*Earth’s future*

Supporting Information for

**How to Achieve a 50% Reduction in Nutrient Loads from Agricultural Catchments under Different Climate Trajectories?**

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**Introduction**

Text S1 is a detailed description of the steps that were taken to construct the model for these two study catchments. Text S2 is a comparison of the projected precipitation and temperature between different climate models.

Figure S1 are spatial maps of elevation and soil texture for both study catchments based on the geospatial data sources described in Materials and Methods section 2.1. Figure S2 and S3 are visualisations of the projected changes in rainfall (intensity) and temperature respectively. Figures S4-S9 are daily time series of the calibration and validation periods for discharge and nutrient loads. Figure S10 depicts the nutrient loads of the Hestadbäcken catchment only under increasing sizes of floodplains & wetlands.

Table S1 provides an overview of the combinations of General Circulation Model and Regional Downscaling model, included representative concentration pathways, and the abbreviation used in this study. Tables S2-S5 provide the P-value outcomes of the t-test comparison between simulated nutrient loads of different climate models. Tables S6-S9 show the simulated nutrient loads for the individual climate models and the ensemble approach under the representative concentration pathways 2.6, 4.5, and 8.5. Moreover, they also show the differences in loads and calculated percentage change between periods.

**Text S1:** Specifications of the HYPE model.

Geodata

The three most dominant SLCs in the Hestadbäcken catchment were “autumn crops on silty clay (20.7%)”, “autumn crops on clay loam” (19.4%), and “forest on moraine (19.3%)”. The upper Sub-catchment was dominated by “autumn crops on loam” (26.8%), “autumn crops on clay loam” (13.9%), and “autumn crops on sandy loam” (9.8%). The mid sub-catchment is dominated by “autumn crops on loam” (28.9%), “autumn crops on sandy loam” (13.1%), and “spring crops on loam” (5.0%). The lower sub-catchment was dominated by “autumn crops on loam” (30.9%), “pasture on Clay moraine” (8.0%), and “autumn crops on sandy loam” (33.1%). For each (sub-) catchment the SLC types were supplemented on their average height difference compared to the (sub-) catchment average. The geodata file was further supplemented with data on the size and design of the wetland buffer zones, river length, percentage of streams with vegetation buffers, presence of agriculture near the streams, atmospheric deposition of N, and the contribution of N and P from rural sewage to the soil and river.

Geoclass

In geoclass, the model further defined the SLCs using their specific combination of land use and soil classes. Moreover, the SLCs were given a vertical dimension by assigning each SLC up to three soil layers with defined depths. Most SLCs were assigned three soil layers, except for Buildup and Thin soils (two layers), and Rock and Water/organic soils (1 layer). Agricultural SLCs were also connected to a specific crop type from the Cropdata file. All agricultural classes were also supplemented with a tile drainage depth, which was based on field estimations. The SLC of wetlands was connected to wetland processes and the SLC of streams to stream processes through special class delineation.

Cropdata: fertilisation and cropping regimes

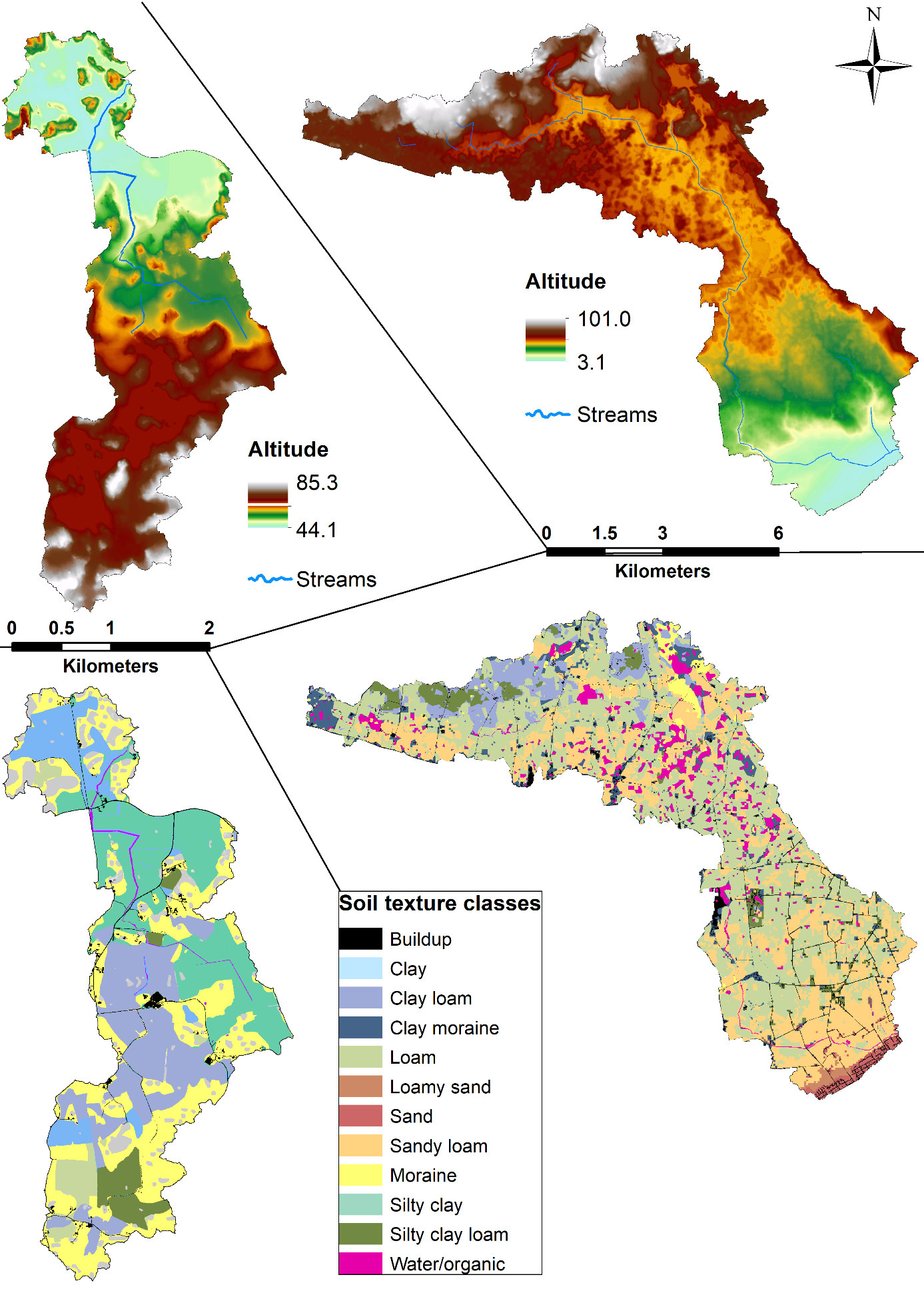
In the cropdata file, the planting, harvesting, and ploughing times of different crop types were defined. The amount and dates of application of mineral fertiliser and manure were also specified based on monitoring programs at nearby catchments. For autumn crops in both study sites, we assumed harvesting end of August, followed by ploughing and planting mid-September. We also assumed a split fertilisation with half of N in autumn and spring, and all P application in autumn together with planting. For spring crops, we assumed harvesting end of August followed by ploughing in September, planting in spring together with a single application of the same amount of fertiliser. We assumed that the spring growing season starts 10 days earlier in Skåne than Östergötland. Each crop type was also given nutrient uptake ratios as a function of their growth, depth of uptake, and N-P ratio of uptake. For autumn crops, these crop growth uptake factors were split into a short autumn growing season, a period of dormancy, and a longer spring and summer growing season. Moreover, the tilling of decaying plants and crop residues, and their decay was specified as another source of nutrient. In the permanent pasture and other permanent land use types, no ploughing was remarked. Finally, the cropdata file was given information on the maximum crop cover and ground cover fractions in both the spring-summer growth period, and the autumn growth period.

