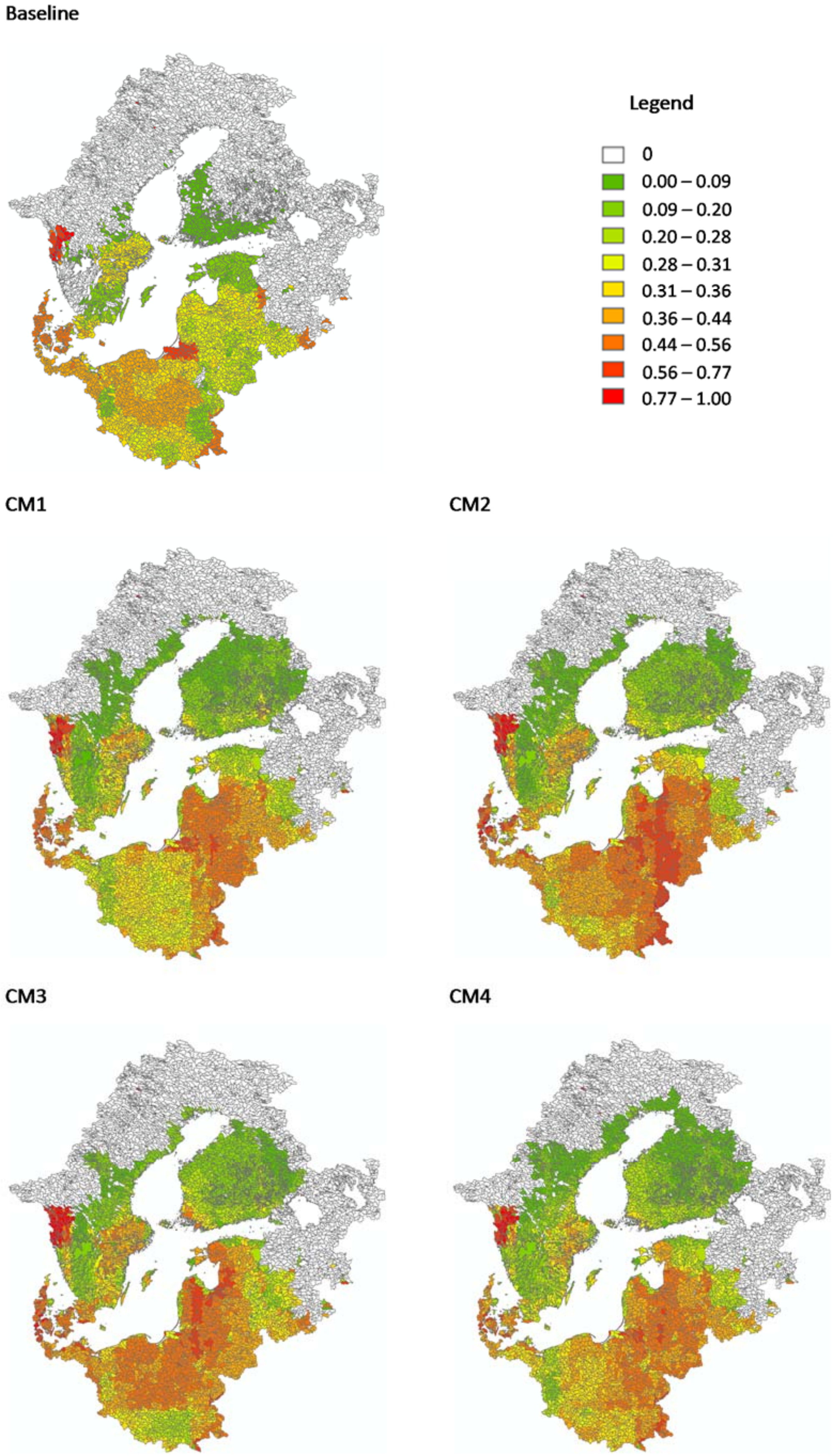

Figure 4. Proportion of autumn sown crops for baseline and different climate models under SSP2 in 2050.

2.4.3 Wastewater

The nutrient contribution from wastewater generated by urban and rural population depends on several factors, such as population, level of urbanization, economic status, diet, treatment technologies, and willingness to invest in sewer and wastewater treatment infrastructure. These are general assumptions incorporated into the SSP storylines:

SSP1. Sustainability. Current EU policies and stringent HELCOM recommendations are met with implementation of sophisticated and comprehensive treatment technologies both in urban and rural areas. All wastewater treatment plants are upgraded to a tertiary level of treatment within 30 years.

SSP2. Middle of the road. Urbanization increases with improvements in wastewater treatment. However, rural areas lag behind. Urban areas are compliant with regulations but not rural areas. The HELCOM recommendations on municipal wastewater treatment plants are only partially implemented in urban areas.

SSP5. Fossil-fueled development. The rapid development of urban areas and population increase are not followed with corresponding upgrade and expansion of the sewage water infrastructure due to a lack of priority. More wealthy areas have high cleansing technology while less wealthy municipalities do not. There is some upgrading in the infrastructure due to technology spill-overs from other sectors. The HELCOM recommendations on municipal wastewater treatment plants are only partially implemented.

The assumptions associated with these SSPs were implemented in a MATLAB script by BalticAPP BONUS project (Hyytiäinen and Pihlainen, 2017). The changes in nutrient loads generated by urban and rural population were transferred from the grid-scale to catchment scale in Baltic HYPE. While there were differences in the initial loading between the BalticAPP sources and those in Baltic HYPE due to different sources of information used to develop the initial estimates, the relative change from 2010 to 2050 is the same for both projects.

2.4.4 Atmospheric Deposition

E-HYPE v.3.1.4. includes dry and wet deposition of nitrogen. Estimates of atmospheric deposition for SSPs are based on two sources, Zandersen et al (2018) and Engard et al (2017). Engard et al (2017) simulated atmospheric deposition with MATCH model, the same model that provided the current values of atmospheric deposition for Baltic HYPE. The conditions described for 2050 were assumed to correspond to SSP2 and the same reduction from 2010 to 2050 was applied to atmospheric deposition in Baltic HYPE. The relative change among SSP1, SSP2, and SSP5 atmospheric depositions from Zandersen et al (2018) was then used to develop the actual estimates of reduction for SSP1 and SSP5. Zandersen et al (2018) considered changes in emissions from number of animals, changes in practices affecting ammonium losses during storage, management, and application of manure.

The reductions in atmospheric deposition for nitrogen used in Baltic HYPE for respective SSPs are shown in Table 2. This change was applied uniformly over the Baltic Sea region, preserving the current spatial variability in atmospheric deposition. Note that there is a decrease in atmospheric deposition rates even for SSP5.

Table 2. Change in atmospheric deposition for SSPs

	SSP1	SSP2	SSP5
Change from current deposition rates	-40%	-30%	-15%

2.5 Upscaling Measures Targeting Reduction of N

The measures evaluated in this study utilize variability in reduction of N on a local scale. E-HYPE and its Baltic part have much coarser resolution with average catchment size of 215 km^2. This coarser resolution enables simulation of the full Baltic Sea region with reasonable resources. However, this resolution is also much coarser than it would be needed to simulate these local variations directly. Thus, the impact of these measures was simulated with detailed local models, the results were analysed, and generalized methods were developed that are appropriate for large-scale models such as E-HYPE.

The upscaling procedures were developed in D3.2 (Upscaling methodologies). This section describes the basic assumptions of the upscaling methods and how they were implemented into Baltic HYPE. The reader is referred to D3.2 and Hansen et al (2018) for more details.

2.5.1 Groundwater

The spatially differentiated groundwater measures applied in this study relocate agricultural activities with high N leaching to areas with high potential to reduce N. For the purpose of this study, it was assumed that spatially differentiated measures were applied in all Baltic HYPE catchments with at least 3% arable land (Figure 5) located in a catchment with average reduction of N at least 5%. Overall, 51% of catchments were selected for this measure.

Empirical relationship between the arable land and the impact on reduction of N in groundwater from implementing spatially differentiated measures was used to estimate the expected impact (D3.2 Upscaling Methodologies):

$$\Delta GW\% = 0.26 * A^2 + 0.07 * A \qquad \text{Equation 2}$$

where *ΔGW%* is the change in reduction of N in groundwater (GW%) and *A* is the fraction of arable land within catchment.

In order to achieve this change in reduction of N in groundwater, coefficient of denitrification in the deepest soil layer, *Denitrlu3*, must be changed in the model parameters. Using values from 10 test catchments, the following relationship was developed in D3.2 to estimate the needed change in the denitrification coefficient:

$$\Delta Denitrlu3 = \exp\left(\frac{\Delta GW\% - (0.009 - 7.52*10^{-5}*SOIM + 0.0043*N\_leach)}{0.039 - 3.26*10^{-5}*SOIM + 0.0022*N\_leach}\right) \qquad \text{Equation 3}$$

where *SOIM* is the average soil moisture in the deepest soil layer and *N_leach* is the average N leaching to the deepest soil layer.

The Baltic HYPE model was then modified to include the new, measure-specific denitrification coefficient. This was achieved in several steps. First, the denitrification coefficient was regionalized for all catchments selected for implementation of the groundwater retention oriented measures. Denitrification coefficient in Baltic HYPE depends on land use in most of the areas, except in three areas where a regionalized denitrification coefficient was specified during the HYPE model calibration (Bartosova et al, 2018). Changing the values of the landuse-based denitrification coefficients would result in a domain-wide change, however, a catchment-specific change was needed to simulate the impact of groundwater retention-oriented measures. The catchment-averaged denitrification coefficient was therefore calculated as an area-weighted average of these land use-dependent denitrification coefficients and then rounded (Table 3) so that an acceptable number of denitrification regions can be created. In total 61 new denitrification regions were created. Each catchment that was selected for implementation of groundwater-oriented measures was assigned into one of the 61 denitrification regions. The model was executed with these regionalized denitrification coefficients to provide a new baseline specifically to evaluate the impact of the groundwater oriented measures.

Then, the measure-specific denitrification coefficient was calculated using Equation 3. The maximum possible change in the denitrification coefficient was assumed to be 2, i.e., the measure-specific denitrification coefficient was limited to thrice the value of the original denitrification coefficient (Equation 4). This was necessary to create reasonable bounds for the values derived from the empirical Equation 3. The measure-specific denitrification coefficient was also rounded and regionalized using Table 3.

$$\Delta Denitrlu3_{lim} = \min(\Delta Denitrlu3, 2) \qquad \text{Equation 4}$$

The model was executed with the measure-specific denitrification coefficient. Upon reviewing the results, it was necessary to further adjust the measure-specific denitrification coefficient for some catchments. The empirical relationship in Equation 3 yielded erroneous values for some combinations of SOIM, N_leaching, and ΔGW% that resulted in a mismatch between the expected ΔGW% and the actually simulated ΔGW%. Rather than revising the Equation 3 to be more robust, Baltic HYPE was executed with two additional sets of denitrification coefficients, one 20% higher and one 20% lower than the measure-specific denitrification coefficient calculated with Equation 4. A simple linear regression was fitted through the 4 combinations of selected denitrification coefficients and resulting reduction of N in groundwater in Baltic HYPE (original denitrification coefficient, measure-specific denitrification coefficient, and 20% higher and 20% lower than the measure-specific coefficient). This regression was then used to determine the final measure-specific denitrification coefficient that was used in simulating the measure. Lastly, Baltic HYPE was executed with the final measure-specific denitrification coefficients.

The model results were processed to calculate the new percent of N reduction in groundwater and compared to the expected values of N reduction in groundwater from Equation 2 (Figure 6). For most catchments, there is a good agreement between the expected and the simulated values. Larger differences are only found in those catchments, where the measure-specific denitrification coefficient was limited to thrice the original denitrification coefficient (blue circles in Figure 6) to retain realistic values for the denitrification coefficient.

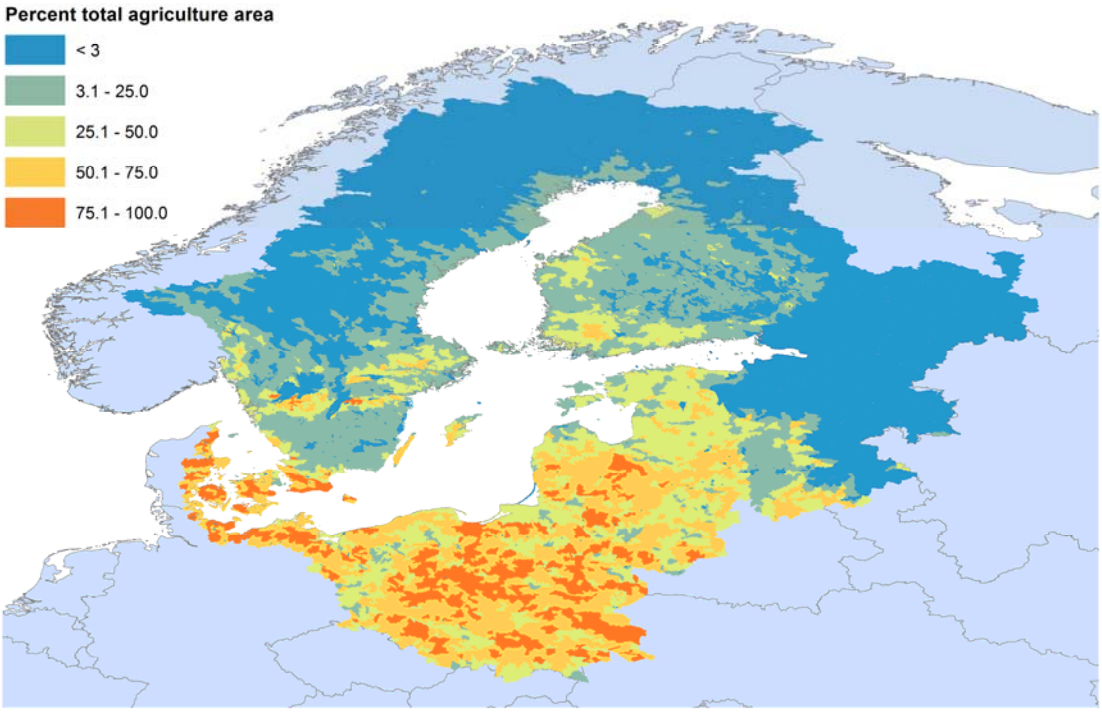

Figure 5. Percent of agriculture area in Baltic HYPE catchments.

Table 3. Criteria for regionalization of the denitrification coefficient

Denitrification coefficient range	Regional denitrification coefficient rounded to a multiple of
< 0.002	0.0002
0.002 – 0.005	0.0005
> 0.005	0.001

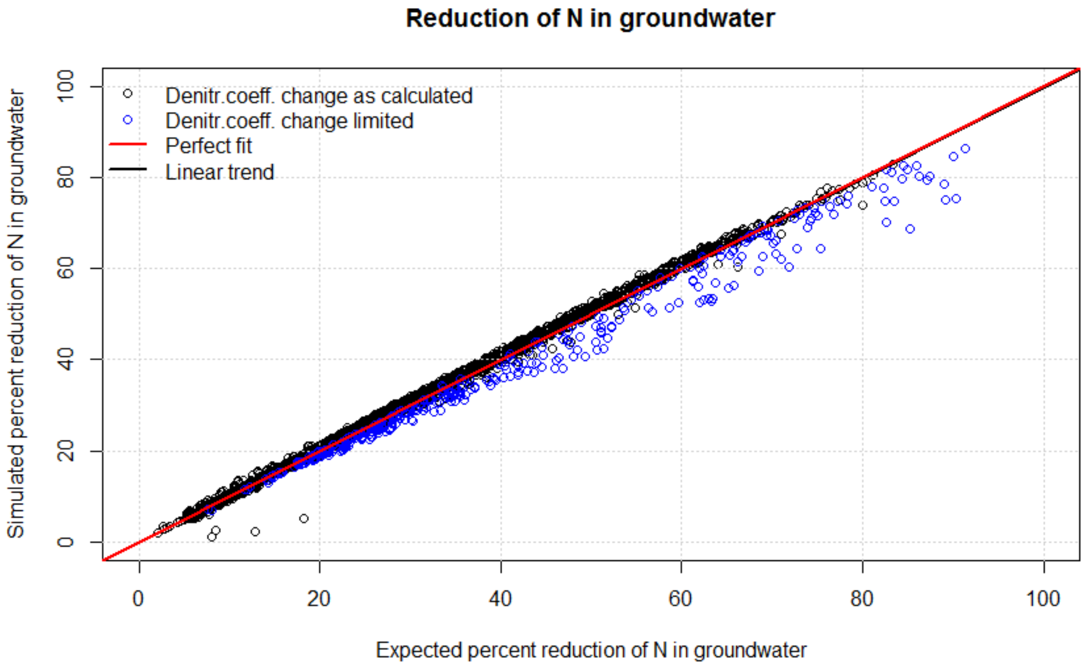

Figure 6. Comparison of the expected reduction of N in groundwater based on the change calculated from Equation 2 and reduction of N in groundwater simulated with regional measure-specific denitrification coefficients in Baltic HYPE. Each circle represents one catchment; the blue circles are catchments where the measure-specific denitrification coefficient was limited to the maximum possible change in Equation 4.

2.5.2 Surface Water

Streams can reduce the nutrient load to the Baltic Sea in two ways. Reduction can be achieved either by increasing the average transport time and thus increasing the deposition of nutrients during the transport, or by increasing the transformation of nitrate into nitrogen gas and thereby completely removing it from the system before it reaches the mouth of the stream. Surface water-oriented measures were tested with a reach scale model validated with monitoring data for Tullstorp Brook. The results were upscaled to Baltic HYPE using the upscaling procedure documented in D3.2 (Upscaling Methodology) that accounts for different routing formulas in the two models.

The surface water-oriented measures were assumed to be applied in all Baltic Sea catchments with at least 5% of agriculture. In HYPE there are two types of streams, local streams and main streams, which both have a generic length derived as the square root of the sub catchment area. Local streams are gathering the water from the landscape and deliver it to the main streams of the catchment. The surface water-oriented measures target smaller streams, thus, the measures were assumed to be implemented in local stream within these selected catchments and mainstreams of headwater catchments.

Furthermore, it was assumed that only part of the stream network in those catchments was degraded and in need of remediation. Under the Water Framework Directive (WFD), European Union (EU) member states have reported the percentage of streams that are under hydromorphologic pressure in the different River Basin Districts (RBD) (Fehér et al., 2012, see Figure 7). Only the proportion of the streams under hydromorphologic pressure was assumed to be remediated with surface water-oriented measures. For the catchments where data was not reported we assumed 10-30% of rivers were under hydromorphologic pressure everywhere. Catchments selected for remediation are shown in Figure 8 with the proportion of local streams where surface-water oriented measures were applied. Overall, 60% of catchments were selected for this measure.

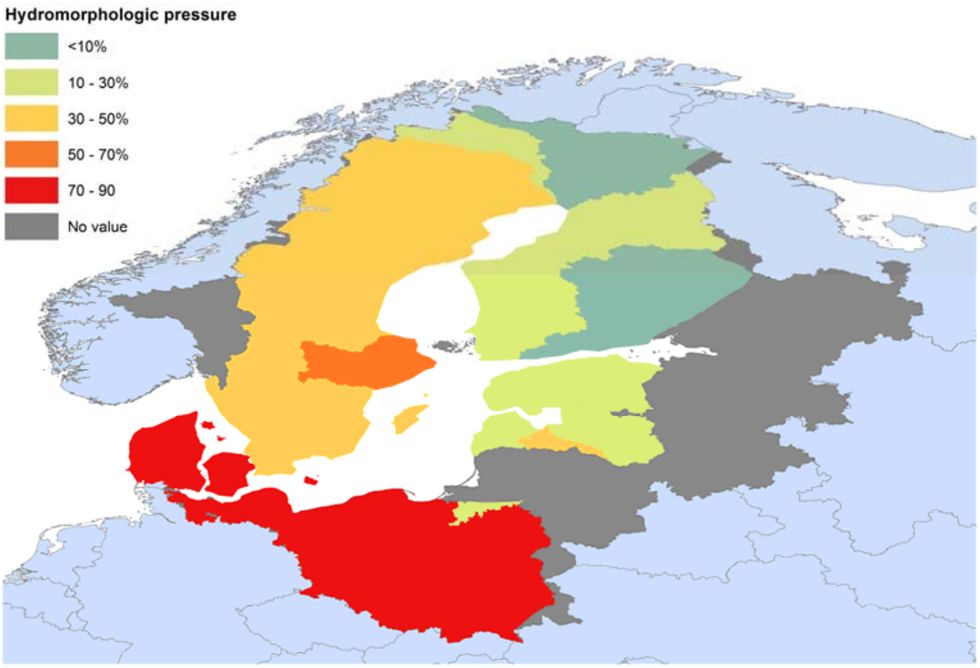

Figure 7. Percent of streams under hydromorphologic pressure within the Baltic Sea catchment. RBDs without data are shown in grey. (after Fehér et al., 2012)

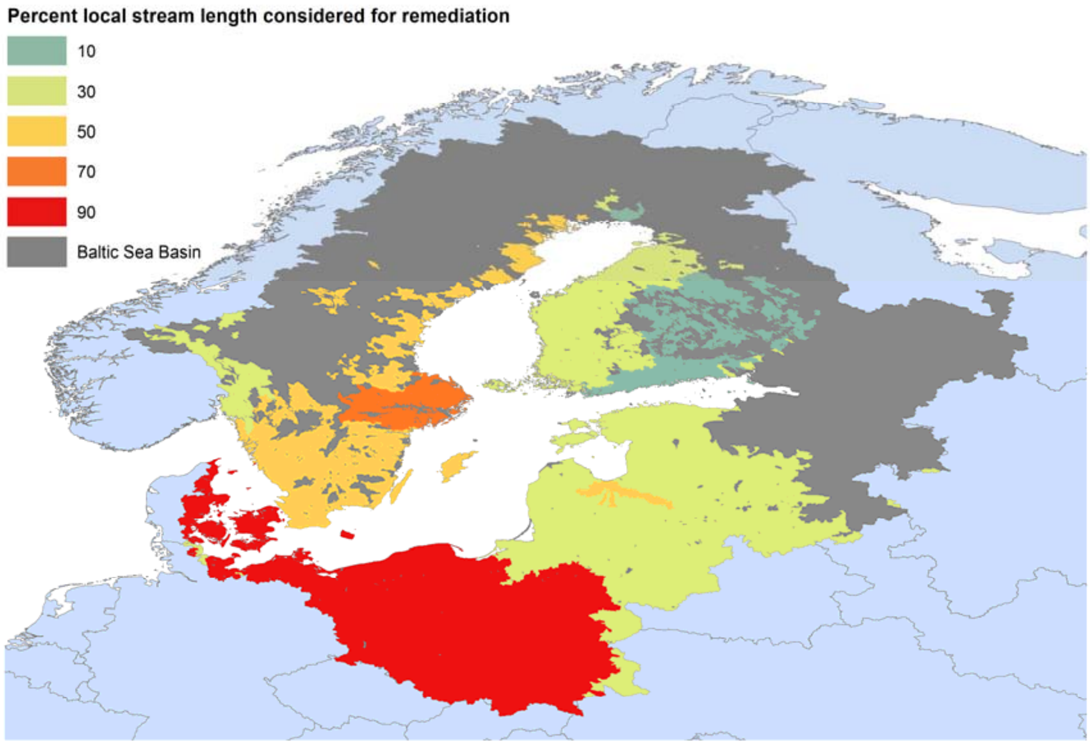

Figure 8. Proportion of local streams remediated with surface water-oriented measures as simulated with Baltic HYPE.

For simplification, the same level of changes in nitrogen losses and hydraulic parameters documented in Tullstorp Brook was assumed to be achievable in all remediated streams. The total percentage mass loss D and the average travel time in the reach τ including both the time in the surface water and the time in the hyporheic zone were derived according to Morén et al. (2017) both for before and after remediation:

$$D = 1 - \exp\left[-\frac{X}{U}(r_{MC} + R)\right] \quad \text{Equation 4}$$

$$\tau = \frac{X}{U}(1 + F) \quad \text{Equation 5}$$

where x is the remediated local stream length, U is the assumed stream velocity, r_{MC} is the first order denitrification rate in the main stream, R is a rate coefficient related to the hyporheic zone processes, and F is a retention factor that quantifies the relative increase in solute travel time due to hyporheic zone processes. The percent changes in D and τ were then calculated for the remediated local streams and main streams in the selected catchments and scaled to the total length of local and main streams.

Table 4. Parameters used in calculating percentage mass loss and the change in average travel time in streams before and after remediation with surface water-oriented measures

Parameter	Unit	Prior to remediation	After remediation	% Change
U	m/s	0.07	0.04	-41
r_{MC} + R	s^{-1}	-9.23E-07	-1.26E-06	36
F	--	0.0382	0.0475	24

The scaled change in D and in τ differs (Figure 9). After testing, the length of local streams and main streams in Baltic HYPE was adjusted using the scaled change in D. This resulted in an acceptable match between the change in simulated D and the expected change (Figure 10). Note that only changes were compared; the absolute value of denitrification losses simulated by Baltic HYPE was kept as calibrated.

