



# OPTAIN

Optimal Strategies to Retain Water and Nutrients

## D4.3: Assessment of NSWRM effectiveness under current and future climate at the field and farm scale

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# Project Consortium



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## Summary

Within the OPTAIN project, the effects of Natural/Small Water Retention Measures (NSWRMs) on water regime, soil erosion and nutrient transport are evaluated at both catchment- and field-scales for present and future climate conditions. The goal of this deliverable report D4.3 is to perform an integrated, model-based assessment of the effectiveness of NSWRMs at the field scale and to use these results for cross-validating the outputs obtained from the catchment-scale modelling. The assessment is based on the adaptation of a field-scale mathematical model (SWAP) to seven pilot sites across three European biogeographical regions and on combined analyses of NSWRM and projected climate scenarios. The scenarios are designed to evaluate the efficiency and potential of different NSWRMs in improving soil water retention and reducing flash floods and the loss of soil and nutrients under changing climate conditions. This report contains a detailed description of the SWAP modelling workflow, from input data preparation, model setup and harmonisation, model calibration and application in climate and NSWRM scenario runs. It presents calibration and NSWRM scenario results from seven OPTAIN case studies from three different biogeographical regions (Boreal, Continental and Pannonia). The report also describes i) the new approaches and tools developed within the OPTAIN project that facilitate the implementation of the scenarios and the interpretation of the modelling results, ii) the methods used to cross-validate the SWAP and SWAT+ models, and iii) the issues faced during the implementation of this work. The SWAP model was calibrated for all the pilot fields with good or satisfactory results. The impact of four in-field NSWRMs - reduced tillage, shifting to grassland, afforestation and drought tolerant crops - on the water balance elements was evaluated. The scenario results indicate that the effects of measures on soil water retention and other water balance elements have some regional pattern, but can be strongly dependent on local conditions (e.g. soil, crop, slope). According to the scenario results, for most of the cases the studied NSWRMs contributed to reducing evaporation, surface and subsurface runoff and percolation to deeper layers, which results in increased soil water retention or plant water uptake within the fields. The cross-validation of the field-scale SWAP and catchment-scale SWAT+ models was a challenging task and could only be performed for selected water balance elements (evaporation, transpiration and drainage outflow). Comparable results were obtained in most of the cases for the baseline scenario, but the differences between the soil water balance elements simulated by the two models increased when implementing the different measures. The increased differences, however, could also reflect the differences in measure implementation, as these were constrained by the model's structure and parameters. We concluded that the implementation of the SWAP field-scale model in the scenario analysis and cross-validation could positively contribute to i) better understanding the effects of NSWRMs at field level and ii) evaluating the outputs of the SWAP and SWAT+ models in a wider context.

We concluded that NSWRMs can contribute to water retention within the landscape, and that this effect seems to decrease and increase in the future for measures related to management and land use change, respectively. The cross-validation of the water balance elements of the two models showed that the SWAP and SWAT+ simulation results were comparable for the status quo (present situation, for which the models have

been calibrated), but differed for the NSWORMs scenarios, depending on how the measures were implemented in the two models.

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## Abbreviations

ADR	Amplitude Domain Reflectometry
AHC	Automatic hard calibration tool
COSMO	cosmic-ray soil moisture probe
CS	Case Study
CSS	Case Study Site
EPI	Environmental Performance Indicators
FC	Field capacity
GCM	Global Circulation Model
HRU	Hydrological Response Units
NSWRM	Natural/Small Water Retention Measures
NSE	Nash-Sutcliffe model efficiency index
ORES	Residual water content
OSAT	Saturated water content
PBIAS	Percent of bias in model performance
pF-curve	Soil water retention curve ( $\theta(h)$ )
PTF	Pedotransfer function
R <sup>2</sup>	Coefficient of determination
RCM	Regional Climate Model
SPI	Socio-economic performance indicators
SWAP	Soil Water Atmosphere Plant (model)
SWAT	Soil and Water Assessment Tool
SWC	Soil Water Content ( $\theta$ )
VGM	Van Genuchten – Mualem model
WOCAT	World Overview of Conservation Approaches and Technologies
WP	Wilting point

# 1 Introduction

## 1.1 Objectives

The primary objective of the EU H2020 OPTAIN project is to identify efficient and easy-to-implement Natural-/ Small Water Retention Measures (NSWRMs) and optimise their spatial allocation and combination for retaining and reusing water and nutrients in small agricultural catchments across Boreal, Continental, and Pannonian biogeographical regions of Europe.

To achieve this objective, OPTAIN considers two different scales. The Soil and Water Assessment Tool+ (SWAT+) is being used for simulating water and nutrient transport processes at (sub-)catchment level. SWAT+ uses simplified approaches for simulating the quality and quantity of surface and ground water and predicting the environmental impact of land use, land management practices, and climate change. On larger scales, the calculated values are usually hard to verify or test. This also raises the question of how accurately SWAT+ can simulate the water balance elements and the effects of different management measures on water regime and plant development at field-scale.

The goal of this deliverable (D4.3) is to perform an integrated, model-based assessment of the effectiveness of NSWRMs at field scale, using a field-scale model - SWAP - and to cross-validate these results with those obtained from the SWAT+ catchment-scale model. The assessment is based on the adaptation of a field-scale (SWAP) mathematical model to selected pilot sites (fields) across three European biogeographical regions and on NSWRM scenario analyses.

Soil hydrological models, like the Soil Water Atmosphere Plant model (SWAP), are commonly run from profile- up to field-scales. These models focus on the soil water regime and are considered to be more precise in describing the water transport in the soil-water-atmosphere system. However, they are not able to describe surface runoff, erosion and nutrient processes from the root zone to surface watercourses and cannot be used to assess the efficiency of structural NSWRMs. On the other hand, field-scale models are suitable for a more precise simulation of in-field (structural) NSWRMs, as the soil and crop input data of these models allow management practices to be incorporated into the modelling procedure in a more accurate and sophisticated way. Therefore, the results of such models at the field and farm scale can be used as a reference for larger scale models such as SWAT+.

The main goals of applying a field-scale model in the OPTAIN project are i) to cross-validate the SWAT+ outputs on water balance elements using the results of the field-scale model; ii) to find the best approach for implementing management related measures in the models, iii) to evaluate the potential of introducing drought tolerant crops in the future for case studies, where they are relevant (a measure that cannot be directly implemented in the SWAT+ model).

This report contains a detailed description of the SWAP modelling workflow, from input data preparation, model setup and harmonisation, model calibration and application in climate and NSWRM scenario runs. It provides model calibration results and scenario results from seven case studies (Czech Republic, Lithuania, Norway, Poland, Switzerland and 2 sites from Hungary). The report also describes the issues faced during the

implementation of the work, but also highlights the new approaches and tools developed within the OPTAIN project that facilitate the implementation of the scenarios and interpretation of the modelling results. Furthermore, this deliverable provides newly developed ideas on how the cross-validation could support linked field- and catchment-scale modelling in the future.

### 1.1.1 Position within OPTAIN

This report is an output of Work Package (WP) 4 “Integrated assessment of NSWORMs” and is part of OPTAIN’s task 4.3 “Assessment of NSWORM effectiveness at the field and farm scale”. Within this task modellers in seven case studies are to set up and calibrate the field-scale SWAP model in accordance with the OPTAIN SWAP protocol (Farkas et al., 2022) and apply it for running scenarios related to climate change and implementation of NSWORMs, following a common approach developed within the project (Marval et al., 2022). This ensures a harmonised approach towards modelling and scenario analysis, which is one of the core concepts in OPTAIN.

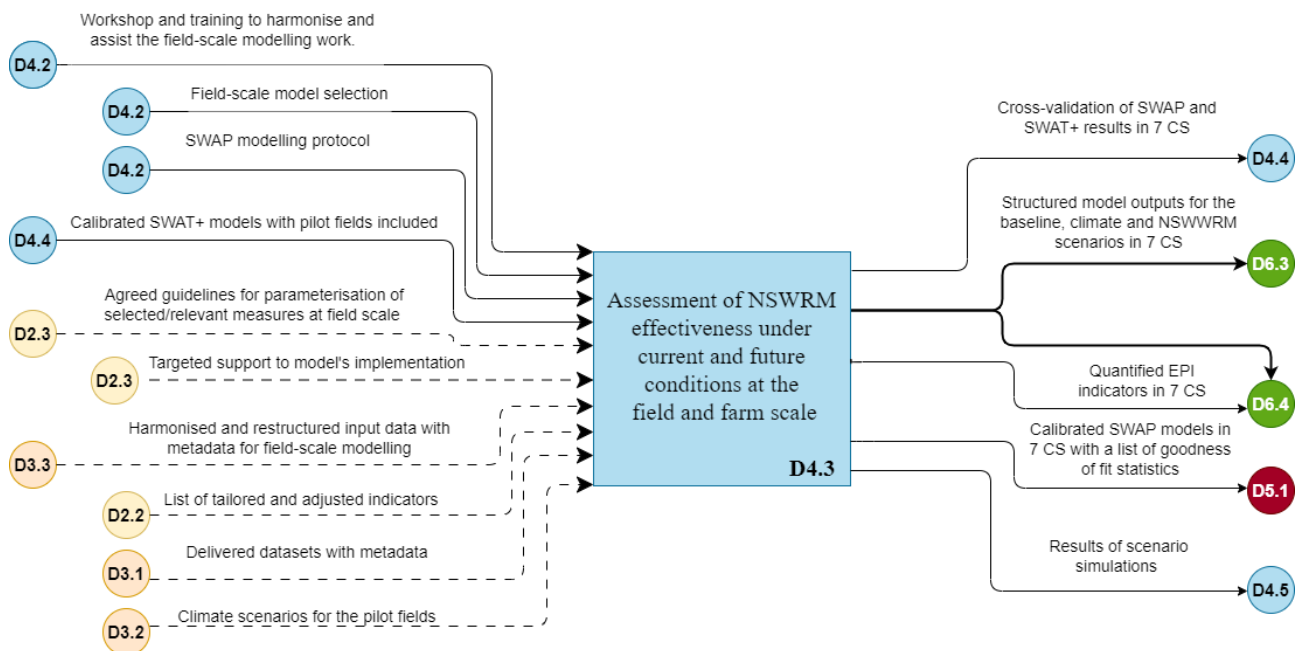
Task 4.3 is being carried out in close collaboration with Task 4.4 on “Assessments of NSWORM effectiveness at the catchment scale” (see sub-chapters 2.4 and 2.9) and is linked to other activities and outputs of OPTAIN (Figure 1.1), especially from WP2, WP3 and WP5. Below we give a short overview of the most important deliverables, related to our work.

WP2 „Measures and indicators” defined and developed a customised set of Environmental and Socio-economic Performance Indicators (EPIs and SPIs, respectively) that allow assessing the effectiveness of selected (either existing or potential future) Natural/Small Water Retention Measures (NSWRMs) in and across the OPTAIN case studies (D2.2, Krzeminska and Monaco, 2022). Furthermore, scale-specific guidelines for the parameterisation of the NSWORMs in modelling approaches were developed for the translation of NSWORMs into SWAT+ (catchment scale) and SWAP (field-scale) model parameters (D2.3, Marval et al., 2022).

The modelling work in WP4 was strongly supported by WP3 on “Retrieval of modelling data and solutions to overcome data scarcity”, which has already provided three valuable deliverables with inputs and tools in the context of the SWAP modelling work. D3.2 (Szabó et al., 2022) provided solutions and tools to overcome data scarcity in input data construction and SWAP model parameterisation. Methods and R-packages, developed within D3.3 (Čerkasova et al., 2022) were successfully applied for data screening and SWAP input files creation as well as metadata construction. The above-listed WP3 deliverables provided, besides others, soil hydraulic input data, crop data and bias corrected future climate simulations for assessing the effects of climate change and in-field measures on relevant EPIs.

Outputs developed within D4.4 (Piniewski et al., 2024) were taken directly to D4.3 and indirectly to several different parts of the OPTAIN project. This task incorporates the cross-validation between SWAT+ and the selected field-scale model SWAP for a few OPTAIN case studies. To our knowledge, no such type of work has been done before. Based on the cross-validation, we evaluated the performance of the SWAT+ model at field scale which may influence the spatial optimization of the size, location, and combination of different measures (D5.1).

D4.3 faced several issues during the implementation of the field-scale modelling work. These issues are detailed in Annex 9.



**Figure 1.1.** Relationship between D4.3 and other OPTAIN deliverables. D4.5, D5.1, D6.3 and D6.4 are influenced indirectly via slightly modified SWAT+ parameters.

## 1.1.2 Implementation

The field-scale modelling work in OPTAIN as part of task 4.3 is carried out by the modellers of the case studies involved in this task. The initial meetings were affected by the COVID-19 pandemic and were held online.

The first in-person meeting on field-scale modelling was organised in September 2021 (Warsaw, Poland) during the first OPTAIN General Assembly. The purpose of this meeting was to present the case studies and the basics of SWAP modelling as well as to discuss the steps and organisation of the field-scale modelling work within the project.

The second session was organised in June 2022 in Budapest, Hungary (hosted by ATK) as a SWAP modelling workshop where, in addition to the OPTAIN field-scale modellers, BSc, MSc and PhD students and researchers from the OPTAIN partner institutions were invited in addition to the OPTAIN field-scale modellers. At the end of the workshop, all the OPTAIN field-scale modellers had setup their initial SWAP model and were trained in the use of the tools developed to and harmonise the SWAP modelling work within the OPTAIN project. The following tools were presented and tested by the participants:

- the RETC computer program (van Genuchten et al., 1991) for fitting different analytical soil hydrological functions to measured soil water retention and soil hydraulic conductivity data;
- the ROSETTA Lite neural network (Schaap et al., 2001) developed to estimate the soil hydraulic functions from easily available soil data;

- an OPTAIN-developed R-script for reference data quality check, described in OPTAIN deliverable D3.3;
- the rSWAP R interface for SWAP model verification, soft-calibration and visualisation (Shore, 2023);
- the SWAP – PEST auto-calibration tool (OPTAIN D3.3).

The third practical SWAP modelling session took place during the second OPTAIN General Assembly in September 2022 (Balatongyörök, Hungary). During this meeting we focused on soft- and hard calibration tools. The NSWORMs to be implemented in the SWAP project of the individual case studies were discussed and finalised.

The fourth field-scale modelling meeting was organised during the third OPTAIN General Assembly in September 2023 (Iseo, Italy), where we put special focus on the cross-validation and reporting tasks.

The OPTAIN field-scale modelling team mainly uses the UFZ GitLab and UFZ Cloud platforms for data exchange and as a repository for supporting materials and scripts developed.

## 2 Data and methods

### 2.1 Pilot fields for field-scale modelling

The field-scale modelling is performed at seven selected sites, representing the boreal (CS8, Dotnuvele, Lithuania and CS10, Kråkstadelva, Norway), continental (CS12, Černiči, Czech Republic, CS2, Petite Glane, Switzerland and CS4, Upper Zgłowiaczka, Poland) and pannonian (CS3a, Csorsza, Hungary and CS11, Tetves, Hungary) biogeographical regions (Figure 2.1). Although not included in the original proposal, case studies from NO, CZ, and PL have joined as pilot sites for the field scale modelling on a voluntary basis. The location of the pilot sites is shown in Figure 2.1.

Two CS are located in the Boreal biogeographic zone (CS8, CS10), two in the Pannonian (CS3a, CS11) and three in the Continental region (CS2, CS4, CS12). Three CS are located in the lowlands (CS4, CS8, CS10), three in the highlands (CS3a, CS11, CS12) and one in partly mountainous regions (CS2, reaching 800 m asl).

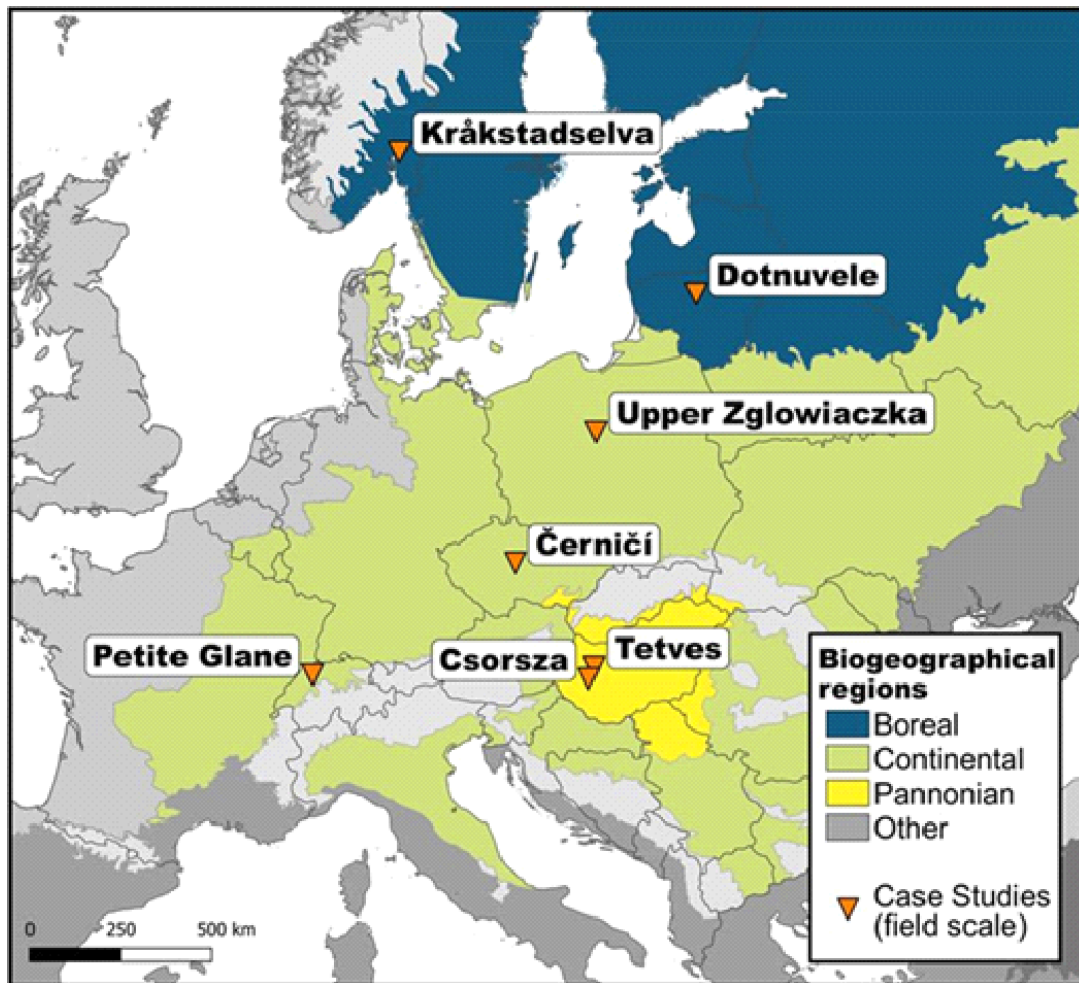


Figure 2.1. Locations of the seven pilot sites involved in field-scale modelling in OPTAIN.

The physiogeographic properties of the sites are summarised in Table 2.2. More information on the case studies can be found in the OPTAIN deliverables D4.1 (Čerkasova & Idzelytė, 2021) and D4.4 (Piniewski et al., 2024).

Table 2.2. Physiogeographic properties of the sites selected for field-scale modelling

Case study	Catchment	Land use	Soil texture		Average annual temperature (oC)	Annual precipitation sum (mm)
			topsoil	subsoil		
CS2 (CH)	Petit Glâne	arable	loam	loam	9.8	855
CS3a (HU)	Csorsza	vineyard	silt loam	silt loam	10.2	545
CS4 (PL)	Boručín	arable	loamy sand	loam	8.5	513
CS8 (LT)	Dotnuvélé	arable			7.8	615
CS10 (NO)	Krakstad	arable	loamy clay	loamy clay	6.3	864
	Krakstad	arable	sandy loam	loamy clay	6.3	864
CS11 (HU)	Tetves	arable	silt loam	silt loam	13.2	625
CS12 (CZ)	Čechtický	arable	silty loam	silty loam	9.0	720

## 2.2 Modelling workflow

To achieve the goals of Task 4.3 and to harmonise the modelling work across different scales and European biogeographical regions, the field-scale modelling work is carried out in a standardised way following the steps presented in Figure 2.2.

The field-scale modellers in the OPTAIN project had to follow the project protocols and develop their SWAP projects so that they would (1) represent all relevant crop rotations and related management operations of the study field, (2) be harmonised with the corresponding SWAT+ setup parameterisation at field scale (if applicable) and (3) be synchronised by all the CS involved in field-scale modelling.

Within Task 4.3, several workflows and tools have been developed to facilitate and ensure a harmonised model setup for field-scale assessments. The following chapters describe in detail the main steps of the SWAP modelling workflow.

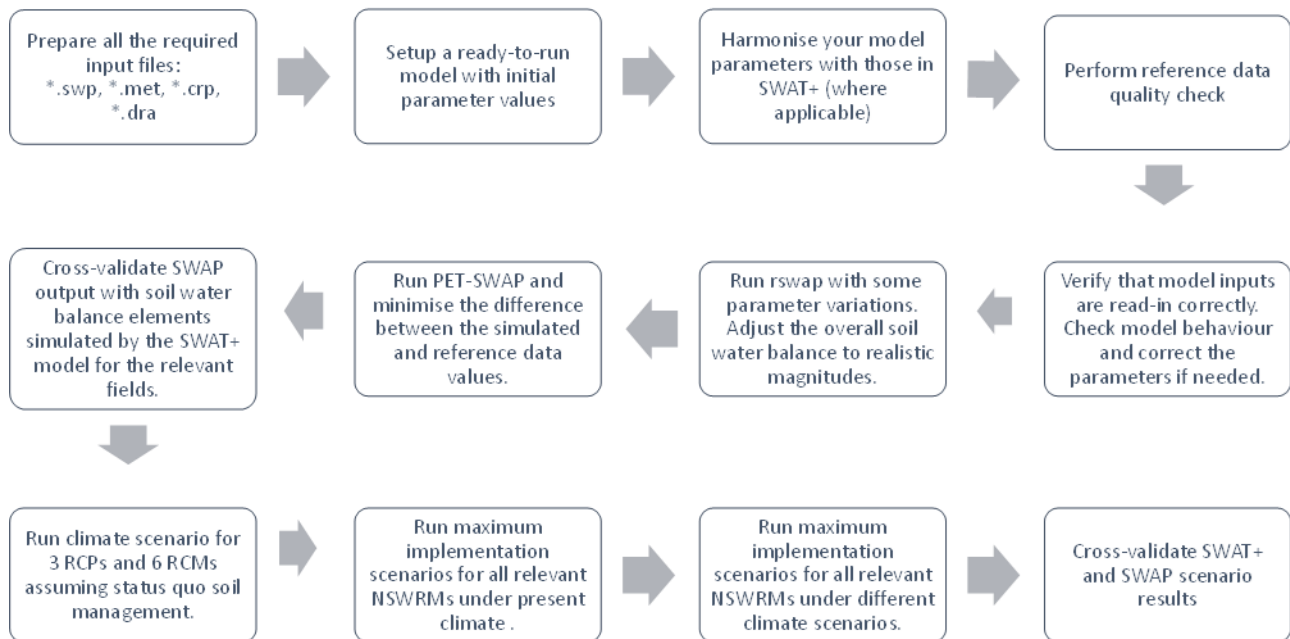


Figure 2.2. Overall modelling workflow to be conducted by each CS involved in field-scale modelling

### 2.3 Input data preparation and model setup

The preparation of input data for the parameterisation of the two models (SWAT+ and SWAP) used in OPTAIN has been harmonised to allow proper cross-validation of the two models. SWAP, handling a far smaller scale than SWAT+, has a relatively simple input file structure. The basic setup of the model consists of three file types: the main SWAP file, the weather data file, and the crop file. Several optional file types can be defined as given in Table 2.1. Processes that are not incorporated in SWAT+, such as macropore flow, water repellency and multi-layer drainage, can be simulated, if needed, by “turning on” the corresponding switches within the main \*.swp input file.

To set up the SWAP projects for the pilot fields, a data inventory of available static and time series information has been compiled by WP3 for all case studies of the project. This work was carried out in line with the data inventory for the SWAT+ catchment scale model described in Task 4.4. Based on the input data requirements of the field and catchment-scale models, a data collection was performed under the WP3, Task 3.1. (Čerkasova et al., 2021). The basic principles of input data preparation and model setup are described in detail in the [SWAP modelling protocol](#) (Farkas et al., 2022).

Task 4.3 developed guidelines and schemes to facilitate and synchronise data collection and SWAP input data preparation, with special focus on meteorological, crop and soil input data. Based on the SWAP model plant parameters (\*.crop files), a plant database was created and cross-validated with SWAT+ plant data input parameters (plants.plt) to facilitate the harmonisation of the input data at the selected sites. The main input parameters and model outputs are listed in Table 2.2.

**Table 2.1.** Input data files to be defined for the SWAP v4.0.1. model and their link to relevant sub-chapters of the SWAP modelling protocol (Farkas et al., 2022).

Description	Extension	Status	Defined	Comment
<b>Main SWAP file</b>	*.swp	required	command line	<b>Described in (sub)chapter</b>
			<b>SECTIONS</b>	General section <b>4.1</b>
				Meteorology section <b>3.2 and 4.2</b>
				Crop section <b>3.4 and 4.3</b>
				Soil water section <b>3.3 and 4.4</b>
				Lateral drainage section <b>3.5</b>
				Bottom boundary section <b>3.6.2</b>
				Heat flow section <b>4.5</b>
				Solute transport section not used at this stage
<b>Meteorological input file</b>	*.yyy	required	in *.swp file	one file per year; defined by METFIL
<b>Crop input file</b>	*.crp	required	in *.swp file	one file per crop; defined by CROPFIL
<b>Lateral drainage input data</b>	*.dra	optional	in *.swp file	if SWDRA = 2, file name defined by DRFIL
<b>Detailed rainfall records</b>	*.yyy	optional	in *.swp file	if SWRAIN = 3, file name defined by RAINFIL
<b>Irrigation data</b>	*.irg	optional	in *.swp file	if SWIRGFIL = 1, file name defined by IRGFIL
<b>Runon data</b>	*.inc	optional	in *.swp file	if SWRUNON = 1, file name defined by RUFIL
<b>User-defined soil input data</b>	*.csv	optional	in *.swp file	if SW SOPHY = 1, file name defined by FILENAMESOPHY
<b>Bottom boundary conditions</b>	*.bbc	optional	in *.swp file	if SWBBCFILE = 1, file name defined by BBCFIL
<b>Top boundary condition - soil temperature</b>	*.tss	optional	in *.swp file	if SwTopbHea = 1, defined by TSOILFILE

The input data collection, preparation and initial model setup were supported by several face-to-face and online meetings, where specificities of each of the case studies were discussed. The following guidelines for input data collection and SWAP model setup were prepared and made available to the field-scale modellers (links are only accessible to OPTAIN partners):

- [Data inventory](#) (carried out by WP3, available on UFZ Cloud)
- [SWAP input and reference data requirement](#) (presentation, available on UFZ Cloud)
- [Data sources for field-scale modelling](#) (presentation, available on UFZ Cloud)
- [Guidelines for setting up your SWAP project](#), including information on reference data availability, SWAP model parameterisation and SWAP test run instructions (Available on UFZ GitLab, <https://git.ufz.de/>)
- [Crop database](#), including readily available swap crop input files for several crops (Available on UFZ GitLab)
- [Meteorological data into SWAP input format](#) (R-script, available on UFZ GitLab)
- [Soil input data](#) (presentation, available on UFZ Cloud)
- [Example SWAP project for each CS](#), considering the peculiarities of each CS site (Available on UFZ GitLab)

**Table 2.2.** The most important input variables/parameters and outputs of the SWAP model (Modified version of the table presented by Jos van Dam in NIBIO, May 2023).

Item	Input	Output
Atmosphere	Air temperature Solar radiation Wind speed Air humidity Rainfall amounts Rainfall duration (optional)	Potential evapotranspiration Actual evapotranspiration Potential evaporation Actual evaporation Potential transpiration Actual transpiration
Vegetation	Crop rotation Sowing and harvesting days Leaf area index Rooting depth Crop height Stress parameters	Relative growth Plant water uptake
Soil	Soil layers Soil water retention function Soil hydraulic conductivity function Bulk density Macropore properties (optional)	Soil water contents Soil pressure heads Water fluxes as: deep percolation surface runoff macropore flow
Drainage (optional)	Drain space and depth Drain parameters Depth of impervious layer	Drainage outflow
Solutes	Irrigation water quality Initial concentrations Groundwater quality	Solute concentrations Solute fluxes

For *weather input data*, two R-scripts were provided for creating meteorological input files in the needed format: one for daily resolution data and one for hourly resolution data.

The *crop input data* files are part of the crop database. SWAP can be run with simple and detailed crop input data. The simple crop routine calculates relative plant growth and actual transpiration as a yield indicator, whilst the detailed routine is capable of simulating crop yields. The crop database contains SWAP input datafiles for different crops and for both, simple and detailed crop subroutines.

*Soil input data* can either be derived from measured soil hydraulic functions or estimated with the help of so-called pedotransfer functions. In the first case, the RETC software (van Genuchten, 1991) should be used to fit the theoretical parameters required by the model to measured data points. Estimation of the parameters of soil hydraulic functions from commonly available soil data (sand, silt and clay content, bulk density, etc.) can be based on locally developed pedotransfer functions. If such functions are not available, pedotransfer functions, incorporated in the ROSETTA neural network (Schapp et al., 2001) can be used. The stepwise explanation of this process and the corresponding links are included in the SWAP modelling protocol (Farkas et al., 2022) and in the “Soil input data” presentation. WP3 supported the preparation of the SWAP soil input data for field-scale modellers, if requested.

In SWAP, the *drainage input file* is optional. Three case studies (CS8, CS10 and CS12) performing field-scale modelling have subsurface drainage and therefore drainage parameters had to be identified for these fields. The basic characteristics of the drain tiles

(depth, spacing, and diameter) are known. The other drainage parameters still need to be calibrated. Out of the three different approaches offered by SWAP for the calculation of subsurface drainage, it is recommended that OPTAIN field-scale modellers use the formula, developed by Hooghoudt or Ernst (Farkas et al, 2022).

*Solute regime* is not simulated by the OPTAIN field-scale modellers, as no reference data for calibrating the SWAP solute routine is available for the pilot sites.

For executing the SWAP model, the initial status (soil water content) of the soil profile has to be described in the model setup (initial conditions). Dynamic simulations also require the knowledge of external flows into or out of the model region for the entire simulation period (boundary conditions). In Task 4.3 all CSs used similar *upper boundary and initial conditions*. The upper boundary conditions were calculated by the model directly from the weather data. The initial conditions were set equal to the soil water content data (as a function of soil depth), measured on the starting day of the simulation. This requires some calculation, as the SWAP model requires water potentials as initial conditions. Thus, the measured soil water content of each soil layer was transformed into water potential using the soil water retention (pF-) curve defined for the layer. An example of such a curve can be seen in Figure 2.4.

Depending on the site and model setup, four types of *bottom boundary conditions* were used for the OPTAIN pilot fields. For the tile-drained fields, “zero bottom flux” conditions were defined (CS8, CS10, CS12), which is the obligatory option if drainage outflow is to be simulated. The depth of the groundwater table was used as a bottom boundary condition for the Polish case study (CS4). For field conditions at the Pannonian sites (CS3a, CS11), “free flux” bottom boundary conditions were set. For the Swiss case (CS2), the SWAP model was set up for lysimeters filled in with soils representative for the SWAT+ CS watershed. In this case, “free outflow at the soil-air interface” bottom boundary conditions were used.

## 2.4 Harmonisation of SWAP and SWAT+ parameters

The SWAT+ and SWAP model parameters, which represent similar processes and can be directly or indirectly cross-validated, are listed in Table 2.3. Parameters that can be directly linked are marked with matching colours in the columns “SWAP” and “SWAT+”. For example, field capacity and wilting point (marked in yellow) are not direct input parameters of the SWAT+ model, but their difference corresponds to the available water capacity, which is a SWAT+ soil input parameter. This shows that the two model setups can be harmonised to a greater extent than just by aligning their parameter lists.

Table 2.3. Types of parameters involved in the model's harmonisation procedure.

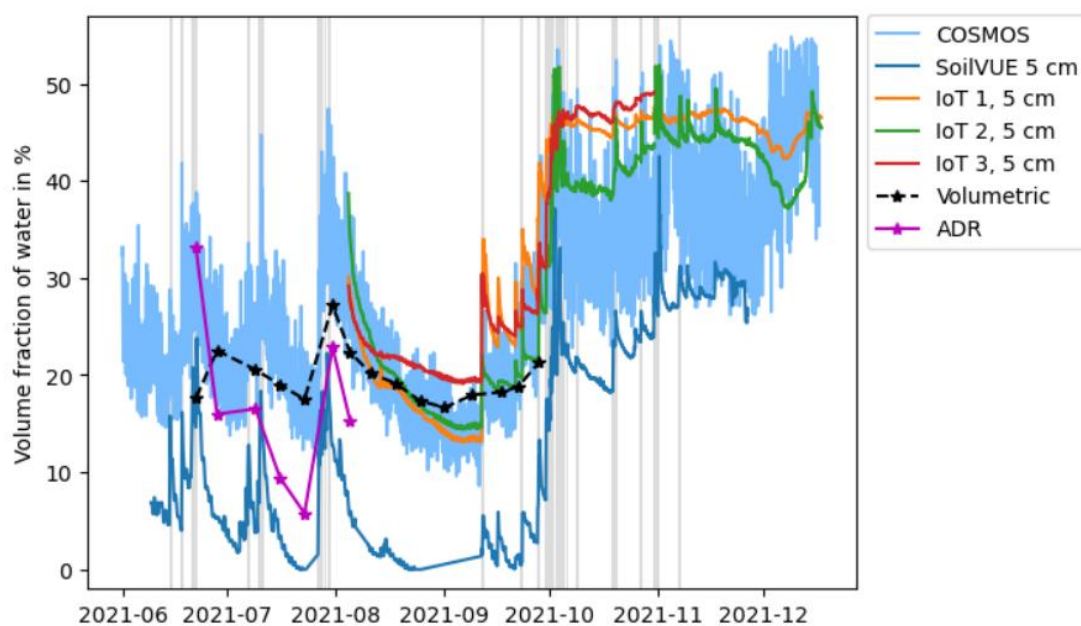
Parameter type and parameters description	SWAP	SWAT+	Parameter type and parameters description	SWAP	SWAT+
<b>Soil parameters</b>			<b>Transpiration</b>		
clay content	+	+	CanDens Max	+	-
sand	+	+	CondMax	+	-
silt	+	+	CondRts	+	-
rock fragment content	(-)	+	CondVPD	+	-
soil moist albedo	-	+	RoughLMin	+	-
organic matter	+	+	WindLessExchangeCanopy	+	-
bulk density	+	+	Plant uptake compensation factor	-	+
<b>Soil hydraulic properties</b>			<b>Evaporation</b>		
saturated water content, $\theta_s$	+	-	Penman surface resistance parameter - psiRts_1p	+	-
field capacity, $\theta_{fc}$	+	-	LAI contribution to aerodynamic resistance - RaincreaseWithLAI	+	-
residual water content, $\theta_{r15}$	+	-	Surface roughness length for bare soil - RoughLBareSoilMom	+	-
available water capacity, $\theta_{AV} = \theta_{fc} - \theta_{r15}$	-	+	Calculate sublimation Yes/NO	-	+
Measured values of soil water retention curve	+	-	Soil evaporation compensation factor - ESCO	-	+
van Genuchten alpha	+	-	<b>Crop parameters</b>		
van Genuchten n	+	-	growth season starting date	+	+
van Genuchten m=1-1/n	+	-	growth period	+	+
wilting point	+	-	growth curve offset	+	+
saturated hydraulic cond., vertical	+	+	growth curve amplitude	+	+
saturated hydraulic cond. Lateral	+	-	maximum rooting depth	+	+
saturated hydraulic cond., matrix	+	-	root distribution		
Crack/bypass flow	+(inactive)	+(inactive)	canopy height	time series	-
<b>Winter: snow</b>			LAI	time series	+
MeltCoefAirTemp	+	-	displacement height	f(canopy)	-
Temperature, above which all precipitation is rain	+	-	roughness	f(canopy)	-
Rain/snow dividing temperature (deg C)	+	+	albedo	+	-
Soil thermal conductivity coefficient	+	-	Plant uptake compensation factor - EPCO	-	+
Water retention capacity of snow	+	-	Temperature sum to maturity	-	+
Snow pack temperature lag factor	-	+	<b>Water uptake</b>		
Snowfall temperature	-	+	CritThreshHoldDry	+	-
Snow melt base temperature	-	+	DemandRelCoef	+	-
Maximum melt rate for snow	-	+	FlexibilityDegree	+	-
Minimum melt rate for snow	-	+	<b>Subsurface / Drainage</b>		
Water equivalent of snow	calculated	-	Distance from surface to impermeable layer	-	+
Density of (new) snow (kg / m <sup>3</sup> )	calculated	+	Depth from drain to permeable layer	+	-
<b>Surface runoff/storage or surface water management</b>			Depth from surface to impermeable layer (m)	-	+
The maximum surface pool cover - SPMaxCover	+	+	Time to drain the soil to field capacity (hours)	-	+
The potential surface cover - SPCovPot	+	-	Drain tile lag time (hours)	-	+
Amount of water on the surface at complete soil cover - SPCoverTotal	+	-	<b>land phase parameters</b>		
Surface runoff (from surface pool) coefficient - SurfCoef	+	-	Coef. for storage time constant of normal flow	-	+
Max amount of water stored in the surface without runoff (cm)	+	-	Coef. for storage time constant of low flow	-	+
Surface runoff lag time (day)	-	+	Lateral flow travel time	-	+
Curve number	-	+	Maximum soil moisture deficit	-	-
Manning's n value for overland flow	-	+	<b>Reach parameters</b>		
Curve number calculation methods	-	+	Parameter controlling water storage in reach	-	+
<b>Interception</b>			Parameter controlling reach evaporation	-	+
WaterCapacityBase	+	-	Manning's coefficient	-	+
WaterCapacityPerLAI	+	-	Channel width/depth ratio	-	+
Maximum canopy storage	-	+	Effective hydraulic conductivity in the main channel alluvium	-	+
<b>Groundwater</b>			base flow index	-	+
GWSourceFlow	+	-			
GWSourceLayer	+	-			
Groundwater delay	-	+			
baseflow recession constant	-	+			
deep percolation fraction	-	+			
groundwater reevaporation coef.	-	+			

## 2.5 Reference data quality check

Soil hydrological models are commonly calibrated and validated against measured soil water balance elements such as surface runoff, drainage outflow, transpiration, etc. The commonly used reference values for calibrating such models is soil water content. The availability and quality of such data is the most important prerequisite for the in calibration of field-scale models for sites.

Difficulties in using soil water content data often arise from the lack of standardisation of the sensor equipment. Additionally, probes installed in the soil are often disturbed by biotic (humans, animals, soil biota) or abiotic (freeze/thaw, shrinking/swelling) factors. The probes can give false – too high - readings if, for some reason, there is water stagnation in the tubes or around the sensors in the soil. Additional problems occur when air is trapped in macropores that have formed for various reasons (swelling and shrinking of clay minerals, freezing, and melting processes, root, and earthworm channels). In this case, the recorded soil moisture content might be too low, as the macropore channel close to the probe misrepresents the whole soil layer.

A study carried out in S-E Norway compared the volumetric soil water content registered by different sensors in the same site (Naalsund, 2022) and found significant differences between the sensors (Figure 2.3).



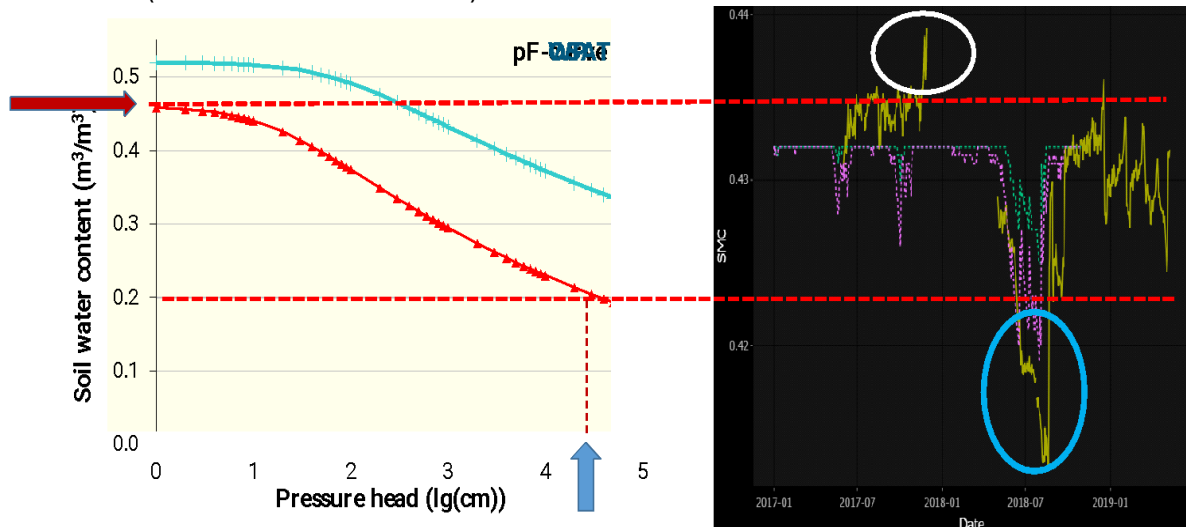
**Figure 2.3.** Time series from different instruments in the period 22 June to 16 December 2021. The occurrence of daily precipitation over 4 mm is indicated by vertical grey lines (source: Naalsund, 2022).

The techniques included a manual soil sampling method (“volumetric”, reference data), three different electromagnetic sensor types (IoT – Theta Probes ML2, SoilVUE 10 sensors and ADR – amplitude domain reflectometry method) and a cosmic-ray soil moisture probe (COSMO) (Figure 2.3).

The authors concluded that the different measurement techniques agreed upon the general soil moisture trends, but on specific dates the absolute values recorded varied by up to 20%. One of the reasons for this could be the spatial variability of soil properties within the field (reflected by the IoT sensors), but also that some of the measurement techniques were biased or not suitable for the soil being studied. For example, the SoilVUE sensor consistently measured lower values than the other sensors. Naalsund (2022) concluded that these sensors are not suitable for heavy clay soils. She also noted that COSMOS was biased by the buildings nearby the pilot sites.

Taking into account the peculiarities of soil water content measurements described above, we have developed an R-script to check the quality of [reference data](#) for OPTAIN field-scale modellers (available for OPTAIN partners only on UFZ GitLab). The script helps to perform quality checks for soil temperature and soil water content data as follows:

- *Soil temperature dynamics of the topsoil* should be in line with the air temperature (graphical check)
- **Soil water content (SWC)**
  - SWC should not be far below the wilting point (WP,  $h=-16000$  cm); values below water content corresponding to water potential of  $-18000$  cm should be removed (blue circle in Figure 2.4 for the red pF-curve).
  - SWC should not be above the total porosity / saturated water content (OSAT) of the particular soil type (white circle in Figure 2.4 for the red pF-curve).
  - SWC for periods when the soil is frozen should be removed unless winter conditions are of special interest; the sensors measure the liquid phase of the water, whilst the default model setup calculates the total water content, including the frozen part. So, the SWC measurements within the frozen soil cannot be used for model calibration. Low SWC values can be removed via a cross-check with the soil temperature of the same layer (records for frozen soil).



**Figure 2.4.** Example for soil water content data quality check using the soil water retention curve (left) and the visualised measured soil water content data (right).

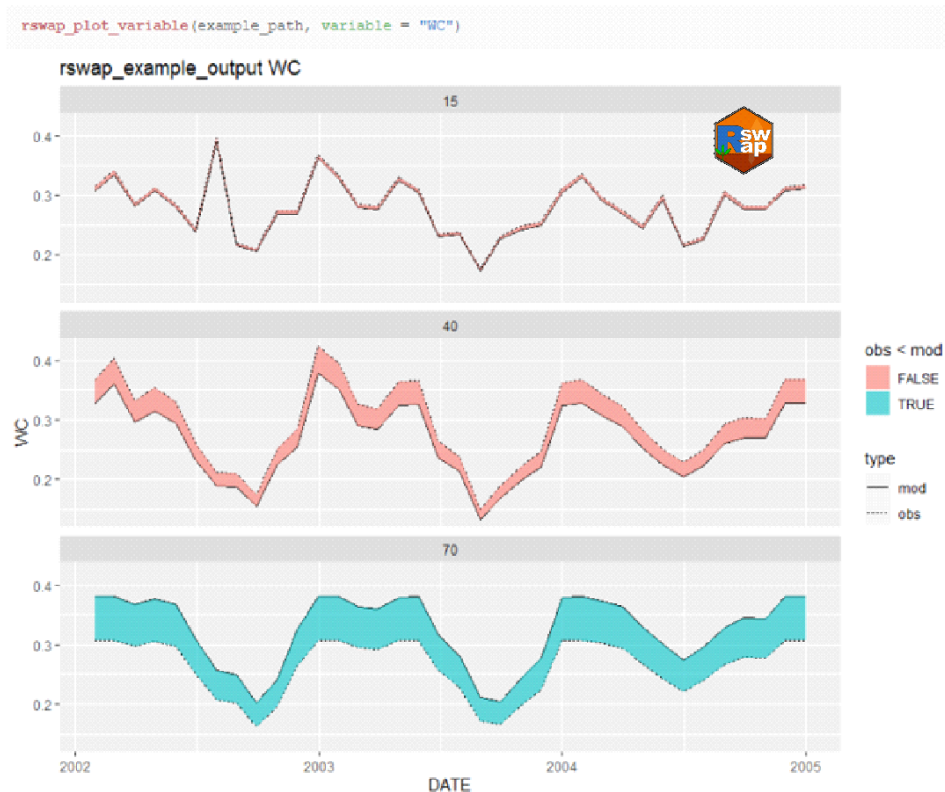
All the OPTAIN field-scale modellers performed a careful quality check of the reference data using the provided R-script and the results were discussed and approved at the SWAP workshop in Budapest in 2022.

## 2.6 SWAP model verification and soft calibration

The input and output of the SWAP model is entirely based on text files, which creates a steep learning curve and difficulty in using the model, especially for non-experienced modellers. Thus, an R package, named “rswap” (Shore, 2023) was developed within the OPTAIN project specifically for the needs of SWAP modelling. “rswap” allows users to

easily set up a SWAP project, verify and calibrate it, and use it for their needs. This R-interface is freely available on [GitHub \(https://github.com/moritzshore/rswap/\)](https://github.com/moritzshore/rswap/).

The rswap package also helps to interface and work with SWAP version 4.2. It consists of a variety of functions that assist the user in otherwise tedious and repetitive tasks during the calibration process. The new version of the package contains new modules that enable sensitivity analyses, multi-core parameterisation. It is expected that the scope of the package will be expanded to include autocalibration and/or PEST integration, and more. For installing and applying rswap, a detailed [user guide](#) was developed and published. Below are some examples of the types of graphs and outputs that rswap can provide:



**Figure 2.5.** Example of rswap plot for comparing the modelled (mod) soil water content values with the observed (obs) ones for three different soil layers (15, 40 and 70 cm). Over- and underestimation are marked green and red colours, respectively.

Rswap also supports the construction of complex plots (Figure 2.6) to discover the relationship between the different water balance elements.

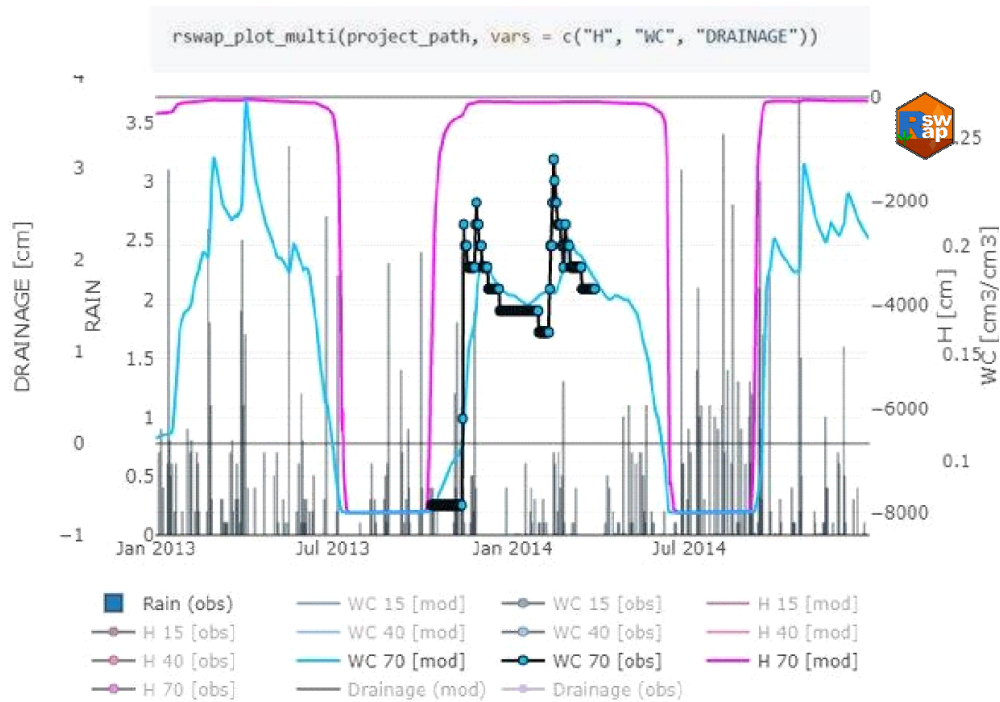


Figure 2.6. Example of rswap plot for visualising the precipitation, drainage outflow as well as the soil water potential (H) and soil water content (WC) for different soil layers.

