Optimal Strategies to Retain Water and Nutrients

# D4.4: Assessment of NSWRM effectiveness under current and future climate at the catchment scale

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# Summary

The objective of this deliverable D4.4 is to provide an integrated, model-based assessment of the effectiveness of Natural/Small Water Retention Measures (NSWRMs) in 14 small agricultural catchments in Europe under current and projected climate conditions. The objective of a harmonised application of the hydrological and water quality model SWAT+ (Soil & Water Assessment Tool) was successfully achieved. The modelling work in each case study closely follows OPTAIN's deliverable D4.2, 'SWAT+ modelling protocol for the assessment of water and nutrient retention measures in small agricultural catchments' (Schürz et al., 2022), as outlined in this deliverable. The report presents the new Contiguous Object COnnectivity Approach (COCOA) as the most significant and novel contribution to process-based modelling. COCOA can represent landscape features at the field scale and account for connectivity between land phase objects.

The report provides a detailed description of the modelling workflow, including input data preparation, model setup, verification, calibration, and application in climate and NSWRM scenario runs. This report presents a synthesis of modelling results, focusing on model evaluation, simulated water and nutrient balance, crop yield outputs, and the impacts of climate change from eight case studies located in Belgium, Germany, Hungary, Italy, Norway, Poland, and Switzerland. The report includes 14 annexes providing in-depth reports dedicated to specific catchments from all OPTAIN CS modelling teams. Seven annexes contain results on the simulated effectiveness of selected NSWRMs quantified by a set of environmental performance indicators. The effectiveness of NSWRMs under future climate scenarios was quantified for illustrative purposes for one catchment located in Germany (CS1). Additionally, this deliverable includes a suite of scripted workflows in R that cover different steps of the SWAT+ modelling process.

The calibrated SWAT+ model setups generated within this task will serve to identify optimal implementation schemes for NSWRMs, including their combination and allocation within the catchment (OPTAIN WP5). The synthesis of modelling results will continue under WP6.

# Table of Contents

# Abbreviations

| | |
|---|---|
| COCOA | COntiguous object COnnectivity Approach |
| CN | Curve Number |
| CS | Case Study |
| DEM | Digital Elevation Model |
| ET | Evapotranspiration |
| ETa | Actual Evapotranspiration |
| EURO-CORDEX | European branch of the Coordinated Regional Climate Downscaling project |
| GIS | Geographic Information System |
| HRUs | Hydrologic Response Units |
| KGE | Kling-Gupta Efficiency |
| LAI | Leaf Area Index |
| LHS | Latin Hypercube Sampling |
| LUCAS | Land Use / Cover Area frame statistical Survey |
| MARG | Multi-Actor Reference Group |
| N | Nitrogen |
| $NO_3$-N | Nitrate nitrogen |
| NSE | Nash Sutcliffe Efficiency |
| NSWRMs | Natural/Small Water Retention Measures |
| OPTAIN | OPtimal strategies to retAIN and re-use water and nutrients in small agricultural catchments across different soil-climatic regions in Europe |
| P | Phosphorus |
| PBIAS | Percent bias |
| PET | Potential Evapotranspiration |
| PHU | Potential Heat Unit |
| RCM | Regional Climate Model |
| RCP | Representative Concentration Pathway |
| RTUs | Routing Units |
| SWAP | Soil Water Atmosphere Plant |
| SWAT | Soil and Water Assessment Tool |
| SWAT+ | Soil and Water Assessment Tool Plus |
| USLE | Universal Soil Loss Equation |
| TN | Total Nitrogen |
| TP | Total Phosphorus |
| WP | Work Package |

# 1. Introduction

## 1.1. Objective

The main objective of task 4.4 of the OPTAIN project is to conduct an integrated, model-based assessment of the effectiveness of Natural/Small Water Retention Measures (NSWRMs) in 14 small agricultural catchments in Europe under both current and projected climate conditions. These 14 Case Studies (CS) range in size from 50 to 234 km2 and are located in three biogeographical regions of Europe and 12 different countries (Fig. 1.1). NSWRMs, the central topic of OPTAIN, are small and multi-functional measures for the retention/management of water and nutrients in the landscape, thus addressing drought/flood control, management of water quality problems, climate change adaptation, biodiversity restoration, etc.


Figure 1.1: Location of 14 OPTAIN case studies in Europe.

The objective was achieved by consistently applying a fit-for-purpose, process-based modelling tool called SWAT+ (Soil & Water Assessment Tool; Arnold et al., 2012; Bieger et al., 2017), which is a hydrological and water quality model. Thus, each CS's modelling work for this deliverable closely follows OPTAIN's deliverable D4.2, 'SWAT+ modelling protocol for the assessment of water and nutrient retention measures in small agricultural catchments' (Schürz et al., 2022; hereafter referred to as 'the protocol'). The protocol incorporates current recommendations from literature and the expertise of the co-authors to provide a fit-for-purpose method for setting up, calibrating, and running NSWRM scenarios using the SWAT+ model. Additionally, a harmonised scripted workflow was developed to facilitate the various stages of the modelling work. The workflows developed cover a broad range of modelling tasks, including preparing and generating input data for the SWAT+ model, setting up the model, parametrizing it, creating land management schedules, verifying the model setup, and calibrating it. While some workflows are tailored to the project's modelling case studies, most functions and workflows are generalised and can be implemented in other SWAT+ model applications. The primary and innovative contribution is the new Contiguous Object COnnectivity Approach (COCOA), which can represent landscape features at the field scale and account for connectivity between land phase objects. This is a fundamental change in process-based hydrological modelling that enables a more realistic representation of measures in the model setup and more realistic model outputs related to the simulated effectiveness of measures. Our workflow allows for the assessment of NSWRM effectiveness both at the catchment scale (e.g. water and nutrient flows at the catchment outlet or for important tributaries) and at the field scale, where the measures were applied or in closest proximity (e.g. reduction of erosion entering the channel by a riparian buffer). This is in contrast to many existing SWAT+ applications that focus solely on modelling the effectiveness of measures at the catchment scale.

Chapter 2 of this report covers the data and methods used in OPTAIN, focusing on various scripted workflows. Chapter 3 presents the main results, starting with an analysis of the generated model setups, followed by a comprehensive model evaluation and scenarios for climate change and NSWRM. Chapter 4 includes a summary and outlook. The annexes (1-14) contain case study-specific results of the entire SWAT+ modelling workflow. The annexes are numbered based on the internal case study numbering in OPTAIN, as shown in Table 3.1 and Figure 3.1. Annex 15 reports on the issues encountered by the SWAT+ modellers in OPTAIN throughout the project and their consequences, such as the delay in publishing this deliverable.

## 1.2. Position within OPTAIN

This report is an output of the Work Package (WP) 4 “Integrated assessment of NSWRMs" and belongs to OPTAIN’s Task 4.4 “Assessment of NSWRM effectiveness at the catchment scale”. Within this task, the case study modellers were supposed to set up and calibrate their SWAT+ models as well as apply them for running scenarios related to climate change and implementation of NSWRMs, following the recommendations of the protocol. This ensures a harmonised modelling approach, which is one of the core concepts of OPTAIN.

This report is also related to other activities and outputs of OPTAIN (Fig. 1.2). It is strongly linked to WP3 “Retrieval of modelling data and solutions to overcome data scarcity”, which has already provided three deliverables with valuable inputs and tools in the context of the SWAT+ modelling work:

1. D3.1 “Climate scenarios for integrated modelling” (Honzak and Pogačar, 2022; Honzak, 2023);
2. D3.2 “Solutions to overcome data scarcity” (Szabó et al., 2022);
3. D3.3 “Created data pre-processors successfully applied for input data restructuring” (Čerkasova et al., 2022).

D4.4 uses bias-corrected climate simulations for the assessment of climate change effects on water and nutrient fluxes as well as to evaluate the effectiveness of measures under future climate. D4.4 also uses model input datasets acquired and restructured within D3.2 and D3.3, along with relevant metadata.

Within WP2 “Measures and indicators”, the following deliverables provided an important foundation for the work in WP4:

1. Deliverable D2.2 “Tailored environmental and socio-economic performance indicators for selected measures” (Krzeminska & Monaco, 2022).
2. Deliverable D2.3 “Participatory modelling settings and standardised guidelines for parameterization of measures” (Marval et al., 2022).

D2.2 developed an initial list and definition of environmental performance indicators (EPIs), that was taken up and further tailored to fit the SWAT+ model requirements in D4.4. D2.3 provided relevant information about parameterisation of selected NSWRM in SWAT+ that was used as a starting point for developing NSWRM scenarios in D4.4.

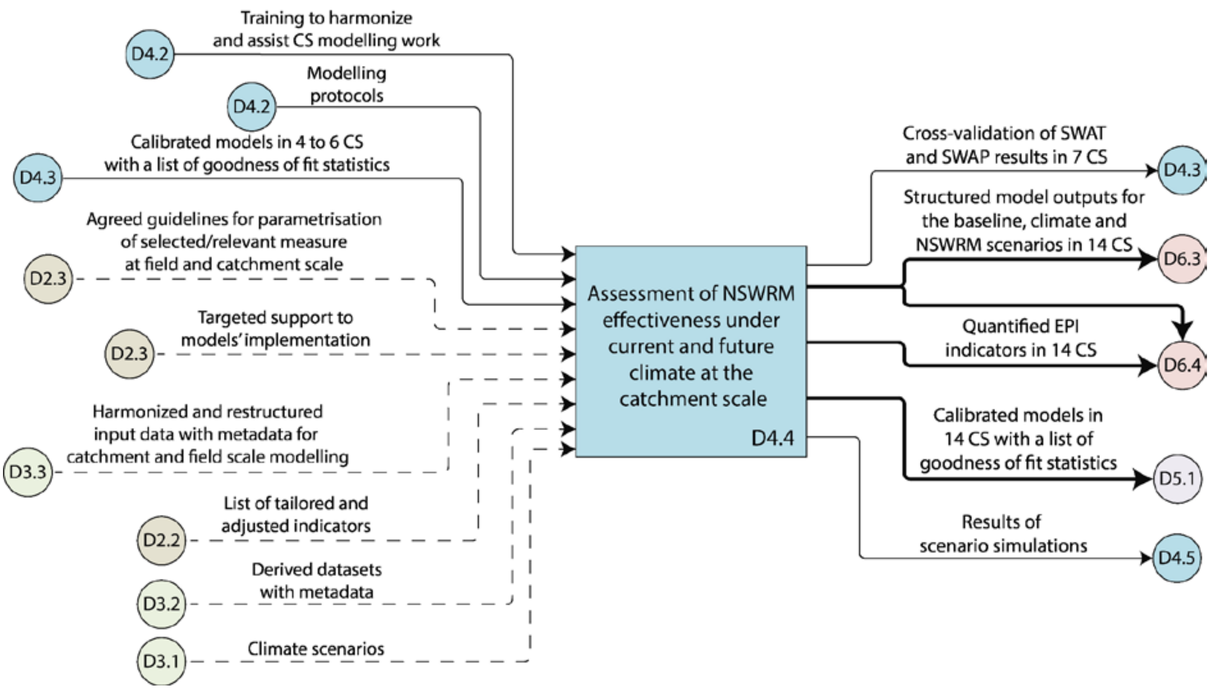


Figure 1.2: Relationships between D4.4 and other OPTAIN deliverables.

The outputs developed within D4.4 will be taken up in several different parts of the OPTAIN project. Within WP4, a cross-validation between SWAT+ and the selected field-scale model SWAP will be performed for a few CS (D4.3). Scenario simulation results (e.g. crop yields and NSWRM parameterisation) are used in the application of a conceptual economic model for assessment of NSWRMs (D4.5). Outside of WP4, the calibrated models developed for all CS are then used for spatial optimisation (D5.1), while the structured model outputs and quantified EPI indicators are used for the development of guidelines for optimal implementation of NSWRMs and their combinations (D6.3) and in the development of incentives for optimal NSWRM strategies (D6.4).

# 2. Data and methods

## 2.1. Input data overview

Based on the input data requirements of the field-scale and catchment-scale models used in "WP4 – Integrated assessment of NSWRMs", a data inventory of available static and time series information has been indicated for all case studies of the project. The data collection was performed under the WP3, Task 3.1: Data collection and harmonisation for model-based assessment (for more details, please refer to Čerkasova et al. (2021a)). Here, we outline the substantial efforts put into the input data collection and pre-processing that was necessary to conduct the modelling tasks and perform the NSWRM assessment.

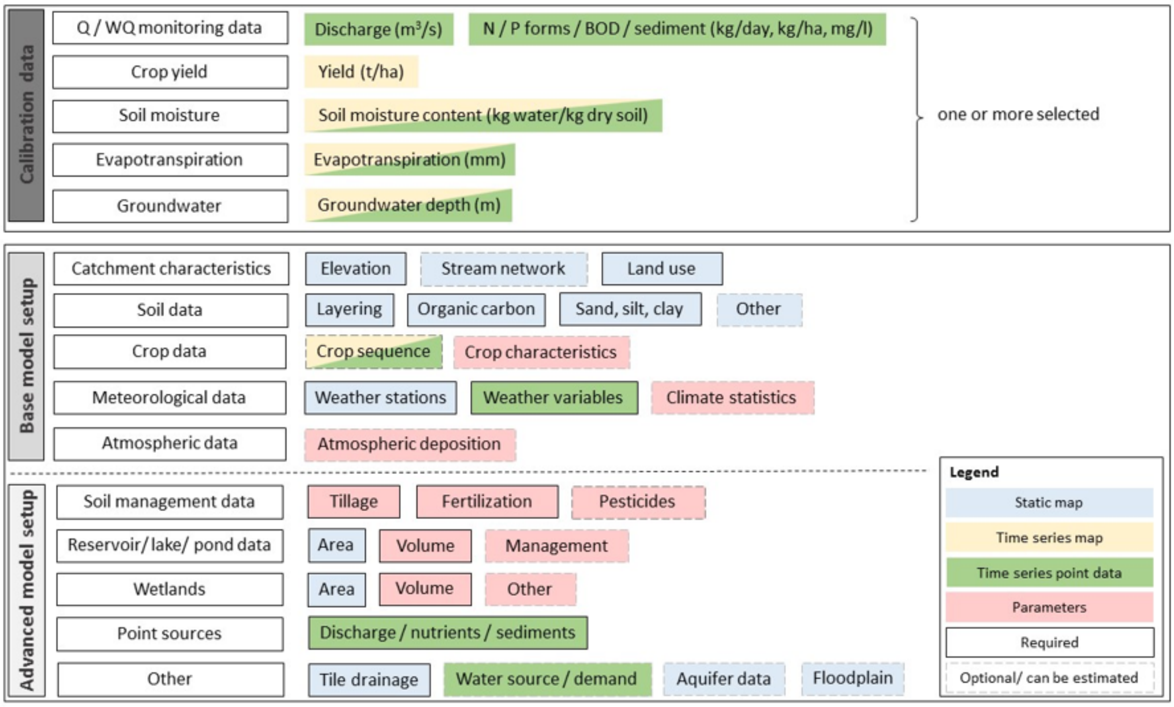


Figure 2.1: Input data requirements for each case study watershed model (Plunge et al., 2024b).

The input data requirements of the SWAT+ model have only recently been documented (the documentation was published in July 2023 on the official website: https://swatplus.gitbook.io/swat+-documentation/), hence the OPTAIN team relied on personal experience and on coordination with the SWAT development team, as well as other sources, such as publications, i.e. Bieger et al. (2017). The input data requirements have been documented (see Fig. 2.1) for all 14 case studies within the project. This data screening has been organised in Excel sheets, stored in the UFZ Cloud in accordance with the OPTAIN Common Working Environment (Čerkasova et al., 2021b) and provides information such as:

- The name and unit of each required and optional input parameter;
- Indication of whether the required parameter is static or in the form of a time series;
- The necessary time frequency for the input data;
- Designation of whether the input parameter is obligatory, optional, or estimable;
- Any additional explanations deemed necessary;
- For the SWAT+ model, the filenames of associated files have also been provided;
- Data crucial for calibration or reference; these particular data points determine the processes that the models can simulate.

After completing the inventory, the necessary data collection and preprocessing was commenced. All CS were requested to collect the data in a timely manner, reformat, and, where necessary, perform the quality checks and harmonisation in order to comply with the high standards set by the OPTAIN project. More information on data standards is covered in the OPTAIN Common Working Environment (Čerkasova et al., 2021b) and Data Management Plan (Witing and Čerkasova, 2021), whereas the scripting approach is covered in D3.3 - Created data pre-processors successfully applied for input data restructuring (Čerkasova et al., 2022).

In the case of the SWAT+ model, a distinction has been made between the base model setup and the advanced model setup at the highest level. Further differentiation of the required data types was made at lower levels of the hierarchy. Due to the adopted harmonisation approach, it was decided that a script-based approach was the best solution for standardising input data pre-processing in the most efficient way. Members of the OPTAIN core team took on the task of preparing the scripts that OPTAIN modellers would use, test and, if necessary, adapt to prepare their datasets. More details on the developed tools (scripts) are given in the following sections of this report. A harmonised data collection approach was also followed by the field-scale modelling group (described in detail in deliverable D4.3). Tools were developed to facilitate input data preparation, putting a special focus on meteorological and soil input data. A plant database was constructed, based on the SWAP model plant parameters (*.crop files) and cross-validated with SWAT+ plant data input parameters (*'plants.plt'*) to facilitate input data harmonisation at the selected sites.

Input data preparation for the two models (SWAT+ and SWAP) as well as parameterisation was carried out in a way to ensure models' harmonisation to the highest extent possible, which will further serve as a basis for cross-validation of the two models.

Detailed overviews of the input data used in each CS, prepared in a tabular format, can be found in chapter 1 of each CS-specific annex (see annexes 1-14). They include official names of data providers, data resolution and other basic characteristics. The listed items can, in some cases, differ from the original meta-data tables developed within WP3 at the beginning of the project. It frequently happens in hydrological modelling that input data from different sources are being tested before the final choice is made. In some cases, newer or better data had become available during the project implementation. Since the OPTAIN project deals with cutting-edge techniques, methods, and tools, we strive to adapt the best data whenever it becomes available. This iterative process ensures that our analyses are founded on the most up-to-date and accurate information, ultimately enhancing the robustness of our findings and predictions.

## 2.2. Modelling workflow

The objective of OPTAIN's task 4.4 is to evaluate the effectiveness of NSWRM under current and future climate conditions at the catchment scale by running scenario simulations with the SWAT+ model. Before running scenarios, a comprehensive modelling workflow has to be accomplished by each CS, including the time-consuming tasks of preparing all necessary input files, setting up initially parameterised SWAT+ models, model setup verification, and model calibration (see Fig. 2.2). The calibration part includes two components: soft calibration, in which plant growth and water balance are adjusted to realistic magnitudes, followed by hard calibration, in which adjustments of larger parameter sets should lead to a better fit between simulated and observed time series (streamflow, sediments, nutrients).

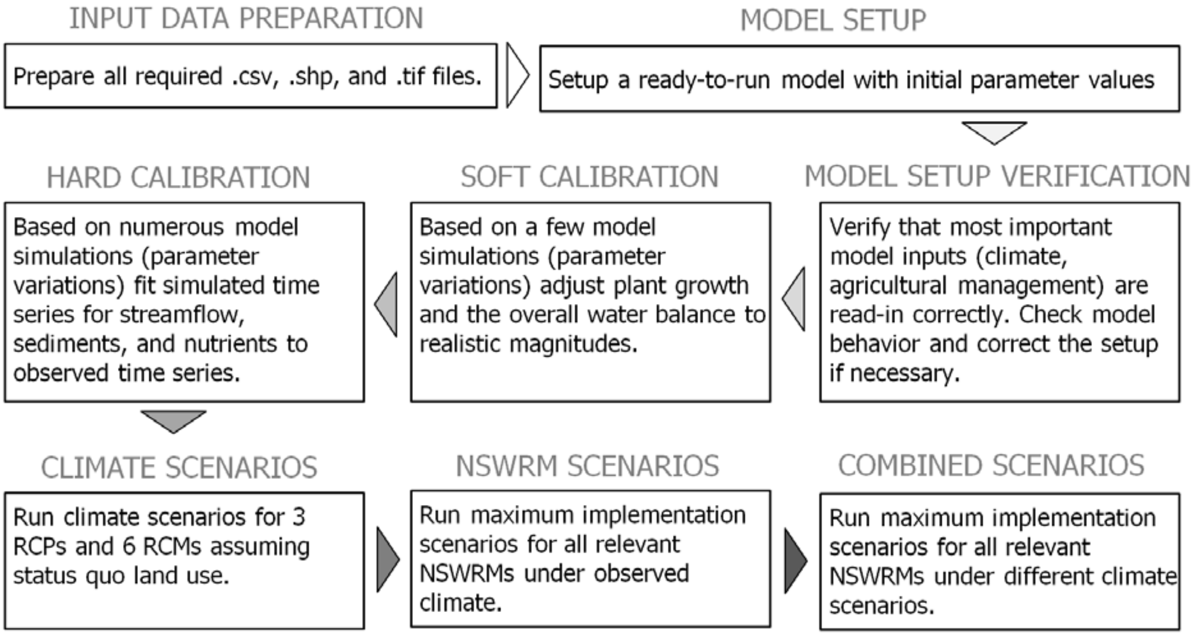


Figure 2.2: Overall modelling workflow to be conducted by each case study. RCP = Representative Concentration Pathway, RCM = Regional Climate Model.

SWAT+ models in OPTAIN must meet a number of standards that go well beyond those of typical SWAT+ model applications. They have to (1) represent all relevant crop rotations and associated management operations at the level of individual fields, (2) allow contiguous routing between all associated land and water objects (see Section 4.3), (3) allow spatially explicit assessment of all potential locations of selected NSWRMs as elaborated together with local stakeholders, and (4) be harmonised across all 14 CS. Overall, this required the development of automated workflows described in the following sections.

### 2.2.1. Input data preparation and model setup

The OPTAIN modelling core group, consisting of experienced modellers from WPs 3, 4 and 5, has developed a variety of R workflows to facilitate the process of input data preparation and model setup. Figure 2.3 shows the functions of all currently developed R workflows, including their required input data, only for setting up a fully parameterised but uncalibrated SWAT+ model according to the OPTAIN standards. The numbering in Figure 2.3 refers to the recommended order of the individual steps, which can be described in more detail as follows.

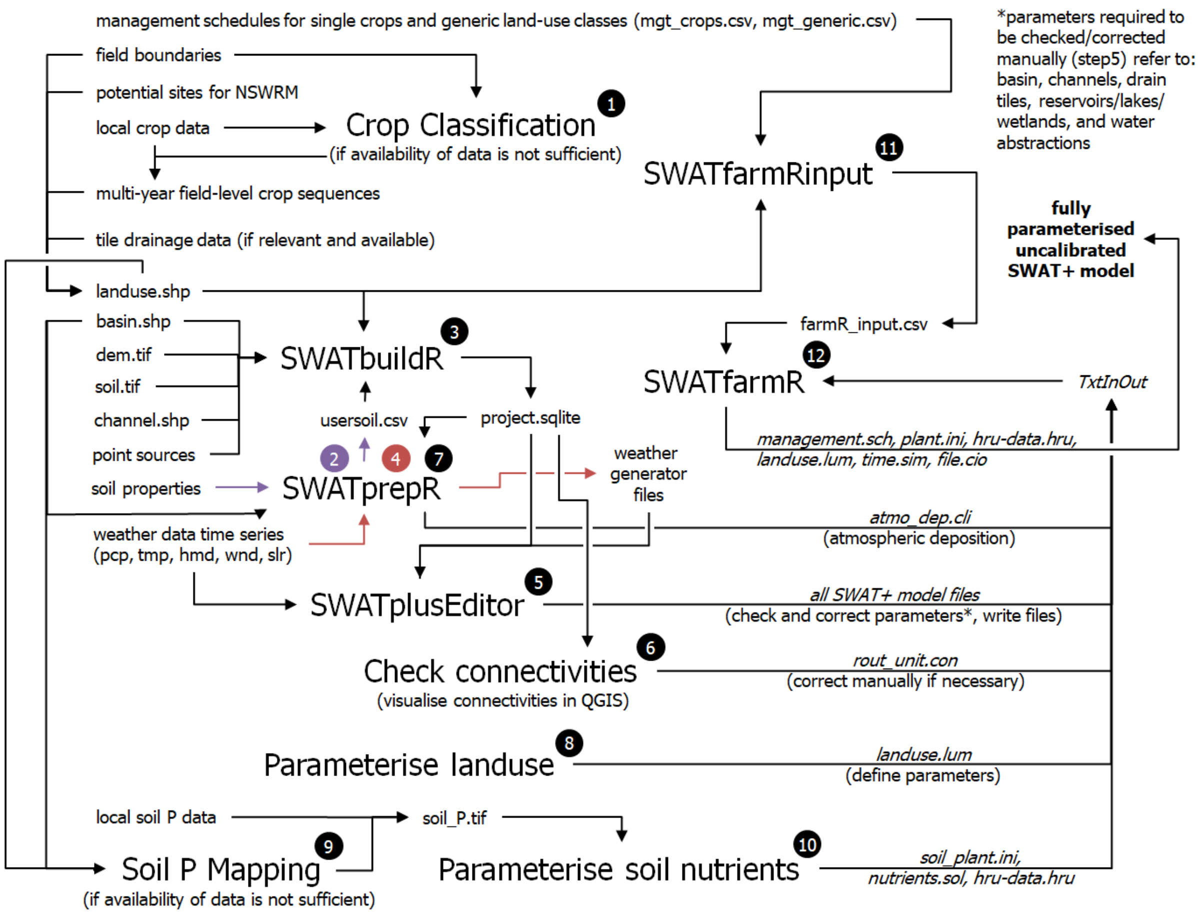


Figure 2.3: OPTAIN workflow for setting up a ready-to-run SWAT+ model ('TxtInOut' folder containing all files required to run the model executable) with defined but not yet calibrated parameter values. R workflows are shown in large type (with numbers indicating the recommended order of application), while required input data and intermediate files are shown in small type (actual SWAT+ model files in italics).

### (1) Classify crops and prepare the land-use shapefile

Each case study was required to produce a land use shapefile containing field boundaries, observed crop rotations for the last few years and, where available, tile drainage information for each field, in addition to all other land use/cover classes (forest, semi-natural habitats, urban areas) at high resolution. Where local data on crop rotation at field level were not available in sufficient detail, an R workflow for classifying crop types from remote sensing data was provided (https://zenodo.org/record/6700122). The crop classification algorithm is trained with the EU Land Use / Cover Area frame statistical Survey (LUCAS) data (D'Andrimont et al., 2020) and can be improved by incorporating local training data. The R package SWATprepR (https://biopsichas.github.io/SWATprepR/) can be used to incorporate the crop rotation information into the land use shapefile in the required format. In addition, all CS were asked to check and correct the land use map for existing semi-natural structures (>5m width), to include all potential implementation sites of relevant NSWRMs, and to split polygons with complex shapes into more compact pieces. There was no way to automate these procedures, so producing the land-use map of sufficient quality was a very labour-intensive task for each CS.

(2) Parameterise soils

Obtaining soil parameters for the SWAT+ model can be difficult. Therefore, we have developed an automated workflow to derive unknown soil physical and hydraulic parameters (e.g. effective bulk density, albedo, USLE soil erodibility K factor, available water capacity, unsaturated hydraulic conductivity) from known, commonly available soil parameters (clay, silt, sand and organic carbon content) using pedotransfer functions. Hydrological soil groups can be derived from data on saturated hydraulic conductivity, tile drainage, depth to groundwater and depth to impervious layer. The workflow can be applied using various functions of the R package SWATprepR. The output of this step is a fully parameterised SWAT+ soil database ('*usersoil.csv*') containing layer-specific information for each soil type in the study area.

(3) Build the basic model setup with all connectivities defined

In contrast to the common/standard SWAT+ models, models in OPTAIN require the definition of connectivity of each land and water object with its neighbouring objects (contiguous objects connectivity approach - COCOA, see also chapter 4.3). To achieve this, the SWATbuildR package (available in the OPTAIN Cloud for all project partners: WPs & Tasks/WP4/Task 4.4/Tools to share) has been developed as an alternative to the standard QSWAT+ model setup workflow. Required inputs for SWATbuildR are the land use shapefile (Step 1), the soil database (Step 2) and a set of other geodata (watershed boundary, digital elevation model - DEM, soil map, stream/channel network, point source locations). Point source loadings can be defined in this step or at a later stage using the SWATplusEditor or SWATprepR. The output of running SWATbuildR is an initial setup of the SWAT+ model (in the form of a sqlite database), which needs to be further parameterised in the following steps.

(4) Derive weather generator files

SWAT+ requires a daily time series of meteorological variables (precipitation - pcp, minimum and maximum temperature - tmp, relative humidity - hmd, wind speed - wnd, and solar radiation - slr). The data should cover the same time period and allow for splitting into a calibration and validation period (plus 2-3 years of the warm-up period). Ideally 15-20 years of weather data are recommended, with 10 years as a minimum. SWATprepR can be used to prepare the data in the format required by the model and, no less importantly, to calculate the parameters of the SWAT+ weather generator.

(5) Write all model files

A SWAT+ model consists of the SWAT+ executable and any input text files required to run the executable. The default way to write the text files is to use the

SWATplusEditor, which can load the previously created sqlite model database (step 3) and weather input files (step 4). The SWATplusEditor allows convenient, but manual editing of model parameters. This step includes defining or adjusting parameter values related to various aspects that may be catchment-specific, e.g. channel properties, reservoir or wetland parameters, water abstractions, tile drainage parameters. As no fit-for-all scripted solution can be provided, modellers should carry out these steps by manually adjusting parameters either in the SWATplusEditor or directly in text files (or by developing their own scripts). In addition, it is important to define all relevant options for modelling different processes (e.g. PET method, channel routing method, etc.) in the 'codes.bsn' file.

The output of this step is a TxtInOut folder containing all input text files required to run SWAT+. An alternative to using the SWATplusEditor has also been developed in OPTAIN. Modellers can simply run an executable file (write.exe, available in the OPTAIN Cloud for all project partners: WPs & Tasks/WP4/Task 4.4/Tools to share/Writing of txtinout) to convert the sqlite database into the required input text files.

(6) Check connectivities

It is strongly recommended to check the connectivities calculated by SWATbuildR, as these connectivities are based solely on the flow accumulation of the input DEM. It may happen that some connectivities are implausible (e.g. due to errors in the DEM or unfavourably shaped routing units). We asked all CS modellers to check the connectivities at least for those routing units that will be used to represent NSWRMs in later scenario and optimisation simulations. To facilitate this task, we developed a routine (OPTAIN Cloud for all project partners: WPs & Tasks/WP4/Task 4.4/Tools to share/check_connectivities) to visualise all connections between routing units in QGIS. If problematic or insufficient connectivities are identified, the user will need to correct them directly in the model input file '*rout_unit.con*' (written in step 5).

(7) Parameterise atmospheric deposition

Atmospheric deposition data ($NH_4$ and $NO_3$, both wet and dry deposition) can be easily derived using SWATprepR. The R package can not only extract (using the catchment boundary as input) and download the data from the European Monitoring and Evaluation Programme (EMEP), but also provides a function to write the data into the model input file '*atmo_dep.cli*'.

(8) Parameterise land use

Parameters describing the hydrological behaviour of different land use classes are essential in any SWAT+ model. The model input file '*landuse.lum*' written in step 5 contains blank spaces for the following model parameters: 'CN2' - average soil moisture curve number, 'USLE_P' - the conservation practice factor of the universal soil loss equation, and 'OVN' - Manning's roughness index for overland flow. To facilitate writing parameter values (more precisely pointers to parameter value look-up tables) for hundreds or even thousands of field-specific management codes into the model file '*landuse.lum*', we developed another R script ('read_and_modify_landuse_lum.R', available on the OPTAIN Cloud for all project partners: WPs & Tasks/WP4/Task 4.4 /Tools to share).

#### (9) Map soil phosphorus

The SWAT+ model requires the labile phosphorus (P) content of the surface layer in ppm for the initialisation of the different P pools. In case the availability of spatially distributed soil P data is insufficient, an R-script ([https://doi.org/10.5281/zenodo.6652572](https://doi.org/10.5281/zenodo.6652572)) (available in the OPTAIN Cloud for all project partners: WPs & Tasks/WP3/Task_3.3/templates/map_soil_P) can be used to automatically extract soil P values from the LUCAS Topsoil Survey database for the CS area and calculate mean values for each land use category. Similar to the crop classification algorithm (step 1), any existing local data can be integrated into the workflow to improve the quality of the predicted map.

#### (10) Parameterise soil nutrients

To ensure that soil P values are correctly written to the model file '*nutrients.sol*' with updated pointers in the files '*soil_plant.ini*' and '*hru-data.hru*', case studies were asked to run another R script ('finalize_nutrients_sol.R', available in the OPTAIN cloud for all project partners: WPs & Tasks/WP3/Task_3.3/templates/finalize_nutrients_sol). The input for this script is a raster map of soil P content for the CS areas, to be produced either based on locally available data or by running the soil P mapping algorithm of step 9.

#### (11) Generate crop rotation and generic management schedules

Finally, agricultural management practices have to be defined and parameterised in the model input files. SWAT+ accepts complete crop rotation schedules, including all relevant management operations such as tillage, planting, fertilisation and harvesting specified by date and type. Considering that each CS area contains several hundred to thousands of agricultural fields with individual crop sequences (step 1), it would be very time-consuming and error-prone to define these schedules manually. Therefore, all CS were asked to produce only single management plans, one for each of the relevant crops (not full rotations). These schedules should include the type and plausible date ranges for all management operations typical for the crop in the CS region. These schedules, together with simple schedules for generic land use classes (which are permanent, such as grassland, orchard or forest) and the crop sequences contained in the land use shapefile, served as input for an R script, which automatically combines all single crop plans into a full crop rotation plan for a user-defined simulation period. The script 'write_farmR_input.R' is available in the OPTAIN Cloud for all project partners: WPs & Tasks/WP4/Task 4.4/Tools to share/SWATfarmR_input. The algorithm checks the combined schedules for any date conflicts (overlapping operation date ranges) and automatically resolves them with the least possible adjustments. In the case of major overlaps, CS were prompted to manually adjust or further differentiate their individual crop schedules. The output is a .csv file with the complete set of crop rotation schedules for all individual fields, which serves as input for the SWATfarmR package (step 12).

(12) Define suitable exact dates for each operation and write into model format

Based on the 'farmR_input.csv' file (step 11) and the precipitation data files (.pcp) in the TxtInOut model folder (written in step 5), the R package SWATfarmR (https://chrisschuerz.github.io/SWATfarmR/index.html) can be used to automatically define a suitable date within the specified date range for each management operation and each field. A "suitable" date is one where the probability of soil saturation is low. This is solved by weighted random sampling, taking into account both the amount of precipitation (pcp) on a given day and the antecedent precipitation index (api, which takes into account the precipitation of the previous days), with higher weights (probabilities to be selected) for lower values of pcp and api. After this step of defining the exact timing of the operations, SWATfarmR writes the management schedules into the corresponding SWAT+ model input file ('*management.sch*'). It also updates the '*landuse.lum*', '*plant.ini*', '*hru-data.hru*', '*time.sim*' and '*file.cio*' files. When SWATfarmR is first used, backups of each of these files will be saved. If it becomes necessary to re-run the schedule, the original files are reloaded as a starting point. The SWATfarmR and the farmR input generation script (step 11) need to be rerun each time the user wants to run SWAT+ for a new simulation period (for which the management schedules need to be rewritten). To avoid SWATfarmR accidentally overwriting already defined parameters (e.g. '*landuse.lum*'), parameters in step 8 or soil nutrient pointers in '*hru-data.hru*' in step 10), it is strongly recommended to start SWATfarmR only after all other parameterisation steps (in particular steps 5, 8 and 10) have been completed.

The main product of the 12-step workflow shown in Figure 2.3 is a ready-to-run SWAT+ model ('TxtInOut' folder containing all files required to run the model executable) with defined but not yet calibrated parameter values. The achievement of this step paves the way for the subsequent steps of the OPTAIN modelling workflow shown in Figure 2.2.

Following this 12-step workflow manually can be cumbersome. Therefore, the OPTAIN modelling core group has also provided a fully scripted version of the workflow. This scripted version only requires the user to provide input data and settings to generate a SWAT+ model setup required for the subsequent steps. An understanding of the underlying methodology is essential to ensure that correct model setups are generated using this tool. Nevertheless, this fully scripted model setup preparation workflow is invaluable as it allows users to to identify and address possible errors and incorporate new data without the burden of repeating multiple manual steps. It also helps to minimise the random errors that can occur during manual data and model operations. The SWAT+ model setup generation scripted workflow with example data can be accessed via the following link to the OPTAIN GitLab (accessible for all OPTAIN modellers):

https://git.ufz.de/optain/wp4-integrated-assessment/swat/swat-setup/full_workflow.

### 2.2.2. Model setup verification

The five-step model setup verification workflow (shown in Figure 2.4) was developed in conjunction with an open source R package developed within OPTAIN, SWATdoctR (https://git.ufz.de/schuerz/swatdoctr), which provides routines to facilitate this important procedure after setting up a SWAT+ model. The developed workflow and R package have already been published in the journal "Environmental Modelling & Software" (Plunge et al., 2024a).

The workflow addresses common issues in model setup. Step 1 is to analyse the model weather inputs and simulated water balance components. A comparison with literature values and observational data allows the user to verify that the weather inputs are correctly interpreted and that the water balance results are plausible.

Steps 2 to 4 focus on the simulation of agricultural management and plant growth. Crop growth is a central part of a SWAT+ simulation and controls the actual evapotranspiration (ETa), which is a significant part of the hydrological water balance. Step 2 serves to verify that the agricultural management operations are carried out correctly during the model run. A comparison with the planned management operations can identify errors in the management inputs.

Step 3 examines the plant growth simulation without activating various growth stresses that can be simulated with SWAT+ (water stress, aeration stress, temperature stress, nitrogen stress, phosphorus stress). Deactivating plant growth stresses in a simulation results in potential maximum biomass and yield. Low simulated values of biomass or yield identified during this verification step may indicate problems with plant parameters (in the *plants.plt* file) or management, such as inadequate duration of plant growth (i.e. problems with heat unit timing). In such cases it is recommended to review and edit the relevant model files. It is also important to check the accumulated heat units at harvest for each crop to ensure complete plant growth cycles in average weather years in subsequent model simulations.

Step 4 investigates plant growth of the simulation with activated stresses. A crop-specific analysis of stressors and yields can help to identify management input issues, such as low fertiliser inputs, adjustments to the timing of certain operations, or the need for additional irrigation or tile drainage. If there are outliers in the simulated crop yields, it is recommended to check their spatial distribution, the spatial distribution of the stresses and the parameterisation of the corresponding HRUs (e.g. problems with soil properties, climate data, etc.).

The final step 5 analyses inputs to the channels from point sources (e.g. sewage treatment plants, water transfers) and tile flow from agricultural land objects. Step 5 determines whether or not point source inputs (units, magnitude, timing) and tile drainage inputs (occurrence of tile flow, etc.) have been correctly parameterised. The results of the verification process can be generalised and supported by visual analysis of the simulation outputs. A model setup verification template has been provided to the modellers, which implements a scripted workflow to generate the required outputs, along with additional information on how to interpret these outputs.

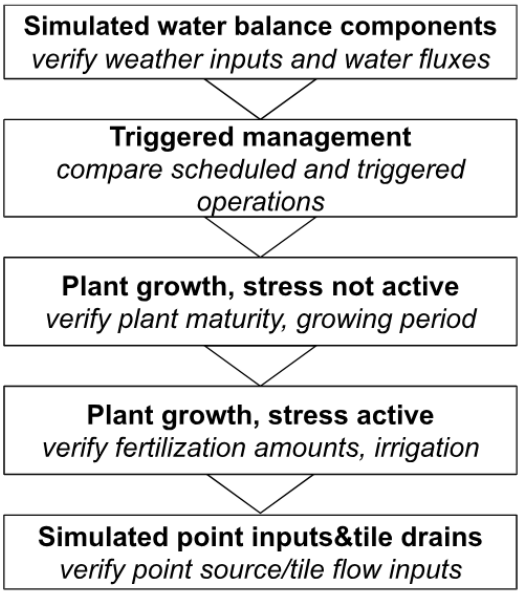


Figure 2.4: Workflow for SWAT+ model setup verification using SWATdoctR.

### 2.2.3. Soft calibration

An R script 'softcal_workflow.R' was developed, which is part of an overall calibration project, to facilitate soft calibration of the crop yields and water balance (accessible on the OPTAIN GitLab for all OPTAIN modellers: https://git.ufz.de/optain/wp4-integrated-assessment/swat/swat-calibration). It uses the SWATrunR R package and consists of several steps that are described below.

(1) Plant growth

After successful verification of the model setup with SWATdoctR, a soft calibration of crop growth and yield is performed. The aim of crop calibration is to adjust relevant crop parameters so that the SWAT+ simulation matches the observed crop yields in the CS.

Important: The crop growth calibration is not intended to compensate for errors in the model setup (e.g. assignment of inappropriate crops from the SWAT+ 'plants.plt' file, incorrect management parameterisation) or errors in the model executable itself (SWAT+.exe). During the model setup, the OPTAIN team discovered several problems with the plant growth simulation (see also Annex 15), mainly affecting the simulation of LAI, biomass, yields, etc. Most of these errors have been fixed by the model developers, but others may still exist.

Preparatory steps: For each crop to be calibrated, reference data of crop yields for the simulation period must be prepared. This could be based on local information (e.g. provided by farmers in the case study) or on regional statistics at the administrative level, which unfortunately are often much larger than the catchments in OPTAIN. It is also important to note that SWAT+ simulation results for crop yield are based on dry matter. Therefore, the reference data (most often fresh matter) must be converted to dry matter. Therefore, raw observed data should be multiplied by a crop specific conversion factor prior to calibration. As these factors may vary slightly between countries, it is recommended to search for national data sources on the moisture (or water) content of different crops. Alternatively, the EU standard moisture content of different crops could be used (EUROSTAT, 2020). For the reference data, it is also important to prepare the range of observed yields over the simulation period, but also the mean/median values to be able to calculate a simple performance criterion.

The OPTAIN core group proposed an overall two-step approach to soft calibration of crop yield. The first step would be to adjust '*days_mat*' (days to maturity). An R-script is provided to define a range of changes to '*days_mat*' (e.g. from -15 to 80 with a step size of 5, resulting in 20 possible values). The changes are applied to the initial values of the crops to be calibrated. After the simulations with changing '*days_mat*', the potential heat unit (PHU) fractions and yields for the crops are plotted. Afterwards, the CS modellers check whether the simulated PHU fraction is overall close to 1.2 (most cereal crops) or 1 (e.g. silage crops) depending on the crop type and whether the yields are in a plausible range. Based on the plots, a change value for 'days_mat' is selected for each crop.

The second step is to calibrate the parameters 'bm_e', 'harv_idx', 'tmp_base' and 'lai_pot'. Based on initial tests, we have found these four parameters to be the most relevant. We recommend sampling the parameters 50 times using Latin Hypercube Sampling and applying a relative change method (+/- 30%) for 'bm_e', 'harv_idx' and 'lai_pot' and an absolute change of 2 for 'tmp_base'. After examining the patterns in the "dotty plots" (illustrating crop yield responses to individual parameter changes) it is recommended to change the parameter ranges, rerun the SWATrunR function for a new set of parameters and re-analyse the results. It is recommended to aim for an average error of less than 10%. In some cases (e.g. rare or problematic crops, not well matched in the SWAT crop database) this may be difficult to achieve. The final step overwrites the parameters in the *'plansts.plt'* file.

(2) Water balance

The aim of the soft calibration of the water balance in OPTAIN is to adjust the proportion of water input (precipitation) that is converted into different forms of runoff in the catchment to a plausible range. The remainder of the water input leaving the catchment is evapotranspiration (ET); and for a sufficiently long period of analysis (at least 10 years), the indicator of interest is therefore the water yield ratio, defined as the ratio of average annual water yield (sum of surface, lateral, tile and base flow) to average annual precipitation. This definition is also a recipe for calculating this value using SWAT+ outputs, while the ratio of the observed water yield ratio could be approximated by a ratio of the average annual discharge measured at the catchment outlet to the average observed precipitation.

After several tests of different SWAT+ parameters in different CS, it was concluded that a single SWAT+ parameter that most strongly controls the amount of water remaining in the system is the hru-level parameter soil evaporation compensation factor ('esco'). While some other parameters such as 'epco' (plant uptake compensation factor) and 'awc' (available soil water capacity) also have a noticeable effect on the water yield ratio, the effect of 'esco' is significantly stronger. Therefore, a simple approach of soft calibration of the water balance has been developed, including 'esco' as a single parameter. In the soft calibration script, the 'esco' parameter is first sampled 20 times in the full range (0, 1), then SWAT+ runs are performed using the SWATrunR package and the calculated water yield ratio is plotted against the 'esco' parameter changes. The last step is to overwrite the *'hydrology.hyd'* file with the 'esco' value that gives the smallest error in the water yield ratio. After overwriting the *'hydrology.hyd'* file, the model should be rerun to check that the soft calibration of the water balance has not caused crop yields, biomass and PHU fractions to fall out of acceptable ranges.

### 2.2.4. Hard calibration

The third and final step of the calibration workflow in OPTAIN (Fig. 2.2) is the 'hard' calibration, where 'hard' data such as measured time series (e.g. streamflow and water quality parameters), typically at a specific point within a catchment, e.g. the main outlet, are used as a reference for calibration. The aim of this step is to improve the realism of the model by comparing its output with the real data and searching for parameter combinations that give a satisfactory fit to the observations. This is expected to improve the simulation of various hydrological processes as well as nutrient fluxes within the catchment. A scripted hard calibration workflow is included in the OPTAIN SWAT calibration R project along with the soft calibration script (accessible on the OPTAIN GitLab for all OPTAIN modellers: https://git.ufz.de/optain/wp4-integrated-assessment/swat/swat-calibration).

(1) Observed data preparation

The first task prior to actual calibration is the preparation of observed data. Traditionally, at least several years of measured data representing average, wet and dry conditions are considered sufficient for hard calibration of a hydrological model. Data (especially water quality parameters) should first be quality checked and assessed for their suitability for the modelling objectives. To address this workflow process, several functions have been included in the R package SWATprepR (Plunge et al., 2024b) with the aim of analysing and pre-processing calibration data. The functions include: i) loading data from templates, ii) various ways to interactively plot data, iii) handling of outliers, iv) checking internal consistency of data and handling of null values. Such simple functions allow potential problems with calibration data to be quickly identified and corrected, saving time and avoiding further problems at a later stage.

(2) Alternative calibration approaches

A sequential calibration approach (i.e. calibrating SWAT+ sequentially for different target variables, e.g. streamflow => sediment => phosphorus or streamflow => nitrogen) has been proposed as a first alternative for modellers in OPTAIN. Streamflow data (time series) are in many cases the most reliable data available for tuning a SWAT+ model setup, whereas the informative value of other data is usually limited due to their lower frequency. As shown in Figure 2.6, the calibration procedure is divided into three main sequences: (i) a process-based calibration of catchment hydrology, (ii) calibration of sediment transport (if sediment transport is a relevant target variable), (iii) calibration of phosphorus and nitrogen cycles.

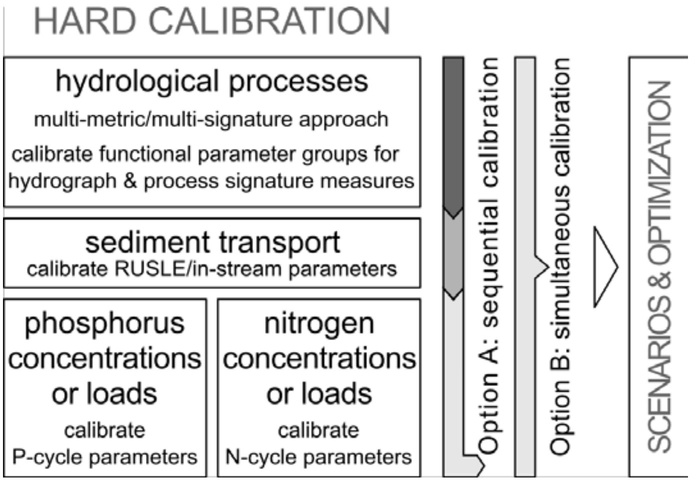


Figure 2.6: Proposed hard calibration workflow in OPTAIN.

The second approach is known as simultaneous or multi-objective calibration. This involves process-based calibration (hydrological, sediment, nutrient) to concurrently adjust relevant model parameters while assessing all defined model performance criteria. All significant parameters are adjusted in a single step, and the results are evaluated based on all relevant model outputs. This approach offers the advantage of improving model performance across all processes simultaneously, without the risk of calibration in one area undoing progress in another dimension.

(3) Objective functions

The model performance evaluation criteria include both commonly used performance metrics (such as Nash-Sutcliffe Efficiency (NSE), Kling-Gupta Efficiency (KGE), percent bias (PBIAS), etc.) and process-specific metrics, i.e. flow signature measures. The latter describe specific streamflow characteristics that may reflect a particular hydrological process that contributed to the runoff. In the proposed workflow, we adapted the set of signature measures from the work of Guse et al. (2020), where signatures describing different segments of the flow duration curve representing very high, high, medium, low and very low flow conditions were used.

(4) Hydrology calibration

The process-specific calibration routine in OPTAIN can be performed using the SWATrunR package. It consists of three main steps: (i) sampling SWAT parameter combinations using Latin Hypercube Sampling (LHS); (ii) running model simulations with SWATrunR; (iii) evaluating model simulations with pre-selected performance metrics and signatures. The process is iterative as the third step should result in modified parameter ranges that can be used to repeat the process. Overall, by performing several iterations of model calibration, the parameter ranges are progressively constrained to identify well performing parameter combinations.

The first step is to define a set of SWAT+ parameters relevant to the calibrated process, the type of change to be applied to each parameter, and the ranges within which each parameter should be changed. The predefined hydrology parameter set includes about 20 parameters representing different hydrological processes. Some parameters may be optional, e.g. tile flow parameters should not be used in catchments with no or very little tile drained areas, snow parameters should not be used in catchments with very low snowfall to total precipitation ratios, etc. Suggested hydrology parameters and their initial ranges have been included in the hard calibration script. The script provides an option to include different parameter ranges for the different leaching and runoff potentials (represented by three SWAT+ parameters: 'perco', 'latq_co' and 'cn3_swf' from the '*hydrology.hyd*' file).

A key setting for the LHS is the number of sampled parameter combinations. For a set of 20 parameters, we recommend 1000 to 2000 samples. However, if the model setups are complex and thus the total run time of 1000 or 2000 simulations is excessive, even with parallel threads, a lower number of samples should still provide informative results in terms of the effect of changing model parameters on model outputs (or performance metrics).

The second step of the proposed procedure is to set up the hard calibration process. This involves setting the basic options for the simulation run, such as the start and end dates (corresponding to the selected calibration period), the definition of output variables/time series and the number of parallel processing threads to speed up the computation time. Once this step has been completed, the process can be initiated. Once the simulation runs are complete, it is recommended, in accordance with the OPTAIN methodology, to proceed to the next step, which is an in-depth analysis of the result data.

The third step is to analyse the "dotty plots", which are a very simple but effective way to evaluate parameter ranges with respect to any scalar value: a simulation output, a performance metric or a signature measure. A visual assessment of the dotty plots should allow the initial parameter ranges to be narrowed down, thereby increasing the identifiability of the parameters. In addition, it is recommended to study the simulated vs. observed hydrographs, as this allows us to evaluate the strengths and weaknesses of the hard calibration performed.

In addition to the generation of "dotty plots", the calibration script also allows the generation of parameter identifiability plots following the approach of Guse et al. (2020). In this approach, parameter identifiability is considered high when the range of the parameter space is narrow and the parameter density is high. The identifiability plots make it possible to constrain the parameters by reducing their ranges to values with a high degree of identifiability (Guse et al., 2020). These plots also allow to identify contradictory behaviour of certain parameters with respect to different metrics (e.g. low 'esco' values leading to high KGE values and low NSE values).

The ultimate goal of the hard calibration is to identify and select several parameter sets that perform sufficiently well with respect to selected criteria. The calculated values of performance metrics and signature measures help to select simulations that perform better than others in a given catchment. Identifying one or a few best model simulations is often challenging, especially when multiple metrics are used to evaluate simulations and they exhibit conflicting behaviour. Two options for selecting the best parameter sets have been included in the calibration script: 1) based on the sum of ranks calculated for particular metrics; 2) based on predefined thresholds for particular metrics. In the first approach, the parameter sets with the highest sum of ranks are designated as the "best" parameter sets, which are then used in subsequent steps of the calibration workflow. In the second approach, the user provides thresholds for each metric or signature they wish to include, and the script identifies model runs for which all conditions are met.

The script allows generating interactive time series plots with a comparison of simulated and observed variables. The user can select model run IDs for which the simulated outputs are to be visualised. In particular, it is possible to visualise the simulated variables for the subset of previously selected well-performing parameters combinations.

### (5) Sediment calibration

According to the calibration workflow scheme (Figure 2.6), sediment transport calibration follows streamflow calibration in the sequential approach, or could be performed simultaneously with streamflow in the multi-objective approach. As sediment transport is mostly driven by large surface runoff events, good streamflow calibration results (especially high flows) are a prerequisite for a sound sediment calibration. In most situations, sediment load and concentration data are limited and only grab sample data or accumulated sediment budgets are available. To reduce the uncertainty associated with sediment load estimation, the sediment calibration workflow in OPTAIN uses sediment concentration data as reference values. This approach is expected to increase the identifiability of sediment parameters, as sediment concentration is generally much less correlated with flow than sediment loads. However, in justified cases, the workflow can be easily adapted to replace sediment concentrations with loads.

The proposed sediment calibration workflow is similar to the iterative streamflow calibration workflow in terms of the steps involved: LHS, model runs with SWATrunR, evaluation of simulations resulting in constrained parameter ranges. The main difference is the lower number of parameters (4-6), resulting in a lower suggested number of parameter samples (200-300). Suggested sediment-related parameters and their initial ranges have been included in the hard calibration script.

(6) Nutrients calibration

The proposed nutrient calibration workflow is similar to the sediment workflow in that the default version focuses on concentration data rather than loads. This is because in most cases only infrequent grab sample data are available to modellers. According to the calibration workflow scheme (Figure 2.6), nutrient calibration follows streamflow and sediment calibration in the sequential approach, or could be done simultaneously with streamflow in the multi-objective approach.

The nitrogen and phosphorus cycles in SWAT+ are rather independent, i.e. the parameters for each nutrient are different and can be calibrated separately. Suggested nitrogen and phosphorus related parameters and their initial ranges have been included in the hard calibration script.

The technical execution of the workflow is also similar to the hydrology and sediment workflows. The number of parameters for the nutrient calibration is lower than for the flow calibration (6-8), which means that the suggested number of parameter samples is also lower (300-400). In the case of sequential calibration approach the final results of this workflow include two optimal parameter sets - one for nitrogen and one for phosphorus.

(7) Validation

Once the "best" parameter sets have been identified for each process (hydrology, sediments and nutrients), the model needs to be validated to ensure that the chosen parameter set accurately represents the system. Model validation is carried out by comparing model predictions with observed data under conditions different from those used for calibration (e.g. temporal validation - a split-sample approach, or spatial validation using data from a different monitoring site). This helps to identify any biases in the model and ensure that it is reliable. The validation process makes the models more trustworthy and increases the likelihood that their scenario results will be accepted by the scientific community and the Multi-Actor Reference Group (MARG). The latter are important end users of the modelling results within the OPTAIN project.

The OPTAIN hard calibration script allows for both temporal and spatial validation. Depending on the available data, at least one type of validation is recommended. As the OPTAIN model setups include management plans generated by SWATfarmR, the simulation time should always match the period for which the '*management.sch*' file was generated by SWATfarmR. Thus, calibration and validation periods would theoretically have different sets of management files, which may be inconvenient. For this reason, we have proposed in the script to perform model runs for the joint calibration and validation periods using a single set of management files (whose time period should match that of the joint calibration and validation). This allows the user to perform all post-processing steps (e.g. calculating performance metrics, assessing parameter identifiability) after each iteration, separately for the calibration and validation periods.

After finished validation, the script allows generating summary box plots visualising selected model performance metrics.

(8) Exporting outputs

In the very last step of the hard calibration, the script allows the writing of *'calibration.cal'* files corresponding to the subset of selected, well-performing parameter combinations (a calibration parameter ensemble). These files can then be used in the scenario simulation workflows (both climate impact and NSWRM scenarios). In addition, the script allows the model to be rerun for the calibration ensemble. In this case, the model runs are not performed using the SWATrunR package, but in the conventional way in several txtinout folders. The water balance, nutrient and crop yield outputs are then extracted from model output files and used to generate plots and export all relevant results outside the R environment. The generated plots are used as a quality check of various processes in the calibrated model to ensure that the model outputs are accurate. At this stage, the SWATdoctR package could also be used again to check that there are no major discrepancies in the calibrated model to be used in scenario modelling.

### 2.2.5. Climate scenario simulations

Bias-corrected EURO-CORDEX RCM datasets have been produced by WP3 and are available on a daily timescale for all CS. The datasets cover the period from 1981 to 2099/2100 for 6 RCMs and 3 RCP scenarios (RCP 2.6, 4.5 and 8.5) with 7 variables (mean, minimum and maximum temperature, precipitation, solar radiation, wind speed at 2 m and relative humidity). Bias correction and further downscaling to 0.1° resolution were performed using local weather data collected by all CS as SWAT+ forcing data for the historical simulation period with non-parametric empirical quantile mapping. The data for each CS are prepared in rectangular domains covering the catchment boundaries.

A workflow has been developed to integrate these data, using functions from the SWATprepR package to prepare and update model weather files (all time series files such as .pcp, .tmp, etc. as well as weather generator .wgn files) for three different time periods. The historical period is from 1988 to 2020, the near future from 2033 to 2065 and the far future from 2067 to 2099/2100. The periods are designed to be 30 years long, with an additional 3 years for model warm-up. Furthermore, the workflow includes the use of SWATfarmR input and SWATfarmR tools (see Figure 2.3) for each climate dataset, with the aim of updating management related files within the SWAT+ model. Finally, the SWATrunR tool is used to run climate scenarios in parallel processing mode using the generated or modified input files. The total number of climate scenario model runs required is 54 (3 RCPs x 6 RCMs x 3 periods). The SWAT model outputs, stored in R, are then used to generate summary plots illustrating projected changes in various modelled variables (divided into hydrology, crops and water quality) in response to climate forcing. Calculation of selected Environmental Performance Indicators (EPIs) is also possible, similar to the NSWRM workflow (see section 2.2.6). Post-processing also includes the generation of interactive maps showing projected changes in variables of interest and the export of results outside the R environment for reporting purposes. The workflow is available on GitHub at github.com/biopsichas/cliwf.

In its current version, the script allows the use of a single '*calibration.cal*' file, so the modeller needs to select a file from the calibrated parameter ensemble (preferably the one that gave the highest rank). In the future, the workflow could be updated to include multiple '*calibration.cal*' files.

### 2.2.6. NSWRM scenario simulations

SWATbuildR was used to generate SWAT+ model setups containing potential sites for structural NSWRMs. All model setups represent field plots by individual land objects. This allows, for example, the management of each field to be changed or the land use of a field to be changed. Fields where parts of the land are to be changed later in their function (e.g. a change in land use due to the implementation of a buffer strip or grassed waterway, or a complete replacement with a water object due to the implementation of a retention pond) have been further subdivided in the model setups into individual units which can then be changed independently of the rest of the field plot. The OPTAIN deliverable D2.3 (Marval et al., 2022) already outlined the technical implementation of structural and management NSWRMs in SWATbuildR model setups and which SWAT+ input files need to be modified to adequately represent the respective NSWRMs in the model setups.

Based on their technical implementation in a SWAT+ model setup, the NSWRMs documented by Marval et al. (2022) can be grouped into general types of measures. Table 2.1 provides an overview of the NSWRMs defined in the OPTAIN case studies, their grouping based on the SWAT+ model implementation and the SWAT+ input files modified by the measure implementation.

A **land use change** is implemented by assigning a new land use to an HRU. The land use consists of a set of land use related parameterisations that are combined to define a land use in the input file *'landuse.lum'*. A new land use is defined there and lum_mgt in *'hru-data.hru'* is updated for the transformed HRUs to point to the newly defined land use.

For a **farm management** change, the management defined for a land use is replaced by another management in the '*management.sch*' file. The updated management plan may include different crops, which will need to be updated in the '*plant.ini*' file.

For a **reservoir implementation**, a land object in the SWAT+ model setup is replaced by a water object. This will disable the land object in the land object files (*'rout_unit.con'*, *'hru.con'*) and add a reservoir object in '*reservoir.con*' and '*reservoir.res*'. All hydrological objects that originally routed water to the replaced land object are now connected to the new reservoir object. The reservoir does not send fluxes to the objects that received fluxes from the land object, but is now only connected to a channel.

Table 2.1: Overview of NSWRMs, their implementation groups and the SWAT+ input files which are modified with the implementation of a measure group.

| Implementation type | NSWRM | NSWRM code | SWAT+ files modified |
|---|---|---|---|
| Land use change | Riparian buffer | buffer | *'hru-data.hru'*<br>*'landuse.lum'*<br>*'management.sch'* |
| | Hedges/field division | hedge | |
| | Grassland cover on erosive slopes | grassslope | |
| | Grassland cover in recharge area | grassrchrg | |
| | Afforestation | afforest | |
| Farm management change | No-till agriculture | notill | *'hru-data.hru'*<br>*'landuse.lum'*<br>*'management.sch'*<br>*'plant.ini'* |
| | Low-till agriculture | lowtill | |
| | Low-till with cover crops | lowtillcc | |
| | Mulching | mulching | |
| | Subsoiling | subsoiling | |
| | Crop rotation | rotation | |
| | Intercropping | intercrop | |
| | Green cover/catch crops | covercrop | |
| | Early sowing | eralysow | |
| | Drought-resistant plants | droughtplt | |
| Reservoir implementation | Pond | pond | *'object.cnt'*<br>*'reservoir.con'*<br>*'reservoir.res'*<br>*'hydrology.res'*<br>*'rout_unit.con'*<br>*'hru.con'*<br>*'chandeg.con'* |
| | Channel restoration | channres | |
| | Constructed wetland | constrwet | |
| Wetland implementation | Wetland/peatland | wetland | *'wetland.wet'*<br>*'hydrology.wet'*<br>*'landuse.lum'*<br>*'hru-data.hru'* |

For a **wetland implementation**, a water storage is added to an existing HRU land object. The dimensions, initialisation and release rules for the newly added water surface are defined in the '*wetland.wet*' and '*hydrology.wet*' files.

A flexible activation and deactivation of NSWRMs in the model setup is essential for testing and running different NSWRM scenarios. Activation of all potential locations of the same NSWRM is required to assess the maximum achievable impact of a type of measure in a catchment. The ability to activate any combination of NSWRMs in a model setup is critical for optimising NSWRM combinations, which is the main task ofWP5.

To allow flexible activation/deactivation of NSWRMs in the SWAT+ model setups, we developed the R package SWATmeasR. A typical NSWRM scenario analysis workflow using SWATmeasR is shown in Figure 2.7. When setting up a SWATmeasR project in R, the workflow loads the status quo of the model input files, which are later modified during the implementation of NSWRMs. A new SWATmeasR project is initiated by calling the new_measr() function and specifying the path to the SWAT+ project folder. Once initiated, the user can define and parameterise NSWRMs for the four main implementation types (defined above) in corresponding measure_settings.csv files, which are then loaded into the measure project using the measr_project$load_nswrm_defintion() function. After defining all potential measures that can be implemented in the model setup, the locations of the potential measures are defined in a measure locations input .csv file, which is then loaded into the SWATmeasR project in R with the function measr_project$load_nswrm_location(). Measure locations are defined by an ID and a corresponding set of HRUs in the model setup, which are transformed when a measure is implemented. Once all potential measures have been parameterised and their locations defined, any combination of NSWRMs can be implemented in the SWAT+ model input files using the measr_project$implement_nswrm() function. The function takes only a vector of location IDs, all of which are then implemented in the model input files.

It is possible that several NSWRMs can be implemented on the same HRUs of a model setup (e.g. no-till farming can be implemented on part of a field plot, while at the same time this HRU is a potential location for the implementation of a grassed waterway). In this case, the implementation of the measure will follow the hierarchy reservoir implementation > wetland implementation > land use change > management change (i.e. if a grassed waterway and no-till are to be implemented, the grassed waterway will "win"). Measures are always implemented in the loaded input files in R. The updated files are written to the SWAT+ project using the measr_project$write_swat_inputs() function. After writing the input files, model simulations can be run to simulate the effect of the implemented NSWRMs. After running the simulations the status quo can be restored using the measr_project$reset() function. After reset, a new set of NSWRMs can be implemented and analysed in model simulations.

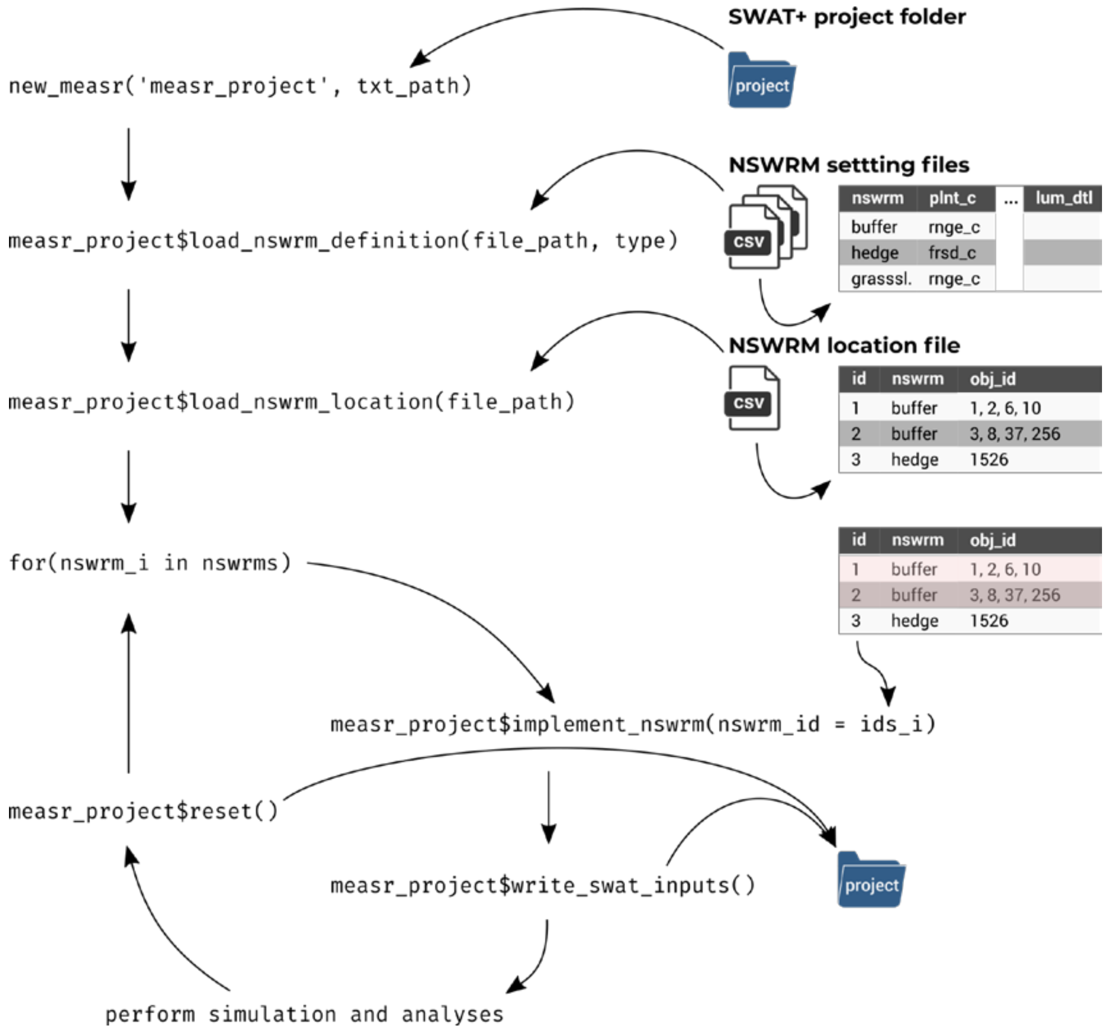


Figure 2.7: Scenario simulation workflow with the R package SWATmeasR.

To reduce the number of possible combinations of NSWRMs that can be combined in the optimisation workflow, potential allocations of measures are aggregated. This is particularly important for farm management-related NSWRMs on individual field plots. If each field plot were kept as an individual potential NSWRM location, the number of potential NSWRM combinations would exceed the computational resources in the NSWRM optimisation. In addition, farmers are unlikely to implement conservation measures on individual fields, but would at least make management changes on several fields. Therefore, if farm level data are available, grouping fields by farm is a plausible approach to reduce the number of combinations. An R script has been written to assist the case study SWAT+ modellers in grouping sites into smaller sets of potential sites, which are then used in the NSWRM scenario simulations and NSWRM optimisation.

Scenario simulations can now be performed in each case study by activating all potential measure locations in a model setup that belong to the same NSWRM, writing them into the model setup, and running the model. By looping over all NSWRMs to be implemented in a model setup, the effect of NSWRMs can be simulated if they are implemented in all potential locations. In comparison, the total effect of all NSWRMs can be simulated by activating all potential NSWRM locations in a SWAT+ model setup.

### 2.2.7. Combined scenarios

At this stage of the modelling workflow, the climate and NSWRM scenarios have already been prepared in folder structures and run using the scripted workflows presented in sections 2.2.5 and 2.2.6. To simulate climate change impacts and NSWRM effects simultaneously, the modified SWAT+ input files representing climate change and those including the NSWRMs must be implemented in a SWAT+ model setup at the same time. For the majority of NSWRMs, the input files used to represent climate change and NSWRMs are independent of each other and can be easily combined. However, this is not the case for management NSWRMs, as both scripted workflows (climate and NSWRM) require the use of SWATfarmR for weather-dependent operation scheduling. Currently, OPTAIN does not have a scripted workflow for running combined climate and NSWRM scenarios. Model runs representing combined scenarios were conducted manually by integrating the weather input files and other climate scenario-related input files into the SWATmeasR projects.

# 3. Results

## 3.1. Status of modelling in different CS

The content of this chapter is based on the information provided by the OPTAIN CS modellers in Annexes 1-14 of this report. All annexes follow the same template previously provided by the task leader. Table 3.1 provides a final overview of the progress made by the different CS up to the submission of this deliverable report. Input data preparation was completed by all CS, partly within WP3. Complete model setups were developed by 12 out of 14 CS (in one case only the SWATfarmR part of the setup was missing). The model evaluation consisted of four steps: setup verification with SWATdoctR, soft calibration, hard calibration and validation. All steps were completed by six CS (in two additional only water quality hard calibration was still ongoing). Eight CS provided results for climate change impacts and seven for NSWRM effectiveness.

Table 3.1 Overview of the progress in SWAT+ modelling tasks by different Case Studies in this report.

| Case Study / catchment | | Model setup | | Model evaluation | | | | Scenarios | |
|---|---|---|---|---|---|---|---|---|---|
| | | SWAT buildR | SWAT farmR | SWAT doctR | Soft calibration | Hard calibration | Validation | Climate change | NSWRM |
| CS1 (DE) | Schwarzer Schöps | completed | completed | completed | completed | completed | completed | completed | completed |
| CS2 (CH) | Petite Glâne | completed | completed | completed | completed | in progress | in progress | completed | in progress |
| CS3 (HU) | Felső-Válicka | completed | completed | completed | completed | in progress | in progress | completed | completed |
| CS4 (PL) | Upper Zgłowiączka | completed | completed | completed | completed | completed | completed | completed | completed |
| CS5 (SI) | Pesnica | completed | completed | in progress | not started | not started | not started | not started | not started |
| CS6 (SI/HU) | Kebele / Kobiljski | completed | completed | not started | not started | not started | not started | not started | not started |
| CS7 (BE) | La Wimbe | completed | completed | completed | completed | completed | completed | completed | completed |
| CS8 (LT) | Dotnuvele | completed | in progress | not started | not started | not started | not started | not started | not started |
| CS9 (IT) | Cherio | completed | completed | completed | completed | completed | completed | completed | completed |
| CS10 (NO) | Kråkstad | completed | completed | completed | completed | completed | completed | completed | completed |
| CS11 (HU) | Tetves | completed | completed | completed | completed | completed | completed | completed | completed |
| CS12 (CZ) | Cechticky | completed | completed | completed | completed | in progress | in progress | not started | not started |
| CS13 (LV) | Dviete | in progress | in progress | not started | not started | not started | not started | not started | not started |
| CS14 (SE) | Sävjaan | completed | completed | in progress | not started | not started | not started | not started | not started |

Note: completed, in progress, not started

There are manifold reasons for delays of particular CS:

1. SWAT+ model development and issues
2. OPTAIN's harmonised approach

3. Spatially discrete model setup with SWATbuildR
4. Correction of climate scenario data
5. Data availability in case studies
6. COVID

All of them have been explained in detail in Annex 15 of this report.

## 3.2. Model setup overview

The location of the catchments for which SWAT+ modelling has been carried out in this report is shown in Figure 3.1. Four CS are located in the Boreal biogeographic zone (CS8, CS10, CS13, CS14), two in the Pannonian (CS3, CS11) and seven in the Continental region (CS1, CS2, CS4, CS5, CS7, CS9, CS12). CS6 catchment intersects with both Pannonian and Continental regions. Five CS are located in the lowlands (CS4, CS8, CS10, CS13, CS14), seven in the highlands (CS1, CS3, CS5, CS6, CS7, CS11, CS12) and two in partly mountainous regions (CS2, reaching 800 m asl and CS9, reaching 1200 m asl).

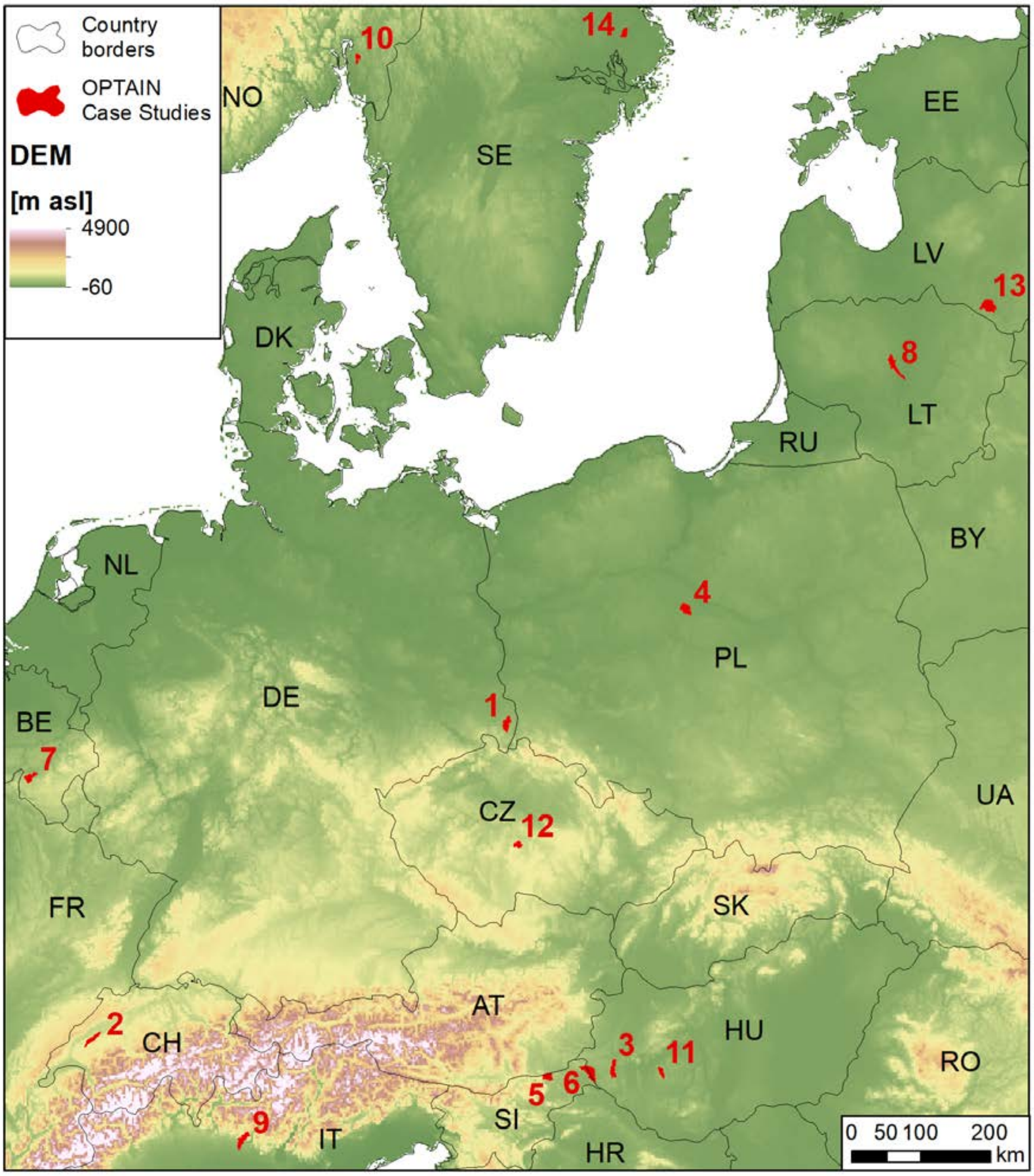


Figure 3.1: Location of catchments for which the SWAT+ modelling work was done in this report.

All catchments for which SWAT+ models were set up in OPTAIN cover areas of similar size, ranging from 50 to 253 km$^2$ (Table 3.2). Despite the small size of the catchments, HRU delineation was detailed, with the total number of HRUs per catchment ranging from 1162 to 10240. The average area of an individual HRU ranged from 0.8 to 4.3 ha. Management schedules included between 5 and 21 different crops. The number of point sources included was typically low (0-3), but could be as high as 187 in cases where more detailed data were available. The number of channels varied over a wide range from 24 to 2314. The majority of model setups included a number of reservoirs and wetlands. In all model setups, the number of routing units was equal to the number of HRUs and a single aquifer was implemented.

Table 3.2: Overview of the model setup features across all CS.

| Case study | Area [km²] | Spatial objects | HRUs | Crops | Recalls (point sources) | Channels | Reservoirs | Wetlands |
|---|---|---|---|---|---|---|---|---|
| CS1 (DE) | 137 | 6463 | 5292 | 9 | 1 | 1017 | 154 | 1 |
| CS2 (CH) | 100 | 16464 | 8056 | 13 | 2 | 314 | 37 | 6 |
| CS3 (HU) | 124 | 10445 | 5196 | 7 | 0 | 47 | 5 | 259 |
| CS4 (PL) | 150 | 20674 | 10240 | 12 | 2 | 164 | 27 | 73 |
| CS5 (SI) | 86 | 14418 | 6020 | 8 | 3 | 2314 | 63 | 0 |
| CS6 (SI/HU) | 234 | 7779 | 7512 | 8 | 0 | 75 | 34 | 157 |
| CS7 (BE) | 116 | 14387 | 6832 | 11 | 2 | 686 | 34 | 0 |
| CS8 (LT) | 175 | 9493 | 4065 | 21 | 187 | 783 | 392 | 0 |
| CS9 (IT) | 141 | 11946 | 5546 | 9 | 0 | 818 | 32 | 105 |
| CS10 (NO) | 50 | 13128 | 6206 | 5 | 26 | 416 | 58 | 13 |
| CS11 (HU) | 72 | 2349 | 1162 | 7 | 0 | 24 | 0 | 24 |
| CS12 (CZ) | 71 | 4948 | 2327 | 12 | 3 | 210 | 80 | 12 |
| CS13 (LV)* | 253 | | | | | | | |
| CS14 (SWE) | 108 | 3163 | 1508 | 6 | 0 | 126 | 20 | 0 |

*The model setup for CS13 has not been completed.

## 3.3. Model evaluation

This section provides a brief summary of the results of the model evaluation. The results are based on the individual CS reports (Annexes 1-14). It should be noted that different CS made different progress in the OPTAIN modelling workflow up to the submission of this deliverable report (see Table 3.1). Therefore, the subset of CS reports from which the results for the synthesis were taken varies between different steps of the modelling workflow.

### 3.3.1. Model setup verification and soft calibration

As shown in Figure 2.2, the first step in the model evaluation was the verification of the model setup using the SWATdoctR tool (Plunge et al., 2024a). Modelling reports from individual CS (Annexes 1-14) provide example plots illustrating the use of various functions within this package. In general, the tool helped to identify problems with weather input data (e.g. radiation data in CS12), some water balance elements (e.g. transpiration in CS10, missing groundwater flow in CS1) and crop growth (too fast development of winter crops in CS1, incorrect LAI development in CS2). These problems might otherwise have gone unnoticed. Correcting them at an early stage prevented potential problems arising in the later stages of model calibration and scenario application.

Soft calibration of crop yields and water balance using the script presented in section 2.2.3 yielded positive results, as reported by CS in Annexes 1-14. For the vast majority of crops, the average annual crop yields after soft calibration agreed well with the observation data. In a few cases, additional manual calibration was carried out for selected crops, focusing on updating the LAI development curve. Table 3.3 shows a summary of the final calibrated values of plant parameters obtained in the soft calibration of crop yields for winter wheat, the only crop present in all model setups. In the first step of the soft calibration, the 'd_mat' parameter was consistently reduced in all CS, due to the fact that the default value of 160 days from the '*plants.plt*' file was too high for a winter cereal (this problem depended on the SWAT+ version used by a particular CS). The rate of reduction of 'd_mat' varied between -30 and -105 days. Of the four other parameters adjusted in the yield soft calibration, 'harv_idx' was the only one that changed in all CS. It was increased in seven out of nine cases. Changes in 'lai_pot' and 'bm_e' were less frequent, and 't_base' was never changed for winter wheat (which is why it is not included in Table 3.3).

Table 3.3: Summary of calibrated plant parameter values for winter wheat ('wwht') across all CS.

| CS | 'd_mat'* | 'lai_pot'** | 'harv_idx'** | 'bm_e'** |
|---|---|---|---|---|
| CS1 | -50 | -0.03 | 0.22 | 0.11 |
| CS2 | -30 | 0 | 0.25 | 0 |
| CS3 | -45 | 0.0 | -0.15 | 0 |
| CS4 | -70 | 0.2 | 0.2 | 0.1 |
| CS7 | -30 | 0.5 | 0.05 | 0.21 |
| CS9 | -105 | 0 | 0.4 | 1.5 |
| CS10*** | -40 | 0.63 | 0.29 | 0 |
| CS11 | -50 | 0 | -0.1 | 0 |
| CS12 | -60 | 0 | 0.3 | 0 |

* Absolute change; ** Relative change; see Annex 10 for other crop parameters used in soft calibration in CS10

### 3.3.2. Hard calibration

Discharge calibration and validation was completed for eight CS, whereas water quality calibration and validation for five CS (Table 3.4). In the case of water quality, we have included in the synthesis only one variable per CS (additional variables may have been reported by CS modellers in their Annexes). In three cases the selected variable was $NO_3$-N concentrations, in one case TN concentrations and in one case TP loads.

Each CS team utilised the hard calibration script presented in section 2.2.4, adapting it to their specific needs. While some teams chose to apply the sequential calibration workflow, others opted for a simultaneous workflow. The selection of performance metrics and their assigned weights were also specific to each team. Table 3.4 summarises the three most widely used performance metrics (KGE, NSE, PBIAS) during the calibration period. The values reported are averages from the ensemble of well-performing simulations, typically consisting of 8-20 parameter combinations. For a more comprehensive analysis of the model performance, including plots of simulated versus observed values, validation results, and additional interpretations, please refer to Annexes 1-14.

Table 3.4: Summary of the performance metrics for discharge and one selected water quality parameter for the calibration period across all CS.

| Case Study | Discharge | | | Water quality | | | |
|---|---|---|---|---|---|---|---|
| | KGE | NSE | PBIAS | WQ variable | KGE | NSE | PBIAS |
| CS1 | 0.79 | 0.69 | -0.4 | TP load | 0.79 | 0.67 | -5.5 |
| CS2 | 0.83 | 0.80 | -3.7 | | | | |
| CS3 | 0.57 | 0.33 | -7.0 | | | | |
| CS4 | 0.81 | 0.63 | -0.9 | $NO_3$-N conc | 0.51 | 0.59 | -7.6 |
| CS7 | 0.81 | 0.75 | -4.2 | $NO_3$-N conc | | | -53.2 |
| CS9 | 0.76 | 0.56 | -3.2 | | | | |
| CS10 | 0.78 | 0.66 | 5.3 | TN conc | 0.78 | 0.68 | 5.2 |
| CS11 | 0.75 | 0.58 | -1.3 | $NO_3$-N conc | 0.33 | -0.33 | -20.1 |

Note: The values presented are averages calculated from the calibration ensemble. Empty cells indicate situations where WQ simulation was not relevant (CS9) or calibration/validation was ongoing (CS2, CS3). In CS7, NSE and KGE were not used as performance metrics for $NO_3$-N calibration.

It is important to acknowledge that there are currently no universally accepted criteria for determining the minimum values of these metrics that indicate acceptable or good model behaviour (Ritter and Muñoz-Carpena, 2013). Therefore, their interpretation is always subjective. The goodness-of-fit of the model is influenced by various climatic and catchment properties, such as baseflow and aridity indices, the fraction of snow in the annual precipitation, and soil depth (Massmann, 2020). Furthermore, the quality of input data varies among case studies, and there is uncertainty in the observation data used for model calibration. With these factors in mind, the results presented in Table 3.4 are primarily intended for reporting purposes rather than for inter-comparison of model performance across different catchments.

The daily discharge calibration was successful, with KGE and NSE values exceeding 0.75 and 0.55, respectively, in all CS except for CS3. Model performance in the validation period was consistently lower than in the calibration period for all CS (refer to Annexes 1-14). The variation in results can be attributed to differences in climatic conditions during the validation period. However, it is important to consider the possibility of overparameterization or model inadequacy, as noted by Arsenault et al. (2018). Drawing such conclusions would require further in-depth analysis.

As the SWAT+ model is an actively developed tool and the nutrient-related routines are still being tested (see Annex 15 for a wider overview of issues with the SWAT+ model code encountered in OPTAIN), this report presents one of the first assessments of the model performance for nitrogen and phosphorus, globally. Table 3.4 shows a wide variation in the reported goodness-of-fit values for nitrogen ($NO_3$-N or TN concentration). In this case, due to the nature of the observation data sets used for calibration, even more caution is required than in the case of discharge. In three out of four cases, the data collected were grab samples taken infrequently (once per month or less). With this type of reference data, it is difficult to assess the dynamics of simulated nutrient fluxes. The only CS with a higher quality dataset was CS4, where an automatic sampler collected water samples daily (with some gaps). Please refer to Annex 4 for more information. The simulated dynamics of $NO_3$-N concentrations in the CS4 catchment were deemed satisfactory.

Phosphorus calibration was only completed for CS1. Here, TP loads were selected as the target variable instead of concentrations. Good calibration results for discharge usually help achieve good results for nutrient loads, which appears to be the case for CS1, where the goodness-of-fit measures for discharge and TP loads were comparable. In CS1, calibration was based on infrequent grab sample data, similar to the majority of CS focusing on nitrogen. The results were strongly influenced by single events, as seen in Annex 1.

### 3.3.3. Simulation outputs for the baseline period

The last step before running climate and NSWRM scenarios using calibrated models was evaluation of the basin-averaged annual water balance (Fig. 3.2), crop yields (Fig. 3.3) and nutrient fluxes (Fig. 3.4) for the baseline period. The latter is in this context defined as a joint calibration and validation period, and therefore does not have to be the same for each CS. It typically covers 12-20 years, ending in 2020 or later. The model runs were made for a subset of 'calibration.cal' files representing a small ensemble of well performing parameter combinations.

The OPTAIN catchments cover geographically different areas in Europe, resulting in heterogeneous climatic conditions that are reflected in precipitation, snowfall, and PET plots (see Fig. 3.2). The average precipitation in most catchments varies between 700 and 900 mm per year, with two catchments, CS4 and CS9, strongly diverging from this pattern with 500 mm and 1200 mm, respectively. The lowest actual ET was simulated for Norwegian CS10, while the highest was for Italian CS9 and Hungarian CS11. Four case studies (CS3, CS4, CS10, CS11) exhibit extremely low percolation and baseflow, which is an order of magnitude lower than in CS7 and

CS9. Tile flow is an important component of the water balance in three catchments (CS2, CS4, CS10). The simulated water yield ratio varies widely, ranging from 0.09 (CS4) to 0.52 (CS10). The fraction of surface runoff in water yield can be as high as 0.7 (CS3) or as low as 0.2 (CS2 and CS4). In most cases, the variability in simulated outputs resulting from different parameter combinations is low. However, there is an exception for CS7 and CS10, where the snowfall amount is directly affected by including the snowfall temperature parameter in the calibration ensemble.

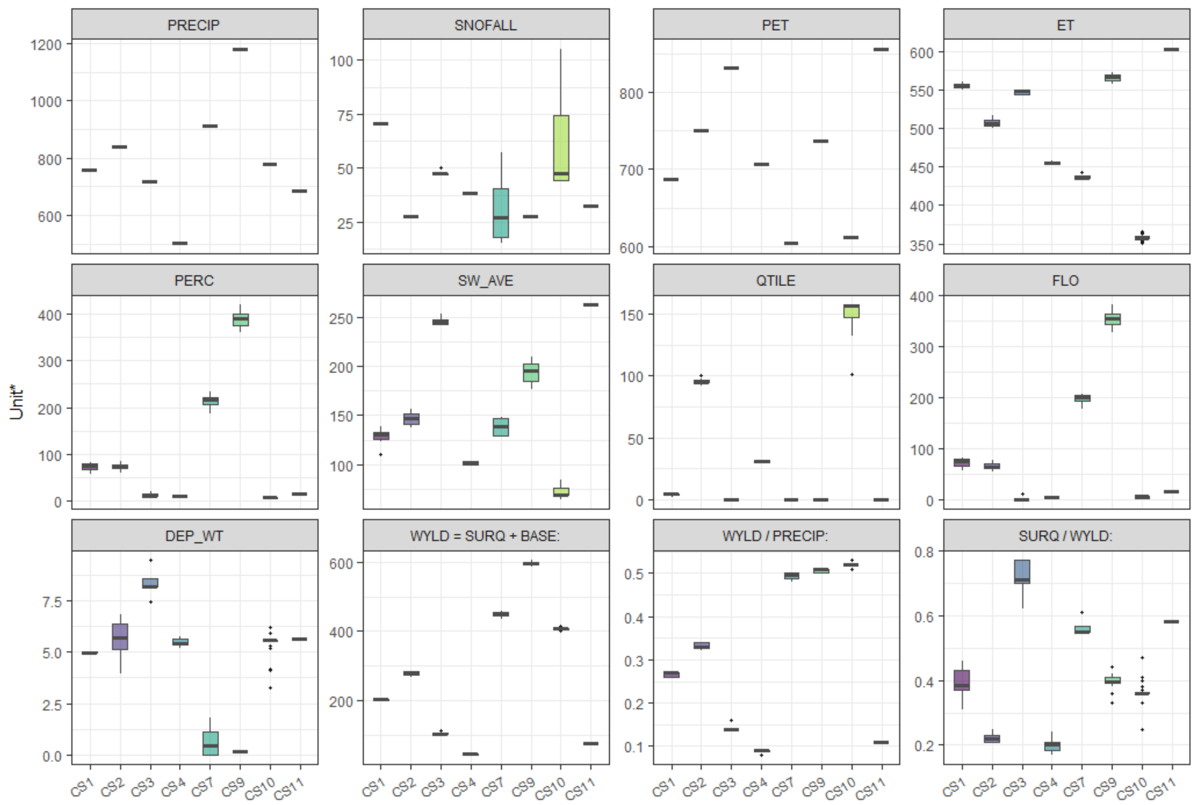


Figure 3.2: Simulated values of selected basin-averaged water balance outputs and indicators for the baseline period for all CS. The unit is [mm] for all variables except for 'DEP_WT' [m], 'WYLD/PRECIP' [-] and 'SURQ/WYLD' [-]. Full description of indicators and their units provided in Annex 16.

Comparison of simulated crop yields for the baseline period between CS is less straightforward because of the diversity of crops included in management schedules in different setups. Therefore, Figure 3.3 shows only those crops that appeared in the model setups of at least 3 CS. The only crop that was present in all model setups was winter wheat ('wwht'). The highest wheat yields were simulated for CS1, CS4 and CS10 (5-6 t/ha), average yields ranging between 3.5-5 t/ha for CS2, CS3, CS7 and CS11, while the lowest yield was found for CS9. The highest variability in yield across case studies, ranging between 5.5 and 14 t/ha, was found for silage corn.

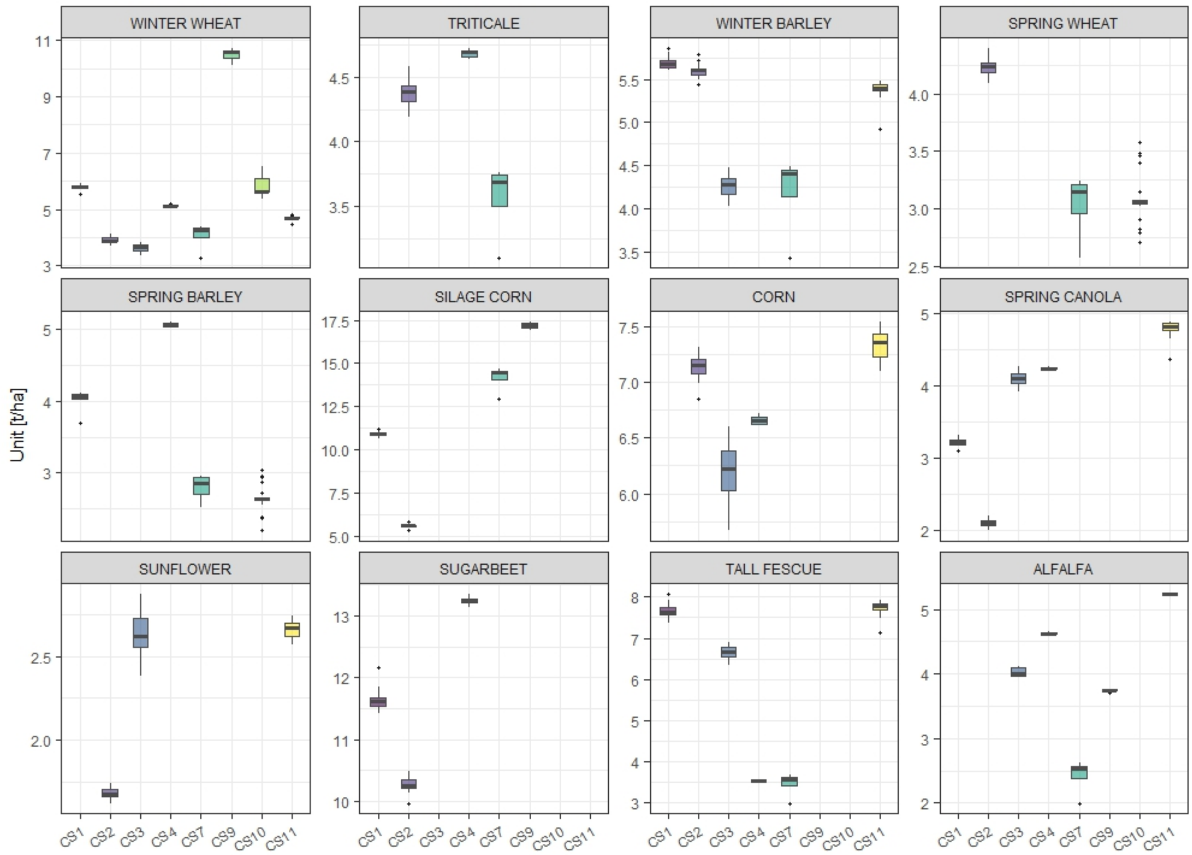


Figure 3.3: Simulated values of selected basin-averaged crop yields for the baseline period for all CS.

Figure 3.4 presents a wide array of outputs related to average annual sediment and nutrient fluxes. In this case caution should be exercised since in many cases, particularly for phosphorus, the nutrient fluxes did not undergo calibration. The simulated variability for nutrient inputs in the form of fertilisers ('FERTN', 'FERTP') is relatively high, which may be partly explained by the lack of normalisation by the agricultural area. Variability in atmospheric deposition ('NO3ATMO', 'NH4ATMO') is also high. Nitrogen outputs via different pathways are dominant in different CS. For example, in CS7 sediment-bound organic N ('SEDORGN') is dominant, in CS10 and CS11 it is nitrate in lateral flow ('LAT3NO3'), while in CS4 it is nitrate in tile flow ('TILENO3'). In CS1, the only case study in which phosphorus was calibrated, soluble phosphorus in surface runoff ('SURQSOLP') is the dominant P transport pathway.

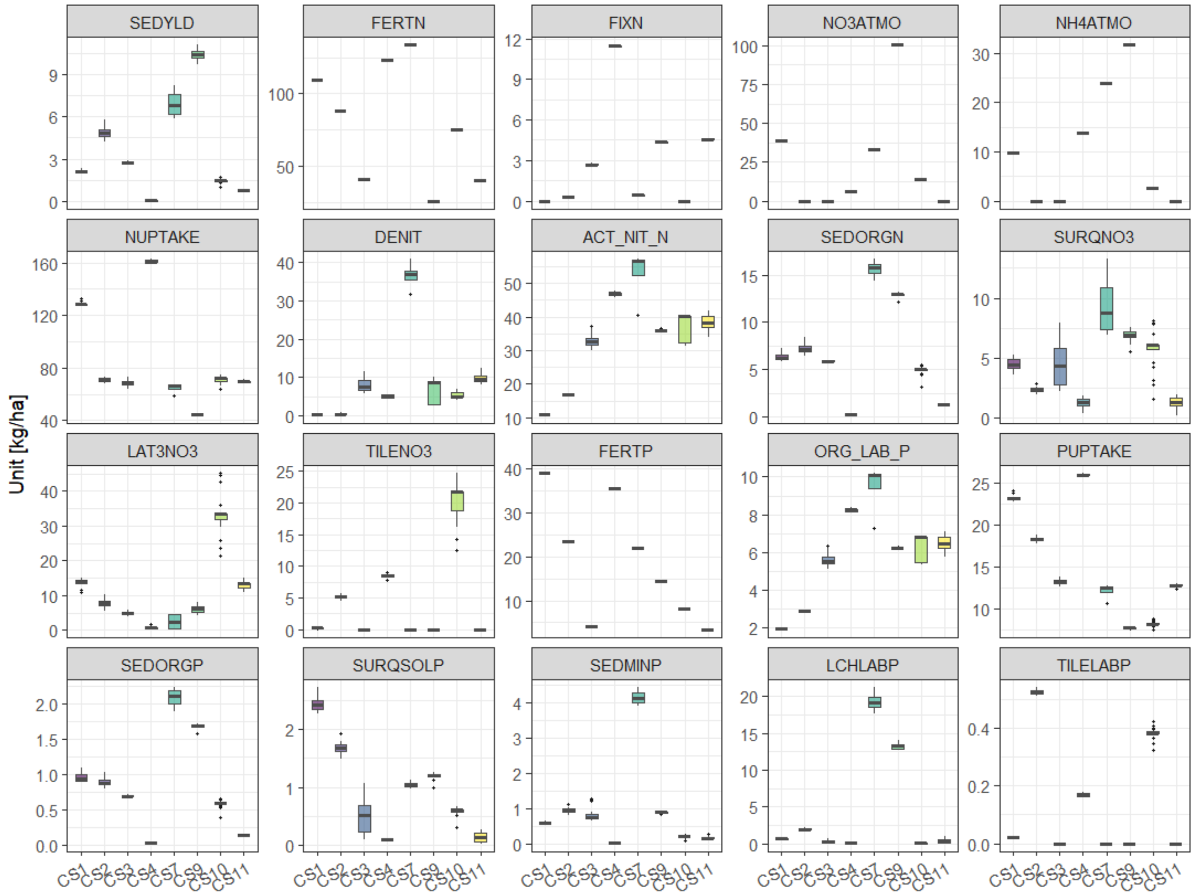


Figure 3.4: Simulated values of selected basin-averaged sediment and nutrient outputs for the baseline period for all CS. Note that the unit for 'sedyld' is [t/ha]. Full description of indicators and their units provided in Annex 16.

## 3.4. Climate change effects

The simulation of climate change impacts on water balance, crop yields and nutrient fluxes was carried out by all eight CS that completed the hard calibration process: CS1, CS2, CS3, CS4, CS7, CS9, CS10 and CS11. This task was fully harmonised as all CS used the climate scenario data provided by WP3 (Honzak, 2023) and applied the scripted workflow described in section 2.2.5. While more detailed results can be found in the respective annexes, here we present a synthesis across the CS for selected variables (Figures 3.5 - 3.8). All results are aggregated in the same way, taking the form of a collection of box plots of relative changes, with three RCPs and two future horizons readily distinguishable. The variability of the box plots represents the ensemble of six bias-corrected RCM simulations. It should be noted, though, that using relative changes as a measure of climate change effect carries the risk of obtaining very high values, only because the base values were low. Some of the base values of variables shown in Figures 3.5-3.8 can be found in Figures 3.2-3.4.

Projected changes in average annual precipitation are relatively low for RCP2.6, with the exception of CS9 (Italy), where they exceed 10% in the far future horizon (Fig. 3.5). A characteristic pattern in precipitation changes occurs for RCPs 4.5 and 8.5, with decreases projected for CS7 and CS9, and increases for all remaining CS. In most cases, changes intensify from one time horizon to the next. The data consistently shows a decreasing pattern in projected snowfall amounts, which intensifies with both RCP number and future horizons. Similarly, there are consistent increases in PET, with the majority of cases showing a magnitude increase of no more than 10%. The exception is RCP8.5, where PET is expected to increase by more than 10%, reaching 20% for CS7 (end of century horizon). In the vast majority of cases, the increase in water inputs (precipitation) and PET leads to an increase in actual ET. The projections for growing season-average soil moisture ('SW_5_6_7_8_9') are highly variable across CS, with only CS4 showing a strong increasing pattern. Changes in surface runoff vary greatly across catchments and RCPs, with some showing increasing patterns and others showing decreasing ones. The projected changes in water yield are primarily driven by changes in precipitation rather than temperature. Most catchments show an increase in water yield, especially for the end of the century horizon. The only exception is CS9, which exhibits a decreasing trend.

The box plots in Figure 3.6 illustrate the projected changes in selected discharge indicators. Mean annual streamflow changes largely follow changes in water yield. The average annual maximum flow and the high flow percentile (Q90) are projected to increase in most analysed catchments, except for CS7 and CS9, where the patterns are mixed. Changes in low flows, both annual average minimum and Q10 percentile, follow a more variable pattern. In general, decreases in low flows are more frequent than decreases in high flows. The annual maximum to annual minimum flow ratio shows an increasing trend for all catchments except for CS4 and CS10.

Analysing the effect of climate change on crop yields is challenging due to the diverse crop structures in different CS. To ensure a common denominator, yields of all crops were transferred into grain units (Fig. 3.7). The projections for grain units show a similar pattern across all CS for all RCPs, with changes intensifying as RCP numbers increase. Notably, grain unit increases are particularly strong for CS7, CS9, and CS10 under RCPs 4.5 and 8.5 in the second time horizon. In contrast, for CS2 and CS11, small decreases in grain units are projected under both RCPs. Winter wheat, the only crop present in all model setups, shows a similar pattern to grain units. The other crops depicted in Fig. 3.7 are included in only a subset of CS. The projected changes in yields of these crops are inconsistent, with the exception of alfalfa, which mostly shows increases.

Figure 3.8 shows changes in selected sediment and nutrient indicators. Caution is required when interpreting the results, especially for phosphorus, as the nutrient fluxes were not calibrated in many cases. The majority of cases project an increase in sediment yield, nitrogen and phosphorus losses, except for CS7 and CS9. This pattern is consistent with the projections for precipitation. Changes in the frequency of days with N and P concentrations exceeding a predefined threshold mostly occur in the opposite direction to changes in N and P loads.

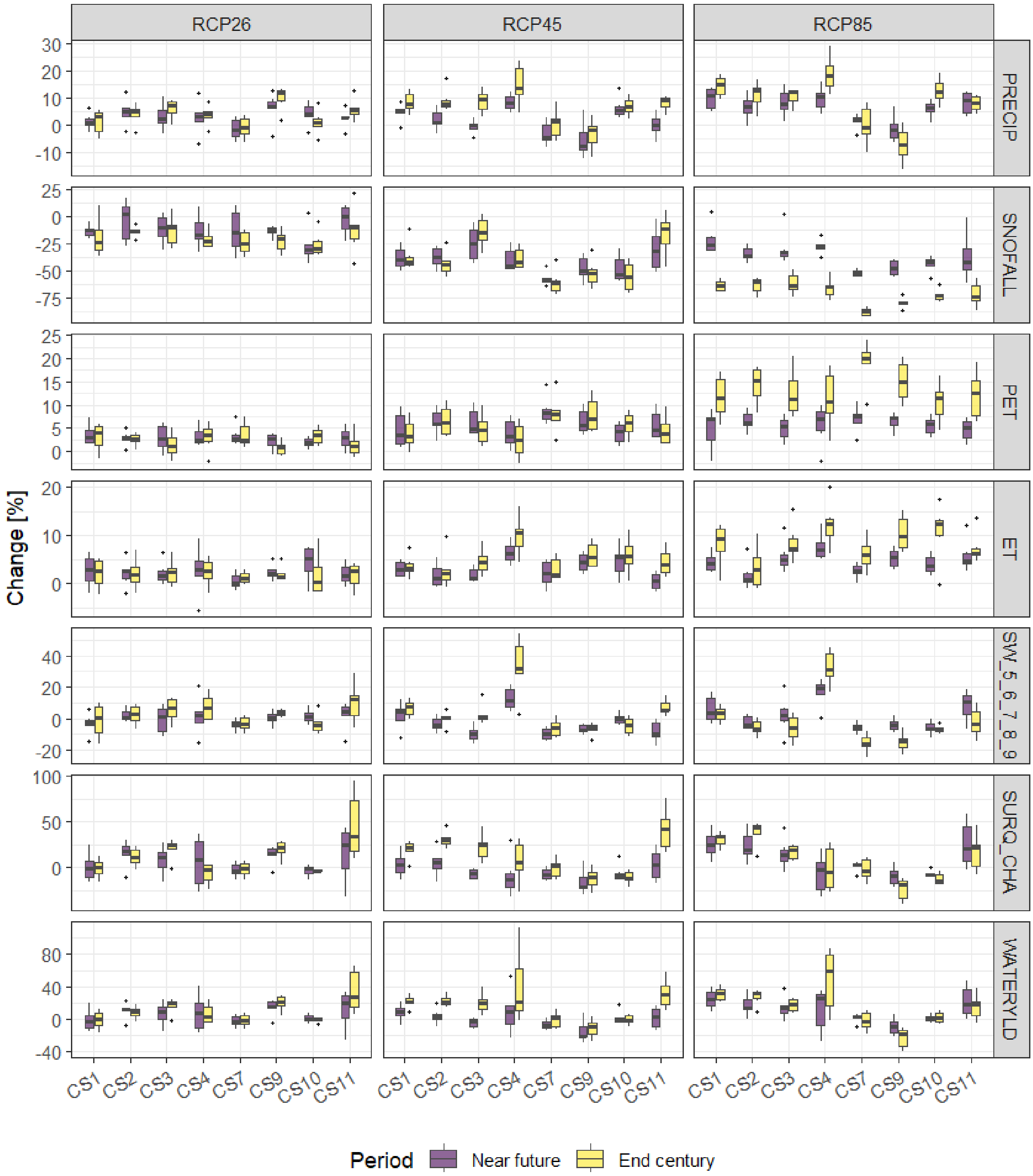


Figure 3.5: Projected changes in selected basin-averaged water balance outputs for three RCPs and two future horizons for all CS. Description of indicators and their units provided in Annex 16.