Parameterisation

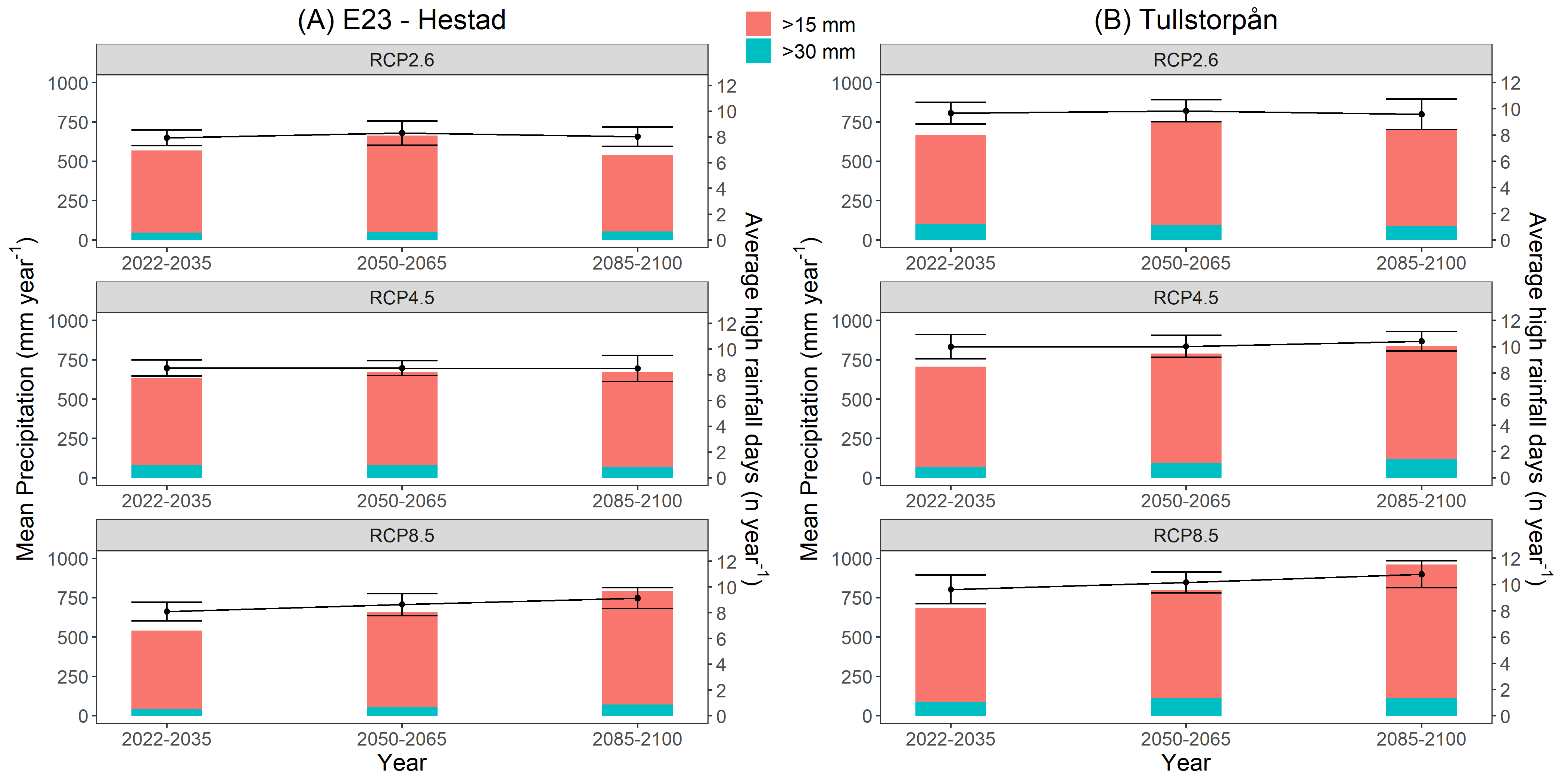
The model consists ran with multiple routines that modulate different aspects of the water and nutrient transport cycles within the catchments. These different routines were governed by parameters, however, certain parameters can have an influence on multiple routines. Some parameters were specific to land use, soil type, river processes, lake processes, and wetland processes. In this set-up, we had 260 land use parameters (26 parameters x 10 land use types), 180 soil class (18 parameters x 10 soil classes), 12 general catchment land routine and nutrient, 2 river discharge celerity and dampening factors, 4 sediment connectivity from soil to stream, 4 local stream nutrient and sediment processes, 1 main river nutrient process, 9 river particle transport, 8 lake nutrient and sediment processes, 7 soil water nutrient processes, and 10 wetland parameters. In our model setup, water entered the modulation through precipitation and left the system through evapotranspiration and discharge. Nutrients entered the modulation through specifications of fertilisation, atmospheric deposition, and rural sewage. They left the system through crop uptake, denitrification, and as nutrient discharges. No point sources were defined in the study catchments. Denitrification rates were specified for each land use type, the local river, main river, lakes and wetlands. For each land use type, nutrient decay rates were specified for immobile humus with slow turnover to organic forms with rapid turnover, mineralisation of rapid organics to soluble inorganic forms, dissolution of solids to particulates in water, and dissolution of organic humus to dissolved organic nutrients. Moreover, each land use type was given parameters governing their filtering capacity of mobilised nutrients and the vertical distribution in the soil. Three soil-specific factors governed the Freundlich equation dynamic equilibrium between Soluble Phosphate and Phosphate bound to soil particles. Moreover, soil-specific erodibility and cohesion parameters governed the susceptibility of soil to detachment. The transport of detached soil and phosphorous particles to the stream was further controlled by delay and removal coefficients. The local stream routine also included nutrient uptake coefficients by macrophytes and their production depth factors, while the wetland routine includes water retention coefficients, macrophyte nutrient uptake coefficients, production depths, outflow thresholds, sedimentation rates of particles, and return of nutrients to the soil by degrading macrophytes. The river resuspension subroutine was based on a modified Bagnold equation, wherein the local stream is represented as a dynamic pool of sediment and PP. This routine allowed the remobilisation of previously deposited sediment and PP and mobilisation of bank sediment through erosion. Finally, HYPE also allowed the introduction of starting concentrations of nutrients in the soil water, and starting pools of nutrients in organic form and bound to soil particles. These are specific for different land use types, and were used to represent legacy pools of nutrients based on estimations of legacy build up in Swedish soils.

