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Framework to Study the Effects of Climate Change on Vulnerability of Ecosystems and Societies: Case Study of Nitrates in Drinking Water in Southern Finland

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Abstract: Climate change may alter the services ecosystems provide by changing ecosystem functioning. As ecosystems can also resist environmental perturbations, it is crucial to consider the different processes that influence resilience. Our case study considered increased NO_3^- concentration in drinking water due to the climate change. We analyzed changes in ecosystem services connected to water purification at a catchment scale in southern Finland. We combined climate change scenarios with process-based forest growth (PREBAS) and eco-hydrological (PERSiST and INCA) models. We improved traditional model calibration by timing of forest phenology and snow-covered period from network of cameras and satellite data. We upscaled the combined modelling results with scenarios of population growth to form vulnerability maps. The boreal ecosystems seemed to be strongly buffered against NO_3^- leaching by increase in evapotranspiration and vegetation NO_3^- uptake. Societal vulnerability varied greatly between scenarios and municipalities. The most vulnerable were agricultural areas on permeable soil types.

Keywords: climate change resilience; catchment scale; modelling framework; nitrate; vulnerability

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1. Introduction

Climate change may alter ecosystem functioning and thus also the services the ecosystems provide. In Finland, annual precipitation is expected to increase by 13–26% and temperature by 2–6 °C by the end of the century, with the increases expected to be greater in winter than in summer [1]. There are often seen risks for increase in dissolved pollutants and nutrients, like nitrate (NO_3^-) leaching to waters due to increase in runoff [2] and acceleration of decay of nutrient rich organic material in soils.

On the other hand, ecosystems can resist an environmental perturbation [3,4]. Ecosystems have the capacity to retain, process and remove dissolved pollutants and excess nutrients. In the climate change context, resilience refers to a tendency to withstand or recover from change. Vulnerability is seen as the degree to which a system is susceptible to sustaining damage from climate change. In general, resilience is often considered to be the opposite of vulnerability. Vulnerability and resilience can be conceptualized to represent different ends in a multidimensional continuum [5]. They emphasize that vulnerability is dynamic and scale-dependent, because changes vary across physical space and over time.

Nitrate is one of the most common groundwater contaminants in rural areas. Its reduced form nitrite is involved in the oxidation of hemoglobin to methemoglobin in humans, so excess levels of nitrite can cause methemoglobinemia. In addition, in the human stomach, nitrite is shown to form N-nitroso compounds, from which many have been found to be carcinogenic. The WHO (World Health Organization gave the guideline value for NO_3^- concentration in drinking water (50 mg L^{-1}) that does not normally result in any significant risk to health over a lifetime of consumption. Guidelines are mainly health risk assessments, and on a society level, the term vulnerability is often used. In Finland, the guideline value is exceeded typically in private wells, though high NO_3^- concentrations are occasionally observed also in surface water supplies [6].

Nitrate can reach both surface water and groundwater because of agricultural activity, from wastewater treatment and from waste products or organic matter. Plants take up NO_3^- during their growth, but due to its high water solubility, NO_3^- can also percolate into groundwater. The presence of high or low water tables, the presence of organic material and other physicochemical properties like temperature and precipitation are important in determining the fate of NO_3^- in soil.

In Finland, agriculture is the dominant diffuse source of excess nutrients. Climate change is projected to favor Finnish agriculture within the coming decades [7] due to the prolongation of the growing season. Forest growth has already more than doubled in the last century due to more effective silviculture, but also due to unspecified environmental effects [8], which likely are related to increased temperature and CO_2 in atmosphere.

Mathematical modelling is widely used in evaluating ecosystem functioning or management, as these approaches can consider the combined effect of different pressures. Process-based models are also considered to be more accurate for simulating conditions outside the current observations than empirical models [9]. Especially, catchment scale nutrient transport models like INCA together with PERSiST [10] and SWAT [11] are valuable in assessing both water quality and quantity. Mathematical models for forest growth and management applications over large geographical areas can be used for making future projections for a given forest stand with known initial state under alternative management options, e.g., PREBAS [12].

Our aim was to create a framework to study the resilience of the boreal ecosystems and the vulnerability of societies to climate change in the context of NO_3^- concentrations in drinking water. We analyzed changes in ecosystem services connected to water purification on the scale of the catchment area in southern Finland. We combined climate change scenarios with process-based forest growth (PREBAS) and eco-hydrological models (PERSiST and INCA). We improved traditional model calibration against observed discharge and water quality by timing of forest phenology and snow-covered period from a network of cameras and satellite data. We upscaled the combined modelling results of NO_3^- leaching with scenarios of population growth to form vulnerability maps for the area and vulnerability estimates at the municipalities.

2. Materials and Methods

2.1. Vanajavesi River Basin and Empirical Data

2.1.1. Land Cover

The Vanajavesi basin is located in southern Finland in the upper reaches of the Kokemäenjoki river basin, which discharges to the Bothnian Bay (Figure 1). The area of the Vanajavesi basin is 2730 km^2. It is divided into 9 sub-basins [13] and altogether covers 12 municipalities. The main water course is a chain of rivers and small lakes, and it starts from Lake Pääjärvi and ends at Lake Vanajavesi. There are also several small groundwater basins in the area.

The basin lies in the southern boreal vegetation zone. Land cover in sub-basins is typical for southern Finland, varying from almost totally forested ones to basins where field percentage is over 40% (Table 1). The forests are dominated by Norwegian spruce, Scots pine and birch, with some European aspen. In all sub-basins, the field percentage is above the average for the whole of Finland (7%). Most typical crops are spring cereals.