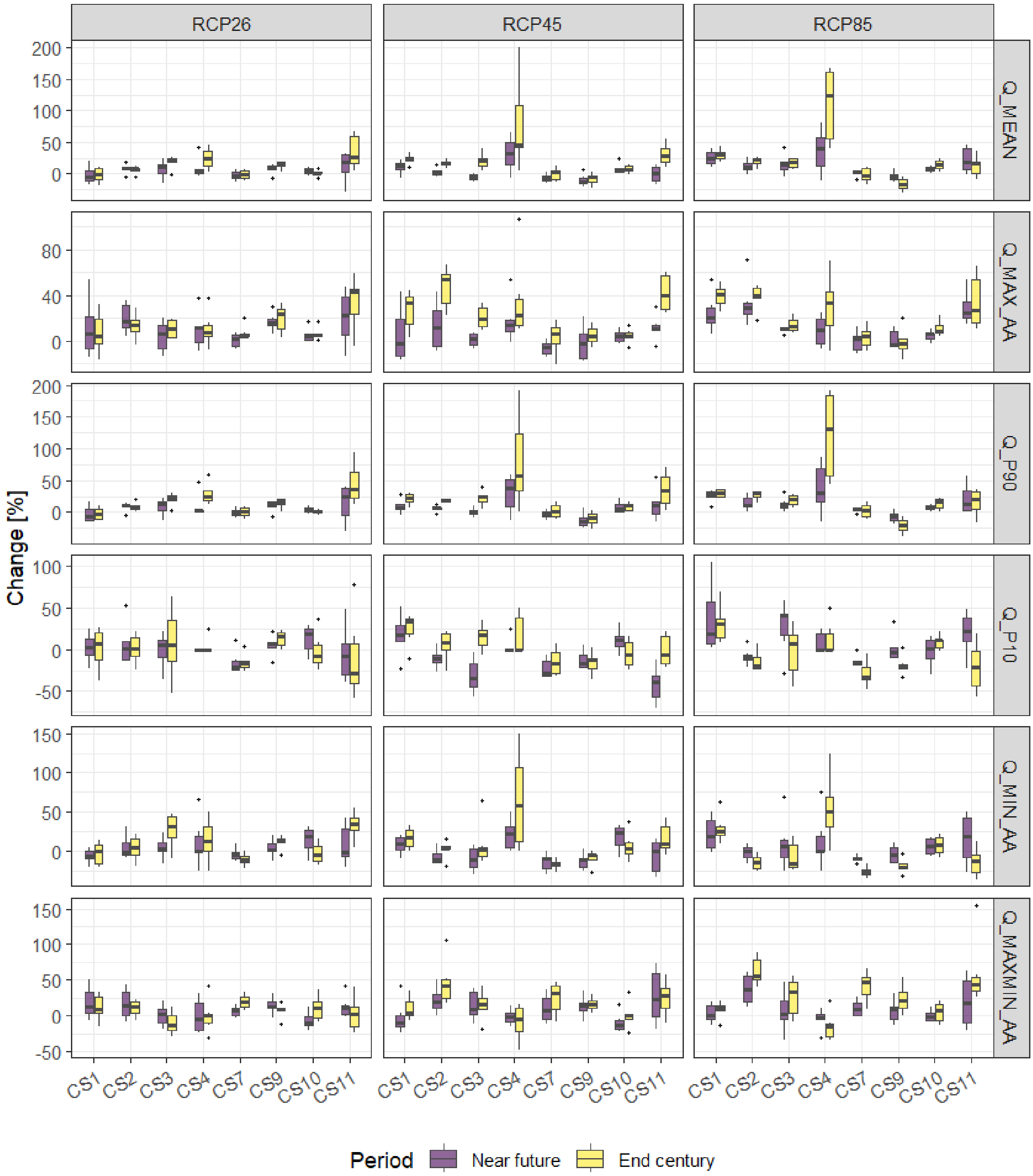


Figure 3.6: Projected changes in selected basin-averaged discharge indicators for three RCPs and two future horizons for all CS. Description of indicators and their units provided in Annex 16.

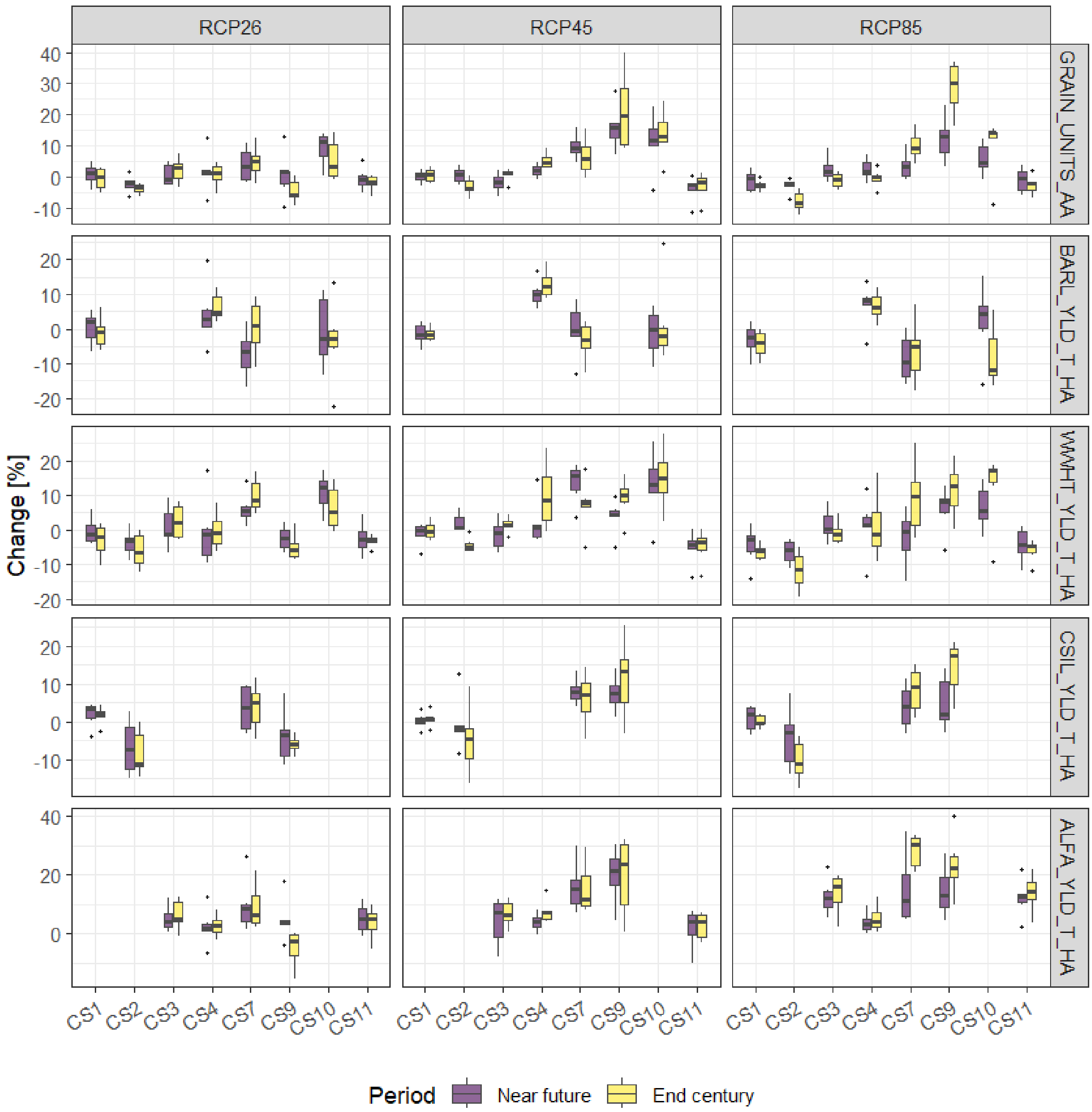


Figure 3.7: Projected changes in selected basin-averaged crop yields for three RCPs and two future horizons for all CS. Description of indicators and their units provided in Annex 16.

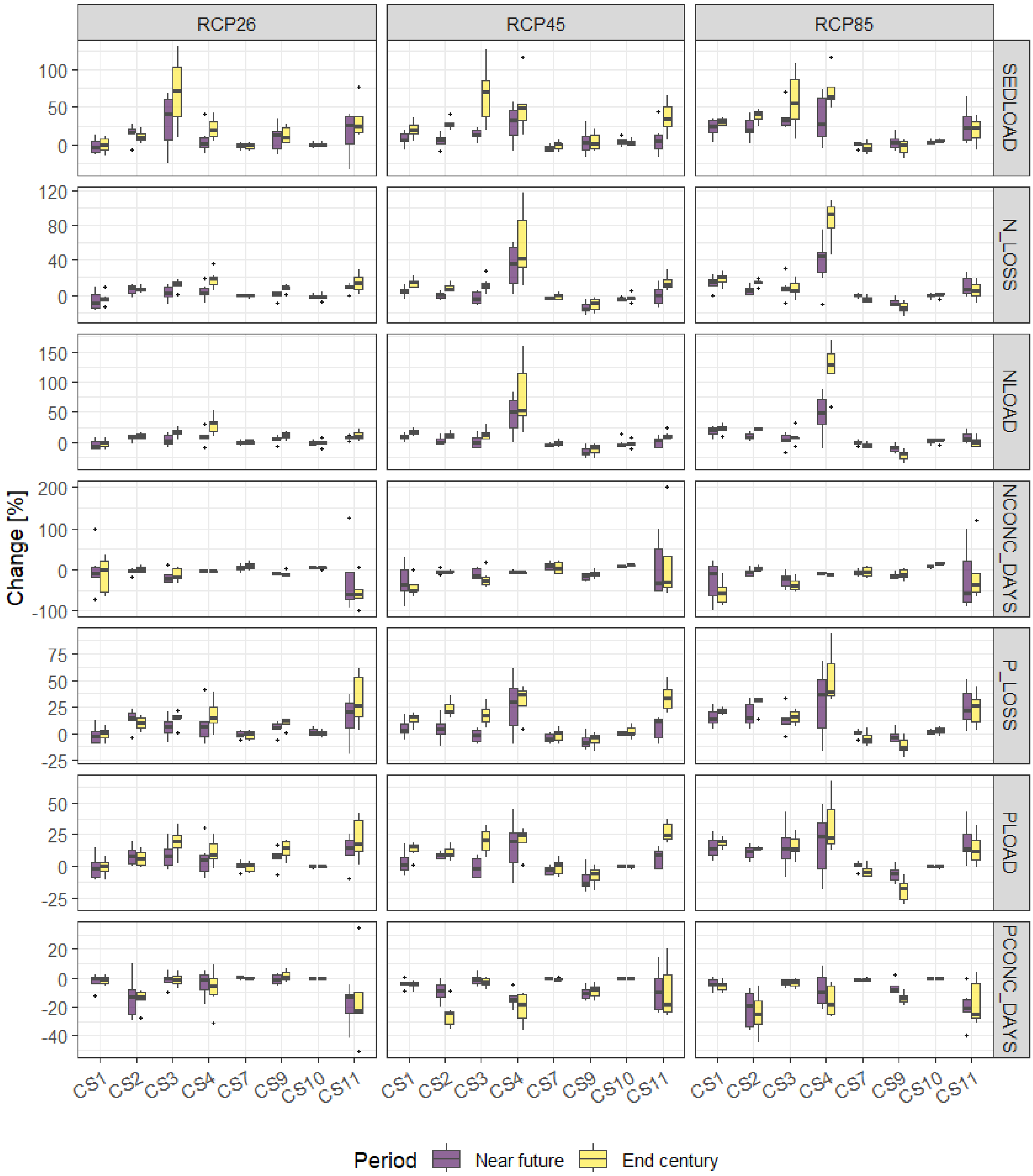


Figure 3.8: Projected changes in selected basin-averaged sediment and nutrient indicators for three RCPs and two future horizons for all CS. Description of indicators and their units provided in Annex 16.

## 3.5. NSWRM effectiveness

### 3.5.1. NSWRM effectiveness under current climate

The simulation of NSWRM effectiveness on water balance, crop yields and nutrient fluxes was carried out by seven CS so far: CS1, CS3, CS4, CS7, CS9, CS10 and CS11. This task was largely harmonised as all CS used and applied the SWATmeasR package and a scripted workflow described in section 2.2.6. A full harmonisation was not possible as the selection of measures and also their parameterisation can vary between CS. While more detailed results can be found in the respective annexes, here we present a qualitative synthesis for the effectiveness of NSWRM across the CS in terms of water retention (manifested by a significant increase in soil moisture or decrease of the Qmax/Qmin ratio), as well as nitrogen and phosphorus retention (significant decrease of N and P loads, respectively, see Table 3.5).

Retention effectiveness varied widely between NSWRM but also betweenCS. Crop and soil management related NSWRMs (e.g. low or no tillage, cover crops) were found to be effective in all of the five CS where this type of measure was modelled (CS1, CS3, CS4, CS10, CS11). In most cases, low or no tillage and cover crops had no significant effect on crop yields, except in CS3 where yields increased by up to 28%. Drought-resistant plants (tested only in CS9) allowed savings in irrigation water, but at the cost of reduced crop yields.

Five NSWRMs are characterised by the conversion of cropland into permanent vegetation cover (greening). Not all of these were found to be effective. Hedges, for instance, were relatively ineffective in each of the four CS (CS1, CS3, CS7, CS10), while grassed waterways had a large effect (especially on sediment retention, not shown in Table 3.5) in both CS that tested this measure (CS1 and CS10). A plausible (and trivial) pattern seems to emerge from the simulation results. The more targeted the spatial implementation of a measure, the greater its impact. Grassed waterways are implemented along erosive thalwegs with the main aim of reducing water erosion while hedges are usually implemented based on other spatial criteria (e.g. connecting habitats for nature conservation). All CS except CS4 included riparian buffers. In 50% of the cases (three CS out of six), riparian buffers showed a significant retention effect (particularly in CS7, where the number and size of the buffers are much larger than in other CS). Afforestation was the NSWRM with the largest area of implementation. It helped to retain nutrients in CS4 and water in CS11, while it was relatively ineffective in CS7. It is clear that greening comes at a cost to crop production. While in the majority of CS, greening measures used only a few percent of the total cropland, afforestation in CS11 was tested on almost 50% of cropland, with a corresponding reduction in total crop production.

The last group of NSWRMs represents artificial impoundments, which did not appear to have a major impact on basin-wide water and nutrient retention. Exceptions are detention ponds in CS4 and CS9 as well as channel restoration (simulated as constructed wetlands along the channel) in CS9.

Not surprisingly, the implementation of combined measures had the greatest impact in all CS, although such a scenario may not be the most efficient, as some measures may partly overlap the effects of other measures (as observed in CS1 with lowtill + cover crops and grassed waterways).

Table 3.5: Overview of modelled NSWRM across case studies (black = NSWRM has been modelled). If a measure was predicted to be effective for retaining water (W), nitrogen (N), and/or phosphorus (P), this is indicated by respective letters (assessment based on a first qualitative screening of results presented in Annexes 1-14).

| NSWRM | Type of change | CS1 | CS3 | CS4 | CS7 | CS9* | CS10 | CS11 |
|---|---|---|---|---|---|---|---|---|
| Afforestation | Land cover | | | N P | ■ | | | W |
| Riparian buffers | Land cover | ■ | W P | | N P | ■ | ■ | P |
| Floodplain restoration | Land cover | | | | ■ | | | |
| Grassed waterways | Land cover | N P | | | | | W | |
| Hedges | Land cover | ■ | ■ | | ■ | | | ■ |
| Cover crops | Crop mgt. | | | N | | | | |
| Drought-resistant plants | Crop mgt. | | | | | ■ | | |
| Low tillage | Soil mgt. | | | | | | W N | |
| Low tillage + cover crops | Crop & soil mgt. | W P | | | | | | |
| No tillage | Soil mgt. | | W N P | | | | | W P |
| Terracing | Land morphology | | | | | ■ | | |
| Controlled drainage | Art. impoundment | | | ■ | | | | |
| Channel restoration | Art. impoundment | | | | | W | | |
| Detention ponds | Art. impoundment | ■ | | N P | | W | ■ | |
| Wetlands | Art. impoundment | | | | | | ■ | |
| Combined** | Depends on comb. | W N P | W N P | N P | N P | W | W N | W P |

* CS did not report nutrient retention effectiveness
** All selected measures implemented at the same time

Overall, the simulated NSWRM effectiveness appears plausible with the novel modelling approach developed and applied in OPTAIN. However, the results presented in Table 3.5 should be treated with caution, as the majority of modelling teams are likely to continue their efforts to make the results as realistic as possible (e.g. by improving the goodness-of-fit in the calibration, adding additional variables in the calibration, e.g. phosphorus, and updating the parameterisation of the measures). There may still be inconsistencies and implausibilities in the behaviour of individual measures that require a more careful investigation by each CS. This is particularly true for the parameterisation of greening measures (e.g. 'cn2' and ‘cons_prac’ parameters) and impoundments (e.g. settling rates of nutrients and decision tables for water release). Before proceeding to the next modelling phase of a multi-objective NSWRM optimisation, each case study is asked to critically reflect on the model behaviour and try to resolve major inconsistencies.

### 3.5.2. NSWRM effectiveness under future climate

Climate change is expected to increase the frequency of extreme weather and hydrological events in Europe, threatening water retention and quality. The results presented in Section 3.4 show that in most cases the magnitude of high flow events and nutrient losses will indeed increase. It is therefore of great practical importance to assess the effectiveness of measures under future climate conditions.

At the time of writing, combined climate change and NSWRM scenarios have only been run for CS1 due to difficulties in integrating the two separate scenario workflows into a single workflow that could be shared with all CSs in a timely manner (as described in 2.2.7). In addition, running all possible combinations of climate (54) and NSWRM (typically 5) scenarios is a significant workload and generates a massive amount of data. As the OPTAIN SWAT+ model setups are very detailed, run time and data storage are a challenge for most CS. Efforts will be made to provide a scripted workflow for running combined scenarios to enable other CS to generate valuable results.

To limit the modelling effort and for illustrative purposes, three different climate scenarios have been selected for CS1 from the ensemble of available RCP-RCM combinations. They are further referred to as 'cool & dry', 'cool & wet' and 'warm & wet'. The selection was based on projected changes in temperature and precipitation by the end of the century. The term 'cool' refers to low levels of warming, as all available scenarios project rising temperatures. As in central Europe high future warming is usually associated with increasing precipitation (Piniewski et al., 2018), no 'warm & dry' scenario could be identified. Selected water balance, water quality and crop yield indicators are plotted in Figures 3.9-3.11 ('cool & dry' scenario), Figures 3.12-3.14 ('cool & wet' scenario) and Figures 3.15-3.17 ('warm & wet' scenario) for the 'historical' and 'end of century' time slices, respectively. The considered NSWRMs include: riparian buffer zones, grassed waterways, hedgerows, low tillage + cover crops, ponds (see Annex 1 for more details).

For the hydrological indicators (Fig. 3.9, 3.12, 3.15), the climate change signal (end of century vs. historical) is stronger than the effect of the NSWRM scenarios (NSWRM vs. status quo), except for the mean annual maximum discharge (‘Q_max_aa’), which indicates high flows and hence, potential flood risk. Under all climate change scenarios, ‘Q_max_aa’ is predicted to increase, particularly for the wet scenarios. However, implementation of the ‘lowtillcc’ scenario may not only prevent this high flow indicator from increasing, but may even reduce ‘Q_max_aa’. According to the model, this NSWRM would also mitigate, but not fully offset, the decrease in the growing season average soil moisture (‘sw_5_6_7_8_9’) under the ‘cool & dry’ scenario.

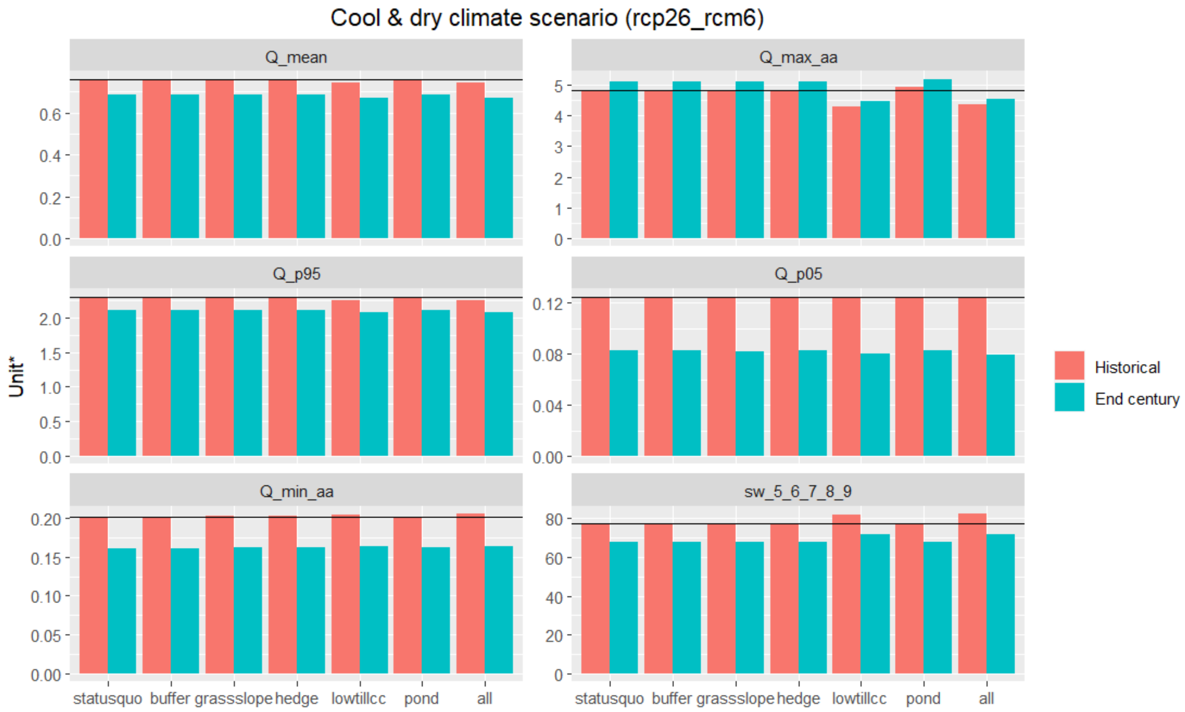


Figure 3.9 Comparison between the combined climate change + NSWRM scenarios for selected hydrological indicators in CS1. The results illustrate simulated indicator values for a single climate scenario called "Cool & dry". The units are [$m^3/s$] for discharge (Q) indicators and [mm] for soil moisture. Black line refers to the indicator level for the historical 'statusquo' scenario that serves as a reference.

Nitrogen and phosphorus loads at the outlet of the CS1 catchment ('Nload' and 'Pload', respectively) are projected to decrease under the 'cool & dry' climate scenario (Figure 3.10). A decrease is certainly desirable for CS1 as nutrient export is one of the main challenges in this catchment. Under the grassed waterways ('grassslope'), 'lowtillcc', and in particular the 'all' NSWRM scenario, the decrease would be much stronger. In contrast, N and P loads are predicted to increase significantly under the wet scenarios (Figures 3.12, 3.15). Such a decrease could be avoided by applying NSWRMs, but according to our model results only with a combined implementation of different NSWRMs ('all' scenario).

For the number of days with high nitrogen and phosphorus concentrations ('Nconc_days' and 'Pconc_days', respectively), the climate change signal was found to be stronger than the NSWRM effect under the 'cool and dry' climate but lower under wet climate. High concentrations are predicted to decrease under all climate scenarios (also despite increasing loads under wet climate due to dilution in the even stronger increasing discharge). Again, selected NSWRM scenarios ('buffer', 'lowtillcc', 'grassslope', 'all') can help to further reduce the number of days with high nutrient concentrations.

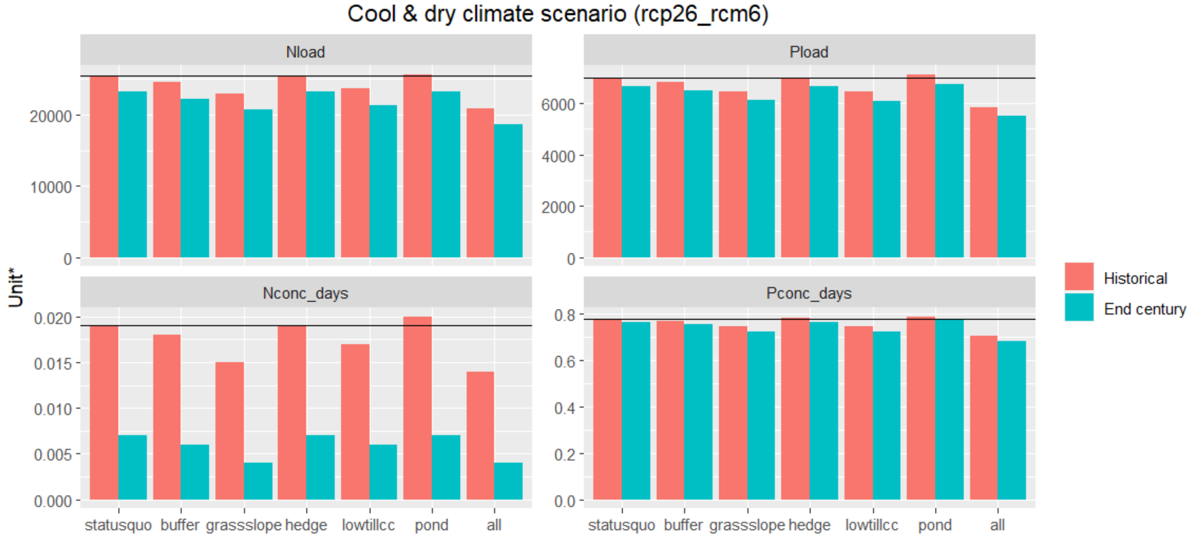


Figure 3.10 Comparison between the combined climate change + NSWRM scenarios for selected water quality indicators in CS1. The results illustrate simulated indicator values for a single climate scenario called "Cool & dry". The units are [kg/year] for load indicators and [-] for frequency indicators. Black line refers to the indicator level for the historical 'statusquo' scenario that serves as a reference.

The predicted impact of NSWRMs on crop yields (Figure 3.11, 3.14, 3.17), in contrast, was only marginal (see also Figure A1.19 in Annex 1). Any climate-induced decreasing crop yields (e.g. under 'cool and dry' climate), might not further decrease in CS1 due to the implementation of the considered NSWRM.

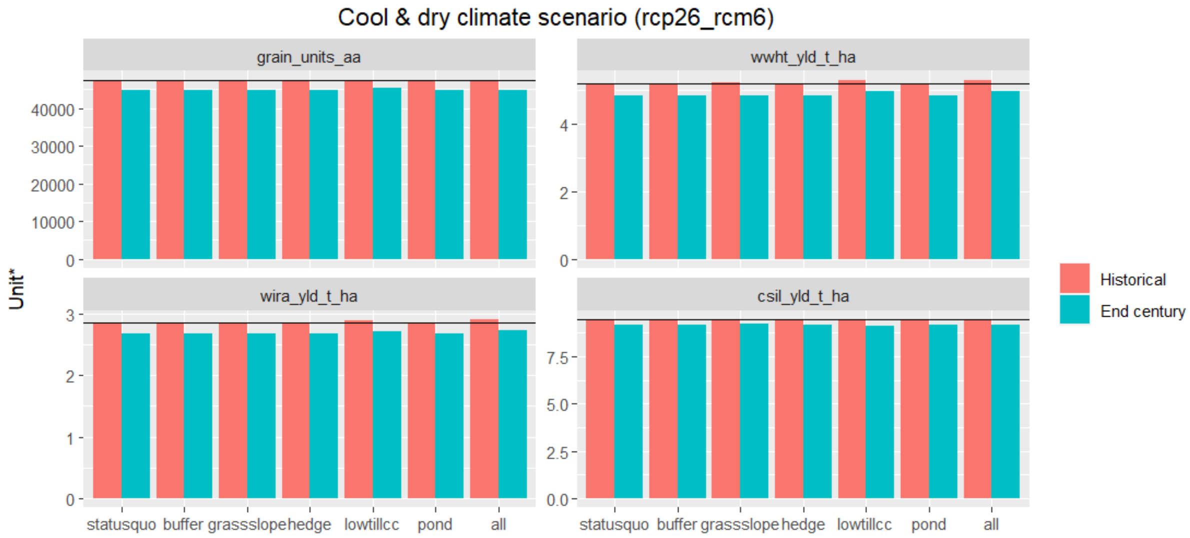


Figure 3.11 Comparison between the combined climate change + NSWRM scenarios for selected crop yield indicators in CS1. The results illustrate simulated indicator values for a single climate scenario called "Cool & dry". The units are [-] for grain units and [t/ha] for crop yields. Black line refers to the indicator level for the historical 'statusquo' scenario that serves as a reference.

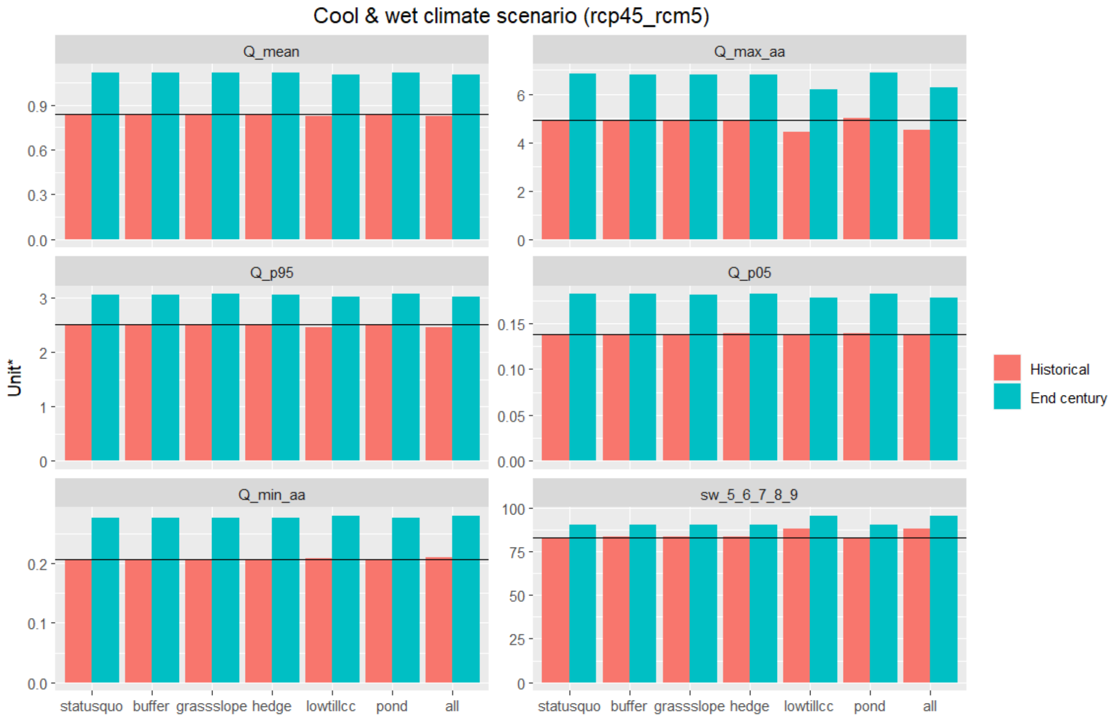


Figure 3.12 Comparison between the combined climate change + NSWRM scenarios for selected water balance indicators in CS1. The results illustrate simulated indicator values for a single climate scenario called "Cool & wet". The units are [m3/s] for discharge (Q) indicators and [mm] for soil moisture. Black line refers to the indicator level for the historical 'statusquo' scenario that serves as a reference.

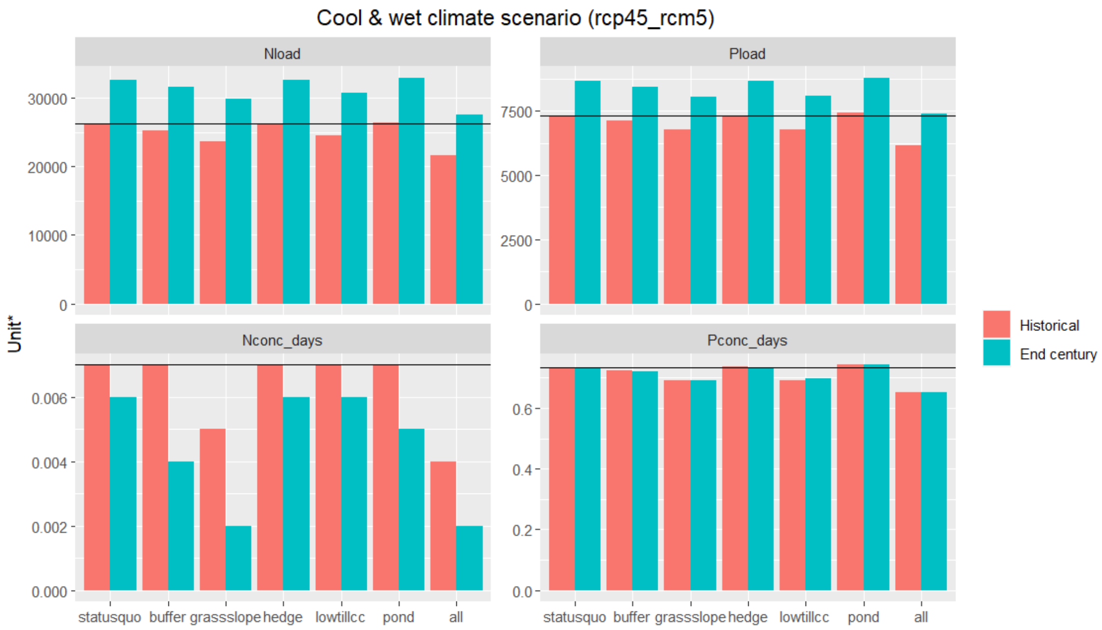


Figure 3.13 Comparison between the combined climate change + NSWRM scenarios for selected water quality indicators in CS1. The results illustrate simulated indicator values for a single climate scenario called "Cool & wet". The units are [kg/year] for load indicators and [-] for frequency indicators. Black line refers to the indicator level for the historical 'statusquo' scenario that serves as a reference.

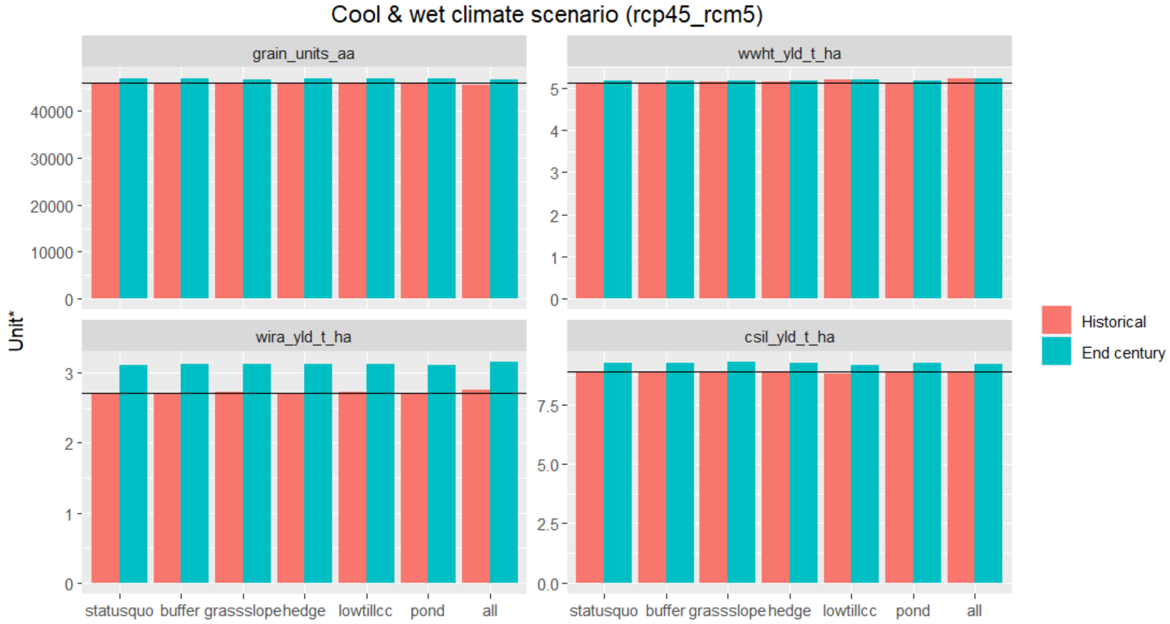


Figure 3.14 Comparison between the combined climate change + NSWRM scenarios for selected crop yield indicators in CS1. The results illustrate simulated indicator values for a single climate scenario called “Cool & wet”. The units are [-] for grain units and [t/ha] for crop yields. Black line refers to the indicator level for the historical ‘statusquo’ scenario that serves as a reference.

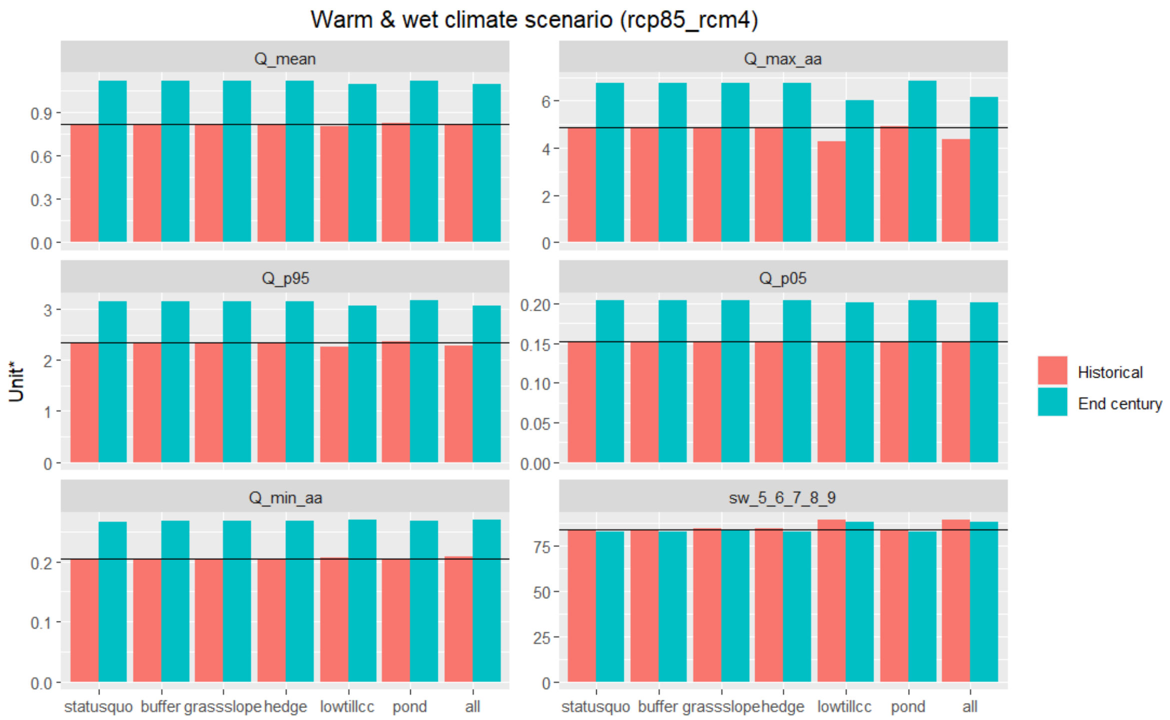


Figure 3.15 Comparison between the combined climate change + NSWRM scenarios for selected water balance indicators in CS1. The results illustrate simulated indicator values for a single climate scenario called “Warm & wet”. The units are [$m^3$/s] for discharge (Q) indicators and [mm] for soil moisture. Black line refers to the indicator level for the historical ‘statusquo’ scenario that serves as a reference.

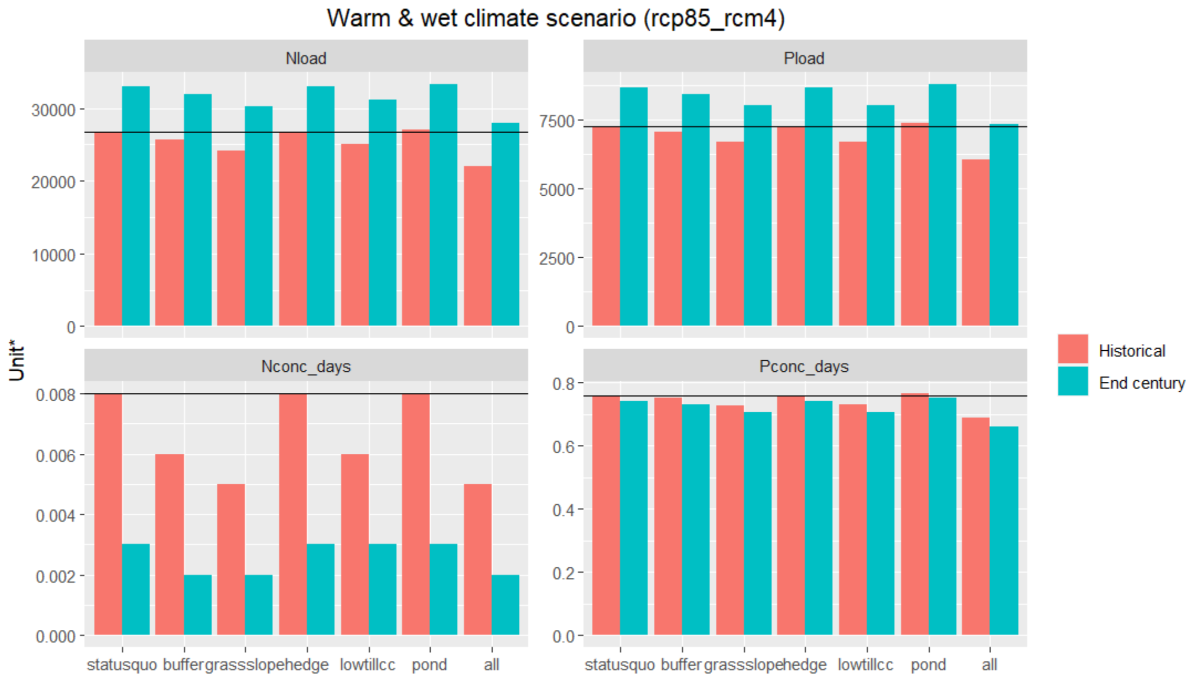


Figure 3.16 Comparison between the combined climate change + NSWRM scenarios for selected water quality indicators in CS1. The results illustrate simulated indicator values for a single climate scenario called “Warm & wet”. The units are [kg/year] for load indicators and [-] for frequency indicators. Black line refers to the indicator level for the historical ‘statusquo’ scenario that serves as a reference.

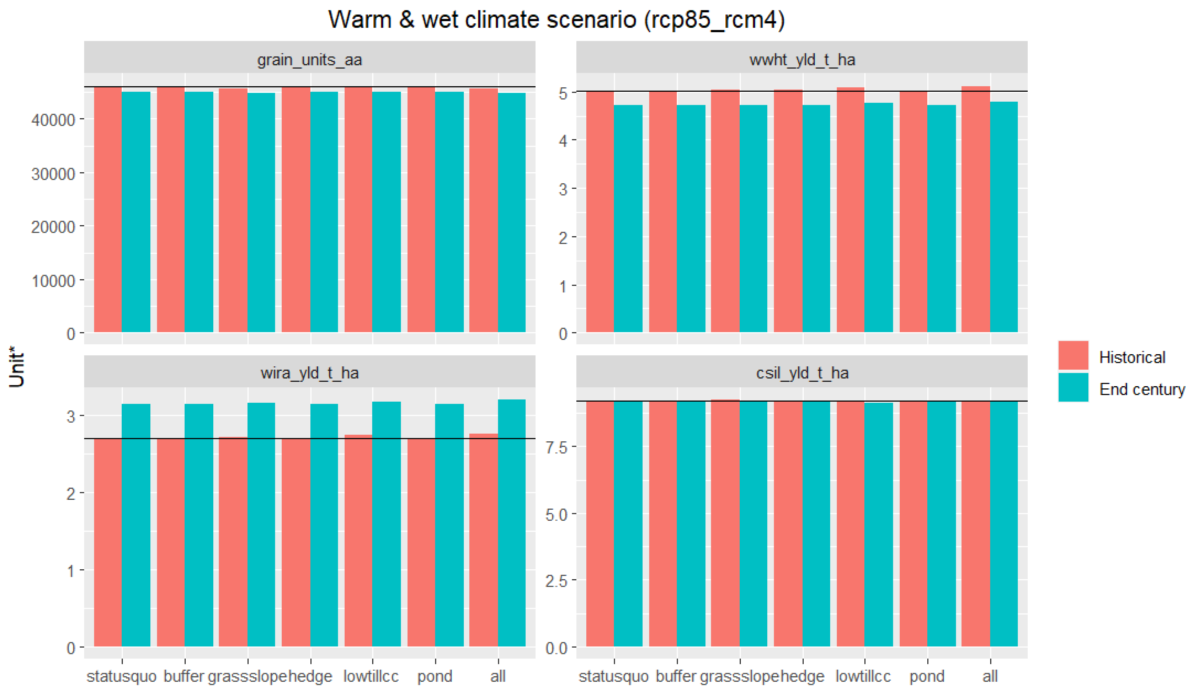


Figure 3.17 Comparison between the combined climate change + NSWRM scenarios for selected crop yield indicators in CS1. The results illustrate simulated indicator values for a single climate scenario called “Warm & wet”. The units are [-] for grain units and [t/ha] for crop yields. Black line refers to the indicator level for the historical ‘statusquo’ scenario that serves as a reference.

# 4. Summary and outlook

This report documents the results of more than three years of work by 12 OPTAIN modelling teams working with 14 small agricultural catchments in Europe. This effort was co-ordinated by a group of co-authors of this report who developed the methodology and tools to carry out the analyses of all CS. While this research used a well-established and widely used hydrological and water quality model, SWAT+, this work significantly advanced several aspects of the use of this tool for the benefit of the scientific and professional communities. To highlight the main achievements:

1. This report presents the first application of the novel concept of developing SWAT+ model setups based on the Contiguous Object COnnectivity Approach (COCOA), which can represent landscape features at the field scale and account for connectivity between land-phase objects (Schürz et al., 2022). This is a fundamental change in process-based hydrological modelling that allows for a more realistic representation of measures in the model setup and more realistic model outputs in terms of simulated effectiveness of measures.
2. It provides the first, to our knowledge, fully scripted SWAT+ modelling workflow in R, covering all steps from input data preparation (new SWATprepR package), generation of COCOA-compliant model setups (new SWATbuildR package), scheduling management practices (enhanced SWATfarmR package), model setup verification (new SWATdoctR package), soft and hard calibration (scripts using the enhanced SWATrunR package), climate change scenario runs (scripts integrating several R packages), and NSWRM scenario runs (new SWATmeasR package).
3. A successful application of this scripted workflow in eight OPTAIN catchments is documented, including a synthesis of results on model evaluation and climate change impacts on water and nutrient balances and crop yields.
4. The report also provides a first overview of the simulated effectiveness of NSWRMs in increasing water retention and reducing nutrient runoff. These results are highly specific to OPTAIN CS, as the way in which they are parameterised and the spatial scale at which they are implemented may vary from case to case.

The intricacies of incorporating such advanced tools as SWAT+ into the project framework introduced complexities that were not initially anticipated. However, it is important to recognise that the use of cutting-edge technologies always carries an inherent level of risk. In addition, OPTAIN's aim to harmonise modelling approaches across all 14 case study sites goes well beyond the state of the art for large research projects. Unfortunately, the harmonised approach resulted in an underestimated high demand for support from CS modellers. Despite the fact that the group of experienced SWAT+ modellers spent a considerable amount of time supporting other modelling teams, for various reasons (e.g. variable modelling expertise, data availability issues, random events) it appeared impossible for several CS teams to complete all modelling tasks in time. As the calibrated SWAT+ model setups are essential for the successful implementation of the OPTAIN optimisation work package (WP5), all CS teams are expected to complete the work within a reasonable timeframe.

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# Annex 1 Modelling results for CS1 (Schwarzer Schöps, DE)

Authors: Michael Strauch, Christoph Schürz, Felix Witing (UFZ)

## 1. Model setup

The SWAT+ model for catchment CS1 (Schwarzer Schöps) was set up following the OPTAIN workflow (Schürz et al., 2022), using the input data listed Table A1.1.

### 1.1. Input data overview

The spatial resolution of all input data in CS1 can be considered sufficient to meet the requirements of OPTAIN (see Table A1.1 and Figure A1.1). A particularly great effort was made for preparing the land use map where the basic land layer (ATKIS-Basis DLM) was manually modified to include field boundaries and small semi-natural structures (>100 m²) within agricultural land. Moreover, polygons with an elongated or complex shape were split into parts of a more compact shape as required for a reasonable routing of water and nutrient fluxes across land units (cf. requirements of COCOA described in Schürz et al. 2022). Field-block level crop information for the period 2016 to 2021 were provided upon request and under strict terms of use by the Saxon State Office for Environment, Agriculture and Geology (LfULG) who extracted the data for the study area from the EU Integrated Administration and Control System (IACS) database.

Required information on agricultural management operations for each crop type were derived from Witing and Volk (2013) and further adjusted by a local farm advisor who is also a core member of the case study's Multi-Actor Reference Group (MARG).

For CS1, a high-resolution soil map was available with layer-specifc soil properties of representative soils for each soil type. Missing soil properties required for SWAT+ were derived from mostly regional pedotransfer functions; and the sand and silt contents were corrected for the US sand-silt grain size limit[1] using the conversion approach of Nemes (2022).

[1] 0.05 mm, in contrast to 0.063 mm of the German system.

Table A1.1 Summary of input data for CS1.

| Input | Number of objects / resolution | Source | Comments |
|---|---|---|---|
| DEM | 2 m | GeoSN (2021): DGM2 | |
| Channel layer | 1,017 channel segments | GeoSN (2021): ATKIS-Basis DLM | Layer was modified (split into more segments) to meet the requirements of the SWATbuildR package. |
| Land layer | 5,446 patches | Land use classification: GeoSN (2021): ATKIS-Basis DLM<br><br>Field block layer: LfULG (2021): IACS Data<br><br>Aerial imagery: GeoSN (2020): SN DOP 020 | Layer was modified to account for NSWRMs planned for scenario simulations (e.g. small semi-natural structures have been included based on aerial imagery). Boundaries of field blocks based on IACS data and field parcels based on aerial imagery were added. Original land use classes were partly aggregated and assigned to SWAT+ land use classes. |
| Soil layer | 542 patches/ 1:50,000 | LfULG (2020a): BK50 | Soil map includes database of representative soil profiles with basic soil properties for each soil type and soil horizons . |
| Usersoil table | 54 soil classes | LfULG (2020a): BK50 Thuerkow (2002), Renger et al. (2008), Gascoin et al. (2009), Auerswald & Ehlhaus (2013), Nemes (2022) | Basic soil properties (content of sand, silt, clay, rock and organic carbon as well as available field capacity) was provided with soil map (BK50). Soil particle size was harmonised using the script by Nemes (2022). Moist bulk density and saturated hydraulic conductivity were derived following Renger et al. (2009). HSG groups are based on Thuerkow (2002), soil albedo based on Gascoin et al. (2009), and USLE K values are based on Auerswald & Ehlhaus (2013). |
| Point sources | 1 | UWB Görlitz (2021) | Central WWTP in Reichenbach/OL with connection rate > 80% in the study area. |
| Weather data | 181/ 6/ 5 virtual stations for precipitation/ temperature, humidity, radiation/ wind speed | SMEKUL (2021): RaKliDa | Centroids of gridded weather data were used as virtual weather stations. While all centroids have been used for precipitation, the number of centroids representing stations of other weather variables was reduced based on a cluster analysis. |
| Atmospheric deposition | 1 | European Monitoring and Evaluation | EMEP data processed by SWATprepR. |

| | | | |
|---|---|---|---|
| | | Programme (MET, 2022) | |
| Crop sequence map | 9 crop types, 699 fields | LfULG (2022): Field-block level IACS data for period 2016-2021 for the Schwarzer Schöps catchment [upon request and under strict terms of use] | Crop types were assigned to the types available in SWAT+. Individual field-specific crop sequences were available for the period 2016-2021. These were extrapolated into the past (1988) by repeating the sequences. |
| Management schedules | 48 | Witing and Volk (2013), agricultural advisor (ISS Löbau) | Schedules prepared based on own literature review and consultation with the local agricultural advisory service. |

GeoSN = State Office for Basic Geoinformation Saxony,
LfULG = Saxon State Office for Environment, Agriculture and Geology
UWB Görlitz = Local Water Authority of the city of Görlitz
ReKIS = Regional Climate Information System of the states of Thuringia, Saxony-Anhalt and Saxony
IACS = EU Integrated Administration and Control System
MET = Norwegian Meteorological institute
ISS Löbau = Löbau Information and Service Center with Technical College for Agriculture

Weather data were derived from gridded datasets of the Regional Climate Information Portal for the States of Saxony, Saxony-Anhalt and Thuringia (ReKIS). In the model setup, all grid cell centroids have been used as virtual precipitation stations, whereas the number of centroids representing stations of other weather variables was reduced based on a cluster analysis. References and details on further input data are provided in Table A1.1.

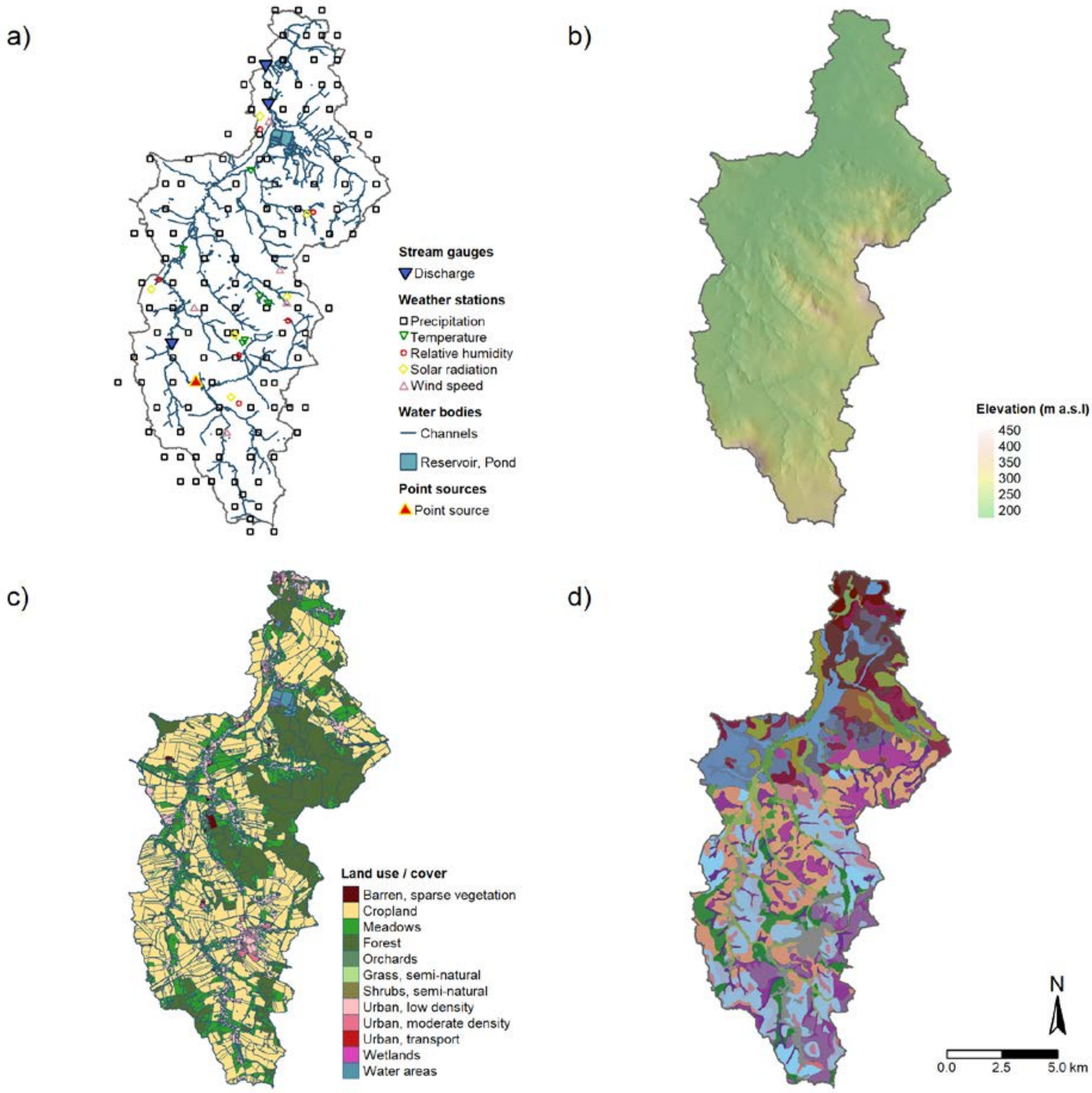


Figure A1.1 GIS input data for CS1: a) flow gauges, water quality monitoring points, ground water gauges, meteorological stations, point source locations, channels and catchment boundary; b) elevation map; c) land use map; d) soil types.

## 1.2. Baseline model setup

Table A1.2 Summary of the model setup features.

| Parameter | Value |
|---|---|
| Total area of the watershed in ha | 13,702 |
| Total number of spatial objects in the simulation | 6,463 |
| Number of HRUs in the simulation | 5292 |
| Number of routing units in the simulation | 5292 |
| Number of aquifers in the simulation | 1 |
| Number of reservoirs in the simulation | 154 |
| Number of recalls (point sources/inlets) in the simulation | 1 |
| Number of SWAT-DEG channels in the simulation | 1017 |
| Number of crops in rotation | 9 |
| Number of wetlands | 0 |

# 2. Model evaluation

Table A1.3 presents observation data for variables used in soft calibration (crop yields, water yield ratio) and hard calibration (discharge, sediment (total suspended solids) concentration and total Phosphorus concentration). Crop yield statistics were only available at county ('Landkreis') level. Longer timeseries for discharge were available for three gauges (Schoeps = Pegel Schoeps, Jaenk = Pegel Jaenkendorf_1, and Quitz = Pegel Quitzdorf). As observed discharge for Quitz is only available in poor temporal resolution (on average every 4-6 weeks) and the daily time series for Schoeps does not start until 2009, we used Jaenk as main calibration gauge for discharge.

Regarding nutrients, CS1 is mainly interested in Phosphorus (P) as high P loads regularly cause blue-green algae blooms in reservoir Quitzdorf. Thus, the model was calibrated and validated for P loads. Because P binds strongly to soil particles, we calibrated the model also for sediment loads (before P calibration). Observed concentrations for both, sediment (total suspended solids) and total P were available for Quitz. Multiplication with corresponding discharge measurements, provided us loads (kg/day) in a 4-6 weekly resolution for almost 30 years (1993-2020).

Table A1.3 Summary of observation data used in different steps of the calibration workflow for CS1.

| Variable | Time step | Calibration period | Validation period | Source | Comments |
|---|---|---|---|---|---|
| Soft calibration | | | | | |
| Crop yields | Average annual | 2009-2020 | NA | Federal and state statistical offices (2021) | Crop yield statistics for Landkreis Goerlitz (county-level) |
| Water yield ratio | Average annual | 2009-2020 | NA | Model input (pcp) and discharge data | Calculated for a flow gauge with the longest record |
| Hard calibration | | | | | |
| Discharge (Jaenk) | Daily | 2009-2020 | 1991-2008 | LfULG | Gauge Jaenkendorf_1 (gauge with longest record of daily discharge) |
| Discharge (Schoeps) | Daily | 2009-2020 | | LfULG | Gauge Schoeps (no data available for validation period) |
| Discharge (Quitz) | 4-6 weekly, higher frequency in case of events | 2009-2020 | 1991-2008 | LTV Betrieb Spree/Neiße | Gauge Zufluss_Quitzdorf (watershed outlet, data not in daily resolution) |
| Sediment load | 4-6 weekly, higher frequency in case of events | 2009-2020 | 1993-2008 | LTV Betrieb Spree/Neiße | Gauge Zufluss_Quitzdorf (watershed outlet, gauge with longest record of sediment concentration). Loads were calculated by multiplying concentrations with measured discharge. |
| P load | 4-6 weekly, higher frequency in case of events | 2009-2020 | 1993-2008 | LTV Betrieb Spree/Neiße | Gauge Zufluss_Quitzdorf (watershed outlet, gauge with longest record of P concentration). Loads were calculated by multiplying concentrations with measured discharge. |

## 2.1. Model setup verification

All steps of the model setup verification were performed in accordance with the OPTAIN workflow (Plunge et al., 2024). Verification of the climate and water balance data (Fig. A1.2) showed that all reported values are mostly in plausible ranges according to the expert knowledge of the studied catchment. Evapotranspiration (ET), however, was underestimated by ~ 50 mm (compared to reference model simulations provided by KliWES). The underestimation of ET was mainly caused by the defined SWAT+ land covers which use plant parameterizations which do not fit the climate of the CS1 study site. This was the case for the land uses frst (Forest) and rngb (Rangeland brushland). Both plant parameter sets use high values for the base temperature at which PHU accumulation starts (t_base = 10°C). This value is unrealistic for temperate climates. Therefore, the plant parametrization for the land uses frst_lum and rngb_lum was changed to frst_test, and rngb_test (forest and range/brush temperate steppe) with t_base temperatures of 0°C. This change increased ET by approx. 30mm.

The comparison of how different stress factors affect crop yields of an uncalibrated model also showed plausible results. The reductions of crop yields considering stress factors were within reasonable ranges (Fig. A1.3).

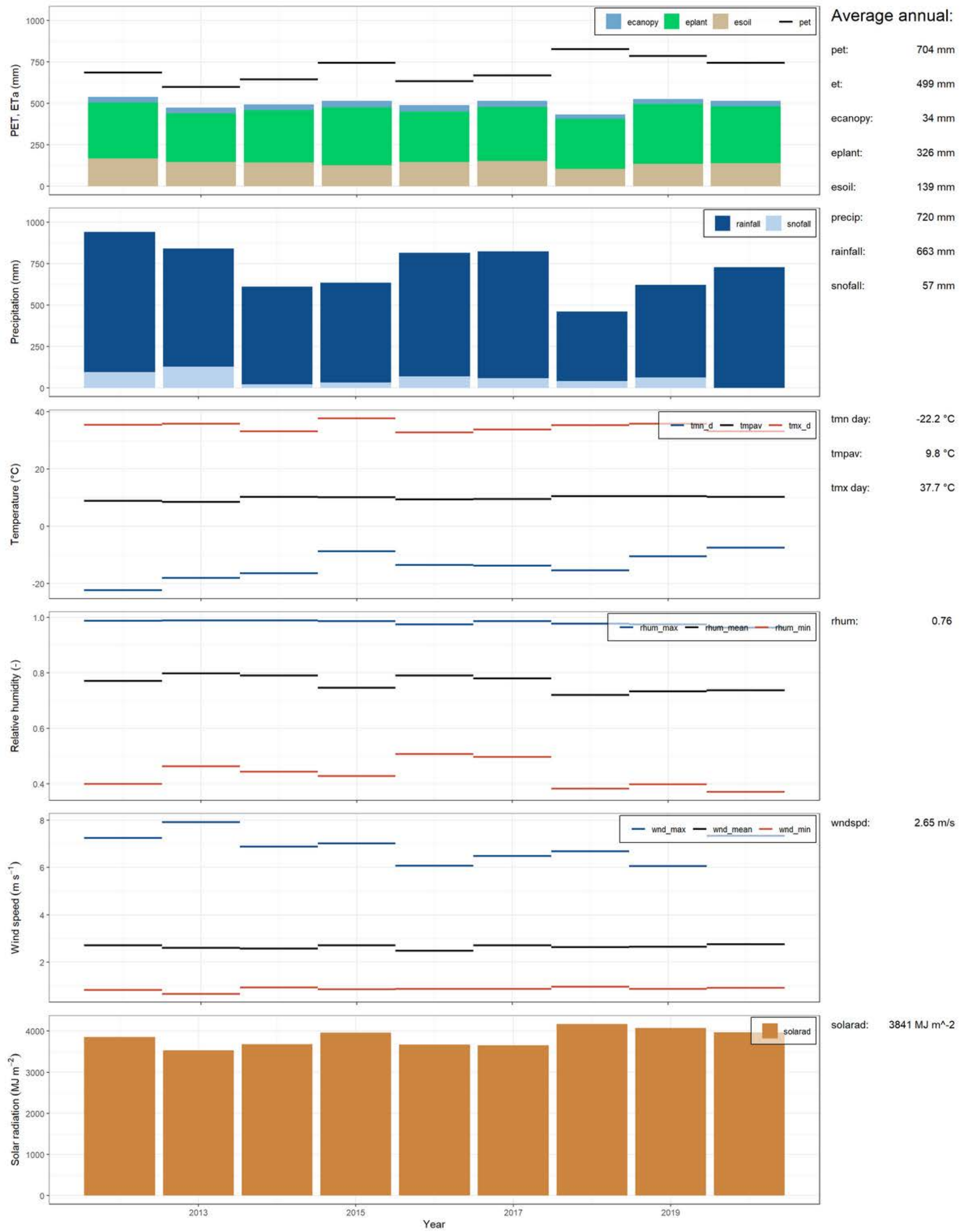


Figure A1.2 Summary of the climate data checks for CS1 by the SWATdoctR.

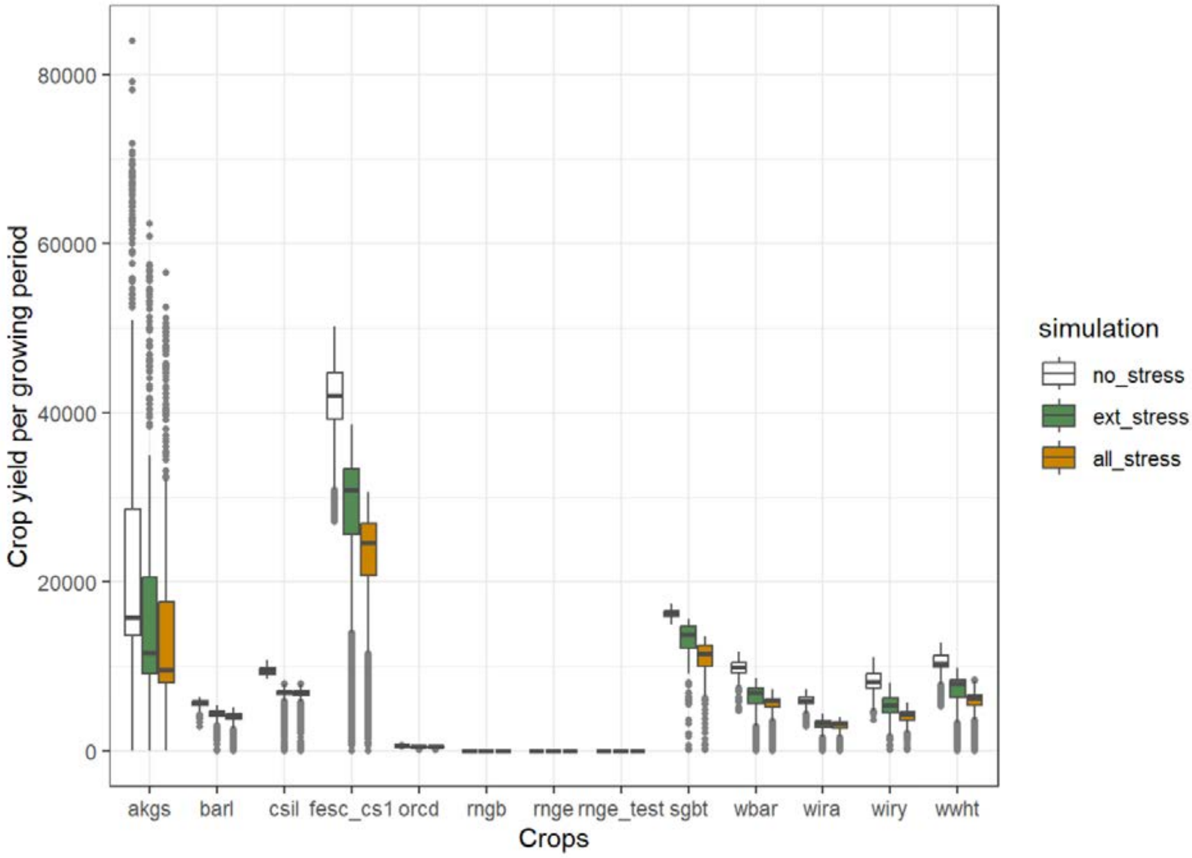


Figure A1.3 Comparison of crop yields with all stress factors, external stress factors and no stress factors for CS1.

The huge magnitude of biomass for farmland grass (akgs) and meadows (fesc_cs1) is an artefact of the plotting method in SWATdoctR because it uses accumulated biomass for the whole period from planting to kill operation and this period is highly variable across hrus ranging from 0.5 years to 5 years.

The analysis of biomass and LAI development (example shown in Fig. A1.4) showed acceptable behaviour, even though LAI appears to develop too fast in autumn for several winter crops, especially winter rapeseed and winter barley.

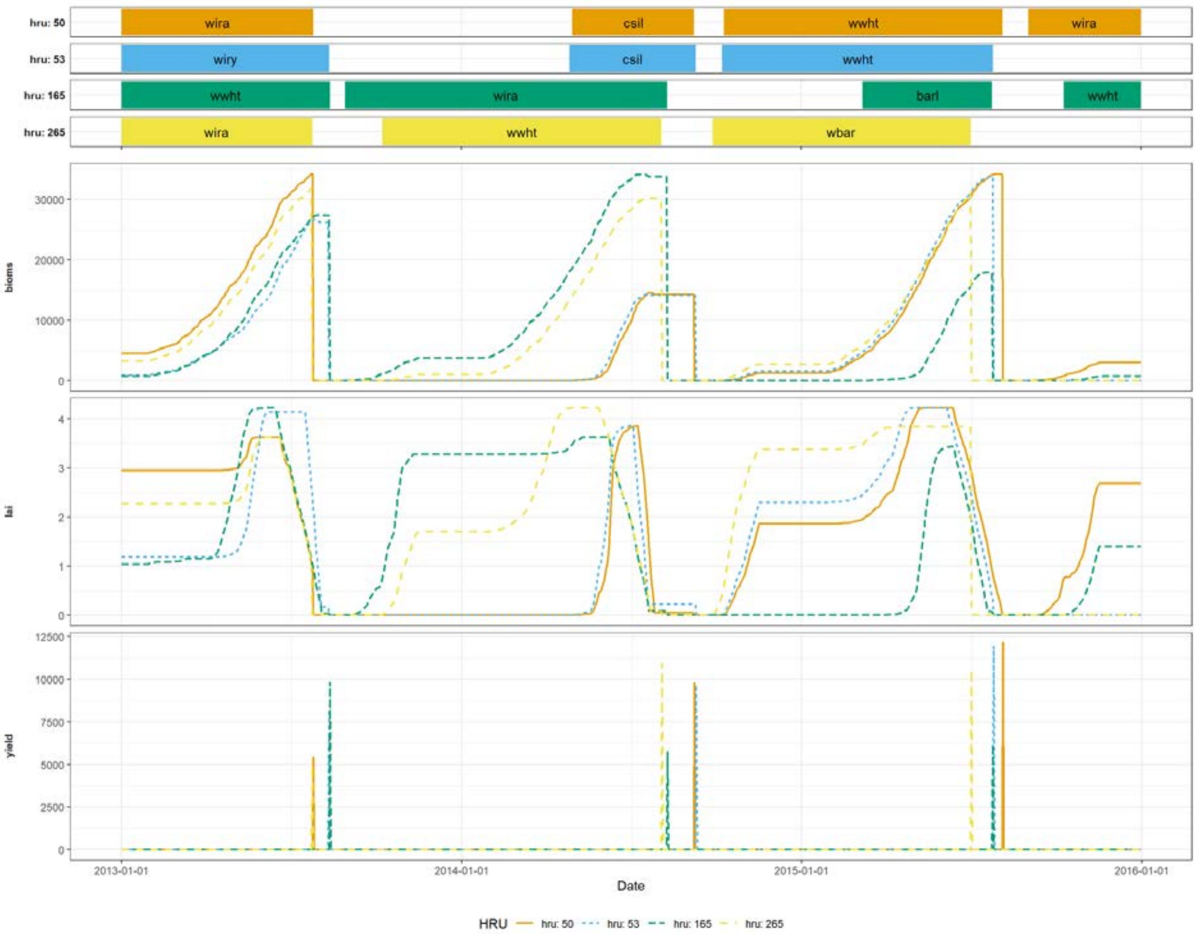


Figure A1.4 Biomass, LAI development and yields for a simulation with all stress factors active for two example HRUs in CS1.

## 2.2. Soft calibration

As shown in Fig. A1.5, the crop yield soft calibration workflow was successfully applied in CS1. In the first step, d_mat (days to maturity) parameter was altered in such a way that the accumulated PHU fraction at harvest/kill is within the predefined range of 1.0-1.2, except for corn silage (csil) and farmland grass (akgs), where we deliberately targeted a PHU fraction lower than 1 because the crops are commonly harvested without reaching maturity. The highest changes in days to maturity parameter (Table A1.4) affected winter wheat (wwht) and sugar beet (sgbt). For sugar beet, the PHU fraction at harvest barely reached 1.0, even after increasing dmat by 80 days.

In the second step, adjustment of four plant parameters for each crop helped achieve satisfactory crop yield calibration results. For the majority of crops, the average observed and simulated yields match reasonably well. For sugar beet, barley (barl) and winter rape (wira), the model tends to slightly underestimate crop yield. Reasonable crop yields were simulated for the majority of hrus. However, for a minority of hrus (up to 25%) crop yields are remarkably low, for some hrus even reaching 0. This phenomenon was observed for all crops and is of course questionable. It is probably attributed to the novel routing approach where water accumulates in depressions and thalwegs. Crops in small field parcels located in such sites (often representing potential sites for implementing nswrm, such as grassed waterways), suffer aeration stress because soil moisture is extraordinarily high. Such a model behavior is not fundamentally implausible (crops can suffer from water logging), but this phenomenon is probably overestimated in our SWAT+ model.

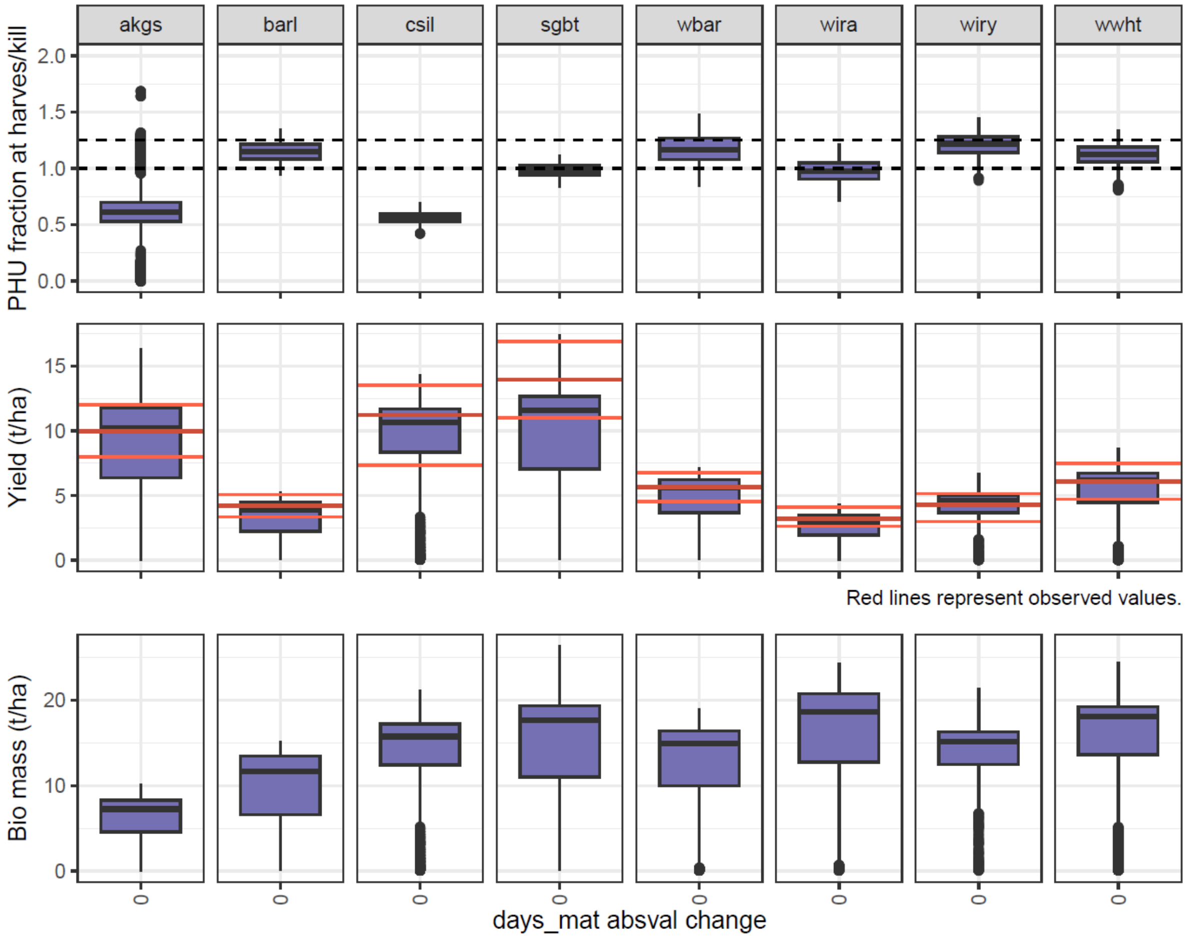


Figure A1.5 Final results of crop yield soft calibration for CS4. Simulated PHU fraction of harvest/kill (top row), crop yields (middle row) and biomass (bottom row).

Table A1.4 Final calibrated values of crop parameters.

| Crop | d_mat* | lai_pot* | harv_idx* | tmp_base* | bm_e* |
|---|---|---|---|---|---|
| barl (spring barley) | -10 | -0.43 | -0.07 | 0 | -0.1 |
| csil (corn silage) | 20 | 0 | 0 | 0 | 0 |
| sgbt (sugar beet) | 80 | 0 | -0.15 | -2 | 3 |
| wbar (winter barley)** | -20 | -0.16 | -0.03 | 0 | -1.79 |
| wwht (winter wheat)** | -50 | -0.12 | 0.09 | 0 | 3.4 |
| wira (winter rape)** *** | -5 | 0.13 | 0.01 | 0 | -1.38 |
| wiry (winter rye)*** | -5 | 0.14 | 0.02 | 0 | -1.09 |
| akgs (farmland grass)**** | -45 | 0 | 0 | 0 | 1.25 |

* Absolute change ** additionally, parameter lai_max2 was adjusted to 0.75 to improve temporal lai development *** added to plant database, mostly based on parameters of canp **** added to plant database, mostly based on parameters of ryeg

The water balance soft calibration provided a routine to estimate the soil evaporation coefficient esco to better fit ET to observed values. The routine included the aquifer return flow (to the stream network) in the calculation of the water yield ratio (wyr). However, we noticed that aquifer return flow was close to zero in the uncalibrated model setup, despite a remarkable annual average groundwater recharge (> 40 mm). This mismatch made us aware that the "default" initialization of aquifer parameters might be inappropriate. Specifically, the combination of flo_min (depth of the groundwater table at which return flow can occur) and dep_wt (the initial depth to water table) were set in a way (flow_min = 5, dep_wt = 10) that the aquifer water storage accumulates over the entire simulation period without releasing water to the channels. Assuming that groundwater recharge and return flow are in equilibrium in the long term (and without major disturbances), we defined dep_wt to be equal with flo_min. After this correction, the soft calibration routine suggested an esco value of 0.95 to meet the reported water yield ratio of 0.27 (KliWES) and further increase ET by approx. 10mm. Yet, for the finetuning of simulated daily discharge inlater hard calibration, we decided to allow esco ranging from 0.5 to 0.95.

Before hard calibration, however, a further round of soft calibration (with 50 simulations) was carried out to fix selected groundwater parameters. In order to match the annual average baseflow rate with the reported value of 111 mm (KliWES), we prevented the loss of groundwater into the deep aquifer by setting rchg_dp to 0 and adjusted revap_co, a parameter controlling the movement of water from the aquifer into the overlying unsaturated zone, to 0.05 as well as bf_max, the baseflow rate at which all streams linked to the aquifer receive groundwater flow, to 0.6. The parameter range for baseflow recession constant alpha was narrowed down to 0.0001 - 0.15 to allow some variation during the following hard calibration.

### 2.3. Hard calibration and validation

CS1 performed the sequential hard calibration workflow, starting with discharge (2500 simulations), then sediment load (500 simulations), and finally total P load (500 simulations).

Discharge calibration included 10 hydrological parameters, of which parameters cn3_swf and latq_co were defined for three different subsets of hrus depending on their initial values (hrus with low, medium, and high initial values of the mentioned parameters). After 2500 calibration runs, we used five objective functions (NSE, KGE, PBIAS, $R^2$ and MAE) to select an ensemble of ten best performing simulations. In our evaluation, each objective function was weighted equally by summing up their individual ranks, whereas the simulation with the minimum rank sum was assumed to perform best.

Calibration results for discharge can be considered very good, with KGE and NSE values up to 0.8 and 0.7, respectively, for gauge Jaenk. Also, for gauges Quitz and Schoeps, discharge was simulated reasonably well during calibration period (Figures A1.6 and A1.7). Unfortunately, the good calibration performance could not be confirmed for the validation period. Here, performance metrics KGE and NSE for gauge Jaenk dropped to values around 0.55 and 0.3, respectively; and PBIAS increased to 30. However, Fig. A1.8 shows that also for the validation period simulated and observed hydrographs match quite well (despite the poor performance metrics). Moreover, performance metrics did not drop similarly for gauge Quitz in model validation (A1.7). We therefore concluded an overall successful calibration for discharge and continued with sediments.

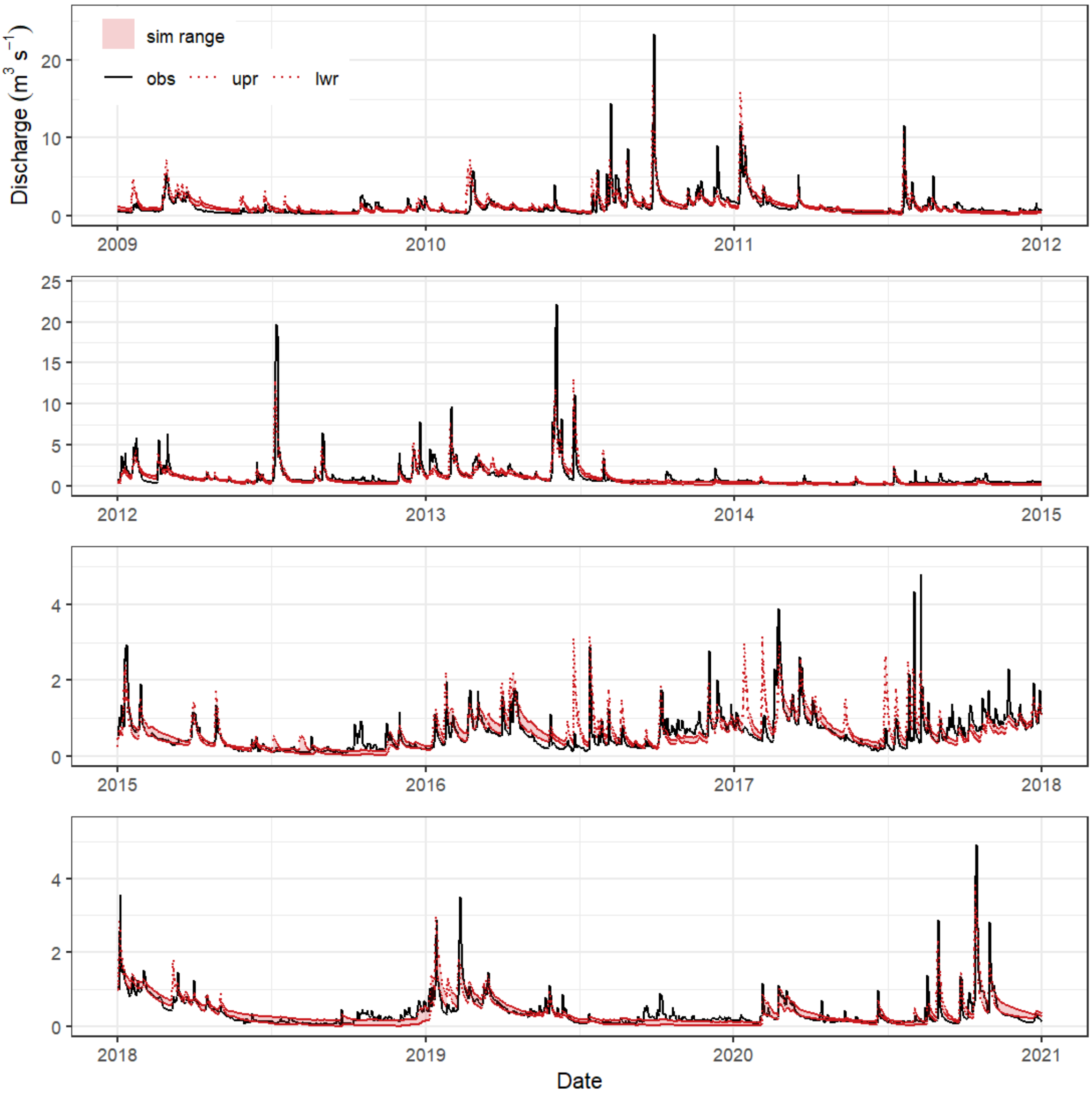


Figure A1.6 Simulated vs. observed daily discharge for flow gauge “Jaenkendorf_1” in CS1 (calibration period). Please note the variable y-axis scale of single subplots.

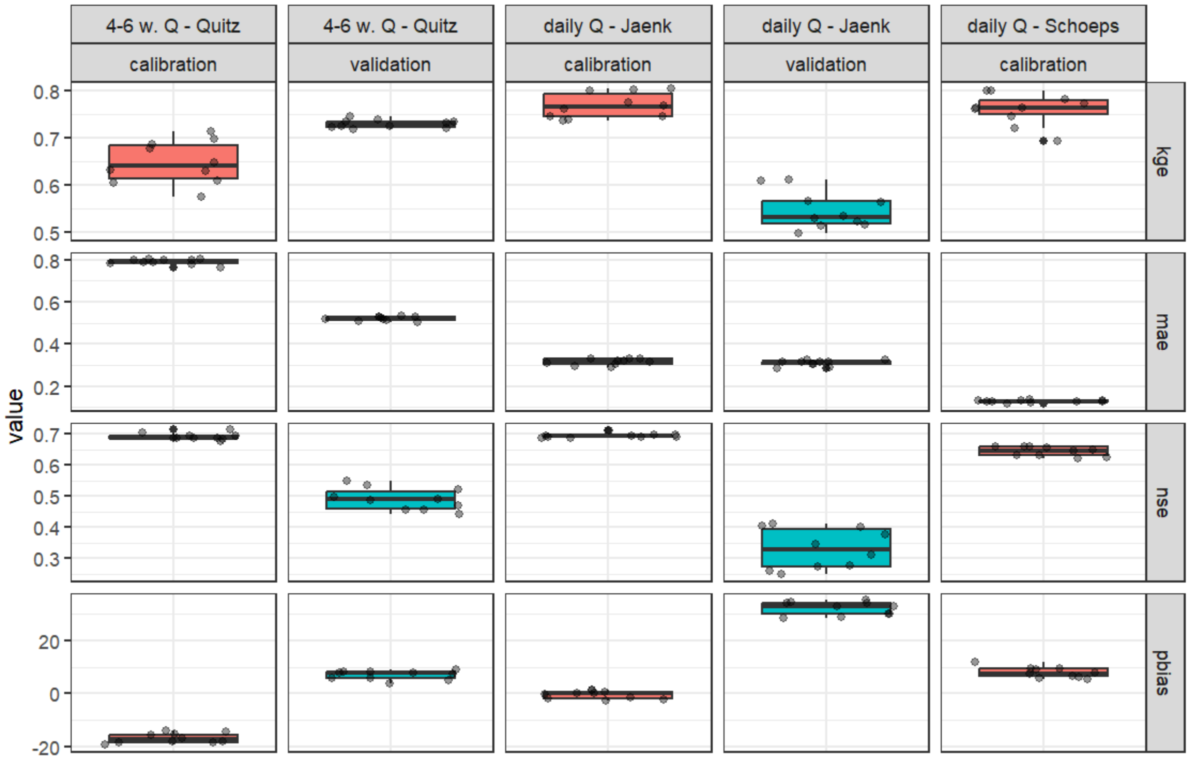


Figure A1.7 Box plots of model performance metrics for simulating daily discharge in calibration and validation period for different gauges (Jaenk = gauge " Jaenkendorf_1", Quiz = gauge "Zufluss_Quitzdorf") in CS1.

Before running the hard calibration for sediments, we manually adjusted parameter adj_pkrt_sed (file parameters.bsn) to match an average sediment loss from cropland of around 4 tons per ha and year. This value was derived from a reference dataset provided by LfULG (2020b). In the current version of SWAT+, adj_pkrt_sed cannot be adjusted using the calibration.cal file. After a few manual trial-and-error simulations, we found that a value of 35 results in plausible sediment loss from cropland hrus (on average 3.5 to 4.5 tons/ha/year across the discharge calibration ensemble). The subsequent variation of seven parameters (mostly addressing channel erosion and sediment transport) in additional 500 model simulations, revealed a very high sensitivity of parameter bedldcoef, for which a very low value (5e-6) had to be defined in order to properly simulate high peaks in sediment load without compromising the overall sediment export out of the catchment (see Figure A1.9). Performance metrics for sediment load were relatively low but still acceptable (Figure A1.10) given the fact that this model output is hard to calibrate due its strong dependence on single storm events.

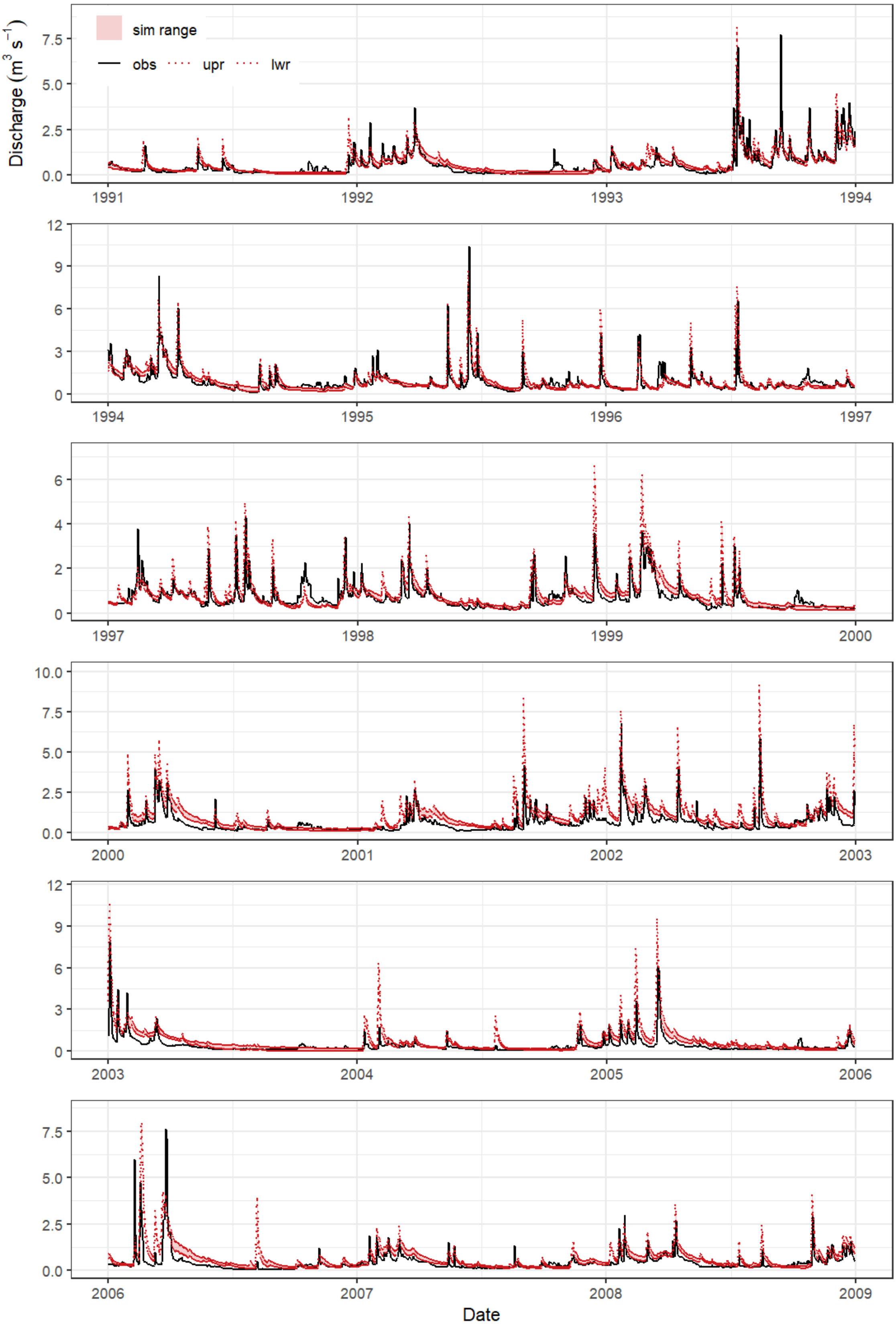


Figure A1.8 Simulated vs. observed daily discharge for flow gauge “Jaenkendorf_1” in CS1 (validation period).

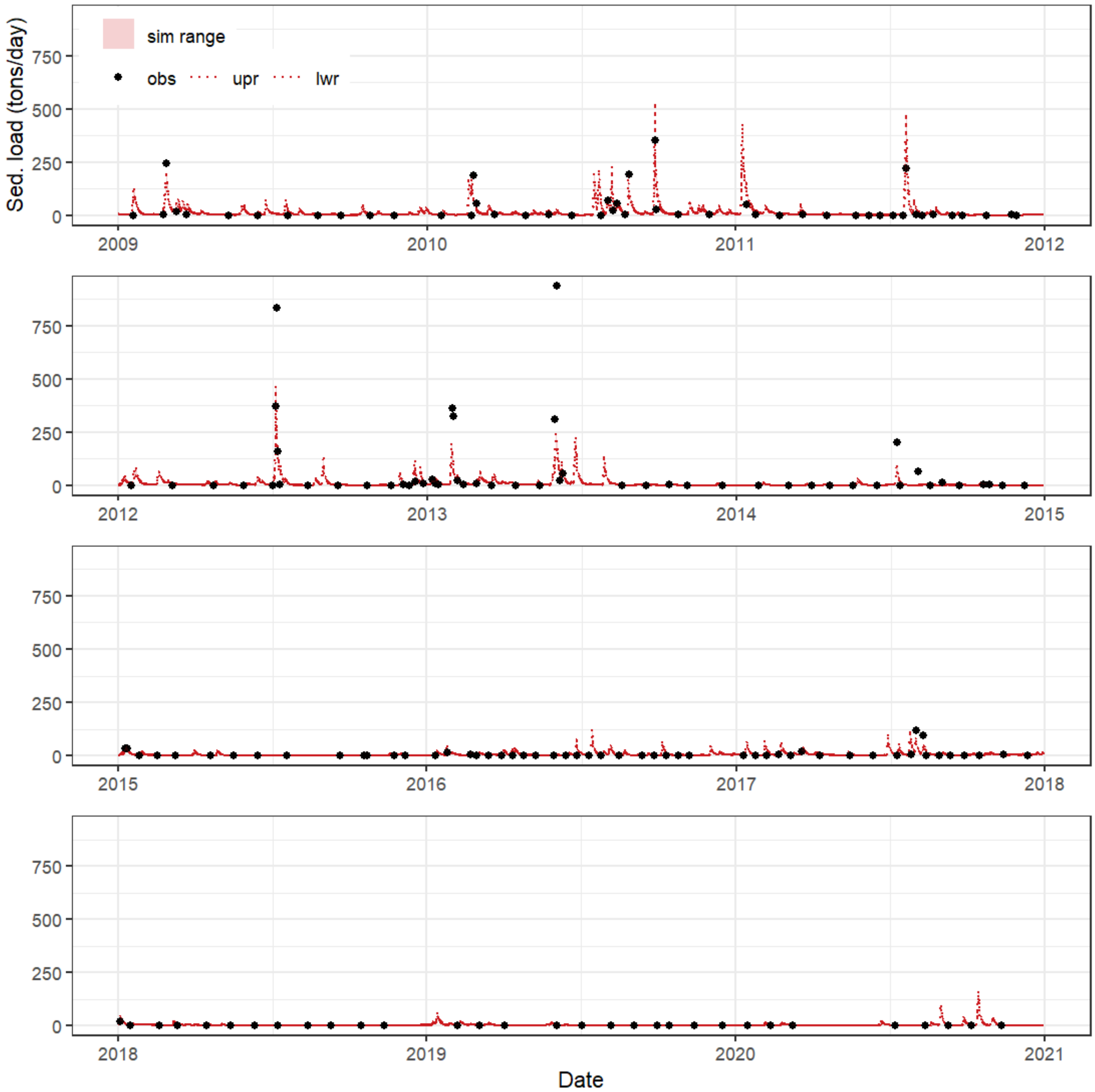


Figure A1.9 Simulated daily vs. observed 4-6 weekly sediment (total suspended solids) load for gauge “Zufluss_Quitzdorf” in CS1 (calibration period).

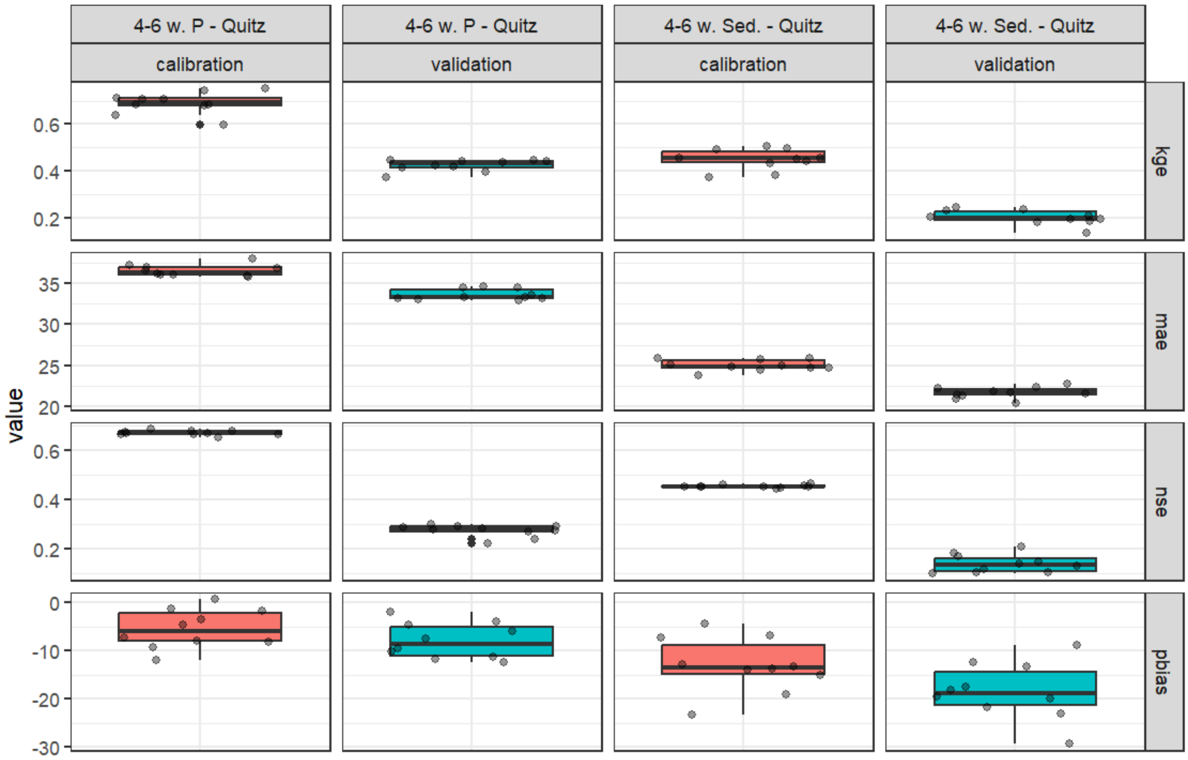


Figure A1.10 Box plots of model performance metrics for simulating 4-6 weekly phosphorus and sediment loads in calibration and validation period for CS1 outlet gauge "Zufluss Quitzdorf".

The last step in hard calibration addressed P loads which is in focus of CS1. We tested three P parameters in 500 additional model simulations: phoskd, psp, pperco. All of them turned out to be somewhat sensitive but the systematic underestimation of P loads (-70 % on average) could not be solved.

We therefore increased our rather conservative P fertilisation rates from 45.5 kg (per ha and year) on agricultural land to 61.4 kg to achieve a PBIAS closer to 0 (cf. Figure A1.10). NSE and KGE also improved to surprisingly high values around 0.7 in the calibration period, confirming a good match between observed and simulated P loads (Figure A1.11). Similar to discharge and sediment loads, model performance for simulating P loads decreased in the validation period, but not below unacceptable values (KGE around 0.4, NSE around 0.3, while the range of PBIAS remained constant, Figure A1.10).

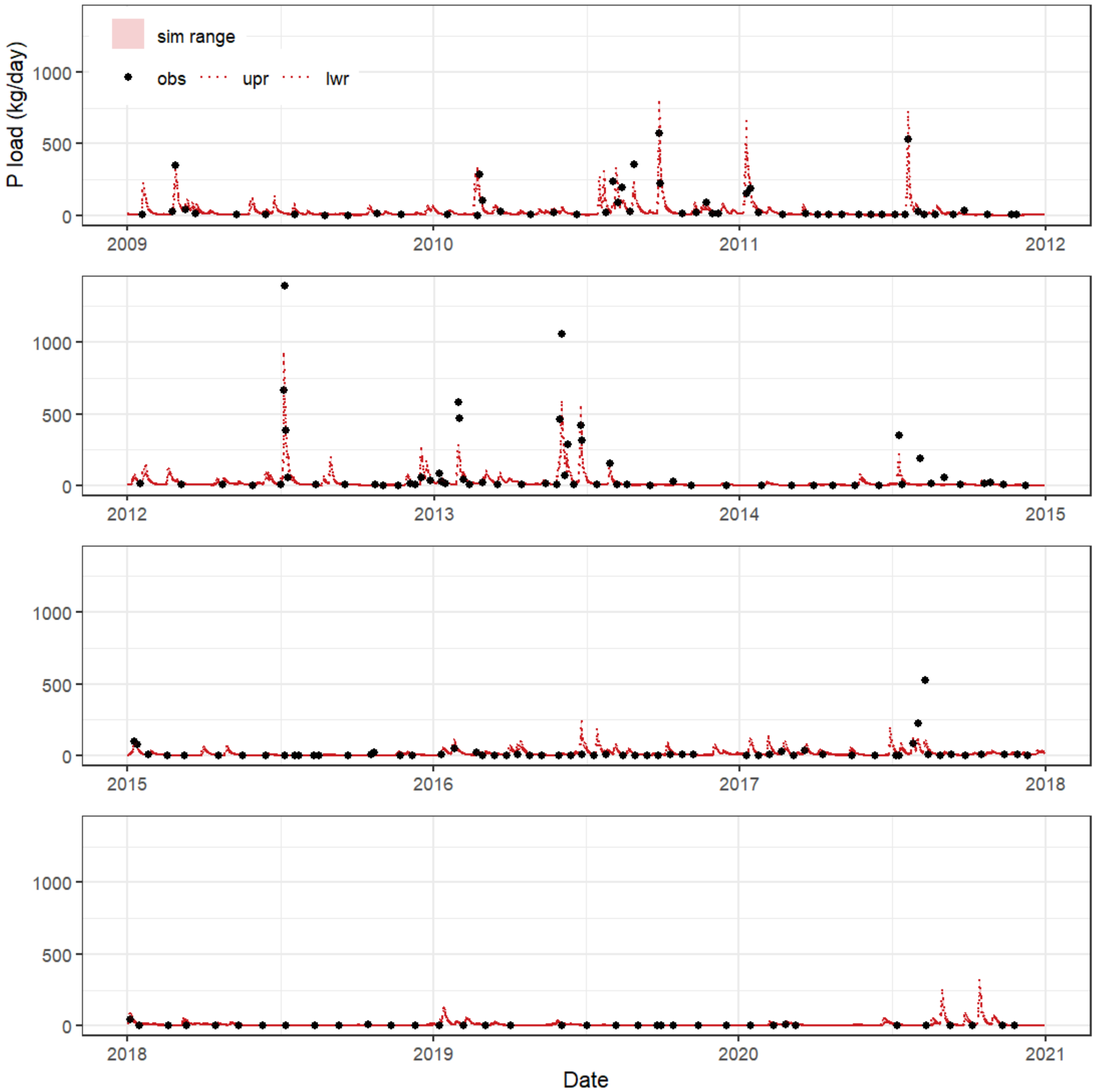


Figure A1.11 Simulated daily vs. observed 4-6 weekly total Phosphorus load for gauge "Zufluss Quitzdorf" in CS1 (calibration period).

Calibrated parameter values for discharge and water quality (phosphorus and sediments are shown in Table A1.5 and A1.6, respectively. Please note that we kept the ten best parameter sets after discharge calibration also for calibrating phosphorus and sediments. Thus, Table A1.6 shows the set of phosphorus and sediment parameters that matched best to discharge calibration ensemble.

Table A1.5: Calibrated discharge parameter values for the selected best ten simulations (cal_1 - cal_10)

| | cal_1 | cal_2 | cal_3 | cal_4 | cal_5 | cal_6 | cal_7 | cal_8 | cal_9 | cal_10 |
|---|---|---|---|---|---|---|---|---|---|---|
| esco.hru* | 0.63 | 0.6 | 0.56 | 0.55 | 0.65 | 0.93 | 0.69 | 0.62 | 0.55 | 0.87 |
| awc.sol** | -0.14 | -0.16 | -0.21 | 0.023 | -0.18 | -0.21 | -0.2 | -0.13 | -0.16 | -0.16 |
| cn2.hru** | 0.11 | 0.1 | 0.083 | 0.093 | 0.086 | 0.11 | 0.091 | 0.091 | 0.1 | 0.095 |
| surlag.bsn* | 1.1 | 1.2 | 1.1 | 1.2 | 1 | 0.85 | 1.2 | 1.2 | 0.97 | 1.1 |
| lat_len.hru* | 14 | -11 | -2.2 | -12 | -27 | -14 | 22 | 26 | 18 | -8.6 |
| latq_co.hru* | 0.59 | 0.77 | 0.7 | 0.96 | 0.39 | 0.28 | 0.84 | 0.83 | 0.22 | 0.18 |
| bd.sol** | 0.18 | 0.071 | 0.17 | 0.24 | -0.12 | 0.19 | 0.15 | 0.21 | 0.18 | 0.15 |
| k.sol** | -0.052 | 2 | 0.68 | -0.46 | 1.9 | 1.9 | 1.5 | -0.13 | 1.9 | 1.5 |
| alpha.aqu* | 0.056 | 0.016 | 0.016 | 0.016 | 0.018 | 0.0069 | 0.0046 | 0.069 | 0.041 | 0.0078 |
| cn3_swf.hru[low]* | 0.6 | 0.62 | 0.62 | 0.58 | 0.55 | 0.52 | 0.74 | 0.67 | 0.67 | 0.7 |
| cn3_swf.hru[mod]* | 0.21 | 0.23 | 0.23 | 0.2 | 0.18 | 0.16 | 0.31 | 0.26 | 0.27 | 0.28 |
| cn3_swf.hru[high]* | 0.064 | 0.078 | 0.082 | 0.051 | 0.033 | 0.01 | 0.16 | 0.11 | 0.12 | 0.13 |
| latq_co.hru[low]* | 0.18 | 0.23 | 0.21 | 0.29 | 0.12 | 0.092 | 0.25 | 0.25 | 0.073 | 0.062 |
| latq_co.hru[mod]* | 0.28 | 0.33 | 0.31 | 0.39 | 0.22 | 0.18 | 0.35 | 0.35 | 0.17 | 0.15 |
| latq_co.hru[high]* | 0.74 | 0.81 | 0.78 | 0.88 | 0.66 | 0.61 | 0.84 | 0.83 | 0.59 | 0.57 |
| cov.rte* | 0.0052 | 0.0052 | 0.0052 | 0.0052 | 0.0052 | 0.0052 | 0.0052 | 0.0052 | 0.0052 | 0.0052 |
| ch_clay.rte* | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 |

* absolute value

* *relative change to initial value (which is variable depending on HRU)

Table A1.6: Calibrated phosphorus and sediment parameter values (these values were combined with all members of the discharge calibration ensemble (cal_1 - cal_10))

| | value |
|---|---|
| cov.rte* | 0.0052 |
| ch_clay.rte* | 68 |
| bedldcoef.rte* | 0.0000058 |
| slope_len.hru* | 38 |
| chs.rte** | -0.22 |
| wd_rto.rte** | 0.16 |
| cherod.rte* | 0.15 |
| phoskd.bsn* | 100 |

| | |
|---|---|
| psp.bsn* | 0.7 |
| pperco.bsn* | 18 |

* change = absolute value

* *relative change to initial value (which is variable depending on HRU)

The simulated water budget of the final model setup (based on parameter set cal_5 which had the highest sum of performance metrics ranks) for the period 2009-2020 is shown in Fig. A1.12. All water balance components for which we had reference data from KliWES (evapotranspiration - et, water yield - wyld, and baseflow - base) showed plausible values.

