

From local measures to regional impacts: Modelling changes in nutrient loads to the Baltic Sea

René Capell^{a,*}, Alena Bartosova^a, Karin Tonderski^b, Berit Arheimer^a, Søren Marcus Pedersen^c, Andis Zilans^d

^a SMHI, Norrköping, Sweden

^b Linköping University, Sweden

^c University of Copenhagen, Denmark

^d University of Latvia, Riga, Latvia

ARTICLE INFO

Keywords:

Baltic Sea

E-HYPE

Hydrological modelling

Nutrient load reduction

Scenario impacts

Water quality

ABSTRACT

Study Region: Our study region is the Baltic Sea Drainage Basin (BSDB), which covers an area of 1.8 Mio km² distributed over 14 countries in northern Europe.

Study Focus: We use a large-scale hydrological and nutrient transport model (E-HYPE) to model basin-wide impacts of measure scenarios on the Baltic Sea, where eutrophication is a critical issue for the marine ecosystem. We constructed measure scenarios based on stakeholder acceptance, established in workshops in different regions around the Baltic. These measures include local stream reach to catchment scale measures aiming to reduce nutrient transport into the stream network (buffer strips, stormwater ponds) and measures aiming to reduce regional nutrient source releases (fertiliser leaching rates, rural household emissions).

New Hydrological Insights for the Region: Nutrient load reductions are often needed to reduce eutrophication and improve overall surface water quality in fresh-water and enclosed bays and seas, where dilution is limited and load emissions have long residence times. To reduce riverine nutrient loads, remediation measures are necessary, e.g. establishment of buffer strips or improved wastewater treatment. Such measures are, however, typically not designed to target nutrient load reductions at sea outlets, but rather focus on local improvements. Here, we show that measures, notwithstanding other meliorating ecosystem benefits, must include reductions in load emissions across large basin areas to impact integrated net loads into coastal sea basins, because reduction measures that only target nutrient delivery to the stream network typically cannot be implemented in a significant enough proportion of the total drainage area of large coastal river basins. Our impact scenarios show BSDB-wide nutrient reductions of up to 9 % for nitrogen and phosphorus compared to a reference scenario, if load emissions are reduced in the scenario assumptions.

1. Introduction

Anthropogenically driven eutrophication is a global problem of surface water bodies in landscapes under human use. Excessive

* Corresponding author.

E-mail addresses: rene.capell@smhi.se (R. Capell), alena.bartosova@smhi.se (A. Bartosova), karin.tonderski@liu.se (K. Tonderski), berit.arheimer@smhi.se (B. Arheimer), marcus@ifro.ku.dk (S.M. Pedersen), azilans@hotmail.com (A. Zilans).

<https://doi.org/10.1016/j.ejrh.2021.100867>

Received 14 December 2020; Received in revised form 13 June 2021; Accepted 4 July 2021

Available online 24 July 2021

emissions of macronutrients such as nitrogen and phosphorus originate from various diffuse and point sources, and are subsequently transported along surface and sub-surface water flow paths. These riverine nutrient loads impact water quality in downstream aquatic ecosystems from local headwater streams through lake and river systems all the way down to marine ecosystems at river outlets where they are discharged into the sea.

In the Baltic Sea drainage basin (BSDB), the impact of nutrient load pollution on the marine ecosystem is amplified because the Baltic Sea is an enclosed sea with limited water exchange with the open ocean, which exacerbates eutrophication compared to more open sea basins. This has been long acknowledged by the scientific and decision-making communities and led to the establishment of the Baltic Sea Action Plan (BSAP) through the Helsinki Commission (HELCOM), which prescribes reduction goals for nitrogen and phosphorus loads for all member states (HELCOM, 2013). It is, however, not clear how these goals can be achieved effectively by the member states and how projected climate change and possible modifications of land uses or other anthropogenic drivers affect future riverine nutrient load dynamics to the Baltic Sea basin in the 21st century.

Large-scale hydrological model applications can serve as effective tools to dynamically predict basin-wide nutrient transports coherently over large areas. Thus, they allow to investigate impacts from environmental change and implementation of remediation measures using projected forcing data across the model domain. In particular, such model frameworks can provide impact estimates of basin-wide load reductions for different types of measures, e.g. source reduction, edge-of-field and in-stream retention/removal. For the BSDB, several such studies have been undertaken previously, for instance Arheimer et al. (2012) used a HYPE model application to estimate the impact of climate change and extensive reductions in diffuse and point nutrient emissions. They then related their results to BSAP reduction targets for the end-century period with results indicating difficulties to achieve all BSAP targets and added uncertainty due to climate change impacts on flow and nutrient loads. Moreover, Wulff et al. (2014) studied impacts and cost-efficiencies of nutrient reduction measures and land use change in the BSDB using a multi-model environment and utilised their basin-scale model to highlight the importance of downstream retention for identifying cost-effective reduction measures. Other studies used modelled discharge projections in combination with other predictors to estimate future trends in nutrient loads to the Baltic Sea, e.g. Hägg et al. (2014) combined Baltic Sea scale climate change discharge scenarios with consumption and population growth scenarios as proxy for changes in anthropogenic sources and used simple regression models to estimate future nutrient transport change trajectories, showing strong impacts of human source changes compared to climate impacts especially in the southern basin parts.

Decisions to support implementation of edge-of-field and in-stream remediation measures for reducing nutrient loads to surface waters, e.g. constructed wetlands (e.g. Arheimer and Wittgren, 2002; Fisher and Acreman, 1999), riparian buffers (Hoffmann et al., 2009), or re-meandering of small streams, are typically made by regional government bodies and target the ecological status of local waters. Moreover, these measures often fulfil multiple purposes along with load reduction, e.g. enhanced fish spawning habitats, increased biodiversity or (re-)establishment of recreation areas. Other policy-based measures, e.g. the Nitrate Directive (Council Directive 91/676/EEC) and the Urban Waste Water Directive (Directive 98/15/EC and Directive 91/271/EEC), take effect more uniformly on national to trans-national scales as changes in fertiliser application rules or stricter legislation on wastewater discharge quality. The latter often target large scale remediation goals such as the overall load to the Baltic Sea. Studies of the cost-effectiveness of measures targeting water quality have indicated that the outcome depends on both the specific location where a measure is implemented and, on the scale, where the effect is considered, whether at the local waters or at the outlet of a larger river basin (c.f. Arheimer et al., 2005; Carolus et al., 2020; Balana et al., 2015). In addition, the process of climate change adds uncertainty to the effect estimates for different measures (e.g. Arheimer et al., 2012). To address this, scenario modelling of the effect of measures in a future climate can provide useful information when planning for cost-effective nutrient reduction.

Here we use the hydrological and nutrient transport model E-HYPE (Hundecha et al., 2016) to investigate the BSDB-wide impacts of four widely applicable remediation measures under present and future climate and socioeconomic conditions. In contrast to previous studies (e.g. Arheimer et al., 2012; Hägg et al., 2014; Wulff et al., 2014), the remediation measures originate from real-life multi-sector stakeholder consultations. Four focus areas in the region were selected: The selection was guided by local stakeholders' acceptance of remedial measures as tools for nutrient load reduction and thus their likeliness to be implemented, rather than their expected efficiency on nutrient load reductions at downstream sea outlets. The reasoning behind the pan-Baltic impact modelling approach presented here is to provide insight into potential large-scale impacts – or lack thereof – of a selected ensemble of remediation measures on nutrient loads to the Baltic Sea Basin. Understanding how the measures can potentially affect future nutrient loads at different spatial scales is essential to policy makers and stakeholders at the Baltic Sea regional scale. Our results add to the understanding of local remediation measure implementation at this scale.

The impact of stakeholder-selected measures is evaluated at three different spatial scales: catchment scale showing the spatial distribution of impacts for individual E-HYPE catchments (most relevant to local decision-making stakeholders), sea outlet basin scale providing impacts of measures in net loads to the Baltic Sea, and Baltic Sea-wide aggregates showing impacts to the overall load from land areas. The latter are contextualised by load change estimates under mid-century climate and socio-economy projections.

2. Material and methods

2.1. HYPE model and E-HYPE set-up for the Baltic Sea drainage basin

For the scenario modelling conducted in this study, we use an integrated hydrological and nutrient transport model set-up for the Baltic Sea Drainage Basin (BSDB). This model set-up is part of the pan-European model E-HYPE, and model calibration was performed on the full European domain (Hundecha et al., 2016). We will therefore refer to the model set-up as E-HYPE here, even though we only use the BSDB sub-domain only.

E-HYPE is a model set-up of the conceptual HYPE model (Hydrological Predictions for the Environment), which is an open source integrated rainfall-runoff and nutrient transport model (for a detailed model process description, see [Lindström et al., 2010](#) and <https://hypeweb.smhi.se/model-water/>). HYPE uses sub-basins to divide the landscape as opposed to uniformly spaced grid cells. This approach allows to use high-resolution catchment delineation and at the same time to aggregate sub-basins to hydrologically meaningful sizes, making HYPE computationally efficient for large-scale applications. Each sub-basin acts as an independent reactor with individual sub-basins being hydrologically connected through a routing scheme. Fluxes and states are computed at each time step for hydrological response units (HRU) defined within these catchments. HRUs are derived from landscape properties, e.g. mapped soil and land cover types. Conceptually, HRUs consist of up to three stacked subsurface storages (linear reservoirs with explicitly defined depths) with a single groundwater table and a number of flow path conceptualisations for recharge and release (e.g. snow cover, evapotranspiration, saturation and infiltration excess, matrix flow, macropore flow, and tile drainage). HYPE also includes a lake module, which is embedded in the river routing scheme. In order to tie nutrient turn-over to modelled hydro-dynamics, HYPE explicitly accounts for soil porosity and field capacity/wilting point storage volumes. Nutrient pools are coupled to these volumes. HRUs in HYPE are parameterised for the whole domain, which allows for consistent parameterisation of ungauged areas (e.g. [Strömqvist et al., 2012](#); [Hundecha et al., 2016](#)). Data required for setting up the model include spatial data for delineation and HRU definition, climate forcing data (precipitation and air temperature), calibration data (some gauges of stream discharge and nutrient concentrations), and land management data sources (e.g. point source releases, crop fractions, and land management practices).

