Assessment of future climate and land use changes on streamflow and phosphorus transport in a Swedish agricultural catchment

Clara Laguna Marín

Master thesis (30 hp)
MSc in Soil, Water and Environment

Department of Aquatic Sciences and Assessment
Swedish University of Agricultural Sciences
Uppsala, 16th of June 2022

Assessment of future climate and land use changes on streamflow and phosphorus transport in a Swedish agricultural catchment

Clara Laguna Marín

Supervisor: Emma Lannergård, Swedish University of Agricultural Sciences
Department of Aquatic Sciences and Assessment

Examiner: Martyn Futter, Swedish University of Agricultural Sciences
Department of Aquatic Sciences and Assessment

Credits: 30 ECTS
Level: Advanced level, A2E
Course title: Independent Project in Environmental Science – Master's thesis
Course code: EX0897
Programme/education: Soil, Water and Environment – Master's programme

Place of publication: Uppsala
Year of publication: 2022
Cover picture: Clara Laguna Marín
Online publication: http://stud.epsilon.slu.se

Keywords: surface water modelling, phosphorus, suspended sediment, climate change scenarios, socio-economic scenarios, INCA-PEco

Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences
Faculty of Natural Resources and Agricultural Sciences
Department of Aquatic sciences and assessment
Geochemistry and Hydrology

Abstract

Despite efforts for reducing nutrient excess in surface waters in the last decades, eutrophication continues to be an important environmental problem in Europe. The presence of excess phosphorus (P) in waters, together with nitrogen (N), is one of its main causes. To adopt adequate management strategies to fight this problem in the long term, it is crucial to understand how P may respond to future environmental change. The present study explored this direction of research by testing the effects of future climate, weather and land use on streamflow and total P using hydrologic and water quality modelling in Sävjaån catchment (722km^2), central Sweden. The scenarios represented future changes in period 2071-2100 derived from representative concentration pathway (RCP) emission scenarios, changes in extreme precipitation patterns and land use changes. Results showed higher maximum P loads when more extreme precipitation events were combined with high emission scenarios (RCP 4.5 and 8.5). Besides, extreme precipitation increase caused bigger differences between maximum and minimum annual P loads, suggesting an increased uncertainty in future projections. Lastly, results indicated a shift in the seasonal distribution in loads, with decreases in winter and spring loads associated with less snowfall and increases in autumn and specially summer loads.

Keywords: surface water modelling, phosphorus, suspended sediment, climate change scenarios, socio-economic scenarios, INCA-PEco

Popular science summary

Phosphorus (P) is a necessary nutrient for plants and algae growth. The source of this nutrient is found in sediments and rocks, but it can also travel to water. In some places, too much P travels to water, and this excess of nutrients causes a problematic process called eutrophication. When eutrophication occurs, the waters become an unpleasant place to live: the excess of nutrients available as food causes the growth of too many organisms such as algae, plants or microorganisms. This excess of living creatures in water can end up all the oxygen in the water, and sometimes even create toxic substances, creating an environment that is damaging for many organisms. When waters suffer from eutrophication, they also become unpleasant places for people, where swimming or drinking can be dangerous, and activities such as fishing are scarce due to the lack of fishes. Therefore, this problem is often accompanied by many social and economic costs related to the loss of natural resources and recreational services provided by healthy freshwaters. Eutrophication is an actual problem that occurs in the whole world, and therefore there are many efforts put into understanding how P contributes to this problem and how to adopt corrective and protective measures to stop it.

To better understand how to mitigate the effect of excessive P in waters it is important to study the factors that contribute to the mobilisation of P and how these will change in the future. In this study, we analysed two of the most important factors for P mobilisation, climate and land use. More specifically, we analysed how future climate change and future changes in land use will affect the transport of P to the surface waters in a Swedish agricultural catchment (Sävjaån) by the years 2071-2100. To do so, we used two models, which are mathematical representations of reality, that in this case simulate the hydrological and chemical processes of the catchment. For the future climate, we tested different changes in climate and temperature predicted by the International Panel on Climate Change (IPCC). Climate related, we also tested the increase of extreme precipitation events, which is expected to occur in the North of Europe. For land use, we tested different changes in land use cover (forestry, agriculture, urban areas…) that accompany possible society developments, following the Nordic Bioeconomy Pathways.

Our results showed that future climate change will influence P export to waters, and therefore eutrophication. Among those, one of the most significant findings was that the strongest change in P transport to waters in Northern Europe will be related to the increase in extreme precipitation events. That change in precipitation distribution will, in addition, produce very high and very low P transport, depending on the year, making in very difficult to make accurate predictions. On the other hand, we found that the seasonal distribution of P transport to waters will shift with climate change, decreasing in winter and spring and increasing in summer. Lastly, we found that land use change related to the Nordic Bioeconomy Pathways will influence the most P transport when this land use change shifts towards an increase of agricultural areas.

From our results, we suggest to future managers that eutrophication control measures will have to focus on handling very high and unpredictable P loads, and that these measures will also have to be adapted to the change in seasonal trends and P loads derived from agriculture.

Table of Contents

Table of figures

Table of tables

List of abbreviations

P	Phosphorus
N	Nitrogen
SS	Suspended Sediment
TP	Total Phosphorus
RCP	Representative Concentration Pathway
IPCC	International Panel on Climate Change
SMHI	Swedish Meteorological and Hydrological Institute
NBP	Nordic Bioeconomy Pathway
NSE	Nash-Sutcliffe Efficiency
KGE	Kling Gupta Efficiency

1. Introduction

1.1 Eutrophication and phosphorus

Eutrophication, the excess of nutrients in lakes, streams and coastal areas, has become a globally widespread problem (Farkas *et al.*, 2013; Jackson-Blake *et al.*, 2016) that has environmental, social and economic consequences at both local and regional scales (Lannergård *et al.*, 2020). The main drivers of this process are anthropogenically derived phosphorus (P) and nitrogen (N) (Smith and Schindler, 2009; Bol *et al.*, 2018) which enter the environment mainly through the use of mineral fertilizers, manure and atmospheric deposition of N (Peñuelas *et al.*, 2013).

One of the main effects of N and P excess in waters is the increase of plant biomass, such as phytoplankton and macrophytes. The excess growth of these organisms often causes a depletion of oxygen levels in water, a shift towards bloom-forming algal species -that may be toxic or inedible-, and an increase in water turbidity (Smith and Schindler, 2009). The combination of these multiple effects also create challenging environmental conditions for life, contributing to a huge loss of biodiversity in water ecosystems (Chen *et al.*, 2015). In addition, eutrophication processes are accompanied by severe economic and social consequences, such as the loss of recreational values of water bodies, costs derived from drinking water treatment, costs for removal of algal toxins and decomposition products, and economic loss from tourism (Pretty *et al.*, 2003).

As a limiting nutrient in freshwater systems, P has been shown to be specially relevant in controlling eutrophication (Wade, Whitehead and Butterfield, 2002; Bechmann *et al.*, 2005). Studies such as the one carried by Schindler *et al.* (2008) for example, prove how freshwaters which do not present N excess, still suffer severe eutrophication problems associated to P, suggesting that the control of P is crucial in regulating nutrient excess problems.

In the landscape, P can be found in dissolved (bioavailable) or particulate forms. Particulate P is easily transformed to dissolved P, therefore it is common to account for both forms as total P (TP). Phosphorus can enter rivers and other water bodies through point sources, such as sewage, or through diffuse sources, such as overland flow or leaching (Crossman et al., 2014). The transport of P from point or diffuse sources to water bodies is mainly conditioned by the catchment's hydrology. Catchment hydrology is in turn influenced by many factors, such as topography, geology, climate or land use. In the case of this study, we focus on the analysis of climate and weather (Murdoch, Baron and Miller, 2000; Darracq *et al.*, 2005; Moore *et al.*, 2007) and land use (Ross *et al.*, 1999; Farkas *et al.*, 2013; Djodjic, Bieroza and Bergström, 2021) as potential drivers of P inputs to river networks.

1.2 Climate and land use change effects on nutrient export

Climate has an influence in catchment hydrology, which is a crucial factor regulating nutrient transport (Crossman et al., 2014). The change in temperatures and precipitation alter catchments hydrology and distribution of water in the landscape (Grusson *et al.*, 2021) changing the timing and magnitude of runoff and soil moisture, conditioning river discharge regimes, groundwater availability and lake levels (Crossman et al., 2014).

In the next decades in Northern Europe, climate change is expected to increase precipitation and heavy rainfall events (IPCC, 2021). One of the effects of this projected precipitation change, is the increase of N and P loadings to surface waters (Murdoch, Baron and Miller, 2000). As stated by Chen *et al.*, (2015), it is common to observe higher P exports in higher precipitation years, as precipitation increases erosion and subsequently transport of particles to streams.

On the other hand, changes in land use are continuously occurring in the landscape, especially due to a growing population and demands for food and other resources experienced in the last decades (Stürck *et al.*, 2018). Many studies have assessed how different land uses -such as agriculture, forest or urban areas- impact the mobilisation of nutrients like P into freshwater (Ross *et al.*, 1999; Farkas *et al.*, 2013; Bai, Ochuodho and Yang, 2019). These studies agree in the fact that differences in soil physical properties or vegetation cover characteristic of each land use type can shape the hydrological regime by increasing runoff or infiltration and regulating water retention times (Grusson *et al.*, 2021).

1.3 Modelling as a tool to assess the future of eutrophication

Despite the successful advances in reducing water nutrient excess in the last decades in Europe, there are still many surface waters suffering from P-related eutrophication (Jackson-Blake *et al.*, 2016). Therefore, it is crucial to study the possible consequences in P mobilisation associated with future climate and land use changes.

To do so, the scientists and decision makers commonly use models that permit the evaluation of changes in water quality under future climate or land use scenarios (Moss *et al.*, 2010). These models are mathematical representations of complex catchment systems, and can be used as a scientifically based tool for decision making (Jackson-Blake *et al.*, 2016). They are used for example to study point and diffuse pollution sources and how these will be affected by changes in precipitation, temperature or land use (Wellen, Kamran-Disfani and Arhonditsis, 2015).

From a management perspective, models can help set water quality goals and explore the best ways to reach them, predict time lags and trade-offs in the systems, explore potential system responses to future changes (Jackson-Blake *et al.*, 2016) and reduce the costs associated to N and P load reduction measures (Wade, Whitehead and Butterfield, 2002). Of course, working with models is not a way of predicting the future, but it makes it easier to assess the uncertainties that accompany a wide range of possible futures (Moss *et al.*, 2010) and the challenges that society may face.

1.4 Objectives

This study aims to assess the effect of future climate, weather and land use scenarios on the transport of phosphorus in Sävjaån catchment. To do so, the study will:

(i) Build representative scenarios to simulate changes in climate, extreme precipitation and land use in Sävjaån catchment
(ii) Evaluate changes in streamflow, suspended sediment, and total phosphorus caused by the future scenarios.

2. Background

2.1 Climate change

In the last decades the Earth has experienced an unprecedented global warming caused by anthropogenic greenhouse gas (GHG) emissions (IPCC, 2021). This increase of temperatures has impacted multiple aspects of the Earth's functioning, such as atmospheric dynamics and the global water cycle (EASAC, 2013), changes that have been reflected in an alteration of precipitation patterns and extreme events occurrence across every region of the globe (Grusson *et al.*, 2021).

The basic science and trends in global warming and associated climate change have been reviewed in detail by the International Panel on Climate Change (IPCC). In the last decades, IPCC has reported consequences of climate warming such as a global increase of precipitation, a decrease in spring snow cover and an increase in frequency and intensity of heatwaves, heavy precipitation events, droughts and tropical cyclones (Bai, Ochuodho and Yang, 2019; IPCC, 2021).

2.1.1 Future perspectives on climate change

Future perspectives on climate change are often assessed with climate models, which picture changes in climate based on possible future scenarios (Moss *et al.*, 2010). Climate models are commonly based on emission scenarios, which describe future possible discharges of substances that affect the Earth radiation balance, like GHGs and aerosols, and make a difference in the future precipitation and temperature patterns. The most recent set of widely used scenarios are based on representative concentration pathways (RCPs) based on changes in radiative forcing (energy uptake by the atmosphere) associated with increased GHG concentrations. The assumption of different possible futures is important because the future is uncertain. The use of these models it is useful to assess both trends in GHG emissions and their consequences in relation to society's development.

In the next decades, climate models point towards a continued increase of global surface temperatures under all emission scenarios (IPCC, 2021). This increase will be notable already in the near-term future and continue up to the end of the century. Similarly, precipitation is expected to increase at a global scale, especially in the northern regions (Hov *et al.*, 2013). Besides precipitation increase, continued global warming is predicted to alter the global water cycle. Precipitation and surface water flow are likely to become more variable within seasons over most land regions. In addition, wet and dry events are expected to become more severe and frequent (IPCC, 2021).

The latest IPCC report (AR6) also predicts a future increase in frequency and intensity of extreme events such as heatwaves, heavy precipitation and agricultural and ecological droughts (IPCC, 2021). The distribution of these events vary between models, but most of them conclude that the increase will occur mainly over land areas in middle and high latitudes (Frei *et al.*, 2006) and are expected to appear in regions where they had never been registered before (IPCC, 2021). The increase of these events is a critical question, since it may greatly affect agricultural systems, ecosystems and livelihoods and threaten the wellbeing of communities, specially the most vulnerable ones (EASAC, 2013).

2.1.2 Tendencies in Europe and Scandinavia

In Europe, average temperatures have been increasing since 1980 (Kovats *et al.*, 2014). In Northern Europe this increase has been higher, especially in winter (EEA, 2017) and cold temperature extremes have become less frequent (IPCC, 2021). There has also been an increase of precipitation (EEA, 2017) and heavy precipitation events, by 45% in 1981-2013 compared to 1951-1980 (Fischer and Knutti, 2016).

In the next decades, similar tendencies are expected to occur. Higher annual mean temperatures in Europe will further alter the occurrence of weather extremes: heat waves are expected to become more intense, long and frequent and winter cold extremes are expected to become rarer (Hov *et al.*, 2013). Precipitation extremes are also expected to change, with an increase of heavy precipitation events in Northern Europe (Larsen *et al.*, 2009; Hov *et al.*, 2013; Grusson *et al.*, 2021).