Overall, the behaviour of the calibrated model has given us confidence to use it for the following nswrm and climate scenario simulations.

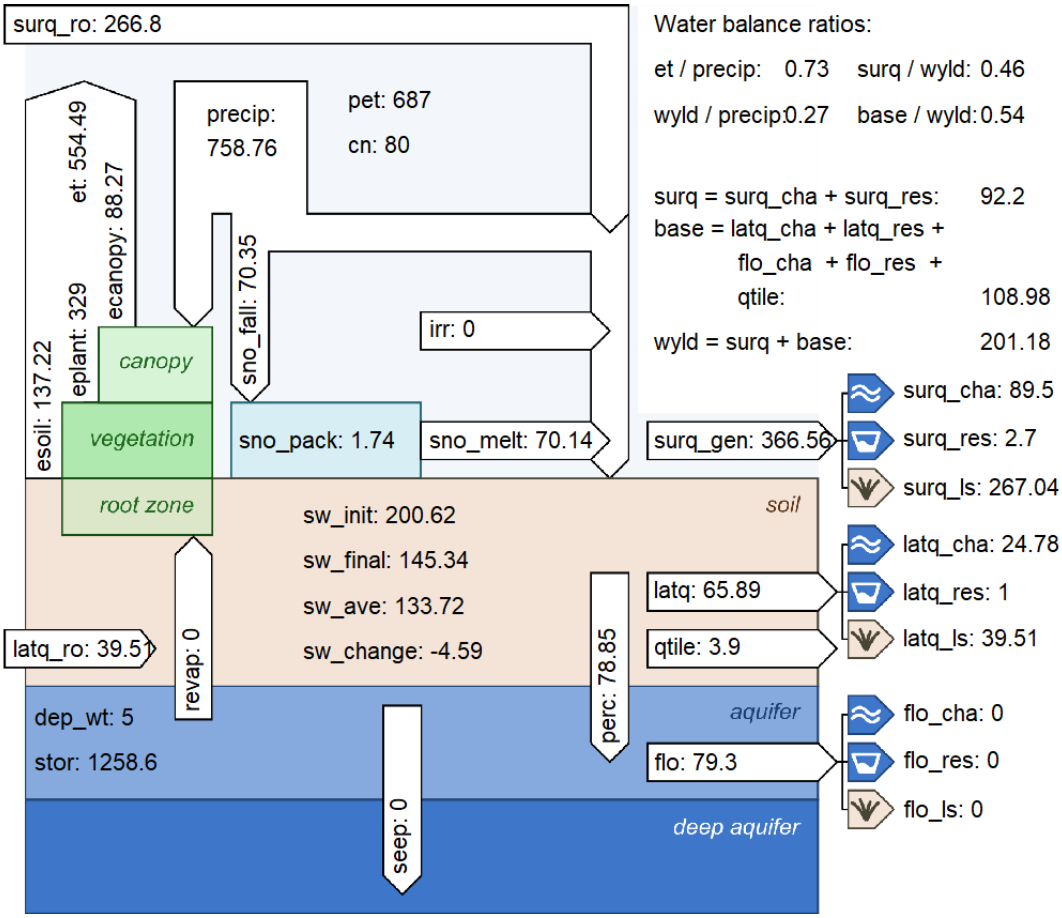


Figure A1.12 Simulated water budget of the final, calibrated model setup for CS1 (years 2009-2020).

## 3. Climate change effects

We used bias-corrected RCM simulations, developed in the WP3 of OPTAIN (Honzak, 2023), as the SWAT+ model forcing in order to assess the effect of climate change on the water balance, nutrient losses and crop yields. We applied all available combinations of six RCMs, three RCPs and three time horizons (1991-2020

- serving as the “baseline”, 2036-2065 - “near future”, 2070-2099 - “end of century”), resulting in a total of 54 model scenarios. More information about the bias correction and climate scenarios can be found in section 2.2.3 of the report as well as in Honzak (2023).

Figure A1.13 shows projected changes in annual and seasonal minimum (Tmin) and maximum (Tmax) temperature as well as precipitation (Prec) for CS1. Note that the time horizons are slightly different than those used in SWAT+ modelling.

A consistent warming pattern emerges, in particular for RCP8.5 in period 2071-2100, for which the projected increase in Tmin and Tmax ranges between 3 and 5 degrees C. The highest magnitude of the warming signal occurs in winter, while the lowest in spring. In contrast, under RCP2.6 the projected change does not generally exceed 1.5 degrees, even at the end of the century. Precipitation projections show a dominant signal of wetter future, in particular under RCP8.5, for which an ensemble median increase equals 16% by the end of the century. Projected changes are higher in winter and spring compared to summer and autumn for all RCPs. A more detailed analysis of climate projections (including other variables) is available at the OPTAIN UFZ cloud https://nc.ufz.de/s/KA9Cr2bbtALGMHr/download. In general, projected changes in wind speed, solar radiation and relative humidity are relatively low, even under RCP8.5, and thus should not contribute a lot to the effect of climate change on the studied indicators.

The following basin-averaged SWAT+ outputs were considered in the analysis: precipitation (PRECIP), snow fall (SNOFALL), snow melt (SNOMLT), potential evapotranspiration (PET), actual evapotranspiration (ET), percolation (PERCO), soil moisture content in the top 300 mm (SW_300) and in the root zone (SW), with SW_5, SW_6, ..., SW_9 referring to root zone soil moisture in months May, June, ..., September, surface runoff (SURQ_CHA), lateral flow (LATQ_CHA), and tile flow (QTILE). The results are presented as box plots in Figure A1.14.

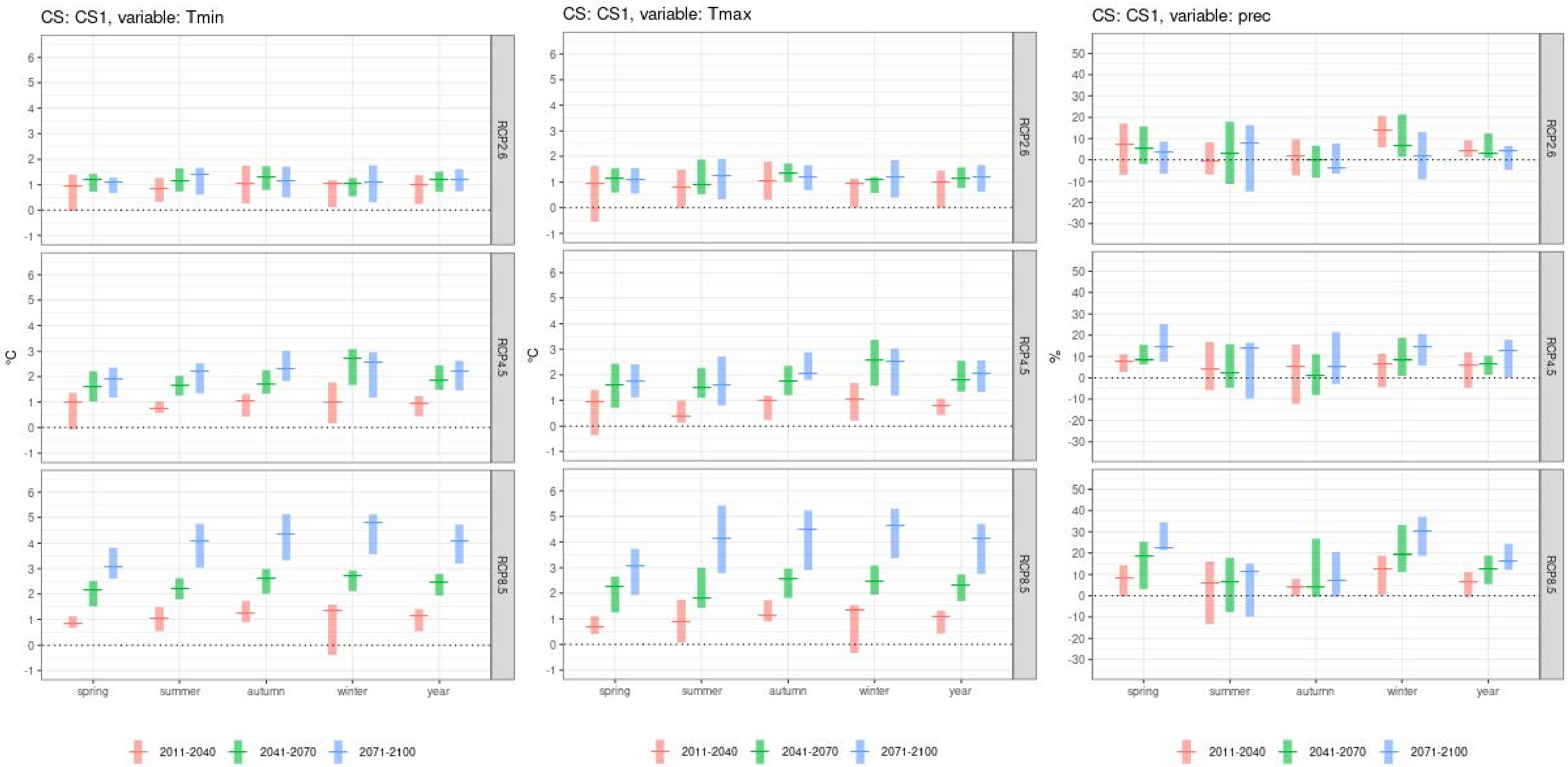


Fig. A1.13 Projected changes in variables Tmin, Tmax and Prec for all RCPs and time horizons for CS1 (Honzak, 2023).

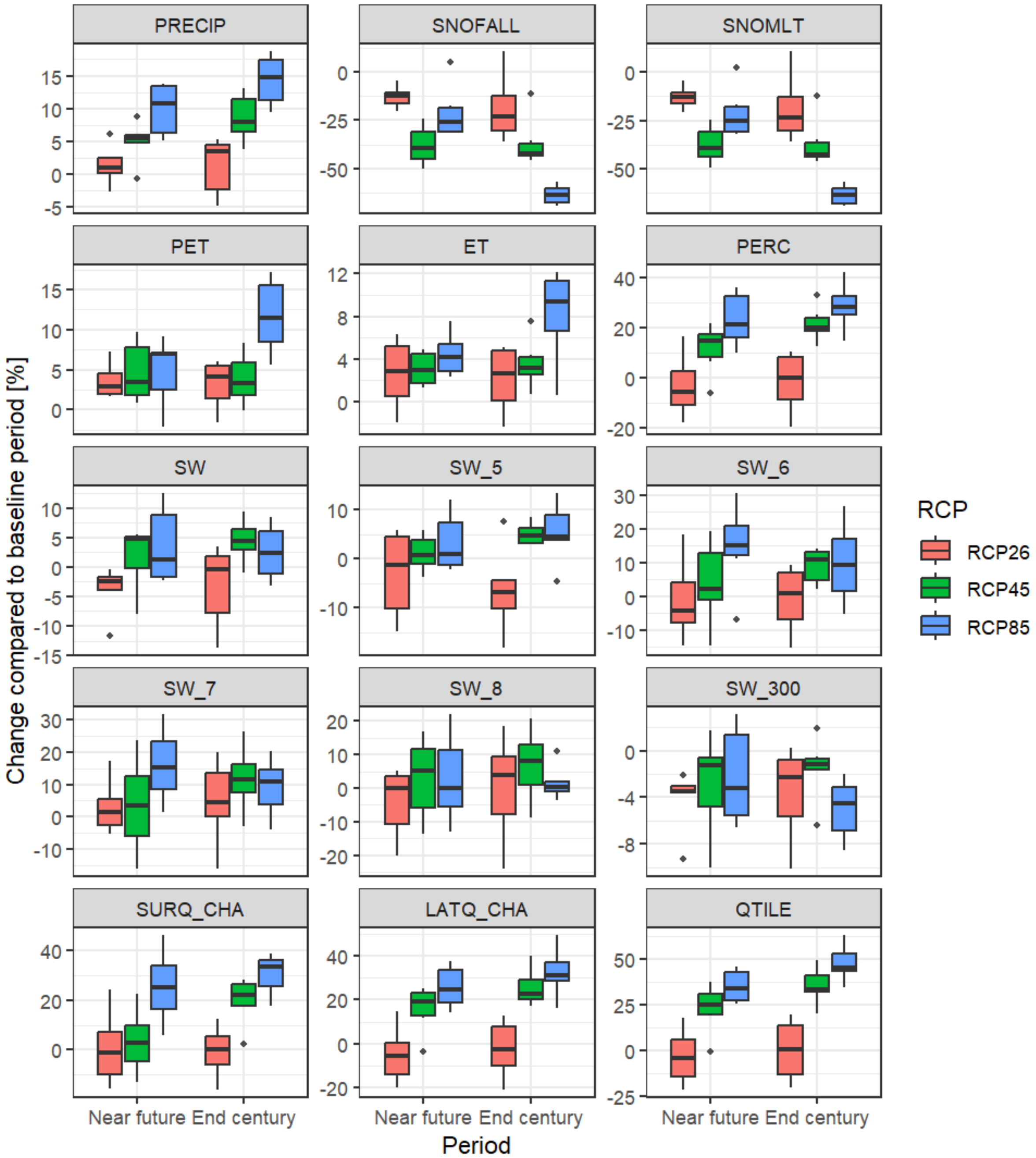


Fig. A1.14 Projected changes in selected basin-averaged water balance components simulated by SWAT+ for CS1.

As discussed before, precipitation is projected to increase with a variable rate, depending on the RCP and future horizon. An increase in winter precipitation combined with a strong warming translates into a strong decrease in snow fall and snow melt, even exceeding 60% under RCP8.5 in the last time horizon. In contrast, the increase in PET triggered by climate warming is rather modest, with an exception of RCP8.5 for which it exceeds 10% for the majority of ensemble members by the end of the century. Changes in ET are also moderate and go predominantly in a positive direction, possibly due to increased availability of water in the soil profile. Percolation increases strongly under RCPs 4.5 and 8.5. Interestingly, changes in the root zone soil moisture (annual average as well as for individual months of the growing season, from May till September) go mostly in an opposite direction to changes in the topsoil soil moisture: while the former is increasing, the latter is decreasing (mostly by less than 5%). Projections of surface runoff are characterised by a high model spread, with a consistent increase (on average more than 20%) only under RCP 8.5. A similar pattern is projected for lateral and tile flow.

The second collection of box plots (Fig. A1.15) includes various indicators referring to daily discharge (Q), where MEAN is the arithmetic mean, MIN_AA and MAX_AA are average annual maximum and minimum values; P95, P90, P50, and P10 express percentiles; and LOW_DAYS and HIGH_DAYS refer to the number of days where discharge is lower than or equal to Q_P05 (low-flow threshold) and higher than Q_P95 (high-flow threshold) of the historical period under RCP 2.6 (averaged across all six RCMs), respectively.

All discharge indicators (low, average and high flows) are mostly projected to increase under RCPs 4.5 and 8.5 while for RCP 2.6 the direction of change is difficult to predict. While the number of days with extremely high discharge almost doubled under RCP 8.5 (+100 %), projected daily discharge did not fall below the low-flow threshold (-100 % across all RCPs and time horizons).

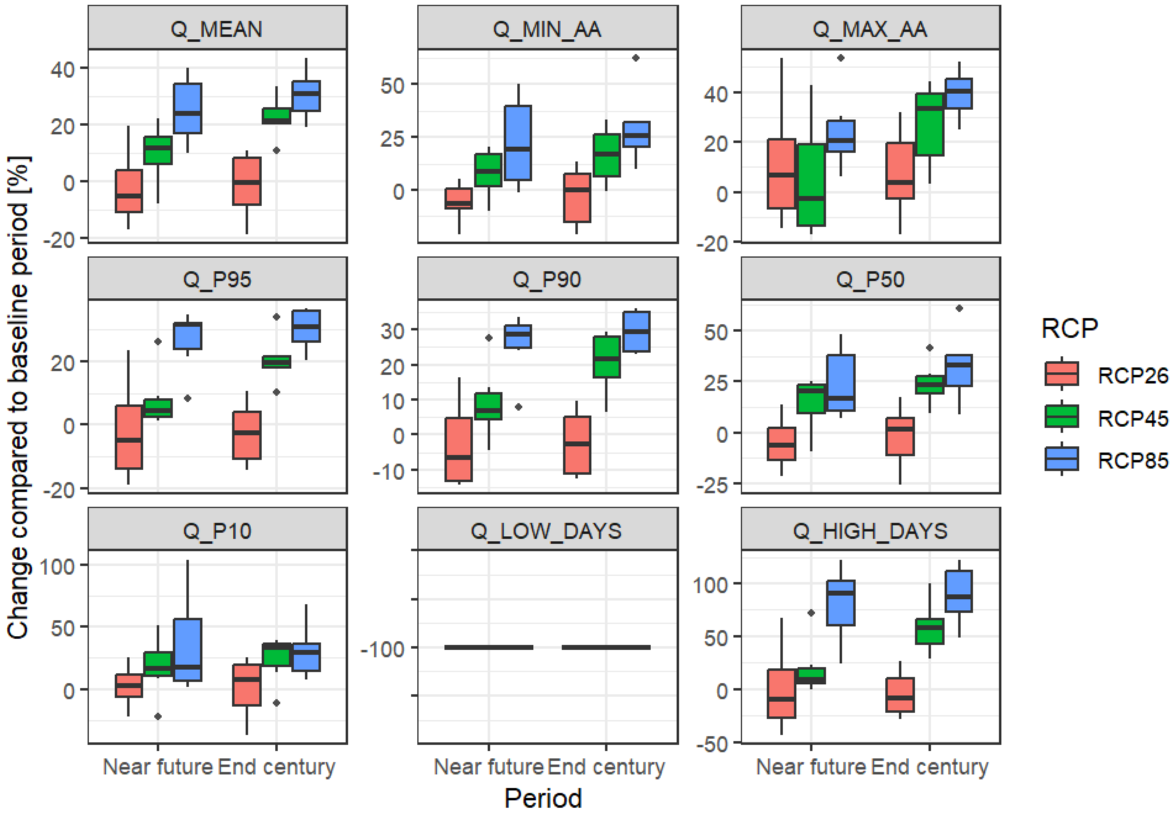


Fig. A1.15 Projected changes in selected streamflow indicators simulated by SWAT+ for CS1.

The third collection of box plots (Fig. A1.16) shows changes in selected water quality indicators. It should be noted that the CS 1 model was not calibrated for nitrogen, for which the reliability of results is thus certainly lower as compared to phosphorus. Under wetter conditions in RCP 4.5 and RCP 8.5, N and P losses are projected to increase significantly, and the same happens to loads carried by the stream. At the same time, however, the frequency of days with high nutrient concentration tends to decrease, most likely due to a dilution effect: In relative terms, the increases in projected loads are less than respective increases in projected discharge). Stream water quality is thus predicted to improve under future climate. And yet, increasing nutrient loads might further foster the blue algae bloom in reservoir Quitzdorf. Nutrient retention in the Schwarzer Schoeps catchment appears to remain an important challenge in the future. The final chapter of Annex 1 will provide insights into how far selected NSWRM might help in this context.

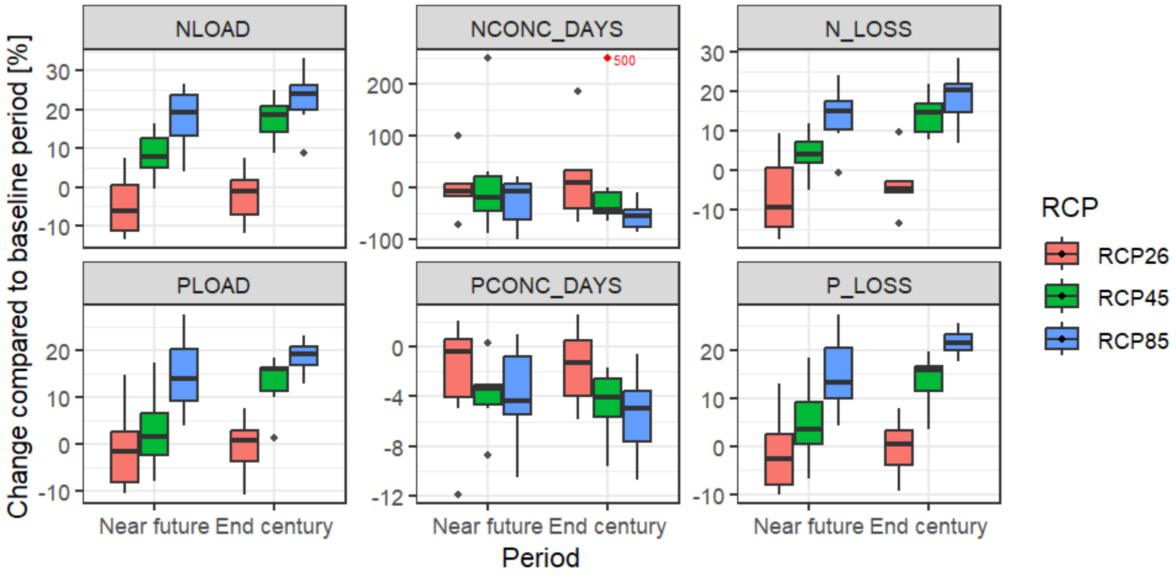


Fig. A1.16 Projected changes in selected water quality indicators simulated by SWAT+ for CS1.

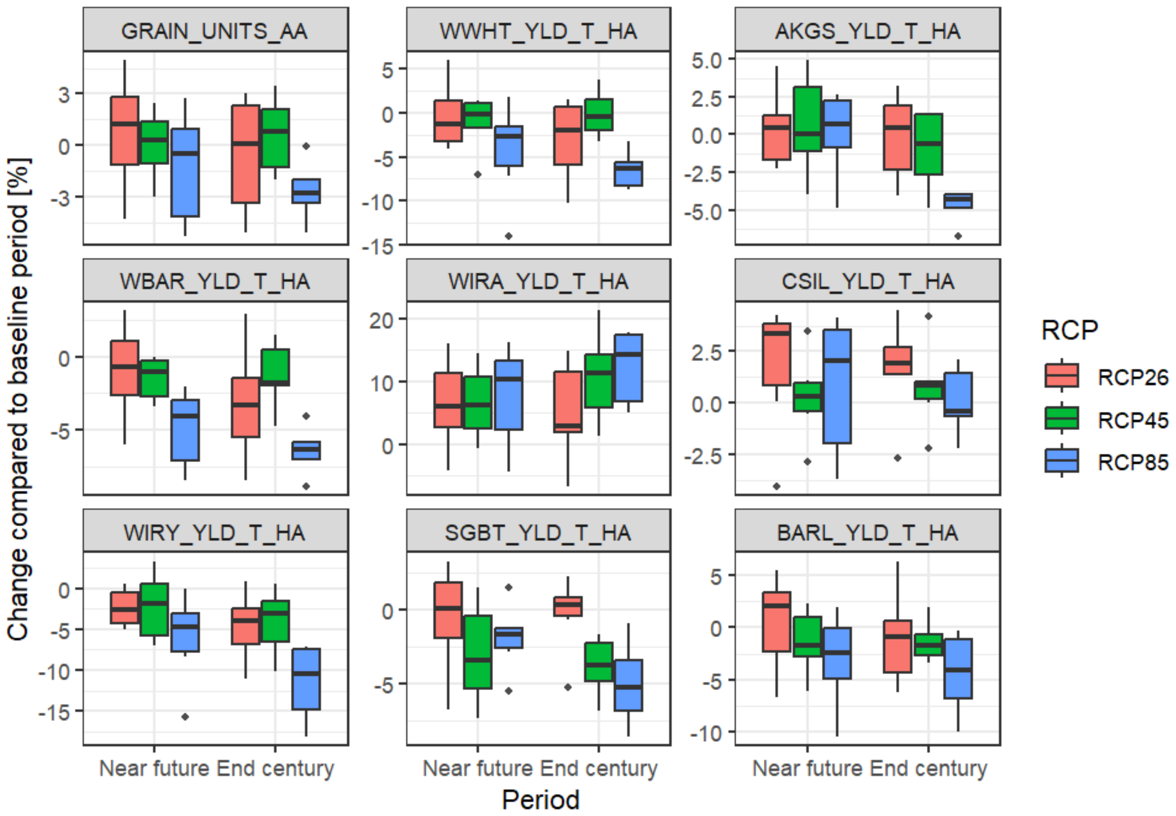


Fig. A1.17 Projected changes in selected crop yields simulated by SWAT+ for CS1.

The fourth collection of box plots presents projections of crop yields (Fig. A1.17). For the majority of crops, a slightly decreasing trend is projected, in particular for winter cereals (winter wheat - WWHT, winter barley - WBAR, and winter rye -

WIRY). The opposite, however, is projected for winter rape (WIRA), with an increase by 5-15% for most cases. Another exception is corn silage (CSIL), where changes are rather low (below 5%) and often go in both directions (similar to farmland grass - AKGS). The indicator grain units sums up all crop yields across the study area and normalised for their respective nutritional value. It shows a slightly decreasing trend only for RCP 8.5, while for RCPs 2.6 and 4.5 the change of direction is difficult to predict. Thus, according to our model simulations, climate change does not appear to pose a huge threat to future crop production in CS1.

## 4. Effectiveness of selected NSWRMs (current climate)

NSWRM effectiveness was simulated for five measures relevant for the German case study: (1) grassed waterways (scenario grassslope), (2) riparian buffers (scenario buffer), (3) hedges (scenario hedge), (4) low tillage combined with cover crops (scenario lowtillcc), and (5) detention ponds (scenario pond). The selection of measures and their potential sites for implementation was done in collaboration with local actors based on the results of the 1st and the 2nd MARG workshop. We investigated measure effectiveness in single scenario runs: One model scenario for each measure, considering all potential sites of implementation (Fig. A1.18), and one additional scenario where all measures were implemented simultaneously (scenario 'all'). Scenario lowtillcc includes a change in the management schedules of selected agricultural fields: a change from normal tillage to low tillage and the inclusion of a cover crop in winter (before planting a summer crop such as corn, spring barley or sugar beet). All other scenarios include straightforward changes of land cover or object type (hru to reservoir for scenario pond). To account for parameter uncertainty, we ran an ensemble of ten model realisations (each with different calibration settings) for each scenario. The results are listed in Table A1.7.

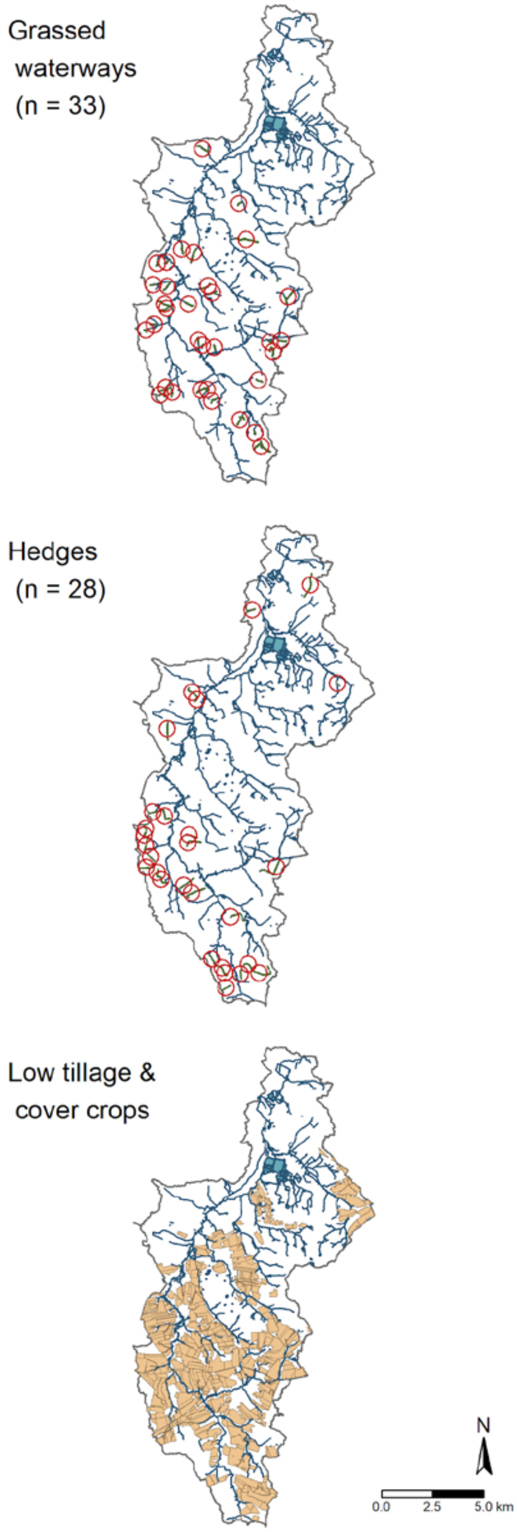


Fig. A1.18 Potential sites for implementing NSWRMs in CS1.

Table A1.7 Results of NSWRM scenarios in CS1. Shown are median values (and in brackets minimum and maximum values) of the model ensemble (n=10) in relative changes (%) compared to status quo (which itself is presented in absolute values).

| Indicator* | statusquo | grassslope | lowtillcc | buffer | hedge | pond | all |
|---|---|---|---|---|---|---|---|
| Nload | 54042 (50733, 55525) | -5.2 (-5.6, -4.9) | -3.1 (-3.8, -2.8) | -1.8 (-1.9, ) | -0.0074 (-0.012, 0.009) | 0.1 (-0.1, 0.33) | -8.9 (-9.3, -8.4) |
| Pload | 7132 (6781, 7769) | -8.5 (-8.7, -8.1) | -8 (-9.3, -6.8) | -2.8 (-2.9, -2.7) | -0.079 (-0.12, -0.064) | 1.1 (0.91, 1.4) | -17 (-18, -16) |
| Sedload | 3376 (3024, 3770) | -36 (-38, -32) | -30 (-32, -29) | -9.5 (-10, -8.2) | -0.25 (-0.36, -0.19) | -5.8 (-6.8, -4.8) | -51 (-54, -47) |
| Q_max | 15 (12, 17) | -0.37 (-0.49, -0.26) | -10 (-12, -9.4) | -0.14 (-0.19, -0.088) | -0.28 (-0.36, -0.22) | 0.74 (0.6, 0.86) | -8.6 (-9.2, -8) |
| Q_max_aa | 6.5 (5.5, 7.2) | -0.47 (-0.73, -0.34) | -13 (-15, -11) | -0.093 (-0.14, -0.015) | -0.39 (-0.42, -0.31) | 0.9 (0.84, 0.98) | -11 (-13, -9.7) |
| Q_p95 | 2.5 (2.3, 2.6) | 0.02 (-0.39, 0.2) | -0.056 (-1.5, 0.79) | 0 (-0.078, 0.081) | 0 (-0.28, 0.21) | 0.24 (-0.33, 0.39) | 0 (-1, 1.2) |
| Q_p90 | 1.8 (1.6, 1.9) | 0.086 (-0.27, 0.22) | -0.25 (-1.2, 0.38) | -0.027 (-0.16, 0.11) | 0.083 (-0.27, 0.34) | 0.029 (-0.33, 0.49) | -0.42 (-1.5, 0.44) |
| Q_p50 | 0.59 (0.54, 0.62) | 0 (-0.56, 0.18) | -0.0048 (-1.7, 0.68) | 0 (-0.37, ) | 0 (-0.37, 0.17) | 0 (-0.19, 0.34) | -0.51 (-1.9, 0.5) |
| Q_p10 | 0.12 (0.069, 0.2) | -1.7 (-3.7, 0) | -3.1 (-6.1, -1.2) | 0 (-1.4, ) | 0 (, 0.87) | 0 (, 0.83) | -3 (-8.5, -1.2) |
| Q_p05 | 0.07 (0.041, 0.17) | -0.71 (-2.9, 0) | -2.9 (-7.1, -0.6) | 0 (-1.4, ) | 0 (-1.4, 1.5) | 0 (, 1.5) | -3.8 (-8.9, -1.2) |
| Q_min | 0.032 (0.019, 0.11) | 0 (-4.8, ) | 0 (-4.8, 1.2) | 0 (-4.5, ) | 0 (-4.5, ) | 0 (-4.5, ) | -0.46 (-4.8, 1.2) |
| Q_min_aa | 0.18 (0.14, 0.3) | 0.17 (0, 1.1) | 1.7 (1.1, 3.3) | 0 (-0.74, ) | 0 (, 0.65) | 0 (-0.74, 0.56) | 1.9 (0.56, 3.4) |
| Q_maxmin | 470 (135, 778) | 0.18 (-0.61, 4.1) | -9.7 (-15, -7.2) | 0.12 (-0.22, 0.86) | -0.15 (-0.56, 1.2) | 1.1 (0.39, 2.2) | -7.1 (-9.7, -3.1) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Q_maxmin_aa | 35 (22, 51) | -0.74 (-1.6, -0.64) | -14 (-17, -13) | -0.13 (-0.16, -0.012) | -0.47 (-1.3, -0.34) | 1 (0.54, 1.4) | -13 (-15, -11) |
| Q_low_days | 0.05 (0.049, 0.051) | 2 (-2, 6) | 8.1 (4, 16) | 0.98 (0, 2) | 0 (-2, 2) | -0.98 (-4.1, 0) | 11 (4, 27) |
| Q_high_days | 0.05 (, ) | 0 (, ) | 0 (-4, 2) | 0 (, ) | 0 (, 2) | 0 (, 2) | 0 (-2, 2) |
| Nconc_days | 0.25 (0.22, 0.34) | -8.1 (-20, -4.5) | -5.7 (-10, -2.8) | -3.4 (-7.6, -1.2) | 0 (-0.59, 0.86) | -0.15 (-4.2, 1.2) | -13 (-26, -8.1) |
| Pconc_days | 0.76 (0.7, 0.86) | -5.8 (-7.5, -2.8) | -6.2 (-7.7, -2.2) | -1.5 (-1.9, -0.58) | 0.06 (-0.14, 0.14) | 1.1 (0.79, 1.6) | -13 (-15, -5.2) |
| Sedconc_days | 0.7 (0.6, 0.78) | -21 (-27, -17) | -17 (-20, -12) | -3.9 (-4.5, -3.2) | 0.29 (0, 0.66) | -3.3 (-5.1, -2.5) | -38 (-45, -31) |
| N_loss | 32 (28, 34) | -5 (-5.3, -4.7) | -13 (-23, -11) | -0.92 (-1, -0.86) | -1.4 (-1.7, -1.2) | -1.5 (-1.8, -1.3) | -20 (-29, -17) |
| P_loss | 5.3 (5.1, 6) | -5.8 (-6, -5.3) | -23 (-25, -20) | -0.99 (-1, -0.92) | -2.2 (, -2) | -2.2 (-2.3, -2.1) | -30 (-32, -27) |
| Sed_loss | 3.2 (2.9, 3.6) | -26 (, -24) | -58 (-59, -56) | -3.2 (-3.4, -3) | -7.1 (-7.2, -6.8) | -7.7 (-7.8, -7.4) | -75 (-76, -73) |
| N_loss_ratio | 0.15 (0.13, 0.16) | -4.4 (-4.7, -3.9) | -13 (-22, -11) | -0.67 (-1.3, -0.63) | -1 (-1.4, -0.65) | -1.3 (-1.4, -0.67) | -19 (-28, -16) |
| P_loss_ratio | 0.093 (0.089, 0.1) | -5 (-5.6, -4) | -22 (-25, -20) | -1.1 (, 0) | -1.5 (-2.2, -0.99) | -1.5 (-2.2, -0.99) | -29 (-30, -26) |
| sw | 134 (113, 141) | 0.088 (0.065, 0.16) | 5 (4.1, 5.3) | 0.0063 (0.00078, 0.016) | 0.072 (0.048, 0.16) | 0.065 (0.042, 0.15) | 5 (4.1, 5.4) |
| perc | 79 (61, 86) | 0.088 (0.068, 0.28) | 3 (2.4, 4.3) | -0.002 (-0.01, 0.01) | 0.15 (0.11, 0.41) | 0.15 (0.11, 0.39) | 3.2 (2.5, 4.4) |
| sw_5_6_7_8_9 | 101 (82, 108) | 0.15 (0.12, 0.23) | 6.6 (5.6, 7.1) | 0.0087 (0, 0.022) | 0.092 (0.059, 0.2) | 0.082 (0.049, 0.18) | 6.6 (5.6, 7.2) |
| sw_5 | 117 (92, 123) | 0.09 (0.07, 0.15) | 5.1 (4, 5.5) | 0.0026 (-0.0037, 0.01) | 0.14 (0.12, 0.23) | 0.13 (0.11, 0.21) | 5.2 (4.1, 5.7) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| sw_6 | 93 (74, 99) | 0.16 (0.13, 0.24) | 6.6 (5.5, 7) | 0.0027 (-0.0068, 0.014) | 0.14 (0.11, 0.25) | 0.13 (0.1, 0.23) | 6.7 (5.6, 7.2) |
| sw_7 | 88 (72, 94) | 0.23 (0.18, 0.32) | 7.6 (6.6, 8.2) | 0.021 (0.011, 0.038) | 0.11 (0.073, 0.23) | 0.1 (0.061, 0.21) | 7.7 (6.6, 8.4) |
| sw_8 | 100 (84, 108) | 0.16 (0.12, 0.25) | 7.3 (6.4, 8) | 0.012 (0.003, 0.028) | 0.042 (0.0061, 0.16) | 0.033 (-0.003, 0.14) | 7.3 (6.3, 8.1) |
| sw_9 | 107 (89, 116) | 0.14 (0.1, 0.22) | 6.8 (5.9, 7.5) | 0.0078 (-0.001, 0.024) | 0.025 (-0.01, 0.14) | 0.016 (-0.018, 0.12) | 6.7 (5.8, 7.5) |
| grain_units_aa | 61216 (59698, 62918) | -0.52 (-0.62, -0.5) | -0.078 (-0.46, 0.49) | -0.18 (-0.19, -0.17) | -0.29 (-0.31, -0.26) | -0.29 (-0.31, -0.26) | -0.96 (-1.3, -0.48) |
| crops_ha_aa | 9825 (, ) | -0.81 (, ) | -0.0053 (, ) | -0.22 (, ) | -0.41 (, ) | -0.41 (, ) | -1.4 (, ) |
| wwht_ha | 2338 (, ) | -0.94 (, ) | 0 (, ) | -0.2 (, ) | -0.45 (, ) | -0.45 (, ) | -1.6 (, ) |
| akgs_ha | 2315 (, ) | -0.75 (, ) | -0.045 (, ) | -0.29 (, ) | -0.23 (, ) | -0.23 (, ) | -1.3 (, ) |
| wbar_ha | 1436 (, ) | -0.78 (, ) | 0.018 (, ) | -0.2 (, ) | -0.6 (, ) | -0.6 (, ) | -1.6 (, ) |
| wira_ha | 1398 (, ) | -0.92 (, ) | 0 (, ) | -0.24 (, ) | -0.52 (, ) | -0.52 (, ) | -1.7 (, ) |
| csil_ha | 1288 (, ) | -0.74 (, ) | 0.02 (, ) | -0.21 (, ) | -0.4 (, ) | -0.4 (, ) | -1.3 (, ) |
| wiry_ha | 608 (, ) | -0.47 (, ) | 0 (, ) | -0.17 (, ) | -0.21 (, ) | -0.22 (, ) | -0.85 (, ) |
| sgbt_ha | 272 (, ) | -0.39 (, ) | 0 (, ) | -0.17 (, ) | -0.54 (, ) | -0.55 (, ) | -1.1 (, ) |
| barl_ha | 169 (, ) | -1.5 (, ) | 0 (, ) | -0.095 (, ) | -0.14 (, ) | -0.14 (, ) | -1.7 (, ) |
| wwht_yld_t_ha | 5.8 (5.5, 5.9) | 0.17 (, 0.35) | 1 (0.52, 1.7) | 0 (, 0.18) | 0.17 (0, 0.18) | 0.17 (0, 0.18) | 1.6 (1, 2.2) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| akgs_yld_t_ha | 2.8 (2.7, ) | 0 (, 0.37) | 0 (-0.37, 0.37) | 0 (, ) | 0 (, 0.37) | 0 (, 0.37) | 0.36 (0, 0.74) |
| wbar_yld_t_ha | 5.7 (5.6, 5.9) | 0.35 (0.17, 0.36) | -0.26 (-0.89, 0.71) | 0 (, 0.18) | 0.18 (0.17, 0.35) | 0.18 (0.17, 0.35) | 0.61 (-0.18, 1.2) |
| wira_yld_t_ha | 3.2 (3.1, 3.3) | 0.31 (0, ) | 0.62 (0.31, 1.6) | 0 (, ) | 0 (, 0.31) | 0 (, 0.31) | 1.2 (0.93, 1.9) |
| csil_yld_t_ha | 11 (, ) | 0.27 (0.18, 0.37) | -0.79 (-1, -0.36) | 0.091 (0, 0.093) | 0.14 (0.089, 0.19) | 0.18 (0.089, 0.19) | -0.18 (-0.46, 0.089) |
| wiry_yld_t_ha | 4.3 (4.2, ) | 0.23 (0, 0.24) | 0.23 (0, 0.48) | 0 (, ) | 0 (, 0.24) | 0 (, 0.24) | 0.58 (0.47, 0.72) |
| sgbt_yld_t_ha | 12 (11, ) | 0.26 (0.16, ) | -2.5 (-3.1, -1.9) | 0 (, 0.088) | 0.26 (0.17, 0.35) | 0.26 (0.17, 0.35) | -2 (-2.5, -1.4) |
| barl_yld_t_ha | 4.1 (3.7, ) | 0.49 (0.25, 0.5) | -2.8 (-3.7, -0.81) | 0 (, ) | 0 (, 0.24) | 0 (, 0.24) | -2.2 (-2.9, -0.27) |

*Indicators *Nload*, *Pload*, and *Sedload* refer to annual average loads of N (kg), P (kg), and sediments (tons). Indicators starting with *Q* refer to daily discharge outputs, where *max* and *min* are total maximum and minimum, *max_aa* and *min_aa* average annual maximum and minimum values; *maxmin* and *maxmin_aa* are respective max/min ratios; p95, p90, p50, p10 and p05 refer to percentiles; *days* refers to the number of days where certain quality thresholds cannot be complied with (*Q_low* and *Q_high* are *p05* and *p95* of the status quo, *Nconc* = 2.3 mg/l, *Pconc* = 0.082 mg/l, Sedconc = 50 mg/l); *loss* = total loss from cropland (kg), *loss_ratio* = loss/input ratio, *sw* = soil water content as annual or periodical average (e.g. *sw_5* = *sw* for May); *perc* = percolation; *grain_units_aa* and *crops_ha_aa* are annual average sums of grain units and ha of total cropland, followed by crop-specific area (*_ha*) and yields (*_t_ha*).

Among all NSWRMs investigated in CS1, low tillage combined with cover crops (scenario lowtillcc) had, by far, the highest impact on catchment hydrology. By reducing maximum flows while increasing minimum flows and soil moisture, this measure turned out to be very effective for water retention. The strong impact found for scenario lowtillcc was not surprising as it includes the largest area of implementation (31 % of total watershed area). The simulated impact on low-percentile flows, p05 and p10, however, was negative, resulting in a higher number of days where discharge fell below the reference lowflow threshold (p05 of the status quo simulation). This appears contradictory and requires a more detailed analysis of model outputs. Grassed waterways (scenario grassslope) had a similar, yet smaller, negative impact on lowflow. Riparian buffer (scenario buffer), hedgerows along contours (scenario hedge), and detention ponds (scenario pond) had a negligible overall impact on catchment hydrology.

All simulated NSWRMs reduced the loss of soil and nutrients from agricultural fields. Here again, low tillage combined with cover crops was most effective, with a soil loss reduction by more than 50 % compared to the status quo. Total N loss and total P loss were reduced by 23 % and 13 %, respectively. This resulted in reduced loads of sediment (-30 %), P (-8 %), and N (-3%) as well as less days with high concentrations of these constituents at the watershed outlet. The positive impact on water quality was even larger for grassed waterways although here the reduction of nutrient losses from fields was lower (which is another contradiction that requires a more detailed investigation of model outputs). The largest impact on nutrient retention on agricultural land and respective improvement of stream water quality can be observed when all NSWRM are implemented at the same time (scenario 'all'). While this is not surprising, it is important to note that the combined effect is not equal to the sum of single scenario effects; often it is slightly smaller because the impact of one measure can superimpose the impact of other measures. This can easily be seen from Fig. A1.21 for simulated soil loss and sediment loads.

Implementing NSWRM might imply losses of cropland and crop yields. In the case of CS1, structural measures (grassed waterways, hedges, buffers, and ponds) take up only a few percent of cropland. The increase in productivity (crop yield per ha) for these measure scenarios is an artefact of our modelling approach: Structural measures are usually defined as small land objects, often located in flow concentration pathways (e.g. erosive thalwegs). Because of their location, these small land objects receive an above-average amount of water from neighbour fields, resulting in saturated soils and aeration stress throughout the year. When taken out of production (scenario case), overall productivity increases for structural measures. For the management scenario lowtillcc, in contrast, both increases (in particular for winter wheat - wwht) and decreases (in particular for sugarbeet - sgbt - and spring barley - barl) were predicted. Similar to climate change (chapter 3 of Annex 1), the overall impact on crop production is rather low (-1 % when all measures are implemented at the same time).

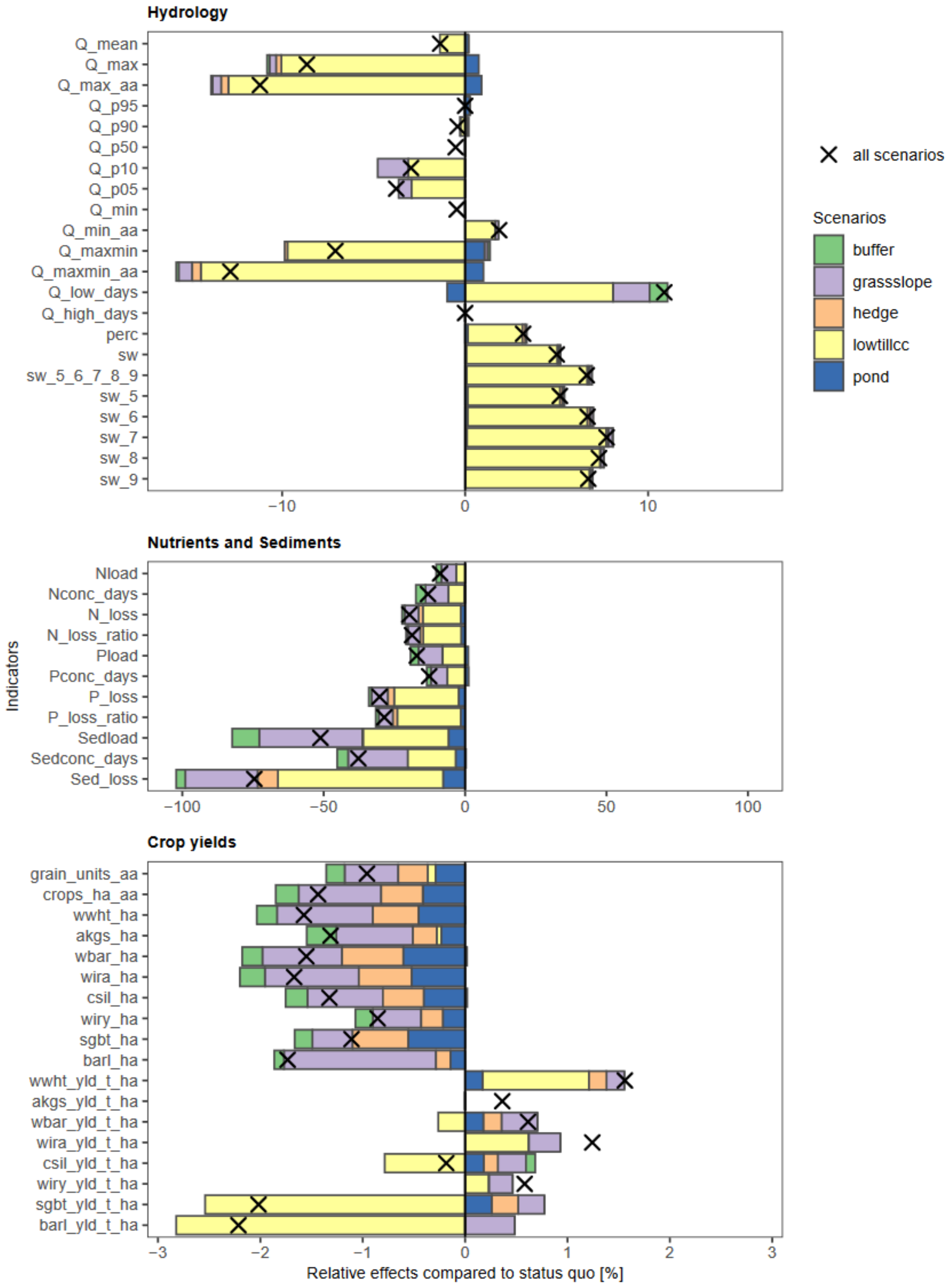


Fig. A1.19 Effectiveness of NSWRM scenarios on indicators (described below Table A1.5) related to the catchment hydrology, nutrient and sediment loads, and crop yields. The stacked bars illustrate the relative effect of an NSWRM scenario to the status quo. Each bar represents the median effect of a measure scenario which results from an ensemble of SWAT model setups. The X symbols show the relative effect of the case when all potential NSWRMs were activated in the catchment. The bars of the NSWRM scenarios were stacked to provide a comparison to the effect of all measures being implemented.

Despite the undesired model behavior of saturated soils in small land objects along flow concentration pathways, results on measure effectiveness appear mostly plausible.

Figures A1.20 and A1.21 illustrate the spatial impact of measures with our modelling approach on the example of scenarios grassslope and lowtillcc (even though these results were generated with an uncalibrated test model for a small head watershed of the study area). Activating grassed waterways led to substantial reductions in surface runoff (Figures A1.20). The reductions were observed for the sites where grassed waterways were activated, but also in downslope neighbouring fields (if the outlet of a grassed waterway is not directly linked with the channel network). Reducing surface runoff means also reducing soil erosion and loss of phosphorus (P) on the affected sites, consequently resulting in reduced P loads in the channel network. This (expected) behaviour could be confirmed for all grassed waterways, albeit to different extents which might be attributed to different conditions (in particular soil properties and the status quo / reference crop management) existing for the respective sites.

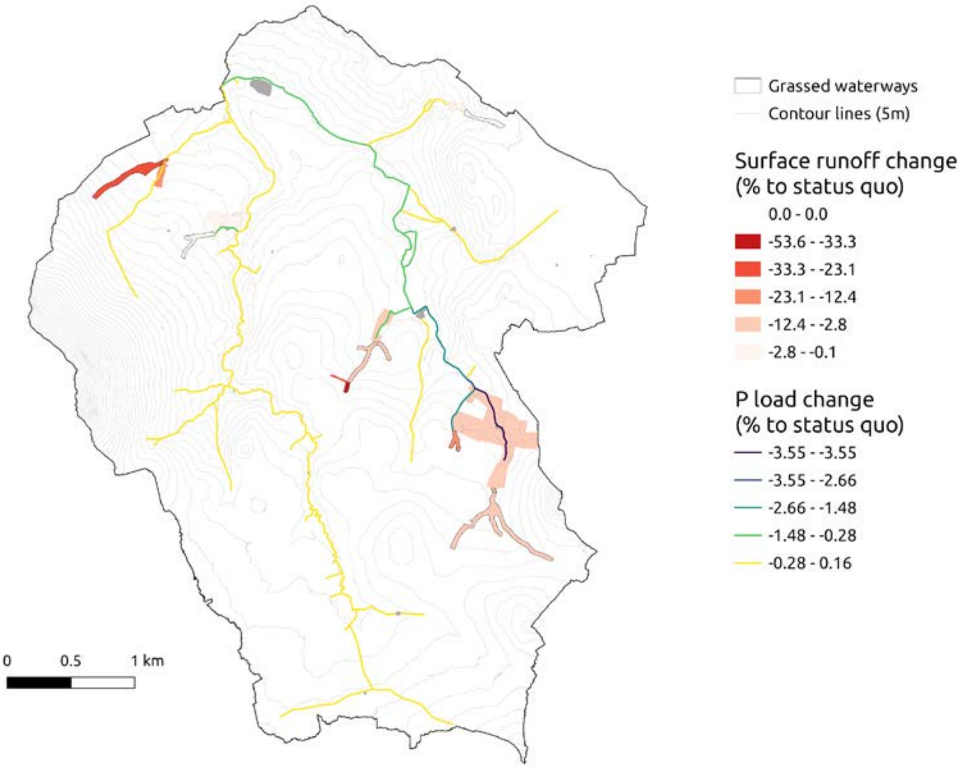


Figure A1.20: Simulated impact of grassed waterways (scenario grassslope) on surface runoff and channel P loads using an uncalibrated test model.

The same principle of effectiveness can be observed for scenario lowtillcc but here for whole field parcels which included the respective change in soil and crop management, with smaller effects also on connected neighbour parcels without scenario management (Figure A1.21).

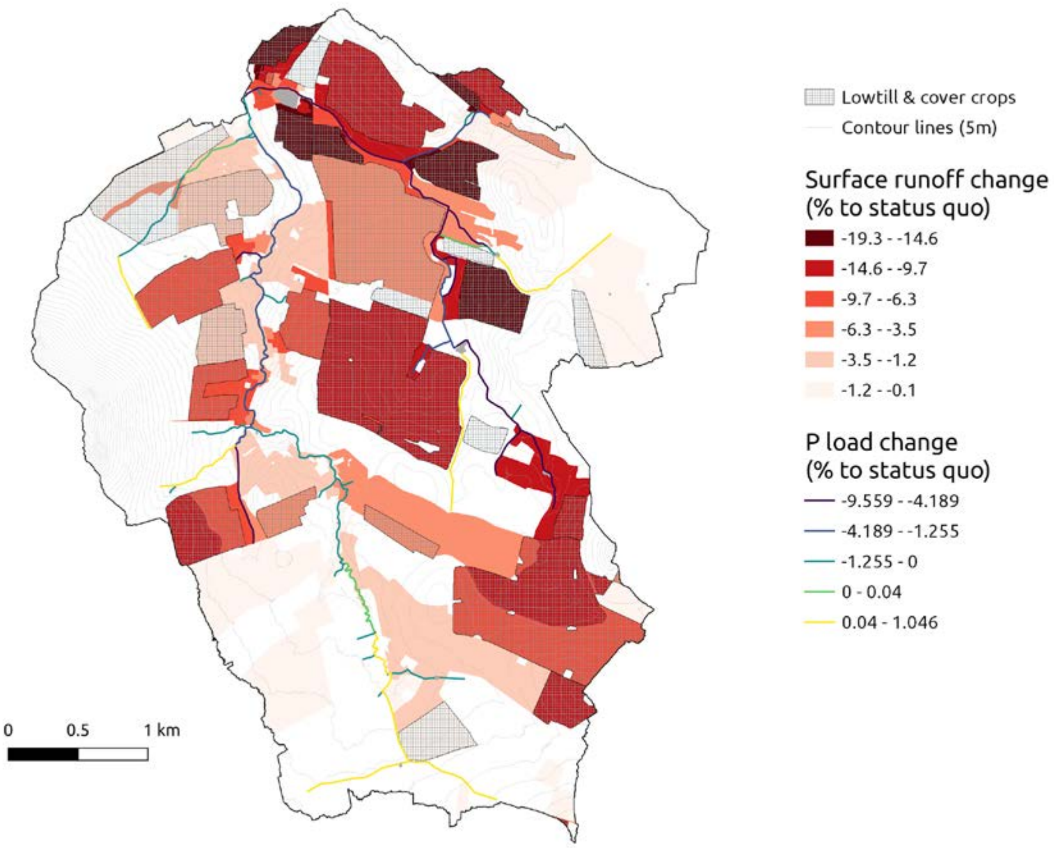


Figure A1.21: Simulated impact of a combined lowtill and cover crop scenario (lowtillcc) on surface runoff and channel P loads using an uncalibrated test model.

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# Annex 2 Modelling results for CS2 (Petite Glâne, CH)

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## 1. Model setup

The SWAT+ model for the CS2 catchment (Petite Glâne) was set up following the SWAT+ modeling protocol (Schürz et al., 2022) and using the R scripts provided by the OPTAIN Project, consisting of both SWATbuildR (version 1.5.16) and SWATfarmR (version 3.2.0).

### 1.1. Input data overview

The study area is the catchment of the Petite Glâne (100km$^2$) in the western Swiss plateau (46°43'-46°56' N to 6°45'-7°01'E) (Fig.1). The altitude ranges from 429 to 810 m.a.s.l., with a mean elevation of 556 m.a.s.l. and a mean slope of 4.6%. The landscape is largely dominated by agriculture: about 75% of the area is arable land, pasture, or meadow and 12% is forest. The soil in the upper zone of the watershed is sandy loam, while the alluvial zone is dominated by clay loam. The meteorological station Payerne, situated near the watershed, offers long-term data, dating back to 1981. This data encompasses precipitation, temperature, wind speed, relative humidity, and solar radiation information. Between 1990 and 2020, the average annual temperature in Payerne ranged from 8.5 to 11.0°C, with an average of 9.8°C. For the same period, average annual precipitation ranged from 581 to 1132 mm, with an average of 855 mm.

The data used for the model setup with SWATbuildR is shown in Table A2.1. Some of the input data needed to be prepared or edited to fit the requirements for SWATbuildR.

*Land layer*: The land layer was created by overlaying different thematic shapefiles (settlement, agricultural area, leisure infrastructure, etc.). Time-consuming manual editing was required to make the resulting shapefile topologically correct.

*Soil layer and user table:* Since regional or national soil maps of Switzerland are sparse, there were three options available as soil input: the freely available Digital Soil Map of the World (DSMW), the Swiss Soil Suitability Map (SSSM) and modelling a high-resolution soil property map based on available soil profile data. Because the DSMW is very coarse and the SSSM is only an interpretation of soils regarding crop suitability, the School of Agricultural, Forest and Food Sciences HAFL at the Bern University of Applied Science (BFH) was mandated to develop a high-resolution soil property map for this study (Nussbaum M, Burgos, S, 2023). A total of 43 individual raster maps were produced: eight soil depths (from 0 up to 120cm, 15 cm spacing) for each soil organic matter, gravel, clay, silt, and sand content, two probability maps for waterlogging classes (0-60 cm, 60-100cm), and soil thickness. To be usable for SWATbuildR, all 43 maps were aggregated for each land layer polygon and based on the land layer polygons a user table was generated.

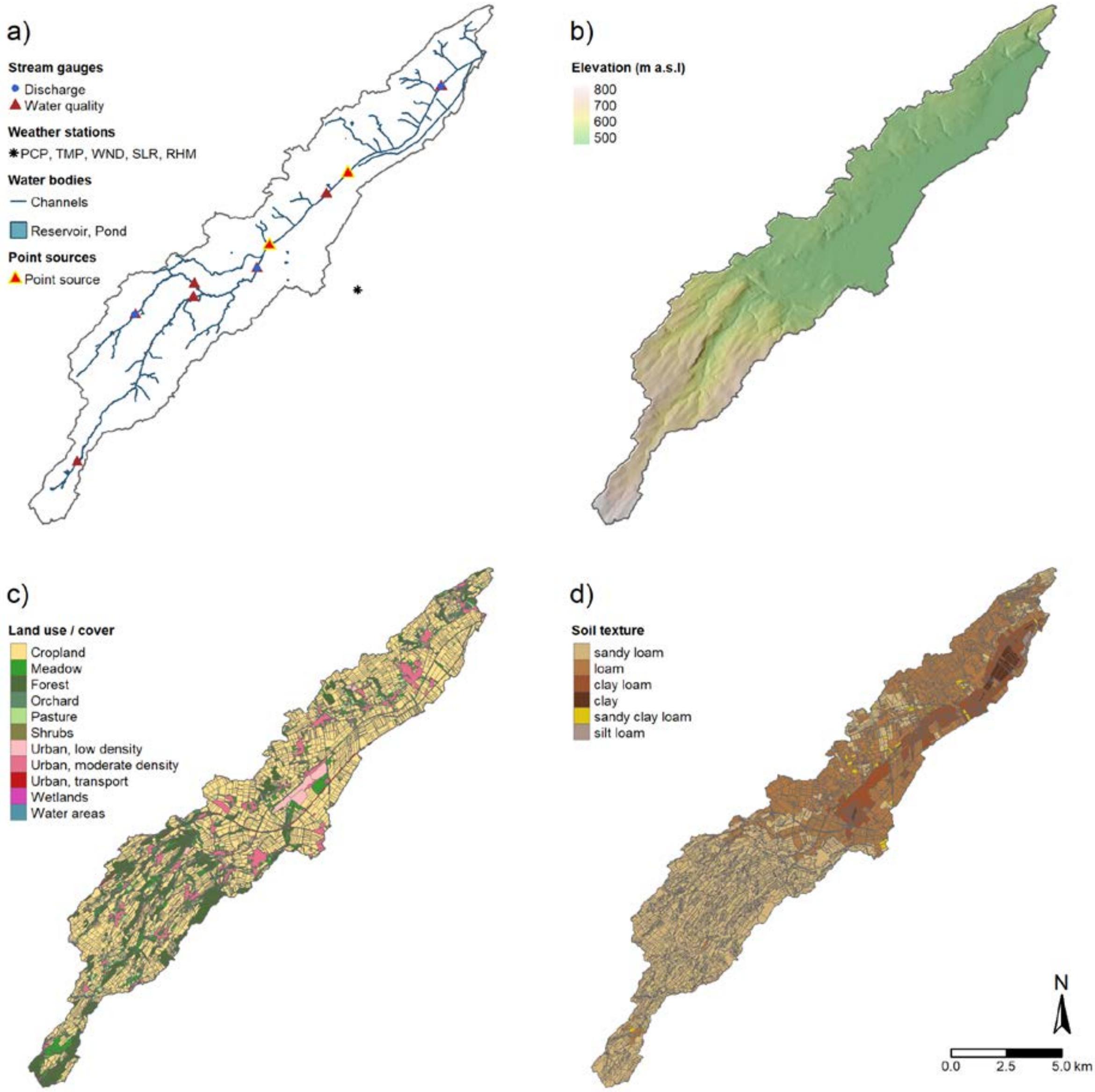


Figure A2.1 GIS input data for CS2: a) locations of discharge gauge and water quality sampling station, weather station (PCP= precipitation, TMP= temperature, WND= wind, SLR= solar radiation, RHM= relative humidity), and point sources, stream network, and catchment boundary; b) elevation map; c) land use/ land cover map; d) soil texture map.

*Crop sequence map*: Based on the agricultural land use map (German: «Landwirtschaftliche Nutzfläche») for 2021 and local statistics the dominant crops were selected: winter wheat (29%), winter rape (10%), sugar beet (9%), corn (8%), silage corn (8%), potatoes (6%), winter barley (5%), sunflower (4%), triticale (4%), protein peas (2%), tobacco (2%), and ley (15%). Keeping this ratio and following the guideline for optimal crop rotation (Jeangros and Courvoisier, 2019), a crop sequence was built for 1988 to 2021. To facilitate the process of building the crop sequence map, winter wheat was replaced by summer wheat where convenient.

Table A2.1 Summary of input data for CS2.

| Input | Number of objects / resolution | Source | Comments |
|---|---|---|---|
| DEM | 2 m | SwissALTI3D Swisstopo (2011) | available as 1 km2 tiles; pre-processing: merging tiles in ArcMap ("Mosaic to Raste") |
| Channel layer | 318 | swissTLM3 Swisstopo (2011) | |
| Land layer | 8056 | swissTLM3 swisstopo (2011), "utilized agricultural area" layer of the cantons of Fribourg and Vaud (geodienste.ch, 2022) | Land layer created by overlapping and adjusting swissTLM and the "utilised agricultural area" layers. Tile drainage information supplemented based on historical maps retrieved from the cantons and visual assessment of satellite images |
| Soil layer | 10m | High-resolution soil property map modeled by M. Nussbaum and S. Burgos | For a regular spacing of 15cm starting at 0 up to 120cm soil depth, the soil organic carbon content and gravel and texture classes were calculated. Moreover, the probability of water logging at 0-60 cm and the soil depth were estimated. |
| Usersoil table | 8056 | | Based on the high-resolution soil property map: for each land object the average soil property values were taken. Additional soil properties (soil hydrologic group, moist bulk density, available water capacity, saturated hydraulic conductivity, moist soil albedo, and USLE soil erodibility factor were calculated with Pedotransfer Functions provided in the modeling guidelines (Schürz et al., 2022) |
| Point sources | 2 | Canton of Fribourg and Canton of Vaud | Two WWTPs from local municipalities: Busy (FR) and Grandcour (VD) |

| | | | |
|---|---|---|---|
| Weather data | 1 station | MeteoSwiss (retrieved from IDAweb portal) | Weather data were processed by svatools weather (version 0.1.0) |
| Atmospheric deposition | 1 | European Monitoring and Evaluation Programme (EMEP) | EMEP data processed by SWATprepR |
| Crop sequence map | 8056 | utilised agricultural area ("landwirtschaftliche Nutzfläche") layer of canton of Fribourg and canton of Vaud for 2021 (geodienste.ch, 2022) and crop rotation guidelines (Agroscope 2019) | All crops covering >1% of the cropland in 2021 were selected and based on guidelines and expert (farmer) knowledge a crop rotation from 1988-2021 was created – ensuring that the crop ratios would remain the same |
| Management schedules | 13 | crop rotation guidelines (Agroscope 2019), factsheets Liebegg, factsheets Stickhof, farmer's knowledge | Schedules prepared based on crop rotation guidelines, crop factsheets, and farmer's knowledge |

## 1.2. Baseline model setup

The baseline model setup created with SWATbuildR consisted of 8056 land objects / HRUs. This is higher than the recommended 5000 objects but considering the characteristics of the land use mosaic within the study area, it was considered acceptable. Further information on the baseline model setup can be derived from Table A2.2

Table A2.2 Key numbers regarding baseline model setup with SWATbuildR.

| Parameter | Value |
|---|---|
| Total area of the watershed in ha | 10,049 |
| Number of HRUs in the simulation | 8,056 |
| Number of routing units in the simulation | 8,056 |
| Number of aquifers in the simulation | 1 |
| Number of reservoirs in the simulation | 37 |
| Number of recalls (point sources/inlets) in the simulation | 2 |
| Number of SWAT-DEG channels in the simulation | 314 |
| Number of crops in rotation | 13 |
| Number of wetlands | 6 |

## 2. Model evaluation

After the model was set up and parameterized, its ability to reproduce observable environmental variables with simulated outputs was assessed. This model evaluation comprises model verification, soft calibration, and hard calibration. Table A2.3 summarizes the observed data for the variables used. For the crop yield soft calibration the minimal, maximal, and mean annual yield for each crop was needed. This data was derived from regional farm accountancy statistics and averaged values from specific crop fact sheets. For the water balance soft calibration, the water yield ratio was needed and approximated by calculating the ratio of average annual discharge and precipitation.

The hard calibration was done based on the discharge data from Villars-le-Grand, the gauging station about 2.5 km before the watershed outlet. The simulation was set for 21 years (2000-01-01 to 2020-12-31) and included 3 year warm-up period. The calibration period was then set for 12 years (2003-2014) and the validation for 6 years (2015-2020). A major challenge is the lack of long-term or continuous observed water quality data. In 2011 and 2017 two monitoring campaigns were held in the Petite Glâne watershed. During these campaigns, samples at 8 different sites were taken each month. Given the time constraints and this lack of data, it was decided not to do a water quality calibration at this stage. If the assessed NSWRMs show a significant impact on water quality and if the values are not in the range of the observed data, a calibration of water quality data will be done retrospectively.

Table A2.3 Summary of observation data used in different steps of the calibration workflow for CS2.

| Variable | Time step | Calibration period | Validation period | Source | Comments |
|---|---|---|---|---|---|
| | | | Soft calibration | | |
| Crop yields | Average annual | 2000-2020 | NA | regional averaged yields from farm accountancy data network (peas, corn, pota, canp, sunf, wbar, wwht), averaged yields from factsheets of specific crops (csil, swht, tobc, trit, ryeg,sgbt) | The yield values needed to correspond to the dry weight. where needed, the wet weight was converted to dry weight using crop specific wet to dry weight ratio. |
| Water yield ratio | Average annual | 1993-2021 | NA | Model input (pcp) and discharge data from the gauging station at Villars-le-Grand provided by the Environment Department, Canton of Vaud | Calculated for the gauge station almost at the outlet, which is the one with the longest record |
| | | | Hard calibration | | |
| Discharge | Daily | 2003-2014 | 2015-2020 | Discharge data from gauging station at Villars-le-Grand | |
| N-$NO_3$ concentrations | monthly (single campaigns) | 2011 | 2017 | grab samples provided by the Environment Department, Canton of Vaud | Not done yet, might be done at a later stage |

## 2.1. Model setup verification

The model setup verification was done with SWATdoctR (version 0.1.23). The examination of climate and water balance data (Fig. A2.3) confirms that the reported values fall within plausible ranges, aligning with the expert knowledge of the studied watershed. Additionally, assessing stress factors, i.e. nutrients, water or temperature stress (Fig. A2.4). Usually, it is expected that different stress factors lead to 10-50% reduction of yield (10-50%). Except for ryegrass (ryeg), the decreases in yield are in the expected range. The analysis of biomass and Leaf Area Index (LAI) development, exemplified in Fig. A2.5, indicates satisfactory behavior. Inconsistencies appearing at earlier stages were fixed by adapting LAI development curve of specific crops in the plant database, i.e. changing "dlai_rate" for potato (pota) from 10 to 5.

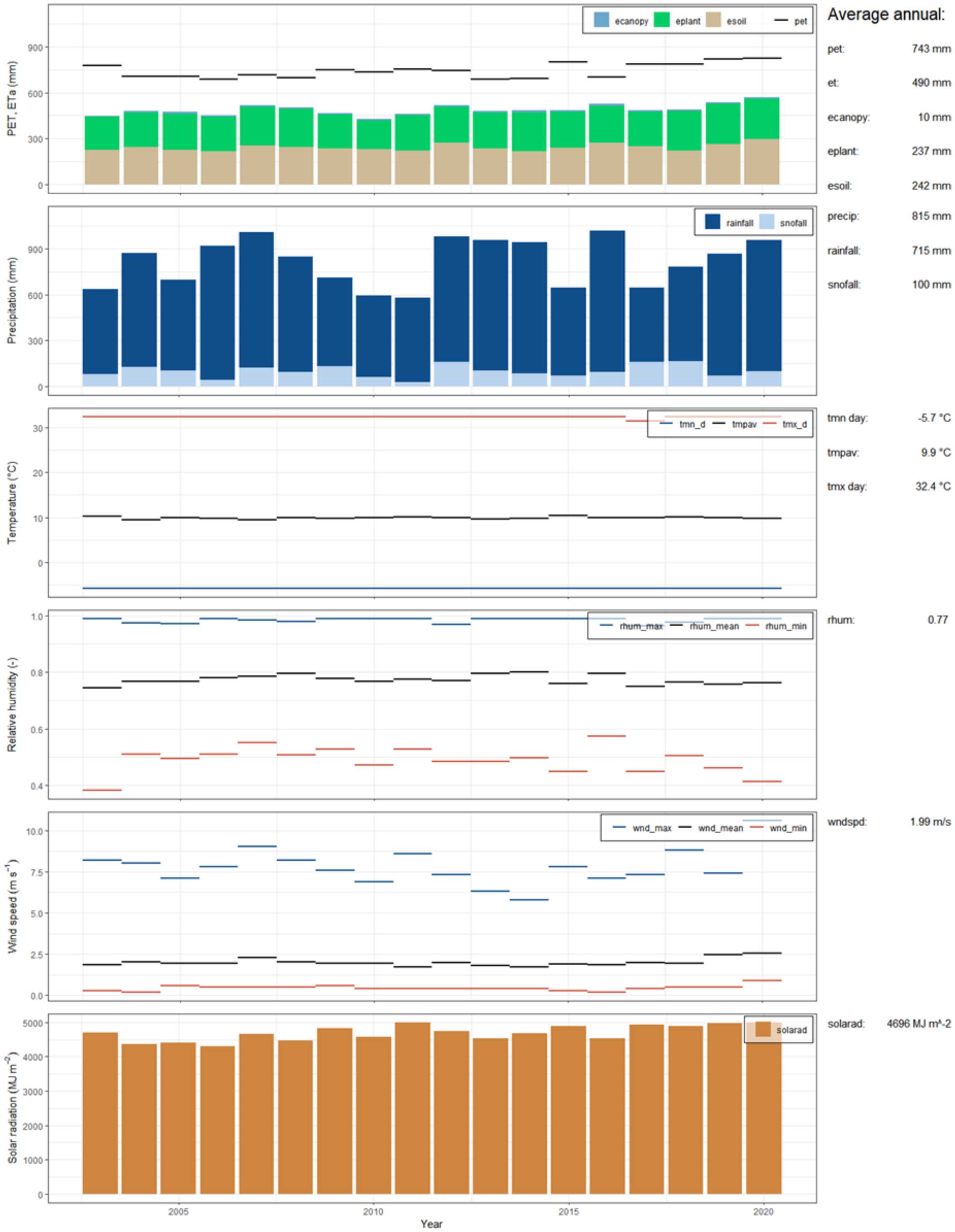


Figure A2.3 Summary of the climate data checks for CS2 by the SWATdoctR.

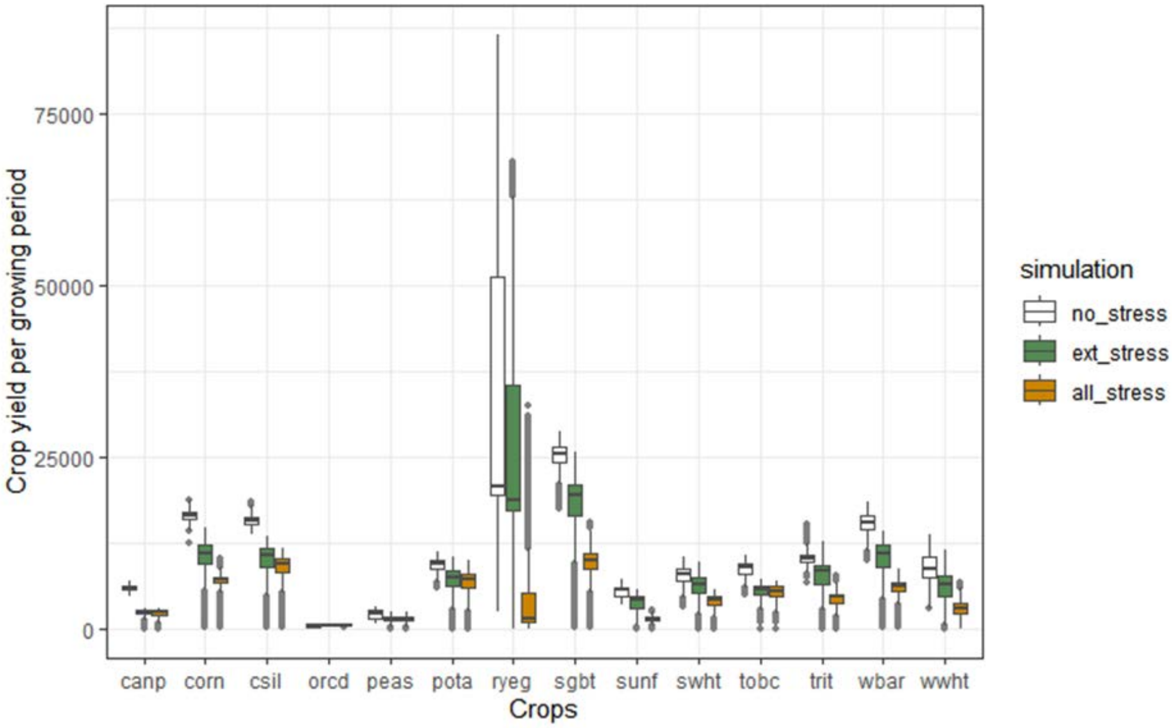


Figure A2.4 Comparison of crop yields with all stress factors (all_stress), external stress factors (ext_stess) and no stress factors (no_stress) for CS2.

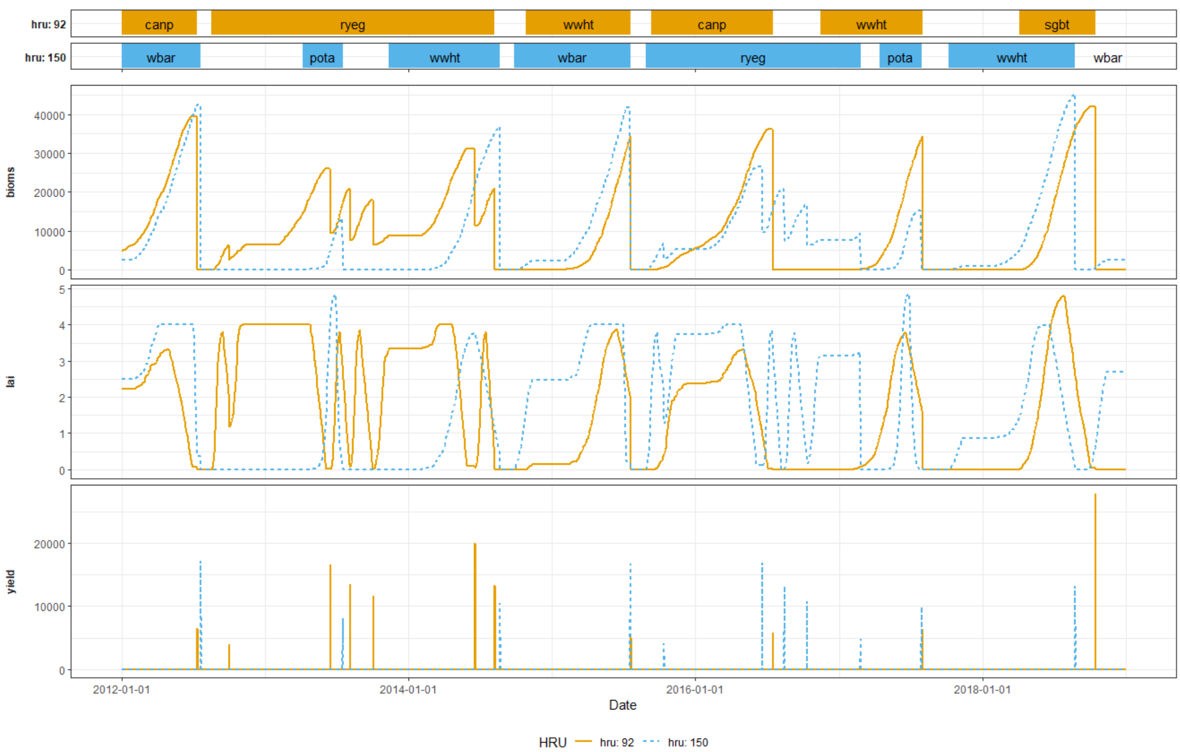


Figure A2.5 Biomass, Leaf Area Index (LAI) development and yields for two example HRUs in CS2.

## 2.2. Soft calibration

As illustrated in Fig. 2.6, the calibration workflow was effectively implemented in CS2. First, the parameter “days to maturity” (d_mat) was adjusted, while ensuring that the accumulated Photo-thermal Units (PHU, originally potential heat units) fraction at harvest/kill falls within the recommended range of 1.0-1.2. Notably, significant changes in d_mat were made for sugarbeet (sgbt: from 100 to 210), tobacco (tobc: from 160 to 90), and ryegrass (ryeg: from 110 to 60). The latter was the most challenging crop which can be explained by the fact that it is a multi-harvest and multi-annual (2 years) crop. Smaller changes were done for silage corn (csil), winter wheat (wwht) and sunflower (sunf).

In the second step, the calibration involved tweaking four plant parameters for each crop to attain satisfactory results (Tab. A2.1). For the majority of crops, the simulated yields closely matched the observed averages. However, for tobc and sunf the average simulated values slightly deviated beyond the observed maximal and minimal yield.

Table A2.1 Final calibrated values of crop parameters.

| Crop | d_mat* | lai_pot** | harv_idx** | tmp_base* | bm_e** |
|---|---|---|---|---|---|
| canp (canola)*** | 20 | 0 | 0 | 0 | 0 |
| corn (grain corn) | 10 | 0 | 0.1 | 0 | 0 |
| csil (silage corn) | 0 | 0 | 0 | 0 | -0.5 |
| peas (peas) | -10 | 0.5 | 0 | 0 | 0 |
| pota (potatoe) | 0 | 0 | 0 | 0 | 0 |
| ryeg (rye grass) | 0 | 0 | 0 | 0 | 0 |
| sgbt (sugar beet) | -30 | 0 | 0 | 0 | 0.1 |
| sunf (sunflower) | 30 | 0 | 0 | 0 | 0.4 |
| swht (summer wheat) | -20 | 0 | 0 | 0 | 0 |
| tobc (tobacco) | -10 | 0 | 0 | 0 | -0.5 |
| trit (winter triticale) | 0 | 0 | 0.05 | 0 | 0 |
| wbar (winter barley) | -10 | 0 | 0 | 0 | 0 |
| wwht (winter wheat) | -30 | 0 | 0.25 | 0 | 0 |

* Absolute change ** Relative change *** crop representing winter rape

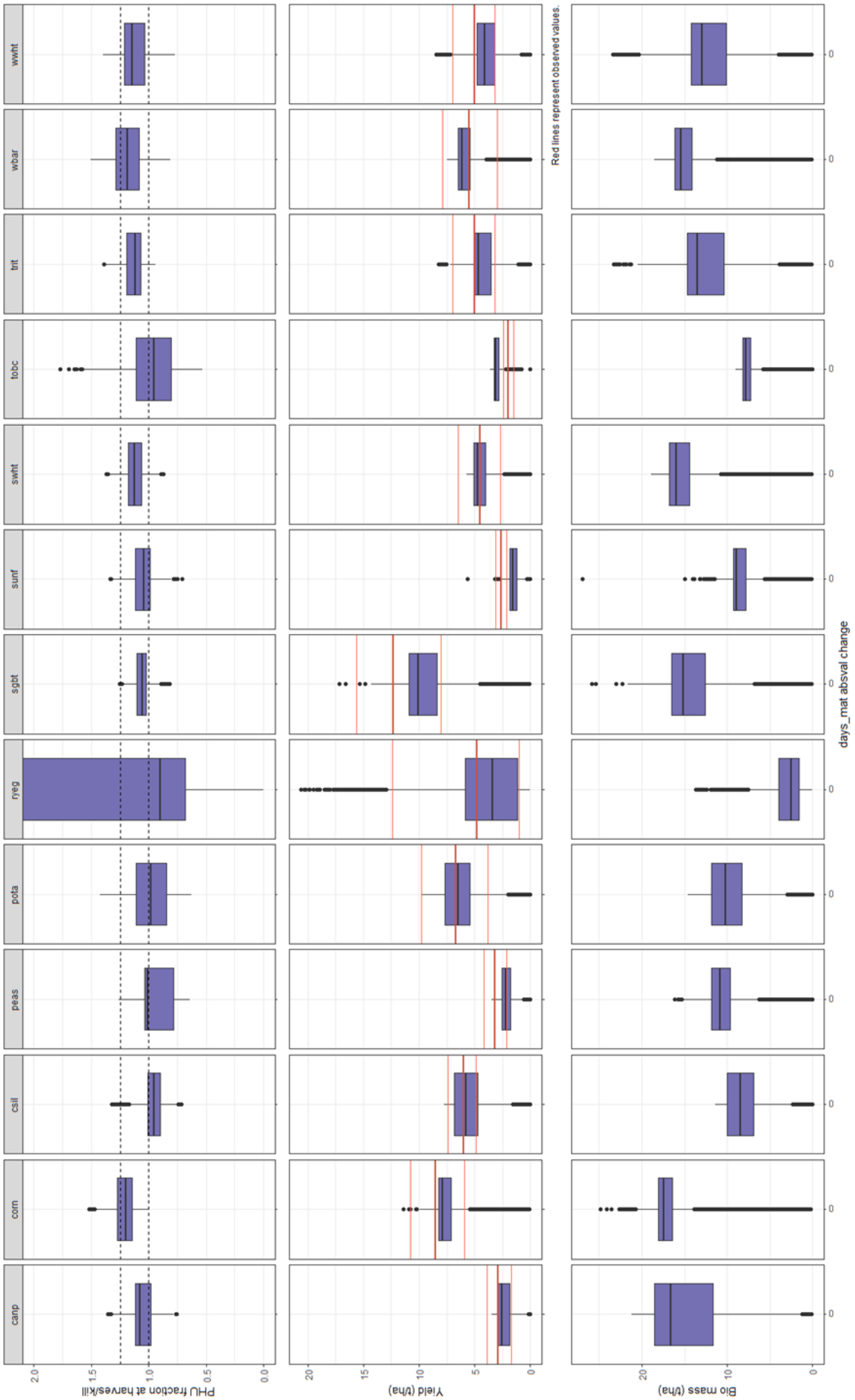

Figure A2.6 Final results of crop yield soft calibration for CS2. Simulated PHU fraction of harvest/kill (top row), crop yields (middle row) and biomass (bottom row).

In addition to calibrating the crops, the soft calibration process also included water yield. Specifically, the "soil evaporation compensation factor" (esco) parameter was fine-tuned to align with the water yield ratio (approximated by the ratio of discharge to precipitation) of 0.34 for the period 2003-2019. The esco parameter value was adjusted to 0.39. The range kept for hard calibration was (0.21, 0.4). Crop yield simulation results did not change significantly after adjusting esco.

### 2.3. Hard calibration and validation

The selected parameters included 15 hydrology parameters. Five objective functions were evaluated for each observed variable: Nash–Sutcliffe model efficiency coefficient (NSE), Kling–Gupta efficiency (KGE), Percent Bias (PBIAS), coefficient of determination ($R^2$), and Mean absolute error (MAE). For each iteration, 500-1000 parameter combinations were run and after analyzing the dotty plot figures, the parameter ranges were adjusted accordingly to improve the model's performance. For most of the parameters, their space was narrowed considerably. Finally, a set of 10 parameter combinations was selected. Fig. 2.7 represents the time series model output variability resulting from the 2% best (according to the sum of ranks for different metrics and variables). The results for the Villars-le-Grand gauge in the validation period were slightly inferior than in the calibration period, which is reflected in lower values of performance metrics (Fig. A2.8).

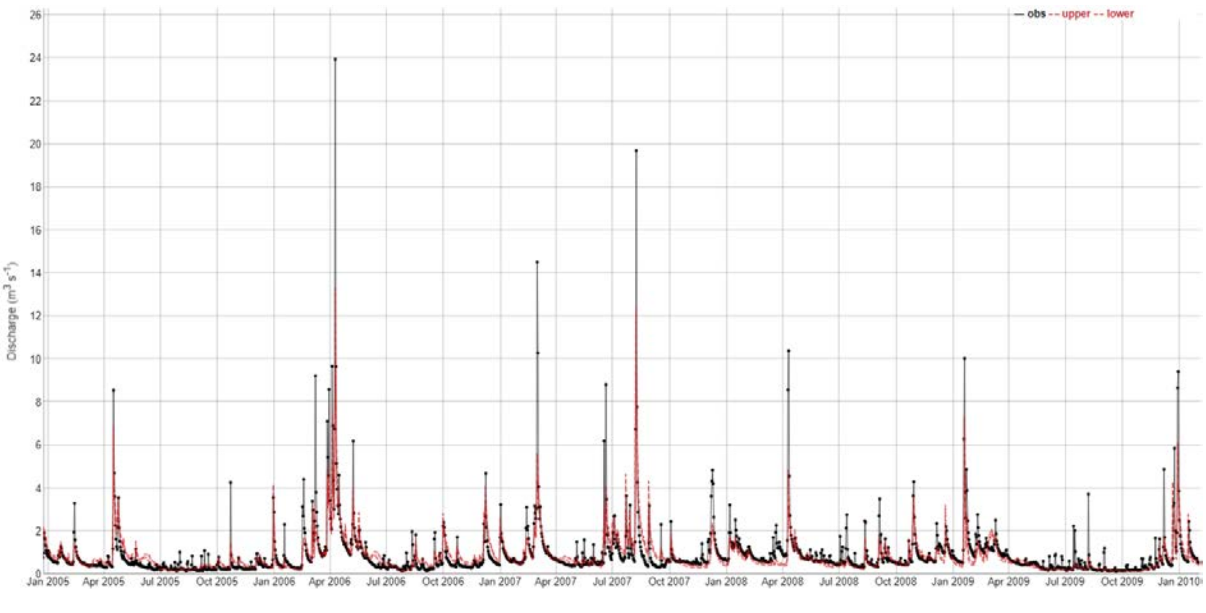


Figure A2.7 Simulated vs. observed daily discharge for flow gauge station Villars-le-Grand in CS2 (extract from calibration period).

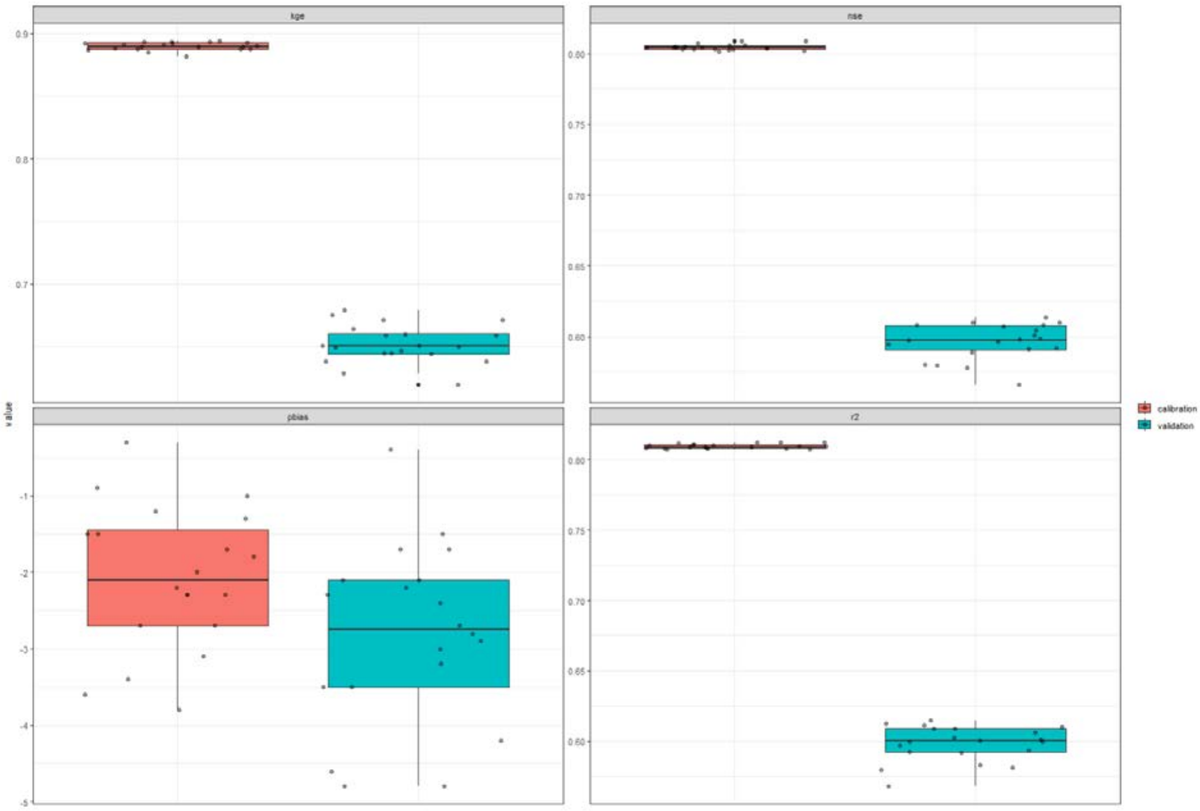


Figure A2.8 Box plot of model performance metrics for discharge in calibration and validation period for CS2.

## 3. Climate change effects

We used bias-corrected RCM simulations developed in the WP3 of OPTAIN (Honzak, 2023) as the SWAT+ model forcing in order to assess the effect of climate change on the water balance, nutrient losses and crop yields. We applied all available combinations of six RCMs, three RCPs and three time horizons (1991-2020 - serving as the “baseline”, 2036-2065 - “near future”, 2070-2099 - “end of century”), resulting in a total of 54 model scenarios.

Figure A2.13 shows projected changes in annual and seasonal minimum and (Tmax) temperature as well as precipitation (Prec) for CS4. Note that the horizons are slightly different than those used in SWAT+ modelling. A consistent warming pattern emerges, in particular for RCP8.5, for which projected increase in annual Tmin and Tmax ranges between 3 and 5 degrees C. The highest magnitude of the warming signal occurs in autumn (Tmax) and summer (Tmin), while the lowest in spring. In contrast, under RCP2.6 the projected change does not exceed 2 degrees, even at the end of the century. Precipitation projections show a dominant signal of wetter future, in particular under RCP8.5, for which an ensemble median increase equals 20% by the end of the century. Projected changes are higher in winter and spring compared to summer and autumn for all RCPs. However, under RCP4.5 the projected changes in summer, autumn as well as annual rainfall for the near future are lower than under RCP2.6 or RCP8.5. A more detailed analysis of climate projections (including other variables) is available at the OPTAIN UFZ cloud[2]. In general, projected changes in wind speed, solar radiation and relative humidity are relatively low, even under RCP8.5, and thus should not contribute a lot to the effect of climate change on the studied indicators.

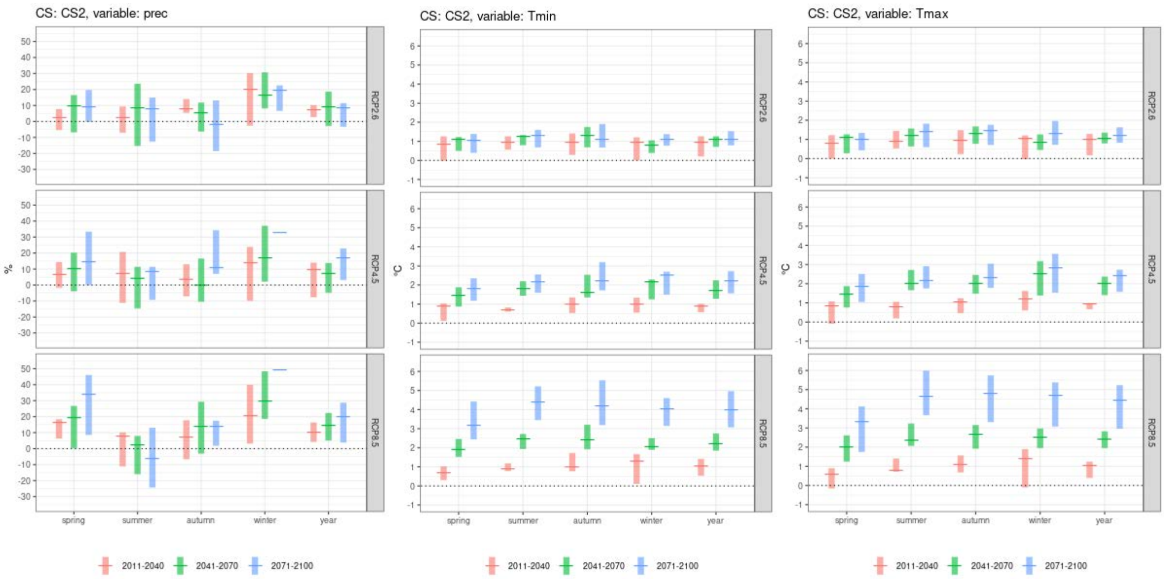


Figure A2.9 Projected changes in variables minimal temperature (Tmin), maximal Temperature (Tmax) and precipitation (prec) for all RCPs and time horizons for CS2 (Honzak, 2023).

The following basin-averaged SWAT+ outputs were considered in the analysis: precipitation, snow fall, potential evapotransipration (PET), actual evapotranspiration (ET), percolation, soil moisture content (in the root one and in top 300 mm), surface runoff, and tile flow. The results are presented as box plots in Figure A2.10. As discussed before, precipitation is projected to increase with a variable rate, depending on the RCP and future horizon - the smallest increase beaing under RCP4.5 for the near future. An increase in winter precipitation combined with a strong warming translates into a strong decrease in snow fall and snow melt, even exceeding 60% under RCP8.5 in the last time horizon. In contrast, an increase in PET triggered by climate warming is rather modest, with an exception of RCP8.5 for which it exceeds 15% for some ensemble members by the end of the century. Changes in ET are also moderate and go predominantly in a positive direction, possibly due to increased availability of water in the soil profile. Percolation increases under all RCPs by the end of the century, however, under RCP4.5 a decrease can be expected for the near future. This goes together with the rainfall changes for the near future under RCP4.5. While the topsoil soil

2 https://nc.ufz.de/s/KA9Cr2bbtALGMHr?path=%2FWPs%20%26%20Tasks%2FWP3%2FTask_3_2%2Flocal%20data%2Fv1a%2Fanalysis

moisture is projected to decrease, changes in the root zone soil moisture depend on the RCP scenario and month. For the annual average as well as for individual months of the growing season, from May till September, soil moisture will predominantly increase under RCP2.6 and decrease under RCP8.5. Projections of surface runoff and lateral flow show an increase, especially for the surface runoff by the end of the century under RCPs 4.5 and 8.5. A similar pattern is projected for tile flow.


Figure A2.10 Projected changes in selected basin-averaged water balance components simulated by SWAT+ for CS2.

The second collection of box plots (Fig. A2.11) includes various streamflow indicators. Mean stream flow is projected to increase under all RCPs and time horizons - except for the near future under RCP4.5 only a very slight increase is projected. Interestingly, changes in the high flow go mostly in the opposite direction to changes in the days of high flow: while the former increases, the latter decreases. Under RCP2.6, changes in low flow might go into both directions, however, under RCP8.5 low flow clearly decreases. In addition, low flow days are projected to increase by 50-75% under RCP8.5 by the end of the century.

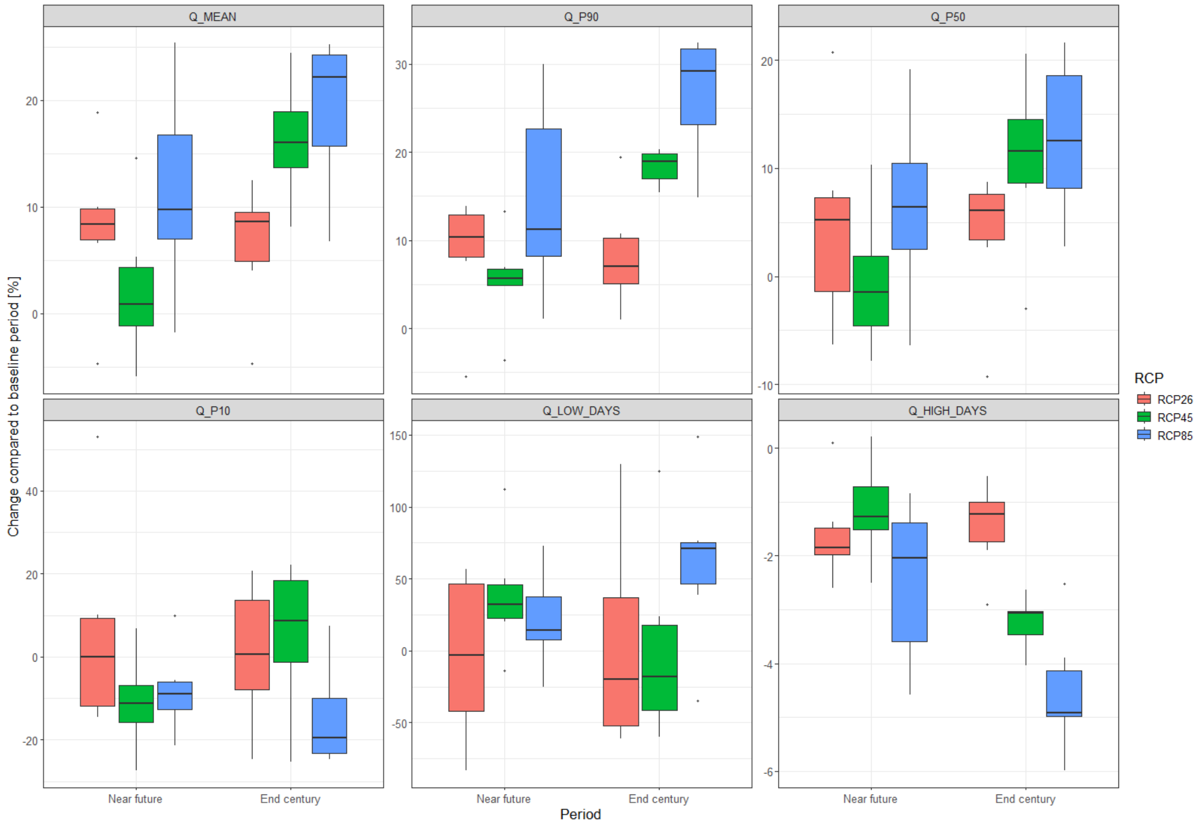


Fig. A2.11 Projected changes in selected streamflow indicators simulated by SWAT+ for CS2.

The third collection of box plots (Fig. A2.12) shows changes in selected water quality indicators. It should be noted that the CS 2 model was not calibrated for nitrogen or phosphorus, for which the reliability of results has to be critically reflected. Under wetter conditions (all RCPs and time horizons - except for the near future under RCP4.5), N and P losses are projected to increase significantly, and the same happens to loads carried by the stream. At the same time, however, the frequency of days with high nutrient concentration does not change significantly - by the end of the century even a decrease of days with high nitrogen concentration is possible under RCPs 2.6 and 8.5. This might be explained with a dilution effect (relative increases in loads are less than respective increases in discharge).

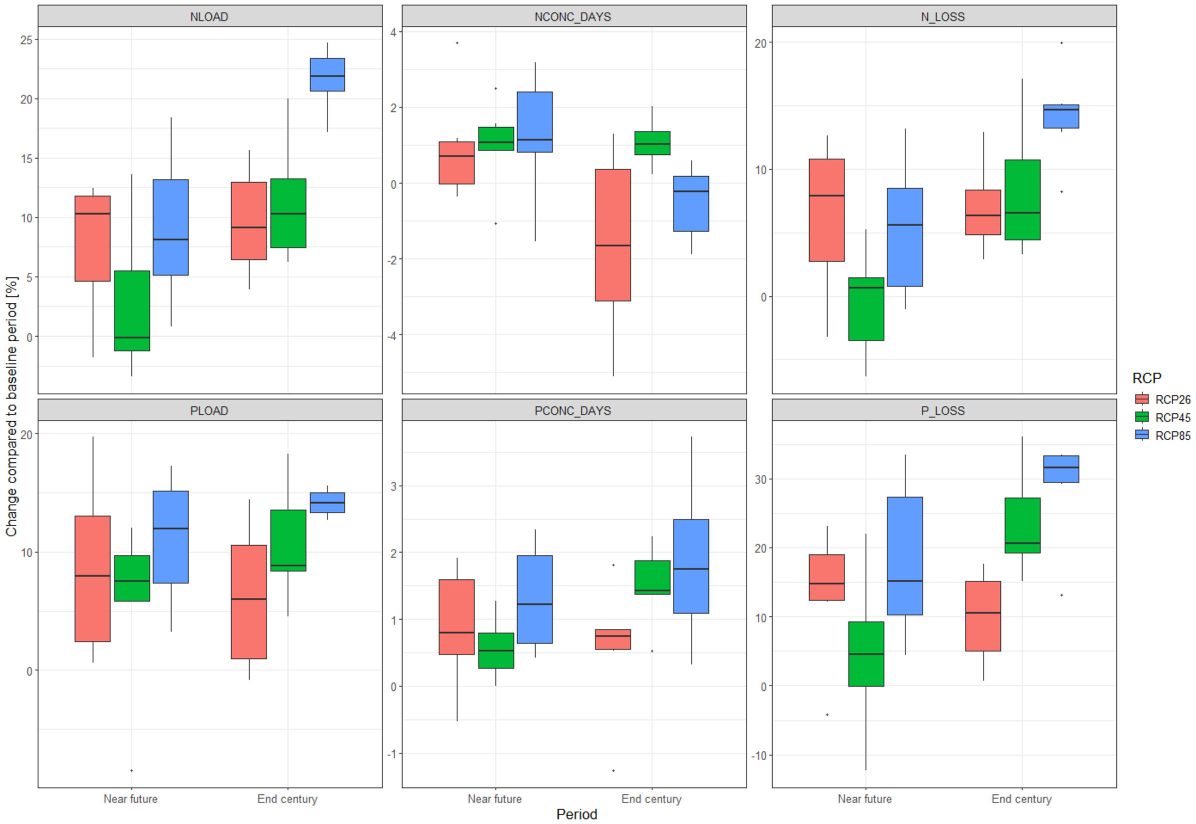


Fig. A2.12 Projected changes in selected water quality indicators simulated by SWAT+ for CS2.

The fourth collection of box plots presents projections of crop yields (Fig. A2.13). The indicator grain units sums up all crop yields across the study area and normalised for their respective nutritional value. For the majority of crops, a decreasing trend is projected. One exception, however, is the near future under RCP4.5, for which a slight increase for several crops is projected, e.g. winter rape (canp), tobacco (tobc) or triticale (trit). Interestingly, RCP2.6 has shows higher decreases in tobacco yield than RCPs 4.5 and 8.5.


Fig. A2.13 Projected changes in selected crop yields simulated by SWAT+ for CS2.

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# Annex 3 Modelling results for CS3b (Felső-Válicka, HU)

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## 1. Model setup

The SWAT+ model for CS3b catchment (Felső-Válicka) was set up in the same way as described in Annex 11 Modelling results for CS11 (Tetves, HU). Hereinafter only the differences are presented.

### 1.1. Input data overview

The list of input data used for the model setup is included in Table A3.1.

Similarly to CS11 (Tetves), the most important crops of the case study are maize (CORN), winter wheat (WWHT), winter barley (WBAR), rape (CANP), sunflower (SUNF) and lucerne (ALFA).