E-HYPE has been developed as a large-scale modelling tool for Europe continuously over several years (for a detailed description of the model set-up and complete lists of data sources see e.g. [Donnelly et al., 2016](#); [Hundecha et al., 2016](#)). The BSDB in E-HYPE is delineated into ~7200 sub-basins, for each of which model results can be computed. The most recent developments of E-HYPE (v.3.1.4) include extensions and updates to input data, e.g. estimates for point sources, crop management, and in-soil nitrate turnover, as well as a re-calibration of model processes using updated observation series of riverine nutrient concentrations. HRUs in E-HYPE are based on aggregated CORINE Land Cover 2006 classes with Global Land Cover 2000 classes for areas not covered by CORINE, in combination with aggregated FAO/UNESCO Soil Map of the World classes. Within the BSDB, 13 land use classes exist (Fig. A1a, in appendix). Agricultural areas are classified into four land use classes, totaling 34 % of the BSDB area. Soils in the BSDB are classified into seven classes, grouping mineral soils into three textural classes plus moraine material and shallow soils, and soils with dominant organic material into another class (Fig. A1b). Soils under agricultural land use are dominated by “medium” and “fine” mineral soil classes, with a total of 74 % of soils under agriculture falling into these classes in the BSDB. All HRUs with agricultural land use are assumed to include tile drainage at a depth of 0.75 m in the model, with the exception of those on coarse soils. Input data assumptions with particular relevance for the scenarios of measures presented here include estimates of rural household emissions and fertiliser rates.

2.2. Modelling nutrients from rural households

Rural household emissions in E-HYPE are conceptualised as constant emissions based on catchment-wide release estimates. Emitted loads are routed partly into subsurface nutrient pools, and partly into local streams. Subsurface releases then undergo a much stronger retention and removal within the catchment, especially for phosphorus, which is efficiently trapped in soil pools. The subsurface fraction is estimated to 75 %, with the remaining 25 % being emitted to the stream network directly. This partition serves as a simplistic conceptualisation of the various retention mechanisms at individual household installations, which range from intentional or accidental seepage of septic tanks to actual removal and transport for off-site treatment. In E-HYPE, releases are estimated from a combination of several data sources: Gross per capita releases amount to 13.5 g d^{-1} for nitrogen and 2.1 g d^{-1} for phosphorus ([Swedish EPA, 1995](#)). Nutrient removal efficiencies for treatment of rural household emissions and percentages of population connected to facilities with different treatment levels were taken from national scale categorised percentages published by the European Environmental Agency (EEA) for 2005 ([EEA, 2013](#)). Rural population number estimates in each E-HYPE catchment were calculated from data of the History Database of the Global Environment (HYDE) for 2005 ([Goldewijk et al., 2011](#)).

These HYDE population estimates, however, do not include information on connectivity to sewer systems, so that EEA treatment percentages and HYDE rural population fractions required an additional merging procedure: EEA treatment percentages were distributed over HYDE population fractions in each E-HYPE catchment, with better treatment first distributed among any urban population in the catchment. This procedure results in varying treatment efficiencies for urban and rural population in individual E-HYPE catchments, but this variation is assumed to lie well within the uncertainty bounds of the overall estimation chain and are therefore deemed acceptable.

2.3. Modelling nutrients from fertiliser inputs

Fertiliser inputs in E-HYPE is tied to regionalised crop classes with nitrogen and phosphorus rates for mineral fertiliser and manure defined for each crop class individually. Application dates are pre-defined with up to two applications possible for each crop class per year. Fertiliser amounts are added to the upper two soil layers at fixed ratios. Across the E-HYPE domain, crop classes are further differentiated into regions, owing to climate gradients and different agricultural structures over the large model domain. E-HYPE crop regions are based on Eurostat NUTS regions (Nomenclature of Territorial Units for Statistics, at level 2). For estimates of regional fertiliser inputs rates, we then used results from the CAPRI model (Common Agricultural Policy Regionalised Impact analysis), a quantitative agricultural sector modelling system ([Britz et al., 2007](#)), and the Eurostat Farm Structure Survey (FSS; [Eurostat, 2016](#)). Growth season and harvesting dates were extracted from the MIRCA2000 data set ([Portmann et al.,](#)

2010). All nutrient-related data sources represent a reference period of around 2001–2010, which was subsequently used in calibration for in-stream nitrogen and phosphorus concentrations.

2.4. Parameter estimation and model evaluation

Like many large-scale hydrological model applications, E-HYPE is calibrated for an optimised performance across the full model domain, as opposed to an optimisation of single observation points. Calibration of model parameters regulating discharge was conducted using automatic calibration routines (Hundecha et al., 2016). Calibration of parameters for riverine nutrients (nitrogen and phosphorus) was then performed with the calibrated discharge model, combining automatic parameter optimisation and manual tuning. Both nutrient and discharge calibration used the representative gauged basin (RGB) approach to estimate parameterisations for ungauged areas within the model domain (Donnelly et al., 2016; Strömqvist et al., 2012).

Discharge calibration was evaluated at a monthly time step during 1981–2000 using Median Nash-Sutcliffe Efficiency (NSE (-), Eq. (1)) and percentage bias (PBIAS (%), Eqn (2)):

$$NSE = 1 - \frac{\sum_{i=1}^n (sim_i - obs_i)^2}{\sum_{i=1}^n (obs_i - \overline{obs})^2} \quad (1)$$

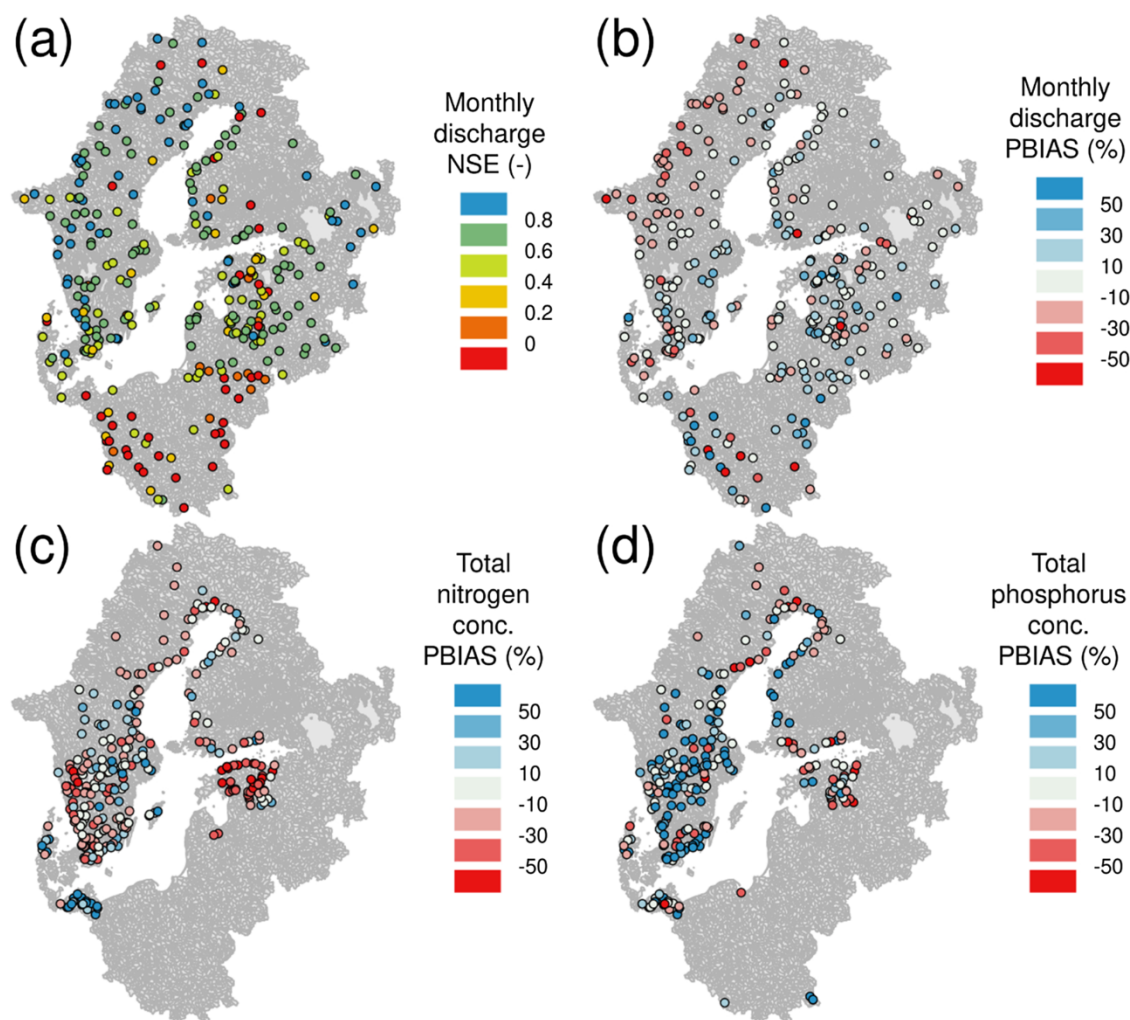


Fig. 1. E-HYPE performance at discharge gauges with no to little regulation influence and nutrient sampling sites in BSDB. Monthly Nash-Sutcliffe Efficiency (NSE) (a) and percentage bias (PBIAS) (b) for discharge during the 1981 to 2000 period. Daily PBIAS for TN (c) and TP (d) for the 2001 monthly snapshot samples.

$$PBIAS = \frac{\sum_{i=1}^n (sim_i - obs_i)}{\sum_{i=1}^n obs_i} \times 100 \quad (2)$$

NSE and PBIAS were 0.55 and 0.5 %, respectively, across stations without strong regulation influence in Europe. Stations were screened visually for evidence of regulation in time series and flow duration curves, and classified accordingly. For the BSDB domain, corresponding medians were slightly better for NSE at 0.66 and similar for PBIAS at 0.6 %. Flow performances were rated satisfactory for NSE and good for PBIAS in the context of large-scale hydrological modelling (Moriassi et al., 2007). There is a considerable spread in performance across gauging stations in the BSDB with regional patterns of under- and over-estimations of long-term discharges (Fig. 1a, b). Large volumetric biases in discharge often coincide with low NSE scores, and are considered to be a combined effect of regional biases in forcing data, evapotranspiration estimates, and effects of water human water abstraction and transfer between river systems unknown to the model. The Scandinavian mountain range is a notable exception to this pattern; discharge volumes are underestimated in this region, while NSE values remain still high due to the strong seasonality of snow-melt dominated discharge dynamics which is adequately captured by the model. Note that Polish gauging stations were only added after the calibration and are shown here for a reference only.