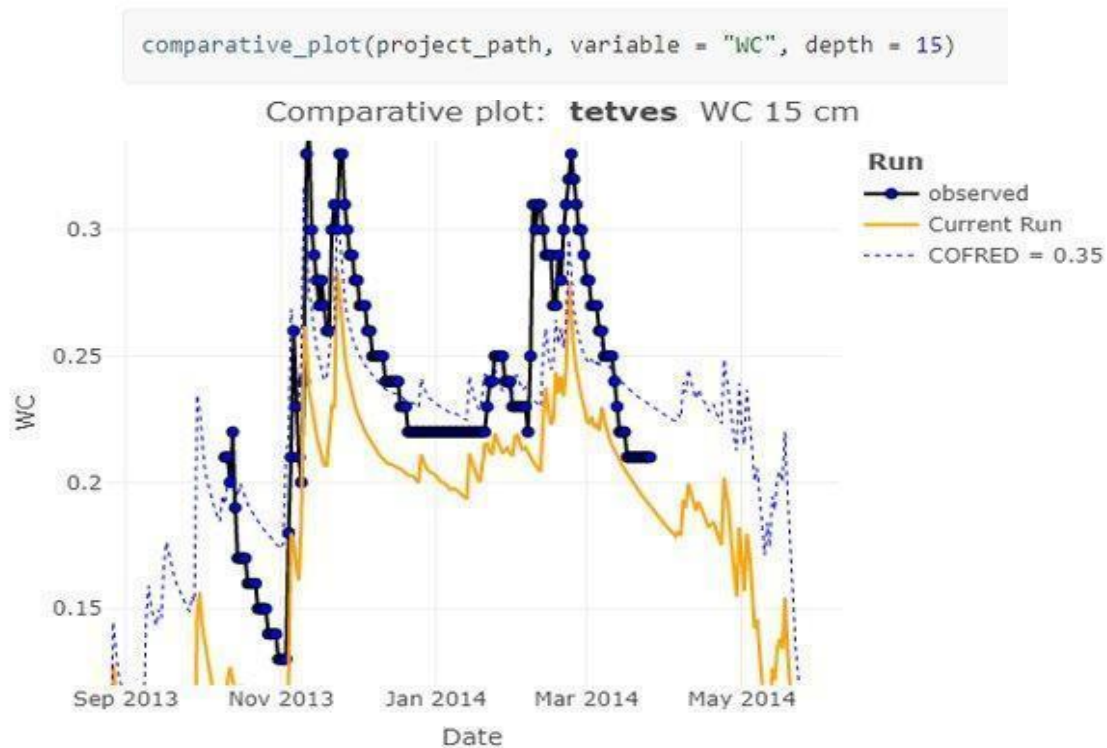
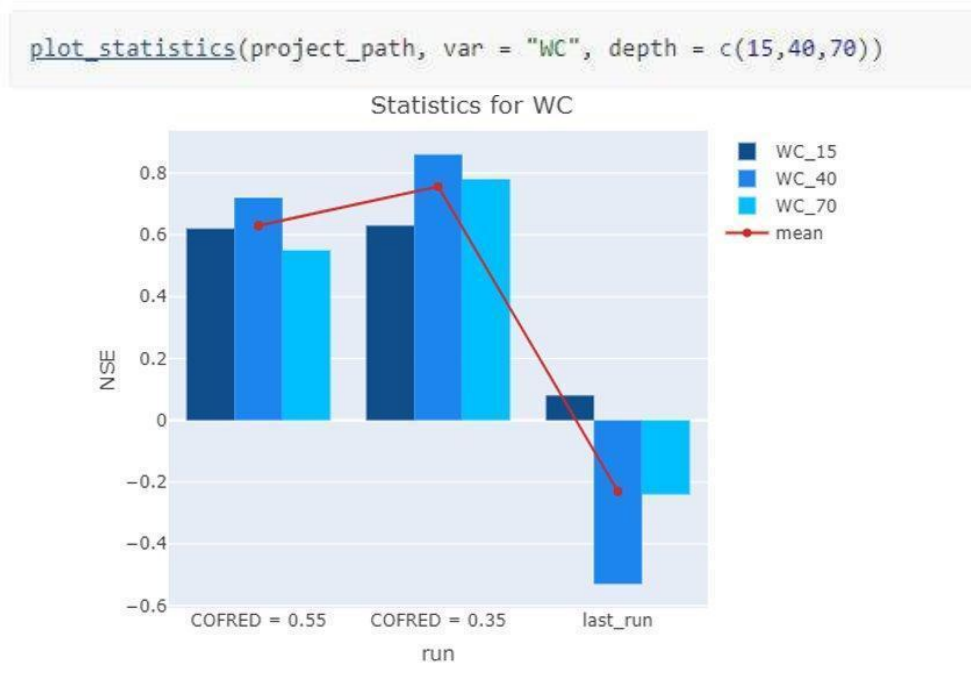


Figure 2.7. Example of rswap plot for visualising the difference between the results of two different model runs and for comparing them with the observed values

During the manual calibration process, rswap also provides the opportunity to compare several model runs at a time (Figure 2.7), allowing the sensitivity of the model outputs to changes in the parameter set to be visually checked. Various statistics can be calculated to objectively select the best performing parameter set (Figure 2.8).



**Figure 2.8.** Example of rswap plot for visualising the statistical evaluation (NSE) of modelled soil water content for three different model runs (COFRED=0.55, COFRED=0.35 and las\_run) and three soil layers.

For the statistical evaluation of the field-scale modelling results, we use those recommended by Moriasi et al. (2016) for field-scale models: the coefficient of determination ( $R^2$ ) and the index of agreement ( $d$ ) (Table 4). In some cases, the NSE, which is commonly used in watershed scale hydrological modelling, is also checked. The rswap R package incorporates the calculation of all the statistics listed in Table 2.4.

**Table 2.4.** Recommended statistical model performance measures for watershed- and field-scale models (after Moriasi et al., 2015).

**Table 9. Final performance evaluation criteria for recommended statistical performance measures for watershed- and field-scale models.**

Measure	Output Response	Temporal Scale <sup>[a]</sup>	Performance Evaluation Criteria			
			Very Good	Good	Satisfactory	Not Satisfactory
<b>Watershed scale</b>						
$R^2$	Flow <sup>[b]</sup>	D-M-A	$R^2 > 0.85$	$0.75 < R^2 \leq 0.85$	$0.60 < R^2 \leq 0.75$	$R^2 \leq 0.60$
	Sediment/P <sup>[c]</sup>	M	$R^2 > 0.80$	$0.65 < R^2 \leq 0.80$	$0.40 < R^2 \leq 0.65$	$R^2 \leq 0.40$
	N	M	$R^2 > 0.70$	$0.60 < R^2 \leq 0.70$	$0.30 < R^2 \leq 0.60$	$R^2 \leq 0.30$
NSE	Flow	D-M-A	$NSE > 0.80$	$0.70 < NSE \leq 0.80$	$0.50 < NSE \leq 0.70$	$NSE \leq 0.50$
	Sediment	M	$NSE > 0.80$	$0.70 < NSE \leq 0.80$	$0.45 < NSE \leq 0.70$	$NSE \leq 0.45$
	N/P <sup>[c]</sup>	M	$NSE > 0.65$	$0.50 < NSE \leq 0.65$	$0.35 < NSE \leq 0.50$	$NSE \leq 0.35$
PBIAS (%)	Flow	D-M-A	$PBIAS < \pm 5$	$\pm 5 \leq PBIAS < \pm 10$	$\pm 10 \leq PBIAS < \pm 15$	$PBIAS \geq \pm 15$
	Sediment	D-M-A	$PBIAS < \pm 10$	$\pm 10 \leq PBIAS < \pm 15$	$\pm 15 \leq PBIAS < \pm 20$	$PBIAS \geq \pm 20$
	N/P <sup>[c]</sup>	D-M-A	$PBIAS < \pm 15$	$\pm 15 \leq PBIAS < \pm 20$	$\pm 20 \leq PBIAS < \pm 30$	$PBIAS \geq \pm 30$
<b>Field scale</b>						
$R^2$	Flow	M	$R^2 > 0.85$	$0.75 < R^2 \leq 0.85$	$0.70 < R^2 < 0.75$	$R^2 \leq 0.70$
$d$	Flow	M	$d > 0.90$	$0.85 < d \leq 0.90$	$0.75 < d < 0.85$	$d \leq 0.75$

<sup>[a]</sup> D, M, and A denote daily, monthly, and annual temporal scales, respectively.

<sup>[b]</sup> Includes stream flow, surface runoff, base flow, and tile flow, as appropriate, for watershed- and field-scale models.

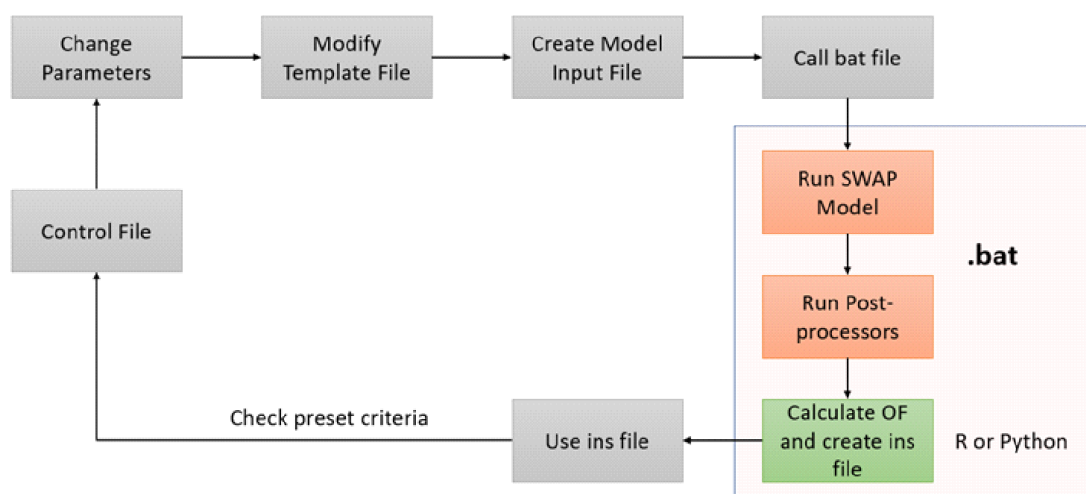
<sup>[c]</sup> Where there were no differences, PEC were grouped for the output responses.

## 2.7 Hard calibration

The automatic hard calibration tool (AHC), developed as part of the OPTAIN project, automates the process of model calibration by analysing the model's inputs and outputs. The tool facilitates a large number (e.g., thousands) of model runs using systematically changed alternative parameterisations and automates the evaluation of the model results against reference data to identify the optimal parameter set. AHC

increases calibration efficiency, harmonises processes across case studies, and documents tested parameter ranges. PEST is a model-independent software that can be used for parameter estimation, sensitivity, and uncertainty analysis and hard calibration. PEST stands for “parameter estimation”. Given its model-independent features, PEST can be used with any model whose input and output files are text files.

PEST runs the SWAP model with an initial guess of the parameters, compares the model results with observations, adjusts selected parameters using an optimization algorithm, and runs the model again. The procedure of adjusting selected parameters continues until the difference between the model results and observations meets user-defined criteria. PEST interacts with a model through the model’s own input and output files. The general workflow of PEST and its interactions with the SWAP model are illustrated in Figure 2.9.



**Figure 2.9.** General workflow of PEST and interactions with SWAP model.  
OF = Objective Function. Ins file = instruction file

Because PEST operates in a model-independent manner, no modifications need to be made to the model code to implement PEST. Two scripts have been developed for the SWAP-PEST integration to facilitate the autocalibration process in the project. When estimating parameters or calculating sensitivities of model outputs to parameters, PEST must run a model many times. This is done by a call to the operating system. Hence the model must be accessible to a user (and therefore to PEST) through the command line. PEST requires an executable file that can be called from a batch file for consecutive operations in calibration.

The objective function (goodness-of-fit statistics, OF), selected for model calibration (Table 2.4) and performance analysis, should be calculated after each model run during the calibration process. To calculate the OF, a script (R and Python versions) has been developed that reads both SWAP model output and measured data. This script must be called after each run and therefore needs to be defined in the batch file. SWAP and PEST have been integrated successfully and all required PEST files (control, template, and instructions files) and introductory documentation together with SWAP files are available for the OPTAIN partners ([SWAP - PEST autocalibration tool](#)).

At present, SWAP-PEST is capable to handle parameters in the main \*.swp file. Its extension for \*.crp (crop) and \*.dra (drainage) files is under development.

The OPTAIN field-scale modelling group follows a common procedure for calibration, which is described in detail in Chapter 6.3 of the [SWAP Protocol](#).

## 2.8 Scenario analysis

One important goal of the OPTAIN project is the evaluation of the effects of various NSWORMs on the water regime, sediment and nutrient fluxes under current and future climate conditions. With respect to NSWORMs, this deliverable focuses on field-scale measures that can be implemented in both the SWAT+ and SWAP models. This makes it enables the performance of the catchment-scale SWAT+ model to be evaluated at field scale. Wherever possible, the climate and management scenarios implemented in the SWAT+ model are transferred/adopted in the SWAP model.

The scenario analyses are carried out using calibrated and validated SWAP projects for each case study site. The OPTAIN field-scale modelling team follows the same principles as the SWAT+ modellers, as described in Chapter 7 of the [SWAT+ Protocol](#). This chapter focuses on the peculiarities of implementing climate scenarios and NSWORMs in the SWAP model.

### 2.8.1 Climate scenarios

[Bias-corrected EURO-CORDEX RCM datasets](#) were prepared by WP3 (deliverable D3.1) and are available on a daily timescale for all CSs. The datasets cover the period from 1981 to 2099/2100 for 6 RCMs and 3 RCP scenarios (RCPs 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 a resolution of 0.1° were performed using local weather data collected by all the case studies.

In addition to gridded data, the climate scenario dataset also contains point data. The latter were downscaled *specifically for the SWAP pilot fields* and contain all the weather variables needed to run the SWAP model in a daily time step. The meteorological input data are derived for six GCM – RCM combinations and for three RCPs (Table 2.5).

**Table 2.5.** List of climate scenarios selected for SWAP (and SWAT+) climate scenario runs in OPTAIN.

<b>Model ID number</b>	<b>Driving Model GCM</b>	<b>RCM</b>	<b>RCP's</b>
1	EC-EARTH	CCLM4-8-17	} 2.6 4.5 8.5
2	EC-EARTH	HIRHAM5	
3	HadGEM2-ES	HIRHAM5	
4	HadGEM2-ES	RACMO22E	
5	HadGEM2-ES	RCA4	
6	MPI-ESM-LR	REMO2009	

A workflow was developed to prepare and update the SWAP model weather files for three distinct time periods. The historical period covered 1991 to 2020, the near future spanned 2036 to 2065, and the far future extended from 2070 to 2099/2100. The periods

are designed to be 30 years long. In order to perform climate scenario runs with the SWAP model, a total of 1260 SWAP meteorological input files have to be prepared for each of the case study fields. The number of SWAP input files has been calculated as follows:

**Reference period (1991-2020):**

6 GCM-RCM runs x 30 years (180 input files)

**Near-future (2036-2065):**

6 GCM-RCM runs x 3 RCPs x 30 years (540 input files)

**Far-future (2070-2099):**

6 GCM-RCM runs x 3 RCPs x 30 years (540 input files)

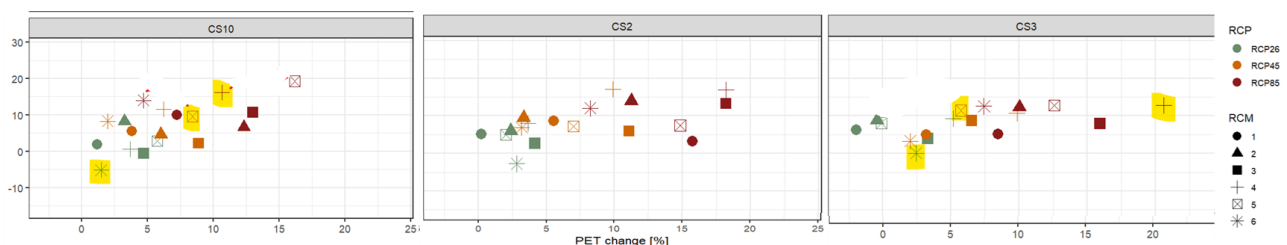
An R-script was developed to run the calibrated SWAP model with all of the 1260 meteorological input files and to analyse the model results with respect to water balance elements. Changes in surface runoff, drainage outflow, soil water regime and transpiration (as a crop yield indicator) are evaluated with respect to the reference period. Uncertainty in climate change predictions is represented by the GCM-RCM combinations in the scenario analyses.

For detailed comparative analyses, three climate scenarios, representing the possible future climate types, were selected for each biogeographical region in Tasks 3.1 and 4.4, as specified in Table 2.6. The scenarios were selected using the relationship between the projected precipitation change (-) and potential evapotranspiration change (-) for all the 18 scenarios.

**Table 2.6.** Selected climate model - RCM - and RCP combinations, representing the possible (and contrasting) future climate types in the three studied regions

Scenario	Biogeographical region		
	Pannonia	continental	boreal
<b>1. Warm &amp; wet</b>	rcm4_rcp85	rcm4_rcp85	rcm5_rcp85
<b>2. Cool &amp; wet</b>	rcm2_rcp26	rcm2_rcp45	rcm6_rcp85
<b>3. Cool &amp; dry</b>	rcm6_rcp26	rcm6_rcp26	rcm6_rcp26

The relationship between precipitation change [%] and potential evapotranspiration change [%] for the 6 RCMs and 3 RCPs for the boreal (left), continental (middle) and Pannonian (right) climate are shown in the figure below.



## 2.8.2 NSWRM scenarios

SWAP is a field-scale model with a spatial validity from profile to field scale. The spatial limitations of the SWAP model determine the NSWRMs that can be implemented in the

model. These are predominantly the so-called conservation management practices that farmers implement to:

- Protect soils from various types of soil degradation (structural, erosion, etc.)
- Increase soil water retention
- Maintain crop yields
- Improve the quality of runoff water coming from agricultural fields

These conservation practices commonly consist of soil management (reduced tillage or no-till approaches), crop rotations, crop management, fertilisation types, application & timing, and amounts. Measures related to the design of drainage systems can also be implemented, including changes in the type, depth and spacing of the drainage pipes, as well as controlled drainage options.

Table 2.7 gives an overview of the NSWRM applied in the field-scale model in OPTAIN and the case studies for which they are relevant.

**Table 2.7.** List of OPTAIN measures introduced in the SWAP model in different case studies.

Management measures			Continental			Pannonia		Boreal	
			CH CS_2	CZ CS_12	PL CS_2	HU CS_3a	HU CS_11	LT CS_8	NO CS_10
<b>Tillage</b>									
<b>A06</b>	No till agriculture	direct seeding no tillage in autumn no-till agriculture	+	+					+
<b>A07</b>	Low till agriculture	subsoiling deep tillage reduced tillage			+				
<b>Other</b>	Resistant plants	mulching drought resistant plants	+	+	+	+	+	+	
<b>Cropping</b>									
<b>A03</b>	Crop rotation	crop rotation							
<b>A05</b>	Intercropping	grain legumes intercropped with cereals & partners	+						
<b>A08</b>	Green cover	green cover in vineyard green cover of arable land				+	+		
<b>A09</b>	Early sowing	early sowing							
<b>Land use change</b>	Afforestation Shift to grassland			+		+	+		+
<b>Drainage</b>	Changing the drainage design (depth, spacing)								+

### 2.8.3 Implementation of NSWRM in the SWAP model

OPTAIN deliverable D2.3 ([Marval et al., 2022](#)) provides a detailed overview of how the key measures presented in Table 2.7 can be implemented in the SWAP model and which of the model parameters should be modified. We also give approximate values on how the key parameters should be changed. The following measures are discussed in detail:

- Afforestation (short- and long-term effects)
- Tillage adjustment
- Cropping adjustment
- Introducing drought-resistant plants

Some measures can be directly included in the SWAP model by using certain parameters. Indirect incorporation of a NSWRM into the SWAP model is accomplished through an expert judgement, where measure-specific parameters are selected and their changes are estimated when considering the impacts of a particular measure (Marval et al., 2022).

To introduce a measure into the SWAP model, soil, crop, or drainage parameters (or combinations thereof) need to be modified/adjusted. Figure 2.11 demonstrates the decision scheme for selecting the input file and parameter type depending on the type of the measure.

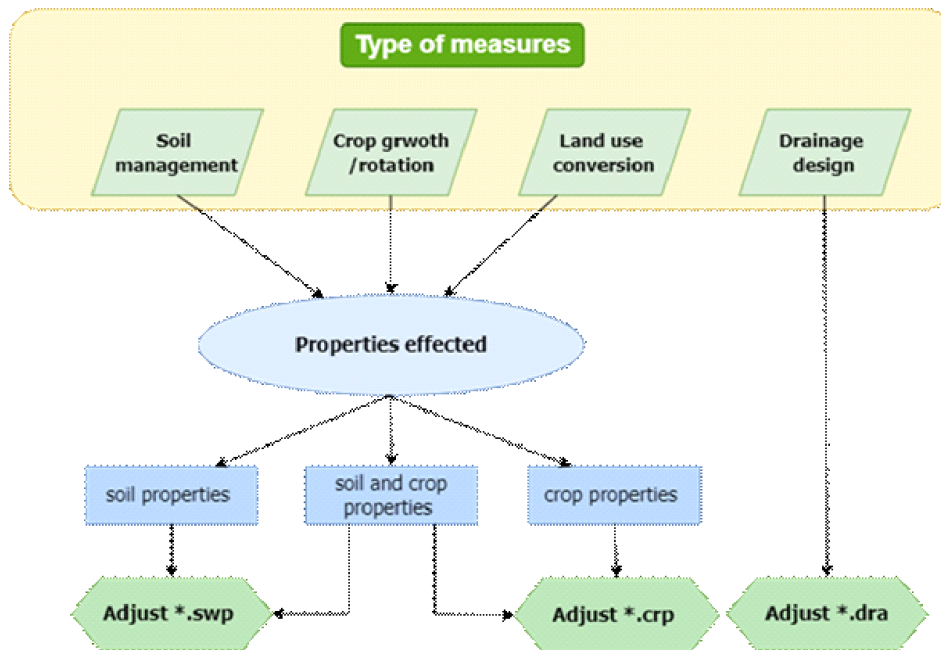


Figure 2.11. Decision scheme on input file selection for designing measures in the SWAP model.

The measures assessed by the different CS and the main characteristics of their implementation are listed in Table 2.8.

Table 2.8. Types of NSWORMs implemented in the SWAP model at the OPTAIN pilot sites.

Case study	Crop types		Land use / soil management		Comment
	Status quo	Scenarios	Status quo	Measure	
CS2 (CH)	grass	maize	conventional tillage	reduced till	20% increase in OSAT, alpha, n, OM in top 30 cm.
	grass	maize		droguth resistant crop	HLIM3H from -400 to -800 cm, HLIM3L from -797 to -2000cm, HLIM4 from -10000 to -15000 cm
	arable	grass	arable	extensive system	grassland instead of cropland
CS3a (HU)	vinyard		conventional tillage	reduced till	topsoil; ORES from 0.06 to 0.06, OSAT from 0.5 to 0.5, Ksat from 90 to 94; layer 2: Ksat 280 to 293, OSAT 0.5 to 0.5
	vinyard			droguth resistant crop	HLIM3L from -1000 to -6000cm, HLIM4 from -10000 to -14000 cm
CS4 (PL)	sugar beat, wwht, corn		conventional tillage	reduced till	topsoil: OSAT + 19%, ORES +6%, ALPHA + 41%, NPAR+ 1%, BDEN + 18%, KSATFIT+18%.
CS8 (LT)	wwht		conventional tillage	droguth resistant crop	HLIM3L from -900 to -2000cm, HLIM4 from -16000 to -20000 cm
	wwht	forest	conventional tillage	afforestation	forest instead of cropland
	wwht		conventional tillage	reduced tillage	topsoil; ORES from 0.03 to 0.06, OSAT from 0.29 to 0.35, Ksat from 7 / 25 to 4
CS10 (NO)	wwht	grass	wwht, conventional tillage in the autumn	extensive system	changing the crop type
	wwht	swht		no autumn tillage	
	wwht	forest		afforestation	
	wwht	swht		no aut till and reduced till	topsoil; ORES from 0.08 to 0.1, OSAT from 0.29 to 0.35, Ksat from 7 / 25 to 4
	wwht	swht		drought resistant crop	HLIM3H from -200 to -900 cm, HLIM3L from -600 to -2000cm, HLIM4 from -8000 to -16000 cm (corn), HLIM4 from -10000 to -20000 cm (wwht),
CS11 (HU)	cropland	forest	cropland	afforestation	changing the "crop" type
CS12 (CZ)	simplified crop rotation (maize, wwht, grasse)		conventional tillage	reduced tillage	topsoil: OSAT + 19%, ORES +6%, ALPHA + 41%, NPAR+ 1%, BDEN + 18%, KSATFIT+18%.
				shifting to grassland	grassland instead of cropland
				afforestation	forest instead of cropland
				drought resistant crops (maize and winter wheat)	HLIM3H from -200/-500 to -800 cm, HLIM3L from -800/-900 to -2000cm, HLIM4 from -8000 to -15000 cm (corn), HLIM4 from -16000 to -20000 cm (wwht),

In five of the seven case studies, the effects of land use changes on the soil water regime were analysed. CS2, CS10 and CS12 analysed the effects of conversion from arable land to grassland, and CS8, CS10, CS11 and CS12 analysed the potential effects of afforestation at the pilot site. Thus, the impact of both grassland and afforestation could be evaluated for all the biogeographical regions, with the exception of grassland for Pannonia.

In four case studies representing all the three OPTAIN biogeographical regions, the possibilities of introducing new, drought tolerant crop genotypes of maize (CS2 and

CS12), grape (CS3) and winter wheat (CS8 and 12) were investigated. The implementation of land use change and drought tolerant crops in the SWAP model is rather straightforward (see Figure 4.2 in Annex 4 for the latter). To simulate the effects of land use changes, the crop file was changed to “grass” or “forest” when conducting the NSWORMs scenario runs. SWAP crop files are available for different forest types, including deciduous forests and pines (Farkas et al., 2022).

Out of the NSWORMs studied, reduced tillage is the most complex measure with respect to its implementation in the SWAP model, because i) no site-specific measurements on reduced tillage-induced changes in soil hydraulic properties were available and ii) the literature data is rather contradictory. In this report, we used the recommendations given by Marval et al. (2022). The changes in key soil hydraulic properties listed in Table 3.5 vary across the case studies, as the effects of soil tillage on soil hydraulic properties depends on soil type, soil texture and other biogeographical factors. Reduced tillage was evaluated across all the three biogeographical regions and CS11 was the only one, not handling this measure.

To implement the OPTAIN NSWORMs scenarios in the SWAP model, the calibrated SWAP model is run for each of the relevant management measures for each of the study sites. While structural measures (like vegetated buffer zones, grassed waterways or constructed wetlands) cannot be implemented in the SWAP model, some management measures can be represented in a more sophisticated way compared to the SWAT+ model. This applies in particular to the effects of various tillage practices, mulching and land use changes on soil hydraulic properties and macropore structure, and consequently on the water regime and soil water retention. Detailed guidelines are given by Marval et al. (2022).

#### 2.8.4 Combined climate and NSWORM scenarios

Combined scenario analyses are being performed by running the SWAP model with management scenario setups for all the meteorological input files representing future and reference climate. R-scripts have been prepared and tested by some of the case studies to enable efficient running of the SWAP model due to the high number of simulations caused by the numerous climate and NSWORMs combinations. The scenario results are being evaluated with respect to soil water balance elements, including:

- surface and subsurface (drainage) runoff and their ratio
- root water uptake
- transpiration / precipitation ratio
- plant available water during the vegetation period.

The NSWORMs are evaluated for their efficiency in reducing surface runoff, increasing soil water retention and increasing the amount of plant available water during droughts.

## 2.9 SWAP-SWAT+ cross validation

Cross-validation of field scale and catchment scale model results is a challenging task. Model comparisons in the scientific literature commonly concerns models executed for similar scales. Figure 2.12 demonstrates the validity of field scale models, like SWAP, within a catchment.

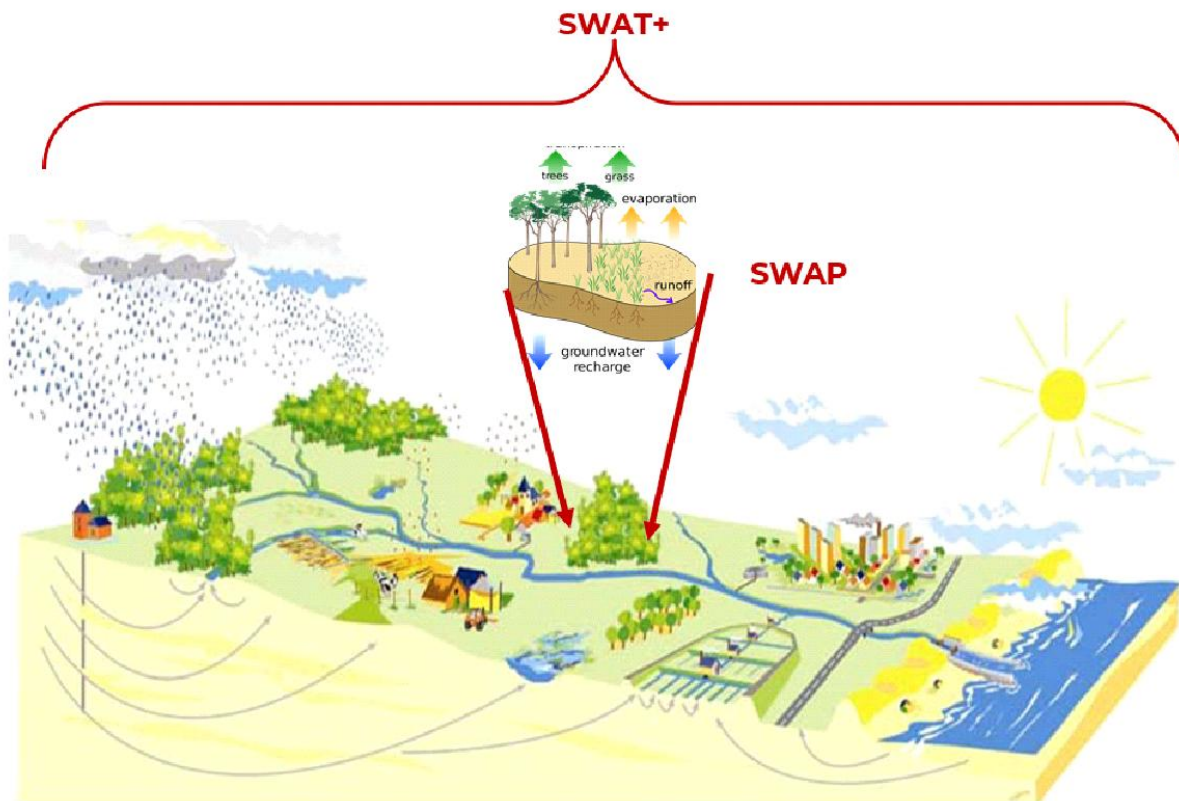


Figure 2.11. Spatial validity of the SWAP and SWAT+ models.

In the OPTAIN project, the SWAP model was used to i) evaluate the validity / accuracy of the water balance elements, simulated by the SWAT+ model at the field scale, ii) explore the possibilities of fine-tuning the SWAT+ parameters for the relevant fields, iii) improve the performance of the catchment-scale model SWAT+ at the field scale and iv) to develop recommendations for multi-spatial hydrological modelling.

Since no standard approach is available for such a procedure, the OPTAIN modelling team developed a methodology to fulfil this task. The cross-validation of the two models was performed as described in the following sub-chapters.

### 2.9.1 Spatial “matching”

The basic *spatial unit* for cross-validation of the SWAP and SWAT+ models is the field/HRU. In SWAT+, the HRUs (Hydrological Response Units) are the smallest spatial units where responses of similar land use, soil and slope classes are lumped together. The specific approach to set-up SWAT+ models within the OPTAIN project uses agricultural fields as HRUs in the cultivated areas. The modelling results of the SWAP model are valid at field scale, where each field is represented by the corresponding soil profile for which the SWAP model was calibrated and applied.

We used two different approaches for identifying the SWAT+ fields (HRUs) for the cross-validation, depending on the location of the pilot field(s) used for SWAP modelling (examples are given in Annex 8):

- **Case 1:** The monitored pilot field is located within the boundaries of the SWAT+ catchment. In such cases, the HRU number(s) corresponding to the location(s) of

the pilot fields were identified and the SWAT+ model outputs related to these HRUs were compared with those of the SWAP model.

- **Case 2:** No monitored field could be found within the SWAT+ catchment area. In this case, the HRUs used for cross-validation were identified using the following scheme:

**Step 1.** Identify the soil type of your pilot field used for field-scale modelling (SOILswap). This can be done either by using the soil types (according to e.g. FAO or other classification systems) or by using the soil textural class.

**Step 2.** Open the *soils.sol* file in the SWAT+ setup and find the soil group(s) that match SOILswap. Finding SOILswat is straightforward when using a soil classification system (column “name” in the *soils.sol* file). In the case of textural classes (column “texture” in the *soils.sol* file), several soil types within *soils.sol* might match SOILswap, so other soil properties (organic matter content, depth of the soil profile, etc.) should be considered to find the best match.

**Step 3.** List all the HRUs having SOILswat soil type from the *hru-data.hru* SWAT+ file (using column “soil”) and select those located in agricultural areas using the “lu\_mgt” column.

**Step 4.** Look up the management for the selected HRUs within the “name” column of the *management.sch* SWAT+ file. Matching the land management is not straightforward, as the nomenclature within the “lu\_mgt” column of the *hru-data.hru* does not directly match the names in the “name” column of the *management.sch* file. The easiest way to match the HRUs is to substitute the text “\_lum\_” from the “lu\_mgt” categories with “\_mgt\_”. (For example, if your lu\_mgt category is “a\_002f\_2\_drn\_lum\_68\_1”, you should look for “a\_002f\_2\_drn\_mgt\_68\_1” within the *management.sch* file).

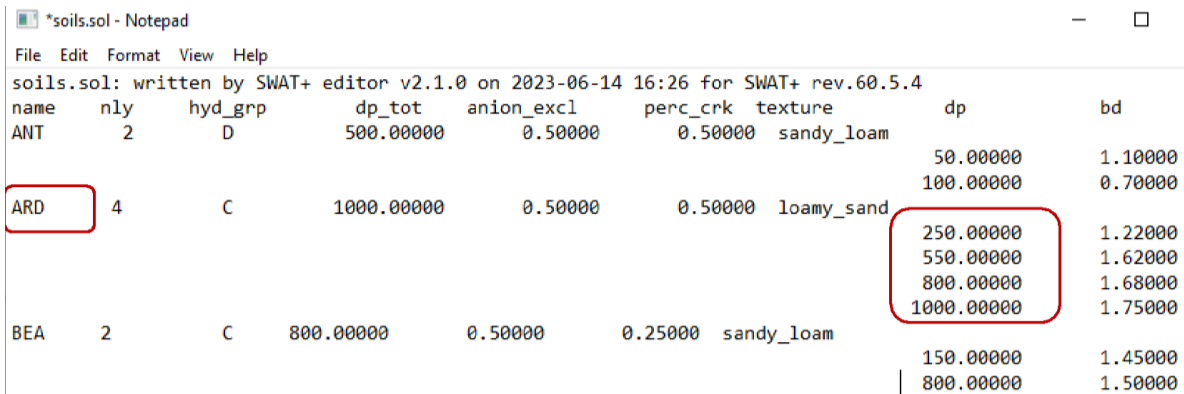
**Step 5.** The list of selected HRUs now contains all the agricultural fields that have the same soil type within the SWAT+ setup as your pilot field. Study the crop rotation for these SWAT+ fields to find those giving the best overlap with the crop rotations used in the SWAP pilot field.

**Step 6.** Using the unique management IDs within the *hru-data.hru*, find the HRU number of the field(s) that will be used for the cross-validation and identify the period for which the crop rotations are matching within the SWAP and SWAT+ models. If no direct match is found, consider re-running the SWAP model following the crop rotation of the selected SWAT+ HRU(s).

## 2.9.2 Matching the soil layers within the two models

Before we perform model runs for cross-validation, we should be sure that we can match the results for the different soil layers in our output files. A simple way to do this is to adjust the SWAP soil layers to those in the *soils.sol* file of the SWAT+ model. This step is necessary if we want to compare the dynamics of water content simulated by the two models in daily resolution.

- **Step 1:** Check the number of soil layers and their thicknesses in the *soils.sol* file for the soil type of your studied HRU in your SWAT+ setup. In the example below, the ARD soil has four layers with thicknesses of 25, 30, 25 and 20 cm, respectively:

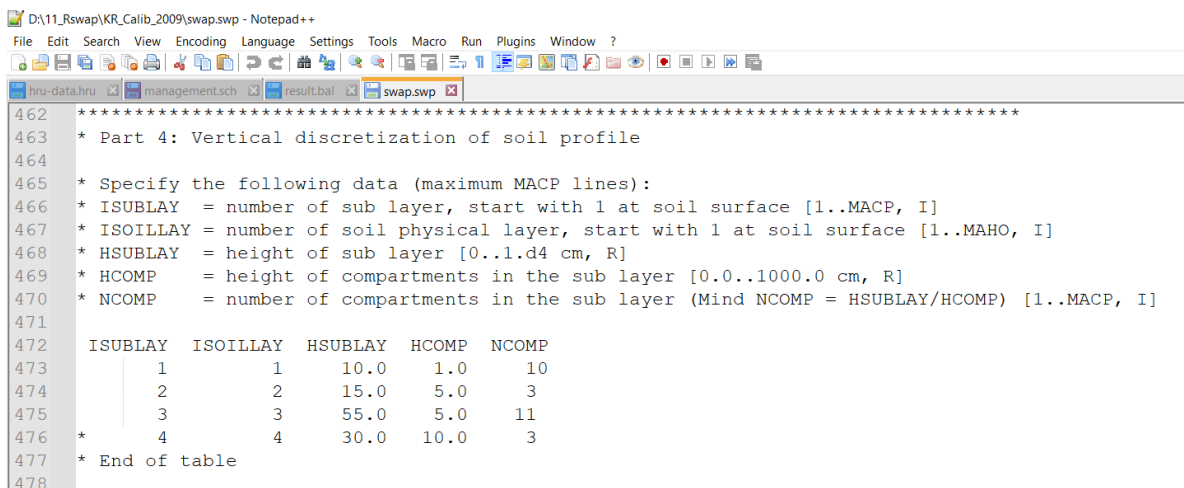


name	nly	hyd_grp	dp_tot	anion_excl	perc_crk	texture	dp	bd
ANT	2	D	500.00000	0.50000	0.50000	sandy_loam	50.00000 100.00000	1.10000 0.70000
ARD	4	C	1000.00000	0.50000	0.50000	loamy_sand	250.00000 550.00000 800.00000 1000.00000	1.22000 1.62000 1.68000 1.75000
BEA	2	C	800.00000	0.50000	0.25000	sandy_loam	150.00000 800.00000	1.45000 1.50000

Figure 2.12. Identifying the layers for the soil type in focus using the soils.sol SWAT+ input file.

- **Step 2:** In the SWAP input file swap.swp, adjust the discretisation of the soil profile so that your results could be easily calculated for the 0-25 cm, 25-55 cm, 55 – 80 cm and 80 – 100 cm soil layers.

In the example below, the average soil water content of the first two layers (10 x 1 cm + 3 x 5 cm in the digital discretisation) could be used to compare the output for the SWAT+ topsoil (25 cm). The upper 6 compartments (NCOMP) of the 3rd layer (ISOILLAY) could be used for cross-validating the results of the next 30 cm layer, etc. A detailed explanation of the vertical discretisation of the soil profile within the SWAP model can be found in the OPTAIN SWAP model protocol (Farkas et al., 2022).



```

462 *****
463 * Part 4: Vertical discretization of soil profile
464
465 * Specify the following data (maximum MACP lines):
466 * ISUBLAY = number of sub layer, start with 1 at soil surface [1..MACP, I]
467 * ISOILLAY = number of soil physical layer, start with 1 at soil surface [1..MAHO, I]
468 * HSUBLAY = height of sub layer [0..1.d4 cm, R]
469 * HCOMP = height of compartments in the sub layer [0.0..1000.0 cm, R]
470 * NCOMP = number of compartments in the sub layer (Mind NCOMP = HSUBLAY/HCOMP) [1..MACP, I]
471
472 ISUBLAY ISOILLAY HSUBLAY HCOMP NCOMP
473 1 1 10.0 1.0 10
474 2 2 15.0 5.0 3
475 3 3 55.0 5.0 11
476 * 4 4 30.0 10.0 3
477 * End of table
478

```

Figure 2.13. Profile discretisation within the swap.swp file of the SWAP model.

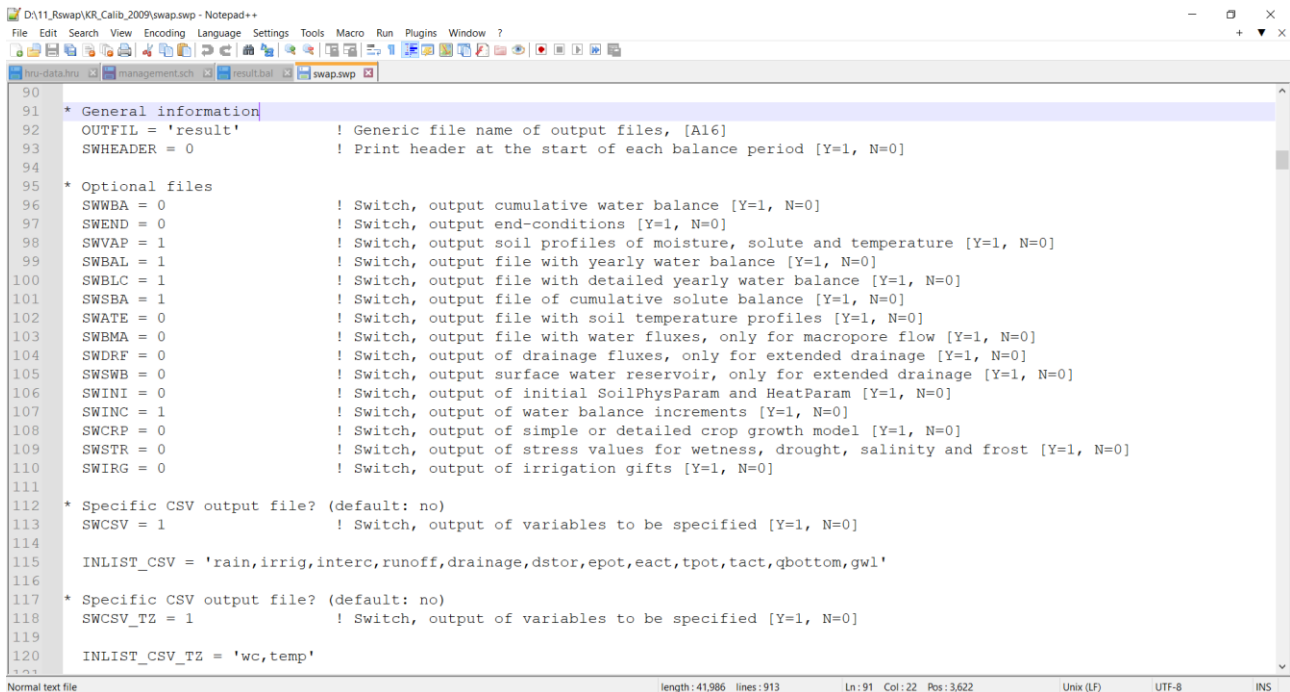
### 2.9.3 Generating daily soil water content dynamics

- **SWAP model:** The name of the output files can be defined in the output file section of the *swap.swp* input file using the “OUTFIL” parameter.

For simulating soil water content data for all the defined soil layers in daily resolution, either the SWVAP or the SWCSV & SWCSV\_TZ switches should be activated. In the first case, a *XXX.vap* file will be generated (XXX standing for the

generic file name of the output files defined via `OUTFIL`). This file, however, is not very convenient to handle.

The `rswap` R package uses the `XXX.csv` output files that can be generated by activating the `SWCSV` & `SWCSV_TZ` switches (setting them to 1). Besides, the required outputs should be defined by `INLIST_CSV_TZ`, as given in Fig. 2.14.



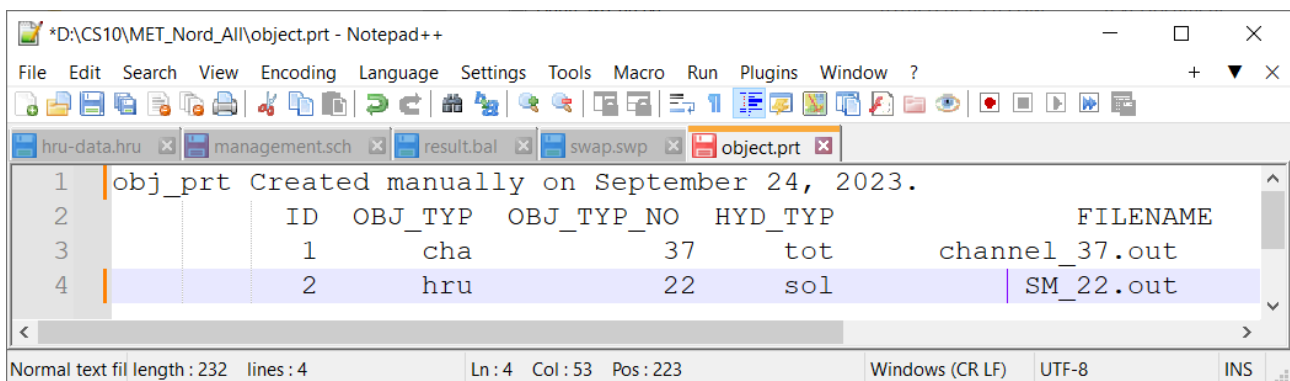
```

90
91 * General information
92 OUTFIL = 'result'          ! Generic file name of output files, [A16]
93 SWHEADER = 0              ! Print header at the start of each balance period [Y=1, N=0]
94
95 * Optional files
96 SWBBA = 0                 ! Switch, output cumulative water balance [Y=1, N=0]
97 SWEND = 0                 ! Switch, output end-conditions [Y=1, N=0]
98 SWVAP = 1                 ! Switch, output soil profiles of moisture, solute and temperature [Y=1, N=0]
99 SWBAL = 1                 ! Switch, output file with yearly water balance [Y=1, N=0]
100 SWBLC = 1                 ! Switch, output file with detailed yearly water balance [Y=1, N=0]
101 SWSBA = 1                 ! Switch, output file of cumulative solute balance [Y=1, N=0]
102 SWATE = 0                 ! Switch, output file with soil temperature profiles [Y=1, N=0]
103 SWBMA = 0                 ! Switch, output file with water fluxes, only for macropore flow [Y=1, N=0]
104 SWDRF = 0                 ! Switch, output of drainage fluxes, only for extended drainage [Y=1, N=0]
105 SWSWB = 0                 ! Switch, output surface water reservoir, only for extended drainage [Y=1, N=0]
106 SWINI = 0                 ! Switch, output of initial SoilPhysParam and HeatParam [Y=1, N=0]
107 SWINC = 1                 ! Switch, output of water balance increments [Y=1, N=0]
108 SWCRP = 0                 ! Switch, output of simple or detailed crop growth model [Y=1, N=0]
109 SWSTR = 0                 ! Switch, output of stress values for wetness, drought, salinity and frost [Y=1, N=0]
110 SWIRG = 0                 ! Switch, output of irrigation gifts [Y=1, N=0]
111
112 * Specific CSV output file? (default: no)
113 SWCSV = 1                 ! Switch, output of variables to be specified [Y=1, N=0]
114 INLIST_CSV = 'rain,irrig,interc,runoff,drainage,dstor,epot,eact,tpot,tact,qbottom,gwl'
115
116 * Specific CSV output file? (default: no)
117 SWCSV_TZ = 1             ! Switch, output of variables to be specified [Y=1, N=0]
118 INLIST_CSV_TZ = 'wc,temp'
119
120

```

Figure 2.14. Defining the output files within the `swap.swp` file of the SWAP model.

- **SWAT+ model:** If you activate daily output for the soil water content data in SWAT+, you will get output for all the HRUs and the file size will be very large. Therefore, the `object.prt` file should be used to generate soil water content data for particular HRU(s) in daily resolution. An example on how this file should look like is given below. Such a file is not automatically generated with the SWAT+ model setup, so you will need to add it to your SWAT+ project if it is missing.



```

1 obj_prt Created manually on September 24, 2023.
2 ID OBJ_TYP OBJ_TYP_NO HYD_TYP FILENAME
3 1 cha 37 tot channel_37.out
4 2 hru 22 sol SM_22.out

```

Figure 2.15. Example of the `object.prt` file in the SWAT+ model setup.

