Catena 226 (2023) 107045

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

# Influence of forest management changes and reuse of peat production areas on water quality in a northern river

Katri Rankinen [a,*], Martyn Futter [b], Joy Bhattacharjee [c], José E. Cano Bernal [a], Emma E. Lannergård [b], Maria Ojanen [a], Anna-Kaisa Ronkanen [a], Hannu Marttila [c], Seppo Hellsten [a]

[a] Finnish Environment Institute, Finland
[b] Swedish University of Agricultural Sciences, Sweden
[c] Water, Energy and Environmental Engineering Research Unit, University of Oulu, Finland

ARTICLE INFO

*Keywords:*
Peatland
Land use
Nitrogen
Phosphorus
Mathematical modelling
Climate change

ABSTRACT

In Northern Finland, the most significant land use challenges are related to bioenergy production from peat extraction and forest biomass. Increasing societal demand for bioenergy may increase production rates. However, environmental impacts of peat extraction are of increasing concern, which has led to a decline in production, thereby freeing up these areas for other uses. Using storylines for different societal futures and process-based models (PERSiST and INCA), we simulated the effect of simultaneous land use change and climate change on water quality (phosphorus, nitrogen and suspended sediments concentration). Conversion of peat extraction areas to arable land, together with climate change, may pose a risk for deterioration of ecological status. On the other hand, continuous forestry may have positive impacts on water quality. Suspended sediment concentrations in the river do not exceed water quality requirements for salmonids, but nitrogen concentrations may exceed threshold values especially during high flows. A storyline emphasizing sustainable development in energy production led to the best outcome in terms of water protection.

## 1. Introduction

Land use and soil management are essential factors affecting terrestrial nutrient losses to rivers and coastal waters. According to the newest review of ecological status of freshwaters in Europe, riverine water quality needs specific attention since it fails to reach good status in more than 50 % of rivers while more than 50 % of lakes have good or high ecological status (Ecological status of surface waters in Europe (europa.eu)). Both phosphorus (P) and nitrogen (N) loads need attention since these are the major nutrients controlling eutrophication in aquatic systems and increased fluxes can cause eutrophication of surface waters. While P has historically been the nutrient of greatest concern area (Bartosova et al., 2019; Savage et al., 2010; Vuorenmaa et al., 2002), N also limits algae growth seasonally or spatially in the Baltic Sea (Howarth and Marino, 2006; Tamminen and Andersen, 2007). Further, some shallow and polymictic lakes may also be *N*-limited (Dolman et al., 2016; Maberly et al., 2020; Pietiläinen and Räike, 1999).

Specific nutrient loading (nutrient load per area) is generally higher from agricultural areas than from forested areas and P loads from agriculture have been seen as a major factor for Baltic Sea eutrophication (Bartosova et al., 2019; Savage et al., 2010; Vuorenmaa et al., 2002). However, at a local scale forestry can induce eutrophication of small lakes (Ahtiainen and Huttunen, 1999; Kenttämies, 1998; Kortelainen and Saukkonen, 1998; Kortelainen et al., 1997). Some measures, especially forest ditching that peaked in the early 1970′s, may have long-lasting and increasing effect on nutrient loading (Finér et al., 2021; Nieminen, 1998; Nieminen et al., 2017; Nieminen et al., 2018a,b; Nieminen et al., 2020). One additional factor that increases N loading from river basins is the clearing of peat soils for fields (Rankinen et al., 2016). In recent years, continuous cover forestry has become more common. The primary objective is to ensure that the forest canopy remains intact, and it is supposed to produce several environmental benefits (Nieminen et al., 2018a,b).

About a third of Finland's land area is peatland, and energy peat supplied a couple of percent of Finland's total energy consumption in 2021. Due to the rapid decline in demand for energy peat, the active peat

* Corresponding author.
*E-mail address:* katri.rankinen@syke.fi (K. Rankinen).

https://doi.org/10.1016/j.catena.2023.107045
Received 5 August 2022; Received in revised form 20 February 2023; Accepted 22 February 2023
Available online 7 March 2023

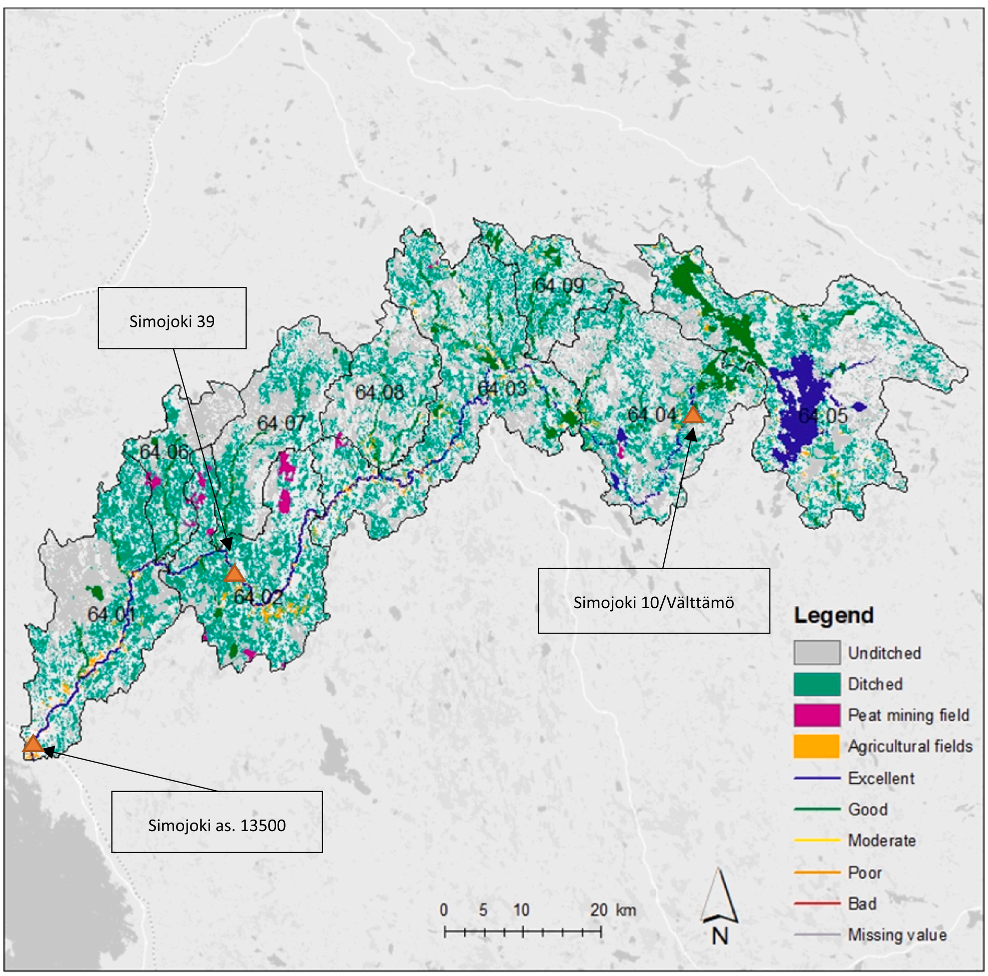



**Fig. 1.** Location of the Simojoki river basin in Finland. Yellow areas are agricultural fields, red areas peat mining fields and green areas ditched forest areas. Triangles are the main water quality sampling points.

**Table 1**
Characteristics of the sub basins.

| Sub-catchment | Area [$km^2$] | Peat mining fields [%] | Agricultural fields [%] | Potential energy tree areas [%] (on peat soils) | Manure input [kg N/ha] | Population density [person/$km^2$] |
|---|---|---|---|---|---|---|
| 64.09 | 147 | 0 | 0.7 | 3.4 (40 %) | – | 0.99 |
| 64.08 | 201 | 0 | 0.9 | 8.5 (24 %) | – | 0.99 |
| 64.07 | 245 | 0.2 | 0.2 | 3.3 (88 %) | – | 1.39 |
| 64.06 | 147 | 1.1 | 0 | 2.7 (0 %) | – | 1.39 |
| 64.05 | 630 | 0 | 1.9 | 2.5 (8 %) | 99 | 0.99 |
| 64.04 | 446 | 0 | 0.9 | 1.1 (20 %) | 101 | 0.99 |
| 64.03 | 557 | 0.1 | 2.8 | 5.6 (41 %) | 74 | 0.99 |
| 64.02 | 375 | 0.5 | 2.7 | 5.3 (0 %) | 135 | 1.39 |
| 64.01 (outlet) | 412 | 1.6 | 2.4 | 12.6 (12 %) | 191 | 1.39 |

production sector has decreased rapidly in recent years (https://www.bioenergia.fi/category/tiedotteet/). There are also climate-related reasons, including carbon neutrality targets, to stop peat extraction (Korkiakoski et al., 2019). In Denmark and Germany, drained peatlands and peatlands used as meadows have caused some water quality problems and they have been re-wetted in the hope of reducing nutrient loads (Hoffmann et al., 2020; Tiemeyer et al., 2007). In Finland, approximately 2000–3000 ha of previous peat extraction areas are converted to new land uses each year: 75 % is afforested, 20 % is cultivated and 5 % has been converted to wetlands. Some areas also have special uses, e.g., windmill parks.

Peat extraction requires an environmental permit (Environmental Protection Act /ympäristönsuojelulaki 527/2014). State and municipal authorities ensure that extraction is carried out responsibly and in an environmentally friendly manner. The environmental permit obligations end when production has ceased, and the area has been converted to a new land use. However, the Environmental Protection Act does not apply to the physical alteration or structural pollution of the environment, nor to land use and nature protection, which are regulated separately (e.g. Lång et al., 2022).

The Water Framework Directive (WFD; EU, 2000) commits European Union member states to achieving good qualitative and quantitative status of all water by 2027. The Finnish Environmental Protection Act (527/2014) and Water Act (587/2011) state only that the permit authority shall consider what is set out in a river basin management plan. The ecological status of surface waters is assessed according to biological, hydromorphological and physico-chemical quality elements with additional chemical status values for specific priority substances. Physico-chemical quality elements specify maximum concentrations for some parameters including total P and total N. If even one such concentration is exceeded, the water body will not be classed as having a "good ecological status".

According to the Weser Ruling (C-461/13) deterioration of a single surface water quality factor is prohibited, even if the status of the water body as a whole is not deteriorated. The European Court of Justice interpreted how the objectives, exceptions, and the non-deterioration requirements of WFD should be applied. The Ruling concerned dredging in the German river Weser, but it has large implications on the admissibility of other activities (Kymenvaara et al., 2019; Paloniitty & Kotamäki, 2021). There is also a precedent in Finland where an environmental permit has been refused on this basis (Thorén et al., 2021).

Simojoki is one of the few rivers draining to the Baltic with a naturally reproducing salmon population. Salmon in the river are likely well adapted to the cool water, low nutrients and high levels of DOC. Any changes in future conditions may negatively impact the resilience of this important fish population (LaMere et al., 2020).

Changing climate is assumed to increase nutrient loading from Nordic river basins due to increases in temperature, precipitation and extreme events (Brookshire et al., 2011; Øygarden et al., 2014; Puustinen et al., 2007; Bartosova et al., 2019; Pihlainen et al., 2020). For example, by 2040–2069, mean temperatures are projected to increase in Finland by 2.4 (1.0–3.8) ∘C in summer and 3.3 (1.2–5.4) ∘C in winter relative to a baseline of 1981– 2010. Precipitation increases average 5 % in summer and 12 % in winter (Ruosteenoja and Jylhä, 2021).