Total nitrogen (TN) and total phosphorus (TP) concentrations produced by the model are more uncertain than discharges. Nutrient turnover processes are more complex and more influenced by management decisions that are largely generalised in the model (e.g. fertiliser amounts and timing). There were also less nutrient observation stations available for the calibration within the E-HYPE domain than for discharges and no stations in the southern Baltic region. X% of nutrient monitoring sites were sampled with at least a bi-weekly time step. E-HYPE nutrient concentrations were calibrated for a 2001–2010 period. The median relative error was 8 % and -10 % for TP and TN, respectively, across the E-HYPE domain, and 6% and -9% for TP and TN, respectively, across the BSDB.

2.5. Remedial measures of Baltic Sea drainage basin

Within the scope of this study, we defined four remediation measures which could be implemented widely in the BSDB as part of programmes of measures which address various local environmental issues while also reduce nutrient loads in surface waters. These measures include (1) the establishment of buffer strips along streams in agricultural areas, (2) decreased fertiliser amounts due to technological advances in farming technology (e.g., precision farming), (3) establishment of storm water retention ponds in (semi-) urban areas, and (4) a theoretical scenario of nearly eliminating rural household sewage releases to explore the overall impact of a significant source load reduction on loads at sea outlets. This set of measures was selected from a larger number of measures identified during multi-sector stakeholder discussions in four case study areas in four countries that border the Baltic Sea (Walczukiewicz et al., 2017). The measures were assumed to be applied uniformly following the same general rules based on land use or soil type across the BSDB. The intent was to apply the measures at a rather extensive scope in order to be able to evaluate their mitigation potential for the Baltic Sea.

Buffer strips were established at two different levels; a basic buffer strip (2 m wide) was simulated along all streams that flow through agricultural land and a wider, 6-meter buffer strip was simulated along streams in agricultural areas for catchments where at least 25 % of the land use was agriculture and at least 10 % of soils were classified as medium or medium-fine, signifying high levels of exposure for erosion and high erodibility of the exposed surfaces. Technological advances in agriculture were assumed to result in a 5% reduction in N and P fertiliser application due to implementation of precision farming and auto-steering on large farms (>100 ha) mainly due to reduced overlap. The area-weighted proportion of large farms from Eurostat (ec.europa.eu, 2016) was used on a country level to estimate the total reduction.

Retention ponds were assumed to be constructed downstream of urban catchments. The proportion of urban area runoff that was treated via retention ponds varied with percent imperviousness. The proportion was determined using a cumulative distribution function and assuming 5%, 15 %, 30 %, 45 %, and 60 % of the area being treated for imperviousness thresholds for 10th, 25th, 50th, 75th, and 90th percentiles. The design characteristics for each retention pond were approximated from directly connected impervious area (Sutherland, 1995) and a surface area to drainage area ratio (USEPA, 1986).

Rural household sewage releases were assumed to decrease to 10 % of the estimated emitted nitrogen and phosphorus loads for 2005 reference conditions. The 90 % load reduction was applied to current net releases in each E-HYPE catchment after current treatment, i.e. to estimates based on rural population and current removal efficiencies. Reductions relative to gross releases are therefore higher in catchments with low treatment efficiency and lower vice versa. Emissions were still routed to streams and sub-surface pools as in the reference model. This reduction assumption should be considered as a more theoretical domain-wide assumption compared to the other scenario measures. This assumption can be unrealistic to achieve in practice in certain parts of the domain due to already high treatment efficiencies and corresponding low releases. It allowed us, however, to provide an indication of possible improvements in BSDB-wide net load releases into the sea under the assumption of a significant BSDB-wide source release reduction.

2.6. Scenario modelling

To allow for long term planning and management on international level within the BSDB, the year 2050 was selected as a projection time frame for simulating future scenarios. This translates to a 30-year model period centred around 2050 (2036–2065). The changes in population using 30 years during a recent time period (1981–2010). Model simulations were started 10

years prior each evaluation period to allow for the model state variables to set. The climate model data were used for both reference (baseline) and the future (2050s) time periods to ensure consistency for the cross-comparison.

During each evaluation period, all other model inputs such as land use, point source discharges, or management practices were considered constant. Precipitation and air temperature were the only time dependent model inputs in order to determine long-term average characteristics for each time period solely as driven by the climate and socioeconomics. The same model inputs used in the calibration reflecting 2010–2012, with the exception of the climate forcing data, were used in the model runs for the reference period. The future period, 2050s, was represented by a combination of climate model projections and a plausible socioeconomic development in the BSDB.

Remediation measures were applied over the BSDB through changes in E-HYPE parametrisation for both the current and future periods. Daily outputs from E-HYPE were aggregated to mean annual loads at three different spatial scales to investigate spatial load patterns and expected impacts of remediation measure scenarios in different regions in the BSDB.

Results were first evaluated at a local scale for individual catchments, which provides an insight into the local impact variation (“local” here being E-HYPE catchments, i.e. the smallest modelled spatial unit). The catchment scale reflects the perspective which local decision makers often take when designing programmes of measures with a focus on improving local to regional conditions of a specific river basin under their responsibility. The second level of spatial aggregation is at the sea outlet basins that integrate the upstream average net load emissions. This reflects a much larger basin perspective, where the focus is on net loads into the Baltic Sea and changes thereof regardless of local impacts of measures throughout the drainage basin upstream of the sea outlets while at the same time considering regional variation from different river basins around the Baltic Sea. The highest level of aggregation is at the BSDB with total loads summarized from all land areas draining to the Baltic Sea. This scale reflects the focus of international cooperation and agreements with the goal of reducing nutrient loads to the Baltic Sea and improving its overall environmental status.

2.7. Climate data

Two climate models were selected from a larger EURO-CORDEX (Coordinated Regional Downscaling Experiment) ensemble of dynamically downscaled climate change projections from the CMIP5 global climate model ensemble (www.cordex.org, e.g. [Jacob et al., 2014](#)) for RCP8.5 ([Riahi et al., 2007](#)). The two chosen climate model projections represent the high end of projected changes over the study area in precipitation and air temperature, respectively, rather than the full ensemble spread. The selection was based on mid-century changes in summer under the assumption that changes in summer most strongly influence changes in nutrient dynamics. However, the higher end of projected changes on annual scale is also represented ([Bartosova et al., 2019](#)).

The chosen climate model projections were further downscaled statistically using distribution-based downscaling (DBS) bias correction ([Yang et al., 2010](#)). This was done on the RCMs' 0.44° grid and towards WATCH Forcing Data – ERA INTERIM (WFDEI) reanalysis forcing data (reference period 1971–2000).

2.8. Socioeconomic assumptions

Land use, agriculture, population, life style, legislation, and economic development are important drivers that change over time and can significantly affect generation and transport of nutrients to the Baltic Sea. We have selected Shared Socioeconomic Pathway 2 (SSP2), the “Middle of the Road” development pathway ([van Vuuren et al., 2011](#)) as interpreted by [Zandersen et al. \(2016\)](#) for the BSDB and implemented in E-HYPE by [Bartosova et al. \(2019\)](#) to represent one plausible development by 2050s. SSP2 follows recent development trends with some progress towards achieving the United Nation's Sustainable Development Goals. All assumptions build on spatially differentiated projections of ultimate change factors population size, urbanisation, sewage treatment efficiency, and food production from the International Institute for Applied Systems Analysis (IIASA) SSP database ([Riahi et al., 2017](#)), adapted into proximate change factors mapped to E-HYPE ([Bartosova et al., 2019](#)): Significant changes in nutrient source releases include a 5 % increase in nitrogen efficiency in agriculture, a 30 % decrease in atmospheric deposition of nitrogen, a 20 % and 25 % reduction of nitrogen and phosphorus loads, respectively, associated with urban wastewater discharges, and a 17 % reduction of nitrogen and phosphorus loads associated with rural wastewater discharges. No land use change was projected for this particular pathway. Note that these changes are expected to affect only the simulated nutrient source loads, not the simulated flows.

3. Results and discussion

3.1. Spatial patterns of current nutrient loads

Average annual TN loads emitted from E-HYPE catchments during the reference period show a strong gradient in a general north-south direction ([Fig. 2a](#), upper map). On top of this general pattern, the mapped loads reveal a local catchment-to-catchment variation as a combined result of differences in catchment properties and size. The north-south gradient reflects the climate gradient and subsequent differences in population density and land cover characteristics with agriculture dominating in the south and production forest in the north. This gradient becomes even more prominent when looking at integrated unit-area loads from Baltic Sea outlets ([Fig. 2a](#), lower map), where the effect of catchment size is cancelled out and the highest unit-area loads occur in areas dominated by intensive agriculture in the south of the basin. Small coastal basins show a more irregular spatial pattern due to larger variation in land use at a smaller local scale. The modelled spatial pattern for TP loads looks similar to TN ([Fig. 3a](#)). However, the highest unit area loads are attributed to agriculture but also to population density and sewage treatment emissions. High unit-area