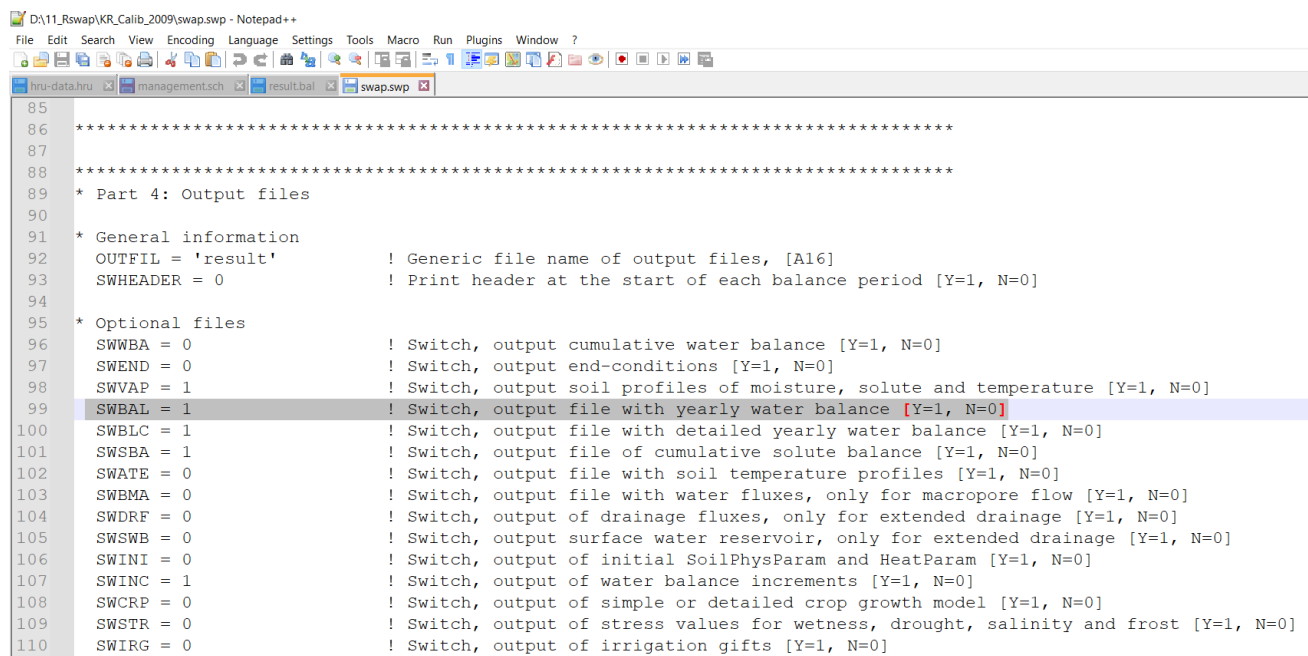
When adding this file to your SWAT+ project, it will generate two additional output files (using the parameterization shown in Figure 2.15 as an example): one with daily output data for channel 37, called `channel_37.out` and one with daily soil water content data for all the soil layers, defined in `soils.sol` for the HRU = 22, with a filename `SM_22.out`.

## 2.9.4 Generating model outputs with yearly water balance elements

During this phase, we generate the SWAP and SWAT+ output files, needed to compare the water balance elements simulated by the two models. The model runs should be performed for the same period in daily time step. Please check whether the soil properties that could be harmonised (Chapter 2, Table 2.3) are the same in the two models and whether the crop rotation is identical in SWAP and SWAT+. The basic model setup (drained or not, irrigated or not) should also match.

The following steps should be done to generate the necessary model outputs:

- **SWAP model:** Activate the “SWBAL” switch (SWBAL = 1) in the `swap.swp` file



```

85
86 *****
87
88 *****
89 * Part 4: Output files
90
91 * General information
92   OUTFIL = 'result'           ! Generic file name of output files, [A16]
93   SWHEADER = 0              ! Print header at the start of each balance period [Y=1, N=0]
94
95 * Optional files
96   SWWBA = 0                  ! Switch, output cumulative water balance [Y=1, N=0]
97   SWEND = 0                  ! Switch, output end-conditions [Y=1, N=0]
98   SWVAP = 1                  ! Switch, output soil profiles of moisture, solute and temperature [Y=1, N=0]
99   SWBAL = 1                  ! Switch, output file with yearly water balance [Y=1, N=0]
100  SWBLC = 1                   ! Switch, output file with detailed yearly water balance [Y=1, N=0]
101  SWSBA = 1                   ! Switch, output file of cumulative solute balance [Y=1, N=0]
102  SWATE = 0                   ! Switch, output file with soil temperature profiles [Y=1, N=0]
103  SWBMA = 0                   ! Switch, output file with water fluxes, only for macropore flow [Y=1, N=0]
104  SWDRF = 0                   ! Switch, output of drainage fluxes, only for extended drainage [Y=1, N=0]
105  SWSWB = 0                   ! Switch, output surface water reservoir, only for extended drainage [Y=1, N=0]
106  SWINI = 0                   ! Switch, output of initial SoilPhysParam and HeatParam [Y=1, N=0]
107  SWINC = 1                   ! Switch, output of water balance increments [Y=1, N=0]
108  SWCRP = 0                   ! Switch, output of simple or detailed crop growth model [Y=1, N=0]
109  SWSTR = 0                   ! Switch, output of stress values for wetness, drought, salinity and frost [Y=1, N=0]
110  SWIRG = 0                   ! Switch, output of irrigation gifts [Y=1, N=0]

```

**Figure 2.16.** Generating output file with yearly water balance elements using the `swap.swp` file of the SWAP model.

- **SWAT+ model:** The output file that contains the yearly water balance elements at HRU level (`hru_wb_y.txt`) should be used for cross-validation. This file should be generated by the SWATmeasR script developed in OPTAIN Task 4.4 and described in OPTAIN Deliverable D4.4 (Piniewski et al., 2024).

The original version of the SWATmeasR script does not generate outputs in yearly time resolution. To do so, the modified version of the `calc_Indis.R` file should be used ([available on UFZ Cloud](#)).

The SWATmeasR script should only be run for the in-field (management) measures, as the SWAP cannot simulate the effects of structural measures, so these cannot be included in the cross-validation.

The output folder “scenario measures” of the SWATmeasR run and the SWBAL output file (\*.bal) of the corresponding SWAP run are the main files used for cross-validation.

### 2.9.5 Cross-validation of the output data

The SWAT+ outputs should be cross-validated with the SWAP model results, both in the calibration phase and for scenario analyses. Depending on the processes involved, the following model outputs could be included:

- Potential and actual evapotranspiration
- Surface runoff
- Deep percolation
- Actual transpiration /root water uptake
- Soil water content
- Drainage outflow

Table 2.7 gives an overview of the output files and output variables to be compared.

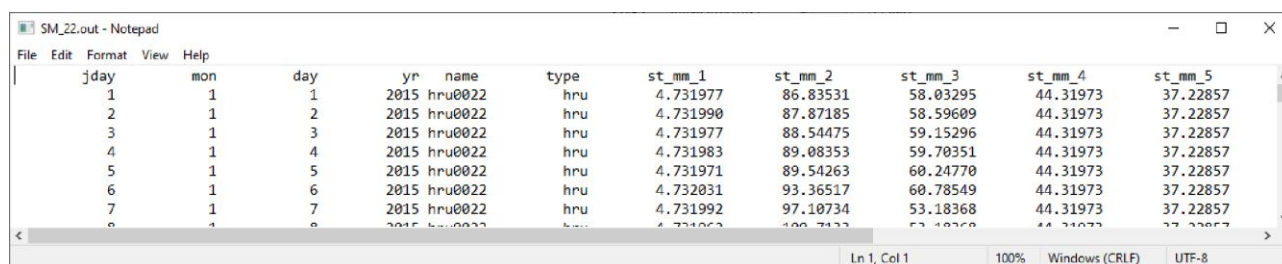
**Table 2.7.** SWAP and SWAT+ output files and variables used for cross-validation.

Variable	Resolution			Relevant output files		Variable name in the output file	
	temporal	spatial		SWAT+	SWAP	SWAT+	SWAP
	SWAP&SWAT+	SWAT+	SWAP				
Soil water content	day	HRU / field	profile / field	SM_XXX.out*	results.vap	st_mm_X	wcontent**
Evaporation	year	HRU / field	profile / field	hru_wb_yr.txt	results.bal	esoil	Soil evaporation
Transpiration	year	HRU / field	profile / field	hru_wb_yr.txt	results.bal	eplant	Transpiration
Surface runoff	year	HRU / field	profile / field	hru_wb_yr.txt	results.bal	surq_gen	Runoff
Percolation	year	HRU / field	profile / field	hru_wb_yr.txt	results.bal	perc	Bottom flux
Tile drain	year	HRU / field	profile / field	hru_wb_yr.txt	results.bal	qtile	Drainage
Pot evapotranspiration	year	HRU / field	profile / field	hru_wb_yr.txt	results.wba	pet	epot***
Interception	year	HRU / field	profile / field	hru_wb_yr.txt	results.wba	ecanopy	Interception
Initial soil water content	year	HRU / field	profile / field	hru_wb_yr.txt	results.bal	sw_init	water storage initial
Final soil water content	year	HRU / field	profile / field	hru_wb_yr.txt	results.bal	sw_final	water storage final
Change in soil water storage	year	HRU / field	profile / field	hru_wb_yr.txt	results.bal	sw_change	change
* SM - soil moisture; XXX - the number of the selected HRU							
** in m3 / m3; discretization follows the ISUBLAY defined in the Swap.swp file							
*** Values for the last day of each year should be taken							

Examples of the output files with the relevant variables are given in sub-chapter 8.2, Annex 8.

Comparing water balance elements in yearly time steps is fairly straightforward, but the SWAT+ soil water content output requires further calculation. Table 2.8 illustrates the output file received when activating soil water content output for a specific HRU using the *object.prt* file. The soil water content (SWC) data is given in mm for each layer, indicated in the *soils.sol* file. Additionally, the water content is calculated (in mm) for the upper 1 cm layer as st\_mm\_1. This data should be neglected, as we need the data from the other layers, starting from st\_mm\_2 (Table 2.8).

**Table 2.8.** SWAT+ output data of soil water content in daily resolutions for HRU 22.



jday	mon	day	yr	name	type	st_mm_1	st_mm_2	st_mm_3	st_mm_4	st_mm_5
1	1	1	2015	hru0022	hru	4.731977	86.83531	58.03295	44.31973	37.22857
2	1	2	2015	hru0022	hru	4.731990	87.87185	58.59609	44.31973	37.22857
3	1	3	2015	hru0022	hru	4.731977	88.54475	59.15296	44.31973	37.22857
4	1	4	2015	hru0022	hru	4.731983	89.08353	59.70351	44.31973	37.22857
5	1	5	2015	hru0022	hru	4.731971	89.54263	60.24770	44.31973	37.22857
6	1	6	2015	hru0022	hru	4.732031	93.36517	60.78549	44.31973	37.22857
7	1	7	2015	hru0022	hru	4.731992	97.10734	53.18368	44.31973	37.22857
8	1	8	2015	hru0022	hru	4.731992	100.7133	53.18368	44.31973	37.22857

In the example case, we will work with columns st\_mm\_2 – st\_mm\_5. To calculate the volumetric soil water content for each of the soil layers, we need to check the thickness of these layers (soil type for HRU22 comes from *hru-data.hru*, the layers for that particular soil type are visible in *soils.so*). The following equations can be used for the calculations (with an example in Annex 8):

$$\text{SWC (m}^3/\text{m}^3) = \text{SWC of layer } i \text{ (mm) / Thickness of the soil layer (mm)}$$

$$\text{SWC (v\%)} = \text{SWC (m}^3/\text{m}^3) \times 100$$

## 3 Results

### 3.1 Field-scale modelling status in different CS

The content of this chapter is based on the information provided by the OPTAIN field-scale modellers in Annexes 1-7 of this report. The SWAT+ modelling results provided by the catchment modellers in Task 4.4 (as described in Chapter 2) were used to perform the cross-validation. Table 3.1 provides a final overview of the progress made by the different CS up to the submission of this deliverable report.

The original plans in the project proposal considered one case study per biogeographical area to be involved in the field-scale modelling. Thus, even with some CS not performing cross-validation, the goals of Task 4.3 were achieved.

**Table 3.1.** Overview of the progress in field-scale modelling tasks by different Case Studies in this report.

Case study	Catchment	Bio-geographical region	SWAP model					Scenarios		Cross-validation
			Input data	Setup	Verification	Calibration	Validation	NSWRM	Climate	
<b>CS2 (CH)</b>	Petit Glâne	Continental								
<b>CS3a (HU)</b>	Csorsza	Pannonia								
<b>CS4 (PL)</b>	Boručín	Continental								
<b>CS8 (LT)</b>	Dotnuvėlé	Boreal					too few data			
<b>CS10 (NO)</b>	Krakstad	Boreal								
<b>CS11 (HU)</b>	Tetves	Pannonia								
<b>CS12 (CZ)</b>	Čechtický	Continental								

Input data preparation, model setup, verification and calibration were completed by all CS, partly within WP3. The SWAP model could not be validated at three pilot sites (CS8, CS10 and CS11) due to data scarcity. Some of the CS started soil water content monitoring within the OPTAIN project period, and sometimes even 2-3 years of monitored soil water content data are not enough to calibrate and validate the SWAP model, because of poor data quality. The R-script developed as part of the project for data quality check ensured that only realistic soil water content data was included in the analyses. The sensors record incorrectly under dry conditions, so some of the data were removed from the analyses. In addition, data recorded in frozen soils were blacklisted, as they could not be used for model calibration or validation, as the sensors register the liquid part of the water in the soil, while the SWAP model simulates the total quantities. The most recent version of the model contained a calculation scheme for liquid and frozen water in partially frozen soils, but we did not see any reduction in the modelled soil water contents when activating this scheme.

All the seven CS that carried out field-scale modelling provided results on the impacts of climate change and the NSWRM effectiveness. Three CSs (CS2, CS10 and CS11) were involved in comparing the SWAP model outputs with the water balance elements simulated by the SWAT+ model. In four cases, cross-validation could not be completed; at three pilot sites, the SWAT+ model calibration had not been completed at the time of submission of this report, while one CS modeller experienced technical problems and severe data loss, preventing them from producing the specific SWAT+ model outputs required for cross-validation in a timely manner.

### 3.2 Overview of the SWAP model setup and evaluation in different CS

The SWAP model projects were created taking into account the specificities of the pilot sites. The variability of the OPTAIN case studies across different biogeographical regions in Europe is well represented by the processes considered or neglected in the models (Table 3.2).

**Table 3.2.** Overview of the processes, modelled within the site-specific SWAP projects. (green - processes considered, grey - processes, not included in the SWAP model setup)

Case study	Catchment	bio-geographical region	Processes / routines in the SWAP model						
			ponding	tile drain	irrigation	macro-pores	snow and frost	bottom boundary conditions	crop routine
CS2 (CH)	Petit Glâne	continental						free flux	WOFOST
CS3a (HU)	Csorsza	Pannonia						free flux	simple
CS4 (PL)	Boručín	continental						ground water table from SWAT+	simple
CS8 (LT)	Dotnuvélé	boreal						zero bottom flux	simple
CS10 (NO)	Krakstad	boreal						zero bottom flux	simple
CS11 (HU)	Tetves	Pannonia						free flux	simple
CS12 (CZ)	Čechtický	continental						zero bottom flux	simple

Some site-specific characteristics were considered via the parameters, describing the water ponding threshold for runoff (PONDMX) and the drainage resistance for surface

runoff (RSRO). None of the case studies implemented the rather complex soil macropore routine, and all of them are from rainfed agriculture (no irrigation).

Three (CS8, CS10 and CS12) out of the seven CS are tile drained, for these cases the drainage routine was activated and the drainage formula of Hooghoudt or Ernst (Farkas et al., 2022) was selected to calculate the water movement to and from the drain pipes.

The calibration and validation periods for the different pilot sites are given in Table 3.3. For calibrating and validating the SWAP model, soil water content dynamics data is commonly used. This can be supplemented with data on yield, drainage outflow and any other on-site measurements of soil water balance elements.

The pilot sites involved in this study had very different backgrounds. Some sites belonged to long-term monitoring programs or experiments with long data series (Swiss and Czech sites, CS2 and CS12). For the Polish, Lithuanian and Norwegian sites (CS4, CS8 and CS10) soil water content measurements started within the OPTAIN project to collect reference data for field-scale modelling. Data collection with soil moisture probes at a high temporal resolution (CS4) supported model validation. However, in CS8 the time series remained too short as much data had to be removed from the evaluation due to different reasons: i) time needed for the sensor to fully establish in the soil without cavities; ii) data for the winter period had to be removed etc.). In Norway the sensors established in the experimental fields got broken and soaked. Therefore CS10, similarly to CS11, used soil water content data available from earlier projects.

**Table 3.3.** Calibration and validation periods used for the different pilot sites

Case study	Catchment	Period		Comment
		calibration	validation	
<b>CS2 (CH)</b>	Petit Glâne	2008-2017	2018-2022	
<b>CS3a (HU)</b>	Csorsza	2021-2022	2021-2022	
<b>CS4 (PL)</b>	Boručín	2022	2021	
<b>CS8 (LT)</b>	Dotnuvėlé	2022-2023		Limited amount of reference data was available to perform model validation.
<b>CS10 (NO)</b>	Krakstad	2009-2010		
	Krakstad			
<b>CS11 (HU)</b>	Tetves	2013-2014		
<b>CS12 (CZ)</b>	Čechtický	2016-2018	2019-2021	

The CS modellers used different model performance statistics to evaluate the calibration and validation results. The most commonly used statistics were those suggested by Moriasi et al. (2015) specifically for soil hydrological models: the index of agreement (d) and the coefficient of determination ( $R^2$ ). Additionally, the PBIAS and the NSE were used. During model calibration, special focus was given to the PBIAS (Percent bias), as it measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999). In our case, similar to the water balance elements, the PBIAS was evaluated on an annual time scale. Thus, if the PBIAS values indicate good model performance, we can assume that the annual values of the water

balance elements are simulated with acceptable uncertainty, even in cases where the daily dynamics - reflected by the  $d$  and NSE values - are not well captured.

The SWAP model performance statistics for the different OPTAIN sites are shown in Table 3.4. Very good, good and satisfactory model calibration / validation according to Moriasi et al. (2015) are indicated by green colours. The SWAP calibration was less successful for sites where the soils are tile drained (CS8, CS10 and CS12), partly because of the lack of reliable data on drainage outflow.

As also outlined in OPTAIN D4.4 (Piniewski et al., 2024), it is important to recognize that there are currently no generally 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.

Table 3.4. SWAP model performance statistics for the OPTAIN pilot sites.

Case study	Catchment	Soil layer cm	Calibration				Validation			
			d	pbias	R <sup>2</sup>	NSE	d	pbias	R <sup>2</sup>	NSE
CS2 (CH)	Petit Glâne	5		-7.7		0.62		2.5		0.81
		10-Jan		4.4		0.78		6.2		0.63
		Jan-00		6.7		0.67		17.5		-0.20
		40		1.7		0.83		1.3		0.56
		65		-3.8		0.51		-2.4		0.34
CS3a (HU)	Csorsza	15	0.81	9.8	0.52	0.52	0.74	-3.9	0.34	0.34
		40	0.81	10.6	0.51	0.52	0.81	-3.9	0.46	0.47
CS4 (PL)	Boručin	10	0.93		0.75	0.71	0.93		0.80	0.70
		30	0.94		0.85	0.72	0.97		0.87	0.60
		50	0.91		0.71	0.64	0.93		0.86	0.60
		70	0.92		0.73	0.7				
		90	0.93		0.78	0.77				
CS8 (LT)	Dotnuvélé	10	0.28							
		40	0.50							
		90	0.20							
		120	0.44							
CS10 (NO)	Krakstad loamy sand soil	10	0.64	7.2						
		20	0.61	6.7						
		40	0.5	-3.0						
	Krakstad loamy clay soil	10	0.83	8.4						
		20	0.59	8.6						
		40	0.65	-5.9						
CS11 (HU)	Tetves	15	0.84	0.8	0.63	0.63				
		40	0.96	-1.4	0.86	0.86				
		70	0.93	0.1	0.78	0.78				
CS12 (CZ)	Čechtický	10	0.71	-1.5			0.70	0.4		
		20	0.65	-8.1			0.66	9.0		
		30	0.81	-18.2			0.52	20.1		
		40	0.76	4.5			0.57	5.0		

very good
  good
  satisfactory

### 3.3 Assessment of NSWRM effectiveness at field scale for present climate conditions

#### 3.3.1 Water balance perspective

The effectiveness of NSWRMs at field scale was evaluated by examining the changes in soil water balance elements (Fig. 3.1). Soil water balance refers to the amount of water in the soil (defined for a certain time period and for the whole soil profile or a particular soil layer), and it reflects the difference between the inputs (e.g. precipitation, irrigation, runoff) and outputs (e.g. interception, runoff, evaporation, transpiration, drainage, percolation). When analysing the water balance of the soil profile as a whole (commonly defined as the root zone), matrix and macropore flows contribute to the redistribution of water between the different soil layers, not to the total balance.

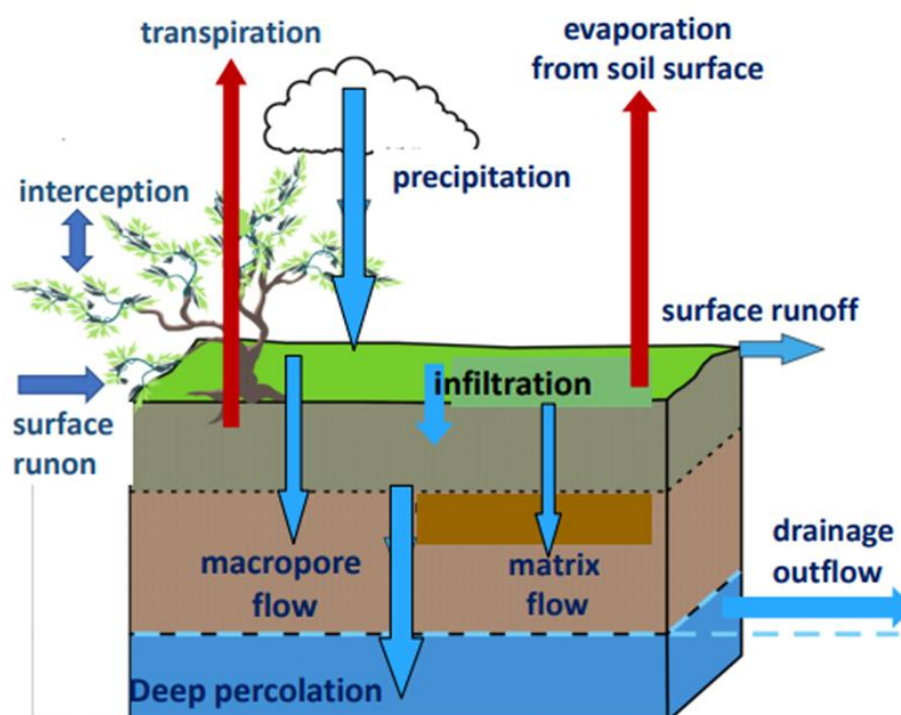


Figure 3.1. Key water balance elements of a soil profile

It is important to mention that the effect of an individual NSWRM on water retention cannot be evaluated directly in terms of increased soil water storage. Plants may benefit from the increase of available water in the soil, which leads to increased transpiration and reduced soil water storage. Thus, the impact of soil water retention measures on the water regime should be evaluated in a more complex way, considering all the water balance elements together. As an example, soil water content of a heavily cultivated soil can be higher in the deeper layers than in a soil with reduced tillage, as the compacted layer at the plough/disk pan prevents the infiltration of the water in the deeper layers, as well as root growth. Thus, the plants are suffering from drought while there can be valuable amounts of water below the compacted layers. That is why the effectiveness of NSWRMs has to be evaluated by looking at all the water balance elements simultaneously. On the other hand, reductions in water balance elements that lead to water loss from the soil profile (interception, surface runoff, evaporation from soil surface,

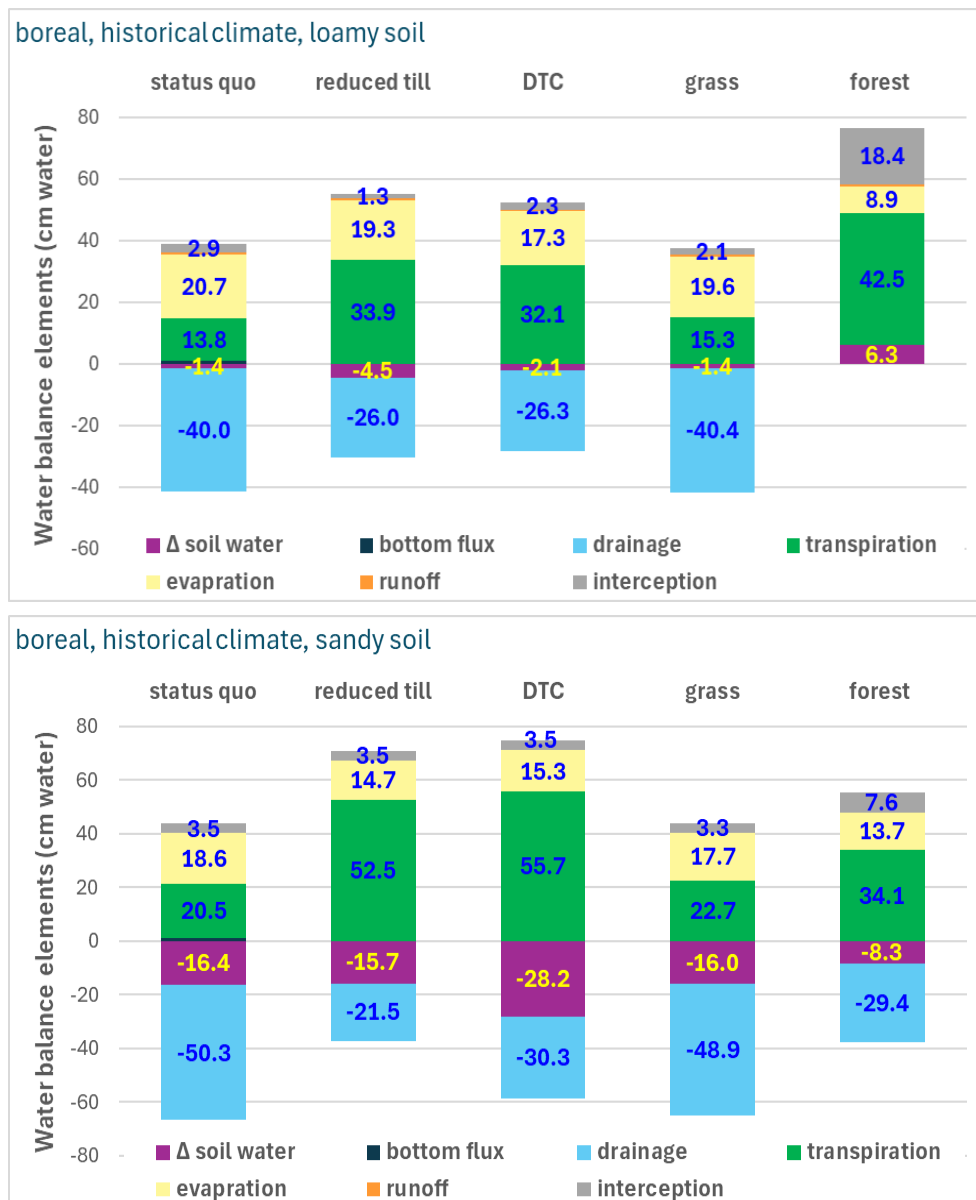
drainage outflow and deep percolation) all indicate increased water retention within the field.

Generally, increased plant transpiration, alongside reduced deep percolation and runoff, indicate improved retention of water within the soil profile. At the bottom of the soil profile, the SWAP model calculates either drainage outflow or percolation to deeper layers. This is because, with subsurface drainage, the model assumes zero percolation to the deeper layers.

Figures 3.2 - 3.4 give an overview of the impact of NSWORMs on water balance elements assessed using the SWAP field-scale model. Changes in soil water content for a certain period are calculated using the following equation:

$$\Delta SW = P - INTCEPT - RUNOFF - EVAP - TRANSP - DRAIN - BFLUX \quad (\text{Eq. 1})$$

Where:  $\Delta SW$  - changes in soil water content (cm), P - precipitation sum (cm), INTCEPT - interception (cm), RUNOFF - surface runoff (cm), EVAP - evaporation from soil surface (cm), TRANSP - transpiration or plant water uptake (cm), DRAIN - drainage outflow (cm) and BFLUX - bottom flux or percolation (cm). Positive and negative values represent upward and downward fluxes, respectively.

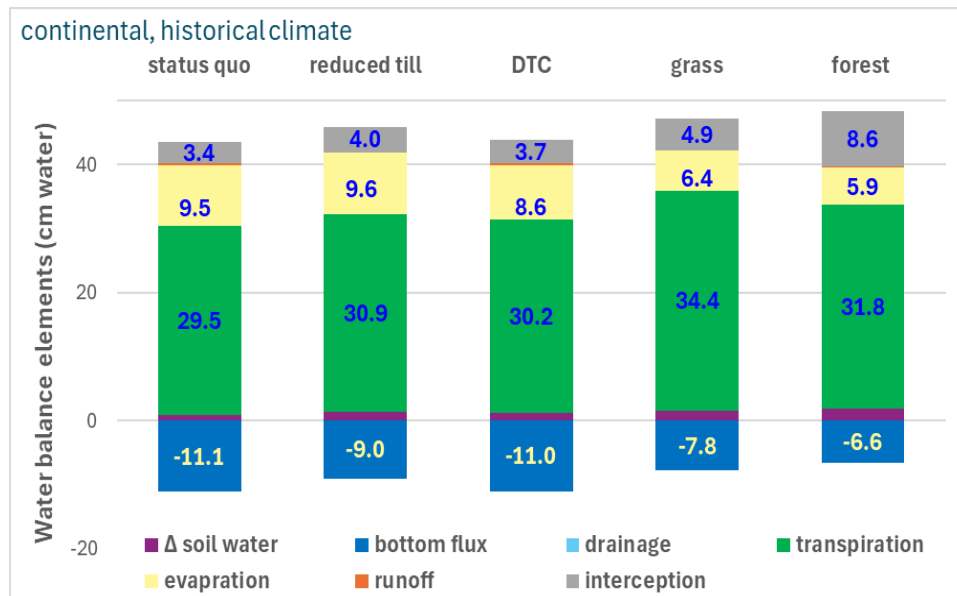


**Figure 3.2.** NSWRM effects on soil water balance elements modelled for two soil types of the boreal region for the historical climate (2009-2019).

In the boreal regions the main goal for implementing soil water retention measures in agricultural areas is to reduce and/or to slow down surface and subsurface runoff towards surface water bodies. Surface runoff and subsurface drainage water, reaching the streams, contribute to soil erosion and nutrient loads, thus, have harmful impact on soil health and on the conditions of freshwater and marine water ecosystems. With ongoing climate change, summer drought has become a new issue in Norwegian agriculture. Thus, soil water retention is also important from this aspect.

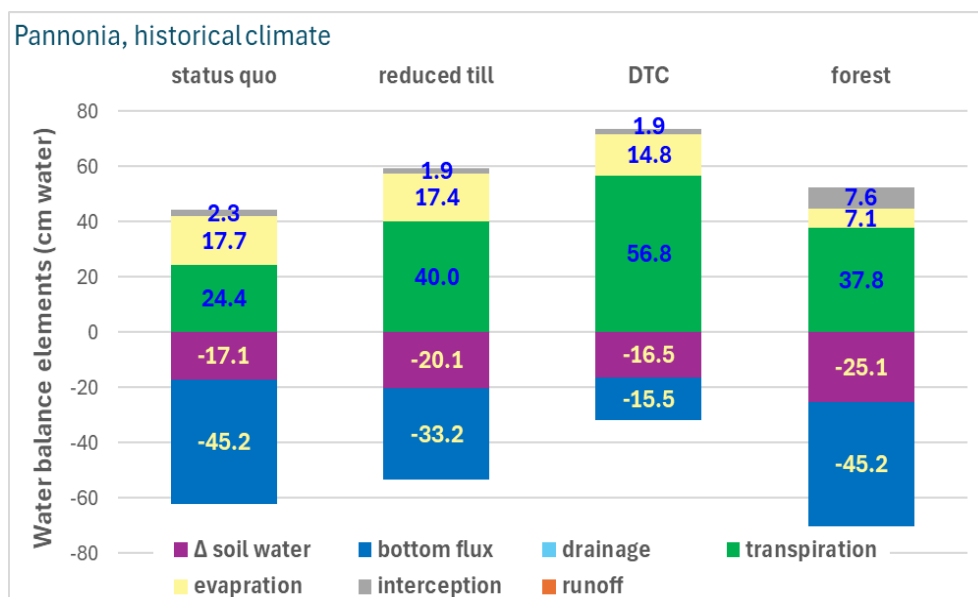
In this region, shifting to grassland seems to have the least impact on soil water balance elements, compared to the baseline scenario. Afforestation, reduced tillage and drought tolerant crops (DTC) reduced drainage outflow significantly, mostly due to increased transpiration, and also interception in case of forest vegetation (Figure 3.2). The effect of NSWRM on soil water content was more visible in the sandy soil, also because sandy soils are more susceptible to drought. DTC increased transpiration more than two times,

as the newly introduced crops could transpire more water at the expense of soil moisture in the sandy soil.



**Figure 3.3.** NSWRM effects on soil water balance elements modelled for the continental region for the historical climate (1991-2020).

Compared to the boreal region, the effect of NSWRMs on soil water balance elements was less pronounced in the continental region, as demonstrated by the Swiss case study (CS2; Fig. 3.3). Land use change (shifting to grassland or afforestation) and reduced tillage resulted in a slight decrease of leaching from the soil profile and also slight increase in transpiration. The largest changes were modelled for interception and changes in soil water storage. However, as these water balance elements represent less than 10% of the total soil water balance, the large relative changes did not influence the overall water budget to a large extent.



**Figure 3.4.** NSWRM effects on soil water balance elements modelled for the Pannonian region for the historical climate (1991-2020).

Drought is the major problem in the Pannonian region. All three of the NSWORMs tested for these sites contributed to significant increase in transpiration (Fig 3.4). The soil profiles of these areas are well developed and more than 1 m deep. Therefore, absolute change in the soil water storage of up to -8 mm (afforestation scenario) does not significantly affect the average soil water content. Planting drought tolerant plant genotypes seems to be the most promising measure to mitigate drought. Hence, transpiration almost doubled in the DTC scenario, as the crop roots could uptake water at higher water potentials (water that is more strongly “bounded” within the unsaturated zone). Meanwhile, percolation to deeper layers is reduced, which is also an important factor as this can prevent nitrate leaching to groundwater, which is another problem in this region. Contradictorily to other regions, where afforestation resulted in a slight (continental region) or very strong (boreal region) reduction in drainage outflow, in the Pannonian region afforestation did not reduce the percolation of water to deeper layers.

Table 3.6 provides an overview of the effects of in-field NSWORMs on the elements of the water balance for all seven pilot sites, representing the three biogeographical regions. Slight (less than 10%) and strong (more than 10%) increases compared to the baseline are highlighted in light and darker green, respectively. Similarly, slight and strong decreases compared to the baseline are highlighted in light yellow and orange colours, respectively.

In some cases, the seemingly large changes (like an increase in interception with afforestation ranging between 118% to 526 %) cover small absolute changes of up to 15-18 mm. However, as the original value was very small (below 3 mm), an increase of 10-15 mm results in a large relative change in interception.

Reduced surface and subsurface runoff can also strongly contribute to reducing flash flood peaks and the loss of soil particles and nutrients to surface waters, resulting in improved water quality in the long term. Reduced deep percolation leads to an increased amount of water stored in the root zone, thereby mitigating the effects of drought. It also prevents the transport of nutrients towards the subsurface water bodies, preventing their further contamination.

The overall picture shows that the impact of the studied in-field NSWORMs on individual soil water balance elements can vary even within the same biogeographical region, depending on factors such as the crop type and rotation, soil type, soil management and other local conditions (e.g. slope). These findings confirm our expectations and the need for site-specific studies and analyses when optimising the NSWORM types within the field and a catchment as a whole. Moreover, it would be very important to gain as many experimental data as possible, as the evaluation of the model response to a particular measure is difficult without site-specific information about the effectiveness of a certain measure for the typical soil, crop and slope combinations of the pilot sites.

In line with our expectations, *reduced tillage* resulted in a decrease of various types of water losses from the soil profile. It reduced surface runoff by 100% and by 30-40% in the continental and boreal regions, respectively. These results are consistent with those of the SWAT+ model for these areas, where it was shown that reduced tillage can mitigate flash floods, prevent soil erosion and reduce the loss of nutrients towards the surface water bodies.

Table 3.6. Effectiveness of in-field NSWORMs in different biogeographical regions

NSWRM	water balance elements	Biogeographical region							
		Pannonia		Continental			Boreal		
		CS3a	CS11	CS2	CS4	CS12	CS8	CS10_L	CS10_S
reduced tillage	interception	10-50%		10-50%		no change	no change	10-50%	no change
	runoff			> 50%			10-50%	no change	10-50%
	evaporation	10-50%		10-50%	10-50%	10-50%		10-50%	10-50%
	transpiration	10-50%		10-50%	10-50%	10-50%	10-50%	10-50%	10-50%
	soil water storage	10-50%		10-50%	10-50%	10-50%	10-50%	10-50%	10-50%
	drainage					10-50%	10-50%	10-50%	10-50%
	percolation	10-50%		10-50%					
from arable to grassland	interception					10-50%		10-50%	10-50%
	evaporation					10-50%		10-50%	10-50%
	transpiration					10-50%		10-50%	10-50%
	soil water storage					10-50%		10-50%	10-50%
	drainage					10-50%		10-50%	10-50%
	percolation					10-50%		10-50%	10-50%

NSWRM	water balance elements	Biogeographical region							
		Pannonia		Continental			Boreal		
		CS3a	CS11	CS2	CS4	CS12	CS8	CS10_L	CS10_S
afforestation	interception		10-50%			10-50%		10-50%	10-50%
	runoff					10-50%	> 50%		> 50%
	evaporation		10-50%			10-50%		10-50%	10-50%
	transpiration		10-50%			10-50%		10-50%	10-50%
	soil water storage		10-50%			10-50%	10-50%	10-50%	10-50%
	drainage					10-50%	10-50%	> 50%	10-50%
	percolation		no change						
drought tolerant crops	interception	10-50%		10-50%		no change		10-50%	10-50%
	runoff			10-50%				10-50%	10-50%
	evaporation	10-50%		10-50%		10-50%		10-50%	10-50%
	transpiration	10-50%		10-50%		10-50%		10-50%	10-50%
	soil water storage	10-50%		no change		10-50%	10-50%	10-50%	10-50%
	drainage					10-50%	10-50%	10-50%	10-50%
	percolation	10-50%		10-50%					

no change	no change
< 10 %	slight reduction
10-50%	moderate reduction
> 50%	strong reduction
< 10 %	slight increase
10-50%	moderate increase
> 50%	strong increase

In the Pannonian and Continental regions without subsurface drainage, reduced tillage resulted in a decrease of deep percolation by approx. 25% and 10%, respectively. This has its own environmental benefits, as reduced percolation means reduced leaching of nutrients (especially nitrate) into the groundwater bodies. Nitrate leaching towards the saturated layer is a major problem in many areas of the Pannonian region.

Similar to percolation, reduced tillage systems lead to lower drainage outflow in the areas with subsurface drainage. This effect became more visible when moving from the south (Continental region) to the north (Baltics and Scandinavia of the boreal region). The more positive the overall water balance, the stronger is the reduction effect of reduced tillage on drainage outflow, varying between approx. 3% (CS12) and 34% (CS10).

The effect was also stronger for heavy soils (CS10 with loamy soil) than on soils with lighter texture (CS10 with sandy soils).

Evaporation, transpiration and changes in soil water storage show a more complex picture between the studied regions, sometimes even between the different sites within the same region. The SWAP model simulated a 16-20% reduction in soil evaporation for the Pannonian and Boreal regions when reduced tillage was introduced, and basically no changes for the pilot sites located in the Continental region.

Transpiration (or plant water uptake) shows a very slight decrease (by 1.8% and 0.2%) in the Pannonian (CS3) region and in CS4 of the Continental region. However, these differences are within the uncertainty range of the model outputs, as well as the slight increases in the other Continental pilot sites (CS2 and CS12). The model predicted a large increase in transpiration values for CS10 (Boreal), independent of the soil type. These results, however, should be interpreted carefully as they don't reflect the impact of reduced tillage itself, but the impact of reduced tillage (indicated with changes in soil hydraulic properties, Table 3.5) and crop type. Reduced tillage in the CS10 of the Boreal region usually means no tillage in the autumn, which is associated with shifting from winter crops to summer crops. Thus, the crop type was also changed in the model setup. The large changes thus reflect the combined effect of changes in both soil and crop management.

***Shifting from arable to grassland*** resulted in an increase and decrease of interception for CS12 (Continental) and CS10 (Boreal), respectively. The impact of this measure on the other water balance elements showed more or less similar patterns, with decreases and increases in evaporation and transpiration, respectively. In general, grasslands represent more dense vegetation compared to cereals (row crops), which leads to a higher soil cover fraction and a reduction in evaporation from the soil surface. This water saving effect most likely increases the amount of plant available water in the soil, which leads to an increase in plant transpiration. The reduction of evaporation is more pronounced in the Continental region (by 33%, CS12), which is characterised by drier conditions and larger atmospheric water demand. In the Boreal region, the effect of grassland is less pronounced (around 5%), as the conditions are more humid and cold.

***Afforestation*** gave the most uniform picture regarding the effect of this measure on water balance elements. The results show a significant decrease in evaporation (from 26 to 60%), drainage outflow (from 42 to 100%) and surface runoff losses (from 35 to 67%) in all the three biogeographical regions. Afforestation also led to an extremely high increase in interception and a valuable increase in transpiration, independently from the location of the pilot sites. The changes in soil water storage compared to baseline reflected the region-specific water balance, leading to a strong - 94% - decrease in the Pannonian region, which is generally characterised by a negative water balance, and a strong increase in the CS12 (Continental) and CS10\_L (Boreal) pilot sites. Two out of the three pilot fields from the Boreal region showed no significant changes in soil water storage.

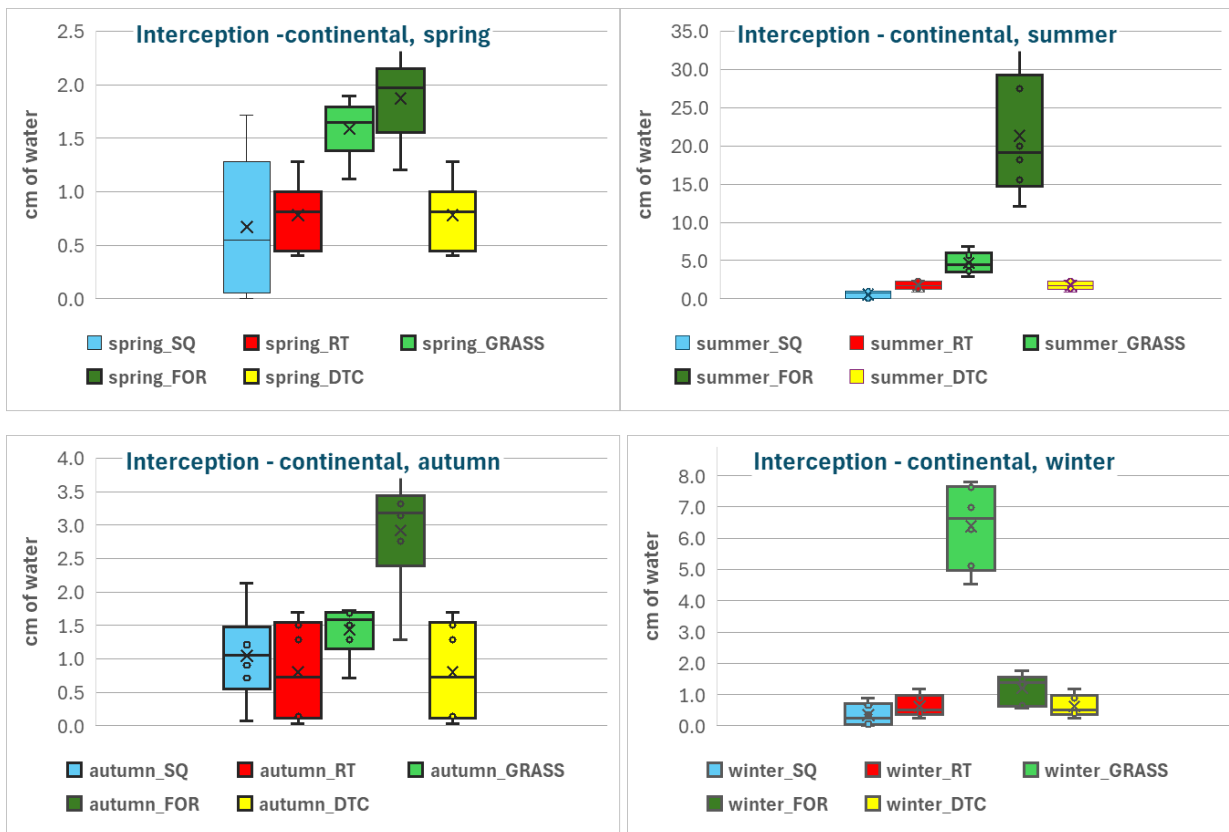
The introduction of ***drought tolerant crops*** had a rather similar effect in all the pilot sites, with CS2 being the only exception. If the effect of this measure was significant, its implementation resulted in decreases in interception (by approx. 15 to 20%), surface runoff (from 30 to 100%), evaporation (by approx. 7-17%) and drainage outflow (by approx.

35-40%). For some case studies, no changes (CS2, CS8 and CS12) or a 10% decrease (CS2) in transpiration was simulated. In CS3 (Pannonia) a slight increase in crop transpiration of 10% was estimated. The most pronounced effect of drought tolerant plants on transpiration was estimated for CS10 in the Boreal region, independent of the soil type. We assume that these results reflect the fact that drought has become an important factor in these regions, which impacts on crop production are still underestimated. Moreover, the SWAP crop database for boreal conditions does not account for drought tolerance. Both summer and winter cereals had the lowest HLIM3 and HLIM4 values (Annex 4, Figure 4.2) among all the crops included in this study. Thus, changes in HLIM3 and HLIM4 parameters were the highest in CS10, which could also lead to a drastic increase in plant transpiration. However, this shows the potential of introducing drought tolerant crops into the crop production system of Boreal regions.

### 3.3.2 Seasonal patterns

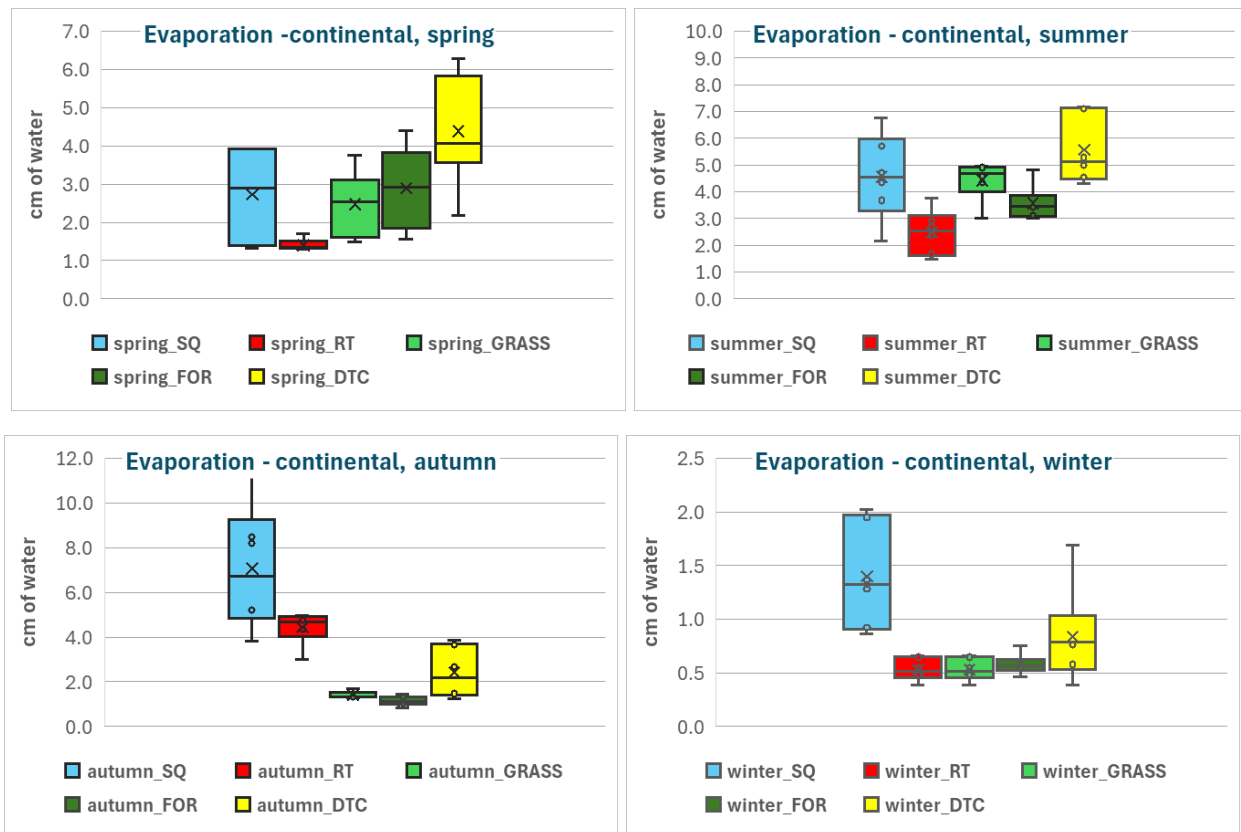
So far, this report focused on the average annual changes in the soil water regime, while it is well known that the elements of the soil water balance vary strongly in time. Hence, we evaluated the seasonal changes in interception, transpiration, evaporation, drainage outflow and soil water content on the example of CS12, located in the Czech Republic.