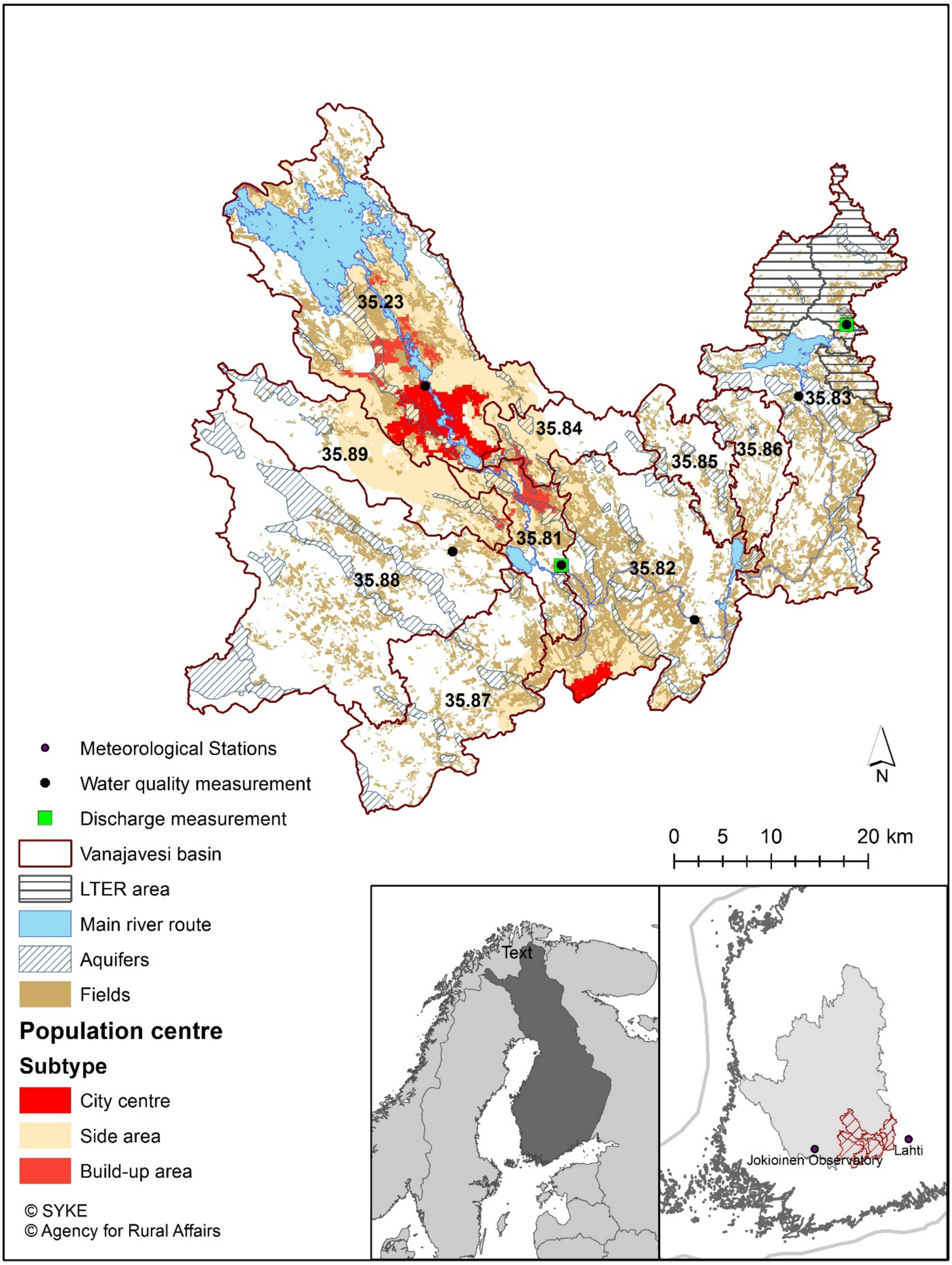


Figure 1. Location of the Vanajavesi basin and its sub-basins.

Table 1. Land cover (%) in the Vanajavesi basin.

Sub-Basin Name	Basin Code	Municipalities	Urban	Fields	Forest on Moist Soils	Forest on Herbal Rich Soils	Water
Sääjärvenoja	35.84	Janakkala	5	11	60	13	11
Räikälänjoki	35.89	Hattula, Hämeenlinna, Janakkala, Tammela	6	10	43	31	10
Hyvikkälänjoki	35.88	Hattula, Hämeenlinna, Janakkala, Loppi, Tammela	5	14	25	48	8
Tervajoki	35.87	Janakkala, Loppi	10	21	18	41	10
Vanajavesi	35.23	Hämeenlinna, Hattula, Pälkäne, Tammela, Valkeakoski	12	20	40	3	25
Hiidenjoki	35.81	Janakkala	15	30	0	46	9
Puujoki	35.82	Hausjärvi, Janakkala, Riihimäki	9	43	35	10	3
Teuronjoki	35.83	Asikkala, Hämeenlinna, Hollola, Kärkölä	7	28	60	0	5
Mustajoki	35.836	Asikkala, Hämeenlinna	9	37	37	15	2

Fields are located on clay (Verbic Cambisol, Eutric Cambisol 2) and sandy soils (Eutric Regosol, Haplic Podzol 2), and forests on tills and moraines (Haplic Podzol 1, Haplic Podzol 2). The mean age of the forest in sub-basins varies between 45 and 60 years. Population density varies from sparsely populated rural areas to the municipality Hämeenlinna of about 68,000 inhabitants.

Land use in the catchments was derived from the CORINE 2000, 2006 and 2012 Geographical Information System data with resolution of 25 × 25 m [14]. In Finland, the classification is based on Landsat ETM+ satellite images and data integration with existing digital maps [15]. CORINE data were defined by the statistics of agriculture [16] to cover the period 1985–2013. Information of forests was available in the spatial forest inventory database of the Forest Research Institute. Soil types are taken from soil maps and databases of Finland [17]. Land-cover data are available in open sources (https://www.syke.fi/avointieto). Agricultural measures are based on monitoring data of the Finnish Agri-Environmental Programme [18–20]. Interventionary studies involving animals or humans, and other studies that require ethical approval, must list the authority that provided approval and the corresponding ethical approval code.

2.2. Discharge, Water Quality and Meteorological Data

In the Vanajavesi basin, there are two discharge and six water quality measurement stations along the main water course. Discharge is measured on a daily basis. Water quality samples are taken usually once in a month or every second month. In the upper reaches around Lake Pääjärvi, there is a Long-Term Ecosystem Research (LTER) (https://www.lter-europe.net/lter-europe) area (sub-basin Mustajoki), where water quality samples have been taken biweekly throughout the year since 1995.