The climate change scenarios and downscaling strategies used in catchment-scale simulations of possible future conditions are based on well-documented sets of assumptions, e.g., the IPCC Representative Concentration Pathway (RCP) greenhouse gas concentration trajectories. More difficult are projections of possible future land use associated with changing socioeconomic conditions. The need for plausible projections of future societal conditions for integrated assessment of social-environmental systems led to the development of a set of global scenarios, the Shared Socioeconomic Pathways (SSPs; O'Neill et al., 2017). The SSPs are qualitative scenarios (storylines) that describe coherent, internally consistent and plausible global societal trends for selected socio-economic elements. They consider a wide range of socioeconomic drivers (e.g. demographics, economy, policies and institutions) and comprise a set of five distinct pathways that can be combined with climate projections to produce integrated scenarios.

Climate change and global change more generally have a direct impact on nutrient loads to waters, but also indirectly on land use change. Socioeconomic conditions are projected to have greater impacts on water quality than climate change in the Baltic Sea region (Bartosova et al., 2019). One way to approach simultaneous change is to create storylines for different developments (e.g. Rakovic et al., 2020). The impact of an individual measure on this type of review is difficult to ascertain, and the results need to be seen as possible developments.

Quantitative, process-based models are widely used to assess combined effects of climate and land use change (e.g., Moe et al., 2019; Whitehead et al., 2013; Bussi et al., 2016; Molina-Navarro et al., 2018) on catchment processes. Different catchment-scale, process-based models have been applied in the Nordic countries to estimate impact of land use and land management on water quality (e.g. Granlund et al., 2004; Rankinen et al., 2010; Rankinen et al., 2019; Farkas et al., 2013; Lu et al., 2016; Arheimer and Pers, 2017). The results have provided an important source of information to decision-makers for estimating impacts of land management alternatives on water quality.

The main aim of our study is to estimate possible threats to water quality associated with forest management change and re-use of peat extraction sites in the Simojoki river basin. We focus on broad trends in

**Table 2**
Basic statistics of water quality parameters at the outlet of Simojoki (station Simojoki as. 13500) in 1985–2020.

| | TN [μg N/l] | $NO_3$-N [μg N/l] | $NH_4$-N [μg N/l] | DON [μg N/l] | TP [μg P/l] | DTP [μg P/l] | DRP [μg P/l] | Susp.sed [mg/l] |
|---|---|---|---|---|---|---|---|---|
| *Simojoki 10 / Välttämö* | | | | | | | | |
| Mean | 298.4 | 16.7 | 8.4 | 275.5 | 9.7 | – | – | 1.4 |
| Var | 3556.5 | 323.2 | 67.5 | 3680.2 | 144.8 | – | – | 0.7 |
| Std | 59.6 | 18.0 | 8.2 | 60.7 | 12 | – | – | 0.8 |
| n | 144 | 107 | 110 | 107 | 146 | – | – | 13 |
| *Simojoki 39* | | | | | | | | |
| Mean | 472.7 | 26.3 | 18.4 | 418.6 | 20 | – | – | – |
| Var | 15903.8 | 1321.1 | 983.6 | 8836.3 | 102.4 | – | – | – |
| Std | 126.1 | 36.3 | 31.4 | 94.0 | 10.1 | – | – | – |
| n | 196 | 126 | 192 | 126 | 191 | – | – | – |
| *Simojoki as. 13,500* | | | | | | | | |
| Mean | 499.4 | 61.5 | 18.6 | 419.0 | 20.5 | 10.7 | 3.1 | 5.3 |
| Var | 19703.4 | 4290.4 | 450.8 | 14417.9 | 80.7 | 11.4 | 3.2 | 110.2 |
| Std | 140.4 | 65.5 | 21.2 | 120.1 | 9.0 | 3.4 | 1.8 | 10.5 |
| n | 521 | 471 | 519 | 471 | 404 | 404 | 234 | 391 |

**Table 3**
Goodness-of-fit values for calibration and validation periods.

| River basin and station | $NO_3$-N | | $NH_4$-N | | ON | | Susp. Sed | | TP | | SRP | | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $R^2$ | RMSE | $R^2$ | RMSE | $R^2$ | RMSE | $R^2$ | RMSE | $R^2$ | RMSE | $R^2$ | RMSE | N-S |
| *Calibration 1990–2002* | | | | | | | | | | | | | |
| 64.08 Välttämö | 0.094 | 0.046 | 0.009 | 0.069 | 0.076 | 0.221 | 0.109 | 56.604 | – | – | – | – | – |
| 64.05 Simojoki 39 | – | – | – | – | – | – | 0.847 | 19.020 | – | – | – | – | 0.593 |
| 64.03 | 0.423 | 0.065 | 0.112 | 0.051 | 0.168 | 0.176 | – | – | – | – | – | – | 0.533 |
| 64.01 Simojoki as. 13,500 | 0.385 | 0.084 | 0.270 | 0.047 | 0.100 | 0.139 | 0.007 | 286.168 | 0.219 | 123.38 | 0.201 | 302.16 | 0.717 |
| *Validation 2003–2015* | | | | | | | | | | | | | |
| 64.08 Välttämö | 0.192 | 0.204 | 0.169 | 0.070 | 0.034 | 0.194 | – | – | 0.160 | 200.080 | – | – | – |
| 64.05 Simojoki 39 | – | – | – | – | – | – | – | – | – | – | – | – | – |
| 64.03 | 0.189 | 0.094 | 0.121 | 0.058 | 0.106 | 0.115 | 0.205 | 176.621 | 0.210 | 102.411 | – | – | 0.621 |
| 64.01 Simojoki as. 13,500 | 0.258 | 0.104 | 0.173 | 0.051 | 0.032 | 0.142 | 0.002 | 197.133 | 0.391 | 117.918 | 0.144 | 325.577 | 0.548 |

land use, the existence of which can already be seen. Further, we evaluate the influence of future storylines in climate and land use changes in these sectors on discharge patterns and water quality of the river by mathematical modelling. We included into storylines three different forestry measures (whole-tree harvesting, stem-only harvesting and continuous cover forestry). Special emphasis is on the possible changes in the ecological status of the river.

## 2. Material and methods

### 2.1. Study site

The river Simojoki is located in northern Finland (Fig. 1) and it is one of the few unregulated large rivers inhabited by a natural salmon population. Thus, the recreational value of the river is considerable. The ecological status of the main channel is excellent and side branches good.

The Simojoki River catchment area (3160 $km^2$) covers the territory of two relatively sparsely populated municipalities (Ranua and Simo) (Statistics Finland, https://www.stat.fi). Most houses are not connected to centralized municipal sewage treatment but there are on-site purification systems for a single household or small communities and other dwellings, such as holiday resorts or schools regulated by national legislation and EU directives (the Urban Wastewater Treatment Directive, (91/271/EEC) and WFD (2000/60/EC)). The number of leisure homes has steadily increased since 1980 (900 dwellings) to 2600 dwellings in 2020. Peat mining and forestry are two other important anthropogenic pressures (Table 1). Most of the forest area, almost half of which is located on organic soils, is used for economic (production) forestry. Forest ditching was intensive in the 1960′s and 1970′s. Old forests (>120 years old) cover around 2 % of the forest area. Old forest is located mainly on organic soils, and the wood volume (100 $m^3$/ha) is higher than in economically exploited forest (65–75 $m^3$/ha).

Agriculture in the area is mainly animal husbandry. Even though the field percentage in the river basin is low, fields are located directly along the river. In some areas N contents of manure (kg N/ha) are higher than the allowed limit in the Nitrate Directive (170 kg N/ha), leading to a risk of increased N loading.

### 2.2. Data

Measurements of river discharge (daily values) and suspended sediment, total phosphorus (TP), total dissolved phosphorus (TDP), and dissolved reactive phosphorus (DRP) concentrations (grab samples: on average 33 per year) were available from national monitoring programs (Niemi, 2006). The main observation site is located close to the river outlet (Fig. 1). Since 1985 water quality sampling has been concentrated on spring high flow periods (weekly to biweekly sampling) to ensure the most accurate annual nutrient flux calculations. In other seasons, samples were taken about once a month. In some mid-winter months, there was++ no sampling. Suspended sediment and dissolved nutrient analysis were less frequent.

In the analysis of TP, polyphosphates and organophosphorus compounds were first converted to orthophosphate by acid peroxodisulphate digestion under pressure at 120 °C. Orthophosphate ions reacted in an acidic solution containing molybdate and antimony ions to form a phosphomolybdate complex. Reduction of the complex with ascorbic acid formed a colored molybdenum blue complex, the absorption of which was measured at 880 nm by a spectrophotometer. TDP was similarly analyzed after first filtering the sample through a Nuclepore polycarbonate membrane (0.4 μm). Phosphate P was analyzed after filtering the sample and used as a measure of DRP. TN determination was initiated by digestion with peroxodisulphate, followed by reduction of $NO_3^-$ with a Cd amalgam and determination of $NO_2$ by the azo color

**Table 4**
Simulated leaching from different land use classes in calibration period and literature values.

| Land use class | Parameter | Unit | Simulated value | Literature value | Observation | Ref. |
|---|---|---|---|---|---|---|
| ForOrg | DON | [kg/ha/a] | 0.85–3.07 | | | |
| | $NH_4$-N | [kg/ha/a] | 0.12–0.41 | 0.29 (0.06–0.82) | Org. soils > 35 % | Kortelainen et al., 1997 |
| | | | | 0.14–0.18 | Northern Finland in general | Saukkonen and Kortelainen, 1995 |
| | $NO_3$-N | [kg/ha/a] | 0.09–0.19 | 0.19 (0.028–0.45) | Org. soils > 35 % | Kortelainen et al., 1997 |
| | | | | 0.14–0.16 | Northern Finland in general | Saukkonen and Kortelainen, 1995 |
| | | | | 0.3–2.0 | minerotrophic peatland | Kaila et al. 2015 |
| | TP | [kg/ha/a] | 0.117–0.218 | 0.121 | Spruce | Kaila et al., 2015 |
| | | | | 0.026–0.052 | | Palviainen et al., 2014 |
| | | | | 0.084 (0.006–0.424) | Managed catchments in general | Finér et al., 2021 |
| | | | | 0.12 (0.11–0,16) | TDP | Joensuu et al., 2001 |
| ForMin | DON | [kg/ha/a] | 0.60–1.67 | | | |
| | $NH_4$-N | [kg/ha/a] | 0.10–0.25 | 0.11 (0.05–0.17) | | Kortelainen et al., 1997 |
| | | | | 0.14–0.18 | Northern Finland in general | Saukkonen and Kortelainen, 1995 |
| | $NO_3$-N | [kg/ha/a] | 0.08–0.30 | 0.27 (0.057–1.0) | | Kortelainen et al., 1997 |
| | | | | 0.14–0.16 | Northern Finland in general | Saukkonen and Kortelainen, 1995 |
| | TP | [kg/ha/a] | 0.059–0.11 | 0.017–0.026 (0.003–0.006) | | Palviainen et al., 2014 |
| | | | | 0.084 (0.006–0.424) | Managed catchments in general | Finér et al., 2021 |
| ForOrgCut | DON | [kg/ha/a] | 1.05–2.77 | 1.78–3.98 | ditched | Nieminen, 2004 |
| | $NH_4$-N | [kg/ha/a] | 0.63–1.8 | 0.15 | cut + ditching, increase | Alatalo, 2000 |
| | | | | 0.39–1.49 | ditched | Nieminen, 2004 |
| | $NO_3$-N | [kg/ha/a] | 0.27–0.66 | 0.18 | cut + ditching, increase | Alatalo, 2000 |
| | | | | 0.45–0.48 | ditched | Nieminen, 2004 |
| | | | | 1.4–3.1 | icut, ncrease | Kaila et al. 2015 |
| | TP | [kg/ha/a] | 0.339–0.618 | 0.150–0.315 | clear felling, extra | Kaila et al. 2015 |
| | | | | 0.001 | 12 % increase in DRP | Joensuu et al., 2001 |
| ForMinCut | DON | [kg/ha/a] | 0.5–1.54 | | | Alatalo 2000 |
| | | | | 1.24 | coniferous, forest cut, site preparation | Piirainen et al., 2007 |
| | $NH_4$-N | [kg/ha/a] | 0.11–0.27 | 0 | increase due to treatment | Alatalo 2000 |
| | | | | 0.88 | coniferous, forest cut, site preparation | Piirainen et al., 2007 |
| | $NO_3$-N | [kg/ha/a] | 0.12–0.44 | 0.1 | increase due to treatment | Alatalo 2000 |
| | | | | 0.46 | coniferous, forest cut, site preparation | Piirainen et al., 2007 |
| | TP | [kg/ha/a] | 0.194–0.354 | 0.002 | 35 % increase in DRP leaching due to clearfelling | Joensuu et al., 2001 |
| OldFor | DON | [kg/ha/a] | 0.58–1.62 | | | |
| | $NH_4$-N | [kg/ha/a] | 0.12–0.37 | | | |
| | $NO_3$-N | [kg/ha/a] | 0.08–0.14 | | | |
| | | | | 1–2 | TN | Mälkönen et al., 1990 |
| | | | | 1.29 (0.37–4.01) | TN, pristine catchments | Finér et al., 2021 |
| | TP | [kg/ha/a] | 0.114–0.213 | 0.041 (0.006 0.209) | pristine catchments | Finér et al., 2021 |
| Peatland | DON | [kg/ha/a] | 0.11–1.17 | | | |
| | $NH_4$-N | [kg/ha/a] | 0.01–0.12 | | | |
| | $NO_3$-N | [kg/ha/a] | 0.01–0.08 | | | |
| | | | | 1.4 | TN, fen and bog in natural state | Sallantaus 1992 |
| | | | | 2.1–2.5 | TN, fen and bog, drained | Sallantaus 1992 |
| | TP | | 0.135–0.213 | 0.04 | fen and bog in natural state | Sallantaus 1992 |
| | | | | 0.11–0.14 | fen and bog, drained | Sallantaus 1992 |