Interception accounts for only a small part of the water balance, and is very small in spring, autumn and winter. For all the scenarios apart from grassland, a significant proportion of the interception occurs during the summer period (Fig. 3.5). Compared to other measure scenarios, grassland intercepts about 6-7 times more water during the winter, most probably because it retains its leaves while deciduous forests lose theirs in autumn. The interception rate is particularly high in forest scenarios during spring (3 times higher), summer (20 times higher) and autumn (4 times higher), compared to the baseline scenario. Hence, afforestation can also contribute to water retention also by intercepting and evaporating a large amount of water. This phenomenon is also important, as it ensures higher air humidity within and around the vegetation than in areas with arable crops.



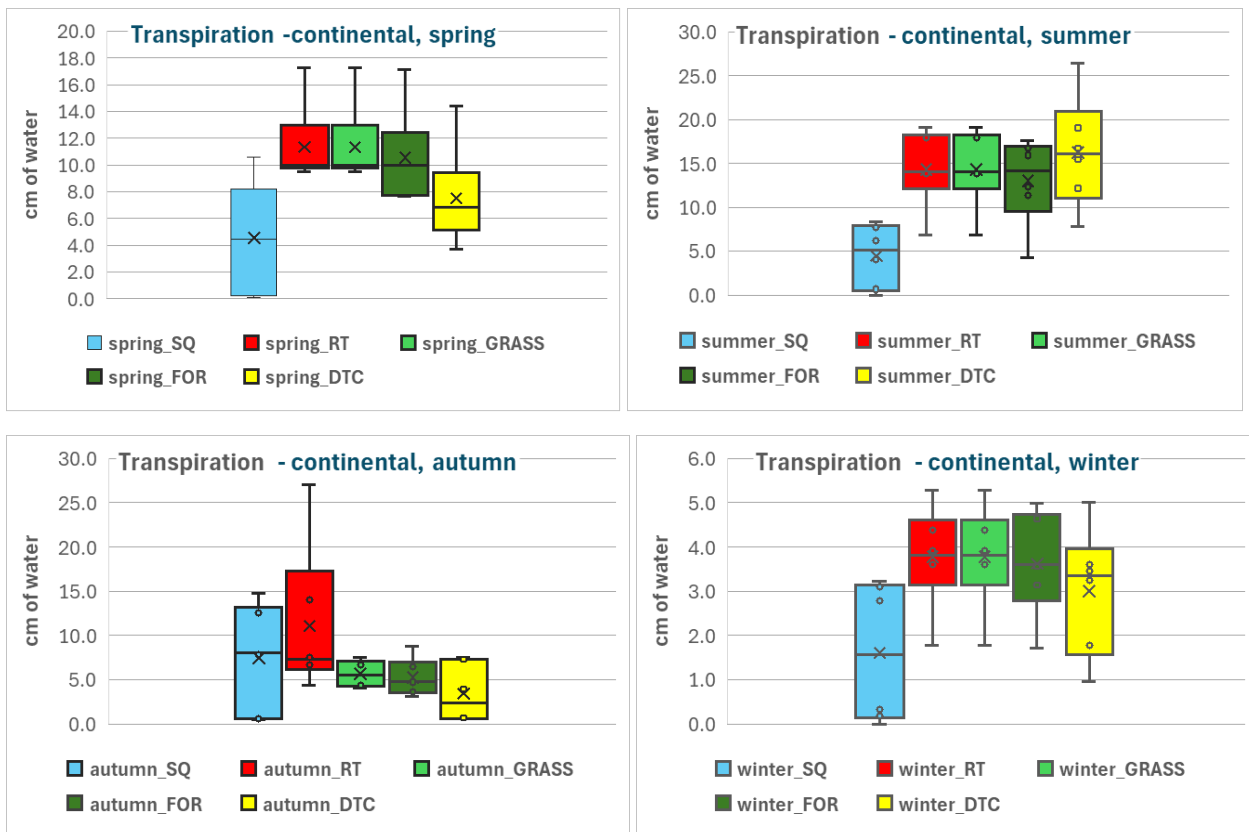
**Figure 3.5.** Seasonal variation of interception (historical climate, years 2015-2021) in the continental region (CS12) for conventional management (SQ) and after implementing different NSWWRMs. RT - reduced tillage, GRASS - shifting from arable land to grassland, FOR - afforestation and DTC - drought-tolerant crops

Evaporation from the soil surface (Fig. 3.6) is the highest during summer and autumn, when the potential evaporation is high due to atmospheric conditions. Apart from the weather conditions, the impact of NSWWRMs on evaporation also reflects soil coverage by vegetation throughout the year. Conventional tillage and drought tolerant crops (DTC) have the highest evaporation amounts during spring, summer and winter. Reduced tillage, that incorporates stubble, cover crops or winter crops ensures plant coverage on the soil surface through the year thus, reduces evaporation losses from the soil compared to conventional tillage and DTC.



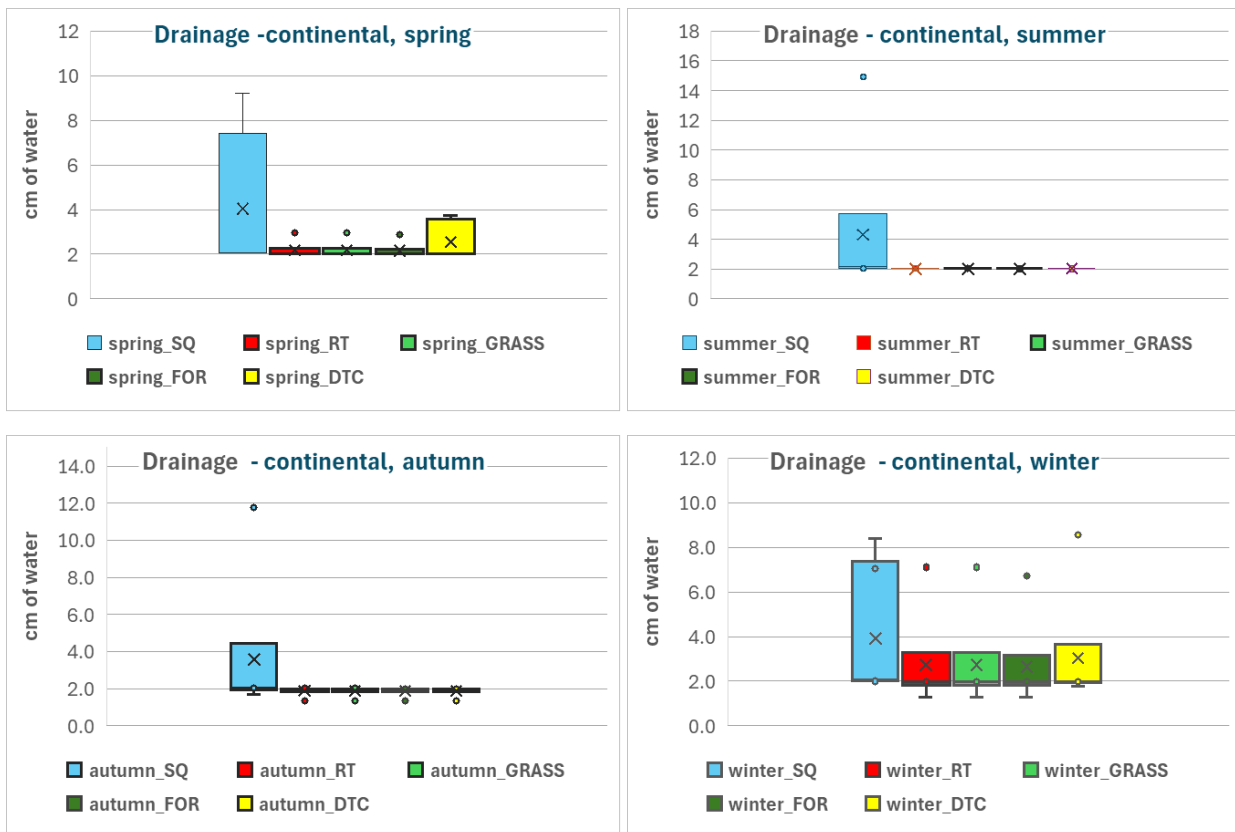
**Figure 3.6.** Seasonal variation of evaporation (historical climate, years 2015-2021) in the continental region (CS12) for conventional management (SQ) and after implementing different NSW RMs. RT - reduced tillage, GRASS - shifting from arable land to grassland, FOR - afforestation and DTC - drought-tolerant crops

The SWAP model considers a relatively small amount of water stored in the vegetation, and thus assumes that transpiration equals the plant water uptake by roots. Transpiration is one of the largest and most important elements of the water balance, as it can also be used as a yield indicator. Conventional tillage showed the lowest transpiration for all the seasons, with autumn being the only exception (Fig. 3.7). The vegetation could transpire more water from reduced tillage systems all around the year. Grassland and forest could not transpire more water than the arable crops in reduced tillage and DTC scenario, probably because their water demand could not be fulfilled from the soil water storage. The higher plant water uptake from reduced tillage and DTC scenarios could probably be explained by increased soil water retention capacity due to improved soil structure and increased suction power of the root system, respectively.



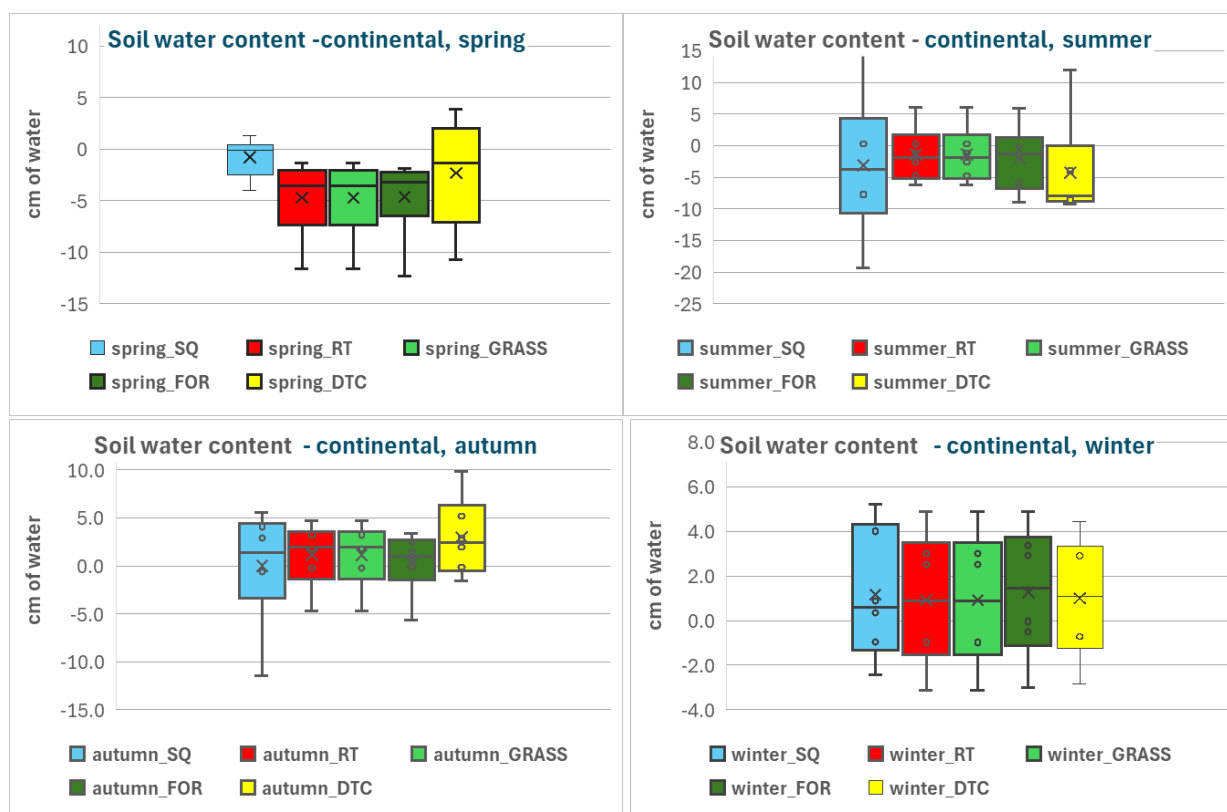
**Figure 3.7.** Seasonal variation of transpiration (historical climate, years 2015-2021) in the continental region (CS12) for conventional management (SQ) and after implementing different NSWORMs. RT - reduced tillage, GRASS - shifting from arable land to grassland, FOR - afforestation and DTC - drought-tolerant crops

Drainage outflow is highly impacted by extreme weather events., therefore, it is difficult to interpret on an annual or seasonal time scale. Indeed, the SWAP simulation results (Fig. 3.8) showed a strong reduction of drainage outflow across all the NSWORMs compared to the baseline scenario (conventional tillage). Our results suggest that the NSWORMs involved in this study could contribute to reduced leaching and drainage, creating more favourable soil water conditions for the vegetation.



**Figure 3.8.** Seasonal variation of drainage outflow (historical climate, years 2015-2021) in the continental region (CS12) for conventional management (SQ) and after implementing different NSWWRMs. RT- reduced tillage, GRASS - shifting from arable land to grassland, FOR - afforestation and DTC - drought-tolerant crops

No significant differences in soil water content were found on a seasonal basis across all the scenarios (Fig.3.9). A slight decrease in soil water storage was simulated during spring and summer, while a slight increase was found for the autumn and winter seasons. This is consistent with long-term observations stating that the soil layers are filled up with water during the colder seasons and dry out during the vegetation period.

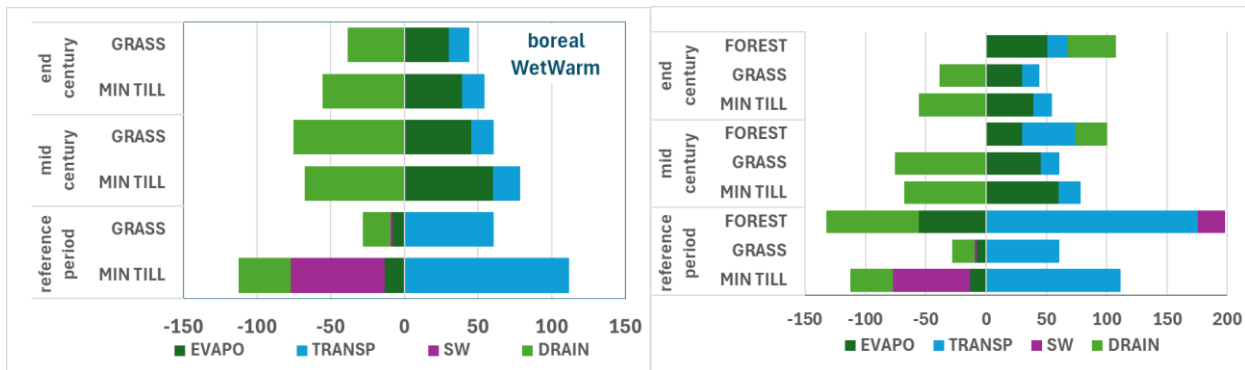


**Figure 3.9.** Seasonal variation of changes in soil water content (historical climate, years 2015-2021) in the continental region (CS12) for conventional management (SQ) and after implementing different NSWORMs. LT - reduced tillage, GRASS - shifting from arable land to grassland, FOR - afforestation and DTC - drought-tolerant crops

### 3.4 Assessment of NSWORM effectiveness at field scale for future climate conditions

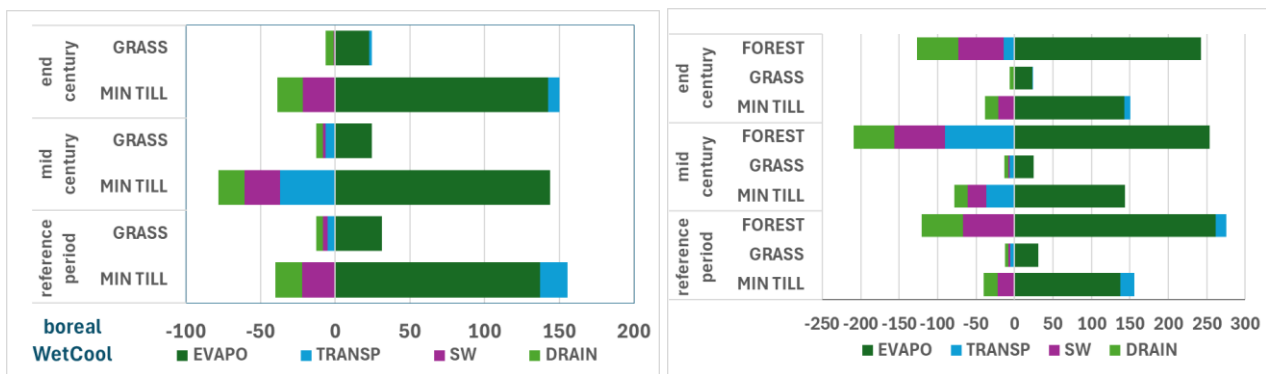
This sub-chapter assesses the impact of different measures on soil water balance elements under future climate conditions. Figures 3.10-3.12, 3.13-3.15 and 3.16-3.18 illustrate the relative changes in water balance elements as compared to current soil and crop management for the boreal, continental and Pannonian biogeographical regions, respectively. For each region, three future climate types are studied: wet and warm, dry and warm, and dry and cool (Table 2.6).

The effect of the selected NSWORMs on water balance elements shows a similar pattern across the three climate types for the continental and Pannonian regions. However, this is not the case for the boreal biogeographical region. In the boreal region, each climate type has its own specific pattern. The SWAP modelling results indicate that wet and warm future conditions (Fig. 3.10) would result in an increase of transpiration and evaporation, while decreasing drainage outflow.

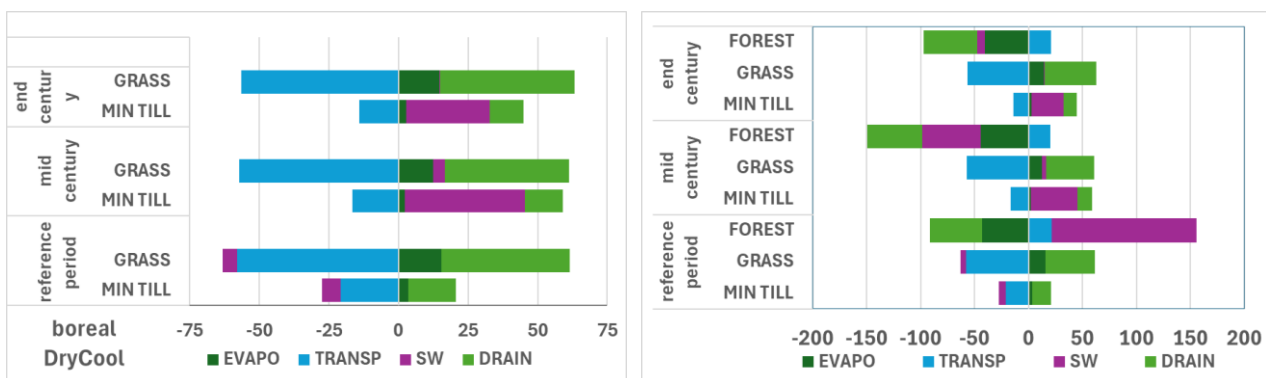


**Fig. 3.10.** Impact of different NSWORMs on soil water balance elements as compared to the status quo (in %) at current and future climate conditions in the **boreal** region for the *wet&warm* climate scenario. MIN TILL - reduced tillage; EVAP - evaporation from soil surface; TRANSP - transpiration or plant water uptake; SW - changes in soil water content; DRAIN - tile drain outflow.

For a wet and cool scenario (Fig. 3.11), the evaporation would be impacted the most, increasing significantly compared to the current levels. This climate type would result in a decrease in soil water storage and drainage under minimum tillage and afforestation scenarios. The dry and cool scenario would have, most probably, the least favourable impact with a high reduction in transpiration.

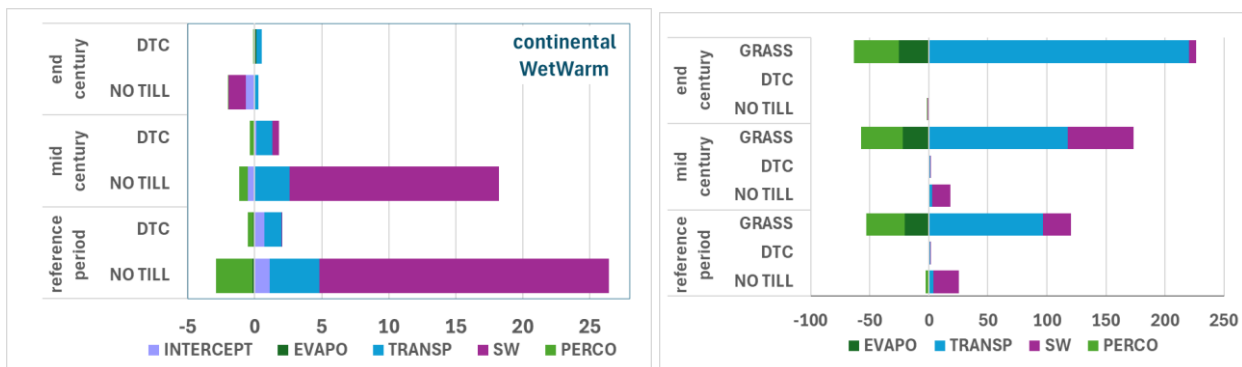


**Fig. 3.11** Impact of different SWORMs on changes in soil water balance elements as compared to the status quo (in %) at current and future climate conditions in the **boreal** region for the *wet&cool* climate scenario. MIN TILL - reduced tillage; EVAP - evaporation from soil surface; TRANSP - transpiration or plant water uptake; SW - changes in soil water content; DRAIN - tile drain outflow.

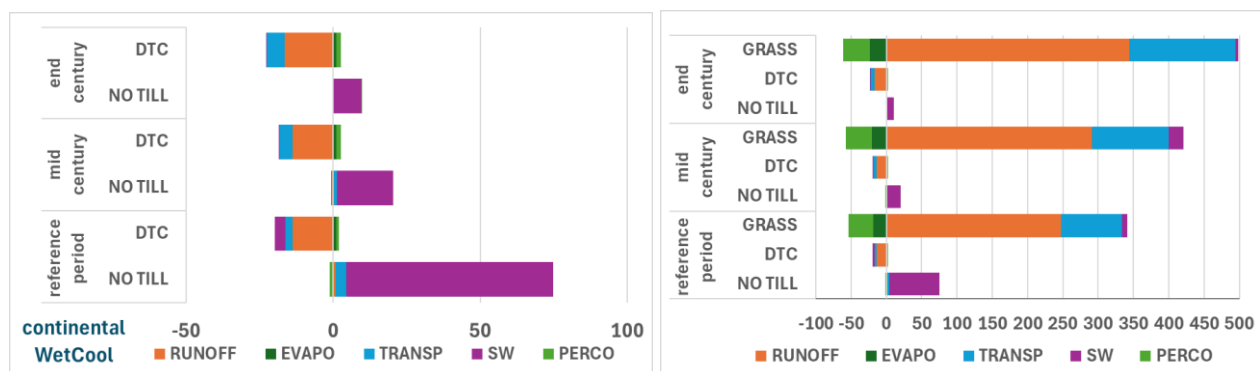


**Fig. 3.12** Impact of different SWORMs on changes in soil water balance elements as compared to the status quo (in %) at current and future climate conditions in the **boreal** region for the *dry&cool* climate scenario. MIN TILL - reduced tillage; EVAP - evaporation from soil surface; TRANSP - transpiration or plant water uptake; SW - changes in soil water content; DRAIN - tile drain outflow.

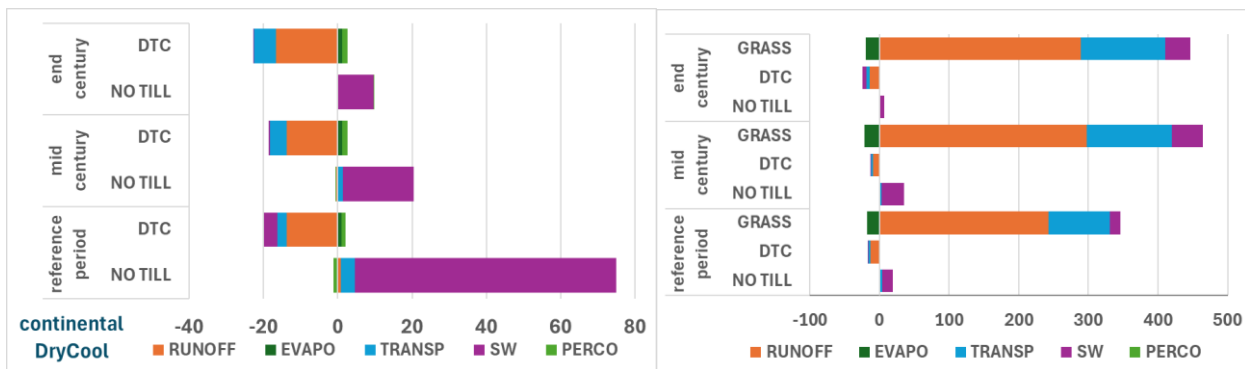
In the continental region, management measures (NO TILL and DTC) have minor impact of below 5% on interception, evaporation, transpiration and percolation compared to the land use change scenario (grassland) for all the climate types. The modelling results indicate that zero tillage increases soil water storage, independently from the climate type. This impact, however, is less expressed under future climate conditions. Grassland increases transpiration and reduces percolation, and this impact is getting stronger with time. Grassland also seems to increase runoff to a large extent; indeed, the status quo value for runoff was around zero (but not zero), therefore any few mm increase in runoff results in a huge relative impact.



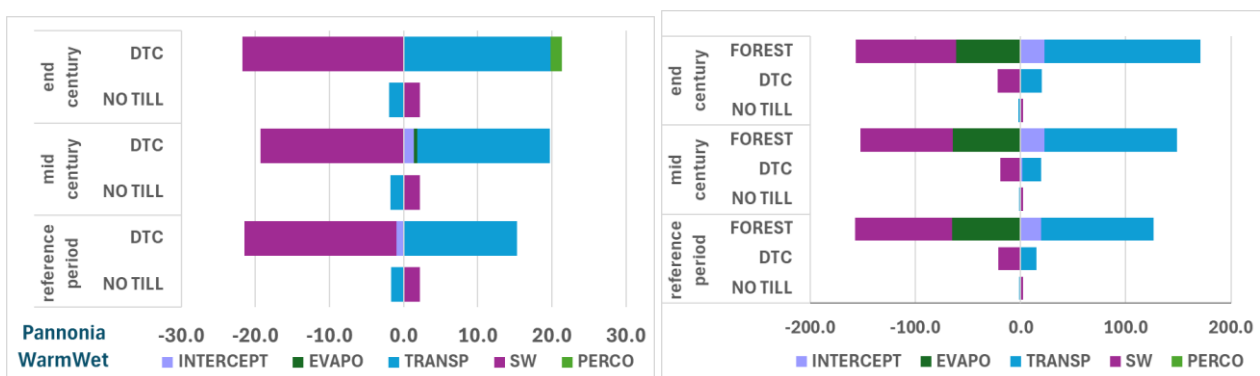
**Fig. 3.13** Impact of different NSWORMs on soil water balance elements as compared to the status quo (in %) at current and future climate conditions in the **continental region** for the *wet&warm* climate scenario. DTC - drought tolerant crops; No till - zero tillage; INTERCEPT - interception; EVAPO - evaporation from soil surface; TRANSP - transpiration or plant water uptake; SW - changes in soil water content; PERCO - percolation.



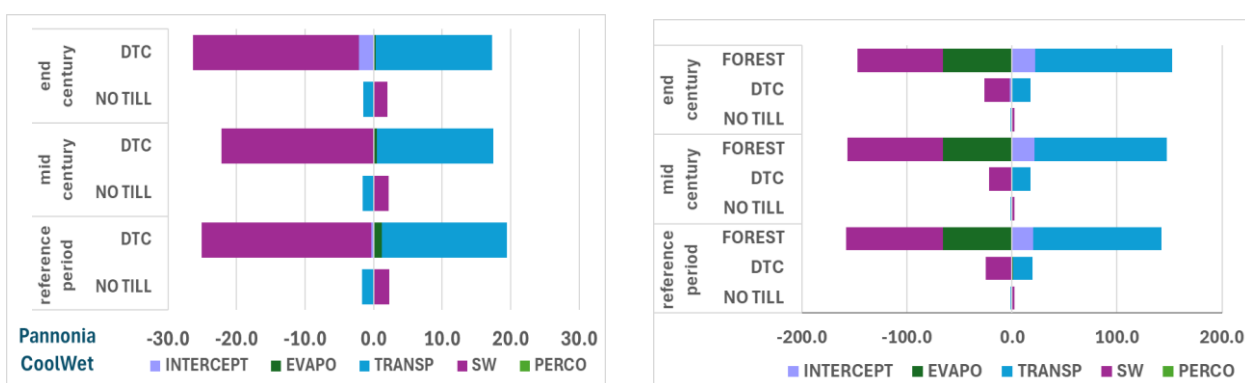
**Fig. 3.14** Impact of different NSWORMs on soil water balance elements as compared to the status quo (in %) at current and future climate conditions in the **continental region** for the *wet&cool* climate scenario. DTC - drought tolerant crops; No till - zero tillage; RUNOFF - surface runoff; EVAPO - evaporation from soil surface; TRANSP - transpiration or plant water uptake; SW - changes in soil water content; PERCO - percolation.



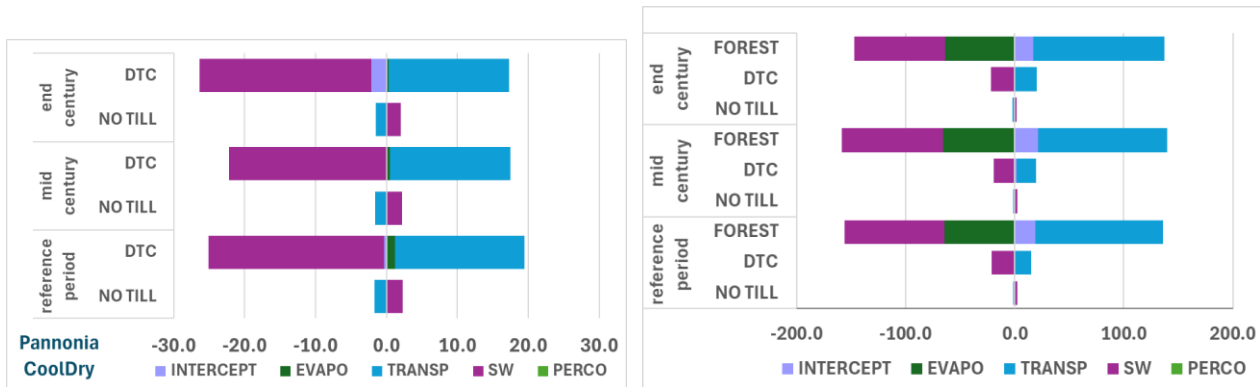
**Fig. 3.15** Impact of different NSWORMs on soil water balance elements as compared to the status quo (in %) at current and future climate conditions in the **continental region** for the *dry&cool* climate scenario. DTC - drought tolerant crops; No till - zero tillage; RUNOFF - surface runoff; EVAPO - evaporation from soil surface; TRANSP - transpiration or plant water uptake; SW - changes in soil water content; PERCO - percolation.



**Fig. 3.16** Impact of different NSWORMs on soil water balance elements as compared to the status quo (in %) at current and future climate conditions in the **Pannonian region** for the *wet&warm* climate scenario. DTC - drought tolerant crops; No till - zero tillage; INTERCEPT - interception; EVAPO - evaporation from soil surface; TRANSP - transpiration or plant water uptake; SW - changes in soil water content; PERCO - percolation.



**Fig. 3.17** Impact of different NSWORMs on soil water balance elements as compared to the status quo (in %) at current and future climate conditions in the **Pannonian region** for the *wet&cool* climate scenario. DTC - drought tolerant crops; No till - zero tillage; INTERCEPT - interception; EVAPO - evaporation from soil surface; TRANSP - transpiration or plant water uptake; SW - changes in soil water content; PERCO - percolation.



**Fig. 3.18** Impact of different NSWORMs on soil water balance elements as compared to the status quo (in %) at current and future climate conditions in the **Pannonian region** for the **dry&cool** climate scenario. DTC - drought tolerant crops; No till - zero tillage; INTERCEPT - interception; EVAPO - evaporation from soil surface; TRANSP - transpiration or plant water uptake; SW - changes in soil water content; PERCO - percolation.

For the Pannonian region, a strong reduction in soil water content and a large increase in transpiration were predicted. Zero tillage, drought tolerant crops and afforestation showed minor, moderate and huge effects on water balance elements, and this impact does not seem to change by the mid- or end of the century.

The combined climate and NSWORMs scenarios show a very diverse pattern, especially for the boreal region. Their interpretation, however, is not trivial, as there are no reference values with which to objectively evaluate the SWAP modelling results. Overall, the land use change measures seem to have a larger and positive impact on the water balance elements than the management measures. Among the management measures, reduced tillage is the most promising alternative in the future.

### 3.5 Cross-validation of the SWAP and SWAT+

This section presents the cross-validation of the water balance simulation results of the SWAP and the SWAT+ models for three case studies representing the Pannonian, Continental, and Boreal biogeographical regions.

The cross-validation of the two models is a rather complex and novel task that requires extensive experience in the application of both models. To our knowledge, no such work has been published before. However, the OPTAIN group considered it interesting and important to evaluate the performance of the catchment-scale SWAT+ model at field level using the simulation results of the field-scale model SWAP for selected fields as described in sub-chapter 2.9, as many of the NSWORMs studied in the project are implemented at the field level. The final goal is to develop recommendations on how we could improve the performance of both models by running them in parallel for the same sites.

Considering the peculiarities of the pilot fields and leaving out the unused and neglectable elements (e.g. irrigation), the water balance equation of the SWAT+ model at the HRU level for a certain time period can be written as:

$$\text{sw\_chang} = \text{precip} + \text{surq\_ro} + \text{latq\_ro} - \text{wateryld} - \text{et} - \text{perc} - \text{qtile} \quad (\text{Eq. 2})$$

$$\text{wateryld} = \text{surq\_gen} + \text{latq} \quad (\text{Eq. 3})$$

$$\text{et} = \text{ecanopy} + \text{eplant} + \text{esoil} \quad (\text{Eq. 4})$$

Where:

sw_chang:	change in soil water storage (mm)
precip:	precipitation (mm)
surq_ro:	surface runoff (mm)
latq_ro:	lateral runoff (mm)
wateryld:	water yield (mm)
et:	evapotranspiration (mm)
perc:	percolation (mm)
qtile:	drainage outflow (mm)
surq_gen:	surface runoff (mm)
latq:	lateral flow (mm)
ecanopy:	canopy evaporation (mm)
eplant:	plant transpiration (mm)
esoil:	evaporation from soil surface (mm)

The soil water balance equation (Eq. 1) visualised in Fig. 3.1 can be written as below:

$$\Delta\text{SW} = \text{P} - \text{INTCEPT} - \text{RUNOFF} - \text{EVAP} - \text{TRANSP} - \text{DRAIN} - \text{BFLUX} \quad (\text{Eq. 5})$$

Where:

$\Delta\text{SW}$ :	change in soil water storage (mm)
P:	precipitation (mm)
INTCEPT:	interception (mm)

RUNOFF: surface runoff (mm)  
 EVAP: evaporation (mm)  
 TRANSP: transpiration (mm)  
 DRAIN: drainage outflow (mm)  
 BFLUX: percolation (mm)

As the SWAP model simulates predominantly processes in the unsaturated zone, having bottom boundary conditions nearby or above the saturated zone, and the water flow is considered to be vertical, the lateral flow components of the SWAT+ model (latq\_ro and latq) could be neglected in the comparison. Table 3.7 describes how the output variables of the two models were matched for cross-validation.

**Table 3.7.** Matching the soil water balance elements of the SWAP and SWAT+ models

Water balance elements	
SWAP model	SWAT+ model
$\Delta SW$	= sw_chang
P	= precip
INTCEPT	= ecanopy
RUNOFF	= surq_gen - surq_ro
EVAP	= esoil
TRANSP	= eplant
DRAIN	= qtile
BFLUX	= perc

The fluxes of evaporation, transpiration and drainage outflow (where relevant) as well as the simulated change in soil water content, interception and percolation were the outputs that could be directly involved in the cross-validation of the models. However, we could not include the simulated runoff values in the cross-validation, because in the SWAT+ model setup the pilot fields are connected to the surrounding land phase and shallow subbasin elements, with lateral in- and outflow. In contrast, the SWAP model projects, in their present setup, cannot account for the surface inflow from other areas.

The next subchapters present the results of the cross-validation of the SWAP and SWAT+ models for the respective simulation periods. The cross-validation was performed for both the baseline and NSWRMs simulation results. Water balance elements that represent a minor part of the total balance in a field scale model, such as interception and runoff, are discussed for the Continental region only, since this case study had the longest time series for comparison.

Please note that the results from the two models for the combined - measure and climate - scenarios could not be compared, as the SWAT+ calculations for these scenarios are not yet available, and the SWAT+ scenario work was not part of this

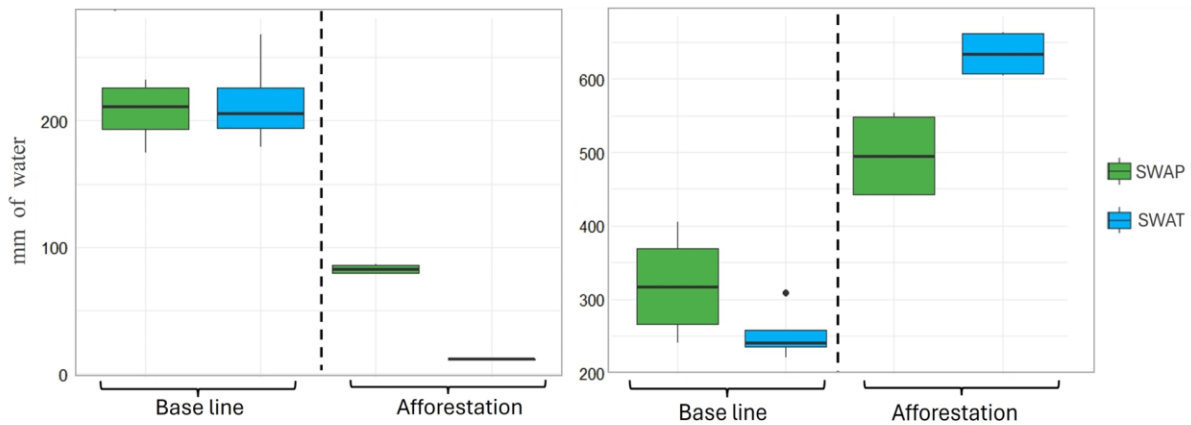
deliverable D4.3. Additional analysis and discussion of the cross-validation will also be provided in an upcoming scientific publication, which is currently in progress.

Concerning the NSWORMs included in the cross-validation, it is important to mention that the field-scale modelling work, using the SWAP model incorporated more scenarios, than the scenario runs performed with the SWAT+ model. As an example, CS10 (Norway) did not have an afforestation or drought tolerant crop scenario in the catchment-level modelling work, thus no SWAT+ scenario results were available for cross-validation. Additional scenarios were included in the SWAP modelling analyses so that more NSWORMs could be compared across the different biogeographical regions.

We faced similar restrictions with the simulation periods: in most of the cases, the watershed-level data (e.g. discharge) were available for a longer period than the reference soil water content data for SWAP model calibration. Results from the two models could only be compared for years, for which we had simulation results from both the SWAP and SWAT+ models.

### 3.5.1 Pannonian biogeographical region

In the Pannonian case study, the outputs of the SWAP and SWAT+ models were compared for the baseline and afforestation scenarios, as shown in Figure 3.1. For evaporation fluxes, the models gave nearly identical results in the baseline scenario. The median and range of the simulated evaporation are almost the same for both SWAP and SWAT+. In the afforestation scenario, there is an average difference of 70 mm between the two models' results. When comparing the simulated transpiration results in the baseline scenario, we found that the results of the SWAP model showed a wider range and median within the different years. Since in SWAP transpiration is estimated by considering the root water uptake for each crop/tree, the wider range in the results for both scenarios is reasonable. For the afforestation scenario, the median transpiration was about 140 mm larger compared to that of the SWAP model. We assume that the differences between the transpiration values simulated by the SWAT+ and SWAP models, increased for the afforestation scenario compared to the baseline, because the interception is a much more important factor in the forest than in croplands. As SWAT+ cannot simulate interception and its evaporation loss, which are important water balance factors for trees, the SWAT+ transpiration results in the afforestation scenario are likely to be overestimated. In the future, these findings could be used to fine-tune the plant parameters in the SWAT+ model for forests in order to make the simulated transpiration values for the Pannonian region more realistic.



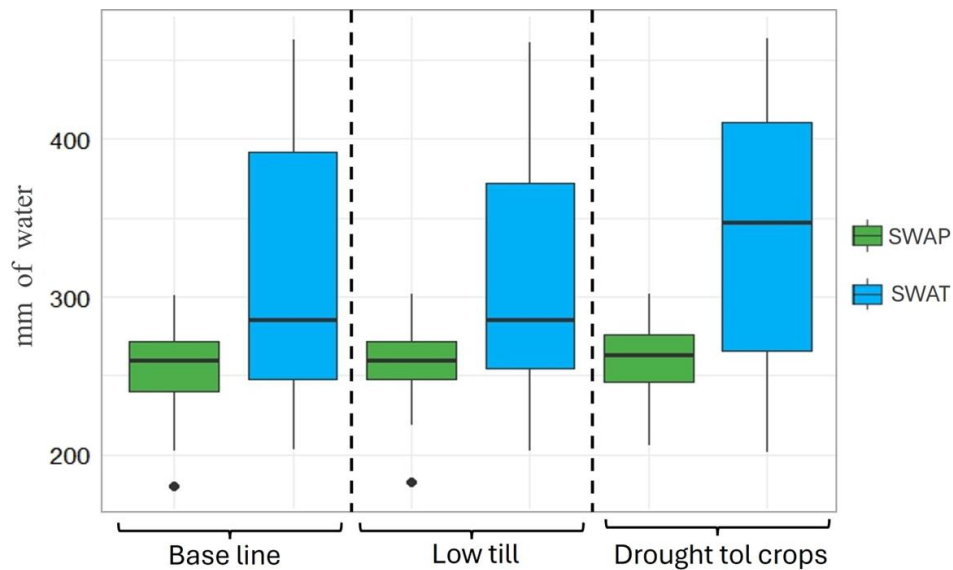
**Figure 3.19.** Annual average evaporation (left) and transpiration (right) simulated by the SWAP and SWAT models for the Tetves pilot site for the present management and afforestation scenario.

### 3.5.2 Continental biogeographical region

For the Continental region, the outputs of the two models were compared for the baseline and the low tillage and drought-tolerant crops scenarios. The results for interception, changes in soil water storage, evaporation and transpiration are given in Figures 3.2-3.5, respectively.

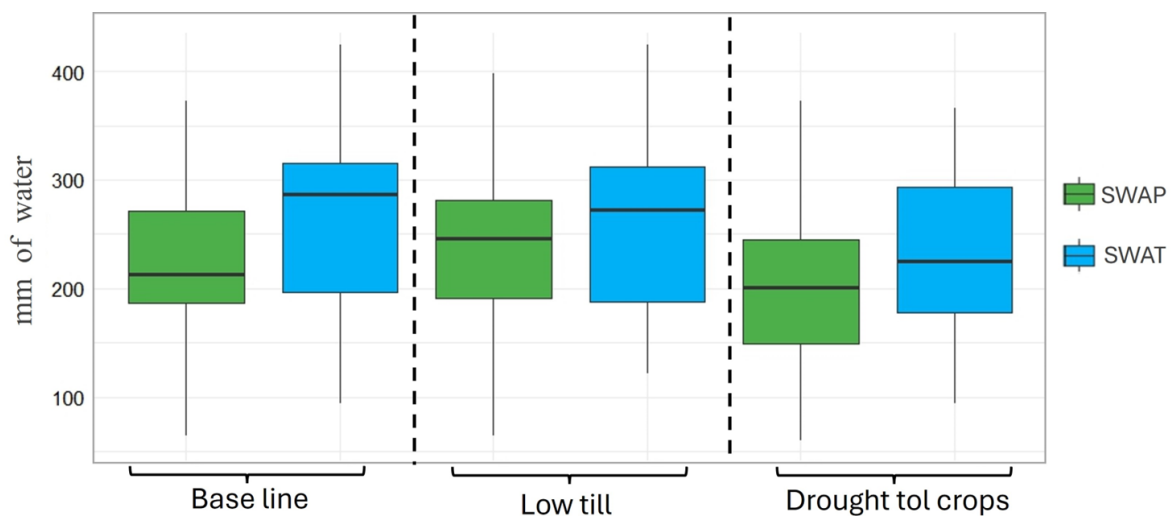
The results for evaporation fluxes (Figure 3.2) show that the SWAP model simulated almost similar evaporation range and median for the baseline and the two scenarios. Compared to the SWAT+ results, SWAP had much smaller ranges for all three scenarios. Similarly, to the SWAP outputs, the SWAT+ results are almost similar for the baseline and the low tillage scenario. However, the drought-tolerant crops scenario showed larger average and median values.

It is important to mention that the medians of the evaporation simulated by the SWAP model for the baseline and the low till scenarios did not differ significantly from those simulated by the SWAT+ model for the same cases, but the range of the SWAT+ outputs is much larger. This could be caused by the fact that the SWAT+ model outputs for the relevant field were more sensitive to the variations within the weather factors, because the field in the SWAT+ setup is also exposed to the influence of the neighbouring fields. Concerning the scenario with the implementation of drought-tolerant crops, this measure cannot be exactly implemented in the SWAT+ model, so that these results are rather uncertain. There is an opportunity here to use the SWAP model results as reference values for fine-tuning the performance of the SWAT+ model for drought-tolerant crops.



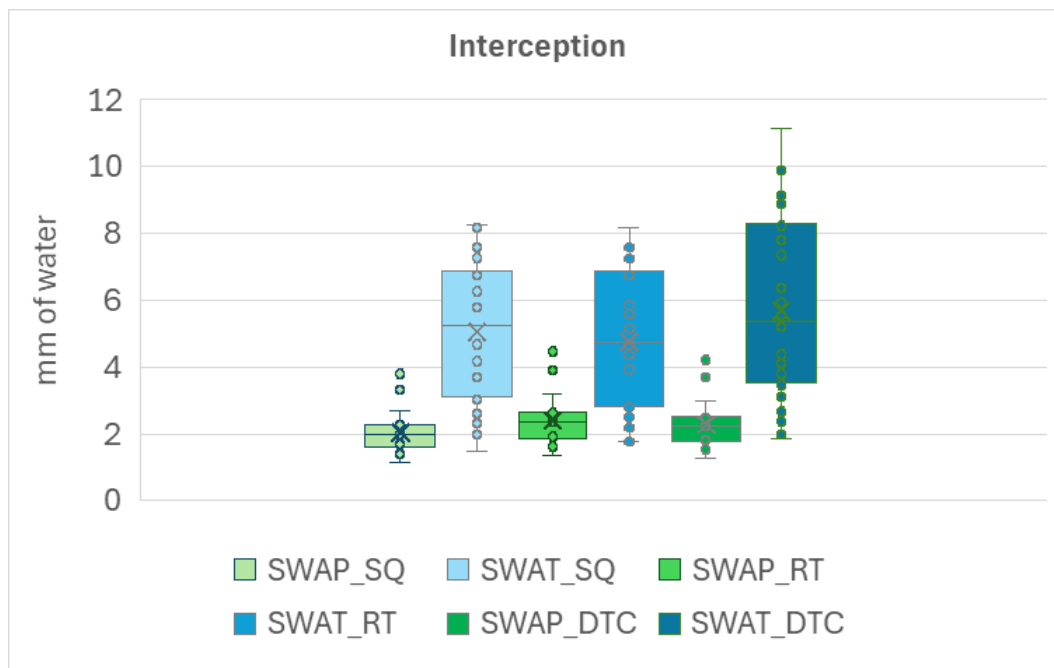
**Figure 3.2.** Annual average evaporation simulated by the SWAP and SWAT+ models for the Petit Glane site (CS2) for the baseline, reduced tillage and drought tolerant plants scenario.

The results for transpiration fluxes (Figure 3.3) are almost similar for both SWAP and SWAT+ for the baseline period and for the low tillage scenario. Concerning the scenario with drought-tolerant crops, the SWAT+ model showed a slightly larger range and median.