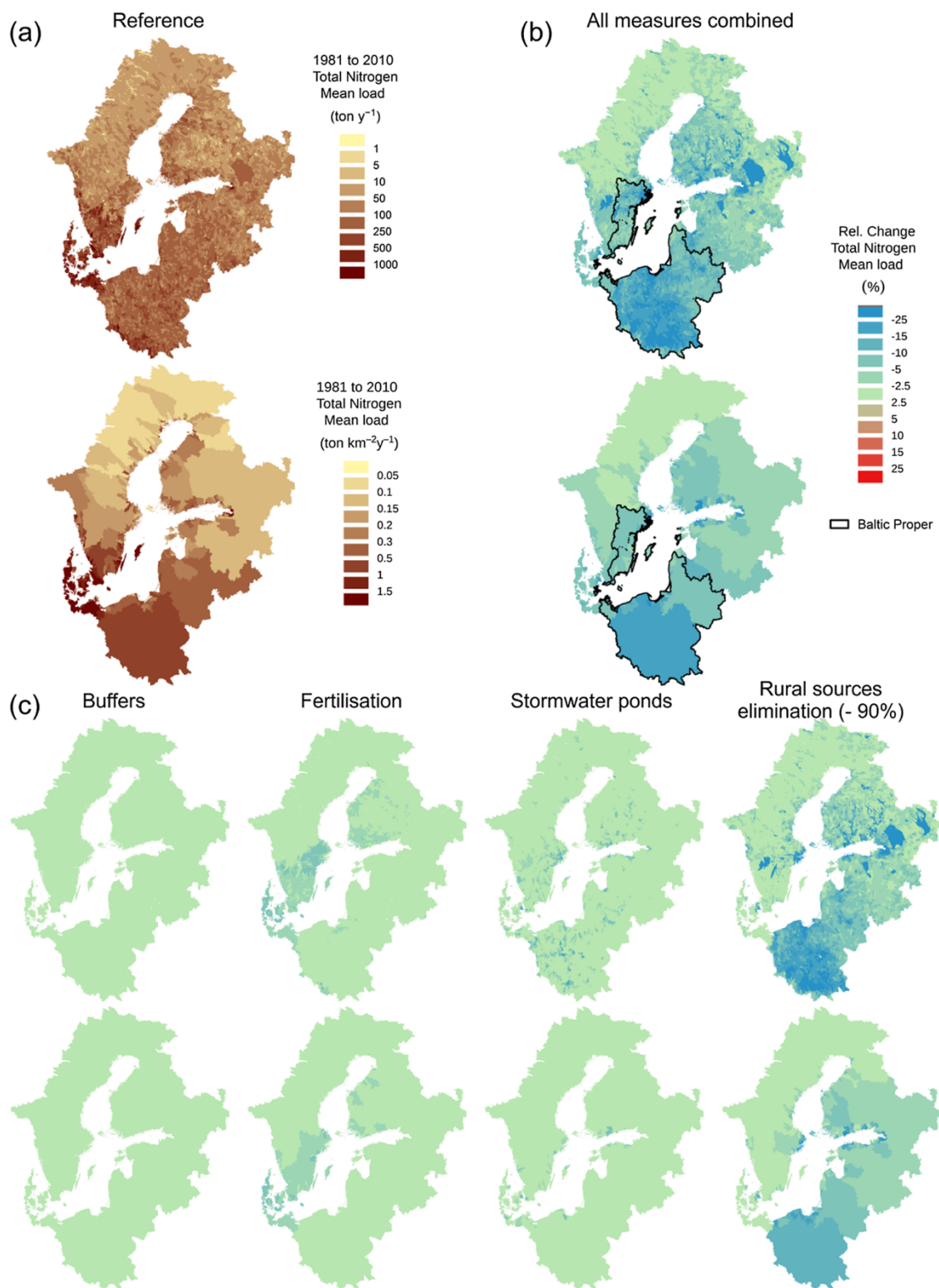


Fig. 2. HYPE-modelled annual total nitrogen loads from the Baltic Sea Drainage Basin for a 30-year period (1981 to 2010). Reference results as absolute annual loads (a), measure scenarios as relative change from reference period (b, c). Top maps showing local catchment results, bottom maps aggregated results for Baltic Sea outlet basins (reference loads normalised by area to highlight inter-basin differences).

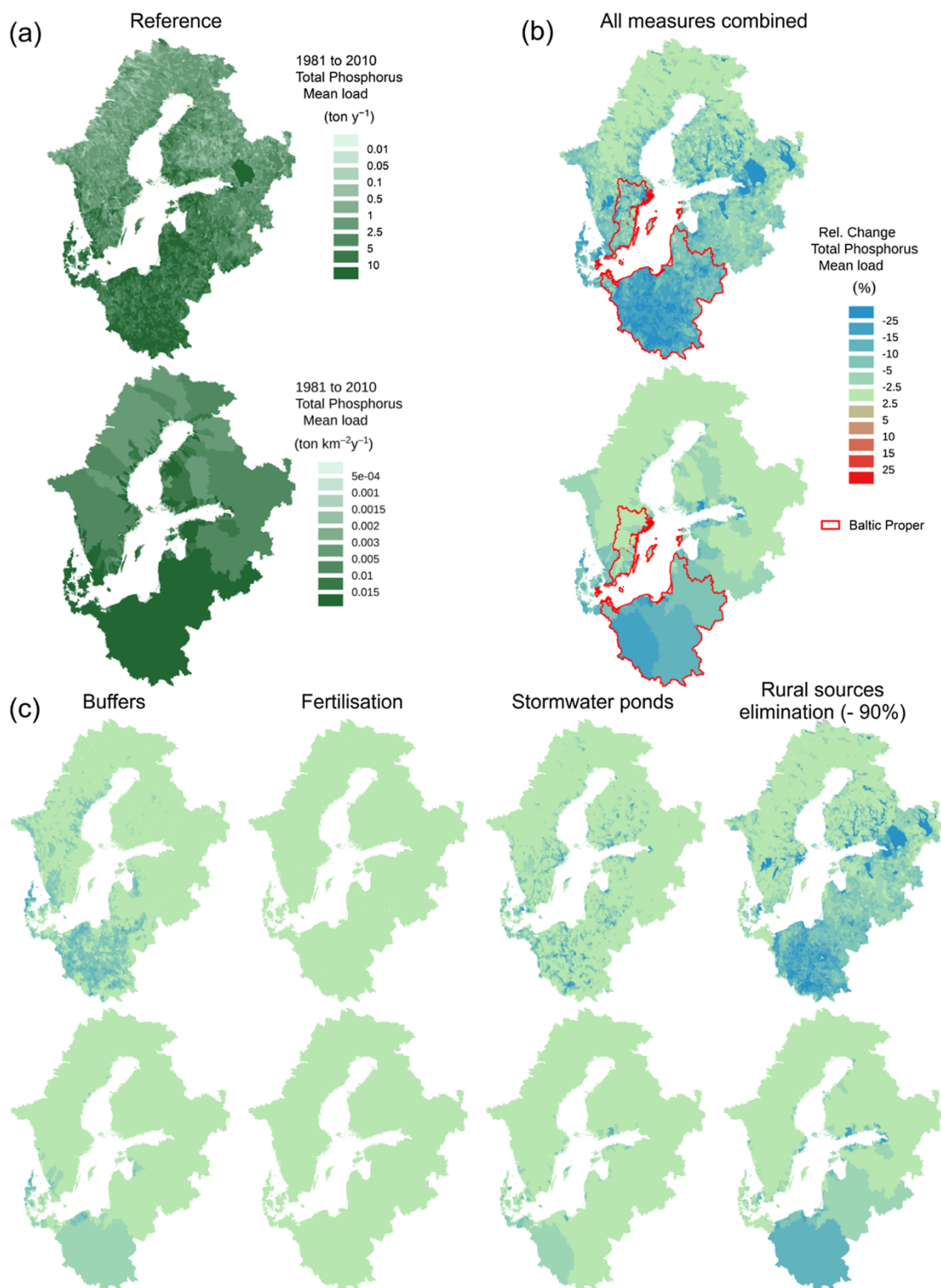


Fig. 3. HYPE-modelled annual total phosphorus loads from the Baltic Sea Drainage Basin for a 30-year period (1981 to 2010). Reference results as absolute annual loads (a). Measure scenarios as relative change from reference period (b, c). Top maps showing local catchment results, bottom maps aggregated results for Baltic Sea outlet basins (reference loads normalised by area to highlight inter-basin differences).

Table 1
Modelled remediation measures in BSDB-wide measure scenarios.

Measure	Description	E-HYPE model implementation
Buffers	Establishment of 2 m buffer strips along all streams in agricultural land 6 m buffer strips where higher contributions expected.	Buffer strips conceptualised as an additional P filter for surface runoff flowpath from near-stream agricultural land classes. Fraction of flow through filter set to 1 for all agricultural surfaces. 6 m buffer strips where ≥ 25 % of catchment area are agriculture and ≥ 10 % of the area are medium or medium-fine soils, parameterised as far-stream agriculture without direct surface flowpath into streams.
Fertiliser application	5 % decrease in effective nitrogen and phosphorus fertiliser application on large farms due to improved technology.	Large farm fraction (> 100 ha) at national scale extracted from Eurostat database (Ec.europa.eu., 2016), and used to proportionally decrease fertiliser releases (mineral and organic) at national scale in E-HYPE.
Stormwater ponds	Retention ponds added to catchments with urban area (percent of the area treated varies with the imperviousness).	Retention pond area added to E-HYPE's catchment-internal lake concept. Internal lakes are connected to the local stream network with a catchment specific drainage area fraction. Internal lake and drainage area updated where urban area is present with a fraction of the area treated varying with imperviousness.
Rural sources elimination	Reduction of rural sewage releases to 10 % of current load estimate (reference year 2005) as a result of improved on-site infrastructure.	No further spatial diversification, rural nitrogen and phosphorus loads reduced in all catchments with rural releases.
All	All above combined.	All above combined

phosphorus loads were modelled even for several south-eastern parts of the basin where unit-area nitrogen loads are comparatively lower (Table 1).

3.2. Impact of measures on nutrient loads at local scale

Modelled impact from the combined measures at the catchment level (Figs. 2b and 3 b, upper maps) shows a large spatial variation with little impact in the northern half dominated by sparsely populated forested areas. The overall pattern is comparable to that of TN and TP loads. This agreement is not surprising since all measures considered here are coupled to either agricultural practice or human population. This similarity in local change patterns is corroborated by change figures summarised as area proportions of the BSDB with classified change magnitudes (Table 2). Local loads were reduced by at least 5 % in 53 % of the BSDB area for both TN and TP loads, and by at least 10 % in 28 % and 30 % of the BSDB area for TN and TP loads, respectively, as a result of all measures combined.

There are, however, marked differences in the responses of the two nutrients when looking at the local impact of individual measures (Figs. 2c and 3 c, upper maps). Buffers showed no noticeable impact on nitrogen loads because nitrogen is predominantly transported in dissolved form along sub-surface pathways in E-HYPE. Phosphorus loads from agricultural areas are, however, reduced when surface runoff with eroded particles flows over the buffers. Buffers had the biggest impact in the southern and south-western parts of the basin with smaller impacts in more easterly agricultural areas. This difference could be explained by differences in soil textures and precipitation patterns and resulting differences in the importance of surface water flow. Dominant crop types and other factors such as fertilization rates and timing or sowing and harvesting dates can also influence the overall impact of buffer strips within E-HYPE's conceptual model framework. Reductions in phosphorus loads of at least 10 % were projected for 14 % of the BSDB area (Table 2).