(continued on next page)

**Table 4** (*continued*)

| Land use class | Parameter | Unit | Simulated value | Literature value | Observation | Ref. |
|---|---|---|---|---|---|---|
| Agri | DON | [kg/ha/a] | 0.85–1.33 | | | |
| | $NH_4$-N | [kg/ha/a] | 0.63–1.33 | | | |
| | $NO_3$-N | [kg/ha/a] | 4.76–10.72 | 2.1–6.3 | Grass lay | Puustinen et al. 2010 |
| | | | | 4.5–19 | Grass lay, TN | Puustinen et al. 2010 |
| | PP | [kg/ha/a] | 0.113–0.213 | 0.18–0.95 | Grass lay | Puustinen et al. 2010 |
| | DRP | [kg/ha/a] | 0.354–0.668 | 0.23–1 | Grass lay | Puustinen et al. 2010 |

method (Niemi, 2006). Organic N was calculated as the difference between total N and inorganic N. Concentration of dissolved organic nitrogen (DON) is calculated as the difference between TN and inorganic N. Water quality is clearly dominated by organic matter, e.g. soluble reactive phosphorus (SRP) is only 30 % of total dissolved phosphorus (Table 2).

A Digital Elevation Model (DEM) and other Geographical Information (GIS) data were available from the Finnish Environment Institute (https://www.syke.fi/en-US/Open_information). Soil data were obtained from Maannostietokanta (Lilja et al., 2006) and land cover data were obtained from the CORINE GIS. Land cover data were supplemented by more detailed field parcel data from the Natural Resources Institute Finland and maps of forest ditches (Bhattacharjee et al., 2021). Time series of effluents from current peat extraction sites were available directly from the peat extraction companies and water quality reports (Lapin vesitutkimus 1995–2004). Detailed information on forest structure was available in the web portal of the Natural Resources Institute Finland (LUKE) (https://www.luke.fi/fi/seurannat/valtakunnan-metsien-inventointi-vmi). LUKE had also annual statistics of domestic animals and main crops (https://www.luke.fi/fi/tilastot). Maps of soil types, land cover, and the DEM all had a grid size of 25 × 25 m.

Meteorological data, including daily measurements of precipitation and temperature (T), were obtained from the open data of the Finnish Meteorological Institute (FMI).

### *2.3. Model description and set-up*

We used a rainfall-runoff modeling toolkit, PERSiST (the Precipitation, Evapotranspiration, and Runoff Simulator for Solute Transport), with the INCA (Integrated Nutrients in Catchments) family of models. PERSiST is designed for simulating present-day hydrology, projecting possible future effects of climate or land use change on runoff and catchment water storage (Futter et al., 2014). PERSiST has limited data requirements and is calibrated using observed time series of precipitation, air temperature and runoff, at one or more points in a river network.

INCA-N (Wade et al., 2002; Whitehead et al., 1998) and INCA-P (Jackson-Blake et al., 2016; Crossman et al., 2021) are dynamic mass-balance models, which attempt to track the temporal variations in the hydrological flow paths and nutrient transformations and stores, in both the land and in-stream components of a river system. Output from INCA models include daily and annual land-use specific nutrient loads for all stores and transformation processes and stores within the land phase, including concentrations in the soil water, ground water, and direct runoff. Decay of the soil organic N pool is described by first-order kinetics, and the decay rate is limited by temperature and moisture. The change in mass of P adsorbed to or desorbed from the soil is calculated using a Freundlich isotherm, where the change in mass adsorbed is proportional to the difference between TDP concentration in soil water and the equilibrium TDP concentration at which no adsorption or desorption occurs. The model separately identifies a labile and an inactive stock of soil P. This allows for the simulation of long-term soil P dynamics as it calculates changes in soil P storages.

#### *2.3.1. Land use change implementation in the models*

Two types of forest harvesting are considered here in the scenarios. Forestry measures are assumed to be traditionally stem-only harvesting. In whole tree harvesting all above-ground biomass is removed, and that leads to greater nutrient removal than stem-only harvest as no cutting residues is left on site (Lundborg, 1997; Palviainen and Finér, 2012). In forest harvest areas temperature is assumed to increase, and runoff is assumed to increase due to decreased evapotranspiration. Sallantaus (1986) estimated the difference to be + 1.14 mm in runoff per cubic meter wood harvested per hectare. In continuous cover half of the trees are assumed to be removed (Routa and Huuskonen, 2022). Evapotranspiration in old forests was assumed to be higher than in economic forests due to their higher tree (stem, branches and needles) volume. On the other hand, rates of increase of both standing volume and biomass decline with stand age (Hopkinson et al., 2016). Thus, nutrient uptake is lower than in economic forests. We used the prioritization approach, Zonation (Mikkonen et al., 2018), to find new forest areas of potential high conservation value. Emissions from rural wastewater is based on nutrient emissions per inhabitant (4.59 kg N/a/person and 0.63 kg P/a/person) and removal efficiency of modern on-site treatment plants (40 % for TN and 80 % for TP) (Lehtoranta et al., 2014).

#### *2.3.2. Calibration and validation*

Catchment scale eco-hydrological models (PERSiST, INCA-ON and INCA-P) were calibrated (years 1990–2002) against observed discharge and water quality in the river. The river basin is divided into nine sub basins along the main river (Ekholm 1993). The main water quality and discharge measurement site is located at the river mouth. Another discharge measurement site is located at the Simojoki 39. These observation sites have monthly water quality sampling. (Table 3). In addition, there were one short intensive observation period of discharge and suspended sediment concentrations at the river basin 64.05.

Land use in the river basin was divided into seven classes based on land cover (CORINE) and soil type (Lilja et al. 2006). Land use classes were forest on mineral soil (ForMin), forest on organic soil (ForOrg), cut forest on mineral soil (ForMinCut), cut forest on organic soil (ForOrgCut), old forest (OldFor), natural peatlands (Peatland), peat extraction fields and agricultural (grass) fields (Agri).

Parameters of P equilibrium equations in forest soil are based on Väänänen (2008), in agricultural soils on Peltovuori (2007) and in aquatic environment on Koski-Vähälä (2001). Nitrogen fluxes (vegetation uptake, N mineralization, N nitrification and N leaching) in different land use classes were calibrated to be on the same level as the values found in the literature. Nutrient fluxes from different land uses were calibrated against literature values (Table 4).

Simulated and observed nutrient concentrations at the outlet are shown in Fig. 2. Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than observation. The optimal

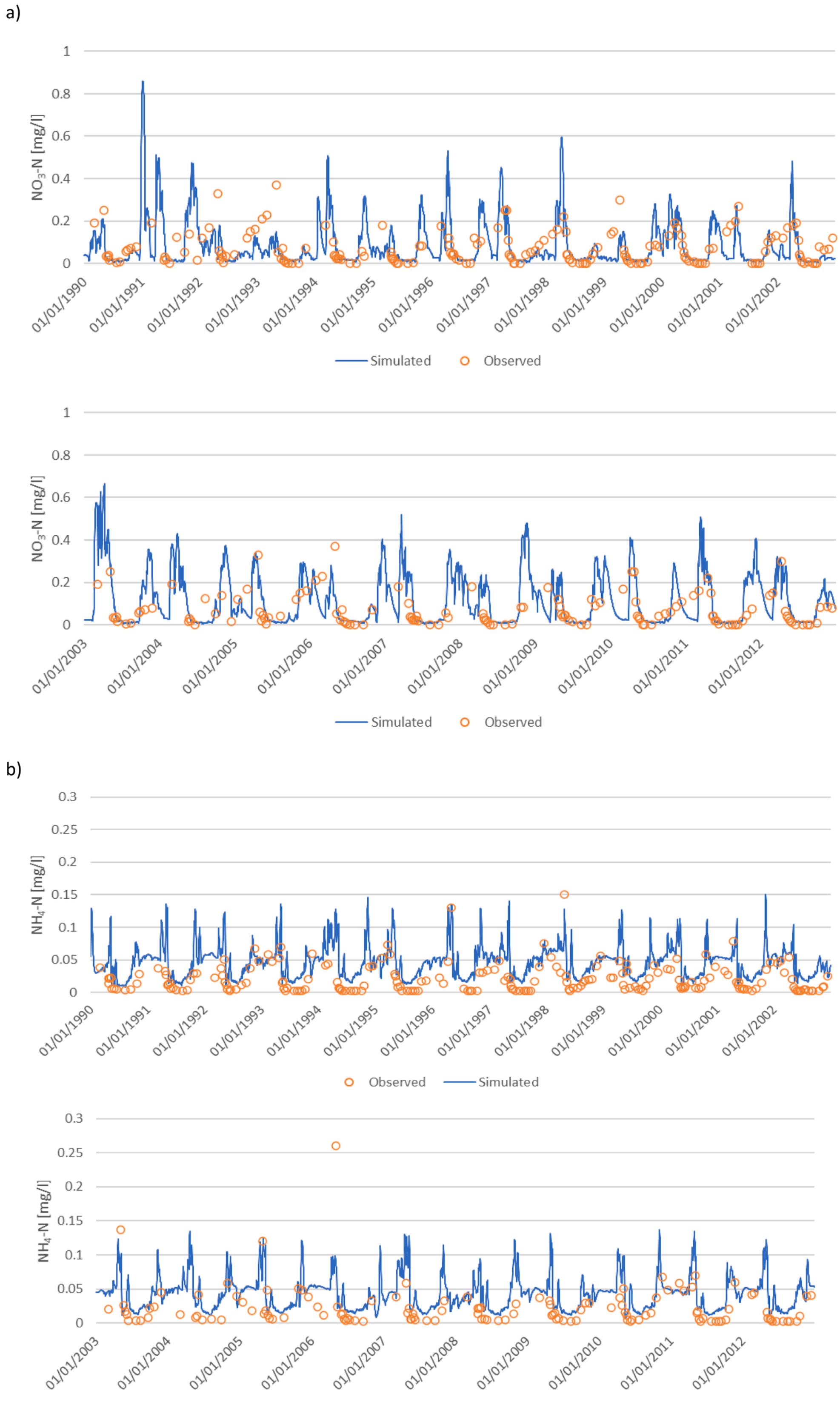



**Fig. 2.** Observed and simulated nutrient concentrations at the outlet of the river a) NO3-N concentration, b) NH4-N concentration, c) ON concentration, d) DRP concentration, e) TP concentration.