The analysis included an oxidization of different N forms to nitrate by means of peroxodisulphate in a buffered alkaline system at 120 °C and under pressure followed by reduction to nitrite with a Cu–Cd reduction column. Nitrite was then determined by diazotizing with sulphanilamide and coupling with N-(1-naph-thyl)-ethylenediamine to form a reddish-purple azo dye measured at 550 nm.

Metadata and discharge and water quality observations of the national network [21] are available at the open database (https://www.syke.fi/fi-FI/Avoin_tieto/Ymparistotietojarjestelmat). All data are quality checked, and we left out all observations that were marked "unsure" and gave the weight 0.5 to those that were under the detection limit.

Meteorological data (daily temperature) were available from the Finnish Meteorological Institute [21]; (https://www.ilmatieteenlaitos.fi/avoin-data). We used data from two meteorological stations, Lahti Laune for the upper reaches and Jokioinen Observatory for the lower reaches. The nearest meteorological station is Lahti Laune, where mean annual temperature was 3.2 °C and mean annual precipitation 633 mm in 1971–2000. At the Jokioinen Observatory, mean annual temperature was 4.6 °C and annual precipitation 627 mm.

Emissions from point sources were taken from the Vahti database (https://wwwp2.ymparisto.fi/scripts/oiva.asp). Emissions from private houses outside sewage treatment are estimated based on number of inhabitants [22]. The LTER area has more detailed emission data that are based on interviews of local inhabitants [23].

2.3. Phenological Development of Vegetation Cover, and Timing of Snowmelt

We drew the estimates of vegetation active season from time-lapse camera images taken at 30 min intervals from a camera Lammi Mixed stand, which belongs to a network of cameras observing 14 ecosystems [24]. The Lammi camera was mounted at landscape view level at location 61.05356; 25.03898 (N; E, WGS84). Image material is openly published in https://www.zenodo.org/communities/phenology_camera [25].

Image material was analyzed using the methods presented in [24]. They analyzed the vegetation active period based on the development of mean green fraction of image pixels in specified image sub-regions. The start and end of season were automatically interpreted from the parametric curves fitted to the time series of mean growth curves that represented seasonal development status of vegetation.

The albedo data used were the second release of the Surface ALbedo (CLARA-A2 SAL) data record Satellite produced by the Satellite Application Facility for Climate Monitoring (CM SAF) CLouds, Albedo and RAdiation [26,27]. It is global, covers the years 1982–2015 and is based on AVHRR satellite data. The albedo used here was defined as broadband shortwave directional-hemispherical reflectance, i.e., the black-sky albedo, and the spatial resolution is 0.25°. The start and end dates of snowmelt were determined by using sigmoid fitting for the yearly pentad (5 day) mean albedos for each pixel [28]. For each pixel and periods, the pentads from the end of January until the end of August were used for this. The date of snowmelt onset was taken to be the date at which the sigmoid reaches 99% of its variation range. Likewise, the end of the snowmelt season was defined to be the day at which the sigmoid reaches 1% of its variation range. The length of the melting season was then the difference between these two. The albedo value corresponding to the onset of melting was used as the representative albedo value presenting the melting season.

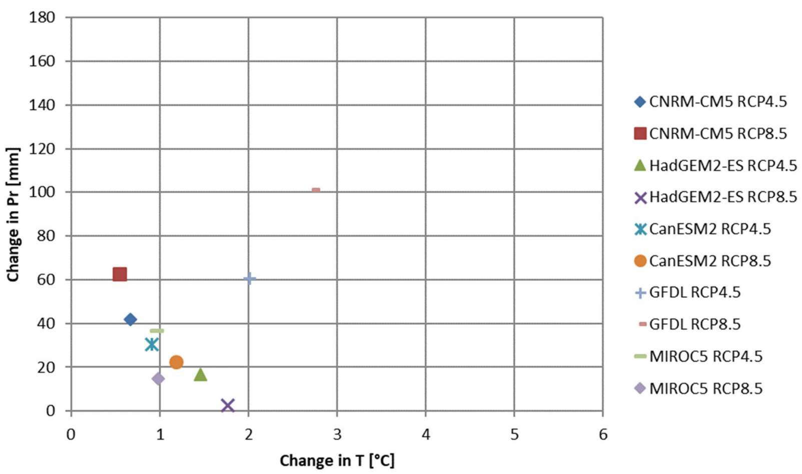
2.4. Scenarios of Future Developement

2.4.1. Climate Change Scenarios

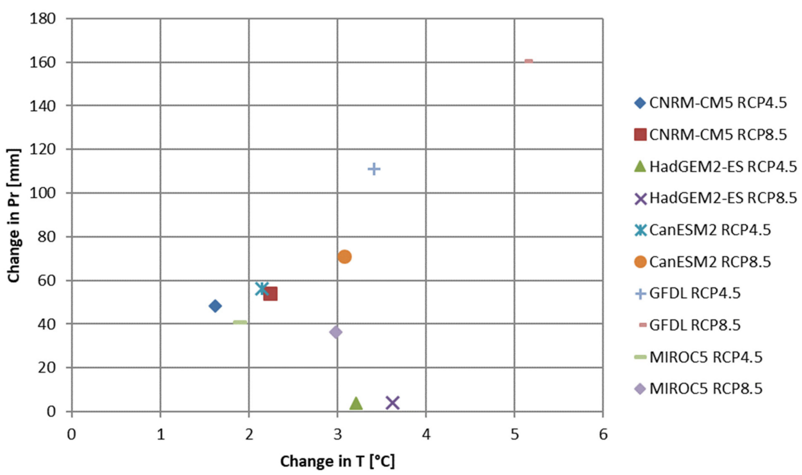
The climate scenarios were based on two representative concentration pathways of the fifth phase of the Climate Model Intercomparison Project (CMIP5, [29]) (https://esgf-node.llnl.gov/projects/cmip5/): RCP4.5 and RCP8.5. The numbers refer to the amount of radiative forcing of the atmosphere in W m^{-2} caused by different levels of greenhouse gas and aerosol concentrations. RCP4.5 imply reduced emissions that stabilize forcing at medium-low levels by 2100, while RCP8.5 assumes that emissions continue to grow close to current rates, with high forcing by 2100. The temperature and precipitation changes under these RCP-based scenarios in Finland have been obtained from 16–32 global climate models. Five climate scenarios were chosen to represent a range of projections over Finland for each of the four RCPs and for two time periods (2010–2039, 2040–2069). One scenario showed close-to-average temperature and precipitation changes, and four scenarios the edge of the range, which have high or low temperature changes (warm/cold) combined with large or small precipitation changes (wet/dry).