The fertiliser reduction measure as modelled here affects only large-scale farms where investing in technological advances is more likely to be economically viable compared to small farms. As a result, the farm structure is visible at a local scale with higher impacts on nitrogen loads occurring in countries where large farms dominate. Another factor reflected in the change pattern is regionally estimated fertiliser application rates with change pattern being the most prominent where the fertiliser application rates are high. At the same time other local characteristics such as soil types or nitrogen reduction processes in soils, groundwater, or surface water can affect the measure performance. Impacts were negligible for phosphorus due to changes in phosphorus loads not being as directly coupled to fertiliser application practices as nitrogen loads due to the effect of legacy phosphorus in modelled loads. The legacy phosphorus pools in agricultural topsoils are large compared to annual fertiliser amounts and can dampen the immediate impact of fertiliser rates on phosphorus loads, especially when the change is relatively small (5% reduction at large farms). Phosphorus load reductions from agricultural soils have been shown to require more profound changes in fertiliser management which aim for effectively reducing the amount of phosphorus stored in agricultural topsoils in relation to what is plant-available during growth periods (Withers et al., 2014). Legacy pools can also delay impacts of reduction measures on nitrogen loads, as subsurface transport paths can significantly delay load exports at catchment level (Howden et al., 2011). Within the conceptual model framework of HYPE, subsurface transport paths estimates are likely to be at the short end, given that the model parametrisation is primarily driven by discharge dynamics which is most effective for fast transport paths whereas nitrogen export delay would be mainly affected by the slow end of the catchment-wide transport path distribution. For the interpretation of modelled reduction scenario effects, this translates into that potential impact delays on nitrogen loads because of legacy nitrogen are likely to be under-estimated as part of the epistemic uncertainty in the HYPE model concept. Overall, the modelled impact of reduced fertiliser application under the chosen assumptions is low with 13 % of the BSDB area showing a local nitrogen load reduction of at least 2.5 % (and only 3 % of the area exceeding 5 % reduction). Projected phosphorus load reductions under the chosen assumptions remain under 2.5 % in all areas (Table 2).

conceptualised as internal lakes in catchments with urban land use, showed a much more localised

Table 2

Modelled nutrient load change from measure scenario analyses. Area fractions (%) of the BSDB impacted by classified change magnitudes, for E-HYPE catchments and aggregated net loads at sea outlets.

Spatial aggregation level	Change magnitude	Buffers	Fertiliser application	Stormwater ponds	Rural treatment	All measures
Total nitrogen	less than -20 %	–	–	0.09	8.7	11
	from -20 % to -15 %	–	–	0.14	5.9	6.6
	from -15 % to -10 %	–	–	0.35	7.6	10
	from -10 % to -7.5 %	–	0.27	0.9	5.6	9.1
	from -7.5 % to -5 %	–	2.5	1.7	11	16
	from -5 % to -2.5 %	–	10	5	23	22
	more than -2.5 %	100	87	92	39	25
Catchment	less than -20 %	–	–	< 0.01	0.49	0.6
	from -20 % to -15 %	–	–	–	0.78	19
	from -15 % to -10 %	–	–	0.02	19	2.6
	from -10 % to -7.5 %	–	0.01	0.02	2.2	14
	from -7.5 % to -5 %	–	1	0.38	11	14
	from -5 % to -2.5 %	–	9.6	1.1	32	32
	more than -2.5 %	100	89	98	35	18
Baltic Sea outlets	less than -20 %	–	–	0.4	4.8	11
	from -20 % to -15 %	0.18	–	0.68	4.9	7.7
	from -15 % to -10 %	2.6	–	1.7	8.8	11
	from -10 % to -7.5 %	4.3	–	2.1	6.9	9.3
	from -7.5 % to -5 %	7.4	–	3.7	12	14
	from -5 % to -2.5 %	11	–	8.8	21	21
	more than -2.5 %	75	100	83	42	26
Total phosphorus	less than -20 %	–	–	< 0.01	0.29	0.51
	from -20 % to -15 %	< 0.01	–	–	0.17	7.2
	from -15 % to -10 %	0.12	–	0.22	18	13
	from -10 % to -7.5 %	0.49	–	0.27	0.67	1.9
	from -7.5 % to -5 %	0.69	–	0.6	1.7	12
	from -5 % to -2.5 %	20	–	8.9	17	16
	more than -2.5 %	79	100	90	63	50
Catchment	less than -20 %	–	–	0.4	4.8	11
	from -20 % to -15 %	0.18	–	0.68	4.9	7.7
	from -15 % to -10 %	2.6	–	1.7	8.8	11
	from -10 % to -7.5 %	4.3	–	2.1	6.9	9.3
	from -7.5 % to -5 %	7.4	–	3.7	12	14
	from -5 % to -2.5 %	11	–	8.8	21	21
	more than -2.5 %	75	100	83	42	26
Baltic Sea outlets	less than -20 %	–	–	< 0.01	0.29	0.51
	from -20 % to -15 %	< 0.01	–	–	0.17	7.2
	from -15 % to -10 %	0.12	–	0.22	18	13
	from -10 % to -7.5 %	0.49	–	0.27	0.67	1.9
	from -7.5 % to -5 %	0.69	–	0.6	1.7	12
	from -5 % to -2.5 %	20	–	8.9	17	16
	more than -2.5 %	79	100	90	63	50

impact on nitrogen and phosphorus loads. Phosphorus loads were affected more than nitrogen loads because lakes are more efficient traps for (mainly particulate) phosphorus than for (mainly dissolved) nitrogen. Stormwater retention ponds are often implemented primarily due to their positive impact on flood reduction and flood water retention in vulnerable areas and thus represent measures with potential benefits for stakeholders across different sectors. Modelled changes to riverine nutrient loads represent a desirable side

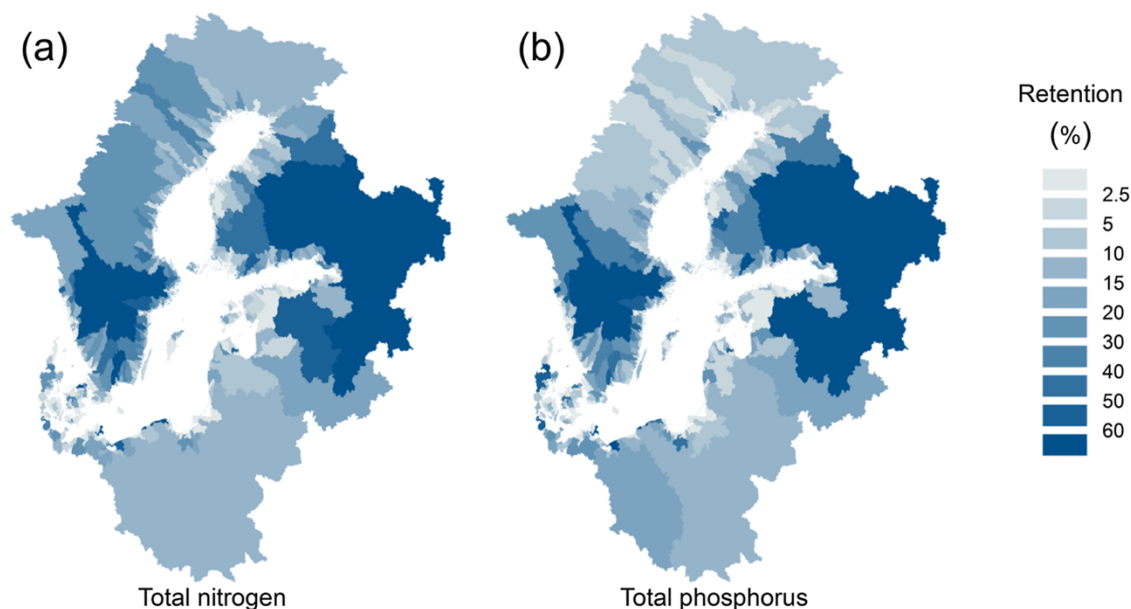


Fig. 4. Annual average HYPE modelled load retention of upstream gross loads at Baltic Sea outlets during the 1981 to 2010 period for (a) TN and



Fig. 5. E-HYPE-modelled nutrient loads under reference conditions and remediation measure scenarios. 30-year average annual total loads to the Baltic Sea (top) and the Baltic Proper (bottom) for TN (left) and TP (right). Red bars show current conditions (1981 to 2010), turquoise bars projected mid-century conditions under RCP8.5 climate and SSP2 socio-economic change. Bar heights show mean results for two climate models, black error bars show the range for individual climate model results. Numbers on top of each bar give the per cent reduction compared to the respective “No measure” model result. For Baltic Proper, cf. drainage area delineation in Fig. 2b (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

effect in this study with the ponds acting similarly to constructed on-stream wetlands that specifically target nutrient load reduction goals. Simulated load reductions exceeding 5 % of the local reference loads were simulated in 3 % of the BSDB area for nitrogen and 9 % for phosphorus. Stronger reductions exceeding 10 % were rare for nitrogen (0.5 % of the area) while such reductions were achieved for phosphorus in 3 % of the area.

The rural treatment measure scenario with the chosen release and reduction assumptions, i.e. near-elimination of rural household releases, showed the greatest impact of all modelled measures. Reductions are particularly pronounced in the southern and eastern half of the basin where the current load contributions from rural sources (i.e., for the reference year 2005) are comparatively high and thus represent a large share of the total loads. Nitrogen and phosphorus loads are reduced significantly at the local scale with reductions of at least 5 % in 39 % and 37 % of the BSDB area for nitrogen and phosphorus loads, respectively, and reductions at least 20 % in 15 % and 10 % of the BSDB area for nitrogen and phosphorus loads, respectively.