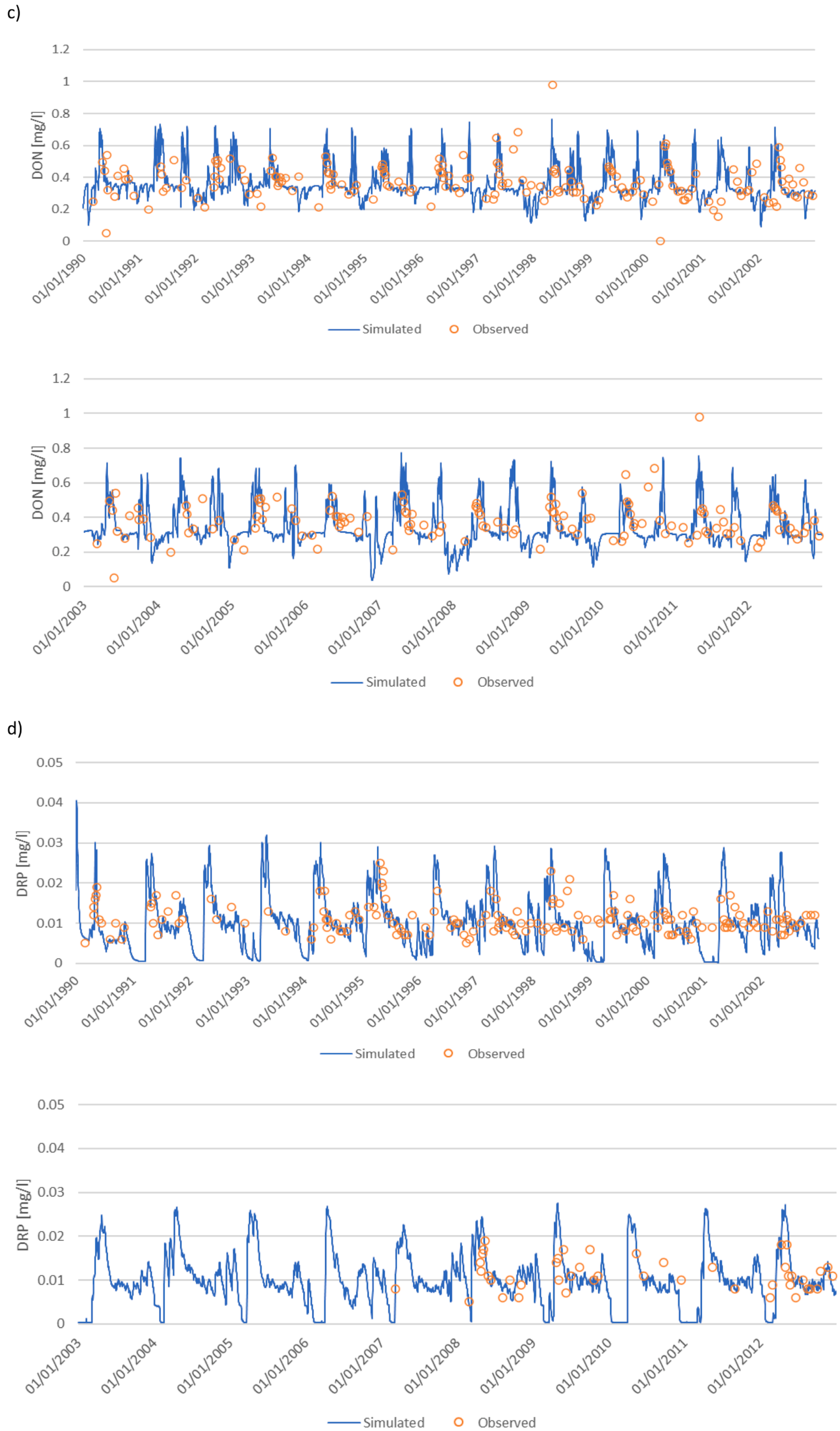



**Fig. 2.** (*continued*).

e)

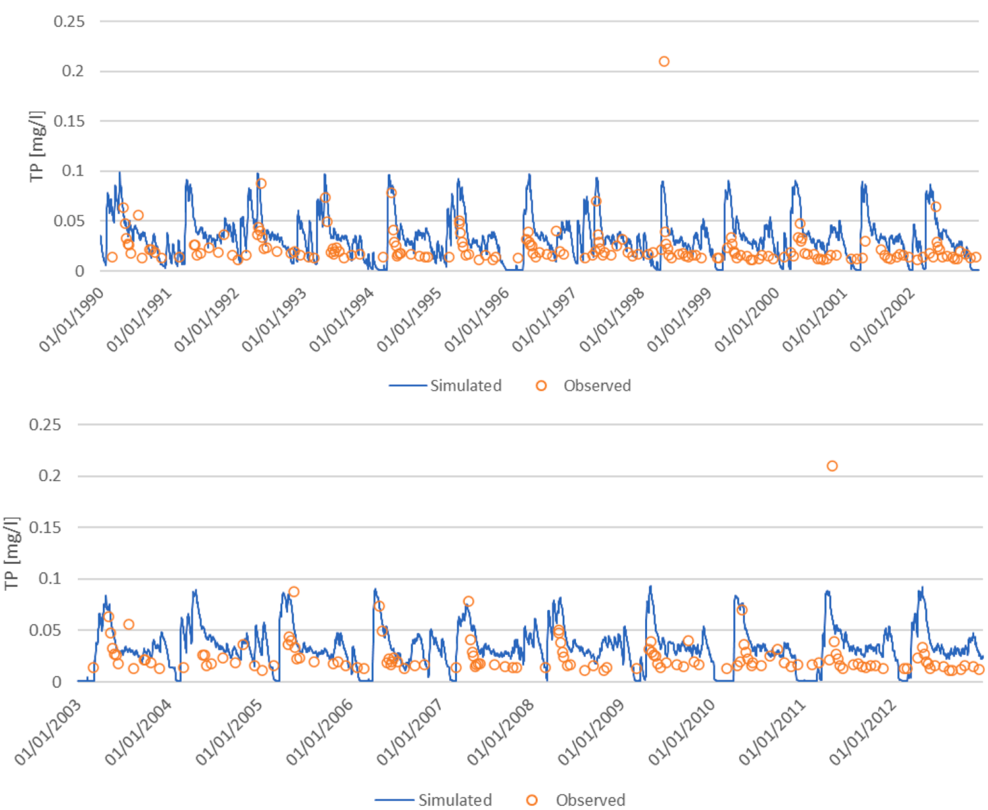



**Fig. 2.** (*continued*).

**Table 5**
Assumptions about the development of society in different storylines (Downscaled from Rakovic et al 2020 to Simojoki).

| | NBP1 | NBP2 | NBP3 | NBP4 | NBP5 |
|---|---|---|---|---|---|
| Policy | Sustainability first | Conventional first | Self-sufficiency first | City first | Growth first |
| Environmental policy | Improved management of local and global issues; tighter regulation of pollutants | Concern for local pollutants but only moderate success in implementation | Low priority for environmental issues | Focus on local environment in MICs, HICs; little attention to vulnerable areas or global issues | Focus on local environment with obvious benefits to well-being |
| Population growth | Relatively low | Medium | Low | Relatively low | Medium |
| Economic growth | Medium | Medium, uneven | Slow | Medium | High |
| Energy use and focus | Low; high focus on sustainable production | Medium; weak focus on sustainable production | High; low priority on environmental issues | Medium; diversified input to renewable energy | Relies on fossil resources |
| Animal husbandry | Small scale; low meat consumption | Medium size farms; medium meat consumption | Specialized large scale farms; material-intensive consumption | Medium scale farms; high meat consumption for wealthier people | Technical solutions, large scale farms |
| Solutions in bioenergy sector | Sustainable; energy forests area increases | Peat mining for energy production continues | Low technology; Old peat fields will turn to agricultural fields | Technical; Old peat fields will turn into wind parks, biogas production on farms | No solution; Old peat fields wetted for birds |
| Forestry | Continuous cover, forestry area increases | Stem only harvesting, no change in forestry area | Whole tree harvesting, no change in forestry area | Stem only harvesting, no change in forestry area | Increase in protected areas, no change in forestry area |
| RCP | 4.5 | 8.5 | 8.5 | 4.5 | 4.5 |

value of PBIAS is 0.0, and based on Moriasi et al. (2007, 2015) it is easy to interpret if the calibration is acceptable or not. For discharge goodness-of-fit value PBIAS was 2.77 for the calibration period and 18.4 for the validation period (2003–2012). According to Moriasi et al. (2007, 2015) the performance statistics for the calibration period were very good and satisfactory for the validation period. For $NO_3$-N PBIAS was very good both for the calibration and validation period (3.38 and 7.67), but for $NH_4$-N only satisfactory (60.3 and 68.3). For TP PBIAS was satisfactory for the calibration period (64.5) but unsatisfactory for the validation period (91.6). On the other hand, for TDP PBIAS was good for both calibration and validation periods (27.7 and 32.0). Other goodness-of-fit statistics along the river are presented in Table 3. Simulated dynamics of the concentration in the upper reaches of the river is not good (coefficient of determination $R^2$), probably because the lake located in the upper reaches equalizes the flow and concentration fluctuations. Even there, the simulated level of concentration (RMSE) is visually acceptable. A clear challenge for modeling was the low concentration and lacking dynamics of suspended sediments in the river, due to low proportion of mineral soils in the river basin. The observed peak during the intensive measurement period at the sub basin 64.05 was simulated correctly.

### 2.4. Climate scenarios and story lines

Five different Nordic Bioeconomy Pathways (NBPs) were created for the Simojoki River basin based on Rakovic et al. (2020) (Table 5). Land use change is assumed to apply to the entire area of current peat extraction sites. The period under review is 2040–2069, when land use change can be expected to level off. The base-line period is 1981–2010. As societal changes influence greenhouse gas emmissions, different RCPs are used in storylines.

#### 2.4.1. Storyline NBP1. Sustainability first

Societies around the world increasingly recognize the environmental, social, and economic costs of resource-intensive production and consumption patterns. Leading policy in energy production is directed towards sustainability and the use of renewables increasing forest harvesting. Thus, peat mining fields predominantly turn to energy forests. Continuous cover harvesting is applied in all forest harvesting areas. Low meat production leads to small scale animal husbandry without excess manure production and thus lower nutrient leaching to waters. Even though forest cutting area increases, nutrient export coefficient is lower due to continuous cover harvesting.