**Text S2:** Comparison of precipitation and temperature under different climate models

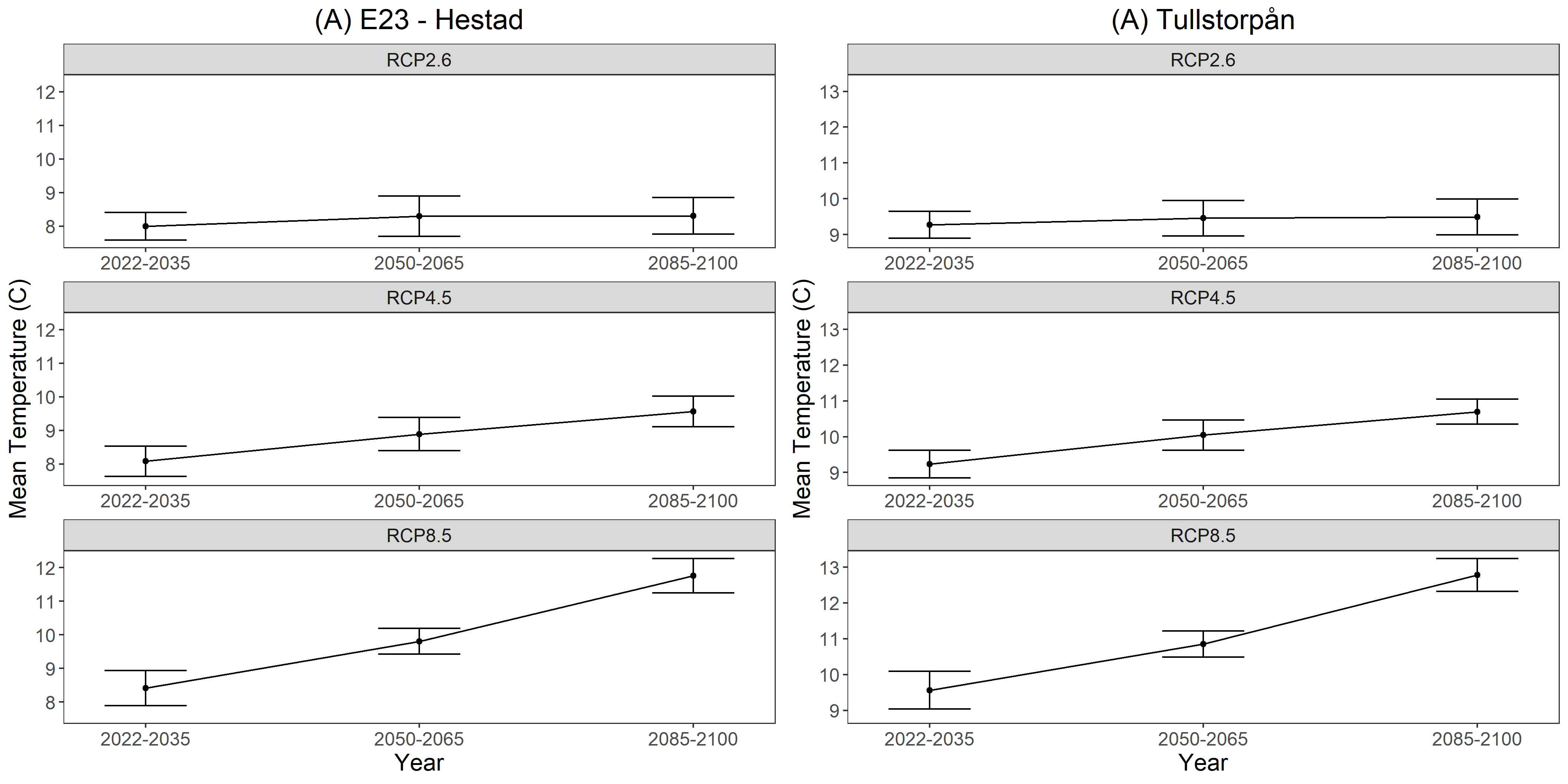
In Hestadbäcken, the precipitation estimation of the ensemble climate model in the 2000-2022 period was significantly higher (ca. 70-100mm per year) under all RCPs compared to the empirically measured values from two local meteorological stations, located in the catchment and 10 km to the northeast. However, the precipitation estimations from the individual ICHEC and MPI models (2000-2022 time series) were not significantly different to the catchment station (2010-2018 time series), even though they were slightly higher. Significant differences between the predicted average precipitations of different climate models were only found for the KNMI model under RCP2.6/2050-2065 and RCP4.5/2085-2100, which predicted higher average precipitations. The predicted mean temperatures from the ensemble and separate models were not significantly different to the observed mean temperatures from SMHI Norrköping. In Tullstorpån, the strong coastal and orographic effects required the use of the SMHI PTHBV gridded rainfall and temperature data, which was found not to be significantly different to the predicted rainfall or temperature from neither the ensemble nor separate climate models. Significant differences between the predicted average precipitations of different climate models were found for RCP2.6/2022-2035, RCP2.6/2050-2065, RCP4.5/2050-2065, RCP8.5/2050-2065, and RCP4.5/2085-2100. In all cases, the KNMI model predicted significantly higher average precipitation compared to at least one of the two other models. The MPI and ICHEC model were only significantly different of each other in RCP2.6/2022-2035. Overall, the rainfall predictions from the ICHEC and MPI models in the 2000-2022 period are more similar to each other and to the empirical measurements compared to those of KNMI for both sites.