Model driving variables were downscaled to a 0.2° × 0.1° longitude-latitude grid by bias-correction methods utilizing gridded harmonized FMI meteorological data [30]. In bias adjustments, a quantile–quantile type bias correction algorithm was used for daily mean temperature, relative humidity, shortwave radiation and windspeed [31] and parametric quantile mapping for daily precipitation [32]. Detailed description of the data processing accounting for the model-inherent biases is given in [33]. Global mean CO_2 concentrations from the RCPs 4.5 and 8.5 were linearly interpolated to monotonously increase through the calendar years.

All downscaled climate change scenarios provide an increase in annual temperature (Figure 2). In 2010–2039, increase in annual temperature remained ≤2 °C except in one scenario, namely GFDL_rcp8. Most of the scenarios provide an increase in precipitation as well. Dispersion of scenarios increased from the period 2010–2039 to the period 2040–2069. Again, GFDL_rcp8 provided the highest increase in annual temperature by over 5 °C and annual precipitation by 160 mm, compared to baseline scenarios 1980–2009.



(a)



(b)

Figure 2. Change in annual temperature and precipitation according to different scenarios at the Lahti Laune meteorological station: (**a**) near future 2010–2039, (**b**) far future 2040–2069.

2.4.2. Future Development of Population

The current population numbers by municipality were obtained for the 2017 situation from Kuntaliitto (Association of Finnish Local and Regional Authorities; 2017) and the corresponding land and total areas for each municipality from the National Land Survey of Finland (2017). Projections concerning population growth or decrease by municipality (Table 2) were available from Statistics Finland (2015).

Table 2. Population density projection by municipality for 2040.

Municipality	Population 2017	Total Area (Land and Surface Water) 2017 (km^2)	Population Density 2017 by Total Area	Population 2040	Population Density 2040 by Total Area
Asikkala	8323	756	11	7888	10
Hattula	9682	427	23	9964	23
Hausjärvi	8641	399	22	9059	23
Hollola	23,791	727	33	21,306	32
Hämeenlinna	67,850	2032	33	73,030	36
Janakkala	16,709	586	29	16,936	29
Kärkölä	4540	259	18	4159	16
Loppi	8098	656	12	8353	13
Pälkäne	6627	738	9	6101	8
Riihimäki	29,160	126	232	31,585	252
Tammela	6241	715	9	5789	8
Valkeakoski	21,346	372	57	22,281	60

2.5. Dynamic Ecosystem Models and Their Set-Ups

2.5.1. Description of the Ecosystem Models

We combined the results of three ecosystem models (PREBAS for forest growth, PERSiST for hydrology and INCA for nitrogen transport) that use air temperature, precipitation, land cover and soil type as inputs. We used the same input data and parameter values from measurements or literature (e.g., decay of organic matter) in all models. Data flow between the models is presented in Figures 3 and 4. The main calculation unit of the ecohydrological models PERSiST and INCA is a hydrologically representative unit (HRU). This is typically a combination of land cover, soil type and elevation or slope that is assumed to have similar hydrological and biogeochemical response to input data in different parts of the catchment. To upscale the results to maps, the simulated specific loading values of HRUs can be connected to land cover, soil type and elevation.

PREBAS is a forest carbon balance and forest growth model [34,35], which has been recently calibrated to boreal conditions based on eddy-covariance [12] and forest growth experiment data [36]. Growth and carbon balance processes are weather sensitive, and the model has been used for making future projections under alternative forest management options. To estimate the growth and carbon balance of a forest, the model first predicts the photosynthesis and water balance of the forest. This requires information about daily weather conditions, and information about radiation absorption in the canopy, which is estimated based on the leaf biomass and stand structure. Thereafter, photosynthesized assimilates are allocated to growth and respiration of tree structures (stem, roots, needles, etc.). A fraction of tree structures dies each year and produces litter to soil. For completing the ecosystem carbon balance, PREBAS has been combined with soil carbon model YASSO07 [37]. All modules have been independently tested or calibrated against data from eddy flux stations, forest experiments and inventories, and observed soil carbon stocks.

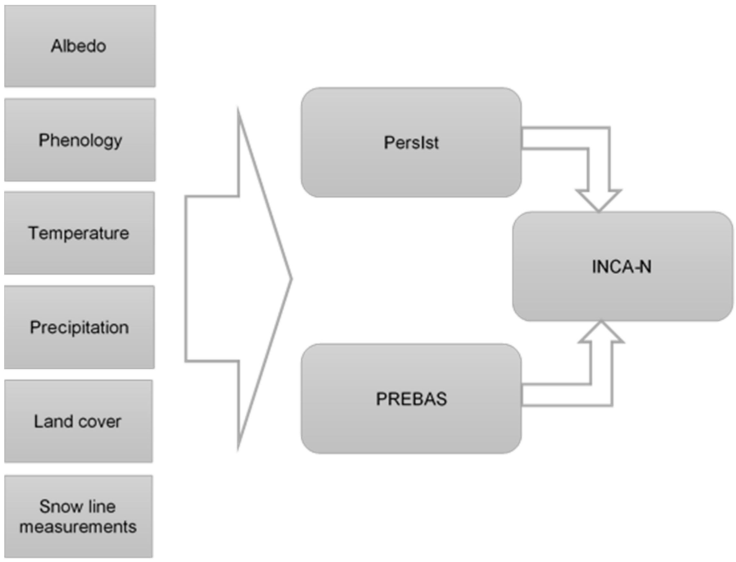


Figure 3. Flow chart of data and combination of models.