#### 2.4.2. Storyline NBP2. Conventional first

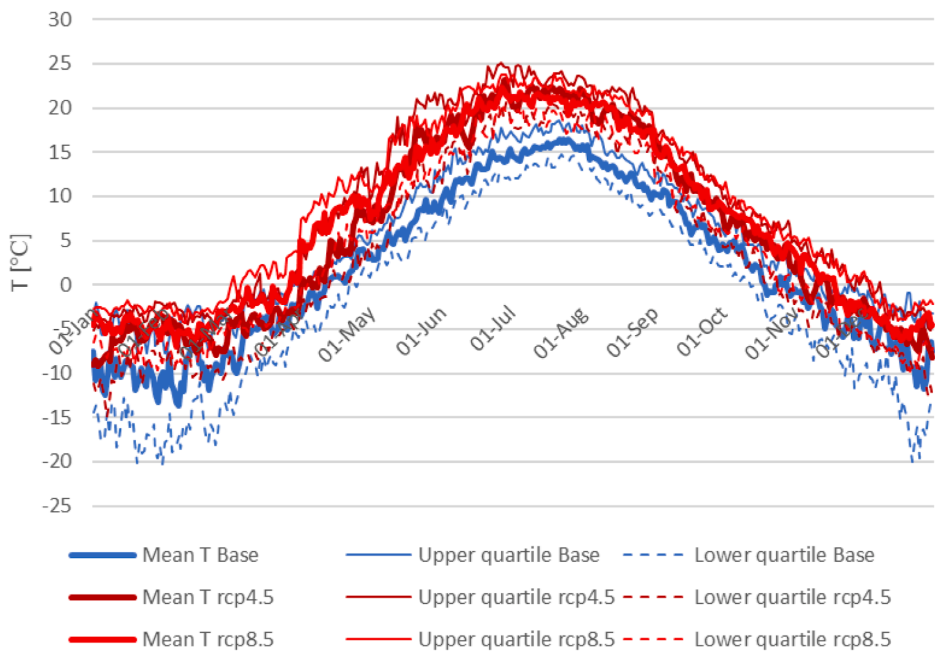
This world follows typical recent (pre 2020) historical patterns. There is moderate success in policy implementation in achieving the sustainable development goals. In the Nordic energy sector, some investments in renewable energy systems are made but society continues to rely on fossil fuels. In policy there is a weak focus on sustainability, and thus peat mining for energy continues. In addition, traditional forest harvesting continues. Medium meat consumption leads to excess manure production and over-fertilization in most intensive production areas. In terms of nutrient leaching, this is ‘business as usual’.

#### 2.4.3. Storyline NBP3. Self-sufficiency first

The world is characterized by rising regional rivalry driven by growing nationalistic forces. The Nordic bioeconomy therefore becomes a matter of regional security. Fragmentation of global markets lead to a stronger need for self-sufficiency and food security, and environmental issues have low priority in societies. Intensification of agriculture leads to larger farms and increased field area peat mining fields become agricultural fields leading to increase in nutrient leaching. Forestry turns to whole-tree harvesting, to compensate for increased energy demand. When all cutting residues are removed there is a threat that soil nutrient pools decrease leading to decreasing nutrient leaching (Storyline NPB3). In alternative storyline NBP3b that depletion is compensated by forest fertilization.

#### 2.4.4. Storyline NBP4. City first

A gap widens between a small affluent higher-income groups and lower-income groups. Environmental policies are centered on local concerns with little attention to vulnerable areas or global issues. Rural areas that are not favorably situated for tourism are increasingly neglected because the policy is oriented toward the benefit of those with economic power. Due to an uncertain fossil fuel market, there are diversified investments in the energy sector, including efficiency and renewables. Big corporations gradually take over the land-based bioeconomy sector. The bioenergy share of energy use follows an upward trend facilitated by rising import of bioresources to the Nordic countries. Most of the solutions are technical. Abandoned peat extraction sites becomes wind parks (on peat soils). In the forestry sector the current Nordic model prevails. Strategies in the agricultural sector are steered towards conventional crop production with more precision agricultural a)




b)

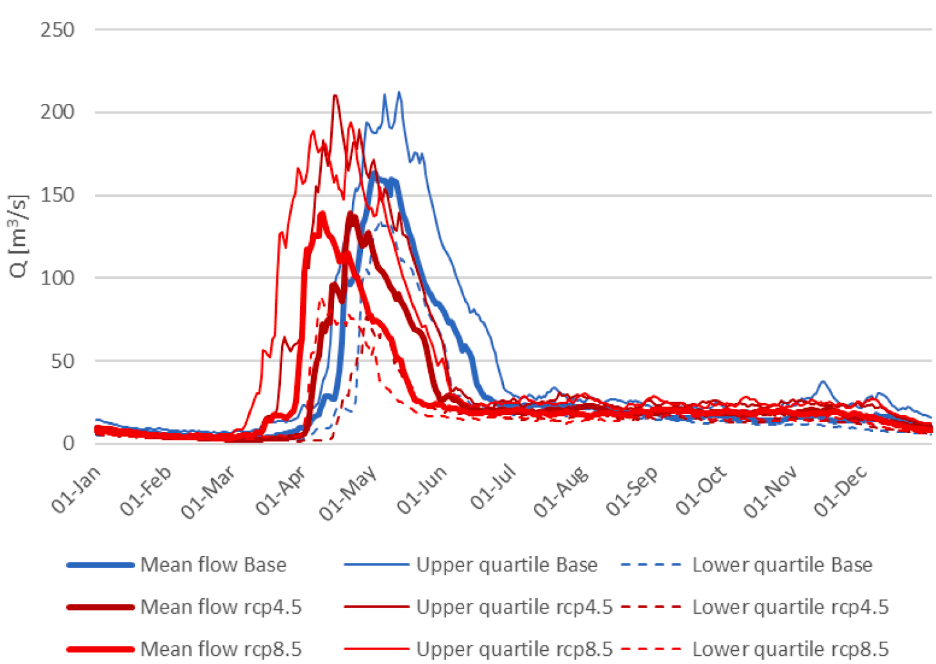



**Fig. 3.** Change of a) temperature pattern, and b) discharge pattern according to different climate scenarios.

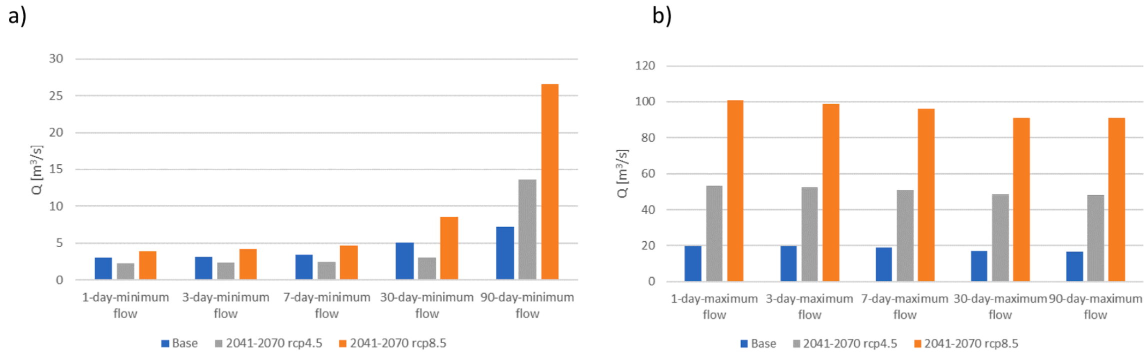



**Fig. 4.** Mean discharge during a) minimum and b) maximum discharge periods in April-March according to different climate scenarios.

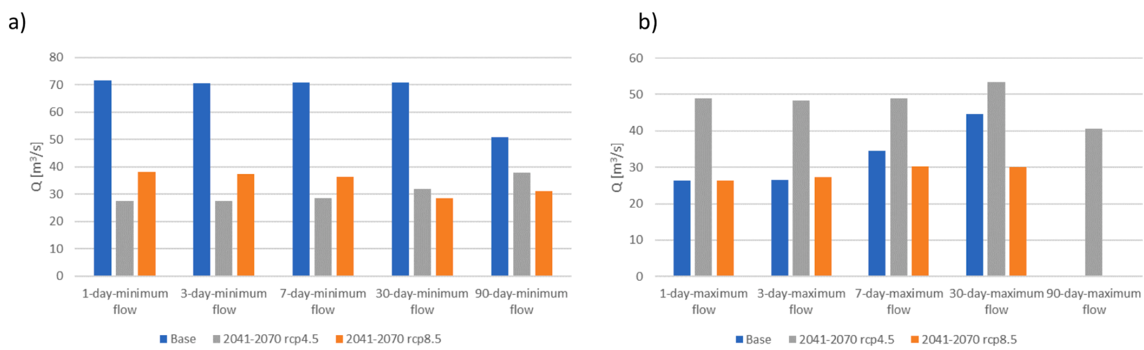



**Fig. 5.** Mean discharge during a) minimum and b) maximum discharge periods in September-October according to different climate scenarios.

approaches, while animal husbandry is diversified. Biogas production on farms reduce pressure to overfertilize fields by manure.

### *2.4.5. Storyline NBP5. Growth first*

This society trusts that competitive markets, new technology and investments in human capital is the path to sustainable development. Regarding environmental policy, there is a focus on local issues with obvious benefits to human wellbeing, whereas global issues receive little attention. In the Simojoki river basin this scenario leads to an increase in the tourism industry with fishing and hunting opportunities. The number of holiday homes doubles from the number of the early 2000′s. The energy and resource use intensity are high and there is a heavy reliance on fossil resources. With increasingly connected global markets, biomass production moves towards more large-scale regionally specialized systems in the Nordic countries where intensification of forestry production systems is driven by rising timber export. There are however limited