3.3. Impact of measures on nutrient loads at sea outlets

Spatial variation of upstream effects is smoothed out in the integrated net loads at sea outlets; only impacts which take effect over large areas in a particular basin result in an effective change at this scale (Figs. 2b/c and 3 b/c, lower maps). Internal retention of local loads in a basin can reduce net loads at the outlets, particularly in lake-rich regions or large basins with long in-stream travel times. In terms of measure impacts at sea outlets, this translates into diminished measure efficiencies where the internal retention is high (cf. phosphorus reductions at catchment and outlet scales for Swedish parts of Baltic Proper basin, Fig. 3b). Average modelled retention amounts ranged from under 2.5 % to more than 60 % for both nitrogen and phosphorus at the BSDB sea outlet basins during the reference period (Fig. 4). The areas of highest retention at sea outlets are basins upstream of the largest lake (systems) in the region: Lake Ladoga and the Finnish lake systems in the eastern parts, and Lake Vänern and Vättern to the west. Lakes with large volumes and long turnover times act as efficient sinks of upstream N and P loads. Retention in basins without large lake systems is lower, with subtle differences between TN and TP. Modelled retention of TN is generally higher than TP in the northern parts of the BSDB, possibly owing to instream denitrification of nitrogen loads originating from atmospheric deposition. This effect is masked in the southern parts of the BSDB where loads are higher and stem from multiple sources for both nitrogen and phosphorus.

For the combined measures scenario, the strongest impact at this scale is projected for the southern basin parts mainly due to the effectiveness of the rural source elimination scenario in these areas. Isolated local effects in small upstream catchments, e.g. most stormwater pond measure impacts, have little effect on loads at the corresponding sea outlets unless they are located in small coastal basins. Moderate over large areas with 18 % and 50 % of the BSDB area showing less than 2.5 % load

reduction (i.e., low impact) for the combined scenario for nitrogen and phosphorus, respectively (Table 2). TN loads are reduced more than the TP loads in most categories with 50 % and 35 % of the area showing a reduction of at least 5 % for nitrogen and phosphorus, respectively. The area fraction with reductions less than 2.5 % is in excess of 90 % for most individual measure scenarios except for the rural treatment scenario, which showed stronger reductions of both phosphorus and nitrogen loads over larger areas, and buffers, which showed a moderate reduction of phosphorus loads (larger than 2.5 %) over about 20 % of the area.

3.4. Cross-scale comparison of load reductions

Our integrated BSDB-wide model approach allows us to quantify scale dependencies of modelled load reductions in response to measure scenarios. While local impacts of measure scenario can be significant, reduction in net loads to the Baltic Sea are much lower. ‘Local’ in this context means E-HYPE model catchments, at a median size of 215 km² in the BSDB. The highest reductions modelled at this scale are in excess of 80 % for individual measures, in a small number of catchments (cf. Table 2, included in of the “less than -20 % “-bracket). Impacts at higher resolution, e.g. down to individual stream reaches may become even higher, but landscape the heterogeneity at these scales is no longer represented adequately in regionally driven hydrological model like E-HYPE to provide meaningful assistance with impact projections. Nonetheless, even the cross-scale comparison between E-HYPE catchment and sea outlet scales highlight the differences in impacts. For nitrogen, e.g., about 2 % of the BSDB area (127 catchments) achieved at least 40 % reduction at a local catchment level but only 3 sea outlet basins with very small areas (about 8600 km² combined, less than 0.1 % of BSDB) show at least 40 % reduction in net loads to the Baltic Sea.

Aggregated average modelled net loads to the Baltic Sea allow assessing the overall impact of the selected measure scenarios at this scale (Fig. 5). E-HYPE results at this scale illustrate a lack of impact of the measure scenarios unless they involve considerable reductions in nutrient source releases. Large scale impacts are almost negligible for measures that target an increased retention/removal without changing the source releases, ranging from no to 2.6 % reduction of the total nutrient loads aggregated to the Baltic Sea (Fig. 5). If the targeted measure significantly reduce nutrient source releases as in the rural source elimination scenario, nutrient loads were reduced to about 7 %. The fertiliser reduction scenario, which also reduced anthropogenic source releases, had lower impact compared to rural treatment because the scenario assumptions translated to a comparatively small area where the reduction was applied. New regulation approaches for fertiliser management, might result in higher reduction impacts than under the assumptions taken here, e.g. spatially differentiated regulation based on reduction potential for nitrogen (Refsgaard et al., 2019), or phosphorus fertiliser application strategies that minimise wash-off and subsequent loss through either soil sorption or direct transfer to the stream network (Kleinman et al., 2011). Miller et al. (2020) reported in a scenario-based analysis of nitrogen loads to the Chesapeake Bay drainage basin, that ca. half of the TN load from fertiliser sources could be removed by eliminating fertiliser leakage from the highest-contributing areas only, which amounted to ca. 10 % of the total agricultural area. This illustrates the potential for improvements under new regulation approaches.

Our integrated model approach also allowed us to compare nutrient loads to the Baltic Sea under combined and individual measures scenarios, in order to examine for evidence of synergies or antergies in the combined load reductions. Combined reductions are slightly lower than individual reductions combined for modelled TN and TP loads to the Baltic Sea (-9.3 % vs. -9.4 % for TN, -8.4 % vs. -8.9 % for TP), but the differences are too small to indicate reduced efficiencies under combined conditions at the BSDB outlet scale.

Most of the impacts were achieved in the part of the BSDB that drains to Baltic Proper (see drainage basin outline in Figs. 2b and 3 b). The Baltic proper is defined as the central sea basin of the Baltic Sea, distinguished from the Gulf of Bothnia to the north, the Gulf of Finland to the east, and the Belt Sea to the east. The Baltic proper drainage basin includes the largest fraction of agricultural land of the overall BSDB as well the largest human population. The nutrient load reductions for the Baltic Proper drainage basins are slightly higher than for the whole BSDB with the largest differences again seen for rural treatment measures. Combining all measures led to about 12 % and 9 % reductions for the Baltic Proper drainage basin and BSDB, respectively (Fig. 5).

As we move from local through sea outlet to the BSDB scale, we see an overall decrease in the magnitude of nutrient load reductions. Spatial aggregation reduces area fractions for the reduction categories at the extreme ends (minimum and maximum reductions) because upstream variation vanishes from the distribution. There are two main reasons for the decrease in the reductions. First, the measures are not applied to all catchments at the same scope but rather the scope varies with anthropogenic activities (agriculture and urbanisation). As the loads move downstream, contributions from catchments with and without the measures are accumulated. The smaller the scope of the implemented measures, the faster the overall load reductions decrease across scales. Second, nutrients can be retained or reduced in surface water for example through sedimentation or denitrification. Hence, measures that are implemented upstream of areas with significant retention or reduction will not have a significant effect on nutrient loads at the sea outlets. In particular, constructed remediation measures typically lack sufficient spatial-allocation scoping to contribute significantly to nutrient load reductions at the large basin scale. The implementation strategy considers local effects but does not necessarily target effects across large areas. This is coherent with previous model-based evaluation of the effects of constructed wetlands in southern Sweden, where negligible impacts were found on nutrient loads at sea outlets despite an extensive implementation effort (Arheimer and Pers, 2017).

3.5. Nutrient load reductions at the Baltic Sea scale under environmental change

Nutrient load reductions can change depending on the environmental conditions (Fig. 5). This is especially true for aggregated loads due to co-dependent effects of nutrients on algae production and transformation processes following higher order rate behaviour. 50s nutrient loads to the Baltic Sea without any mitigation measures, nitrogen loads show an overall

decrease under 2050s conditions, whereas phosphorus shows an overall increase. Climate change itself is projected to increase nutrient loads significantly as a result of increased discharge volumes (Bartosova et al., 2019). However, large reduction in nitrogen sources under SSP2 and especially the expected 30 % decrease of atmospheric deposition of nitrogen counteracts the increase projected from the climate change alone. While the SSP2 assumptions also include decrease in phosphorus load released into the BSDB, it is not sufficient to counteract the larger projected increase in phosphorus load (Ockenden et al., 2017). Changes in phosphorus loads are more closely related to changes in precipitation due to their close association with surface runoff.

The spatial pattern of impacts associated with individual or combined measures projected for 2050s conditions did not change from the overall pattern under current conditions. However, we see mostly similar or lower load reductions under 2050s conditions compared to the reference conditions for both nutrients (Fig. 5). Modelled nitrogen reductions for the “Rural treatment” scenario, e.g., are 6.7 % under reference conditions, and 6 % during the 2050s period with RCP8.5 and SSP2. The only notable exceptions are phosphorus load reductions for buffers and stormwater ponds. The projected increased phosphorus load reductions for buffers (from 1.8 % to 2.6 % reduction) can be likely related due to the higher proportion of surface flows projected for the 2050s.

3.6. Confidence and uncertainty in modelled scenario impacts

Modelling the impact of scenarios always carries considerable uncertainty with sources of uncertainty originating in all steps of the modelling chain from climate forcing data through the impact model structure and calibration to scenario assumptions. Modelling the effects of remediation measures on riverine nutrient loads at large basin scales is particularly challenging in this regard because of the lack of detailed data on nutrient source releases and the unpredictability of local management choices, both of which require strong assumptions and simplifications in conceptual model representation. Hydrological model approaches are, on the other hand, effective tools (i) to estimate over large areas and with adequate spatial resolution variables such as nutrient loads for which measurements are not readily available, and (ii) to dynamically assess impacts of change in climate and other environmental conditions using a scenario approach.

For impact modelling in this study, we used a minimal climate model ensemble with 2 members which allows us in a limited way to explore uncertainty in projected climate change impacts and relate it to overall modelled change magnitudes under measure scenarios. Modelled TN loads at the Baltic Sea scale under 2050s RCP8.5 and SSP2 assumptions showed an impact range of less than 1% between the two climate model members while TP loads showed a larger range around 6% between the two members, illustrating larger climate projection uncertainty for TP mobilisation and transport processes (cf. Fig. 5) than for TN processes. Total water discharge to the Baltic Sea was projected to increase between 14 % and 19 % with the two models, i.e. a strong change signal despite a wide range in projected magnitude. Bartosova et al. (2019) used a four-member ensemble designed to represent a range of projected changes in temperature and precipitation that included the two climate models chosen here for a similar impact analysis on BSDB-wide nutrient loads. One of the four members projected lower impacts particularly on TP loads compared to the impact range of our ensemble but none projected higher impacts. They found, however, a strong impact of socio-economic management scenario alternatives on nutrient loads, which outweighed the climate ensemble impact spread. This highlights the relative importance of considering the management scenario uncertainty in nutrient load projections for mid-century projections in this region.