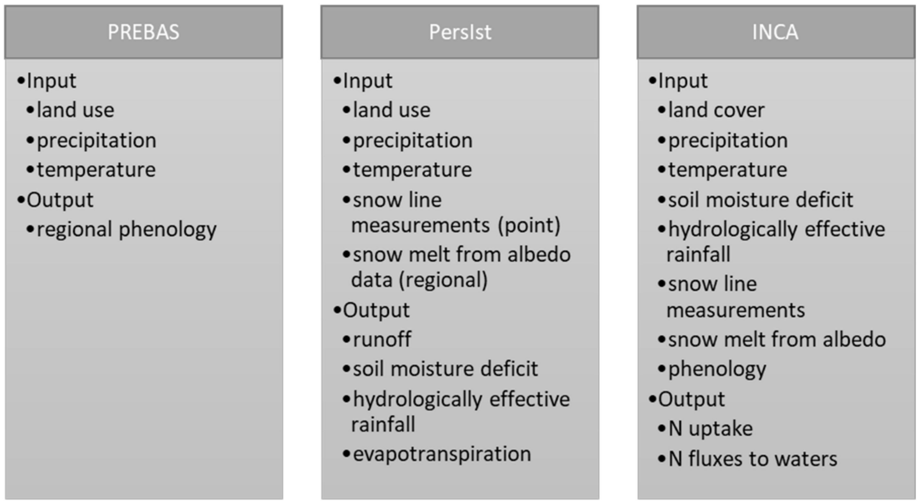


Figure 4. Data flow between the ecosystem models.

The PERSiST (the Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport) [38] model is a flexible, semi-distributed landscape-scale rainfall-runoff modelling toolkit suitable for simulating a broad range of user-specified perceptual models of runoff generation and stream flow occurring in different climatic regions and landscape types. It is designed for simulating present-day hydrology, projecting possible future effects of climate or land-use change on runoff and catchment water storage, and generating hydrologic inputs for the Integrated Catchments (INCA) family of models. 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 is a dynamic, mass-balance model [10,39], and as such, attempts to track the temporal variations in the hydrological flow paths and nitrogen transformations and stores, in both the land and in-stream components of a river system. INCA considers whole catchments, and because it is process-based, it can be scaled up from small to large catchments. INCA provides outputs of daily and annual land-use specific inorganic nitrogen fluxes (kg ha^{-1} yr^{-1}) for all transformation processes and stores within the land phase. Processes are regulated by temperature and moisture, but not by CO_2 level.

2.5.2. Model Set-Up and Upscaling to the Vanajavesi Basin

The PERSiST and INCA models were calibrated and validated to the Vanajavesi basin against observed discharge at two stations and water quality at six stations (Figure 1) for years 1995–2003 (calibration period) and 2004–2010 (validation period). Baseline scenario was 1980–2009. Precipitation and air temperature data were measured at the Lahti Laune and Jokioinen Observatory meteorological stations. Land-use data were derived from the CLC databases, and more detailed information of field crops from the parcel data.

The main calibration point was the densely monitored LTER site at the outlet of the river Mustajoki. The first phase of calibration was done manually against NO_3-N and NH_4-N concentrations to cover the N cycle and to guarantee that process rates stay on a realistic level. Manual calibration was then fine-tuned by automatic calibration [40]. It aims to minimize the weighted sum of squared differences between the model simulation and an observed set of data. The optimization problem is iteratively solved by linearizing the relationship between model output and parameters by using a Taylor series expansion. The other sites had clearly more space data (one to two samples per month), and they were used mainly to check the correct level and dynamics of the simulations. At this stage, parameterization of land processes was not changed, but river processes were changed based on river length, width and flow velocity, and emissions from local point sources were added.

Snow accumulation and melting dynamics were solved with degree-day equation, e.g., [41,42], which was calibrated against snowline measurements, observed albedo (reflectance) and images of snow melting. Snow reflects a clearly large proportion of sunlight compared to bare soil, and thus the start of snow accumulation or end of snow melting can be defined from change of albedo. Snow melting started on day 66 (±25) and ended on day 115 (±15). The depth of the snowmelt was calibrated against snowline measurement at the LTER area. Forest phenology was estimated based on PREBAS simulations calibrated against internet camera images. Forest phenology started to develop on day 127 (±6). Phenology of agricultural crops on our previous work [43], by changing parameters defining growing season start, length and forcing function to the growth.

2.6. Concept of Vulnerability

We followed the definition of vulnerability to climate change given by the IPCC [44], in which vulnerability (V) is described as a function of exposure (E), sensitivity (S) and adaptive capacity (A) of the system or process:

$$V = f(E, S, A) \tag{1}$$

Exposure is the degree of climate stress, describing what changes may occur, e.g., long-term changes in climate conditions, or frequency of extreme events. In this case, exposure is NO_3^- load as kg ha^{-1}, calculated to each HRU. Sensitivity refers to the impact response per unit of climate change moderated. It describes how sensitive ecosystems and people are to these changes. Sensitivity is described as population density on municipality level. Finally, adaptability describes how capable ecosystems and societies are in adapting these changes. In this case study, adaptation is 1 all over the catchment, as it is assumed that no areal differences in environmental policy will exist. Finally, calculated vulnerability was connected to land cover (in 25 × 25 m grids) to draw maps. These maps were then cut by borders of different municipalities to calculate vulnerability on municipality level.

3. Results

3.1. Calibration and Validation of the Eco-Hydrological Models

Goodness-of-fit value PBIAS for discharge was around 25% for calibration and validation periods. The performance of watershed-scale models can be considered to be "satisfactory" when PBIAS < 25% at daily time step for discharge [45].

PBIAS for NO_3^- varied between 1% and 23% in the calibration period, and between 1% and 46% in the validation period in most of the sub-basins. Corresponding values for NH_4-N were 10% and 150% in the calibration period, and 7% and 178% in the validation period. For nutrients, PBIAS < 25% is considered "very good" and PBIAS < 70% is still considered satisfactory. The lowest PBIAS was in the catchments with a low number of observations. R^2 and RMSE values for Q and NO_3^- are presented in Table 3.