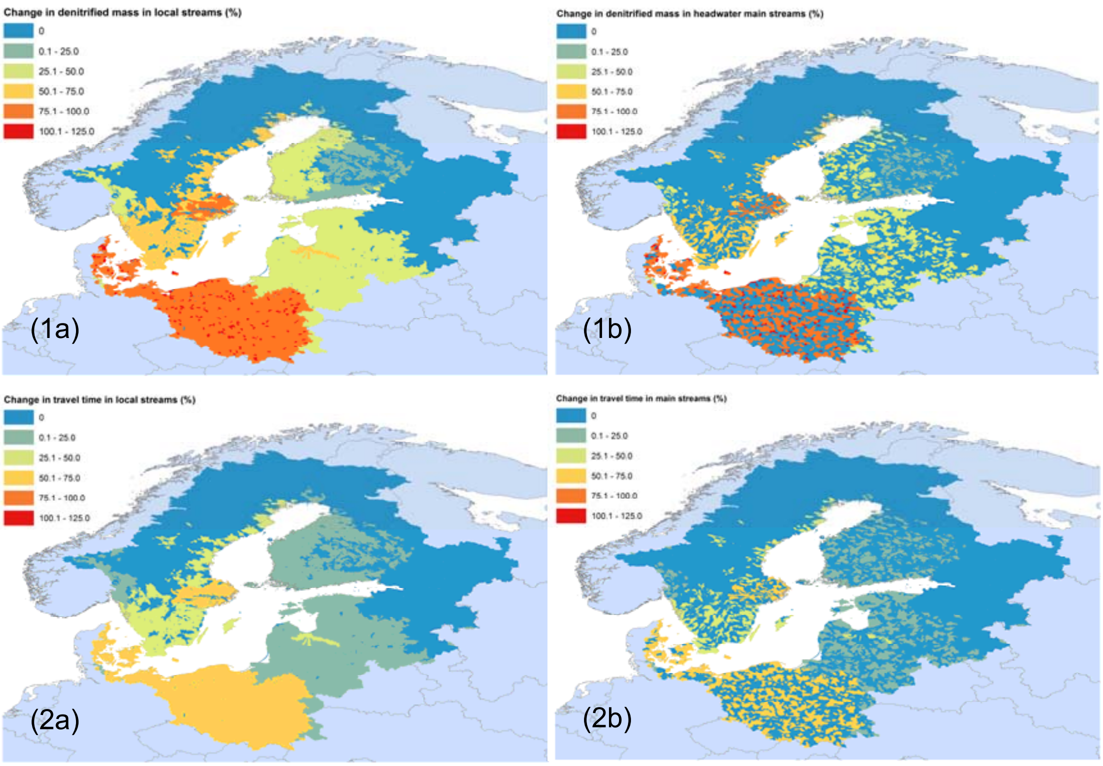

Figure 9. Calculated relative changes in percentage mass loss (1) and the average travel times (2) in local (a) and main (b) streams due to surface water-oriented measures

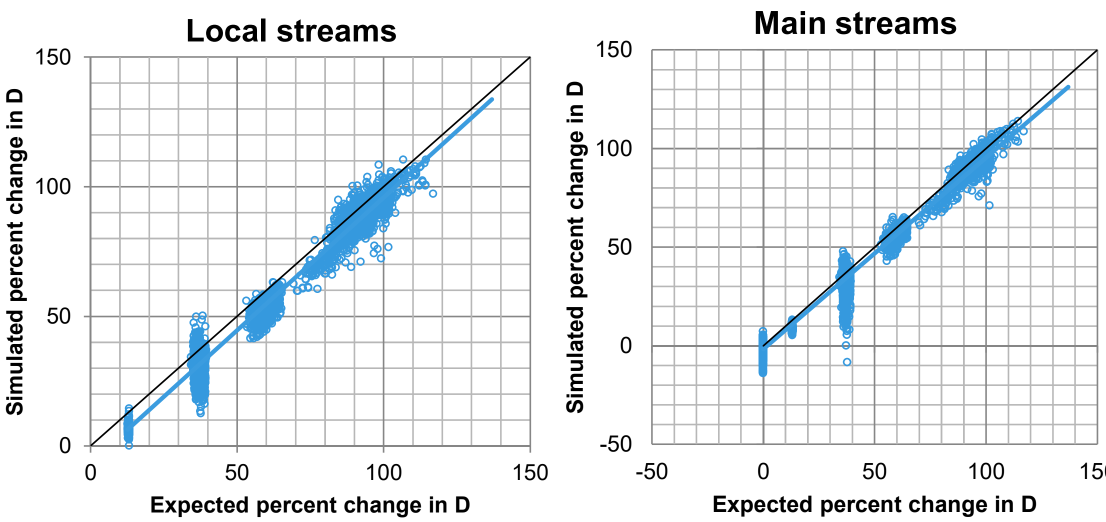

Figure 10. Comparison of relative changes in percentage mass loss through denitrification (D) simulated with Baltic HYPE and expected from reach-scale estimates in local streams and main streams.

3. Results and Discussion

3.1 Current nutrient loads

Figure 11 shows current total nitrogen loading rate for Baltic Sea region drainage basins as simulated with Baltic HYPE. Area-specific loading rates allow comparing the amount of nitrogen generated in the drainage basin over a unit area. The highest nitrogen loading rates occur in drainage basins in southern Sweden and Denmark. Several comparatively small drainage basins produce relatively high loading rates. Typically, those are drainage basins with a significant population density and agriculture as dominating land use. In terms of total load contribution to the Baltic Sea, however, the large river systems in the southern Baltic still play a dominating role. Similarly, Figure 12 shows total phosphorus loading rate for Baltic Sea region drainage basins. The highest phosphorus loading rate was simulated for drainage basins in southern part of the Baltic Sea region.

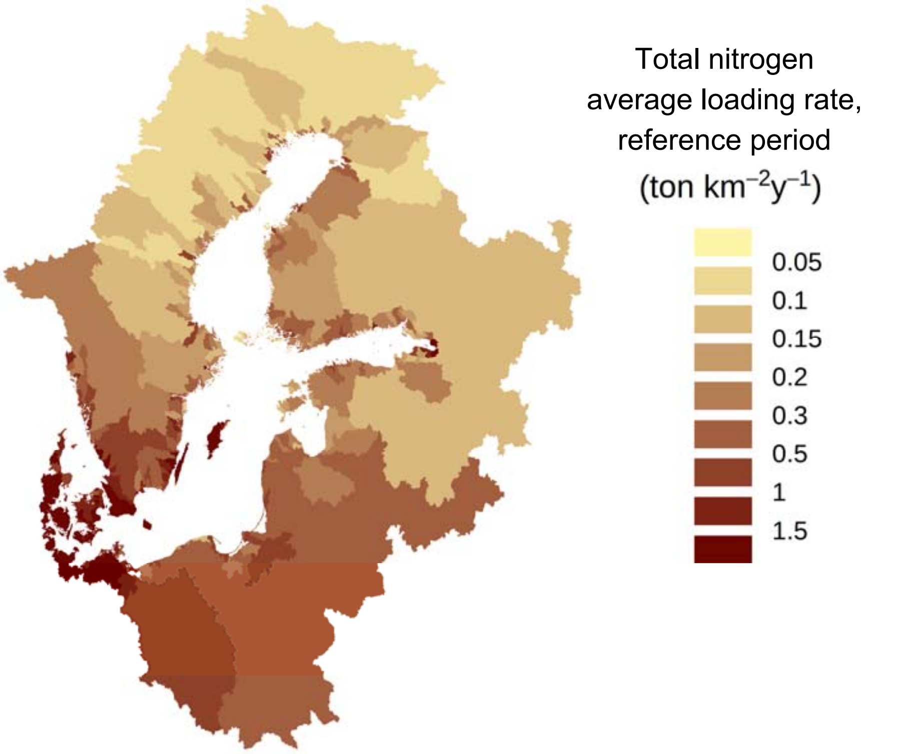

Figure 11. Average total nitrogen loading rate simulated for BSR drainage basins with Baltic HYPE. The load represents a long-term average load for the four selected climate models under the current climate.

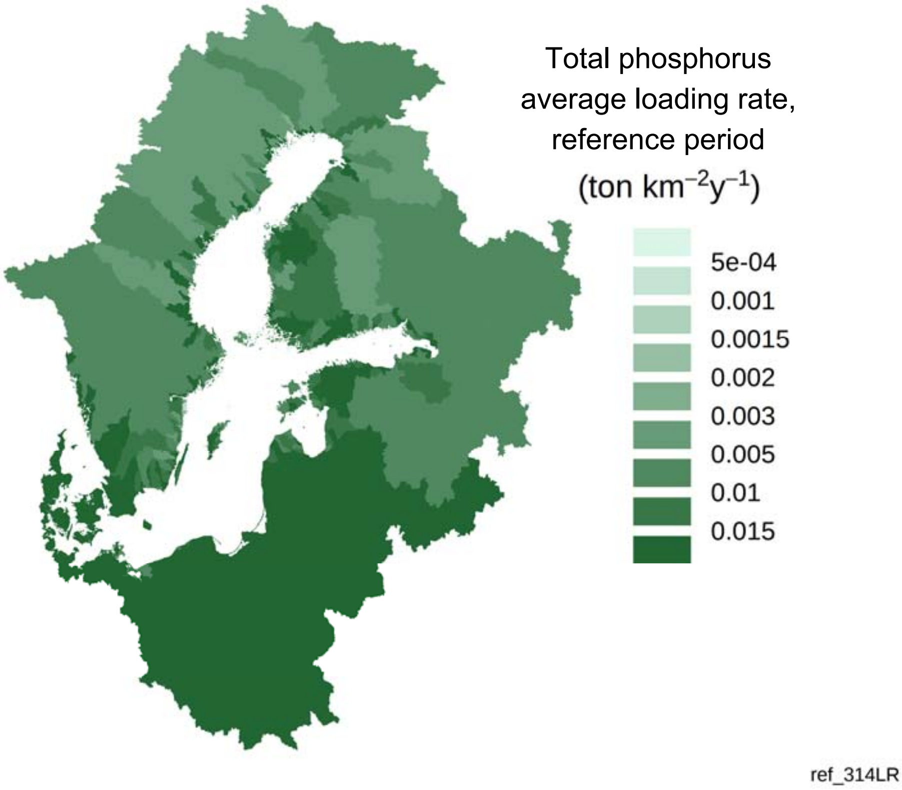

Figure 12. Average total phosphorus loading rate simulated for BSR drainage basins with Baltic HYPE. The load represents a long-term average load for the four selected climate models under the current climate.

The average simulated total nitrogen and total phosphorus loads were 540 thousand tons per year and 29 thousand tons per year, respectively (Figure 13 and Figure 14). The actual total nitrogen and total phosphorus loads discharged to the Baltic Sea with riverine flow as simulated with Baltic HYPE using observed climate data during 2000-2010 vary from year to year depending on the climate. The smallest loads were simulated for 2003 and the highest loads for 2007. Note that the changes simulated with Baltic HYPE are only related to variability in the observed climate. Nutrient sources such as land use and related anthropogenic activities or population with wastewater discharges were constant during this time period.

The averages simulated with Baltic HYPE were compared with those reported by HELCOM (2015) in their "Updated Fifth Baltic Sea pollution load compilation" as total riverine load (Figure 15). There is a very good match between Baltic HYPE and HELCOM (2015) for total phosphorus with only a 2% difference. For total nitrogen load, the difference is higher at 14% but still acceptable considering the difference in approaches as well as the uncertainty in the monitored values.

The loads from both Baltic HYPE and HELCOM (2015) were aggregated by Baltic Sea Basins (HELCOM, 2018, see Figure 16). Figure 17 and Figure 18 show total nitrogen and total phosphorus loads, respectively, delivered to individual Baltic Sea Basins with riverine flow. Baltic Proper receives by far the largest amount of nutrients among the Baltic Sea Basins (280 thousand tons of nitrogen and 16 thousand tons of phosphorus per year as simulated by Baltic HYPE). Gulf of Finland, receiving the second largest load, receives significantly smaller amount of nutrients (64 thousand tons of nitrogen and 4.2 thousand tons of phosphorus per year as simulated by Baltic HYPE).

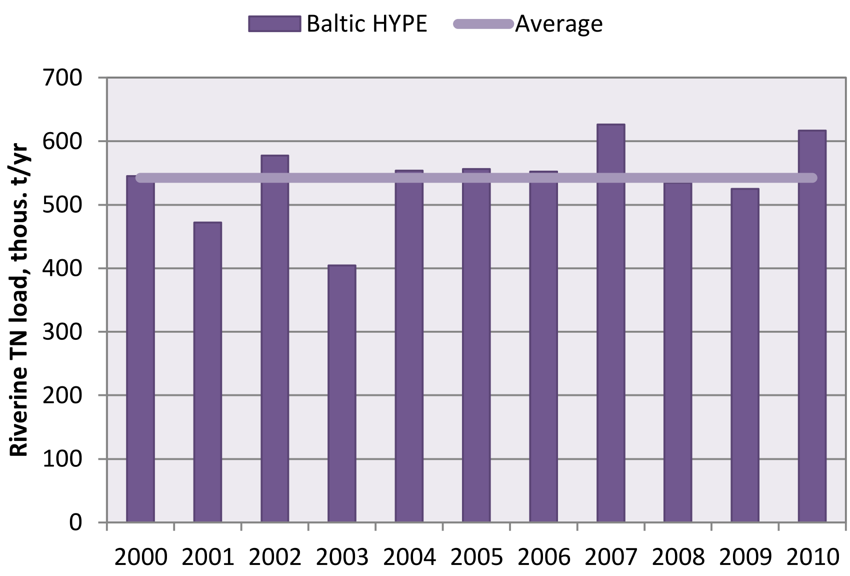

Figure 13. Total nitrogen (TN) load to Baltic Sea simulated with Baltic HYPE using observed climate data for the 2000-2010 period.

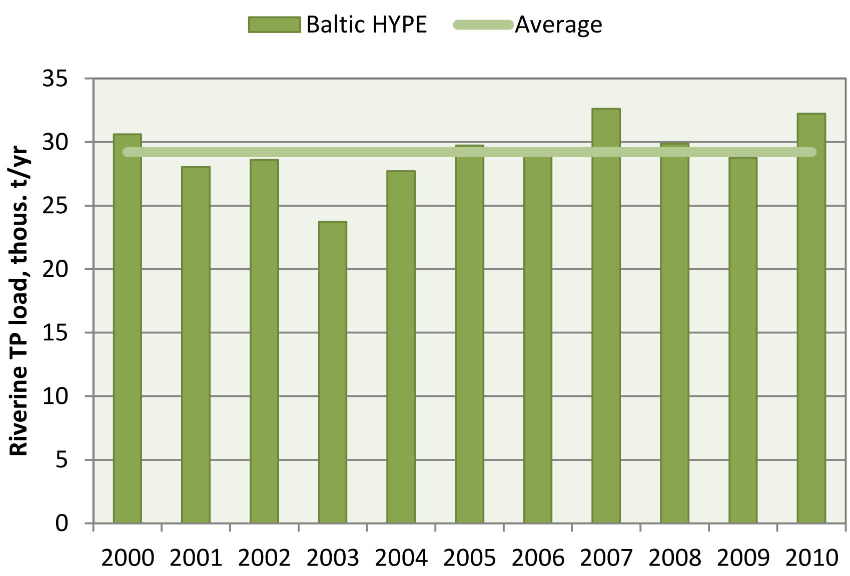

Figure 14. Total phosphorus (TP) load to Baltic Sea simulated with Baltic HYPE using observed climate data for the 2000-2010 period.

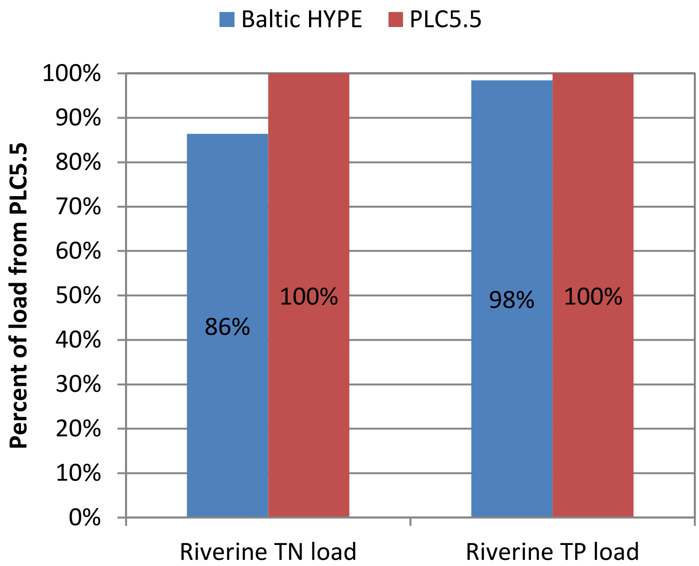

Figure 15. Comparison of average total nitrogen and phosphorus loads delivered to Baltic Sea Basins through river flow simulated with Baltic HYPE and from PLC5.5 (HELCOM 2015). Loads were averaged for years 2000-2010 and expressed relative to PLC5.5 loads.

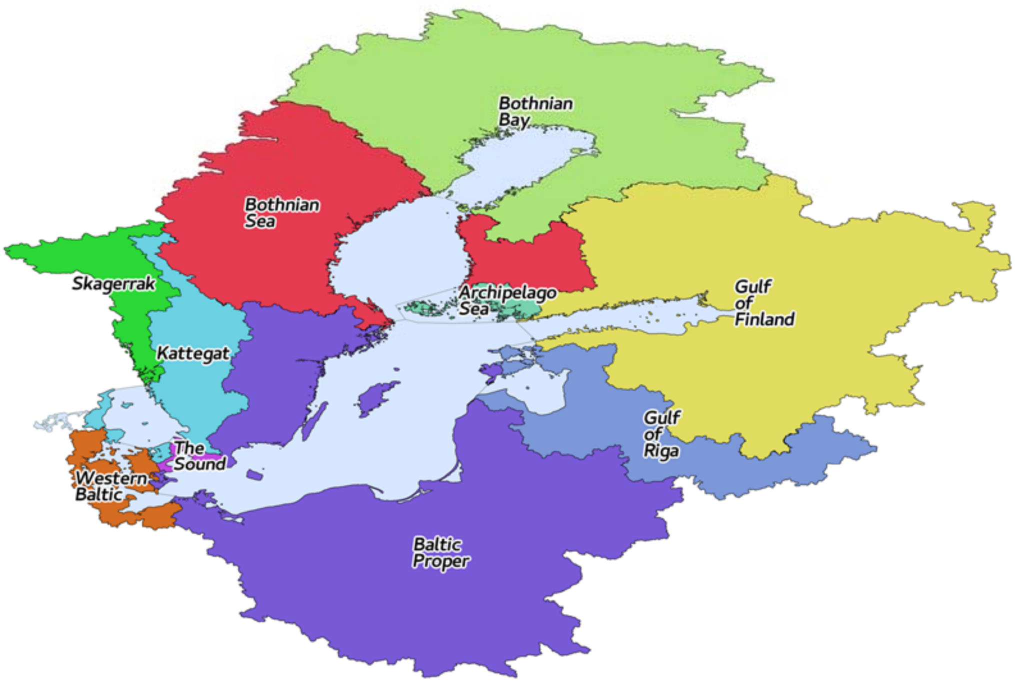

Figure 16. Baltic HYPE catchments aggregated to HELCOM Baltic Sea Basins for comparison with PLC5.5 (after HELCOM, 2018).

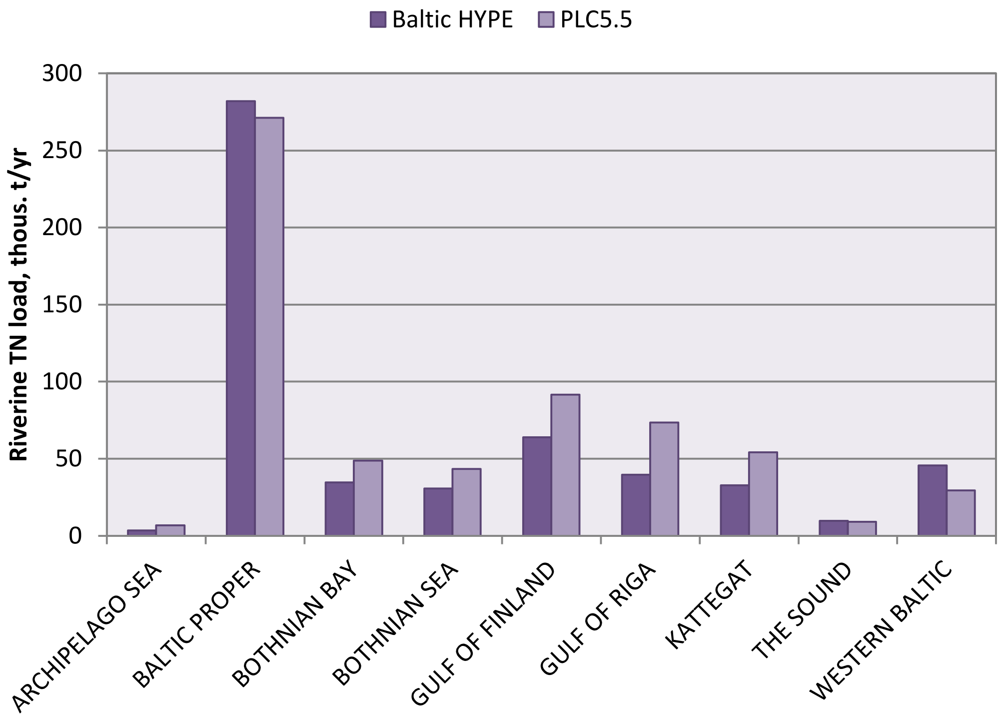

Figure 17. Comparison of average total nitrogen loads delivered to Baltic Sea basins through river flow simulated with Baltic HYPE and from PLC5.5 (HELCOM 2015). Loads are averaged for years 2000-2010.

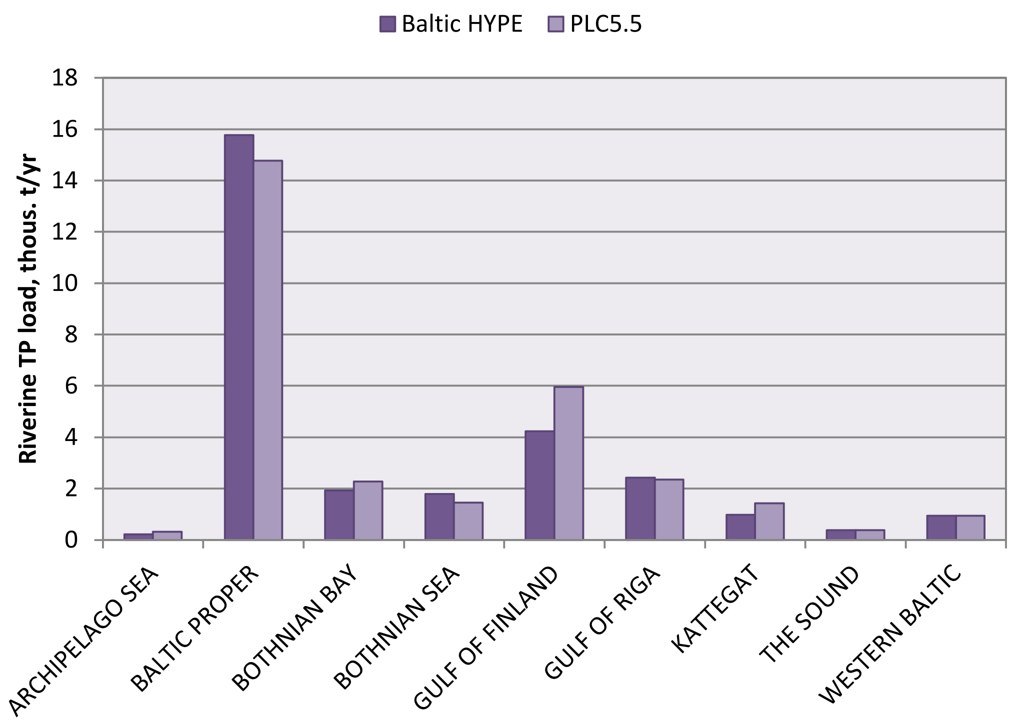

Figure 18. Comparison of average total phosphorus loads delivered to Baltic Sea Basins through river flow simulated with Baltic HYPE and from PLC5.5 (HELCOM 2015). Loads are averaged for years 2000-2010.