In Sweden, temperatures and precipitation are expected to increase by the end of the century. The Swedish Meteorological and Hydrological Institute (SMHI) predicts an increase of 2-6ºC in temperature (SMHI, 2021b) and 20-60% in precipitation (SMHI, 2021a) (depending on the RCP scenario) by the end of the century, compared to 1961-1990. Besides, climate change is expected to alter the precipitation pattern and produce more intense rainfall events (Grusson *et al.*, 2021). This increase is expected to occur in all seasons, but especially during the months of winter and more notably in the northern areas. Besides, it is predicted that the permafrost thaw will increase as well as the loss of seasonal snow cover (IPCC, 2021).

2.2 Land use change

Land systems respond closely to the way in which society changes in an economic, politic, and technological way. In the last decades, a growing population and changing consumption habits have led to an intensification of land use, causing increasing pressures on natural systems such as land and water bodies, and the ecosystem services they provide (Stürck *et al.*, 2018). Even if studies point towards the continuation of these trends (Lotze-Campen *et al.*, 2008), future world societal development inherently contains a high level of uncertainty (Moss *et al.*, 2010). Land use change is therefore not as easy to model as climate change, but it is equally important when talking about nutrient export and eutrophication change in the future.

To assess the uncertainty of societal development in the future, often the research and management community uses socioeconomic scenario studies (Moss *et al.*, 2010; O'Neill *et al.*, 2017; Stürck *et al.*, 2018) which describe future possible developments for society. They are based on credible and legitimate future storylines, and they are very useful in exploring possible futures of land use change (Stürck *et al.*, 2018). The use of these scenarios has been proved to be a valuable tool for planning when facing complexity and uncertainty (Kok *et al.*, 2019), helping to prepare the mitigation measures needed for different situations.

2.2.1 Global socio-economic scenarios: The Socioeconomic Pathways

The Shared Socioeconomic Pathways (SSPs) (O'Neill *et al.*, 2017) are one of the most extended alternative futures for societal development. They describe the evolution of key aspects of society such as demography, human development, economy, politics and technology (EEA, 2017). These scenarios are set at a global scale and are intended to be used as a basis for emissions and land use scenarios, as well as climate change impact, adaptation and vulnerability analyses.

2.2.1.1 The Nordic Bioeconomy Pathways

The Nordic Bioeconomy Programme (Nordic Council of Ministers, 2018) is a strategic programme for the development of the Nordic Countries that focuses on the development of the bioeconomy (bioresource-based economy). The main goal of the Nordic Bioeconomy Programme is to achieve a more sustainable society, however, there are concerns about how it will affect the state of land and water resources. Firstly, the development of a bioeconomy based future will demand an increase of biomass production for bioresource-based materials and fuels, increasing the pressure on land resources (Rakovic *et al.*, 2020). Secondly, the production of biomass will increase nutrient and sediment loads to the waters, (Marttila *et al.*, 2020) threatening the quality and ecological status of water resources.

To assess the uncertainties that a future bioeconomy based society poses towards the maintenance of ecosystem services, Rakovic et al. (2020) developed the Nordic Bioeconomy Pathways (NBPs), regional future storylines that picture possible outcomes of the Nordic Bioeconomy Programme. These storylines follow the basic structure of the SSPs but are downscaled to a regional scale. They are intended to be used for catchment modelling, ecosystem service studies and stakeholder dialogue to assess changes in agricultural and forestry management (Rakovic *et al.*, 2020).

3. Methodology

3.1 Study site

The study was carried out in Sävjaån catchment, Uppsala County, Sweden. It is a lowland catchment characteristic of central Sweden, located to the east of Uppsala city. Nutrient excess has become a problem for the catchment, where almost 50% of the lakes and streams are considered eutrophic (Vattenmyndigheten Norra Östersjön, 2016). Covering 722 km^2 the main land use is forest (70%), but it also contains agricultural land (14.8%), pasture (10.7%), wetlands (2.5%) and urban areas (2%). Agriculture common crops are winter wheat (17%), ley (14%), spring barley (11%) and fallow (6%) (Hansson *et al.*, 2019).

The region has a temperate climate and four clearly distinguished seasons. The annual average precipitation is 639mm, and annual average runoff is 189 mm (1981-2010) (SMHI, 2020). The geomorphology of the catchment is mostly flat, with a maximum elevation of 70m, and it is dominated by sandy till deposits, postglacial/glacial clay and bare rock (Lannergård et al., 2020). Agricultural areas are generally located in clay soils whilst forests are more present on till soils (Lannergård *et al.*, 2019).

The catchment is crossed by multiple streams and lakes that drain the area into its lowest point (Figure 1) and later connect with the Fyrisån river. Flow in streams is usually higher in spring, caused mainly by seasonal snow melt. On the other hand, flow is lower in summer. In autumn, flows are higher than summer. In winter flows are generally low due to the low temperatures and are only sustained by sporadic rainfall and some snowmelt. Those streams that cross agricultural areas are generally managed, usually deepened and straightened to obtain better drainage.

Figure 1. Sävjaån catchment, waterways and lakes. Red dot indicating sampling station where measurements for model calibration were taken, close to catchment outlet.

3.2 Streamflow - nutrient modelling

Two complementary models, PERSiST (version 1.6) and INCA-PEco (version 1.0 beta 5) were used to model streamflow and P transport under climate and land use scenarios (Figure 2). PERSiST was used to model runoff changes in the catchment and INCA-PEco to model export of suspended sediment (SS) and total phosphorus (TP). Both models were set-up to represent Sävjaån catchment and calibrated to discharge and water chemistry data. Precipitation and temperature data from climate scenarios were the driving data in PERSiST. This model produced soil moisture deficit (SMD) and hydrologically effective rainfall (HER). Time serioes of SMD, HER, precipitation and temperature were then used as inputs to INCA-PEco. In INCA-PEco different land use classes were specified, as inputs from land use scenarios, and the catchment was split into different geographic units with the aim of modelling nutrient transport throughout the catchment.

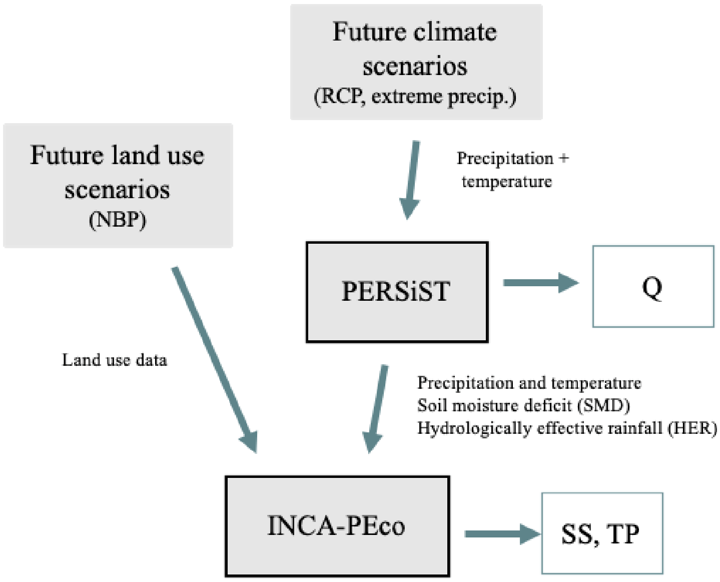

Figure 2. Schematic representation of the models and scenarios used, with main inputs and outputs.

3.2.1 Rainfall-runoff model (PERSiST): characterization and calibration

PERSiST (Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport) (Futter *et al.*, 2014) is a semi distributed landscape scale rainfall-runoff model. It is designed to simulate actual catchment hydrology as well as to evaluate future changes in runoff and storage. PERSiST has already been successfully used in studies to model potential impacts of future extreme precipitation events on stream runoff generation (Futter *et al.*, 2014; Ledesma *et al.*, 2021). In this study PERSiST (version 1.6) was used to evaluate impacts on streamflow derived from precipitation and temperature changes associated with climate change.

The model is structured in four spatial levels (Figure 3) that can be adjusted to represent specific catchments. It is composed by one watershed (Level 1) divided in subcatchments or reaches (Level 2). Each of these subcatchments contains different landscape or hydrological response units (e.g. forest, agriculture) (Level 3) which contain buckets (level 4) through which water is routed (e.g. surface runoff, groundwater).

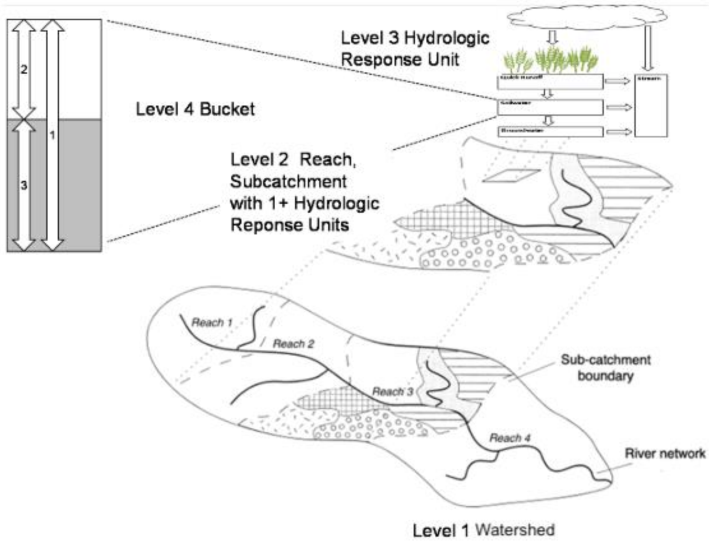

Figure 3. PERSiST conceptual structure, modified from Futter et al. (2014).

In the present study, the model was set up to represent the Sävjaån catchment. For simplification, the model was defined with one subcatchment/reach unit. This structure gave enough resolution to adequately evaluate the results for the purpose of this study whilst increasing notably the efficiency of later data processing. The catchment was divided in five land use classes (Table 1) that represent land use in the Sävjaån catchment. Each of the landscape units contained the following buckets: snow, direct runoff, upper unsaturated, lower unsaturated and groundwater.

Table 1. Sävjaån hydrological response / landscape units used in PERSiST model setup with their occupied area in the catchment (Hansson et al., 2019), total area 722km^2.

Landscape Unit	**Catchment area (%)**
Forest	70
Arable	14,8
Pasture	10,7
Wetlands	2,5
Urban	2

Once the structure was defined, the model was calibrated to field observations. The streamflow measurements were taken from Sävja SMHI station (Station number 2243) which is located close to the hydrological outlet of the catchment. This process was done by manually adjusting the model's parameters to produce a streamflow as close as possible to real streamflow measurements.

The manual calibration results were used as a starting point parameter sensitivity exploration with Monte Carlo (MC) analysis. The MC run 50 chains of 500 samples and the process was repeated 10 times. The analysis identified credible parameter sets among which the one with best model performance was chosen.

The metrics used to validate model performance were the Pearson correlation (r^2) and Nash-Sutcliffe Efficiency (NSE), commonly used in watershed model evaluation (Seibert and McDonnell, 2002; Moriasi *et al.*, 2015; Wellen, Kamran-Disfani and Arhonditsis, 2015;

Onyutha, 2022) and where higher value indicate a better fit. The model presented performance metrics of r^2 = 0,757 and NSE = 0,74. These parameters are considered satisfactory in model performance for daily watershed scale models when r^2 > 0,6 and NSE = 0,5 (Moriasi *et al.*, 2015).

After performance evaluation, the model was applied for different precipitation and temperature sets of data arranged in future scenarios, described in Chapter *3.2 Future change scenarios*.

3.2.2 Phosphorus model (INCA-PEco): Characterisation and calibration

INCA-PEco (Integrated Catchment model for Phosphorus dynamics) (Crossman *et al.*, 2021) is a dynamic, mass balance hydrochemical model that simulates temporal variations of P pools and fluxes in a catchment. It aims to help evaluate the transport and retention processes of P in the aquatic and terrestrial environment, and the effect on aquatic biodiversity. In this study, INCA-PEco was used to simulate SS and TP transport in Sävjaån catchment in order to characterise the response to climatic and land use changes.

The model can be adjusted to a specific catchment by including representations of land use, river networks and stream properties (Crossman *et al.*, 2021). It is structured in a terrestrial (or land) phase and a stream phase which contain different buckets and compartments that simulate P dynamics. In the simulation P can potentially originate from storage in the soil, groundwater or eroded material and can be delivered to the stream from quick flow, soil water flow or directly from groundwater. The model also considers point sources and instream processes, and maintains mass balances.

For this study, the model structure was set up to represent Sävjaån catchment by including 4 subcatchments: Lejstaån, Stora Hopan, Sävjaån and Storån. The land cover classes used were the same as the used in PERSiST (forest, arable, pasture, urban and wetland) and were specified for each subcatchment (Table 2).

Table 2. Land cover area distribution in Lejstaån, Stora Hopan, Sävjaån and Storån subcatchments (Hansson et al., 2019).

Land cover	Area (km^2)			
type	Lejstaån	Stora Hopan	Sävjaån	Storån
Forest	94.71	249.28	28.86	127.38
Arable	13.53	32.8	31.2	32.81
Pasture	13.53	29.52	9.36	27.02
Urban	0	6.56	7.8	0
Wetlands	1.23	9.84	0.78	5.79
TOTAL	123	328	78	193

As inputs, INCA-PEco required daily time series of hydrologically effective rainfall (HER), soil moisture deficit (SMD), precipitation and mean air temperature. This information was obtained from PERSiST, since it can only be generated through an external hydrological model.

After characterisation, the model was calibrated to monthly water chemistry observations from the station Sävjaån Kuggebro. The first calibration was done manually. From this calibration, the parameters were further adjusted by defining parameter ranges to explore with a Monte Carlo analysis. The MC run three sets of 60 chains containing 400 samples. The result of MC analyses provided the parameter set which gave the best model performance.

To evaluate model performance the metrics used were the Pearson correlation (r^2) and Kling Gupta Efficiency (KGE) (Gupta *et al.*, 2009). Whilst r^2 is one of the most historically used metrics for model evaluation, KGE has become very popular in hydrologic models in the last decade (Lamontagne, Barber and Vogel, 2020), presenting a decomposition of NSE that provides easier access to the analysis of hydrological models components of goodness of fit. The model performance for last model was $r^2 = 0.376$ and KGE = 0.550 for SS, and $r^2 = 0.269$ and KGE = 0.471 for TP. In water chemistry modelling, the values obtained for r^2 are considered satisfactory when and for KGE model performance is considered satisfactory when KGE> 0.5 (Babalola *et al.*, 2021).