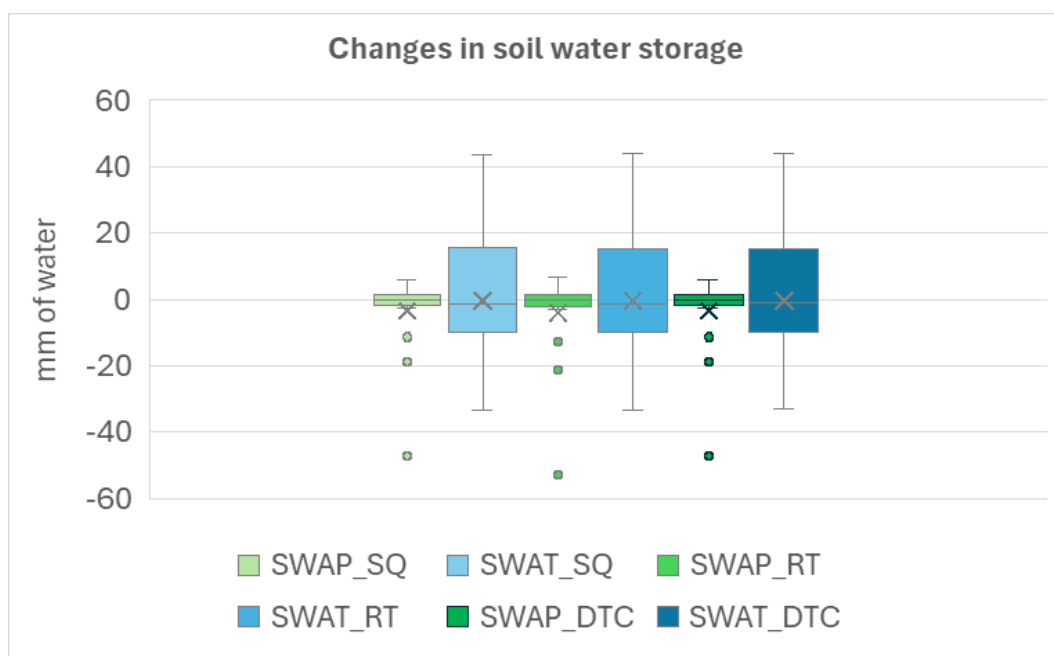
**Figure 3.3.** Annual average transpiration simulated by the SWAP and SWAT+ models for the Petit Glane site (CS2) for the baseline, reduced tillage and drought tolerant plants scenario.

Interception gives less than 2% of the total water balance. Small amounts of water are comparable to the mass balance error and difficult to evaluate. For the Continental region, the SWAP model simulated about 2-3 times lower interception values than the SWAT+ model (Fig. 3.4) and with less deviation across the years.



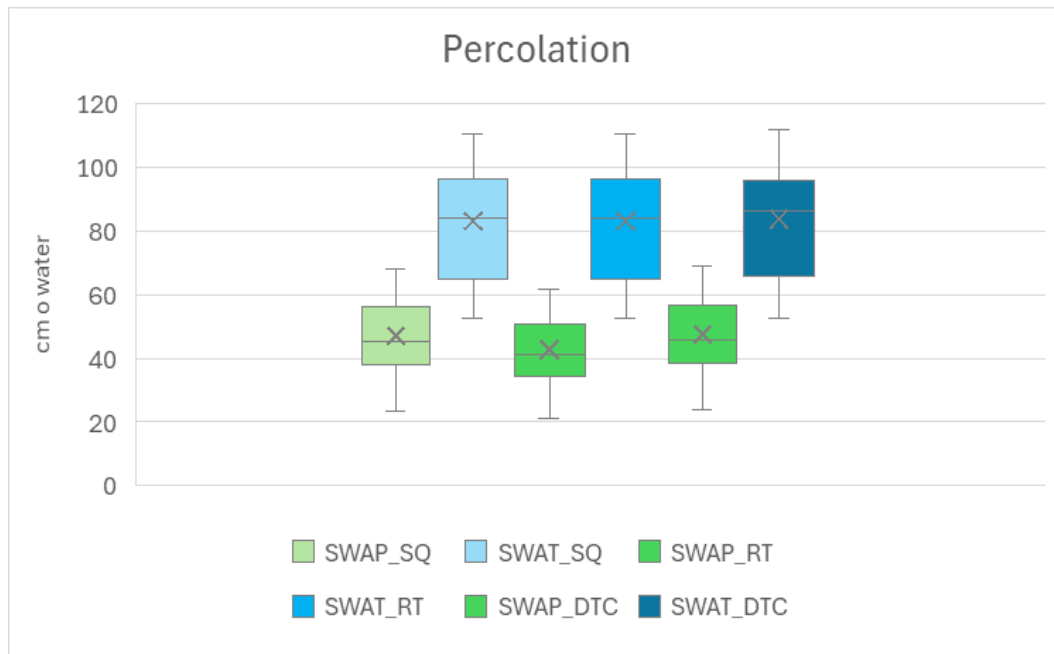
**Figure 3.4.** Annual average interception simulated by the SWAP and SWAT+ models for the Petit Glane site (CS2) for the baseline, reduced tillage and drought tolerant plants scenario.

Changes in soil water storage (Fig. 3.5) are the residual part of the water balance and normally sum up to zero on long run. The two models calculated similar average values for soil water storage changes. Similarly to interception, SWAT+ results showed higher deviation than the SWAP calculations.



**Figure 3.5.** Annual changes in soil water storage simulated by the SWAP and SWAT+ models for the Petit Glane site (CS2) for the baseline, reduced tillage and drought tolerant plants scenario.

Similarly to runoff, percolation values differed a lot and were difficult to compare between the two models. The reason could be that the SWAP model calculates “percolation” as the flux of water from the bottom of the soil profile, which can be in the unsaturated zone and does not account for shallow and deep aquifers, as the SWAT+ model does.

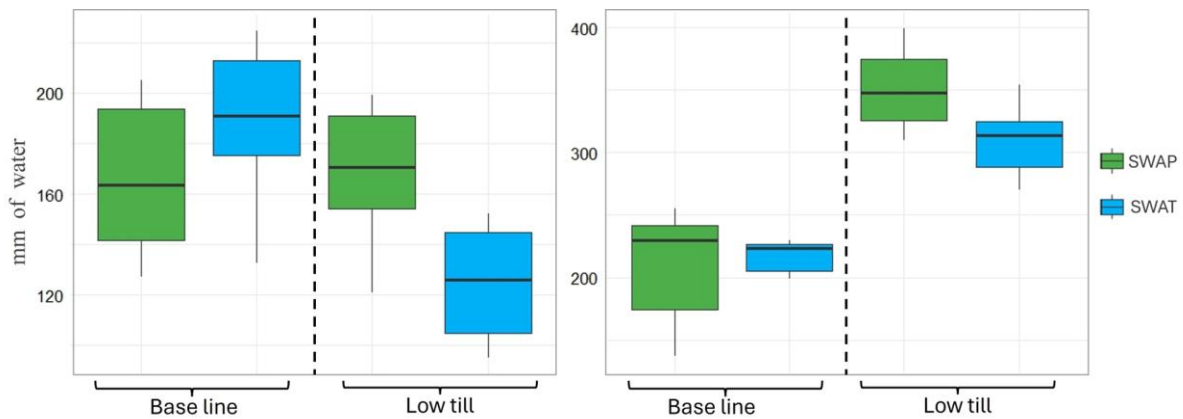


**Figure 3.6.** Annual changes in percolation simulated by the SWAP and SWAT+ models for the Petit Glane site (CS2) for the baseline, reduced tillage and drought tolerant plants scenario.

### 3.5.3 Boreal biogeographical region - loamy sand soil type

For the loamy sand soils of the Boreal region, the results of the SWAP and SWAT+ models are presented in Figure 3.4. During the baseline period, the evaporation fluxes simulated by the SWAT+ model showed somewhat larger average and median values, with a difference of approximately 20 mm. However, for the low tillage scenario, the SWAP results indicated larger values with a difference of 40 mm.

The average and the median values of the transpiration values calculated by the two models are similar, with the SWAP model showing a larger range. Concerning the low tillage scenario, SWAP showed larger values in both its range and median. The difference in the average values of the two models was about 40 mm. However, these differences are not marginal as a 40 mm difference corresponds to approx. 11% of the total transpiration calculated by the SWAP model.

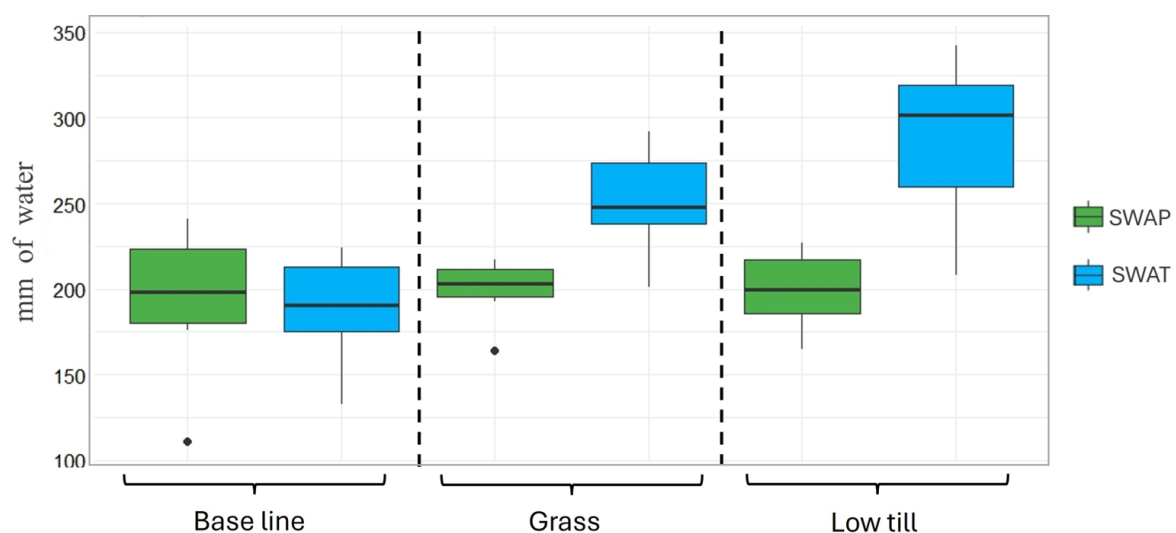


**Figure 3.4.** Annual average evaporation (left) and transpiration (right) simulated by the SWAP and SWAT+ models for the Krakstad pilot site (CS10) for the baseline and reduced tillage scenario.

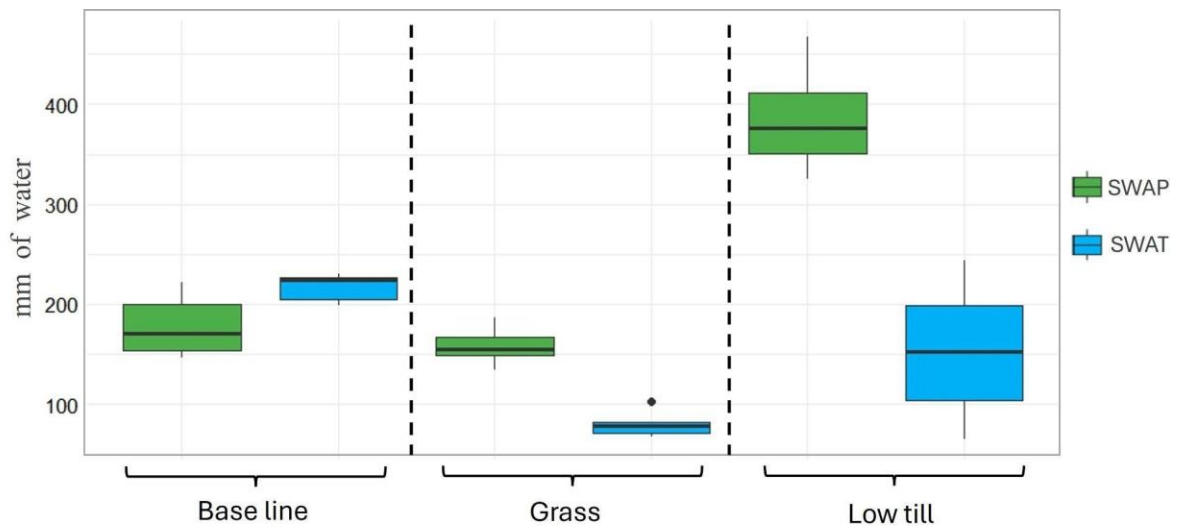
### 3.5.4 Boreal biogeographical region - loamy clay soil type

For the loamy clay soils of the Boreal region, the results of the SWAP and SWAT+ models were compared for the baseline period and the “moving to grassland” and low till scenarios as shown in Figures 3.5 and Figure 3.6. Both models gave almost similar results for the evaporation during the baseline period. However, in the case of the grassland and low tillage scenarios, the SWAT+ model gave significantly higher values.

The SWAT+ model simulated larger (by about +35 mm) annual transpiration values than the SWAP model for the baseline. For the grassland and low tillage scenarios, SWAP simulated significantly larger values than SWAT+. Thus, for the grassland and low tillage scenarios, the SWAP model simulated about 30 and 100 mm larger median values for transpiration than the SWAT+ model, respectively.

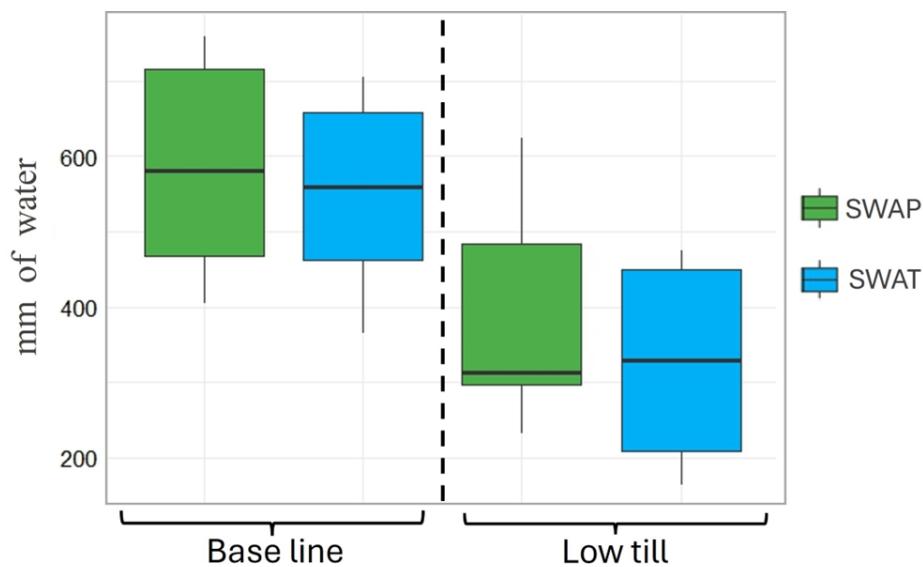


**Figure 3.5.** Annual average evaporation simulated by the SWAP and SWAT+ models for the Krakstad pilot site (CS10) for the baseline, grassland and reduced tillage scenarios.



**Figure 3.6.** Annual average transpiration simulated by the SWAP and SWAT+ models for the Krakstad pilot site (CS10) for the baseline, grassland and reduced tillage scenarios.

The loamy clay soil type of the Boreal region was the only case in which the average annual drainage outflow values simulated by the two models could be compared. The two models produced almost identical results for the baseline scenario and fairly similar medians for the low till scenario (Figure 3.7).



**Figure 3.7.** Annual average drainage outflow simulated by the SWAP and SWAT+ models for the Krakstad pilot site (CS10) for the baseline and the reduced tillage scenario.

## 4 Evaluation of the modelled NSWRM efficiency using the WOCAT database

As models are simplified representations of natural systems and the real world in general, their performance highly depends, among other factors, on the data and expert knowledge incorporated in the models and used during the evaluation of the results. This is particularly true for NSWRMs, since i) the available information is insufficient to directly estimate the effect of a certain measure without experimental data; and ii) the effectiveness of a measure depends on how it is introduced into a model, since the implementation of most of these measures in the models is not straightforward. Thus, the modelled results on NSWRMs effectiveness cannot be improved without experimental and expert knowledge.

As the OPTAIN project benefited from and contributed to the development of the WOCAT database (Lemann et al., 2022), it was used to evaluate the modelling results with respect to the efficiency of NSWRMs in retaining water within the soil profile and reducing losses to surface and subsurface water bodies.

Table 3.8 demonstrates the approach we used to connect the WOCAT evaluation of measure's efficiency with the modelled results presented in Table 3.6. The colour scheme is reversed for runoff and evaporation, as a reduction in these values is indicated by a higher qualitative evolution scale in WOCAT. The opposite applies to the other water balance elements (soil water storage, percolation, etc.).

**Table 3.8.** Connecting the field-scale modelling results to WOCAT

Modelled water balance element	WOCAT		Colour scale harmonised with Table 3.6
	reported impact category	Qualitative evolution scale 4 being neutral - no change	
<b>Interception</b>	no		
<b>Runoff</b>	Surface runoff	1 (increase)-7 (decrease)	<div style="display: flex; flex-direction: column; align-items: center;"> <div style="background-color: #e0f0ff; padding: 2px;">4 no change</div> <div style="background-color: #ffffe0; padding: 2px;">5 slight reduction</div> <div style="background-color: #ffff00; padding: 2px;">6 moderate reduction</div> <div style="background-color: #ff0000; padding: 2px;">7 strong reduction</div> </div>
<b>Evaporation</b>	Evaporation	1 (increase)-7 (decrease)	
<b>Transpiration</b>	no		
<b>Soil water storage</b>	Water quantity	1 (decrease)-7 (increase)	<div style="display: flex; flex-direction: column; align-items: center;"> <div style="background-color: #e0f0ff; padding: 2px;">4 no change</div> <div style="background-color: #e0ffe0; padding: 2px;">5 slight increase</div> <div style="background-color: #00ff00; padding: 2px;">6 moderate increase</div> <div style="background-color: #008000; padding: 2px;">7 strong increase</div> </div>
	Soil moisture	1 (decrease)-7 (increase)	
	harvesting/ collection of water	1 (reduced)—7 (improved)	<div style="display: flex; flex-direction: column; align-items: center;"> <div style="background-color: #e0f0ff; padding: 2px;">4 no change</div> <div style="background-color: #e0ffe0; padding: 2px;">5 slight improvement</div> <div style="background-color: #00ff00; padding: 2px;">6 moderate improvement</div> <div style="background-color: #008000; padding: 2px;">7 strong improvement</div> </div>
<b>Drainage</b>	Excess water drainage	1 (reduced) -7 (improved)	
<b>Percolation</b>	Groundwater table	1 (lowered) -7 (recharge)	

Tables 3.9 - 3.12 show the results of comparing the SWAP results with the relevant information available in the WOCAT database. Our analysis revealed that there is a strong need for region-specific reports on the effects of NSWRMs, as little information is available about their region-specific impact on soil water balance elements. Not all the water balance elements are evaluated in WOCAT, and in

some cases no WOCAT data was available to evaluate the SWAP modelling results (e.g. grassland in boreal regions, afforestation in boreal and continental regions, etc.).

The modelled effectiveness of reduced tillage by SWAP and the experimental effectiveness by WOCAT (Fig. 3.9) matched quite well for the Continental and Boreal regions, indicating a reduction in surface runoff and evaporation, as well as an increase in soil water storage. For Pannonia, however, the modelled and reported impacts of reduced tillage on soil moisture content were contradictory. The reason could be the transpiration, which is a good indicator of increased soil water content: WOCAT does not contain information about the impact of NSWORMs on transpiration, only on soil water content. The WOCAT database reports an increase in soil water storage when introducing reduced tillage, which is in a way also reflected by the SWAP model in terms of increased transpiration (water uptake from the soil) by the plants, rather than soil water content values. Thus, the seemingly contradicting results indicate the same process: reduced tillage facilitates an increase in soil water storage and plant available water.

**Table 3.9.** Comparison of the effectiveness of **reduced tillage** on soil water balance elements as simulated by the SWAP model, and the NSWORM impact described in WOCAT.

Scenario	NSWRM	SWAP	WOCAT	NSWRM effectiveness								
				Pannonia			Continental			Boreal		
				SWAP		WOCAT	SWAP		WOCAT	SWAP		WOCAT
				CS2	CS11		CS2	CS4		CS8	CS10	
Reduced tillage	Interception											
	Runoff	Surface runoff			5-6			5		5		
	Evaporation	Evaporation			5			5		5		
	Transpiration											
	Soil water storage	Water quantity										
		Soil moisture			5-6			5			5	
		Water harvesting			5-6							
	Drainage	Excess water drainage										
	Percolation	Groundwater table										

The conversion of arable land to grassland scenario could only be evaluated for the continental region (Fig 3.10). While this NSWORM is described and evaluated in the WOCAT database for the Pannonian region, no such measure was selected for the OPTAIN Pannonian pilot sites. Consequently, there were no SWAP model outputs that could be compared with the WOCAT findings. On the other hand, SWAP modelling results for this measure were available for two different sites in the boreal region. However, the WOCAT database contained no information about the effectiveness of grassland in retaining soil water for this region.

For the continental region, the SWAP model simulated a strong increase in water storage under grassland, while WOCAT indicated a slight increase in the amount of water in the soil. Thus, while the foreseen tendencies are similar, there is a difference in the magnitude of changes.

**Table 3.10.** Comparison of the effectiveness of **grassland** on soil water balance elements as simulated by the SWAP model, and the NSWRM impact described in WOCAT.

NSWRM	SWAP	WOCAT	NSWRM effectiveness								
			Pannonia			Continental			Boreal		
			SWAP		WOCAT	SWAP		WOCAT	SWAP		WOCAT
			CS2	CS11		CS2	CS4		CS10 L	CS10 S	
<b>From arable to grassland</b>	Interception										
	Runoff	Surface runoff			6			5			
	Evaporation	Evaporation									
	Transpiration										
	Soil water storage	Water quantity						5			
		Soil moisture			5						
		Water harvesting									
	Drainage	Excess water drainage			5						
	Percolation	Groundwater table									

The WOCAT database does not contain any information about the effectiveness of afforestation in retaining water in the continental and boreal landscapes. For the Pannonian region, WOCAT indicated no changes in soil water storage, while the SWAP model estimated a moderate decrease (Fig. 3.11). The reason could be the same as for the reduced tillage scenario: WOCAT considered soil water storage as an indicator, while SWAP calculates both, soil water content and transpiration. Hence, the SWAP model predicts a reduced soil water content but also an increased transpiration in situations where plants benefit from an increase in soil water storage due to afforestation. This means that the SWAP model results do not contradict the information available in WOCAT with respect to soil water storage. On the other hand, the SWAP model did not capture the strong decrease in surface runoff indicated by the WOCAT database for afforestation cases in the Pannonian region.

Introducing new, drought tolerant crops in the Pannonian and continental region is an important measure under warming climate. The effectiveness of this measure depends on many factors and can be strongly site specific. For the Pannonian region, the case described in the WOCAT database indicated slight improvement in drainage conditions (Fig. 3.12), but the Pannonian sites involved in the OPTAIN project are not drained. This means that the whole water regime of the Pannonian pilot fields involved in the OPTAIN project differs from the water regime of the site introduced in the WOCAT database, and the results can hardly be compared. Concerning the continental region, the SWAP model estimates showed similar tendencies in changes in surface runoff and soil water storage, as the WOCAT database.

**Table 3.11.** Comparison of the effectiveness of **afforestation** on soil water balance elements as simulated by the SWAP model with the NSWRM impact described in WOCAT

Scenario	Water balance element	Impact category	Pannonia			Continental			Boreal		
			SWAP		WOCAT	SWAP		WOCAT	SWAP		WOCAT
			CS2	CS11		CS2	CS4		CS8	CS10	
Afforestation	Interception										
	Runoff	Surface runoff			7						
	Evaporation	Evaporation									
	Transpiration										
	Soil water storage	Water quantity									
		Soil moisture			5						
		Water harvesting									
	Drainage	Excess water drainage									
	Percolation	Groundwater table									

**Table 3.12.** Comparison of the effectiveness of **drought tolerant crops** on soil water balance elements as simulated by the SWAP model with the NSWRM impact described in WOCAT

NSWRM	SWAP	WOCAT	NSWRM effectiveness								
Scenario	Water balance element	Impact category	Pannonia			Continental			Boreal		
			SWAP		WOCAT	SWAP		WOCAT	SWAP		WOCAT
			CS2	CS11		CS2	CS12		CS8	CS10	
Drought tolerant crops	Interception										
	Runoff	Surface runoff			7			5			
	Evaporation	Evaporation									
	Transpiration										
	Soil water storage	Water quantity						5			
		Soil moisture			5						
		Water harvesting									
	Drainage	Excess water drainage			5						
	Percolation	Groundwater table									

The most important message from comparing the SWAP modelling results on the NSWRM effectiveness with the information available in the WOCAT database is that the latter is a valuable resource for such assessments, though it could be further improved. It would be important to focus on region-specific aspects and incorporate more water balance elements, especially transpiration, in the evaluation.

Below we provide information and links to the WOCAT records involved in this study.

#### Drought resistance crop:

- Switzerland: [Drought-resistant crops | SLM Technology #6272 | WOCAT](#)

#### From arable to grazing:

- Czechia: [Grassing of Recharge Areas | SLM Technology #5934 | WOCAT](#)
- Slovenia: [Converting cropland to grazing land | SLM Technology #2823 | WOCAT](#)
- Hungary: [Meadows and pastures | SLM Technology #6195 | WOCAT](#)

#### Afforestation:

- Hungary: [Afforestation of arable land | SLM Technology #5930 | WOCAT](#)

#### Reduced tillages

- Norway-[Reduced tillage: no tillage in autumn | SLM Technology #1245 | WOCAT](#)
- Poland (subsoiling) - [Subsoiling | SLM Technology #6250 | WOCAT](#)
- Hungary (no till): [No-till agriculture | SLM Technology #6199 | WOCAT](#)
- Hungary (not OPTAIN) - [Conservation tillage | SLM Technology #3065 | WOCAT](#)
- Hungary (not OPTAIN). [Conservation tillage | SLM Technology #1080 | WOCAT](#)
- Slovenia: [Conservation tillage with incorporated mulched plant residues \(mulch-till\) | SLM Technology #5494 | WOCAT](#)

## 5 Summary and outlook

This report documents the results of more than three years of work by six OPTAIN modelling teams working with seven pilot fields from three European biogeographical regions. This effort was coordinated by NIBIO and resulted in a developed methodology and tools to carry out the impact analyses of various in-field NSWORMs for the pilot sites. Three groups volunteered to join the field-scale modelling team. The SWAP model outputs – selected water balance elements – were cross-validated with those calculated for the corresponding HRU's of the SWAT+ model. The main achievements and conclusions can be highlighted as follows:

- ❖ New tools and a harmonised approach on applying the SWAP model for European pilot sites are documented.
- ❖ The OPTAIN field-scale modellers have gained knowledge on i) new tools for model verification, soft calibration, and hard calibration; ii) setting up the SWAP model even under conditions of data scarcity and iii) on applying the SWAP model for monitored sites in a harmonised way.
- ❖ We present the results of the calibration and validation of the SWAP model to seven different pilot sites across three different European biogeographical regions, using the tools and methods developed within the OPTAIN project.

- ❖ The report also provides an overview of the simulated effectiveness of NSWORMs in increasing water retention and reducing the loss of water from the root zone. Though these results are highly specific to OPTAIN pilot sites, their evaluation provided an opportunity to search for patterns, specific for each biogeographical region.
- ❖ The report describes a newly developed methodology on harmonising the inputs and cross-validating the outputs of the field-scale SWAP model with water balance elements, simulated for the same or representative fields by the SWAT+ catchment scale model. To our knowledge, no such methodology has been developed before. We recognise that our efforts are only the first step on a long journey, but we believe that if we continue along this path we can use field- and catchment-scale hydrological models in a mutually beneficial manner, so that the performance of both models would improve by taking advantage from the known strengths of each of the models.
- ❖ We concluded that the impacts of some of the NSWORMs (like afforestation) on the water regime have little region-specific character. On the other hand, the effects of other measures on certain water balance elements are site-specific and may depend on soil type, crop rotations and other factors within the same biogeographical region.
- ❖ Concerning the cross-validation of the SWAP and SWAT+ model's outputs, we concluded that the median and the range of the simulated evaporation, transpiration and drainage outflow are commonly comparable for the baseline period, but differ for the NSWORM scenarios. Thus, the discrepancy between the methods used to implement measures in the two different models has a strong influence on the simulation results.
- ❖ The SWAP modelling results on the effectiveness of NSWORMs were compared with the experimental data from the WOCAT database. Our analysis revealed that there is a strong need for region-specific reports on the effects of NSWORMs on soil water balance elements, as little information is currently available in this regard. This information is essential for improving the simulation results of the NSWORMs effectiveness in retaining water within the soil profile and the landscape.

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# Annex 1. Modelling results for CS2 (Petite Glâne, CH)

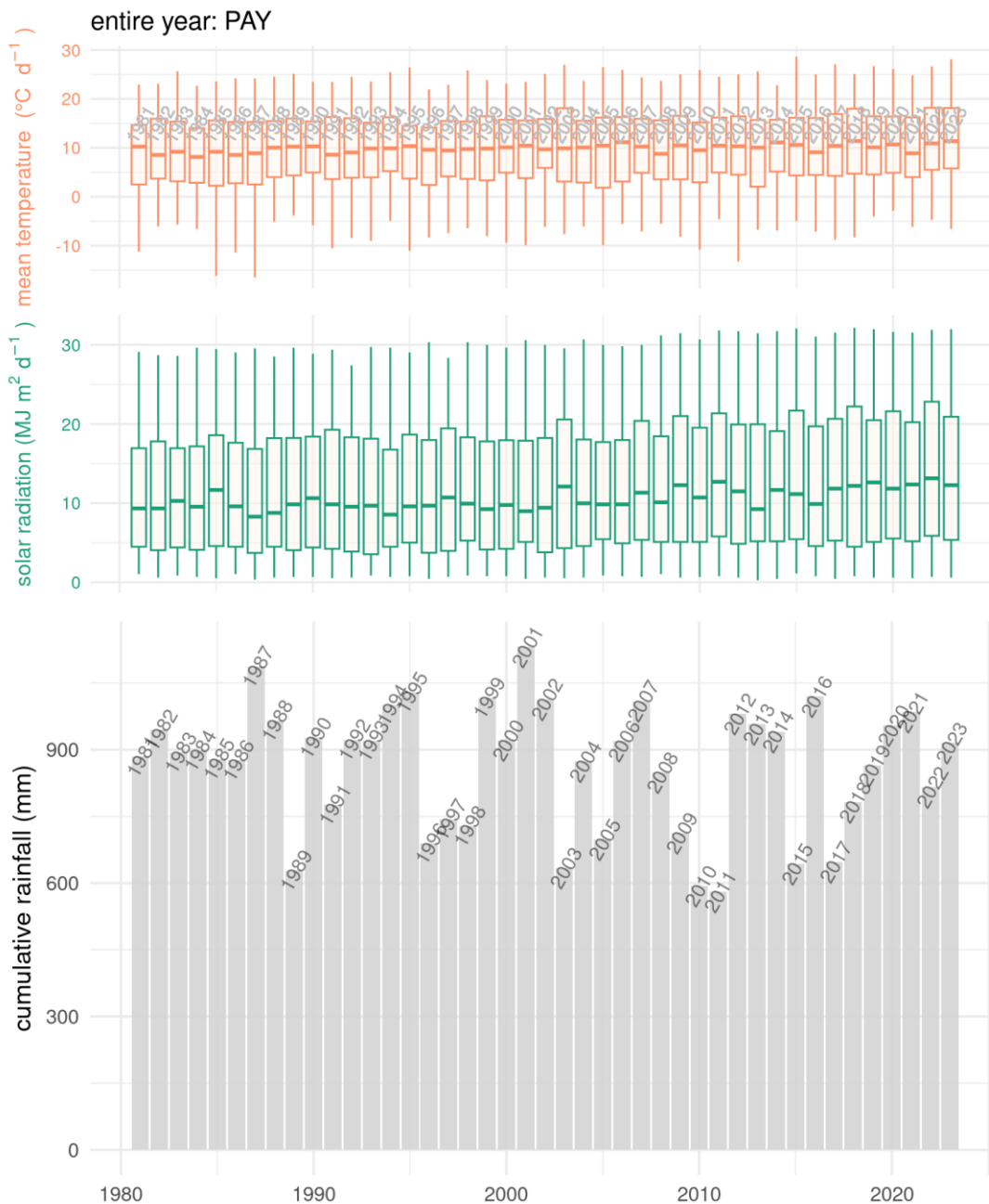
Authors: Maria Eliza Turek, Annelie Holzkämper

## 1. Experimental site and model setup

The case study area “Petite Glâne” belongs to the Broye catchment in the southwestern part of the Swiss Plateau. The river Petite Glâne is about 30 km long, repeatedly crosses borders between the cantons of Vaud and Fribourg, and has a catchment area of 94 km<sup>2</sup>. Its upper reaches have remained fairly natural and are lined with forest, whereas its lower reaches in the Broye plain have been canalized and straightened. The soils and climate here are highly suitable for arable farming. Overall, the catchment of the Petite Glâne is strongly characterized by agriculture: nearly three quarters of its area consists of pastures and cropland. However, the region is increasingly experiencing water shortages in summer, and there is often not enough water in the Broye and Petite Glâne to irrigate the fields. Climate change will further aggravate the situation. Farmers are therefore considering new options to mitigate the increasing drought events – for example an irrigation project using water from Lake Neuchâtel.

There are no monitored fields in the catchment area, thus, monitoring results from a pilot field - Pay - located nearby the catchment border were used to set up the SWAP model.

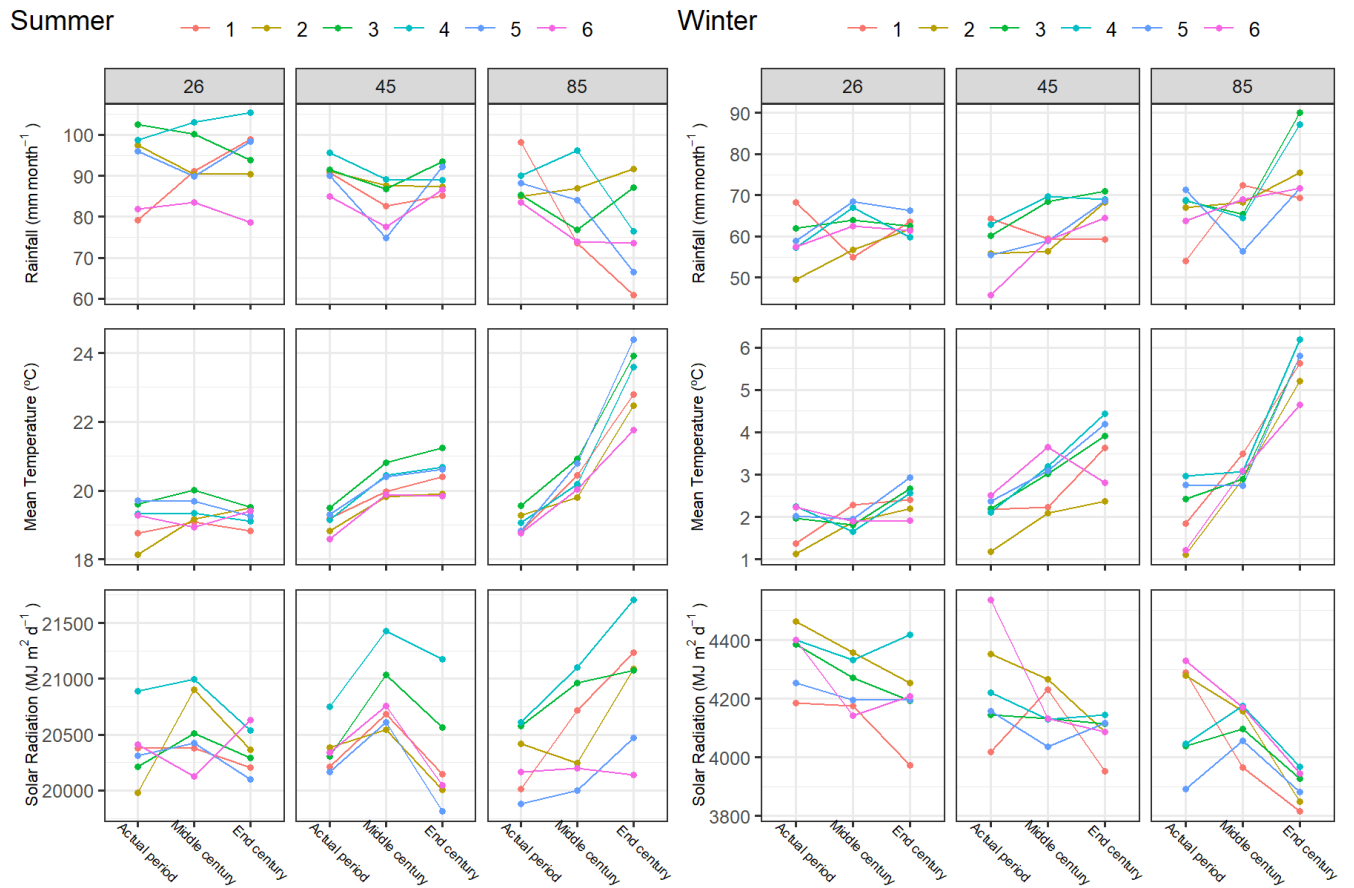
## 2. Baseline climate summary



**Figure 1.** Annual variability of climatic variables observed at the meteorological station PAY between 1981 and 2022. Rainfall corresponds to year sums, while other variables represent daily values averaged by year.

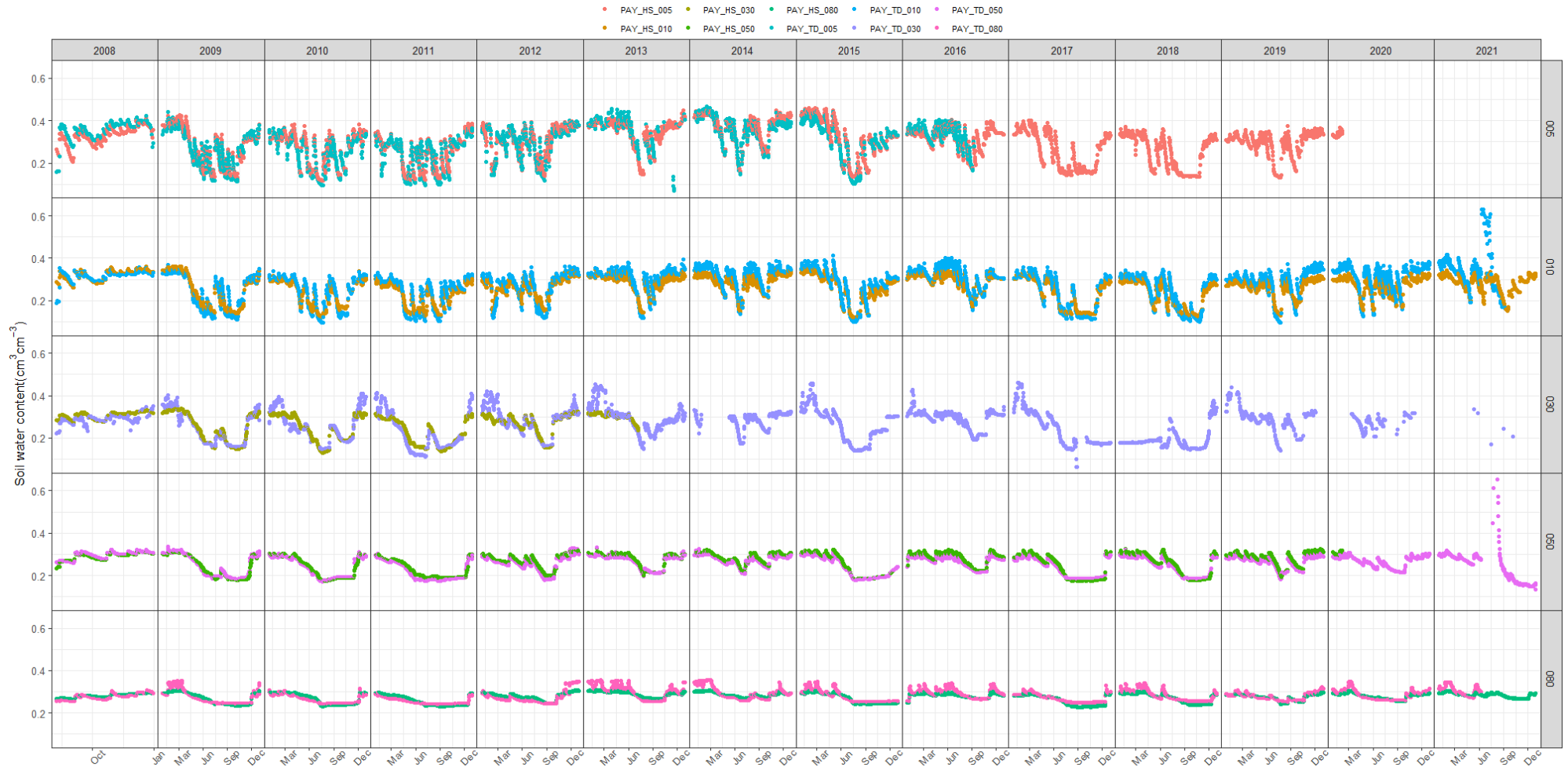
## 3. Climate projections summary

From the model chains obtained in the OPTAIN repository, only the station with the code "id\_3" had all the necessary climate variables to run on SWAP, resulting in 6 model chains for each RCP.



**Figure 2.** Summary of climatic variables considering monthly mean values at the stations using a selection of 6 climate projections from the OPTAIN repository, considering RCP26, RCP45 and RCP85. Summer was considered as the months June, July and August, winter corresponds to December, January, and February. Actual period: 2010-2029, mid-century: 2040-2059, end-of-century: 2080-2099. Rainfall corresponds to monthly sums, mean temperature is the mean between maximum and minimum temperature per day, averaged by month, solar radiation corresponds to daily values averaged by month.

## 4. Measured soil water content and temperature



**Figure 3.** Overview of soil water content measurements at the station PAY between 2008 and 2021, in duplicates, at the depths 5, 10, 30, 50 and 80 cm. The soil water content and temperature data come from a profile located at the MeteoSwiss meteorological station PAY. The land use is grassland; soil texture is loam in the entire profile (0-80 cm).

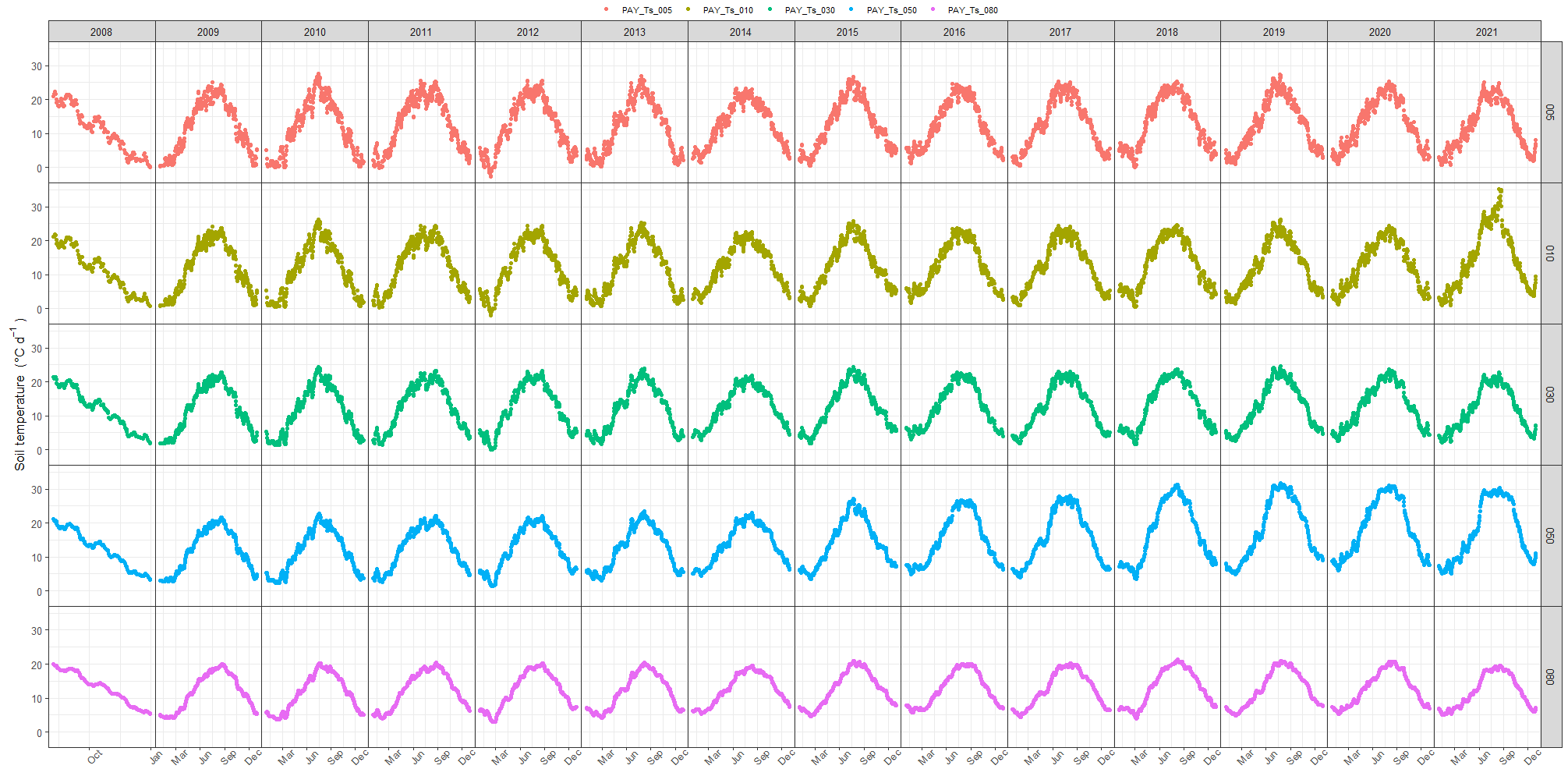
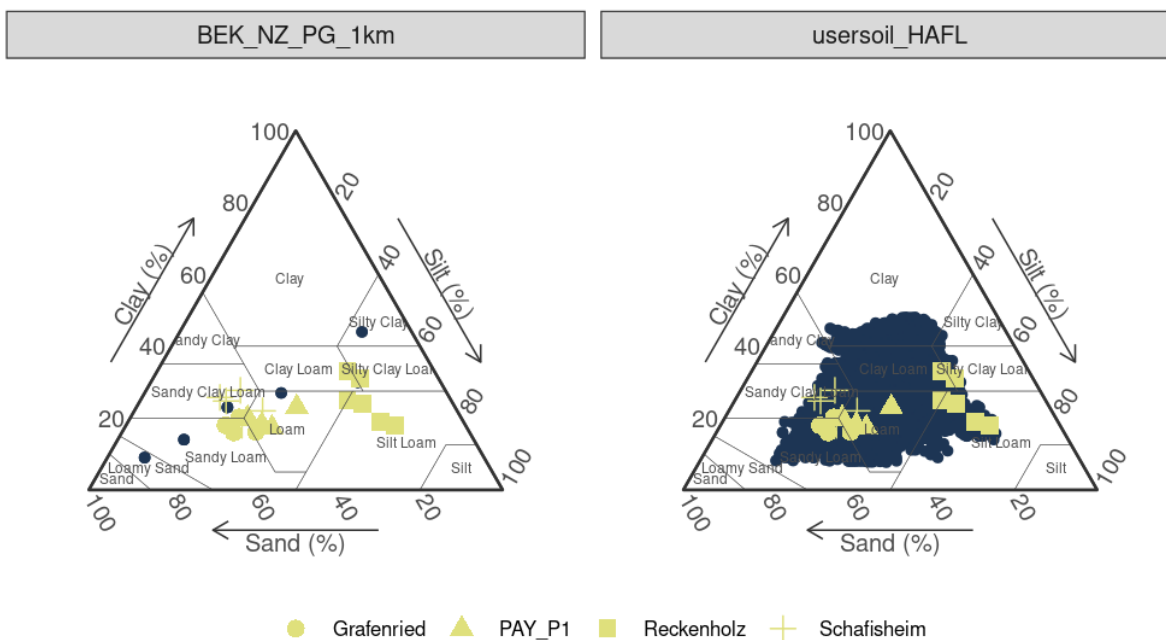


Figure 4. Overview of soil temperature measurements at the station PAY between 2008 and 2021 at the depths 5, 10, 30, 50 and 80 cm.

## 5. Soil hydraulic properties

The soil profile defined from the measurements in the MeteoSwiss station is a loam, and according to the soil moisture measurements (Figure 1.3), it seems to have different hydraulic properties in the top and subsoil. To avoid too many parameters and since the measurements look similar in the first 30 cm and last 50 cm, only two layers were defined to predict the soil hydraulic properties. For the calibration using PEST (Table 1.1), a soil profile with 180 cm depth were set in SWAP, with free drainage at the bottom. The dataset was separated for calibration (2008-2017) and validation (2018-2022).

The triangle with the presence of all soils in the maps from the Petit Glâne (Figure 1.5) shows that the loam texture is present in the catchment. The soils from the lysimeter station Reckenholz (Prasuhn et al., 2016) are also part of the textures that compose the soil map as well as the profile “PAY\_P1”, in the station Payerne.



**Figure 5.** Soil texture as observed in the Petit Glâne according to the two maps of soil texture used in the SWAT+ model. On top, the three soils present at the lysimeter station Reckenholz.