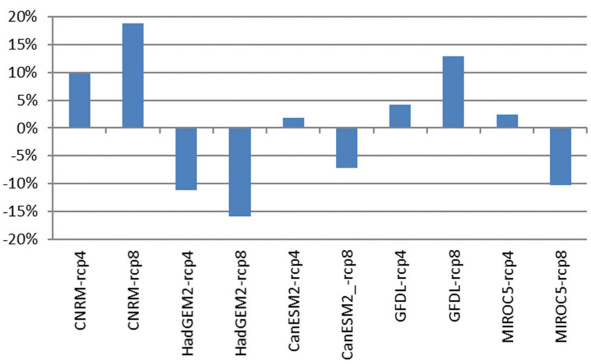
Table 3. Goodness-of-fit values of PERSiST and INCA model application.

Station	Calibration				Validation			
	R^2		RMSE		R^2		RMSE	
	Q	NO_3^-	Q	NO_3^-	Q	NO_3^-	Q	NO_3^-
LTER	0.702	0.197	96.6	119.9	0.665	0.177	64.424	233,6
35.83	-	0.194	-	70.4		0.16		60.4
35.82	-	0.015	-	98.1		0.072		58.1
35.81	0.709	0.155	152.2	156.4	0.410	0.11	56.986	166.1
35.88	-	0.138		89.1		0.02		62.6
35.23	-	0.104		114.1		0.12		111.4

In general, we reached "satisfactory" calibration and validation results on a watershed scale, and at the outlet on the river Mustajoki, the calibration for NO_3-N and NH_4-N was "very good" (PBIAS < 25%). NH_4-N calibration and validation were not satisfactory (based on PBIAS) only in one sub-basin, probably due to uncertainties in estimated sewage flow from houses outside municipal wastewater treatment. NO_3-N was unsatisfactory in the same basin based on R^2-value.

3.2. Hydrological Processes

Most of the climate change scenarios provided moderate increase in annual discharge in the near future (2010–2039) but decrease after that. The increase was highest according to the CNRM scenarios, because temperature rise was relatively small, but increase in precipitation high. In the far future (2040–2069), discharge might be 5–20% smaller than current discharge according to all scenarios (Figure 5) because of an increase in annual evapotranspiration (Figure 6). Further, all scenarios lead to slightly decreased recharge to groundwater, though the trend was not statistically significant.



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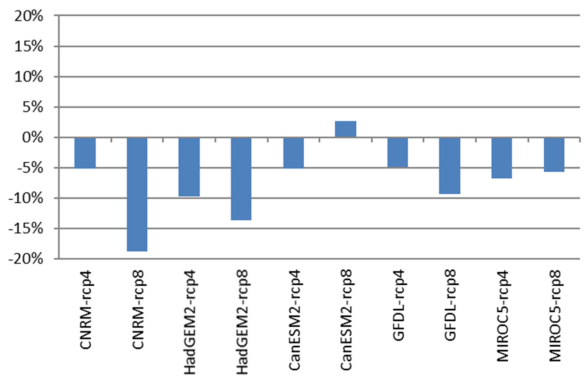
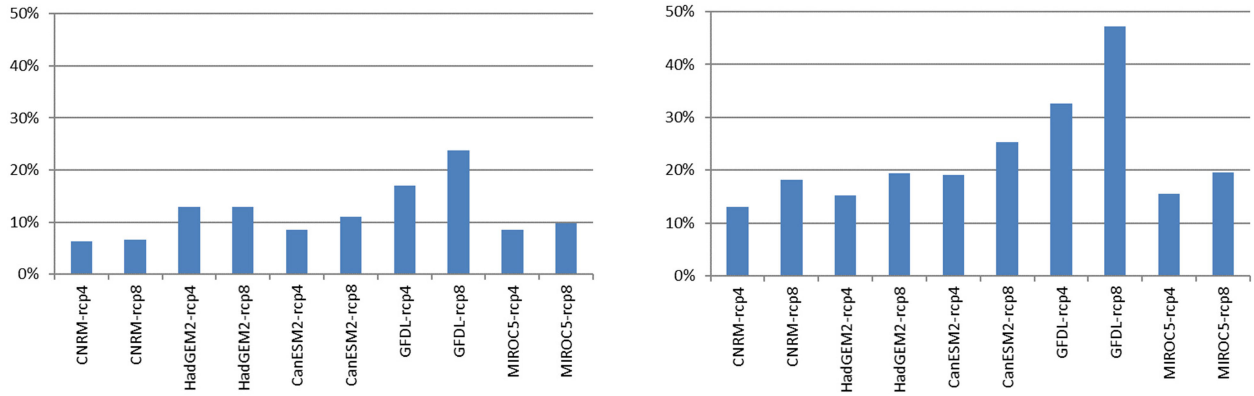


(**b**)

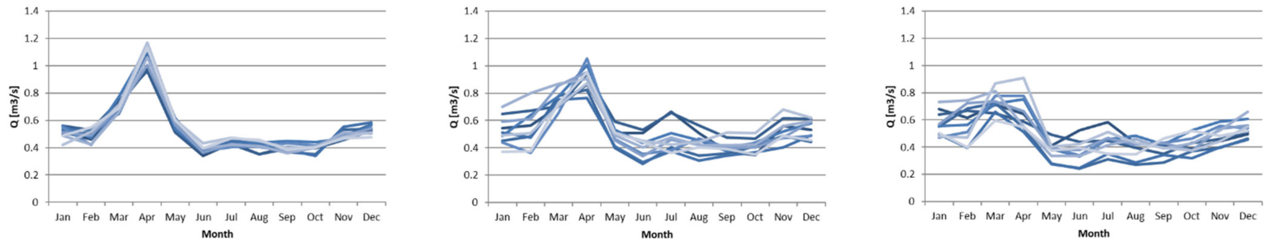
Figure 5. Changes in annual discharge: (**a**) 2010–2039, (**b**) 2040–2069.

There was also a shift towards earlier peak discharge due to snowmelt, which occurred in April in the period 1980–2009 (Figure 7). Snowmelt peak diminished, but discharge increased somewhat in winter and in summer. Discharge dispersed according to different scenarios towards 2040–2069.