3.2 Impact of climate change by 2050s

3.2.1 Discharges

The changes in total outflow of fresh water to Baltic Sea averaged over the simulated 30-year periods are presented in Figure 19. The relative changes are shown with respect to the average of the four climate models (CM1 – CM4) for the current time period. The differences in the discharge to the Baltic Sea for the current period are minimal with variability due to the four climate models of about 2%. For the 2050s, the discharge is projected to increase between 4 and 25% with an average increase of 16%. This is significantly higher than the variability in the current climate due to the climate model selection. Figure 20 shows a relative change in the average runoff from 512 drainage basins that directly flow to Baltic Sea, i.e., at the outlet of these drainage basins to Baltic Sea. All drainage basins show an increase in the total outflow that varies from 4% to 30%.

Figure 21 shows current average specific runoff from individual catchments simulated with E-HYPE v.3.1.4. While shown as runoff per unit area, the runoff values are cumulative, i.e. they include not only runoff generated within the catchment itself but also any runoff coming in from the upstream catchments. Runoff values are therefore rather stable within river basins. Figure 22 shows a relative change in average runoff for all catchments in the Baltic Sea region. Most catchments show a significant increase in average flows.

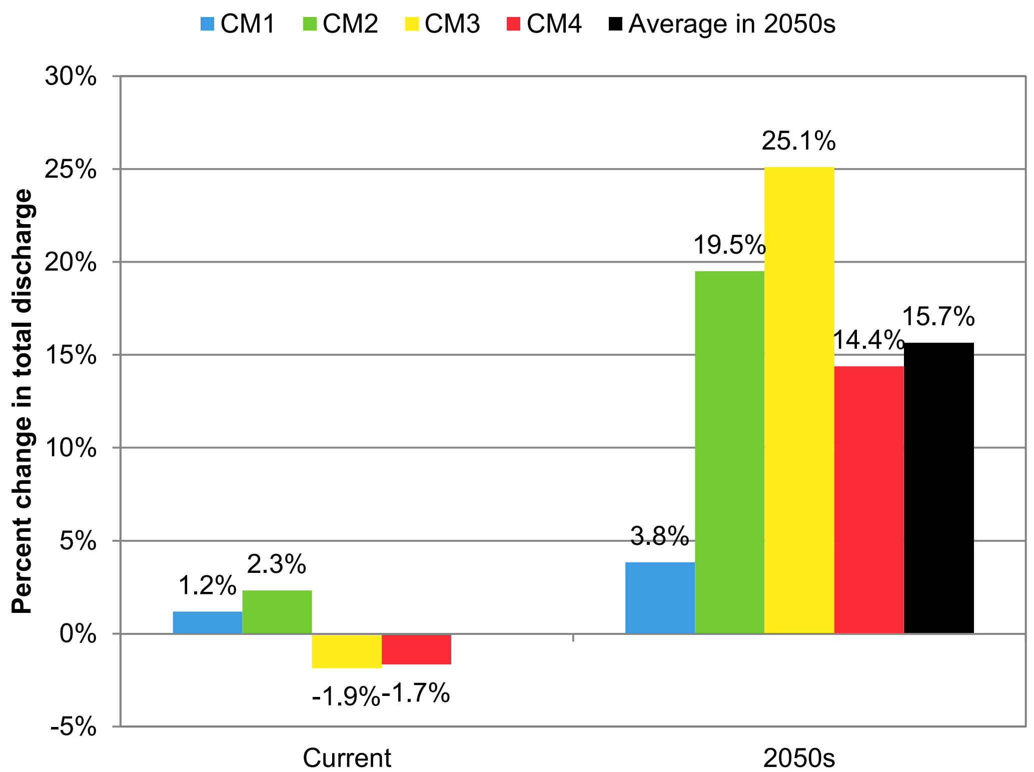

Figure 19. Variability in the total outflow to Baltic Sea due to the climate model selection. Relative change with respect to the average current discharge for four climate models shown.

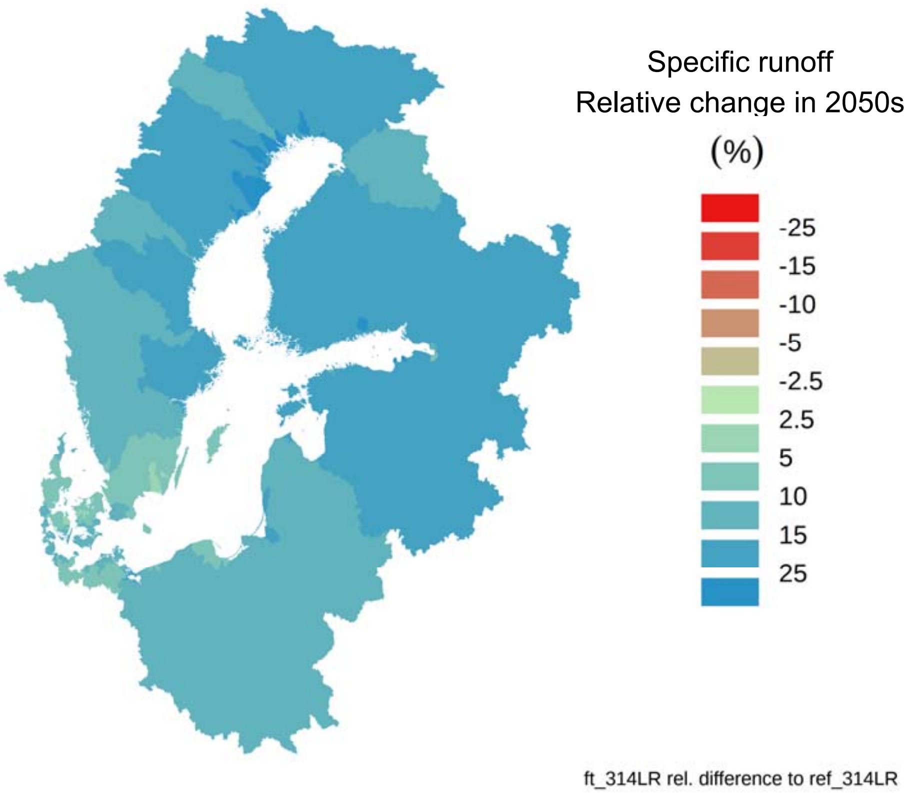

Figure 20. Relative change in average specific runoff due to a change in climate data by 2050s simulated for BSR drainage basins with Baltic HYPE. The change represents an average change for the four selected climate models.

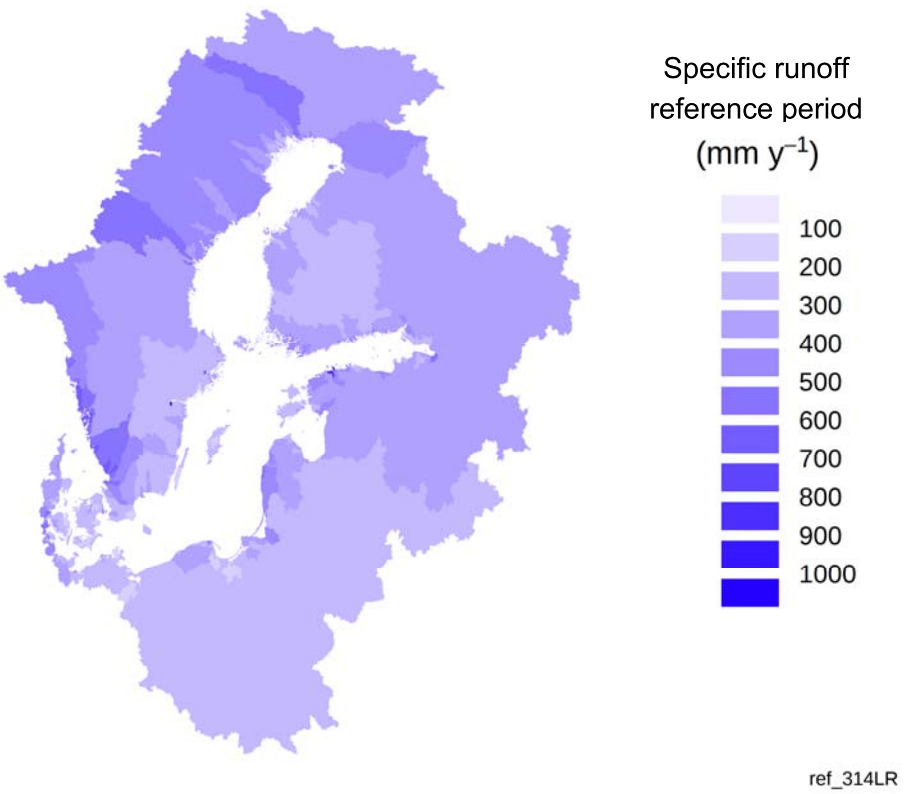

Figure 21. Specific runoff simulated at the outlet of each catchment in BSR with Baltic HYPE during the current period. The values represent an average of the four selected climate models.

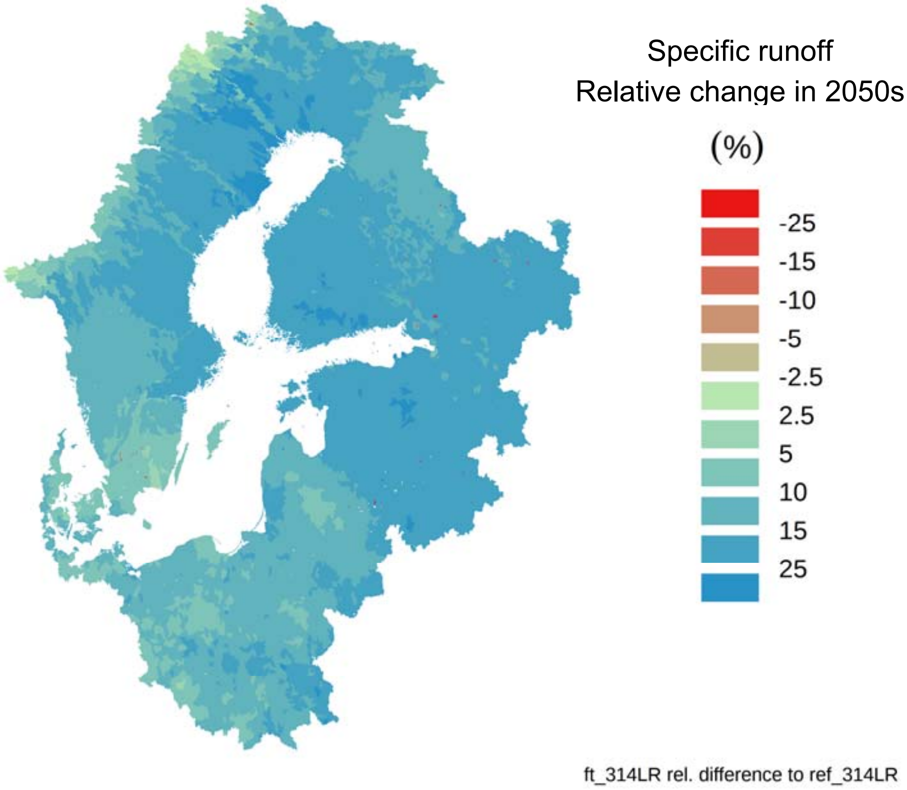

Figure 22. Relative change in specific runoff due to a change in climate data by 2050s simulated at the outlet of each catchment in BSR with Baltic HYPE. The change represents an average change for the four selected climate models.

3.2.2 Loads

Figure 23 and Figure 24 show the change in total loads due to the climate change as well as the uncertainty from the climate model for nitrogen and phosphorus, respectively. The loads are projected to increase by 8% and 14% on average for nitrogen and phosphorus, respectively, by 2050s. This increase is largely associated with the increased total outflow. Note that the average outflow of fresh water is expected to increase by 17%, i.e. more than either of the nutrient loads. This signifies that the average flow-weighted concentrations are expected to decrease.

The expected change for total phosphorus load is closer to the expected change in total outflow than the expected change for total nitrogen load. However, there is no clear relationship between the expected change in the outflow and the expected change in the nitrogen or phosphorus load. While one can identify a general relationship where the higher the change in outflow, the higher the change in the loads, the relationship itself is rather weak and there is a large variability among the individual drainage basins.

Figure 25 and Figure 26 show a relative change in the total phosphorus load and total nitrogen load, respectively, due to climate change as compared to the current average loads. Here the loads are presented as total loads from 512 drainage basins flowing directly to the Baltic Sea. Most drainage basins show an expected increase in both nitrogen and phosphorus loads. Several drainage basins in Poland, Germany, Denmark and Sweden show either a decrease (21 drainage basins) or a relatively minor change (72 drainage basins) in total nitrogen load. Only a few smaller drainage basins in Sweden and Denmark show a relatively minor change in total phosphorus load (23 drainage basins). A change was considered minor if the simulated value was within 2.5% from the current longterm average.

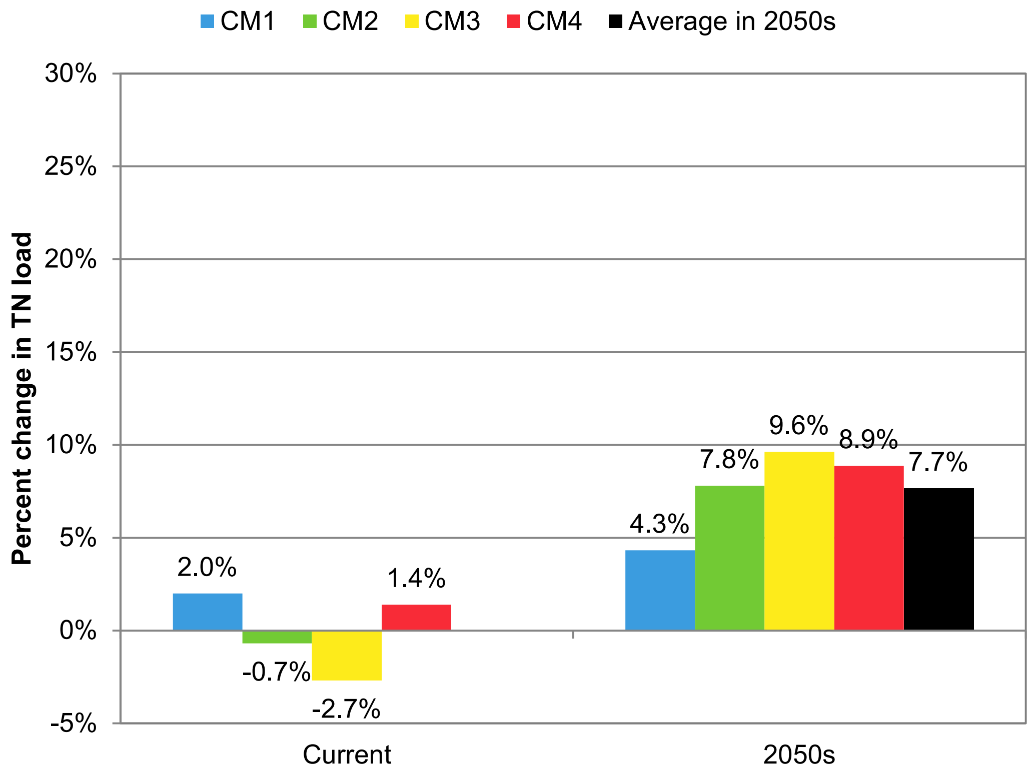

Figure 23. Variability in the total nitrogen load to Baltic Sea due to the climate model selection. The relative change with respect to the average current total nitrogen load from the four climate models shown.

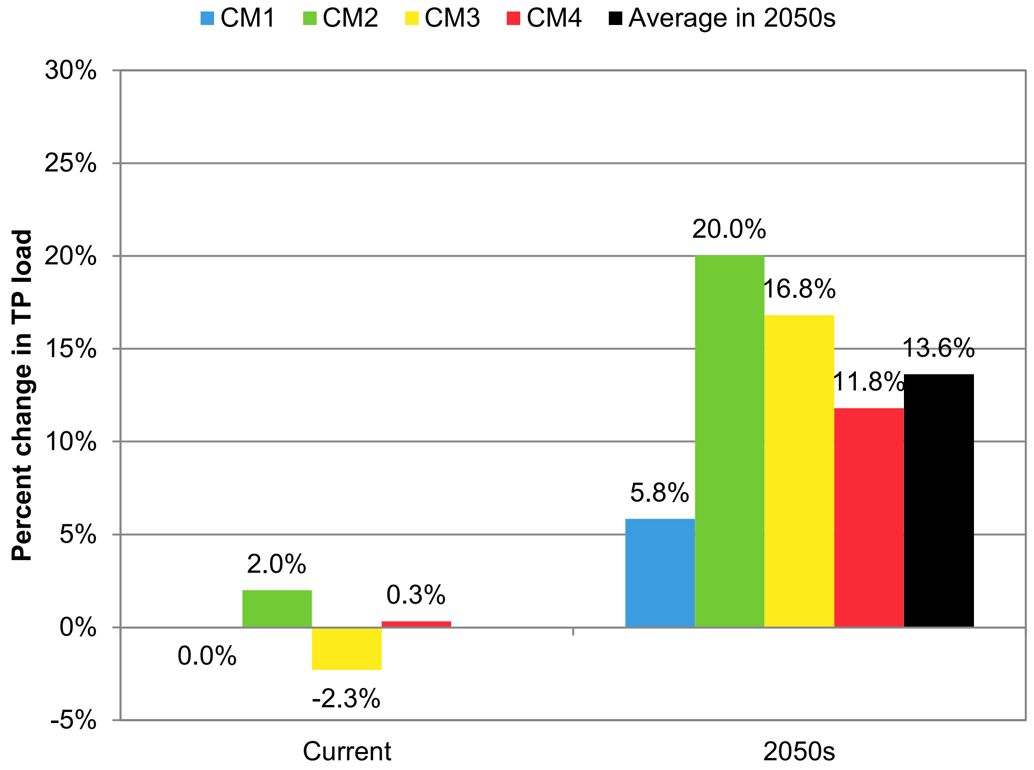

Figure 24. Variability in the total phosphorus load to Baltic Sea due to the climate model selection. The relative change with respect to the average current total phosphorus load from the four climate models shown.

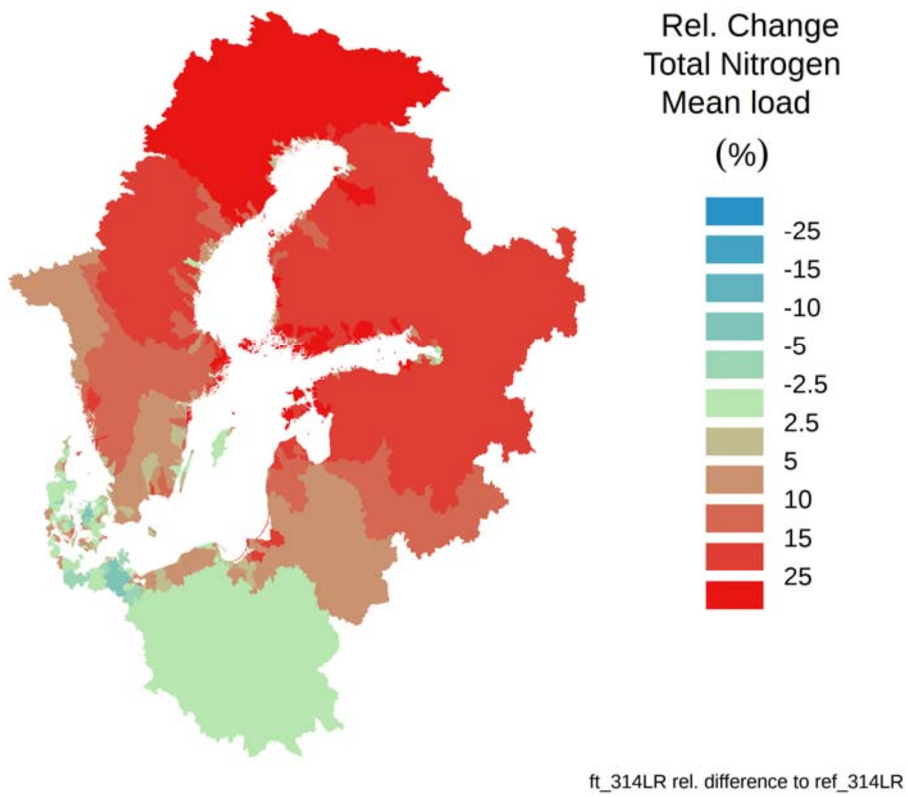

Figure 25. Relative change in average total nitrogen load due to a change in climate data by 2050s simulated for BSR drainage basins with Baltic HYPE. The change represents an average change for the four selected climate models.

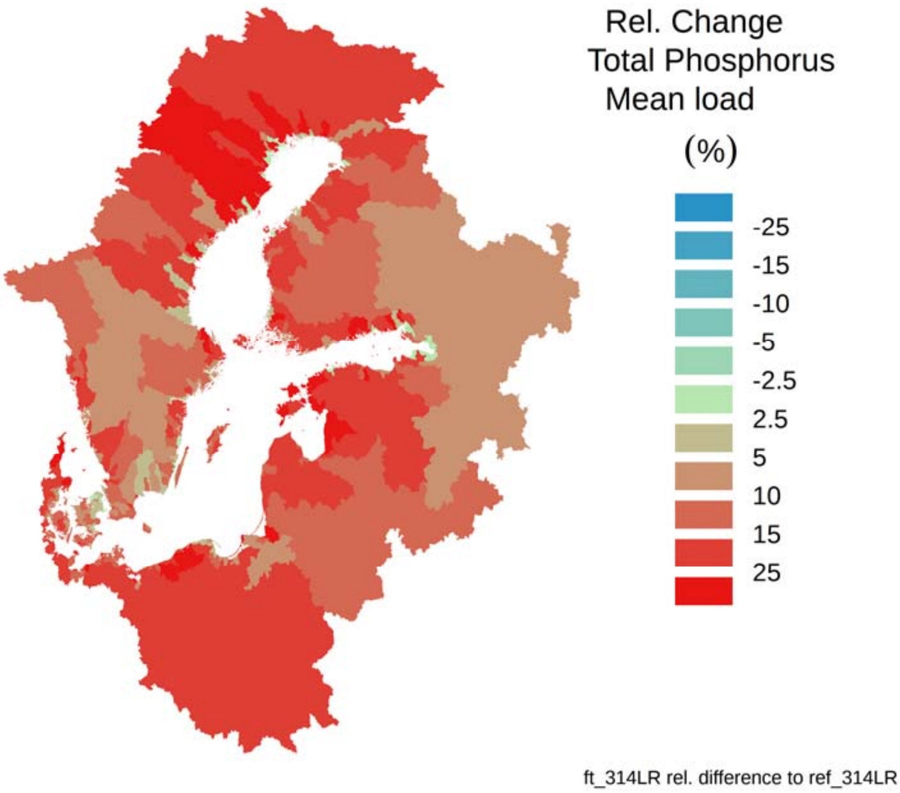

Figure 26. Relative change in average total phosphorus load due to a change in climate data by 2050s simulated for BSR drainage basins with Baltic HYPE. The change represents an average change for the four selected climate models.

3.2.3 Concentrations

Figure 27 and Figure 28 show average total nitrogen concentration and average total phosphorus concentration, respectively, in the outflow to Baltic Sea as simulated by Baltic HYPE for each climate model. The average nitrogen concentration is expected to decrease by 5% by 2050s. However, the variability is rather large also; one climate model results in 5% increase and another in 16% decrease. The average phosphorus concentration also shows a decrease by 2050s but the decrease is much smaller (1.4%) and much more consistent between the four climate models with all climate models projecting a change within 5% of the current average concentration. Note that this decrease in average concentrations does not result in a decrease in nutrient loads due to significant increase in total outflow to the Baltic Sea.

Figure 29 and Figure 30 show a relative change in total nitrogen concentration and total phosphorus concentration, respectively, at the outlet of the 512 drainage basins directly contributing to the Baltic Sea. There is an expected increase in total nitrogen concentration in the outflow from the drainage basins in the northern Baltic Sea area as well as in several smaller coastal drainage basins, but a major portion of the area shows a decrease or an insignificant change. Several drainage basins in the northern Sweden also show an expected increase in total phosphorus concentration in their outflow to Baltic Sea but even larger proportion of the area shows a decrease or an insignificant change.

Figure 31 and Figure 32 show current average total nitrogen and total phosphorus concentrations, respectively, simulated at the outlets of the individual catchments in the BSR. Figure 33 and Figure 34 show a relative change in the average nitrogen and phosphorus concentrations, respectively, for the same catchments. The areas in northern BSR where the nutrient concentrations are expected to increase have lower current average nutrient concentrations.