Projection uncertainties in the measure scenarios themselves are arguably impossible to quantify but originate from a number of distinguishable sources. Measure efficiency itself varies with local conditions and can be hard to quantify exactly a priori. Phosphorus load reduction in buffer strips, e.g., depends on biogeochemical processes in a several flow paths within the buffer zone, with strong local variations (Hoffmann et al., 2009). Our results aim to show what load reductions can be expected over larger areas, and furthermore to highlight the importance of source reductions for large-scale effects using a theoretical elimination scenario for one of the relevant load sources in the BSDB. Nutrient reductions are also a function of hydrological conditions and thus variable in time (e.g. Johannesson et al., 2015). We aimed to alleviate the effects of this uncertainty by showing changes in long-term averages, which cover a wide range of hydrological conditions. Nonetheless, while models as E-HYPE simulate time-dynamic flow processes, small-scale dynamics at field scale are necessarily simplified in the model framework, reducing the real-world variation in the model results. Management-related effects pose another uncertainty source in the scenarios. For example, agricultural production is governed by changing climate and economic conditions and adaptation of farmers to these conditions, which translates into uncertainty in agricultural practices relevant to nutrient loads, e.g. crop cover and fertiliser rates (Huttunen et al., 2015).

Our integrated BSDB-wide measure scenario impact modelling should thus be interpreted as benchmarks which provide an understanding of change directions and relative impact magnitudes although they have to be contextualised with the underlying model assumptions. This holds particularly true for the rural source elimination scenario, which assumes load reductions that are unrealistic real-world targets, but serves as a theoretical end-point benchmark to illustrate impact ranges at the BSDB scale as a whole. Large-scale dynamic model approaches necessarily simplify local catchment variations, which have an influence on actual measure efficiency at the individual sites. Stormwater ponds, e.g., were assumed here to be implemented whenever the urban area-criterion in an E-HYPE catchment was fulfilled. The meaningfulness of an actual implementation in a specific place would of course depend on many more factors in the local settings, as would its design properties such as e.g. the drainage area of the constructed ponds. Other important factors for actual implementation are cost effectiveness and acceptance. For instance, fertilizer reductions and reductions in point source emissions have been shown to be important measures for reducing nitrogen loads across the BSDB in a cost-effective way (Elofsson, 2003). Carolus et al. (2020) reveal from a hydrological modelling study of 16 nutrient mitigation measures for three different European catchment areas (the Latvian Berze, the Swedish Helge and the German Selke rivers) a substantial local variability of the effectivity of measures due to different conditions such as land-use, soil or hydrological pathways, pointing towards the need for regionally tailored effectivity. The effectiveness of constructed wetlands to reduce nutrient loads has been shown to

depend on source emission amounts upstream of implemented wetlands, with cost efficiencies out-competing buffer zones and catch crops in cases where large sources were filtered efficiently (Gachango et al., 2015). Such studies illustrate that overall the cost effectiveness always also depend on local conditions, in addition to the effects of large-scale scoping and within-basin retention as highlighted by our large-scale impact-model results. Nonetheless, our results provide a set of what if-benchmarks for large scale impacts of locally implemented measures and as such can provide useful boundary conditions for scenario impact analyses of the Baltic Sea ecosystem itself (e.g. Neumann and Schernewski, 2005) and guide effective policy development to support HELCOM load reduction goals established in the BSAP.

In addition to the variation in efficiency of constructed measures, large-scale modelling approaches face the challenge of correctly estimating the current state of measure implementation. Data on rural wastewater emissions, e.g., are not available in detail over large areas, and thus have to be estimated using appropriate proxy data. Here, we used published data sources on population numbers and treatment efficiencies as proxies to calculate rural wastewater emissions for the reference period (2001–2010) at the E-HYPE catchment resolution. Updated data on treatment efficiencies (EEA, 2017) indicate an improved treatment in some of the HELCOM member states during the period up to the most recent published data for 2015. For Poland, e.g., overall fraction of population with treated wastewater increased from 60.2 % of the population in 2005 to 72.6 % in 2015, and the fraction for tertiary treatment increased from 37.3 %–58.9 % during the same period. This suggests that a part of the load reductions we projected for the rural wastewater measure have already been achieved as of today.

4. Conclusions

This study focussed on the integrated large-scale effects of local nutrient load reduction measures, modelled for the Baltic Sea region, where current nutrient loads at sea outlets have a negative impact on marine ecosystems. The key message from our scenario-driven model analysis is that reduction of source releases and scoping of measures should be the first considerations for choosing effective measures at this scale. Our results illustrate a diminishing effect of local measures on nutrient load reductions as the evaluation point moves from local to the BSDB scale if (i) measures do not include substantial reductions of nutrient source releases, or (ii) do not have a wide scope, i.e. are not applied over large areas. Even though our scenario assumptions themselves were not driven by nutrient reduction goals for the Baltic Sea, it is worth noting that the mean modelled reductions in nutrient loads the Baltic Sea under reference climate conditions and our combined measures scenario amount to 54 kilotons for total nitrogen and 2.2 kilotons for total phosphorus, respectively. This falls short of the estimated reduction needs of 118 kilotons for nitrogen and 15 kilotons for phosphorus to achieve good environmental status in the Baltic Sea as targeted in the Baltic Sea Action Plan (HELCOM, 2013) and highlights the need to specifically design programmes of measures which target large scale reduction goals alongside local, i.e. stream reach to catchment scale, goals.

These findings are not per se conflicting with significant load reductions in local catchments and other potential remediation goals such as increased biodiversity within the basin. They do, however, indicate a need to consider specifically basin-wide load reductions because adequate reductions might not be achieved merely as a by-product of locally effective remediation measures. This in turn may pose a challenge for policy makers and other decision makers involved in designing programs of measures which integrate local and large-scale improvements. In order to achieve substantial nutrient load reduction at the BSDB scale, we need to reduce nutrient emissions sufficiently at their sources.

We also found these conclusions to apply under 2050s conditions, combining climate change and socio-economic changes, which showed similar effects of measure scenarios as under reference conditions. 2050s “Middle of the Road” conditions also indicate decreasing loads for nitrogen mainly as a result of reduced atmospheric deposition, which compensated the increased loads projected from climate change alone. 2050s phosphorus loads, which did not include significant source changes, indicate a net increase as a result of the projected climate and socioeconomic conditions, albeit with a wide uncertainty range depending on the climate model.

CRedit authorship contribution statement

René Capell: Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition. **Alena Bartosova:** Conceptualization, Methodology, Writing - original draft, Visualization, Supervision, Funding acquisition. **Karin Tonderski:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition. **Berit Arheimer:** Conceptualization, Writing - original draft, Supervision, Funding acquisition. **Søren Marcus Pedersen:** Conceptualization, Methodology, Writing - review & editing, Funding acquisition. **Andis Zilans:** Conceptualization, Methodology, Funding acquisition.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgements

The study was performed at the SMHI Hydrological Research unit, building on previous work. Hence, input from more people other than the authors was essential for the basis of this study. We would especially like to acknowledge contributions from Johan Strömrovič, Thomas Roschard, and Kristina Isberg. The present work was funded by the BONUS project ‘Mediating integrated actions in a changing climate (MIRACLE)’ with contributions from BONUS project ‘Reducing nutrient

loadings from agricultural soils to the Baltic Sea via groundwater and streams (SOILS2SEA)'. The projects received funding from BONUS, the joint Baltic Sea research and development programme (Art 185), funded jointly from the European Union's Seventh Framework Programme for research, technological development and demonstration and from Innovation Fund Denmark, The Swedish Environmental Protection Agency (Naturvårdsverket), The Polish National Centre for Research and Development, The German Federal Ministry of Education and Research (BMBF), The Russian Foundation for Basic Research (RFBR), Latvian Ministry of Education and Science, Academy of Finland, Projektträger Jülich, and Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.ejrh.2021.100867>.