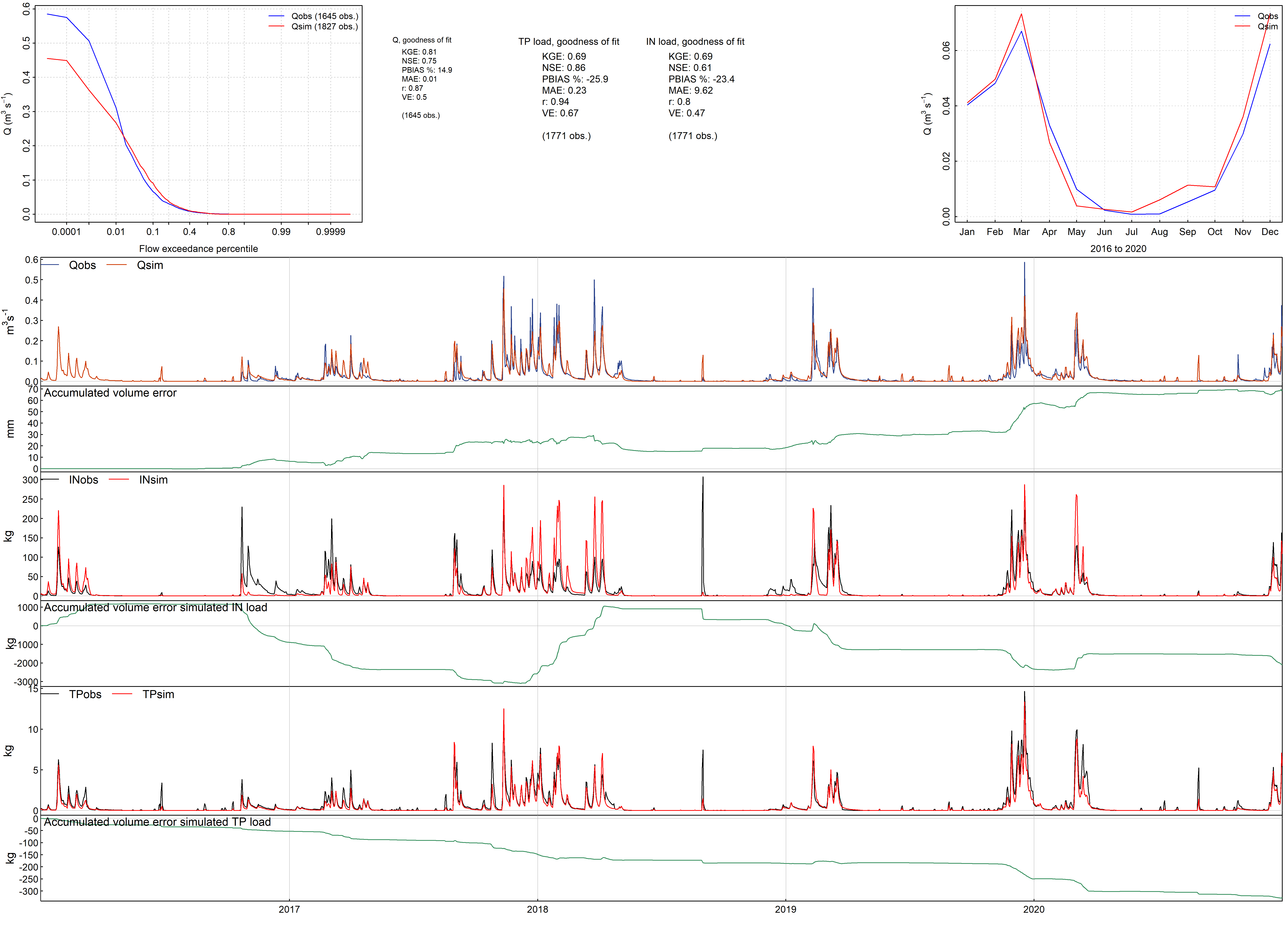
**Figure S1**: Spatial representation of altitude and soil textural classes in the study catchments



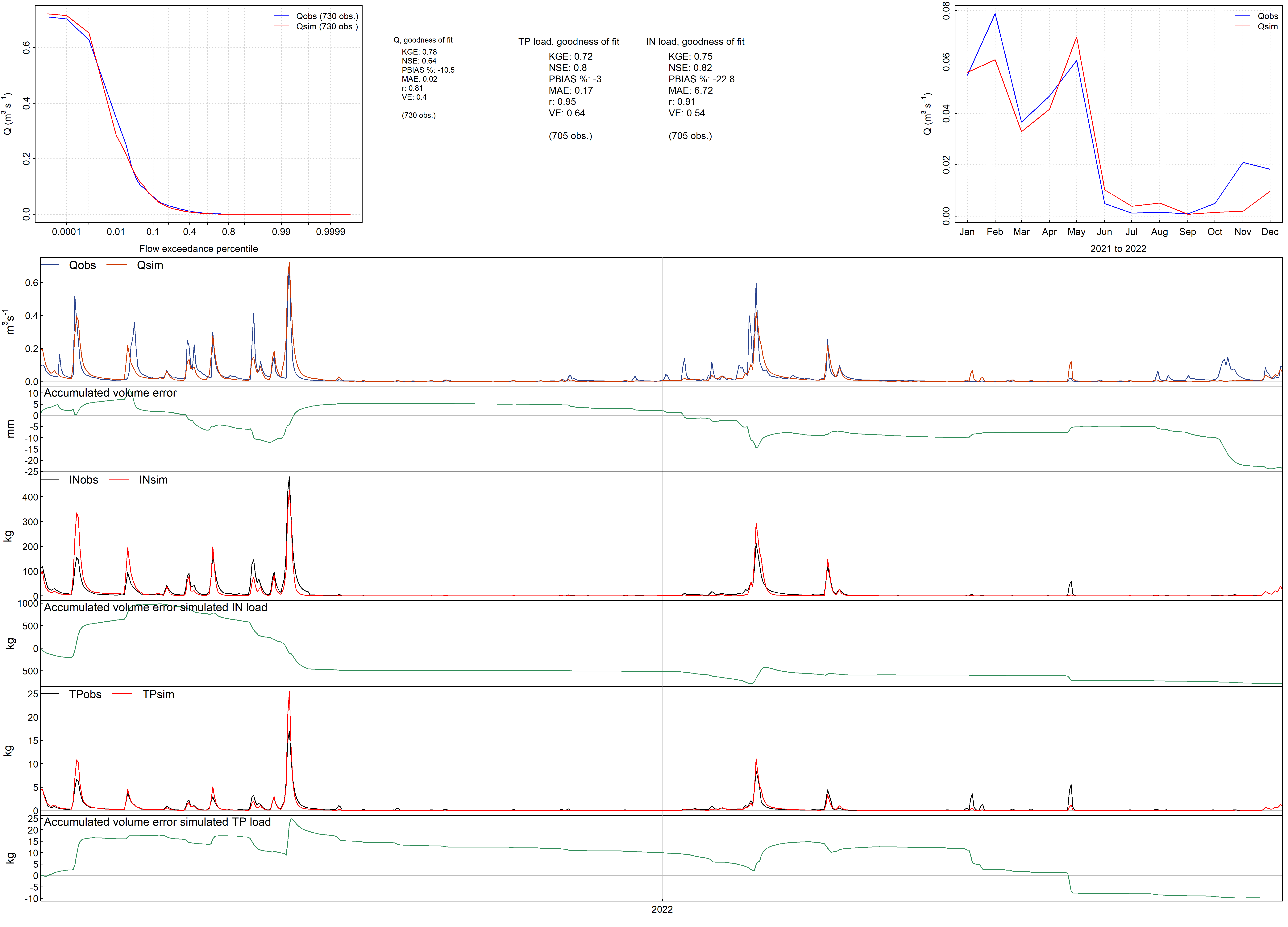
**Figure S2**: The predicted changes in average rainfall per year and high rainfall days from the ensemble of climate models. Average rainfall is presented with mean values and standard deviation of the three different models. The high rainfall days are presented in red columns for number of days with more than 15mm of rainfall, and in green columns for more than 30mm.