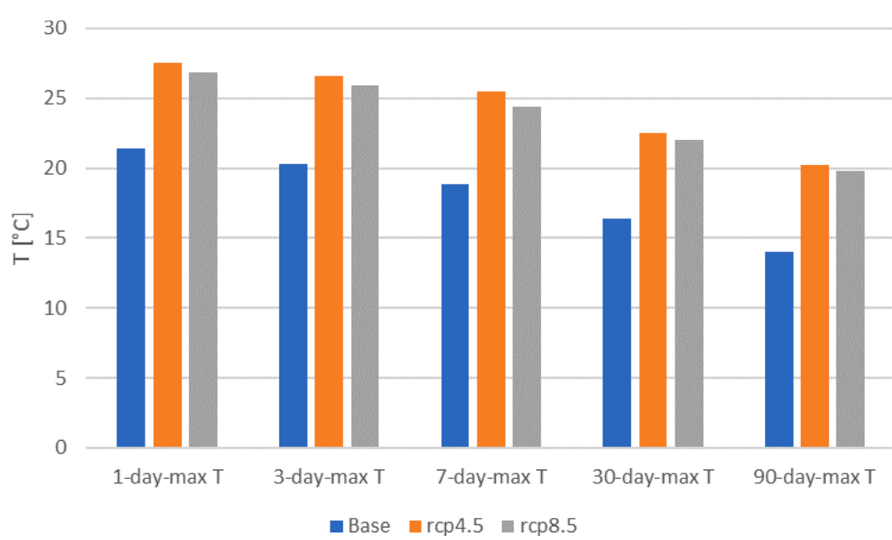



**Fig. 6.** Mean temperature during maximum temperature periods according to different climate scenarios.

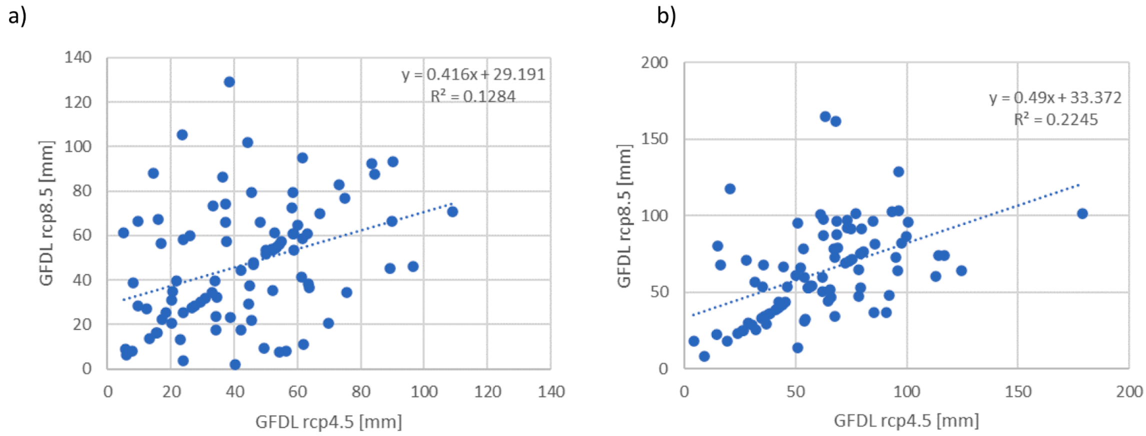



**Fig. 7.** Relationship of monthly precipitation sum a) in May, and b) in October.

incentives to develop the bioenergy sector. Traditional forestry continues, but part of the forest in age class 80–120 years old turns to old, protected forests. In the agricultural sector animal husbandry becomes more specialized and concentrated in large-scale farms with technical solutions.

## 3. Results and discussion

### 3.1. Climate scenarios and hydrology

The increases in mean annual air temperature (T) in the Simojoki river basin are 4.0 °C (RCP 4.5) and 4.8 °C (RCP 8.5) in 2041–2070 compared to the 1981–2010 baseline. Mean annual precipitation increases by 26 % (RCP 4.5) and 36 % (RCP 8.5) respectively. In general, winter temperatures and winter precipitation are higher in RCP 8.5 than in RCP 4.5 (Fig. 3). Both RCP 4.5 and RCP 8.5 give the same temperature increase for summer, but RCP 8.5 gives a higher winter increase. The difference in precipitation is highest in late winter and early spring. As a result, peak discharge due to snow melt occurs earlier in spring, but there is no fundamental change in general discharge patterns, though discharges during maximum flow periods are increasing in spring and discharges during low flow periods are decreasing (Figs. 4 and 5).

Water temperature increases as it follows air temperature with a lag. Thermal limits for salmonids are species specific (Solbé 1988, Jonsson and Jonsson 2009) but the mean air temperature does not exceed the threshold set for several species (20–25 °C). The peak temperatures (Fig. 6) are becoming higher, which may increase temperature especially in low flowing reaches. There is a high variation between years and months, and the description and timing of extremes are different in RCP 4.5 and RCP 8.5. Especially in some spring and autumn months RCP 4.5 gives higher precipitation than RCP 8.5 (Fig. 7).

### 3.2. Suspended sediment and nutrient concentrations

Nutrient concentrations are among the WFD status classification criteria. Finnish national values for excellent state in large humic rivers are TN less than 0.45 mg/l and TP less than 0.02 mg/l. In good state TN is less than 0.9 mg/l and TP less than 0.04 mg/l (Aroviita et al., 2012).

There were no major differences in the storylines for TN load, though the highest concentrations were produced by NBP3 and NBP3b, in which the field area increased together with pressure to spread manure on agricultural fields.

When considering TP concentration thresholds, there was a clear difference between excellent and good ecological status. In 'Self Sufficiency first' scenarios (NBP3 and NBP3b) only 40 % of the modelled days predict TP concentrations that remained under the threshold value, while in other scenarios the number is 70 % (Fig. 8). The corresponding numbers between good and satisfactory status were roughly 80 % and 90 %. Developments leading to the conversion of peat mining fields to arable land, together with climate change, may pose a risk of deterioration of the ecological status, especially in sub catchments with a high proportion of peat mining. This poses challenges for the agricultural water protection. At the EU level, agricultural policy is regulated by the Common Agricultural Policy (EC, 2011). The application of manure and the N it contains to fields is regulated in the Nitrates Directive (EEC, 1991). In addition, some of the agri-environmental measures are regulated nationally, and large livestock farms need an environmental permit.

In both the NBP3 and NBP3b storylines TP loading from fields increased, but in NBP3 TP loading from forestry areas decreased (and compensated increased loading from agricultural fields) due to whole-tree harvesting that depleted nutrient storage in soil. In reality, that depletion is probably compensated by forest fertilization (NBP3b), which leads to higher losses of soluble nutrients. In general, development according to the storyline NBP1 is best for water quality. In that storyline current peat extraction fields are transformed into energy forests. The area of energy forests is also growing elsewhere, but the increase in area is compensated by shifting to continuous cover forestry, which leads to smaller nutrient runoff. Low meat consumption does not cause pressure to intensify livestock farming, so nutrient emissions from fields do not increase.

Seasonality was clearly seen in monthly mean concentrations (Fig. 9), the highest concentrations occurred during high flow events in spring and autumn. The highest variability in $NO_3$-N concentrations was in agricultural storylines NBP3 and NBP3b. The highest variation in TDP concentrations occurred in storylines NBP1, 4 and 5 in spring and autumn. That was probably due to the high precipitation amount in some years in climate scenario GLFM RCP 4.5.

Slightly higher temperatures can be beneficial to salmonids as they facilitate faster growth (Todd et al. 2012). The projected higher

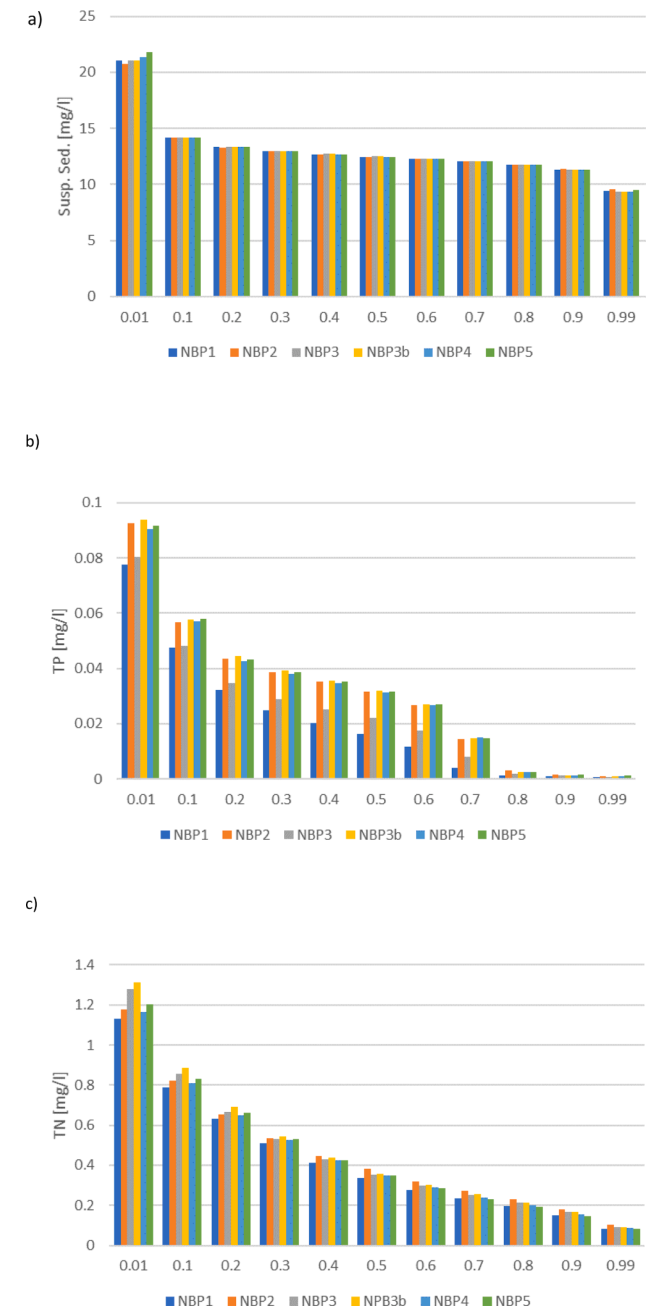



**Fig. 8.** Total nutrient concentrations a) suspended sediment concentration, b) TP concentration and c) TN concentration. X-axis shows the number of days (as percentage of total number of days) when concentration in Y-axis is exceeded.

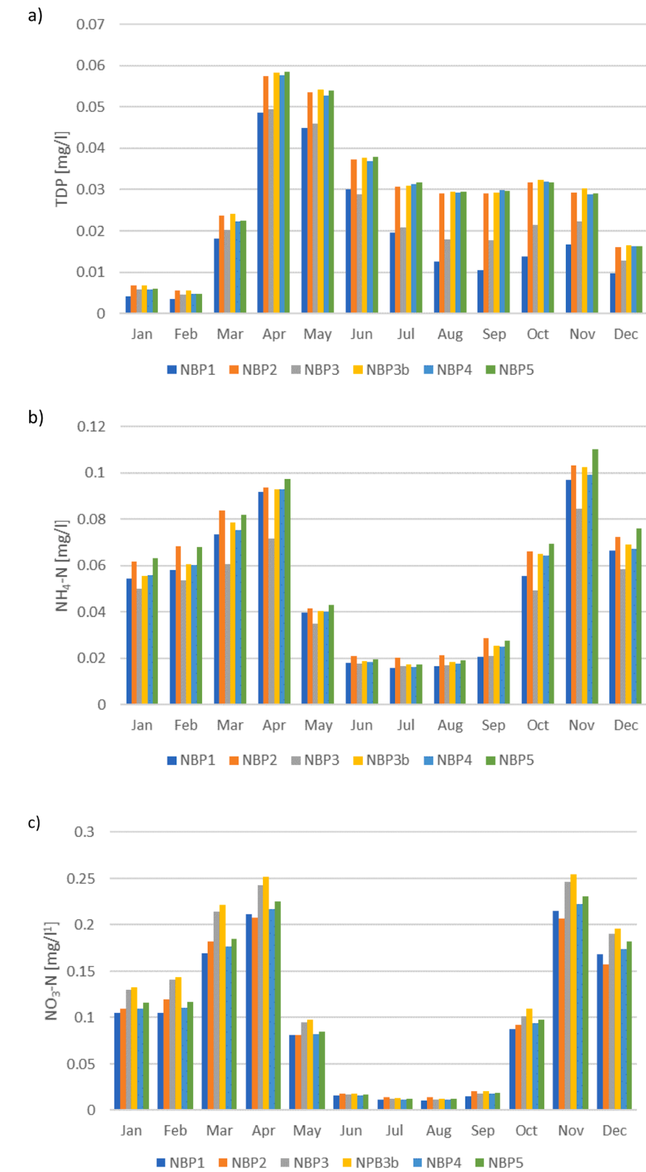



**Fig. 9.** Monthly mean values of a) TDP concentrations, b) $NH_4$-N concentrations, and c) $NO_3$-N concentration.

temperatures would facilitate faster growth and the higher nutrient concentrations could support higher levels of primary and secondary productivity in the river, which in turn would provide juvenile salmon with the food they need to grow. These generic conclusions related to juvenile salmonid growth must be balanced against the reality that the Simojoki population is adapted to cooler temperatures, and both invasive salmon species and more southerly Atlantic salmon populations are encroaching on Simojoki. These fish, which are adapted to warmer conditions, may outcompete the native Simojoki population in a warmer future (Jonsson and Jonsson, 2009).