After performance evaluation, the model was applied for the same climate scenarios tested in PERSiST. In addition to that, land use change scenarios (section 3.2.3 Land Use Change Scenarios) were tested in this model. The land use scenarios were tested only with the baseline climate scenario due to time restrictions.

3.3 Future change scenarios

The scenarios tested in PERSiST and INCA-PEco aim to represent future possible changes in in climate and land use in Sävjaån catchment. The conditions tested were divided in: climate change associated scenarios (RCPs), extreme precipitation change weather scenarios (Stretch), and land use change scenarios (NBPs) (Table 3). The reference period used as a baseline for streamflow and P measurements was 1971-2000, and the scenarios were made to simulate the long term changes for the period 2071-2100.

Table 3. Overview of the scenarios created for climate change, extreme precipitation and land use change.

	Climate Change (RCPs)	**Extreme precipitation (Stretch)**	**Land use change (NBPs)**
Scenarios			Baseline
	Baseline	Baseline	NBP1
	RCP 2.6	Stretch 1.5 (+150%)	NBP2
	RCP 4.5	Stretch 2 (+200%)	NBP3
	RCP 8.5	Stretch 3 (+300%)	NBP4
			NBP5

3.3.1 Climate change scenarios (RCPs)

Climate change scenarios represent future changes in precipitation and temperature caused by the anthropogenic GHG emissions (IPCC, 2021). For this study, the scenarios were built based on regional climatic models from the Swedish Meteorological and Hydrological Institute (SMHI). These models predict future meteorological changes at a county scale in Sweden and are part of the international research programme CORDEX and the Copernicus Climate Change Service. The data used was extracted from the SMHI Advanced Climate Change Scenario Service (SMHI, 2022), which includes predictions for changes in temperature and precipitation for Sweden at a spatial resolution of 2.5x2.5 km for different IPCC emission scenarios and periods. The predictions for Sävjaån catchment were obtained with the mean of all the 2.5x2.5 grids within the catchment.

The projected changes in precipitation and temperature applied follow seasonal variations for four IPCC emission scenarios: RCP 2.6, RCP 4.5 and RCP 8.5 (Table 4). Scenario RCP2.6 assumes that strong climate regulations will make greenhouse gas emissions end by 2020, and the radiative forcing will reach 2.6 W/m² year 2100. In RCP4.5 scenario strategies to reduce greenhouse gas emissions will lead to a stabilisation of the radiative forcing at 4.5 W/m² before year 2100. Lastly, RCP8.5 scenario assumes an increase of greenhouse gas emission that causes radiative forcing to reach 8.5 W/m² year 2100 (IPCC, 2014).

Table 4. Projected changes in precipitation and temperature in different RCP scenarios for the period 2071-2100, reference period 1971-2000 (SMHI, 2022).

	RCP 2.6		**RCP 4.5**		**RCP 8.5**	
Period	Precip (mm/month)	Temp (ºC/month)	Precip (mm/month)	Temp (ºC/month)	Precip (mm/month)	Temp (ºC/month)
Dec-Feb	+3	+2.25	+6.375	+3.75	+10.375	+5.75
Mar-May	+5.5	+1.75	+8.125	+2.75	+11.375	+4.25
Jun-Aug	+4.5	+1.75	+8.125	+2.75	+8.5	+4.25
Sep-Nov	+1	+1.25	+4	+2.25	+9.875	+4.25

3.3.2 Extreme precipitation scenarios (stretch)

The extreme precipitation scenarios represent an increase in heavy precipitation events, which are expected to increase in the next century (Hov *et al.*, 2013). The scenarios were created by modifying precipitation distribution in the baseline scenario (1971-2000 measurements). The extreme precipitation stretch did not alter the total amount of precipitation, which was the same in every scenario. To do so, precipitation (mm) in the extreme precipitation days was increased and precipitation in the rest of the days was decreased, keeping a constant total precipitation.

Extreme precipitation days were considered the days on the top 95th percentile (Crespi *et al.*, 2020) in precipitation amount. Precipitation on those days was increased by a constant percentage, highest increases in the maximum values and lower increases close to the break point at 95th percentile (Figure 4). These amount of precipitation, was subtracted from the rest of the days, so those under the 95th percentile. The amount of precipitation subtracted increased with increasing distance from the breaking point, with low subtraction on those days right under the 95th percentile and larger decreases in days with very low precipitation amounts.

Three extreme precipitation scenarios were created, increasing the intensity of the extreme precipitation events by 150, 200 and 300 %, also called stretch 1.5, stretch 2 and stretch 3 respectively.

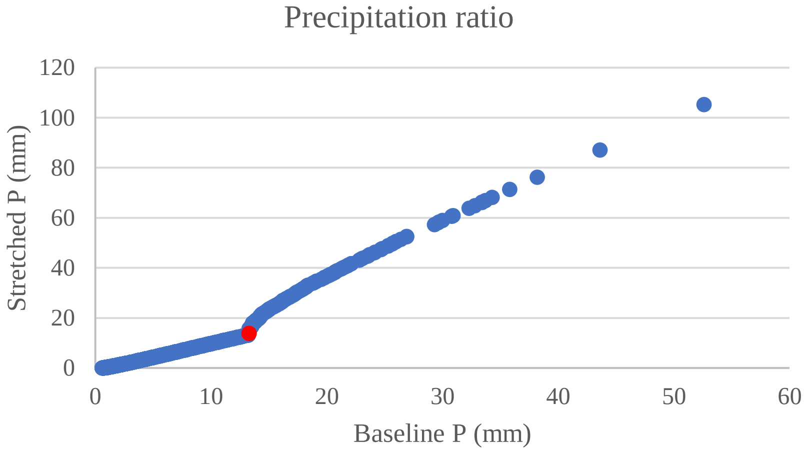

Figure 4. Example of changes applied with precipitation stretch (stretch 200%). Red point indicating 95th percentile. Points on the left of red point indicate values under 95th percentile, and on the right values on top of 95th percentile.

3.3.3 Land use change scenarios

Land use change scenarios were made based on the Nordic Bioeconomy Pathways (NBPs) (Rakovic *et al.*, 2020), a set of storylines that describe potential future societies created from the convergence of different trends in politics, international trade, social equity and environmental concerns, among others.

The used models (PERSiST, INCA-PEco) were structured representing the five land use types in Sävjaån catchment: forest, arable, pasture, wetlands and urban. The NBP storylines were used to create different scenarios in which the current land use distribution may change. Each of the NBP storylines presents different characteristics on management policies for forestry and agriculture as well as different projections on urban and demographic growth (Table 5), which leads to many possible outcomes on land use change.

NBP1 (*Sustainability first - closing the loops*) presents a future society that has shifted towards a sustainable lifestyle, where humans' well-being is on top of the development priorities and economic growth has slowed down. Environmental impacts of intensive production have become a global concern and policies are directed towards reducing environmental footprint. Land use has become more resource efficient, getting close to a circular model.

NBP2 (*Conventional first – don't rock the boat*) continues with the global historical trends in development and growth. The progress towards reaching sustainable development goals is slow and even if there are concerns for local environmental problems, policy implementation is just partly successful.

NBP3 (*Self-sufficiency first – Building walls*) pictures a world where conflicts and regional rivalry drives society development. Frontiers become more closed, countries prioritize auto sufficiency and international trade becomes very limited. The environmental policies are not an important point in the political agenda, that focuses on statal security.

NBP4 (*City first - Maintaining the divide*) projects a future where inequalities in human development have led to high differences in economic growth and political power between regions. In Nordic countries, the cities are prioritized to the benefit of economically powerful stakeholders and rural areas are left apart in development policies. Environmental policies are focused in local concerns and big companies take over small scale farms and forest properties.

In NBP5 (Growth first – running on the treadmill) the world lives under a continuous economic growth at the expenses of high resource exploitation. Development is focused on human well-being, lifestyles are material intensive and diets are meat rich. Environmental issues are only locally addressed, and competition and technology advances are believed to be a sustainable development solution.

Table 5. Description of relevant elements used to describe the Nordic Bioeconomy Pathways (NBPs) scenarios (Adapted from Rakovic et al., 2020)

NBP element		NBP1 Sustainability	NBP2 Conventional	NBP3 Self sufficiency	NBP4 City first	NBP5 Growth
Forestry	General	Directed towards **continuous cover** with greater consideration of sensitive areas	**Current** Nordic model i.e., dominance of even aged stands of coniferous trees	Current Nordic model, but **intensified management**, low priority for environmental concerns	Current Nordic Model	Current Nordic model, **some intensification** as Nordic timber export increases
	Land use	Strong regulations to avoid environmental tradeoff	Medium regulations lead to **slow decline in the rate of deforestation**	Hardly any regulation: continued **deforestation** due to competition over land	Highly regulated in MICs, HICs: largely unmanaged in LICs leading to tropical deforestation	Medium regulations lead to **slow decline in the rate of deforestation**
Agriculture	General	Improvements in productivity: rapid diffusion of **best practices**	Medium pace of tech change in ag. sector; entry barriers to ag markets reduced slowly	Rapid **expansion of agriculture** Low technology development, restricted trade	High productivity for large scale industrial farming, low for small scale farming	Highly managed, resource intensive, rapid increase in productivity
	Crop production	**Diversification**, locally adapted systems, focus on multifunctionality	**Intensification** with conventional approaches, moderate attempts to limit nutrient losses	Conventional **input intensive, expansion** where possible, whole removal of biomass	**Conventional**, with more precision agricultural approaches	**Intensification** of monocultures, resource-intensive high-tech farms
Animal husbandry		Small scale, adjacent to arable land for diversity and circularity	Medium scale farms, some adjacent to arable land	Specialized, large scale, domestic feed	Medium scale farms, some free range for elite consumption	Specialized large scale farms
Urbanization level		High	Medium	Low	Medium	High
Population growth		Relatively low	Medium	Low	Relatively Low	Medium

Following the land use trends in each of the NBPs (Table 5), changes in land use percentages were applied to create the different scenarios used in this study (Table 6). These changes in land cover percentage were then incorporated to INCA-PEco by adjusting the land cover change for each of the four subcatchments in Sävjaån. (Supplementary Table 1).

Table 6. Changes in land cover type (area %) in Sävjaån catchment projected for different land use scenarios following NBP storylines.

Land cover type	Scenario 1 (NBP1)	Scenario 2 (NBP2)	Scenario 3 (NBP3)	Scenario 4 (NBP4)	Scenario 5 (NBP5)
Forest areas	7%	1%	-10%	2%	-5%
Arable areas	-26%	0%	32%	-5%	20%
Pasture	-22%	-9%	20%	-10%	3%
Urban	10%	4%	-5%	15%	20%
Wetlands	50%	8%	0%	10%	-13%

3.4 Data analysis

Modelled data from PERSiST and INCA-PEco gave daily values for streamflow (m^3/s), SS and TP concentration (mg/l). To complement this information, TP and SS loads (kg/s) were further calculated from TP and SS concentration and streamflow. The analysis of this data was carried out using Microsoft Excel (Version 16.62) for data clean-up and R studio (Version 1.2.1335) for graphical display. Streamflow, TP and SS loads and concentrations were analysed annually, totally and seasonally. Daily values were not treated in data analyses to facilitate data interpretation and avoid outliers.

The studied seasons were divided as follows: Winter (January, February, March), spring (April. March, June), summer (July, August, September) and autumn (October, November, December). Days with high flow, high SS and high TP were also analysed. Those days were considered days with values over the 95th percentile among the total values for all scenarios.

A significance analysis of the results was carried out for TP and SS data using JMP® Pro 16.0.0. A Tukey test for All Pairwise Comparisons with adjustments for multiple comparisons was used. This method examines all pairwise comparisons of the effect of least squares mean using the Tukey adjustment for multiplicity (JMP, 2021). To do that, Tukey test uses a pairwise post-hoc testing to determine the differences between the mean of all possible pairs through a studentized range distribution (Lee and Lee, 2018).

4. Results

4.1 Climate change (RCP) and extreme precipitation (stretch) scenarios

4.1.1 Streamflow

The average annual streamflow distribution shows relevant differences when applying different scenario categories. First, climate change (RCP emission) scenarios produce a more homogeneous distribution of streamflow (Figure 5a) which increases in relation to the degree of radiative forcing, lower increase for RCP 2.6, higher in RCP 8.5. On the other hand, extreme precipitation scenarios (stretch) produce a more uneven distribution of streamflow throughout the time period (Figure 5b), with some years showing higher and some lower flows in comparison to baseline. Extreme precipitation also produces higher maximum streamflow values.

A combination of RCPs and extreme precipitation scenarios (Figure 6) further enhances the unevenness of distribution in streamflow (Figure 7). Highest flows are produced by RCPs 4.5

and 8.5 combined with stretch 3, whilst RCP 2.6 combined with stretches produced lower flows (Supplementary Table 2). When accounting for accumulated flow, similar patterns are observed for all the scenarios (Supplementary Fig 1).

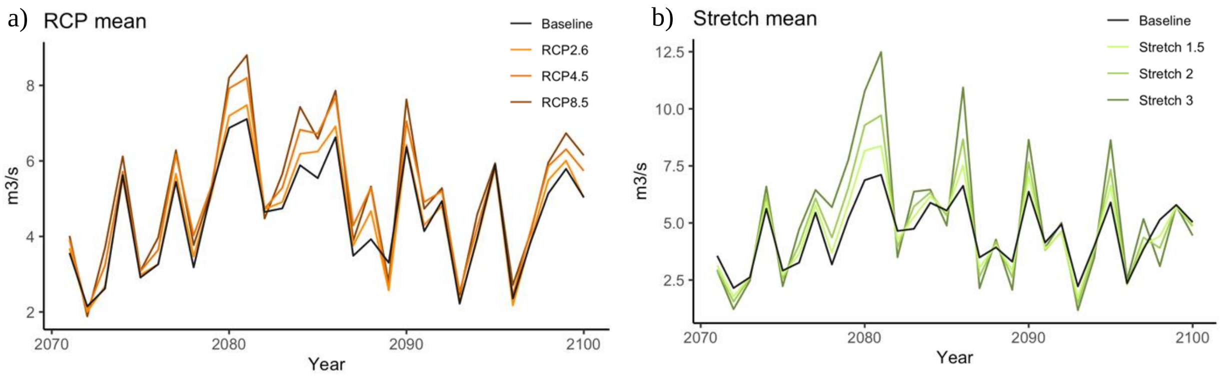

Figure 5. Average annual streamflow in a) RCP emission scenarios, b) stretch scenarios, for 2070-2100 period.