Table A3.1 Summary of input data for CS3b.

| Input type | Input variables | Unit | Time frequency | Reso-lution | Time period | Source | Reference |
|---|---|---|---|---|---|---|---|
| Field boundary | - | - | - | 5 m | static | digitised | - |
| Land cover and land use | land cover with time series crop map | - | yearly | 10 m | 2015-2021 | NÖSZTÉP database and remote sensing based crop maps | (Szabó et al., 2022; Tanács et al., 2019) |
| NSWRMs | - | - | - | 10 m | 2020 | farm advisor, farmers, NÖSZTÉP | - |
| Agricultural manage-ment data | - | - | - | 10 m | 2020 | farm advisor, agronomist, farm activity log | - |
| DEM | - | m | - | 5 m | static | Lechner Knowledge Center | https://lechnerkozpont.hu/oldal/domborzatmodell |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Soil data | depth of layers | mm | - | 100 m | static | DOSoReMI.hu | (Pásztor et al., 2018) |
| | maximum rooting depth | mm | - | 100 m | static | DOSoReMI.hu | (Pásztor et al., 2018) |
| | moist bulk density | g/cm3 | - | 100 m | static | computed | (Wessolek et al., 2009) |
| | available water capacity | mm/mm | - | 100 m | static | computed | (Assouline and Or, 2014; Szabó et al., 2021) |
| | saturated hydraulic conductivity | | - | 100 m | static | computed | (Assouline and Or, 2014; Szabó et al., 2021) |
| | organic carbon content | g/100 g | - | 100 m | static | DOSoReMI.hu | (Szatmári and Pásztor, 2019) |
| | sand, silt, and clay content | g/100 g | - | 100 m | static | DOSoReMI.hu | (Laborczi et al., 2019) |
| | rock fragment content | g/100 g | - | 250 m | static | SoilGrids | (Poggio et al., 2021) |
| | moist albedo of the top layer | - | - | 100 m | static | computed | (Gascoin et al., 2009) |
| | USLE soil erodibility factor (K) | t ha h/ha MJ mm | - | 100 m | static | computed | (Sharpley and Williams, 1990) |
| Stream characteristics | stream reaches | - | - | 1:10000 | static | Western Transdanubia Water Directorate | - |
| Meteorological data | precipitation | mm/day | daily | 0.1° | 1998.01.01-2020.12.31 | Hungarian Meteorological Service (OMSZ), interpolated, 6 virtual stations | https://odp.met.hu/climate/homogenized_data/gridded_data_series/ |
| | temperature | °C | daily | 0.1° | same as above | same as above | same as above |
| | wind speed | m/s | daily | 0.1° | same as above | same as above | same as above |
| | relative humidity | % | daily | 0.1° | same as above | same as above | same as above |
| | solar radiation | MJ/m2/day | daily | 0.1° | same as above | same as above | same as above |
| Atmospheric data | atmospheric deposition | kg/ha/yr | annual | 0.1° | 1990-2020 | European Monitoring and Evaluation Programme (EMEP) | https://www.emep.int/ |

In the case of mapping soil phosphorus content of the topsoil, monitoring data measured on 34 agricultural parcels were available from a local agricultural company. For these parcels the mean phosphorus values were replaced with the measured ones. Figure A3.2 shows the Olsen phosphorus content of the topsoil used for the modelling.

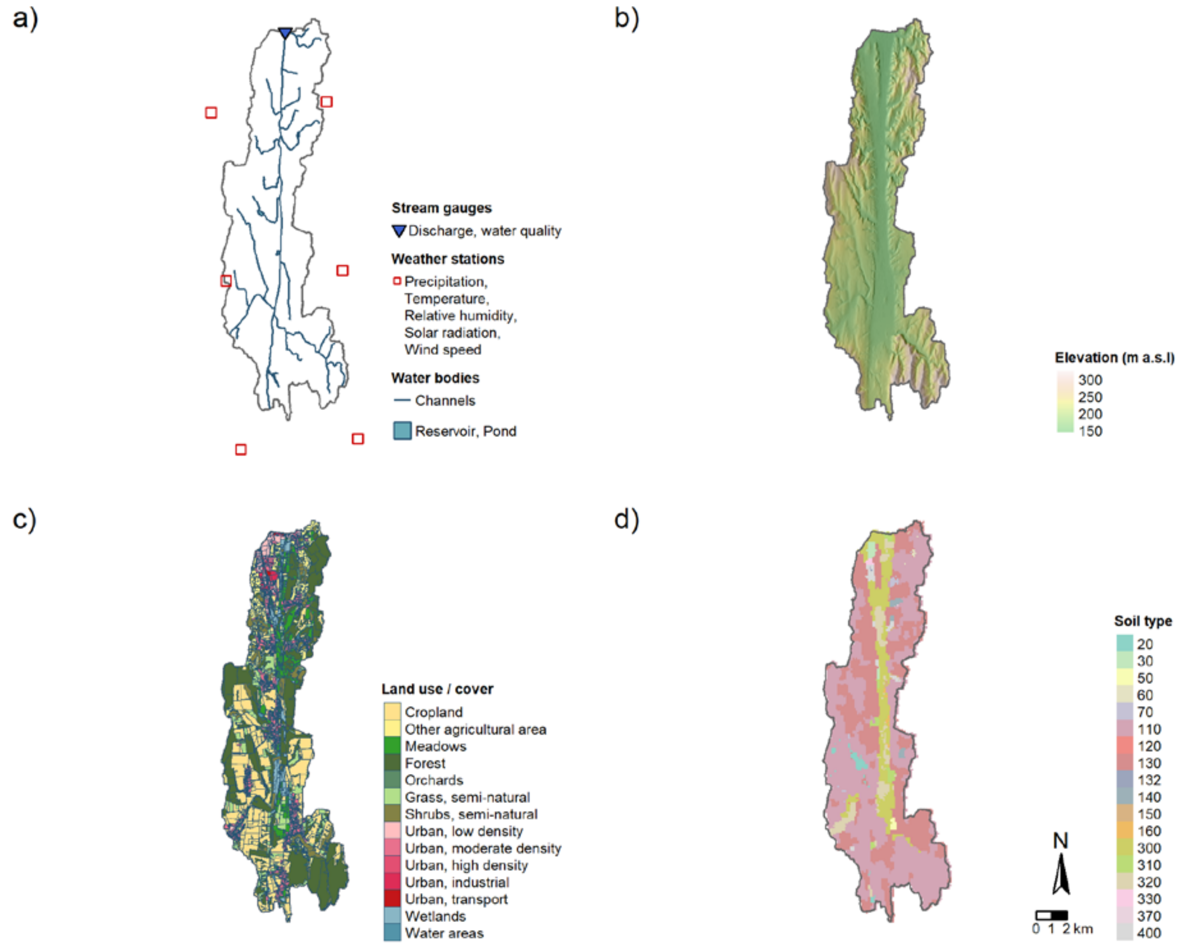


Figure A3.1 GIS input data for CS3b: a) flow gauge, water quality monitoring points, meteorological stations, channels, reservoirs, ponds and catchment boundary; b) elevation map; c) land use map; d) soil types, with the following most dominant soil types: Luvisols (code 110), Cambisols (code 130, 400), and Gleysols (300).

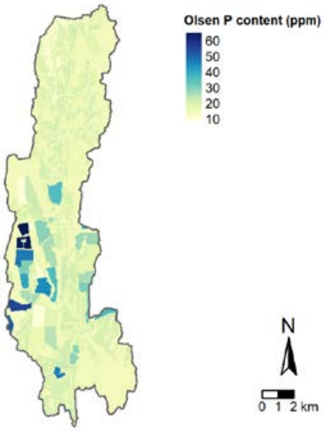


Figure A3.2 Olsen phosphorus content of the topsoil layer in CS3b.

## 1.2. Baseline model setup

The area of the watershed defined by the QSWAT based on the 5 m resolution DEM was 12,444 ha. HRUs were defined in the same way as described in Annex 11 Modelling results for CS11 (Tetves, HU). The final number of HRUs was 5,196. There were 5 reservoirs. Further details about the model setup are included in Table A3.2.

Table A3.2. Summary of the mode setup features based on the input file object.cnt.

| Parameter | Value |
|---|---|
| Total area of the watershed in ha | 12,444 |
| Total number of spatial objects in the simulation | 10,445 |
| Number of HRUs in the simulation | 5,196 |
| Number of routing units in the simulation | 5,196 |
| Number of aquifers in the simulation | 1 |
| Number of reservoirs in the simulation | 5 |
| Number of SWAT-DEG channels in the simulation | 47 |
| Number of crops in rotation | 7 |
| Number of wetlands | 259 |

# 2. Model evaluation

For the soft calibration – similarly as it was done for CS11 – we used crop yield and water yield ratio as observation data. Hard calibration was performed based on discharge and $N\text{-}NO_3$ concentrations.

Table A3.3 presents information about the observation data. Data on discharge and $N\text{-}NO_3$ concentration was acquired from the Western Transdanubia Water Directorate. Discharge data was available at daily scale. Unfortunately, $N\text{-}NO_3$ concentration is measured monthly as a grab sample for the Felső-Válicka stream, which limits the calibration and validation accuracy of the water quality simulation.

Table A3.3 Summary of observation data used in different steps of the calibration workflow for CS3b.

| Variable | Time step | Calibration period | Validation period | Source | Comments |
|---|---|---|---|---|---|
| | | | Soft calibration | | |
| Crop yields | average annual | 2001-2020 | NA | https://www.ksh.hu/stadat_files/mez/hu/mez0070.html | County statistical data. |
| Water yield ratio | average annual | 2001-2020 | NA | Model input (pcp) and discharge data | Calculated for the outlet flow gauge. |
| | | | Hard calibration | | |
| Discharge | daily | 2002.07.01-2007.12.31 | 2008.01.01-2020.12.31 | Western Transdanubia Water Directorate | Daily data received from the local water authority (Western Transdanubia Water Directorate). |
| $N\text{-}NO_3$ concent-rations | monthly (grab sample) | 2002.07.01-2007.12.31 | 2008.01.01-2020.12.31 | Western Transdanubia Water Directorate | Discrete, grab sample measurements for one gauge measured by the local water authority (Western Transdanubia Water Directorate), data available for 2002.08.01-2013.01.16.. |

## 2.1 Model setup verification

During the model setup verification, we followed the OPTAIN workflow, which is presented by Plunge et al. (2024).

Figure A3.3 shows the verification results of the climate and water balance data. The simulated evapotranspiration, precipitation, temperature, relative humidity, wind speed and solar radiation data is in line with the values available from the literature for the catchment, thus the model reads these data correctly during the simulation.

In the case of plotting crop yields under different stress factors – all stress and external stress factors – and no stress factors (Figure A3. 4.) - the simulated values are in plausible ranges.

Biomass and LAI development analysed by HRUs showed acceptable behaviour.

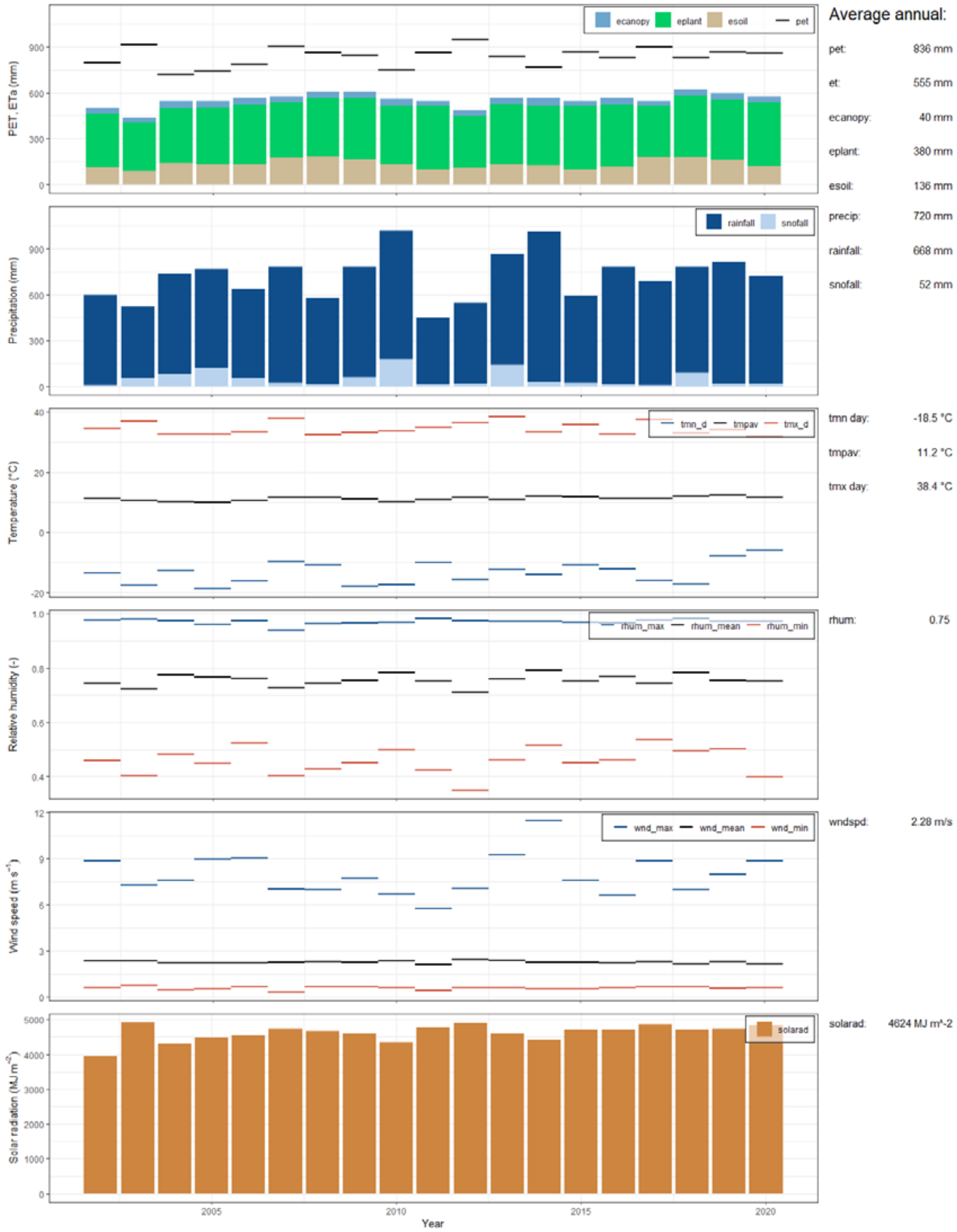


Figure A3.3 Summary of the climate data checks for CS3b by the SWATdoctR.

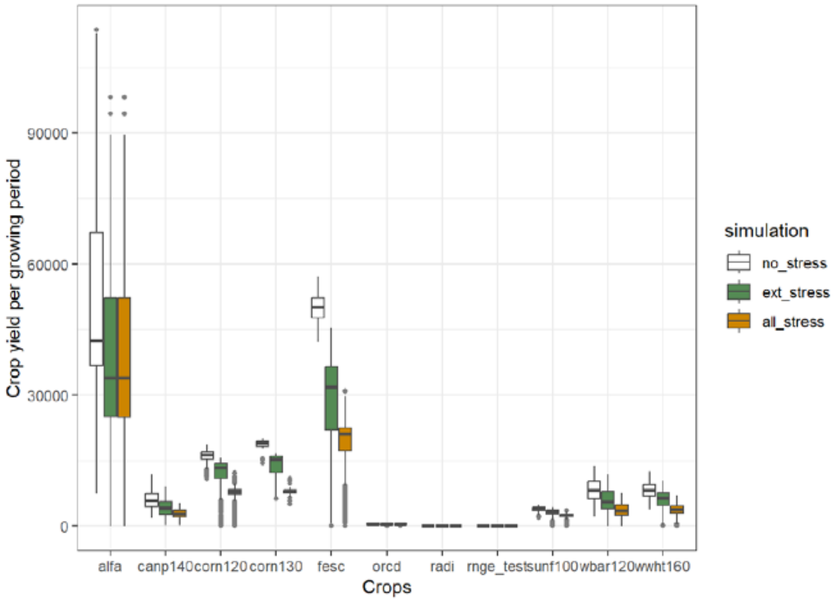


Figure A3.4 Comparison of crop yields with all stress factors (all_stress), external stress factors (ext_stress) and no stress factors (no_stress) for CS3b.

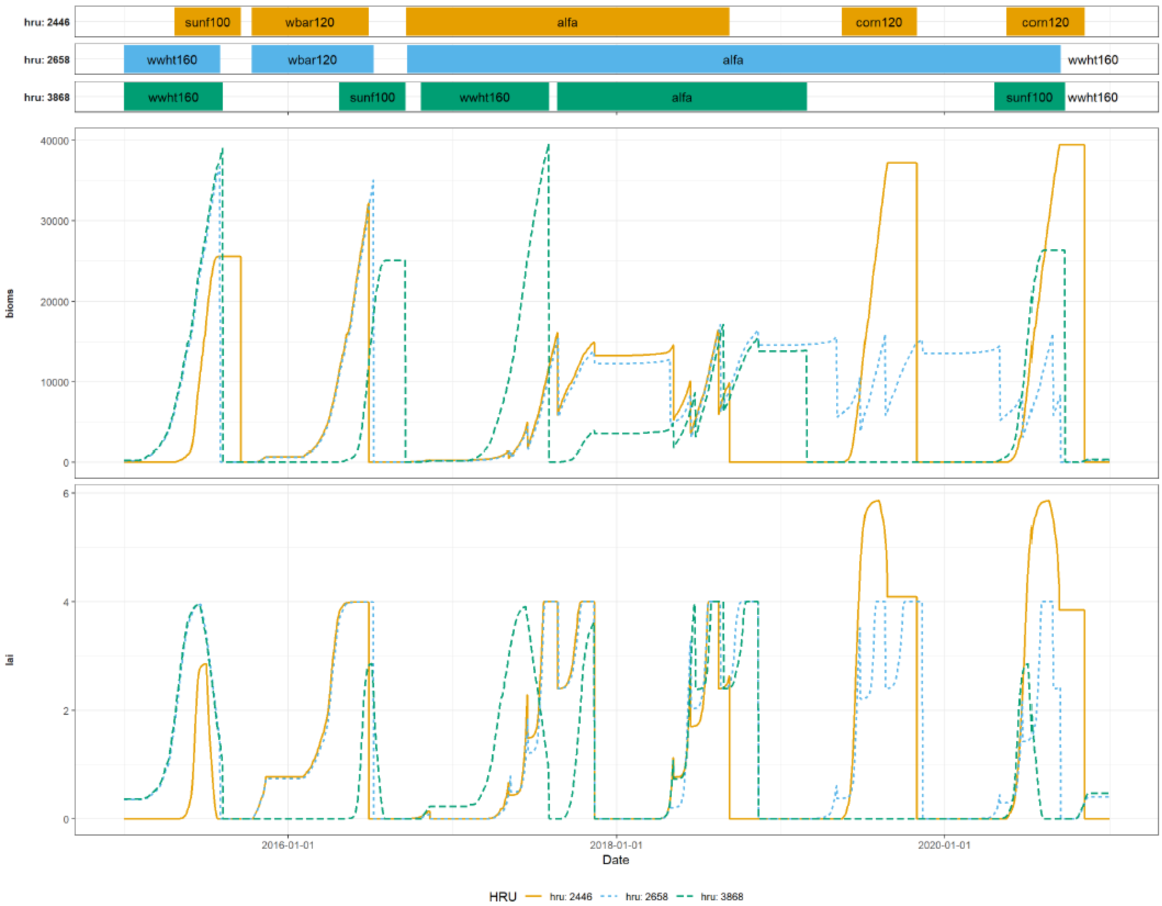


Figure A3.5 Biomass and LAI development for a simulation with all stress factors active for three example HRUs in CS3b.

## 2.2. Soft calibration

The result of the crop yield soft calibration workflow is shown in Fig. A3.6.

Similarly, as it was done for CS11, first the days to maturity parameter (d_mat) was set to meet the desired accumulated plant heat unit value (PHU), which should reach the 1.0-1.2 range at the date of harvesting or killing the plants, except for alfa, for which a value below 0.5 is acceptable. The highest modification was needed in the case of winter crops – winter rape, winter barley and winter wheat (Table A3.4).

Then four plant parameters, namely maximum potential leaf area index (lai_pot), harvest index for optimal growth condition (harv_idx), minimum temperature for plant growth (tmp_base) and biomass-energy ratio (bm_e), were adjusted to simulate the expected crop yield values.

The model could successfully predict the crop yield for alfa, corn, sunflower, winter barley and winter wheat. In the case of winter rape, there is some overprediction of the yield.

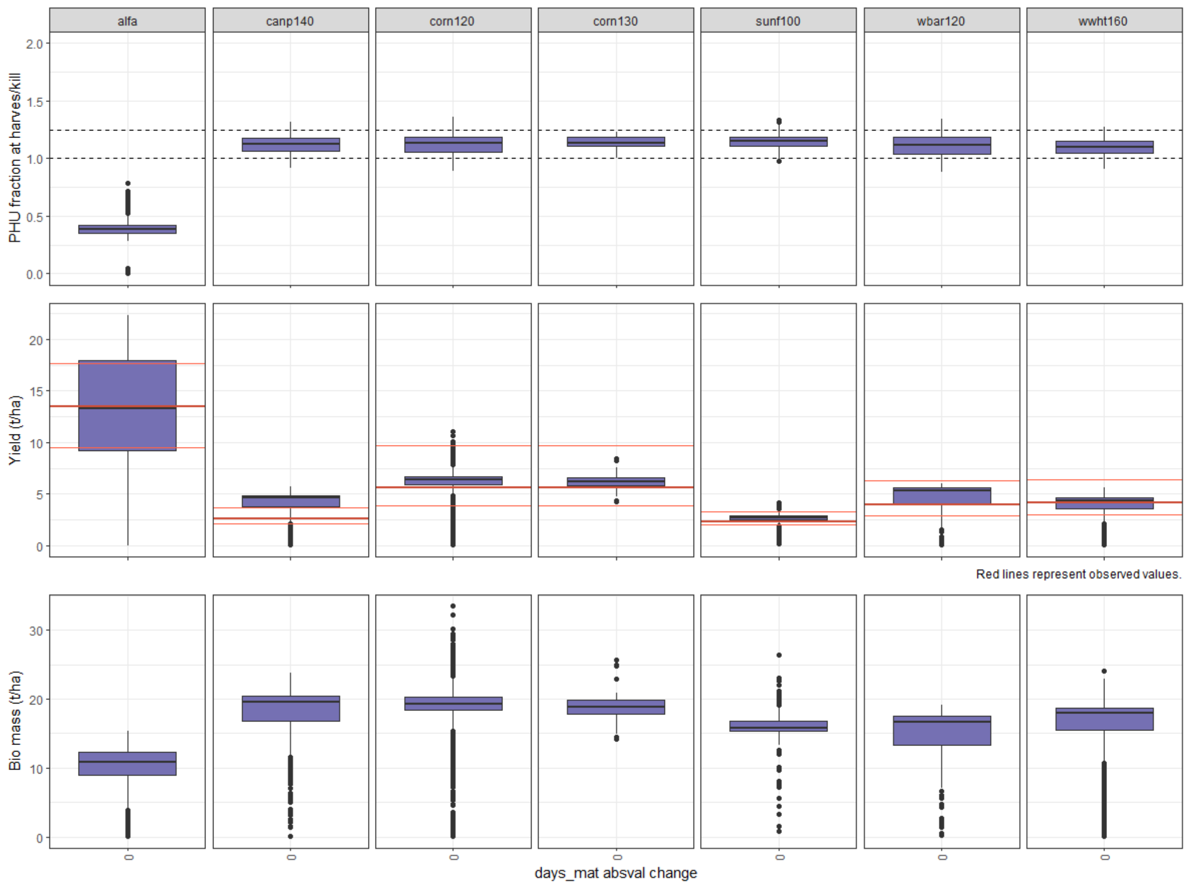


Figure A3.6 Final results of crop yield soft calibration for CS3b. Simulated PHU fraction of harvest/kill (top row), crop yields (middle row) and biomass (bottom row).

Table A3.4 Final calibrated values of crop parameters.

| Crop | d_mat* | lai_pot** | harv_idx** | tmp_base* | bm_e** |
|---|---|---|---|---|---|
| alfa (alfalfa) | 0 | -0.1 | 0.00 | 0 | -0.15 |
| canp (winter rape)*** | -50 | 0.0 | -0.20 | 0 | 0 |
| corn120 (grain corn) | 10 | 0.0 | -0.20 | 0 | 0 |
| corn130 (early grain corn) | 30 | 0.0 | -0.20 | 0 | 0 |
| sunf (sunflower) | 30 | 0.0 | -0.15 | 0 | 0 |
| wbar ( winter barley) | -35 | 0.0 | -0.20 | 0 | 0 |
| wwht (winter wheat) | -45 | 0.0 | -0.15 | 0 | 0 |

* Absolute change ** Relative change

The observed water yield ratio is 0.13 for the time period 2001-2007. During the soft calibration we considered this value to adjust depth distribution used to meet the soil evaporative demand to account for the effect of capillary action, crusting and cracks (esco parameter). The range kept for hard calibration was between 0.12 and 0.33. Crop yield simulation results did not change significantly after adjusting esco.

## 2.3. Hard calibration and validation

In the hard calibration discharge and N-$NO_3$ was considered (Table A3.3). Similarly, to CS11, sediment and phosphorus load would also be interesting in CS11 due to high erosion sensitivity of the catchment. However, the frequency of available phosphorus (P) and sediment concentration measurements was deemed insufficient for a successful calibration. Based on the suggested workflow derived in OPTAIN, first we performed calibration for discharge. For the calibration of nitrogen parameters, we considered the parameters from hydrology calibration. However, the calibration of N-$NO_3$ was not successful, we could not obtain satisfactory results at the time of the reporting period.

In hard calibration we considered 21 hydrology and 5 nitrogen parameters. Similarly, as it was done for CS11, for both observed variables the following five objective functions were computed and analysed: NSE, KGE, PBIAS, $R^2$ and MAE.

We followed the suggested workflow derived in OPTAIN, i.e. in each consecutive iteration the parameter space was being modified in order to improve the performance metrics, trying to account for possible conflicts between responses of different metrics to parameter changes. For the great majority of parameters, their ranges were considerably narrowed down based on interpretation of the dotty plots. The final selection included twenty-one different parameter combinations and was based on setting threshold values for NSE, KGE and PBIAS and the sum of ranks for different metrics and variables. Time series plots for daily discharge, including observed and simulated values are shown in Figs. A3.7-A3.8 with model output variability resulting from the selected ten flow parameter sets.

Discharge varied between 0.02 and 3.60 $m^3 s^{-1}$ in the period of 2002 and 2020. This variability could be captured both in calibration and validation (Fig. A3.7 and 8.). The majority of both high and low flows are described well by the model. The model underestimated high flow events with discharge above 2 $m^3 s^{-1}$ in 2006 and 2017 and some events in 2003 where discharge was around 0.2 and 0.5 $m^3 s^{-1}$. Overestimation occurred for the validation period for some days after high flow events, which caused weaker performance for this period than during the calibration (Fig. A3.9).

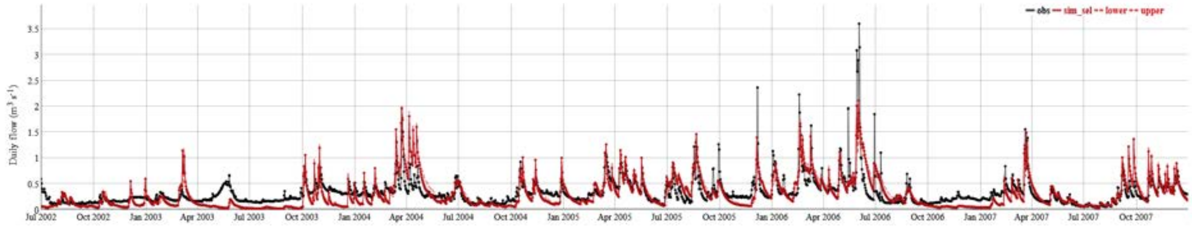


Figure A3.7 Simulated vs. observed daily discharge for flow gauge "Zala" in CS3b (calibration period).

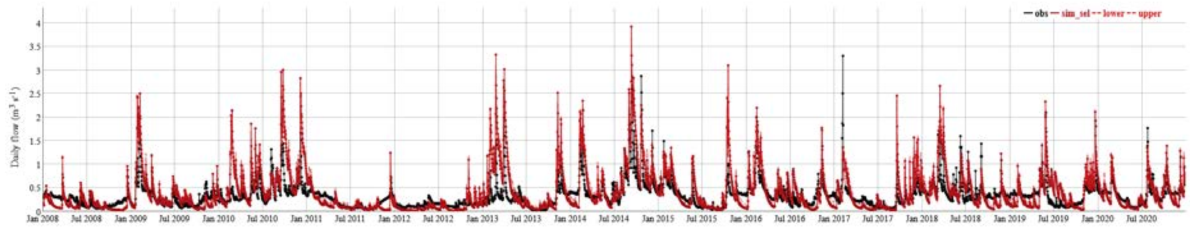


Figure A3.8 Simulated vs. observed daily discharge for flow gauge "Zala" in CS3b (validation period).

We could not obtain satisfactory results for the simulation of N-$NO_3$ concentrations for flow gauge "Zala", therefore those results are excluded from the report.

The model performance metrics are shown in Figure A3.9. The simulations could be further improved because performance for the validation period is poor. There is overestimation for that period due to the problematic behaviour of the model related to very frequent sharp peaks that are usually not present in the observation data.

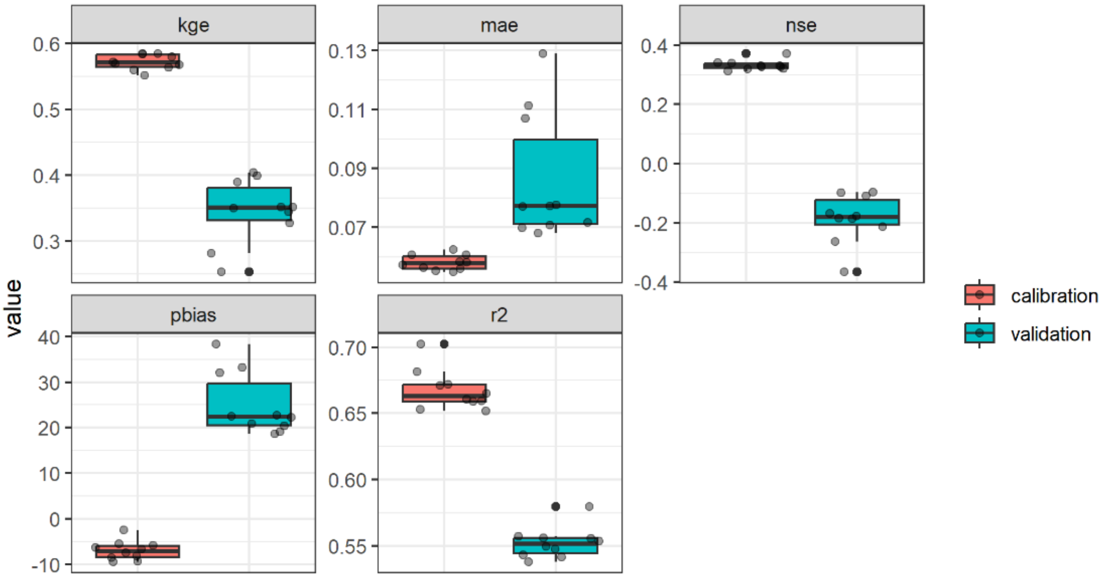


Figure A3.9 Box plots of model performance metrics for discharge in calibration and validation period for CS3b.

Figure A3.10 shows the simulated water budget of the final version of the calibrated model setup, based on a single parameter set with the highest sum of ranks, for the period 2002-2020. 14 % of the precipitation becomes water yield. 76 % of the water yield is surface runoff. 84 % of the generated surface runoff flows onto the landscape. 68 % of the total evapotranspiration (et) comes from the plant component (eplant). Total evapotranspiration-precipitation ratio (et/precip) is 0.8, base flow ratio (base/wyld) is 0.2.

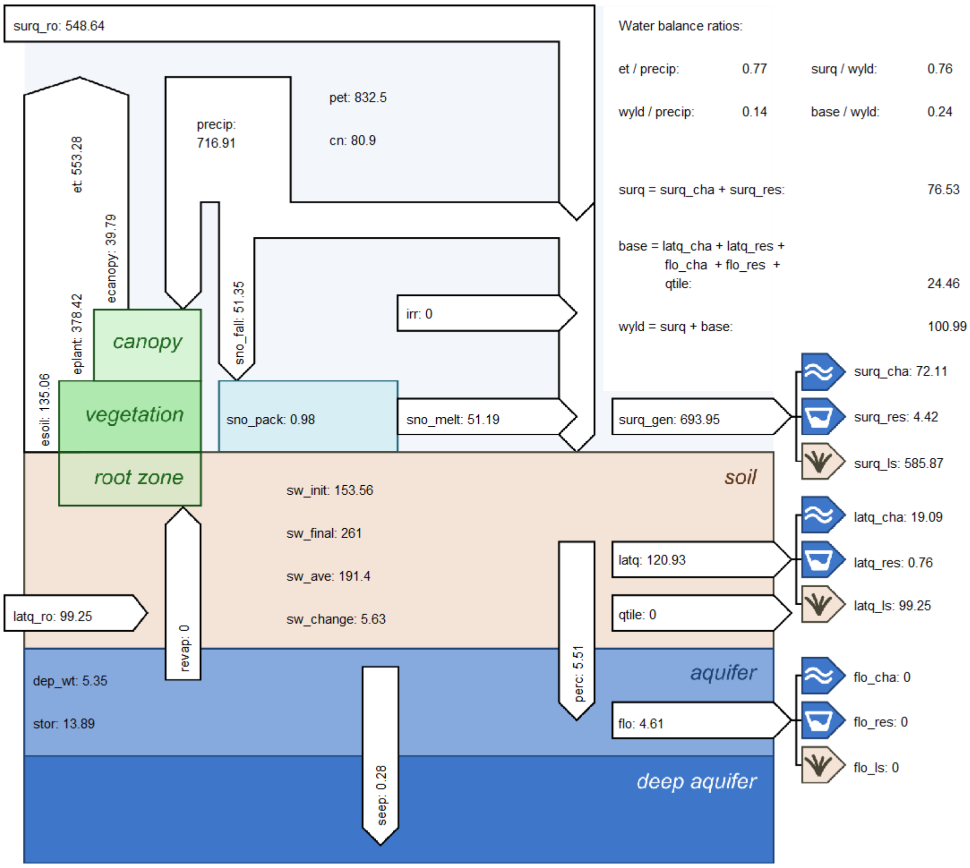


Figure A3.10 Simulated water budget of the final, calibrated model setup for CS3b (years 2002-2020).

## 3. Climate change effects

Similarly, as described in Annex 4, we followed the OPTAIN protocol, therefore we used bias-corrected RCM simulations developed in the WP3 (Honzak, 2023) as the SWAT+ model forcing in order to assess the effect of climate change on the water balance, nutrient losses and crop yields. For the bias correction, locally measured data was considered. We applied all available combinations of six RCMs, three RCPs and three-time horizons, resulting in a total of 54 model scenarios:

- 1991-2020 - serving as the “baseline”,
- 2036-2065 - “near future”,
- 2070-2099 - “end of century”.

Figure A3.11 shows projected changes in annual and seasonal minimum (Tmin) and (Tmax) temperature as well as precipitation (prec) for CS3. There is a warming pattern in the case of RCP8.5, for which projected increase in Tmin and Tmax ranges between 2.5 and 3.5 degrees C. The highest magnitude of the warming signal occurs in winter, while the lowest in spring. In contrast, under RCP2.6 the projected change does not generally exceed 1 degree. Precipitation projections show a signal of wetter future in the case of all RCPs. Under RCP8.5 spring and winter is wetter, summer is drier close to the end of the century. Under RCP2.6 autumn is drier, winter is wetter close to the end of the century. The 2071-2100 period is characterised by the highest model spread. In general, projected changes in wind speed, solar radiation and relative humidity are relatively low, even under RCP8.5, and thus should not contribute a lot to the effect of climate change on the studied indicators.

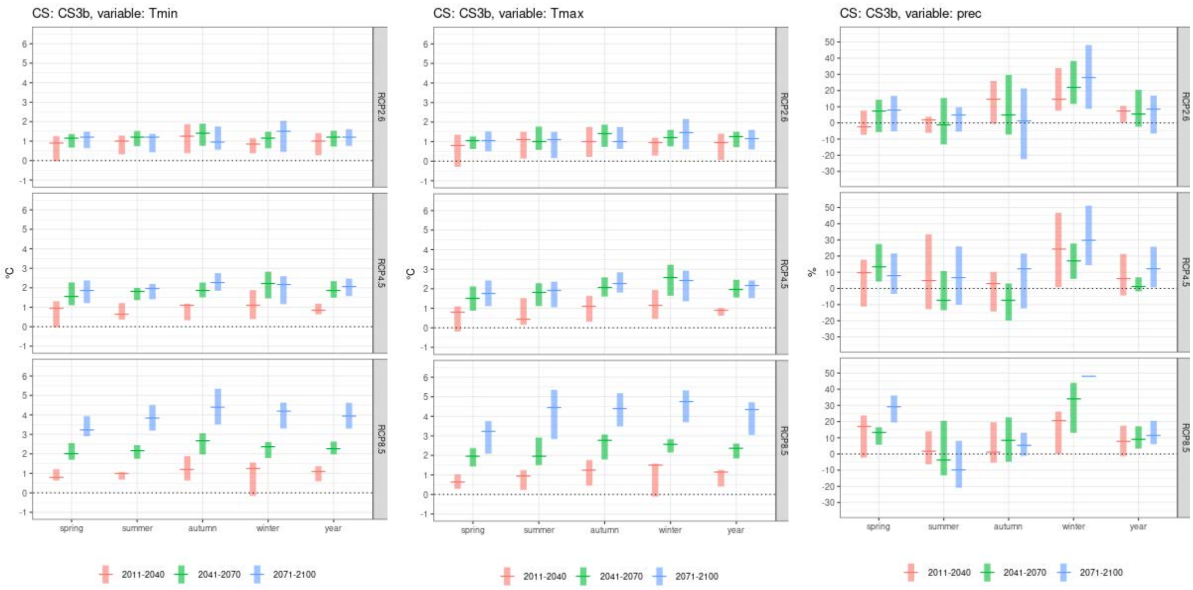


Figure A3.11 Projected changes in variables Tmin, Tmax and prec for all RCPs and time horizons for CS3 (Honzak, 2023).

In the analysis we included precipitation (precip), snowfall (snofall), snow melt (snomlt), potential evapotranspiration (pet), actual evapotranspiration (et), percolation (perc), soil moisture content (in the root zone and in top 300 mm) (sw), surface runoff flowing into channels (surq_cha), lateral soil flow into channels (latq_cha) and tile flow (qtile) (Fig. A3.12). There is no tile drainage in CS3, therefore no effect of climate change was observed. As described above, an increase of precipitation is expected for all examined RCPs. Decrease of snowfall and melt and soil water content in the upper 300 mm is projected. Potential and actual evapotranspiration, surface runoff flowing into channels and lateral soil flow into channels are expected to increase in general. Increase of potential evapotranspiration might be triggered by increasing temperature. Increasing surface runoff flowing into channels (up to 25 % average value) and lateral soil flow into channels (up to 15 % average value) is triggered by the expected increase in precipitation.

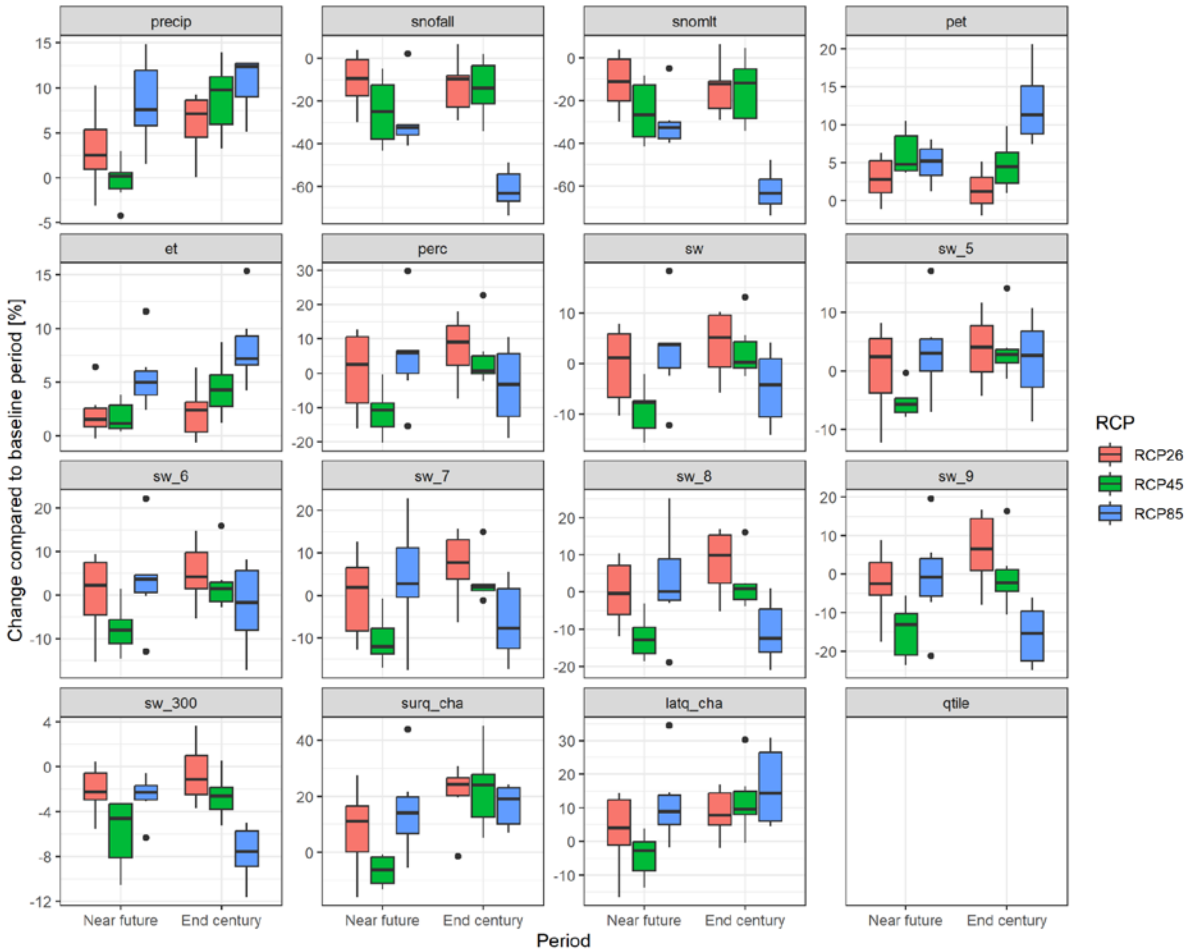


Figure A3.12 Projected changes in selected basin-averaged water balance components simulated by SWAT+ for CS3. There is no tile drainage in the case study, therefore qtile plot does not show any boxes.

Figure A3.13 shows projected changes in selected streamflow (Q) indicators simulated by SWAT+ for CS3. In the case of RCP2.6 average and median flow is projected to increase 10-20 %. In the case of RCP4.5 average flow is projected to decrease in the near future but is expected to increase 20 % by the end of the century. For RCP8.5, average flow is projected to increase in the near future and at the end of the century by 15 and 18 % respectively. Low flow days are projected to increase in RCP4.5 in the near future. In the case of RCP8.5 low flow days are expected to decrease in the near future and no change is projected at the end of the century. High flow days are expected to increase 100-200 % by the end of the century in the case of all scenarios.

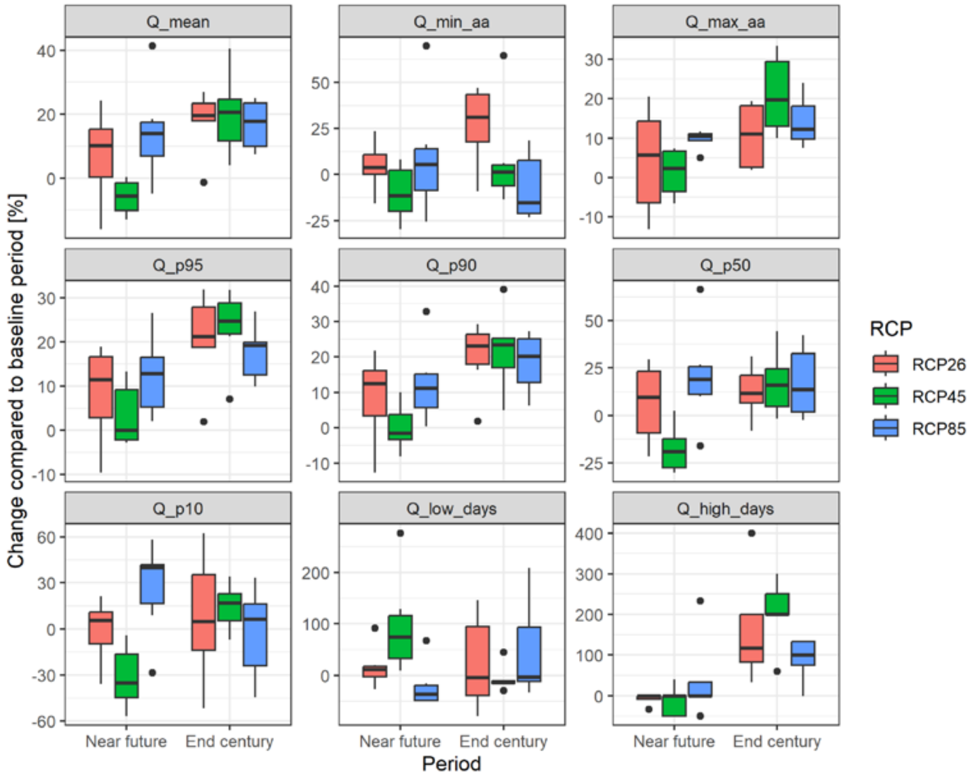


Figure A3.13 Projected changes in selected streamflow indicators simulated by SWAT+ for CS3.

Figure A3.14 shows projected changes in water quality for CS3. $NO_3$-N and phosphorus (P) were not calibrated with the SWAT+ model, therefore the reliability of the water quality related results is lower. In general, under wetter conditions in the future, total nitrogen (TN) and P loads and losses are projected to increase in RCP2.6 and 8.5. The frequency of days with high TN concentration is projected to increase in RCP2.6 and 8.5. The opposite happens to N and P concentration. Average nitrogen load of the stream is projected to increase up to 10 % at the end of the century in RCP2.6. Expected trends are different for RCP4.5. for N and P loss. In the near future those will slightly decrease (2-5 %) and the increase is expected by the end of the century. Average phosphorus load of the stream is projected to increase up to 20 % at the end of the century in the case of RCP4.5.

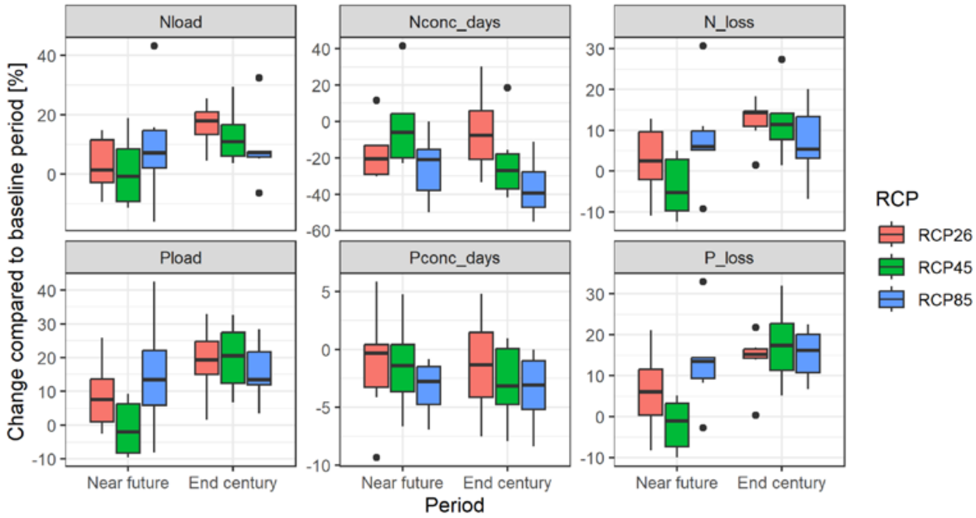


Figure A3.14 Projected changes in selected water quality indicators simulated by SWAT+ for CS3.

The mean crop yield of winter rape (canp), winter barley (wbar), corn and sunflower (sunf) is projected to decrease 1-7.5 % on average in the case of RCP4.5 and 8.5 (Figure A3.15). For RCP8.5 yield decrease is projected for all crops but the lucerne (alfa). For lucerne (alfa) 3-17 % yield increase is projected depending on the RCP, with highest values projected under RCP8.5 by the end of the century. Highest yield decrease is expected for sunflower (7.5 %) under RCP4.5 in the near future. The direction in change in the case of winter wheat is not uniform, it is projected to change between -2 and 2.5 %.

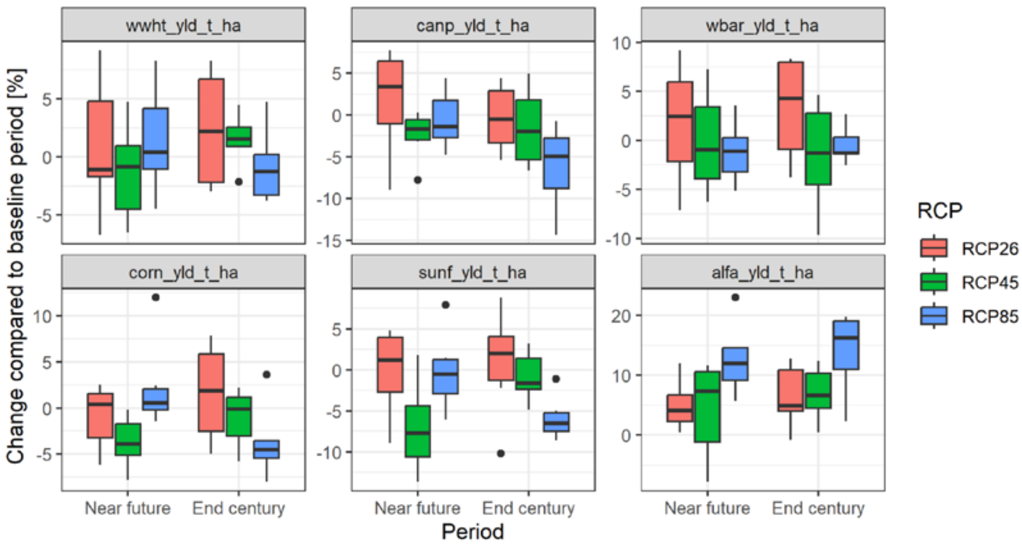


Figure A3.15 Projected changes in selected crop yields simulated by SWAT+ for CS3.

## 4. Effectiveness of selected NSWRMs (current climate)

For the analysis of possible NSWRM scenarios we identified the following possible measures:

- Field dividing: halving the agricultural fields above 50 ha and implementing buffer strips between the fields, based on the suggestion of the local agricultural advisor.
- Forested buffer strips: between the halved parcels - perpendicular to the water course, size: 20 m wide (NAK, 2018).
- Cover crop: on croplands where mean soil loss is 15-40 t/ha (MSZ 1397:1998, 1998; Verheijen et al., 2009).
- No till: on croplands where mean soil loss > 40 t/ha (Verheijen et al., 2009) and on the parcels of an agricultural company, who is interested in implementing no-till, regardless of the value of soil loss.
- Riparian forest buffer: along the stream.

From the above list (1) implementation of riparian buffer, (2) field dividing and implementing forested buffer strips between the fields and (3) no-till management with cover crops were included in the NSWRMs scenario analysis (Fig. A3.16). Figure A3.17. summarises the projected changes due to NSWRMs implementation. The SWAT+ model was not calibrated for nitrogen, phosphorus and sediment concentration, therefore the uncertainty of the projected changes in their indicators is not known.

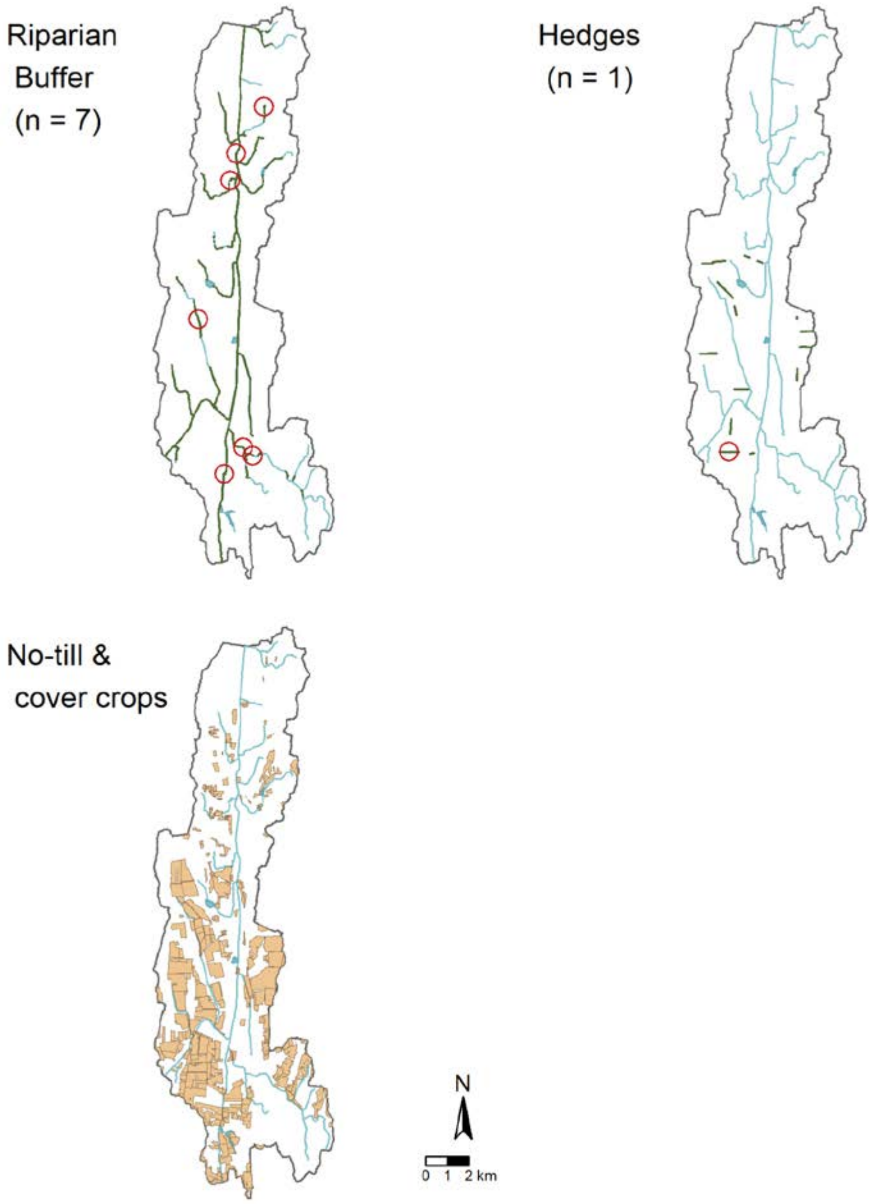


Figure A3.16. Location of measures selected for the NSWRMs scenario analysis.

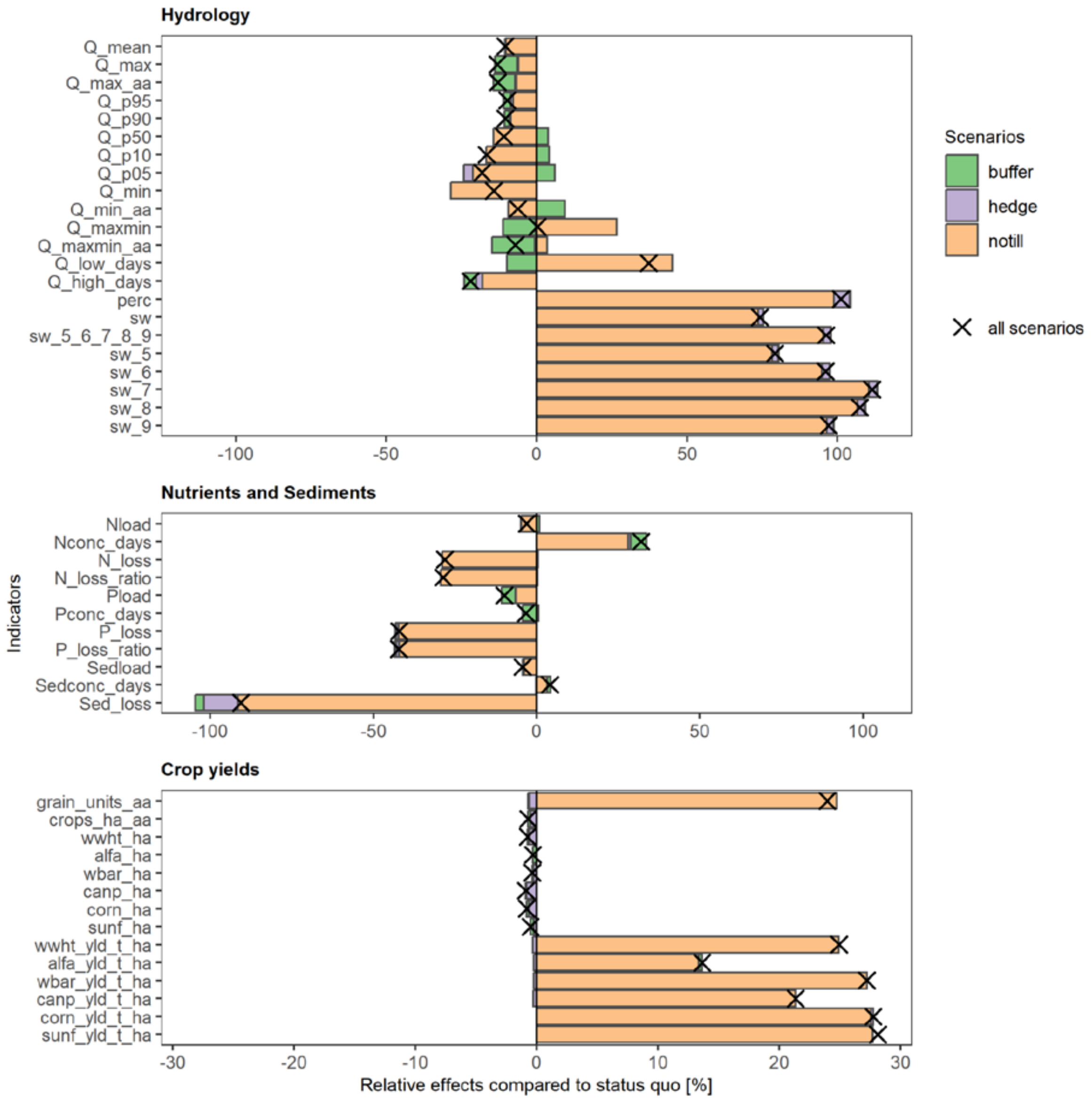


Figure A3.17 Projected changes in selected hydrological, water quality and crop yield indicators simulated by SWAT+ for CS3 for the selected NSWRMs scenarios.

## Riparian forest buffer

Riparian forest buffers were applied along the stream 20 m wide on those HRUs which had land cover type other than forest.

Regarding hydrology indicators, mean discharge does not projected to change if riparian forest buffers are implemented. High flows are expected to decrease by 7 %. Median flows (Q_p50) are expected to increase by 4 %. Differences between high and low flows (Q_maxmin) are expected to decrease by 11 %. Number of days with low flow (Q_low_days) is projected to decrease by 10 %. Percolation (perc) and soil water content (sw) are not expected to change. Regarding water quality indicators, the daily nitrogen concentration is projected to increase 5 %. Nitrogen load and loss are projected to be negligible. Phosphorus daily concentration and load is projected to decrease by 5 %, loss is negligible. Sediment loss is projected to decrease by 3 %.

#### Field dividing and implementing forested buffer strips between the fields

Field diving and implementing buffer strips was applied on those agricultural fields which are currently larger than 50 ha. Their projected change is not notable for discharge. Percolation is projected to increase by 5 %. Increase in soil water content is slight, between 2-3 %. Their influence on nutrients and sediments is notable only in the case of sediment loss, which is projected to decrease by 10 %. The expected change of the crop indicators is negligible, it is between -3 and 0.2 %. The area of the crops obviously changes, due to the area needed for implementing the buffer strips.

#### No-till management with cover crops

No-till management with cover crops was applied on all croplands of CS3. No-till with cover crops has the highest projected impact on all analysed indicators. Mean flow is projected to decrease by 10 %, high flow by 6 %, low flow by 29 %. Number of days with low flow is expected to increase by 45 %, the difference between low and high flow by 27 %. Percolation is expected to increase by 99 %. Soil water content is expected to increase by 73 % on average, by 95 % between May and September. Regarding nutrients and sediments, almost all indicators are expected to decrease, except daily nitrogen and sediment concentration. N and P loss is expected to increase by 29 % and 42 %, respectively. Sediment loss is projected to decrease by 91 %. These findings are in line with the fact that no-till management combined with cover crops significantly decrease surface runoff, increase infiltration - due to improved soil structure - therefore decrease nutrient and sediment loss. No-till combined with cover crops has a positive projected influence on crop yield - between 13 and 28 % - which might be due to the expected high increase in soil water content and decrease of nutrients loss.

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# Annex 4 Modelling results for CS4 (Upper Zgłowiączka, PL)

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## 1. Model setup

The SWAT+ model for CS4 catchment (Upper Zgłowiączka) was set up following the OPTAIN workflow (Schürz et al., 2022). The majority of input data were prepared with the help of the SWATprepR package (Plunge et al. 2024b), which was developed along with model preparation steps. The uncalibrated model setup was developed using the R script for the model setup generation workflow (https://git.ufz.de/optain/wp4-integrated-assessment/swat/swat-setup/full_workflow) consisting of both SWATbuildR and SWATfarmR (version 3.2.0 and 4.0.2). The SWAT+ model revision 61.0 (from 1/12/2024) was used in all simulations.

### 1.1. Input data overview

Table A4.1 presents all major SWAT+ input data, their resolution and sources. Additional comments provide explanations on pre-processing particular data items. Selected spatial datasets (flow gauges, water quality monitoring points, ground water gauges, meteorological stations, point source locations, channels, catchment boundary, elevation map, land use map and soil types. The CS4 catchment occupies 150 km$^2$ and is characterised by a flat relief, high fraction of arable land and variable soil types (predominantly loamy sands and sandy loams).

Table A4.1 Summary of input data for CS4.

| Input | Number of objects / resolution | Source | Comments |
|---|---|---|---|
| DEM | 5 m | Head Office of Geodesy and Cartography (GUGiK) | |
| Channel layer | 164 | Database of topographic objects (BDOT10) | Layer was modified to account for NSWRMs planned for scenario simulations |
| Land layer | 10,267 | Database of topographic objects (BDOT10), State Water | Tile drainage information supplemented based on historical |

| | | | |
|---|---|---|---|
| | | Holding Polish Waters (PGW WP) | maps retrieved from PGW WP; land layer was modified to account for NSWRMs planned for scenario simulations |
| Soil layer | 839 | Institute of Soil Science and Plant Cultivation (IUNG) | Raw vector layer from IUNG pre-processed in GIS and later processed in SWATprepR |
| Usersoil table | 846 | | Derived from SWATprepR; soil particle size data harmonized using the script by Nemes (2022); organic soil parameters and HSG groups derived by soil experts |
| Point sources | 2 | Central Statistical Office (GUS) | Two WWTPs from local municipalities |
| Weather data | 13 stations | Institute of Meteorology and Water Management (IMGW), Institute of Technology and Life Sciences (ITP), Agricultural Advisory Centre (ODR) | Weather data were processed by SWATprepR |
| Atmospheric deposition | 1 | European Monitoring and Evaluation Programme (EMEP) | EMEP data processed by SWATprepR |
| Crop sequence map | 7,859 (fields) | The Agency for Restructuring and Modernisation of Agriculture (ARiMR) | Derived from the crop classification script (Meszaros et al., 2022) using local training data from ARiMR and later processed by SWATprepR |
| Management schedules | 12 | Agricultural Advisory Centre (ODR) | Schedules prepared in consultation with the local agricultural advisory service |

## 1.2. Baseline model setup

The most important features of the model setup were included in Table A4.2. Most of them were extracted from the object.cnt file. A very detailed input land layer resulted in a high number of HRUs (10,240), which in consequence affected the model run time.

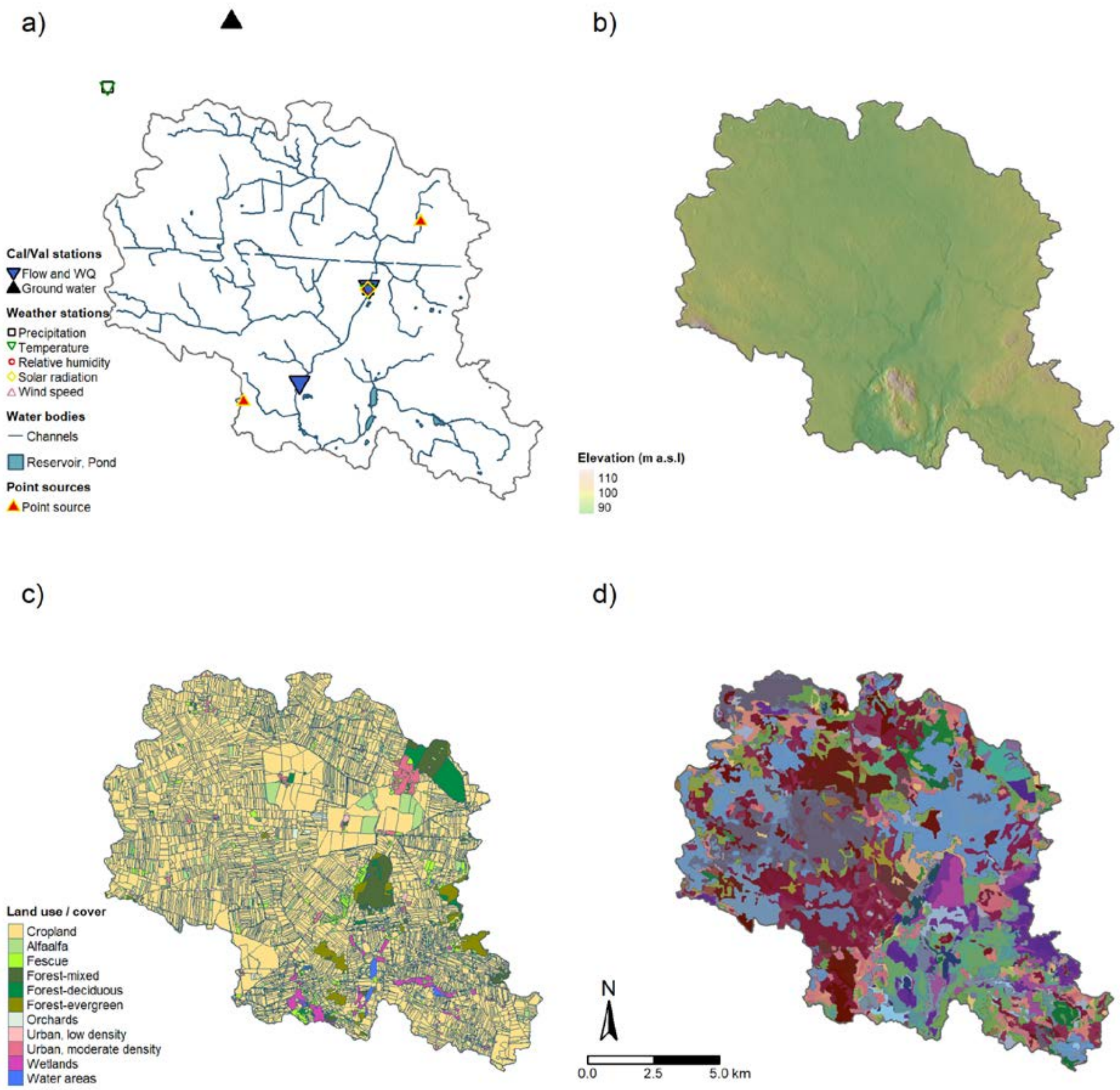


Figure A4.1 GIS input data for CS4: a) flow gauges, water quality monitoring points, ground water gauges, meteorological stations, point source locations, channels and catchment boundary; b) elevation map; c) land use map; d) soil types (the legend was not added as there are 845 soil types).

Table A4.2 Summary of the model setup features.

| Parameter | Value |
|---|---|
| Total area of the watershed in ha | 15005 |
| Total number of spatial objects in the simulation | 20674 |
| Number of HRUs in the simulation | 10240 |
| Number of routing units in the simulation | 10240 |
| Number of aquifers in the simulation | 1 |
| Number of reservoirs in the simulation | 27 |
| Number of recalls (point sources/inlets) in the simulation | 2 |
| Number of SWAT-DEG channels in the simulation | 164 |
| Number of crops in rotation | 12 |
| Number of wetlands | 73 |

## 2. Model evaluation

Table A4.3 presents observation data for variables used in soft (crop yields, water yield ratio) and hard calibration (discharge, groundwater depth, $N\text{-}NO_3$ concentrations). Since crop yield statistics in Poland are available only for major crops and only at voivodeship level, we preferred to use local expert-based estimates (average values and ranges). Discharge data in CS4 are problematic, as there is no flow gauge operated by the hydromet service. Thus, we relied on data from a gauge operated by ITP, with frequent gaps and some issues with homogeneity. Surface water level logger readings for the period 2006-2011 and a database of discharge measurements were used to develop a flow rating curve. Due to a difficulty with development of the flow rating curve for the validation period, we used a dataset of 98 instantaneous flow measurements for that period. Hydrology calibration workflow in CS4 included an optional variable, groundwater depth, in order to better constrain aquifer parameters. A major advantage of the observation dataset in CS4 are high-frequency (daily) $N\text{-}NO_3$ concentrations available for a relatively long period (2012-2022). This dataset is available thanks to the automatic water quality sampling equipment operated by ITP since 2012.

Table A4.2 Summary of observation data used in different steps of the calibration workflow for CS4.

| Variable | Time step | Calibration period | Validation period | Source | Comments |
|---|---|---|---|---|---|
| **Soft calibration** | | | | | |
| Crop yields | Average annual | 2006-2022 | NA | Local agricultural advisory board | Expert-based values |
| Water yield ratio | Average annual | 2006-2011 | NA | Model input (pcp) and discharge data | Calculated for a flow gauge with the longest record |
| **Hard calibration** | | | | | |
| Discharge | Daily (calibration), fortnightly (validation) | 2006-2011 | 2018-2022 | ITP Bydgoszcz & SGGW | Own calculation based on readings of the water level loggers and the rating curve developed for one gauge. For the validation period instantaneous discharge measurements. |
| Groundwater depth | Weekly | 2006-2017 | 2018-2022 | Polish Geological Institute (PGI) | One gauge located at the border of the catchment |
| $N\text{-}NO_3$ concentrations | Daily (autosampler), monthly (grab sample) | 2012-2017 | 2018-2022 | ITP Bydgoszcz & SGGW | Daily composite sample data collected by automatic sampling equipment for one gauge and discrete, grab sample measurements for one additional gauge |

## 2.1. Model setup verification

All steps of the model setup verification were performed in accordance with the OPTAIN workflow (Plunge et al., 2024a). Verification of the climate and water balance data (Fig. A4.3) showed that all reported values are in plausible ranges according to the expert knowledge of the studied catchment. The comparison of how different stress factors affect crop yields of an uncalibrated model also showed plausible results, i.e. reductions of crop yields within reasonable ranges (Fig. A4.4). Analysis of biomass and LAI development (example shown in Fig. A4.5) showed acceptable behaviour (inconsistencies appearing at earlier stages were related to the SWAT+ executables, and were later fixed).

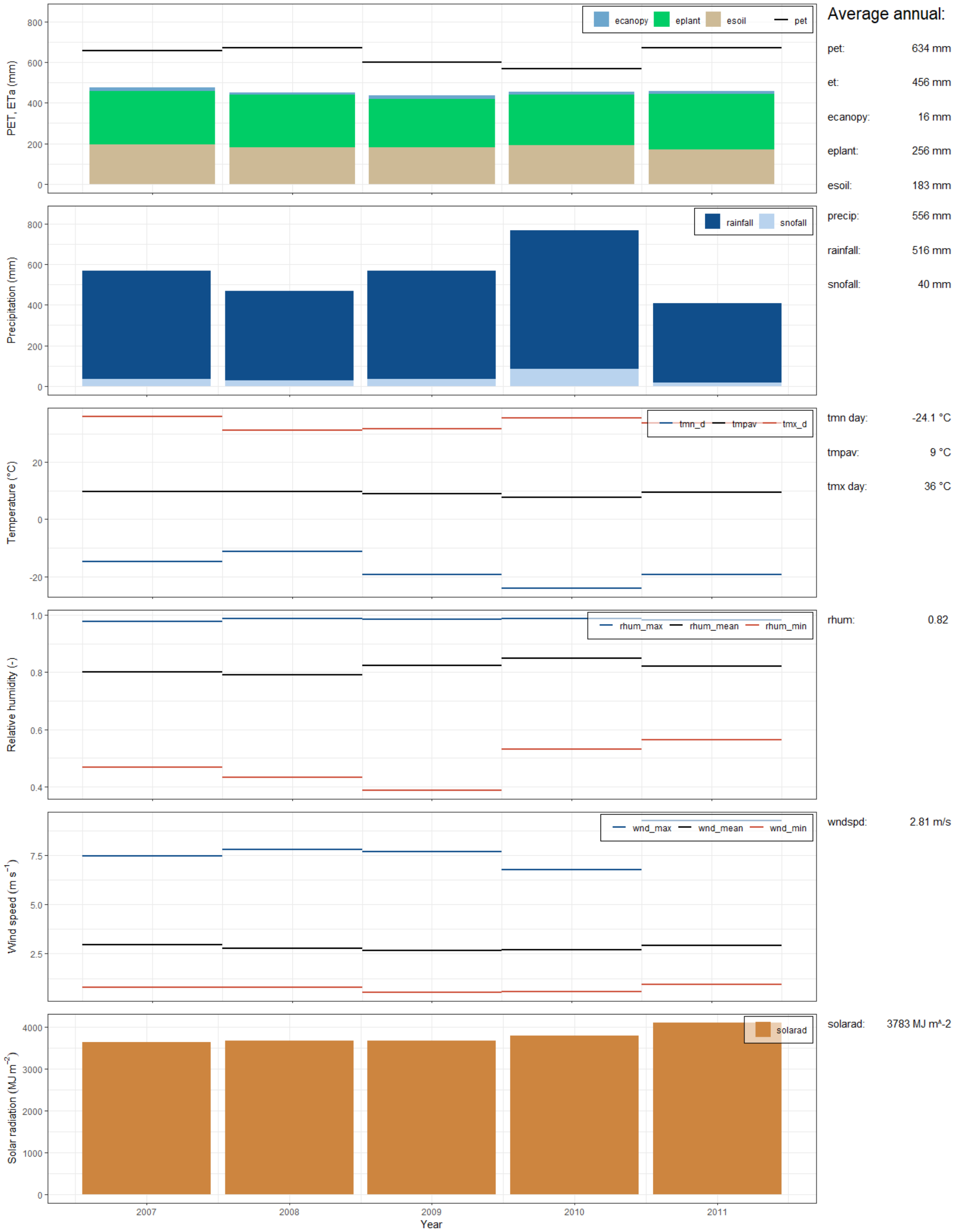


Figure A4.3 Summary of the climate data checks for CS4 by the SWATdoctR.

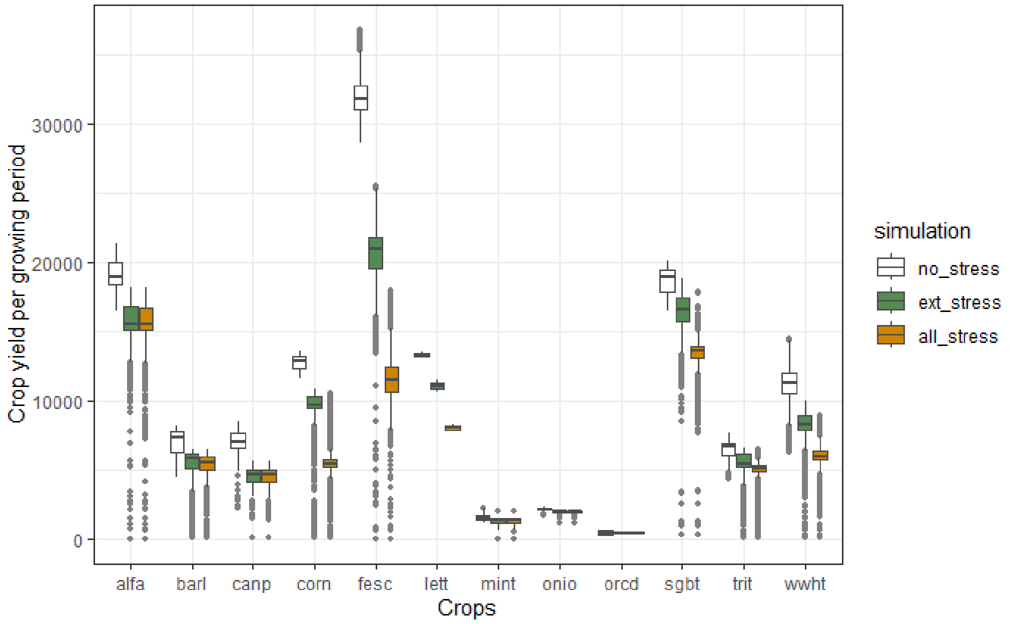


Figure A4.4 Comparison of crop yields with all stress factors, external stress factors and no stress factors for CS4.

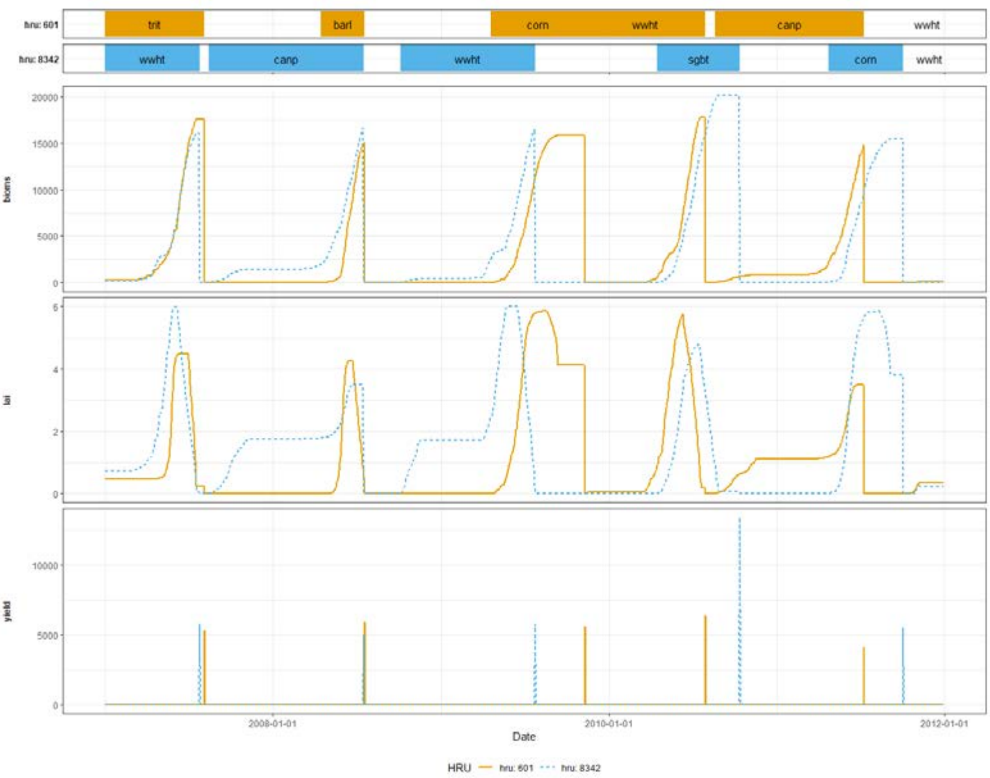


Figure A4.5 Biomass, LAI development and yields for a simulation with all stress factors active for two example HRUs in CS4.

## 2.2. Soft calibration

As shown in Fig. A4.6, the crop yield soft calibration workflow was successfully applied in CS4. In the first step, d_mat (days to maturity) parameter was altered in such a way that the accumulated PHU fraction at harvest/kill is within the predefined range of 1.0-1.2. The highest changes in days to maturity parameter affected winter crops (wwht, trit, canp - see Table A4.3). A different situation can be noted only in case of crops having multiple harvests (alfa, fesc and lett), for which the values below 0.5 are acceptable. In the second step, adjustment of four plant parameters for each crop helped achieve satisfactory crop yield calibration results. For the majority of crops, the average observed and simulated yields match reasonably well. Only in case of canp, fesc and lett the average simulated values fall outside of the min/max observed range. These three cases were the most problematic ones, as selected crops from the SWAT+ plant database are only an approximation of the "real" crops growing in CS4 (winter rapeseed and leaf parsley). Fesc was perhaps more difficult to simulate as a perennial crop.

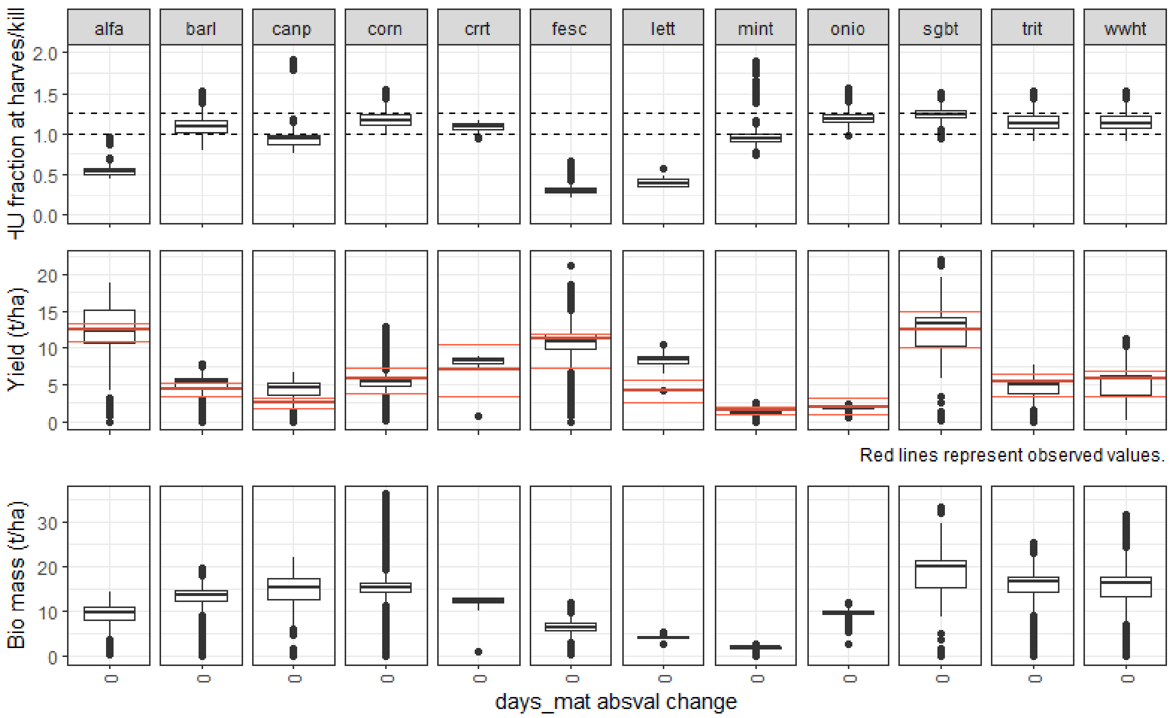


Figure A4.6 Final results of crop yield soft calibration for CS4. Simulated PHU fraction of harvest/kill (top row), crop yields (middle row) and biomass (bottom row).

Table A4.3 Final calibrated values of crop parameters.

| Crop | d_mat* | lai_pot** | harv_idx** | tmp_base* | bm_e** |
|---|---|---|---|---|---|
| alfa (alfalfa) | -20 | 0 | 0 | 1 | -0.25 |
| barl (spring barley) | -25 | 0.1 | 0 | 0 | 0 |
| canp (canola)*** | -80 | -0.3 | 0 | 0 | -0.4 |
| corn (grain corn) | 10 | 0 | -0.15 | 0 | 0 |
| crrt (carrot) | 0 | 0 | -0.2 | 0 | 0 |
| fesc (tall fescue) | 0 | -0.12 | 0.1 | 1 | -0.33 |
| lett (lettuce)**** | -20 | 0 | 0 | 0 | -0.4 |
| mint (mint)***** | -50 | 0 | 0 | 0 | 0.1 |
| onio (onion) | 0 | 0.3 | 0 | 0 | 0.1 |
| sgbt (sugar beet) | 25 | 0 | 0 | 0 | 0.1 |
| trit (winter triticale) | -70 | -0.1 | -0.1 | 0 | 0 |
| wwht (winter wheat) | -70 | 0.2 | 0.2 | 0 | 0.1 |

* Absolute change ** Relative change *** crop representing winter rape **** crop representing leaf parsley ***** crop representing satureja

Water balance soft calibration enabled it to match the observed water yield ratio of 0.16 for the time period 2006-2011 by adjusting the value of esco parameter to 0.27. The range kept for hard calibration was (0.2, 0.35). Crop yield simulation results did not change significantly after adjusting esco.

## 2.3. Hard calibration and validation

In CS4 the major water quality variable of interest was N-$NO_3$ (Table A4.2). Since nitrate concentrations are typically (and in this case as well) well correlated with discharge, we decided to perform a simultaneous calibration of hydrology and nitrogen parameters. The sequential workflow (first hydrology, then N-$NO_3$) was also tested, but appeared to be more challenging to obtain satisfactory results, as several hydrology parameters were significantly affecting nitrate concentrations.

The selected parameters included 16 hydrology and 6 nitrogen parameters. Five objective functions were evaluated for each observed variable: NSE, KGE, PBIAS, $R^2$ and MAE. In the final ranking of parameter sets the following weights were applied for discharge, groundwater depth and N-$NO_3$ concentrations, respectively: 0.5, 0.2, 0.3. In each consecutive iteration the parameter space was being modified in order to improve the performance metrics, trying to account for possible conflicts between responses of different metrics to parameter changes. For the great majority of parameters, their ranges were considerably narrowed down based on interpretation of the dotty plots. The final selection included eight different parameter combinations and was based on the sum of ranks for different metrics and variables. Time series plots shown in Figs. A4.7-A4.9 represent model output variability resulting from these eight parameter sets.

CS4 catchment exhibits huge variability of discharge that was reasonably well captured in calibration (Fig. A4.7). A series of flood events that occurred in 2010-2011 were represented in the model in a satisfactory way. The model fit for low flows was also good, although the relative errors could have been greater than for high flows. The model overestimated two moderate flood events in 2007 and 2008. The validation period contained less high flow events compared to the calibration period. Three largest flood events were underestimated by the model during this period. Low flows were represented well, although an important limitation of this validation was the use of instantaneous instead of continuous flow measurements. Since the validation dataset is not fully homogenous with the calibration dataset, it partly explains lower values of some performance metrics shown in Fig. A4.10.

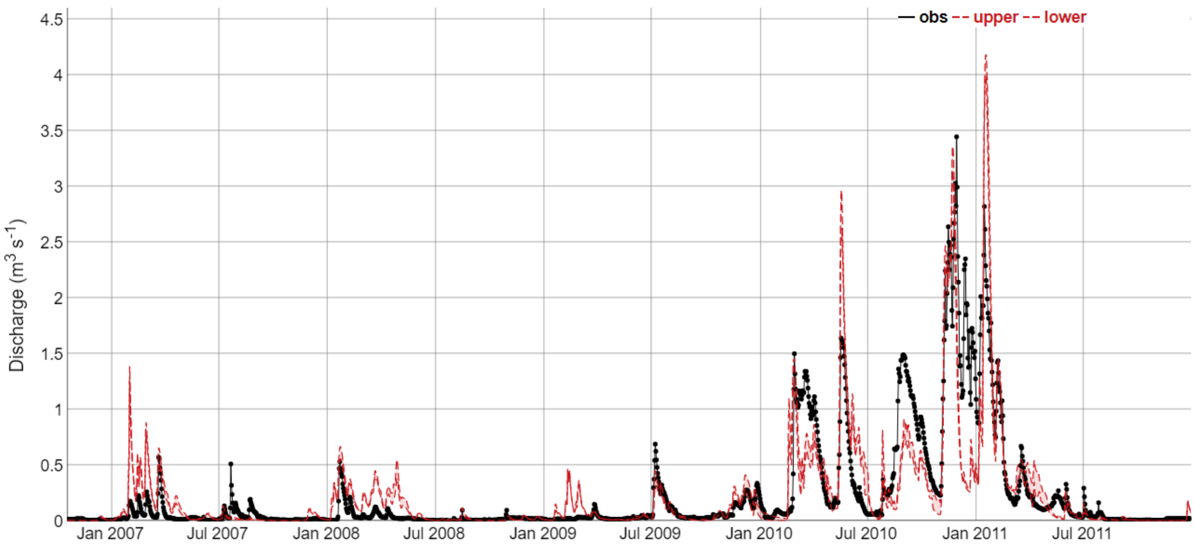


Figure A4.7 Simulated vs. observed daily discharge for flow gauge "Samszyce" in CS4 (calibration period).

Prediction of groundwater depths was surprisingly good in both calibration (Fig. A4.8) and validation periods. Both the intra- and inter-annual variability of groundwater depths was captured well by the model. The model correctly predicted 2010 and 2015 as the wettest and driest years for the depths to aquifer, respectively.

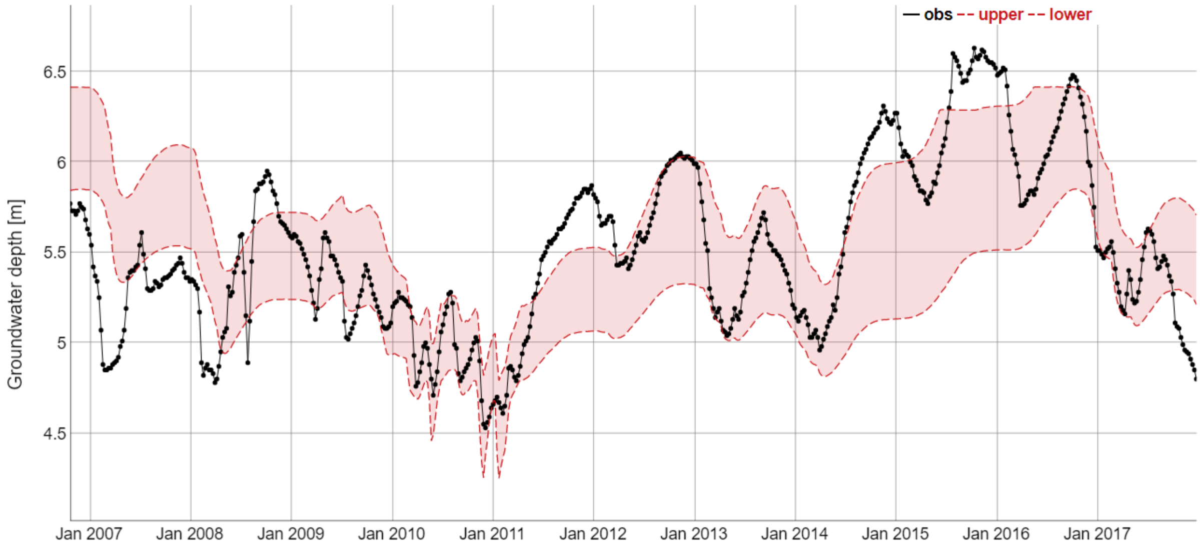


Figure A4.8 Simulated vs. observed groundwater depths for gauge "Bodzanowo" in CS4 (calibration period).

CS4 features high nitrate pollution as shown in Fig. A4.9. The model performance for N-$NO_3$ concentrations was good. The model represented well the inter-annual dynamics showing significantly higher N-$NO_3$ concentrations in wet years compared to dry years. However, low concentrations were consistently over-estimated, and peak concentrations were typically under-estimated. The results for Samszyce gauge in the validation period were somewhat worse than in the calibration period, which is reflected in lower values of performance metrics (Fig. A4.11). However, the model performed well in spatial validation, i.e. in predicting N-$NO_3$ concentrations for a gauge located upstream of the main calibration gauge (not shown here). KGE and NSE values for the validation gauge exceeded corresponding values for the calibration gauge.

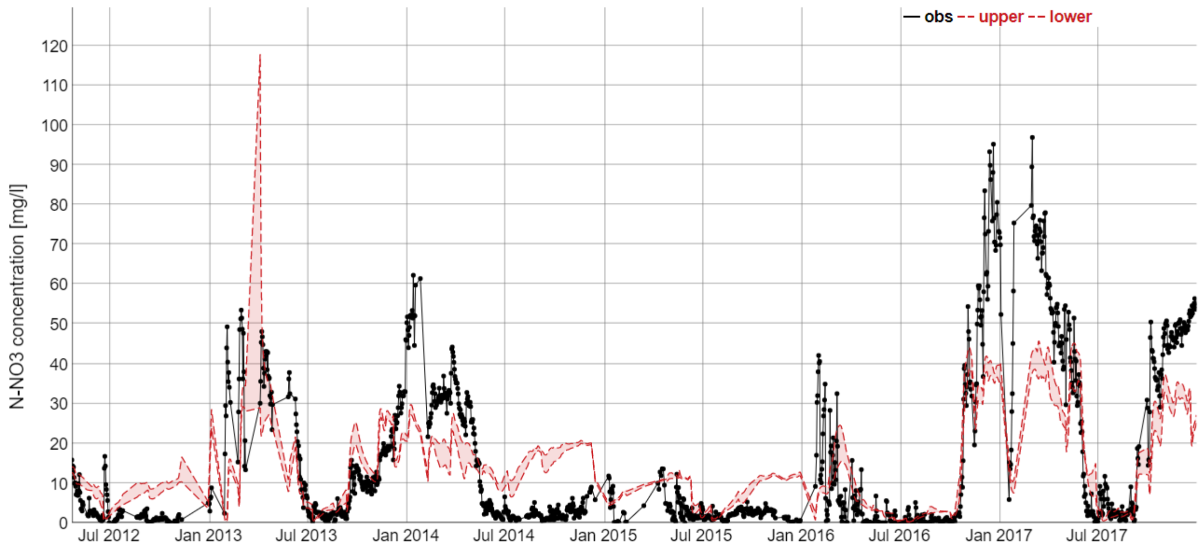


Figure A4.9 Simulated vs. observed daily N-$NO_3$ concentrations for flow gauge "Samszyce" in CS4 (calibration period).

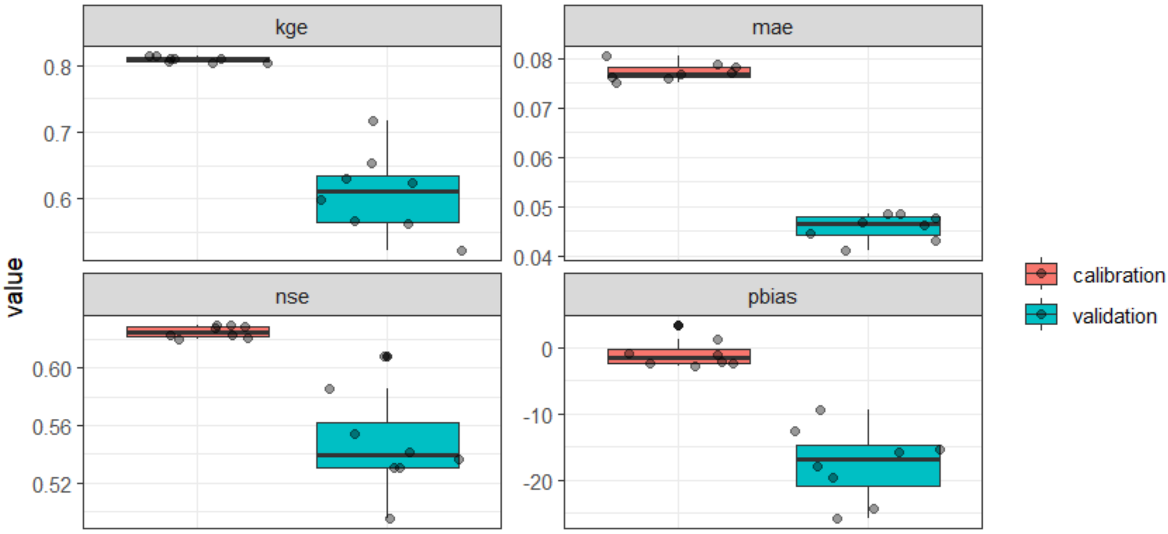


Figure A4.10 Box plots of model performance metrics for discharge in calibration and validation period for CS4.

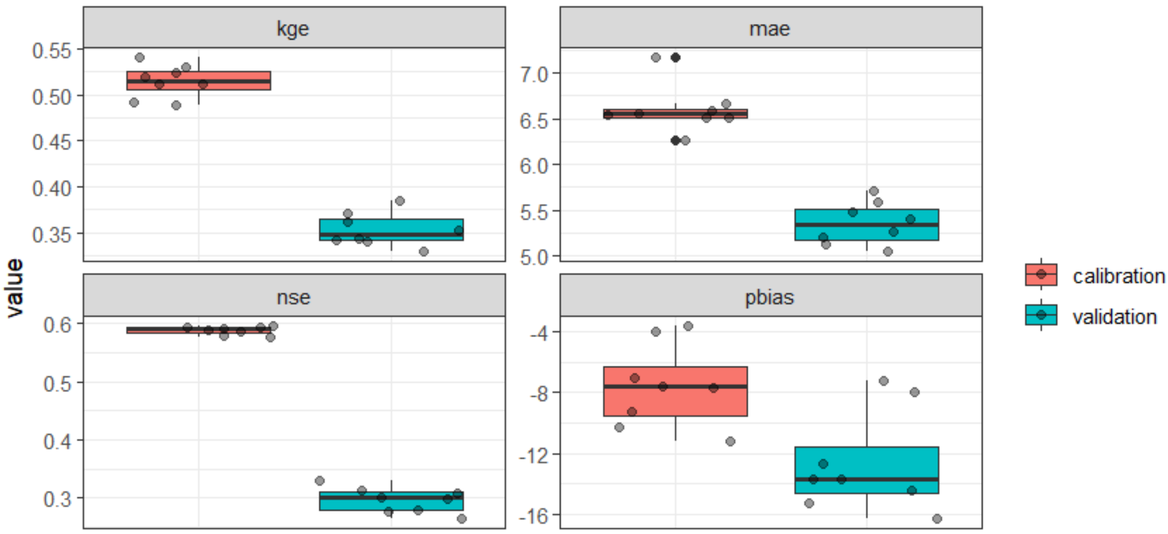


Figure A4.11 Box plots of model performance metrics for NO3-N concentrations in calibration and validation period for CS4.

Simulated water budget of the final version of the calibrated model setup (based on a single parameter set with the highest sum of ranks) for the period 2007-2022 is shown in Fig. A4.12. As expected, only around 10% of precipitation becomes water yield. Tile flow is the dominant flow pathway constituting approximately half of the total flow, followed by baseflow (37%). Plant component of evapotranspiration constitutes 55% of the total ET.

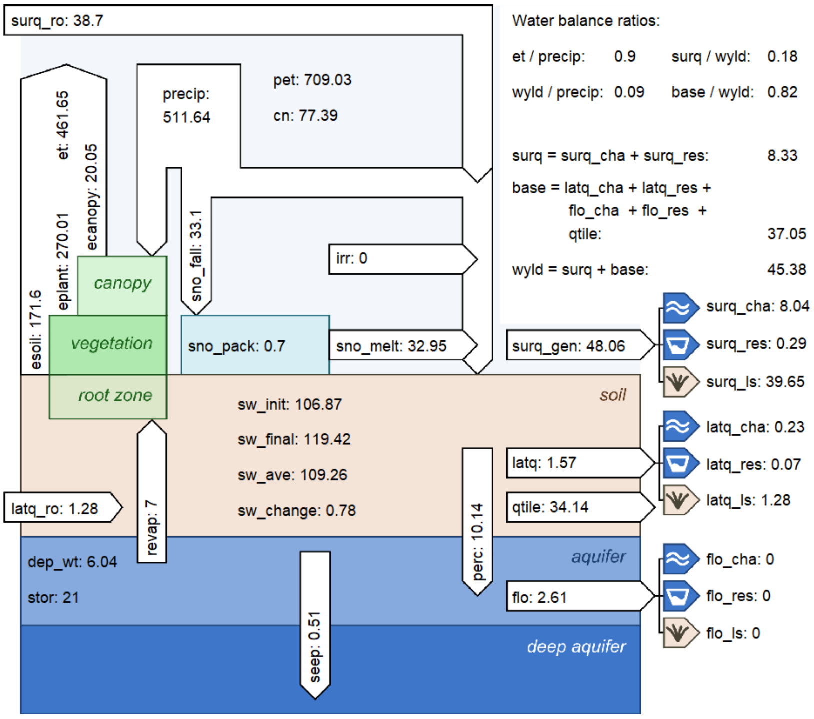


Figure A4.12 Simulated water budget of the final, calibrated model setup for CS4 (years 2007-2022).

## 3. Climate change effects

We used bias-corrected RCM simulations developed in the WP3 of OPTAIN (Honzak, 2023) as the SWAT+ model forcing in order to assess the effect of climate change on the water balance, nutrient losses and crop yields. We applied all available combinations of six RCMs, three RCPs and three time horizons (1991-2020 - serving as the "baseline", 2036-2065 - "near future", 2070-2099 - "end of century"), resulting in a total of 54 model scenarios. More information about the bias correction and climate scenarios can be found in section 2.2.5 of the report as well as in Honzak (2023).

Figure A4.13 shows projected changes in annual and seasonal minimum and (Tmax) temperature as well as precipitation (Prec) for CS4. Note that the horizons are slightly different than those used in SWAT+ modelling. A consistent warming pattern emerges, in particular for RCP8.5, for which projected increase in Tmin and Tmax ranges between 3 and 5 degrees C. The highest magnitude of the warming signal occurs in winter, while the lowest in spring. In contrast, under RCP2.6 the projected change does not generally exceed 2 degrees, even at the end of the century. Precipitation projections show a dominant signal of wetter future, in particular under RCP8.5, for which an ensemble median increase equals 17% by the end of the century. Projected changes are higher in winter and spring compared to summer and autumn for all RCPs. The summer season is characterised by the highest model spread, in the most extreme case ranging from -20 to +30% under RCP2.6 in the 2041-2070 period. A more detailed analysis of climate projections (including other variables) is available at the OPTAIN UFZ cloud[3] . In general, projected changes in wind speed, solar radiation and relative humidity are relatively low, even under RCP8.5, and thus should not contribute a lot to the effect of climate change on the studied indicators.

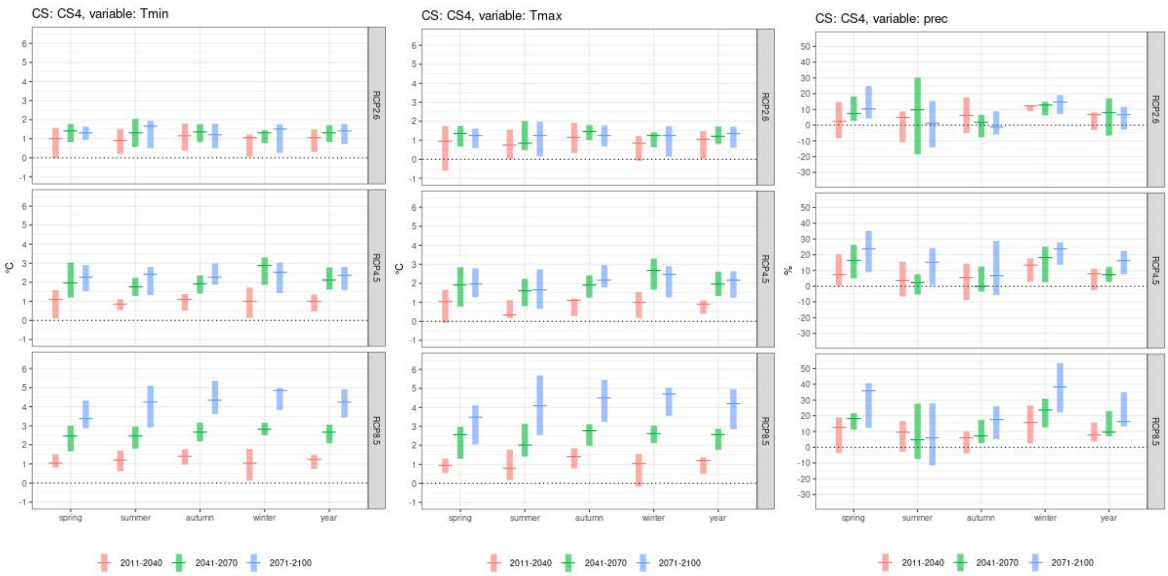


Fig. A4.13 Projected changes in variables Tmin, Tmax and Prec for all RCPs and time horizons for CS4 (Honzak, 2023).

The following basin-averaged SWAT+ outputs were considered in the analysis: precipitation, snow fall, potential evapotranspiration (PET), actual evapotranspiration (ET), percolation, soil moisture content (in the root one and in top 300 mm), surface runoff, and tile flow. The results are presented as box plots in Figure A4.14. As discussed before, precipitation is projected to increase with a variable rate, depending on the RCP and future horizon. An increase in winter precipitation combined with a strong warming translates into a strong decrease in snow fall and snow melt, even exceeding 60% under RCP8.5 in the last time horizon. In contrast, an increase in PET triggered by climate warming is rather modest, with an exception of RCP8.5 for which it exceeds 10% for some ensemble members by the end of the century. Changes in ET are also moderate and go predominantly in a positive direction, possibly due to increased availability of water in the soil profile. Percolation increases strongly under RCPs 4.5 and 8.5. Interestingly, changes in the root zone soil moisture (annual average as well as for individual months of the growing season, from May till September) go mostly in an opposite direction to changes in the topsoil soil moisture: while the former is increasing, the latter is decreasing (mostly by less than 5%). Projections of surface runoff are characterised by a high model spread, so that even the dominant

3 https://nc.ufz.de/s/KA9Cr2bbtALGMHr?path=%2FWPs%20%26%20Tasks%2FWP3%2FTask_3_2%2Flocal%20data%2Fv1a%2Fanalysis

direction of change is difficult to predict. Very high (by over 40%) increases in tile flow, the dominant flow pathway in CS4, are projected under RCPs 4.5 and 8.5. In one extreme case, tile flow is projected to increase by nearly 200%. Such values seem huge and hardly realistic, however, it is important to note that CS4 catchment is highly water-limited, and for example, the annual tile flow amount from the calibrated model equalled only 29 mm (Fig. A4.12). The triple of this value is still relatively low compared to annual precipitation (500-600 mm).

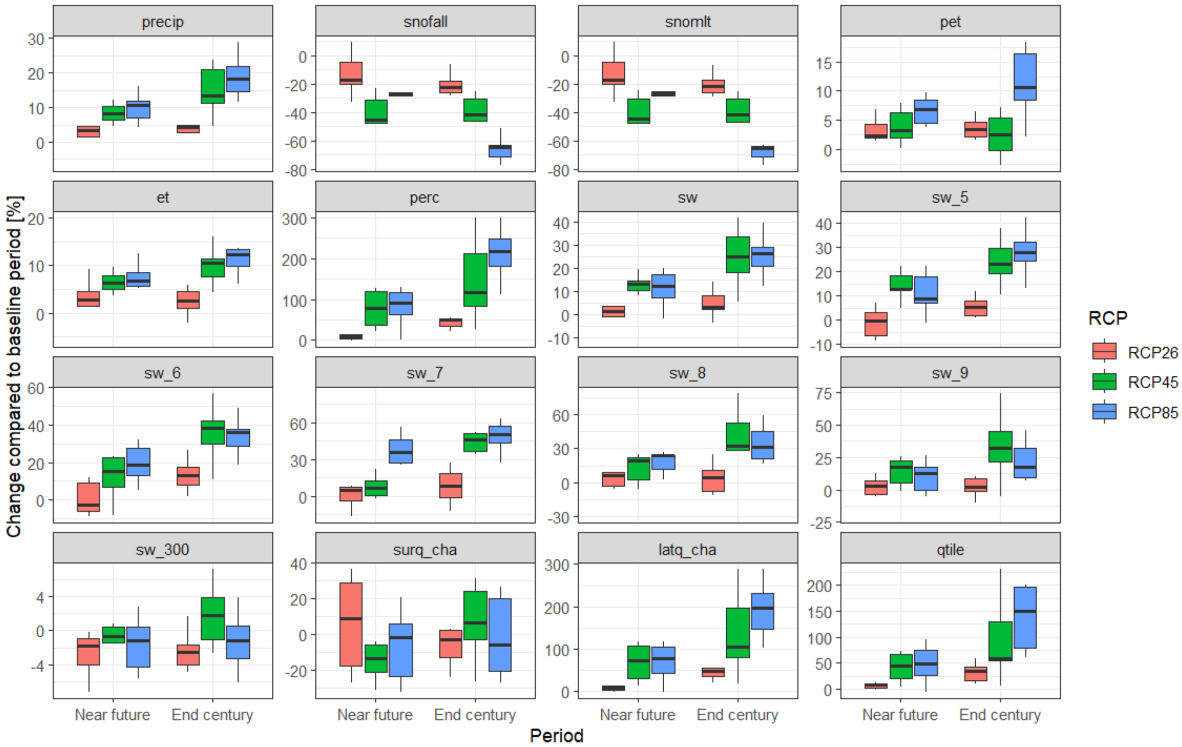


Fig. A4.14 Projected changes in selected basin-averaged water balance components simulated by SWAT+ for CS4.