Model results suggest no exceedance of sediment thresholds in the main river channel. While this is good news, it must be interpreted with caution as the simulations presented here did not explicitly consider consequences for headwaters. Increased disturbance in the landscape due to, e.g., road building or other forestry operations has the potential to cause local sediment mobilization and damage to spawning habitat.

The projected changes will decrease the resilience of the ecologically important wild salmon population in Simojoki.

## 4. Conclusions

Our research shows that there are different ways to end up with the same water quality. The main reach of the river Simojoki is currently in excellent or good ecological condition. Developments leading to the conversion of peat extraction to arable land, together with climate change, may pose a risk of deterioration of the ecological status, especially in branches which are currently in good ecological status. This is especially evident in the increase in TP concentrations if no compensating measures are done in other land uses. A storyline that emphasizes sustainable development in energy production (NBP1) will lead to the best outcome in terms of water protection. Even though the area of energy forests growth, this is compensated by shifting to continuous cover forestry. Nutrient emissions from agricultural fields do not increase as there is no pressure to intensify livestock farming.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Land use and sischarge and water quality data in rivers is open. Emmissions from peat extraction sites are either published or available from producers.

## Acknowledgements

Nordic Council of Ministers (BIOWATER; Nordic Centre of Excellence, No 82263) and European Union (MERLIN; Horizon 2020 grant agreement No 101036337) provided financial support for the conduct of the research.

## References

Ahtiainen, M., Huttunen, P., 1999. Long-term effects of forestry managements on water quality and loading in brooks. BER 4, 101–114.
Alatalo, M., 2000. Metsätaloustoimenpiteistä aiheutunut ravinne- ja kiintoainekuormitus. (The effects of forest management on the loading of nutrient and suspended solids.). Suomen ympäristö 381. Suomen ympäristökeskus, Helsinki., 64 p.
Arheimer, B., Pers, B.C., 2017. Lessons learned? Effects of nutrient reductions from constructing wetlands in 1996–2006 across Sweden. Ecol. Eng. 103, 404–414.
Aroviita, J., Hellsten, S., Jyväsjärvi, J., Järvenpää, L., Järvinen, M., Karjalainen, S.M., Kauppila, P., Keto, A., Kuoppala, M., Manni, K., Mannio, J., Mitikka, S., Olin, M., Perus, J., Pilke, A., Rask, M., Riihimäki, J., Ruuskanen, A., Siimes, K., Sutela, T., Vehanen, T., Vuori, K.-M. 2012. Ohje pintavesien ekologisen ja kemiallisen tilan luokitteluun vuosille 2012–2013 – päivitetyt arviointiperusteet ja niiden soveltaminen, Ympäristöhallinnon Ohjeita 7. Suomen ympäristökeskus, Helsinki. (In Finnish with English abstract).
Bartosova, A., Capell, R., Olesen, J.E., Jabloun, M., Refsgaard, J.C., Donnelly, C., Hyytiäinen, K., Pihlainen, S., Zandersen, M., Arheimer, B., 2019. Future socioeconomic conditions may have a larger impact than climate change on nutrient loads to the Baltic Sea. Ambio 48, 1325–1336.
Bhattacharjee, J., Marttila, H., Haghighi, A.T., Saarimaa, M., Tolvanen, A., Lepistö, A., Futter, M.N., Kløve, B., 2021. Development of Aerial Photos and LIDAR Data Approaches to Map Spatial and Temporal Evolution of Ditch Networks in Peat-Dominated Catchments. J. Irrig. Drain. Eng. 147, 04021006.
Brookshire, J., E. N., Gerber, S., Webster, J.R., Vose, J.M., Swank, W.T., 2011. Direct effects of temperature on forest nitrogen cycling revealed through analysis of long-term watershed records. Global Change Biol. 17, 297-308.
Bussi, G., Dadson, S.J., Prudhomme, C., Whitehead, G., 2016. Modelling the future impacts of climate and land-use change on suspended sediment transport in the River Thames (UK). J. Hydrol. 542, 357–372. https://doi.org/10.1016/j.jhydrol.2016.09.010.
Crossman, J., Bussi, G., Whitehead, P.G., Butterfield, D., Lannergård, E., Futter, M.N., 2021. A New, Catchment-Scale Integrated Water Quality Model of Phosphorus, Dissolved Oxygen, Biochemical Oxygen Demand and Phytoplankton: INCA-Phosphorus Ecology (PEco). Water 13, 723.
Dolman, A.M., Mischke, U., Wiedner, C., 2016. Lake-type-specific seasonal patterns of nutrient limitation in German lakes, with target nitrogen and phosphorus concentrations for good ecological status. Freshw. Biol. 61, 444–456.
EC, 2011. Proposal for a regulation of the European parlament and of the council on support for rural developement by the European Agricultural Found for Rural Developement (EAFRD). COM (2011) final/2. Brussels.
EEC, 1991. Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. Official J. L 375, 1–8.
Ekholm, M., 1993. Suomen vesistöalueet. Vesi- ja ympäristöhallinnon julkaisuja - sarja A 126., 166 p. (In Finnish with English abstract).
EU, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. OJ L 327 22.12.2000, 1-73.
Farkas, C., Beldring, S., Bechmann, M., Deelstra, J., 2013. Soil erosion and phosphorus losses under variable land use as simulated by the INCA-P model. Soil Use Manag 29, 124–137. https://doi.org/10.1111/j.1475-2743.2012.00430.x.
Finér, L., Lepistö, A., Karlsson, K., Räike, A., Härkönen, L., Huttunen, M., Joensuu, S., Kortelainen, P., Mattsson, T., Piirainen, S., Sallantaus, T., Sarkkola, S., Tattari, S., Ukonmaanaho, L., 2021. Drainage for forestry increases N, P and TOC export to boreal surface waters. Sci. Tot. Environ. 762, 144098.
Futter, M.N., Erlandsson, M.A., Butterfield, D., Whitehead, P.G., Oni, S.K., Wade, A.J., 2014. PERSiST: A flexible rainfall-runoff modelling toolkit for use with the INCA family of models. Hydrol. Earth Syst. Sci. 18, 855–873.
Granlund, K., Rankinen, K., Lepistö, A., 2004. Testing the INCA model in a small agricultural catchment in southern Finland. HESS 8 (4), 717–728.
Hoffmann, C.C., Zak, D., Kronvang, B., Kjaergaard, C., Carstensen, M.V., Audet, J., 2020. An overview of nutrient transport mitigation measures for improvement of water quality in Denmark. Ecol. Eng. 155, 105863.
Hopkinson, C., Chasmer, L., Barr, A.G., Kljun, N., Black, T.A., McCaughey, J.H., 2016. Monitoring boreal forest biomass and carbon storage change by integrating airborne laser scanning, biometry and eddy covariance data. Remote Sens. Environ. 181, 82–95.
Howarth, R.W., Marino, R., 2006. Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. Limnol. Oceanogr. 51, 364–376.
Jackson-Blake, L.A., Wade, A.J., Futter, M.N., Butterfield, D., Couture, R.M., Cox, B.A., Crossman, J., Ekholm, P., Halliday, S.J., Jin, L., Lawrence, D.S.L., Lepistö, A., Lin, Y., Rankinen, K., Whitehead, P.G., 2016. The INtegrated CAtchment model of phosphorus dynamics (INCA-P): Description and demonstration of new model structure and equations. Env. Mod. Soft. 83, 356–386.
Joensuu, S., Ahti, E., Vuollekoski, M., 2001. Long-term effects of maintaining ditch networks on runoff water quality. Suo 52 (1), 17–28.
Jonsson, B., Jonsson, N., 2009. A review of the likely effects of climate change on anadromous Atlantic salmon Salmo salar and brown trout Salmo trutta, with particular reference to water temperature and flow. J. Fish Biol. 75, 2381–2447.
Kaila, A., Laurén, A., Sarkkola, S., Koivusalo, H., Ukonmaanaho, L., O'Driscoll, C., Xiao, L., Asam, Z., Nieminen, M., 2015. Effect of clear-felling and harvest residue removal on nitrogen and phosphorus export from drained Norway spruce mires in southern Finland. BER 20, 693–706.
Kenttämies, K. 1998. The effects of modern boreal forestry practices on waters., XX Nordic Hydrological Conference. Nordic Hydrological Programme NHP Report 44: 142-162, Helsinki, Finland 10.-13. August 1998, pp. 142-162.
Korkiakoski, M., Tuovinen, J.P., Penttilä, T., Sarkkola, S., Ojanen, P., Minkkinen, K., Rainne, J., Laurila, T., Lohila, A., 2019. Greenhouse gas and energy fluxes in a boreal peatland forest after clear-cutting. Biogeoscience 16, 3703–3723.
Kortelainen, P., Saukkonen, S., Mattson, T., 1997. Leaching of nitrogen from forested catchments in Finland. Global Biogeochem. Cycles 11, 627–638.
Kortelainen, P., Saukkonen, S., 1998. Leaching of nutrients, organic carbon and iron from Finnish forestry land. Water Air Soil Pollut. 105, 239–250.
Koski-Vähälä, J., 2001. Role of resuspension and silicate i internal phosphorus loading. Doctoral Thesis. University of Helsinki.
Kymenvaara, S., Baaner, L., Anker, H.T., Leino, L., Belinskij, A., 2019. Variations on the same theme: Environmental objectives of the Water Framework Directive in environmental permitting in the Nordic countries. Review of European, Comparative & International Environmental Law 28, 197–209.
La Mere , K.M., Mäntyniemi , S., Haapasaari , P. 2020. The effects of climate change on Baltic salmon : Framing the problem in collaboration with expert stakeholders. Sci. Tot. Env. 738.
Lång, K., Aro, L., Assmuth, A., Haltia, E., Hellsten, S., Larmola, T., Lempinen, H., Lindfors, L., Lohila, A., Miettinen, A., Minkkinen, K., Nieminen, M., Ollikainen, M., Ojanen, P., Sarkkola, S., Sorvali, J., Seppälä, J., Tolvanen, A., Vainio, A., Wall, A., T., V. 2022. Turvemaiden käytön vaihtoehdot hiilineutraalissa Suomessa. . Suomen ilmastopaneelin raportti2/2022. (In Finnish with English abstract).
Lapin ympäristökeskuksen alueen turvetuotantosoiden käyttö, kuormitus- ja vesistötarkkailu. Yhteenvetoraportti 1995. (In Finnish).
Lehtoranta, S., Vilpas, R., Mattila, T.J., 2014. Comparison of carbon footprints and eutrophication impacts of rural on-site wastewater treatment plants in Finland. J. Cleaner Prod. 65, 439–446.
Lilja, H., Uusitalo, R., Yli-Halla, M., Nevalainen, R., Väänänen, T., Tamminen, P. 2006. Suomen maannostietokanta. Maannoskartta 1:250 000 ja maaperän ominaisuuksia., MTT:n selvityksiä 114, p. 70. (In Finnish with English abstract).
Lu, Q., Futter, M.N., Nizzetto, L., Bussi, G., Jürgens, M.D., Whitehead, P.G., 2016. Fate and transport of polychlorinated biphenyls (PCBs) in the River Thames catchment – Insights from a coupled multimedia fate and hydrobiogeochemical transport model. Sci. Tot. Env. 572, 1461–1470. https://doi.org/10.1016/j.scitotenv.2016.03.029.
Lundborg, A., 1997. Reducing the Nitrogen Load: Whole-Tree Harvesting: A Literature Review. Ambio 26, 387–393.
Maberly, S.C., Pitt, J.-A., Davies, P.S., Carvalho, L., 2020. Nitrogen and phosphorus limitation and the management of small productive lakes. Inland Waters 10, 159–172.
Mikkonen, N., Leikola, N., Lahtinen, A., Lehtomäki, J., Halme, P. 2018. Monimuotoisuudelle tärkeät metsäalueet Suomessa. Puustoisten elinympäristöjen monimuotoisuusarvojen Zonation -analyysien loppuraportti, in: Institute, F.E. (Ed.), Suomen Ympäristökeskuksen Raportteja 9 p. 99. (In Finnish with English abstract).
Mälkönen, E., Derome, J., Kukkola, M., 1990. Effects of Nitrogen Inputs on ForestEcosystems Estimation Based on Long-Term Fertilization Experiments. In: Kauppi (Ed.), Acidification in Finland. Springer Verlag, Berlin, pp. 325–345.
Moe, S.J., Couture, R.-M., Haande, S., Lyche Solheim, A., Jackson-Blake, L., 2019. Predicting Lake Quality for the Next Generation: Impacts of Catchment Management and Climatic Factors in a Probabilistic Model Framework. Water 11, 1767. https://doi.org/10.3390/w11091767.
Molina-Navarro, E., Andersen, H.E., Nielsen, A., Thodsen, H., Trolle, D., 2018. Quantifying the combined effects of land use and climate changes on stream flow and nutrient loads: A modelling approach in the Odense Fjord catchment (Denmark). Sci. Tot. Env. 621, 253–264. https://doi.org/10.1016/j.scitotenv.2017.11.251.
Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmet, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50, 885–900.