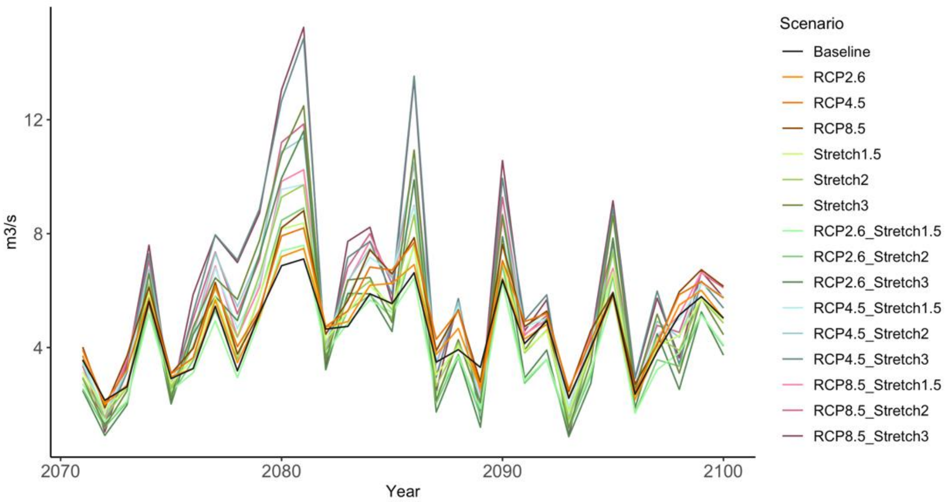

Figure 6. Average annual streamflow per scenario, 2070-2100 period.

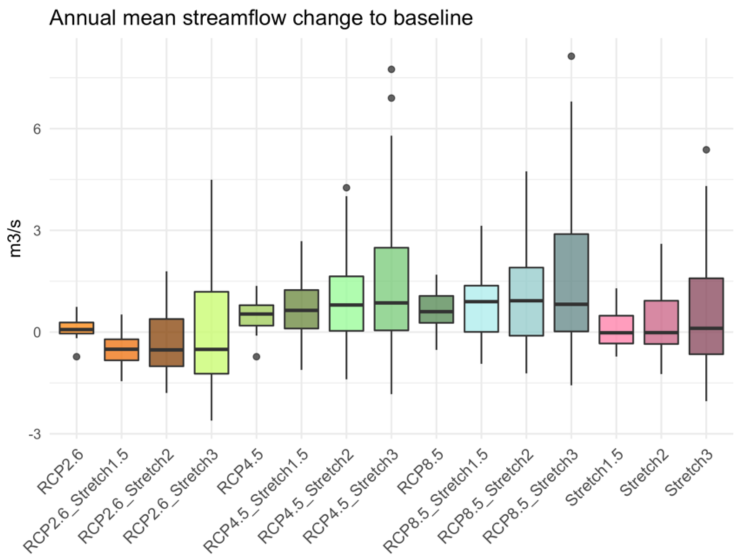

Figure 7. Average annual streamflow per scenario, 2070-2100 period.

4.1.1.1 Seasonal streamflow

Scenarios also cause streamflow distribution to change throughout the year (Figure 8). In winter, some scenarios cause higher and some lower streamflow compared to the baseline. In spring, streamflow decreases in all scenarios. On the contrary, in summer and autumn all scenarios produce higher streamflow than the baseline.

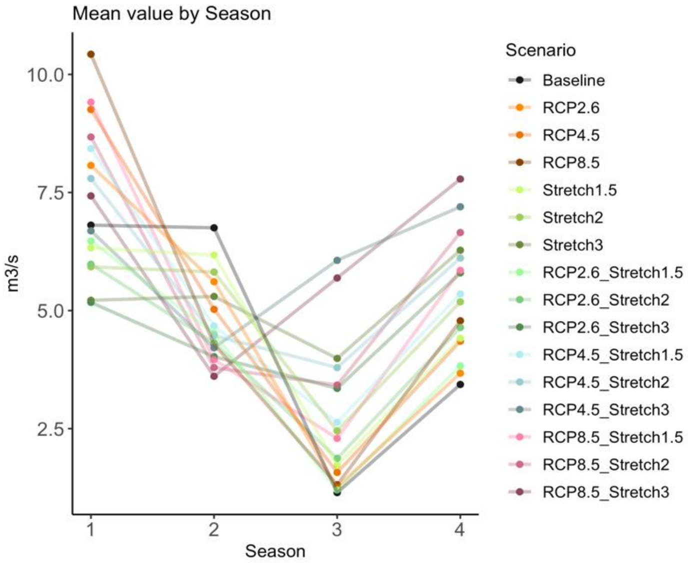

Figure 8. Average seasonal streamflow per scenario (m3/s) for 2071-2100. Winter (1), Spring (2), Summer (3), Autumn (4).

Looking closely to the streamflow values, it is possible to obtain more detailed information about seasonal differences. The strongest average streamflow increase occurs in summer, with streamflow increasing up to 429% in comparison to baseline, whilst the strongest decrease occurs in spring, with -47% (Table 3). In winter, stretch and stretch + RCP 2.6 generate decreases in streamflow, whilst RCPs and RCP 4.5, 8.5 + stretch generate higher flows. In spring, all scenarios produce a decrease in flow. In that case, high stretch and high RCP cause strongest decrease in streamflow, especially with the combination of both. In summer the strongest increase is in this case clearly produced by strong precipitation stretch (Table 3). In autumn there is also an increase of streamflow, following a similar pattern than the increases produced in summer, but on a smaller scale.

Table 7. Mean seasonal streamflow change for projections to years 2071-2100 in future scenarios, change in percentage compared to Baseline scenario values. Increase is indicated by blue colour and decrease orange.

Scenario	Winter	Spring	Summer	Autumn
RCP 2.6	19%	-17%	10%	7%
RCP 4.5	36%	-26%	37%	27%
RCP 8.5	53%	-37%	14%	39%
Stretch 1.5	-7%	-9%	50%	28%
Stretch 2	-13%	-14%	114%	51%
Stretch 3	-23%	-22%	248%	83%
RCP 2.6 + Stretch 1.5	-5%	-33%	5%	11%
RCP 2.6 + Stretch 2	-12%	-36%	63%	35%
RCP 2.6 + Stretch 3	-24%	-40%	192%	69%
RCP4.5 + 1.5Stretch	24%	-31%	130%	56%

RCP 4.5 + Stretch 2	14%	-34%	231%	78%
RCP 4.5 + Stretch 3	-2%	-38%	429%	109%
RCP 8.5 + Stretch 1.5	38%	-41%	100%	70%
RCP 8.5 + Stretch 2	27%	-44%	199%	94%
RCP 8.5 + Stretch 3	9%	-47%	396%	127%

4.1.1.2 High flows

Since variation between minimum streamflow does not appear significant compared to the maximum streamflow (Supplementary Figure 2), the data analysis was mostly directed to understanding the behaviour of high flows. The highest flows are observed in RCP 8.5 + stretch 3 and RCP 4.5+stretch 3, with maximum values that reach 284 and 280 m^3/s, respectively (Supplementary Table 3). In addition, there are important differences in the number of high and low flow days between scenarios (Figure 9). The number of high flow days, with flow over 15 m^3/s (Lannergård, Fölster and Futter, 2021) increases in most of the scenarios in comparison to baseline. High flow days appear more frequently in scenarios with high RCP and high precipitation extremes (stretch).

The distribution of high flow days also changes between seasons. In the baseline scenario high flow days are mostly found in spring and winter, whilst high flow days appear in summer with increasing RCPs and stretches (Figure 9). The scenarios that create significantly higher flows are RCPs 4.5 and 8.5 when stretch 3 is applied.

In winter, the maximum flows do not show significant changes (Supplementary Figure 2), whilst in summer the increase compared to the baseline scenario is the largest, which can also be seen in the number of high flow days.

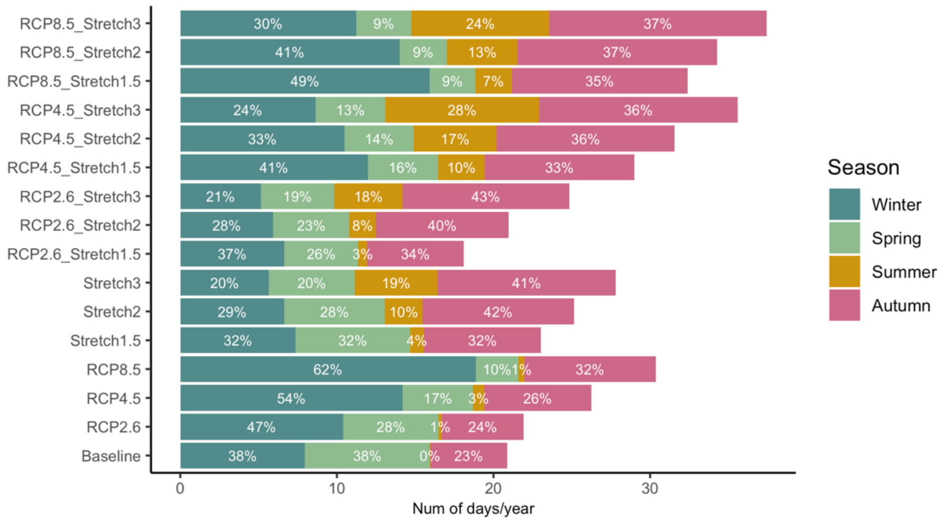

Figure 9. Average high flow days per year (>15m^3/s) by season, period 2071-2100.

4.1.1.3 Snow cover

Results also show relevant differences in the snow patterns derived from both RCP and extreme precipitation. There is less snow accumulation in all the scenarios which is reflected in fewer days with snow cover (Table 8). This decrease in cover is more notable in scenarios that include an increase in temperature (all RCPs), and especially with RCP 8.5, which includes the highest temperature increase. This may indicate that the temperature change may have the greatest effect on snow accumulation and melt. However, scenarios that only apply a change in the precipitation pattern (stretch 1.5, 2 or 3) show smaller changes in snow cover.

Table 8. Number of days with snow cover per year. Annual average for period 2071-2100.

Scenario	Num. of days with snow cover / year
Baseline	110
Stretch1.5	105
Stretch2	99
Stretch3	92
RCP2.6	58
RCP2.6_Stretch1.5	52
RCP2.6_Stretch2	49
RCP2.6_Stretch3	42
RCP4.5	34
RCP4.5_Stretch1.5	32
RCP4.5_Stretch2	29
RCP4.5_Stretch3	25
RCP8.5	17
RCP8.5_Stretch1.5	15
RCP8.5_Stretch2	14
RCP8.5_Stretch3	13

In coherence with this decrease in snow cover, there is a reduction in snow melt (Figure 10) in all scenarios. In this case though, there is a clear shift on the season when most snow is melted. In the baseline the maximum melt is produced in spring, whilst in all scenarios where temperature increases melt is higher in winter.

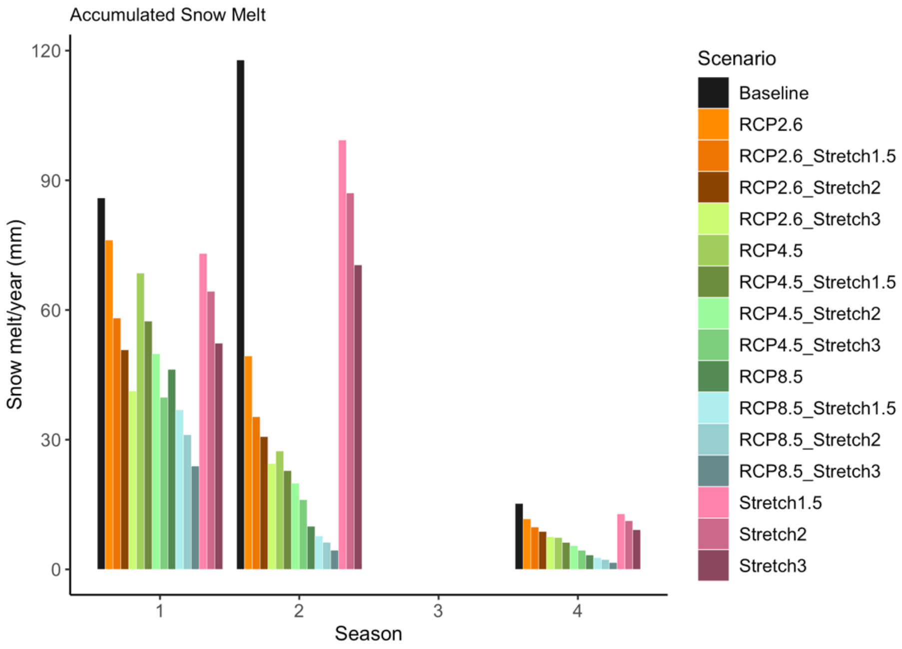

Figure 10. Annual average snow melt (mm SWE) for period 2071-2100. Comparison between scenarios and seasons. Winter (1), Spring (2), Summer (3), Autumn (4).

4.1.2 Suspended sediment

Suspended sediment (SS) loads increase under most scenarios. The different emission scenarios (RCPs) cause a variable effect on SS transport, with 1% increase in RCP 2.6 in comparison to baseline, and 18% increase in RCP 8.5 (Table 9). The combination of low emission scenario RCP 2.6 and precipitation extremes (stretch), seems to cause a decreasing or stable tendency in SS transport. However, higher emission scenarios RCP 4.5 and RCP 8.5 combined with the increase in precipitation extremes cause an increase in SS transport. The highest increases are produced by high RCP and high stretch combined, causing up to 40% increase in SS transport (Table 9).

There is considerable variation in total annual loads for the period 2071-2100 (Table 11). The highest range in loads is produced by the highest extreme precipitation (Stretch 3). We can see how that scenario, especially in combination with RCP 4.5 and 8.5, produces the widest range in annual SS loads. Therefore, extreme precipitation seems to produce years with very high SS transport and years with very low SS transport.

Significance test Tukey-t results show no significant difference in mean SS loads in any scenario compared to Baseline. However, they show significant differences in maximum loads. RCP 4.5 + stretch 3 and RCP 8.5 + stretch 3 both differ significantly from Baseline with a p value of 0.0001.