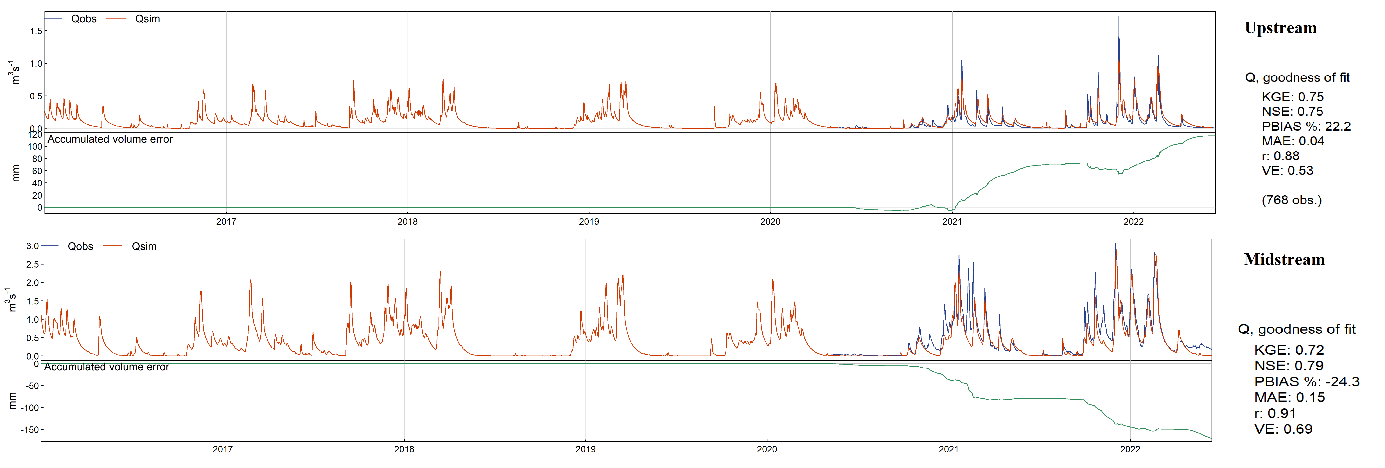
**Figure S3:** Ensemble model predictions of temperature change under different RCPs



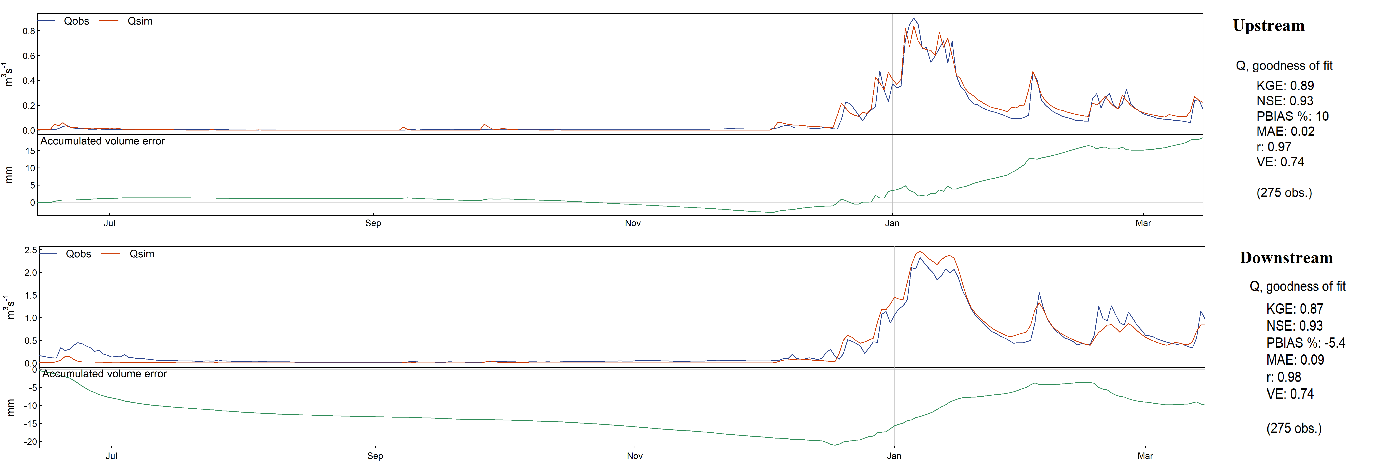
**Figure S4**: Daily observed and simulated discharge, IN loads, and TP loads in Hestadbäcken during the 2016-2020 calibration period. Goodness-of-Fit values in top. Flow-exceedance and discharge distribution plots in top corners.



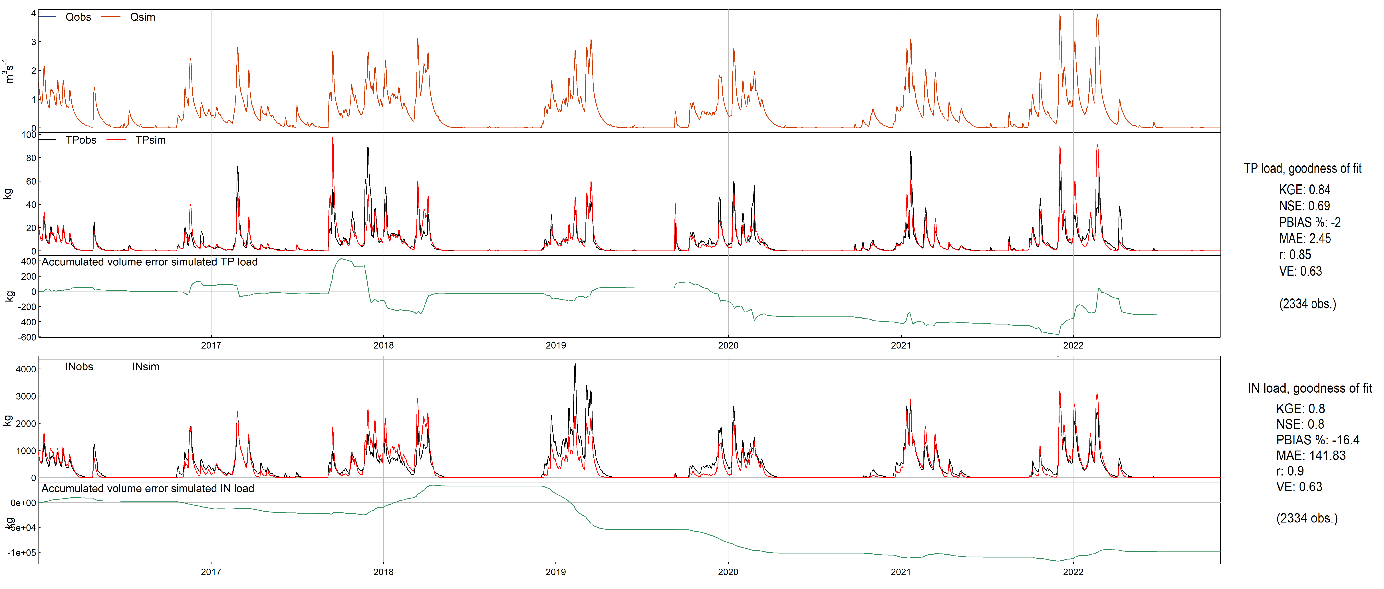
**Figure S5**: Daily observed and simulated discharge, IN loads, and TP loads in Hestadbäcken during the 2021-2022 validation period. Goodness-of-Fit values in top. Flow-exceedance and discharge distribution plots in top corners