(**a**) (**b**)

Figure 6. Changes in evapotranspiration: (**a**) 2010–2039, (**b**) 2040–2069.



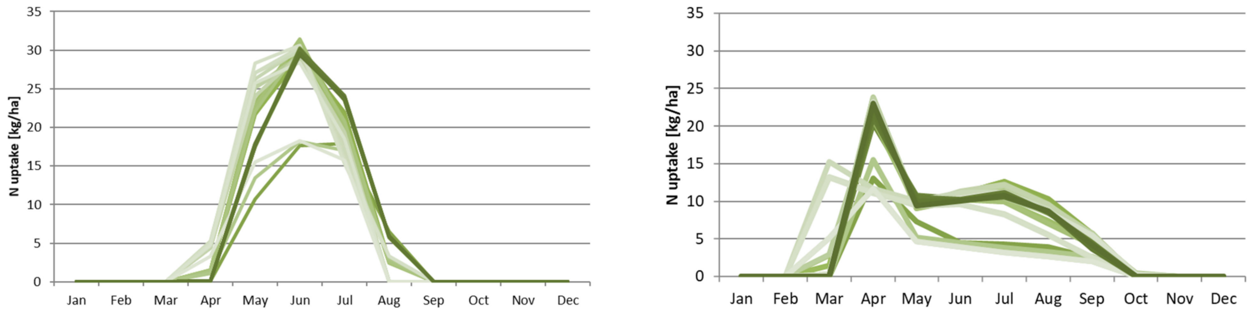
(**a**) (**b**) (**c**)

Figure 7. Shift in peak discharge from basin according to different climate scenarios: (**a**) 1980–2009, (**b**) 2010–2039, (**c**) 2040–2069.

The number of low pulses (NQ90) of discharge slightly increased from an average of 5.9 in 1980–2009 to 6.1 in the near future and 6.2 in the far future, but their average duration decreased slightly. The number of high pulses (HQ90) did not change, but their duration decreased.

3.3. Ecosystem Vulnerability

Simulated vegetation uptake of N did not significantly increase, even though the growing period became longer. Spring cereals might be sown earlier, but the length of their yield season did not change. The growing season of forest became longer, but only two scenarios showed shifts of maximum N uptake from April to March (Figure 8).



(**a**) (**b**)

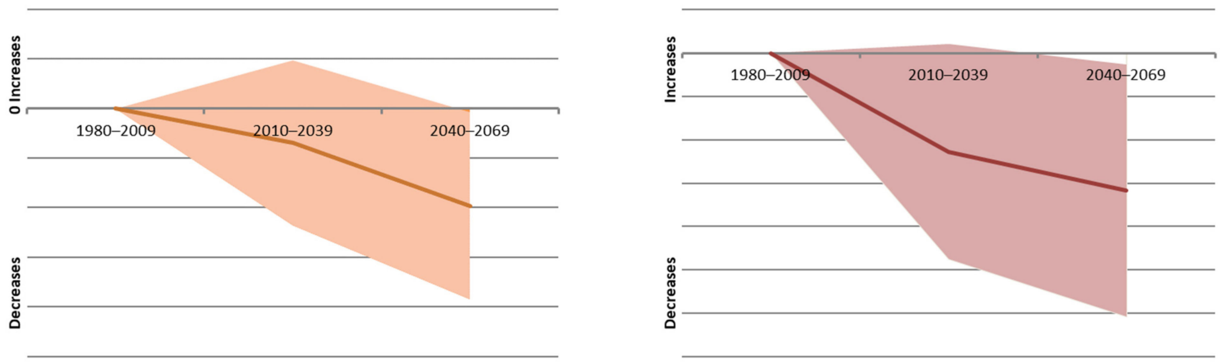
Figure 8. Nitrogen uptake of (**a**) spring cereals, (**b**) forest on moist soil. Baseline is presented by the darkest color.

Nitrogen leaching from forests followed the general pattern of discharge, so that in the current climate, the peak occurred in April. In the future, the peak would occur earlier in spring, and there would be more leaching in winter. In spring cereal fields, the peak leaching occurred in May, though there would be more dispersion between scenarios in the future. Leaching from fields decreased less than 10% in the far future, though there was no change in the near future. Nitrogen loading from forests decreased by 9% in the near future and by 15% in the far future.

The most vulnerable land-cover type was spring cereals on sandy soils. The land-use specific load varied between 10 and 22 kg ha^{-1} a^{-1}, depending on the scenario.

3.4. Societal Vulnerability

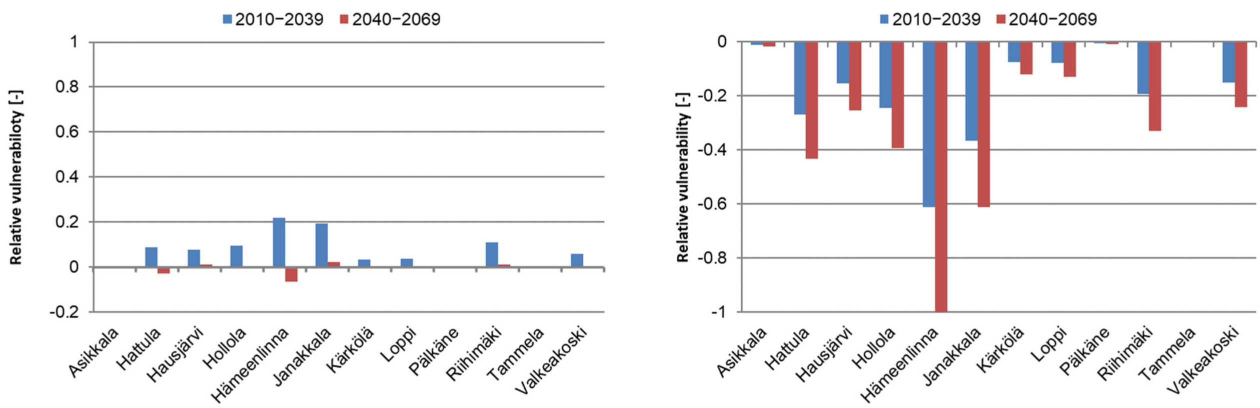
Nitrate loading (exposure) rather decreased than increased in future (Figure 9), even though different scenarios gave a slightly different pattern for the development. As NO_3-load follows discharge pattern, the highest increase occurred according to the CNRM, and lows according to Had scenarios, both in annual load and discharge.