**Table 1.** Soil hydraulic parameters obtained using PEST, with calibration period between 2008-2017.

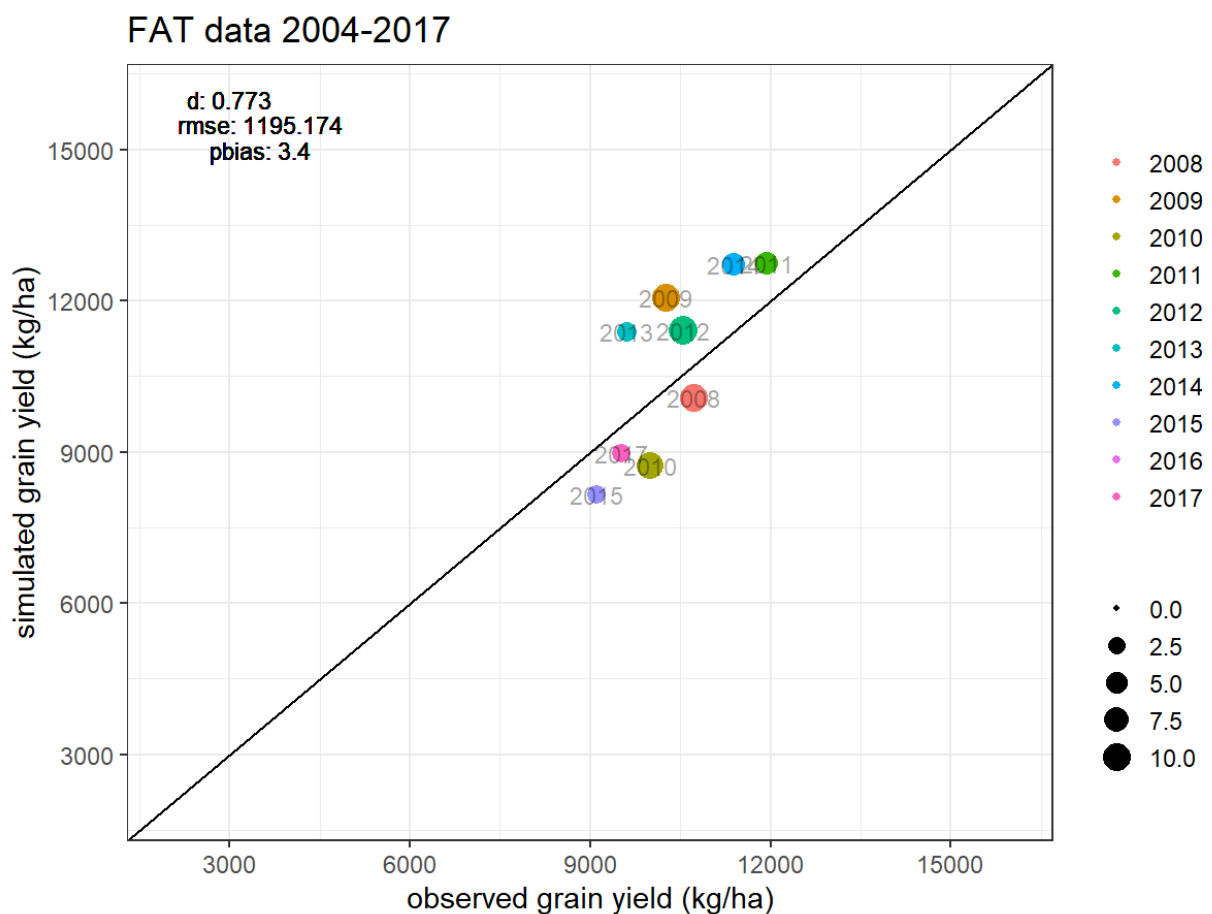
Depth cm	ORES cm <sup>3</sup> cm <sup>-3</sup>	OSAT cm <sup>3</sup> cm <sup>-3</sup>	ALFA cm <sup>-1</sup>	NPAR	KSATFIT cm d <sup>-1</sup>	LEXP	BDENS mg cm <sup>-3</sup>
0-30	0.037	0.354	0.008	1.230	14.02	-3.431	1460.0
30-180	0.032	0.348	0.018	1.230	14.02	-0.247	1620.0

## 6. Additional information about the modelling setup

- Model version: SWAP42
- Soil compartments: profile with topsoil 30 cm, subsoil 150 cm.
- Bottom boundary condition: free drainage
- Initial condition: warming up period of 8 months
- Runoff: no ponding allowed
- No hysteresis, no macropore flow, no lateral drainage, no solutes simulation
- Grassland simulated with cuttings defined by SWAP

## 7. Validation of the crop file

To evaluate the soil parameters and the entire setup of the modelling, we used an independent crop yield dataset. The data contains statistical results of grain maize yield in the region of PAY, between the years 2008-2017. The validation using the soil parameters estimated by PEST listed in Section 4 is shown in Figure 6. The crop file was initially calibrated for the region of Reckenholz, but in validation at PAY, a good agreement ( $d=0.773$ ) between observed and simulated values was obtained. Notice that the soil hydraulic parameters were obtained with the grassland.



**Figure 6.** Validation of the SWAP maize crop file using statistical data at the region of PAY between 2008 and 2017.

## 8. Soil water content calibration/validation with PEST

Calibration (2008-2017)

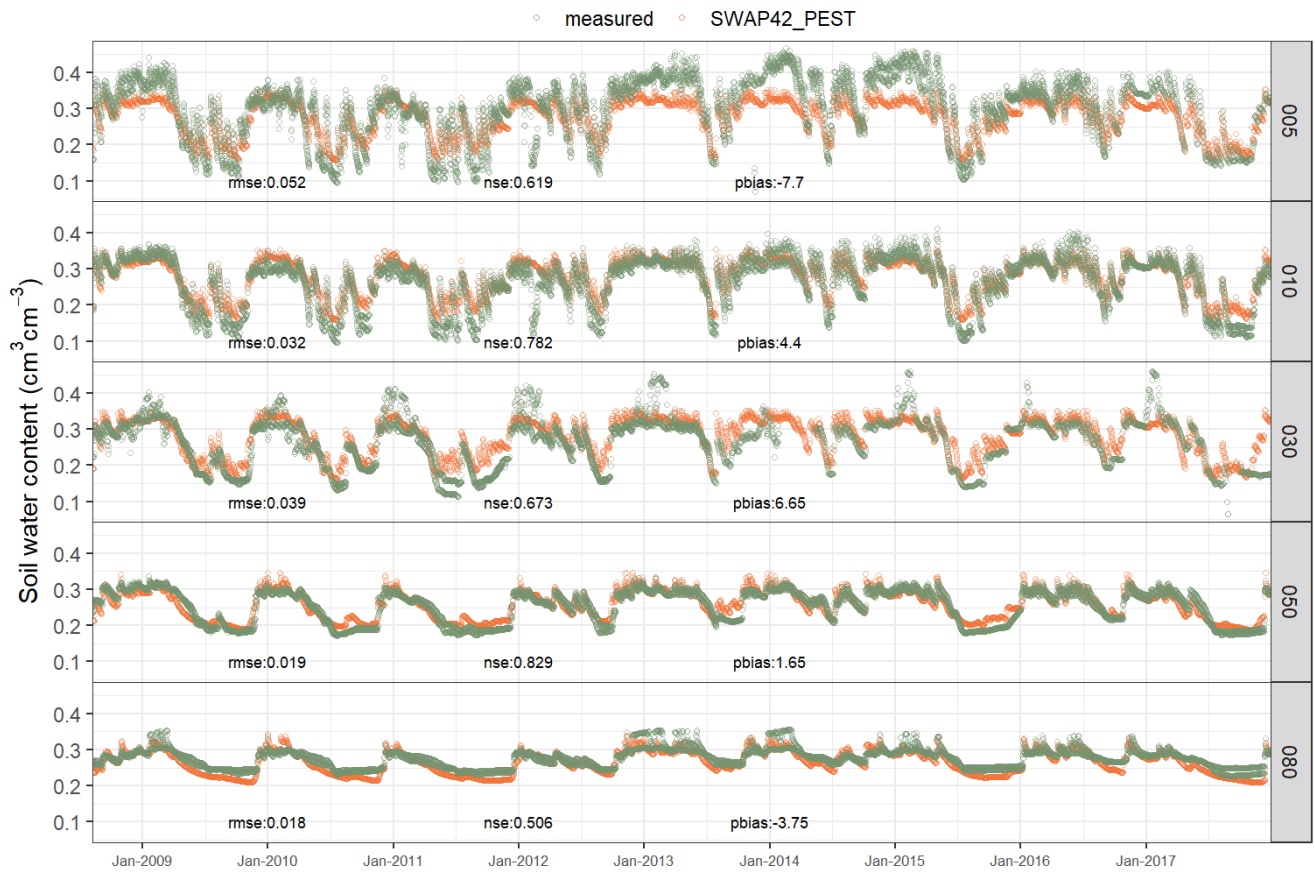


Figure 7. Calibration of soil hydraulic parameters using PEST at the depths of 5, 10, 30, 50, and 80 cm. Crop: grassland.

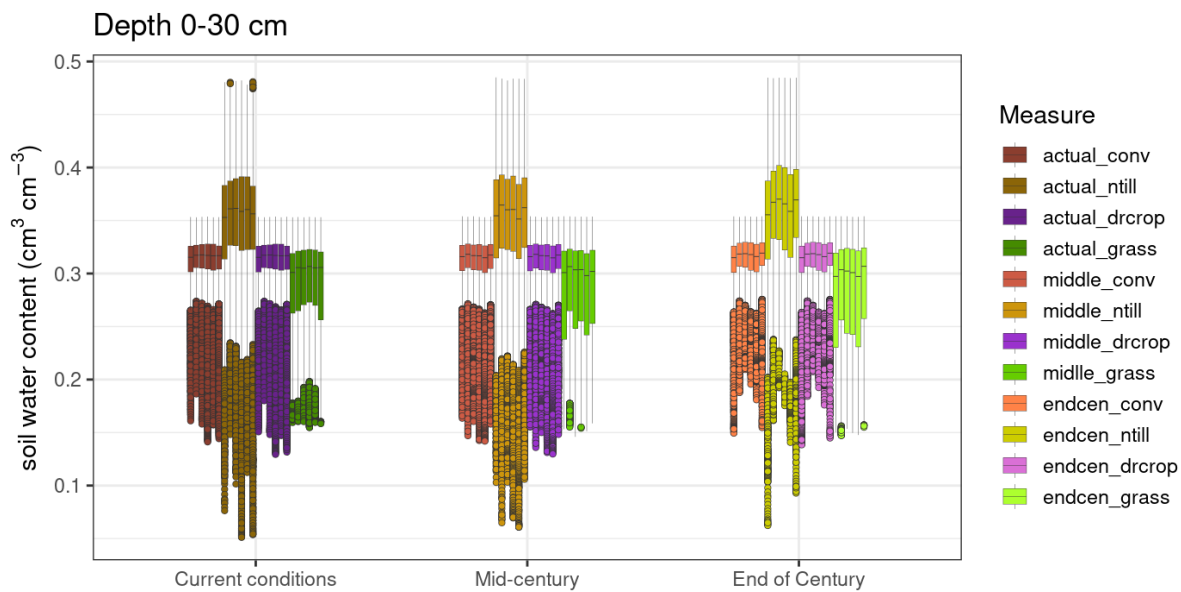
Validation (2018-2022)

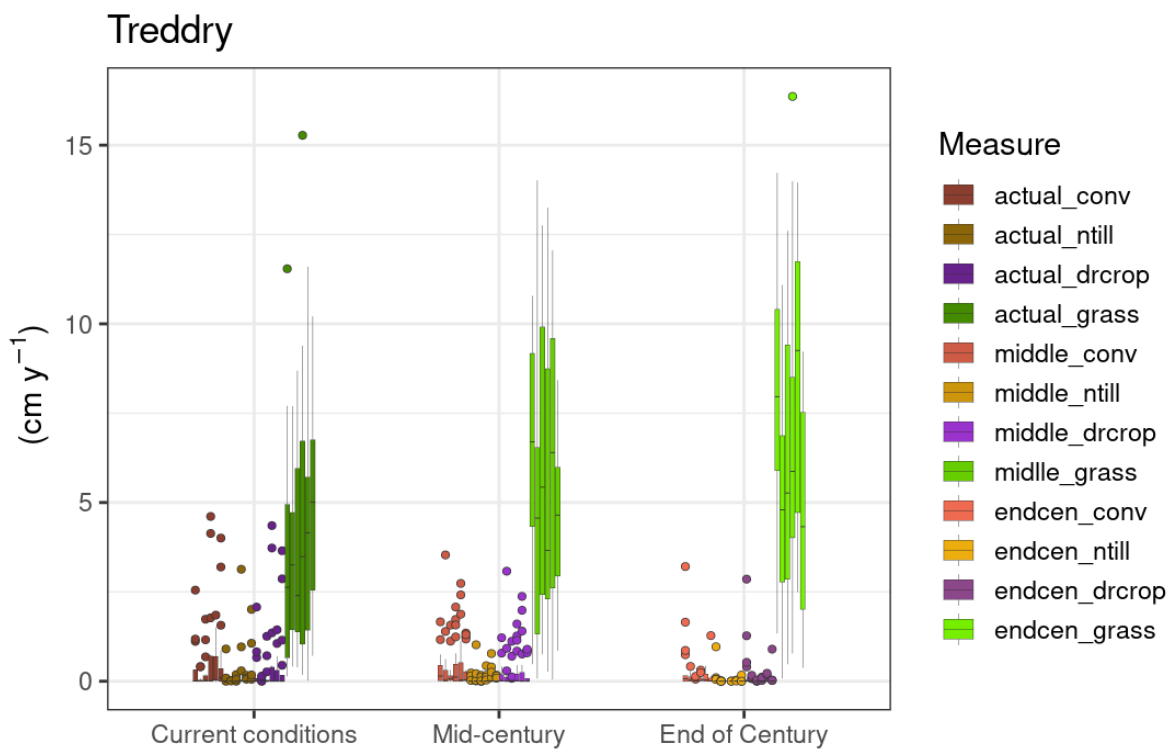
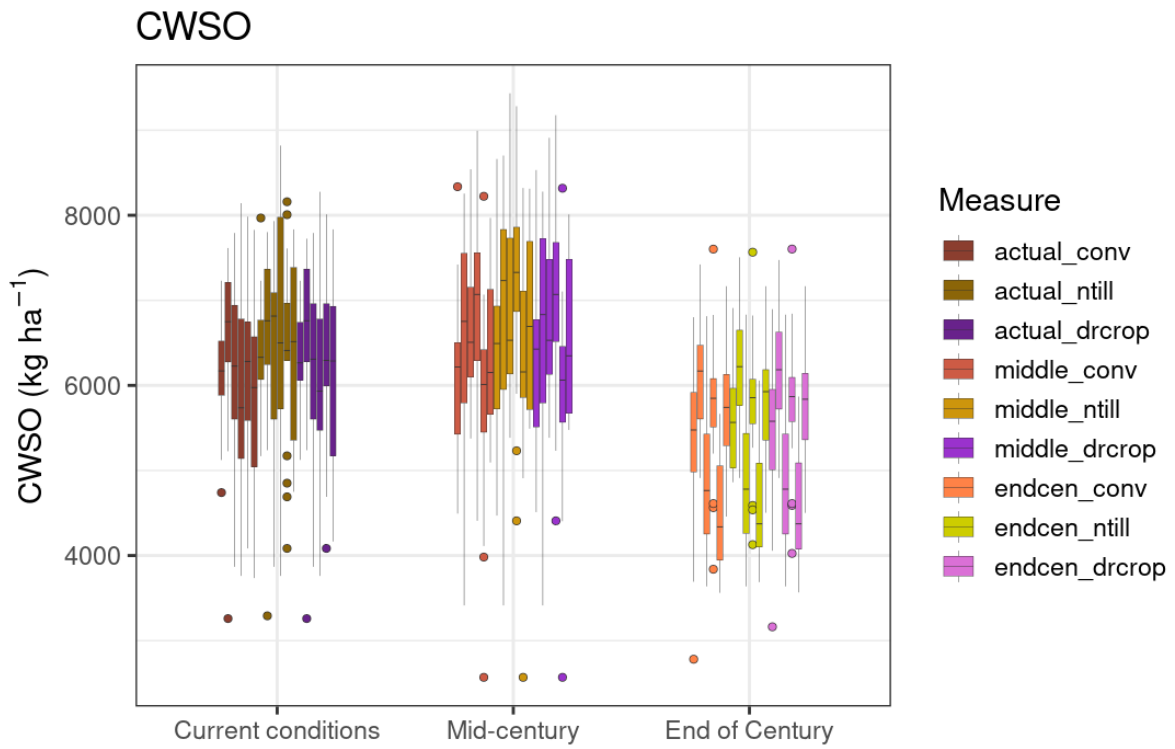


Figure 8. Validation of soil hydraulic parameters using PEST at the depths of 5, 10, 30, 50, and 80 cm. Crop: grassland.

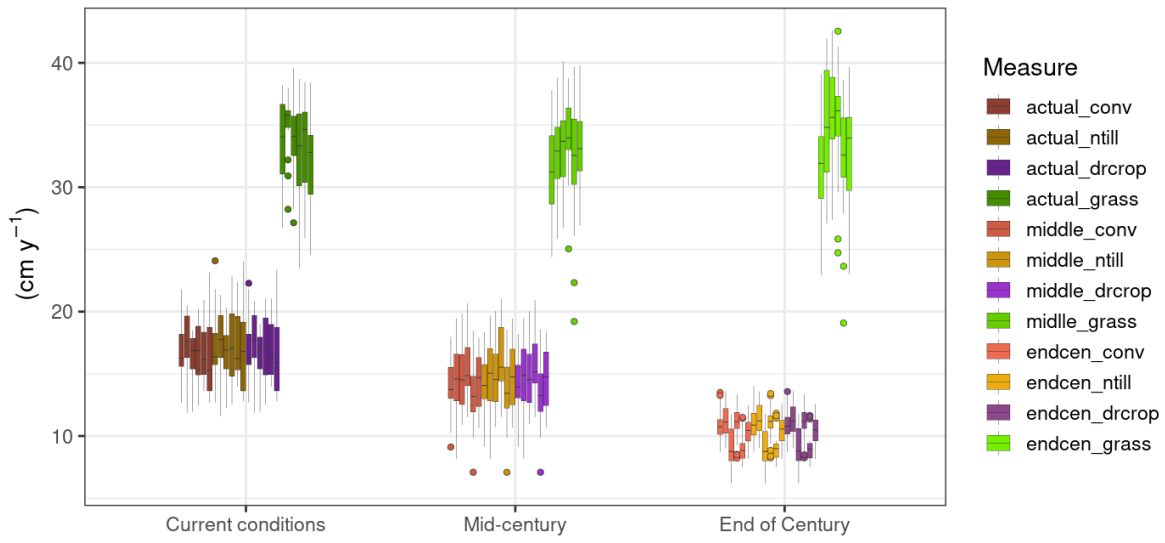
## 9. Effectiveness of management scenarios under future climate

The management applied to the climate scenarios were conventional tillage, reduced tillage, and drought resistant crops, all of them set for maize as a monoculture. Conventional tillage was parameterised based on the PEST autocalibration results, while for reduced tillage we assumed a 20% increase in saturated water content, the alpha and npar parameters of the Van-Genuchten function and organic matter in the top 30 cm of soil. The crop resistance to drought was defined by setting HLIM4 = -15,000 cm, HLIM3H = -800 cm and HLIM3L = -2000 cm. Additionally, we evaluated the conversion of the arable land to grassland. Below are the results of the changes in water content, soil water balance components, crop yield (for maize only) and predicted stress to the plant due to drought, considering the model chains with RCP 8.5.

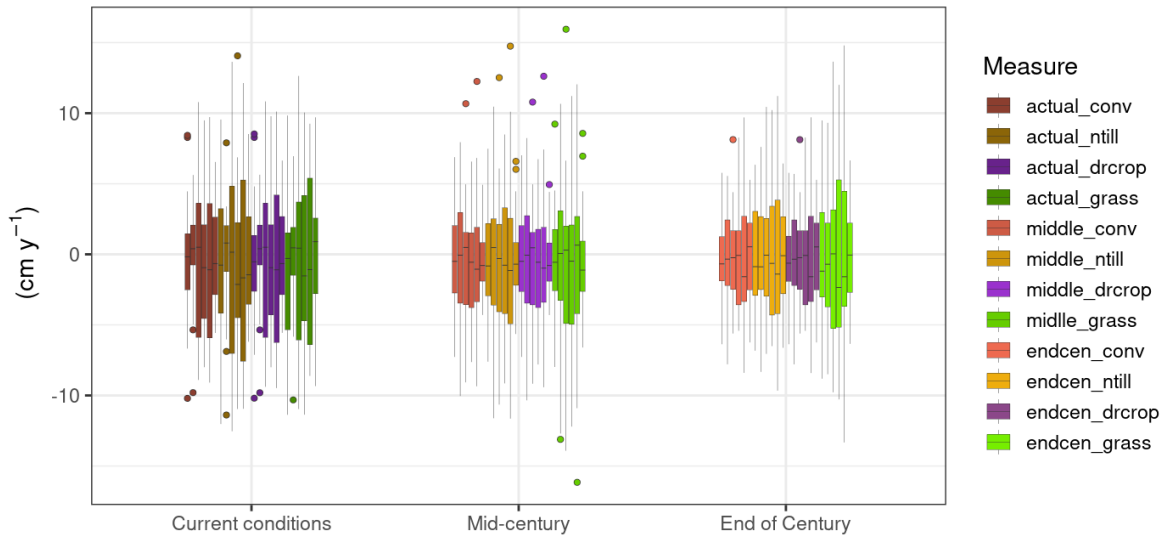




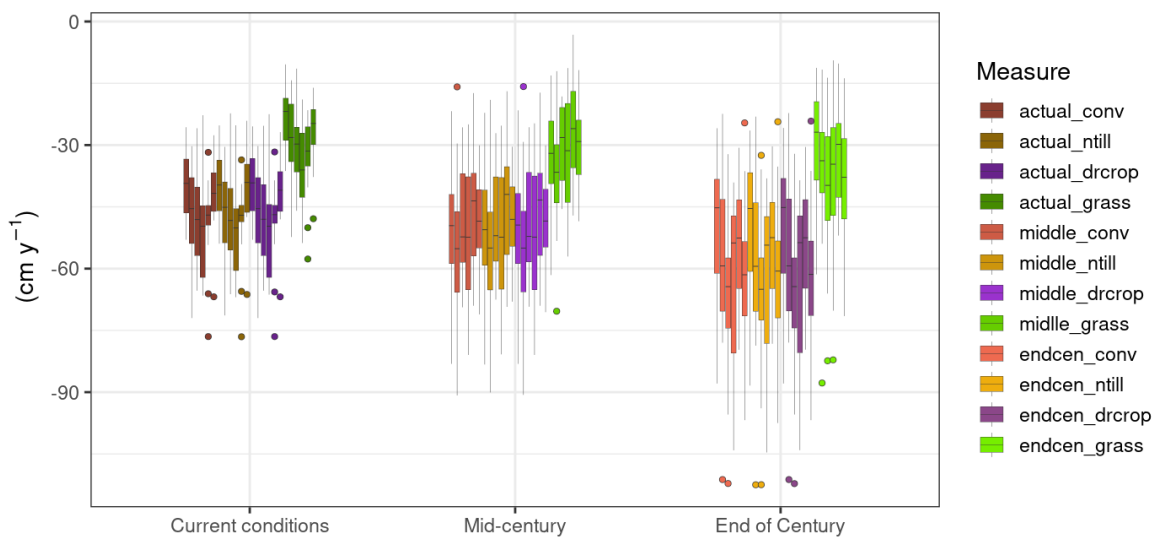
### Tact



### dstorage



### QBottom



## 10. Comparison of PAY\_P1 to Grafenried

The Grafenried soil present at the lysimeter station has fairly similar soil hydraulic parameters as compared to the soil profile in Payerne, at least as predicted by the euptfv2. When compared to the optimization results from PEST, the differences that are more pronounced (Figure 9).

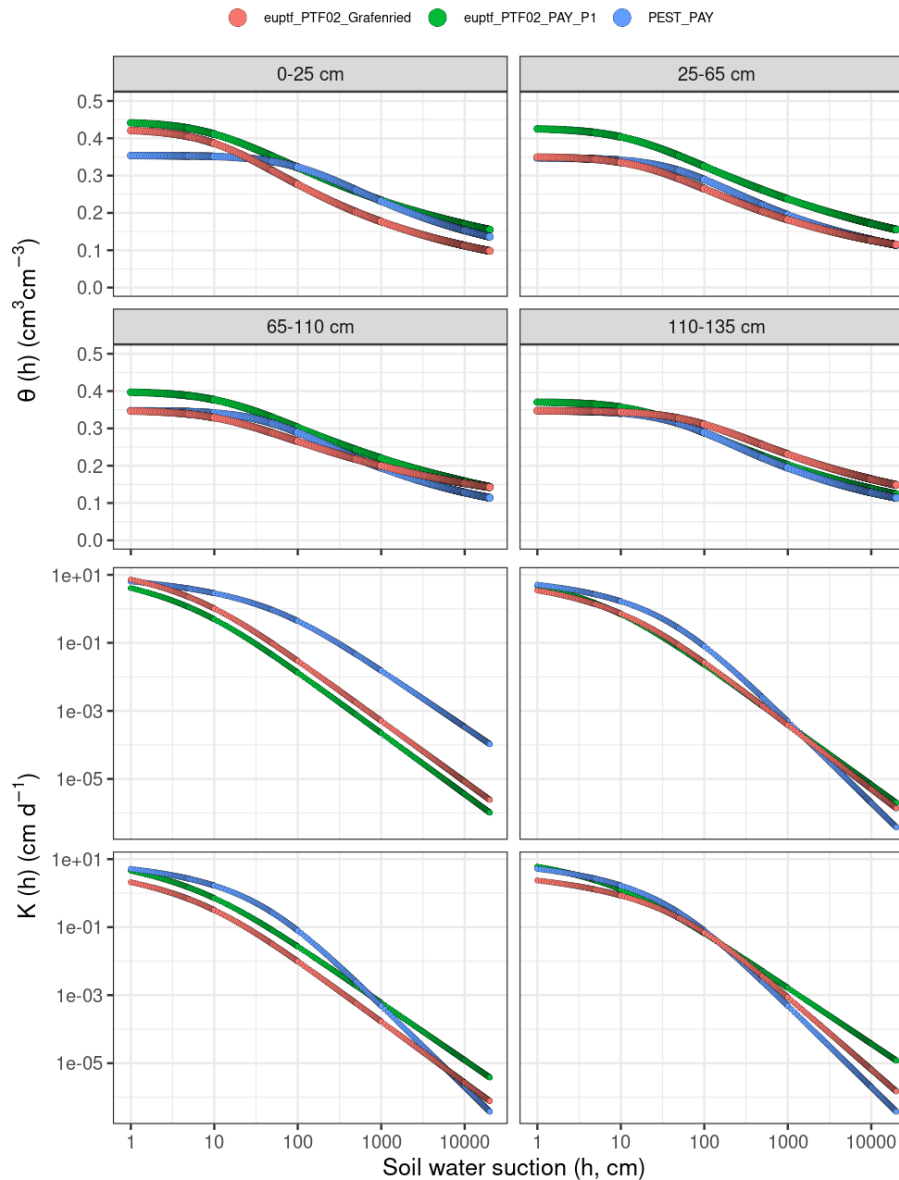


Figure 9. Comparison of Grafenried soil with the soil profile data from Payerne.

## 11. Data availability

Data, codes and scripts are available upon request.

## 12. References

Prasuhn, V., Humphys, C., & Spiess, E. (2016). Seventy-Two Lysimeters for Measuring Water Flows and Nitrate Leaching under Arable Land. NAS International Workshop on Applying the Lysimeter Systems to Water and Nutrient Dynamics, Wanju, Korea.

# Annex 2. Modelling results for CS3a (Csorsza, HU)

Authors: Ágota Horel, Levente Czelnai, Tibor Zsigmond

## 1. Experimental site and model setup

The Csorsza OPTAIN case study catchment is located in Veszprém County, Hungary. The size of the catchment is 21.3 km<sup>2</sup>. 29% of the total catchment area is forest, 29% orchards and vineyards, 17% shrubs, 13% is arable land, 6% is grassland, and 5% is urban.

In 2015, soil water content (SWC) and temperature sensors were installed at different locations representing vineyard, arable land, and forested areas. Meteorological data were retrieved from the nearby meteorological station (Zánka), located at the catchment outlet, which was installed in 2016. The temporal resolution of the SWC and meteorological data were 10 minutes. Later within the OPTAIN project several rain gauges were placed at different parts of the catchment (i.e., arable site, vineyard site, a grassland near the forest site) to better capture local precipitation events and their intensities.

For this report, SWC measurements from 01/08/2020 to 31/08/2021 were used for the arable site, and the SWC measurements between 01/09/2021 to 31/08/2022 for the forest site as input for the SWAP field-scale model.

## 2. Model calibration and validation

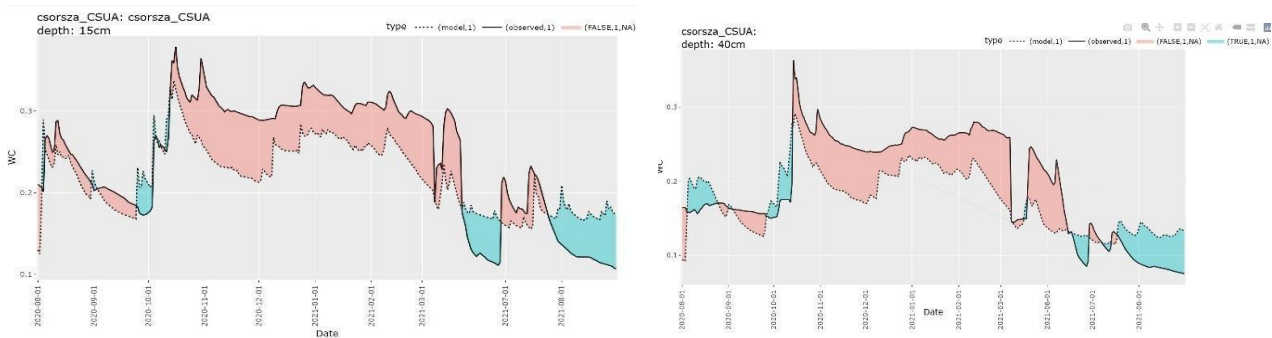
For the soft calibration of the SWAP model the rswap package was used, and manual calibration was applied. The NSE, RMSE, PBIAS, R<sup>2</sup>, and the Index of Agreement (d; daily and monthly), assessing the model's performance along with its associated layers, are presented in Table 2.1. We only had two layers at the vineyard sites. While the NSE values were higher during the calibration period, the Index of Agreement (d) showed better performance of the model during the validation period. We also observed that the model overestimated SWC during the calibration period, while mostly underestimating during the validation period. Some adjustments are still needed.

Table 2.1. SWAP model performance statistics for the vineyard in Csorsza CS.

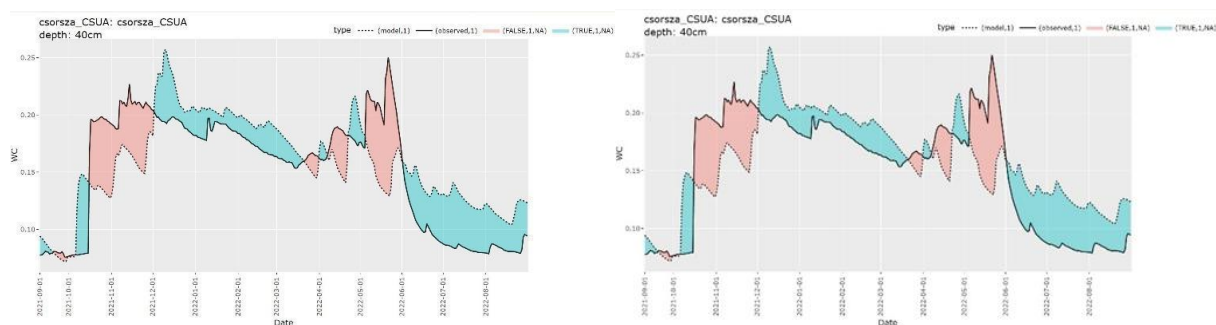
Layer (cm)	NSE	PBIAS	RSR	RMSE	R <sup>2</sup>	d daily	d monthly
<b>Calibration</b>							
15	0.52	9.75	0.71	0.05	0.52	0.81	0.77
40	0.52	10.6	0.71	0.05	0.51	0.81	0.78
<b>Validation</b>							
15	0.34	-3.9	0.83	0.05	0.34	0.74	0.81
40	0.47	-3.93	0.80	0.04	0.46	0.81	0.87

If evaluating the calibration and validation results according to Moriasi et al. (2015), our soft-calibration results are satisfactory (Table 2.1) and could be used for scenario analysis.

Indeed, when looking at SWC dynamics (Figures 2.1 -2.2), we could clearly see that the model needs further adjustment using the SWAP-PEST autocalibration tool.



**Figure 2.1.** Modelled vs. observed soil water content in the 15 cm (left) and 40 cm (right) soil layer for the calibration run (Csorsza vineyard, 2020-2021).



**Figure 2.2.** Modelled vs. observed soil water content in the 15 cm (left) and 40 cm (right) soil layer for the validation run (Csorsza vineyard, 2021-2022).

### 3. Effectiveness of selected in-field NSWORMs under present and future climate conditions

Two management scenarios were applied in Csorsza vineyard land, namely introducing drought-tolerant plants and reduced tillage. We used the nearby vineyard data with no-tillage performed for the low-till scenario. The scenarios are presented in 2.1. The same abbreviations are used in the following figures to show model results.

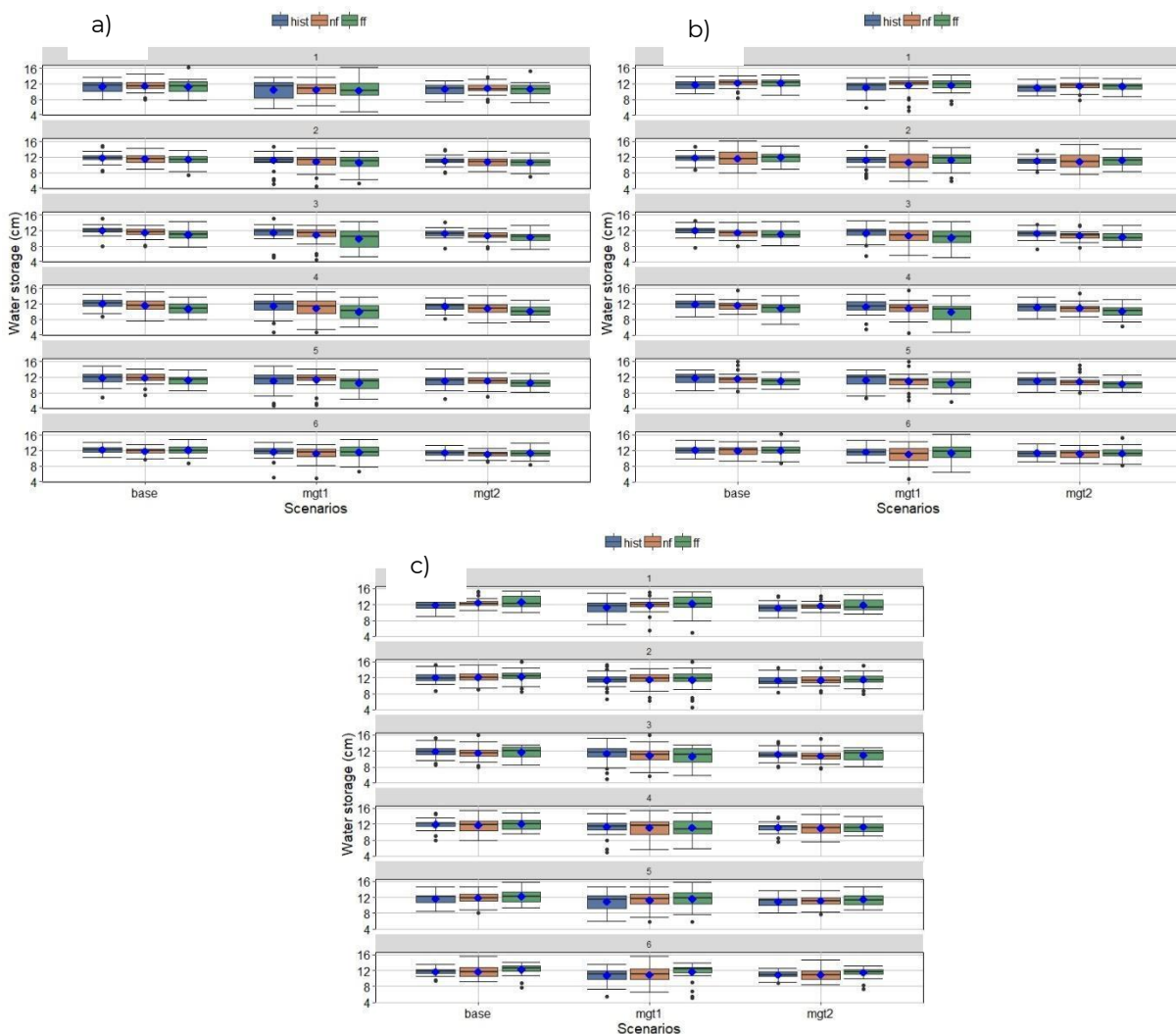
**Table 2.1.** Measures applied for the Csorsza vineyard field (CS3a).

Management Scenario Abbreviation	Explanation
Base	Baseline
Mgt1	Drought tolerant plant
Mgt2	Reduced tillage

For scenario analyses we run the SWAP model for six climate models for three RCP scenarios (Chapter 2, Table 2.5) together with the baseline and three management scenarios (Table 2.1). In total 54 simulations were performed for the period from 1991 to 2099 in a daily step. The results were evaluated for three distinct time periods: historical (1991-2022), near future (2030-2060) and far future (2070-2099).

Some of the results for the model outputs (water storage and transpiration) are shown in Figures 2.3 – 2.4. We included all 6 climate models in the figures. Since the model did

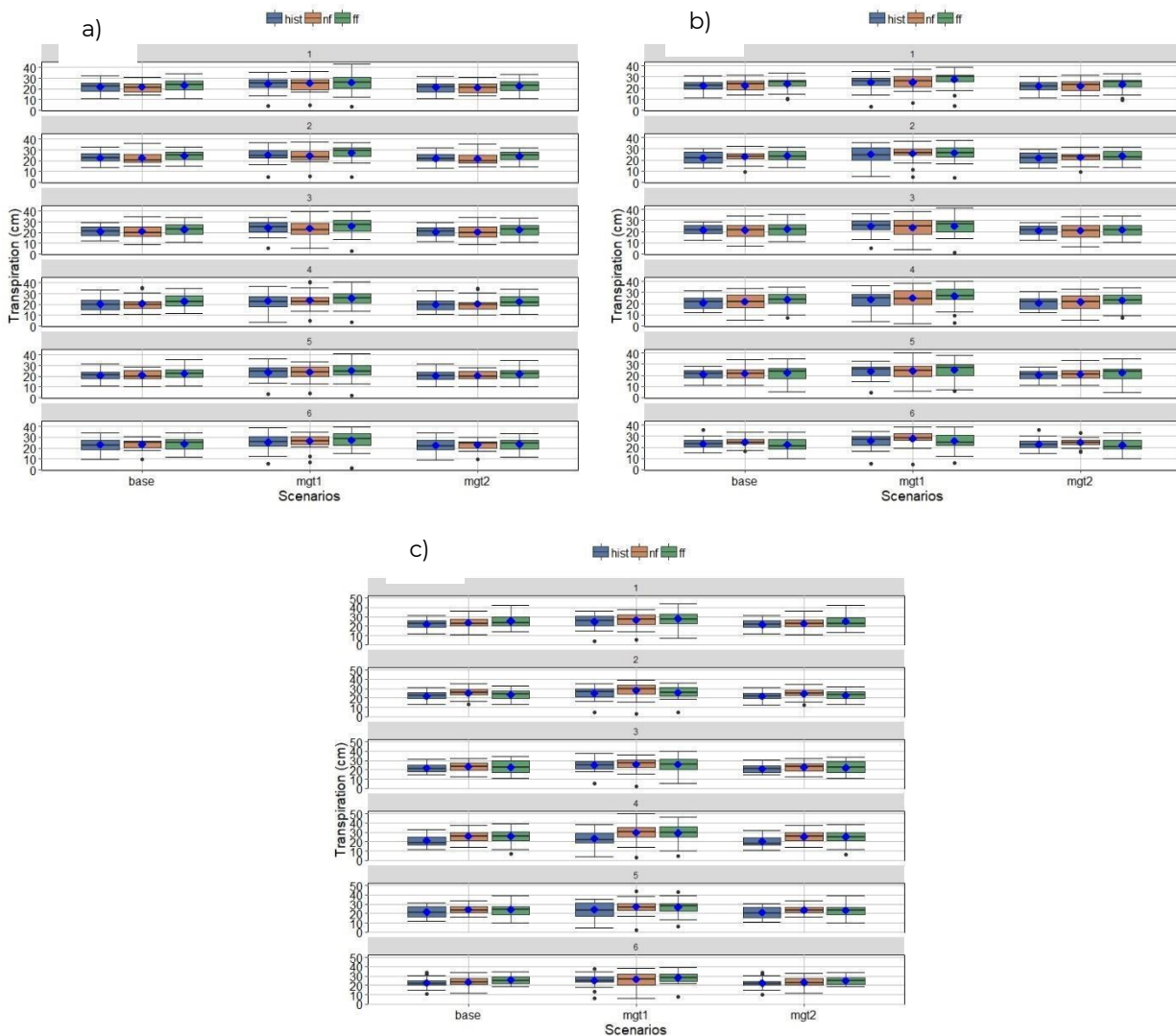
not estimate runoff data, we chose not to include it in the report. Further investigation of the model parameters is underway to understand the causes.



**Figure 2.3.** Boxplots of modelled mean soil water storage (cm) for hist (1991-2020), near future (nf, 2030-2060), and far future (ff, 2070-2099) periods derived from all the six climate models where a) RCP2.6, b) RCP4.5, and c) RCP8.5. Each data point represents the median (solid black line), the mean (blue diamond), the upper and lower quartiles, and the minimum and maximum values (whiskers; data plus/minus 1.5 interquartile range).

Most models for RCP2.6 and RCP4.5 showed a decline in soil water storage over time, with the largest deficit expected in the far future. When RCP8.5 was considered, the water storage increased steadily in the far future (Figures 5.11a-c). However, the differences were not significant.

Among the management methods, it was found that reduced tillage had the lowest amount of stored water (10.98 cm per year), followed by drought-resistant plant (11.03 cm), and the highest was observed for the baseline (11.73 cm per year). However, these differences are within the range of uncertainty of the model. In addition, reduced water storage does not necessarily mean reduced water retention, as increased soil evaporation or deep percolation (increased water storage in the deeper soil layers) may also occur.



**Figure 2.4.** Boxplots of modelled mean transpiration (cm) for hist (1991-2020), near future (nf, 2030-2060), and far future (ff, 2070-2099) periods derived from all the six climate models where a) RCP2.6, b) RCP4.5, and c) RCP8.5. Each data point represents the median (solid black line), the mean (blue diamond), the upper and lower quartiles, and the minimum and maximum values (whiskers; data plus/minus 1.5 interquartile range).

Using the transpiration data, we found that the values for RCP2.6 and RCP4.5 increase by the end of the century, while this trend for RCP8.5 either decreases or not as pronounced (Figure 2.4a-c). This is true for both management methods and for the baseline scenario. Among the management methods, we found that the reduced tillage had the lowest amount of transpiration (22.15 cm per year), just after the baseline scenario (22.55 cm), and the highest was observed for the drought-resistant crop (25.47 cm per year). Thus, the drought resistant plants were able to extract more water from the soil than traditional plants.

# Annex 3. Modelling results for CS4 (Borucin, PL)

Authors: Dorota Mirosław-Świątek

## 1. Experimental site and model setup

The Borucin experimental site is located in N-W Poland within the Upper Zgłowiączka catchment (Figure 3.1), which is the pilot watershed for SWAT+ modelling in the OPTAIN project (Piniewski et al., 2024 (Annex 4)).



Figure 3.1. The Borucin experimental site.

Based on field and laboratory measurements, 6 soil layers were distinguished in the 1D soil profile (total thickness of profile is 380 cm). The characteristics of soil layers are summarized in Table 3.1.

Table 3.1. Soil data for the Borucin soil profile.

soil layer	fraction			$\Theta_r$ [cm <sup>3</sup> /cm <sup>3</sup> ]	$\Theta_s$ [cm <sup>3</sup> /cm <sup>3</sup> ]	$\alpha$ [1/cm]	n	$K_s$ [cm/d]	bulk density [g/cm <sup>3</sup> ]	thickness [cm]
	sand [%]	silt [%]	clay [%]							
1	80	13	7	0.0432	0.3601	0.040	1.730	79.94	1600	30
2	79	15	6	0.0383	0.3161	0.048	1.603	42.67	1750	10
3	68	20	12	0.0394	0.3213	0.044	1.316	15.04	1750	20
4	50	32	18	0.0421	0.3111	0.031	1.235	4.58	1800	10
5	50	32	18	0.0421	0.3111	0.031	1.235	4.58	1800	30
6	79	15	6	0.0383	0.3161	0.048	1.603	42.67	1750	280

The Borucin profile is not drained and agricultural crops are not irrigated. The SWAP model uses the groundwater level (below soil surface) measured by an automatic sensor with a time step of one day as the lower boundary condition (Fig.3.2).

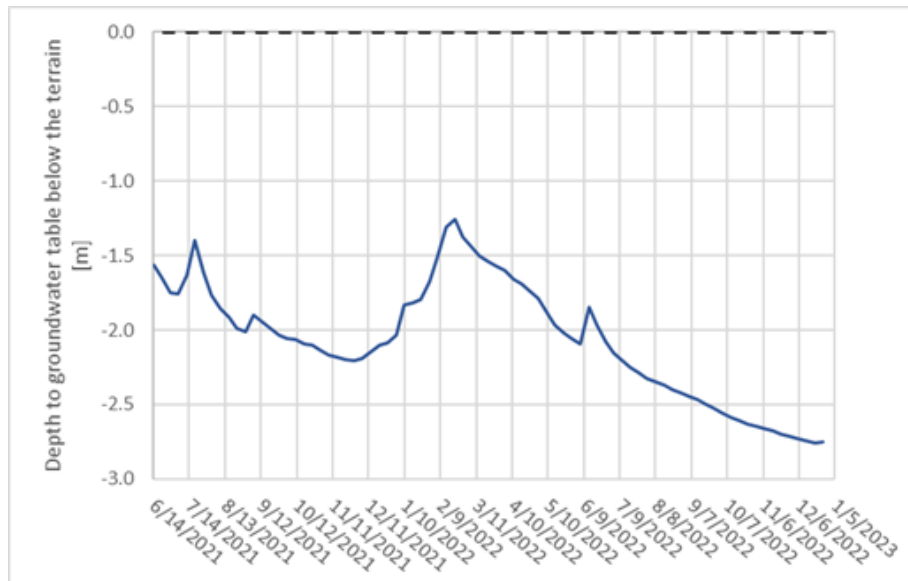


Figure 3.2. Variability of the groundwater level (calibration and validation run of the model).

## 2. Model calibration and validation

The model was calibrated and validated using automatic moisture measurements recorded from 16.06.2021 to 31.12.2022 by the ECH2O system sensors. The model calibration covered the period 01.01 - 31.12.2022 and model validation was performed for the period from 16.06 - 31.06.2021.