The second collection of box plots (Fig. A4.15) includes various streamflow indicators. Average and median flow are projected to increase under all RCPs and time horizons, similar to the tile flow in Fig. A4.14. In each case, the rate of increase for RCP2.6 is moderate compared to RCPs 4.5 and 8.5. Both high and low flows are also projected to increase. In consequence, the frequency of low flow days is projected to decrease by 10-20% under RCPs 4.5 and 8.5.

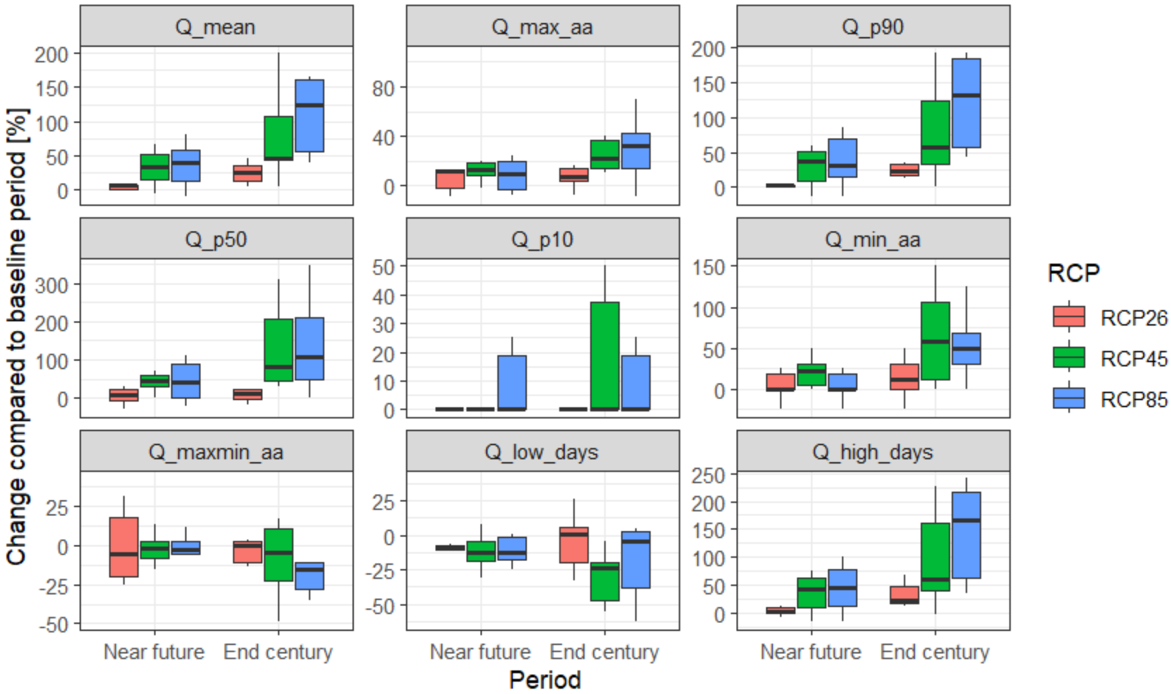


Fig. A4.15 Projected changes in selected streamflow indicators simulated by SWAT+ for CS4.

The third collection of box plots (Fig. A4.16) shows changes in selected water quality indicators. It should be noted that nitrate nitrogen was calibrated and validated for CS4, whereas the plots show total nitrogen (TN). However, according to measurements, $NO_3$-N constitutes over 90% of TN in CS4. Phosphorus was not calibrated at all, so the reliability of results is certainly lower. In general, under wetter conditions in the future, N and P losses are projected to increase significantly, and the same happens to loads carried by the stream. The difference between N and P can be observed for concentration indicators: while the frequency of days with high TN concentration is projected to increase, the opposite happens to TP concentration. This is related to different transport pathways of both elements.

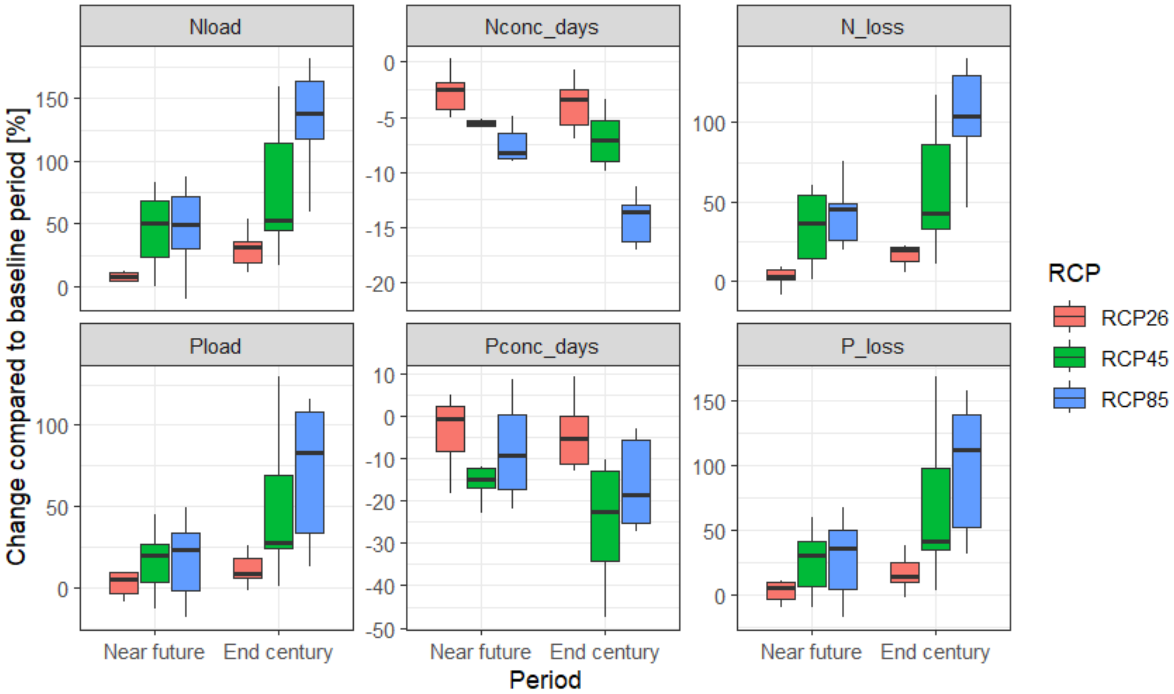


Fig. A4.16 Projected changes in selected water quality indicators simulated by SWAT+ for CS4.

The fourth collection of box plots presents projections of crop yields (Fig. A4.17). For the majority of crops, the signal is not clear. Changes are relatively low and often go in both directions. One of the exceptions is spring barley (barl) and fescue (fesc - grassland), for which an increase by 5-15% is projected for most of the cases. The most extreme change, a decrease of yield by more than 30%, is projected for rapeseed (canp) under RCP8.5 at the end of the century. In this case, the results may be biased due to potentially inaccurate timing of planting and harvesting operations under a significantly warmer climate.

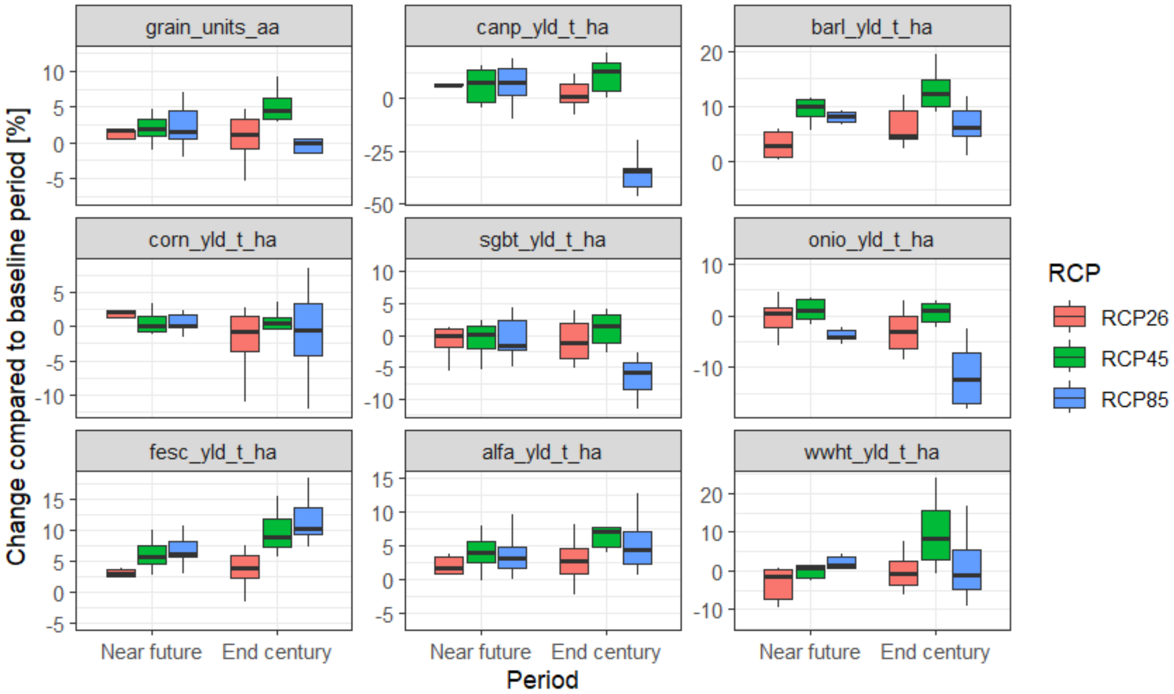


Fig. A4.17 Projected changes in selected crop yields simulated by SWAT+ for CS4.

## 4. Effectiveness of selected NSWRMs (current climate)

NSWRM effectiveness was simulated for four measures relevant for the Polish case study: (1) afforestation, (2) controlled drainage on degraded peatlands, (3) micro-reservoirs on ditches (simulated as ponds), (4) cover crops (combined with low till). The selection of measures and their potential sites for implementation was done in collaboration with local actors based on the results of the 1st and the 2nd MARG workshop. Small deviations in selected measures occurred due to difficulties in plausible representation of mulching and subsoiling measures in SWAT+. As a replacement of these two management measures cover crops combined with low till was selected in consultation with the local farmer advisors.

We investigated measure effectiveness in single scenario runs: One model scenario for each measure, considering all potential sites of implementation (Fig. A1.18), and one additional scenario in which all measures were implemented simultaneously (scenario ‘all’). Scenario ‘afforestation’ is based on changing land use from non-forest to forest for selected HRUs. The aim of the measure was to increase the mosaicity/diversity/roughness of the landscape and thus reduce evaporation and groundwater pollution. Afforestation was planned on agricultural land located on light (sandy) soils adjacent to lakes, ponds, wetlands and small patches of existing forests within a buffer of 50 m from them. In addition, afforestation has been introduced on extensive, intensively used agricultural land on selected fragments of light soils. Afforestation was applied in total on 604 HRUs.

Scenario 'controlled drainage' is based on defining a decision table simulating the effects of controlled drainage in selected HRUs with degraded peatland. The NSWRM was planned on degraded peat soils (muck) located in an area drained by tiles and/or directly adjacent to deep drainage channels and the main river. This measure was applied to 91 HRUs.

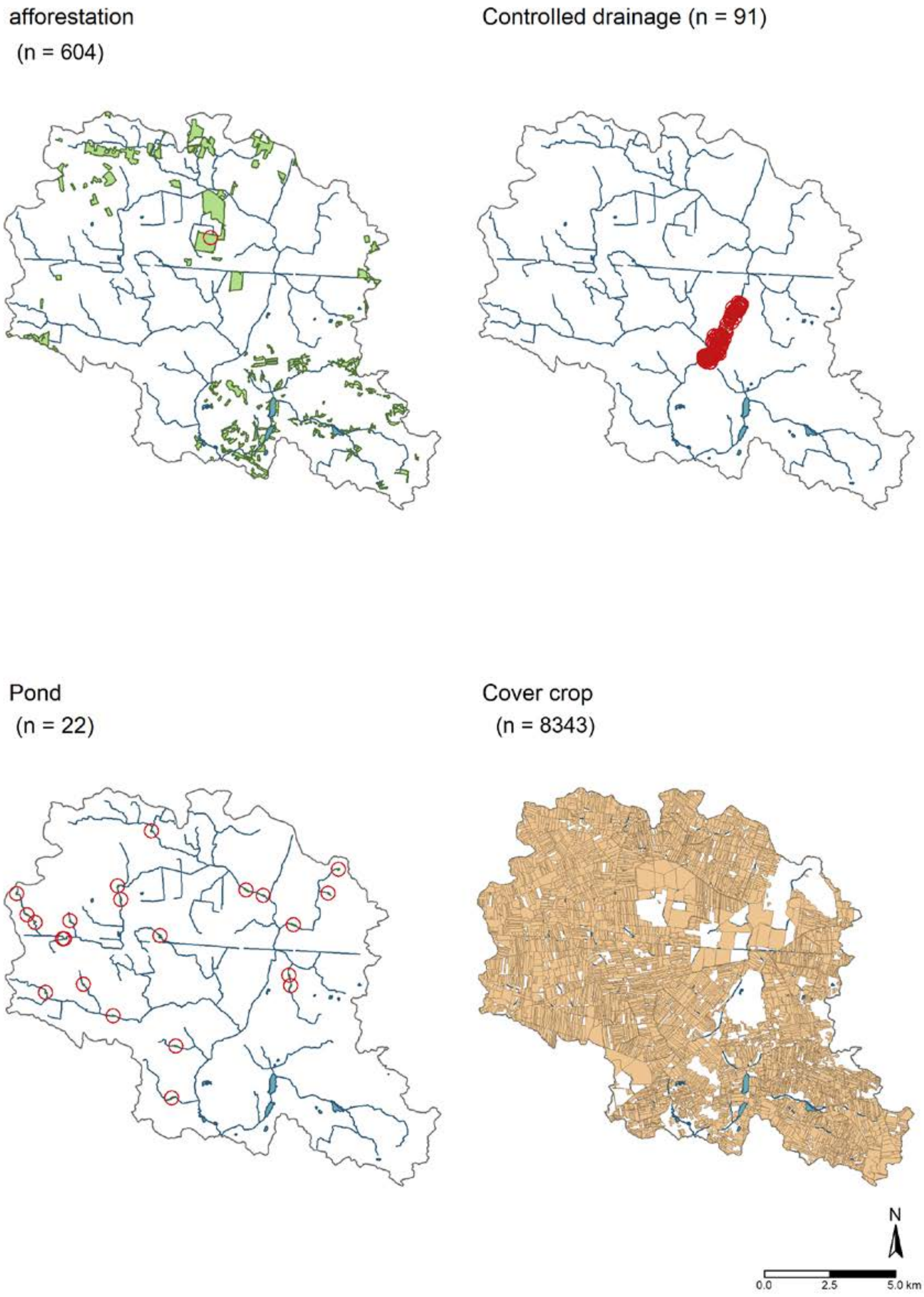


Fig. A4.18 Potential sites for implementing NSWRMs in CS4.

Scenario ‘pond’ (representing micro-reservoirs on ditches) assumes a change in object types from HRU to reservoirs. This measure was planned for the infiltration of clean rainwater or the horizontal filtration of nutrient-contaminated drainage water. The first type of measures was applied in built-up areas and along roads. The second on ditches and channels more than 2 m deep flowing through agricultural or forested areas near culverts located on agricultural roads. In total, 22 ponds were defined for this measure.

Scenario 'cover crop' includes a change in the management schedules of selected agricultural fields: inclusion of a cover crop in winter (before planting a summer crop such as corn, spring barley or sugar beet) and a change from normal tillage to low tillage. This measure was implemented on all agricultural fields in which corn, spring barley or sugar beet occurred in crop rotations (8343 HRUs). Although this number is very high and as shown in Fig. A4. 18 covers the majority of agricultural land, in reality, this measure was active only in selected years for a given HRU, depending on the crop rotation.

To account for parameter uncertainty, we ran an ensemble of eight model realisations (each with different calibration settings) for each scenario. The results are listed in Table A4.4.

Table A4.4 Results of NSWRM scenarios in CS4. Median values are shown (and in brackets minimum and maximum values) of the model ensemble (n=8) in relative changes (%) compared to status quo (which itself is presented in absolute values). See Annex 16 for indicator definitions.

| Indicator | statusquo | covcrop | contr_drn | pond | afforestation | all |
|---|---|---|---|---|---|---|
| **Nload** | 1125403 (1100422 : 1170332) | -30 ( : ) | 0 ( : ) | -20 (-21 : -19) | -18 ( : -17) | -40 ( : ) |
| **Pload** | 782 (624 : 858) | -0.93 (-1.1 : -0.63) | 0 ( : ) | -14 (-15 : -12) | -16 (-19 : -14) | -16 (-19 : -15) |
| **Sedload** | 25 (20 : 26) | -38 (-41 : -37) | 0 ( : ) | -0.9 (-0.97 : -0.81) | -0.9 (-1.1 : -0.48) | -39 (-42 : -38) |
| **Q_max** | 4.8 (4.7 : 5) | 0.042 (-0.64 : 1.4) | 0 ( : ) | -0.063 (-0.1 : -0.04) | -0.052 (-0.59 : 1.2) | 0.22 (-0.95 : 2.7) |
| **Q_max_aa** | 1.4 ( : 1.5) | 2.4 (2 : 3.3) | 0 ( : ) | 0.034 (-0.07 : 0.21) | -2.2 (-2.5 : -2) | 0.43 (-0.07 : 1.4) |
| **Q_p95** | 0.53 (0.52 : 0.57) | 1.3 (0.52 : 2.6) | 0 ( : ) | -0.091 (-0.19 : 0.56) | -3 (-3.6 : -1.9) | -1.6 (-3.5 : 0) |
| **Q_p90** | 0.33 (0.32 : 0.36) | -0.31 (-1.2 : 0.6) | 0 ( : ) | -0.29 (-0.61 : 0.29) | -1.7 (-2.5 : 0) | -2.9 (-4.4 : -1.7) |
| **Q_p50** | 0.026 (0.022 : 0.028) | -11 (-15 : -7.4) | 0 ( : 4) | -1.8 (-4.5 : 0) | 3.7 (-3.7 : 4.3) | -4.2 (-7.4 : -3.6) |
| **Q_p10** | 0.002 ( : ) | 0 ( : ) | 0 ( : ) | 0 ( : ) | 0 ( : ) | 0 ( : ) |
| **Q_p05** | 0.001 ( : ) | 0 ( : ) | 0 ( : ) | 0 ( : ) | 0 ( : ) | 0 ( : ) |
| **Q_min_aa** | 0.002 ( : ) | 0 ( : ) | 0 ( : ) | 0 ( : ) | 0 (-50 : ) | 0 (-50 : ) |
| **Q_low_days** | NA ( : ) | NA ( : ) | NA ( : ) | NA ( : ) | NA ( : ) | NA ( : ) |
| **Q_high_days** | NA ( : ) | NA ( : ) | NA ( : ) | NA ( : ) | NA ( : ) | NA ( : ) |
| **Nconc_days** | 0.048 (0.04 : 0.062) | 4.8 (1.7 : 9.7) | 0 ( : ) | 7.4 (-3.4 : 18) | 7.5 (-3.4 : 15) | 15 (1.7 : 20) |
| **Pconc_days** | 0.05 ( : ) | 2 (0 : 4) | 0 ( : ) | 0 ( : ) | -4 (-6 : -2) | -2 (-6 : 0) |
| **Sedconc_days** | 0.99 (0.98 : 1) | -0.76 (-1.2 : -0.2) | 0 ( : ) | 0.1 (-0.5 : 0.3) | 0.1 (-0.4 : 0.3) | 0.35 (-0.1 : 0.81) |

| | | | | | | |
|---|---|---|---|---|---|---|
| **N_loss** | 193 (180 : 195) | -27 (-28 : ) | 0 ( : ) | 0.018 (0.011 : 0.019) | 7.6 (7.4 : 8.2) | -20 ( : -19) |
| **P_loss** | 0.71 (0.57 : 0.82) | -0.47 (-0.7 : -0.12) | 0 ( : ) | -0.25 (-0.28 : -0.15) | -2.9 (-4.4 : -2.4) | -3.4 (-4.8 : -3) |
| **Sed_loss** | 0.037 (0.029 : 0.045) | -24 ( : -22) | 0 ( : ) | -2.6 (-3.4 : 0) | -5.1 (-6.7 : -2.8) | -27 (-28 : -25) |
| **N_loss_ratio** | 0.28 (0.26 : 0.29) | -10 (-11 : -9.9) | 0 ( : ) | 0 ( : ) | 7.7 (7.4 : 8.3) | -1.1 (-1.4 : -0.36) |
| **P_loss_ratio** | 0.003 ( : 0.004) | 33 (25 : ) | 0 ( : ) | 0 ( : ) | 0 (-25 : ) | 29 (0 : 33) |
| **sw** | 108 (106 : 111) | -0.068 (-0.16 : 0) | 0 ( : ) | -0.0041 (-0.0056 : -0.0027) | -0.25 (-0.3 : -0.13) | -0.29 (-0.42 : -0.13) |
| **perc** | 9.1 (8 : 9.6) | -1.8 (-1.9 : -1.6) | 0 ( : ) | -0.21 (-0.25 : -0.17) | -1.9 (-2.2 : -1.4) | -3.3 (-3.7 : -3) |
| **sw_5_6_7_8_9** | 81 (79 : 84) | -0.093 (-0.2 : -0.0012) | 0 ( : ) | -0.0056 (-0.0072 : -0.0036) | 0.017 (-0.071 : 0.2) | -0.047 (-0.23 : 0.19) |
| **sw_5** | 114 (110 : 117) | 0.091 (-0.008 : 0.17) | 0 ( : ) | -0.0034 (-0.0052 : -0.0017) | 1.4 (1.3 : 1.7) | 1.6 (1.4 : 1.9) |
| **sw_6** | 78 (75 : 81) | 0.53 (0.43 : 0.61) | 0 ( : ) | -0.0038 (-0.0063 : -0.0025) | 1.3 (1.2 : 1.6) | 1.9 (1.7 : 2.2) |
| **sw_7** | 64 (61 : 66) | 0.084 (-0.046 : 0.2) | 0 ( : ) | -0.0056 (-0.0092 : -0.0031) | 0.29 (0.2 : 0.5) | 0.38 (0.16 : 0.65) |
| **sw_8** | 71 (68 : 73) | -0.69 (-0.8 : -0.59) | 0 ( : ) | -0.0084 (-0.011 : -0.0056) | -1.6 (-1.7 : -1.5) | -2.3 (-2.5 : -2.1) |
| **sw_9** | 80 (77 : 82) | -0.57 (-0.7 : -0.49) | 0 ( : ) | -0.0058 (-0.0086 : -0.0049) | -2.1 (-2.2 : -2) | -2.7 (-2.8 : -2.5) |
| **grain_units_aa** | 172164 (170706 : 173249) | 0.16 (0.14 : 0.21) | 0 ( : 1.2e-05) | -0.053 (-0.054 : -0.052) | -6.9 (-7 : ) | -6.8 (-6.9 : ) |
| **crops_ha_aa** | 15757 ( : ) | -0.046 ( : ) | 0 ( : ) | -0.056 ( : ) | -5.5 ( : ) | -5.5 ( : ) |
| **wwht_ha** | 4473 ( : ) | 0.45 ( : ) | 0 ( : ) | -0.04 ( : ) | -2.2 ( : ) | -1.7 ( : ) |
| **corn_ha** | 4364 ( : ) | 0.64 ( : ) | 0 ( : ) | -0.055 ( : ) | -8.6 ( : ) | -8.1 ( : ) |
| **trit_ha** | 1270 ( : ) | -0.18 ( : ) | 0 ( : ) | -0.049 ( : ) | -15 ( : ) | -15 ( : ) |
| **canp_ha** | 662 ( : ) | -1.5 ( : ) | 0 ( : ) | -0.039 ( : ) | -2.9 ( : ) | -4.4 ( : ) |
| **onio_ha** | 214 ( : ) | -3.1 ( : ) | 0 ( : ) | -0.047 ( : ) | -0.62 ( : ) | -3.7 ( : ) |
| **sgbt_ha** | 1362 ( : ) | -0.54 ( : ) | 0 ( : ) | -0.043 ( : ) | -2.2 ( : ) | -2.6 ( : ) |
| **barl_ha** | 1750 ( : ) | -0.83 ( : ) | 0 ( : ) | -0.15 ( : ) | -6.3 ( : ) | -7 ( : ) |
| **mint_ha** | 1348 ( : ) | -1 ( : ) | 0 ( : ) | -0.014 ( : ) | -2.1 ( : ) | -3.2 ( : ) |
| **lett_ha** | 275 ( : ) | -0.16 ( : ) | 0 ( : ) | -0.12 ( : ) | -1.7 ( : ) | -1.9 ( : ) |
| **crrt_ha** | 38 ( : ) | 0 ( : ) | 0 ( : ) | 0 ( : ) | -6 ( : ) | -6 ( : ) |
| **wwht_yld_t_ha** | 4 ( : 4.1) | -4.2 (-4.5 : -4) | 0 ( : ) | 0 ( : ) | 0 (-0.25 : ) | -4.3 (-4.5 : -4.2) |
| **corn_yld_t_ha** | 9.4 (9.2 : ) | 3.5 (3.4 : ) | 0 ( : ) | 0 ( : ) | 0.11 ( : 0.22) | 3.7 (3.6 : 3.9) |
| **trit_yld_t_ha** | 6.8 (6.7 : ) | -5.3 (-5.4 : ) | 0 ( : ) | 0 ( : ) | 0.15 (0 : ) | -5.6 ( : -5.4) |
| **canp_yld_t_ha** | 1.8 (1.7 : ) | 2.3 (1.7 : ) | 0 ( : ) | 0 ( : ) | 0 ( : 0.57) | 1.7 ( : 2.3) |
| **onio_yld_t_ha** | 1.2 ( : ) | -3.4 ( : ) | 0 ( : ) | 0 ( : ) | 0 ( : ) | -3.4 ( : ) |
| **sgbt_yld_t_ha** | 12 ( : ) | -1.5 (-1.7 : -1.1) | 0 ( : ) | 0 ( : ) | -0.082 (-0.083 : 0) | -1.5 (-1.7 : -1.2) |
| **barl_yld_t_ha** | 5.4 (5.3 : ) | -1.7 ( : -1.5) | 0 ( : ) | 0 ( : ) | 0.093 (0 : 0.19) | -1.7 ( : -1.5) |
| **mint_yld_t_ha** | 0.37 ( : ) | 8.1 ( : ) | 0 ( : ) | 0 ( : ) | 0 ( : ) | 8.1 ( : ) |
| **lett_yld_t_ha** | 3 ( : ) | -12 (-13 : ) | 0 ( : ) | 0 ( : 0.33) | 0 ( : ) | -12 (-13 : ) |
| **crrt_yld_t_ha** | 6.2 ( : ) | -19 ( : ) | 0 ( : ) | 0 ( : ) | 0.16 (0 : ) | -19 ( : ) |

Among all NSWRMs investigated in CS4, cover crops and afforestation had the highest effect on catchment hydrology. Afforestation led to reduction of different high flow indices by around 2% and an increase in the median flow by 3%. Low flow indices were not affected by any NSWRM which is partly due to their extremely low values in CS4 (cf. Fig. A4.7). Application of cover crops led to a decrease in median flow by 10%, whereas other flow indices were much less affected. The effect of ponds on hydrological indicators was very low and that of controlled drainage practically negligible. This may be due to the low volume of ponds and relatively low area of application of controlled drainage, especially compared to the area of application of afforestation and cover crops.

low tillage combined with cover crops (scenario lowtillcc) had, by far, the highest impact on catchment hydrology. By reducing maximum flows while increasing minimum flows and soil moisture, this measure turned out to be very effective for water retention. The strong impact found for scenario lowtillcc was not surprising as it includes the largest area of implementation (31 % of total watershed area). The simulated impact on low-percentile flows, p05 and p10, however, was negative, resulting in a higher number of days where discharge fell below the reference lowflow threshold (p05 of the status quo simulation). This appears contradictory and requires a more detailed analysis of model outputs. Grassed waterways (scenario grassslope) had a similar, yet smaller, negative impact on lowflow. Riparian buffer (scenario buffer), hedgerows along contours (scenario hedge), and detention ponds (scenario pond) had a negligible overall impact on catchment hydrology.

The most positive aspect of NSWRM application in CS4 was related to nitrogen load reduction. Three measures: cover crops, ponds and afforestation led to significant reductions, reaching even 30% for cover crops. However, application of all three measures applied together did not lead to any synergistic effect. The reduction of N loads was much below the sum of reductions of individual measures. Although positive effects were found also in the case of sediment and phosphorus, these numbers should be treated with caution since the model was not calibrated for these two variables.

Implementing NSWRM might imply losses of cropland and crop yields. In the case of CS4, the highest changes in production area were simulated for afforestation. In this scenario particularly, sharp decreases were found for the triticale and corn, which are often cultivated on light, less productive soils. Crop yields were affected only by cover crop scenario. The direction of changes was different for different crops, but reductions in yields were more frequent. The highest reductions were simulated for carrots and leaf parsley. Since the area of these crops is relatively small, these can be some artefacts that require further investigation.

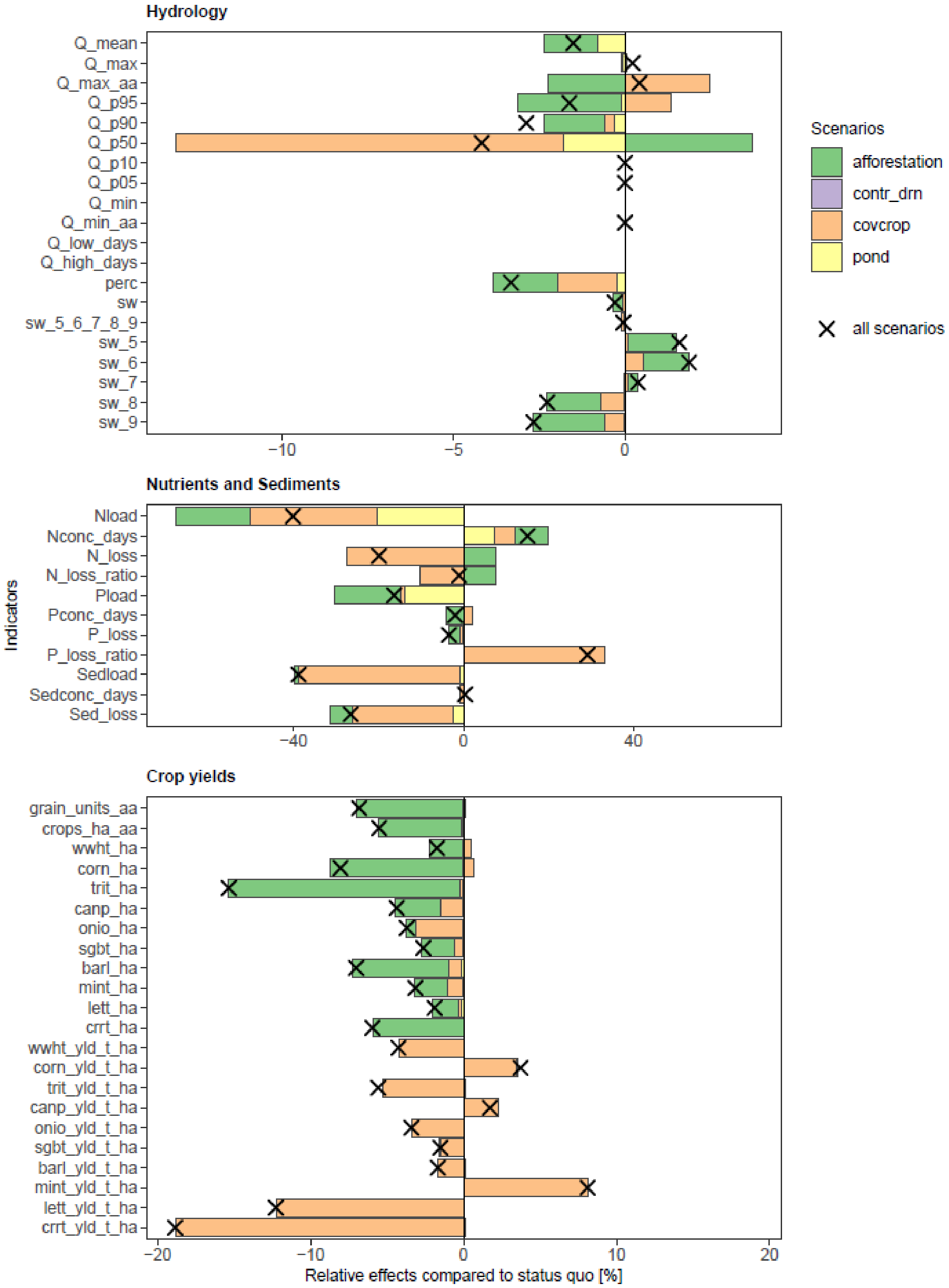


Fig. A4.19 Effectiveness of NSWRM scenarios on indicators (described below Table A1.5) related to the hydrology, nutrient and sediment loads, and crop yields for CS4. The stacked bars illustrate the relative effect of an NSWRM scenario to the status quo. Each bar represents the median effect of a measure scenario which results from an ensemble of SWAT model setups. The X symbols show the relative effect of the case when all potential NSWRMs were activated in the catchment. The bars of the NSWRM scenarios were stacked to provide a comparison to the effect of all measures being implemented.

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# Annex 5 Modelling results for CS5 (Pesnica, SI)

Authors: Miha CURK, Matjaž GLAVAN (UL)

## 1. Model setup

The SWAT+ model for the CS5 catchment (Pesnica) was set up following the OPTAIN workflow (Schürz et al., 2022). The majority of input data were prepared by manually modifying existing data from Slovenian state agencies. The uncalibrated model setup was developed using the R script for the model setup generation workflow (https://git.ufz.de/optain/wp4-integrated-assessment/swat/swat-setup/full_workflow) consisting of both SWATbuildR (version 1.5.18) and SWATfarmR (version 4.0.2). The SWAT+ model revision 61.0 (from 1/12/2024) was used in all simulations.

### 1.1. Input data overview

Table A5.1 presents all major SWAT+ input data, their resolution, and sources. Additional comments provide explanations on pre-processing particular data items. The CS5 catchment occupies 86 km$^2$ of transboundary land in both Slovenia (69 km$^2$) and Austria (17 km$^2$). It is characterized by hilly terrain (ranging from 251 m to 819 m above sea level), highly diversified land use, and variable soil types (mostly silty loams, but also sandy and clay loams).

Table A5.1 Summary of input data for CS5.

| Input | Number of objects / resolution | Source | Comments |
|---|---|---|---|
| DEM | 1 m (SI), 10m (AT) | LIDAR data - GURS (SI) Copernicus (AT) | Transboundary raster datasets were merged using the ArcGIS “Mosaic to New Raster” tool |
| Channel layer | 2,314 | Line objects of surface water bodies - DRSV (SI) | Layer was modified to include channels for AT side - manual delineation based on aerial imagery |
| Land layer | 6,083 | Actual land use map - MKGP (SI) | Land layer was modified to reduce the number of objects, manually delineate the cross-boundary areas in AT, and account for NSWRMs planned for scenario simulations; tile drainage information based on SI drainage systems archive |
| Soil layer | 22 | Soil map - MKGP (SI) | Vector layer with soil types modified to include the cross-boundary areas in AT |
| Usersoil table | 22 | Soil profiles database - MKGP (SI) | SI survey data extended to corresponding transboundary soil types in AT |
| Point sources | 3 | ARSO | 6 WWTP |
| Weather data | 1 station | ARSO | Slovenian official measurement data |
| Atmospheric deposition | 1 | European Monitoring and Evaluation Programme (EMEP) | EMEP data processed by SWATprepR |
| Crop sequence map | 966 | Crops database - ARSKTRP | Actual data for crops grown in each field |
| Management schedules | 13 | KGZS | Schedules prepared in consultation with the local agricultural advisory service |

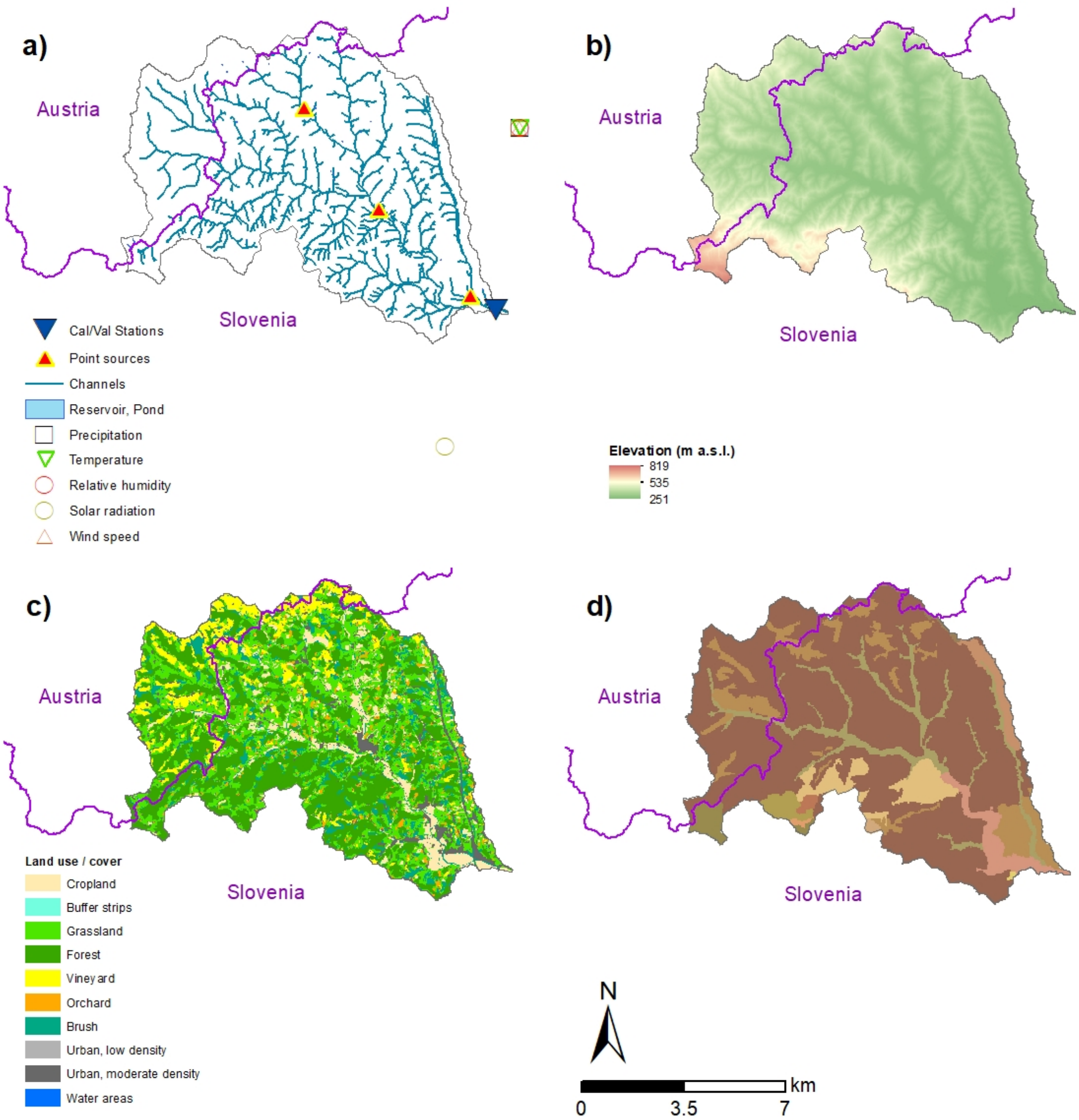


Figure A5.1 GIS input data for the transboundary CS5: a) flow gauges, point source locations, channels, ponds, catchment boundary, water quality monitoring points, and meteorological stations; b) elevation map; c) land use map; d) soil types.

## 1.2. Baseline model setup

The most important features of the model setup are included in Table A5.2. Most of them were extracted from the *object.cnt* file. A detailed input land layer resulted in a high number of HRUs (6,020), which in consequence affected the model run time.

Table A5.2 Summary of the model setup features.

| Parameter | Value |
|---|---|
| Total area of the watershed in ha | 8,607 |
| Total number of spatial objects in the simulation | 14418 |
| Number of HRUs in the simulation | 6020 |
| Number of routing units in the simulation | 6020 |
| Number of aquifers in the simulation | 1 |
| Number of reservoirs in the simulation | 63 |
| Number of recalls (point sources/inlets) in the simulation | 3 |
| Number of SWAT-DEG channels in the simulation | 2314 |
| Number of crops in rotation | 8 |
| Number of wetlands | 0 |

## 2. Model evaluation

Table A5.3 presents the observation data for variables used in soft calibration (crop yields, water yield ratio) and hard calibration (discharge, groundwater depth, N-NO3 concentrations). Since crop yield statistics in Slovenia are available only for major crops and only at the statistical region level, we also relied on local expert-based estimates (average values and ranges). Discharge data in CS5 are quite good, with only shorter gaps between longer periods of observations.

Table A5.3 Summary of observation data used in different steps of the calibration workflow for CS5.

| Variable | Time step | Calibration period | Validation period | Source | Comments |
|---|---|---|---|---|---|
| Soft calibration | | | | | |
| Crop yields | Average annual | 2010-2021 | NA | SURS and local agricultural advisory board | Regional statistical data enhanced by expert-values |
| Hard calibration | | | | | |
| Discharge | Daily | 2000-2010 | 2011-2021 | ARSO | |
| $N\text{-}NO_3$ contentrations | every 2 (calibr.) or 3 (valid.) months | 2016-2020 | 2007-2014 | ARSO | |

## 3. Missing elements of the report and time plan to complete these tasks

Model evaluation and scenario analysis are still ongoing and the results are not yet included in the report. There are two main reasons for this. The first one is the shift to an R-based instead of the QSWAT+ based workflow. The shift demanded time to familiarize and adapt to the R environment, but led to further delays as scripts were released in an “alpha” version. The iterative process, in which the scripts were constantly changed/improved, meant that a lot of time was invested on site to fix bugs in R with the help of the developer group.

The second reason for the delays is connected to CS5 being a transboundary catchment. Implementation of the SWAT BuildR tool was significantly delayed because of issues that resulted from merging the different spatial datasets for Slovenian and Austrian parts of the catchment.

Now that the baseline model has been set up, the completion of the modeling tasks should be much faster. Fortunately, as outlined in this report, OPTAIN has developed a comprehensive harmonized workflow. This will facilitate a smooth and relatively rapid completion of the remaining tasks. Looking ahead, the OPTAIN consortium has scheduled a modellers’ meeting in May 8-10, 2024. The CS5 has committed to provide the working setup by this meeting, ensuring timely progress and collaboration within the consortium.

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# Annex 6 Modelling results for CS6 (Kobilje/Kebele, SI)

Authors: Miha CURK, Matjaž GLAVAN (UL)

## 1. Model setup

The SWAT+ model for the CS6 catchment (Kobilje/Kebele) was set up following the OPTAIN workflow (Schürz et al., 2022). The CS6 catchment is a transboundary catchment which is located partly in Slovenia and partly in Hungary. Both SI and HU teams were involved in acquiring the input data. For the SI part, the majority of input data were prepared by manually modifying existing data from Slovenian state agencies, while data for the HU part was mostly prepared using the svatools (https://github.com/biopsichas/svatools) package. The uncalibrated model setup was developed using the R script for the model setup generation workflow (https://git.ufz.de/optain/wp4-integrated-assessment/swat/swat-setup/full_workflow) consisting of both SWATbuildR (version 1.5.18) and SWATfarmR (version 4.0.2). The SWAT+ model revision 61.0 (from 1/12/2024) was used in all simulations.

### 1.1. Input data overview

Table A6.1 presents all major SWAT+ input data, their resolution, and sources. Additional comments provide explanations on pre-processing particular data items. The CS6 catchment occupies 234 $km^2$ of transboundary land in both Slovenia (80 $km^2$) and Hungary (154 $km^2$). It is characterized by quite flat terrain (ranging from 191 m to 388 m above sea level), quite diversified land use, and variable soil types (mostly loamy sand).

Table A6.1 Summary of input data for CS6.

| Input | Number of objects / resolution | Source | Comments |
|---|---|---|---|
| DEM | 1 m (SI), 5m (HU) | LIDAR data - GURS (SI)<br><br>Lechner Knowledge Center (HU) | Transboundary raster datasets were merged using the ArcGIS “Mosaic to New Raster” tool |
| Channel layer | 75 | Line objects of surface water bodies - DRSV (SI)<br><br>Western Transdanubia Water Directorate (HU) | Cross-boundary layers were joined after verification based on aerial imagery |
| Land layer | 7,512 | Actual land use map - MKGP (SI)<br><br>NÖSZTÉP database and remote sensing-based crop maps (HU) | Land layer was modified to reduce the number of objects, achieve a seamless join between cross-boundary datasets, and account for NSWRMs planned for scenario simulations |
| Soil layer | 22 | Soil map - MKGP (SI)<br><br>DOSoReMI.hu (HU) | Vector layer with soil types for SI was joined with raster datasets for HU. |
| Usersoil table | 22 | Soil profiles database - MKGP (SI)<br><br>DOSoReMI.hu (HU) | National survey data and computations |
| Weather data | 3 stations | ARSO (SI)<br><br>OMSZ (HU) | Slovenian official measurement data |
| Atmospheric deposition | 1 | European Monitoring and Evaluation Programme (EMEP) | EMEP data processed by SWATprepR |
| Crop sequence map | 3718 | Crops database - MKGP(SI)<br><br>NÖSZTÉP (HU) | Actual data for crops grown in each field for SI, NÖSZTÉP database and remote sensing-based crop maps for HU |
| Management schedules | 15 | KGZS (SI)<br><br>ATK (HU) | Schedules prepared in consultation with the local agricultural advisory services in both SI and HU |

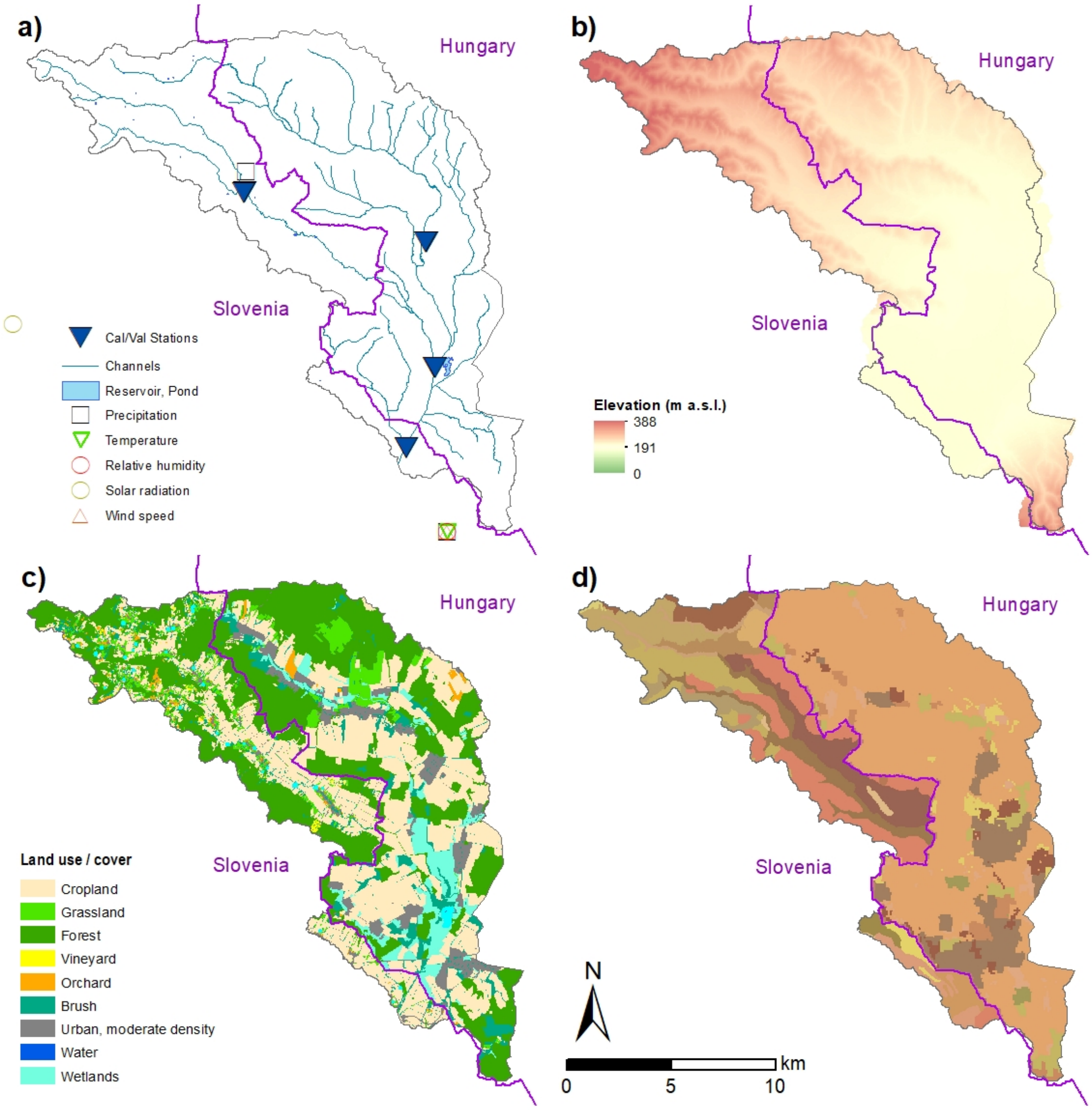


Figure A6.1 GIS input data for the transboundary CS6: a) flow gauges, p, channels, ponds, catchment boundary, water quality monitoring points, and meteorological stations; b) elevation map; c) land use map; d) soil types.

## 1.2. Baseline model setup

The most important features of the model setup are included in Table A6.2. Most of them were extracted from the *object.cnt* file. A detailed input land layer resulted in numerous HRUs (7,512), consequently affecting the model run time.

Table A6.2 Summary of the model setup features.

| Parameter | Value |
|---|---|
| Total area of the watershed in ha | 23,400 |
| Total number of spatial objects in the simulation | 7,779 |
| Number of HRUs in the simulation | 7,512 |
| Number of routing units in the simulation | 7,512 |
| Number of aquifers in the simulation | 1 |
| Number of reservoirs in the simulation | 34 |
| Number of SWAT-DEG channels in the simulation | 75 |
| Number of crops in rotation | 8 |
| Number of wetlands | 157 |

## 2. Model evaluation

Table A6.3 presents observation data for variables used in soft (crop yields, water yield ratio) and hard calibration (discharge, groundwater depth, N-$NO_3$ concentrations). Since crop yield statistics in Slovenia are available only for major crops and only at the statistical region level, we also relied on local expert-based estimates (average values and ranges). Discharge data in CS6 are quite good, with only shorter gaps between longer periods of observations.

Table A6.3 Summary of observation data used in different steps of the calibration workflow for CS6.

| Variable | Time step | Calibration period | Validation period | Source | Comments |
|---|---|---|---|---|---|
| Soft calibration | | | | | |
| Crop yields | Average annual | 2010-2021 | NA | SURS and local agricultural advisory board | Regional statistical data enhanced by expert-values |
| Hard calibration | | | | | |
| Dischar ge | Daily | 2000-2010 | 2011-2021 | ARSO | |
| N-$NO_3$ contentr ations | every 2 (calibr.) or 3 (valid.) months | 2016-2020 | 2007-2014 | ARSO | |

## 3. Missing elements of the report and time plan to complete these tasks

Model evaluation and scenario analysis are still ongoing and the results are not yet included in the report. There are two main reasons for this. The first one is the shift to an R-based instead of the QSWAT+ based workflow. The shift demanded time to familiarize and adapt to the R environment, but led to further delays as scripts were released in an "alpha" version. The iterative process, in which the scripts were constantly changed/improved, meant that a lot of time was invested on site to fix bugs in R with the help of the developer group.

The second reason for the delays is connected to CS5 being a transboundary catchment. Implementation of the SWAT BuildR tool was significantly delayed because of issues that resulted from merging the different spatial datasets for Slovenian and Austrian parts of the catchment.

Now that the baseline model has been set up, the completion of the modeling tasks should be much faster. Fortunately, as outlined in this report, OPTAIN has developed a comprehensive harmonized workflow. This will facilitate a smooth and relatively rapid completion of the remaining tasks. Looking ahead, the OPTAIN consortium has scheduled a modellers' meeting in May 8-10, 2024. The CS5 has committed to provide the working setup by this meeting, ensuring timely progress and collaboration within the consortium.

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# Annex 7 Modelling results for CS7 (Wimbe catchment, BE)

**Authors: Marie Anne Eurie Forio, Diego Gustavo Panique Casso, Peter Goethals**

## 1. Model setup

The SWAT+ model for CS7 catchment (Wimbe) was set up following the OPTAIN workflow (Schürz et al., 2022). The majority of input data were prepared with the help of the SWATprepR package (version 1.0.1). The uncalibrated model setup was developed using the R script for the model setup generation workflow (https://git.ufz.de/optain/wp4-integrated-assessment/swat/swat-setup/full_workflow) consisting of both SWATbuildR (version 1.5.10) and SWATfarmR (version 3.2.0). The SWAT+ model revision 61.0 (from 1/12/2024) was used in all simulations.

### 1.1. Input data overview

Table A4.1 presents all major SWAT+ input data, their resolution, and sources. Additional comments provide explanations on pre-processing particular data items. Selected spatial datasets can be visualized in Figure A7.1 (flow gauges, water quality monitoring points, meteorological stations, point source locations, channels, catchment boundary, elevation map, land use map, and soil types). The CS4 catchment occupies 116 km$^2$ and is characterized by a flat relief with rolling hills. Most of the agricultural fields (about 40% of the basin) are located in the middle to downstream of the basin and on the western part. The soil is relatively shallow (i.e., 600 – 1250 mm, and one soil type with only 300 mm depth) with variable soil types predominantly silty and a small fraction of clayish and sandy soil.

Table A7.1 Summary of input data for CS7.

| Input | Number of objects / resolution | Source | Comments |
|---|---|---|---|
| DEM | 1 m | Géoportail de la Wallonie - SPW | The DEM was upscaled into 2 m resolution in the model setup |
| Channel layer | 686 | Generated by QSWAT+ (https://swat.tamu.edu/software/plus/) | |
| Land layer | 6,832 | Géoportail de la Wallonie - Carte d'Occupation du Sol de Wallonie [COSW] (Version 2_07) | The original land layer had a high resolution (1 m) and therefore was too detailed. It was therefore simplified but without losing relevant information using various tools of the QGIS to obtain only 6,832 objects. |
| Soil layer | 56 | Géoportail de la Wallonie - SPW | Soil organic carbon data was merged into the soil layer data as they were in separate files. |
| Usersoil table | 56 | | Derived from SWATprepR; HSG groups derived from the modelling protocol of OPTAIN |
| Point sources | 2 | Data obtained from Idelux and INASEP | Two WWTPs from local municipalities of Beauraing and Haut-Fays (Daverdisse). |
| Weather data | 10 stations | RMI Belgium and SPW | Weather data were processed by SWATprepR |
| Atmospheric deposition | 1 | European Monitoring and Evaluation Programme (EMEP) | EMEP data processed by SWATprepR |
| Crop sequence map | 4693 polygons | Géoportail de la Wallonie – The anonymous agricultural plots (situation 2016-2021) - SPW | Crop sequence was derived from 2016-2021 using QGIS tools and following the OPTAIN modelling protocol. |
| Management schedules | 10 crops | Data were obtained from the grassland advisors and agricultural advisors, a white paper for cereals (Bodson & Watillon, 2017), and from the report of Borgers et al. (2007) | Management and practices as well as regulations were consulted with various agricultural advisers. |

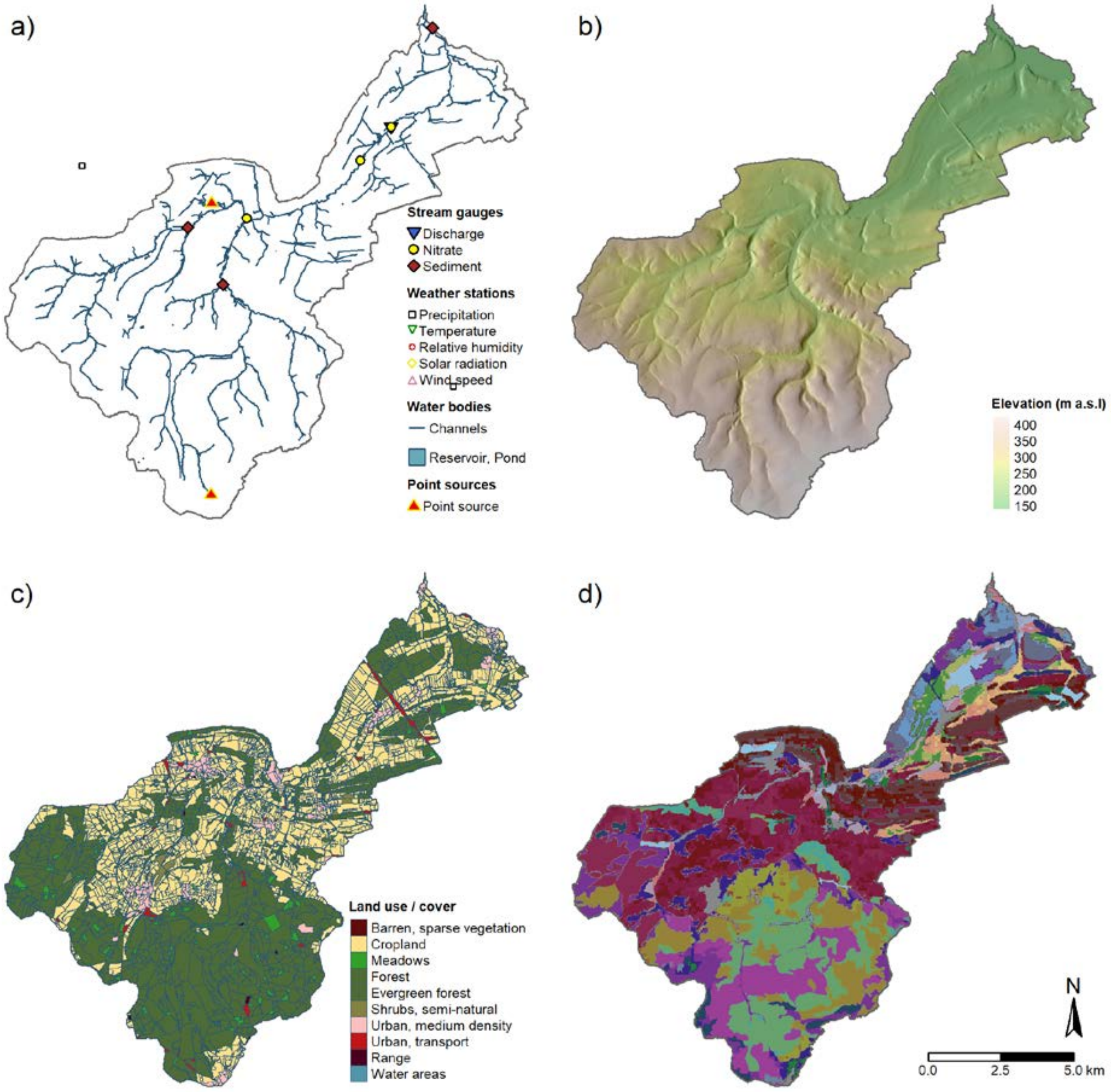


Figure A7.1 GIS input data for CS7: a) flow gauges, water quality monitoring points, meteorological stations, point source locations, channels and catchment boundary. Some meteorological stations are located outside the case study catchment and are thus not visible in the map; b) elevation map; c) land use map; d) soil types.

### 1.2. Baseline model setup

The most important features of the model setup were included in Table A7.2. Most of them were extracted from the object.cnt file. A very detailed input land layer, which was simplified resulted in a moderate number of HRUs (i.e. 6832).

Table A7.2 Summary of the mode setup features based on the input file

| Parameter | Value |
|---|---|
| Total area of the watershed in ha | 11617 |
| Total number of spatial objects in the simulation | 14387 |
| Number of HRUs in the simulation | 6832 |
| Number of routing units in the simulation | 6832 |
| Number of aquifers in the simulation | 1 |
| Number of reservoirs in the simulation | 34 |
| Number of recalls (point sources/inlets) in the simulation | 2 |
| Number of SWAT-DEG channels in the simulation | 686 |
| Number of crops in rotation | 11 |
| Number of wetlands | 0 |

## 2. Model evaluation

Table A4.3 presents observation data for variables used in soft (crop yields, water yield ratio) and hard calibration (discharge, N-$NO_3^-$ and suspended sediments concentrations). Since crop yield statistics in the case study region are available on fresh weight basis; we have estimated the dry weight of it based on the humidity and conversion factor as described in the Eurostat Handbook for Annual Crop Statistic (EU, 2017). Reference values for water yield were obtained from a water balance study for the Lesse catchment (Bauwens et al. 2011). The crop yield data for the grasses in meadows were obtained from the experimental results of the grassland advisors which were already on dry weight basis. The yield data of alfalfa was obtained from a published paper in a study in Belgium (Raes et al., 2023). Both the observed data of nitrate-N and sediments in the study area are sparse and irregular, monthly or every two months observations.

Table A7.3 Summary of observation data used in different steps of the calibration workflow for CS7.

| Variable | Time step | Calibration period | Validation period | Source | Comments |
|---|---|---|---|---|---|
| Soft calibration | | | | | |
| Crop yields | Average annual | 2016-2022 | NA | StatBel (Belgian statistical office) | Fresh weight data were converted into dry weights data as described in the Eurostat Handbook for Annual Crop Statistic |
| Water yield ratio | Average annual | 2005-2021 | NA | (Bauwens et al., 2011) | This study estimated the water balance for the Lesse and Vesdre catchment in Wallonia, Belgium. The Wimbe basin is a subbasin of the Lesse catchment. These values were used as reference to estimate water yield in our case study. |
| Hard calibration | | | | | |
| Discharge | Daily | 2005-2013 | 2014-2021 | Service public de Wallonie (SPW) | |
| Sediment concentration | Monthly | 2005-2013 | 2014-2021 | SPW | There were three stations for the observed data of sediments. One station was used in the calibration and validation while the data from the 2 stations were used in the validation |
| N-$NO_3$ concentrations | Monthly | 2005-2013 | 2014-2021 | SPW | |

## 2.1. Model setup verification

All steps of the model setup verification were performed in accordance with the OPTAIN workflow (Plunge et al., 2024). Verification of the climate data (Fig. A7.3) showed that all reported values are in plausible ranges according to the expert knowledge of the studied catchment. However, the water balance was not in accordance with the expected values in the region and was therefore adjusted in the soft calibration.

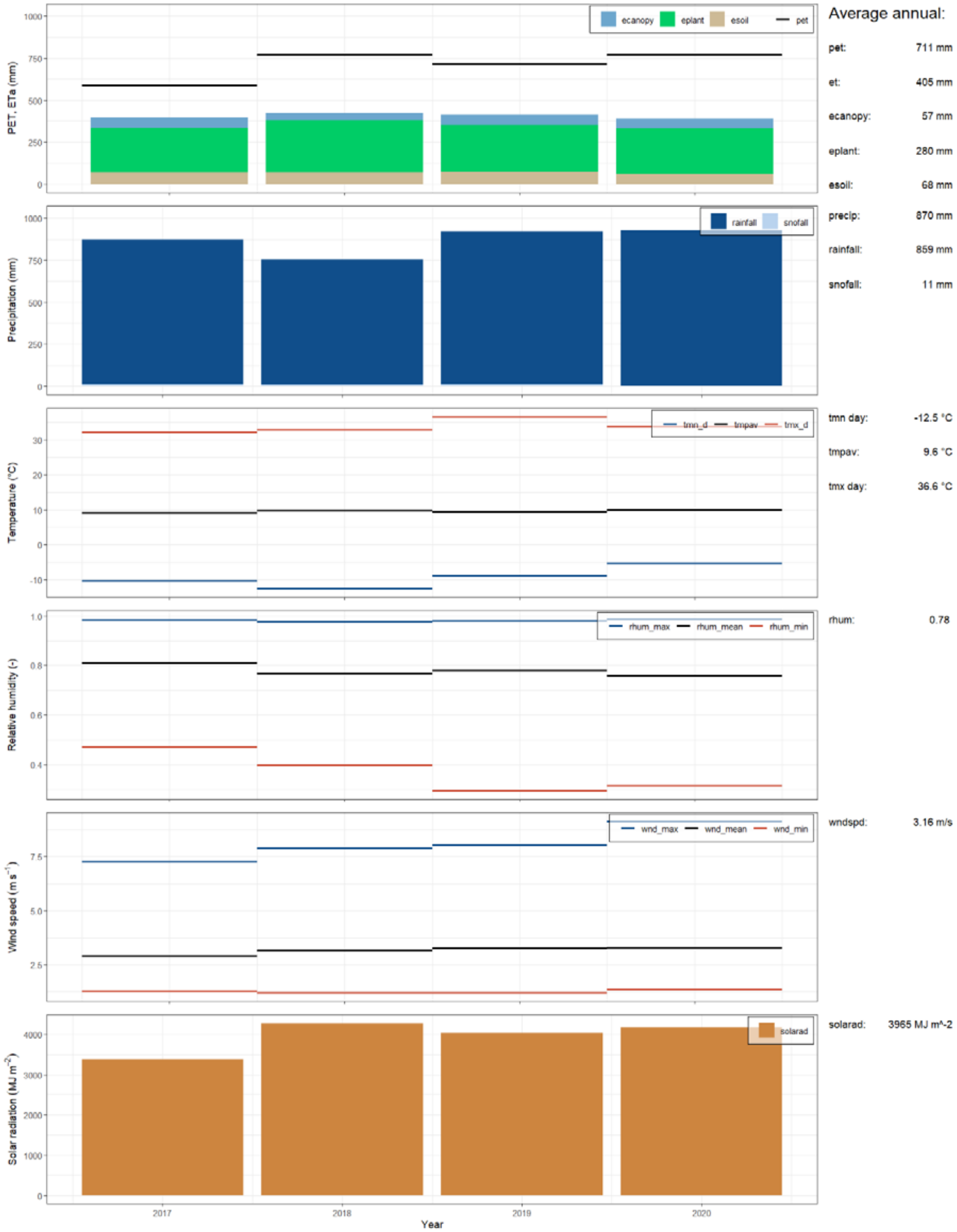


Figure A7.3 Summary of the climate data checks for CS7 by the SWATdoctR.

## 2.2. Soft calibration

As shown in Fig. A7.4, the crop yield soft calibration workflow was successfully applied in CS7. In the first step, d_mat (days to maturity) parameter was altered in such a way that the accumulated PHU fraction at harvest/kill is within the predefined range of 1.0-1.2. A different situation can be noted only in case of crops having multiple harvests (alfa and fesc1), for which the values between 0.5-1.0 are acceptable. In the case of corn silage (csil), the PHU fraction was also lower than 1.0, as the crop parameters adjustment were focused to reach the acceptable yield values. This is due to the fact that the harvesting dates in Belgium can be highly variable from year to year depending on the weather (ranging from early September to early November). For all crops, the average observed and simulated yields match reasonably well.

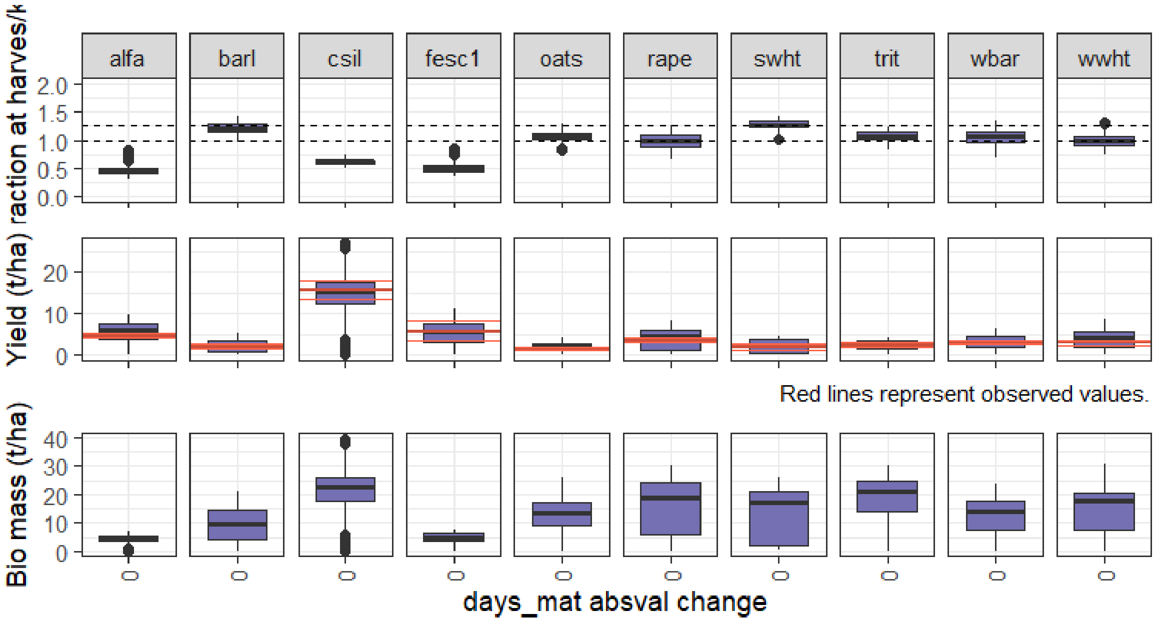


Figure A7.4 Final results of crop yield soft calibration for CS7 for the crops alfa (alfalfa), summer barley (barl), corn silage (csil), fesc1 (grasses), oats (summer oats), winter rapeseed (rape), summer wheat (swht), winter triticale (trit), winter barley (wbar), and winter wheat (wwht). Simulated PHU fraction of harvest/kill (top row), crop yields (middle row) and biomass (bottom row).

Table A7.4 Final calibrated values of crop parameters.

| crops | days_mat | lai_pot | harv_idx | tmp_base | bm_e |
|---|---|---|---|---|---|
| alfa (alfalfa) | 110 | 5.22 | 0.029 | 4 | 6.43 |
| barl (spring barley) | 100 | 5.6 | 0.38 | 0 | 42 |
| csil (corn silage) | 150 | 15.52 | 0.79 | 2 | 47.19 |
| oats (spring oats) | 120 | 5.28 | 0.24 | 0 | 35 |
| swht (spring wheat) | 120 | 4.4 | 0.28 | 0 | 42 |
| trit (winter triticale) | 120 | 9 | 0.19 | 0 | 46.2 |
| wbar (winter barley) | 105 | 4.4 | 0.38 | 0 | 33 |
| wwht (winter wheat) | 130 | 6 | 0.42 | 0 | 36.3 |
| rape (winter rapeseed) | 110 | 5.06 | 0.36 | 0 | 44.4 |
| fesc1 (grasses) | 110 | 2.94 | 0.67 | 0 | 7.98 |

Water balance soft calibration enabled it to match the observed water yield ratio of 0.46 for the time period 2005-2013 by adjusting the value of petco, perco, and latq_co parameters to 1.5, 0.97, and 2.41, respectively.

## 2.3. Hard calibration and validation

In CS7, the major water quality variables of interest were N-$NO_3^-$ and sediments (Table A7.2). The case study area is prone to erosion and considered a nitrate-vulnerable zone, wherein the area is protected against the pollution of groundwaters caused by nitrates from agricultural sources. The sequential calibration workflow (first hydrology, then N-$NO_3$ , and subsequently sediments) was tested, but appeared to be challenging to obtain satisfactory results, as several hydrology parameters were significantly affecting nitrate concentrations. Thus, a parallel workflow of calibration was performed (i.e. the hydrology, sediment and nitrates). The selected parameters included hydrology (26), sediments (6) and nitrogen (7) parameters. Four objective functions were evaluated for each observed variable: NSE, KGE, PBIAS and MAE. In the final ranking of parameter sets the following weights were applied for discharge, sediment concentration and N-$NO_3^-$ concentrations respectively: 0.5, 0.1, 0.4. While hydrology was easier to calibrate, the sediment and nitrate were more challenging to calibrate, probably due to the limited data. In each consecutive iteration, the parameter space was modified to improve the performance metrics, trying to account for possible conflicts between responses of different metrics to parameter changes. For most parameters, their ranges were narrowed down based on interpretation of the dotty plots. The final selection included four different parameter combinations and was based on the sum of ranks for different metrics and variables. Time series plots shown in Figures A7.5-A7.7 present model output variability resulting from these four parameter sets.

The hydrographs from the calibration and validation of stream flow in the case study catchment are in line with the observed values (Figure A7.5and Table A7.5). The observed nitrate and sediment concentrations data were limited in the case study basin. The simulated nitrate concentrations after calibration show slight deviation from the observed values; however, the dynamics was captured quite well (Figure A7.6). The model performance for sediment concentrations was less satisfactory, although observed data was extremely sparse; nevertheless, the simulated concentrations only slightly deviate from the observed and to some extent the dynamics was captured (Figure A7.7). It is observed that after the calibration and validation, the values indicating the water balance have improved and were more in line with the reported values in the region (Figure A7.8).

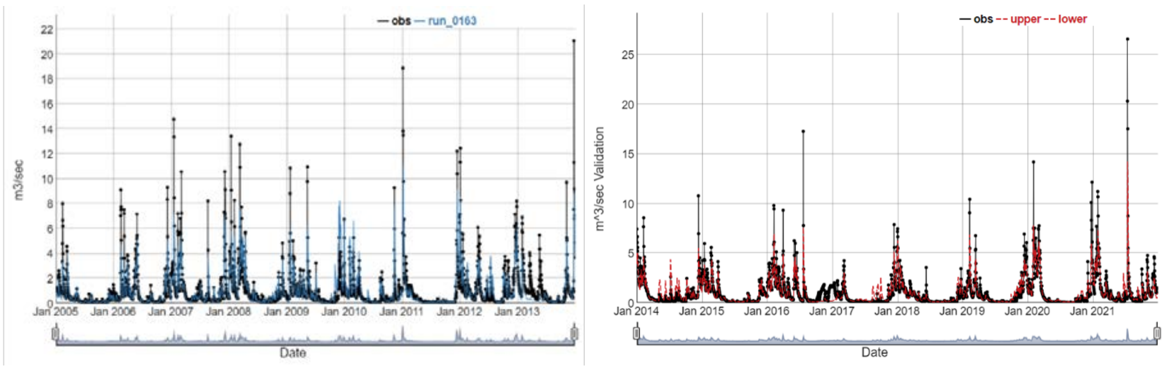

Figure A7.5. Calibration (2005-2013) and validation (2017-2021) hydrographs in one flow station within the CS7 catchment.

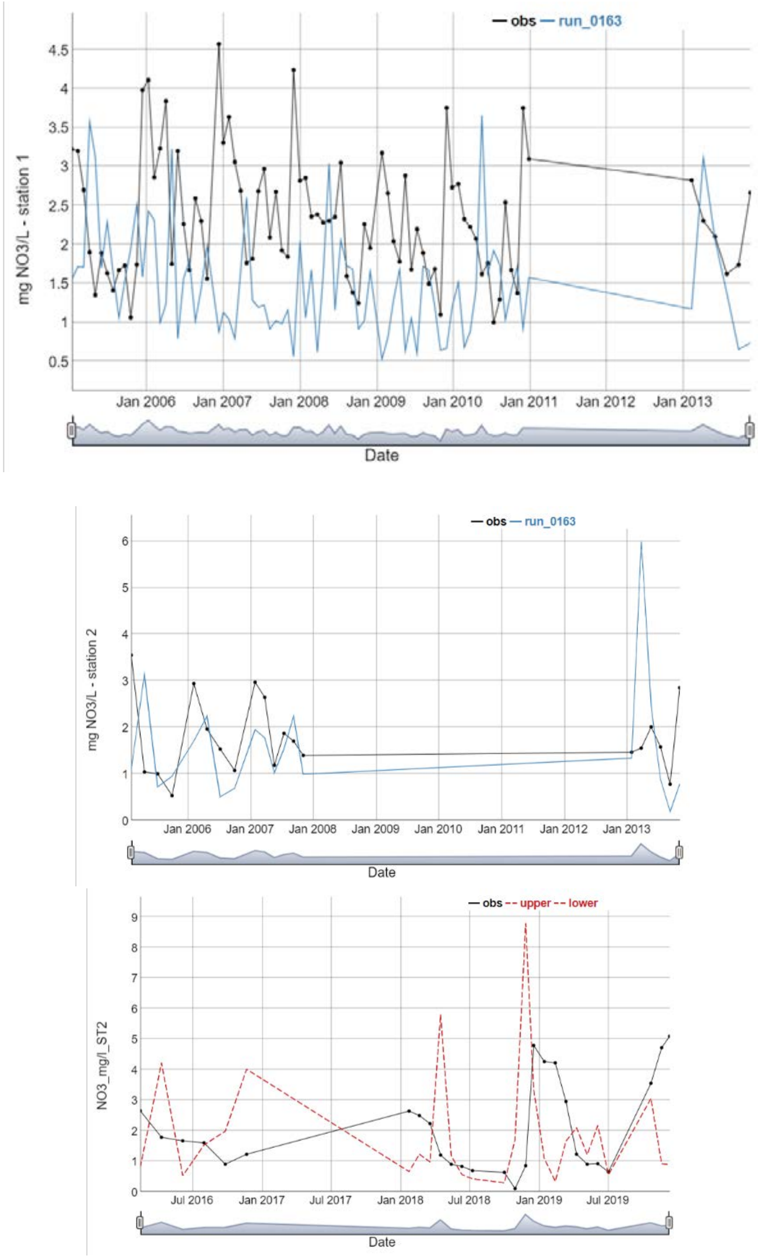


Figure A7.6. Observed and simulated concentrations of nitrate in the first station (upper graph) and for the second station (lower graph) for the calibration (2005-2013) and validation (2014-2021).

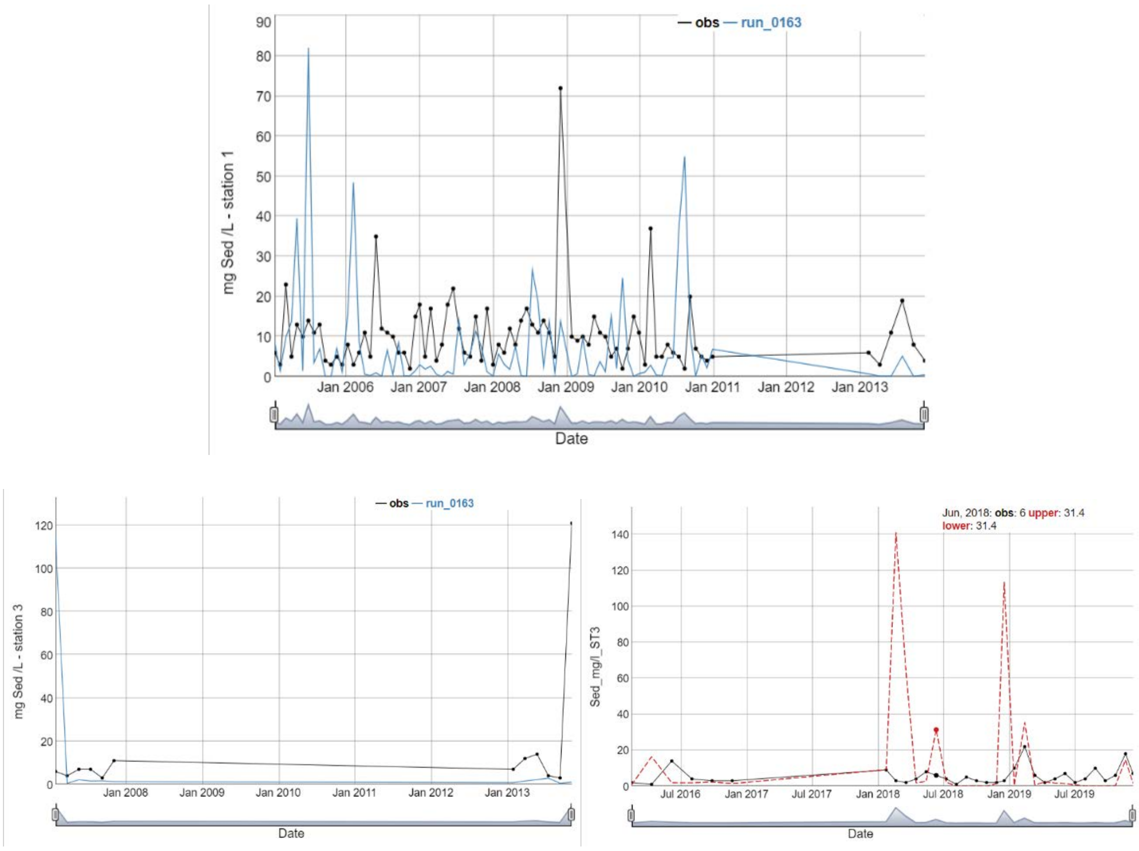


Figure A7.7. Observed and simulated sediment concentration in the first station (upper graph) and for the third station (lower graph) for the calibration (2005-2013) and validation (2014-2021).

Table A7.5. The MAE, NSE, KGE and PBIAS values of discharge, nitrate concentration and sediment concentration during the calibration and validation.

| | | Calibration | | | | Validation | | | |
|---|---|---|---|---|---|---|---|---|---|
| Station No. | Variable | MAE | NSE | KGE | PBIAS | MAE | NSE | KGE | PBIAS |
| 1 | Discharge | 0.145 | 0.747 | 0.797 | -0.600 | 0.187 | 0.792 | 0.766 | 0.5 |
| 1 | N-NO3- | 0.832 | -2.263 | -0.153 | -33.200 | | | | |
| 2 | N-NO3- | 0.646 | -5.045 | -0.621 | -10.200 | 1.325 | -2.074 | -0.190 | -6.6 |
| 3 | N-NO3- | 0.500 | -1.664 | 0.003 | 30.200 | 0.791 | -16.278 | -1.583 | 44.8 |
| 1 | Sediments | 4.349 | -1.172 | -0.097 | -33.900 | | | | |
| 3 | Sediments | 10.669 | -4.744 | -0.843 | 108.800 | 13.448 | -49.574 | -5.059 | 150.5 |

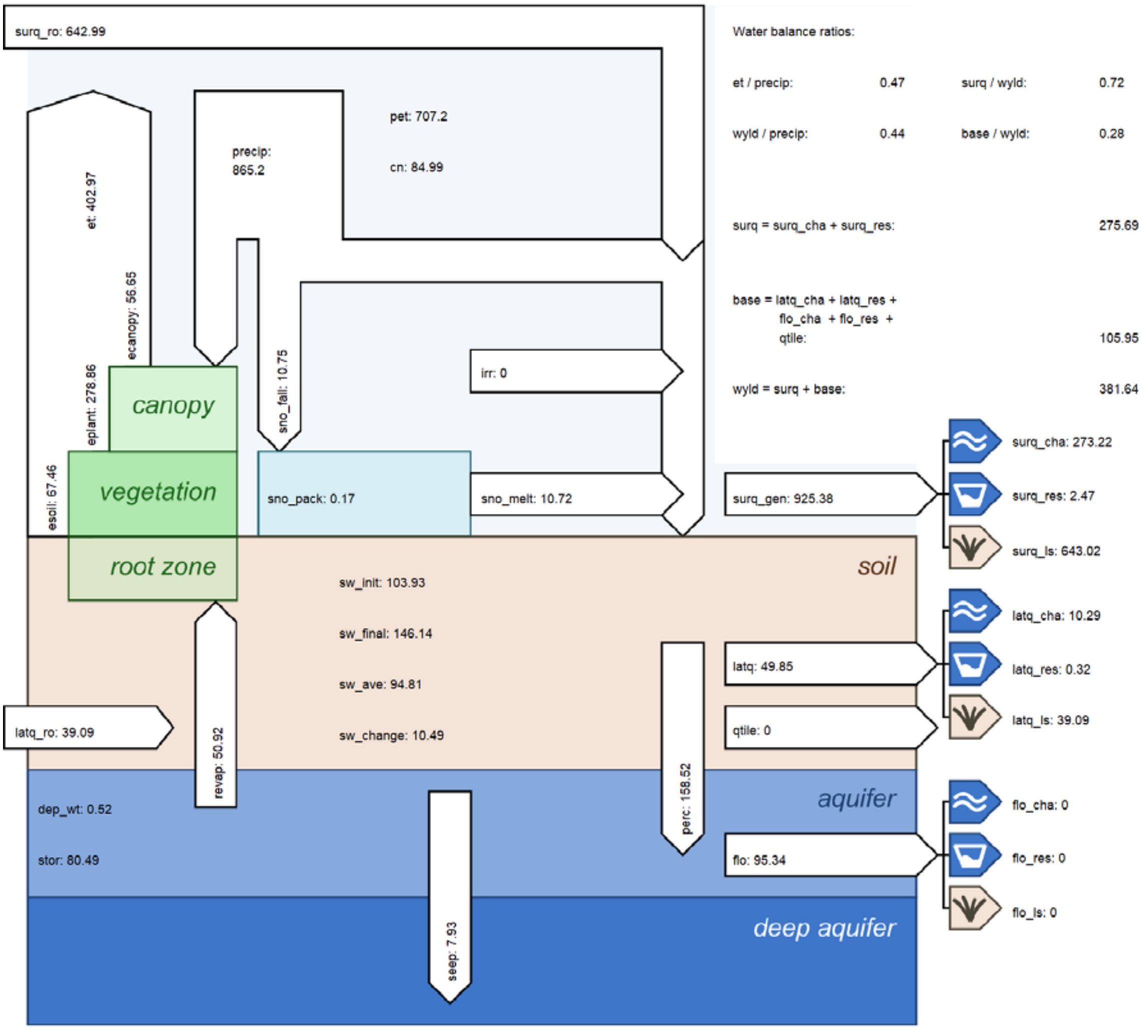


Figure A7.8 Simulated water budget of the final, calibrated model setup for CS7 (years 2005-2021).

## 3. Climate change effects

We used bias-corrected RCM simulations developed in the WP3 of OPTAIN (Honzak, 2023) as the SWAT+ model forcing in order to assess the effect of climate change on the water balance, nutrient losses and crop yields. We applied all available combinations of six RCMs, three RCPs and three time horizons (1991-2020 - serving as the “baseline”, 2036-2065 - “near future”, 2070-2099 - “end of century”), resulting in a total of 54 model scenarios. More information about the bias correction and climate scenarios can be found in section 2.2.3 of the report as well as in Honzak (2023).

Based on the results of the climate scenarios, it can be observed that there will be a decline in snowfall at RCP4.5 and RCP8.5 in comparison to the baseline period, and it follows that snowmelt also declines (Figure A7.9). Soil-water tends to decline at the end of the century at RCP8.5 in comparison to the baseline period. Precipitation tends to change between -5% to 5% in comparison to the baseline period. Percolation is a variable which ranges between -10% to 5% of the percolation in the baseline period. Soil water also tends to decline. Surface runoff and lateral flow also varies between -10 to 10%, and -10% to 5%, respectively, in comparison with the baseline period. Figure A7.10 also indicates that there are more low flow days (5 percentile of the observed flow in 2002-2021) while high flow days (95 percentile of the observed flow in 2002-2021) relative to the baseline period. The average flow tends to be variable between -10% to 10% of the baseline period.

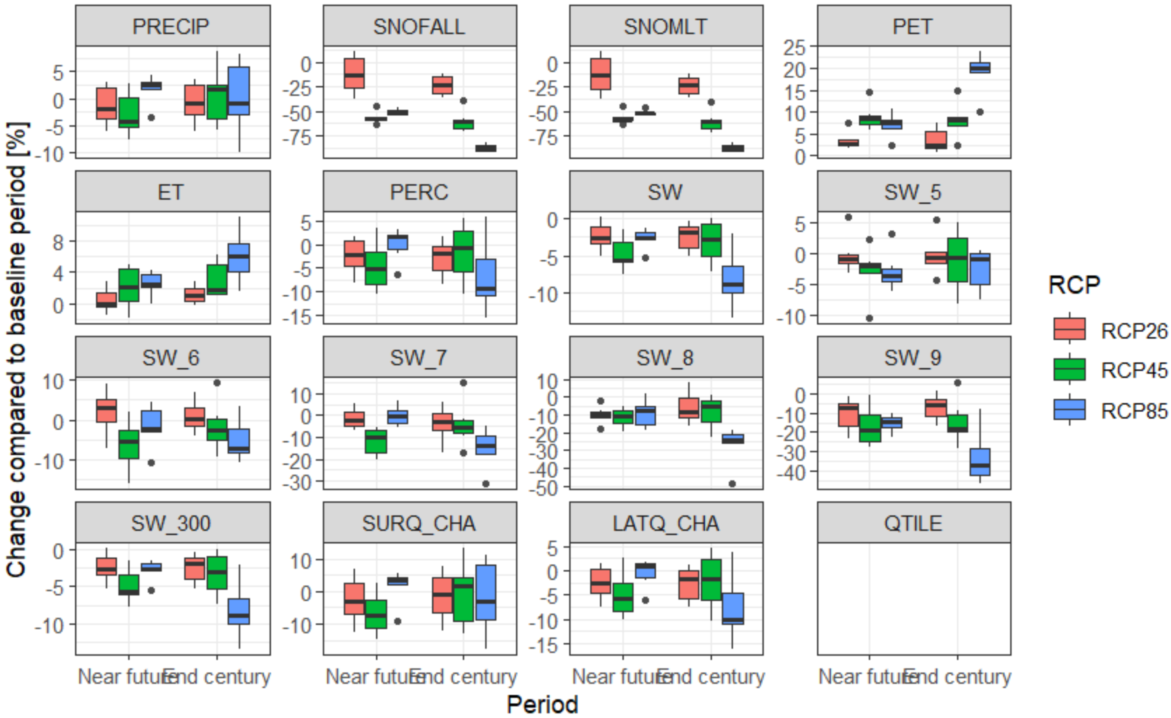


Figure A7.9. Projected changes in selected basin-averaged water balance components simulated by SWAT+ for CS7.

The nutrient load (N and P) tends to decline relative to the baseline at RCP 8.5 at the end future (Figure A7.11). However, considering RCP 2.6 and 4.5, there are more days where N concentration of 2.3 mg/L was exceeded compared to the baseline.

The yield of crops tends to vary between RCPs (Figure A7.12). Alfalfa, oats, silage corn and rapeseed tend to increase in yield. Furthermore, winter wheat and winter barley tend to increase in most RCPs relative to the baseline. On the other hand, the crops triticale, meadows (i.e. fesc), summer wheat and winter barley tend to vary their yield of -10% to 10% relative to the baseline.

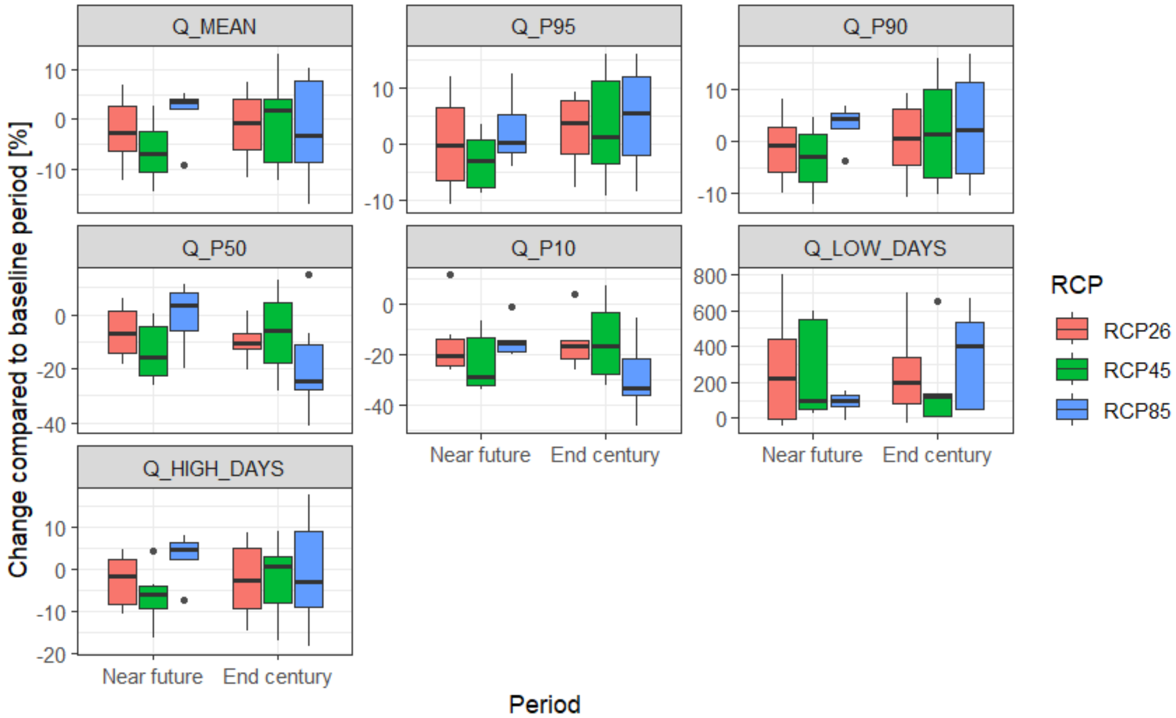


Figure A7.10. Projected changes in selected streamflow indicators simulated by SWAT+ for CS7.

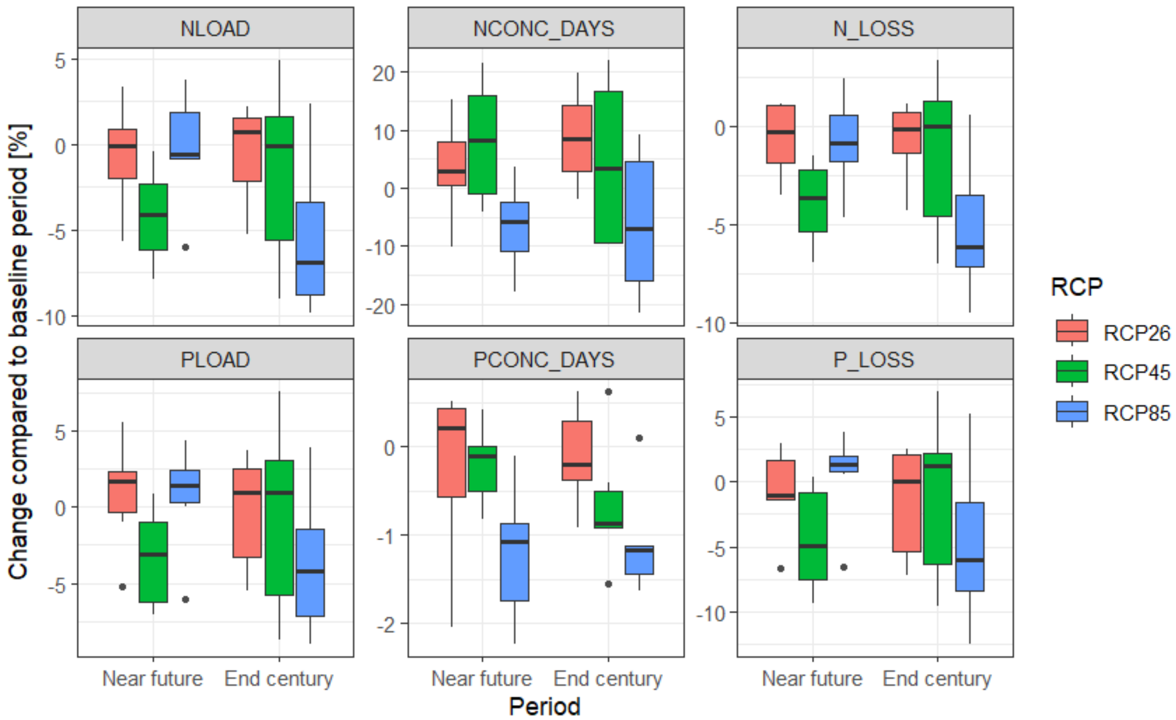


Figure A7.11 Projected changes in selected water quality indicators simulated by SWAT+ for CS7.

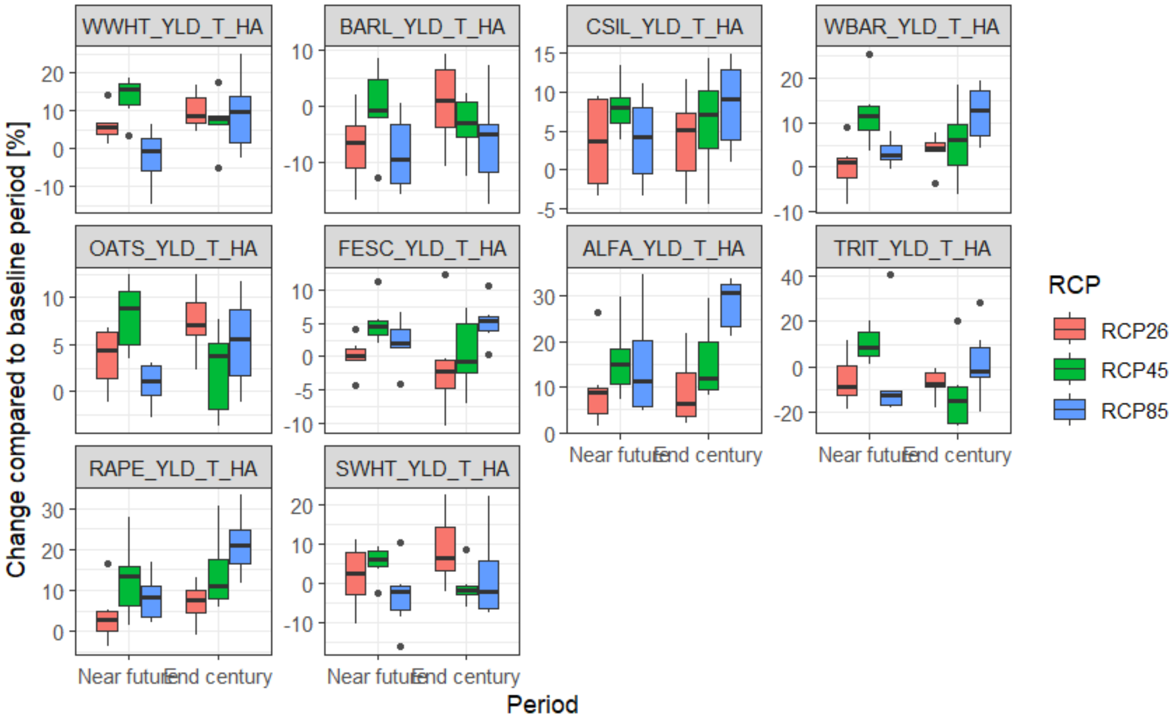


Figure A7.12 Projected changes in selected crop yields simulated by SWAT+ for CS7

## 4. Effectiveness of selected NSWRMs (current climate)

Seven NSWRMs were selected by the stakeholders during the multi-actor reference group (MARG) workshops held in May 2021 and June 2022. The selected NSWRMs are afforestation, riparian forest buffers, buffer strips along the stream, hedges at the edge of agricultural fields, wetlands, floodplain restoration and cover crops. Only the five NSWRMs are presented in this document, i.e. are afforestation, riparian forest buffers, buffer strips along the stream, hedges at the edge of agricultural fields, and floodplain restoration. The wetlands simulations and settings are currently being adapted to make it possible for the SWAT+ model to simulate. The cover crops are currently implemented in the status quo model set up; we, however, added a scenario removing these cover crops which will be shown to the stakeholders during our next MARG workshop for their interest in the effectiveness of these cover crops.

Based on the MARG workshop held last June 2022, different criteria were agreed on where to implement the measures. Below are the criteria for the selection of the measures locations and are indicated in Figure A7.13

Wetlands

- Topsoil must contain at least 10% clay but important that water can still infiltrate the groundwater
- Organic carbon should not exceed 2%
- Loam soil must dominate
- The surface slope must be low or the area is flat
- Occupy meadows/pastures
- High-risk flooded area
- Reference conditions – natural wetlands in the in historical map
- Preferably at Natura2000 sites

Buffer strips and hedges

- Edge of a sloping agricultural field (6 m width at least) and when the universal soil loss equation (USLE) value is greater than 5 tons/ha/year. (Background: The Universal Soil Loss Equation (USLE) predicts the long-term average annual rate of erosion on a field slope based on rainfall pattern, soil type, topography, crop system and management practices. USLE only predicts the amount of soil loss that results from sheet or rill erosion on a single slope and does not account for additional soil losses that might occur from gully, wind or tillage erosion). Also, the field needs to have a surface area of 3 ha or more and at the edge of the field where majority of the run-off takes place.
- To start the buffer strips from visible sediment runoff and erosion rills
- Along the river bank (6 m width at least) and when the adjacent agricultural field is arable. Wider might be needed but might not be easy to implement or is not practical.

- Can be also placed in urban/residential areas.

Riparian forest buffer

- Along the river bank (6 m width at least) and when the adjacent agricultural field is pasture/grasses/meadows
- In areas high in biodiversity such as Natura2000 sites

Floodplain management and restoration

- Only grasses/meadows or trees in highly flooded areas should be cultivated using the flood hazard map (both in the very highly and the moderately flooded areas)
- Installation of wetlands in the high-flood risk areas – (see Section 3.2.1)
- Urban/residential areas are excluded from this measure

Cover crops (Nitrate trapping crops)

- For arable lands during winter (with different cover crops listed in the PGDEIII – as long as parameters are available in the literature or SWAT+ database, this can be done)

Maintenance or establishment of upstream forest

- In planned areas for afforestation within the basin
- Conversion of another type of trees (e.g. coniferous trees converted into deciduous trees): priority criterium
- In land less suitable for agriculture, i.e., not fertile, low organic matter
- Adjacent to existing patches of forest

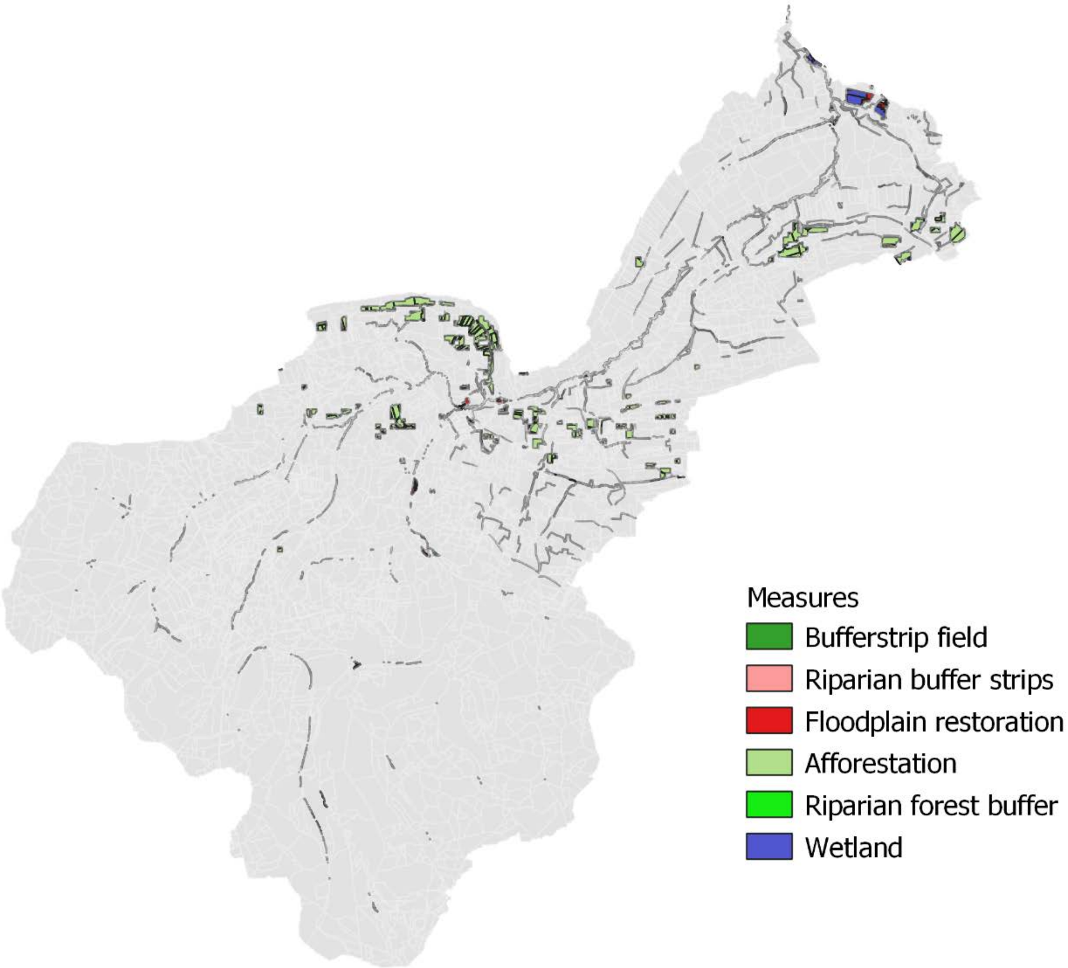


Figure A7.13. Locations of NSWRMs based on the criteria indicated above, which was simulated in the scenario runs.

The model simulations which implement the different NSWRMs suggest that by implementing each or all the measures simultaneously will result in a decline in water flow by up to 5% (Figure A7.14). Particularly, the number of days with low flow, i.e. 5 percentile of the observed flow values increased relative to the status quo, with the measure buffer strips along the stream results to the highest number of days with low flows while both afforestation and hedges at the edge of the stream, resulted in the same number of days with low flows. The combined implementation of all measures resulted in an increase in the number of days with low flows to about 8% compared to the status quo scenario. This indicates the retention of water by their measures which results in lower flows.