Table 9. Difference in total accumulated loads in the period 2071-2100 compared to baseline period 1971-2000.

Scenario	Baseline	Stretch1.5	Stretch2	Stretch3
Baseline	0%	2%	7%	14%
RCP2.6	1%	-14%	-9%	0%
RCP4.5	13%	18%	25%	37%
RCP8.5	18%	17%	28%	40%

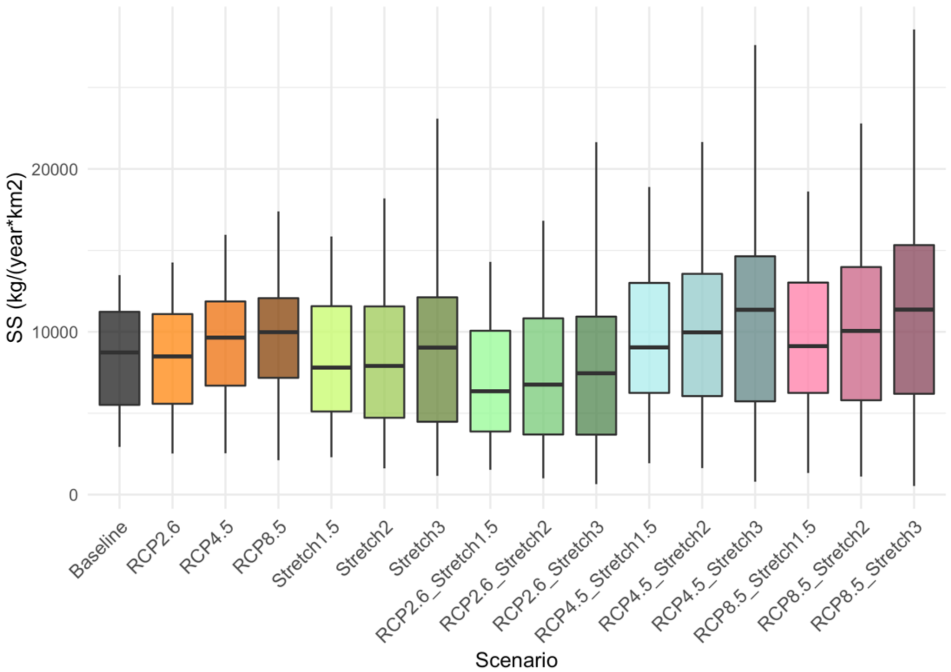

Figure 11. Suspended sediment, annual loads for the period 2071-2100.

Interestingly, SS concentration (Figure 12) does not seem to follow the same pattern. When any stretch is applied, concentration seems to follow the opposite trend than load. The only increase in average concentration seems to be associated with RCP emission scenarios.

Significance test was also run for SS concentration. No significant difference was found in average or maximum concentration between scenarios. This suggests that increases in temperature and precipitation may not significantly affect SS concentration.

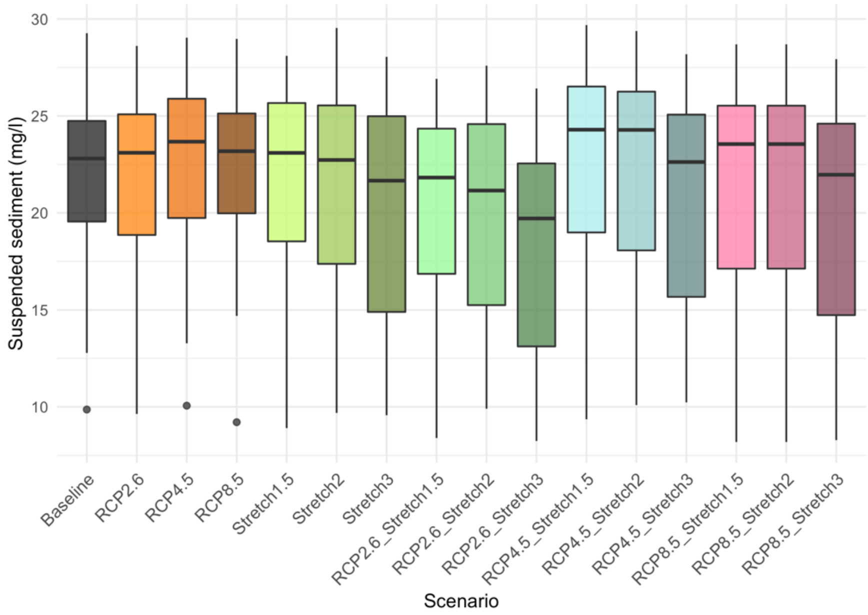

Figure 12. Suspended sediment annual average concentration (mg/l), period 2071-2100.

Seasonal SS loads (Figure 13) in winter increase compared to baseline with RCPs, RCP 4.5 and RCP 8.5 with Stretch 1.5, 2. However they decrease when precipitation stretches are applied. In spring, all scenarios cause a decrease in SS seasonal loads, especially with high RCP and high stretch. In summer, all scenarios cause an increase in SS loads, which increases significantly when stretch 3 is applied. In autumn, SS loads also increase compared to baseline, especially when RCP 8.5 and stretched are combined.

SS distribution along the year also changes. In baseline scenario, the lowest SS load is found in summer and the highest in spring. However, this changes in RCP 4.5 + stretch 2 and 3 and RCP 8.5 + Stretch 2 and 3, where lowest loads are found in spring.

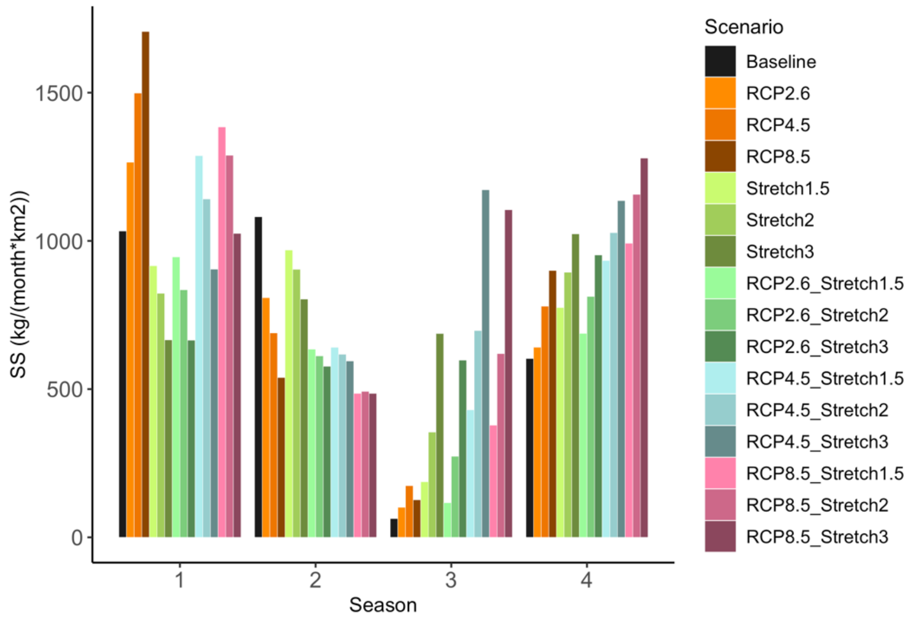

Figure 13. Suspended sediment monthly loads (kg/km²), distribution by season, period 2071-2100. Winter (1), Spring (2), Summer (3), Autumn (4).

Days with high suspended sediment concentration also change, shifting from more days with high concentration in winter and spring in the baseline scenario, towards more days with high SS concentration in summer with the increase of RCP scenario and stretch (Figure 14).

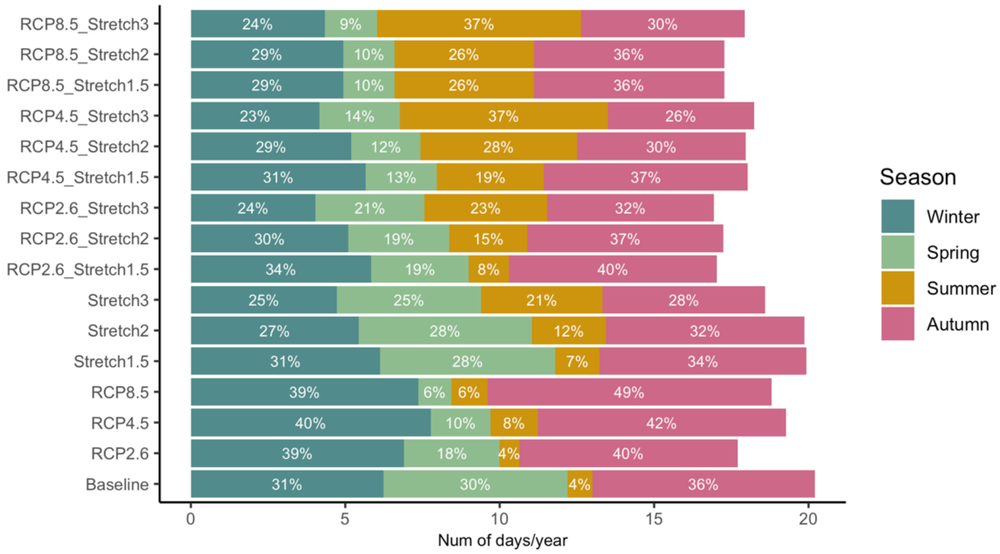

Figure 14. Annual average number of high concentration days (>66mg/l) per season, period 2071-2100.

4.1.3 Total phosphorus

Total phosphorus (TP) results show similar patterns to suspended sediment. Compared to baseline, RCP scenarios produce an increase in total accumulated TP load, especially with RCP 8.5 (Table 10). Extreme precipitation (stretch) scenarios, on the other hand, produce small variations in comparison to Baseline. The combination of RCP 2.6 and stretch produces a decrease in accumulated TP loads. Lastly RCP 4.5 and 8.5 combined with stretches produce an increase in accumulated loads, up to 27 %.

Annual TP loads differ amongst scenarios (Figure 15). This display of data shows the variation of TP loads among years in one same scenario. It can be seen how the application of stretch scenarios increase the variation of TP loads among years, especially with RCP 4.5 and 8.5. Therefore, extreme precipitation seems to increase variability in P loads.

Significance test Tukey-t results show no significant difference in average TP loads in any scenario compared to Baseline. However, they show significant differences in maximum loads. RCP 4.5 + stretch 3 and RCP 8.5 + stretch 3 both differ significantly from Baseline with a p value of 0.0001.

Table 10 Difference in total accumulated loads in the period 2071-2100 compared to baseline period 1971-2000.

Scenario	Baseline	Stretch1.5	Stretch2	Stretch3
Baseline	0%	-5%	2%	2%
RCP2.6	2%	-13%	-14%	-10%
RCP4.5	7%	16%	20%	27%
RCP8.5	14%	13%	22%	25%

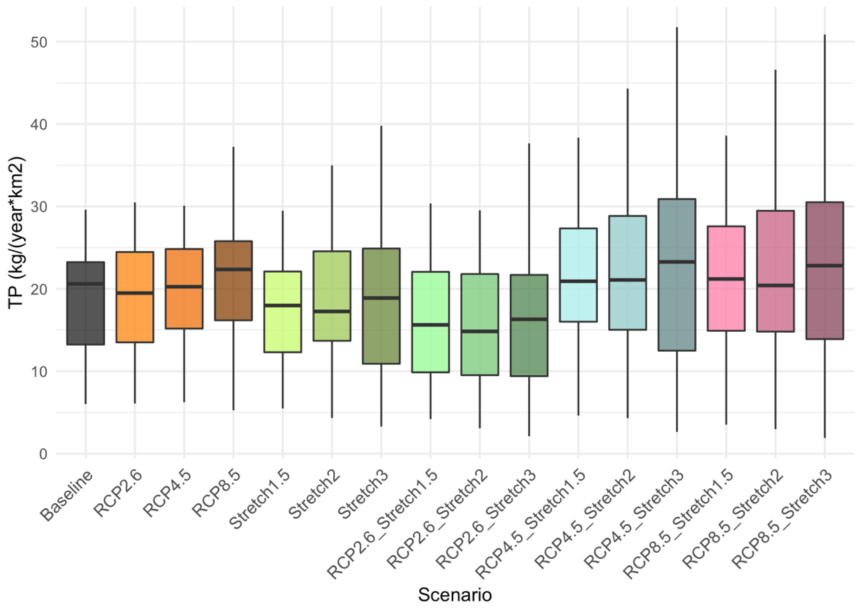

Figure 15. Total phosphorus loads (kg/year) in the period 2071-2100.

TP concentrations (Figure 16) seem to follow the opposite trends to TP loads. When any stretch is applied, TP concentration seems to generally decrease in comparison to baseline. Significance test found mean TP concentration to be significantly lower in scenario RCP 2.6 + stretch 3 compared to baseline, with a p value of 0.004

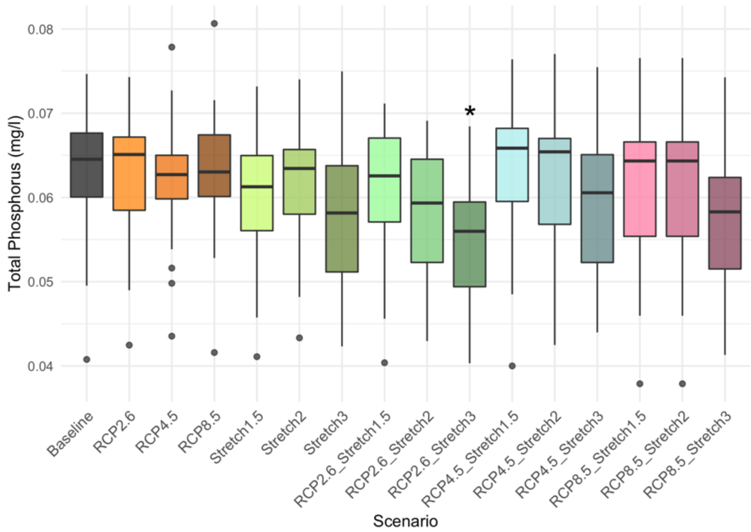

Figure 16. Total phosphorus daily concentration (mg/l), period 2071-2100.

The seasonal changes that TP follows under the different scenarios are similar to SS. The baseline scenario shows higher TP export in winter and spring, and lower in summer. With the scenarios, generally TP loads decrease in winter and specially spring, and increase in summer and autumn (Figure 17).