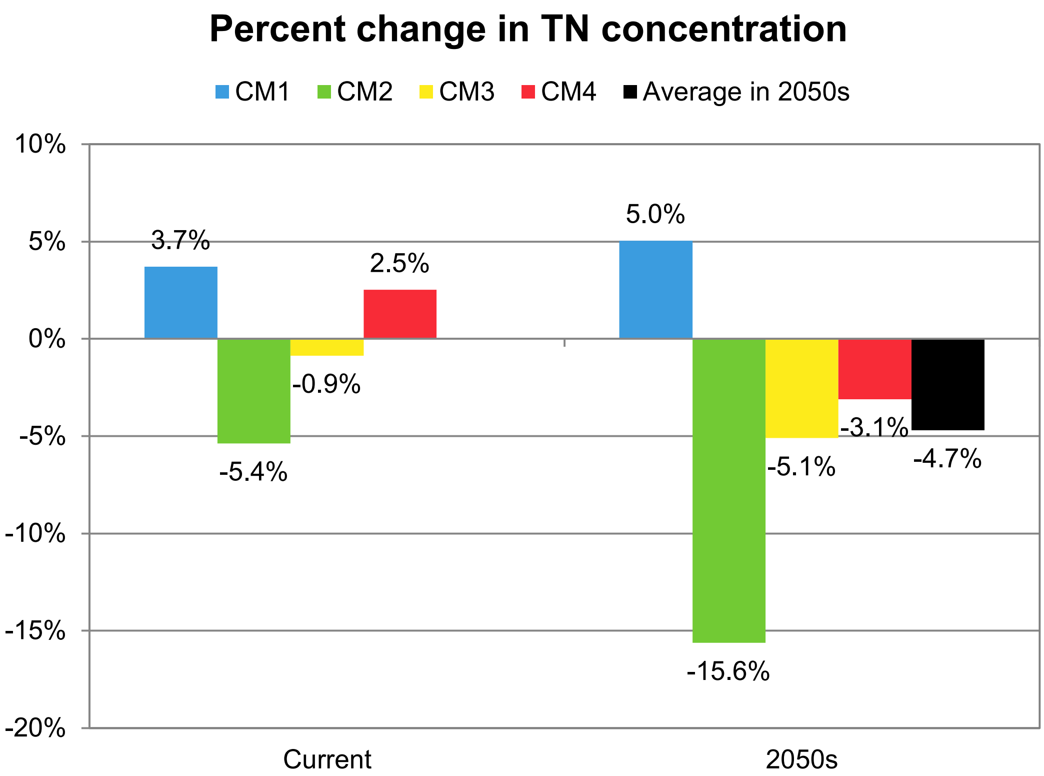

Figure 27. Variability in the average total nitrogen concentration in the outflow to Baltic Sea due to the climate model selection. Relative change with respect to the average current total nitrogen concentration shown as labels.

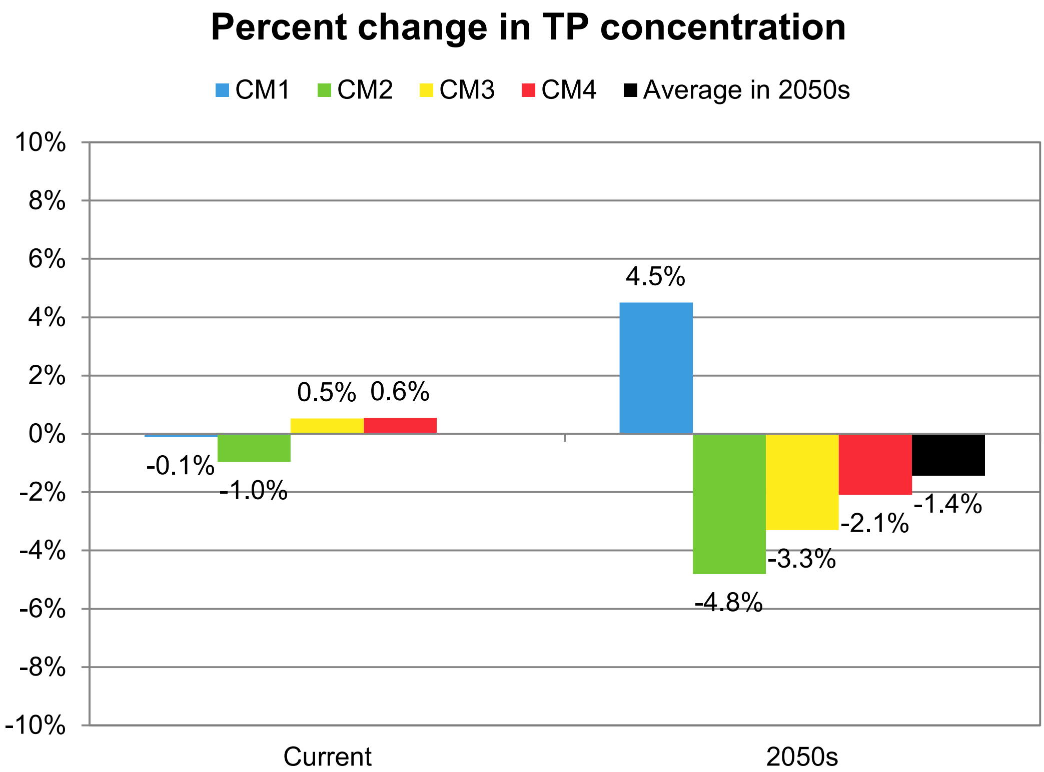

Figure 28. Variability in the average total phosphorus concentration in the outflow to Baltic Sea due to the climate model selection. Relative change with respect to the average current total phosphorus concentration shown as labels.

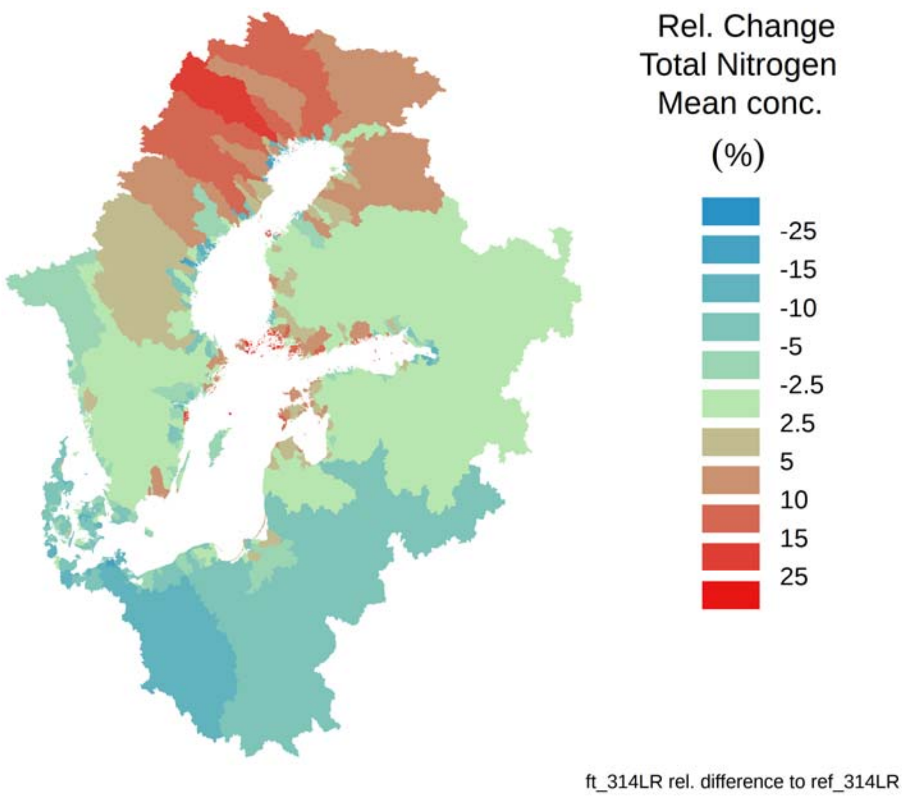

Figure 29. Relative change in average total nitrogen concentration at the outlet to Baltic Sea due to a change in climate data by 2050s simulated for BSR drainage basins with Baltic HYPE. The change represents an average change for the four selected climate models.

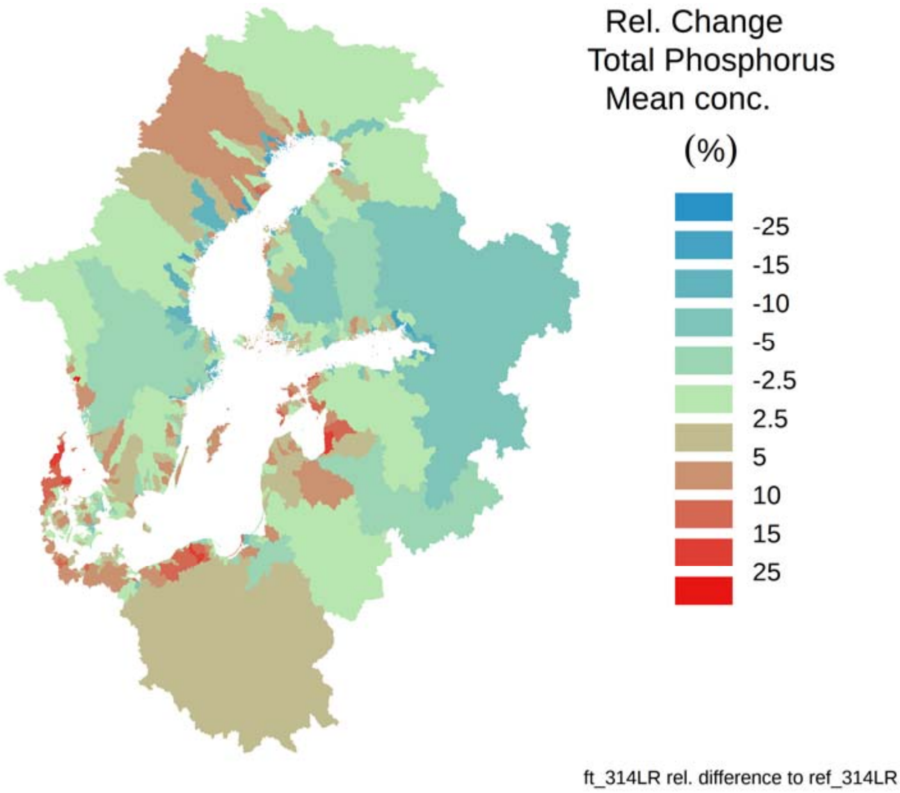

Figure 30. Relative change in average total phosphorus concentration at the outlet to Baltic Sea due to a change in climate data by 2050s simulated for BSR drainage basins with Baltic HYPE. The change represents an average change for the four selected climate models.

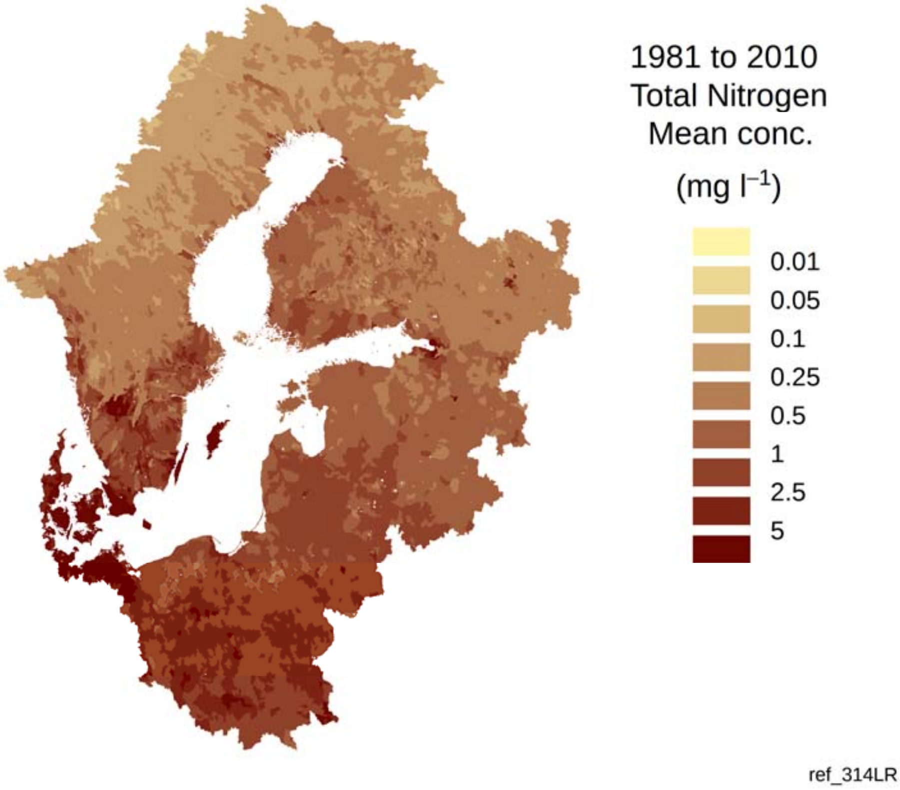

Figure 31. Current average total nitrogen concentration simulated at the outlet of each catchment in BSR with Baltic HYPE. The values represent average of the four selected climate models.

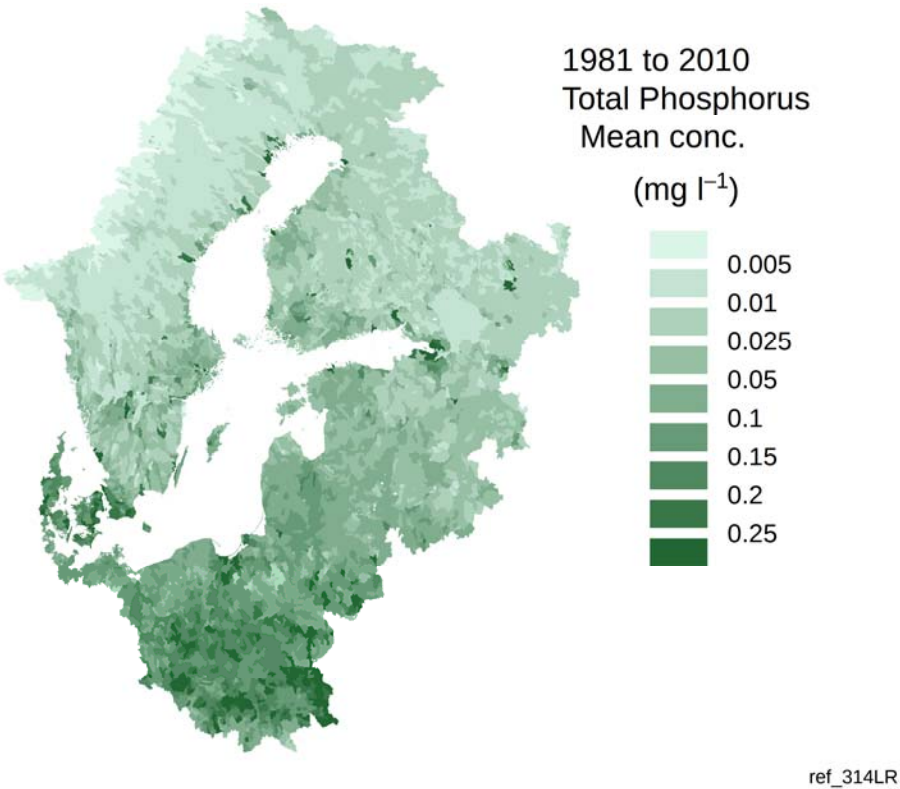

Figure 32. Current average total phosphorus concentration simulated at the outlet of each catchment in BSR with Baltic HYPE. The values represent average of the four selected climate models.

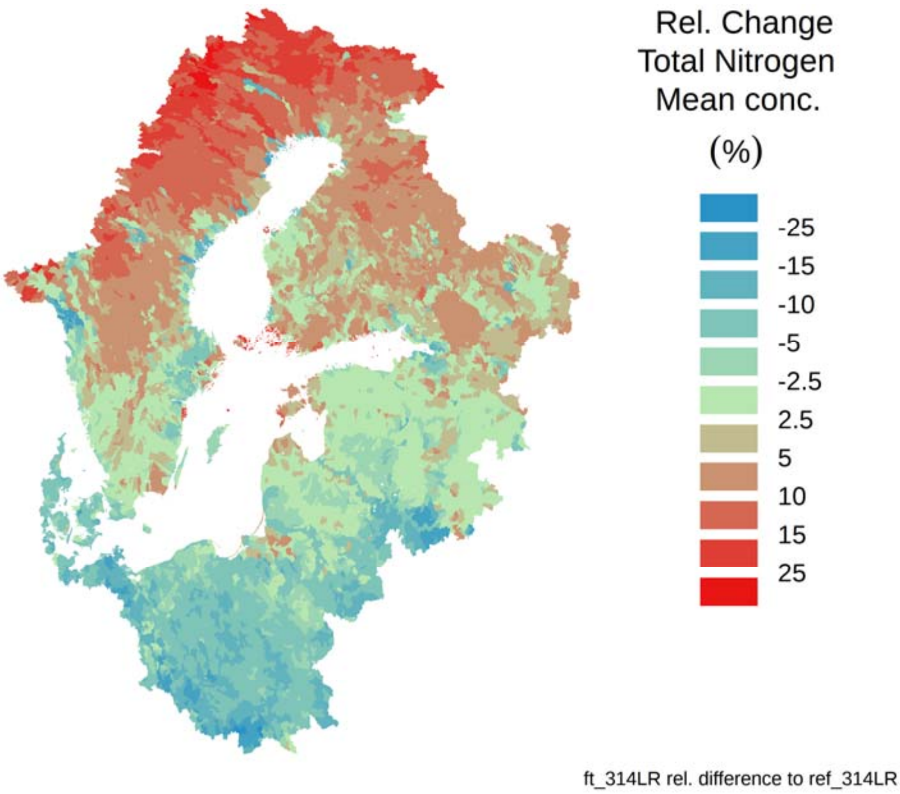

Figure 33. Relative change in average total nitrogen concentration due to a change in climate data by 2050s simulated at the outlet of each catchment in BSR with Baltic HYPE. The change represents an average change for the four selected climate models.

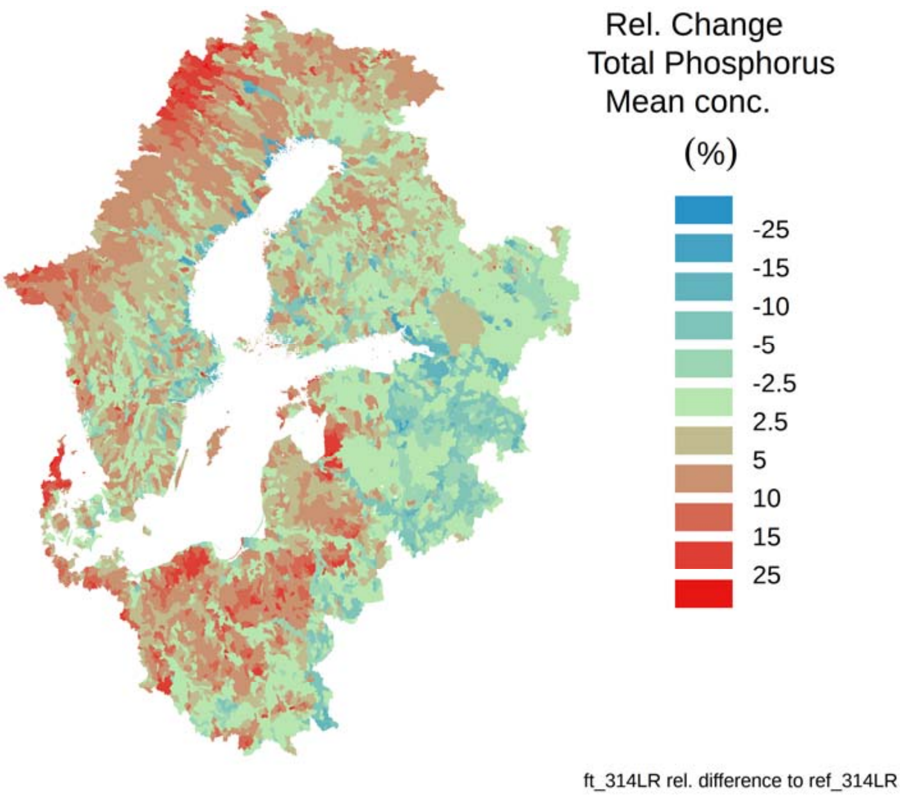

Figure 34. Relative change in average total phosphorus concentration due to a change in climate data by 2050s simulated at the outlet of each catchment in BSR with Baltic HYPE. The change represents an average change for the four selected climate models.

3.2.4 Annual Regime

Annual regimes illustrate averaged intra-annual dynamics of environmental variables over longer time periods. Here, we use them to compare regimes of discharge and riverine total nitrogen (TN) and total phosphorus (TP) concentrations and loads under current and projected (2050s) scenario conditions. All regimes shown here are based on weekly aggregates of Baltic HYPE model results. Each regime plot contains one line along with a transparent ribbon for the current period and another for the future period. Lines show the average values. Ribbons show a 25 % to 75 % percentile range to illustrate inter-annual variation. The size of the ribbon overlap between the current and the future periods is a soft measure of significance of the change signal. It allows relating the change between the periods to the inter-annual variation within each period. Averages and percentile ranges are calculated from the four model climate ensemble, i.e. all four climate model runs were concatenated into one long time series and averages and percentile ranges were calculated from this concatenated series. The percentile range thus represents a combination of climate variability within the 30-year period and climate model uncertainty.

Regimes are shown for eight rivers in seven HELCOM Baltic Sea Basins (Figure 35). The largest river from each Baltic Sea Basin was chosen. For Baltic Proper, the largest Baltic Sea Basin, Helgeå was also included as an additional river draining from south-eastern Sweden. No river basin was included for the Archipelago Sea Basin because of its similarity with neighbouring basins and the lack of a large river.

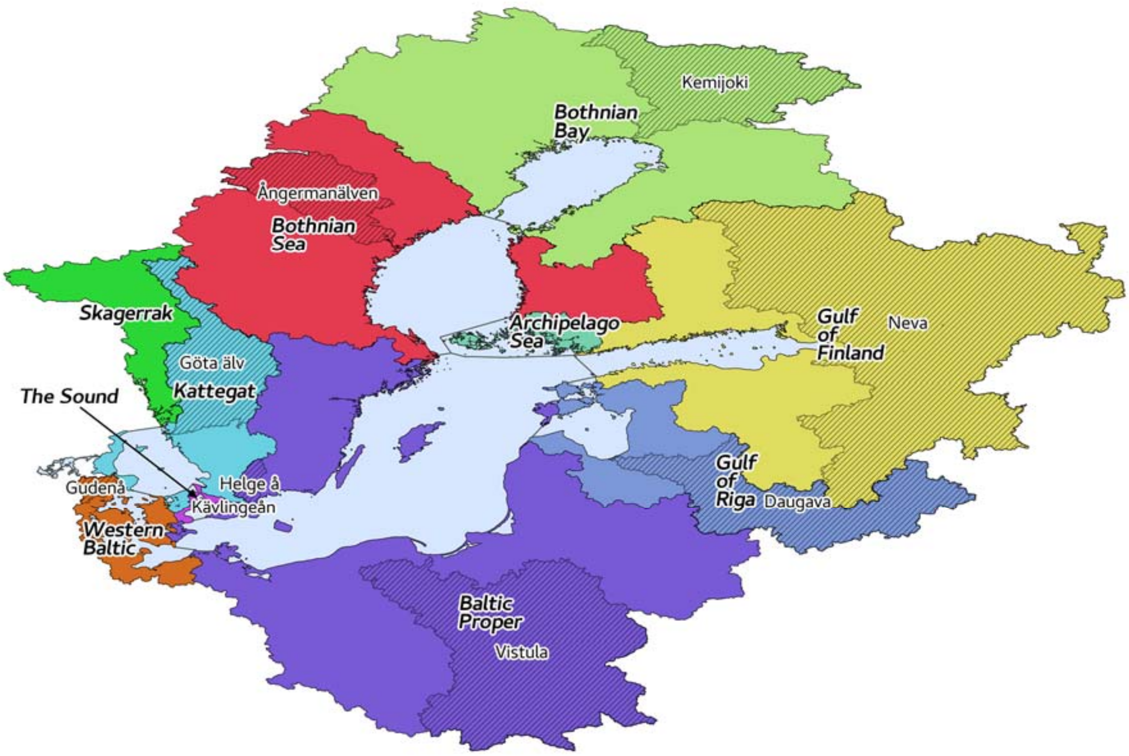

Figure 35. River basins selected for annual regime analysis (hatched overlays) for individual HELCOM Baltic Sea Basin (after HELCOM 2018).

Not all results are shown for all rivers, in order not to repeat similar results. Note that y-axes on all regime plots are scaled freely, i.e. not fixed from zero to a fixed maximum value. While this makes it harder to compare between plots quantitatively, it supports visual analysis of regime changes, which is the primary goal here.