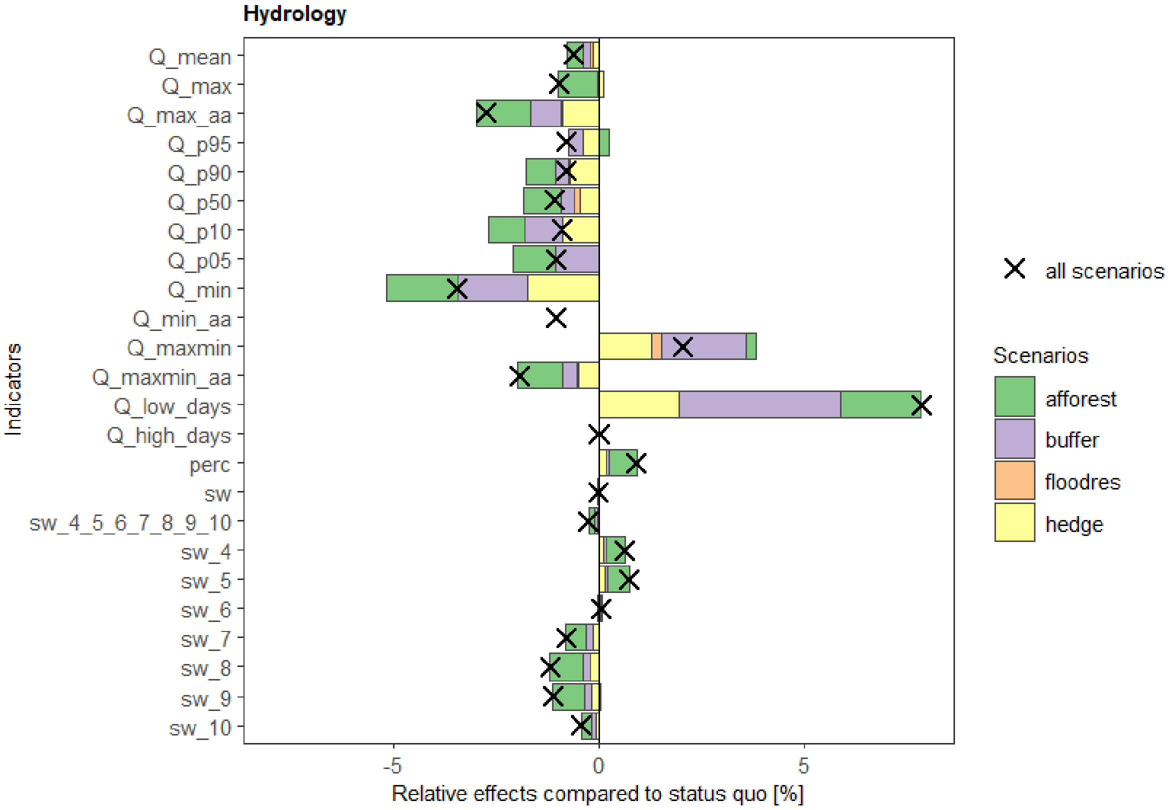


Figure A7.14. Percent changes in selected stream flow (Q) and soil water (sw in the month of April (4), May (5), June (6), July (7), August (8), September (9), October (10)) indicators relative to the status quo upon the implementation of riparian forest buffers and afforestation (afforest), riparian buffers-hedges (buffer), flood restoration (converting land cover into natural grasses for flood prone areas), buffer hedges on agricultural fields (hedge), and combined implementation of all measures (all) in CS7.

With the implementation of the different measures, it is clear that there is a decline in the nutrients (N and P) load in the water (Figure A7.15). Particularly the implementation of buffer strips along the streams resulted in the most decline of N load while the combination of all measures resulted in the highest decline of N load in water. Similar trend is also observed for the P load. Strikingly, the implementation of the measures resulted in a decline in the sediment loss with afforestation resulting in the highest amount of sediment being retained followed by buffer strips along the stream and hedges on the edge of the field. This indicates that these measures are good at retaining both sediments and nutrients.

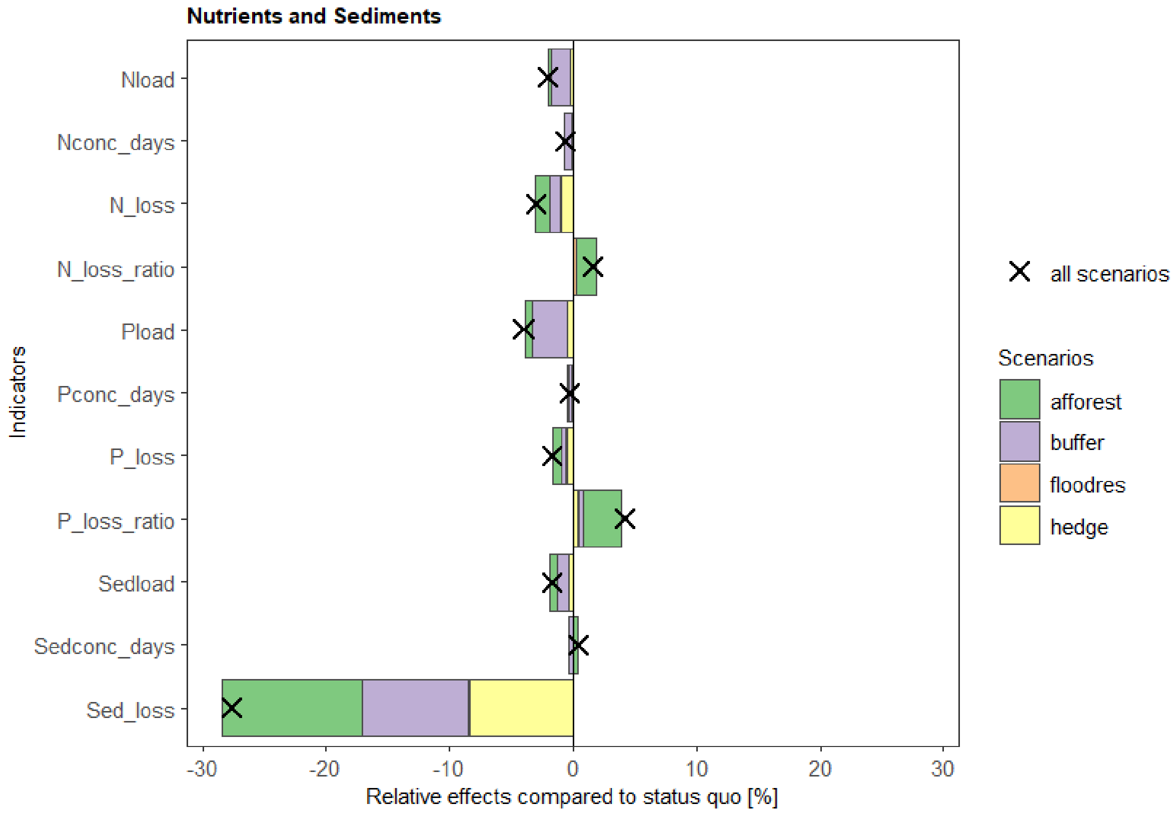


Figure A7.15. Percent changes in selected water quality indicators relative to the status quo upon the implementation of riparian forest buffers and afforestation (afforest), riparian buffers-hedges (buffer), flood restoration (converting land cover into natural grasses for flood prone areas), buffer hedges on agricultural fields (hedge), and combined implementation of all measures (all) in CS7.

By implementing the measures, it can be observed that the yields of most crops increased (in terms of yield per ha – Figure A7.16). The implementation of afforestation on the other hand resulted in a decline in the yield of winter barley and rapeseed. However, due to the implementation of the measure, some lands were not anymore used for crop production and thus a decline in the total yield per crop within the basin.

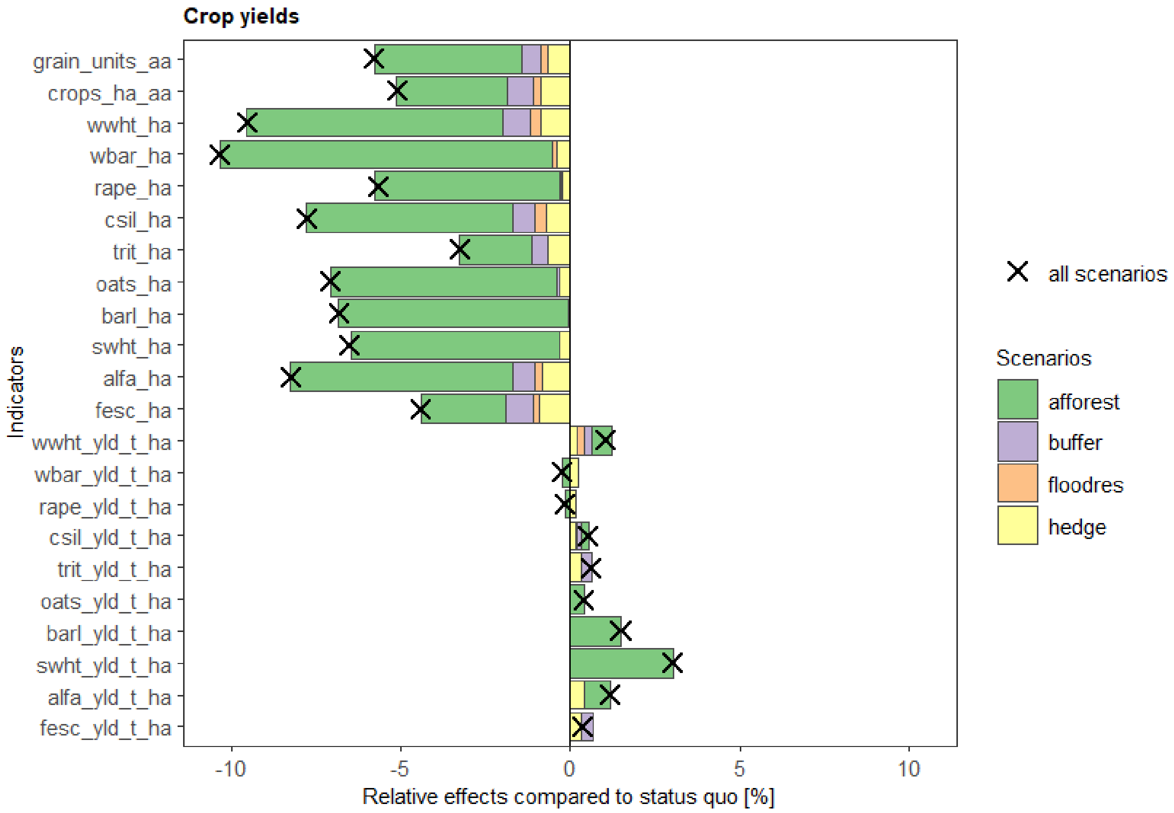


Figure A7.16. Percent changes in selected crop yields relative to the status quo upon the implementation of riparian forest buffers and afforestation (afforest), riparian buffers-hedges (buffer), flood restoration (converting land cover into natural grasses for flood prone areas), buffer hedges on agricultural fields (hedge), and combined implementation of all measures (all) in CS7.

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# Annex 8 Modelling results for CS8 (Dotnuvėlė, LT)

Authors: Natalja Čerkasova, Rasa Idzelytė (KU)

## 1. Model setup

The SWAT+ model for CS8 catchment (Dotnuvėlė) was set up following the OPTAIN workflow (Schürz et al., 2022). Most input data were prepared manually. The uncalibrated model setup was developed using the R script for the model setup generation workflow (https://git.ufz.de/optain/wp4-integrated-assessment/swat/swat-setup/full_workflow) consisting of both SWATbuildR (version 1.5.9) and SWATfarmR (version 4.0.2).

### 1.1. Input data overview

Table A8.1. presents all major SWAT+ input data, their resolution, and sources. Comments provide explanations on pre-processing of certain datasets. Selected spatial datasets: main river channels, catchment boundary, elevation map, land use map and soil types. The CS8 catchment occupies 175 km$^2$ and is characterised by a flat relief, high fraction of arable land and productive soils, which places the watershed in an agriculturally intensive region (Figure A8.1.).

Table A8.1. Summary of input data for CS8.

| Input | Number of objects / resolution | Source | Comments |
|---|---|---|---|
| DEM | 5 m | National Land Service under the Ministry of Agriculture of Republic of Lithuania (digital spatial laser scanning points data of land surface of the Republic of Lithuania | Data for 2019 was used for the DEM |
| Channel layer | 164 | National Land Service under the Ministry of Agriculture of Lithuania (National Land Service under the Ministry of Agriculture) | Layer was modified to account for NSWRMs planned for scenario simulations |
| Reservoirs and wetlands | 392 | GRPK – Spatial data set of (geo) reference base cadastre (The Ministry of Agriculture of | Layer was modified to account for NSWRMs planned for scenario simulations |

| | | | |
|---|---|---|---|
| | | the Republic of Lithuania); and Map of The National Atlas of Lithuania - Distribution of lakes and ponds (Kavaliauskienė and Krikščiūnienė, 2013) | |
| Land layer | 4065 | The National Reference Base Data Set from the National Land Service under the Ministry of Agriculture | Tile drainage information supplemented based on National Land Service under the Ministry of Agriculture.<br>Land layer was modified to account for NSWRMs planned for scenario simulations |
| Soil layer | 8009 | National Land Service under the Ministry of Agriculture and Lithuanian Soil atlas (Volungevičius and Kavaliauskas, 2012) | Raw vector layer pre-processed and reclassified. |
| Usersoil table | 8 | Adopted from Lithuanian Soil atlas (Volungevičius and Kavaliauskas, 2012) | Harmonised according to the requirements of the USDA and SWAT+ inputs |
| Point sources | 187 | Wastewater management accounting data from Lithuanian EPA. | |
| Weather data | 1 station | Lithuanian Hydrometeorological Service under the Ministry of Environment | Data was procured for the study period |
| Atmospheric deposition | 1 | European Monitoring and Evaluation Programme (EMEP) | EMEP data processed by SWATprepR |
| Crop sequence map | 2046 (fields) | National Land Service under the Ministry of Agriculture of Republic of Lithuania | Lithuanian Statistical Yearbook was used to determine average yields. |
| Management schedules | 12 | Lithuanian Agricultural Advisory Service and consultation with farmers | Schedules prepared in consultation with the local agricultural advisory service and local farmers |

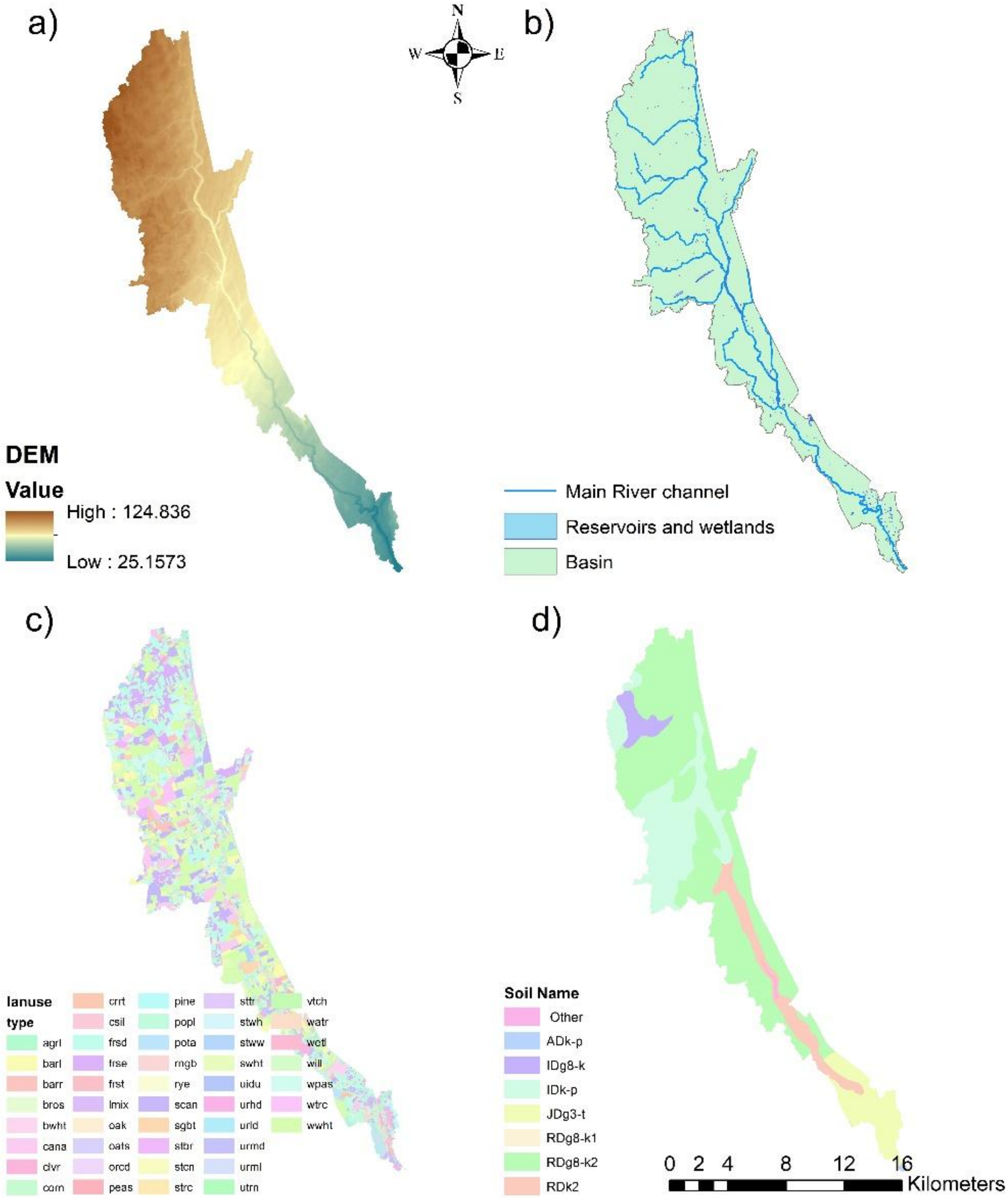


Figure A8.1. GIS input data for CS8: a) flow gauges, water quality monitoring points, ground water gauges, meteorological stations, point source locations, channels, catchment boundary; b) elevation map; c) land use map; d) soil types.

## 1.2. Baseline model setup

The most important features of the model setup are included in Table A8.2. Most of them were extracted from the object.cnt file. A very detailed input land layer resulted in a high number of HRUs (4065) and streams (783), which in consequence affects the model run time, prolonging this process substantially.

Table A8.2. Summary of the model setup features.

| Parameter | Value |
|---|---|
| Total area of the watershed in ha | 17468 |
| Total number of spatial objects in the simulation | 9493 |
| Number of HRUs in the simulation | 4065 |
| Number of routing units in the simulation | 4065 |
| Number of aquifers in the simulation | 1 |
| Number of reservoirs and wetland in the simulation | 392 |
| Number of recalls (point sources/inlets) in the simulation | 187 |
| Number of SWAT-DEG channels in the simulation | 783 |
| Number of crops in rotation | 21 |

## 1.3. Missing elements of the report and time plan to complete these tasks

In the report, certain elements regarding the Lithuanian CS lead modeller's tasks are notably absent. This omission stems from an unforeseen shift in responsibilities within the project. During the post-project agreement signing period, the Lithuanian CS lead modeler was tasked with co-developing the core modeling tool used in the OPTAIN project, known as SWAT+. This stems from a close collaboration between the Lithuanian CS modeller and the USDA-ARS and Texas A&M AgriLife Research, where the model is developed and maintained.

Given that the entire consortium relies heavily on the functionality and accuracy of SWAT+, the priority of individual CS-specific tasks was adjusted. This adjustment was made to accommodate the pressing need to develop and debug specific functionalities within SWAT+ to meet the modelling targets set forth by the OPTAIN project. Consequently, the Lithuanian CS lead modeller's focus shifted towards the development and refinement of SWAT+, leading to a temporary halt in their CS-specific modeling tasks. In essence, the absence of certain elements in the report reflects the strategic decision to prioritize the collective efforts of the consortium in ensuring the successful development and functionality of the SWAT+ tool, which is integral to the overall success of the OPTAIN project.

With the OPTAIN consortium's decision to finalize the model revision version for implementation (revision of March 2024), the previously unforeseen responsibilities have been lifted from the Lithuanian CS lead modeller. Now, the main focus can return to completing the model setup. Fortunately, as outlined in this report, OPTAIN has developed a comprehensive set of scripts and established a harmonized workflow. These resources will facilitate a smooth and relatively rapid completion of the remaining tasks. Looking ahead, the OPTAIN consortium has scheduled a modellers' meeting on May 8-10, 2024. The Lithuanian CS has committed to provide the working setup by this meeting, ensuring timely progress and collaboration within the consortium.

# Annex 9 Modelling results for CS9 (Cherio River, IT)

**Authors:** Enrico Antonio Chiaradia, Paolo Gaini, Lorenzo Sanguanini, Claudio Gandolfi

## 1. Model setup

The CS9 is the Cherio River Basin in the eastern sector of the Bergamo province (Lombardy, Italy). The basin stretches from the pre-alpine terrain, peaking at 1380 meters above sea level atop Mount Grione, to the inlet in the Oglio River at 142 m a. s. l., with a total extension of 153 $km^2$. The basin can be divided into two: the Northern part is mountainous with steep slopes and valleys while the southern part is mainly flat (Fig. A9.1).

Within the study basin, the Cherio River originates from the Endine Lake and it reaches the length of 30 km, intersecting with several small tributaries along its course. Two stream gauges have been measuring discharges for the last years: one at the outlet of the lake (Casazza), the other at the inlet of the rural channel that derives from the Cherio river at Bolgare. A hydrometer is currently working at the section of Carobbio while few discharge measurements were done in the past at Trescore station (Fig. A9.1a).

Weather data are measured by 4 stations, one is located inside the basin. Annual average precipitation is around 1200 mm, with slightly higher values in the Northern part of the basin. Heavy precipitation events that had occurred in the past have occasionally caused flooding (years 2014, 2016 and 2018). In contrast, the lack of precipitation during the first part of the year is jeopardizing the feasibility of maintaining environmental flow and irrigation requirements during the summer season.

Soil map includes up to 21 types. The GVN1 soil type is the dominant one, covering approximately 30% of the basin area, mostly in the middle zone (see Fig. A9.1d). This soil is deep, with no or little skeleton, and medium to moderately coarse texture. The RCH1 soil type represents 12% of the basin and it is deep with skeleton common on the surface and very abundant in depth, and medium texture. All the other types of soils represent less than 10% of the basin area. All profiles have a high depth, except for some areas in the northernmost part of the basin where slopes are steeper.

Land cover consists mostly of forested and agricultural/pastural areas, respectively 42% and 39% of the total; the remaining land cover is represented by low-medium density populated settlements.

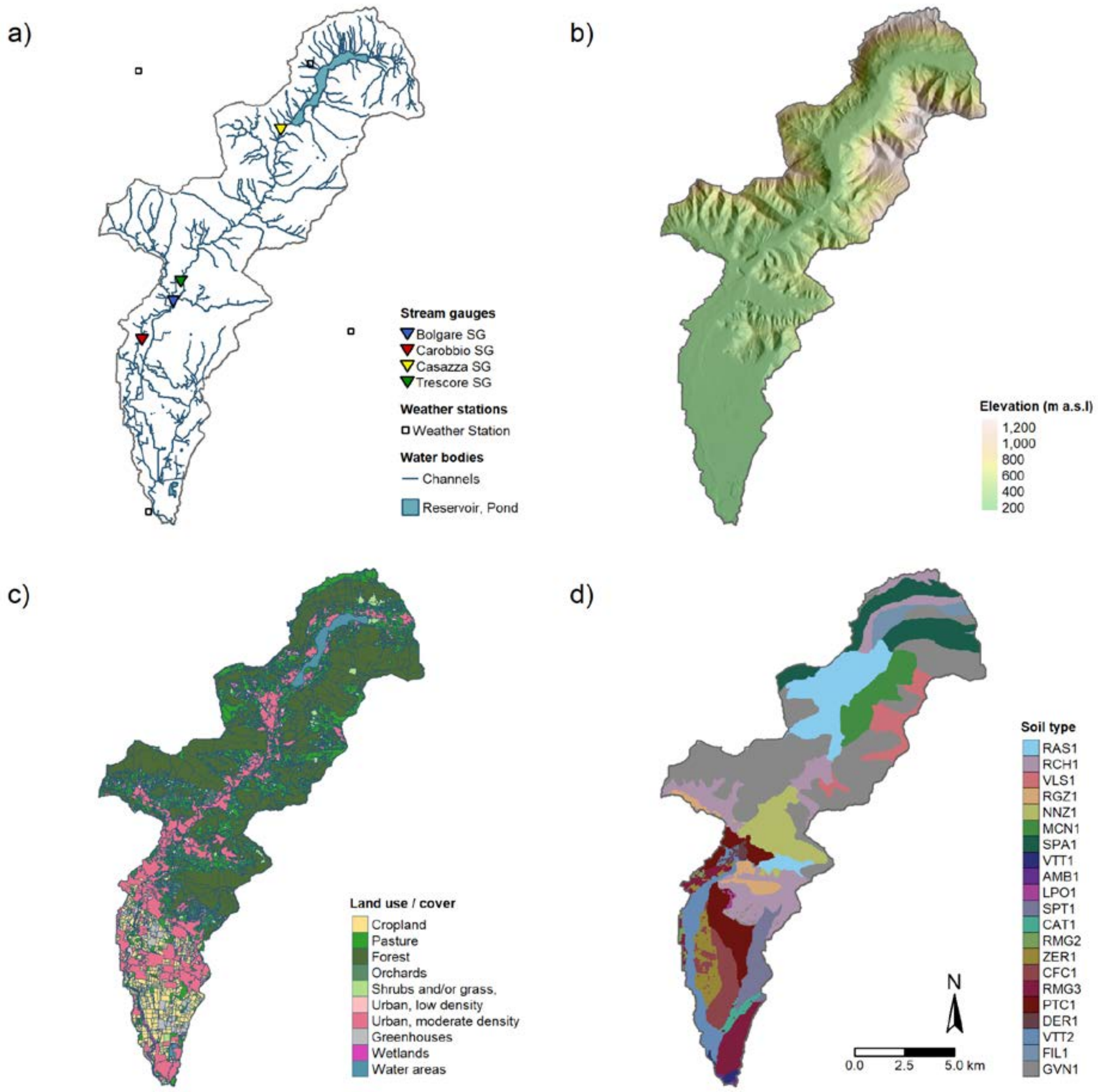


Figure A9.1 Model input data: a) stream network, weather stations and stream gauge location; b) elevation map; c) land use map and d) pedologic map.

Following the above-mentioned characteristics, the main modeling challenges are:

1. different hydrological dynamics that characterized the mountainous area and the plain area;
2. presence of a relative extended reservoir in the upstream part of the basin;

3. geo-morphological aspects that drive the groundwater storage and release behavior, referring in particular to the transition edge between the hilly area and the plain;
4. presence of karst system;
5. withdrawals for irrigation purposes, both directly from the Cherio River and other unmonitored sources outside the watershed.

In the following paragraphs the entire modelling workflow has been presented.

## 1.1. Input data overview

The SWAT+ model requires a set of specific information related to land use, soil properties, weather and other case study relevant aspects. For all the initial raw data categories reported in Tab. A9.1, various degrees of processing were required. First of all, starting from the original shapefile, land use polygons had to be aggregated to obtain a more manageable dataset. Two different soil maps had to be partially merged to retrieve all the soil parameters required by the model. Moreover, measured meteorological data had to be integrated with the ones provided by ERA5-land simulation (www.climate.copernicus.eu, 2021). The crop sequence map's attribute table was filled by combining different data sources and then validated with interviews to local agronomists. More details regarding the input data, their resolution and their source were presented in Tab. A9.1.

Table A9.1 Summary of input data for CS9.

| Input | Resolution/scale/ Number of objects | Source | Comments |
|---|---|---|---|
| DEM | 5m | Lombardy Region online catalog | |
| River/channel network | 1:10,000 | Lombardy Region online catalog | |
| Land use | < 1m | Geo-Topographic Database (DBGT), Lombardy Region online catalog | An algorithm was implemented to aggregate the smaller shapes. |
| Soil types | 1:250,000 | Regional Agency for Agricultural and Forestry Services (ERSAF) | The two maps were integrated, since the 1:50,000 map only covered the lower part of the basin. |
| | 1:50,000 | Regional Agency for Agricultural and Forestry Services (ERSAF) | |
| Measured weather data | 4 stations | Regional Environmental Protection Agency (ARPA) | Only one of the stations is located within the basin. Lack of measured variables in certain stations. |

| | | | |
|---|---|---|---|
| Simulated weather data | 0.1° | ERA5-land (www.climate.copernicus.eu, 2021) | The missing ARPA data were integrated with ERA5 |
| Crop sequence/ management schedules | | Italian National Institute of Statistics (ISTAT)<br>Agricultural Accounting Information Network (RICA)<br>Lombardy Region Agriculture Information System (SIARL)<br>Agronomists interview | SIARL data have been combinedwith ISTAT and RICA and further validated by agronomists' interviews. |

## 1.2. Baseline model setup

The OPTAIN workflow (Schürz et al., 2022) was successfully transferred to the CS9 catchment: a baseline model was created, encompassing all necessary inputs to generate all the spatial components, accordingly with the COCOA approach, utilizing the SWATbuildR script (version 1.5.10).

The land use map was carefully prepared to assess topological issues, such as overlapping features, and prevent infinite loops by optimizing element sizes. For the Cherio River basin, a custom procedure was created to address urban areas with internal drainage networks, concentrating floods at specific points during intense rainfall, mimicking the sewer system outflows. This procedure, implemented as an R script, improves the representation of issues related to urban drainage, ensuring proper routing and accounting for retention/detention ponds in localized conditions, while resolving potential infinite loop problems, often automatically adjusted by SWATbuildR.

Weather data were implemented into the model using the SWAT+ Editor (version 2.3.1) and the so obtained preliminary simulation was integrated with the agronomical component using the SWATfarmR package (version 0.4.1.9001). The latter required crop management schedules, based on field-specific crop information, and generic land use management schedules (Schürz et al., 2022). The above-described workflow produced a complete and functioning simulation, ready for calibration and validation as described in the following paragraphs.

The Cherio Basin baseline model, obtained by the above-mentioned procedure, consisted in a total of 5672 HRUs (see Tab. A9.2 for details).

Table A9.2 Summary of the model setup features for CS9

| Parameter | Value |
|---|---|
| Total area of the watershed in ha | 14150 |
| Total number of spatial objects in the simulation | 11946 |
| Number of HRUs in the simulation | 5546 |
| Number of routing units in the simulation | 5546 |
| Number of aquifers in the simulation | 1 |
| Number of reservoirs in the simulation | 32 |
| Number of recalls (point sources/inlets) in the simulation | 0 |
| Number of SWAT-DEG channels in the simulation | 818 |
| Number of crops in rotation | 9 |
| Number of wetlands | 105 |

## 2. Model evaluation

Model evaluation is based on the comparison between observed and modelled variables, both in aggregated terms (soft calibration) and time specific variation (hard calibration). Table A9.3 presents observation data for variables used both in soft (water yield ratio, crop yields) and hard calibration (discharge).

Since crop yield statistics are not available from public sources, we collected information from specialized journals, manuals and local experts' interviews. Land crops are mainly used for feeding livestock. In the plain area, most of the cultivated fields are affected by alternation between a summer crop (1° or 2° harvest of silage corn/soybean) with a winter crop (wheat, ryegrass, or mustard as cover), sometimes interrupted by 4/5 years of alfa-alfa or polyphite lawn. Only 15% of the fields are cultivated with a continuous cropping of maize, while 17 % are maintained as permanent meadow. On the other hand, more than 80% of the cultivated fields in the mountainous area are occupied by permanent meadow. Except for polyphite lawn in mountainous areas, all the crops are normally irrigated.

Discharge data in CS9 are critical: the flow gauge in Casazza represents only a small portion of the basin and it is affected by many missing data in the latest years that generates suspicion about their quality. On the other hand, the gauge station at Gorlago measures only the flow in the irrigation channel. In order to increase the quality of the available information, a stage-discharge relationship was finally implemented at Carobbio station where only water depth is recorded.

Water pollution elements are recorded occasionally by the regional environmental protection agency (ARPA). Water quality is not a relevant issue for the Cherio basin as nutrients content is commonly low. For this reason, pollutants are not considered during calibration.

Table A9.3 Summary of observation data used in different steps of the calibration workflow for CS9.

| Variable | Time step | Calibration period | Validation period | Source | Comments |
|---|---|---|---|---|---|
| Soft calibration | | | | | |
| Crop yields | Average annual | 2005-2022 | NA | Local experts | Bibliography, Expert-based values |
| Water yield ratio | Average annual | 2010-2015 | NA | Model input (pcp) and discharge data | Calculated for the flow gauge of Casazza with the more reliable dataset |
| Hard calibration | | | | | |
| Discharge | Daily | 2007-2012 | 2013-2016 | Interregional Agency of the Po River – AIPO | Own calculation based on readings of the water level loggers and the rating curve developed for gauge at Carobbio. |

## 2.1. Model setup verification

Model verification was conducted between 2002 and 2020 considering a warm-up period of 3 years. Fig. A9.2 shows the annual statistics of the main weather variables under no stress conditions (i.e. no limitation to the plant growth).

Potential evapotranspiration is never reached, and actual evapotranspiration is determined mainly by plant transpiration according to the presence of dense and rich canopy during most of the years.

Annual average precipitation depth during the investigation period is 1226 mm. On the contrary, average snowfall is only 25 mm; this aspect, together with the absence of perennial snow and glaciers in the basin, influences the water availability during the crop season.

Temperatures range between -12.3 and 36.3 °C and show a gradually increasing trend in the mean value over the considered period.

Humidity, wind velocity and radiation don't show any meaningful differences between years and they are strictly related to temperature and precipitation.

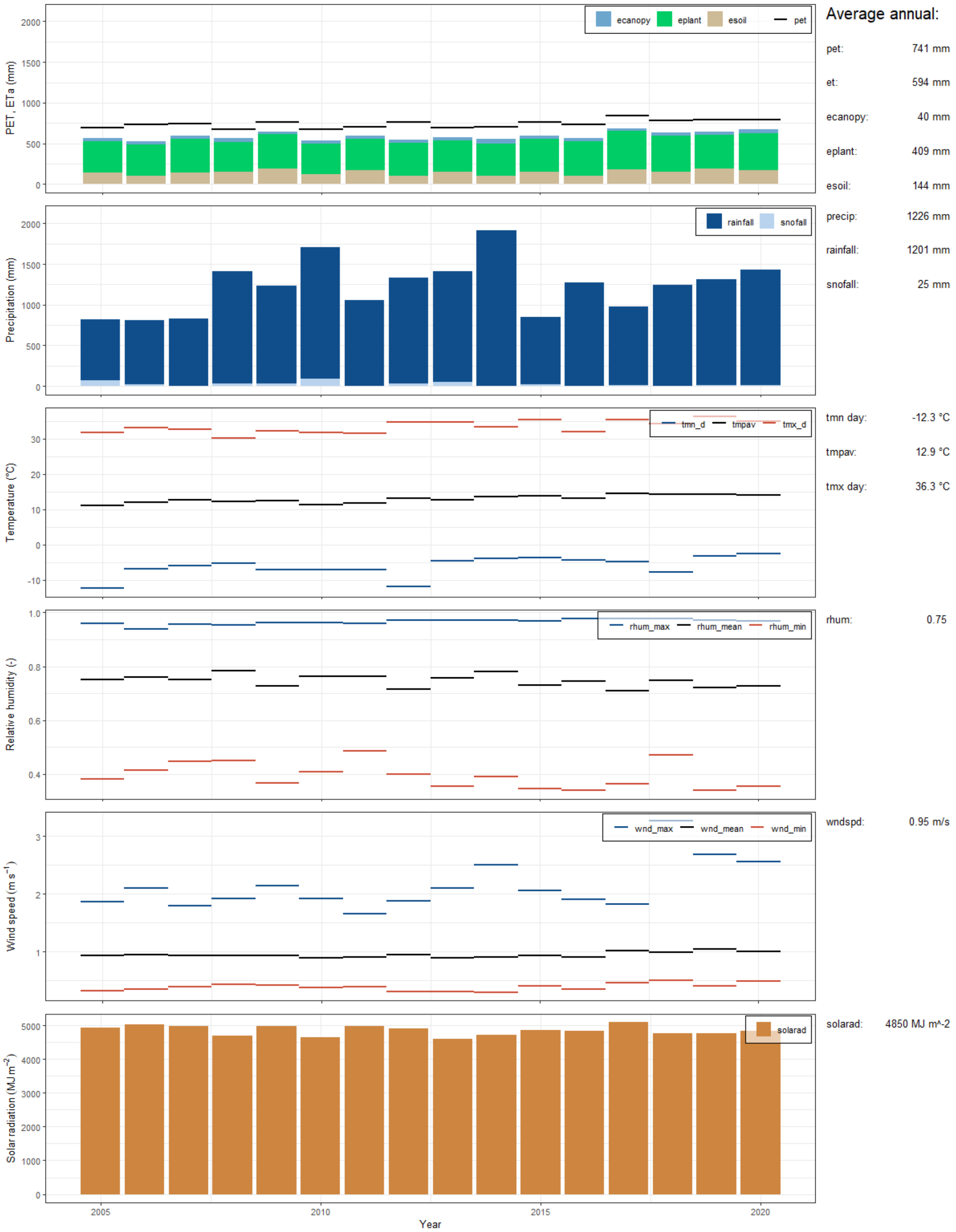


Figure A9.2 Summary of the climate data checks for the CS9 - Cherio Basin obtained by the SWATdoctor.

Fig. A9.3 reports the main fluxes obtained under no stress conditions from the uncalibrated model. In particular, it shows that the water budget is unbalanced to the superficial and lateral flow; this is far from the actual nature of the basin and indicates that, probably, some aspects relative to the percolation process should be adjusted during calibration. Low percolation volumes also affect groundwater recharge that is one of the main processes in the basin to determine base flows. To confirm that, the Water Yield Ratio (WYR = wyld/precip) and the Base flow Ratio (BFR = base/wyld) are respectively 0.93 and 0.6.

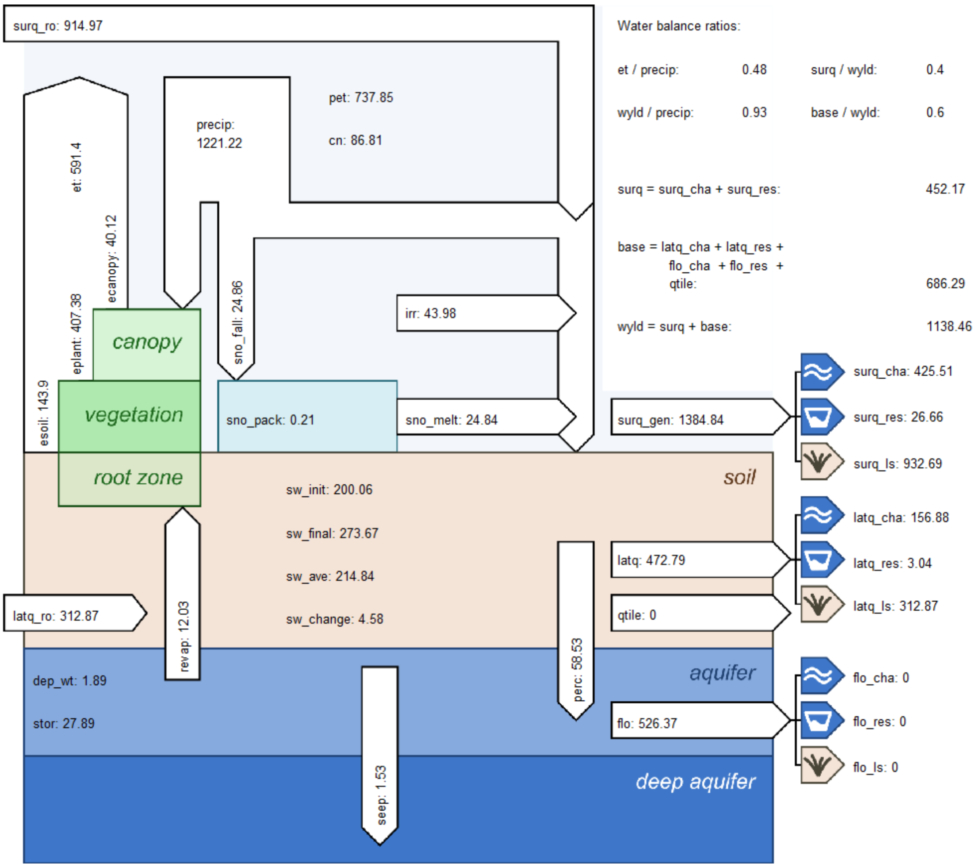


Figure A9.3 Summary of the average annual water balance fluxes during the considered period (obtained by SWATdoctor).

## 2.2. Soft calibration

*Preliminary adjustments*

Due to the nature of the considered basin, in order to better represent the specific characteristics of the geo-morphological structure of the landscape (e.g. the difference between the mountainous and the plain areas), some adjustments were performed manually. In particular, the aquifer, considered as single in the SWATbuildr script, was divided in 4 elements (Fig. 9.4): aquifer 1 for the plain area, aquifer 2 for the sub-basin of the Endine Lake, aquifer 3 and 4 for the remaining valleys. Each aquifer contributes to the base flow and is drained by selected elements along the basin: channel 247 for aquifer 1 (basin outlet), reservoir 9 (Endine Lake) for aquifer 2, channel 551 (Trescore monitoring section, upstream the diversion) for aquifer 3, and channel 367 (Carobbio station) for aquifer 4.

Secondly, some sections of the main river and of its tributaries, artificial connections (i.e. sewer conduits) and rural channels were manually corrected in order to match the actual sections widths and heights, according to the artificial nature of most of the reaches of the hydrological network. The SWATbuildr in fact assigns width and depth of the river section according to geomorphological law already implemented in QSWAT. This approach can induce error in systems where the hydrological network is highly altered by human activity or in the case of artificial channels.

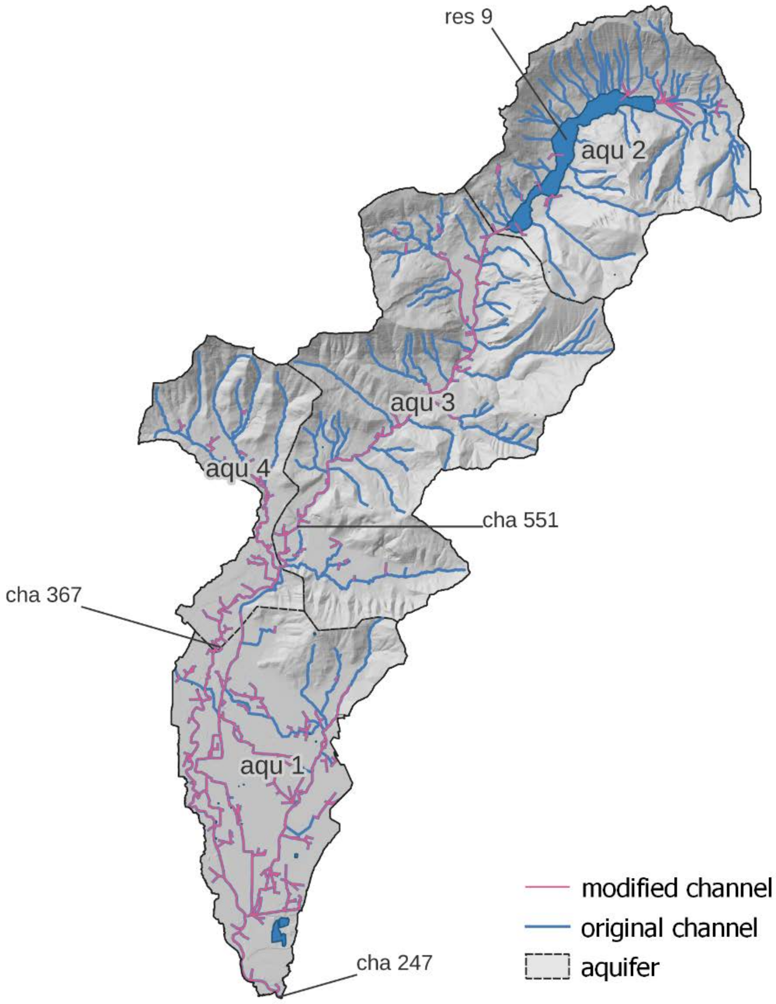


Figure A9.4 Aquifer subdivision and channel correction (original = obtained by SWATbuildr, modified = manually edited).

*Hydrological soft calibration*

Hydrological soft calibration started from the analysis of the discharges at the outlet of the Endine Lake, where daily time series from 2006 to 2020 are available but with a 37% of missing values, concentrated mainly in the last years, with intermittent functioning that suggests poor data quality. Under this condition, the analysis of the baseflow was performed for the period 2010-2015 in order to determine the target values for WYR and BFR (Chiaradia et al., 2023). Base flow was evaluated by applying the method of Boughton (1993) implemented in the grwat R package (Samsonov et al., 2022). The resulting WYR and BFR were 0.63 and 0.66 respectively.

Hydrological soft calibration follows the procedure described in White et al. (2022). The process primarily targeted the "perco" parameter, governing percolation from the root zone to recharge the deep aquifer, and "cn3_swf," defining the soil water factor for CN3. After some repetitions, the soft calibration process returns the satisfying values for WYR and BFR, respectively 0.55 and 0.65. Although the calibration successfully reduced superficial flow, it failed to improve daily flow representation (NSE < 0), warranting further investigation.

## 2.3. Crop yield soft calibration

Crop soft calibration was successfully carried out for CS9. As indicated by the OPTAIN crop soft calibration workflow, the days_mat parameter was adjusted first, to allow all the simulated crops to accumulate the correct PHU fraction at harvest/kill (Tab. 9.4).

Silage corn is harvested at 0.75 PHU, prior to the grain reaching physiological maturity. Soybean is harvested at full pod maturity, corresponding to PHU values ranging from 1.0 to 1.2. Ryegrass is harvested right after stem-elongation which occurs roughly halfway through the plant maturation cycle. For multi-harvest crops (alfalfa and polyculture lawn) a 0.5 - 0.6 PHU range was considered appropriate, corresponding to the beginning of the flowering stage. Following this step, crop parameters were fine-tuned, resulting in the model's capability to generate simulated yields that closely match observed values. Winter wheat simulated yield is slightly underestimated due to its challenge in accumulating the necessary heat units to reach the appropriate phenological stage of grain maturation (Fig. A9.5).

Table A9.4 Crop parameters variations for target PHU fraction and yields calibration (* Absolute change ** Relative change).

| Crop | d_mat* | lai_pot** | harv_idx** | tmp_base* | bm_e** |
|---|---|---|---|---|---|
| csil160 (silage corn 160) | -50 | 0.2 | +0.03 | 0 | -0.74 |
| csil120 (silage corn 120) | -10 | 0 | +0.03 | 0 | -0.74 |
| soyb (Soybean 1st harv.) | 0 | 0 | 0 | 0 | 0 |
| soyb2 (Soybean 2nd harv.) | 0 | 0 | 0 | 0 | 0 |
| ryeg (ryegrass) | -55 | 0 | 0 | -5 | 0 |
| wwht (silage winter wheat / barley) | -105 | 0 | +0.4 | 0 | 1.5 |
| alfa (alfalfa) | +80 | 0 | 0 | -10 | 0 |

| | | | | | |
|---|---|---|---|---|---|
| hay (polyphite meadow) | +80 | 0 | 0 | -6 | -0.57 |
| hayd (dry polyphite meadow) | +95 | 0 | 0 | -6 | -0.28 |

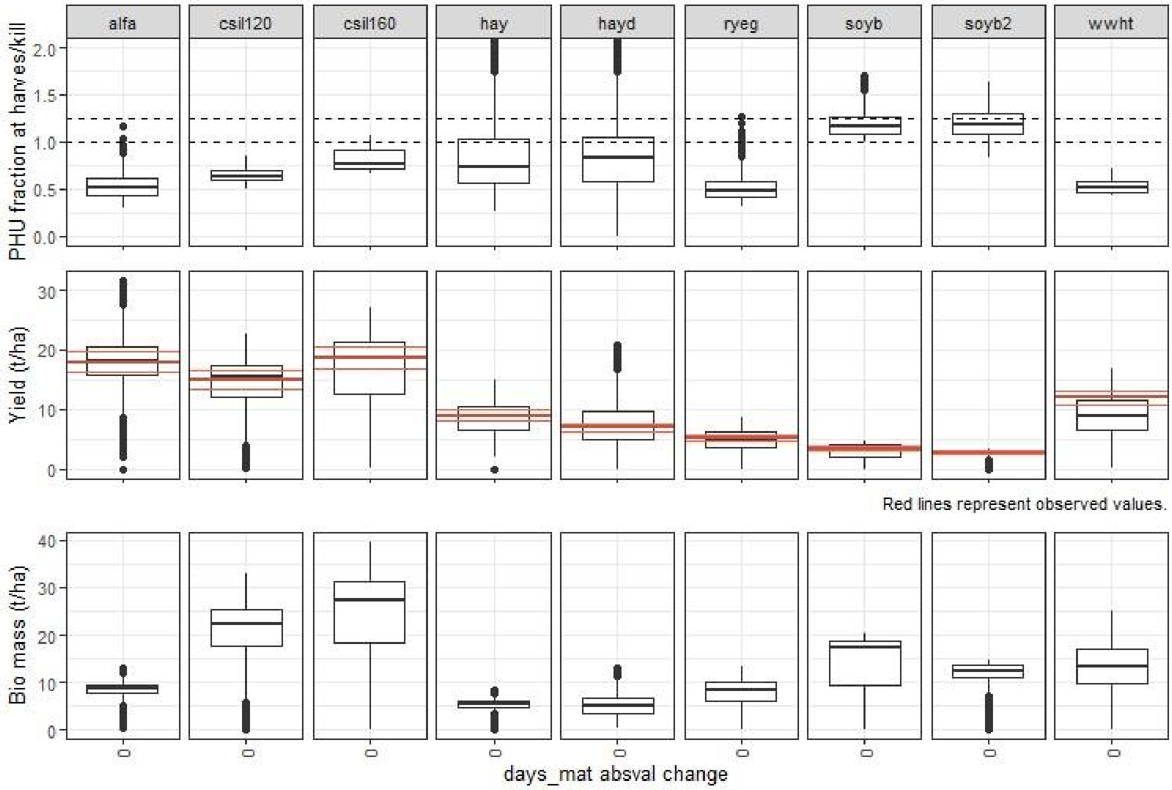


Figure A9.5 Final results of crop yield soft calibration for CS9. Simulated PHU fraction at harvest/kill (top row), crop yields expressed in dry matter (middle row) and biomass (bottom row). Red lines define target crop yield used for calibration.

## 2.4. Hard calibration and validation

Manual hard calibration was performed considering the Casazza station (see par 2.1) in order to better represent the aspects related to the release from the Endine Lake. In particular, the release rule defined by the decision table was created to represent the reservoir outflows during raining events. Secondly, base flow from the reservoir was manually calibrated adjusting the contribution of the aquifer and in particular the release time parameter “alpha_bf”. After these changes, the model performed a better representation of the flows (NSE > 0.75) and the calibrated parameters were applied to the whole basin.

Following, the automatic hard calibration procedure from the OPTAIN protocol was performed considering the stream gauge at Carobbio. Compared to Casazza station, used for soft and manual calibration, the watershed upstream of Carobbio is larger and the available time series is longer and more complete during the simulated period. On the other hand, the quality of measured data is lower, in particular at low flows, because of the presence of a natural movable bed (the gauge itself is actually used for flood risk alert and not for discharge measurements). Discharges were also corrected in order to consider the withdrawals for irrigation purposes just upstream of the Carobbio gauge. Finally, the time series was divided into two periods: one for calibration (2007-2012) and the other for validation (2013-2016).

Tab. A9.5 reports the final setup used to run the calibration. The calibration ranges are the results of repeated processes that were conducted in order to identify the most meaningful parameters. Figure A9.6 shows the effect of each parameter on the NSE value. Awc, cn2 and surlag are the most influential parameters. Lower values of Awc show better performance, while both cn2 and surlag seem to be underestimated in the model setup. Tab. A9.5 also reports the ranges and the best calibration set for comparison.

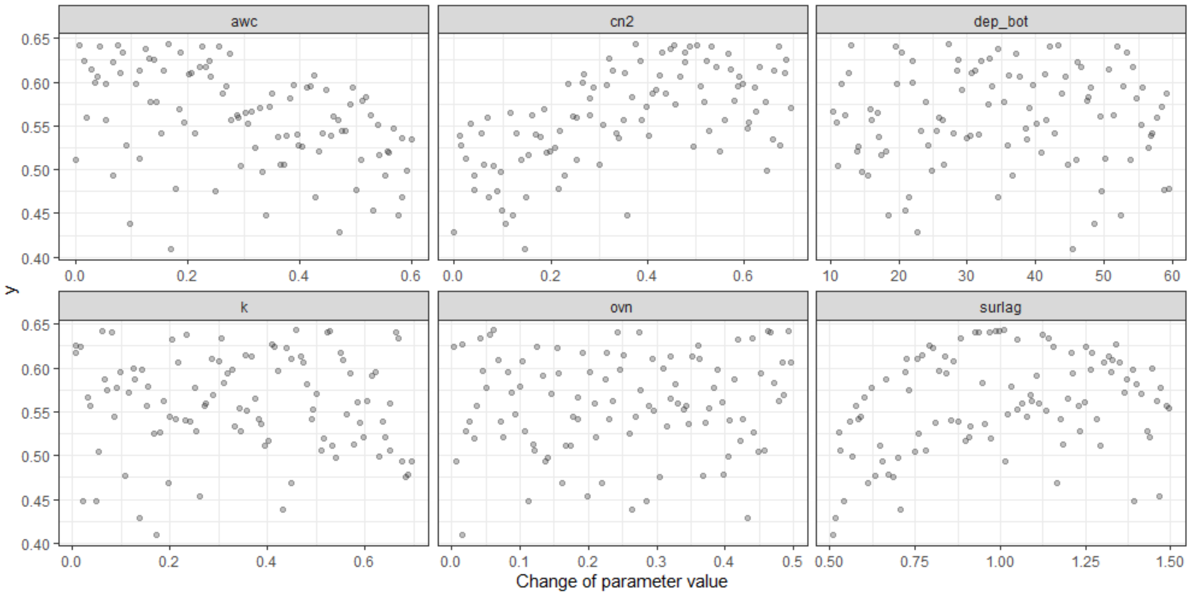


Figure A9.6 Parameters effects on NSE values.

Table A9.5 Parameter used in hard calibration workflow.

| Parameter | Change | Min | Max | Best calibration |
|---|---|---|---|---|
| awc.sol | Relchg | 0.0 | 0.6 | 0.166 |
| cn2.hru | Relchg | 0.0 | 0.70 | 0.376 |
| dep_bot.aqu | Absval | 10 | 60 | 27.212 |
| k.sol | Relchg | 0.0 | 0.7 | 0.458 |
| ovn.hru | Relchg | 0.0 | 0.5 | 0.376 |
| surlag.bsn | Absval | 0.5 | 1.5 | 1.009 |

A total of 14 parameter sets were isolated considering all the simulations that returned NSE > 0.6, KGE > 0.7 and PBIAS < 15. Calibration and validation results are reported in Fig. A9.7. Although the objective function returned lower values in case of KGE and NSE and higher for PBIAS, the validation can be considered sufficient considering the peculiarities of the case study (i.e. quick flood response to precipitation, flooding time less than the day, low values of base flows, etc.).

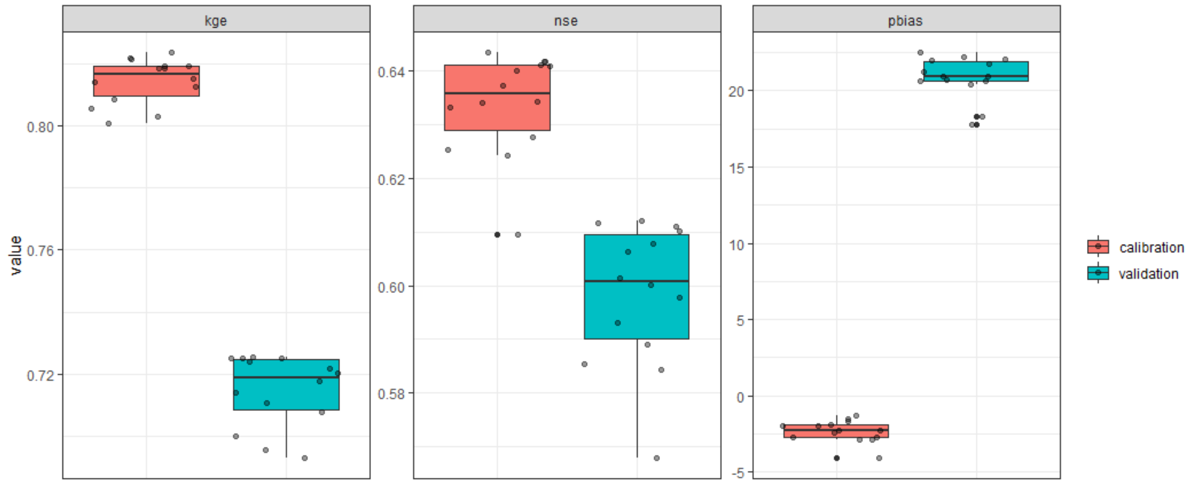


Figure A9.7 comparison between calibration and validation at Carobbio d/A.

Fig. A9.8 also shows the ability of the model to predict high flows at Carobbio. In order to consider the capacity of the model to estimate the water availability for irrigation purposes, best simulation outputs were compared to the measured flows at the upstream of the diversion at Trescore station (Fig. A9.9a). It is important to note that observations at Trescore are not continuous for the simulation period and, on the contrary, are spotted and rare in time. For this reason, they are not considered in the calibration approach but are useful for extra validation in a river section different from those used for calibration and helpful in predicting water availability for agriculture.

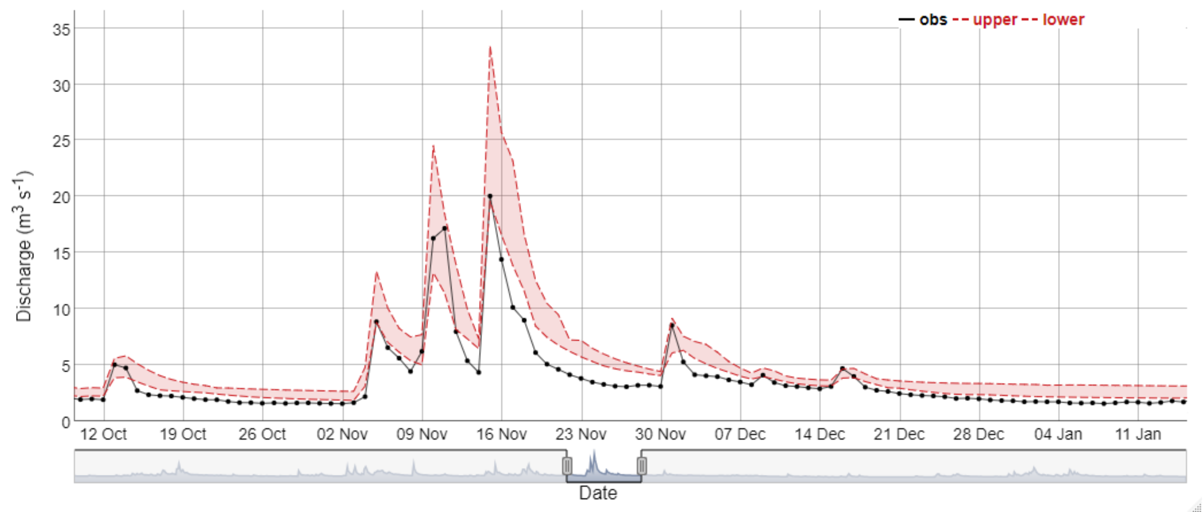


Figure A9.8 Comparison between observed and simulated discharge for the extreme event in 2014 (highest peak flow recorded in the simulation period at Carobbio).

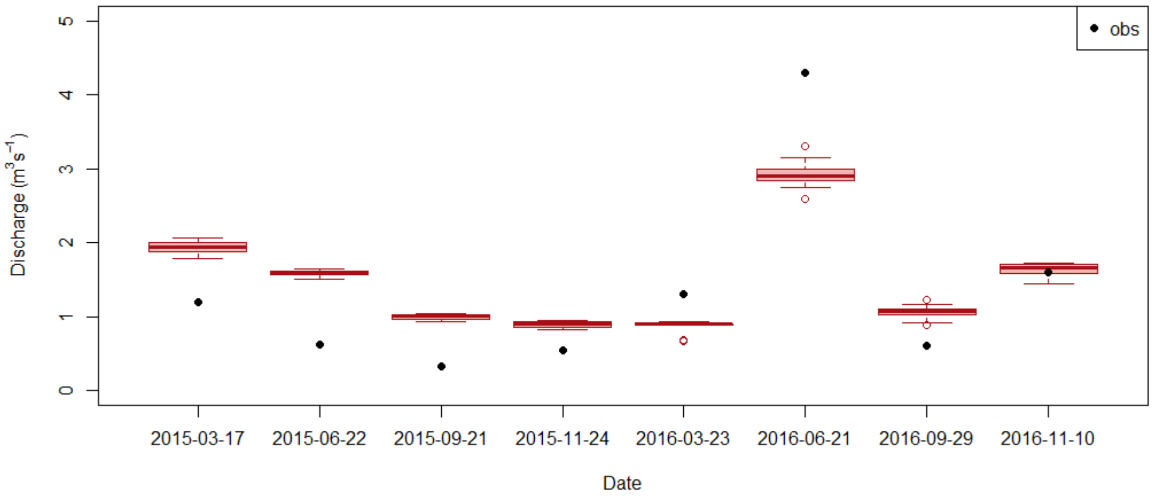


Figure A9.9 comparison between observed and simulated discharge for a section upstream the Bolgare Channel diversion (note that dates are not continuous).

## 3. Climate change effects

In order to assess the effect of climate change on the water balance, nutrient losses and crop yields, the bias-corrected RCM simulations developed in the WP3 of OPTAIN (Honzak, 2023) were used as the SWAT+ model forcing.

Figure A9.10 shows projected changes in annual and seasonal minimum (Tmin) and maximum (Tmax) temperature as well as precipitation (Prec) for CS9 for 3 periods (2011-2040, 2041-2070 and 2071-2100). Apparently, RCP2.6 doesn't show meaningful changes in the average values while RCP4.5 and RCP8.5 scenarios show that temperatures will increase from 1 to 3 degrees over the considered period (2011-2100). The highest temperature increase occurs in summer and autumn, while the lowest in winter and spring. Furthermore, projections show that average annual precipitation will increase in RCP2.6 while the seasonal distribution of the volumes will concentrate in winter and spring. In RCP4.5, the average annual precipitation increases in the nearest period only. In the long-term period, although the difference is negligible, the precipitation will concentrate in winter. In the RCP8.5 scenario, the average annual precipitation will decrease. In particular, summer will experience the greatest reduction. Finally, the modification of the other variables (i.e. wind speed, solar radiation and relative humidity) are relatively low and partly correlated with temperature and precipitation.

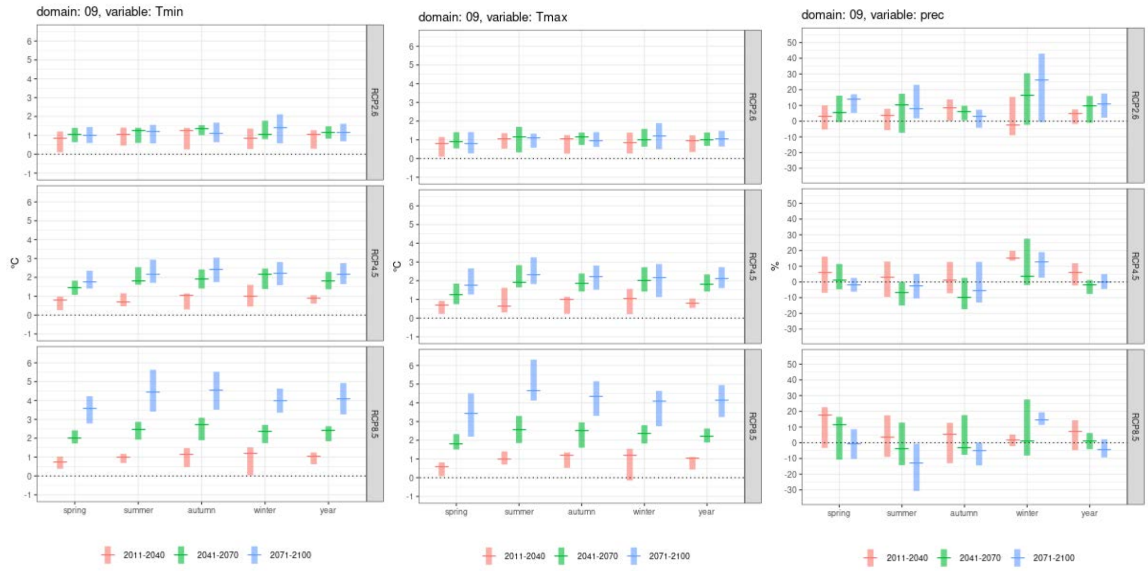


Figure A9.10 Projected changes in variables Tmin, Tmax and Prec for all RCPs and time horizons for CS9 (Honzak, 2023).

All available combinations of 6 RCMs, 3 RCPs and 3 time horizons (1988-2020 - serving as the “baseline”, 2033-2065 - “near future”, 2066-2098 - “end of century”) were applied resulting in a total of 54 model scenarios. More information about climate scenarios can be found in Honzak (2023).

The first climate change scenario impact evaluation concerns water balance components, which are shown in Figure A9.11. The increase of precipitation amount projected in RCP26 positively affects the annual average soil water content. However, throughout cropping season months, this trend is not consistently maintained: only the central months exhibit a slight increase (never above 5%), while May shows no significant change and September demonstrates a decrease. The other two scenarios, despite manifesting different behaviors depending on the future horizon, both predict a decrease in precipitation, translating in a steadily lower SW throughout the cropping season: peaks are observable in August and September, with 10% reductions for RCP45 and 20 to 25% reductions for RCP85. Moreover, in contrast to RCP26, both channel superficial runoff and lateral flow are expected to decrease in RCP45 and RCP86, accurately reflecting the anticipated reduction in precipitation. The three scenarios manifest common trends in physical processes that are conditioned by the projected temperature increase: snowfall and snowmelt are negatively affected, meanwhile PET and ET are expected to increase. Snow-related processes are projected to undergo the most substantial reduction in percentage, reaching up to 75% reduction in the case of RCP86. However, even within the context of RCP26, which is characterized by temperature variations of less than one degree, there is a 20% reduction in snowfall deposition. These slight temperature changes are less impactful relatively to PET and ET, but 2.5% increases for both are still noticeable.

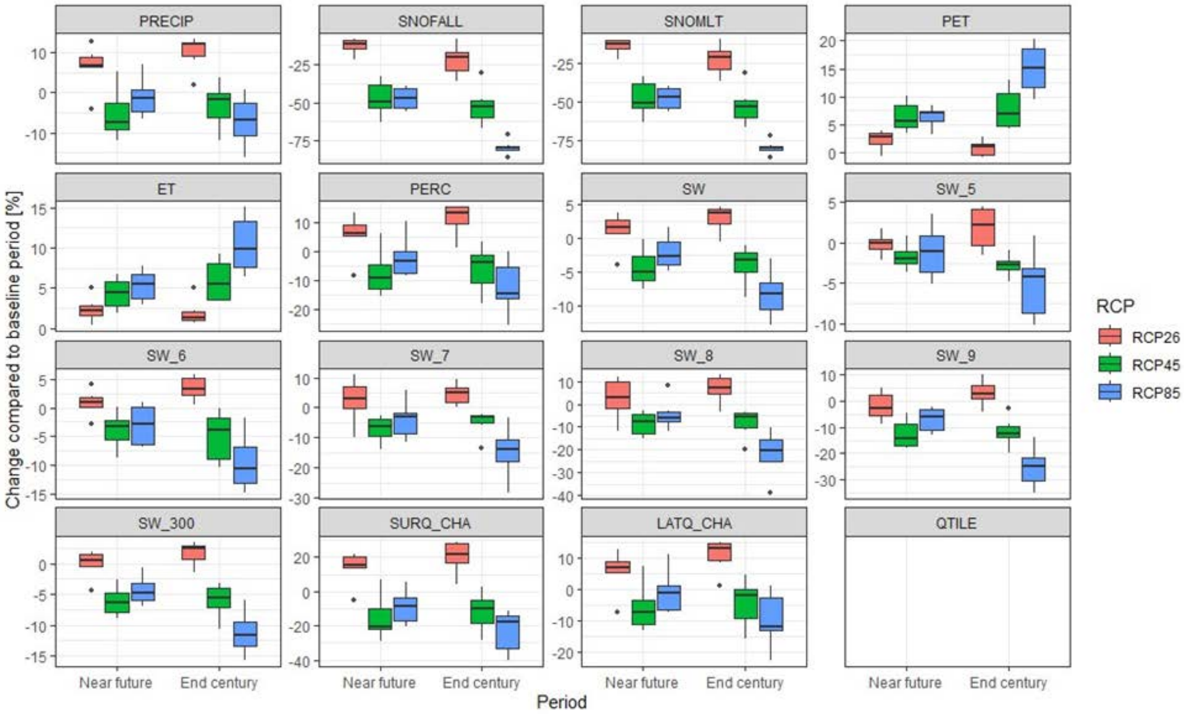


Figure A9.11 Projected changes in selected basin-averaged water balance components simulated by SWAT+ for CS9.

Secondly, the impact on flow amounts and distributions was evaluated (Fig. A9.12). Under RCP26, in harmony with the precipitation trends, flows are expected to increase, meanwhile under RCP45 and RCP85 they are projected to decrease. These patterns are closely mirrored by variations in the percentages of high flows and low flows. For both future horizons, under RCP26, more severe and frequent flooding events might occur, but environmental flow during drought spells might be more constantly maintained. Contrarily, RCP45 and RCP85 entail lower high flows, potentially preventing the occurrence of floods, but the projected reduction of low flows might exacerbate drought events. In any case, it is worth considering that the model uses daily time step data that might not completely represent the actual flow processes that in case of small catchment and steep slopes can be concentrated (i.e. flood duration is 2-3 hrs) and are not correctly represented by the model.

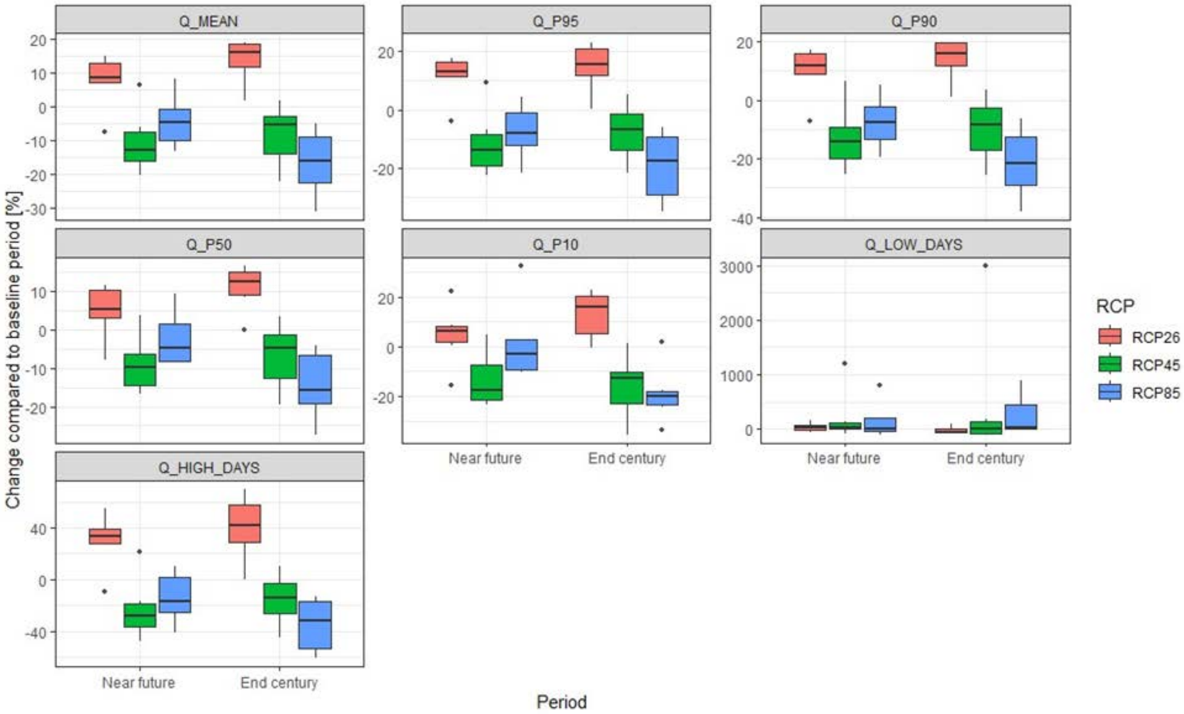


Figure A9.12 Projected changes in selected streamflow indicators simulated by SWAT+ for CS4.

The last boxplots collection (Fig. A9.13) shows CS9 projected crop yields. Under RCP45 and RCP85, an overall increased crop production is expected. The reason for this positive trend might be related to irrigation being implemented in all the summer and perennial crops management, regardless of the actual available water within the basin, which is expected to be lower. In these scenarios, in a simulated condition of absence of water stress, the other climatic variables, such as temperature and radiation, would then favor plants metabolism. Another reason that could justify the great yield increment occurring mainly in the cases of hay and ryegrass (more than 100 and 60% respectively) might be related to the calibration process. The base temperature and optimal temperature parameters have been assigned values that allowed the model output to properly match the observed yields during the status-quo climate period. However, these values may lead to overestimated yields if the input temperature values were to be increased. The only yield decreases are observed under RCP26, in the case of summer crops (soybean and maize), winter wheat, and alfalfa (end of century time horizon only). An explanation could be an increased aeration stress due to more abundant rainfall during the most vulnerable phenological stages. Further investigation regarding the precise stress factor hindering plant growth could be carried out through the workflow proposed by the SWATDoctR for any specific climate scenario.

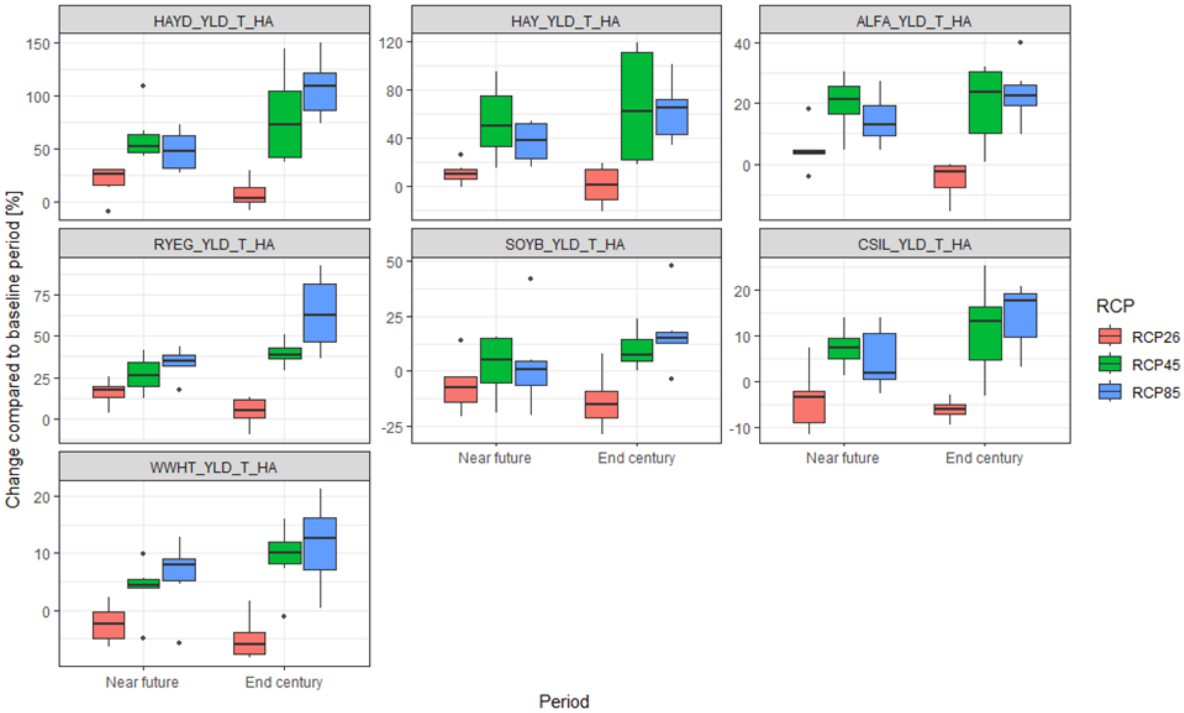


Figure A9.13 Projected changes in selected crop yields simulated by SWAT+ for CS9.

# 4. Effectiveness of selected NSWRMs (current climate)

## Measures selection and implementation

The following NSWRMs were selected for CS9 and implemented in the SWAT+ model: 1. Riparian buffers (buffer), 2. Drought-resistant plants (droughtplt), 3. Terracing (terrace), 4. Channel restoration (constr_wetland), 5. Retention/detention ponds (pond).

Fig. A9.14 shows an overview of the position of the selected measures. Riparian buffers are widely distributed along both natural and artificial channel networks; drought-resistant plants are located in different parts of the basin, also in marginal areas in order to represent an extreme scenario where fields in the North of the basin are cropped. Terraces are located mainly in the valleys while channel restoration mainly affects the main reaches. Finally, detention ponds are located mainly in the South and along the Cherio River where urban lands are concentrated.

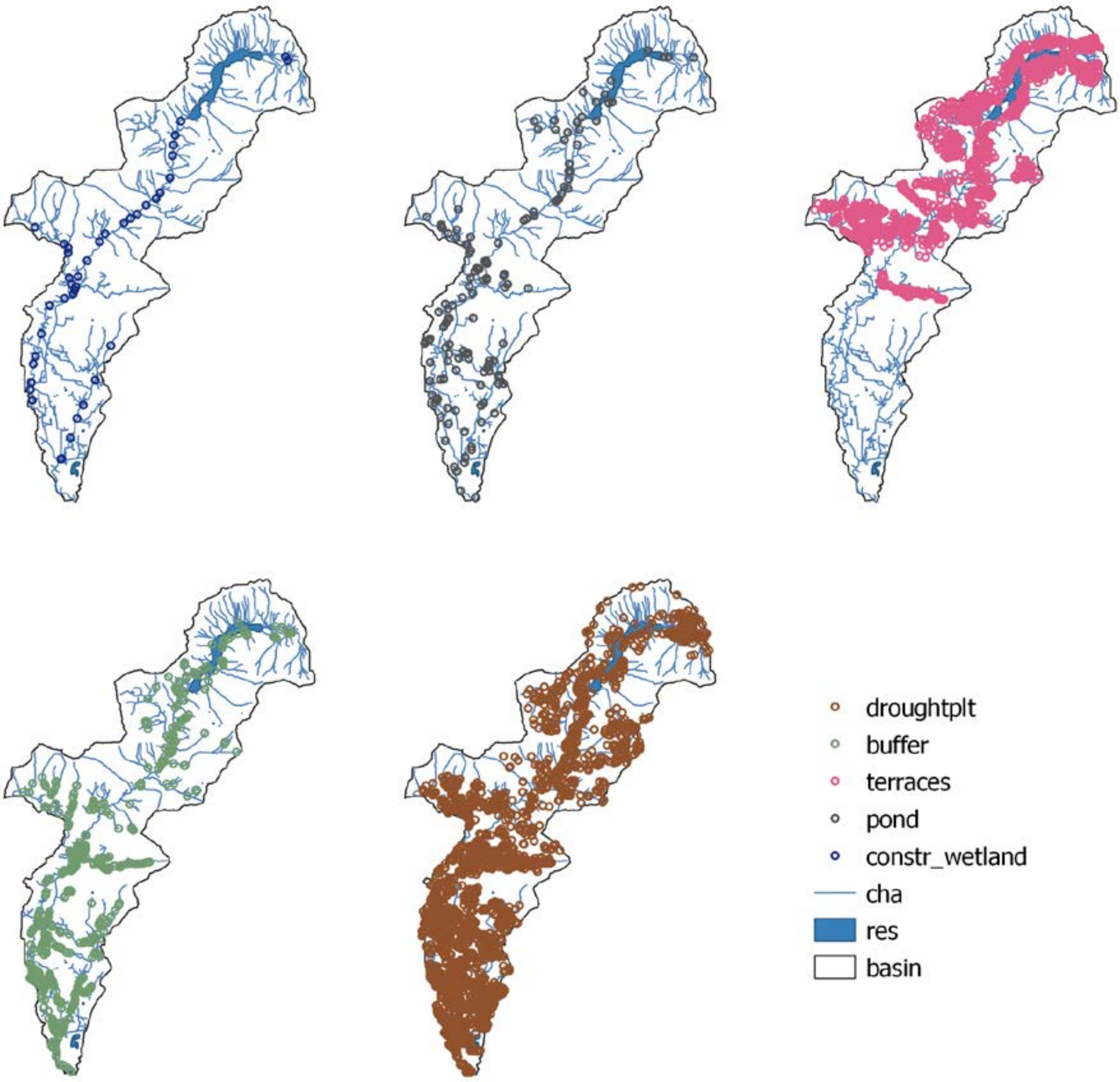


Figure A9.14 Location of the implemented measure (res = SWAT+ reservoir object, cha = SWAT+ channel object).

### Riparian buffers

Riparian buffers are areas of land maintained with permanent vegetation, mainly consisting of bushes, along channels networks. The position of riparian buffers was selected considering the network of both the natural and the rural channels, keeping a distance of 8 m from the top channel bank, if visible from aerial images, or a 10 m width as minimum if only the channel path was available. Only arable land was considered eligible for conversion into riparian buffers, so permanent meadow, woodland, natural vegetation and urbanized areas were excluded. For the sake of simulation, riparian buffers are modeled as range vegetation land use ("rnge" in SWAT+ default dataset).

Drought-resistant plants

Due to the increasing number of water scarcity events occurring during summer, the CS9 management scenario focuses on the insertion of drought resistant plants within the existing crop rotation scheme. As a crop with high water requirements, silage corn was completely substituted with silage sorghum. The choice of the latter is imputable to its broad spectrum of physiological features and responses to modulate its water status, facilitating adaptation to environmental conditions, such as root morphology, rooting depth and leaf cuticle thickness. Moreover, in the North of the basin where more rain availability is expected, for those polyphite lawn pastural areas whose orography allowed, (not too steep or hard to reach) a mustard/ crop rotation was implemented. The SWATmeasR script allows the user not only to replace the status -quo land use type with NSWRMS, but also to redefine their management according to the above-mentioned strategy.

Terracing

Terracing entails the alteration of natural slopes by the construction of dry-stone walls or other artificial embankments used to decrease the gradient of mountainous terrain, thereby enabling or enhancing agricultural activities. Many CS9 upstream areas were terraced in the past, but they were subsequently abandoned and replaced mainly by woodland. The current land management framework provides the possibility for their recovery in specific areas. From a modeling point of view, terraces are implemented with a unique land use configuration: orchard-like management and plant community, row crops in good conditions, contour tillage with 1-2% slopes and medium forest-like cover.

Channel restoration

With the term of channel restoration, we considered an ensemble of actions able to reintegrate natural features into river networks (e.g. bed modification and bank revegetation). Typically, a restored channel is characterized by greater hydraulic roughness than the artificialized one, due to the presence of obstacles and bed shape irregularities. At the moment, the measures-concerning section of the OPTAIN protocol, doesn't consider the possibility to change the Manning's coefficient related to the channel resistance. Then, in order to represent the flow capacity reduction determined by an increase of the total hydraulic resistances of the restored channel section, the "constructed wetland" option was implemented, and a specific release rule was created in order to reproduce the reduction in flow capacity (Fig. A9.15).

```
name                 conds    alts     acts
riverrest              2        3        3
var                    obj   obj_num        lim_var        lim_op    lim_const                    alt1 alt2  alt3
res_inflo              res        0            null        null        1.00                          <    >=    -
res_inflo              res        0            null        null        5.00                          -    <     >=
act_typ                obj   obj_num           name        option       const       const2          fp  outcome
release                res        0     low_flo_cond        days     2.44000      0.00000         evol  y    n     n
release                res        0     med_flo_cond        days     1.80000      0.00000         evol  n    y     n
release                res        0     high_flo_cond       days     1.16000      0.10000         evol  n    n     y
```

Figure A9.15 Release decision table for "river restoration" reservoir object (constructed wetland in OPTAIN measures implementation protocol).

In the release table "riverrest", 3 flow conditions were implemented: low flows ("low_flo_cond") when incoming discharge is less than 1 $m^3s^{-1}$, medium flows ("med_flo_cond") when discharge ranges between 1 and 5 $m^3s^{-1}$ and high flows ("high_flo_cond") when discharge is higher than 5 $m^3s^{-1}$.

The effects of the river restoration on the hydraulic processes are highly variable because they depend on different aspects, such as the intensity of the flow, the geometry of the channel, the type of cover and the extension of the restoration project among others. This leads to an extreme difficulty in the determination of the actual effect on the hydraulic aspects (Sholtes et al., 2011), particularly when a simplified modeling approach is adopted.

Despite the above-mentioned limitations, a preliminary hypothetical solution was formulated based on literature review, technical reports and expert knowledge. In particular, the number of days of the release rule, defined by the "const" variable (see Fig. A9.15), was differently configured, depending on the flow conditions: at low flows, it was estimated that the restored channel Manning's roughness coefficient increased from 0.05 to to 0.15 (see Cowan's method in Coon, 1998), causing a 60% reduction of the section hydraulic capacity. At higher flows, the effect of river restoration decreases and it was estimated that the reduction consisted in about 10% of the peak flow (Liu et al., 2004, Sholtes et al., 2011). The effect of a single channel restoration measure on the flow release is shown in Fig. A9.16: peak discharges decrease immediately and part of the flow volume is released in the following days.

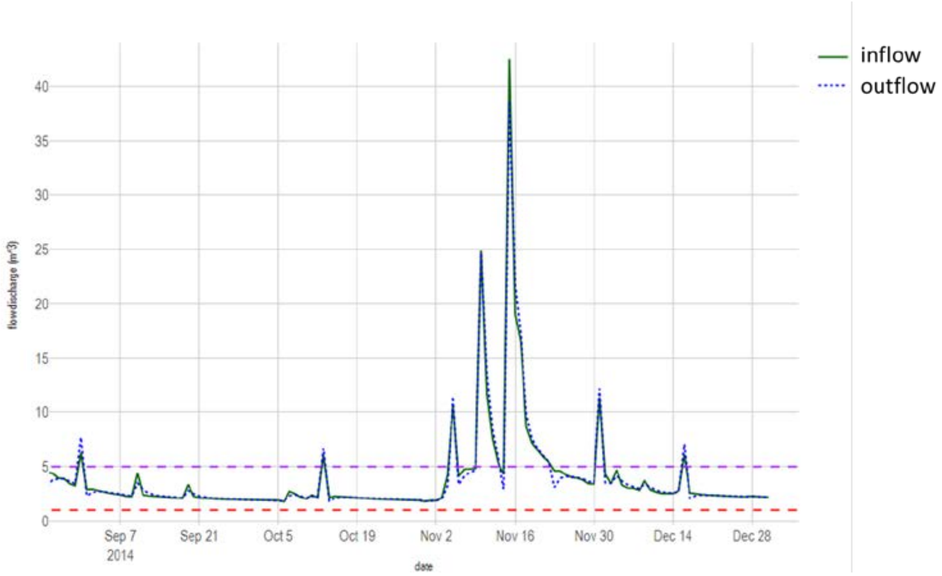


Figure A9.16 Effect of a single "river restoration" reservoir considering the upstream flow (inflow) and the discharges that are released by the restored reach (outflow).

### Retention/detention ponds

A retention/detention pond is a constructed depression that receives and stores stormwater runoff from urban drainage areas. Typically, retention ponds hold a certain amount of permanent water, while detention ponds return to an empty state after a few hours from the flooding event. In CS9, the only measure prescribed for implementation by the current regional regulations is the construction of detention ponds. From a modeling point of view, detention ponds are represented by reservoir objects connected to the existing channel network. The dimension of each pond is calculated considering an uniform precipitation of 10 yrs return period, and a limited outflow from the basin of 40 l/s for each impermeable hectare of drained area. The pond volume is evaluated considering the duration of the precipitation events (from 1 minute to 24 hours) that returns the maximum value. Then, the area necessary to implement the measure was calculated considering a maximum water depth of 1 m. Detention ponds must be emptied within 48 hrs. To replicate this behavior, a specific release table was developed (Fig. A9.17) in which, if the available volume ("vol") is lower than the emergency volume ("evol"), the flow is released over 2 days ("def_48h"), otherwise ("over_emercency") the flow is totally released within one day.

```
name                    conds      alts      acts
release_48h                 1         2         2
var                       obj   obj_num            lim_var        lim_op    lim_const       alt1       alt2
vol                       res         0               evol             *      1.00000          <         >=
act_typ                   obj   obj_num               name        option        const     const2                  fp  outcome
release                   res         0            def_48h          days      2.00000    0.00000                evol  y    n
release                   res         0    over_emergency          days      1.00000    0.10000                evol  n    y
```

Fig. A9.17 Release decision table for "detention pond" reservoir.

### Scenario results

Scenario results are presented as percentage variations relative to the status quo scenario. Indicators are categorized into “Hydrology”, “Nutrients and sediments” and “Crop yields”. In the subsequent sections, hydrology and crop yields indicators are presented in more detail.

### Hydrology results

Hydrological indicators consider both discharges and soil water content. In particular, discharges are evaluated at the channel section immediately upstream the rural canal diversion (Bolgare SG in Fig. A9.1). The reference discharge for minimum flow was set to the minimum environmental flow equal to 0.3 $m^3s^{-1}$.

Although the mean discharge did not change significantly from the status quo in all implemented scenarios, the distribution of discharges indicates a higher flows reduction and a lower flow increase. The main contribution to this trend is primarily attributable to river restoration measures, and secondly to detention ponds. Terraces, instead, seem to negatively affect both higher and lower flows. Moreover, the introduction of drought resistant crops, negatively affects the minimum flow. When considering the combined effects on both low and high flows, the difference between extreme values is reduced by measures implementation, particularly through river restoration actions.

At the hru level, encompassing the entire basin, both average soil water content (sw_*) and percolation (perc) decrease, in particular in drought resistance plant scenario (“droughplt” in Fig. A9.18). The reason could be found in the reduction of the amount of water used for crop irrigation. Notably, the reduction is more pronounced during the summer season (sw_7, sw_8, sw_9).

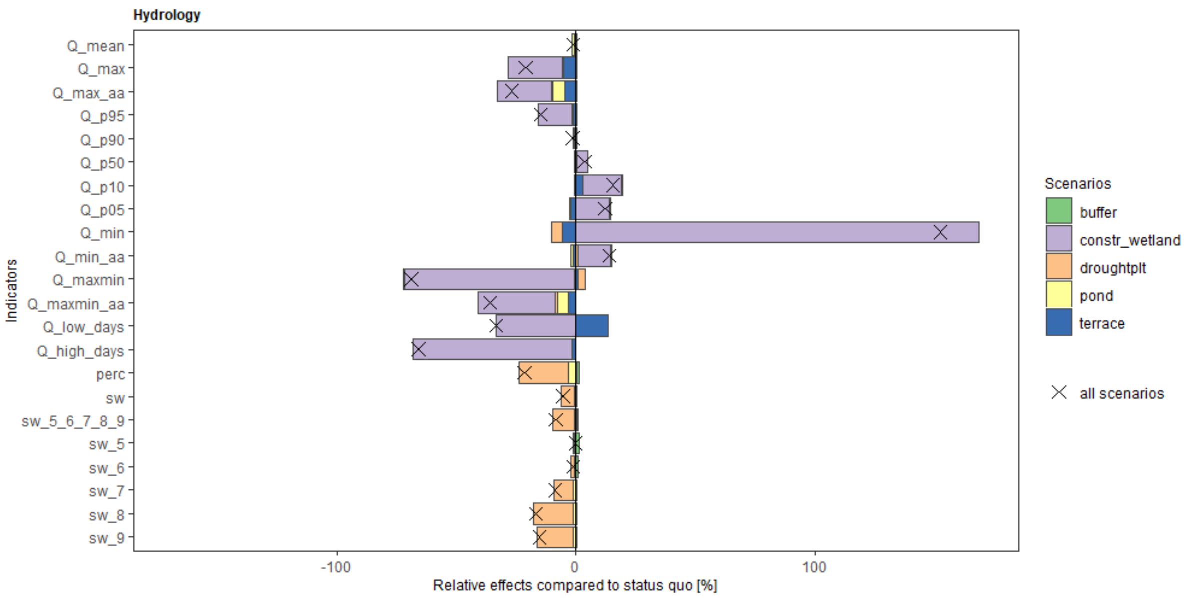


Fig. A9.18 Hydrological indicators for CS9.

### Crop yields results

Crop yields indicators pertain to the entire basin and the results are shown in Fig. A9.19. Overall, crop production (expressed by the grain_units_aa indicator) decreases in most of the scenarios. The reasons vary depending on the type of measure implemented: in case of riparian buffers and detention ponds, the reduction stems from the decrease in surface area while, in case of drought resistant plants, it is related to sorghum being less productive than corn. Terraces contribute to the reduction because part of the polyphit lawns are converted to orchards (which are not considered in the budget). Similar explanations are also applicable to the case of total crop area (crop_ha_aa) except for droughtplt scenario, where the reduction in lawns harvested multiple times throughout the year influences the indicator. Regarding specific crops extension, sorghum (grsg in Fig. A9.19) is not shown due to inability to calculate the indicators, since in the status quo the reference values are null (actually, sorghum is little or not at all widespread). All crop extensions are reduced by measures, except for "terrace" in relation to alfalfa (alfa_ha). Silage corn (csil) undergoes the greatest reduction because it is totally replaced by sorghum in the droughtplt scenario. The general increase in crop yields per hectare indicates that the measures affect the least productive areas.

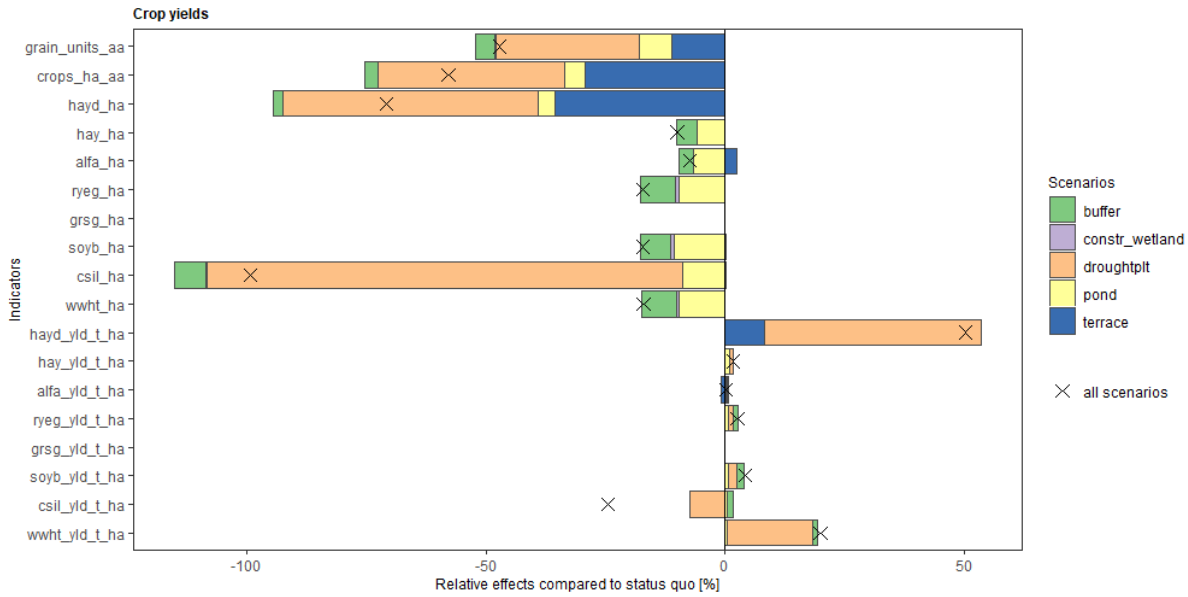


Fig. A9.19 Crop yields indicators for CS9.

## 5. Conclusion

The application of the SWAT+ model and the OPTAIN protocol in particular, has proven to be a useful tool for the analysis of hydrologically complex systems such as the one presented in the current case study.

The analysis of climate scenarios revealed the actual weather condition potential alteration due to temperature increase and the redistribution of precipitation over the year. The reduction in snowmelt and percolation fluxes in particular, are the main factors that could compromise water availability in the next future.

This perspective highlights the necessity of testing the effectiveness of water retention measures in the case study and, once again, the OPTAIN modeling framework proved to be a useful tool.

From a hydrological standpoint, river restoration actions appear to be the most impactful measure. Since they didn't affect crop lands, there is no impact on farmers' activity compared to other measures that actively reduce the amount of available crop land. However, it should be noted that despite the reduction in cropland, specific crop yields have increased, indicating that, in scenarios, mainly marginal lands were converted. Additionally, the conversion of land into terraces would likely result in greater income, thanks to the cultivation of profitable crops (e.g. vineyards, olive trees, etc.), accounted for in the economic analysis (the subject of subsequent steps).

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# Annex 10 Modelling results for CS10 (Kråkstadelva, NO)

Authors: Csilla Farkas, Moritz Shore (NIBIO)

## 1. Model setup

The OPTAIN workflow (Schürz et al., 2022) was used to set up the SWAT+ model for the Kråkstad catchment (CS10). Most input data were processed applying the SWATprepR package (versions 0.1.0 (svatools) and 1.0.3 at different stages of the work). The uncalibrated model setup was developed using the R script for the model setup generation workflow (https://git.ufz.de/optain/wp4-integrated-assessment/swat/swat-setup/full_workflow) consisting of both SWATbuildR (version 1.5.1) and SWATfarmR (version 3.1). The SWAT+ model revision 61.0 (from 1/12/2024) was used in all simulations.

### 1.1. Input data overview

The type and the source of the input data is described in Table A10.1. Figure A10.1 demonstrates the GIS layers processed by SWATbuildR.

Table A10.1 Summary of input data for CS10

| Input | Number of objects / resolution | Source | Comments |
|---|---|---|---|
| DEM | 10 m | The Norwegian Mapping Authority (karverket.no) | https://hoydedata.no/ |
| Channel layer | 416 | Norwegian Water and Energy Directorate (NVE) | Catchment boundaries and stream network https://nevina.nve.no/ |
| Land layer | 1947 | Norwegian Institute of Bioeconomy Research (NIBIO) | AR50 Land cover data, Scale: 1:50000 Land layer was modified by implementing the agricultural fields and to account for potential NSWRMs planned for scenario simulations. |
| Soil layer | 839 | Norwegian Institute of Bioeconomy Research (NIBIO) and Geological Survey | Raw vector layer of soil types for agricultural areas (Jordsmonn, NIBIO) and soil forming materials, derived from the geological map of Norway (Løsmasser, NGU) for the forested areas. The combined layers were later processed in SWATprepR |

| | | | |
|---|---|---|---|
| | | of Norway (NGU) | |
| Usersoil table | 94 | Norwegian Institute of Bioeconomy Research (NIBIO) | Basic soil properties (texture, organic matter content) were derived from NIBIO soil database (Jordsmonn, NIBIO) and own measurements in the forested areas; soil particle size data harmonized using the script by Nemes (2022); soil properties were derived using pedotransfer functions developed for Norwegian soils (Riley, 1996); organic soil parameters and HSG groups derived by soil experts. |
| Point sources | 215<br>(5 WWTPs) | NIBIO database on point sources | WEBGIS Avløp ; access to part of the data was achieved with the permission of the relevant municipalities. There are 6 WWTPs in the catchment area, while the rest 119 point sources are associated with scattered dwellings. |
| Weather data | 121 stations | Norwegian Meteorological Institute (MET) | MetNordic Re-analyses data (Lussana et al., 2023), available from 2013. The data were retrieved and processed using Miljøtools, developed within OPTAIN and SWAprepR. |
| Atmospheric deposition | 1 | European Monitoring and Evaluation Programme (EMEP) | EMEP data processed by SWATprepR |
| Crop sequence map | 1947 | Ministry of Agricultural register on subsidies received by the farmers for implementing various measures | As the LUCAS database is not available for Norway, the crop sequence map was derived from the “subsidy database”. Autumn cereals were assumed for areas that were not included in the database. As the database had poor spatial references, an R-script was developed to distribute the crop types among the fields following the typical crop sequences for the area. |
| Management schedules | 12 | Norwegian Agricultural Environmental Monitoring Programme (JOVA) | Schedules were derived using information available for the Skuterudbekken catchment, which is located in the neighbourhood of the pilot catchment. The JOVA database contains field-level detailed information for Skuterud on management and crop rotations for 30 years. |

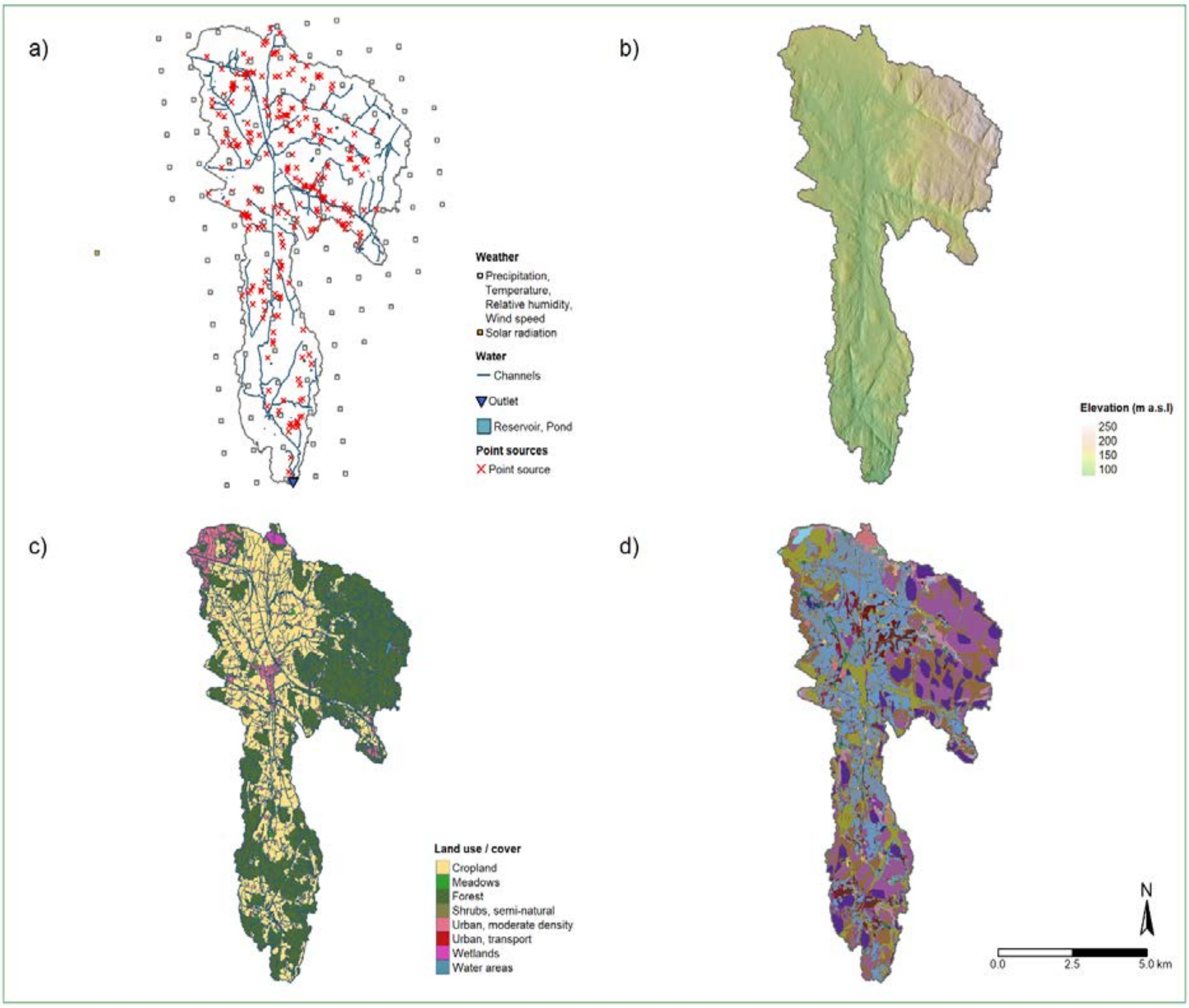


Figure A10.1 GIS input data for CS10: a) water quality sampling station at the catchment outlet, MetNordic virtual meteorological stations, point source locations, reaches and catchment boundary; b) DEM map; c) land use map, classes defined as in AR50 land cover database and d) soil type map.

## 1.2. Baseline model setup

For the baseline model setup, recommendations given in the OPTAIN SWAT+ modelling protocol were followed. Table 10.2 incorporates the main model setup features.

Table A10.2 Summary of the model setup features.

| Parameter | Value |
|---|---|
| Total area of the watershed in ha | 4976 |
| Total number of spatial objects in the simulation | 13128 |
| Number of HRUs in the simulation | 6206 |
| Number of routing units in the simulation | 6206 |
| Number of aquifers in the simulation | 1 |
| Number of reservoirs in the simulation | 58 |
| Number of recalls (point sources/inlets) in the simulation | 26 |
| Number of SWAT-DEG channels in the simulation | 416 |
| Number of crops in rotation | 5 |
| Number of wetlands | 13 |

## 2. Model evaluation

Table A10.3 presents observation data for variables used in soft calibration (crop yields, water yield ratio) and hard calibration (discharge and TN concentrations). The crop yield statistics were taken from the JOVA database. Yields reported by farmers between 2010 and 2020 for each field of the monitored Skuterudbekken, situated at the northwestern boundary of Kråkstadelva river basin were used as reference values during the calibration procedure.

Discharge data in CS10 are problematic, as no flow gauge is being operated directly at the catchment outlet. Thus, data from a gauge operated by the Norwegian Water and Energy Directorate (NVE) at Høgfoss, located approx. 10 km downstream from the catchment outlet were downscaled and used for model calibration. The downscaling was performed using a simple area-proportional approach. Data on total nitrogen (TN) and total phosphorus (TP) concentrations are available from NVE at the outlet of the Kråkstad catchment.

Table A10.3 Summary of observation data used in different steps of the calibration workflow for CS10

| Variable | Time step | Calibration period | Validation period | Source | Comments |
|---|---|---|---|---|---|
| Soft calibration | | | | | |
| Crop yields | Average annual | 2015-2020 | NA | JOVA database | Data taken from a reference catchment located at the NW border of Kråkstadelva for years 2010-2020 |
| Water yield ratio | Average annual | 2015-2020 | NA | Model input (pcp) and discharge data | Calculated using data between 2010-2020 |
| PET, transpira-tion, evapora-tion | Average annual | 2015-2020 | NA | WATER JPI IRIDA project FINAL report | Reference water balance element values were collected for the study area using air-born measurements, literature review and mathematical models. |
| Hard calibration | | | | | |
| Discharge | Daily | 2014-2015 | 2016-2017 | Norwegian Water Directorate | https://sildre.nve.no/ |
| Water quality (TN & TP concentrations) | Every 2nd week | 2014-2015 | 2016-2017 | Norwegian Water Directorate | https://sildre.nve.no/ |

## 2.1. Model setup verification

The verification of the model setup was performed in accordance with the OPTAIN workflow (Plunge et al., 2023), using the SWATdoctR package. The first steps of the model verification included the evaluation of the basin-level water balance elements, which highlighted that the transpiration values were underestimated by the original model setup. The EPCO (plant water uptake compensatory factor) parameter values were changed and differentiated between land use categories to solve this problem. During the calibration procedure the land use-specific differentiation of EPCO was kept (e.g. only relative changes were defined).

After slight adjustments, verification of the climate and water balance data (Fig. A10.3) showed that the simulated water balance elements are in plausible ranges according to expert knowledge of the studied catchment (Table A10.3).