Moriasi, D.N., Gitau, M.W., Pai, N., Daggupati, P., 2015. Hydrologic and water quality models: performance measures and evaluation criteria. Trans. Am. Soc. Agric. Biol. Eng. 58, 1763–1785.
Niemi, J., 2006. Ympäristön seuranta Suomessa 2006–2008. Suomen ympäristö 24, 151.
Nieminen, M., 1998. Changes in nitrogen cycling following the clearcutting of drained peatland forests in southern Finland. BER 3, 9–21.
Nieminen, M., Sallantaus, T., Ukonmaanaho, L., Nieminen, T.M., Sarkkola, S., 2017. Nitrogen and phosphorus concentrations in discharge from drained peatland forests are increasing. Sci. Tot. Env. 609, 974–981.
Nieminen, M., Sarkkola, S., Hellsten, S., Marttila, H., Piirainen, S., Sallantaus, T., Lepistö, A., 2018a. Increasing and Decreasing Nitrogen and Phosphorus Trends in Runoff from Drained Peatland Forests—Is There a Legacy Effect of Drainage or Not? Water Air Soil Pollut. 229, 286.
Nieminen, M., 2004. Export of Dissolved Organic Carbon, Nitrogen and Phosphorus Following Clear-Cutting of Three Norway Spruce Forests Growing on Drained Peatlands in Southern Finland. Silva Fennica 38 (2), 123–132.
Nieminen, M., Hökkä, H., Laiho, R., Juutinen, A., Ahtikoski, A., Pearson, M., Kojola, S., Sarkkola, S., Launiainen, S., Valkonen, S., Penttilä, T., Lohila, A., Saarinen, M., Haahti, K., Mäkipää, R., Miettinen, J., Ollikainen, M., 2018b. Could continuous cover forestry be an economically and environmentally feasible management option on drained boreal peatlands? For. Ecol. Man. 424, 78–84.
Nieminen, M., Sarkkola, S., Tolvanen, A., Tervahauta, A., Saarimaa, M., Sallantaus, T., 2020. Water quality management dilemma: Increased nutrient, carbon, and heavy metal exports from forestry-drained peatlands restored for use as wetland buffer areas. For. Ecol. Man. 465, 118089.
O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environ. Change 42, 169–180.
Øygarden, L., Deelstra, J., Lagzdins, A., Bechmann, M., Greipsland, I., Kyllmar, K., Povilaitis, A., Iital, A., 2014. Climate change and the potential effects on runoff and nitrogen losses in the Nordic-Baltic region. Agric. Ecosyst. Env. 198, 114–126.
Paloniitty, T., Kotamäki, N., 2021. Scientific and Legal Mechanisms for Addressing Model Uncertainties: Negotiating the Right Balance in Finnish Judicial Review? J. Environ. Law 33, 283–308.
Palviainen, M., Finér, L., 2012. Estimation of nutrient removals in stem-only and whole-tree harvesting of Scots pine, Norway spruce, and birch stands with generalized nutrient equations. Eur. J. For. Res. 131, 945–964.
Palviainen, M., Finér, L., Laurén, A., Launiainen, S., Piirainen, S., Mattsson, T., Starr, M., 2014. Nitrogen, Phosphorus, Carbon, and Suspended Solids Loads from Forest Clear-Cutting and Site Preparation: Long-Term Paired Catchment Studies from Eastern Finland. Ambio 43 (2), 218–233.
Peltovuori, T., 2007. Sorption of phosphorus in field-moist and air-dried samples from four weakly developed cultivated soil profiles. Eur. J. Soil Sci. 58, 8–17.
Pietiläinen, O.-P., Räike, A., 1999. Typpi ja fosfori Suomen sisävesien minimiravinteena. Suomen ympäristö, ympäristönsuojelu 313, 64.
Pihlainen, S., Zandersen, M., Hyytiäinen, K., Andersen, H.E., Bartosova, A., Gustafsson, B., Jabloun, M., McCrackin, M., Meier, H.E.M., Olesen, J.E., Saraiva, S., Swaney, D., Thodsen, H., 2020. Impacts of changing society and climate on nutrient loading to the Baltic Sea. Sci. Tot. Env. 731, 138935.
Piirainen, S., Finér, L., Mannerkoski, H., Starr, M., 2007. Carbon, nitrogen and phosphorus leaching after site preparation at a boreal forest clear-cut area. Forest Ecology and Management 243 (1), 10–18. https://doi.org/10.1016/j.foreco.2007.01.053.
Puustinen, M., Tattari, S., Koskiaho, J., Linjama, J., 2007. Influence of seasonal and annual hydrological variations on erosion and phosphorus transport from arable areas in Finland. Soil Tillage Res. 93, 44–55.
Puustinen, M., Turtola, E., Kukkonen, M., Koskiaho, J., Linjama, J., Niinioja, R., Tattari, S., 2010. VIHMA-A tool for allocation of measures to control erosion and nutrient loading from Finnish agricultural catchments. Agric. Ecosyst. Env. 138, 306–317.
Rakovic, J., Futter, M.N., Kyllmar, K., Rankinen, K., Stutter, M.I., Vermaat, J., Collentine, D., 2020. Nordic Bioeconomy Pathways: Future narratives for assessment of water-related ecosystem services in agricultural and forest management. Ambio 49, 1710–1721.
Rankinen, K., Cano Bernal, Holmberg, M., Vuorio, K., Granlund, K., 2019. Identifying multiple stressors that influence eutrophication in a Finnish agricultural river. Sci. Tot. Env. 658, 1278–1292.
Rankinen, K., Keinänen, H., Cano Bernal, J.E., 2016. Influence of climate and land use changes on nutrient fluxes from Finnish rivers to the Baltic Sea. Agric. Ecosyst. Env. 216, 100–115.
Rankinen, K. Thouvenot-Korppoo, M., Lazar, A., Lawrence, D. S. L., Butterfield, D., Lepistö, A., 2010. Application of catchment scale erosion and sediment delivery model INCA-Sed to four small study catchments in Finland. CATENA 83, 64-75.
Routa, J., Huuskonen, S. 2022. Jatkuvapeitteinen metsänkasvatus, Luonnonvara- ja biotalouden tutkimus 40/2022. Natural Resources Institute Finland, p. 129. (In Finnish with English abstract).
Ruosteenoja, K., Jylhä, K., 2021. Projected climate change in Finland during the 21st century calculated from CMIP6 model simulations. Geophysica 56, 39–69.
Sallantaus, T., 1992. Leaching in the material balance of peatlands - preliminary results. Suo 43, 253–258.
Sallantaus, T., 1986. Soiden metsä- ja turvetalouden vesistövaikutukset-kirjallisuuskatsaus. Maa- ja metsätalousministeriö, Helsinki, p. 203.
Saukkonen, S., Kortelainen, P., 1995. Metsätaloustoimenpiteiden vaikutus ravinteiden ja orgaanisen aineen huuhtoutumiseen. In: Saukkonen, S., Kenttämies, K. (Eds.), Metsätalouden Vesistövaikutukset Ja Niiden Torjunta. Suomen ympäristökeskus, Helsinki, pp. 15–32.
Savage, C., Leavitt, P.R., Elmgren, R., 2010. Effects of land use, urbanization, and climate variability on coastal eutrophication in the Baltic Sea. Limnol. Oceanogr. 55, 1033–1046.
Solbé, J. 1988. Water quality for salmon and trout, in: Trust, T.A.S. (Ed.). The Atlantic Salmon Trust, Perthshire, p. 63.
Tamminen, T., Andersen, T., 2007. Seasonal phytoplankton nutrient limitation patterns as revealed by bioassays over Baltic Sea gradients of salinity and eutrophication. Mar. Ecol. Prog. Ser. 340, 121–138.
Thorén, H., Soininen, N., Kotamäki, N., 2021. Scientific models in legal judgements: The relationship between law and environmental science as problem-feeding. Environ. Sci. Policy 124, 478–484.
Tiemeyer, B., Frings, J., Kahle, P., Köhne, S., Lennartz, B., 2007. A comprehensive study of nutrient losses, soil properties and groundwater concentrations in a degraded peatland used as an intensive meadow – Implications for re-wetting. J. Hydrol. 345, 80–101.
Todd, C., Friedland, K., MacLean, J., Whyte, B., Russell, I., Lonergan, M., Morrissey, M., 2012. Phenological and phenotypic changes in Atlantic salmon populations in response to a changing climate. ICES J. Mar. Sci. 69, 1686–1698.
Väänänen, R. 2008. Phosphorus retention in forest soils and the functioning of buffer zones used in forestry, Dissertationes Forestales 60.
Vuorenmaa, J., Rekolainen, S., Lepistö, A., Kenttämies, K., Kauppila, P., 2002. Losses of nitrogen and phosphorus from agricultural and forest areas in Finland during the 1980s and 1990s. Environ. Monit. Assess. 76, 213–248.
Wade, A., Durand, P., Beaujoan, V., Wessels, W., Raat, K., Whitehead, P.G., Butterfield, D., Rankinen, K., Lepistö, A., 2002. Towards a generic nitrogen model of European ecosystems: New model structure and equations. HESS 6, 559–582.
Whitehead, P.G., Wilson, E.J., Butterfield, D., 1998. A semi-distributed Integrated Nitrogen model for multiple source assessment in Catchments (INCA): Part I-model structure and process equations. Sci. Tot. Env. 210 (211), 547–558.
Whitehead, P. G., Crossman, J., Balana, B. B., Futter, M. N., Comber, S. Jin, L., Skuras, D., Wade, A. J., Bowes, M. J., Read, D. S., 2013. A cost-effectiveness analysis of water security and water quality: impacts of climate and land-use change on the River Thames system. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 371.