Figure 36 and Figure 37 show the projected impact of climate change (2050s) on discharge, total nitrogen loads, and total phosphorus loads to the Baltic Proper for Vistula and Helgeå, respectively. Both rivers show pronounced seasonality with high flows during winter (Helgeå) and spring (Vistula) season. Seasonal high flows are projected to increase, with peak flows happening earlier for the 2050s impact period. Notably, total nitrogen loads in Vistula show less increase compared to total phosphorus loads and loads from Helgeå, so leaching here seems more limited during the early spring season. Daugava river (not shown), draining into the Gulf of Riga, exhibits a similar flow and change pattern as Vistula.

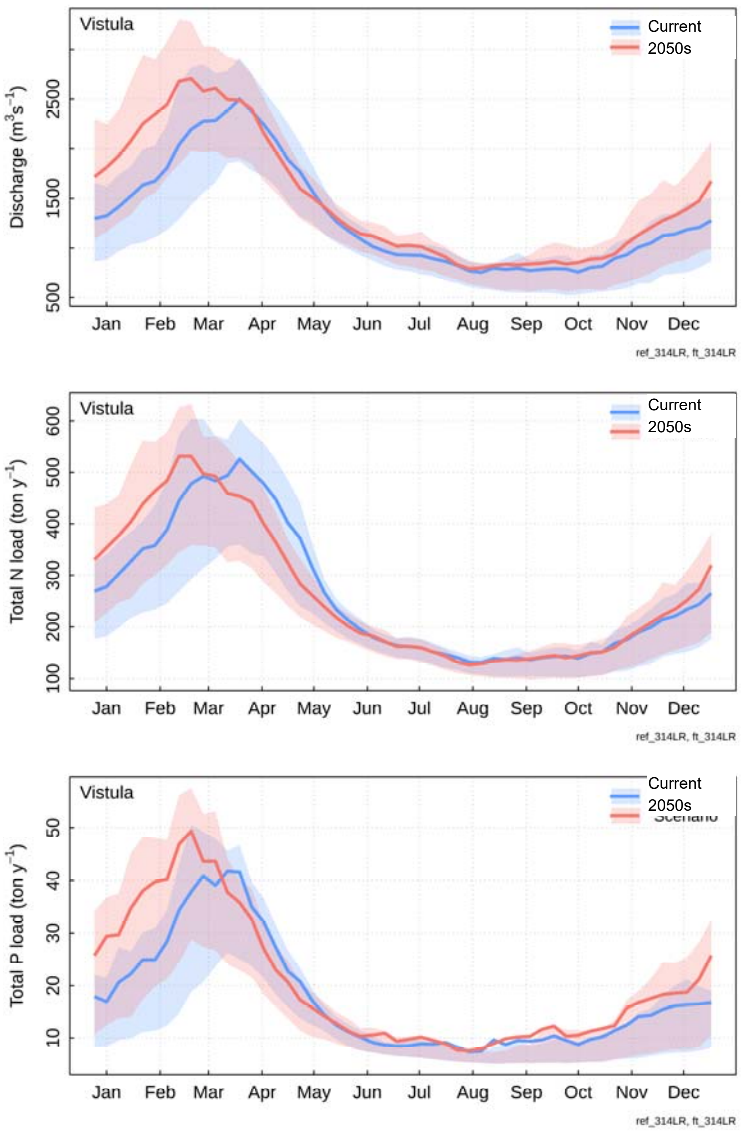

Figure 36. Annual regimes for Vistula under the current and 2050s climate conditions for discharge, total nitrogen (N), and total phosphorus (P) loads.

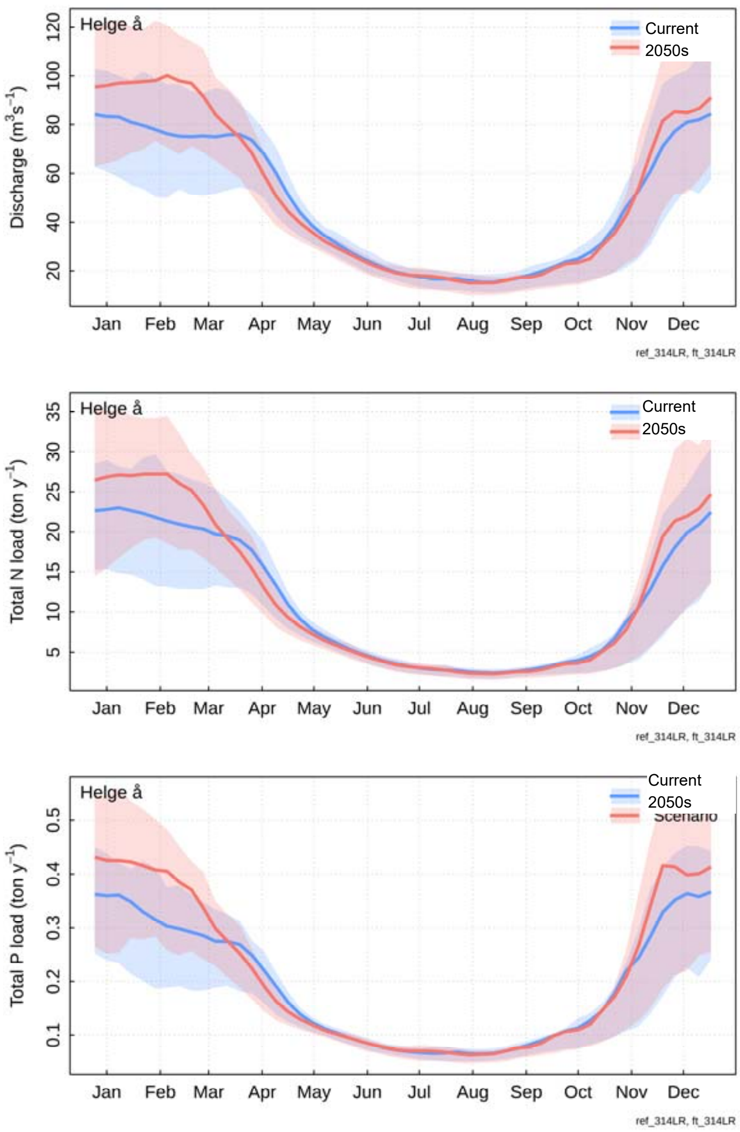

Figure 37. Annual regimes for Helgeå under the current and 2050s climate conditions for discharge, total nitrogen (N), and total phosphorus (P) loads.

Discharges into the Gulf of Finland from river Neva, the largest river to drain into the Baltic Sea Basin (2800 km^2), show a regime heavily modified by large lakes (Lake Ladoga most downstream) and regulation (Figure 38). High flows occur during summer with sharp transitions into winter low flows. Under current regulation assumptions, flows are projected to increase year-round, and total loads follow the same trend.

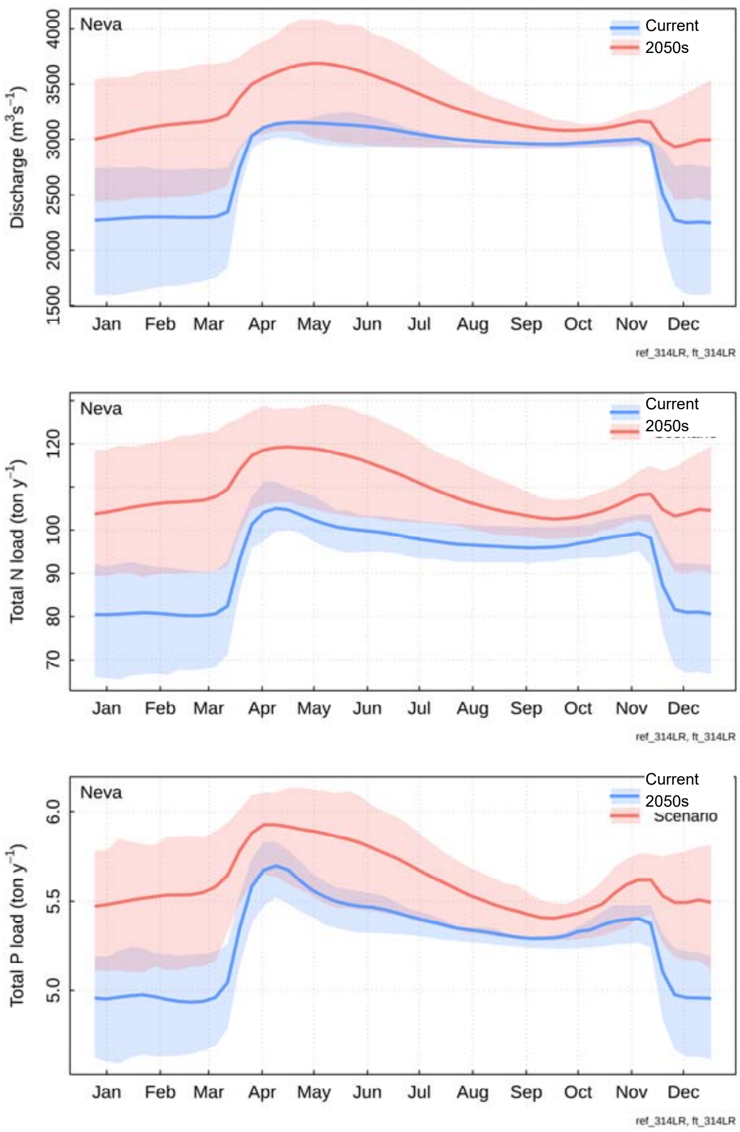

Figure 38. Annual regimes for Neva under the current and 2050s climate conditions for discharge, total nitrogen (N), and total phosphorus (P) loads.

Climate change impacts on flows and loads form northern rivers with mainly forested catchments into Bothnian Bay and Bothnian Sea are shown for the Kemijoki (Figure 39), with results for Ångermanälven looking similar. Flow here is very much dominated by snow melt peak flows during late spring/early summer, and overall volumes are projected to increase along with an earlier onset and peak time. Loads follow the pattern and are generally much lower than those from more agriculturally dominated southern rivers.

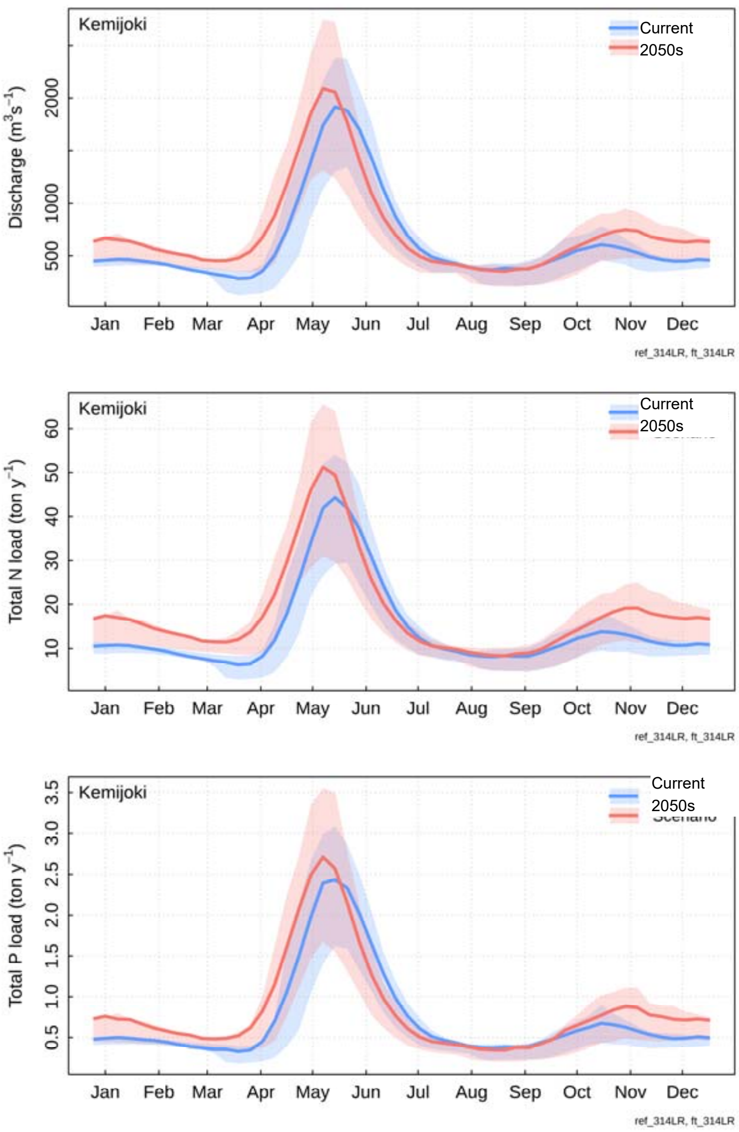

Figure 39. Annual regimes for Kemijoki under the current and 2050s climate conditions for discharge, total nitrogen (N), and total phosphorus (P) loads.

River Gudenå draining to the Western Baltic Basin shows annual regimes and their changes similar to those observed in Helgeå. Projected flows and loads increase during winter high flows. A change in peak timing is not visible because seasonal snow cover plays a minor role in the western Baltic already today.

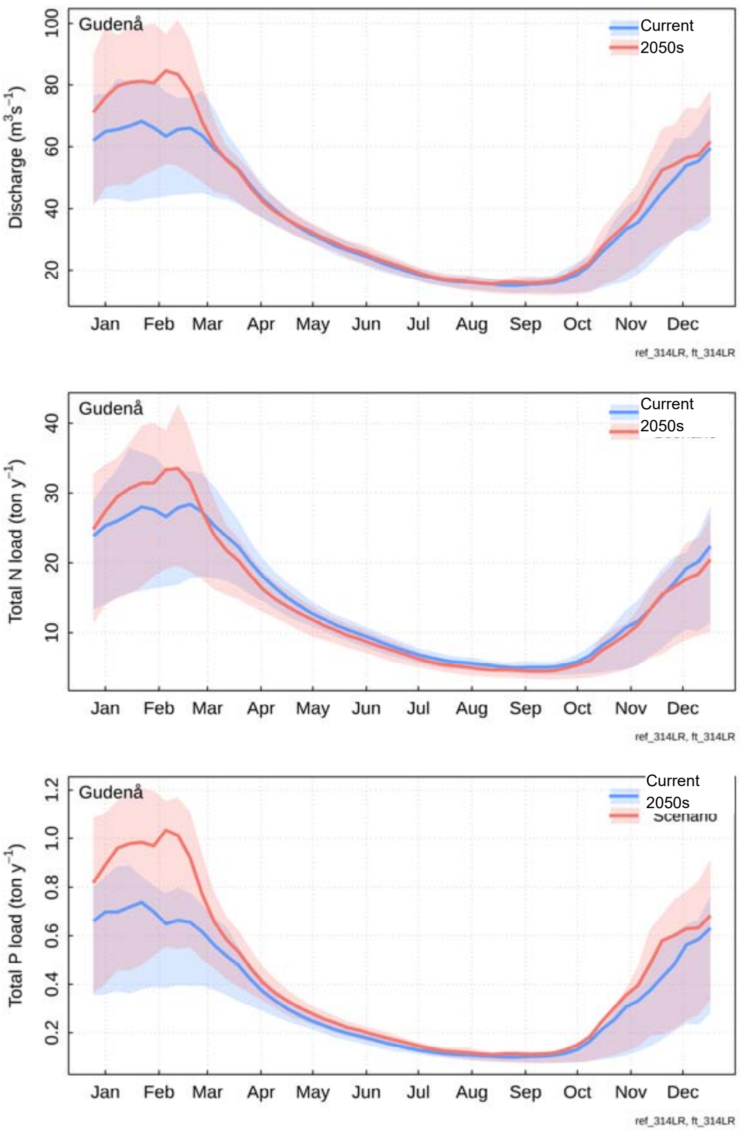

Figure 40: Annual regimes for the Gudenå under the current and 2050s climate conditions for discharge, total nitrogen (N), and total phosphorus (P) loads.

3.2.5 Sources of Nutrients

Nutrient loads to the Baltic Sea originate from multiple sources. Contributions of different sources from the Baltic Sea region through riverine loads as simulated by Baltic HYPE are shown for nitrogen (Figure 41) and phosphorus (Figure 42) under current (reference) and 2050s climate change conditions. The largest source for both nitrogen and phosphorus loads are diffuse agricultural sources. For nitrogen, the next largest source group is forests. It accounts for less than half of the agricultural contribution. For phosphorus, wastewater treatment plants contribute nearly as much as agricultural sources with the remaining sources being much less significant.

There is some variation in simulated loads due to variability in the climate models both during current and 2050s scenario time periods. This variation is most pronounced for agricultural source contributions to phosphorus loads. The differences in contributions simulated from the individual climate models could be explained by changing mobilisation through surface erosion, and the uncertainty in climate model change projections of extreme precipitation event patterns.

As a result of climate change, contributions from some sources increase beyond the range of climate model variation, highlighting the need for adaptation measures to counter the adverse effect of climate change on nutrient loads. Notably, the load contribution from agriculture for total nitrogen is not predicted to change at the Baltic Sea region level. Baltic HYPE actually predicts a decrease in agricultural total nitrogen loads from the south-western half of the Baltic Sea region, while the contributions increase from other parts. An explanation for this pattern could be (a) that the temperature increase in this area improves plant uptake due to the longer growth season, and (b) that the combination of low to moderate precipitation increases with higher temperatures result in more reduction of nitrogen during subsurface and instream transport.

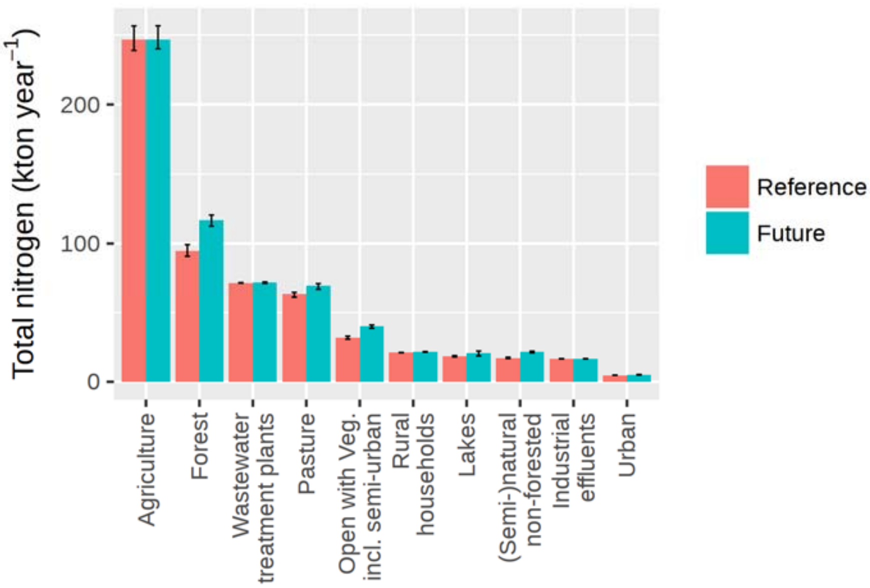

Figure 41: Grouped source contributions to TN loads from the Baltic Sea region under reference and future conditions. The values represent the average of the four selected climate models. Error bars show the range due to variability in the climate models. Lakes category represents internal loading.

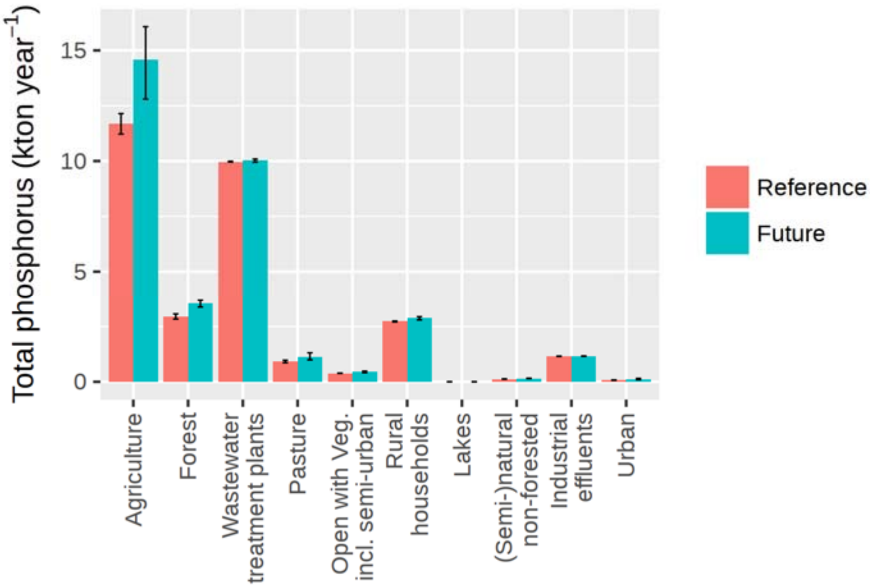

Figure 42: Grouped source contributions to TP loads from the Baltic Sea region under reference and future conditions. The values represent an average of the four selected climate models. Error bars show the range due to variability in the climate models. Lakes category represents internal loading.

3.3 Impact of SSPs

The following sections describe changes in discharges and nutrient loads and concentrations due to socio-economic changes represented by the three SSPs (SSP1, SSP2, and SSP5). The SSPs represent a range of possible developments in society by 2050s. Since these scenarios focus on outlook for 2050s, they were simulated with 2050s climate using the four-model climate ensemble discussed in Section 2.3 Climate Models (p. 6).

3.3.1 Discharges

Discharges to Baltic Sea are not expected to change significantly due to socio-economic assumptions simulated with Baltic HYPE. Most of the assumptions associated with SSPs affect only nutrients with the exception of the land use change. The projected impacts are within 1% with climate in 2050s having the most significant influence over the expected discharges to Baltic Sea (Figure 43).

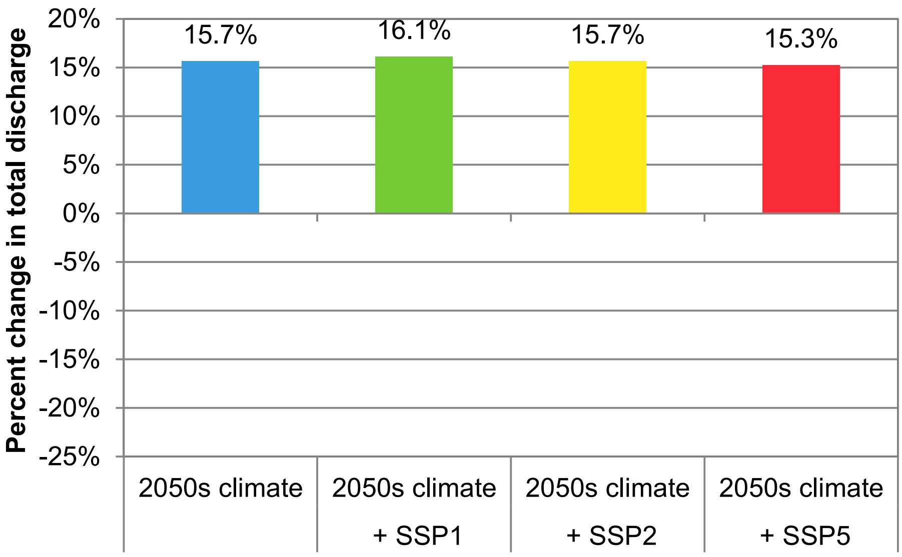

Figure 43. Change in the total outflow to Baltic Sea due to the SSPs. Relative change with respect to the average current discharge for four climate models shown.

3.3.2 Loads

Figure 44 and Figure 45 show relative changes in total nitrogen and phosphorus loads, respectively, for different socio-economic assumptions with respect to the average current load. The projected change is 8% and 14% for phosphorus and nitrogen loads, respectively, if only climate change is considered but other sources remain the same as in present. The different assumptions in individual SSPs result in very different nutrient loads, especially for nitrogen.

Under SSP1 the nitrogen and phosphorus loads decrease by 19% and 6%, respectively, relative to the current loads despite the climate change impacts being also included in the simulations. On the other hand under SSP5 the nitrogen and phosphorus loads increase by 11% and 10%, respectively, relative to the current loads. This is a very significant result that highlights the importance of the societal development and management of nutrients at their sources.

The impacts from SSPs are not evenly distributed across the Baltic Sea region (Figure 46 - Figure 57). Northern Sweden shows sustained increases in total nitrogen and phosphorus loads for all SSPs. As the assumptions progress from the sustainable development in SSP1 to fossil-fuelled development in SSP5, more drainage basins switch from showing a decrease in nutrient loads as compared to the current loads to showing an increase in nutrient loads.