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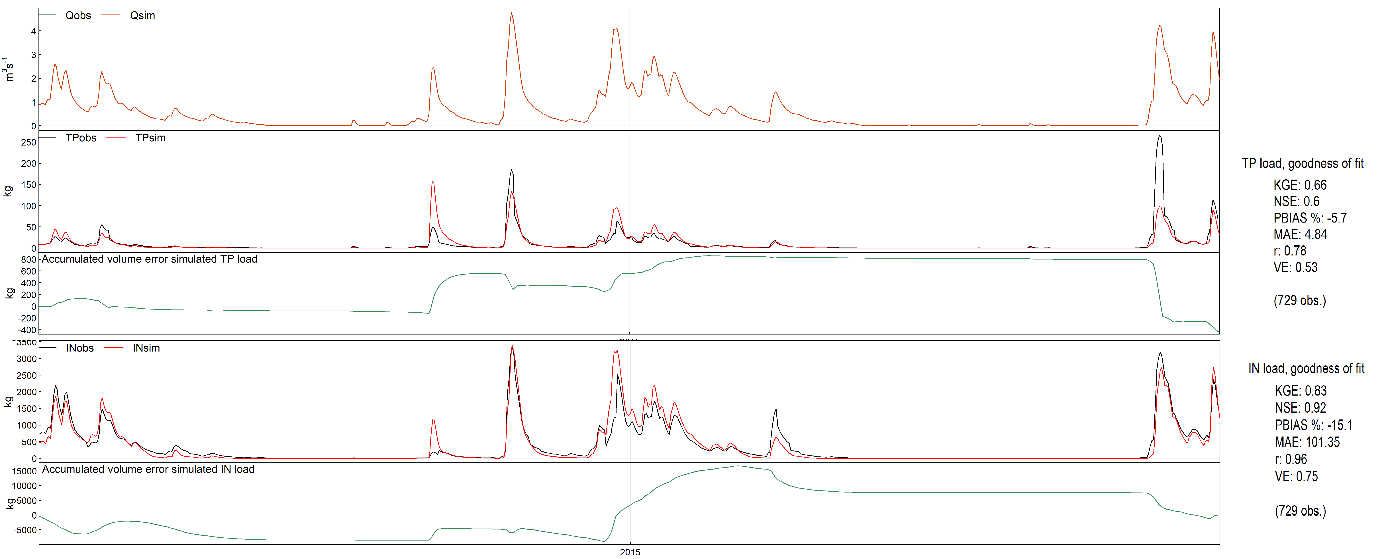
**Figure S6**: Daily observed and simulated discharge for the upstream and midstream gauge in Tullstorpån during the 2021-2022 calibration period. Goodness of fit values to the right.

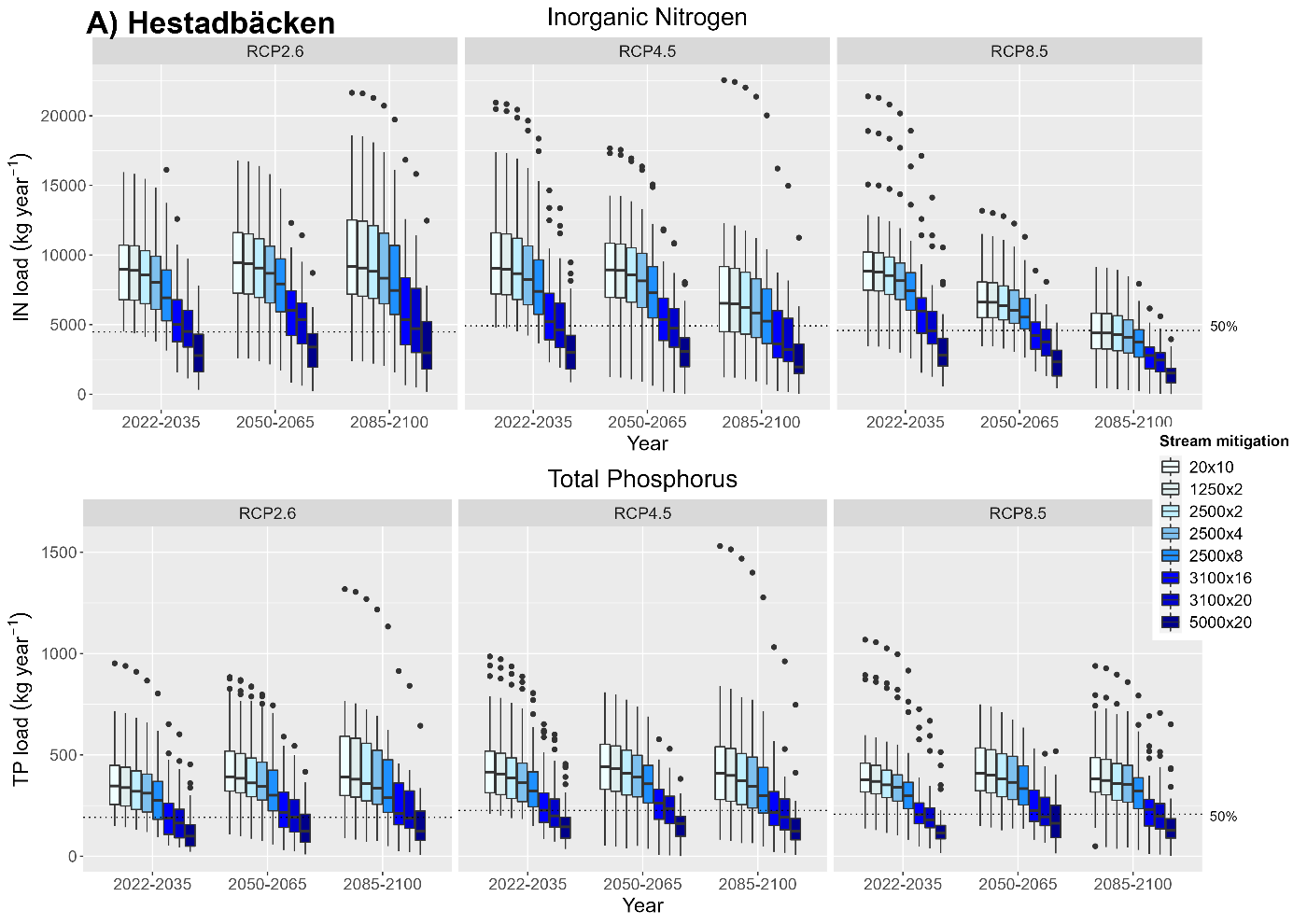


**Figure S7**: Daily observed and simulated discharge for the upstream and midstream gauge in Tullstorpån during the 2022-2023 validation period. Goodness of fit values to the right.