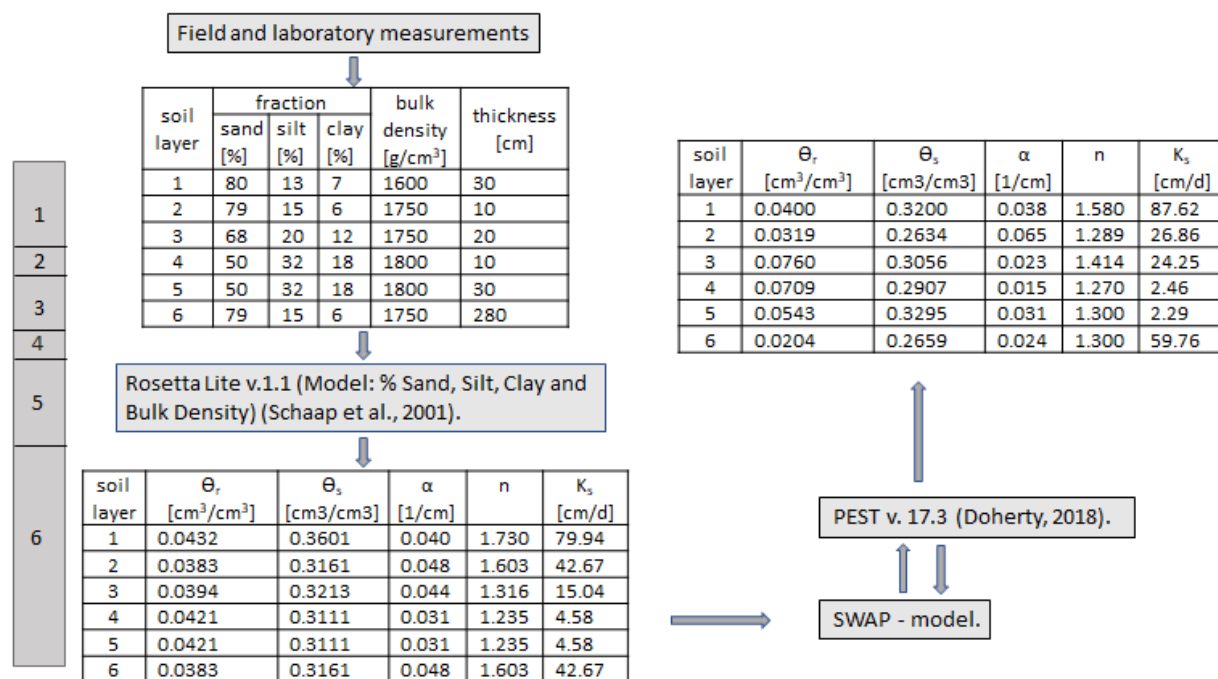


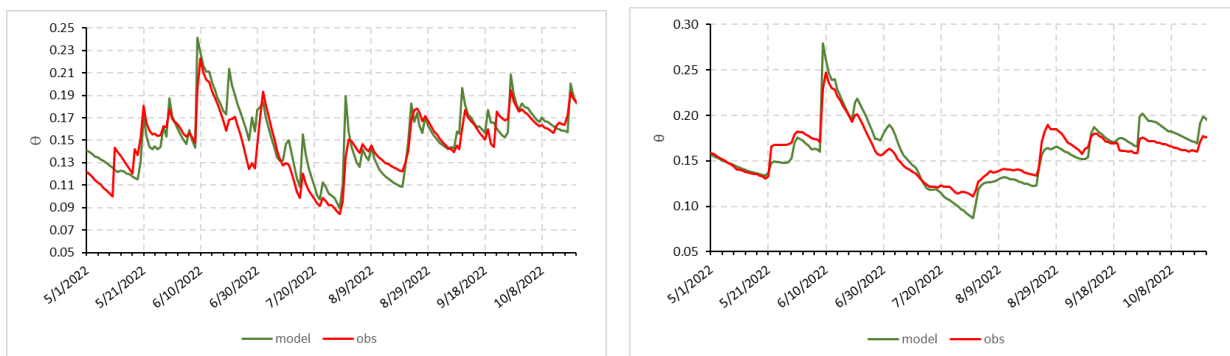
Fig.3.3. Algorithm for calibrating the model parameters.

In 2022, moisture measurements were recorded at depths of 10, 30, 50, 70 and 90 cm. In 2021, moisture content was measured at depths of 10, 30 and 50 cm. Due to measurement errors resulting from negative temperatures, model performance

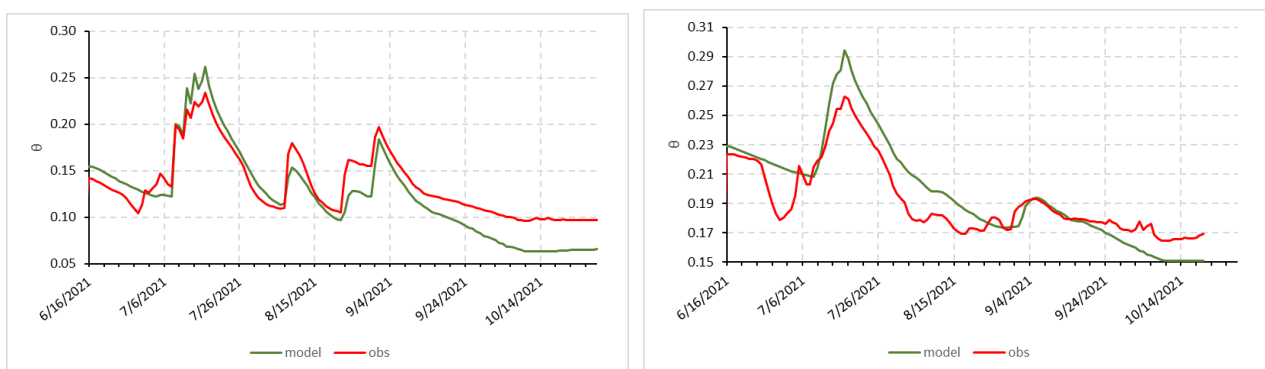
evaluation criteria were estimated for the period with positive air temperatures (01.05-30.10.2022 - calibration run, 16.06 - 15.11.2021 - validation run). In 2021, sugar beets were grown on the plot field (19.04.2021- 10.10.2021), and in 2022 winter wheat was grown (20.10.2021 – 31.07.2022). Fig.3.3 shows the algorithm for calibrating the model parameters, in which the Rosetta Lite v. 1.1 and PEST v.17.3 computer software was used.

Figure 3.4 shows the volumetric water content calculated by the model for the calibration run (selected examples) and Figure 3.5 for the validation run. The criteria for the evaluation of the model performance are summarised in Table 3.2.

The obtained values allow us to evaluate the quality of the model as very good. This model can be used as a tool to evaluate the impact of measures to improve retention at the field scale.



**Figure 3.4.** Modelled vs. observed soil water content in the 10 cm (left) and 30 cm (right) soil layer for the calibration run (Borucin, 2022).



**Figure 3.5.** Modelled vs. observed soil water content in the 30 cm (left) and 50 cm (right) soil layer for the validation run (Borucin, 2022).

**Table 3.2.** SWAP model performance statistics for the Borucin site.

Depth [cm]	R <sup>2</sup>		Index of Agreement (d)		NSE	
	calibration	validation	calibration	validation	calibration	validation
10	0.75	0.80	0.93	0.93	0.71	0.70
30	0.85	0.87	0.94	0.97	0.72	0.60
50	0.71	0.86	0.91	0.93	0.64	0.60
70	0.73	-	0.92	-	0.70	-
90	0.78	-	0.93	-	0.77	-

### 3. Climate change effects

Climate change effects were analysed on the basis of six bias-corrected RCMs simulations, three RCPs (2.6, 4.5, 8.5) and three time horizons (1991-2020 - “baseline” (BL), 2036-2065 - “near future” (NF), 2070-2099 - “end of century” (EC), resulting in a total of 54 model scenarios (Piniewski et al., 2024). The following SWAP outputs were considered in the analysis: actual evaporation (Eact.), actual transpiration (Tact.), interception (Interc.), soil moisture content in the whole profile above the groundwater table (wcontent profile) and in top profile of 30 cm (wcontent profile 30 cm), depth to groundwater table (Groundwater depth). The bottom boundary condition (depth to groundwater) was adopted from the results of the SWAT+ model, and crop rotation schemes followed the scheme adopted in this model (Piniewski et al., 2024). The results are presented as box plots in Figure 3.6 and 3.7.

**Table 3.3** Calculated medians for the indicators analysed (BL time horizon)

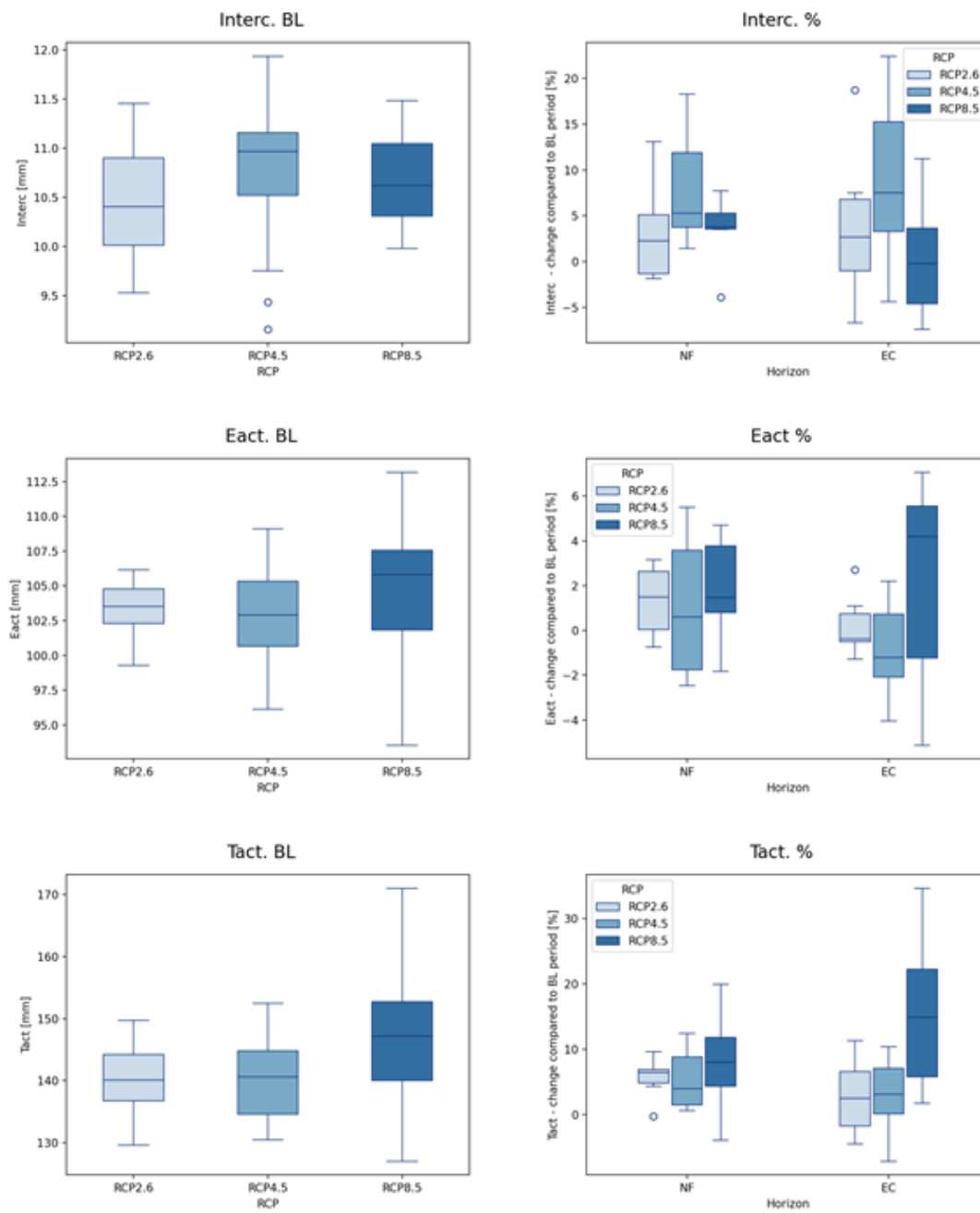
Indicator	RCP2.6	RCP4.5	RCP8.5
Interc. [mm]	10.4	10.8	10.5
Eact. [mm]	102.6	102.5	106.1
Tact. [mm]	140.1	140.3	145.2
wcontent profile [cm]	61.11	55.21	57.53
wcontent profil 30 cm [cm]	4.68	7.74	4.69
Groundwater depth [m]	2.71	2.42	2.45

Table 3.7 summarises the median values calculated for the analysed indicators for the BL time horizon (1991-2020) and the RCP2.6, RCP4.5, RCP8.5 scenarios. Further analyses compare the changes in median indicators for the NF and EC horizons and present them relatively (%) to the BL horizon.

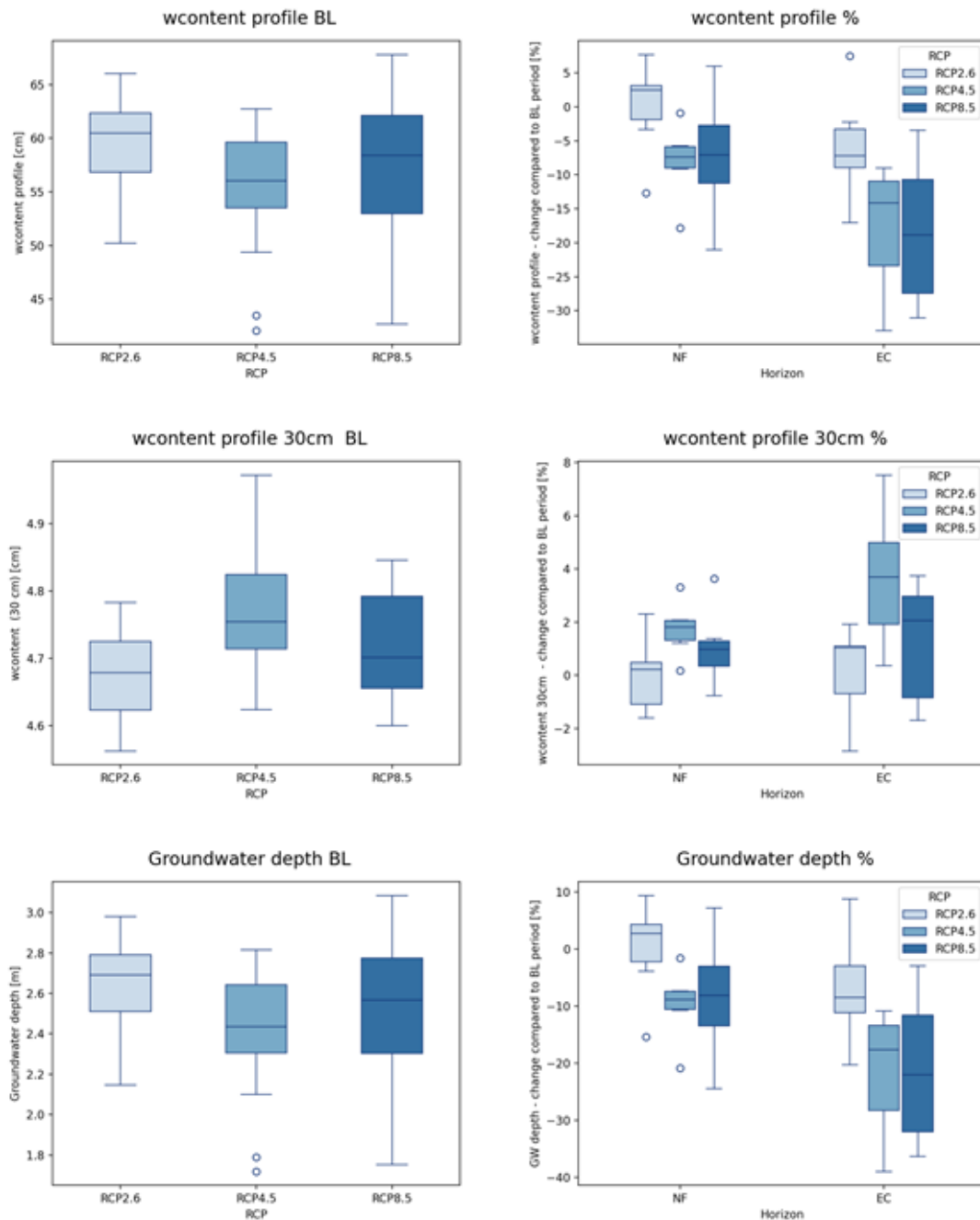
Figure 3.6 shows that the median of interception of projected changes in time horizon NF and EC will increase relative to the BL horizon. Its percentage differences are in the range of 1-7 %. The largest increase in Interc. (22 %) occurs for the EC horizon and RCM8.5. The median of Eact. increases for NF from 0.5 to 1 % for the three RCPs. For EC, it decreases in the range of 0.2 - 1% for RCP2.6 and RCP4.5, with the largest increase (4.2%) occurring for RCP8.5. The maximum increase in Eact. is 6.5% in this scenario. The median Tact. increases for the NF horizon from 3%(RCP4.5) to 8%(RCP8.5). For the EC horizon, its increase is in the range of 2 - 12%. The largest change of Tact. 32% is assumed in this horizon for RCP8.5.

Figure 3.7 shows that the median of 'wcontent profile' increases (2%) for the NF horizon only for RCP2.6. For RCP4.5 and RCP8.5 it decreases by 7%. For the EC horizon it decreases from 7% (RCP2.6) to 18% (RCP8.5), and the largest decrease of soil moisture content is 30% (RCP8.5). For the top profile (30cm) the median of soil moisture content increases from 0.2% (NF RCP2.6) to 3% (EC RCP4.5). The largest increase in soil moisture content is 7.5% (EC RCP4.5).

The groundwater table rises for most scenarios. The median of depth to the groundwater table decreases from 10% (NF RCP4.5) to 25% (EC RCP8.5). The maximum depth reduction of 38% occurs for EC RCP8.5. Only for the NF horizon and RCP2.6 does the depth decrease by 3%.



**Figure 3.6** Boxplots of modelled mean actual interception (Interc. [mm]), actual evaporation (Eact. [mm]), actual transpiration (Tact. [mm]), and boxplots of their relative changes for the NF and EC time horizons.



**Figure 3.7.** Boxplots of modelled mean soil moisture content in the whole profile above the groundwater table (wcontent profile [cm]) and in top profile of 30 cm (wcontent profile 30 cm [cm]), depth to groundwater table (Groundwater depth [m]) and boxplots of their relative changes for the NF and EC time horizons.

#### 4. Effectiveness of selected in-field NSWORMs under present and future climate conditions

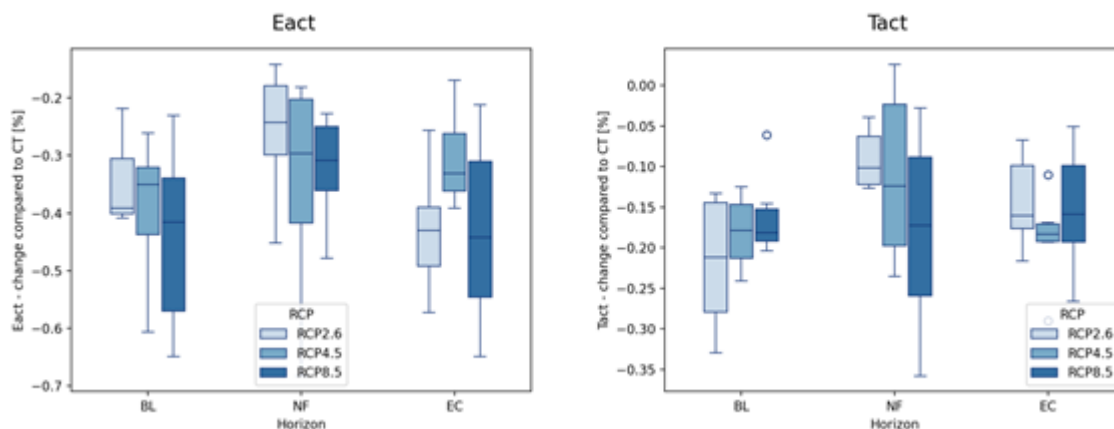
On the basis of the available data for the SWAP model and the possibility of implementing NSWORMs in the model, a tillage adjustment was selected for the Borucin

profile, consisting of the application of low till (LT) agriculture (Marval et al., 2020). LT was implemented by changing in the soil hydraulic parameters: the saturated water content (OSA), saturated hydraulic conductivity (KSATFIT), parameter n (NPAR), parameter (ALFA), and residual water content (ORES) were increased, and the bulk density (BDENS) was decreased. The assumed relative changes (Marval et al., 2020) in these parameters in relation to conventional tillage (CT) are summarised in Table 3.3.

**Tab.3.3.** Tillage adjustment - low tillage agriculture (shift from CT to LT)

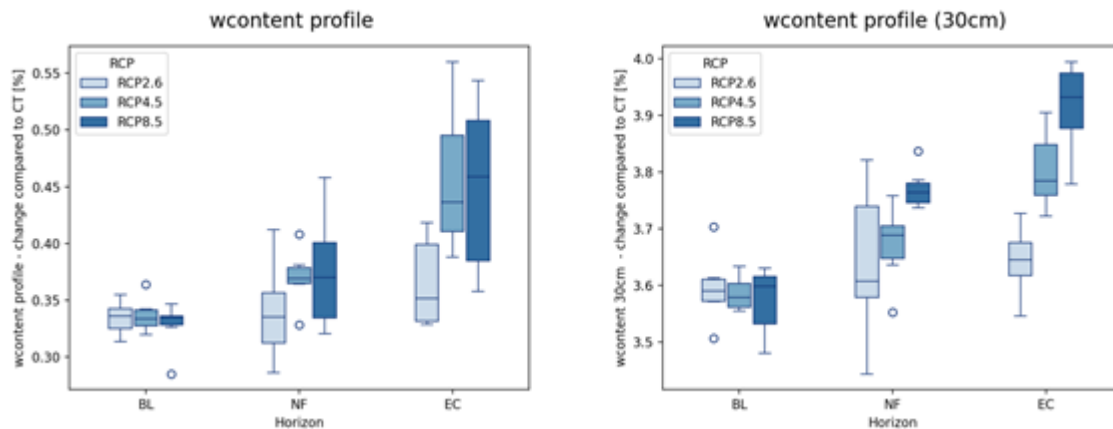
Parameter	Relative change
BDENS	-8%
KSATFIT	+18%
NPAR	+1%
ALFA	+41%
ORES	+6%
OSAT	+19%

Figure 3.8 shows the percentage changes in actual evaporation (Eact) and actual transpiration (Tact) related to these indices calculated for CT. The use of LT slightly decreases the median of Eact for both present climate (BL: 0.39 - 0.42 %) and future climate (NF: 0.25 - 0.31 % and EC: 0.33 - 0.45 %). The median for Tact decreases in a similar range (BL: 0.17 - 0.22 %, NF: 0.11 - 0.17 % and EC: 0.16 - 0.18 %).



**Figure 3.8.** Changes in Eact and Tact calculated for time horizon BL, NF and EC, after changing conventional tillage (CT) to low tillage (LT)

The effect of LT on soil moisture content both in the whole profile above the groundwater table (wcontent profile) and in the top profile of 30 cm (wcontent profile 30 cm ), was also analysed (Figure 3.9). The use of LT slightly increases the median of wcontent profile for the three time horizons (BL: 0.32 - 0.34 %, NF: 0.32 - 0.37 %, CE: 0.35 - 0.37 %). Stronger increase in the median of soil water content occurs in the top 30 cm of the profile and is respectively: 3.57 - 3.60 %, 3.60 - 3.75 %, 3.65 - 3.93 % for BL, NF and EC.



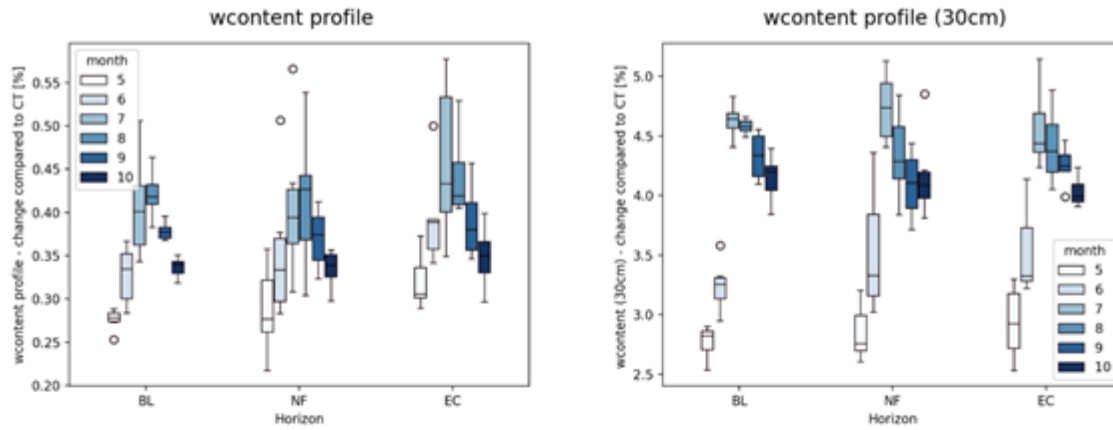
**Figure 3.9.** Changes in soil moisture content in soil profile and top 30 cm of the profile calculated for time horizon BL, NF and EC, after changing conventional tillage (CT) to low tillage (LT)

The largest increases in the median of *soil moisture content in soil profile* occur in July and vary from 0.39 - 0.40%, 0.42 - 0.47%, 0.42 - 0.55% for BL, NF and EC time horizons, respectively. Similarly, for the top *30 cm of the profile*, the largest median increases occur in July and increase for further time horizons (BL: 4.50 - 4.70%; NF: 4.70 - 4.75%; EC: 4.3 - 5.0%) (Figure 3.9).

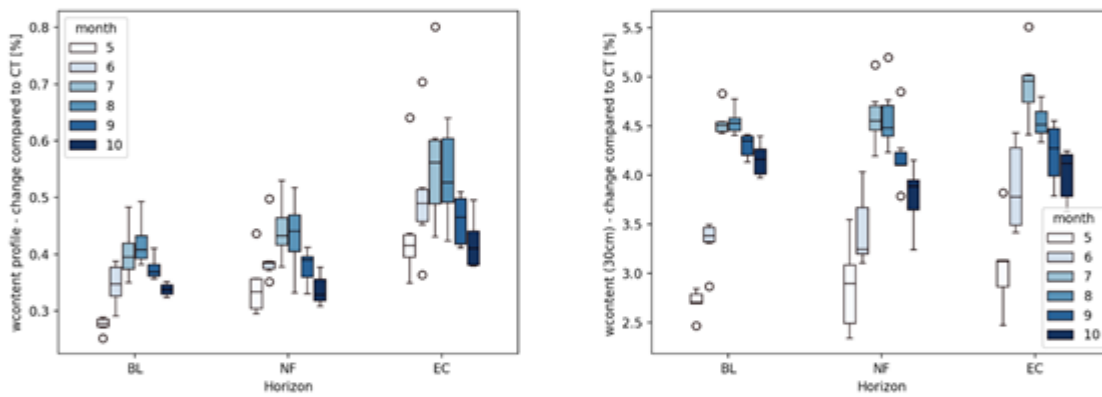
The calculations carried out for the Borucin profile, allow us to make the following quantitative conclusions about the changes in the analysed indicators (the numerical values are described by the median for the six RCMs):

- For future time horizons, interception will not increase by more than 5%, evaporation by 4% and transpiration by 15%.
- Soil moisture content will decrease for future time horizons by up to 18% for the soil profile, and in the top 30 cm the reduction will not exceed 3%.
- Depth to the water table will decrease by a maximum of 25%.
- Application of low till agriculture for both present and future time horizons will slightly reduce actual evaporation (max 0.45%) and actual transpiration (max 0.22%).
- The maximum increase in soil moisture content occurs in July and does not exceed 0.55%. In the top 30 cm the increase does not exceed 5%. For further time horizons there are larger changes of soil moisture content than for the present horizon.

RCP2.6



RCP4.5



RCP8.5

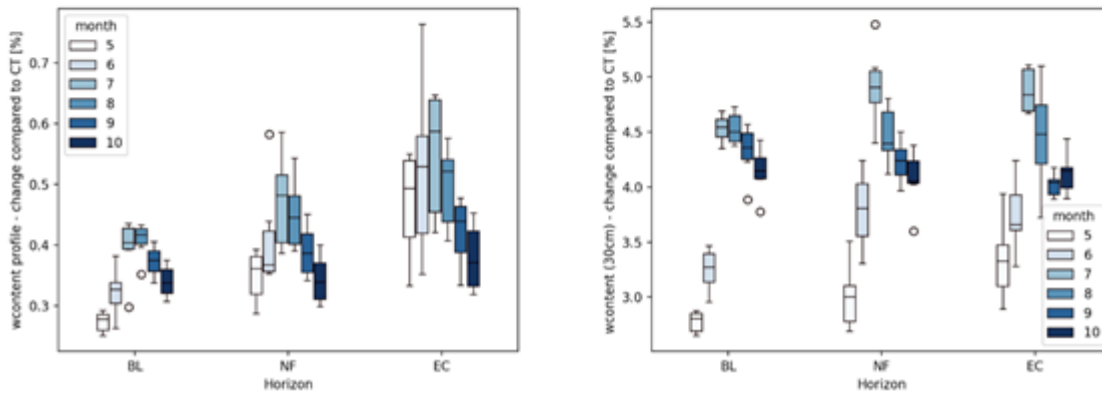


Figure 3.10. Changes in soil moisture content (month: May - October) in soil profile and top 30 cm of the profile calculated for time horizon BL, NF and EC, after changing conventional tillage (CT) to low tillage (LT)

## 5. References

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# Annex 4. Modelling results for CS8 (Dotnuvėlė, LT)

Authors: Gökhan Cuceloglu, Natalja Cerkasova

## 1. Experimental site and model setup

### Short site description

The Dotnuvėlė case study area is located in central Lithuania in the Dotnuvėlė river basin with an area of 192.7 km<sup>2</sup>. This basin is situated in the Central Lowlands, which is characterised by its abundant moist soils. Agricultural land covers 69.2% of the area, the proportions for the other land use types are 24.5% for forests and natural zones, 5.8% for artificial surfaces, and 0.5% for water bodies (0.5%). The state authorities monitor the river's health and determine a poor ecological status for the Dotnuvėlė upstream and moderate status downstream.

The field in CS8 (Lithuania) is a part of a private farm, located in the lower part of the river Stabė (an upstream branch of Dotnuvėlė River), 1.8 km from its mouth. Soil texture is sandy loam with high organic carbon. The field is adjacent to a recently constructed wetland on the stream, which serves the purpose of trapping nutrients and sediments from the adjacent fields and the drained land. The field produces different crops, depending on the year and the demand for crops, as well as available subsidies.



Figure 4.1. Dotnuvėlė experimental site.

## Main challenges

Lithuania, and the farm located in the CS are suffering from increased droughts, followed by severe floods, soil erosion and nutrient loss. The effects of changing climate are already acknowledged by the MARG and the local farmers: warm periods are getting warmer, winters are getting warmer as well, and the spring sowing season sometimes can start earlier than in previous decades. The farmers in the area have to cope with many challenges and trade-offs: tightening environmental regulations, changing climate, and the efforts to sustainably increase farmland production, where trade-offs and environmental consequences are not easily identifiable.

## Monitoring Station

During the OPTAIN project an automatic weather station and soil moisture and temperature probes were installed in the field. This equipment can automatically measure and log precipitation, solar radiation, temperature of the air and in the soil profile, as well as measure soil moisture at different depths, as well as other parameters. This data is available to the farmer and to the public via the IKMIS system (in Lithuanian and partially in English. Registration is required: <https://www.ikmis.lt/Bundles/ep1/agrometeorologines-stotys>). This data was used for model calibration by the OPTAIN group. The farmer uses this data to adjust his farming practices. The station is operational for two years, and so far, the feedback is positive, meaning that this automatic station is helping the farmer.



Figure 4.2. The monitoring station in the Dotnuvele experimental site.

A monitoring station was established in the study area, where meteorological and soil data (soil moisture and temperature) were measured hourly between 29/08/2022 to 01/08/2023. The sensors record soil moisture and temperature between 10 cm and 120 cm depth with a resolution of 10 cm. The station is still active and monitoring the corresponding parameters in the field. For this report, measurements between 29/08/2022 to 01/08/2023 were used as input for the model to represent a complete cycle of winter wheat grown in the field.

## 2. Model calibration and validation

The rswap package was used to perform the soft-calibrate of the SWAP model. The Index of Agreement statistics (d), which evaluate the performance of the model along with the associated layers, are presented in Table 4.1.

**Table 4.1.** Values of index of agreement achieved by soft calibration.

Layer	Index of Agreement
10 cm (topsoil)	0.60
40 cm	0.62
90 cm	0.20
120 cm	0.44

While a higher Index of Agreement is obtained for most of the layers, it is essential to perform additional parameterization for the layers (specifically at a depth of 90 cm) to improve its calibration.

Figure 4.1 shows the modelled and observed water contents during the simulation periods, with the blue and red areas indicating overestimation and underestimation, respectively. Overall, the current model overestimates water content in the soil profile likely due to the underestimation of surface runoff.

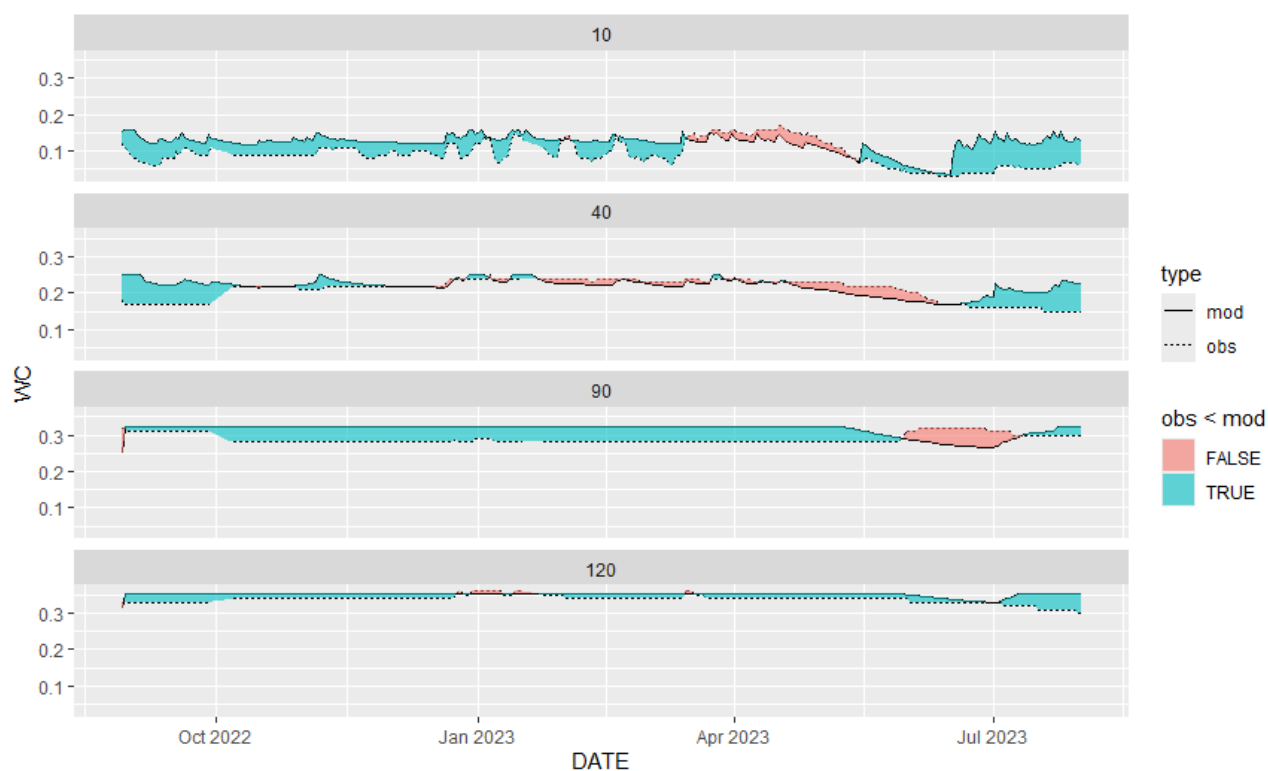


Figure 4.1. Modelled and observed water content (WC) for the 10, 40, 90 and 120 cm soil layers.

Four different management scenarios were applied in Dotnuvélė. All scenarios are presented in Table 4.2. The same abbreviations are used in the following figures to represent the results.

Table 4.2 Measures applied for Dotnuvélė pilot field (CS8)

Management Scenario Abbreviation	Explanation
Base	Baseline
Mgt1	Introducing drought tolerant crops
Mgt2	Land cover change (afforestation)
Mgt3	Reduced tillage

For scenario analyses, we run the SWAP model for six climate models for three RCP scenarios (Chapter 2, Table 2.5) along with the baseline and three management scenarios (Table 4.2). A total of 72 simulations were run for the period from 1991 to 2099 in a daily step. The results were evaluated for three different time periods: historical (1991-2022), near future (2030-2060) and the far future (2070-2099).

The three different NSWORMs were implemented in the model according to the recommendations of the OPTAIN NSWORMs implementation handbook (Marval et al., 2022) as follows:

- To “increase” the drought tolerance of the winter wheat grown in the area (Mgt1), we changed the parameters of the plant stress response function to soil water status (Figure 4.2). Thus, the values of  $h_{3low}$  and  $h_4$  were decreased to shift the shape of the function from the black line to the purple line (Figure 4.2).

- Afforestation was implemented by simply changing the crop file (and consequently all plant parameters) from winter wheat to deciduous forest.
- Reduced tillage was implemented by changing the soil hydraulic parameters: the saturated water content, saturated hydraulic conductivity and residual water content were increased, and the bulk density was decreased.

### Introducing drought tolerant crops

1. Drought-tolerant crop genotypes have been developed for decades to ensure crop production and food safety under conditions of water scarcity
2. In SWAP, drought stress is introduced by Feddes water stress function
3. Drought-tolerant crops can extract water from soil at lower soil water potentials.

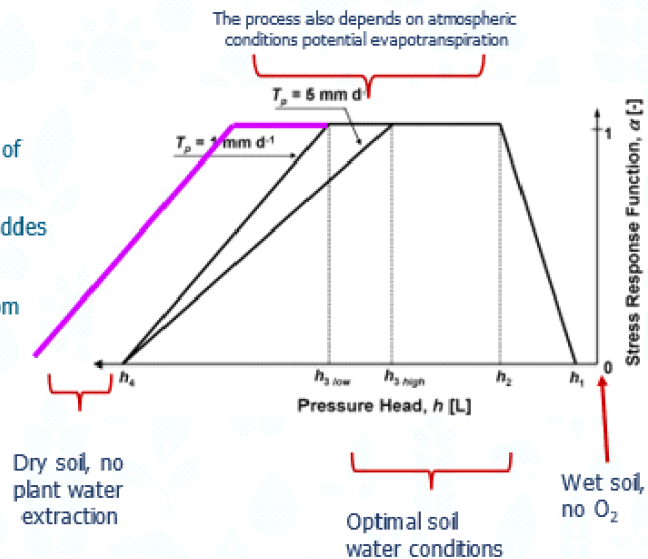


Figure 4.2. Visualisation of the crop stress response function for extremely wet and dry conditions. (presented by Csilla Farkas during the OPTAIN Summer School in July 2023).

### 3. Effectiveness of selected in-field NSWORMs under present and future climate conditions

We evaluated the effect of various NSWORMs on changes in soil water storage, actual transpiration (which equals to the plant water uptake), the surface runoff, drainage outflow and soil evaporation under present and various future climate conditions. Selected results are shown in Figures 4.3 – 4.6.

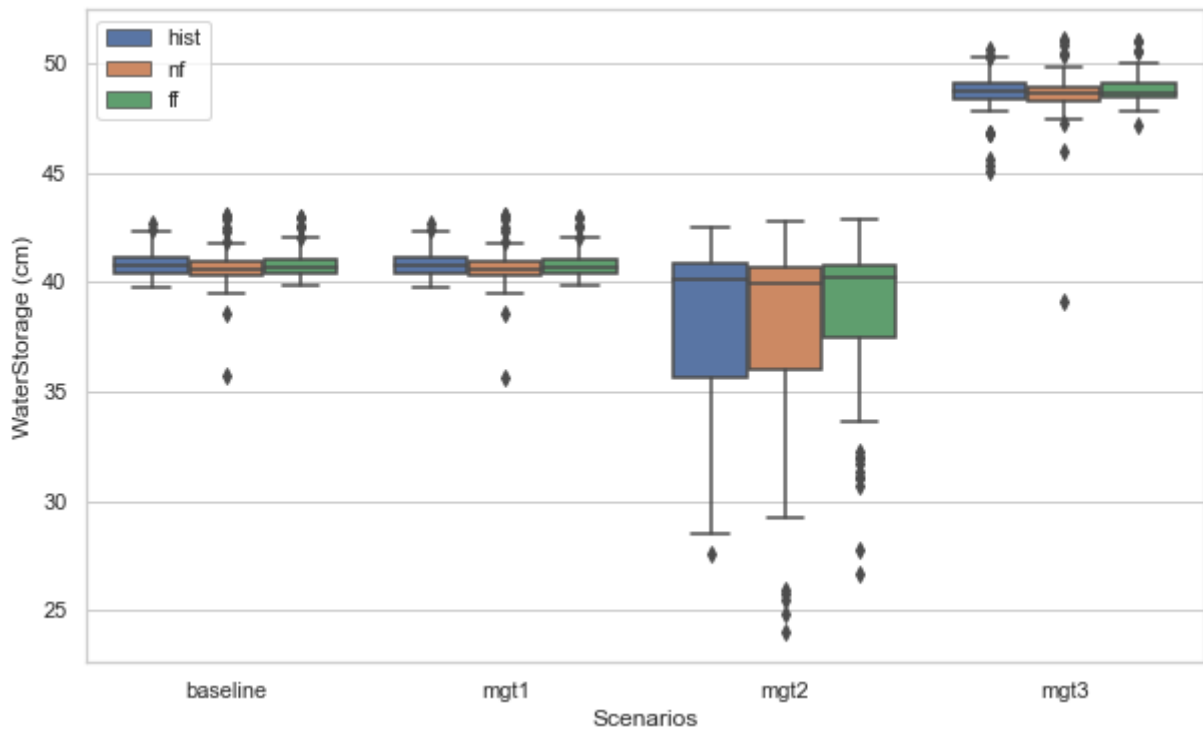


Figure 4.3. Boxplots of modelled mean soil water storage (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060), and far future (ff, 2070-2099) periods, derived from climate model (2).

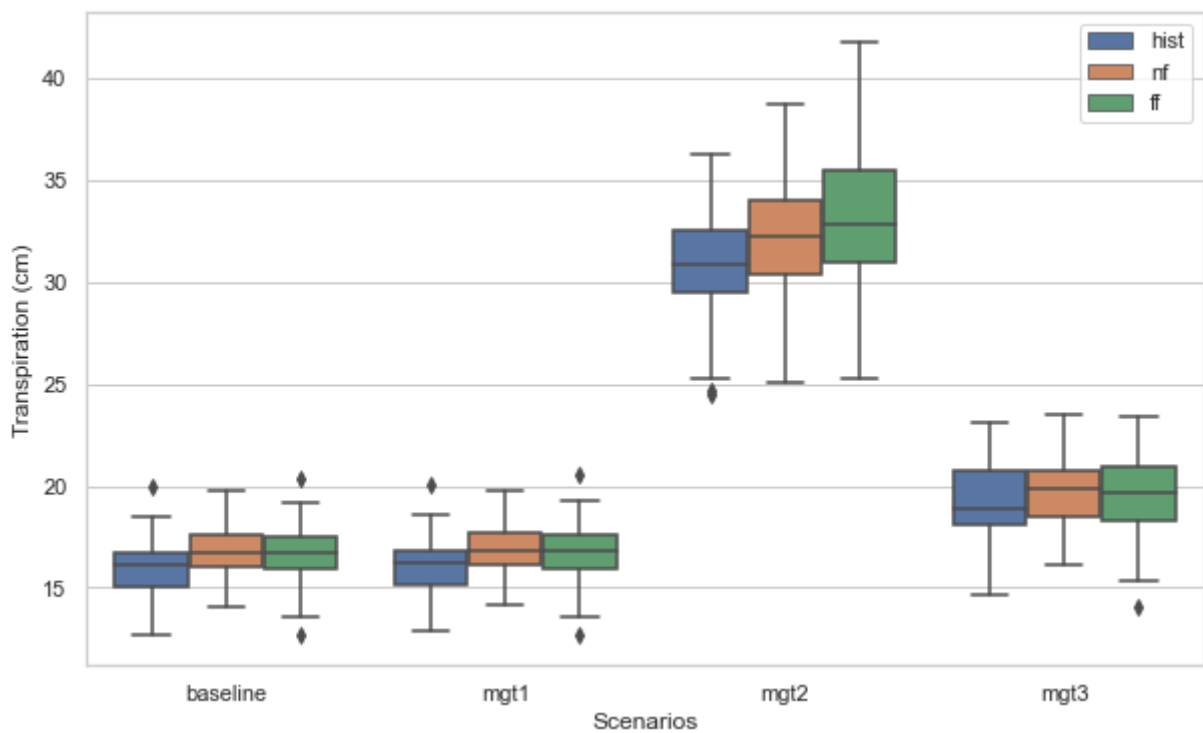


Figure 4.4. Boxplots of modelled mean transpiration (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060), and far future (ff, 2070-2099) periods, derived from climate model (5).

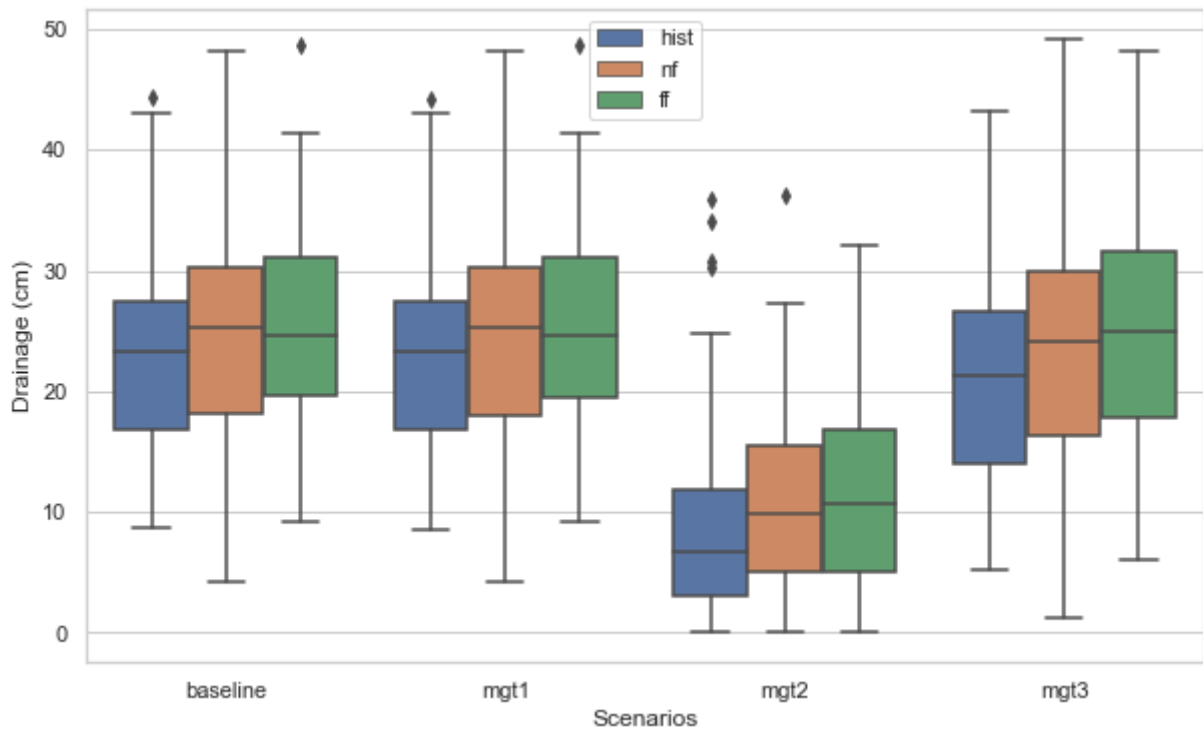


Figure 4.5. Boxplots of modelled mean drainage (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060) and far future (ff, 2070-2099) periods, derived from climate model (3).

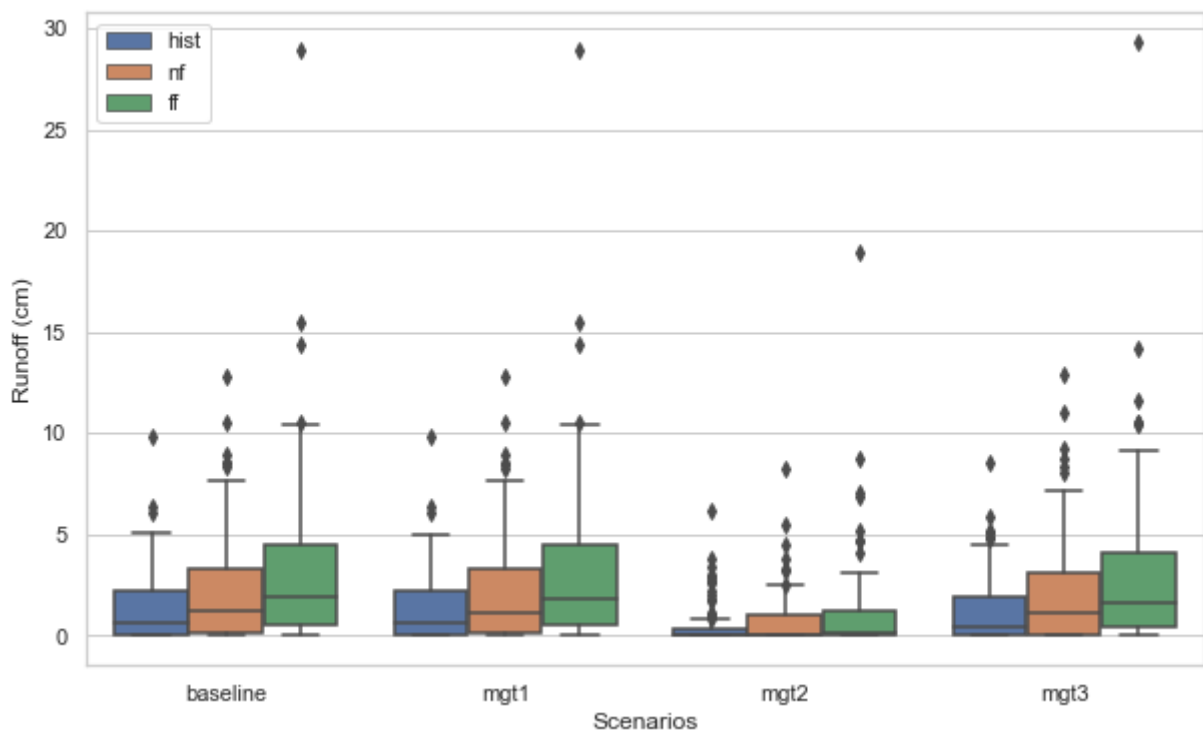


Figure 4.6. Boxplots of modelled mean runoff (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060) and far future (ff, 2070-2099) periods, derived from climate model (5).