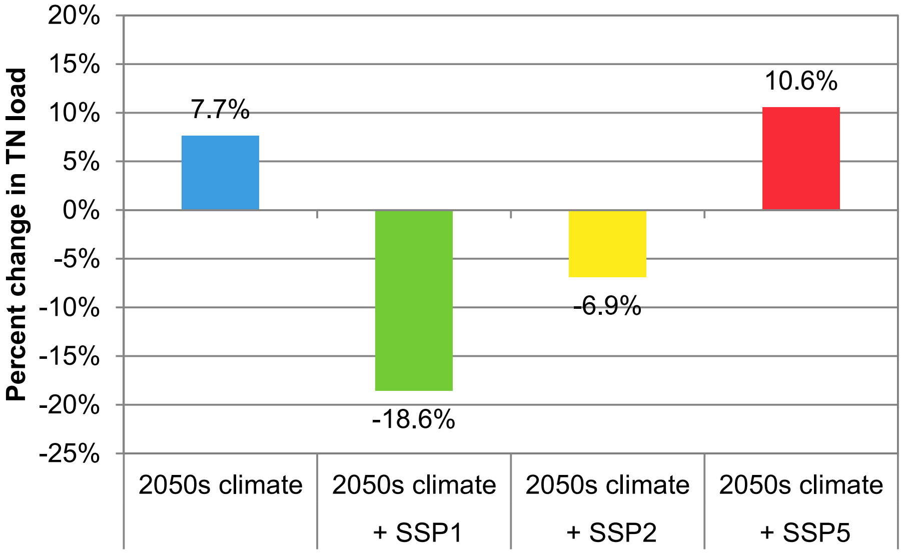

Figure 44. Change in the total nitrogen (TN) load to Baltic Sea due to the SSPs. Relative change with respect to the average current load for four climate models shown.

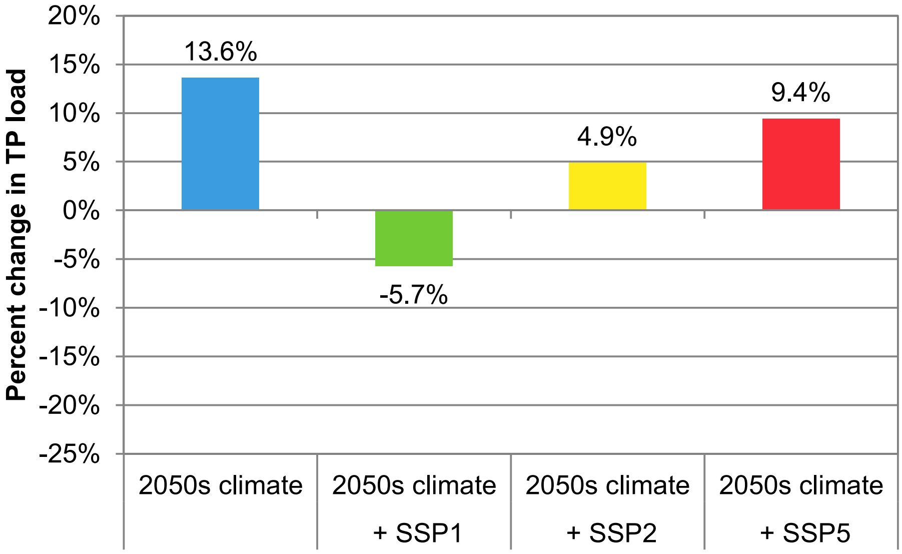

Figure 45. Change in the total phosphorus (TP) load to Baltic Sea due to the SSPs. Relative change with respect to the average current load for four climate models shown.

Figure 52 shows relative changes in total nitrogen loads with respect to the current loads for the three SSPs in 2050s as well as 2050s climate with current sources summarized by HELCOM Baltic Sea Basins. The largest variability is observed in Archipelago Sea where the impact fluctuates between 24% reduction for SSP1 and 62% increase for SSP5. Bothnian Bay is a notable exception in showing an increase in nitrogen loads also for SSP1, although a very small increase (3%). The smallest variability was simulated for Gulf of Riga where the impact fluctuates between 6% reduction for SSP1 and 12% increase for SSP5.

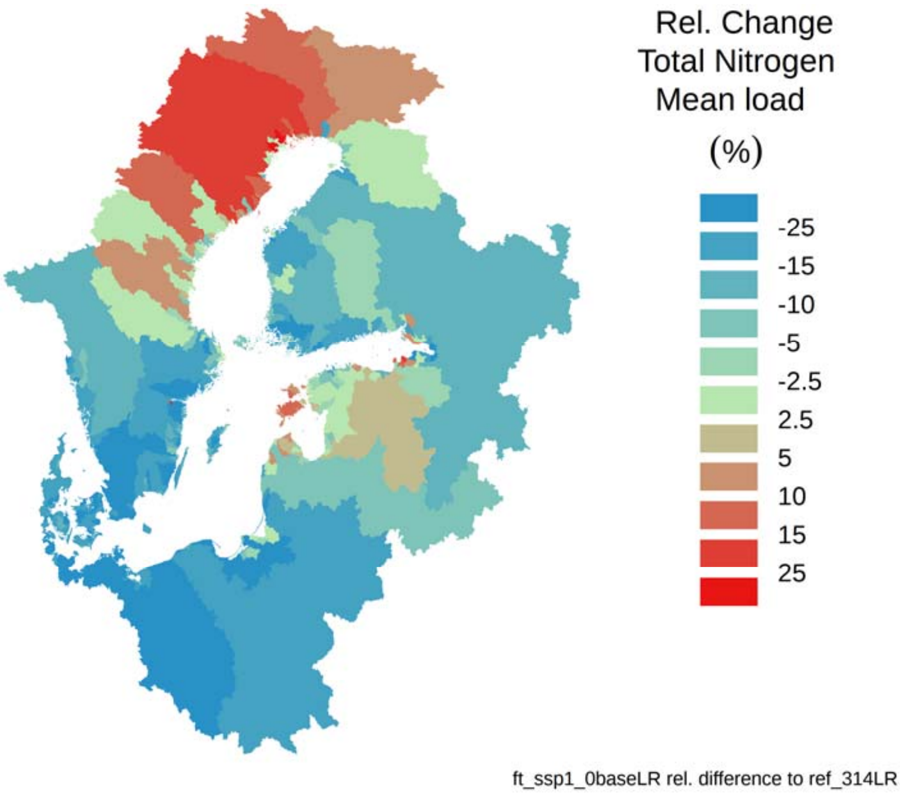

Figure 46. Relative change in average total nitrogen load due to SSP1 in 2050s simulated for BSR drainage basins with Baltic HYPE. The change represents an average change for the four selected climate models.

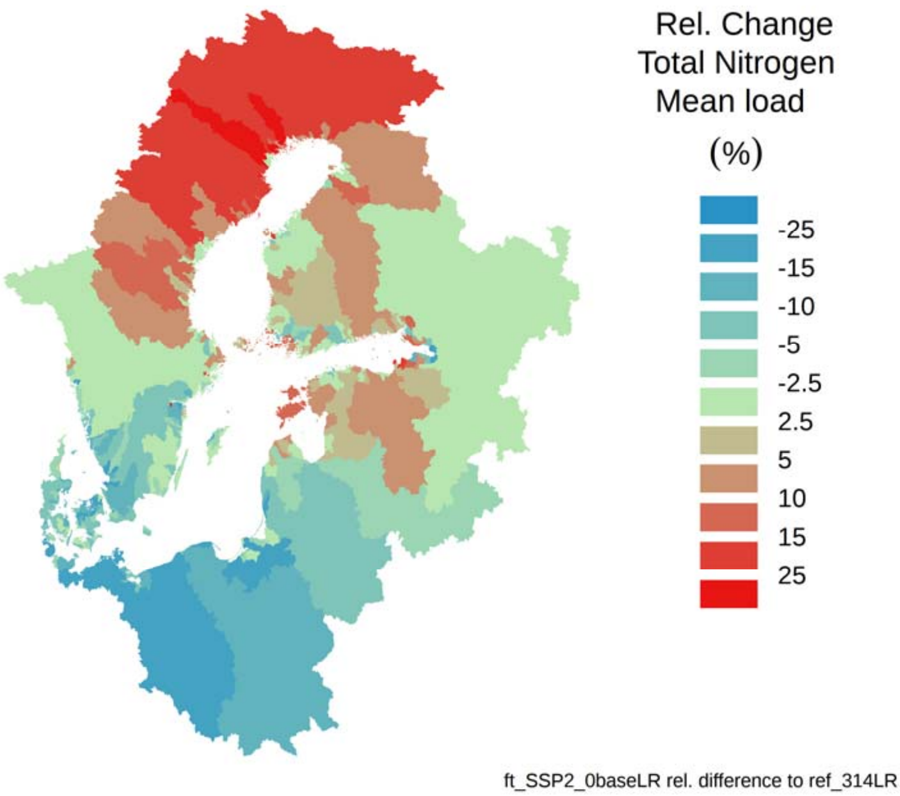

Figure 47. Relative change in average total nitrogen load due to SSP2 in 2050s simulated for BSR drainage basins with Baltic HYPE. The change represents an average change for the four selected climate models.

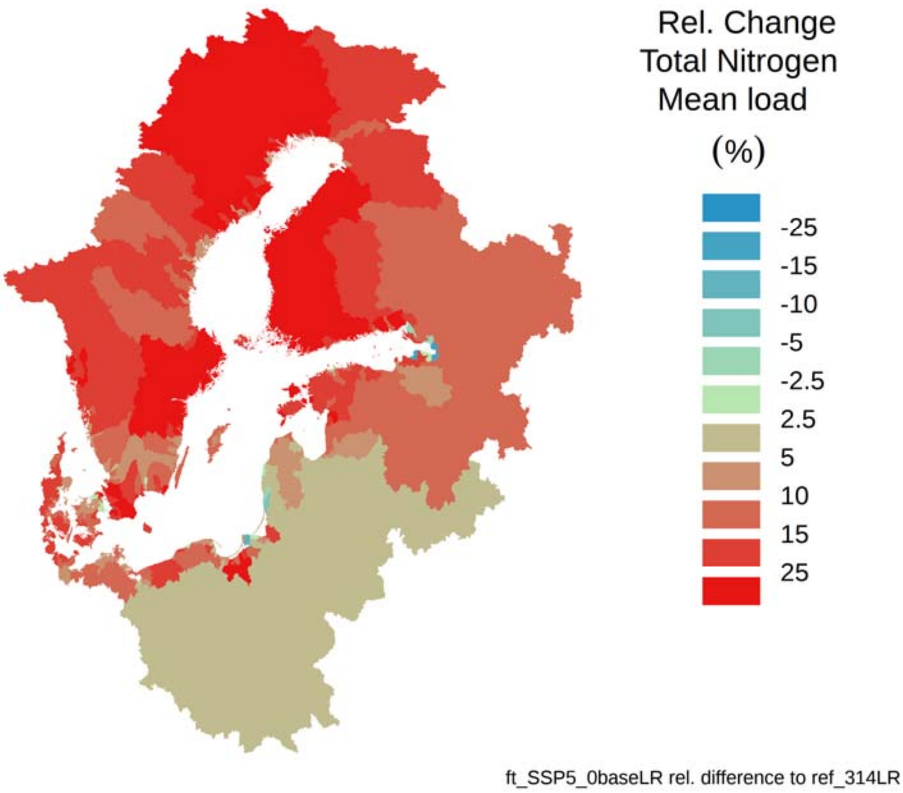

Figure 48. Relative change in average total nitrogen load due to SSP5 in 2050s simulated for BSR drainage basins with Baltic HYPE. The change represents an average change for the four selected climate models.

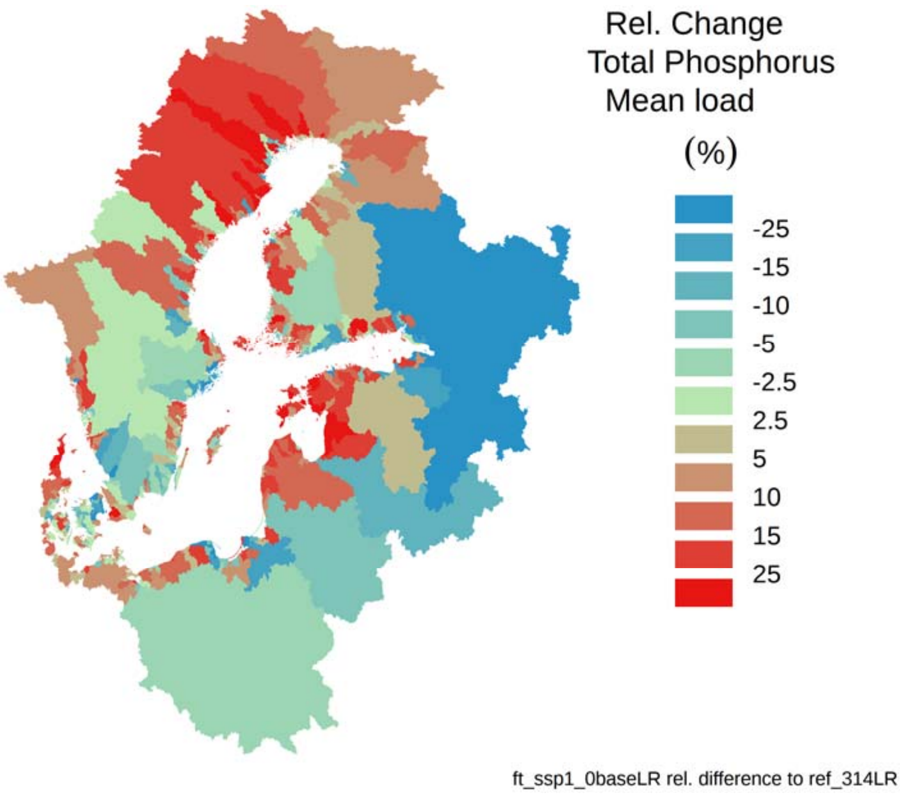

Figure 49. Relative change in average total phosphorus load due to SSP1 in 2050s simulated for BSR drainage basins with Baltic HYPE. The change represents an average change for the four selected climate models.

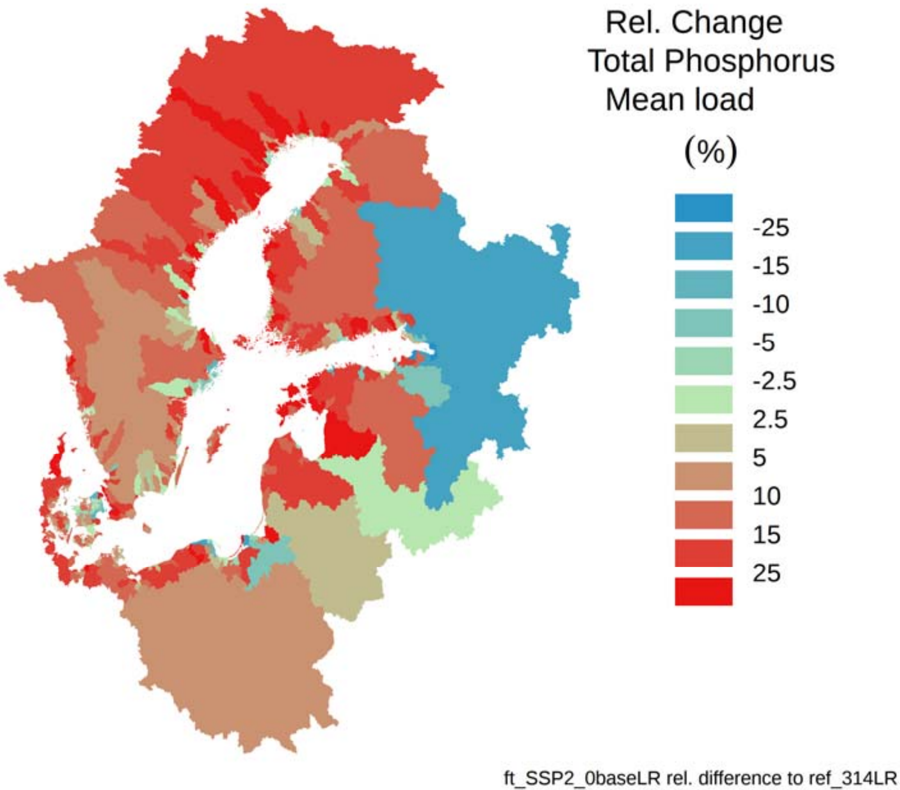

Figure 50. Relative change in average total phosphorus load due to SSP2 in 2050s simulated for BSR drainage basins with Baltic HYPE. The change represents an average change for the four selected climate models.

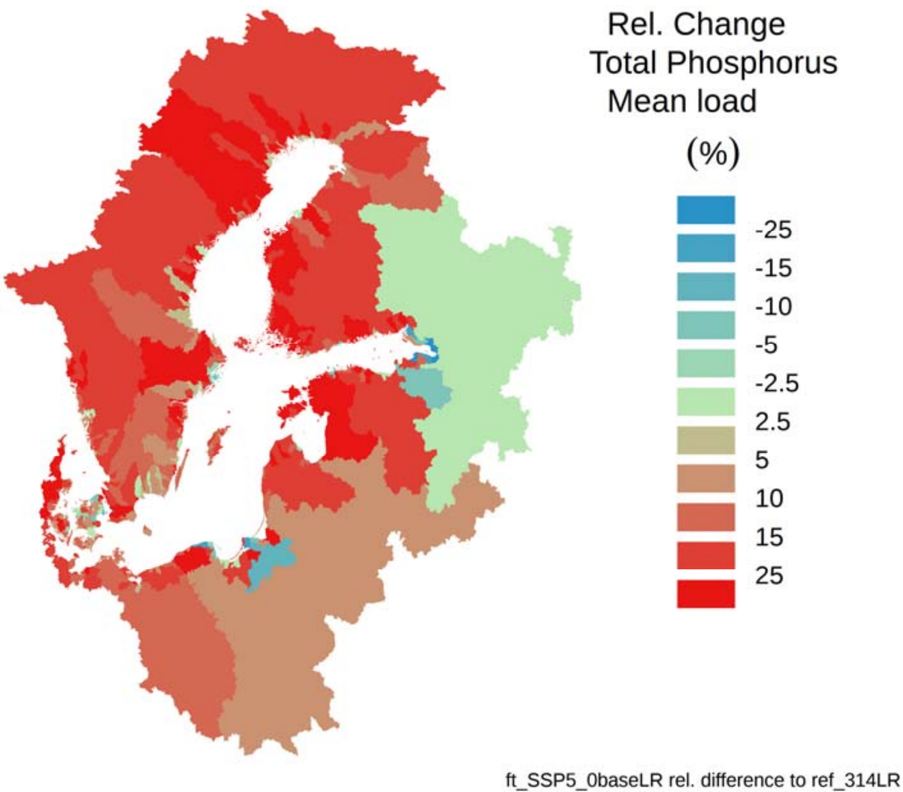

Figure 51. Relative change in average total phosphorus load due to SSP5 in 2050s simulated for BSR drainage basins with Baltic HYPE. The change represents an average change for the four selected climate models.

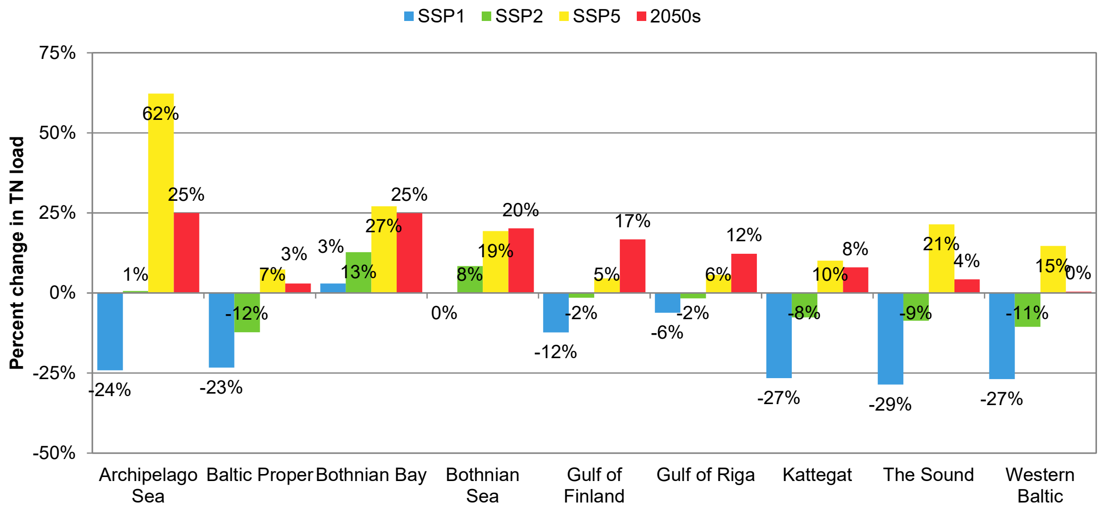

Figure 52. Relative change in average total nitrogen (TN) loads delivered to HELCOM Baltic Sea Basins through river flow for SSPs. Relative change with respect to the current loads is shown.

3.3.3 Annual Regime

Socioeconomic assumptions on future development in the form of SSPs show virtually no effect on flow regimes, whereas there is a pronounced effect on nitrogen and phosphorus concentrations and loads as discussed in previous sections. The SSPs, however, do not change the intra-annual dynamics in any of the rivers investigated here.

SSP 1 results in lower concentrations and loads compared to SSP 2, and SSP 5 shows consistently higher concentrations and loads (Figure 53, showing TN concentration regimes for river Vistula as representative example). There is a difference in magnitude of the change simulated for these two rivers due to differences in land cover and climate, with e.g. the northern Ångermanälven showing less pronounced differences between SSP1 and SSP2 than the Vistula (Figure 54).

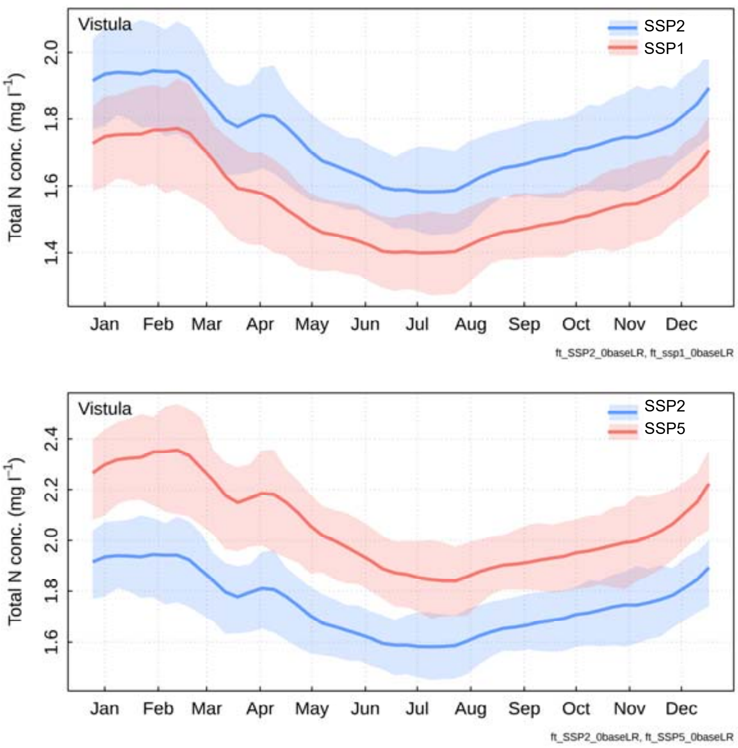

Figure 53. Effect of SSPs on TN concentrations (Vistula), shown as a comparison a) between SSP2 and SSP1 (top) and b) between SSP2 and SSP5 (bottom).

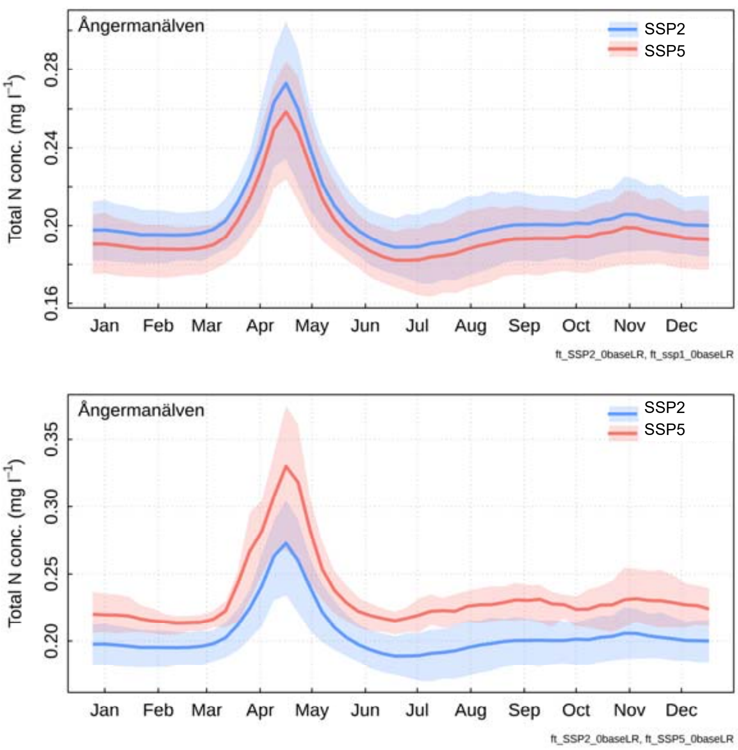

Figure 54. Effect of SSPs on TN concentrations (Ångermanälven), shown as a comparison between a) between SSP2 and SSP1 (top) and b) between SSP2 and SSP5 (bottom).