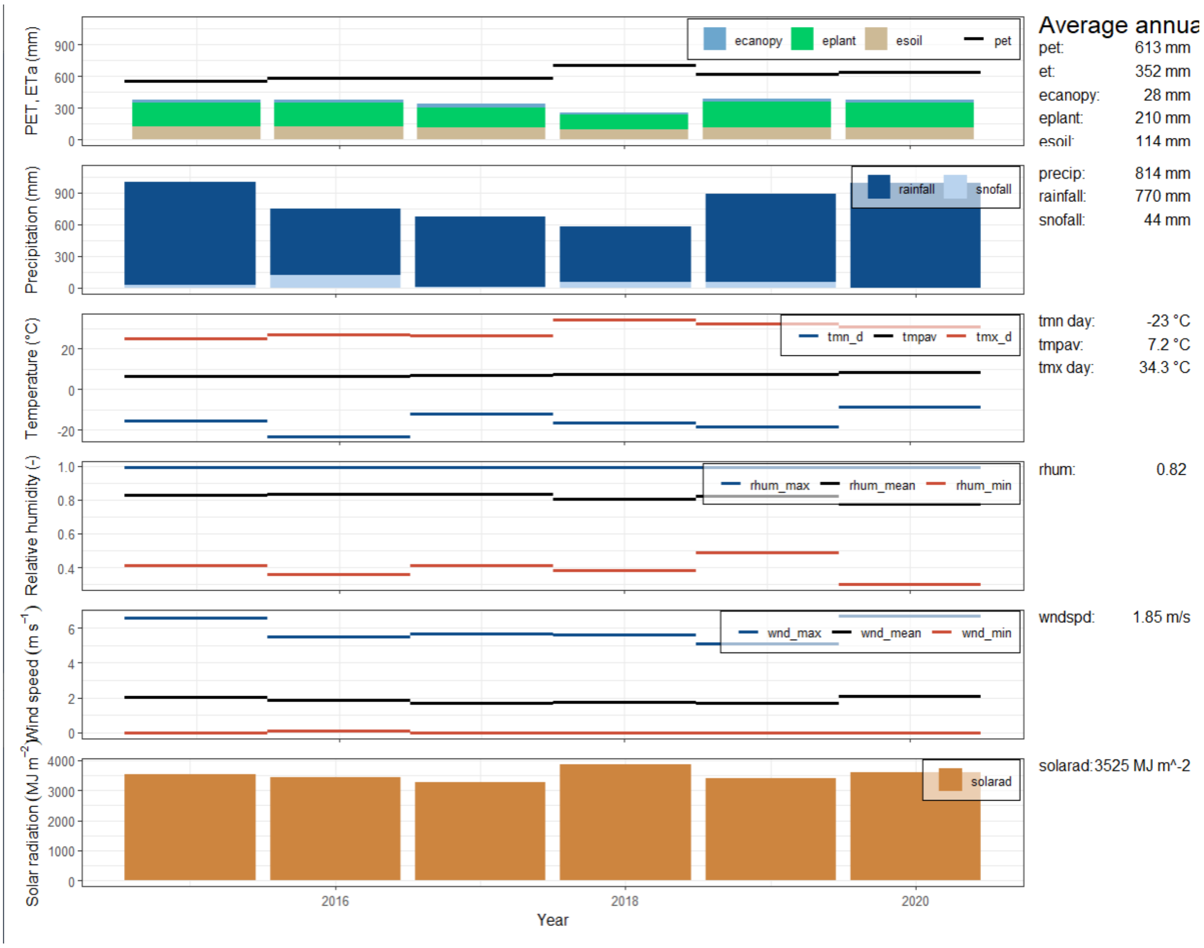


Figure A10.3 Summary of the climate data checks for CS10 by the SWATdoctR.

The comparison of how different stress factors affect crop yields of an uncalibrated model also showed plausible results, i.e. reductions of crop yields within reasonable ranges (Fig. A10.4). The simulated yields were still lower than the measured ones. The yields were calibrated at a later stage, during the soft-calibration using the SoftCal R-script (Fig. A10.6)

Analysis of biomass and LAI development (example shown in Fig. A10.5) showed acceptable behaviour (inconsistencies appearing at earlier stages were related to the SWAT+ executables, and were later fixed).

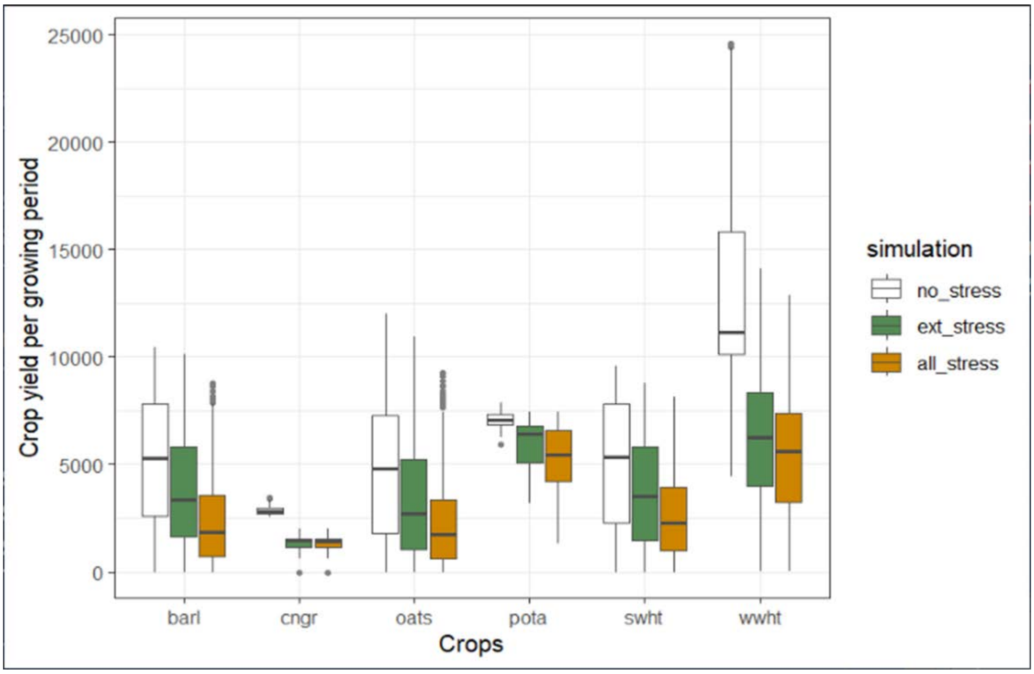


Figure A10.4 Comparison of crop yields with all stress factors, external stress factors and no stress factors for CS10.

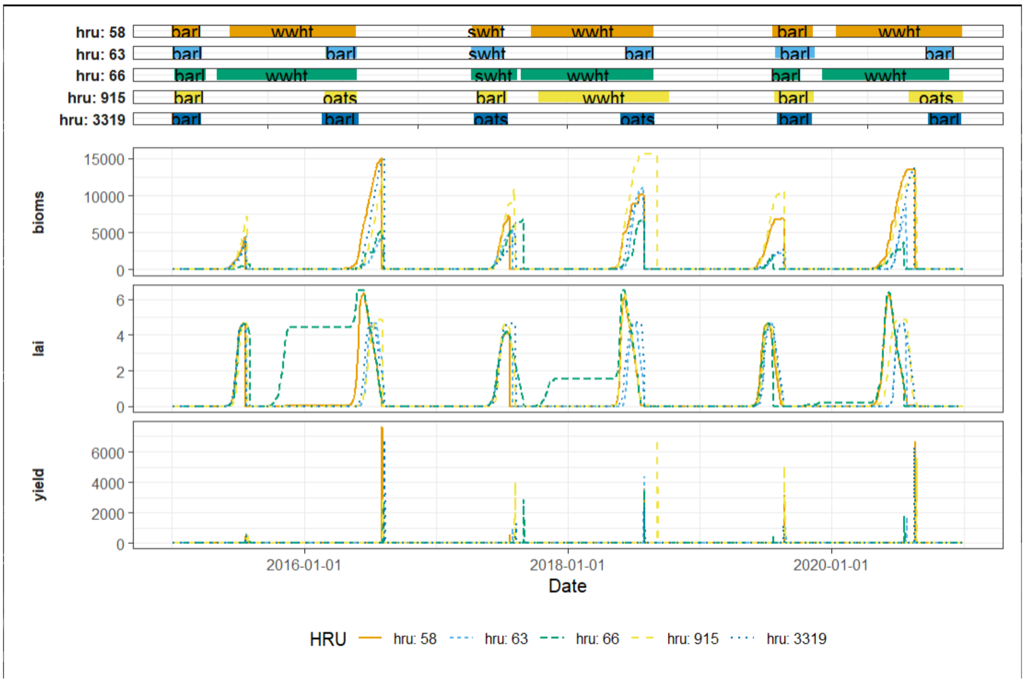


Figure A10.5 Biomass, LAI development and yields for a simulation with all stress factors active for five example HRUs in CS10.

## 2.2. Soft calibration

Results of soft calibration for crop yield in CS10 are given in Figure A10.6. The calculated heat units and yields fall into expected and measured ranges, respectively. This indicates that the crop yield soft calibration workflow was successfully applied for the Kråkstad catchment.

During the soft-calibration, the d_mat (days to maturity) parameter was adjusted first by altering it in such a way that the accumulated PHU fraction at harvest/kill would be within the predefined range of 1.0-1.2. The highest changes in days to maturity parameter affected potato and winter wheat (see Table A10.4).

In the second step, seven plant parameters were adjusted individually for each crop to achieve satisfactory crop yield calibration results. For the majority of crops, the average observed and simulated yields match reasonably well; the simulated yields fall in the measured range with a slight overestimation of the average yield for oats and swht and underestimation for wwht (Fig. 10.6).

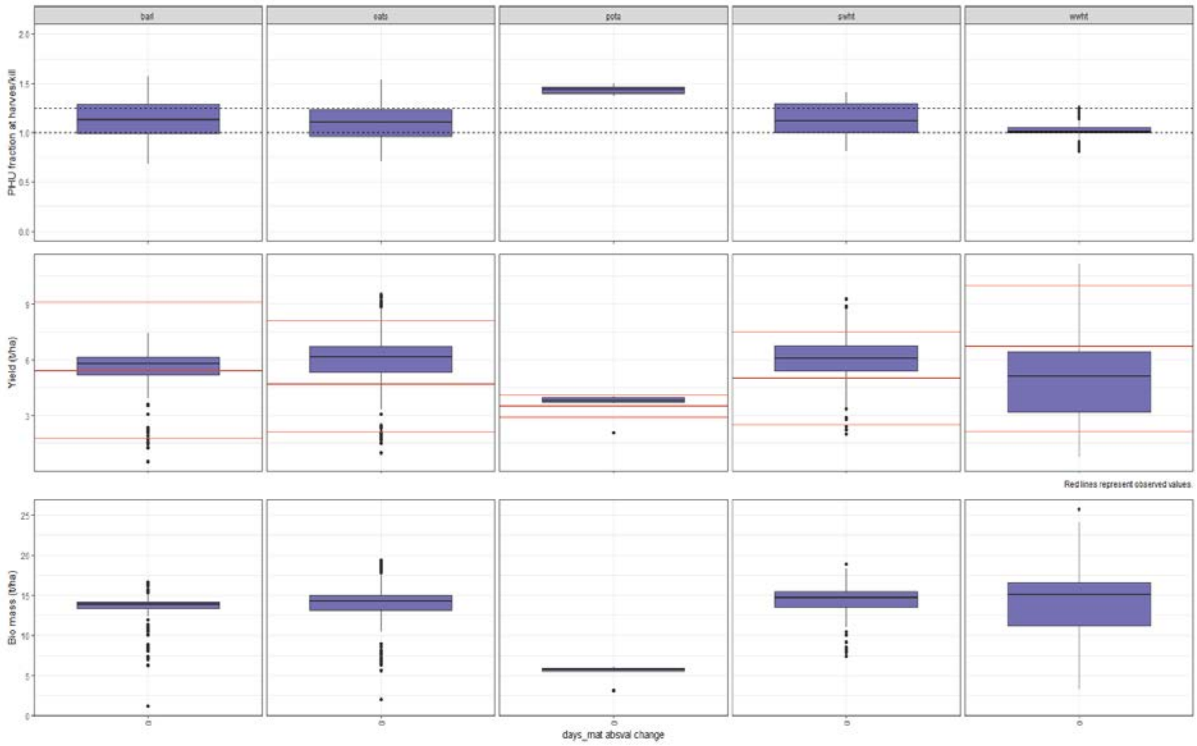


Figure A10.6 Final results of crop yield soft calibration for CS10. Simulated PHU fraction of harvest/kill (top row), crop yields (middle row) and biomass (bottom row). Red lines stand for measured values.

Table A10.4 Crop parameters variations for target PHU fraction and yields calibration (* Absolute change ** Relative change).

| parameter | Crops | | | | |
|---|---|---|---|---|---|
| | barl | oats | pota | swht | wwht |
| | spring barley | spring oats | potato | spring wheat | winter wheat |
| d_mat* | -10 | -5 | +50 | +5 | -40 |
| lai_pot** | 0.20 | 0.25 | -0.12 | 0.10 | 0.63 |
| harv_idx* | 0.11 | 0.18 | -0.20 | 0.16 | 0.29 |
| bm_e** | 0.00 | 0.11 | -0.17 | -0.09 | 0.00 |
| frac_hu1* | -0.03 | -0.03 | 0.00 | 0.00 | -0.25 |
| tmp_base* | 0.0 | 0.0 | -4.4 | 0.0 | 0.0 |
| tmp_opt* | -8.0 | -0.5 | -2.0 | -1.0 | 7.0 |

Water balance soft calibration enabled matching the observed water yield ratio of 0.56 for the 2010-2020 time period by adjusting the value of ESCO parameter to 0.1. The range kept for hard calibration was (0.05, 0.2). Crop yield simulation results did not change significantly after adjusting the ESCO parameter.

## 2.3. Hard calibration and validation

In CS10 the major concern about water quality is related to soil erosion and P release, causing eutrophication of the surface freshwaters. In the last few years, however, the attention has shifted to nitrogen loads towards marine ecosystems, due to the bad condition of the Oslofjord. As nitrogen is moving with water and its concentration normally correlates well with water discharge, we performed a simultaneous calibration of hydrology and nitrogen parameters of the model, using water discharge and measured total nitrogen (TOT-N) concentrations as reference data. Water samples for detecting TOT-N concentration are taken approximately two times per month. Sampling is suspended during the winter period. This also means that the amount of TOT-N concentration data used for model calibration and validation is rather limited and does not capture the peaks.

The selected parameters consisted of 21 hydrological (including 3 tile drain related) and 6 nitrogen parameters. Five objective functions were evaluated for each observed variable: NSE, KGE, PBIAS, R2 and MAE. In the final ranking of parameter sets equal weights (0.5 and 0.5) were applied for discharge and TOT-N concentrations. In each consecutive iteration the parameter space was modified in order to improve the performance metrics, trying to account for possible conflicts between responses of different metrics to parameter changes. The ranges of most of the parameters were considerably narrowed down based on interpretation of the dotty plots. The final selection included twenty different parameter combinations and was based on the sum of ranks for different metrics and variables. Out of the 20 parameter sets, the best 10 were used further for - climate change and measure implementation - scenario analyses. Time series plots shown in Figs. A10.7-A10.8 represent model output variability resulting from these twenty parameter sets.

The discharge at the outlet of the Kråkstad catchment has a huge variability. The overall dynamics, the baseflow and the discharge during the low flow periods were captured quite well, however, the SWAT+ model failed to simulate the high peaks (Fig. A10.7). The reason for that could be the relatively small size and high flashiness of the catchment. The model is executed in daily timestep, whilst the response of this relatively small catchment to heavy rainfall events can happen in a shorter time period. Figure A10.9 demonstrates the performance metrics of discharge for the calibration and validation periods. The daily and monthly (not shown) performance metrics indicate satisfactory and good calibration of water discharge, respectively.

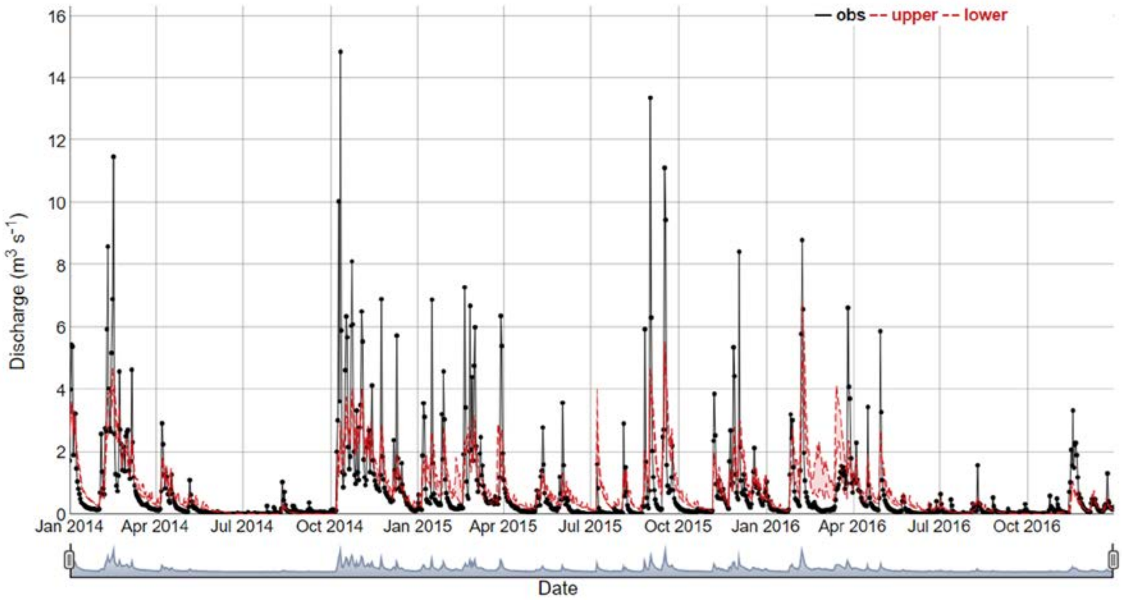


Figure A10.7 Simulated vs. downscaled observed daily discharge for the Kråkstad catchment outlet in CS10 (calibration period).

The nutrient boundaries reported by the different European countries with their 2nd River Basin Management Plans (RBMPs) raised a concern in the EC/EEA and ECOSTAT about the compatibility of these boundaries with good ecological status for sensitive biological quality elements (BQEs) (Kelly et al. 2021). That is why the good/moderate (G/M) boundaries for different Nordic lowland river types have recently been revised within the frames of the Nordbalt-Ecosafe project (Table 1., Solheim et al., 2023). Based on this factsheet and expert evaluation (personal communication with Dr. Eva Skarbøvik, NIBIO), the G/M boundaries for the clay-type Kråkstad River for total nitrogen (TOT-N) and total phosphorus (TOT-P) were identified as 775 ug/l and TP 60 ug/l, respectively.

Considering the above given TOT-N boundaries, the Kråkstad River is heavily polluted by nutrients (Fig. A10.8), as the measured values never go below 900 ug/l. The model performance for TOT-N concentrations was very good and poor for the calibration and validation periods, respectively (Fig. A10.10). The reason for poor validation results could be data scarcity. At first, water quality measurements have low frequency in the pilot sites. Thus, only 23 data records fall in the calibration period. Water quality information for the calibration period was probably not enough for parameterising the nitrogen-related parameter values so that they would fully represent the overall conditions in the sense of nitrogen transport and storage for longer periods. The absence of precise information on nitrogen fertilisation timing and amounts, as well as on point sources could also contribute to poor model validation results.

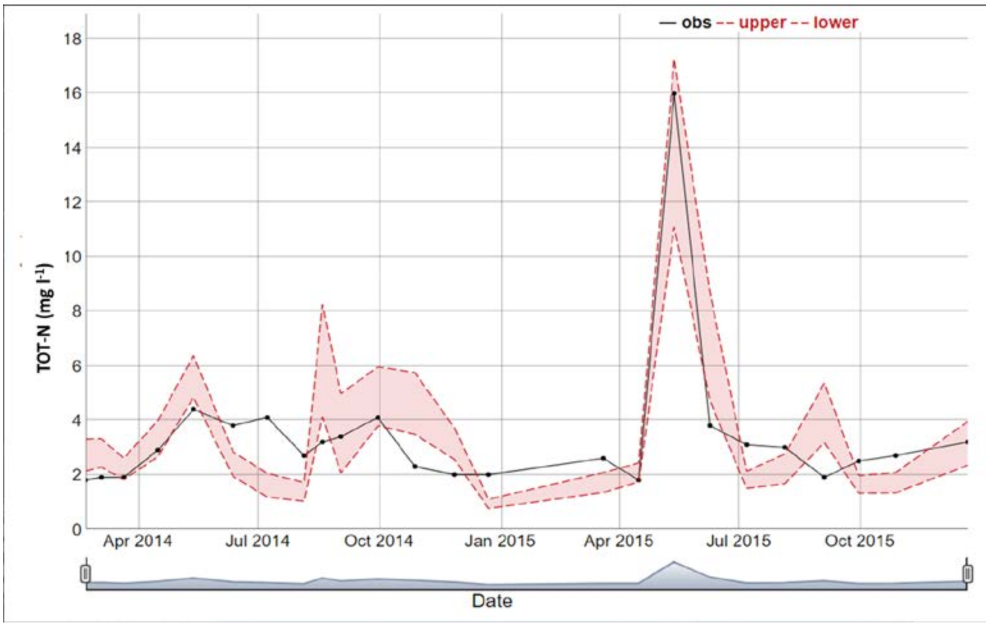


Figure A10.8 Simulated vs. observed daily TOT-N concentrations at the outlet of the Kråkstad catchment (CS10, calibration period).

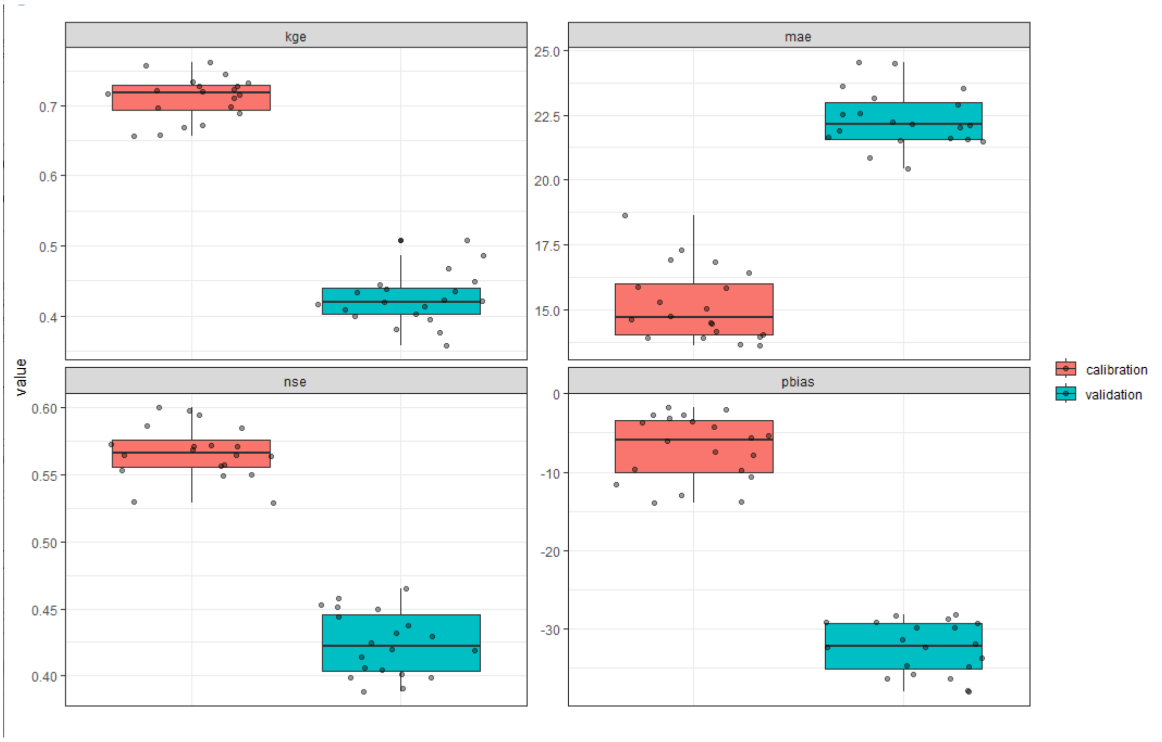


Figure A10.9 Box plots of model performance metrics for discharge in calibration and validation periods for CS10.

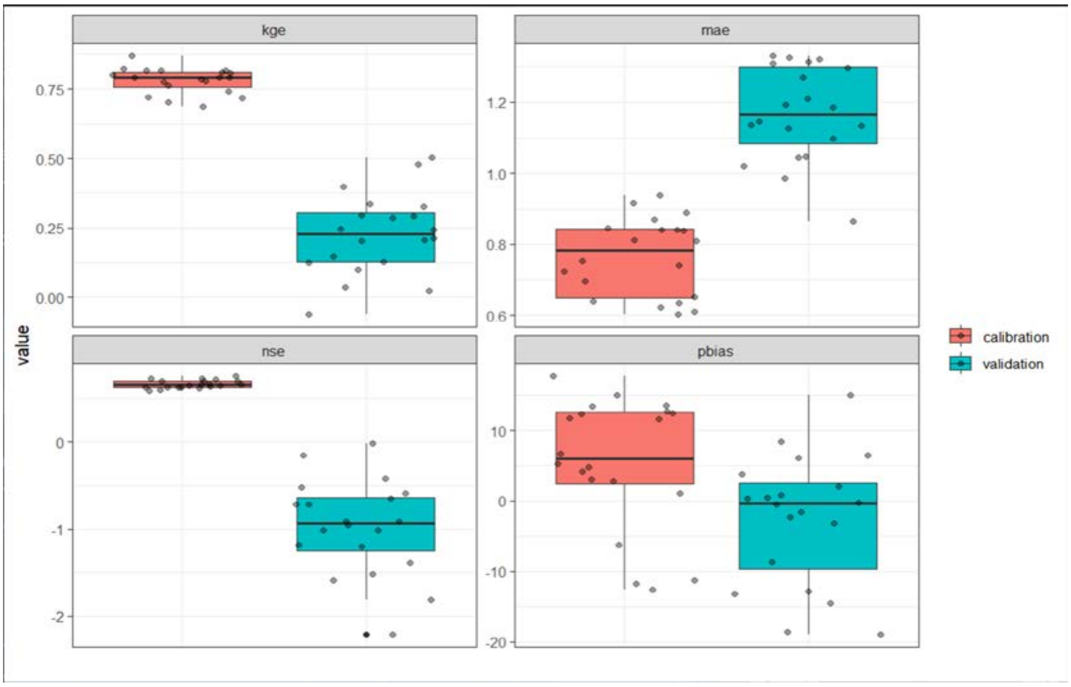


Figure A10.10 Box plots of model performance metrics for TOT-N concentrations in calibration and validation periods for CS10.

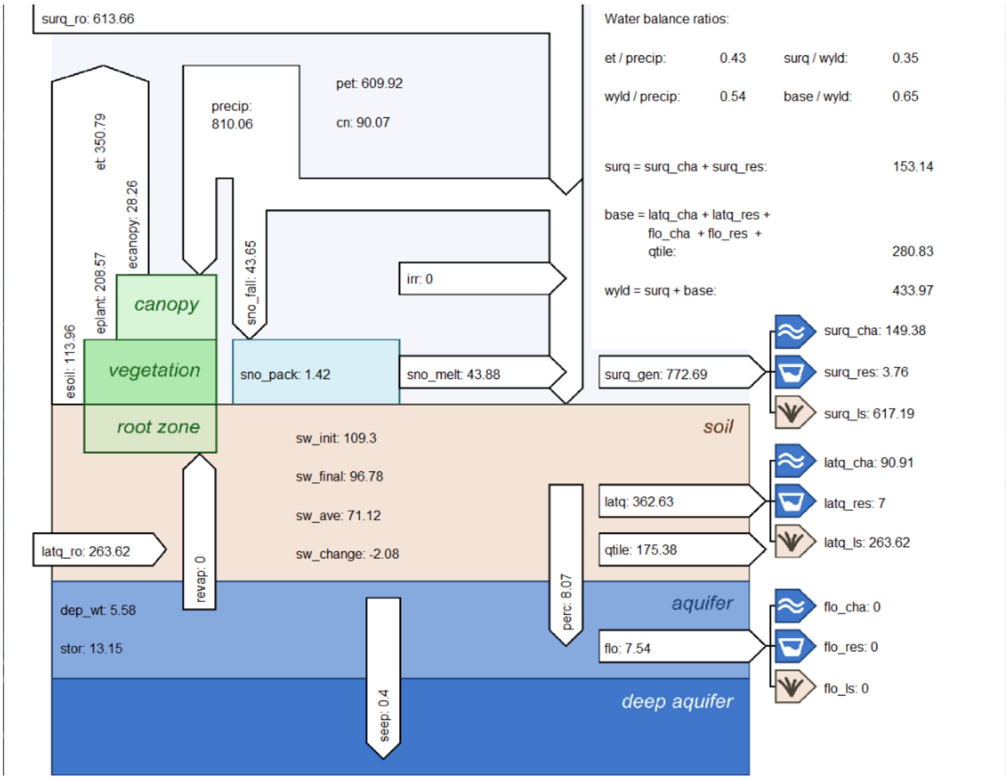


Figure A10.11 Simulated water budget of the final, calibrated model setup for CS10 (years 2015-2020).

Simulated water budget of the final version of the calibrated model setup (based on a single parameter set with the highest sum of ranks) for the 2015-2020 period is shown in Fig. A4.11. The observed water yield ratio was 0.55 on average, which corresponds well to the simulated value of 0.54. Thus, a bit more than 50% of the total precipitation contributes to surface runoff. Plant component of evapotranspiration constitutes approx. 60 % of the total ET.

## 3. Climate change effects

For evaluating the effect of climate change on selected indicators the bias-corrected RCM simulations developed in the WP3 of OPTAIN (Honzak, 2023) were used within the SWAT+ model as driving variables. The indicators consisted of water balance elements, hydrological, water quality and crop yield metrics. We applied all available combinations of six RCMs, three RCPs and three time horizons (1991-2020 - serving as the "baseline", 2036-2065 - "near future", 2070-2099 - "end of century"), resulting in a total of 54 model scenarios. More information about the bias correction and climate scenarios can be found in section 2.2.5 of the report as well as in Honzak (2023).

Figure A10.12 shows projected changes in annual and seasonal minimum and (Tmax) temperature as well as precipitation (Prec) for CS10. Note that the horizons are slightly different than those used in SWAT+ modelling. A consistent warming pattern emerges, in particular for RCP8.5, for which projected increase in Tmin and Tmax ranges between 3 and 3.5 degrees C, respectively. The highest magnitude of the warming signal for Tmin (of up to 4 degrees C) occurs in winter, while the lowest in spring. In contrast, under RCP2.6 the projected changes do not generally exceed one degree C, even by the end of the century.

Precipitation projections on a yearly basis show a somewhat wetter future compared to the present conditions, with different trends, depending on the RCP scenarios; for RCP2.6, increase in yearly precipitation amounts by approx. 4 % is predicted for near-future, which reduces to 2% by the end of the century. RCP8.5 scenario predicts 7% and 12% increase in yearly precipitation for the near- and far future, respectively. There is a strong variation in seasonal changes of precipitation amounts, depending on the scenario and time period. For the near-future (2041-2070), the projected changes are higher in summer, winter and spring for RCP2.6, 4.5 and 8.5, respectively. Regarding the far-future, the highest increase is predicted for the spring and winter periods for all the scenarios.

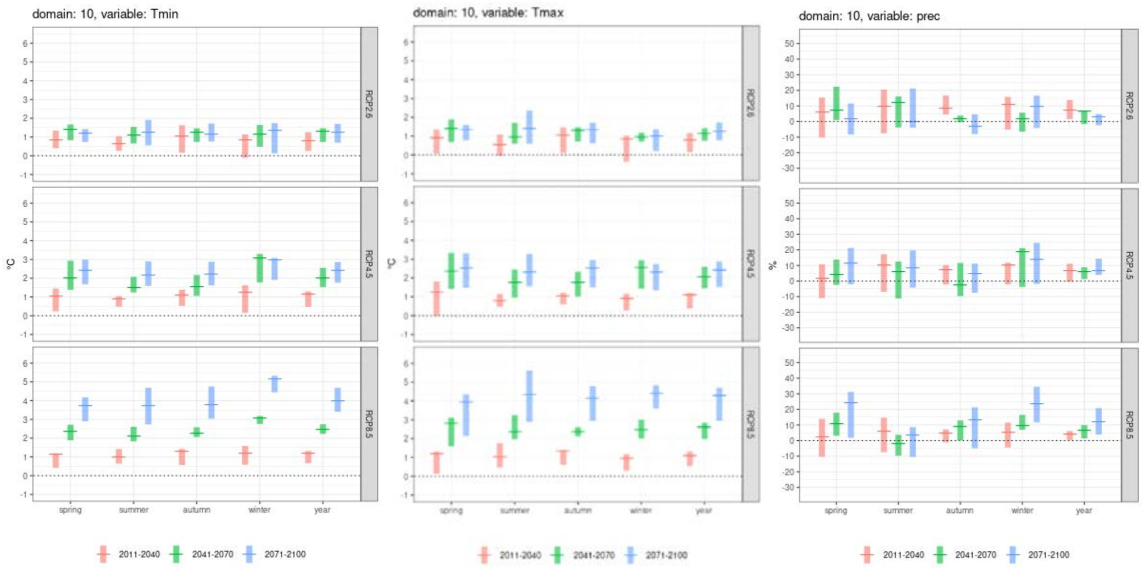


Fig. A10.12 Projected changes in variables Tmin, Tmax and Prec for all RCPs and time horizons for CS10 (Honzak, 2023).

A more detailed analysis of climate projections is available at the OPTAIN UFZ cloud https://nc.ufz.de/s/KA9Cr2bbtALGMHr/download.

In general, projected changes in wind speed, solar radiation and relative humidity are relatively low, even under RCP8.5, and thus should not contribute a lot to the effect of climate change on the studied indicators.

The following basin-averaged SWAT+ outputs were considered in the analysis: precipitation, snow fall, snow melt, potential evapotranspiration (PET), actual evapotranspiration (ET), percolation, soil moisture content (at different layers of the root zone and in the top 300 mm), surface runoff, and tile flow. The results are presented as box plots in Figure A10.13. As discussed before, precipitation is projected to increase with a variable rate, depending on the RCP and future horizon.

For the near-future all RCP scenarios predict an approximately 5% increase in total precipitation amounts; depending on the scenario, from 3 to 13% increase in precipitation is predicted by the end of the century (Fig. A10.13). Due to increase in air temperature, the solid part of the precipitation (snow fall) as well as the snow melt decreases by 30%, 57% and 40% and by 30%, 57% and 70% for RCP2.6, RCP4.5 and RCP8.5 in the near-future and far-future, respectively. In contrast, smaller increases in PET and ET are predicted due to climate warming, varying from 2 to 6% (PET, near future) and 3 to 12 % (PET, far future). The largest increase in PET of 12% (exceeding 15% for some ensemble members) is predicted for the RCP8.5 scenario by the end of the century.

Changes in ET follow rather well the tendencies and rate of changes of PET for the far-future period. An average relative change of 5% in ET is predicted for near-future by all the three scenarios. Increase in precipitation amounts could be one of the reasons for predicted increase in both, ET and PET. On the other hand, the climate scenario results show a stable decrease in soil water content in all the soil layers for all the periods, resulting in a total decrease of water amount stored in the upper 30 cm of the soil profile by 6 to 9% (near-future) and 5 to 15% (far-future). This decrease can be the result of increased evapotranspiration due to higher crop demands combined with increased percolation. Percolation increases for all the scenarios, especially under RCP8.5, reaching 23% for the far-future. Projections of surface runoff show an up to 10% and 17% decrease for near-future and far-future periods, respectively. High - from 9 to 7% for near-future and from 3 to 25% for far future) increase in tile flow is projected.

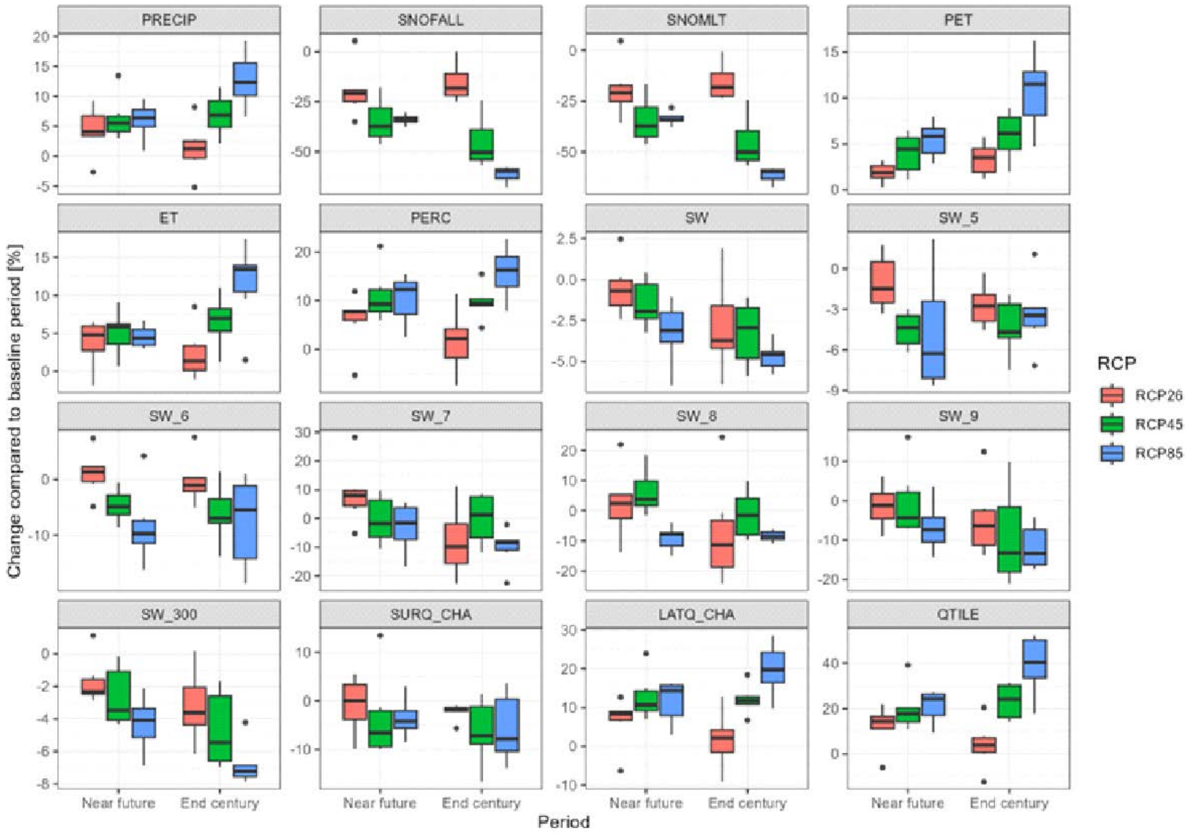


Fig. A10.14 Projected changes in selected basin-averaged water balance components simulated by SWAT+ for CS10.

The second collection of box plots (Fig. A10.14) includes various streamflow indicators. Average and median flow are projected to increase under all RCPs and time horizons. For the far-future, the rate of increase for RCP2.6 is moderate compared to RCPs 4.5 and 8.5. The number of days with high flows is predicted to increase significantly for the whole-time span and all the scenarios, reaching a maximum increase of more than 40% for RCP8.5 by the end of the century. The frequency of low flow days is projected to decrease by 5-25% for near-future under RCPs 2.6 and 4.5 and for far-future under RCP8.5, and to increase for the other cases by approx. 17%. However, the prediction of changes in frequency of low flow days shows high model spread, therefore it is difficult to predict the dominant direction of change in the future.

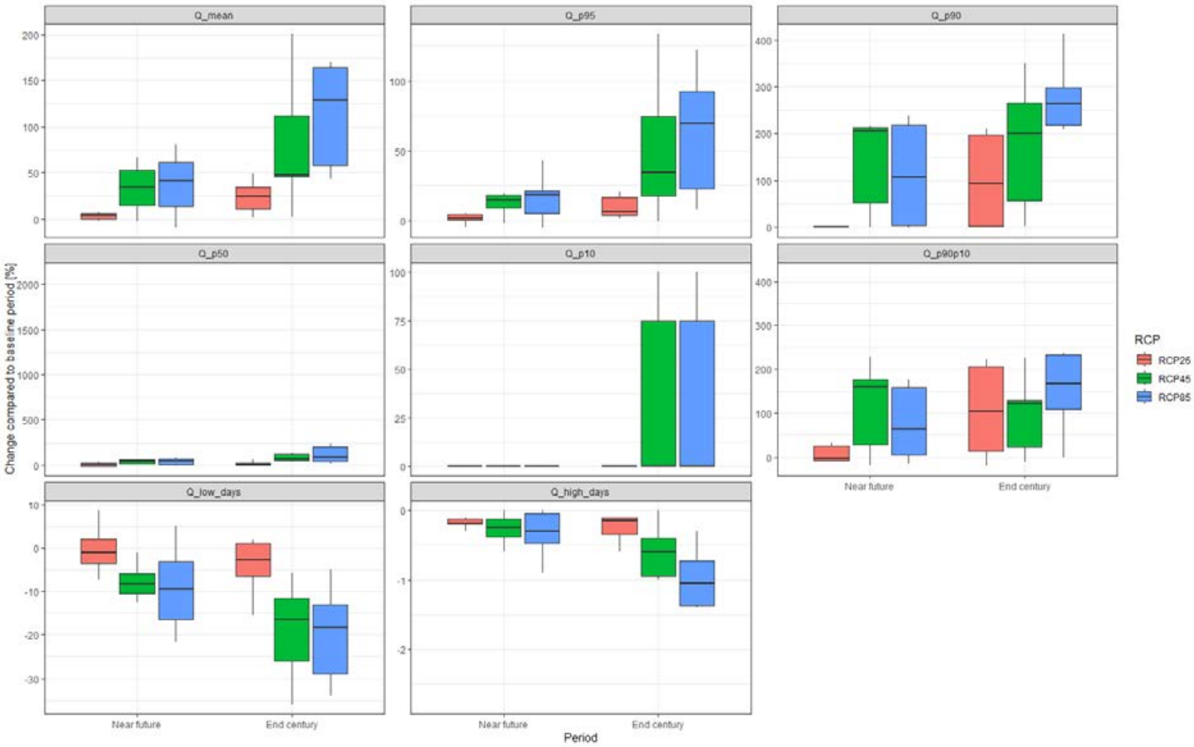


Fig. A10.15 Projected changes in selected streamflow indicators simulated by SWAT+ for CS10.

The third collection of box plots (Fig. A10.15) shows changes in selected water quality indicators. For CS10, TOT-N concentrations were calibrated so the results related to total N are more reliable. The phosphorus calibration was not accomplished, so the reliability of these results is certainly lower.

In general, it is difficult to predict the changes in N loads and losses under wetter and warmer future conditions; a slight up to 5% decrease seems to be more realistic for RCP 2.6 and 4.5 scenarios, while a slight, up to 5 and 2% increase can be foreseen in case of RCP 8.5 for near and far future, respectively. The predicted changes in P loads are very small, varying within +-1%. A slight, from 2 to 5% increase in P losses is predicted for all the scenarios, except RCP8.5 for the far future, where the P losses exceed 10% for some cases.

The frequency of days with high TN concentration is projected to increase, especially for RCP 4.5 and 8.5 and by the end of the century.

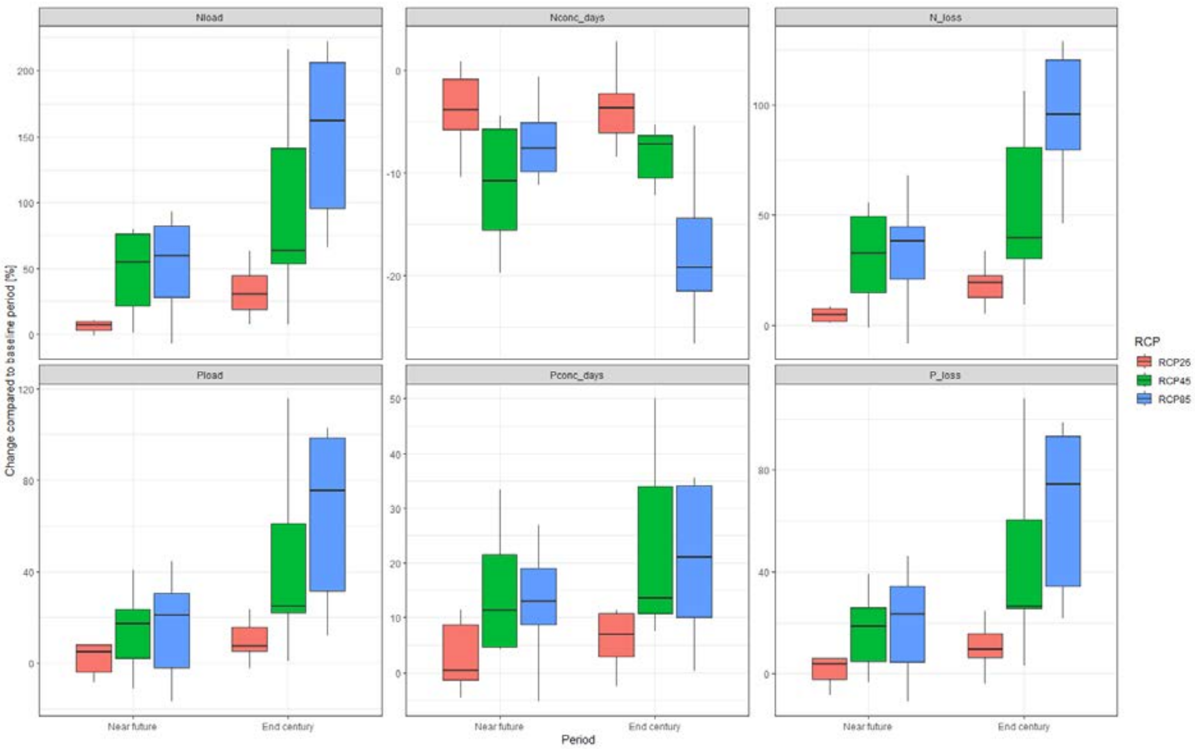


Fig. A10.16 Projected changes in selected water quality indicators simulated by SWAT+ for CS10.

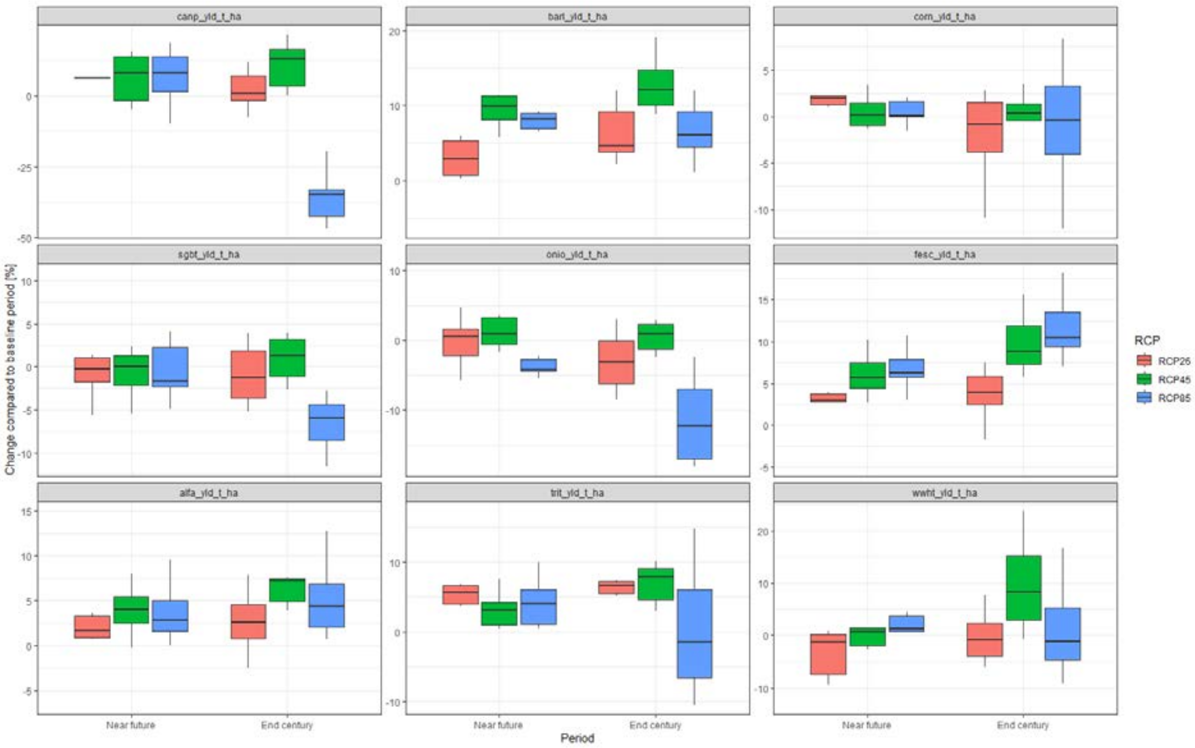


Fig. A10.17 Projected changes in selected crop yields simulated by SWAT+ for CS10.

The fourth collection of box plots presents projections of crop yields (Fig. A10.16). A moderate (from 2 to 6%) and larger (from 4 to 16%) decrease in potato yields is predicted for the near- and far-future, respectively. Winter wheat is the only crop showing an increase in predicted yields for all the cases. For the summer cereals, the signal is not clear, as the changes go in both directions. The overall picture, however, suggests a decrease in yields of summer cereals in the future.

## 4. Effectiveness of selected NSWRMs (current climate)

NSWRM effectiveness was simulated for the following five measures relevant for the Kråkstad catchment: (1) grassed waterways (scenario grassslope), (2) riparian buffers (scenario buffer), (3) low tillage combined with stubble during the winter period (scenario lowtill), (4) sedimentation ponds, including constructed wetlands (pond) and (5) wetlands. The selection of measures was carried out in collaboration with local actors based on the results of the 1st and the 2nd MARG workshop. The methodology of identifying the potential location of NSWRMs was developed by Robert Barneveld (NIBIO).

### Grassed waterways

Grassed waterways are located in talweg and represent linear areas of concentrated overland flow. On agricultural soils in Norway, these areas are prone to ephemeral gully erosion (Barneveld et al., 2022). An ephemeral erosion risk map was developed by NIBIO and published in 2020 as part of the national erosion risk map (NIBIO, 2022).

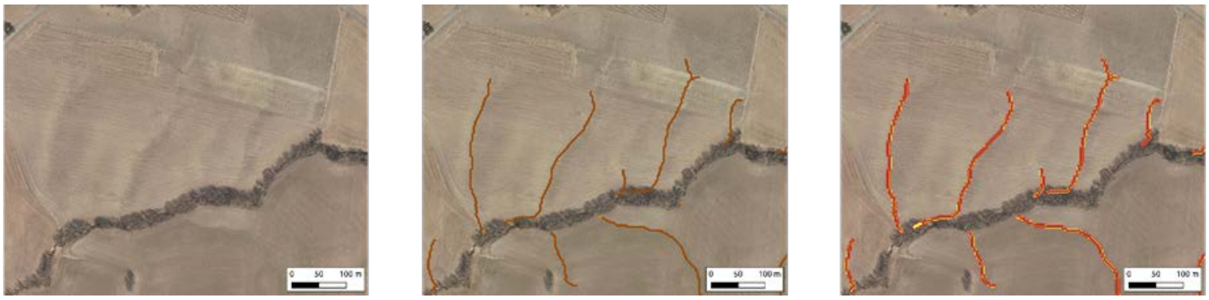

Fig. A10.18 Placement of grassed waterways: terrain > gully erosion risk > grassed waterways (6 m width). Source: Robert Barneveld (NIBIO)

The optimal placement of grassed waterways was obtained by drawing a 6 m wide buffer (as prescribed by law) with the existing gully erosion risk lines as the centre lines (Fig. A10.18).

### Riparian buffers

Buffer zones are measures applied in Norway to uncouple a hillslope from a waterway. The increased surface roughness that results from the perennial or permanent vegetation reduces the velocity of the overland flow coming from the hillslope. This reduces the sediment transport capacity and increases the infiltrating fraction of the surface runoff.

Buffer zones are situated alongside riverbanks and creeks, and as such, they are easily mapped for small or large areas. In Norway, the geodata source that represents surface waters best is FKB-vann (Kartverket, 2015). This map contains two layers: one containing lines and one containing polygons. The first represents small watercourses and creeks, the latter more sizable rivers and lakes. Once the line and polygon elements are checked against aerial imagery or another source of verification, a polygon is created by drawing a buffer with a certain width at either side. In the case of CS10, 6 m buffer strips were defined along surface watercourses.

### Low tillage

For the Norwegian pilot site "lowtill" is interpreted as shifting from winter crops (with main tillage operations in the autumn) to summer crops (reduced tillage or no till during spring), as this measure is considered to be the most important one in the Norwegian cereal productive areas. Results from experimental plots confirm that there is a large effect of tillage method and tillage timing on soil loss (Fig. A10.18). Omitting tillage in the autumn reduces soil loss four times in average; moreover, in some field experiments shifting to spring tillage reduced soil losses to 10% compared to autumn ploughing (Skøien et al., 2012). Puustinen et al. (2005) highlighted that the stubble as well as the undisturbed soil contribute to soil protection and erosion reduction during winter and spring.

The potential areas for representing reduced tillage are all the agricultural areas within the catchment. For representing different levels of implementation in the COMOLA optimisation (further steps within the OPTAIN project), the potential areas with reduced tillage were grouped according to sheet erosion risk classes, usen the NIBIO erosion risk map. Thus, four different groups were identified:

- Very high erosion risk (potential risk of soil loss is more than 80 kg/ha)
- High erosion risk (potential risk of soil loss is from 20 to 80 kg/ha)
- Moderate erosion risk (potential risk of soil loss is from 5 to 20 kg/ ha)
- Low erosion risk (potential risk of soil loss is below 5 kg/ha)

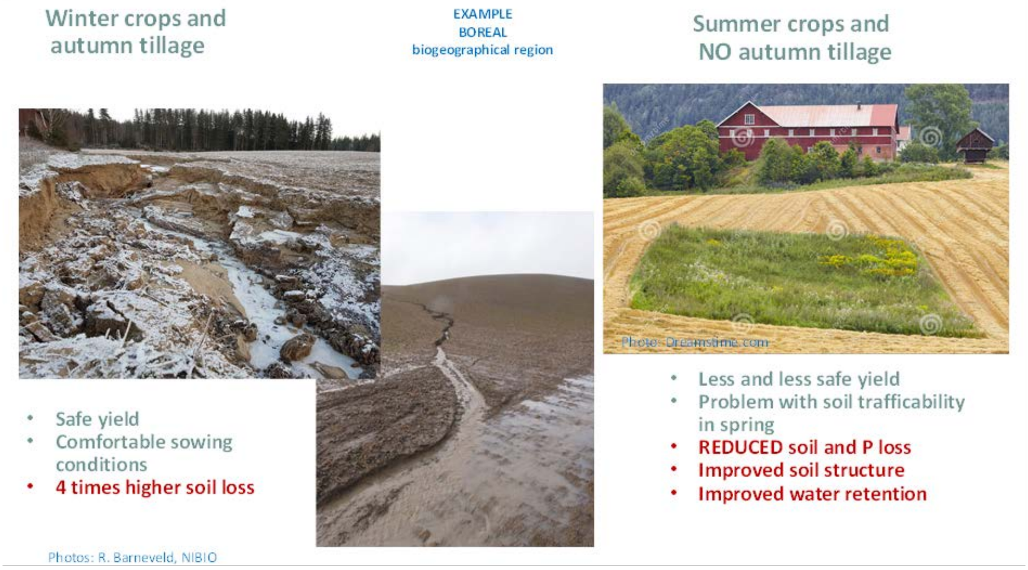


Fig. A10.19 Visualisation of the effects of autumn and spring tillage systems on soil losses in Norwegian cereal production areas.

### Constructed wetlands

The main function of constructed wetlands within an integrated water management strategy is the improvement of runoff from agricultural soils by removing sediment and nutrients. The optimal placement of constructed wetlands is prescribed by this function, and its hydraulics. Wetlands are efficient in locations in the watershed where overland flow contains significant amounts of sediment and/or nutrients. It filters out sediments primarily by reducing the velocity of the overland flow by flow divergence and retention and increased surface roughness (i.e. vegetation). These conditions can be mapped quantitatively at any spatial scale because of the availability of the required geodata.

Constructed wetlands are mainly aimed at the reduction of sediment delivery from agricultural soils. The first condition for optimal placement therefore is the percentage of agricultural land use in the contributing area of the wetland. The hydraulic function of constructed wetlands requires the presence of a longitudinal flat area with a natural depression, or at least characterised by terrain that can be excavated and/or levelled. Earlier research by NIBIO showed that the optimal location of a constructed wetland has a contributing area between 0.5 and 3.0 $km^2$. Once the number of possible locations is reduced, additional suitability indicators that can be included in an optimisation exercise are i) nature value, ii) the presence of quick clays (prone to landsliding), and iii) hydrological connectivity.

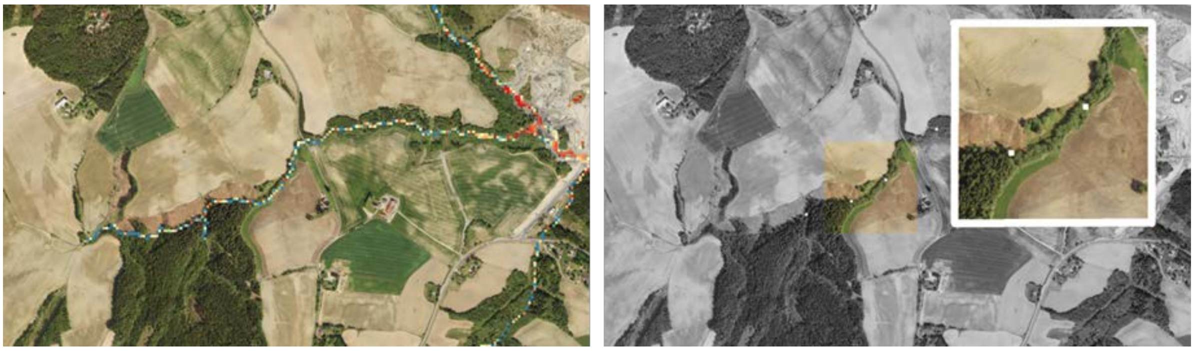

Fig. A10.20 Identifying potential locations for constructed wetlands (by R. Barneveld, source: Farkas et al., 2023). Left: Ranking the locations for constructed wetlands by combining the size of the contributing area, location and slope (First step). Right: Reducing the number of locations of (50 m or more along the profile with slope inclinations of 1% or less).

### Sedimentation ponds

While constructed wetlands aim at the retention of sediments, retention dams are planned for peak flow reduction and flood prevention. The primary qualification for locations in the landscape is the possibility to store significant volumes of water, and to release it naturally with a lower discharge rate. Retention dams can be constructed to protect infrastructure, built up areas and agricultural areas. NIBIO has undertaken mapping exercises for large areas in South-eastern Norway (Stolte and Barneveld, 2020).

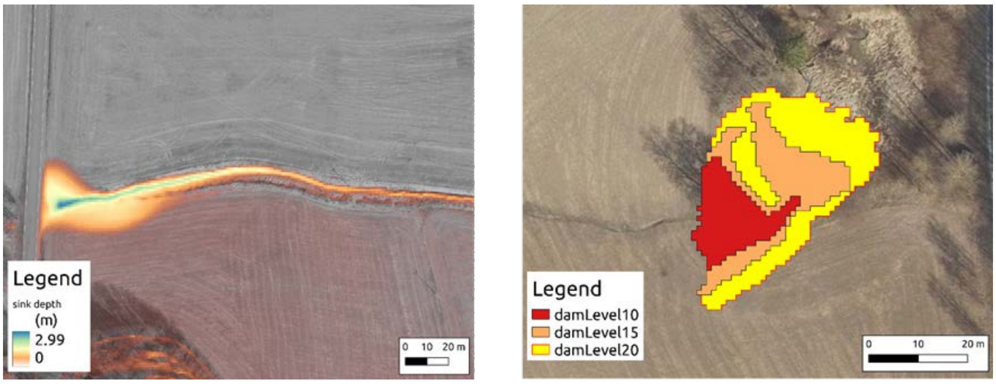


Figure A10.21 Sink depth mapping to identify retention dam potential areas for retention. b: Three scenarios for a location: dam heights of 1.0, 1.5 and 2.0 m. (by R. Barneveld, source: Farkas et al., 2023)

The initial mapping of possible locations starts with identifying sizeable sinks in the landscape. The availability of the 1 m Digital Elevation Model for Norway allows for the mapping of small and narrow sinks that might not be detectable with lower resolution elevation data (Fig. A10.21). Once the large sinks are identified from the DEM analysis, their suitability can be ranked according to the preferences set by the objective of the dams. In the example by Stolte and Barneveld (2020) retention dams were projected to protect agricultural land. A further selection of the locations was created by finding sinks in forested areas, upstream from agricultural land. Dams with small contributing areas are generally not efficient and can be filtered out from the selection. The extent of the area that could be flooded can be mapped tentatively by selecting the downstream area of the lowest point of the potential dam. This in turn can be included in a ranking exercise that further reduces the number of locations.

For the Kråkstad catchment SWAT+ model setup, sedimentation ponds and constructed wetlands were implemented as “ponds”. There are three sedimentation ponds within the forested areas, one of them covering several HRUs so that its size could be optimised as well (Fig. A10.21, right).

The other 39 “ponds" represent constructed wetlands. At present, it is not possible to implement constructed wetlands directly in the SWAT+ model. As “wetlands" cannot have outflows, and the Kråkstad case study contains a few functioning cascades of wetlands and several potential ones, the “pond” measure option was chosen to estimate the efficiency of constructed wetlands in retaining water, sediments and nutrients within the catchment and reducing flash floods and nutrient loads to the surface watercourses. Within the model setup, reservoirs were defined with connection to the existing channel network. The drawback of this approach is that constructed wetlands, in reality, are covered with vegetation that also contributes to water retention and nutrient uptake, whilst no vegetation cover can be defined for ponds within the model setup. Hence, ponds representing constructed wetlands in the model setup were parameterized with the aim to account for this extra retention capacity compared to bare ponds.

When evaluating the effect of “ponds” as measures on different indicators, detention ponds and constructed wetlands were regarded as one measure type implemented to a maximum level in the landscape.

### Investigating the effectiveness of measures

We investigated the effectiveness of measures in single scenario runs: one model scenario for each measure, considering all potential sites of implementation (Fig. A10.22), and one additional scenario where all measures were implemented simultaneously (scenario ‘all’).

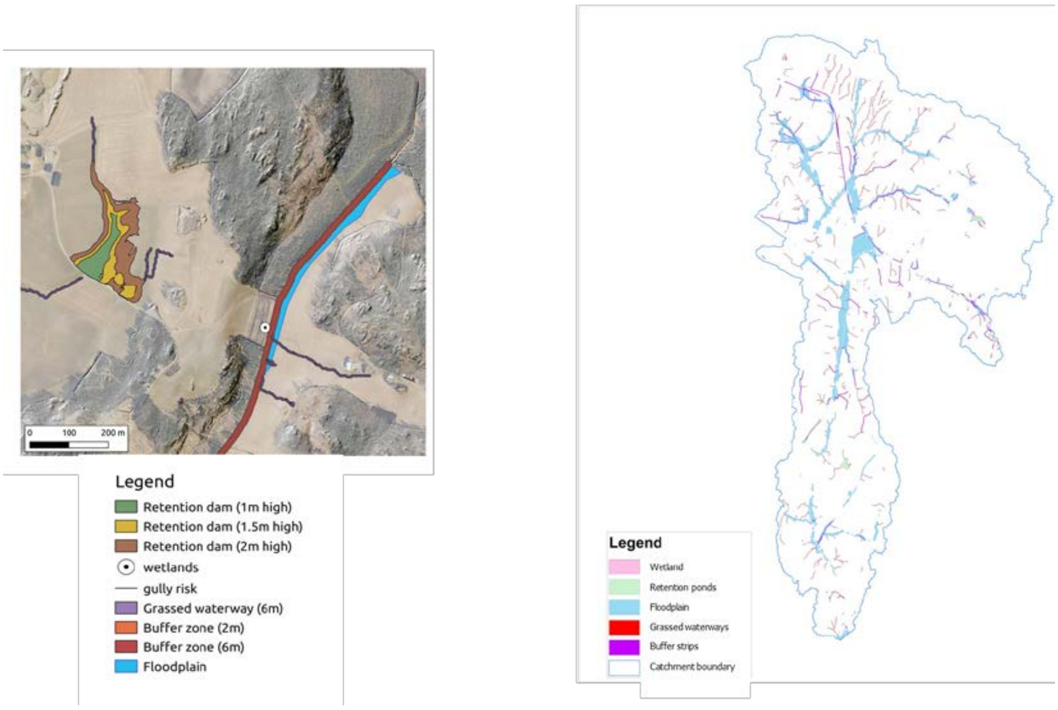


Figure A10.22 Locations of NSWRMs in the Kråkstad catchment - identified using the methods indicated above- which were simulated in the scenario runs

As described above, scenario "lowtill" consisted of changing the management schedules of all the agricultural fields having winter cereals in the status quo to summer crops, and shifting from normal tillage to reduced tillage. All other scenarios include straightforward changes of land cover or object type (hru to reservoir for scenario pond). To account for parameter uncertainty, we ran an ensemble of ten model realisations (each with different calibration settings) for each scenario. Figure A10.23 demonstrates the effectiveness of the NSWRMs for the Kråkstad catchment under current climate conditions.

### Grassed waterways

Activating grassed waterways affected mainly the low flow. It contributed to increasing the low-flow threshold (Q_P05) by 9% and reducing the number of days with low flow (Q_low_days) by 3% (Fig. A10.23). A slight increase in percolation and soil water content in some of the soil layers is expected. The relative contribution to the catchment-level indicators is small, but considering how small areas are occupied by grassed waterways, the local effect could be significant. The effect of grassed waterways on water balance elements indicates that grassed waterways increase water retention within the landscape and thus contribute to mitigating flash floods. Regarding water quality indicators, N and P loads are expected to slightly decrease by 2% and 5%, respectively, but no effect on concentrations was found. The strongest positive effect is projected for sediments; sediment losses are expected to decrease by 20 %, probably due to the fact that this measure ensures constant vegetation cover on the open surfaces prone to gully erosion.

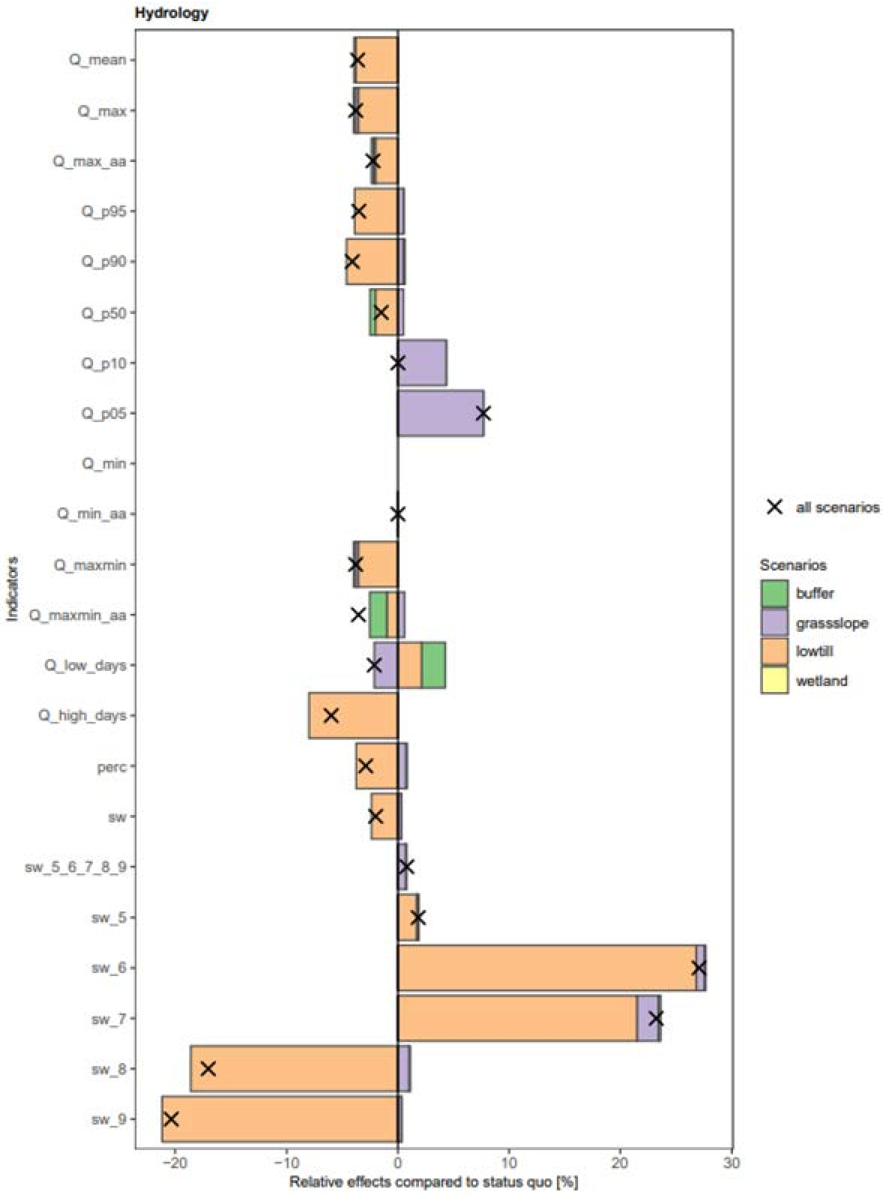


Fig. A10.23 Effectiveness of NSWRM scenarios on catchment hydrology indicators. The stacked bars illustrate the relative effect of an NSWRM scenario to the status quo. Each bar represents the median effect of a measure scenario which results from an ensemble of SWAT model setups. The bars of the NSWRM scenarios were stacked to provide a comparison to the effect of all measures being implemented.

## Riparian buffers

Riparian buffers did not show significant effects on hydrological and water quality indicators compared to the status quo, apart of slight (4%) decrease in differences between high and low flows (Q_maxmin), slight (3%) increase in days with low flow (Q_low_days) (Fig. A10.23) and a 2% decrease in sediment loads (Fig A10.24). Besides, a 7% increase in sediment loads was predicted. There might be several reasons for such results. The first possible reason is the fact that within the pilot region, tile drains transport major parts of nutrients and sediments directly in the streams, and buffer strips have no effect on this transport. Janssen et al. (2018) dedicated their study to the effectiveness of buffer strips on nitrate transport in a tile drained field. They concluded that buffer strips at tile-drained fields are inadequate to reduce surface water nitrate loads. Our modelling results are in line with these findings. On the other hand, riparian buffers are very common in the study area, so there were quite many of them in the status quo model setup. The reason for still including this measure in the NSWRMs scenario analysis is rather to prove their effectiveness, thus showing the expected negative effect of removing buffer strips as one single scenario during the optimisation. We found it important as some farmers would prefer removing the riparian buffers and thus extending their productive farmland.

#### Wetlands, constructed wetlands and sedimentation ponds

According to our NSWRMs scenario results, no effects of wetlands were found or the effects were extremely low compared to the larger impact of "lowtill" and "grassed waterway" scenarios. This reason could be that wetlands cover very small areas. In total, 5 wetlands were implemented occupying 7 HRUs on 3466 $m^2$. We assume that the effects of these measures might be local, thus, we need to evaluate them at a smaller scale.

The implementation of ponds (including sedimentation ponds and constructed wetlands) was not satisfactory (data not shown). We need to carefully evaluate whether these measures were correctly implemented and parameterised in the scenario setup before drawing further conclusions. We assume, that the effect of "pond" scenario should be visible at catchment scale, as in total 35 constructed wetlands and 3 sedimentation ponds were implemented, occupying 28787 $m^2$ and 53734 $m^2$, respectively.


Fig. A10.24 Effectiveness of NSWRM scenarios on indicators related to the nutrient and sediment loads. The stacked bars illustrate the relative effect of an NSWRM scenario to the status quo. Each bar represents the median effect of a measure scenario which results from an ensemble of SWAT model setups. The bars of the NSWRM scenarios were stacked to provide a comparison to the effect of all measures being implemented.

## Low tillage

In accordance with our expectations, low tillage had the highest impact on all the studied indicators, as this is the spatially most spread and quite effective measure for reducing flash floods, soil erosion and nutrient losses from the agricultural fields. Even though this measure is subsidised, it is not widely practised in the Krakstad catchment. Activating low tillage (e.g. shifting from autumn to spring tillage in our case) resulted in decrease in mean (Q_mean), maximum (Q_max, annual average maximum flows (Q_max_aa) and low-flow threshold (Q_P05) by 6%, 6%, 4% and 6%, respectively. The number of high- and low flow days was predicted to decrease (by 9%) and increase (by 3%), respectively. A 5% and 3% decrease in percolation (perc) and soil water content (sw) was projected. Seemingly no changes in average soil water content were predicted for the vegetation season (sw_5_6_7_8_9), but only because averaging smoothed the strong within-seasonal variability, expressed by a 23-27% increase in soil water content during June and July and by an approx. 18-22% decrease in sw during August and September. These results clearly demonstrate how important it is to evaluate the effect of measures at finer spatio-temporal scales.

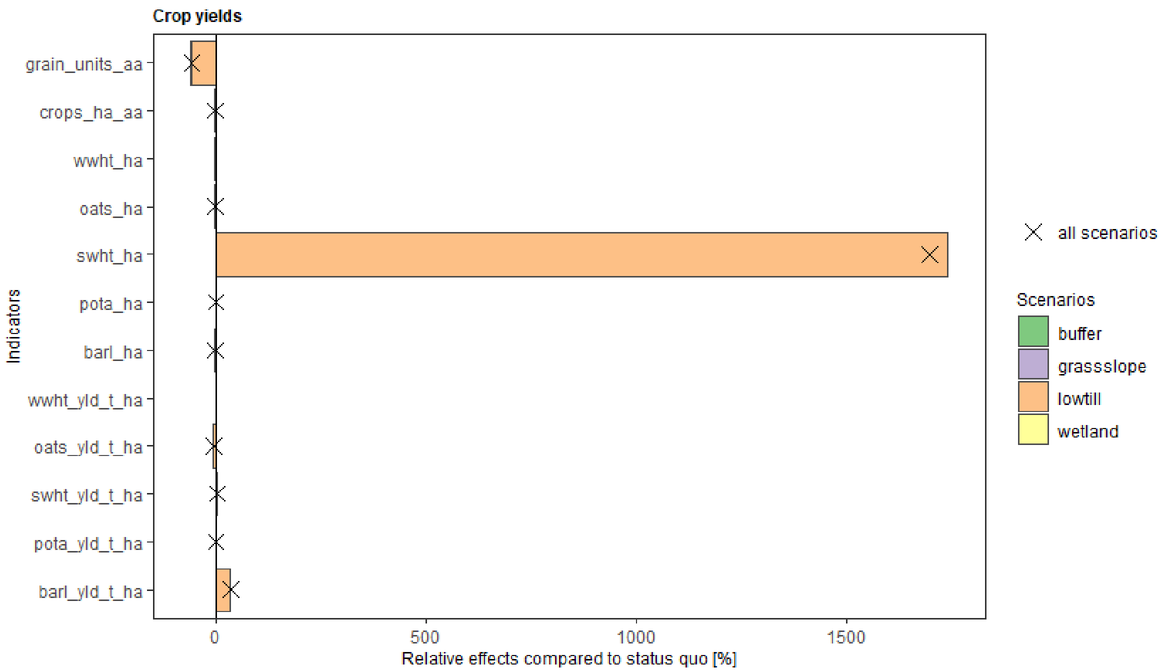


Fig. A10.25 Effectiveness of NSWRM scenarios on indicators related to crop yields. The stacked bars illustrate the relative effect of an NSWRM scenario to the status quo. Each bar represents the median effect of a measure scenario which results from an ensemble of SWAT model setups. The bars of the NSWRM scenarios were stacked to provide a comparison to the effect of all measures being implemented.

The low tillage scenario had a strong positive effect on water quality expressed by significant reduction in most of the water quality indicators: N, P and sediment losses are projected to decrease by 18%, 60% and 58%, respectively. Changes in concentration concerned reduction of nitrogen concentrations only.

None of the measures was projected to influence crop yields significantly (Fig. A10.25). The only exemption was the yield of barley for the low till scenario, which showed an increase of 34%. The low till scenario largely increased the area used for summer wheat production compared to the status quo. This clearly shows how large areas are used commonly for winter cereal production, resulting in high erosion and nutrient losses within the CS10 catchment and also reflects the potential of this measure in regulating the water regime and reducing soil erosion and loss of nutrients at catchment scale.

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# Annex 11 Modelling results for CS11 (Tetves, HU)

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## 1. Model setup

The SWAT+ model for CS11 catchment (Tetves) was set up based on the OPTAIN workflow (Schürz et al., 2022). The missing soil chemical, physical and hydraulic properties were derived based on the workflow prepared in WP3 (Szabó et al., 2022). Time series crop maps were predicted based on Sentinel time series reflectance data of Sentinel-1A and -1B satellite radar images with the method derived in WP3 (Mészáros and Szabó, 2022). The uncalibrated model setup was developed using the SWATbuildR (version 1.5.10) and SWATfarmR (version 3.2.0). The SWAT+ model revision 61.0.64 (from 1/12/2024) was used in all simulations.

### 1.1. Input data overview

The list of input data used for the model setup is included in Table A11.1 which is shortly described hereinafter.

Meteorological data was available for four virtual stations, retrieved from the gridded database of the Hungarian Meteorological Service (OMSZ) (Figure A11.1 a).

We used the 5 m resolution Digital Elevation Model (DEM) derived by the Lechner Knowledge Center (Figure A11.1 b) to represent the earth's topography.

In the case of the land cover and land use map (Figure A11.1 c) it was necessary to add more details about the arable land to be able to analyse the effectiveness of NSWRMs. Therefore, we generated time-series crop rotation maps for arable land categories using remote sensing data and crop classification method derived in WP3. To refine the crop rotation maps, we digitised the field boundaries of CS covered by arable land and converted the pixel-based results into vector files. The predicted time series crop map was revised to meet the county statistics on the proportion of the crops' area and eliminate implausible crop sequences. The most important crops of the case study are maize (CORN), winter wheat (WWHT), winter barley (WBAR), rape (CANP), sunflower (SUNF) and lucerne (ALFA). Based on data provided by a local farmer and the farm advisor, we randomly added cover crop to the 50 % of those fields where an autumn crop (WWHT or WBAR) is followed by a summer crop (SUNF or CORN).

Table A11.1 Summary of input data for CS11.

| Input type | Input variables | Unit | Time frequency | Reso-lution | Time period | Source | Reference |
|---|---|---|---|---|---|---|---|
| Field boundaries | - | - | - | 5 m | static | digitised | - |
| Land cover and land use | land cover with time series crop map | - | yearly | 10 m | 2015-2021 | NÖSZTÉP database and remote sensing based crop maps | (Szabó et al., 2022; Tanács et al., 2019) |
| NSWRMs | - | - | - | 10 m | 2020 | farm advisor, farmers, NÖSZTÉP | - |
| Agricultural manage-ment data | - | - | - | 10 m | 2020 | farm advisor, agronomist, , farm activity log | - |
| DEM | - | m | - | 5 m | static | Lechner Knowledge Center | https://lechnerkozpont.hu/oldal/domborzatmodell |
| Soil data | depth of layers | mm | - | 100 m | static | DOSoReMI.hu | (Pásztor et al., 2018) |
| | maximum rooting depth | mm | - | 100 m | static | DOSoReMI.hu | (Pásztor et al., 2018) |
| | moist bulk density | g/cm3 | - | 100 m | static | computed | (Wessolek et al., 2009) |
| | available water capacity | mm/mm | - | 100 m | static | computed | (Assouline and Or, 2014; Szabó et al., 2021) |
| | saturated hydraulic conductivity | | - | 100 m | static | computed | (Assouline and Or, 2014; Szabó et al., 2021) |
| | organic carbon content | g/100 g | - | 100 m | static | DOSoReMI.hu | (Szatmári and Pásztor, 2019) |
| | sand, silt, and clay content | g/100 g | - | 100 m | static | DOSoReMI.hu | (Laborczi et al., 2019) |
| | rock fragment content | g/100 g | - | 250 m | static | SoilGrids | (Poggio et al., 2021) |
| | moist albedo of the top layer | - | - | 100 m | static | computed | (Gascoin et al., 2009) |
| | USLE soil erodibility factor (K) | t ha h/ha MJ mm | - | 100 m | static | computed | (Sharpley and Williams, 1990) |
| Stream characteristics | stream reaches | - | - | 1:10000 | static | South Transdanubian Water Directorate | - |
| Meteorological data | precipitation | mm/day | daily | 0.1° | 1998.01.01 - 2020.12.31 | Hungarian Meteorological Service (OMSZ), interpolated, 4 virtual station | https://odp.met.hu/climate/homogenized_data/gridded_data_series/ |
| | temperature | °C | daily | 0.1° | same as above | same as above | same as above |
| | wind speed | m/s | daily | 0.1° | same as above | same as above | same as above |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | relative humidity | % | daily | 0.1° | same as above | same as above | same as above |
| | solar radiation | MJ/m2/day | daily | 0.1° | same as above | same as above | same as above |
| Atmospheric data | atmospheric deposition | kg/ha/yr | annual | 0.1° | 1990-2020 | European Monitoring and Evaluation Programme (EMEP) | https://www.emep.int/ |

Information about present and possible NSWRMs has been gathered based on data provided by farm advisors and farmers (management related NSWRMs), the available land cover and land use map (forest riparian buffers, buffer strips and hedges, meadows and pastures), remote sensing data (green cover on vineyards).

Agricultural management data was defined based on data from farm advisors, an agronomist experienced in local management practices and farm activity logs.

Basic soil data – soil layering, maximum rooting depth, organic carbon content, clay, silt, and sand content – was retrieved from the national Digital, Optimized, Soil Related Maps and Information in Hungary database (DOSoReMI.hu) (Pásztor et al., 2018). Rock fragment content was downloaded from the SoilGrids dataset (Poggio et al., 2021). The mean value of all available soil properties were computed for each HRU, then soil physical and hydraulic properties were computed from the basic soil properties based on the workflow derived in WP3 (Plunge et al., 2024; Szabó et al., 2024).

For the moist bulk density first dry bulk density was computed based on organic matter content. Then moist bulk density was computed based on dry bulk density, organic carbon content and particle size distribution. Available water capacity and saturated hydraulic conductivity were computed from van Genuchten parameters predicted based on soil depth, particle size distribution and organic carbon content. Moist albedo of the top layer was computed from field capacity. USLE soil erodibility K factor was predicted from sand, silt, clay, and organic carbon content. Figure A11.1 d) shows the soil types of the catchment, 44 % of the area is covered by Cambisols, 22 % by Luvisols, 17 % by Regosols, 6 % by Gleysols (IUSS Working Group WRB, 2022), the rest of the soil types is present with less than 5 % proportion.

We also defined the characteristic soil phosphorus content of the HRUs in the nutrients.sol file. We computed the geometric mean of soil phosphorus content by land use categories based on the LUCAS Topsoil database and assigned these values to the HRUs (Szabó et al., 2024). Figure A11.2 shows the Olsen phosphorus content of the topsoil used for the modelling.

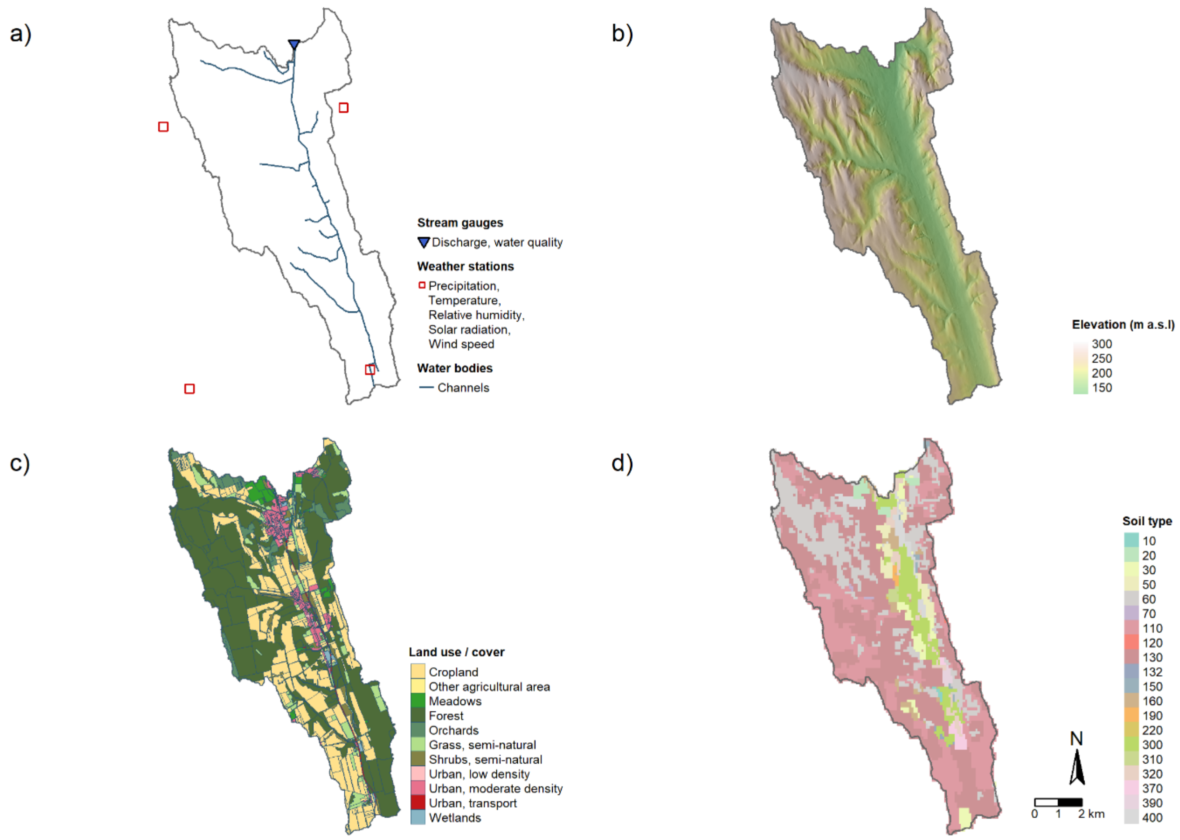


Figure A11.1 GIS input data for CS11: a) flow gauge, water quality monitoring points, meteorological stations, channels and catchment boundary; b) elevation map; c) land use map; d) soil types, with the following most dominant soil types: Cambisols (code 130, 400), Luvisols (code 110), Regosols (code 60), Gleysols (300).

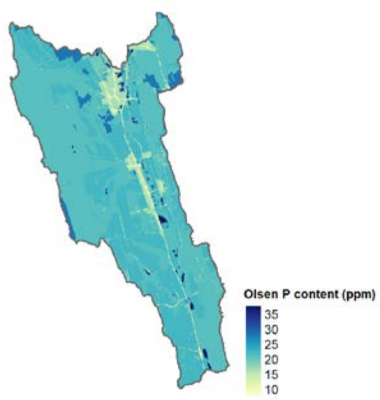


Figure A11.2 Olsen phosphorus content of the topsoil layer in CS11.

## 1.2. Baseline model setup

The area of the watershed defined by the QSWAT – QGIS interface for SWAT – based on the 5 m resolution DEM is 7,236 ha. HRUs were defined based on the land use map in the following way: 1) each agricultural field was defined as a separate HRU to be able to analyse the effect of management related NSWRMs, 2) for non-agricultural areas the boundary of the field blocks were used to define the HRUs. If an infinite loop has occurred during the SWATbuildR setup, the problematic HRU was further divided based on the DEM. The final number of HRUs was 1,162. There were no reservoirs in CS11. Further details about the model setup are included in Table A11.2.

Table A11.2. Summary of the mode setup features based on the input file object.cnt.

| Parameter | Value |
|---|---|
| Total area of the watershed [ha] | 7,236 |
| Total number of spatial objects in the simulation | 2,349 |
| Number of HRUs in the simulation | 1,162 |
| Number of routing units in the simulation | 1,162 |
| Number of aquifers in the simulation | 1 |
| Number of reservoirs in the simulation | 0 |
| Number of recalls (point sources/inlets) in the simulation | 0 |
| Number of SWAT-DEG channels in the simulation | 24 |
| Number of crops in rotation | 7 |
| Number of wetlands | 24 |

# 2. Model evaluation

For the soft calibration we used crop yield and water yield ratio as observation data. Hard calibration was performed based on discharge and N-$NO_3$ concentrations. Table A11.3 presents information about these observation data. Crop yield data was collected from the Hungarian Central Statistical Office, which includes yearly statistics at county level. Data on discharge and N-$NO_3$ concentration was acquired from the South Transdanubian Water Directorate. Discharge data was available at daily scale. Unfortunately, N-$NO_3$ concentration is measured monthly as a grab sample for Tetves stream, which limits the calibration and validation accuracy of the water quality simulation.

Table A11.3 Summary of observation data used in different steps of the calibration workflow for CS11.

| Variable | Time step | Calibration period | Validation period | Source | Comments |
|---|---|---|---|---|---|
| | | | Soft calibration | | |
| Crop yields | average annual | 2001-2020 | NA | https://www.ksh.hu/stadat_files/mez/hu/mez0070.html | County statistical data. |
| Water yield ratio | average annual | 2001-2020 | NA | Model input (pcp) and discharge data | Calculated for the outlet flow gauge. |
| | | | Hard calibration | | |
| Discharge | daily | 2001-2011 | 2012-2020 | South Transdanubian Water Directorate | Daily data received from the local water authority (South Transdanubian Water Directorate). |
| N-$NO_3$ concent-rations | bi-weekly/ monthly (grab sample) | 2001-2011 | 2012-2020 | South Transdanubian Water Directorate | Discrete, grab sample measurements for one gauge measured by the local water authority (South Transdanubian Water Directorate). |

## 2.1. Model setup verification

During the model setup verification, we followed the OPTAIN workflow, which is presented by Plunge et al. (2024).

Figure A11.3 shows the verification results of the climate and water balance data. The simulated evapotranspiration, precipitation, temperature, relative humidity, wind speed and solar radiation data is in line with the values available from the literature for the catchment, thus the model read these data correctly during the simulation.

In the case of plotting crop yields under different stress factors – all stress and external stress factors – and no stress factors (Figure A11. 4.), the simulated values are in plausible ranges.

Biomass and LAI development analysed by HRUs showed acceptable behaviour.

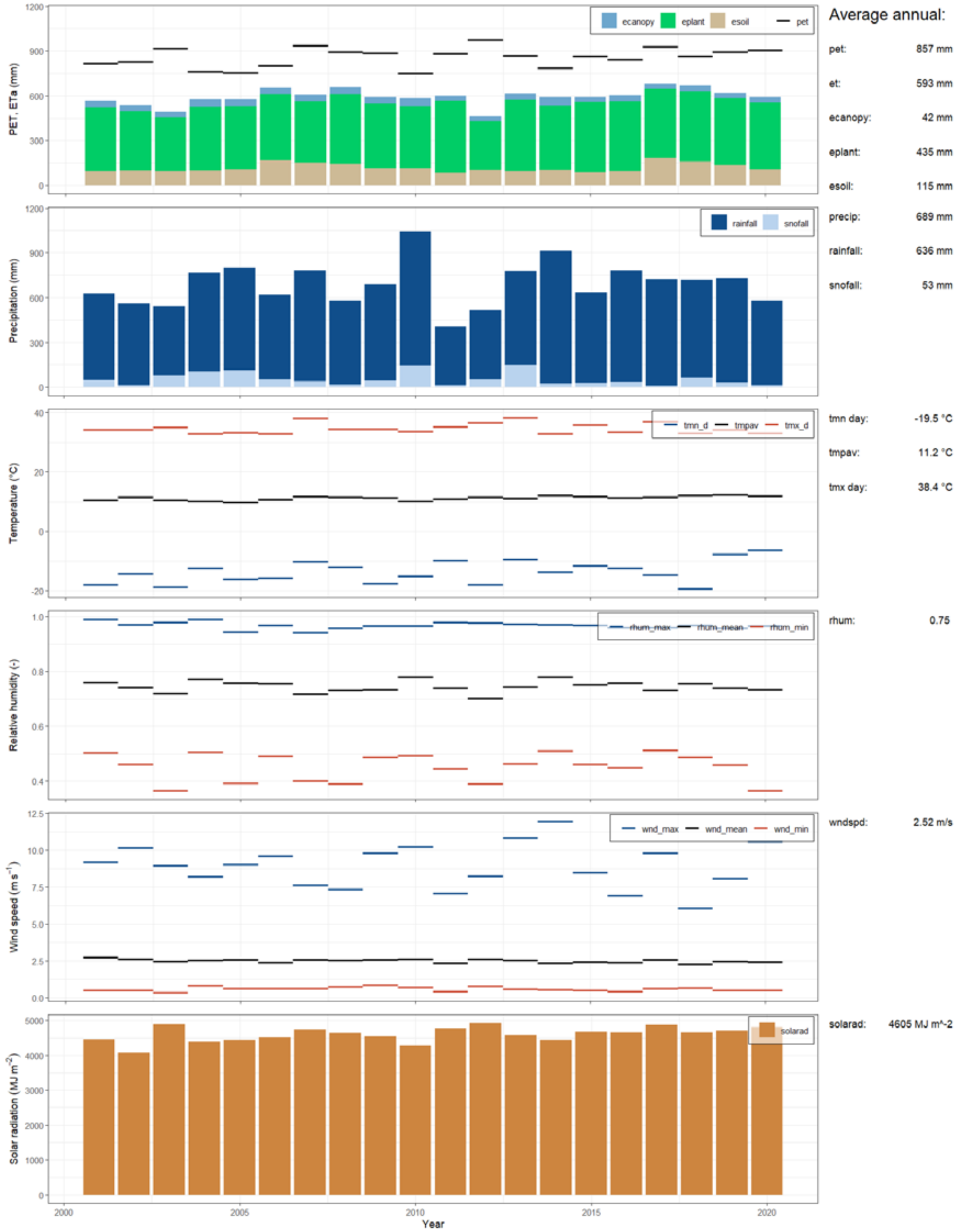


Figure A11.3 Summary of the climate data checks for CS11 by the SWATdoctR.

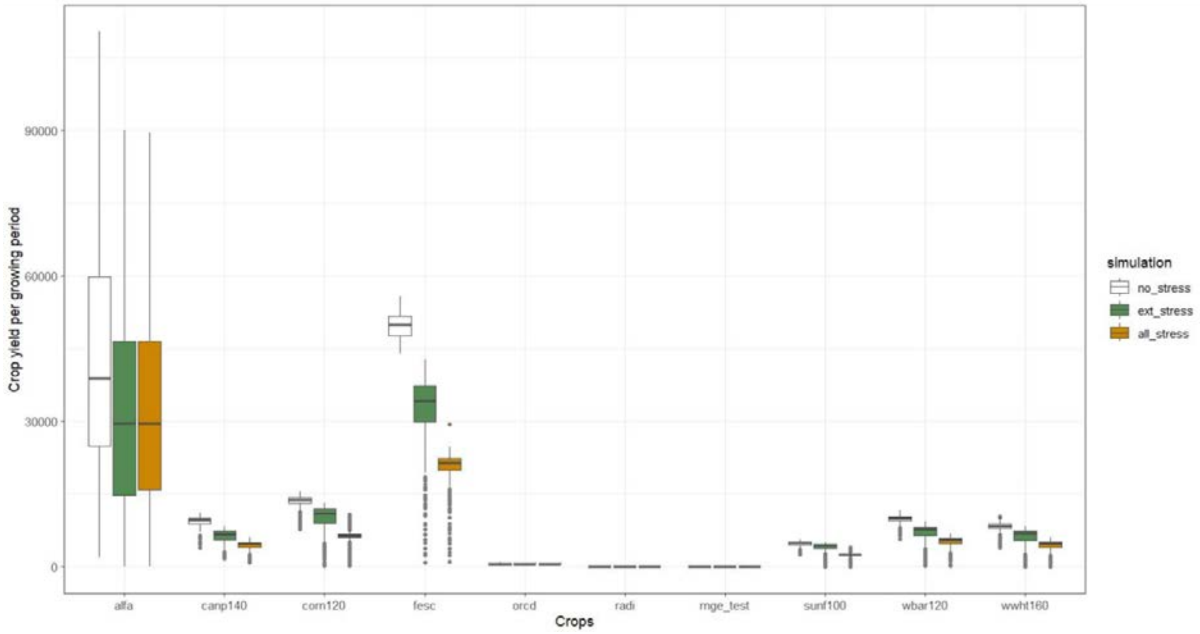


Figure A11.4 Comparison of crop yields with all stress factors (all_stress), external stress factors (ext_stress) and no stress factors (no_stress) for CS11.

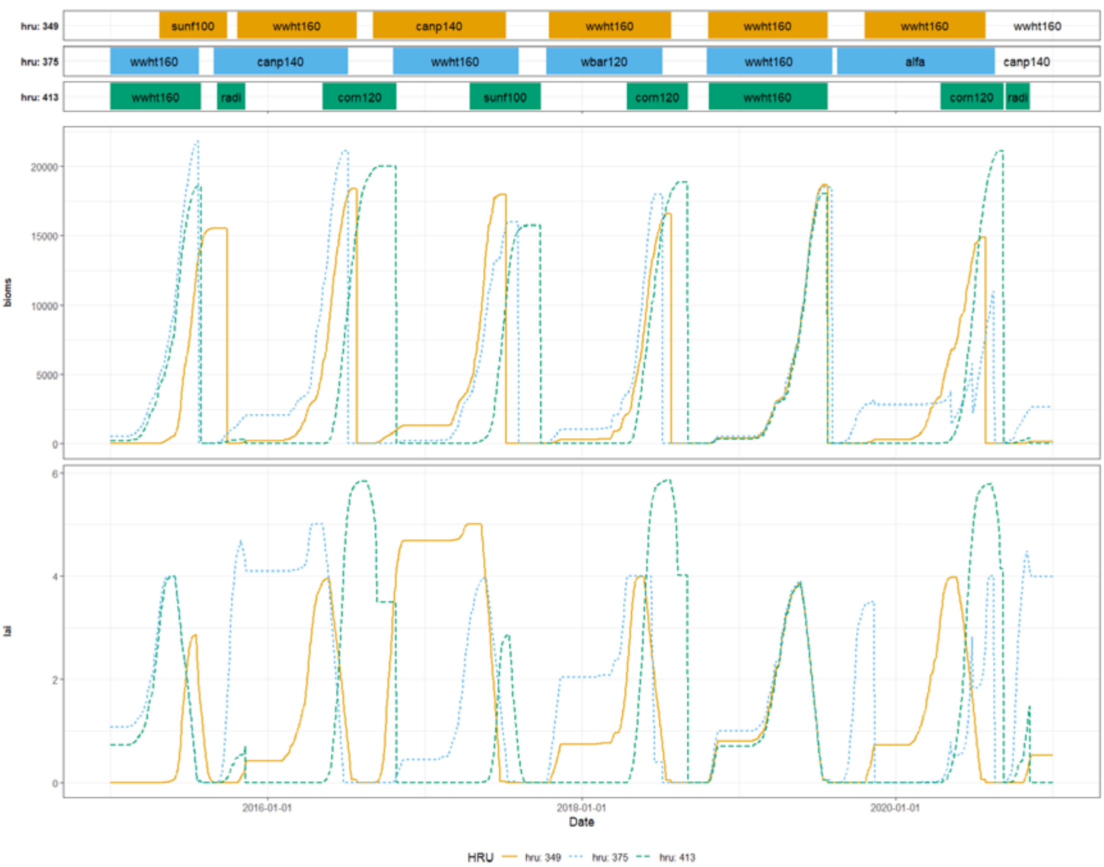


Figure A11.5 Biomass and LAI development for a simulation with all stress factors active for three example HRUs in CS11.

## 2.2. Soft calibration

The result of the crop yield soft calibration workflow is shown in Fig. A11.6.

First the days to maturity parameter (d_mat) was set to meet the desired accumulated plant heat unit value (PHU), which should reach the 1.0-1.2 range at the date of harvesting or killing the plants, except for alfa, for which a value below 0.5 is acceptable. The highest modification was needed in the case of winter crops – winter rape, winter barley and winter wheat (Table A11.4).

Then, four plant parameters, namely maximum potential leaf area index (lai_pot), harvest index for optimal growth condition (harv_idx), minimum temperature for plant growth (tmp_base) and biomass-energy ratio (bm_e), were adjusted to simulate the expected crop yield values.

The model could successfully predict the crop yield for corn, sunflower, winter barley and winter wheat. In the case of alfa and winter rape, there is some overprediction of the yield. In the case of these crops, we have to highlight that the SWAT+ plant database is only an approximation of the "real" crops growing in CS11 and might need some further specification based on local characteristics, but this is out of the scope of our analysis.

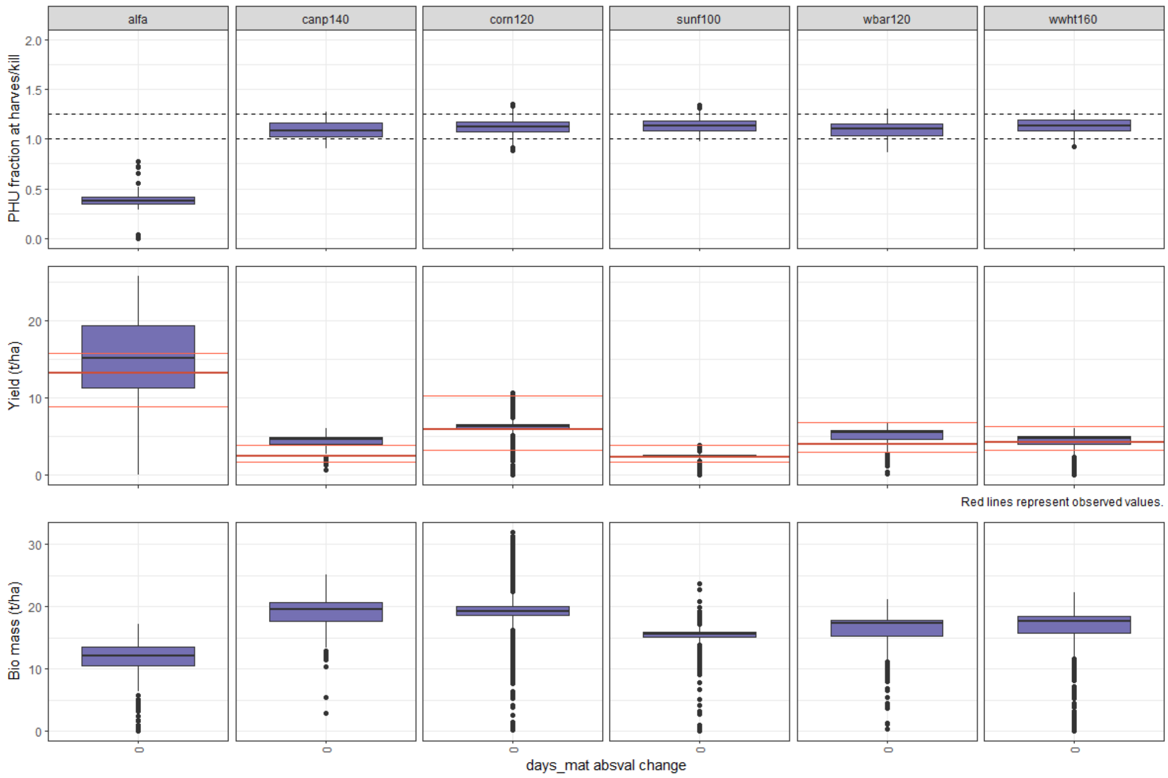


Figure A11.6 Final results of crop yield soft calibration for CS11. Simulated PHU fraction of harvest/kill (top row), crop yields (middle row) and biomass (bottom row).

Table A11.4 Final calibrated values of crop parameters.

| Crop | d_mat* | lai_pot** | harv_idx** | tmp_base* | bm_e** |
|---|---|---|---|---|---|
| alfa (alfalfa) | 0 | 0 | 0 | 0 | 0 |
| canp (winter rape)*** | -50 | 0 | -0.2 | 0 | 0 |
| corn (grain corn) | 10 | 0 | -0.2 | 0 | 0 |
| sunf (sunflower) | 30 | 0 | -0.2 | 0 | 0 |
| wbar ( winter barley) | -35 | 0 | -0.2 | 0 | 0 |
| wwht (winter wheat) | -50 | 0 | -0.1 | 0 | 0 |

* Absolute change ** Relative change

The observed water yield ratio is 0.12 for the time period 2001-2011. During the soft calibration we considered this value to adjust depth distribution used to meet the soil evaporative demand to account for the effect of capillary action, crusting and cracks (esco parameter). The range kept for hard calibration was between 0.44 and 0.95. Crop yield simulation results did not change significantly after adjusting esco.

## 2.3. Hard calibration and validation

In the hard calibration discharge and N-$NO_3$ was considered (Table A11.3). Sediment and phosphorus load would also be interesting in CS11 due to high erosion sensitivity of the catchment. However, the frequency of available phosphorus (P) and sediment concentration measurements was deemed insufficient for a successful calibration. Based on the suggested workflow derived in OPTAIN, first we performed calibration for discharge. For the calibration of nitrogen parameters, we considered the parameters from hydrology calibration. The simultaneous calibration workflow (hydrology and N-$NO_3$) was also tested, but appeared to be more challenging to obtain satisfactory results.

In hard calibration we considered 21 hydrology and 5 nitrogen parameters. For both observed variables the following five objective functions were computed and analysed: NSE, KGE, PBIAS, $R^2$ and MAE.

We followed the suggested workflow derived in OPTAIN, i.e. in each consecutive iteration the parameter space was being modified in order to improve the performance metrics, trying to account for possible conflicts between responses of different metrics to parameter changes. For the great majority of parameters, their ranges were considerably narrowed down based on interpretation of the dotty plots. The final selection included eighteen different parameter combinations and was based on setting threshold values for NSE, KGE and PBIAS and the sum of ranks for different metrics and variables. Time series plots including observed and simulated values are shown in Figs. A11.7-A11.10 with model output variability resulting from these nine parameter sets.

Discharge varied between 0 and 3.98 $m^3 s^{-1}$ in the period of 2001 and 2020. This variability could be captured both in calibration and validation (Fig. A11.7 and 8.). The majority of both high and low flows are described well by the model. The model underestimated some events with discharge below 0.25 $m^3 s^{-1}$ and some high flow events. Overestimation occurred for the validation period for some days after high flow events, which caused weaker performance for this period than the calibration one (Fig. A11.11).

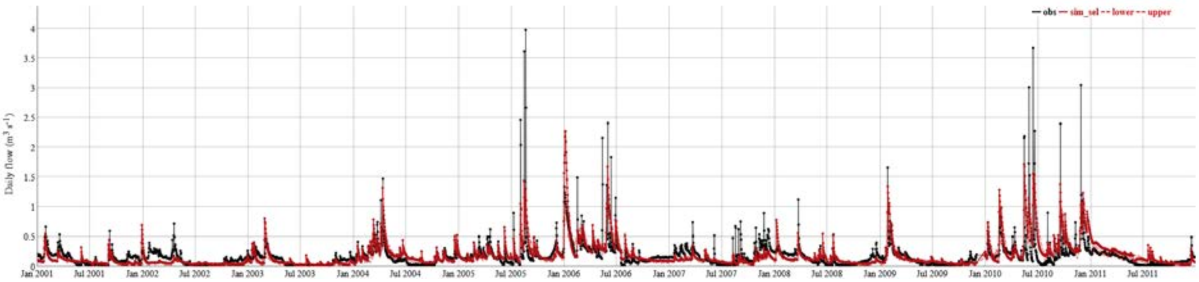


Figure A11.7 Simulated vs. observed daily discharge for flow gauge "Visz" in CS11 (calibration period).

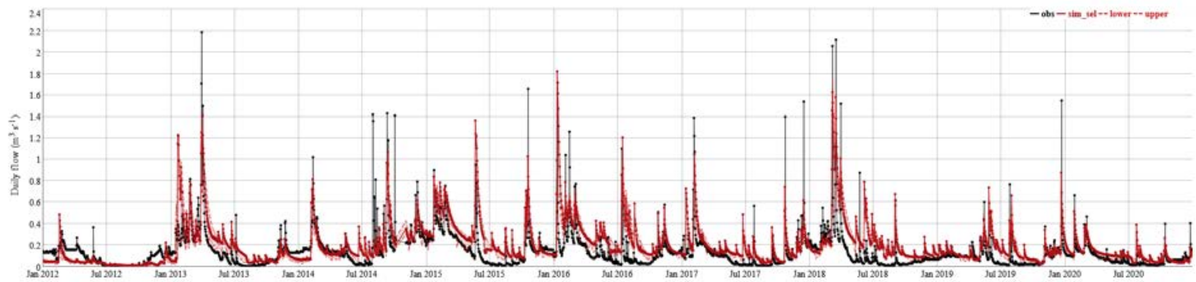


Figure A11.8 Simulated vs. observed daily discharge for flow gauge "Visz" in CS11 (validation period).