**Figure S8**: Daily observed and simulated IN and TP loads for the downstream gauge in Tullstorpån during the 2016-2022 calibration period. Goodness of fit values to the right.

**Figure S9**: Daily observed and simulated IN and TP loads for the downstream gauge in Tullstorpån during the 2014-2016 validation period. Goodness of fit values to the right.

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**Figure S10**: Effects of the size of modelled floodplains and wetlands on IN and TP loads in Hestadbäcken. The legend indicates the corresponding average lengths multiplied by the average widths of stream mitigation.

|  |  |  |  |
| --- | --- | --- | --- |
| Used name | RCP | General Circulation Model | Regional Downscaling |
| KNMI2.6 | 2.6 | MOHC-HadGEM2-ES | KNMI-RACMO22E |
| KNMI4.5 | 4.5 | MOHC-HadGEM2-ES | KNMI-RACMO22E |
| KNMI8.5 | 8.5 | MOHC-HadGEM2-ES | KNMI-RACMO22E |
| ICHEC2.6 | 2.6 | ICHEC-EC-EARTH | SMHI-RCA4 |
| ICHEC4.5 | 4.5 | ICHEC-EC-EARTH | SMHI-RCA4 |
| ICHEC8.5 | 8.5 | ICHEC-EC-EARTH | SMHI-RCA4 |
| MPI2.6 | 2.6 | MPI- ESM-LR | SMHI-RCA4 |
| MPI4.5 | 4.5 | MPI- ESM-LR | SMHI-RCA4 |
| MPI8.5 | 8.5 | MPI- ESM-LR | SMHI-RCA4 |

**Table S1**: Overview of used downscaled climate models

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Parameter range | NSE range | | |
| Discharge | IN load | TP load |
| wlfastfrac | 0.0035-0.9863 | 0.4732-0.4732 | 0.5619-0.5630 | 0.7026-0.7034 |
| iwet0 | 0.0004-0.9999 | 0.1295-0.5952 | 0.4913-0.6000 | 0.4786-0.7139 |
| partfrac | 0.0153-0.9889 | 0.4732-0.4732 | 0.5619-0.5619 | 0.7020-0.7036 |
| wetexp | 0.5073-2.4936 | 0.3843-0.6247 | 0.5473-0.5766 | 0.6613-0.7577 |
| wetrate | 0.1070-1.8932 | 0.2272-0.5463 | 0.5139-0.5627 | 0.4232-0.7412 |
| wlmphuptin | 0.0020-0.4996 | 0.4732-0.4732 | 0.5552-0.5627 | 0.7026-0.7026 |
| wlmphuptsp | 0.0004-0.4994 | 0.4732-0.4732 | 0.5619-0.5621 | 0.6795-0.7031 |
| wlproddep | 0.1010-1.4949 | 0.4732-0.4732 | 0.5619-0.5622 | 0.7026-0.7030 |
| wlsed | 0.0085-0.9891 | 0.4732-0.4732 | 0.5503-0.5630 | 0.6887-0.7477 |
| wltmpexp | 0.0114-0.9858 | 0.4732-0.4732 | 0.5612-0.5620 | 0.7021-0.7027 |

**Table S2**: Sensitivity analysis outcomes for the wetland parameters with the ranges of the parameters and the ranges of the NSE outcomes. Description of parameters can be found on <http://www.smhi.net/hype/wiki/doku.php?id=start:hype_file_reference:par.txt>

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | RCP2.6 | | | RCP4.5 | | | RCP8.5 | | |
| ICHEC | MPI | KNMI | ICHEC | MPI | KNMI | ICHEC | MPI | KNMI |
| 2022-2035 | ICHEC |  |  |  |  |  |  |  |  |  |
| MPI | 0.93 |  |  | 0.12 |  |  | *0.08* |  |  |
| KNMI | 0.31 | 0.32 |  | 0.42 | 0.35 |  | **0.026** | 0.79 |  |
| 2050-2065 | ICHEC |  |  |  |  |  |  |  |  |  |
| MPI | 0.42 |  |  | 0.26 |  |  | **0.008** |  |  |
| KNMI | 0.48 | 0.96 |  | 0.84 | 0.16 |  | 0.24 | *0.065* |  |
| 2085-2100 | ICHEC |  |  |  |  |  |  |  |  |  |
| MPI | 0.92 |  |  | 0.46 |  |  | **0.021** |  |  |
| KNMI | 0.89 | 0.82 |  | 0.26 | 0.54 |  | 0.69 | **0.036** |  |

**Table S3**: P-values of t-test of difference between IN loads in Hestadbäcken of different models

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | RCP2.6 | | | RCP4.5 | | | RCP8.5 | | |
| ICHEC | MPI | KNMI | ICHEC | MPI | KNMI | ICHEC | MPI | KNMI |
| 2022-2035 | ICHEC |  |  |  |  |  |  |  |  |  |
| MPI | 0.87 |  |  | 0.22 |  |  | 0.64 |  |  |
| KNMI | 0.28 | 0.32 |  | *0.075* | 0.74 |  | **0.020** | 0.16 |  |
| 2050-2065 | ICHEC |  |  |  |  |  |  |  |  |  |
| MPI | 0.95 |  |  | 0.34 |  |  | **0.033** |  |  |
| KNMI | *0.060* | **0.048** |  | 0.11 | 0.46 |  | **0.030** | 0.90 |  |
| 2085-2100 | ICHEC |  |  |  |  |  |  |  |  |  |
| MPI | 0.66 |  |  | 0.57 |  |  | 0.83 |  |  |
| KNMI | 0.40 | 0.24 |  | 0.18 | 0.10 |  | 0.72 | 0.84 |  |