(a) (b)

Figure 9. Direction where (**a**) environmental exposure, (**b**) societal vulnerability develop in future. Shaded area is an ensemble of different climate change scenarios.

In different municipalities, exposure depended very much on climate change scenario, land use and soil type (Figure 10), and it was the highest in municipalities with a high percentage of agricultural land on permeable soil types. These were also the municipalities where population density increases (Table 2). In the future, population number in forested municipalities was decreasing, which decreased societal vulnerability (described as relative number, where the highest change got value 1 and other changes were related to that).



(a) (b)

Figure 10. Highest and lowest vulnerability in different municipalities according to two extreme scenarios: (**a**) CNRM RCP4.5, (**b**) Had CRP4.5.

4. Discussion

Climate change may alter the services ecosystems provide by changing ecosystem functioning. These changes are not necessarily straightforward, as ecosystems have a capacity to resist an environmental perturbation [3]. When assessing the impacts of climate change on ecosystem functioning, it is crucial to understand and to be able to consider the different feedback processes in modelling. Intensive monitoring areas (e.g., LTER) provide essential information on the functioning of ecosystems, which may reveal missing processes in the conceptualization of the modelling.

Dense and versatile measurement data are also valuable in calibrating ecohydrological models. On the other hand, different sensitivity/uncertainty analysis has shown that the ecosystem models can usually be calibrated even with lower amounts of observations if literature values are used to supplement missing measurement data [46,47]. A well-calibrated model can be upscaled to other or larger areas if all necessary ecosystem processes are described with the required accuracy. That is shown also in other studies [36,47–49].

The interpretation of the results must be proportionate to the details of the modelling. For example, INCA repeatedly overestimates the lowest concentrations, which have a minor influence on the total nutrient load. Failure may be due to the fact that low concentrations (under detection limit) are underestimated. The other option is that some river processes are not correctly described [50], or denitrification in groundwater is underestimated [51].

Snowmelt period is important for Nordic hydrology. It defines the timing of spring floods and increases discharge to groundwater aquifers. If the snowmelt is calibrated incorrectly, the hydrological model will fail in climate change scenarios. Typically, hydrological models are calibrated against observed discharge. Snowline measurements provide information on snow accumulation at a particular point, but these data are seldom widely available to cover larger river basins. We used here albedo data to improve simulation of the timing of the snow-covered period. For example, [52] showed a large mean decline in land surface albedo between dry snow and snow-free conditions, so that the lower wet snow albedo contributed to growing season onset and activation of biological and hydrological processes.

Nitrate is easily transported from terrestrial environments to waters. Nitrogen loading is highest outside the growing season, when vegetation uptake is low. In the start of the growing period, perennial vegetation has high nutrient demand. Thus, the other critical issue in calibration is to describe phenology correctly. We used here data from a network of cameras that are observing phenological changes in boreal ecosystems to calibrate forest growth in a nutrient leaching model. This additional calibration data may increase the reliability of modelling, also by decreasing equifinality [47].

In the Vanajavesi basin, domestic water is mainly groundwater or artificial groundwater. Lake water is pumped and filtered through the ridges to form artificial groundwater. Water quality of domestic water is good, e.g., the highest observed nitrate concentrations are <0.25 mg L^{-1} (https://hsvesi.fi/vesi-ja-vesihuolto/).

Boreal mixed landscape seemed to buffer NO_3^- leaching efficiently. Increased precipitation did not lead to higher discharge because of an increase in evapotranspiration. A longer and warmer growing period enhanced vegetation growth, which was already observed [8]. An increase in vegetation productivity and canopy cover due to climate change also resulted in higher N uptake by forests. Nitrate leaching from agriculture was more disperse than from forests, according to the different climate scenarios. Thus, leaching of NO_3^- to surface and groundwater rather decreased than increased, suggesting that, in the future, the quality of drinking water would not be an issue in general. Only in the "near future" some scenarios provided an increase in NO_3^- leaching. However, the number of drought periods might increase in the future, having an effect especially on the amount of water in private wells.

Environmental and societal vulnerability varied greatly between scenarios and municipalities. The most vulnerable areas were those municipalities where large agricultural areas locate on permeable soil types. Demographic scenarios showed a population decrease in forested rural municipalities and an increase in agricultural municipalities and towns in the future. This tendency aggravates vulnerability in municipalities with a high percentage of agricultural land.

On the other hand, adaptation capacity in agriculture is high due to the Finnish Agri-Environmental Programme [18]. Further, the Nitrates Directive regulates fertilizer use mainly by controlling manure spreading on fields [53]. Nitrate loading may increase the outside growing season due to increased runoff in autumn and winter. Common measures like wintertime vegetation cover, catch crops and reduced fertilization are designed to tackle the changes [18]. Climate change may also change crop distribution and [54,55], leading to crops that demand higher amounts of fertilizers than spring cereals, which fertilization level is effectively regulated. Thus, climate change sets challenges to agri-environmental policies to find measures that work in the future climate and for land use.

5. Conclusions

When modelling effects of climate change on water quality, it is crucial to be able to consider different forms of feedback in ecosystem processes. Hydrologically mediated central ecosystem services in the Vanajavesi river basin were resilient to climate-induced changes. The annual runoff did not rise, as more precipitation was buffered with greater evaporation. Vegetation nitrate uptake increased due to longer and warmer growing periods. Thus, leaching of nitrate to surface and groundwater rather decreased than increased, suggesting that, in the future, the quality of drinking water would not be an issue in general. Particularly, nitrate concentration in groundwater was nearly unaffected. Nitrate leaching from agriculture was more disperse than from forests according to the different climate scenarios. The most vulnerable areas were in municipalities where agricultural areas locate on permeable soil types. Problems concerning groundwater in private wells may be more quantitative than qualitative, because drought periods may become more common.

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