References

- Arheimer, B., Pers, B., 2017. Lessons learned? Effects of nutrient reductions from constructing wetlands in 1996–2006 across Sweden. *Ecol. Eng.* 103 (June), 404–414. <https://doi.org/10.1016/j.ecoleng.2016.01.088>.
- Arheimer, B., Wittgren, H.B., 2002. Modelling nitrogen retention in potential wetlands at the catchment scale. *Ecol. Eng.* 19 (1), 63–80.
- Arheimer, B., Löwgrén, M., Pers, B.C., Rosberg, J., 2005. Integrated catchment modeling for nutrient reduction: scenarios showing impacts, potential and cost of measures. *Ambio* 34 (7), 513–520. <https://doi.org/10.1579/0044-7447-34.7.513>.
- Arheimer, B., Dahné, J., Donnelly, C., 2012. Climate change impact on riverine nutrient load and land-based remedial measures of the Baltic Sea Action Plan. *Ambio* 41 (6), 600–612. <https://doi.org/10.1007/s13280-012-0323-0>.
- Balana, B.B., Jackson-Blake, L., Martin-Ortega, J., Dunn, S., 2015. Integrated cost-effectiveness analysis of agri-environmental measures for water quality. *J. Environ. Manage.* 161, 163–172. <https://doi.org/10.1016/j.jenvman.2015.06.035>.
- Bartosova, Alena, Capell, René, Olesen, Jørgen E., Jabloun, Mohamed, Refsgaard, Jens Christian, Donnelly, Chantal, Hyytiäinen, Kari, Pihlainen, Sampo, Zandersen, Marianne, Arheimer, Berit, 2019. Future socioeconomic conditions may have a larger impact than climate change on nutrient loads to the Baltic Sea. *Ambio* 48 (11), 1325–1336. <https://doi.org/10.1007/s13280-019-01243-5>.
- Britz, W., Pérez, I., Zimmermann, A., Hecke, T., 2007. Definition of the CAPRI Core Modelling System and Interfaces with Other Components of SEAMLESS-IF, SEAMLESS Report no.26, January 2007.
- Carolus, J.F., Bartosova, A., Olsen, S.B., Jomaa, S., Veinbergs, A., Zilans, A., Pedersen, S.M., Schwarz, G., Rode, M., Tonderski, K., 2020. Nutrient mitigation under the impact of climate and land-use changes: a hydro-economic approach to participatory catchment management. *J. Environ. Manage.* 271, 110976 <https://doi.org/10.1016/j.jenvman.2020.110976>.
- Donnelly, C., Andersson, J.C.M., Arheimer, B., 2016. Using flow signatures and catchment similarities to evaluate the E-HYPE multi-basin model across Europe. *Hydrol. Sci. J. Des Sci. Hydrol.* 61 (2), 255–273. <https://doi.org/10.1080/02626667.2015.1027710>.
- Ec.europa.eu, 2016. Small and Large Farms in the EU - Statistics from the Farm Structure Survey [online] Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Small_and_large_farms_in_the_EU_-_statistics_from_the_farm_structure_survey (Accessed 2017-09-26).
- EEA, 2013. Urban Waste Water Treatment. Available at: European Environment Agency <https://www.eea.europa.eu/data-and-maps/indicators/urban-waste-water-treatment/urban-waste-water-treatment-assessment-3>.
- EEA, 2017. Changes in Urban Waste Water Treatment in Eastern Europe. <https://www.eea.europa.eu/data-and-maps/daviz/changes-in-wastewater-treatment-in-11#tab-dash-board-01>.
- Elofsson, K., 2003. Cost-effective reductions of stochastic agricultural loads to the Baltic Sea. *Ecol. Econ. Manage. Eutroph. Coast. Ecosyst.* 47, 13–31. <https://doi.org/10.1016/j.ecolecon.2002.10.001>.
- Eurostat, 2016. Farm Structure Survey. Available at: <http://ec.europa.eu/eurostat/web/agriculture/data/database>.
- Fisher, J., Acreman, M.C., 1999. Wetland nutrient removal: a review of the evidence. *Hydrol. Earth Syst. Sci.* 8 (4), 673–685. <https://doi.org/10.5194/hess-8-673-2004>.
- Gachango, F.G., Pedersen, S.M., Kjaergaard, C., 2015. Cost-effectiveness analysis of surface flow constructed wetlands (SFCW) for nutrient reduction in drainage discharge from agricultural fields in Denmark. *Environ. Manage.* 56, 1478–1486. <https://doi.org/10.1007/s00267-015-0585-y>.
- Goldewijk, K.K., Beusen, A., van Drecht, G., de Vos, M., 2011. The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Glob. Ecol. Biogeogr.* 20 (1), 73–86. <https://doi.org/10.1111/j.1466-8238.2010.00587.x>.
- Hägg, H.E., Lyon, S.W., Wallstedt, T., Mörtz, C.-M., Claremar, B., Humborg, C., 2014. Future nutrient load scenarios for the Baltic Sea due to climate and lifestyle changes. *Ambio* 43 (3), 337–351. <https://doi.org/10.1007/s13280-013-0416-4>.
- HELCOM, 2013. Summary Report on the Development of Revised Maximum Allowable Inputs (MAI) and Updated Country Allocated Reduction Targets (CART) of the Baltic Sea Action Plan. Baltic Marine Environmental Protection Commission. 2013 HELCOM Ministerial Declaration.
- Hoffmann, C.C., Kjaergaard, C., Uusi-Kamppa, J., Bruun Hansen, H.C., Kronvang, B., 2009. Phosphorus retention in riparian buffers: review of their efficiency. *J. Environ. Qual.* 38 (5), 1942–1955. <https://doi.org/10.2134/jeq2008.0087>.
- Howden, N.J.K., Burt, T.P., Mathias, S.A., Worral, F., Whelan, M.J., 2011. Modelling long-term diffuse nitrate pollution at the catchment-scale: data, parameter and epistemic uncertainty. *J. Hydrol.* 403, 337–351. <https://doi.org/10.1016/j.jhydrol.2011.04.012>.
- Hundecha, Y., Arheimer, B., Donnelly, C., Pechlivanidis, I., 2016. A regional parameter estimation scheme for a pan-European multi-basin model. *J. Hydrol. Reg. Stud.* 6, 90–111. <https://doi.org/10.1016/j.ejrh.2016.04.002>.
- Huttunen, I., Lehtonen, H., Huttunen, M., Piirainen, V., Korppoo, M., Veijalainen, N., Viitasalo, M., Vehviläinen, B., 2015. Effects of climate change and agricultural adaptation on nutrient loading from Finnish catchments to the Baltic Sea. *Sci. Total Environ.* 529, 168–181. <https://doi.org/10.1016/j.scitotenv.2015.05.055>.
- Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., et al., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. *Reg. Environ. Change* 14 (2), 563–578. <https://doi.org/10.1007/s10113-013-0499-2>.
- Johannesson, K.M., Kynkäänniemi, P., Ulén, B., Weisner, S.E.B., Tonderski, K.S., 2015. Phosphorus and particle retention in constructed wetlands—a catchment comparison. *Ecol. Eng.* 80, 20–31. <https://doi.org/10.1016/j.ecoleng.2014.08.014>.
- Kleinman, Peter J.A., Sharpley, Andrew N., McDowell, Richard W., Flaten, Don N., Buda, Anthony R., Tao, Liang, Bergstrom, Lars, Qing, Zhu, 2011. Managing agricultural phosphorus for water quality protection: principles for progress. *Plant Soil* 349 (1–2), 169–182. <https://doi.org/10.1007/s11104-011-0832-9>.
- Lindström, G., Pers, C., Rosberg, J., Strömqvist, J., Arheimer, B., 2010. Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales. *Nord. Hydrol.* 41 (3–4), 295–319. <https://doi.org/10.2166/nh.2010.007>.
- Miller, M.P., Capel, P.D., Garcia, A.M., Ator, S.W., 2020. Response of Nitrogen Loading to the Chesapeake Bay to Source Reduction and Land Use Change Scenarios: A SPARROW-Informed Analysis. *J. Am. Water Resour. Assoc.* 56, 100–112. <https://doi.org/10.1111/1752-1688.12807>.
- Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* 50 (3), 885–900.
- ... ecological model evaluation of two nutrient abatement strategies for the Baltic Sea. *J. Mar. Syst.* 56 (1), 195–206. <https://doi.org/10.1016/j.jmarsys.2005.06.002>.

- Ockenden, M.C., Hollaway, M.J., Beven, K.J., Collins, A.L., Evans, R., Falloon, P.D., Forber, K.J., Hiscock, K.M., Kahana, R., Macleod, C.J.A., Tych, W., Villamizar, M. L., Wearing, C., Withers, P.J.A., Zhou, J.G., Barker, P.A., Burke, S., Freer, J.E., Johnes, P.J., Snell, M.A., Surridge, B.W.J., Haygarth, P.M., 2017. Major agricultural changes required to mitigate phosphorus losses under climate change. *Nat. Commun.* 8, 161. <https://doi.org/10.1038/s41467-017-00232-0>.
- Portmann, F.T., Siebert, S., Doell, P., 2010. MIRCA2000-global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochem. Cycles* 24 (March), GB1011. <https://doi.org/10.1029/2008GB003435>.
- Refsgaard, Jens Christian, Hansen, Anne L., Hojberg, Anker L., Olesen, Jorgen E., Hashemi, Fatemeh, Wachniew, Przemyslaw, Worman, Anders, Bartosova, Alena, Steljes, Nico, Chubarenko, Boris, 2019. Spatially differentiated regulation: can it save the Baltic Sea from excessive N-loads? *Ambio* 48 (11), 1278–1289. <https://doi.org/10.1007/s13280-019-01195-w>.
- Riahi, K., Grübler, A., Nakicenovic, N., 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol. Forecast. Soc. Change* 74 (7), 887–935. <https://doi.org/10.1016/j.techfore.2006.05.026>.
- Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Streffer, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob. Environ. Change* 42, 153–168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>.
- Strömqvist, J., Arheimer, B., Dahne, J., Donnelly, G., Lindström, G., 2012. Water and nutrient predictions in ungauged basins: set-up and evaluation of a model at the national scale. *Hydrol. Sci. J. Des Sci. Hydrol.* 57 (2), 229–247. <https://doi.org/10.1080/02626667.2011.637497>.
- Sutherland, R.C., 1995. Methodology for estimating the effective impervious area of urban watersheds. *Watershed Protect. Tech.* 2 (1), 282–284.
- Swedish, E.P.A., 1995. Vad innehåller avlopp från hushåll? Report 4425 (in Swedish). ISBN 91-620-4425-4427.
- USEPA, 1986. Methodology for Analysis of Detention Basins for Control of Urban Runoff Quality. United States Environmental Protection Agency Report, EPA440/5-87-001.
- van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. *Clim. Change* 109, 5–31. <https://doi.org/10.1007/s10584-011-0148-z>.
- Walczkiewicz, T., Bartosova, A., Capell, R., Jomaa, S., Lagzdīņš, A., Skonieczna, M., Veinbergs, A., Woźniak, Ł., 2017. Report and Data Set on Scenario Modelling of Measures Suggested by Stakeholders to Reduce Flooding, Eutrophication, Enhance Biodiversity and Contribute to Other Goals, As Well As Climate Change Scenarios. Report D 2.3, BONUS MIRACLE Project. Available on. <http://bonus-miracle.eu>.
- Withers, P.J.A., Sylvester-Bradley, R., Jones, D.L., Healey, J.R., Talboys, P.J., 2014. Feed the Crop Not the Soil: Rethinking Phosphorus Management in the Food Chain. *Environ. Sci. Technol.* 48, 6523–6530. <https://doi.org/10.1021/es501670j>.
- Wulff, F., Humborg, C., Andersen, H.E., Blicher-Mathiesen, G., Czajkowski, M., Elofsson, K., Fonnesbech-Wulff, A., et al., 2014. Reduction of Baltic Sea nutrient inputs and allocation of abatement costs within the Baltic Sea Catchment. *Ambio* 43 (1), 11–25. <https://doi.org/10.1007/s13280-013-0484-5>.
- Yang, W., Andréasson, J., Graham, Phil., Olsson, J., Rosberg, J., Wetterhall, F., 2010. Distribution-based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies. *Hydrology Research* 41, 211. <https://doi.org/10.2166/nh.2010.004>.
- Zandersen, M., Olesen, J.E., Jabloun, M., Andersen, H.E., Hyytiäinen, K., Pihlainen, S., Sihvonen, M., Gustafsson, B., Tomczak, M., Bauer, B., Smedberg, E., Humborg, C., McCrackin, M., Swaney, D., Refsgaard, J.C., 2016. Report on Regionalized SSPs and RCPs Resulting in a Coherent Set of Climate and Socioeconomic Scenarios for the Baltic Sea Region. Report D 1.1, BONUS BALTICAPP Project. Available on. https://blogs.helsinki.fi/balticapp/files/2015/05/BONUS_BalticAPP_D1_1_Regionalized-SSPs.pdf.