**Table S4**: P-values of t-test of difference between TP loads in Hestadbäcken of different models

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | RCP2.6 | | | RCP4.5 | | | RCP8.5 | | |
| ICHEC | MPI | KNMI | ICHEC | MPI | KNMI | ICHEC | MPI | KNMI |
| 2022-2035 | ICHEC |  |  |  |  |  |  |  |  |  |
| MPI | 0.72 |  |  | 0.32 |  |  | 0.48 |  |  |
| KNMI | 0.54 | 0.10 |  | *0.067* | **0.012** |  | 0.71 | 0.31 |  |
| 2050-2065 | ICHEC |  |  |  |  |  |  |  |  |  |
| MPI | *0.082* |  |  | 0.18 |  |  | **0.008** |  |  |
| KNMI | 0.51 | 0.51 |  | 0.46 | **0.038** |  | 0.26 | 0.13 |  |
| 2085-2100 | ICHEC |  |  |  |  |  |  |  |  |  |
| MPI | 0.73 |  |  | **0.011** |  |  | 0.14 |  |  |
| KNMI | 0.91 | 0.86 |  | 0.13 | 0.38 |  | 0.29 | **0.034** |  |

**Table S5**: P-values of t-test of difference between IN loads in Tullstorpån of different models

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | RCP2.6 | | | RCP4.5 | | | RCP8.5 | | |
| ICHEC | MPI | KNMI | ICHEC | MPI | KNMI | ICHEC | MPI | KNMI |
| 2022-2035 | ICHEC |  |  |  |  |  |  |  |  |  |
| MPI | 0.13 |  |  | 0.84 |  |  | 0.94 |  |  |
| KNMI | **0.040** | 0.26 |  | 0.71 | 0.63 |  | 0.52 | 0.48 |  |
| 2050-2065 | ICHEC |  |  |  |  |  |  |  |  |  |
| MPI | 0.14 |  |  | 0.68 |  |  | **0.011** |  |  |
| KNMI | *0.058* | 0.42 |  | 0.39 | 0.62 |  | *0.053* | 0.94 |  |
| 2085-2100 | ICHEC |  |  |  |  |  |  |  |  |  |
| MPI | 0.68 |  |  | 0.51 |  |  | 0.29 |  |  |
| KNMI | 0.29 | 0.19 |  | *0.076* | **0.031** |  | 0.91 | 0.35 |  |

**Table S6**: P-values of t-test of difference between TP loads in Tullstorpån of different models

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| RCP | Model | Mean (kg) 2022-2035 | Mean (kg) 2050-2065 | % change | Mean (kg) 2085-2100 | % change |
| RCP 2.6 | ICHEC | 9298 | 8633 | -7% | 9674 | 4.% |
| KNMI | 8177 | 9659 | 18% | 9903 | 21% |
| MPI | 9204 | 9602 | 4% | 9525 | 3% |
| Ensemble | 8893 | 9298 | 5% | 9701 | 9% |
| RCP 4.5 | ICHEC | 8638 | 8599 | -0.4% | 6430 | -26% |
| KNMI | 9638 | 8351 | -13% | 8100 | -16% |
| MPI | 11029 | 10084 | -9% | 7152 | -35% |
| Ensemble | 9768 | 9011 | -8% | 7227 | -26% |
| RCP 8.5 | ICHEC | 7480 | 5962 | -20% | 4132 | -45% |
| KNMI | 10094 | 6838 | -32% | 3865 | -62% |
| MPI | 9705 | 8263 | -15% | 5524 | -43% |
| Ensemble | 9093 | 7021 | -23% | 4507 | -50% |

**Table S7**: IN Load and percentage change over time in Hestadbäcken

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| RCP | Model | Mean (kg) 2022-2035 | Mean (kg) 2050-2065 | % change | Mean (kg) 2085-2100 | % change |
| RCP 2.6 | ICHEC | 347 | 369 | 7% | 412 | 19% |
| KNMI | 424 | 527 | 24% | 485 | 15% |
| MPI | 355 | 373 | 5% | 380 | 7% |
| Ensemble | 375 | 423 | 13% | 426 | 14% |
| RCP 4.5 | ICHEC | 371 | 383 | 3% | 385 | 4% |
| KNMI | 492 | 481 | -2% | 516 | 5% |
| MPI | 466 | 438 | -6% | 353 | -24% |
| Ensemble | 443 | 434 | -2% | 418 | -6% |
| RCP 8.5 | ICHEC | 349 | 343 | -2% | 391 | 12% |
| KNMI | 488 | 462 | -5% | 417 | -15% |
| MPI | 379 | 457 | 21% | 402 | 6% |
| Ensemble | 405 | 420 | 4% | 403 | -1% |

**Table S8**: TP Load and percentage change over time in Hestadbäcken

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| RCP | Model | Mean (kg) 2022-2035 | Mean (kg) 2050-2065 | % change | Mean (kg) 2085-2100 | % change |
| RCP 2.6 | ICHEC | 128949 | 118314 | -8% | 125207 | -3% |
| KNMI | 117471 | 131026 | 12% | 127409 | 8% |
| MPI | 135270 | 143273 | 6% | 131137 | -3% |
| Ensemble | 127230 | 130871 | 3% | 127918 | 1% |
| RCP 4.5 | ICHEC | 136010 | 115717 | -15% | 92149 | -32% |
| KNMI | 108335 | 103245 | -5% | 115406 | 7% |
| MPI | 155351 | 137109 | -12% | 129890 | -16% |
| Ensemble | 133232 | 118691 | -11% | 112482 | -16% |
| RCP 8.5 | ICHEC | 116228 | 90277 | -22% | 90277 | -22% |
| KNMI | 110847 | 108452 | -2% | 75376 | -32% |
| MPI | 127408 | 140286 | 10% | 114691 | -10% |
| Ensemble | 118161 | 113005 | -4% | 93448 | -21% |

**Table S9**: IN Load and percentage change over time in Tullstorpån

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| RCP | Model | Mean (kg) 2022-2035 | Mean (kg) 2050-2065 | % change | Mean (kg) 2085-2100 | % change |
| RCP 2.6 | ICHEC | 2514 | 2620 | 4% | 2957 | 18% |
| KNMI | 3649 | 3771 | 3% | 3668 | 1% |
| MPI | 3120 | 3276 | 5% | 2776 | -11% |
| Ensemble | 3094 | 3223 | 4% | 3134 | 1% |
| RCP 4.5 | ICHEC | 3298 | 2915 | -12% | 3173 | -4% |
| KNMI | 3128 | 3434 | 10% | 4907 | 57% |
| MPI | 3415 | 3150 | -8% | 2822 | -17% |
| Ensemble | 3280 | 3167 | -3% | 3634 | 11% |
| RCP 8.5 | ICHEC | 2975 | 2404 | -19% | 2784 | -6% |
| KNMI | 3378 | 3590 | 6% | 2850 | -16% |
| MPI | 2933 | 3640 | 24% | 3464 | 18% |
| Ensemble | 3096 | 3212 | 4% | 3032 | -2% |

**Table S10**: TP Load and percentage change over time in Tullstorpån