3.4 Impact of measures targeting reduction of N

3.4.1 Groundwater-oriented measures

Spatially differentiated regulation using measures targeting reduction of N in groundwater can reduce nitrogen concentration in local runoff in local catchments (Figure 55). The highest simulated reduction was 47% in a single catchment; however, in most catchments the local total nitrogen concentration decreased by 1% to 10% (Figure 56). Note that by definition, these measures do not result in any change in total phosphorus load. The discussion of results thus focuses only on changes in total nitrogen.

The reduction in local concentrations does not necessarily translate to the same reduction of nitrogen loads to the Baltic Sea. The nitrogen goes through additional transport and retention processes on its way from local runoff to Baltic. The highest percent reductions in nitrogen load to Baltic Sea were simulated for the agricultural catchments in Denmark, Germany, and Poland (Figure 57). Nitrogen load was reduced by more than 25% for 21 Baltic Sea drainage basins but most of these are relatively small drainage basins in Denmark with smaller overall contribution to the Baltic Sea.

The implementation of the groundwater-oriented measures is constrained to agriculture areas with a sufficient reduction of N in groundwater. This limits the overall reduction in nitrogen loads to the Baltic Sea from the measures targeting reduction of N in groundwater to about 5% (Figure 58), both under the current climate and sources and future climate with SSP2 sources. This translates to about 25 thousand tons of nitrogen removed per year on average.

These measures have a quite significant impact in several Baltic Sea Basins, namely the Western Baltic where they reduce the total nitrogen load by 17% (Figure 59). Reduction of about 5% can be expected in Baltic Proper, Kattegat, and The Sound Basins. Baltic Proper Basin receives the largest load by far so this represents about 14 thousand tons of nitrogen per year on average (i.e., about 60% of all nitrogen reduced due to the groundwater-oriented measures). Slight reduction of 1-2% was simulated for Gulf of Riga and Archipelago Sea Basins.

Reduction of N simulated by Baltic HYPE (or, HYPE in general) varies with total load and other factors. Simulation of the reduction in HYPE is driven by denitrification, which is highly dependent on temperature and seasonality of the N leaching through the soils and groundwater. This is illustrated in Figure 60. The reduction of N in groundwater was plotted for each catchment for individual climate models. There is much less variability in the simulated reduction of N in groundwater for the current time period than for 2050s for the same climate models, which one can think of as a proof of robustness of the reduction estimates.

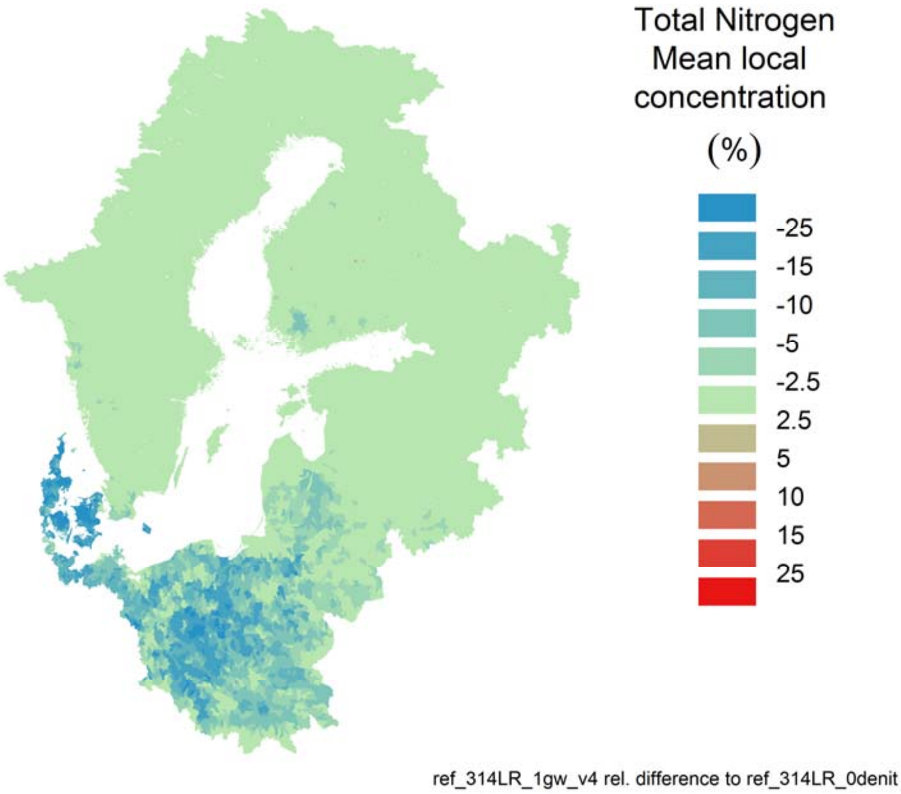

Figure 55. Relative change in average total nitrogen concentration in the local runoff due to groundwater-oriented measures simulated for each catchment in BSR with Baltic HYPE. The change represents an average change for the four selected climate models.

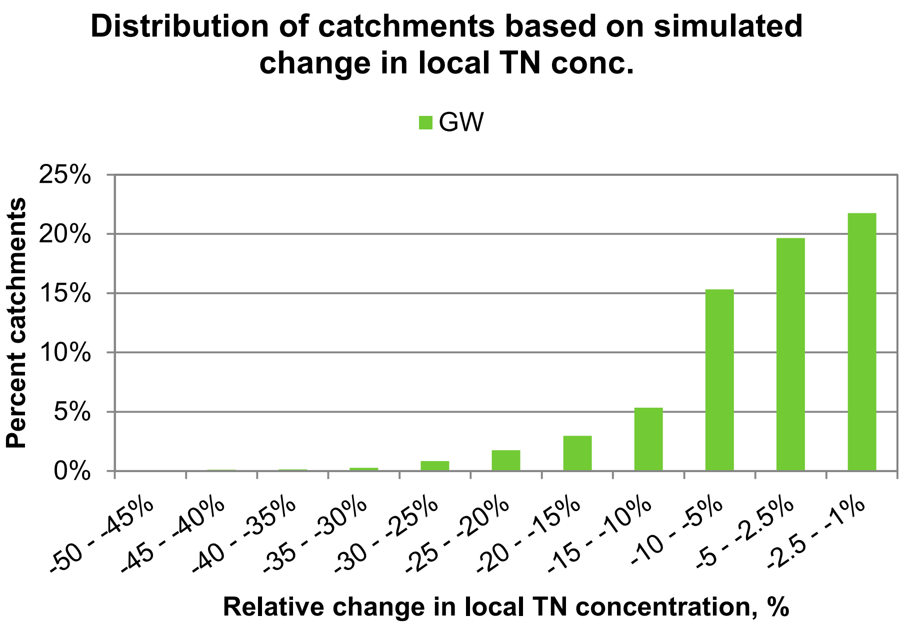

Figure 56. Percent of catchments within categories of relative change in local TN concentration simulated at the outlet of each catchment in BSR with Baltic HYPE for measures targeting reduction of N in groundwater.

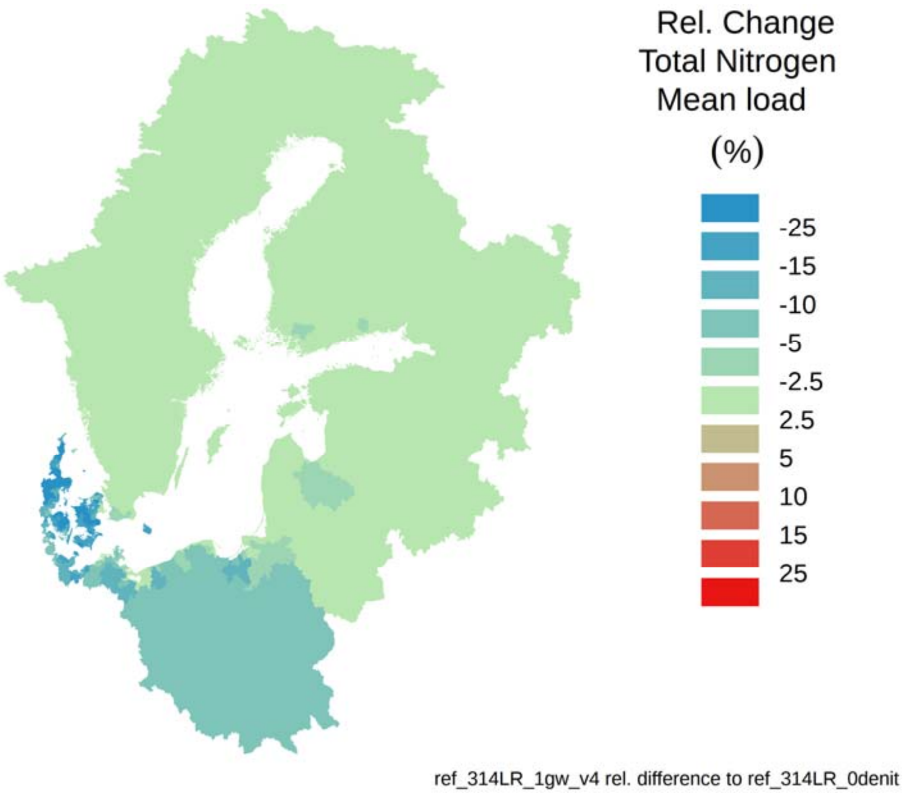

Figure 57. Relative change in average total nitrogen load due to groundwater-oriented measures at the outlet to Baltic Sea simulated with Baltic HYPE. The change represents an average change for the four selected climate models.

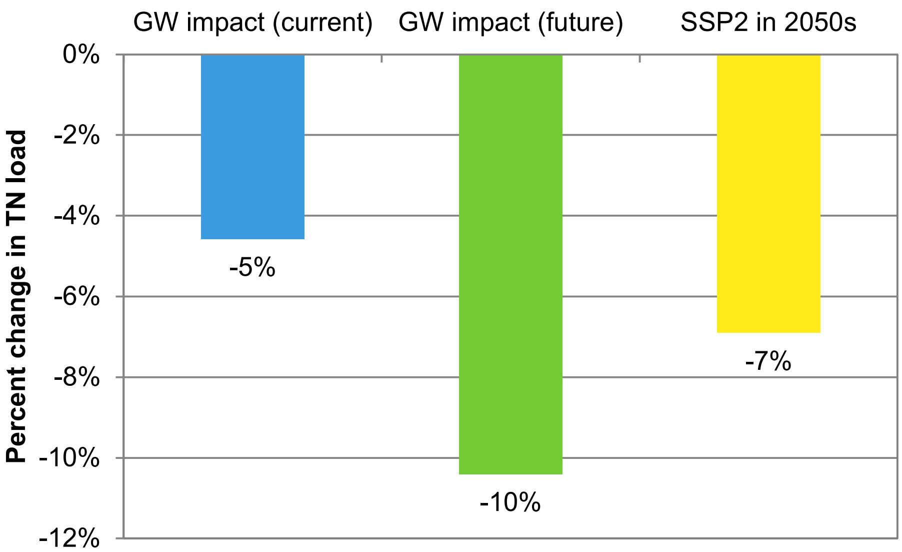

Figure 58. Change in average total nitrogen load for a) groundwater-oriented measures in the current climate, GW impact (current), b) groundwater-oriented measures simulated with SSP2 conditions under the 2050s climate, GW impact (future), and c) SSP2 conditions in 2050s climate with no additional measures implemented, SSP2 in 2050s. Percent change calculated with respect to the average total nitrogen load for current sources in the current climate. Note that the future impact also includes impacts due to SSP2 conditions in 2050s shown for comparison separately. Average loads calculated from long-term averages of the four climate models.

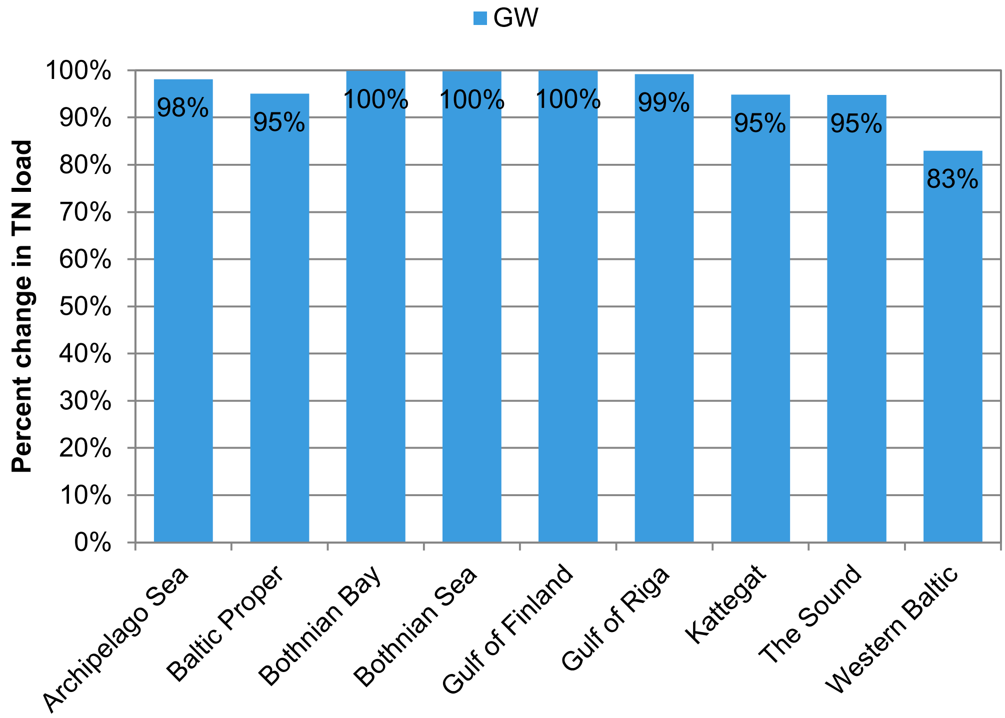

Figure 59. Impact of groundwater-oriented measures (GW) under the current climate on the total nitrogen load to Baltic Sea Basins. Relative change with respect to the average current total nitrogen load from the four climate models shown.

Upscaled spatially differentiated measures for nutrient reduction targeting groundwater only show an effect in drainage basins where substantial fractions of the area are in agricultural use (cf. Figure 5). Among the drainage basins considered for evaluating changes in annual regime, river Gudenå showed the most pronounced response to groundwater measures (Figure 61), resulting in a strong decrease in total nitrogen concentrations all-year round, and an effective reduction of total nitrogen loads during winter peak transports.

The measures' effect seems to be unaffected by climate change conditions, showing a similar response during the 2050s period (Figure 62). However, the modelled effect on TN loads from the similar Kävlingeån drainage basin is much less pronounced, as is the effect in the larger but also agricultural Vistula drainage basin (Figure 63). This further illustrates that the effect of differentiated regulation has varying potential depending on the specific conditions present in a particular drainage area.

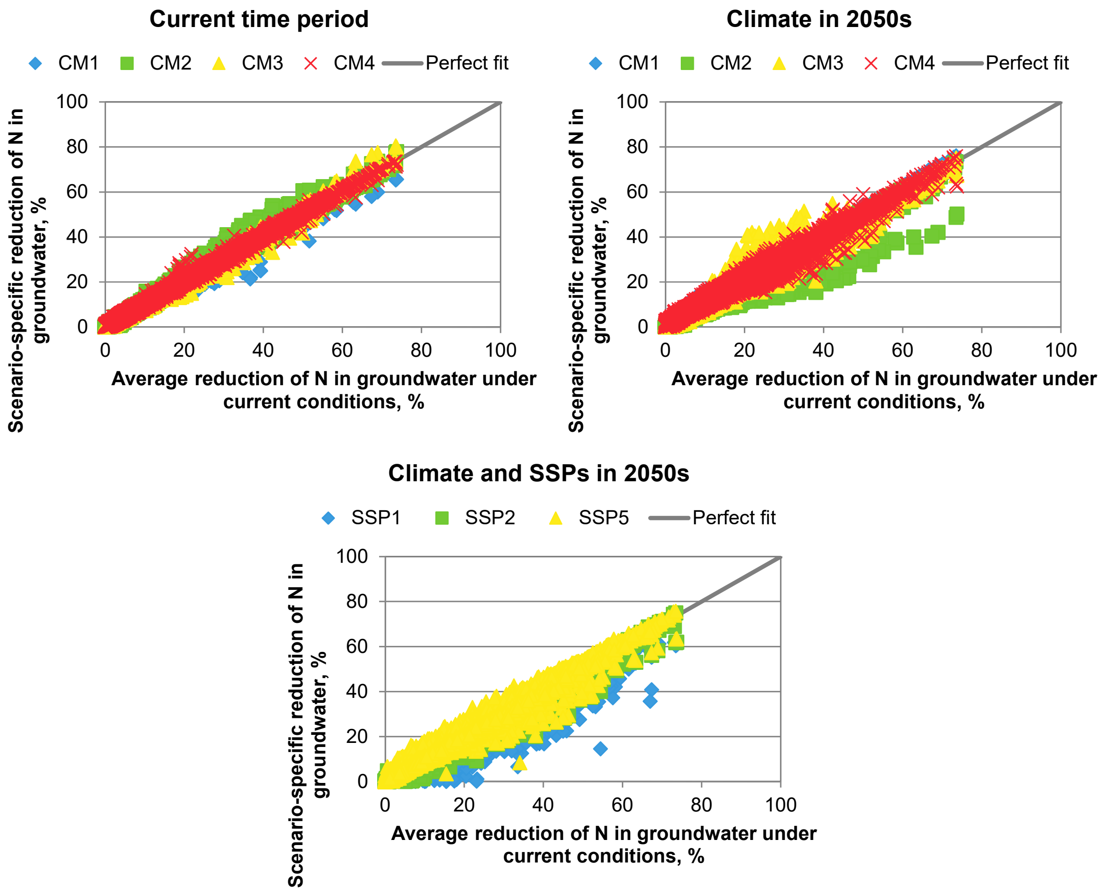

Figure 60. Variability in the average reduction of N in groundwater in the catchments of Baltic Sea region due to the climate model selection, simulation time period, and sources of nutrients. Simulated reductions for individual model options are plotted against the average current reduction of N in groundwater from the four climate models.

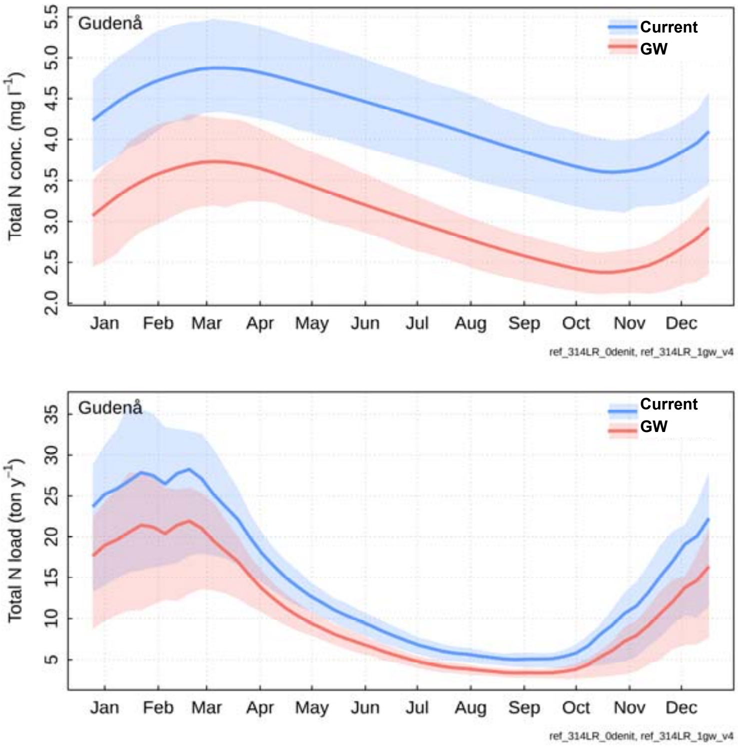

Figure 61. Effect of groundwater measures on total nitrogen (TN) concentrations (top) and loads (bottom) in river Gudenå during the current period. Current conditions and simulated impact of groundwater-oriented measures (GW) shown.

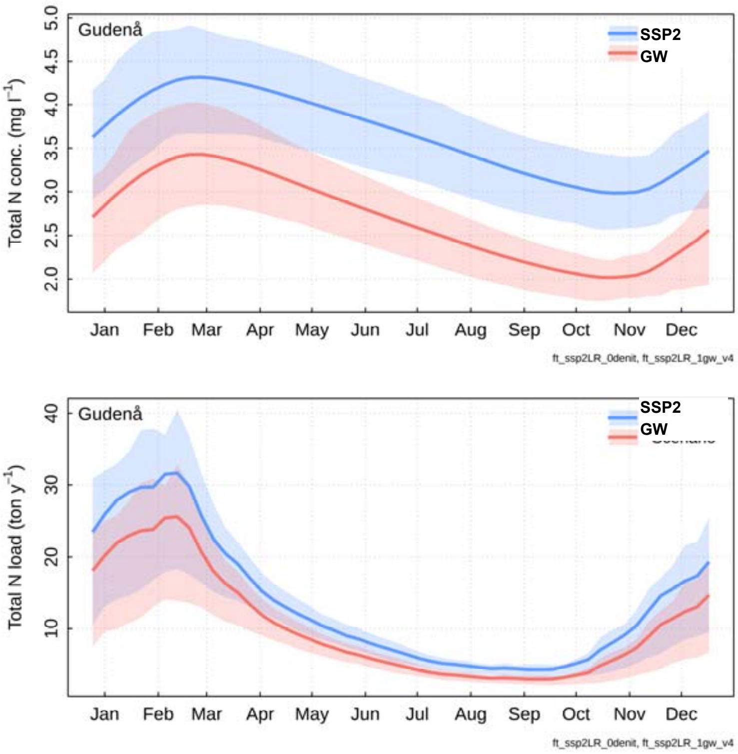

Figure 62. Effect of groundwater measures on total nitrogen (TN) concentrations (top) and loads (bottom) in river Gudenå during 2050s. SSP2 conditions in 2050s (SSP2) and simulated impact of groundwater-oriented measures (GW) shown.

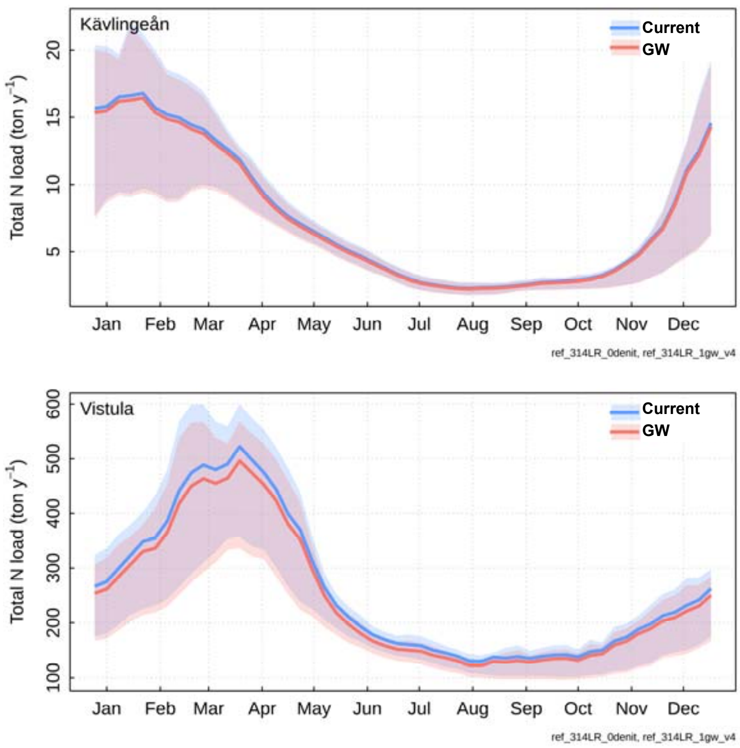

Figure 63. Effect of groundwater measures on total nitrogen (N) loads from Kävlingeån and Vistula during the current period. Current conditions and simulated impact of groundwater-oriented measures (GW) shown.

3.4.2 Surface water-oriented measures

Spatially differentiated regulation using measures targeting reduction of N in surface water can reduce nitrogen concentration in local runoff in local catchments (Figure 64). The highest simulated reduction was 5% in a single catchment; however, in most catchments the local total nitrogen concentration decreased by 1% to 2.5% (Figure 65). The highest percent reductions in nitrogen load to the Baltic Sea were simulated for the agriculture catchments in Denmark, Germany, and Poland.

The reduction in local concentrations does not necessarily translate to the same reduction of nitrogen loads to the Baltic Sea. The nitrogen goes through additional transport and retention processes on its way from local runoff to Baltic. All simulated reductions in nitrogen load to the Baltic Sea are less than 5% (Figure 66).