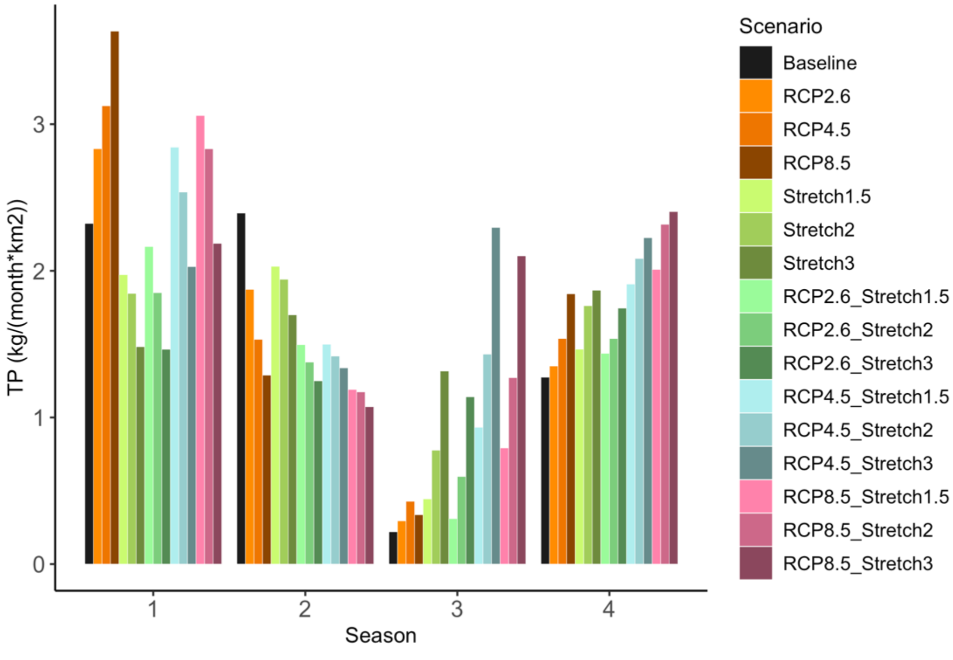

Figure 17. Total phosphorus monthly loads (kg/km^2), distribution by season, period 2071-2100. Winter (1), Spring (2), Summer (3), Autumn (4).

On the other hand, there seems to be a shift in the season where days with high TP concentration appear (Figure 18). In baseline scenario, high TP concentrations were mostly found in winter and spring, whilst with increasing RCP and stretch, these high concentrations days appear more frequently in summer.

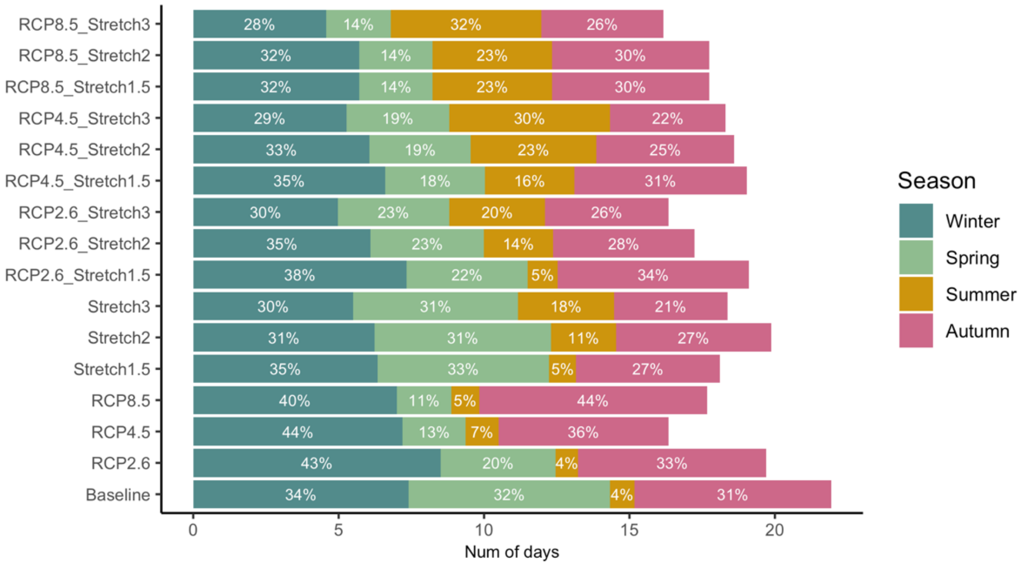

Figure 18. Annual average number of high concentration days (>0.14mg/l) per season, period 2071-2100

4.2 Land use change scenarios

Land use change scenarios were tested directly in INCA-PEco and therefore the results presented are only SS and TP. NBPs do not cause any seasonal change in SS or TP distribution, since there are no seasonal changes applied in these scenarios.

4.2.1 Suspended sediment

Suspended sediment loads (Figure 19) seem to generally decrease in NBP1 (sustainability first), and an increase in NBP3 (self-sufficiency first). Changes in NBP2, NBP4 and NBP5 are smaller. Tukey test did not find significant differences in average SS loads nor average SS concentrations in NBP scenarios compared to baseline.

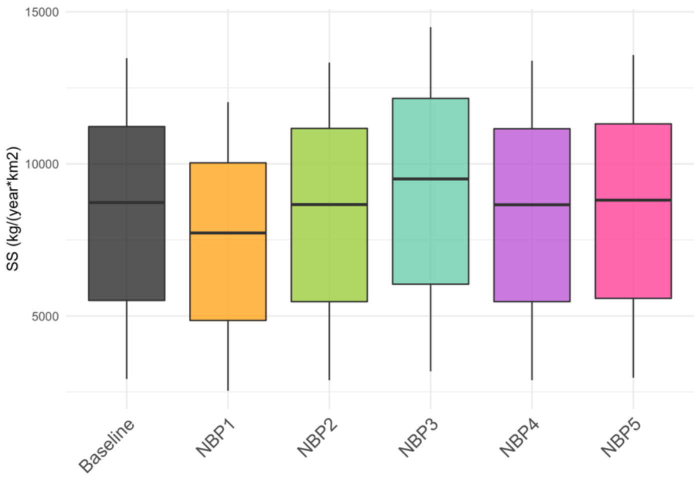

Figure 19. Annual suspended sediment loads for 2071-2100 in NBP land use scenarios.

4.2.2 Total phosphorus

Total phosphorus changes derived from land use scenarios (NBPs) (Figure 20) follow the same direction than changes in SS. The highest decrease in accumulated TP load appears in NBP1 (Sustainability first) with a -12% decrease in accumulated load (Table 11). The highest increase in accumulated TP load is found in NBP3 (Self-sufficiency first), with a 12 % increase. NBP2, NBP4 and NBP5 present smaller changes in accumulated loads: NBP2 causes a decrease of -1%, NBP3 causes a decrease of 2% and NBP5 causes an increase of 4%.

Tukey test did not find significant differences in average TP loads among scenarios, but found significant differences in average concentrations. In NBP1, TP average concentration is significantly lower than baseline, with a p-value of 0.0085. In NBP3, TP average concentration is significantly higher than baseline, with a p-value of 0.0033.

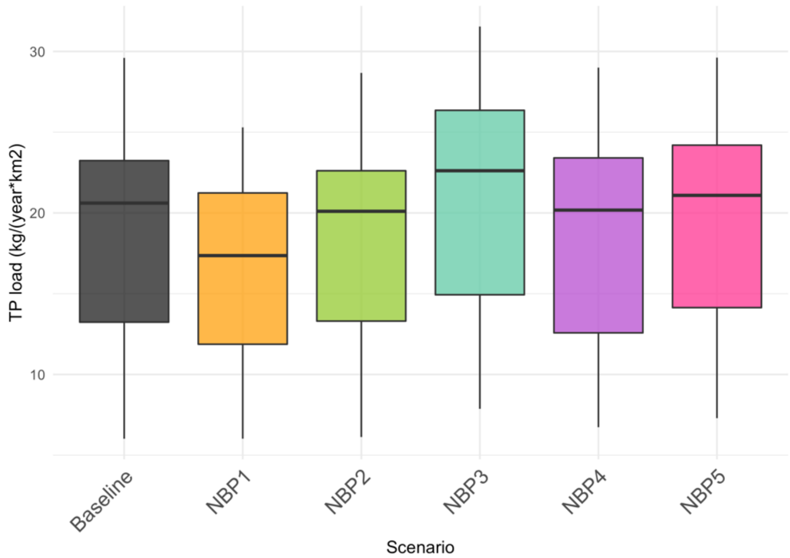

Figure 20. Annual total phosphorus loads for 2071-2100 in RCP and land use scenarios.

Table 11. Difference in total accumulated TP loads in the period 2071-2100 compared to baseline period 1971-2000.

Scenario	TP load change
NBP1	-12%
NBP2	-1%
NBP3	12%
NBP4	-2%
NBP5	4%

5. Discussion

This study modelled future changes in streamflow, SS and TP under future climate and land use scenarios in Sävjaån catchment, Sweden. As highlighted in previous research, climate (Murdoch, Baron and Miller, 2000; Darracq *et al.*, 2005; Moore *et al.*, 2007) and land use (Ross *et al.*, 1999; Farkas *et al.*, 2013; Djodjic, Bieroza and Bergström, 2021) are relevant factors in controlling the hydrological dynamics of a catchment, conditioning SS and P transport to surface waters. Results showed how increases in streamflow were accompanied by increases in SS and TP loads, and decreases in streamflow were followed by decreases in SS and TP loads, creating a synchronicity in the direction of response among the three modelled parameters. Additionally, each of the scenario groups tested (precipitation and temperature, extreme precipitation events and land use change) appeared to effect differently P export in the catchment.

Model responses to changes in climate

Climate change scenarios (RCPs) accounted for changes in temperature and precipitation for the period 2071-2000. These changes derived from SMHIs regional climatic models and included different emission scenarios: low emissions (RCP 2.6), medium emissions (RCP 4.5) and high emissions (RCP 8.5). The higher the emission scenario, the higher the precipitation and temperature increase. Results showed how P transport was higher in higher emission scenarios, with the highest increase in P load found in RCP 8.5 (14%). Therefore, suggesting that temperature and precipitation increase derived from climate change will contribute to an increase in P export in the catchment.

Climate change scenarios were also combined with extreme precipitation scenarios (Stretch). Stretch scenarios simulated the increase in heavy rainfall events expected for the next century in northern Europe (Larsen *et al*., 2009; Hov et al., 2013). Surprisingly, the addition of heavy precipitation events to the climate scenarios did not always result in an increase of P loads. Extreme precipitation increase added to low emission scenario (RCP 2.6) seemed to generally reduce P loads, whilst the combination with medium (RCP 4.5) and high (RCP 8.5) emission scenarios seemed to generally produce an increase in P loads. This leads to believe that predictions for future changes in climate may not always result in increases in TP loads.

The explanation for these differences may be found in the relationship between temperature and precipitation in each RCP scenario. The lower P loads found in RCP 2.6 + stretch may have been associated with the specific effect of temperature in RCP 2.6. Temperature is a strong component in regulating the hydrological cycle, especially when the increase in precipitation is not high enough. Darracq *et al.*, (2005) for example, in a modelling study in Stockholm, found that future temperature increase in the area will have the strongest effect in evapotranspiration. This may be the case in RCP 2.6, where the increase in precipitation may not be high enough to compensate for the increase in temperatures, giving room for evapotranspiration to act significantly. In consequence, higher evapotranspiration rates in low emission scenario could have changed the tendency of the water cycle in the catchment. There could have been more water lost into the atmosphere, instead of being directed to streams and rivers, and therefore less P would have been transported form soils to surface waters.

On the other hand, the addition of extreme precipitation scenarios to medium and high emission scenarios (RCP 4.5 and RCP 8.5) produced generally higher P loads and a very notable increase on the maximum P loads registered. This increase may have be explained by the changes in water dynamics associated to heavy precipitation events, such as a decrease in soil infiltration and an increase in surface runoff (Grusson *et al.*, 2021), since surface runoff and its subsequent erosion are considered to be responsible for one of the main transport mechanisms of P to surface waters (Chen *et al.*, 2015). Additionally, in these scenarios there was an increase in the range of possible values for P loads during that period, going from very low to very high values for different years in the same period. This trend towards heterogeneity in climate makes us think that possibilities of predicting streamflow and P loads will become a challenge in the future.

Besides changes in P loads, changes in concentration of P in streams associated to future climate were also evaluated. Results showed how generally the increase in P loads was not accompanied by an increase in P concentration. On the contrary, scenarios with the highest loads presented the lowest concentrations. An explanation for these results may be found in the increase in streamflow volume, which could be high enough to compensate for P loads and lower P concentration. Nutrient concentration is a relevant parameter for eutrophication, since high concentrations, especially during low flows can trigger the undesired growth of algae (Jarvie *et al.*, 2014). However, even if modelled concentrations appear low in this study, the high loads modelled are a warning sign that needs to be evaluated. These loads can travel to other places where water remains stagnant, like lakes, where P concentration can increase, facilitating the occurrence of eutrophication processes.

Climate related scenarios also caused a change in seasonal distribution of streamflow, SS and TP. The biggest changes were found in spring, where streamflow and P loads decreased in all scenarios. As reported by Moore et al., (2007), we suggest this decrease in flow was associated to the decrease in snow fall in winter due to elevated temperatures and lower snow accumulation. This translates into a decrease in spring melt peak flows, which is an important source of SS and P transport to surface waters (Ulén, 2003). In summer, streamflow increase caused higher P loads, especially with heavy precipitation events. In this season, we also saw how there was an increase in high P concentration days. Summer is one of the most vulnerable seasons for freshwater ecosystems, due to lower flows concentrating higher amounts of nutrients and pollutants (Wade et al., 2002). Therefore, these high concentration days in summer may pose a threat in the equilibrium of streams and lakes.

Model responses to changes in land use

In land use change scenarios, main changes were associated to NBP1 (Sustainability first) and NBP3 (Self-sufficiency first). In NBP1 scenario society has shifted towards a more sustainable way of living. In that scenario, forest and wetlands have been conserved and promoted, and the need for extensive agriculture has decreased. These changes may explain the reduction in P export in this scenario. Forests areas have lower contributions to P export -in comparison to agricultural or urban areas- (Farkas *et al.*, 2013) and wetlands are a proven efficient natural method in retaining nutrients and avoiding transport to freshwaters.