Nitrate pollution is an issue in CS3 (Fig. A11.9). The model captures the inter-annual dynamics of $N\text{-}NO_3$ concentrations, but highly overpredicted it for some years (2003, 2006). The model performance is limited by observed data availability. The frequency of grab sample data used for the calibration was not sufficient to accurately describe the changes in $N\text{-}NO_3$ concentrations. For better coupling between the hydrological and chemical dynamics, more frequently measured time series water quality data would be needed (Piniewski et al, 2019).

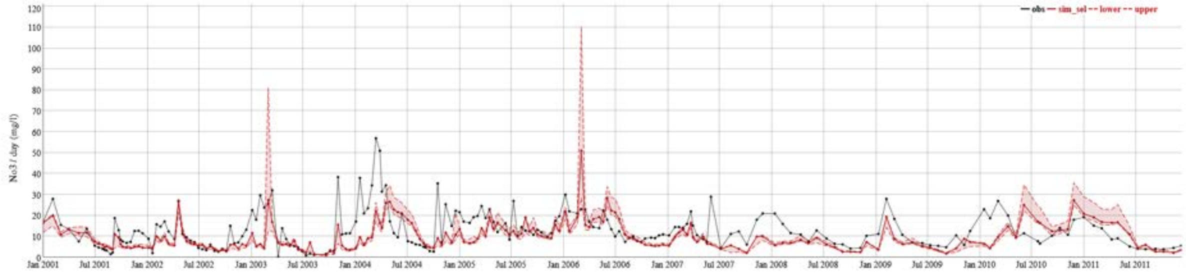

Figure A11.9 Simulated vs. observed bi-weekly/ monthly N-$NO_3$ concentrations for flow gauge “Visz” in CS11 (calibration period).

Figure A11.10 Simulated vs. observed monthly N-$NO_3$ concentrations for flow gauge “Visz” in CS11 (validation period).

Since the validation dataset is not fully homogenous with the calibration dataset, it partly explains lower values of the performance metrics shown in Fig. A11.11. As mentioned above, the model performance for N-$NO_3$ concentration is limited by observed data availability.

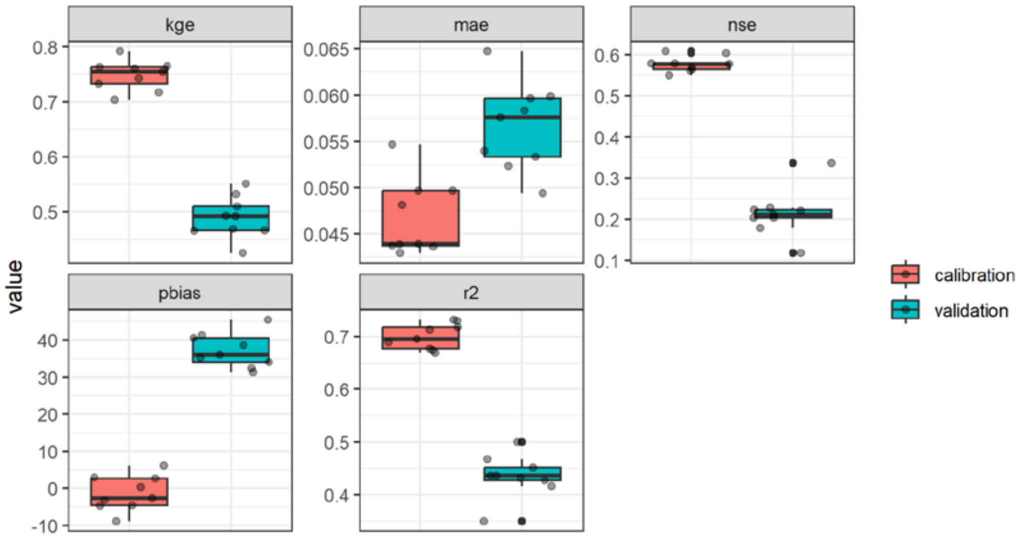


Figure A11.11 Box plots of model performance metrics for discharge in calibration and validation period for CS11.

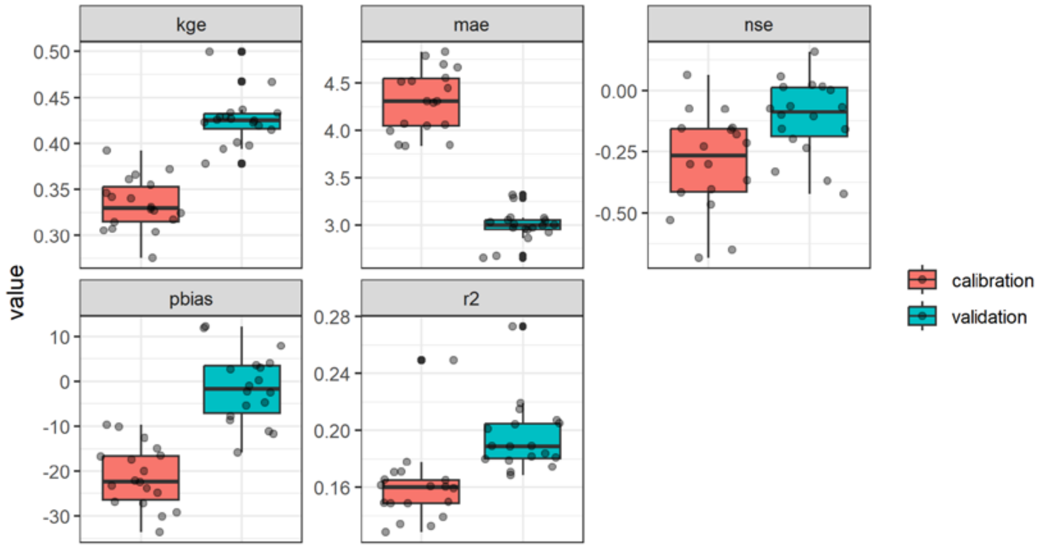


Figure A11.12 Box plots of model performance metrics for N-$NO_3$ concentrations in calibration and validation period for CS11.

Figure A11.13 shows the simulated water budget of the final version of the calibrated model setup, based on a single parameter set with the highest sum of ranks, for the period 2001-2020. 12 % of the precipitation becomes water yield. 81 % of the water yield is surface runoff. 81 % of the generated surface runoff flows onto the landscape. 73 % of the total evapotranspiration (et) comes from the plant component (eplant). Total evapotranspiration-precipitation ratio (et/precip) is 0.9, base flow ratio (base/wyld) is 0.2.

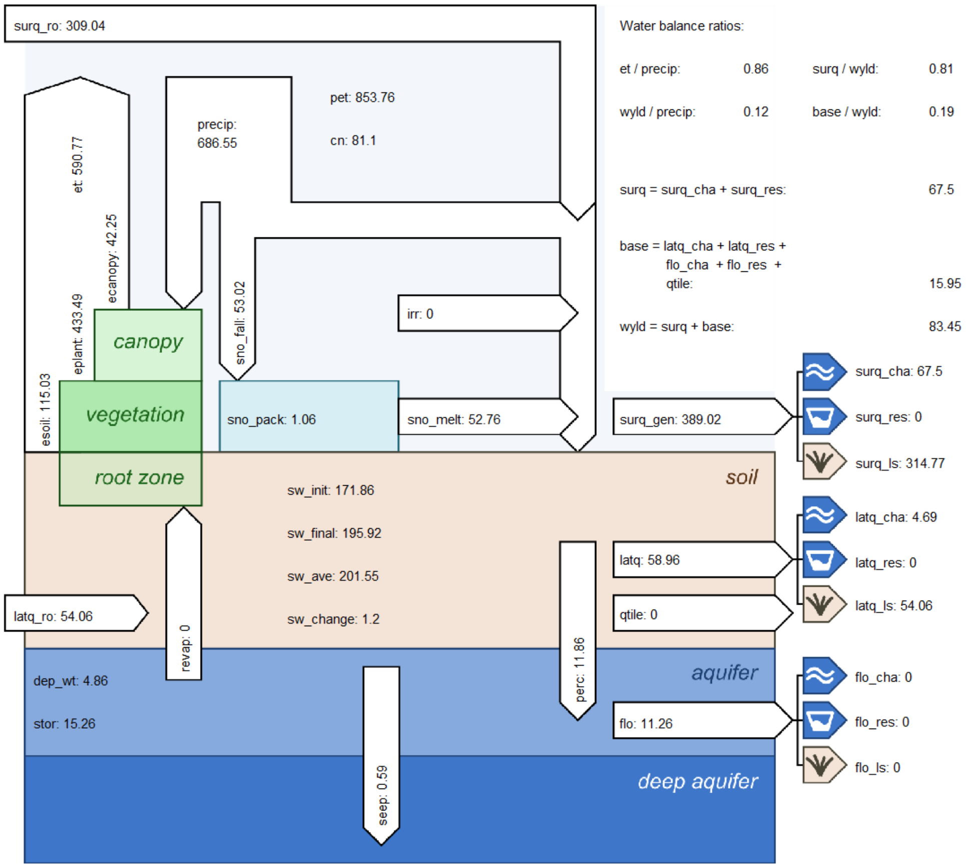


Figure A11.13 Simulated water budget of the final, calibrated model setup for CS11 (years 2001-2020).

## 3. Climate change effects

Similarly, as described in Annex 4, we followed the OPTAIN protocol, therefore we used bias-corrected RCM simulations developed in the WP3 (Honzak, 2023) as the SWAT+ model forcing in order to assess the effect of climate change on the water balance, nutrient losses and crop yields. For the bias correction, locally measured data was considered. We applied all available combinations of six RCMs, three RCPs and three time horizons, resulting in a total of 54 model scenarios:

- 1991-2020 - serving as the “baseline”,
- 2036-2065 - “near future”,
- 2070-2099 - “end of century”.

Figure A11.14 shows projected changes in annual and seasonal minimum (Tmin) and (Tmax) temperature as well as precipitation (prec) for CS11. There is a warming pattern in the case of RCP8.5, for which projected increase in Tmin and Tmax ranges between 2.5 and 3.5 degrees C. The highest magnitude of the warming signal occurs in winter, while the lowest in spring. In contrast, under RCP2.6 the projected change does not generally exceed 1 degree. Precipitation projections show a signal of wetter future in the case of all RCPs. Under RCP8.5 spring and winter is wetter, summer is drier close to the end of the century. Under RCP2.6 autumn is drier, winter is wetter close to the end of the century. The 2071-2100 period is characterised by the highest model spread. In general, projected changes in wind speed, solar radiation and relative humidity are relatively low, even under RCP8.5, and thus should not contribute a lot to the effect of climate change on the studied indicators.

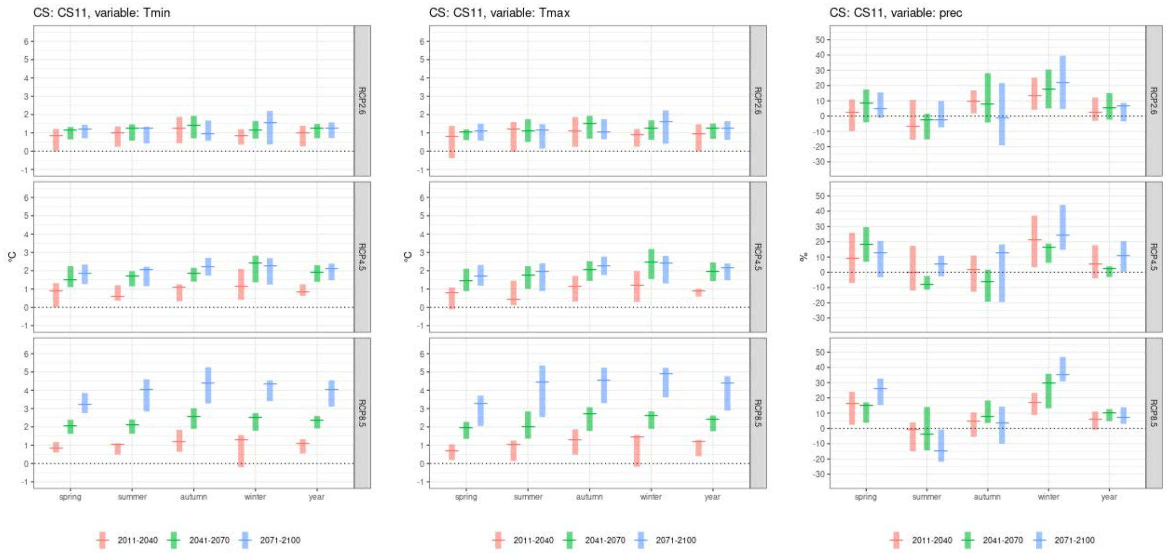


Figure A11.14 Projected changes in variables Tmin, Tmax and prec for all RCPs and time horizons for CS11 (Honzak, 2023).

In the analysis we included precipitation (precip), snowfall (snofall), snow melt (snomlt), potential evapotranspiration (pet), actual evapotarnspiration (et), percolation (perc), soil moisture content (in the root zone and in top 300 mm) (sw), surface runoff flowing into channels (surq_cha), lateral soil flow into channels (latq_cha) and tile flow (qtile) (Fig. A11.15). There is no tile drainage in CS11, therefore no effect of climate change was observed. As described above, an increase of precipitation is expected for all examined RCPs. Decrease of snowfall and melt and soil water content in the upper 300 mm is projected. Potential and actual evapotranspiration, surface runoff flowing into channels and lateral soil flow into channels are expected to increase in general. Increase of potential evapotranspiration might be triggered by increasing temperature. Increasing actual evapotranspiration can be due to higher soil water content. Increasing surface runoff flowing into channels (up to 45 % average value) and lateral soil flow into channels (up to 15 % average value) is triggered by the expected increase in precipitation.

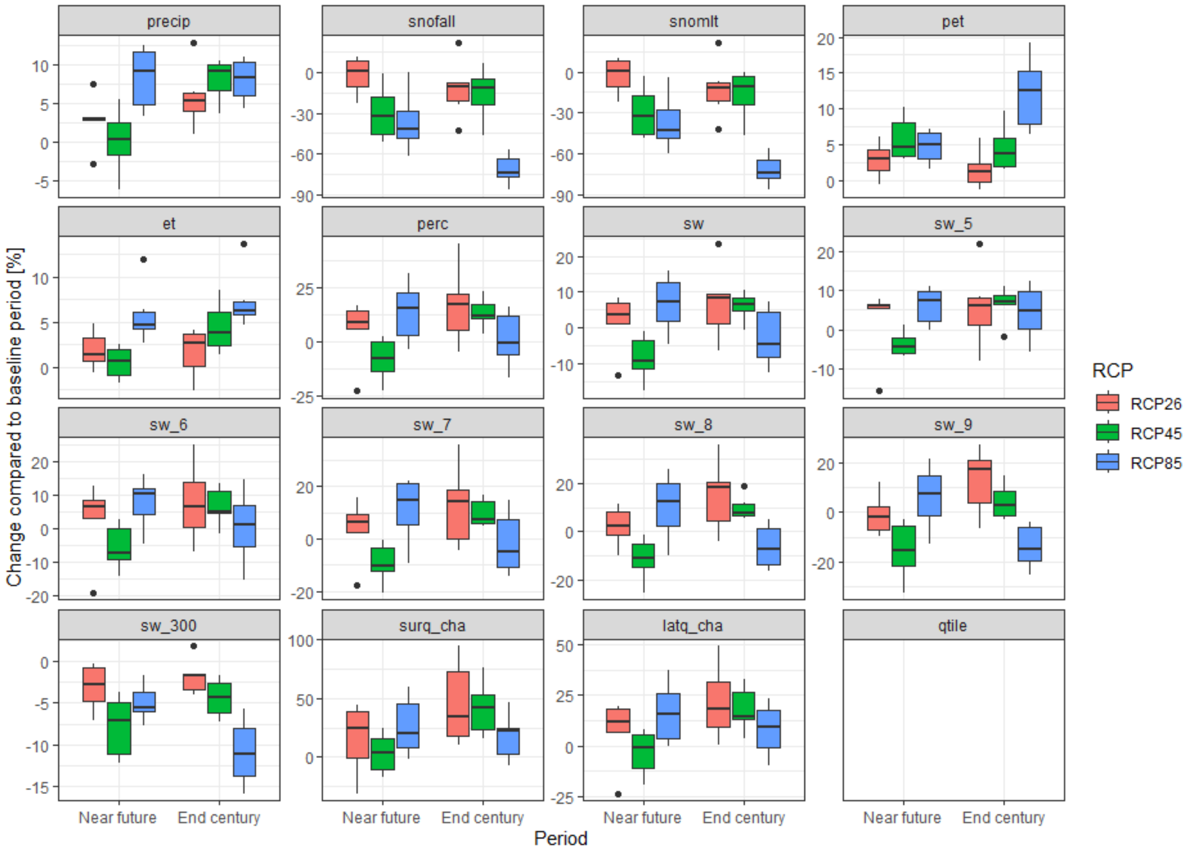


Figure A11.15 Projected changes in selected basin-averaged water balance components simulated by SWAT+ for CS11. There is no tile drainage in the case study, therefore qtile plot does not show any boxes.

Figure A11.16 shows projected changes in selected streamflow (Q) indicators simulated by SWAT+ for CS11. In the case of RCP2.6 average and median flow is projected to increase 20-25 %. In the case of RCP4.5 average flow does not change in the near future but is expected to increase in the end of the century. For RCP8.5, average flow is projected to increase 20 % in the near future which is kept at the end of the century. Low flow days are projected to increase in RCP2.6 and 4.5. In the case of RCP8.5 low flow days are expected to decrease in the near future and increase at the end of the century.

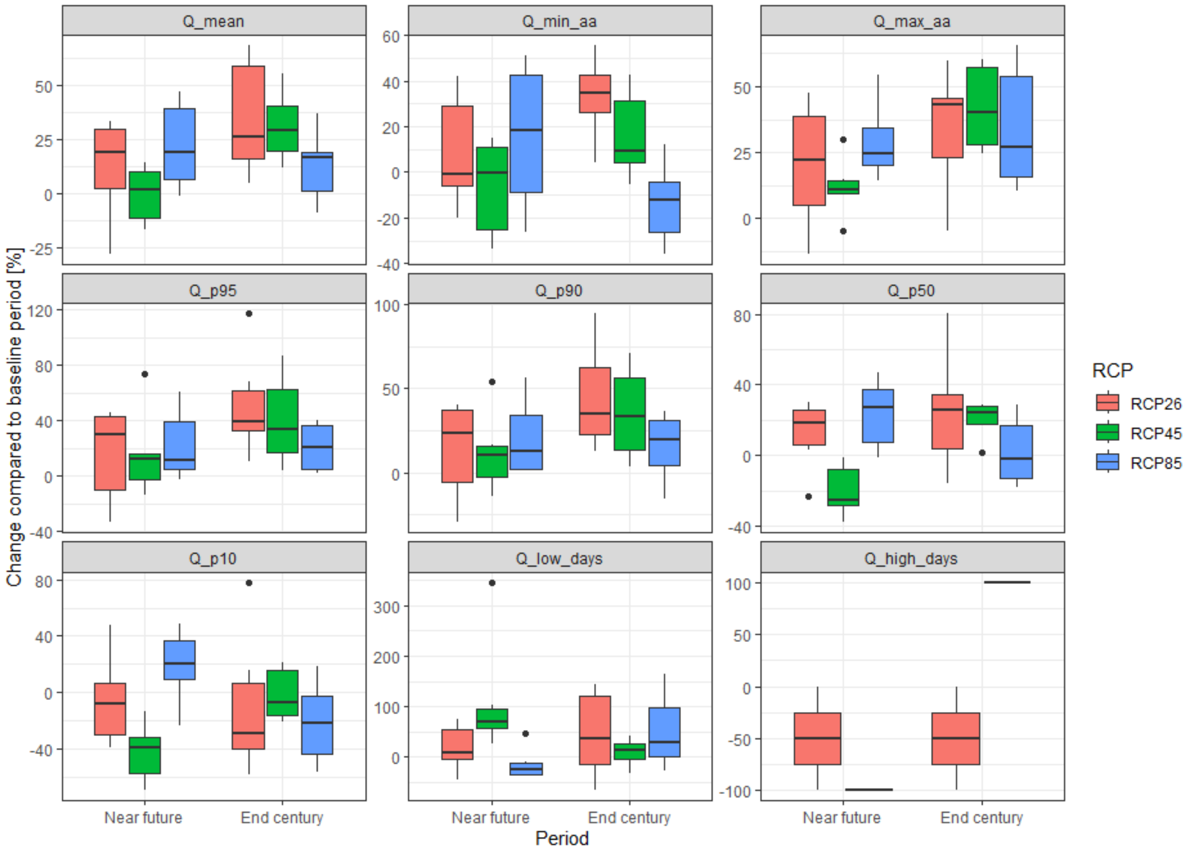


Figure A11.16 Projected changes in selected streamflow indicators simulated by SWAT+ for CS11.

Figure A11.17 shows projected changes in water quality for CS11. During the SWAT+ modelling nitrate nitrogen was calibrated and validated for CS11. The plots show total nitrogen (TN), of which 90 % constitutes from $NO_3$-N. Phosphorus was not calibrated, therefore the reliability of phosphorus related results is lower. In general, under wetter conditions in the future, TN and P losses are projected to increase. The frequency of days with high TN concentration is projected to increase (with an extreme case which might be erroneous), the opposite happens to TP concentration. Average nitrogen load of the stream is projected to increase up to 10 % at the end of the century in RCP2.6. Expected trends are different for RCP4.5 and 8.6. Average phosphorus load of the stream is projected to increase up to 25 % at the end of the century in the case of RCP4.5.

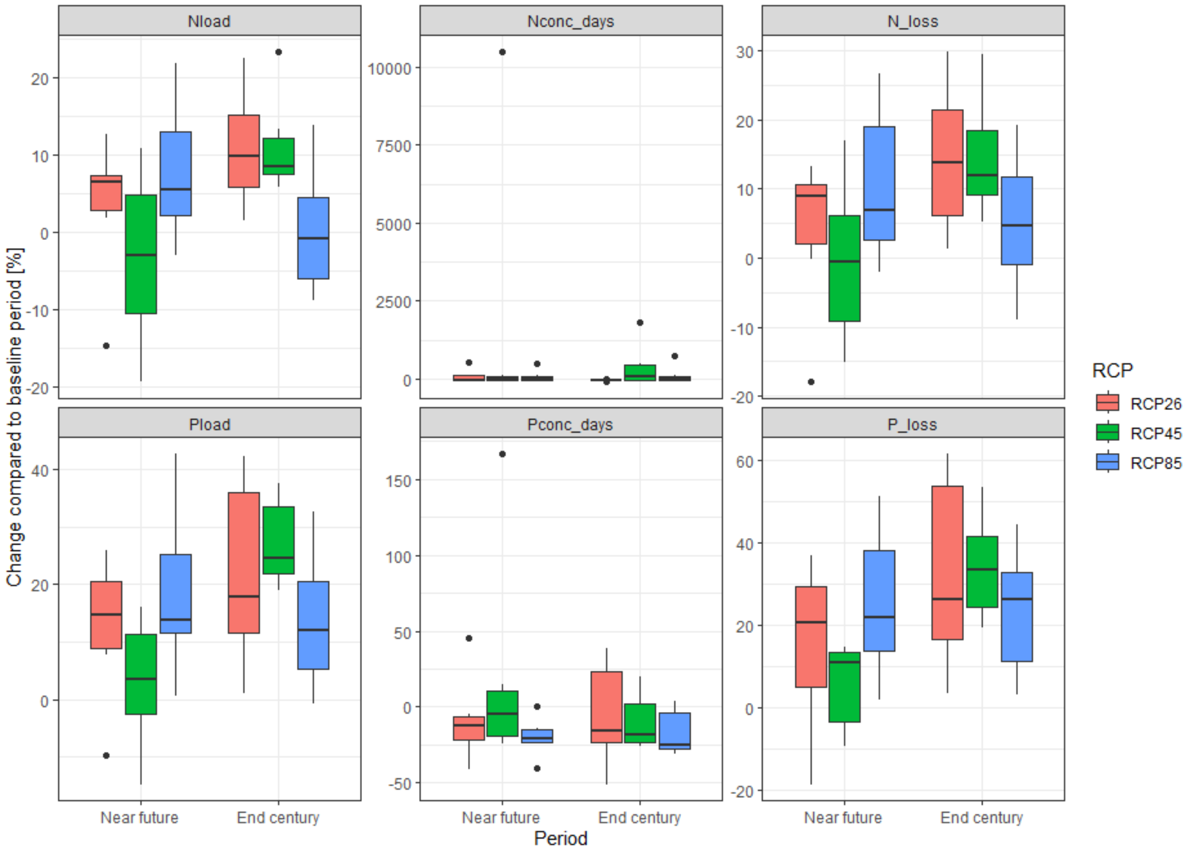


Figure A11.17 Projected changes in selected water quality indicators simulated by SWAT+ for CS11.

The mean crop yield of winter wheat (wwht), winter rape (canp), winter barley (wbar), and sunflower (sunf) is projected to decrease 1-8 % in the case of all analysed RCPs (Figure A11.18). Highest decrease is expected in the case of RCP8.5, especially for winter rape and sunflower. For corn, a slight increase is expected in the near future in RCP2.6, but in all other cases a 1-4 % decrease is projected. For lucerne (alfa) yield increase is projected, around 5 % under RCP2.6 and 4.5 and 12-15 % under RCP 8.5.

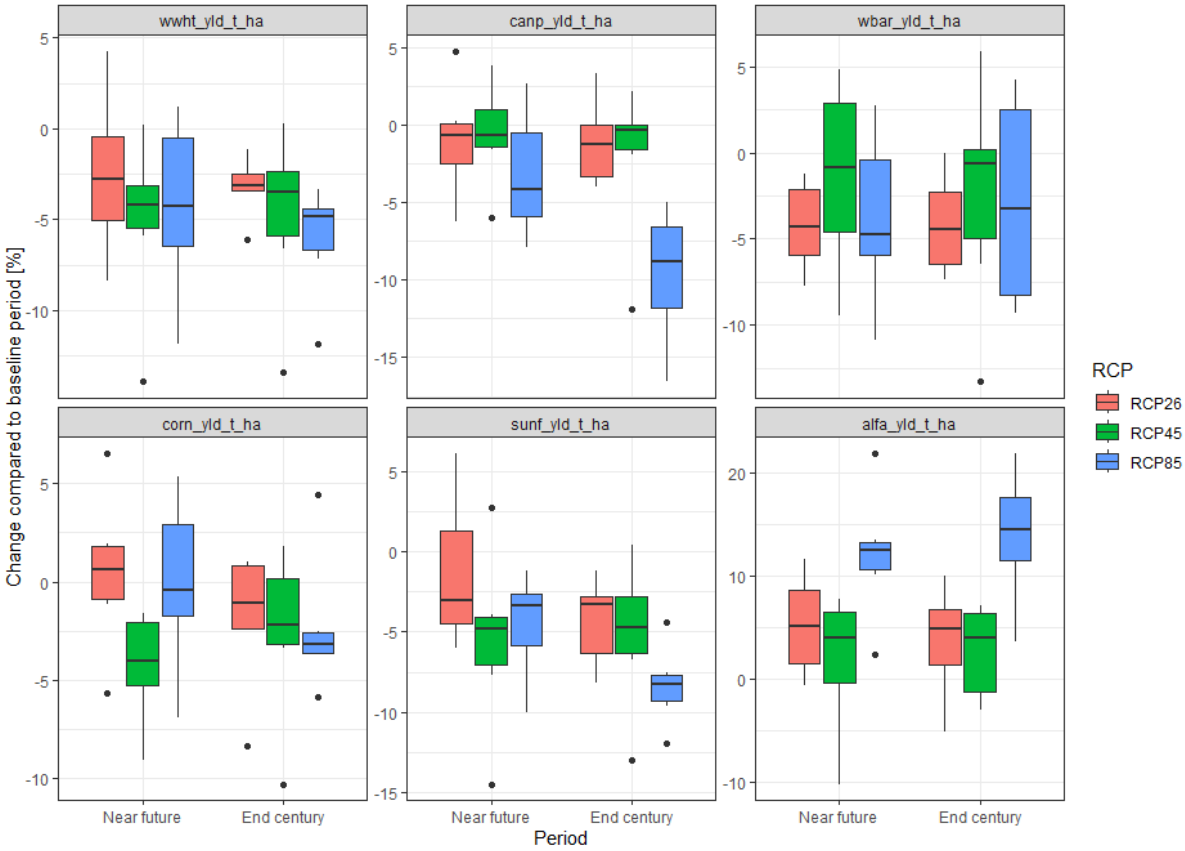


Figure A11.18 Projected changes in selected crop yields simulated by SWAT+ for CS11.

## 4. Effectiveness of selected NSWRMs (current climate)

For the analysis of possible NSWRMs scenarios we identified the following measures:

- Field dividing: halving the agricultural fields above 50 ha and implementing buffer strips between the fields, based on the suggestion of the local agricultural advisor.
- Forested buffer strips: between the halved parcels - perpendicular to the water course (+ based on the visual review of the satellite image some extra buffers strips were placed between some highly erosion prone parcels), size: 20 m wide (NAK, 2018).
- Cover crop: on croplands where mean soil loss is 15-40 t/ha (MSZ 1397:1998, 1998; Verheijen et al., 2009).
- No till: on croplands where mean soil loss > 40 t/ha (Verheijen et al., 2009).
- Afforestation: on cropland parcels above 12% mean slope.
- Riparian forest buffer: along the stream.

From the above list (1) afforestation, (2) implementation of riparian buffer, (3) field dividing and implementing forested buffer strips between the fields and (4) no-till management with cover crops were included in the NSWRMs scenario analysis (Fig. A11.19).

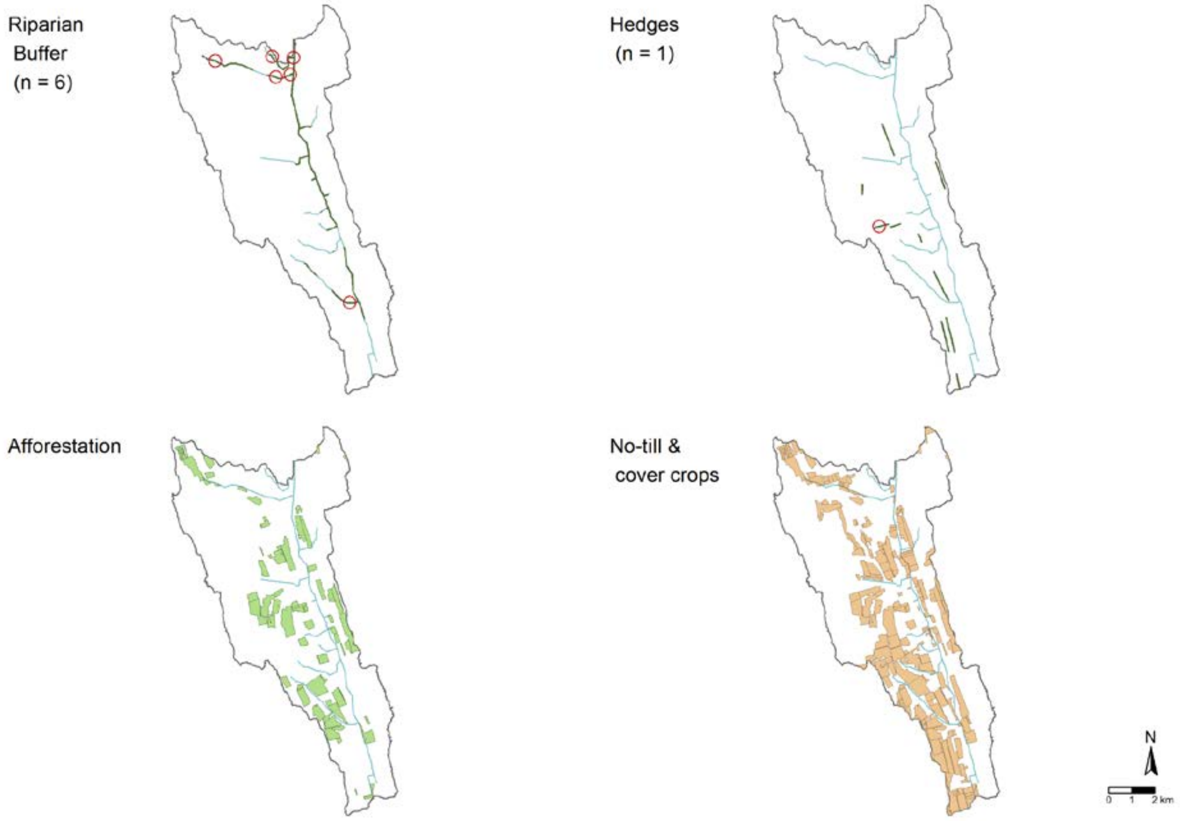


Figure A11.19. Location of measures selected for the NSWRMs scenario analysis.

Figure A11.20 shows the projected changes in the selected hydrological, nutrients and sediments and crop yield indicators. The SWAT+ model was not calibrated for phosphorus and sediment concentration, therefore the uncertainty of the projected changes in their indicators is not known.

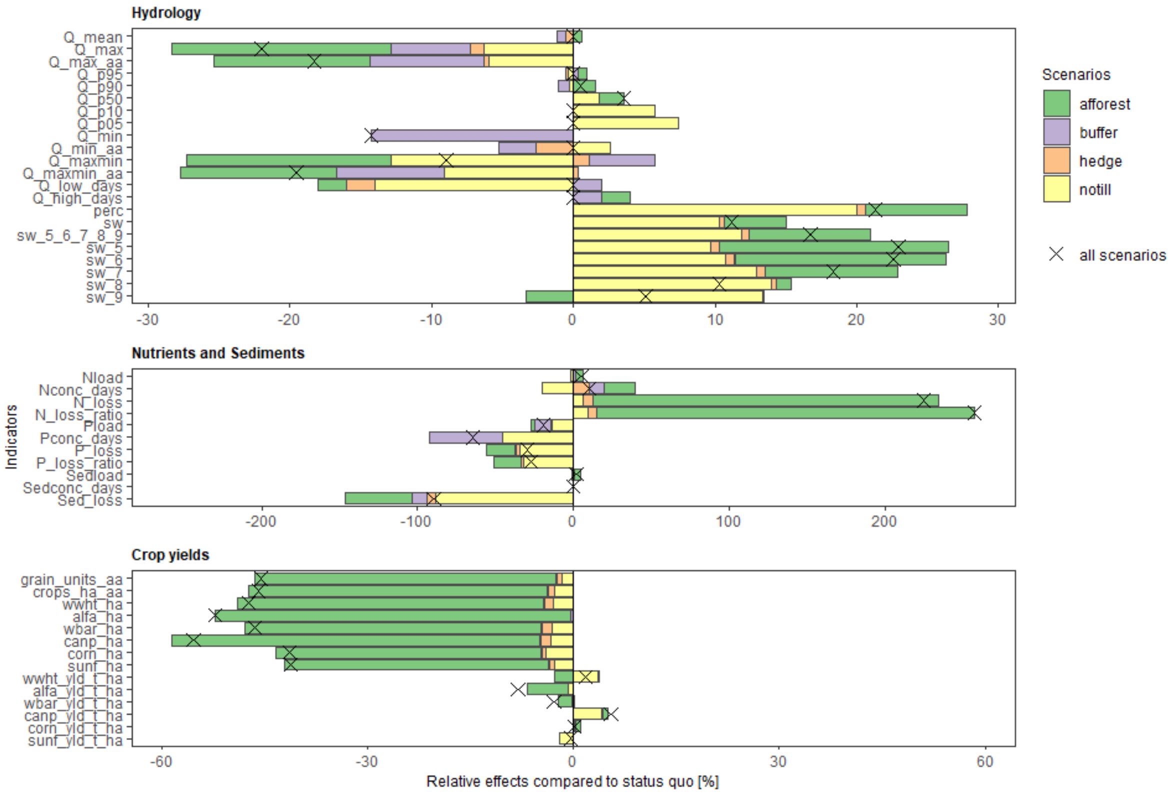


Figure A11.20 Projected changes in selected hydrological, water quality and crop yield indicators simulated by SWAT+ for CS11 for the selected NSWRM scenarios.

### Afforestation

Afforestation was applied on fields i) with mean soil loss higher than 40 t/ ha/ year or ii) located on slopes steeper than 12 %. Regarding hydrology indicators, mean discharge is not projected to notably change for the implementation of afforestation. High flows are expected to decrease by 16 %. Median flows (Q_p50) are expected to increase by 2 %. Differences between high and low flows (Q_maxmin) are expected to decrease by 16 %. Number of days with low flow (Q_low_days) is projected to decrease by 2 %. Percolation (perc) is expected to increase by 7 %. Soil water content (sw) is projected to increase by 5 %, in the period from May to August the expected increase is even higher, between 9 and 17 %. Regarding water quality indicators, the daily nitrogen concentration and nitrogen loss are projected to increase by 20 % and 200 %, respectively. This increase might originate from the significant increase in total nitrogen due to changing crops to forest. Phosphorus loss is projected to decrease by 20%, and load is projected to decrease by 5 %. Sediment loss is projected to decrease by 50 %. The decrease of phosphorus and sediment load is in line with the expected effect of land use change from arable land to forest. The area of arable land obviously decreases by the area of forest implementation. The crop yield does not notably change.

### Riparian forest buffer

Riparian forest buffers were applied along the stream 20 m wide on those HRUs which had land cover type other than forest. Regarding hydrology indicators, mean discharge is not projected to notably change for the implementation of riparian forest buffers. High flows are expected to decrease by 4 %. For the Median flows (Q_p50) there are no expected effects. Differences between high and low flows (Q_maxmin) are expected to increase by 5 %. Number of days with low flow (Q_low_days) is projected to increase by 2 %. Percolation (perc) there is no expected effect. For Soil water content (sw) there is no expected effect. Regarding water quality indicators, the daily nitrogen concentration is projected to increase by 10 % for nitrogen loss, there is no expected effect. For Phosphorus loss there is no expected effect, and load is projected to decrease by 10 %. Sediment loss is projected to decrease with 10 %. The decrease of phosphorus and sediment load is in line with the expected effect of land use change from arable land to riparian forest buffer. The area of arable land obviously decreases by the area of riparian forest buffer implementation. The crop yield does not notably change.

### Field dividing and implementing forested buffer strips between the fields

Field diving and implementing buffer strips (hedge) was applied on those agricultural fields which are currently larger than 50 ha. Their projected change is not notable for discharge. Percolation is projected to increase by 2 %. Increase in soil water content is slight, between 1-2 %. Their influence on nutrients and sediments is in the case of the daily nitrogen concentration is projected to increase by 5 % for nitrogen loss, increase by 3 %, in the case of sediment loss, is projected to decrease by 5 %. The expected change of the crop indicators is negligible, it is between -3 and 0.2 %. The area of the crops obviously change, due to the area needed for implementing the hedges.

### No-till management with cover crops

No-till management with cover crops was applied on all croplands of CS11. No-till with cover crops has a high projected impact on all analysed indicators. High flow decreases by 6 %, low flow by 12 %. Number of days with low flow is expected to increase by 14 %, the difference between low and high flow by 13 %. Percolation is expected to increase by 20 %. Soil water content is expected to increase by 10 % on average, by 12 % between May and September. Regarding nutrients and sediments: N loss is expected to increase by 5 % and P loss is expected to decrease by 30 %. Sediment loss is projected to decrease by 90 %. These findings are in line with the fact that no-till management combined with cover crops significantly decrease surface runoff, increase infiltration - due to improved soil structure - therefore decrease nutrient and sediment loss. However, it has a slightly negative effect on crop yields between -1 % and -5 %.

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# Annex 12 Modelling results for CS12 (Čechticky Catchment, CZ)

Authors: Štěpán Marval, Petr Slavík, Petr Fučík, Antonín Zajíček (VÚMOP)

## 1. Model setup

The SWAT+ model for CS12 catchment (Čechticky Catchment) was set up following the OPTAIN workflow (Schürz et al., 2022). The majority of input data were prepared with the help of GIS/QGIS.

The uncalibrated model setup was developed using the R script for the model setup generation workflow (https://git.ufz.de/optain/wp4-integrated-assessment/swat/swat-setup/full_workflow) consisting of both SWATbuildR (version 1.5.9) and SWATfarmR (version 4.0.2). The SWAT+ model revision 61.0 (from 1/12/2024) was used in all simulations.

### 1.1. Input data overview

The input data for the Čechtický catchment case study was mainly obtained from official sources. Most of the data were subsequently modified for modelling purposes within the OPTAIN project. Our own (Department of Hydrology and Water Conservation - VUMOP) data sources and observations were also used as input data. A long series of crop data (1988 - 2021) had to be estimated based on data for the years (2016 - 2021). The source, resolution and possible modification of the input data is summarised in Table A12.1.

Table A12.1 Summary of input data for CS12.

| Input | Number of objects / resolution | Source | Comments |
|---|---|---|---|
| DEM | 5 m | State Administration of Land Surveying and Cadastre | |
| Channel layer | 210 | The Digital Database of Water Management Data (DIBAVOD) - T.G. Masaryk Water research institute | |
| Land layer | 2407 | State Administration of Land Surveying and Cadastre, Land Parcel Identification System (LPIS), Povodí Vltavy, State Enterprise, own survey. | Linking datasets current Database of Topographic Objects with crop maps and the scenario maps for structural measures. Information on drainage from historical maps and remote sensing has also been added. |
| Soil layer | 19 | State Land Office, The Forest Management Institute (FMI) | A map of the valuated soil-ecological unit was used, which was then simplified to the main soil unit. The database of forest soils of the Czech Republic was also used. |
| Usersoil table | 19 | Complex soil survey 1960 - 1971 | Historically measured soil probe data were used to determine specific soil characteristic values. |
| Point sources | 4 | Povodí Vltavy, State Enterprise | |
| Weather data | 1 station | Own observed data (VUMOP) | |
| Atmospheric deposition | 1 | European Monitoring and Evaluation Programme (EMEP) | EMEP data processed by SWATprepR |
| Crop sequence map | 2407 | Land Parcel Identification System (LPIS) | Crop data from LPIS were obtained for the years 2016-2021. Subsequently, the series was linearly extended to 1988. |
| Management schedules | 12 | Local farmers | Schedules prepared in consultation with local farmers. |

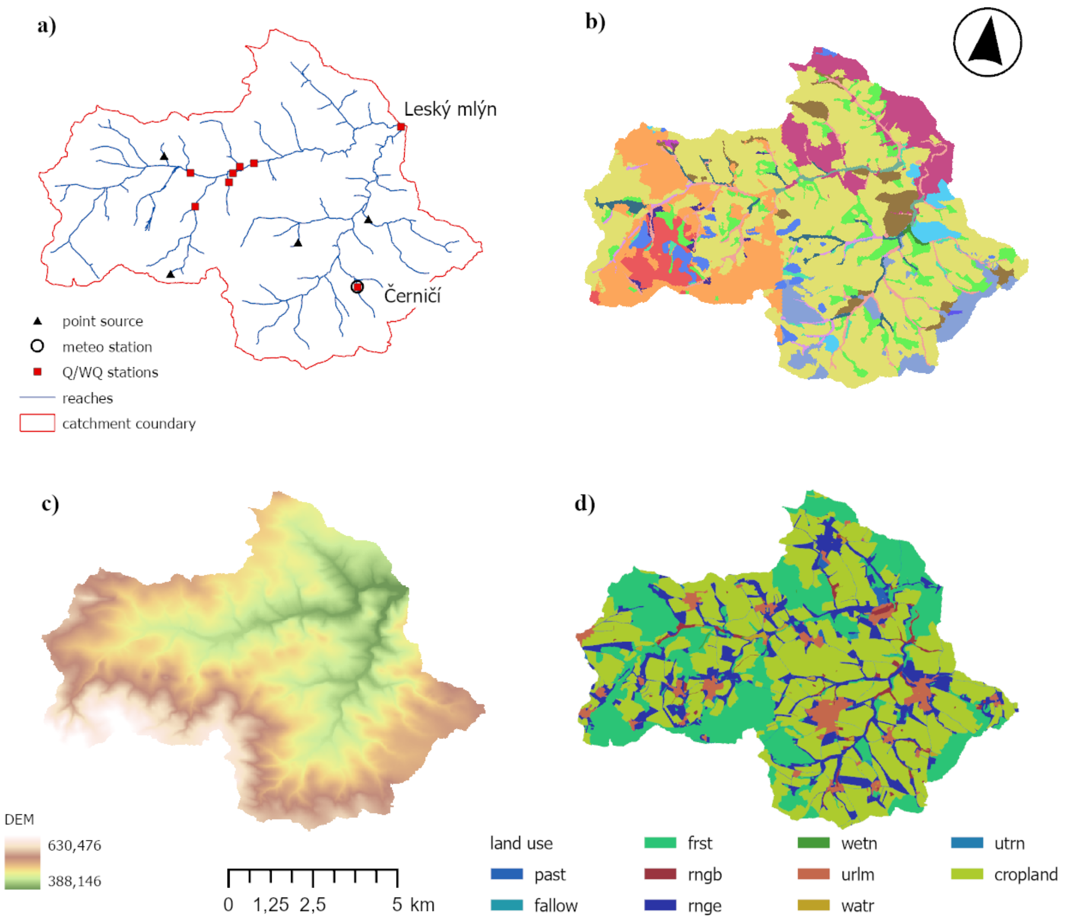


Figure A12.1 GIS input data for CS12: a) water flow, water quality (Q/WQ), meteorological stations, point source locations, reaches and catchment boundary; b) soil type map; c) DEM map; d) land use map with crop type specification for 2021, classes defined as in land cover/plant growth database (Arnold et al., 2012).

## 1.2. Baseline model setup

The following table A12.2 shows a summary of the number of individual parameters entering the simulation for CS12 Čechtický catchment.

Table A12.2 Individual parameters entering the simulation.

| Parameter | Value |
|---|---|
| Total area of the watershed in ha | 7143 |
| Total number of spatial objects in the simulation | 4948 |
| Number of HRUs in the simulation | 2327 |
| Number of routing units in the simulation | 2327 |
| Number of aquifers in the simulation | 1 |
| Number of reservoirs in the simulation | 80 |
| Number of recalls (point sources/inlets) in the simulation | 3 |
| Number of SWAT-DEG channels in the simulation | 210 |
| Number of crops in rotation | 12 |
| Number of wetlands | 12 |

## 2. Model evaluation

Table A12.3 shows the observation data for the variables used in the soft (crop yields, water yield ratio) and hard calibration (discharge, N-NO3 concentrations). The crop yield values were derived from published data from the Czech Statistical Office, which provides average values across the regions of the Czech Republic. Discharge data were obtained from two points. One is the closure profile of the whole case study (Leský mlýn), here the data were obtained from the Vltava River Basin, state enterprise in the period 1991-2020. The second point is the actual data from the experimental catchment Černičí in the period 2006-2021. For both observation points the data were provided in a daily time step. For the Leský mlýn point, nutrient data were provided at the same length as the runoff data at a monthly time step. In addition, for the other sites (see A12.1), several values (up to ten values) were obtained for the various nutrients listed above.

Table A12.3 Summary of observation data used in different steps of the calibration workflow for CS12.

| Variable | Time step | Calibration period | Validation period | Source | Comments |
|---|---|---|---|---|---|
| Soft calibration | | | | | |
| Crop yields | Average annual | 2014-2022 | NA | Czech Statistical Office | Average annual for closest region |
| Water yield ratio | Average annual | 2014-2022 | NA | Povodí Vltavy, State Enterprise, our own observed data | Calculated from observed discharge and precipitation |
| Hard calibration | | | | | |
| Discharge - Leský mlýn | Daily | 2014-2017 | 2018-2021 | Povodí Vltavy, State Enterprise | |
| Discharge - Černičí | Daily | 2014-2017 | 2018-2021 | Own observed data | |
| N-NO3 - Leský mlýn | Monthly | 2014-2017 | 2018-2021 | Povodí Vltavy, State Enterprise | Grab samples |

## 2.1. Model setup verification

All steps of the model setup verification were performed in accordance with the OPTAIN workflow (Plunge et al., 2023). Verification of the climate and water balance data (Fig. A12.3) showed that all reported values are in plausible ranges according to the expert knowledge of the studied catchment. The comparison of how different stress factors affect crop yields of an uncalibrated model also showed plausible results, i.e. reductions of crop yields within reasonable ranges (Fig. A12.4). Analysis of biomass and LAI development (example shown in Fig. A12.5) showed acceptable behaviour.

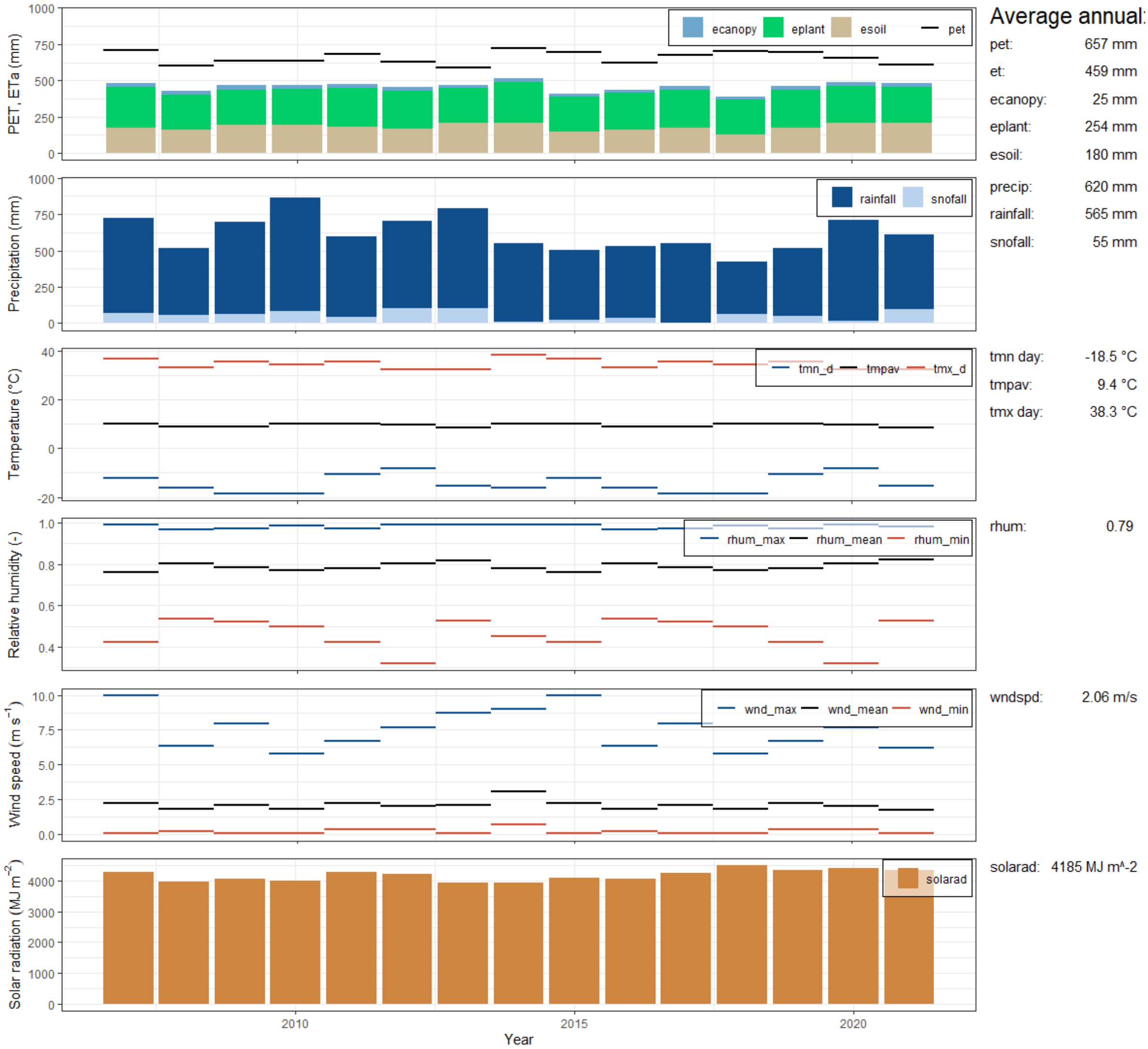


Figure A12.3 Summary of the climate data checks for CS12 by the SWATdoctR.

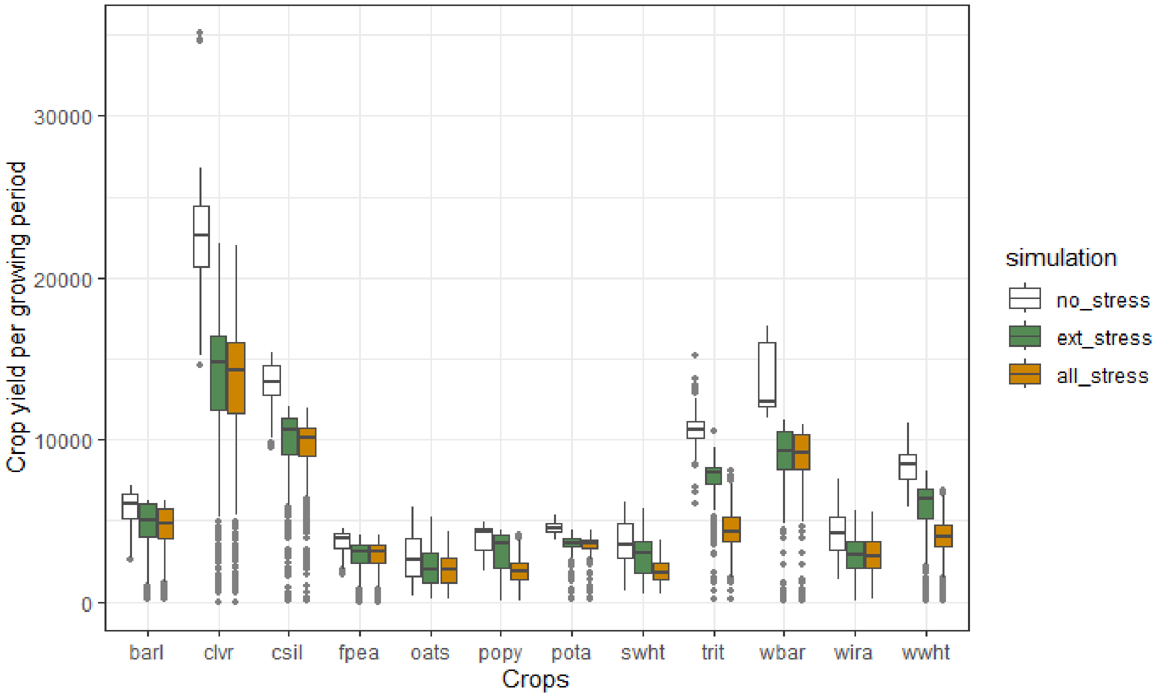


Figure A12.4 Comparison of crop yields with all stress factors, external stress factors and no stress factors for CS12.

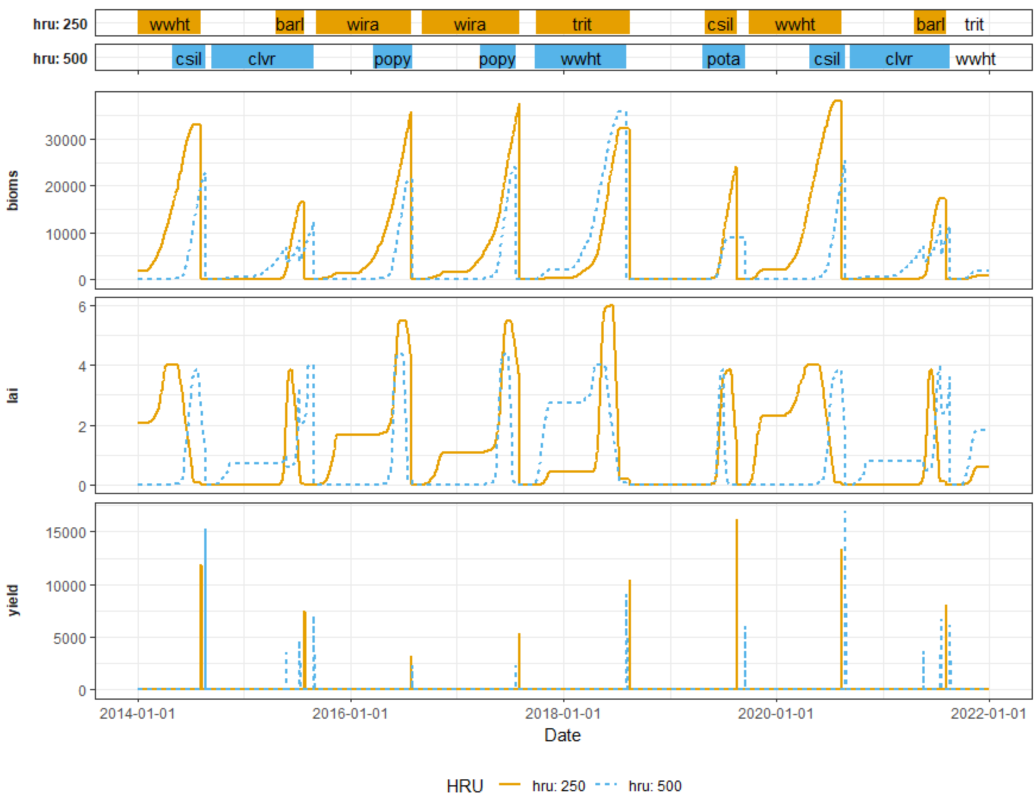


Figure A12.5 Biomass, LAI development and yields for a simulation with no stress factors active for two examples HRU in CS12.

## 2.2. Soft calibration

The soft crop yield calibration workflow has been used successfully in CS12, see Figure A12.6. The standard soft calibration workflow was applied for every crop. This consisted in changing the parameter d_mat (days to maturity) that the accumulated PHU fraction at harvest/kill was of desired value. For cereals 1.2 - 1.5, for green harvested crops 0.5 - 0.8, for multiple harvested crops even below 0.5 depending on the number of harvests per year (e.g. clover with three harvests).

In the second step, efforts were made to achieve the observed yield values by adjusting 4 other parameters. Our simulated crop yield values after the first step were akin to the observed ones, so only small adjustments had to be made.

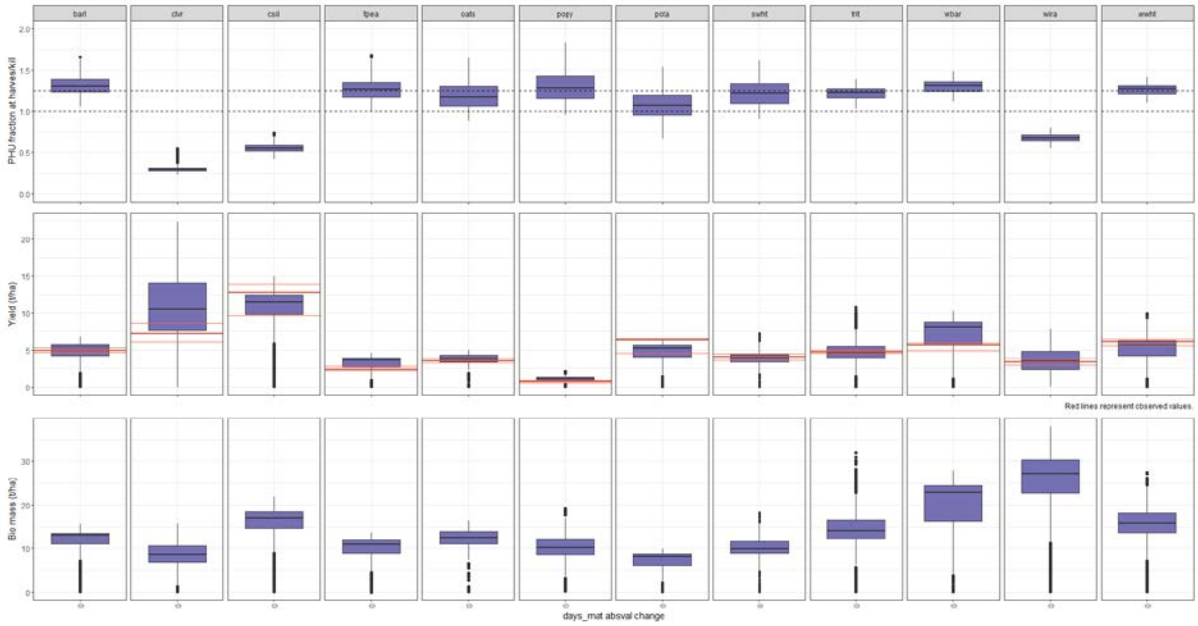


Figure A12.6 Final results of crop yield soft calibration for CS12. Simulated PHU fraction of harvest/kill (top row), crop yields (middle row) and biomass (bottom row).

Table A12.4 Final calibrated values of crop parameters.

| Crop | d_mat* | lai_pot** | harv_idx** | tmp_base* | bm_e** |
|---|---|---|---|---|---|
| barl (spring barley) | -30 | 0 | 0.1 | 0 | 0 |
| clvr (clover) | 0 | 0 | 0 | 4 | 0 |
| csil (corn silage) | 0 | 0 | 0 | 0 | 0 |
| fpea (field pea grain) | -20 | 0 | 0 | 0 | 0 |
| oats (grain oats) | -40 | 0 | 0 | 0 | 0 |
| popy (grain poppy) | -20 | 0 | -0.5 | 0 | 0 |
| pota (potatoes) | 10 | 0 | 0 | 0 | 0.1 |
| swht (spring wheat) | -40 | 0 | 0.3 | 0 | 0 |
| trit (winter triticale) | 10 | 0 | 0 | 0 | 0 |
| wbar (winter barley) | -20 | 0 | 0.1 | 0 | 0 |
| wira (winter rape) | 0 | 0 | 0.3 | 0 | 0 |
| wwht (winter wheat) | -60 | 0 | 0.3 | 0 | 0 |

* Absolute change ** Relative change

Soft calibration of the water balance was done by adjusting the value of esco parameter. We managed to match the observed water yield value of 0.184 exactly to the simulated one by setting the esco parameter to 0.26. The simulated crop yield results didn't change notably after calibrating the water yield ratio.

# Annex 13 Modelling results for CS13 (Dviete, LV)

Authors: Arturs Skute, Juris Soms, Davis Gruberts (DU)

## 1. Model setup

### 1.1. Input data overview

The input data for the Dviete catchment case study was mainly obtained from official sources. Most of the data were subsequently modified for modelling purposes within the OPTAIN project. Our own (Department of Ecology of Life Science and Technology Institute, Daugavpils University) data sources and observations were also used as input data. Hydrology of the Dviete River is determined by temperate continental climate and long-term human activity (melioration, deforestation, agriculture) within its drainage area. The catchment C13 occupies 253 km$^2$, the annual runoff of the 37 km long river is 0,057 km$^3$. The slope of the riverbed is around 4 m km$^{-1}$ at the upland and 0,2 m km$^{-1}$ at the lowland. The hydrological regime of the Dviete floodplain is significantly influenced by the Daugava River, whose floodwaters enter the Dviete valley almost each year in late March and accumulate here in large quantities for 2-3 months. The peak flood discharge of the Daugava's floodwaters that enter the Dviete floodplain at the Dviete village exceeds 400 m$^3$ sec$^{-1}$. Therefore, a strong reverse flood-flow is observed at the lower reach of the Dviete River each spring (Skute et al., 2008). The Dviete floodplain area is a Natura-2000 site: *The Dviete Floodplain Nature Park*, that was established in 2004 in the area of almost 5000 hectares. The source, resolution and possible modification of the input data is summarised in Table A13.1.

Table A13.1 Summary of input data for CS13.

| Input | Number of objects / resolution | Source | Comments |
|---|---|---|---|
| DEM | 2 m | Latvian Geospatial Information Agency open data | LiDAR-derived DEMs with spatial resolution 0.4 m; 1 m; 2 m and 5 m |
| Channel layer | 2478 | Manual digitizing of all channels | DEM (0.4 m resolution) + flow direction + flow accumulation = on-screen identification of channels. Total length = 763.37 km; Drainage density = 3.02 km · $km^{-2}$ |
| Land layer | 10259 | Orthorectified aerial RGB + NIR images (flown of 2021). | LiDAR-derived surface model and vegetation height model plus forest inventory data was used. |
| Soil layer | 17 | Manual digitization of soil inventory maps M 1 : 25 000, plus Soil Atlas of Europe, European Soil Database v2.0 | For non-agricultural areas maps of Quaternary deposits M 1 : 50 000 was used. |
| Usersoil table | 17 | State Regional Development Agency database | |
| Point sources | 0 | | |
| Weather data | 1 station | Own observed data (DU) | The meteorological station has been operating since 2008 |
| Atmospheric deposition | 1 | European Monitoring and Evaluation Programme (EMEP) | EMEP data processed by SWATprepR |
| Crop sequence map | 2109 | Rural Support Service (RSS) Republic of Latvia database | Crop data from RSS were obtained for the years 2017-2022 |
| Management schedules | 9 | Local farmers | Schedules prepared in consultation with local farmers. |

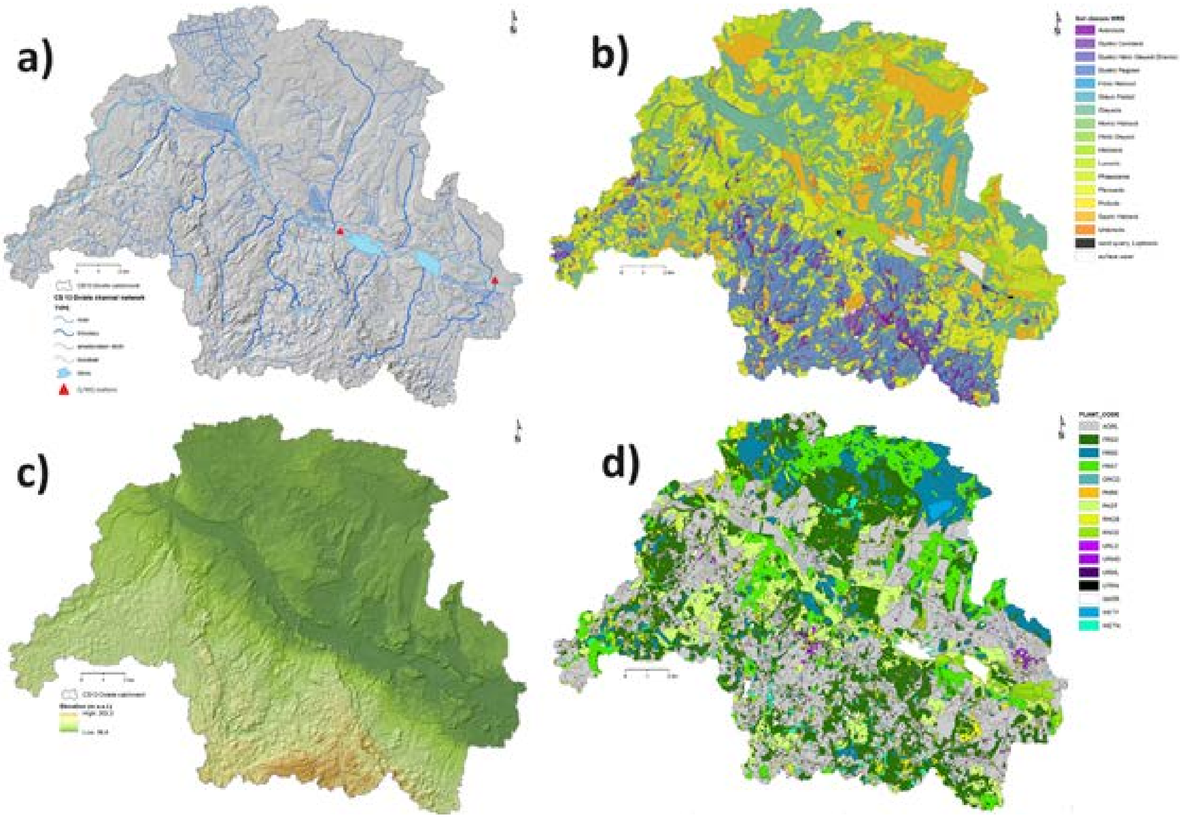


Figure A13.1 GIS input data for CS14: a) water flow, water quality (Q/WQ), channels and catchment boundary; b) soil type map; c) DEM map; d) land use map

## 1.2. Missing elements of the report and time plan to complete these tasks

Model evaluation is still ongoing and cannot be presented in its current form. There have been multiple reasons for the delay in the project. They can be summarized as follows: A change in workflow from using the SWAT+ modelling interface to a totally R-scripted workflow required a significant and unplanned investment of time to develop the necessary R expertise to test, apply and evaluate the R scripts.

The modelling process was significantly affected by the personnel change at Daugavpils University. It was difficult to find a suitable person after the departure of the previous SWAT+ modelling specialist. Once we had found a new employee to take over the modelling work, it took some time to make him aware of and involve him in all the nuances of the project. A full calibration and production of scenario results will be completed until autumn 2024. This extension will allow us to complete the task in a manner that supports project requirements without compromising the time planned for optimization in a significant way.

# 2. References

Schürz, C., Čerkasova, N., Farkas, C., Nemes, A., Plunge, S., Strauch, M., Szabó, B. and Piniewski, M.: SWAT+ modeling protocol for the assessment of water and nutrient retention measures in small agricultural catchments., 2022.

Skute A., Gruberts D., Soms J, Paidere J. 2008. Ecological and hydrological functions of the biggest natural floodplain in Latvia. Ecohydrology & Hydrobiology, vol 8, No 2-4:77-92 ISSN 1642-3593 (Print) 2080-3397 (Online); DOI: 10.2478/v10104-009-0023-y

# Annex 14 Modelling results for CS14 (Sävjaån headwaters, Sweden)

Authors: Emma Lannergård

## 1. Model setup

The SWAT+ model for the CS14 catchment (Sävjaån headwaters) was set up following the OPTAIN workflow (Schürz et al., 2022). The majority of input data were prepared by following the model protocol (Schürz et al., 2022). An uncalibrated model setup was developed using the R script for the model setup generation workflow consisting of both SWATbuildR (version 1.5.17) and SWATfarmR (version 1.4.2). The SWAT+ model revision 61.0 (from 1/12/2024) was used in all simulations.

### 1.1. Input data overview

Table A14.1 presents all major SWAT+ input data, their resolution and sources. Additional comments provide explanations on modifications made to adapt the input data to sufficient format. The catchment C14 occupies 35 km$^2$ and has a flat topography (65 m variation from highest to lowest point) (Figure A14.1). Land use is dominated by forest but with some agricultural and open areas along the main stream channel. Soil types in the forested areas are mainly moraine and partly organic soil, in the agricultural areas silty clay loam, clay loam and silty clay are the dominating soil types. The stream network comprises a primary channel with three smaller tributaries joining it, each contributing water from different areas.

Table A14.1 Summary of input data for CS14.

| Input | Number of objects/ resolution | Source | Comments |
|---|---|---|---|
| DEM | 2 m | Digital elevation model (Swedish Land Survey) | |
| Channel layer | 139 | Property map (network hydrography) | The layer was modified to account for NSWRMs planned for scenario simulations |
| Land layer | 1498 | National land cover database (Swedish Environmental Protection Agency) | Some categories were merged (e.g., as it would not be possible to parametrize them differently. |

| | | | |
|---|---|---|---|
| Soil layer | 9762 | Digital soil map: soil classes and texture (agricultural land), soil classes 1:25 000-1:100000 classes based on Swedish soil classification (Swedish Geological Survey) | Two data sources were merged, to get as specific representation as possible of all types of land (forest/agriculture). |
| Usersoil table | 20 | Based on soil profile data (Andersson and Wiklert, 1977a, Andersson and Wiklert, 1977b; Andersson et al., 1983a, Andersson et al., 1983b, Andersson et al., 1983c; Wiklert et al., 1983b, Wiklert et al., 1983a, Wiklert et al., 1983c, Wiklert et al., 1983d). | Data was grouped depending on soil texture (FAO classification), and depth (0-30, 30-60, 60-100cm); a median of the subsets of data was determined for dry bulk density, available water capacity, saturated hydraulic load, percentage of clay/silt/sand and rock. Soil albedo was calculated according to Sughatan et al. (2014), and SOC (%) was based on Ljung, 1987. |
| Point sources | - | - | Due to confidentiality, no locations of point sources could be shared from the authorities and hence were not used. |
| Weather data | 2 | Swedish Meteorological and Hydrological Institute | Weather data were processed by SWATprepR |
| Atmospheric deposition | 1 | European Monitoring and Evaluation Programme (EMEP) | EMEP data processed by SWATprepR |
| Crop sequence map | 379 | Swedish Agricultural Board | Derived from data on what was produced in the specific fields for 4 years, and reported to the authorities. In cases where the fields from the land use map were not exactly overlapping with the fields in the crop map, the crop that composed the majority of the land use unit was used. |
| Management schedules | 8 | Reports (Johnsson et al. 2016, Statistics Sweden, Swedish Agricultural Board, 2010, 2022, Andersson, 2016) and complementary interviews (Mårtensson, 2023; Heeb, 2023). | Schedules were prepared in consultation with the agricultural advisory service and other experts. |

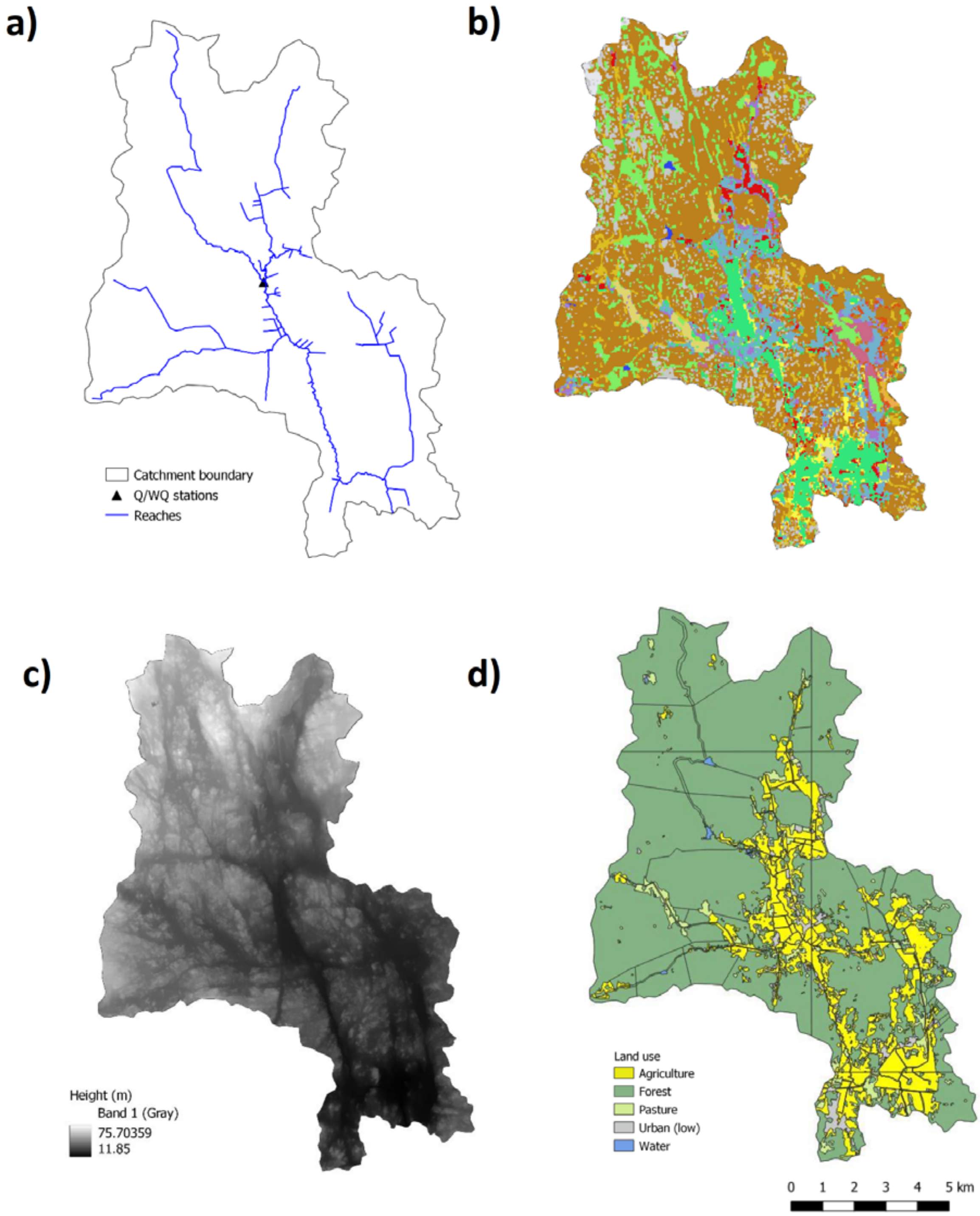


Figure A14.1 GIS input data for CS14: a) water flow, water quality (Q/WQ), reaches and catchment boundary; b) soil type map; c) DEM map; d) land use map

## 1.2. Baseline model setup

The most important features of the model setup are included in Table A14.2. Most of them were extracted from the object.cnt file.

Table A14.2 Summary of the model setup features.

| Parameter | Value |
|---|---|
| Total area of the watershed in ha | 10792 |
| Total number of spatial objects in the simulation | 3163 |
| Number of HRUs in the simulation | 1508 |
| Number of routing units in the simulation | 1508 |
| Number of aquifers in the simulation | 1 |
| Number of reservoirs in the simulation | 20 |
| Number of recalls (point sources/inlets) in the simulation | 0 |
| Number of SWAT-DEG channels in the simulation | 126 |
| Number of crops in rotation | 6 |
| Number of wetlands | 0 |

## 1.3. Missing elements of the report and time plan to complete these tasks

Model evaluation is still ongoing and cannot be presented in its current form. There have been multiple reasons for the delay in the project. They can be summarized as follows: A change in workflow from using the SWAT+ modelling interface to a totally R-scripted workflow required a significant and unplanned investment of time to develop the necessary R expertise to test, apply and evaluate the R scripts.

The shift to an R-based workflow led to further delays as scripts were released in an "alpha" version. The iterative process where scripts were continually changed/improved resulted in significant time being invested locally to troubleshoot R and to liaise with the developer group.

Designing the project in a manner such that case studies work in the exact same manner has led to significant bottlenecks related to data harmonization and the availability of key OPTAIN personnel for troubleshooting. The key people have been very supportive, but more support during critical times or alternative ways forward would have been needed to complete the project on time.

As a result of changes in approach (to an R environment), a monolithic approach, personnel changes at SLU and the need to follow an iterative as opposed to a linear process, delivery has been delayed. It must be stressed that a lot of time has been invested in the project, both at SLU and by key OPTAIN personnel.

A full calibration and production of scenario results will be completed until summer 2024. This extension will allow us to complete the task in a manner that supports project requirements without compromising the time planned for optimization in a significant way.

# Annex 15 - Issues and implications

## 1. SWAT+ model development and issues

Over the last two decades, the SWAT model has gained widespread worldwide acceptance. The continuous addition of features and alterations to individual components have made the code increasingly complex to manage and maintain. In response to these challenges and to address present and future water resources modelling demands, significant revisions have been made to the SWAT code, resulting in SWAT+, a fully restructured iteration of the model (Bieger et al, 2017). Although the core algorithms used to compute processes within the updated model remain unchanged, substantial modifications have been made to both the code (utilising an object-based structure) and the input files (employing a relational-based structure). These changes streamlined model maintenance, accommodated code adjustments, and fostered collaboration with other researchers for incorporating new scientific advances (also developed in OPTAIN) into SWAT+ modules. Moreover, the enhanced spatial representation of interactions and processes within watersheds provided by SWAT+ is fully utilised by the modellers of the OPTAIN project.

It is important to note that SWAT+ is developed and maintained by USDA-ARS (USA) and Texas A&M AgriLife Research (USA) scientists. The model and the tools are in open access and are constantly updated in the official website: https://swatplus.gitbook.io/docs/release-notes.

The OPTAIN core team initiated the model testing phase early in the project implementation phase to i) familiarise themselves with the model input/output, data requirements, and parameterisation, ii) to identify and report potential issues (bugs) in the tool in hopes, that they will be fixed in a timely manner by the model development team in the US. In Table 4.1 we outline the major identified modelling tool issues which were reported to the development team and addressed.

Table A15.1: Major SWAT+ issues identified and reported over the course of the task in WP4.

| ID | Issue | Explanation | Status |
|---|---|---|---|
| 1 | Double accounting for crop temperature stress | Resulted in severe temperature stress and unreasonable plant growth restriction | Issue resolved in June 2023 |
| 2 | Unrealistic values found for channel evaporation | Resulted in the inability to verify if the channel ET was functioning correctly. May had an impact on the water balance estimations | Issue was resolved in April 2023 |
| 3 | No output for snow cover and snow melt printed | Resulted in the inability to verify if the snow-formation/melting processes functioned properly | Issue was resolved in April 2023. |

| | | | |
|---|---|---|---|
| 4 | Inconsistencies with model parameter changes across various input files | Resulted in the inability to perform model sensitivity analysis and hard calibration | Issue is still not fully resolved. |
| 5 | Instability with Leaf Area Index over the simulation period. | LAI does not always drop to minimum LAI during dormancy, or reaches unreasonable values at the start of simulation. Resulted in unreasonable plant growth representation. | Issue with the overestimation of LAI is resolved in June 2023. Issue with LAI not dropping to zero is not yet resolved. |
| 6 | Instability with leaf senescence | Resulted in model error mid-simulation with the inability to continue the simulation | Issue resolved in July 2023. |
| 7 | Instability with tile drainage-related parameters | Resulted in model crashes mid-simulation | Issue is partially resolved in July 2023 |
| 8 | Aquifer storage was not initialised after changing specific yield | Resulted in faulty model initialisation and inconsistencies in water balance estimation | Issue was resolved in April 2023 |
| 9 | Infinite loops if small channels are modelled | Model was not able to finish the simulations, as it was "stuck" in infinite loops | Issue was resolved in April 2023 |
| 10 | Model was unable to run through the soft calibration if more than one wetland was present | Resulted in the inability to conduct the soft-calibration of the models | Issue was resolved in April 2023 |
| 11 | Some header names in output files (i.e. channel output files) were missing | Resulted in the inability to interpret the model results | Issue was resolved in April 2023 |
| 12 | Instability with PHU accumulation for winter crops | Resulted in the inability to accurately represent winter crop growth | Issue in not yet resolved |
| 13 | Faulty fertilisation application in the model | Fertiliser applied is double to what a user input | Issue resolved in August 2023 |
| 14 | Channel dissolved phosphorus was not represented correctly | The units of the benthic source were converted to liters, and didn't include the benthic source when computing the outgoing soluble phosphorus. Resulted in underestimation of soluble P in streams | Issue resolved in August 2023 |

This deliverable (D4.4) delay has been attributed to a range of issues and bugs that emerged during the software implementation phase, majority of which are listed above. The intricacies of incorporating such advanced tools into the project's framework introduced complexities that were not initially anticipated. However, it is important to acknowledge that the utilisation of cutting-edge technologies always carries an inherent level of risk. In the case of OPTAIN, the decision to employ SWAT+ as a pivotal component of the project exemplifies the team's commitment to pushing the boundaries of model development and application. While the team has had to navigate through uncharted waters and essentially serve as testers for the new software, this situation can be reframed as a significant achievement. The project stands at the forefront of pioneering advancements, underlining its role as a trailblazer in the domain. This delay, though a temporary setback, underscores the OPTAIN project's dedication to innovation and willingness to embrace challenges as opportunities for growth.

## 2. OPTAIN's harmonised approach (supervision & scripting)

OPTAIN aims to standardise and harmonise its approaches across all 14 case study sites, which is beyond the state of the art for large research projects. Common guidelines and protocols for stakeholder engagement, data retrieval, NSWRM parameterisation and cataloguing, modelling and optimisation have been and will be developed. This will avoid problems of inconsistency and lack of comparability, ensure high methodological standards and enable a strong synthesis potential of OPTAIN's results across multiple biogeographical regions.

Unfortunately, the harmonised approach of OPTAIN across all case studies resulted in an underestimated high demand for support. This was particularly true for WP4 and all modelling related tasks. The WP4 task leaders and co-leads spend an enormous amount of time on: (1) guiding the case study modelling teams and (2) developing workflows that are applicable in all of the specific cases. Furthermore, the need to develop and test scripts and procedures for (semi-)automated and harmonised processing of different datasets and workflows was underestimated.

The WP4 team implemented several measures to mitigate the risk of delays or missed project goals. A core group of experienced modellers developed and tested all workflows and scripts and discussed upcoming steps in bi-weekly meetings. Some of the workflows and scripts are shown in Figure 2.3 above. To ensure proper guidance and supervision of other case studies, a combination of virtual and in-person workshops, as well as bi-weekly question-and-answer (Q&A) meetings of all case study modellers, was used.

## 3. Spatially discrete model setup with SWATbuildR

The Soil and Water Assessment Tool (SWAT) is an eco-hydrological catchment scale model that is implemented on a wide range of spatial scales, from small catchments, which only cover a few square kilometres to entire continents (Gassman et al., 2014). Despite the wide range of scales for model implementations, SWAT model setups are typically all set up in a default way using tools such as QSWAT+ (Dile et al., 2023). In such a "conventional" model setup, the smallest spatial land unit that has a spatial reference is a routing unit (RTU). RTUs usually contain multiple hydrological response units (HRUs), which lump areas with the same land use, soil and similar slope in a unit without a spatial reference. Thus, HRUs usually aggregate areas in an RTU which are scattered across the landscape, and which are not connected.

The new and revised version of SWAT, SWAT+ introduced spatial objects in model setups, that represent land areas, channels, reservoirs, aquifers, and other components of a watershed system. Spatial objects can be mutually connected to enable different types of fluxes between them, such as surface runoff, lateral flow, and groundwater recharge. The introduction of spatial objects and their connectivity is a substantial improvement and allows a flexible representation of hydrological catchment systems. Yet, tools such as QSWAT+ neglect this novelty in the model setup process.

In OPTAIN it is key to appropriately represent the sum of local effects of NSWRMs on the water and nutrient balance on the catchment scale. Particularly, the representation of structural measures such as implementing permanent grassland cover on concentrated runoff slopes, wood and shrubland buffers along channels (e.g. where intensive land management was initially performed with no buffer zone to a water body), or hedgerows to reduce the slope lengths of erosive hill slopes impact upslope and downslope areas in a runoff cascade. Thus, the representation of such measures in an eco-hydrological model setup must account for the local terrain, and the contiguous landscape features of a location where a structural measure is planned to be implemented.

Figure 4.1 shows examples for potential locations of structural NSWRMs in an OPTAIN SWAT+ model setup, such as grassed waterways, hedgerows, riparian buffers, or retention ponds. The impact of all illustrated structural measures strongly depends on the local terrain and their actual location of implementation. The main goal of these structural measures is to collect the runoff of water, sediments, and nutrients from the surrounding agricultural field plots, reduce and trap runoff of those components and eventually reduce the loss of water, sediments and nutrients on the catchment scale.

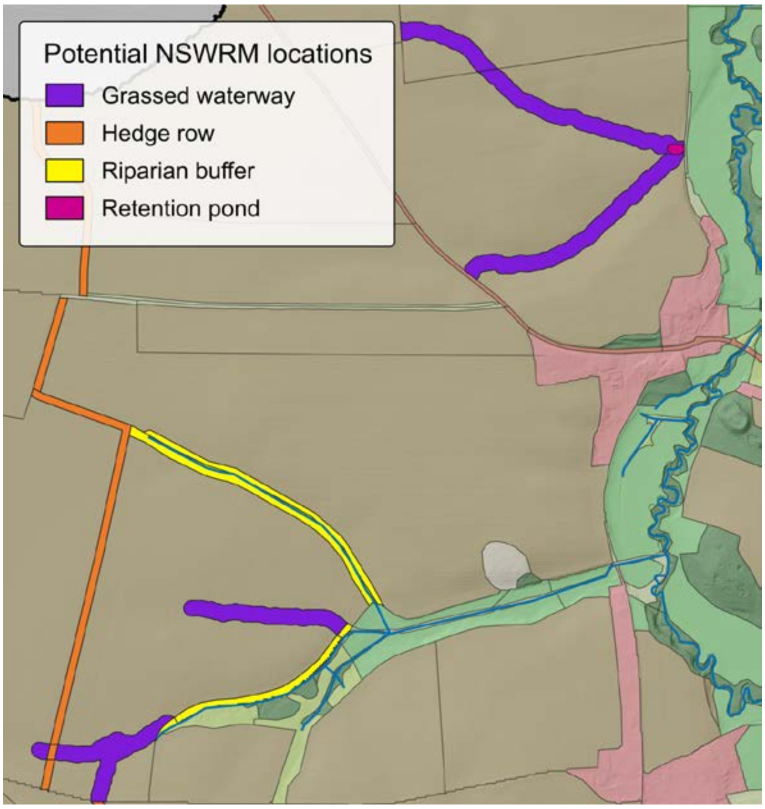


Figure A15.1: Land object and channel object layers for an OPTAIN SWATbuildR model setup. The bright colored polygons indicate potential locations for structural NSWRMs which are planned to be implemented. Brown polygons show agricultural field plots, light and dark green are pastures and forested areas. The channels are shown as blue lines.

The importance of local effects in the landscape became clear at an early stage of the OPTAIN project. Although SWAT+ would be capable of representing the landscape which accounts for structural measures, the available tools for model setup lack the required functionality and were considered to be insufficient. As a consequence, a new approach called COCOA (Contiguous Object COnnectivity Approach which is implemented in the model setup tool SWATbuildR) was developed within the OPTAIN project which fully employs the new concept of spatial objects and their flexible connectivities. The COCOA approach is explained with great detail in Schürz et al. (2022). Figure 4.2 shows in a minimum example how potential NSWRM locations of a grassed waterway and a pond in the landscape (a) would be represented in a model setup which was set up with QSWAT+ (b) and COCOA (c and d). In the example, water from field plots would be collected by the concentrated runoff slope where a grassed waterway is planned. To catch the runoff, a pond as a second measure can be implemented. In a conventional model setup, all landscape features could only be located in the same RTU and would therefore not have any spatial reference. Hydrological processes would be calculated separately for all land objects (HRUs) and the planned measures would not have any effect on the routing of water, sediment, and nutrients through the landscape (Fig. 4.2 b). In a COCOA model setup, the field objects would route water through the landscape feature where the grassed waterway implementation is planned and therefore a change in landuse in this object (HRU3) affects the runoff of water and sediments which it receives from the HRUs 1 and 2 and which it passes on to HRU4 (Fig. 4.2 c). The implementation of a pond (Fig. 4.2 d) is even more complex and requires a change of the object type (a land object is replaced by a reservoir) and the connectivity between the spatial objects. Water would not be further routed in the landscape, but would be collected and retained in the pond and released into the channel (red arrows in Fig. 4.2 d).

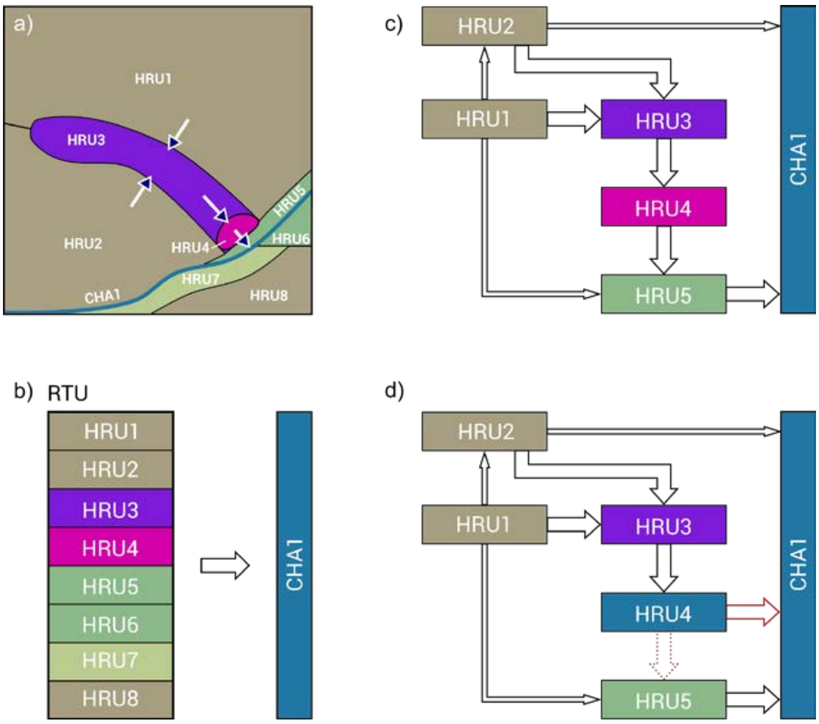


Figure A15.2: Example for the (a) implementation of the structural NSWRMs grassed waterway (purple) and pond (pink) in the landscape and (b) their representations as spatial objects in SWAT+ model setups when the model is set up in a conventional way with QSWAT+ and (c) with SWATbuildR employing the COCOA approach. Activating (d) the pond as a measure in a SWATbuildR setup also changes the connectivity between objects.

The short example above illustrates that the novel COCOA approach enables an improved representation of the landscape and the representation of the implementation of more complex structural NSWRMs in SWAT+ model setups. However, the decision to implement and employ COCOA in all OPTAIN SWAT+ case studies created issues and delays in the SWAT+ modelling timeline. The following paragraphs summarise the main sources for delays for the harmonised setting up of SWAT+ models in all OPTAIN case studies.

SWATbuildR development

- The tool SWATbuildR was entirely developed in R within the OPTAIN project. No existing software and R code was available prior to the development on which the final tool could be based on.
- Although the exchange with the SWAT+ developers' team in the US is well established, the implementation of different conceptual ideas to adequately represent connectivity in the landscape had to be tested by trial and error due to potential unknown behaviour of specific process implementations in the SWAT+ model code, but also due to limited SWAT+ documentation.
- The effort to introduce defensive code which checks the input data and reduces the risk of errors in the model setup process was underestimated. Particularly the analysis of spatial properties of vector input layers required substantial code development. Yet this is crucial to guarantee a safe operation of the tool by all case study modellers.
- SWATbuildR allows the input of official channel networks and land feature layers which must not necessarily match the terrain which is defined by the Digital Elevation Model (DEM) input. This allows the modellers to represent complex and artificial river networks, but at the same time complicates to derive realistic parameterisations for the spatial objects in a SWAT+ model setup. Particularly for the parameterisation of the channel network, additional routines had to be developed to provide robust parameterisation workflows to the users. This additional code development was initially unforeseen.

SWATbuildR input data preparation and processing

- In contrast to the raster inputs which are required to set up a SWAT+ model with QSWAT+, SWATbuildR requires topologically correct polygon and line vector layers which define the spatial objects. First model setups with test data for a small US catchment brought good experiences. Yet the effort for the vector input data preparation without any topological issues was underestimated in the larger OPTAIN case studies.
- For the preparation of the land layer, both initial situations, a very detailed or a coarse land cover product, can be problematic. Detailed land products must be simplified (e.g. aggregating single houses, or trees to respective grouped urban or forest land uses) and may require substantial manual work in processing to reduce the total number of land objects to eventually facilitate computationally efficient SWAT+ model setups. Coarse land cover products require the addition of polygon features which represent features in the landscape (e.g. derived from orthophotos). Such data preparation is very likely infeasible to be automated and also requires substantial manual data processing.

- The SWATbuildR model setups must represent individual field plots in the final model setups to enable the simulation of changes in agricultural practices, or the implementation of structural NSWRMs on single fields. Typically, land cover products do not delineate individual field plots and workflows were necessary to introduce field parcels in the land cover products. A harmonisation of multiple (and sometimes from year to year changing) land cover inputs was a challenging and labour-intensive task in all case studies.
- To derive the flow directions in complex channel networks (which cannot be safely derived from the DEM properties in the model setup process) SWATbuildR sets strict requirements for the user provided channel input layer, such as a direction of line features or the snapping of nodes at channel confluence points. Typically, official channel networks provided by national or regional authorities fulfil the defined data requirements. Nevertheless, in many cases manual editing was necessary in the preparation of the channel input layers.

Testing and verification of COCOA model setups

- Due to limited available documentation of SWAT+ and particularly the model input files, the plausibility of how spatial objects are employed in model simulations can only be tested in a trial and error procedure. The implementation of process representations such as the connection of channels and aquifers with geomorphic flow is for example not documented at all, but provided the required solution for channel/aquifer recharge in COCOA model setups. The implementation of geomorphic flow required several iterations in testing to result in the correct input file implementation.
- Some empirical and conceptual submodels in the SWAT+ code which simulate certain hydrological processes were not developed with the full connectivity approach of COCOA in mind. Thus, a comprehensive testing of COCOA model setups was a requisite to identify limitations in the SWAT+ model simulations with a detailed landscape connectivity. A crucial module, which was identified in model testing to be limiting for the COCOA approach is the empirical Soil Conservation Service runoff curve number (CN) concept. It determines the amount of immediate runoff from a land object in a SWAT+ model setup. The CN value is controlled by the soil water storage of a land object. The soil water storage in COCOA model setups is very sensitive to the area of a land object and their connections to larger neighbouring land objects, resulting in generally large values of soil water storage. Consequently, there is a risk that the calculated CN values particularly for small land objects (which is the case for potential NSWRM locations) are large and impact the water balance simulation on such land

objects and eventually may impede the simulation of NSWRM effectiveness. This issue requires further substantial testing.

# 4. Correction of climate scenario data

OPTAIN deliverable D3.1, submitted in February 2022, included bias-corrected climate model simulations based on the ERA5-Land (Honzak and Pogačar, 2022), as indicated in the project proposal, and agreed upon the preliminary project phase. The product was a set of netCDF datasets for each CS, each containing gridded time series of meteorological variables used as SWAT+ climate forcing (temperature, precipitation, wind speed, radiation and relative humidity) representing different RCP emission scenarios and Regional Climate Models (RCMs) from EURO-CORDEX. Testing of this set of forcing data with SWAT+ models in WP4 was not possible until first model setups were ready (early 2023), which is related to the complex model setup workflow designed in OPTAIN (Fig. 2.3). The first tests were done by the WULS team in March 2023. In a first step, bias-corrected climate simulations from D3.1 were compared with station data for CS4 in Poland, CS2 in Switzerland and CS12 in Czech Republic. Large differences were found, especially for maximum temperature (up to 5 °C) and precipitation (overestimation by up to 30 % on mean annual basis). From the literature, which was unfortunately not available when the reference dataset was selected, it appears that precipitation overestimation of ERA-5 and ERA5-Land is a known problem (e.g. Bandhauer et.al, 2022; Gomis-Cebola et.al, 2023).

The next step was to perform a short analysis for CS4 that focused on how the precipitation overestimation affects the SWAT model outputs. It was found that simulated discharge can be up to five times higher when the model is forced with ERA5-based historical data than when the model is forced with local monitoring data (Figure 4.3). Such a high bias is unacceptable from a hydrological point of view, considering that the goal of OPTAIN is to evaluate water retention measures in catchments using the SWAT+ model. Moreover, this bias was found to be much higher than the climate change signal for the end of the 21st century, which means that the climate change effects projected with SWAT+ would be obscured by the ERA5-Land bias.

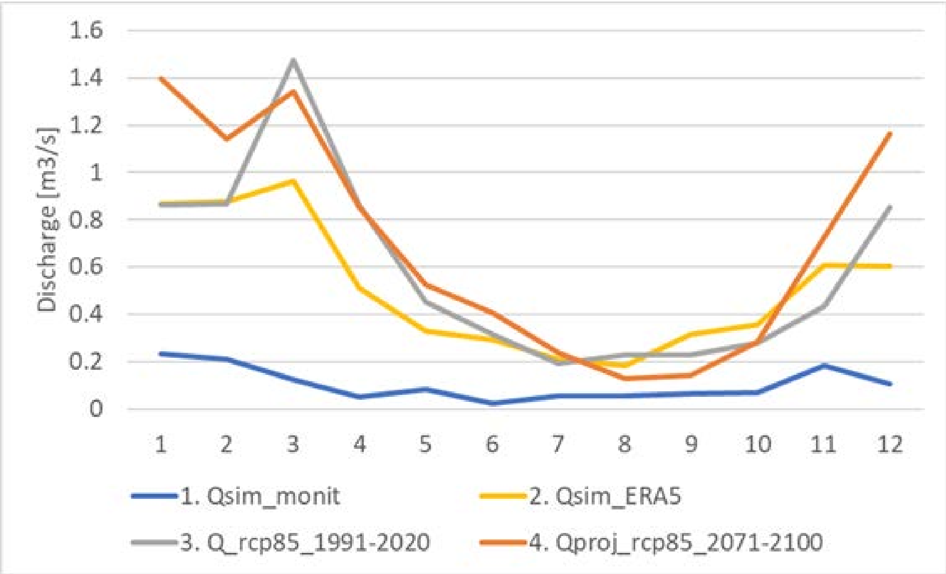


Figure A15.3: Simulated mean monthly discharge for CS4 (Poland) using four different climate datasets: 1. Local monitoring data; 2. ERA5-Land data; 3. Example bias-adjusted RCM simulation for historical period; 4. Example bias-adjusted RCM simulation for the future period.

This required an urgent solution, and after discussion between WP3, WP4 and the coordinator it was agreed that bias-corrected climate simulation using ERA5-Land data as reference data should not be used. The new bias-correction should be performed using local station data, reusing the already prepared data (e.g. raw EURO-CORDEX simulations) and procedures (e.g. bias-correction using quantile mapping) to reduce the amount of work and time as much as possible. Nevertheless, the entire process from the identification of a problem to the quality check and release of the new dataset took three months, which of course was not foreseen. The newly developed dataset was briefly described in the D3.1 addendum (Honzak, 2023).

## 5. Data availability in case studies

Although the importance of high-quality input data for SWAT+ modelling was clear from the very beginning and reflected in the project structure through the existence of Work Package 3 "Retrieval of modelling data and solutions to overcome data scarcity", development of new modelling concepts and workflows led to some unforeseen problems with availability of suitable input data. By far the most important bottleneck was the appropriate land use layer for the SWATbuildR package. The land use layers procured by the CS were either too coarse or too detailed, which in both cases required significant manual effort to pre-process the layer (see more in section 4.3).

The second major problem related to data availability involved crop sequence data. As discussed in section 2.2.1 each CS was expected to prepare field-based crop sequence data. In some cases, the data acquired at national level were either incomplete or had many errors or simplifications. In other cases, where national-level data were not available, a significant amount of work was required to either derive crop maps based on the EU LUCAS product (e.g. CS3a/b, CS11) or to develop a custom solution when EU data were not available (CS10). Overall, this resulted in much more time spent on preparation of the crop data than originally anticipated.

Other data availability issues noted and reported by several CS involved the discharge time series that form the backbone of SWAT+ calibration in OPTAIN (see Section 2.2.1). To ensure that the discharge data were of sufficient quality, additional field measurements (CS4, CS11) and desktop work such as development of flow rating curve (CS4) had to be conducted. Availability of a high-quality soil map was a major problem for CS2. Problems with adequate information on agricultural management practices were reported by CS10. CS5 and CS6 reported problems with acquiring or merging GIS data in trans-boundary catchments. Finally, a major issue reported by CS13 was availability of the correct channel network layer to be used as input for SWATbuildR.

# 6. COVID

The implications of the COVID-19 pandemic led to several obstacles for OPTAIN in general, but also specifically for WP4 and deliverable D4.4. Most of the individuals of the project had to bear a variety of additional burdens (diseases, home office, child care, mental stress), which partly affected project activities. Project internal communication, teamwork and trust are crucial for a successful implementation of OPTAINs harmonised approach across all CS. Physical meetings are very important in this context, but of the physical meetings and workshops originally planned during the last three years of the project, only a minority could be held completely physically (some virtual only and some hybrid meetings).

Further impacts on the schedule of D4.4 have occurred from activities that are indirectly related to modelling (e.g. COVID induced delays in stakeholder engagement activities and data acquisition). This also meant that not all case study processes ran in parallel, which challenged OPTAINs harmonised approach and intensified the requirements for supervision/guidance. In response, however, the OPTAIN project team developed a number of innovative tools to facilitate decentralised synchronisation of project tasks, particularly in the area of modelling. These tools, which were not envisioned in the initial preparation of the project, proved to be indispensable for making progress under the difficult and challenging circumstances. Despite the unforeseen challenges posed by the pandemic, the OPTAIN project demonstrated adaptability and resourcefulness, which ultimately enhanced its resilience and effectiveness.

# Annex 16 – List of SWAT+ output variables and derived indicators

Table A16.1 includes all SWAT+ output variables and indicators derived from them that were used in chapter 3 of the report as well as in all result sections of respective CS annexes.

Table A16.1: Indicator abbreviations used in the report, their descriptions, and units.

| Indicator | Description | Unit |
|---|---|---|
| ACT_NIT_N | Nitrogen moving from active organic pool to nitrate pool | kg/ha |
| ALFA_YLD_T_HA | Average alfalfa yield in whole basin | t/ha |
| BARL_YLD_T_HA | Average spring barley yield in whole basin | t/ha |
| CSIL_YLD_T_HA | Average silage corn yield in whole basin | t/ha |
| DENIT | Nitrogen lost from nitrate pool by denitrification | kg/ha |
| DEP_WT | Depth from surface to aquifer water table | m |
| ET | Actual evapotranspiration | mm |
| FERTN | Total nitrogen applied to soil through fertilization | kg/ha |
| FERTP | Total phosphorus applied to soil through fertilization | kg/ha |
| FIXN | Nitrogen added to plant biomass via fixation | kg/ha |
| FLO | Flow at outflow | mm |
| GRAIN_UNITS_AA | Average annual sum of grain units in whole basin | t/ha |
| LAT3NO3 | Nitrate nitrogen transported in lateral flow | kg/ha |
| LCHLABP | Soluble (labile) phosphorus leaching past bottom soil layer | kg/ha |
| N_LOSS | Average annual Nitrogen loss from land objects | kg N/ha/yr |
| NCONC_DAYS | Frequency total N concentrations is below threshold | ratio |

| | | |
|---|---|---|
| NH4ATMO | Ammonia added to the soil from atmospheric deposition | kg/ha |
| NLOAD | Total N load | kg/yr |
| NO3ATMO | Nitrate added to the soil from atmospheric deposition | kg/ha |
| NUPTAKE | Plant nitrogen uptake | kg/ha |
| ORG_LAB_P | Phosphorus moving from the organic pool to labile pool | kg/ha |
| P_LOSS | Average annual Phosphorus loss from land objects | kg P/ha/y |
| PCONC_DAYS | Average annual Phosphorus loss from land objects | kg P/ha/yr |
| PERC | Percolation | mm |
| PET | Potential Evapotranspiration | mm |
| PLOAD | Total P load | kg/yr |
| PRECIP | Precipitation | mm |
| PUPTAKE | Plant phosphorus uptake | kg/ha |
| Q_MAX_AA | Average annual maximum daily discharge | m3/s |
| Q_MAXMIN_AA | Average annual max/min daily discharge ratio | ratio |
| Q_MEAN | Mean discharge | $m^3/s$ |
| Q_MIN_AA | Average annual  minimum daily discharge | $m^3/s$ |
| Q_P10 | 10 percentile daily discharge | $m^3/s$ |
| Q_P90 | 90 percentile daily discharge | $m^3/s$ |
| QTILE | Tile flow | mm |
| SEDYLD | Sediment yield leaving the landscape through water erosion | t/ha |
| SEDLOAD | Total sediment load | t/yr |
| SEDMINP, | Mineral phosphorus leaving the landscape attached to sediment | kg/ha |
| SEDORGN | Organic nitrogen transported in surface runoff | kg/ha |

| | | |
|---|---|---|
| SEDORGP | Organic phosphorus transported in surface runoff | kg/ha |
| SNOFALL | Snowfall | mm |
| SURQ / WYLD: | Surface runoff to water yield ratio | [-] |
| SURQ_CHA | Surface runoff to channels | mm |
| SURQNO3 | Nitrate nitrogen transported in surface runoff | kg/ha |
| SURQSOLP | Soluble phosphorus transported in surface runoff | kg/ha |
| SW_5_6_7_8_9 | Growing season-average soil moisture (from May to September) | mm |
| SW_AVE | Average soil water content | mm |
| TILELABP | Soluble (labile) phosphorus in tile flow | kg/ha |
| TILENO3 | Nitrate nitrogen transported in tile flow | kg/ha |
| WATERYLD | Water yield | mm |
| WYLD / PRECIP: | Water yield to precipitation ratio | [-] |
| WYLD = SURQ + BASE: | Water yield = Surface runoff + Base flow | mm |
| WWHT_YLD_T_HA | Average winter wheat yield in whole basin | t/ha |