The implementation of the surface water-oriented measures is constrained to small streams in agriculture areas with hydromorphologic pressure. This limits the overall reduction in nitrogen loads to the Baltic Sea due to the surface water-oriented measures to about 0.6% (Figure 67), both under the current climate and sources and future climate with SSP2 sources. This translates to about 3.5 thousand tons of nitrogen removed per year on average.

Reduction of about 1% can be expected in Western Baltic, Baltic Proper, Kattegat, and The Sound Basins (Figure 68). Baltic Proper Basin receives the largest load by far so this represents about 2.6 thousand tons of nitrogen per year on average (i.e., about 75% of all nitrogen reduced due to the surface water-oriented measures).

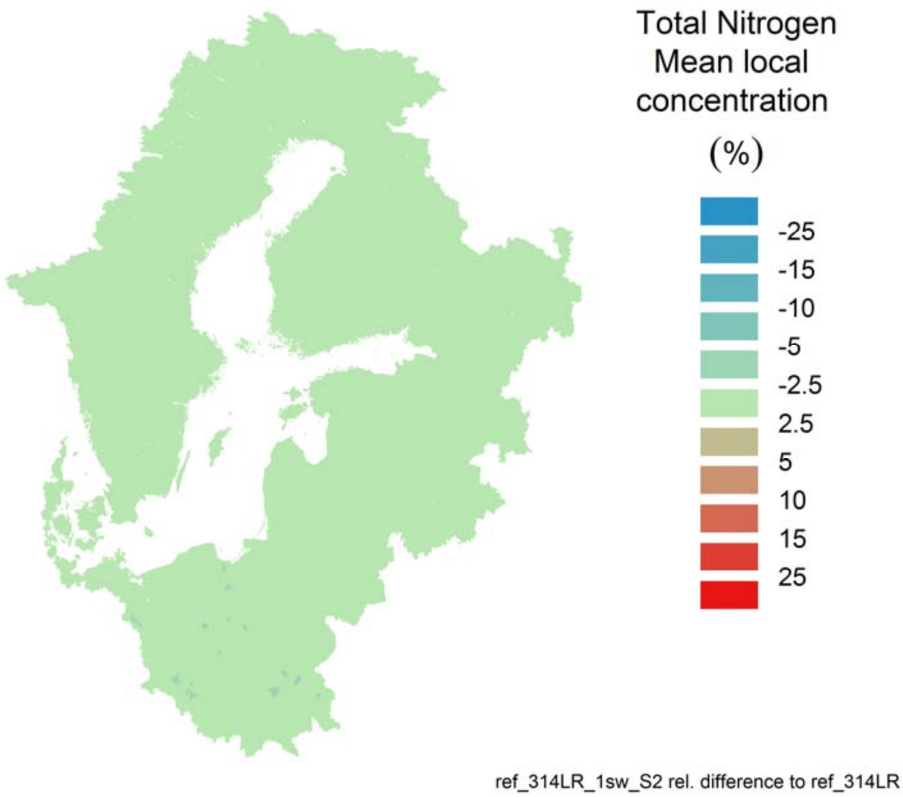

Figure 64 Relative change in average total nitrogen concentration in the local runoff due to surface water-oriented measures simulated for each catchment in BSR with Baltic HYPE. The change represents an average change for the four selected climate models.

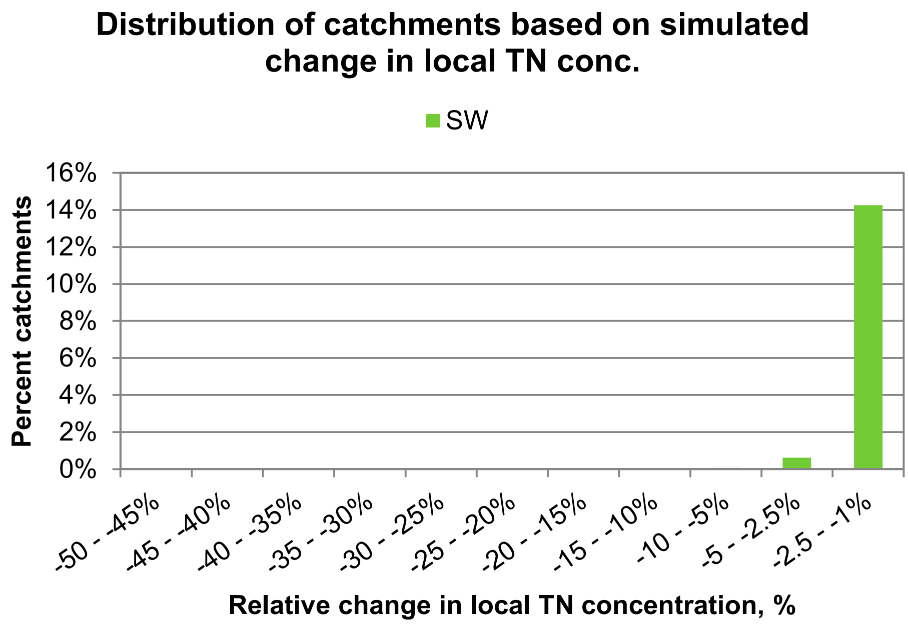

Figure 65. Percent of catchments within categories of relative change in local TN concentration simulated at the outlet of each catchment in BSR with Baltic HYPE for measures targeting reduction of N in surface water.

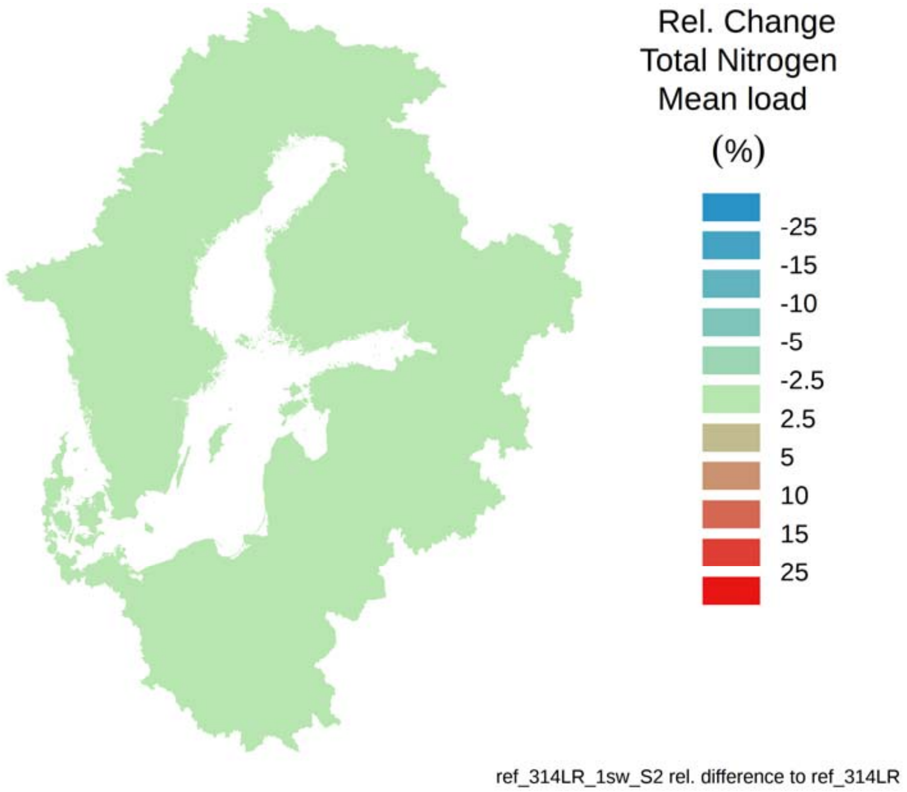

Figure 66. Relative change in average total nitrogen load due to surface water-oriented measures at the outlet to Baltic Sea simulated with Baltic HYPE. The change represents an average change for the four selected climate models

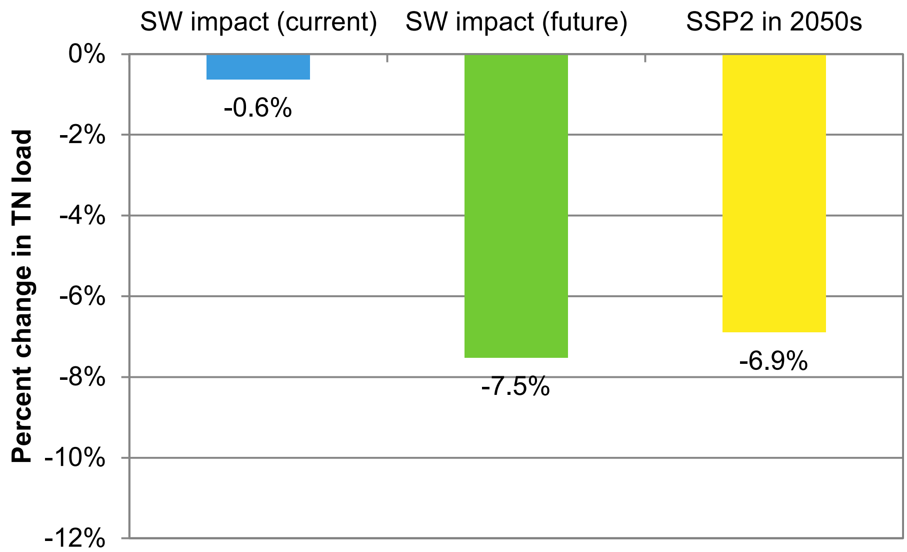

Figure 67. Impact of surface water-oriented measures (SW) under the current climate and under future SSP2 conditions in 2050s on the total nitrogen load to Baltic Sea. Relative change with respect to the average current total nitrogen load from the four climate models shown. Note that the future impact also includes impacts due to SSP2 conditions in 2050s shown for comparison separately.

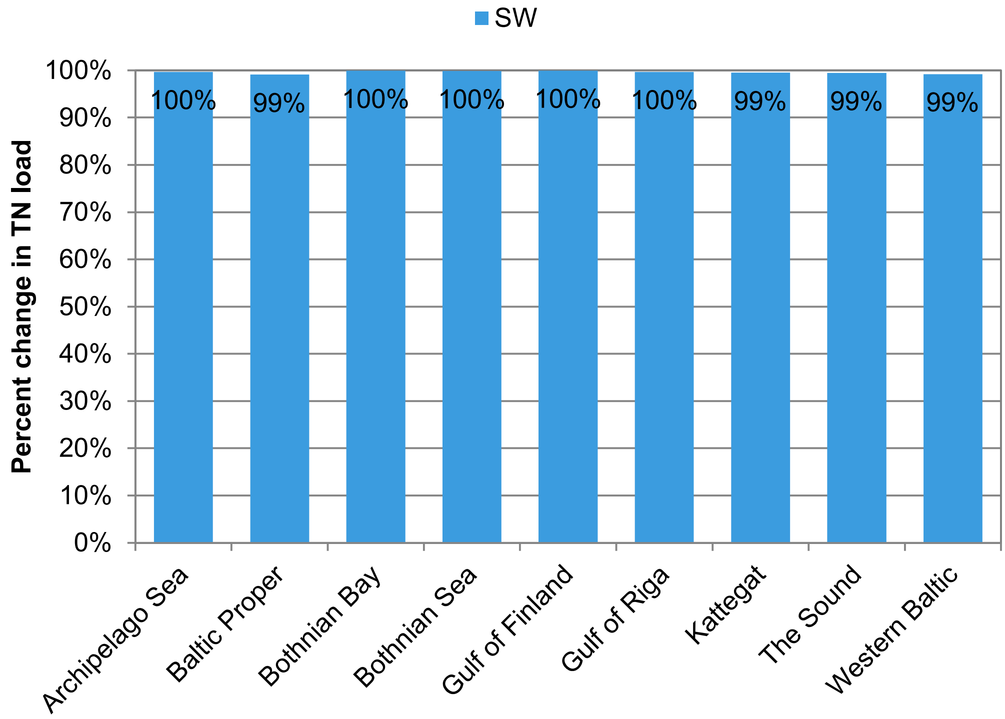

Figure 68. Impact of surface water -oriented measures (SW) under the current climate on the total nitrogen load to Baltic Sea Basins. Relative change with respect to the average current total nitrogen load from the four climate models shown.

Surface water-oriented measures show little change in regime properties for either total nitrogen or total phosphorus concentrations or loads. For example, Figure 69 shows results for river Daugava during the reference period. Total nitrogen concentrations show small decreases in average during winter and spring high flows at the expense of equally small increases during summer low flows. The increase at the receding part of the hydrograph is related to the storage of water in local streams and lakes simulated in the model as so called "dead volume", which also provides attenuation of flows. In terms of loads the simulated impact becomes negligible. For total phosphorus, the simulated effect of surface water-oriented measures is negligible for both concentrations and loads. There is no change in timing of the peaks either.

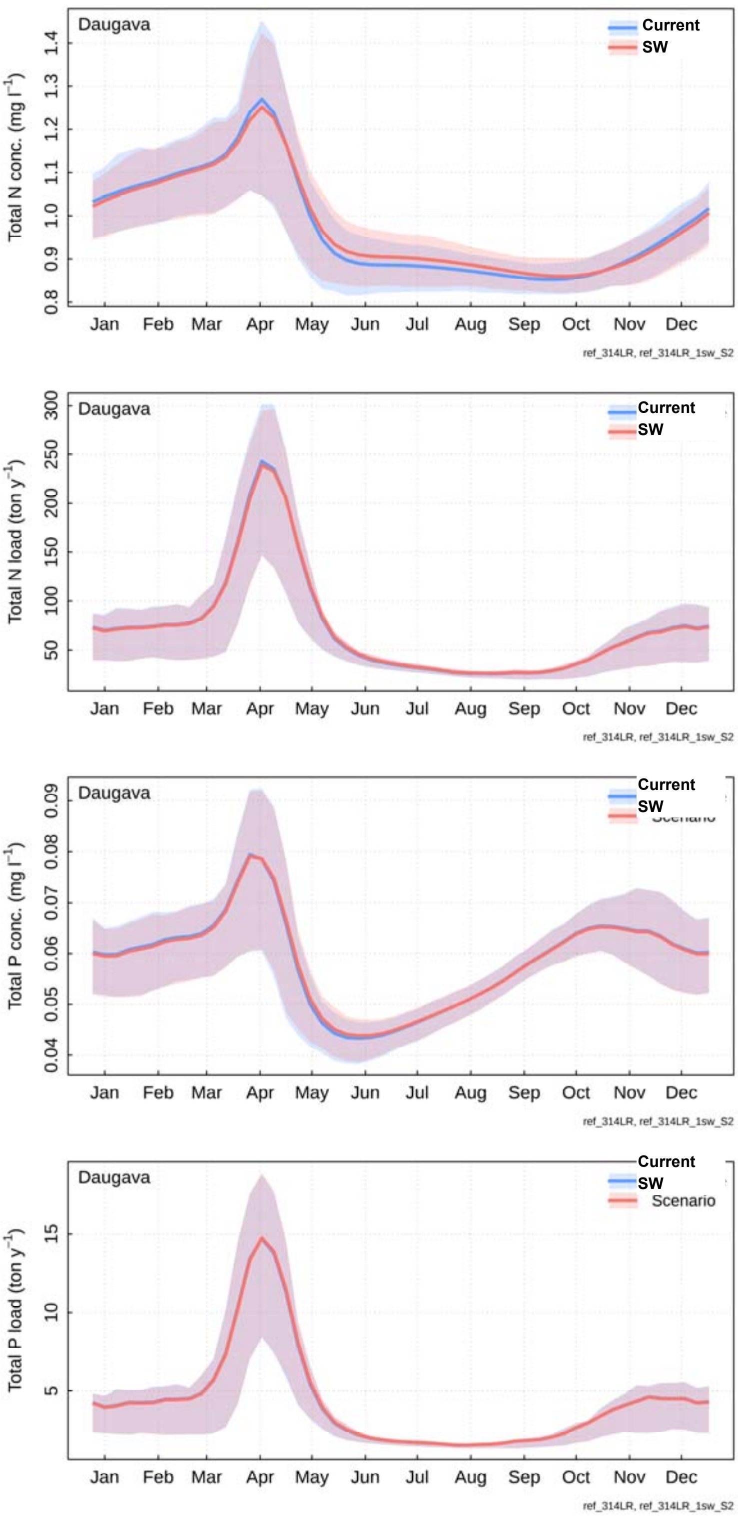

Figure 69. Effect of surface water measures on nutrient concentrations and loads from Daugava during the current period. Current conditions and simulated impact of surface water-oriented measures (SW) shown.

There are quite significant differences between the effects simulated with Baltic HYPE for the upscaled surface water-oriented measures and the effects observed in Tullstorp Brook case study or tested in D4.4 (In-streams water management strategies for reducing nutrient loads to the Baltic Sea) on Baltic scale. These differences can be attributed to different assumptions and approaches in these two parallel efforts and are best viewed as a measure of uncertainty in estimating the impacts of surface water-oriented measures at a large basin scale. Little general knowledge exists about the effects of specific remediation designs on larger scale.

The same level of changes in nitrogen losses and hydraulic parameters documented in Tullstorp Brook was assumed to be achieved in all remediated streams. This is a simplification that most likely results in overestimation of the rate of impacts. The Tullstorp experiment was conducted under summer low flow conditions. The effects of varying temperature were tested with the reach-scale model in D4.4 although they were not implemented with the Baltic Sea scale model in D4.4.

Additional effects that were not considered in D4.4 estimates are impacts of varying discharges on the amount of nitrogen reduced in the streams, effect of local catchment conditions such as bed material or slope are also expected to play a role in the efficiency of the surface water-oriented measures. Last but not least, retention in large lakes and reservoirs was not considered. Such retention already limits the total amount of nutrients transported to Baltic Sea. If the surface water-oriented measures are applied upstream of an area with large retention, local quality is improved but the overall reduction in loads is not realized at the outlet to the sea.

However, certain assumptions in the Baltic HYPE model may lead to other uncertainties in simulating the impact of surface water-oriented measures on total nitrogen loads. For example, the water quality data used in calibrating the HYPE model were only available at the outlets of the catchments. These data typically do not include enough information to explicitly separate retention and reduction effects in local streams from effects in main streams in the model calibration. Denitrification processes in HYPE model are limited to the channel bottom of the simulated streams with a constant stream length and a calculated stream width that varies with flow. Baltic Sea scale model in D4.4 assumed denitrification across the full channel cross-section.

Despite these uncertainties, these two approaches help to frame the expected impact of surface water-oriented measures on both local and large scale and to initiate the much needed discussion and scientific exploration of the evaluation methods.

3.4.3 Combined impact on loads to Baltic Sea

Groundwater-oriented measures have a larger impact on nutrient loads delivered to Baltic Sea than surface water-oriented measures. This is mainly due to different magnitudes of reduction of N in groundwater versus local streams as simulated by Baltic HYPE. The overall patterns described for groundwater-oriented measures are also seen in the combined impact of both types of measures. Combining the measures reduces total nitrogen load to Baltic Sea by 5.2% (Figure 70), resulting in a reduction of about 30 thousand tons per year on average.

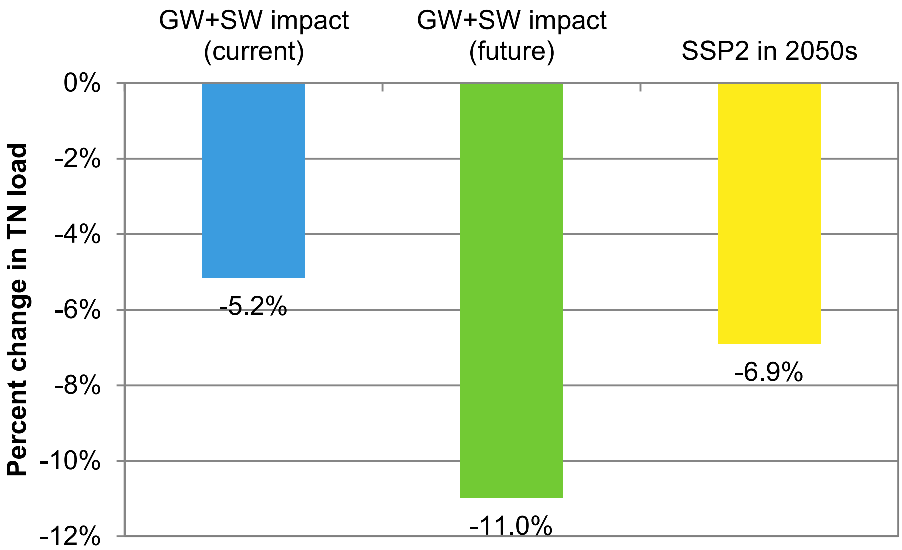

Figure 70. Impact of combined impact from groundwater-oriented measures (GW) and surface water-oriented measures (SW) under the current climate and under future SSP2 conditions in 2050s on the total nitrogen load to the Baltic Sea. Relative change with respect to the average current total nitrogen load from the four climate models shown. Note that the future impact also includes impacts due to SSP2 conditions in 2050s shown for comparison separately.

4. Summary

Baltic HYPE, a part of E-HYPE model v3.1.4, was used with four different climate models to simulate the expected impact of climate change on discharge and nutrient loads and concentrations in the outflow to Baltic Sea by 2050s. The averages of the four climate models depicting RCP8.5 were compared over two 30-year periods. The average total discharge to Baltic Sea is expected to increase by 4-25%. The average nitrogen load is expected to increase by 5-10%. The average phosphorus load is expected to increase by 6-20%.

Nutrient loads are expected to increase even though the actual average concentration in the outflow to Baltic Sea is expected to decrease on average by 5% and 1.5% for total nitrogen concentration and total phosphorus concentration, respectively. Three of the climate models project a decrease of 3-15% and 2-5% for total nitrogen concentration and total phosphorus concentration, respectively. One climate model projects an increase of 5% and 4.5% for total nitrogen concentration and total phosphorus concentration, respectively.

In addition, a change in seasonality of the high and low discharges and loads has been observed at most major rivers. The biggest effect on intra-annual regime changes can be attributed to changes in flows as a response to climate change. The strongest response to climate change is expected where seasonal snow cover is reduced as a response to rising temperatures. The seasonal pattern of total nitrogen and phosphorus concentrations and loads was projected to change along with the flow signal.

In addition to climate change, the impacts of socioeconomic drivers on future discharges and loads were evaluated using the SSP framework. Note that all simulations for SSPs included the climate change associated with 2050s as described above. The SSPs have minimal impact on discharges but very significant impact on loads and concentrations. SSP1 (sustainability) assumptions lead to a reduction of 19% and 6% for total nitrogen and total phosphorus loads, respectively, as compared to the current load despite the impact of 2050s climate being included in the simulation. SSP2 (middle of the road) assumptions lead to 7% reduction and 5% increase for total nitrogen and total phosphorus loads, respectively, although it should be noted that 5% increase compared to the total load is still significantly lower than the 14% increase projected due to 2050s climate only. SSP5 (fossil-fuelled development) assumptions lead to an increase of 11% and 10% for total nitrogen and total phosphorus loads, respectively. The increase in total nitrogen load is above the increase of 8% projected due to the 2050s climate only. Projected changes as a response to SSPs and measures are distributed more uniformly over the year, having little effect on regime shapes.

Two types of measures that utilize variability in reduction of nitrogen on a local scale were evaluated in this study and simulated with Baltic HYPE using upscaling procedures developed previously in the project: measures targeting reduction of nitrogen in groundwater and measures targeting reduction of nitrogen in surface water. Groundwater-oriented measures were applied to all catchments in Baltic Sea region with more than 3% agriculture land and reduction of nitrogen in groundwater higher than 5%. This application resulted in 5% reduction of total nitrogen load to Baltic Sea (25 thousand tons of nitrogen per year on average). The impact was much higher locally in Western Baltic Basin (17% reduction). Groundwater measures are modelled to be effective for reduction of peak total nitrogen loads during winter high flows.

Surface water-oriented measures were applied to all catchments in Baltic Sea region with more than 5% agriculture land but the extent of the application was limited to streams classified as under hydromorphologic pressure. This application resulted in 0.6% reduction in total nitrogen load to Baltic Sea (3.5 thousand tons of nitrogen per year on average).

The changes that are simulated with the SSPs are focusing on the processes that generate loads within the catchment (agriculture area, fertilization rate, population, wastewater treatment efficiencies, level of urbanization, atmospheric deposition) rather than on how the already generated loads can be reduced on their way to Baltic Sea. This is a very significant distinction and the level of impact of this on the changes in loads to Baltic Sea is much higher for such changes when compared to impact of mitigation measures.

Both surface water- and groundwater-oriented measures show a promise in removing nitrogen loads from riverine systems despite the uncertainty that lies in the large scale simulation of the impacts. The effectiveness is expected to vary significantly throughout the Baltic Sea region with largest impacts anticipated in catchments and drainage basins with intensive agriculture.

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