The other scenario that showed some notable change in P loads was NBP3 (Self-sufficiency first). In this scenario, conflicts have cut resource trading and self-sufficiency is a need. The environmental issues have become a low priority. This socioeconomic situation translates into a scenario with a decrease in forest areas, which are needed for material and/or energy production, and a notable increase in agricultural areas needed for population supply. This increase in P loads found for this scenario may be associated to the fact that agricultural areas increase hydrologic connectivity through drainage (Jarvie *et al.*, 2014), especially when tillage is applied (Farkas *et al.*, 2013), which facilitates P transport from land to the river system, together with the use of P rich fertilisers.

In the case of NBP5 (growth first), there is an increase of agricultural and urban areas, which accompany a wealthy society in economic growth. In this case, the increase in urban areas can increase the inputs of P to waters, due to the decreased infiltration rates of urban soils, which limit the time for soil retention of particles, that are carried with runoff to surface waters (Chen *et al.*, 2015). In this scenario, we expected the increase in agricultural and urban areas to produce an increase in P transport to streams, but on the contrary, there was no significant change in comparison to the baseline values.

The biggest increase in P loads to surface waters was found in NBP3, which includes the highest increase in arable area (+32%), suggesting this land use to be the main contributor to P export. Indeed, much literature (Carpenter, 2008; Farkas *et al.*, 2013; Chen *et al.*, 2015) reports arable areas as the land use type which is most responsible for the P input to waters. In the case of this scenario, there are many strategies that can be used to mitigate the effects of agriculture in water quality, such as reducing the use of fertilisers, containment and treatment of manure, conservative tillage and the construction of vegetated buffer strips along agricultural streams (Darracq *et al.*, 2005; Carpenter, 2008).

5.1 Limitations and further work

We believe the results of this study are sensitive enough to present reliable approaches to future changes in P in freshwaters, which can be used in management decisions. However, there are some refinements from which the method could benefit in order to increase its precision.

Firstly, a deeper insight into model parametrisation and equifinality, which could not be tested due to time restrictions. Secondly, it would be interesting to test the model suitability against different time periods. In the case of this study, the model was calibrated to 1971-2000, because that was the period where changes in climate were applied, but further work could assess its adequacy to more recent time periods. To do so, a percent bias (PBIAS) model evaluation statistic could be used to carry an uncertainty analysis, as it evaluates the tendency of the modelled data to be larger or smaller than the observed measures (Moriasi *et al.*, 2007).

Results presented relevant differences in the scale of changes in flow, SS and P export produced by each scenario. Some studies expect land use change to have a greater impact on P export than climate change (Sala *et al.*, 2000), since land use is shown to impact on soil retention in a higher level (Bai, Ochuodho and Yang, 2019). However, in this study, the greatest impacts on P appear to be related to extreme precipitation scenarios in combination with climate change. On the other hand, NBP scenarios and climate change scenarios alone, seem to produce changes in a smaller scale. In regards of these differences, it would be interesting to better assess the intensity of changes applied in both land use and extreme precipitation scenarios. These changes were subjectively composed from literature and historical records, but not from reviewed models. Therefore, the quality of this work could be enhanced by using models that allow to improve the level of confidence in land use change and extreme precipitation projections for the studied region.

Further work should test the combined effects of climate and land use change, since both affect water quality way (El-Khoury *et al.*, 2015) and are necessary to assess ecosystem health in a holistic way (Bai, Ochuodho and Yang, 2019). Besides, it is an interesting next step to test the applicability of the models to other catchments, landscapes or countries. This method is specially calibrated to Sävjaån catchment. However, it would be interesting to test if similar catchments could benefit from the main structure of this methodology, applying only specific trends.

6. Conclusion

In the last decades, human actions have caused unprecedented changes in climate. Since 1970, temperature has raised at a scale that has not been registered in the last 2000 years (IPCC, 2021), altering precipitation patterns and weather extremes. This rise in temperatures is likely to continue and strengthen in the next decades, accentuating the consequences we have registered so far. A future temperature and precipitation increase is expected to influence the export of P to surface waters, since these factors are crucial in regulating the hydrological dynamics at a catchment scale.

At the same time, an increasing population and the type of future societal development will shape land use distribution in the landscape in the next decades. Land use, is also a crucial factor in controlling P transport to waters, due to the capacity of the land use type to shape soil physical characteristics, and the important P inputs associated to certain land uses, like agriculture.

Therefore, in this study we tested how future changes in both climate and land use will affect the loading of P to freshwater systems through streamflow and water quality modelling. The results of this modelling work led to the following conclusions.

i. Comparing temperature, precipitation and extreme precipitation events, the highest TP loads are produced by the increase in extreme precipitation events, which are also accompanied by the increase in streamflow.
ii. The change of precipitation patterns associated to climate change in northern Europe will increase the occurance of very high and very low TP loads, increasing the uncertainty in predictions.
iii. Seasonal occurrence of extreme flows and TP loads will shift with climate change, decreasing in winter and spring and increasing towards summer.
iv. Changes in TP export associated to Nordic Bioeconomy Pathways will be shaped mostly by the increase or decrease in agricultural land use.

Therefore, we believe that management strategies will have to focus on handling very high and unpredictable loads, adapting strategies to changes in seasonal trends and mitigating P loads derived from agriculture.

References

Babalola, T.E. *et al.* (2021) ‘Evaluating a finer resolution global hydrological model’s simulation of discharge in four West-African river basins’, *Modeling Earth Systems and Environment*, 7(4), pp. 2167–2178. doi:10.1007/S40808-020-00948-X/TABLES/5.

Bai, Y., Ochuodho, T.O. and Yang, J. (2019) ‘Impact of land use and climate change on water-related ecosystem services in Kentucky, USA’, *Ecological Indicators*, 102, pp. 51–64. doi:10.1016/J.ECOLIND.2019.01.079.

Bechmann, M.E. *et al.* (2005) ‘Phosphorus transfer from agricultural areas and its impact on the eutrophication of lakes—two long-term integrated studies from Norway’, *Journal of Hydrology*, 304(1–4), pp. 238–250. doi:10.1016/J.JHYDROL.2004.07.032.

Bol, R. *et al.* (2018) ‘Challenges of reducing phosphorus based water eutrophication in the agricultural landscapes of Northwest Europe’, *Frontiers in Marine Science*, 5(AUG), pp. 1–16. doi:10.3389/fmars.2018.00276.

Carpenter, S.R. (2008) ‘Phosphorus control is critical to mitigating eutrophication’, *Proceedings of the National Academy of Sciences of the United States of America*, 105(32), pp. 11039–11040. doi:10.1073/PNAS.0806112105.

Chen, D. *et al.* (2015) ‘Influence of legacy phosphorus, land use, and climate change on anthropogenic phosphorus inputs and riverine export dynamics’, *Biogeochemistry*, 123(1–2), pp. 99–116. doi:10.1007/S10533-014-0055-2/TABLES/3.

Crespi, A. *et al.* (2020) ‘Climate-related hazard indices for Europe’, p. 64. doi:10.25424/cmcc/climate.

Crossman, J. *et al.* (2014) ‘Flow pathways and nutrient transport mechanisms drive hydrochemical sensitivity to climate change across catchments with different geology and topography’, *Hydrology and Earth System Sciences*, 18(12), pp. 5125–5148. doi:10.5194/HESS-18-5125-2014.

Crossman, J. *et al.* (2021) ‘A new, catchment-scale integrated water quality model of phosphorus, dissolved oxygen, biochemical oxygen demand and phytoplankton: Inca-phosphorus ecology (peco)’, *Water (Switzerland)*, 13(5). doi:10.3390/w13050723.

Darracq, A. *et al.* (2005) ‘Nutrient transport scenarios in a changing Stockholm and Mälaren valley region, Sweden’, *Water Science and Technology*, 51(3–4), pp. 31–38. doi:10.2166/wst.2005.0572.

Djodjic, F., Bieroza, M. and Bergström, L. (2021) ‘Land use, geology and soil properties control nutrient concentrations in headwater streams’, *Science of The Total Environment*, 772, p. 145108. doi:10.1016/J.SCITOTENV.2021.145108.

EASAC (2013) ‘Trends in extreme weather events in Europe: implications for national and European Union adaption strategies’, *Trends in Extreme weather events in Europe:Implications for national and European Union adaptation strategies*, (November), p. 28. Available at: www.easac.eu.

EEA (2017) *Climate change, impacts and vulnerability in Europe 2016. An indicator-based report.* Available at: https://www.eea.europa.eu/publications/climate-change-adaptation-and-disaster.

El-Khoury, A. *et al.* (2015) ‘Combined impacts of future climate and land use changes on discharge, nitrogen and phosphorus loads for a Canadian river basin’, *Journal of Environmental Management*, 151, pp. 76–86. doi:10.1016/J.JENVMAN.2014.12.012.

Farkas, C. *et al.* (2013) ‘Soil erosion and phosphorus losses under variable land use as simulated by the INCA-P model’, *Soil Use and Management*, 29(SUPPL.1), pp. 124–137. doi:10.1111/J.1475-2743.2012.00430.X.

Fischer, E.M. and Knutti, R. (2016) ‘Observed heavy precipitation increase confirms theory and early models’, *Nature Climate Change*, 6(11), pp. 986–991.

doi:10.1038/nclimate3110.

Frei, C. *et al.* (2006) 'Future change of precipitation extremes in Europe: Intercomparison of scenarios from regional climate models', *Journal of Geophysical Research Atmospheres*, 111(6). doi:10.1029/2005JD005965.

Futter, M.N. *et al.* (2014) 'PERSiST: A flexible rainfall-runoff modelling toolkit for use with the INCA family of models', *Hydrology and Earth System Sciences*, 18(2), pp. 855–873. doi:10.5194/hess-18-855-2014.

Grusson, Y. *et al.* (2021) 'Influence of climate change on water partitioning in agricultural watersheds: Examples from Sweden', *Agricultural Water Management*, 249, p. 106766. doi:10.1016/J.AGWAT.2021.106766.

Gupta, H. V. *et al.* (2009) 'Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling', *Journal of Hydrology*, 377(1–2), pp. 80–91. doi:10.1016/J.JHYDROL.2009.08.003.

Hansson, K. *et al.* (2019) 'Näringsbelastningen på Östersjön och Västerhavet 2017 Sveriges underlag till HELCOM:s sjunde Pollution Load Compilation', *Havs och Vattenmyndigheten*, Rapport 20.

Hov, Ø. *et al.* (2013) *Extreme Weather Events in Europe: preparing for climate change adaptation*.

IPCC (2021) *Technical Summary. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Climate Change 2021: The Physical Science Basis.* Edited by V. Masson-Delmotte et al. Available at: www.ipcc.ch.

Jackson-Blake, L.A. *et al.* (2016) 'The INtegrated CAtchment model of phosphorus dynamics (INCA-P): Description and demonstration of new model structure and equations', *Environmental Modelling and Software*, 83(September), pp. 356–386. doi:10.1016/j.envsoft.2016.05.022.

Jarvie, H.P. *et al.* (2014) 'Phosphorus retention and remobilization along hydrological pathways in karst terrain', *Environmental Science and Technology*, 48(9), pp. 4860–4868. doi:10.1021/ES405585B/SUPPL_FILE/ES405585B_SI_001.PDF.

JMP (2021) *Multiple Comparisons*. Available at: https://www.jmp.com/support/help/en/16.2/index.shtml#page/jmp/multiple-comparisons.shtml%23ww1348930 (Accessed: 11 July 2022).

Kok, K. *et al.* (2019) 'New European socio-economic scenarios for climate change research: operationalising concepts to extend the shared socio-economic pathways', *Regional Environmental Change*, 19(3), pp. 643–654. doi:10.1007/s10113-018-1400-0.

Kovats, R.S. *et al.* (2014) *Europe. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Meriwether Wilson.

Lamontagne, J.R., Barber, C.A. and Vogel, R.M. (2020) 'Improved Estimators of Model Performance Efficiency for Skewed Hydrologic Data', *Water Resources Research*, 56(9). doi:10.1029/2020WR027101.

Lannergård, E.E. *et al.* (2019) 'An evaluation of high frequency turbidity as a proxy for riverine total phosphorus concentrations', *Science of the Total Environment*, 651, pp. 103–113. doi:10.1016/j.scitotenv.2018.09.127.

Lannergård, E.E. *et al.* (2020) 'New Insights Into Legacy Phosphorus From Fractionation of Streambed Sediment', *Journal of Geophysical Research: Biogeosciences*, 125(9), p. e2020JG005763. doi:10.1029/2020JG005763.

Lannergård, E.E., Fölster, J. and Futter, M.N. (2021) 'Turbidity-discharge hysteresis in a meso-scale catchment: The importance of intermediate scale events', *Hydrological Processes*, 35(12), p. e14435. doi:10.1002/HYP.14435.

Larsen, A.N. *et al.* (2009) 'Potential future increase in extreme one-hour precipitation events over Europe due to climate change', *Water Science and Technology*, 60(9), pp. 2205–2216. doi:10.2166/wst.2009.650.

Ledesma, J.L.J. *et al.* (2021) 'Future changes in the Dominant Source Layer of riparian lateral water fluxes in a subhumid Mediterranean catchment', *Journal of Hydrology*, 595. doi:10.1016/j.jhydrol.2021.126014.

Lee, S. and Lee, D.K. (2018) 'What is the proper way to apply the multiple comparison test?', *Korean Journal of Anesthesiology*, 71(5), pp. 353–360. doi:10.4097/KJA.D.18.00242.

Lotze-Campen, H. *et al.* (2008) 'Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach', *Agricultural Economics*, 39(3), pp. 325–338. doi:10.1111/J.1574-0862.2008.00336.X.

Marttila, H. *et al.* (2020) 'Potential impacts of a future Nordic bioeconomy on surface water quality', *Ambio*, 49(11), pp. 1722–1735. doi:10.1007/s13280-020-01355-3.

Moore, K. *et al.* (2007) 'Effects of warmer world scenarios on hydrologic inputs to Lake Mälaren, Sweden and implications for nutrient loads', *European Large Lakes Ecosystem changes and their ecological and socioeconomic impacts*, pp. 191–199. doi:10.1007/978-1-4020-8379-2_23.

Moriasi, D.N. *et al.* (2007) 'Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations', *Transactions of the ASABE*, 50(3), pp. 885–900.

Moriasi, D.N. *et al.* (2015) 'Hydrologic and water quality models: Performance measures and evaluation criteria', *Transactions of the ASABE*, 58(6), pp. 1763–1785. doi:10.13031/trans.58.10715.

Moss, R.H. *et al.* (2010) 'The next generation of scenarios for climate change research and assessment', *Nature 463^{o}*, 463(7282), pp. 747–756. doi:10.1038/nature08823.

Murdoch, P.S., Baron, J.S. and Miller, T.L. (2000) 'Potential effects of climate change on surface-water quality in North America', *Journal of the American Water Resources Association*, 36(2), pp. 347–366. doi:10.1111/J.1752-1688.2000.TB04273.X.

Nordic Council of Ministers (2018) *Nordic Bioeconomy Programme*, *Nordic Bioeconomy Programme*. doi:10.6027/anp2018-785.

O'Neill, B.C. *et al.* (2017) 'The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century', *Global Environmental Change*, 42, pp. 169–180. doi:10.1016/J.GLOENVCHA.2015.01.004.

Onyutha, C. (2022) 'A hydrological model skill score and revised R-squared', *Hydrology Research*, 53(1), pp. 51–64. doi:10.2166/NH.2021.071.

Peñuelas, J. *et al.* (2013) 'Human-induced nitrogen–phosphorus imbalances alter natural and managed ecosystems across the globe', *Nature Communications 2013 4:1*, 4(1), pp. 1–10. doi:10.1038/ncomms3934.

Pretty, J.N. *et al.* (2003) 'Environmental costs of freshwater eutrophication in England and Wales', *Environmental Science and Technology*, 37(2), pp. 201–208. doi:10.1021/ES020793K/ASSET/IMAGES/MEDIUM/ES020793KE00014.GIF.

Rakovic, J. *et al.* (2020) 'Nordic Bioeconomy Pathways: Future narratives for assessment of water-related ecosystem services in agricultural and forest management', *Ambio*, 49(11), pp. 1710–1721. doi:10.1007/S13280-020-01389-7/TABLES/6.

Ross, D.J. *et al.* (1999) 'Land-use change: effects on soil carbon, nitrogen and phosphorus pools and fluxes in three adjacent ecosystems', *Soil Biology and Biochemistry*, 31(6), pp. 803–813. doi:10.1016/S0038-0717(98)00180-1.

Sala, O.E. *et al.* (2000) 'Global biodiversity scenarios for the year 2100', *Science*, 287(5459), pp. 1770–1774. doi:10.1126/SCIENCE.287.5459.1770/ASSET/A0209186-7C7A-4372-8261-B95BC35D8854/ASSETS/GRAPHIC/SE0208204003.JPEG.

Schindler, D.W. *et al.* (2008) *Eutrophication of lakes cannot be controlled by reducing* *nitrogen input: Results of a 37-year whole-ecosystem experiment*. Available at: www.pnas.org/cgi/content/full/.

Seibert, J. and McDonnell, J.J. (2002) 'On the dialog between experimentalist and modeler in catchment hydrology: Use of soft data for multicriteria model calibration', *Water Resources Research*, 38(11), pp. 23-1-23–14. doi:10.1029/2001wr000978.

SMHI (2020) *Modelldata per område | SMHI - Vattenwebb*. Available at: https://vattenwebb.smhi.se/modelarea/ (Accessed: 18 May 2022).

SMHI (2021a) *Climate indicators - precipitation*, *Swedish Meteorological and Hydrological Institute*. Available at: https://www.smhi.se/en/climate/climate-indicators/climate-indicators-precipitation-1.91462 (Accessed: 25 April 2022).

SMHI (2021b) *Climate indicators - temperature*, *Swedish Meteorological and Hydrological Institute*. Available at: https://www.smhi.se/en/climate/climate-indicators/climate-indicators-temperature-1.91472 (Accessed: 25 April 2022).

SMHI (2022) *Basic Climate Change Scenario Service*, *Future Climate*. Available at: https://www.smhi.se/en/climate/future-climate/advanced-climate-change-scenario-service/met/uppsala_lan/medeltemperatur/rcp45/2071-2100/winter/anom (Accessed: 10 May 2022).

Smith, V.H. and Schindler, D.W. (2009) 'Eutrophication science: where do we go from here?', *Trends in Ecology & Evolution*, 24(4), pp. 201–207. doi:10.1016/J.TREE.2008.11.009.

Stürck, J. *et al.* (2018) 'Simulating and delineating future land change trajectories across Europe', *Regional Environmental Change*, 18(3), pp. 733–749. doi:10.1007/S10113-015-0876-0/FIGURES/10.

Ulén, B. (2003) 'Concentrations and transport of different forms of phosphorus during snowmelt runoff from an illite clay soil', *Hydrological Processes*, 17(4), pp. 747–758. doi:10.1002/HYP.1164.

Vattenmyndigheten Norra Östersjön (2016) 'Förvaltningsplan för Norra Östersjöns vattendistrikt 2016–2021'. Available at: www.vattenmyndigheterna.se (Accessed: 19 June 2022).

Wade, A.J. *et al.* (2002) 'A nitrogen model for European catchments: INCA, new model structure and equations', *Hydrology and Earth System Sciences*, 6(3), pp. 559–582. doi:10.5194/hess-6-559-2002.

Wade, A.J., Whitehead, P.G. and Butterfield, D. (2002) 'The Integrated Catchments model of Phosphorus dynamics (INCA-P), a new approach for multiple source assessment in heterogeneous river systems: Model structure and equations', *Hydrology and Earth System Sciences*, 6(3), pp. 583–606. doi:10.5194/HESS-6-583-2002.

Wellen, C., Kamran-Disfani, A.R. and Arhonditsis, G.B. (2015) 'Evaluation of the current state of distributed watershed nutrient water quality modeling', *Environmental Science and Technology*, 49(6), pp. 3278–3290. doi:10.1021/es5049557.

7. Supplementary figures

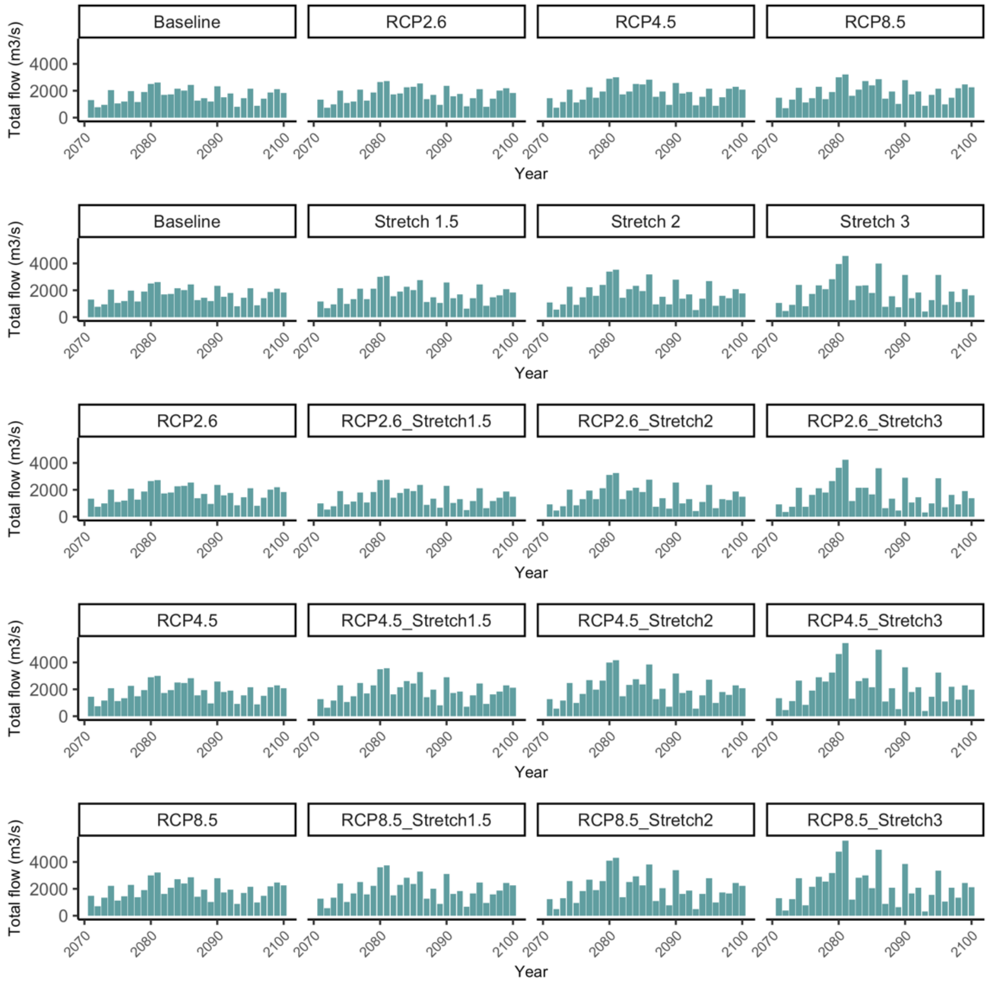

Figure S1. Total yearly streamflow for all scenarios. Predictions to period 2071-2100.

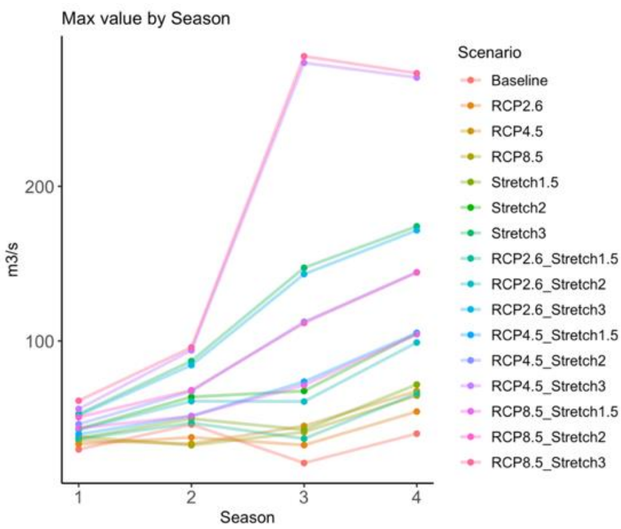

Figure S2. Seasonal maximum streamflow per scenario (m^3/s) for period 2071-2100. Winter (1), Spring (2), Summer (3), Autumn (4).

8. Supplementary tables

Table S1. Proportion of cover in different NBP scenarios applied to each of Sävjaån subcatchments, Lejstaån Stora Hopan, Sävjaån and Storån.

Scenario NBP1					
	Lejstaån	Stora Hopan	Sävjaån	Storån	Total catchment
Forest	81%	80%	49%	71%	74%
Arable	8%	7%	30%	13%	11%
Pasture	9%	7%	9%	11%	9%
Urban	1%	1%	11%	2%	2%
Wetlands	2%	5%	1%	4%	4%
TOTAL (km2)	100%	100%	100%	100%	100%

Scenario NBP2					
	Lejstaån	Stora Hopan	Sävjaån	Storån	Total catchment
Forest	79%	76%	38%	67%	70%
Arable	11%	10%	40%	17%	15%
Pasture	10%	8%	11%	13%	10%
Urban	0%	2%	10%	0%	2%
Wetlands	1%	3%	1%	3%	3%
TOTAL (km2)	101%	100%	100%	99%	100%

Scenario NBP3					
	Lejstaån	Stora Hopan	Sävjaån	Storån	Total catchment
Forest	72%	70%	27%	58%	62%
Arable	15%	13%	53%	22%	20%
Pasture	13%	12%	10%	17%	13%
Urban	0%	2%	9%	0%	2%
Wetlands	1%	3%	1%	3%	2%
TOTAL (km2)	101%	100%	100%	99%	100%

Scenario NBP4					
	Lejstaån	Stora Hopan	Sävjaån	Storån	Total catchment
Forest	79%	78%	35%	68%	71%
Arable	10%	9%	38%	16%	14%
Pasture	10%	8%	11%	13%	10%
Urban	0%	1%	15%	0%	2%
Wetlands	1%	3%	1%	3%	3%
TOTAL (km2)	101%	100%	100%	99%	100%

Scenario NBP5					
	Lejstaån	Stora Hopan	Sävjaån	Storån	Total catchment
Forest	74%	73%	35%	61%	66%
Arable	13%	14%	43%	20%	19%
Pasture	11%	9%	9%	14%	11%
Urban	1%	1%	12%	1%	2%
Wetlands	1%	3%	1%	3%	2%
TOTAL (km2)	101%	100%	100%	99%	100%

Table S2. Average streamflow range by scenario. Strength in red colour in relation to lowest values, strength in blue colour in relation to higher values, strength in green colour in relation to difference in lowest and highest values.

Year	**Lowest**	**Highest**	**Difference**
Baseline	2.15	7.11	4.96
RCP 2.6	2.00	7.48	5.48
RCP 4.5	2.04	8.20	6.15
RCP 8.5	1.88	8.80	6.92
Stretch 1.5	1.74	8.37	6.63
Stretch 2	1.47	9.71	8.24
Stretch 3	1.18	12.49	11.31
RCP 2.6 + Stretch 1.5	1.33	7.59	6.26
RCP 2.6 + Stretch 2	1.15	8.90	7.76
RCP 2.6 + Stretch 3	0.87	11.60	10.73
RCP4.5 + 1.5Stretch	1.74	9.72	7.99
RCP 4.5 + Stretch 2	1.52	11.37	9.84
RCP 4.5 + Stretch 3	1.07	14.86	13.79
RCP 8.5 + Stretch 1.5	1.55	10.25	8.70
RCP 8.5 + Stretch 2	1.32	11.85	10.53
RCP 8.5 + Stretch 3	0.89	15.25	14.35

Table S3. Highest daily streamflow event per scenario. Values obtained from the maximum daily values in streamflow simulation.

Highest streamflow registered (m^3/s)	
RCP8.5_3Stretch	284
RCP4.5_3Stretch	280
3 Stretch	174
RCP2.6_3Stretch	172
RCP4.5_2Stretch	145
RCP8.5_2Stretch	144
RCP4.5_1.5Stretch	105
2 Stretch	105
RCP8.5_1.5Stretch	105
RCP2.6_2Stretch	99
1.5 Stretch	72
RCP4.5	68
RCP2.6_1.5Stretch	66
RCP8.5	65
RCP2.6	54
Baseline	46