The SWAP modelling results for the Dotnuvéle pilot site can be summarised as follows:

- The soft calibration of the model was not fully successful. We need to continue the calibration and validation work using rswap and the SWAP-PEST auto calibration tool to achieve better fit between the modelled and measured soil water content values.
- No changes in soil water balance elements compared to the baseline were found when growing drought tolerant crops under present and future climate conditions, most likely due to the fact that water scarcity will not be a serious problem on growing winter wheat in the future.
- Afforestation (Mgt2) had the most significant effect on soil water regime for both the historical and the future periods, resulting in a drastic decrease in surface and drainage runoff and significant decrease in soil water storage. Afforestation also increased transpiration substantially compared to other scenarios.
- Reduced tillage resulted in a significant increase in soil water storage but had no effect on the other water balance elements.

# Annex 5. Modelling results for CS10 (Kråkstad, NO)

Authors: Csilla Farkas, Moritz Shore (NIBIO)

## 1. Experimental site and model setup

The Kråkstadelva catchment, as a case study area, is located within the Hobølelva watershed, located ca. 30 km S-SE of Oslo, Norway. The area of the Kråkstadelva catchment is approximately 51 km<sup>2</sup>. Agricultural land covers ca. 43% of the catchment (22 km<sup>2</sup>) and it is dominated by cereal production. Forest covers ca. 45% of the catchment. Heavy clay soils (with up to 80% of clay content) dominate in the area. The mean annual temperature is 5.3°C and the average annual precipitation sum is approx. 864 mm. Floods of varied magnitude occur frequently in the catchment, typically during spring snowmelt and autumn rainstorms. The main challenge in the area is water quality (incl. high phosphorus pollution) and soil erosion (incl. riverbank erosion and quick-clay landslides). There is already high focus on environmental mitigation measures, for example reduced tillage (no tillage in autumn), buffer zones, grass-covered waterways, constructed wetlands and the use of catch-crops.

### Model calibration and validation

The rswap package was used to perform the soft-calibrate of the SWAP model. The Index of Agreement statistics (d), which evaluate the performance of the model along with the associated layers, are presented in Table 4.1.

Figure 5.1 and 5.2 show the modelled and observed water contents during the simulation periods, with the blue and red areas indicating overestimation and underestimation, respectively. Overall, the current model overestimates water content in the soil profile likely due to the underestimation of surface runoff.

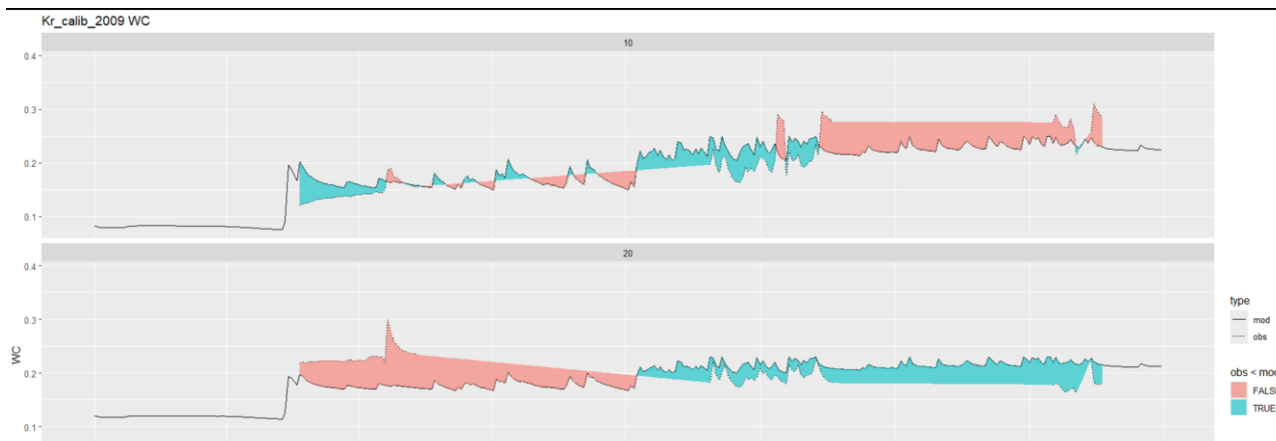


Figure 5.1. Modelled and observed water content (WC) for the 10 and 20 cm soil layers in loamy clay soil



Figure 5.2. Modelled and observed water content (WC) for the 10, 20 and 40 cm soil layers in the loamy sand soil

Four different management scenarios were applied (Table 4.2). The same abbreviations are used in the following figures to represent the results.

Table 5.2. Measures applied for Kråkstad pilot field (CS10)

Management Scenario Abbreviation	Explanation
Base	Baseline
Mgt1	Introducing drought tolerant crops
Mgt2	Land cover change (afforestation)
Mgt3	Reduced tillage

For scenario analyses, we run the SWAP model for six climate models for three RCP scenarios (Chapter 2, Table 2.5) along with the baseline and three management scenarios (Table 4.2). A total of 72 simulations were run for the period from 1991 to 2099

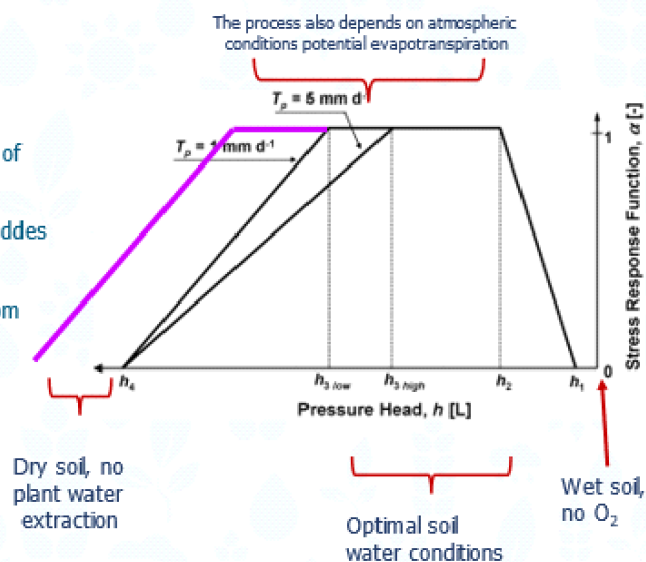
in a daily step. The results were evaluated for three different time periods: historical (1991-2022), near future (2030-2060) and the far future (2070-2099).

The three different NSWORMs were implemented in the model according to the recommendations of the OPTAIN NSWORMs implementation handbook (Marval et al., 2022) as follows:

- To “increase” the drought tolerance of the winter wheat grown in the area (Mgt1), we changed the parameters of the plant stress response function to soil water status (Figure 5.3). Thus, the values of  $h_{3\text{ low}}$  and  $h_4$  were decreased to shift the shape of the function from the black line to the purple line (Figure 5.3).
- Afforestation was implemented by simply changing the crop file (and consequently all plant parameters) from winter wheat to deciduous forest.
- Reduced tillage was implemented by changing the soil hydraulic parameters: the saturated water content, saturated hydraulic conductivity and residual water content were increased, and the bulk density was decreased.

### Introducing drought tolerant crops

1. Drought-tolerant crop genotypes have been developed for decades to ensure crop production and food safety under conditions of water scarcity
2. In SWAP, drought stress is introduced by Feddes water stress function
3. Drought-tolerant crops can extract water from soil at lower soil water potentials.

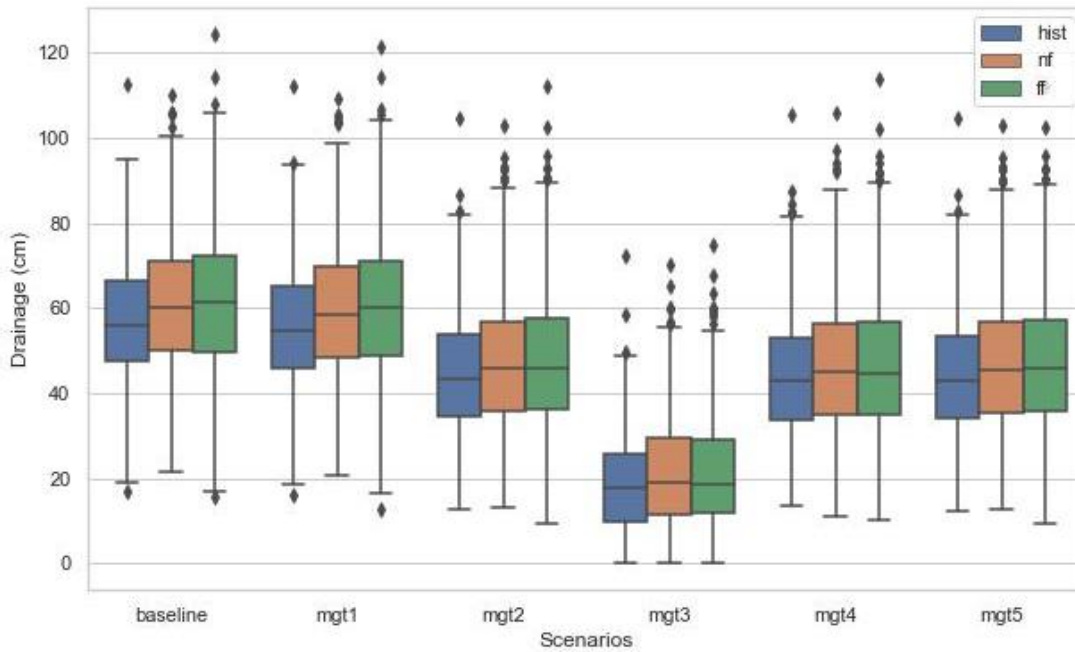


**Figure 5.3.** Visualisation of the crop stress response function for extremely wet and dry conditions. (presented by Csilla Farkas during the OPTAIN Summer School in July 2023).

## 2. Effectiveness of selected in-field NSWORMs under present and future climate conditions

We evaluated the effect of various NSWORMs on changes in soil water storage, actual transpiration (which equals to the plant water uptake), the surface runoff, drainage outflow and soil evaporation under present and various future climate conditions. Selected results are shown in Figures 5.4 – 5.7 related to loamy clay soil and Figures 5.8 – 5.12 for the loamy sand soil. In the case of Loamy clay soil, in soil water storage simulation, both near and far future for all management scenarios show similar results. However, the results of both the near and far future are slightly larger, compared to the historical

period. In the transpiration simulation, the near future results for all scenarios show much larger values except for the mgt1 scenario. In the drainage simulation, all of the climate and management scenarios show almost similar results and no significant changes are observed. In the soil evaporation simulation, both near and far future for all management scenarios show similar results and slightly larger than the historical period.



**Figure 5.4.** Boxplots of modelled drainage outflow (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060), and far future (ff, 2070-2099) periods, derived from climate model (2).

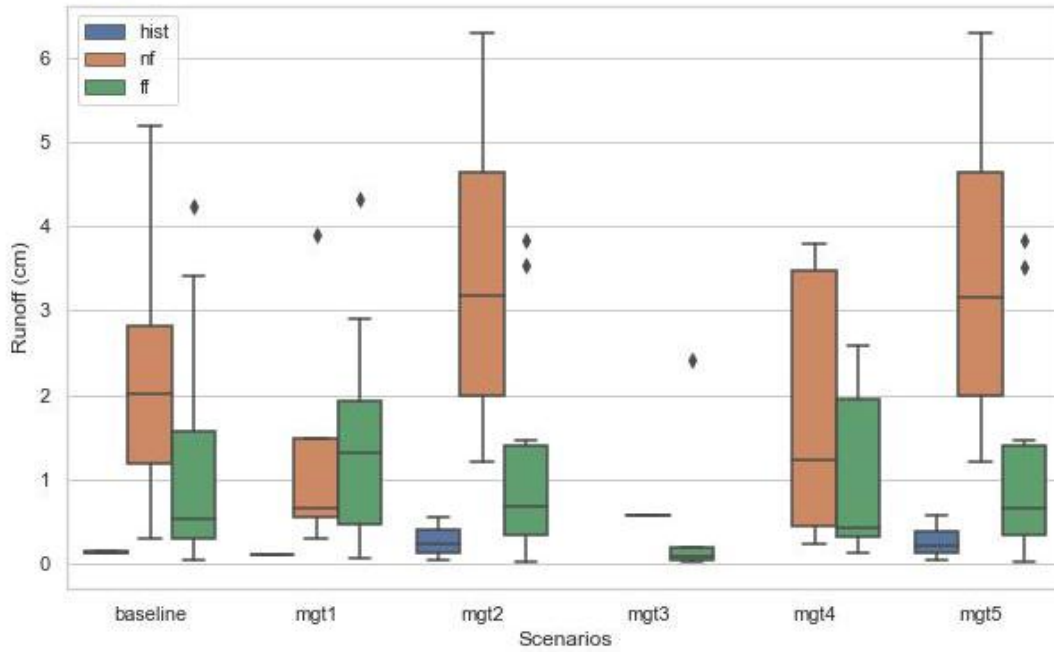


Figure 5.5. Boxplots of modelled runoff (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060), and far future (ff, 2070-2099) periods, derived from climate model (5).

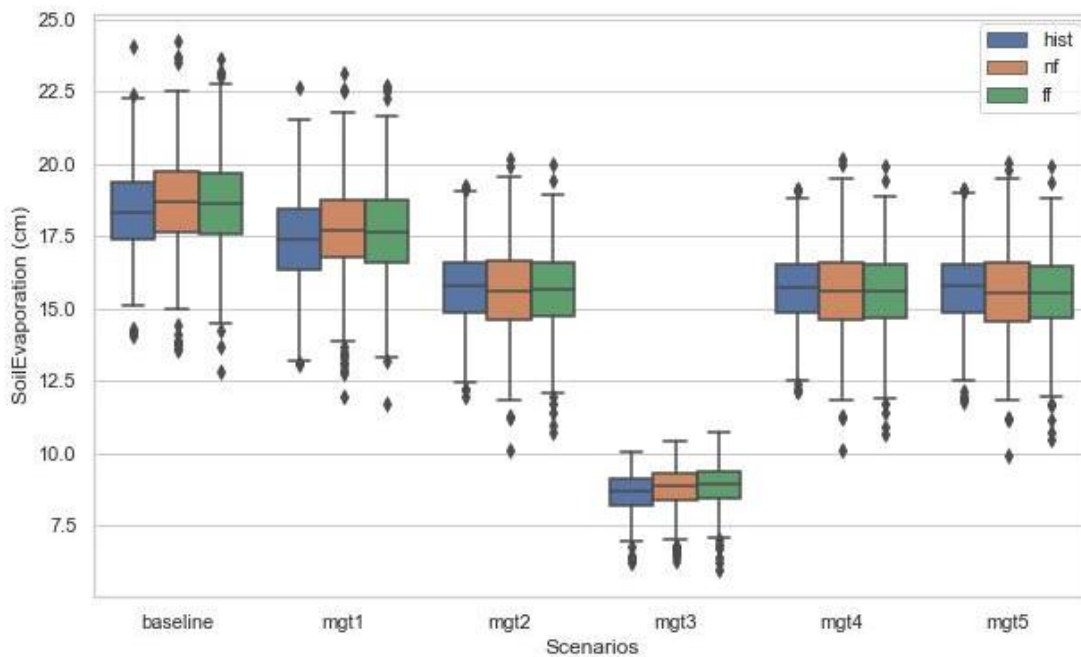
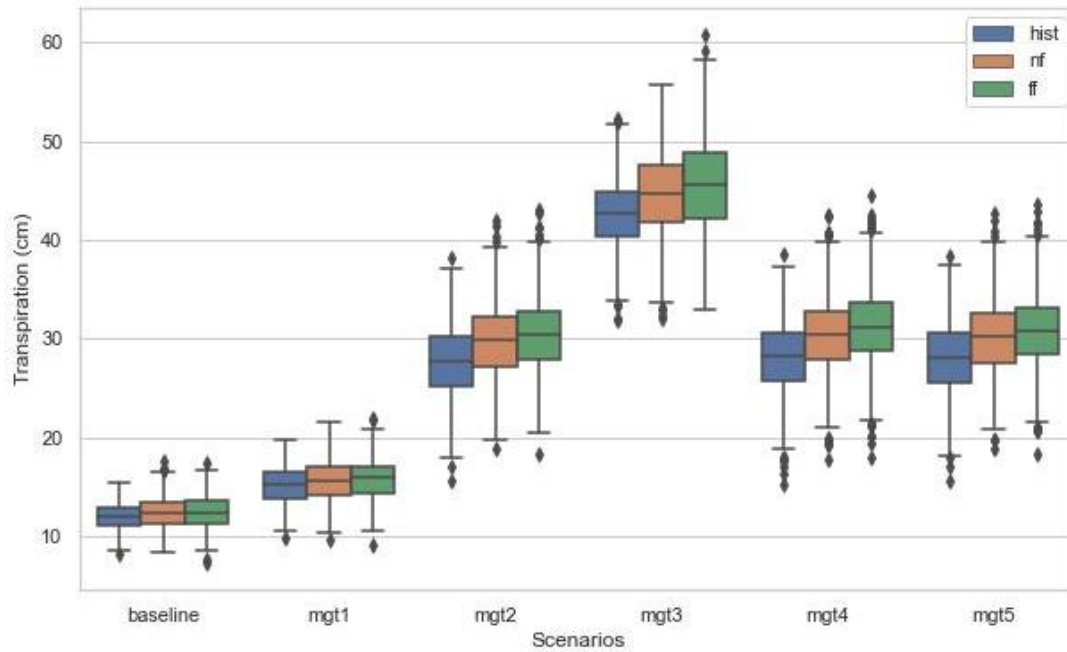
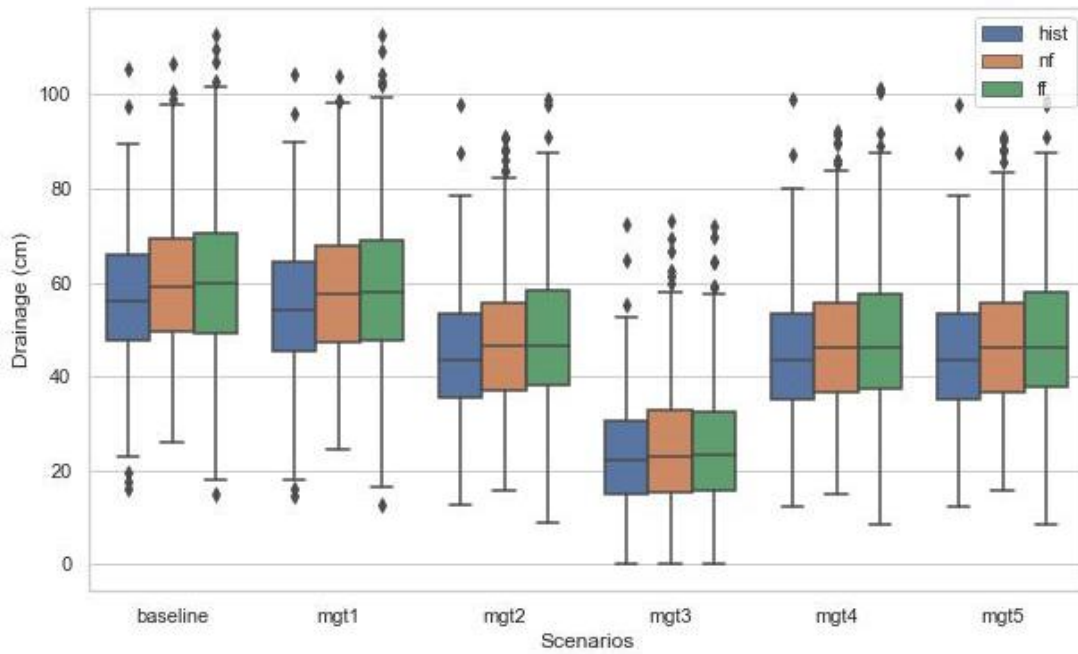


Figure 5.6. Boxplots of modelled soil evaporation (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060) and far future (ff, 2070-2099) periods, derived from climate model (3).

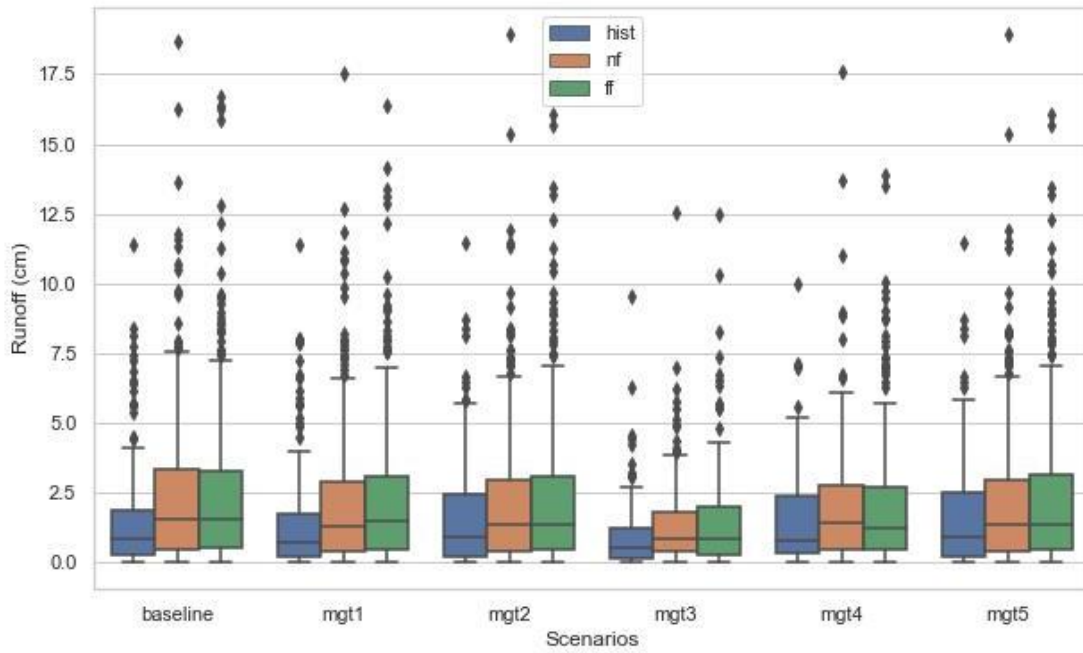


**Figure 5.7.** Boxplots of modelled transpiration (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060) and far future (ff, 2070-2099) periods, derived from climate model (3).

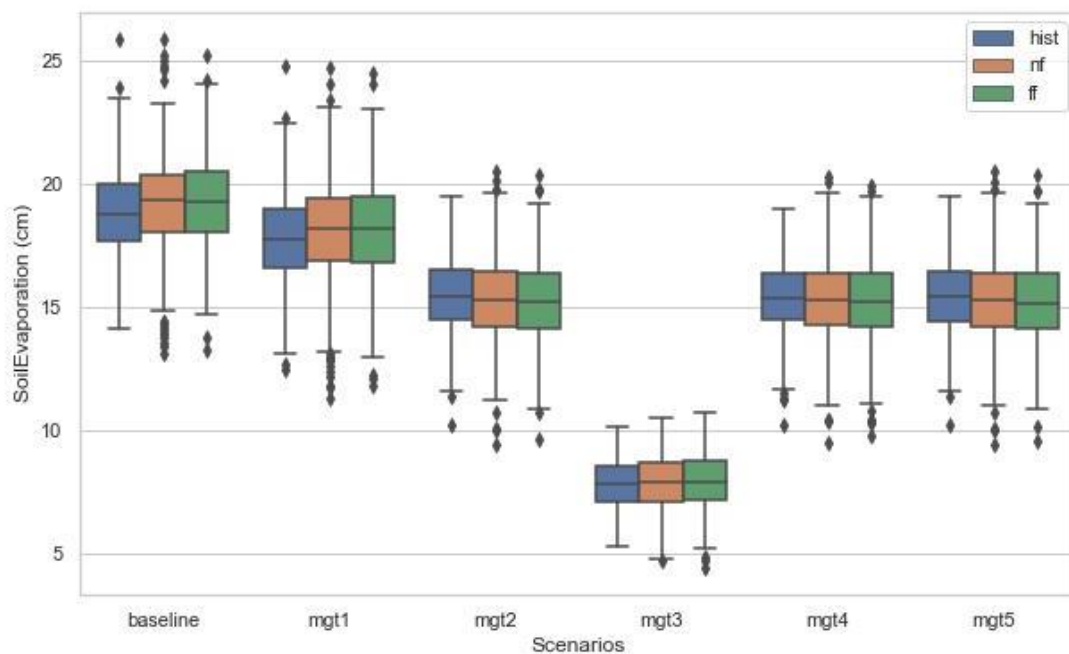
In the case of loamy sand soil, in soil water storage simulation, both near and far future for all management scenarios show similar results. However, the results of both the near and far future are slightly larger, compared to the historical period. In the transpiration simulation, the near and far future results are similar for all scenarios and show slightly larger values compared to the historical period. In the drainage simulation, all of the climate and management scenarios show almost similar results and no significant changes are observed. In the soil evaporation simulation, both near and far future for all management scenarios show similar results and slightly larger than the historical period.



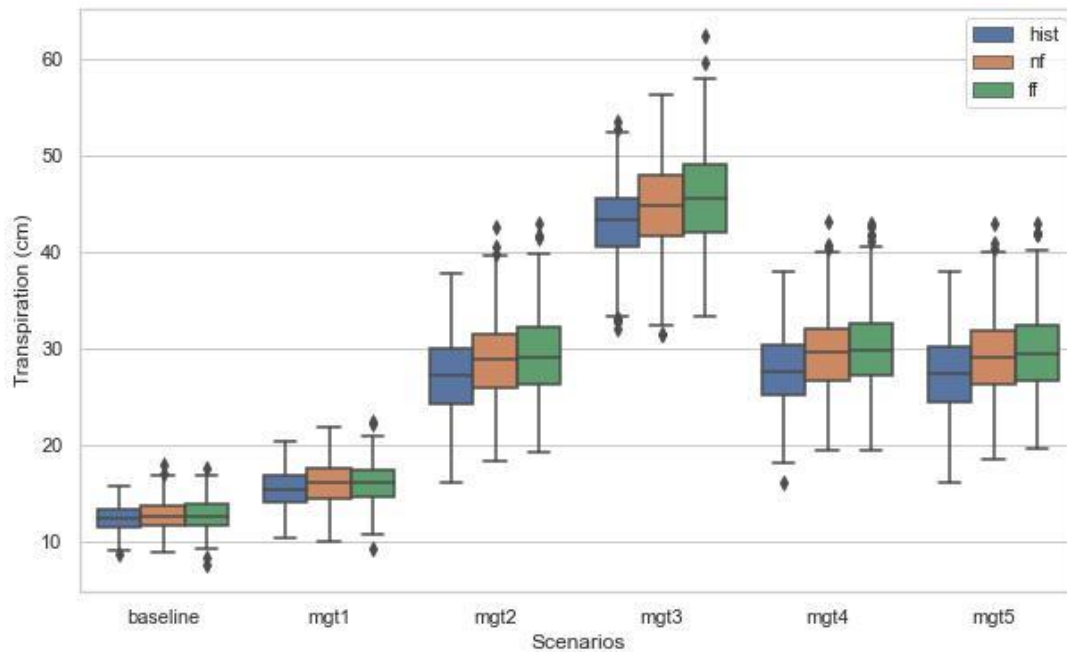
**Figure 5.8.** Boxplots of modelled drainage (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060), and far future (ff, 2070-2099) periods, derived from climate model (5).



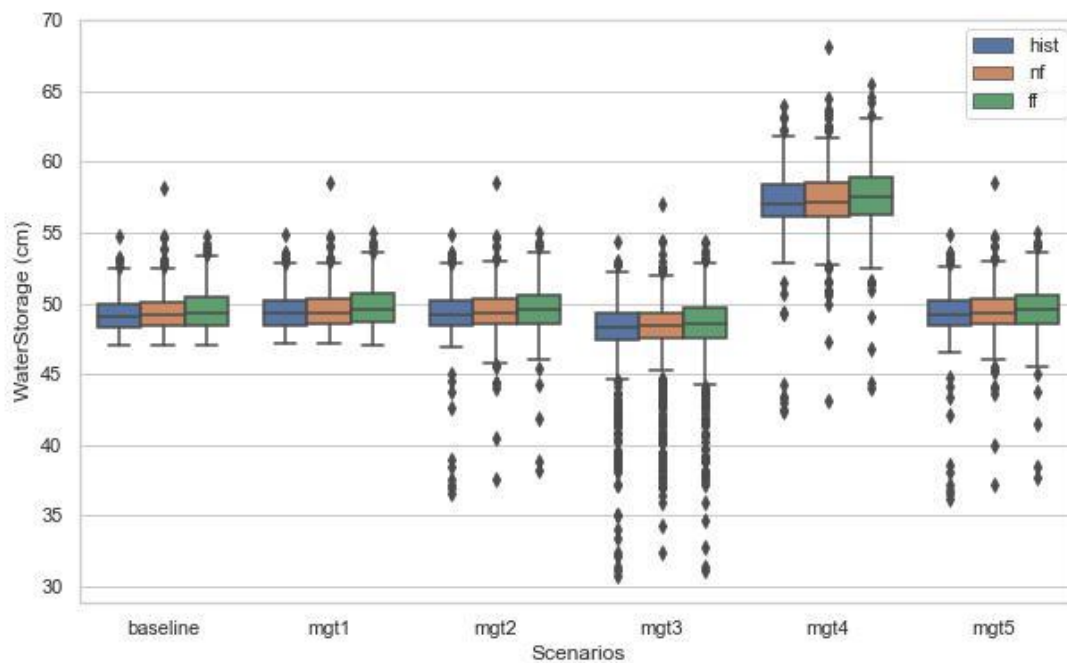
**Figure 5.9.** Boxplots of modelled runoff (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060), and far future (ff, 2070-2099) periods, derived from climate model (5).



**Figure 5.10.** Boxplots of modelled evaporation (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060) and far future (ff, 2070-2099) periods, derived from climate model (3).



**Figure 5.11.** Boxplots of modelled transpiration (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060) and far future (ff, 2070-2099) periods, derived from climate model (3).



**Figure 5.12.** Boxplots of modelled soil water storage (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060) and far future (ff, 2070-2099) periods, derived from climate model (3).

# Annex 6. Modelling results for CS11 (Tetves, HU)

Authors: Ágota Horel, Levente Czelnai, Tibor Zsigmond

## 1. Experimental site and model setup

The study site is the sub catchment of Tetves, which is a priority area for water protection, as it belongs to the catchment of Lake Balaton in Hungary. The size of the OPTAIN CS catchment is 68 km<sup>2</sup>. 49% of the total catchment area are forests, 39% arable land, 1% orchards, 1% vineyard, 1% grassland and 2% urban areas.

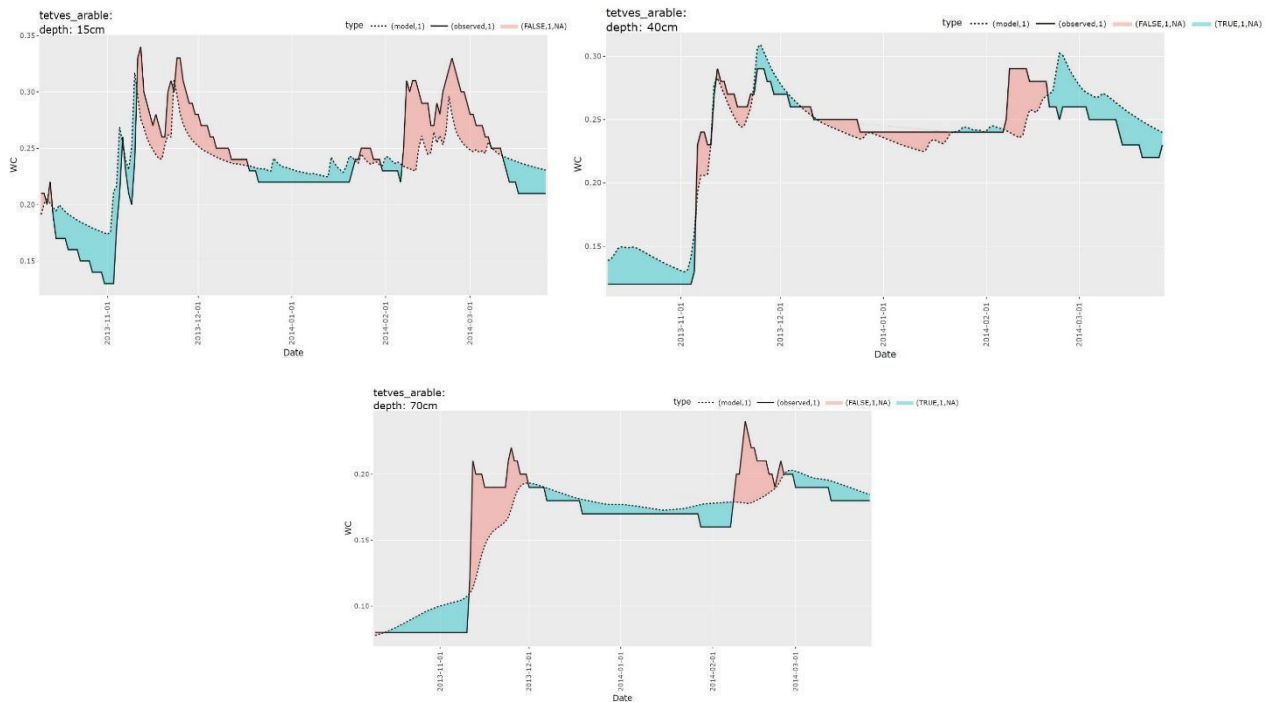
Sensors for soil water content (SWC) and temperature sensors were installed on areas with different land use (cropland and forest) in 2013. Meteorological data were retrieved from the nearby meteorological station (Fonyód). For this report, SWC measurements from 11.10.2013 to 28.03.2014 for cropland and SWC measurements from 15.08.2014 to 31.12.2016 for forest land were used as input to the model. Data were retrieved from the dataloggers at 6-hour intervals. For management purposes, this report only contains the results of the arable site.

The rswap package was used for the soft calibration of the SWAP model, and a manual calibration was performed. The NSE, RMSE, PBIAS, R<sup>2</sup>, and the Index of Agreement (d; daily and monthly), which evaluate the performance of the model along with the associated layers, are shown in Table 6.1.

**Table 6.1.** SWAP model performance statistics for the arable land in the Tetves CS.

<b>Laye (cm)</b>	<b>NSE</b>	<b>PBIAS</b>	<b>RSR</b>	<b>RMSE</b>	<b>R<sup>2</sup></b>	<b>d daily</b>	<b>d monthly</b>
15	0.63	0.78	0.6	0.03	0.63	0.84	0.91
40	0.86	-1.42	0.4	0.02	0.86	0.96	0.98
70	0.78	0.11	0.5	0.02	0.78	0.93	0.98

Figure 6.1 shows modelled and observed water content during the simulation periods, with the blue and red areas indicating overestimation and underestimation, respectively. Overall, water content of the soil profile is slightly overestimated in the current model.



**Figure 6.1.** Modelled vs. observed soil water content in the 10 (upper left), 40 (upper right) and 70 (lower) cm soil layers.

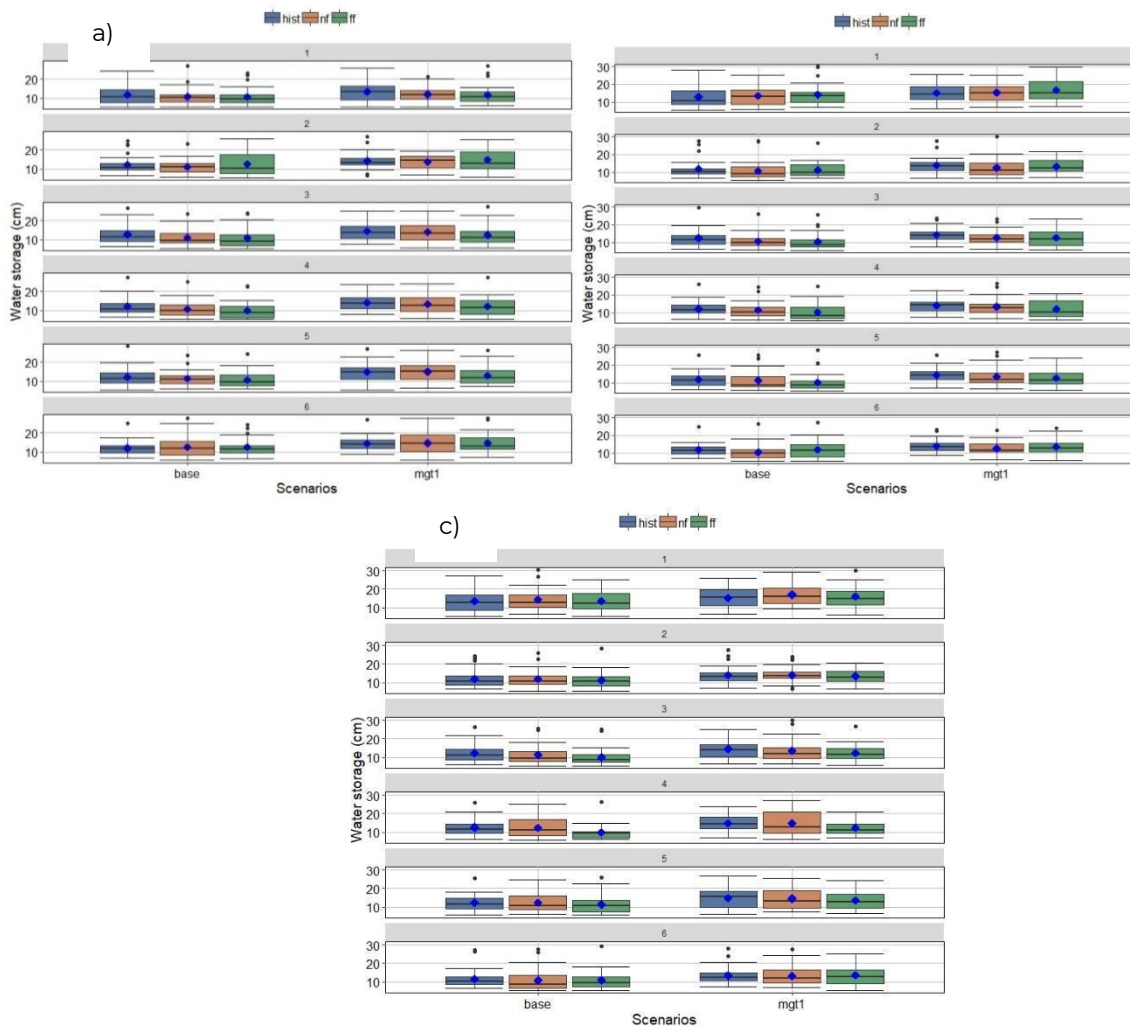
Because of the short period of time in which we measured soil water contents, the calibration and validation periods were not separated, and the total NSE and d values and other statistical measures showed very good simulations by the SWAP model (Table 6.1). According to Moriasi et al. (2025, Table 2.4), simulations with monthly d values exceeding 0.9 can be considered very good. At 40 cm depth, the model slightly underestimated the SWC, while a slight overestimation was observed for the other soil layers.

One management scenario was applied to Tetves' arable land, namely afforestation. For the afforestation scenario, data from the nearby forests (main crop file) were used, as these data were based on our own site-specific measurements. The scenarios are presented in Table 6.2. The same abbreviations are used in the following figures to represent the model results.

**Table 6.2.** Measures applied for the Tetves arable land (CS11)

Management Scenario Abbreviation	Explanation
Base	Baseline
Mgt1	Land cover change (afforestation)

For scenario analyses, we ran the SWAP model with six climate models for three RCP scenarios (Chapter 2, Table 2.5) along with the baseline and the afforestation scenarios (Table 5.8). A total of 36 simulations were run for the period from 1991 to 2099 in a daily step. The results were evaluated for three different time periods: historical (1991-2022), the near future (2030-2060), and the far future (2070-2099).

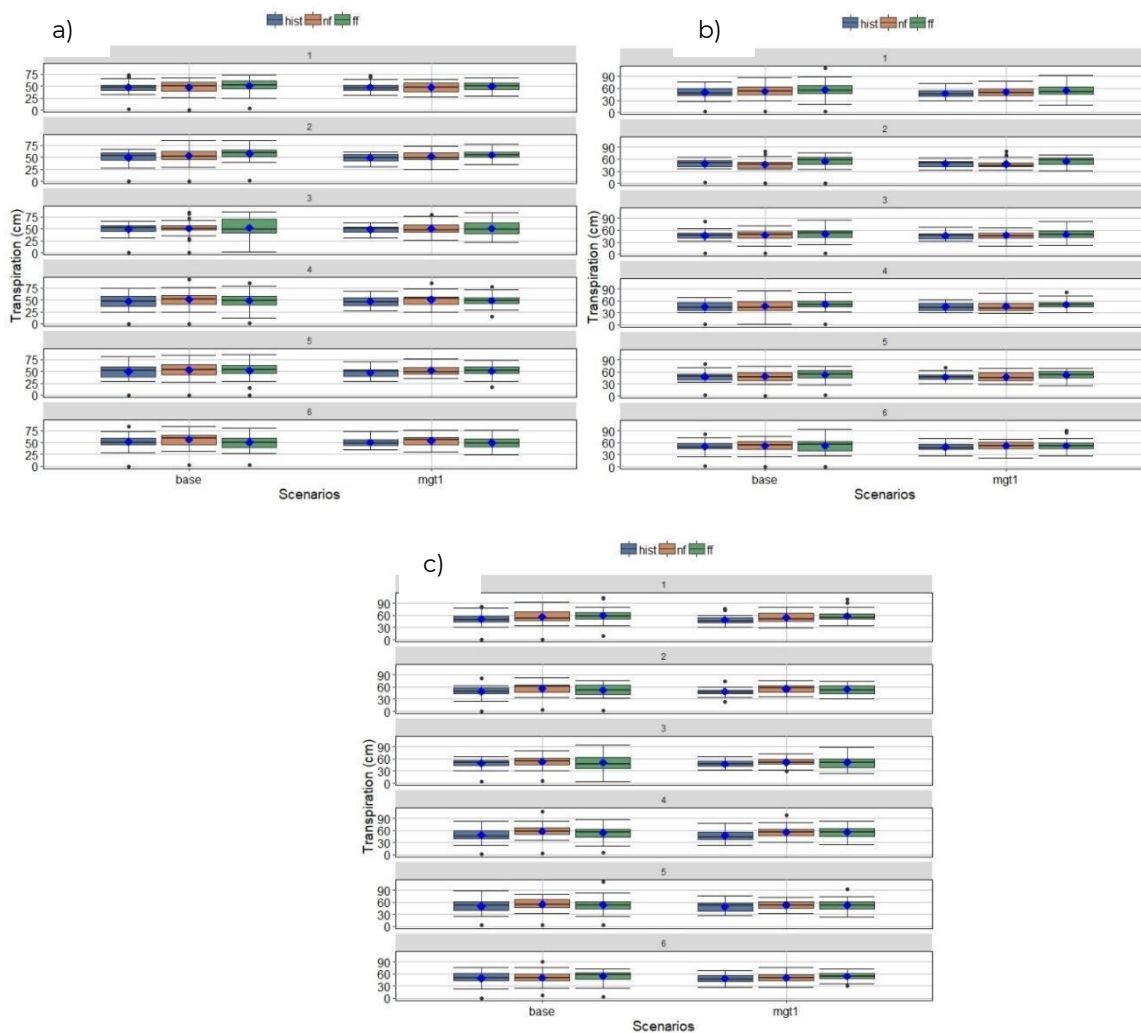


**Figure 6.2.** Boxplots of modelled mean soil water storage (cm) for current (hist, 1991-2020), near future (nf, 2030-2060), and far future (ff, 2070-2099) periods derived from all the six climate models where a) RCP2.6, b) RCP4.5, and c) RCP8.5. Each data point represents the median (solid black line), the mean (blue diamond), the upper and lower quartiles, and the minimum and maximum values (whiskers; data plus/minus 1.5 interquartile range).

Selected results for the model outputs are presented in Figures 6.2 – 6.4. Most of the models for RCP2.6, RCP4.5, and RCP8.5 showed a decline in soil water storage over time, with the largest deficit expected in the far future (Figure 6.2). Without afforestation, soil water is projected to decrease by 5.25% in the near future, and 8.2% by the end of the century, and 3.2% and 6.8%, respectively, if afforestation is implemented. We found that the lowest soil water storage in case of the RCP8.5 scenario for the baseline (current) management is expected in the far future (11.1 cm per year), while the highest can be expected for RCP8.5 in the near future (14.5 cm per year).

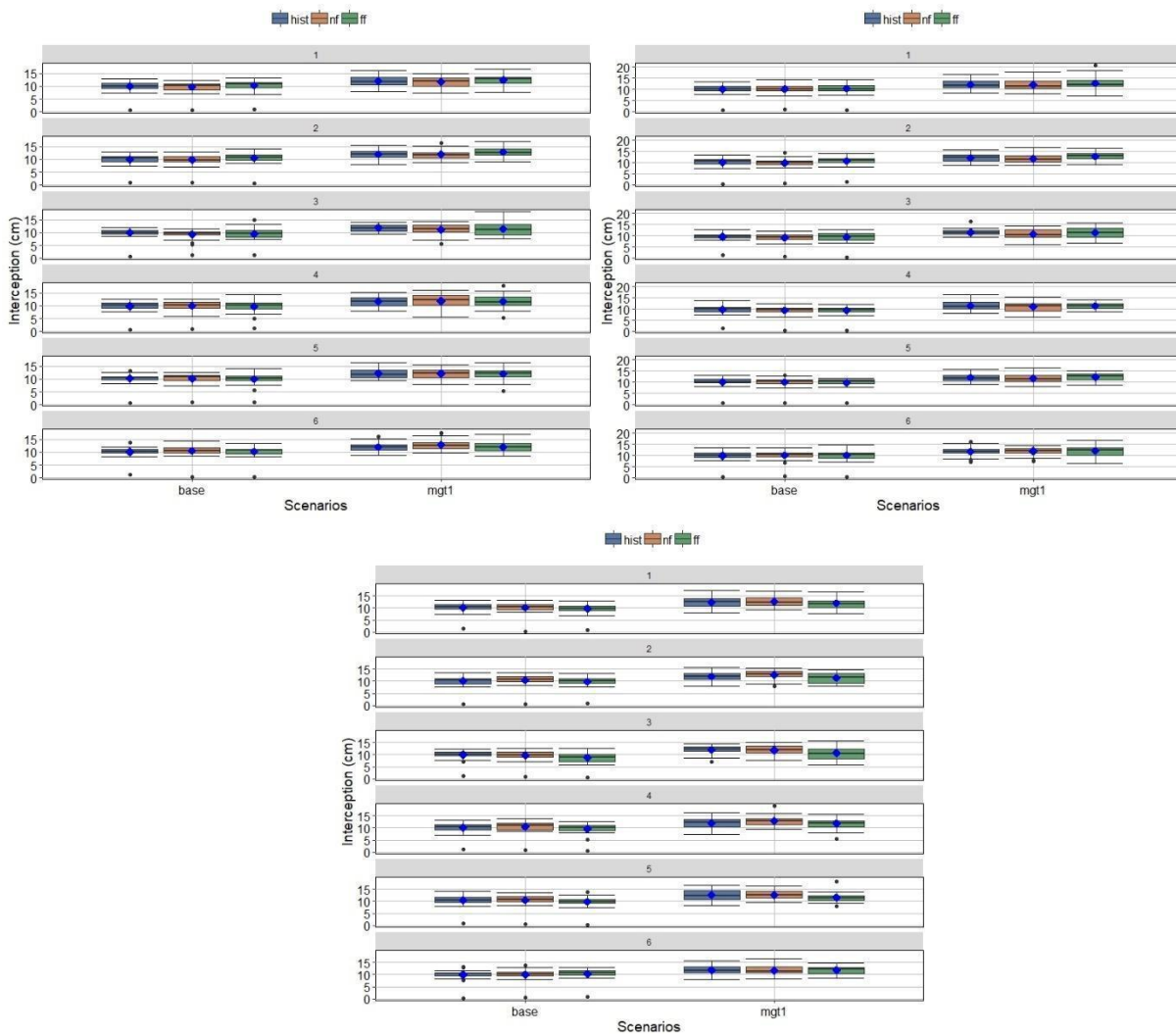
Using the transpiration data, we found that values increase in all three RCP scenarios (RCP2.6, RCP4.5, and RCP8.5) by the end of the century (Figure 6.3) for both management options. In the current data (hist), transpiration is expected to average 47-49 cm per year, while these values are around 48-54 cm, and 50-54 cm per year by the end of the century. That could be due to the increase in potential plant water demand (due to warming). Increasing transpiration and decreasing soil water storage indicate

that plants both, cropland and forest can get enough water from the soil in under changing climatic conditions.



**Figure 6.3.** Boxplots of modelled mean transpiration (cm) for hist (1991-2020), nf (2030-2060), and ff (2070-2099), derived from all 6 climate model where a) RCP2.6, b) RCP4.5, and c) RCP8.5. Each data point represents the median (solid black line), the mean (blue diamond), the upper and lower quartiles, and the minimum and maximum values (whiskers; data plus/minus 1.5 interquartile range).

Among the management methods, we found that afforestation reduced transpiration by 1.1 to 2.3 % for all three RCP scenarios (except in one case for RCP8.5 (far future) with 0.1% change). This is something we did not expect, but still these results are not significant.



**Figure 6.4.** Boxplots of modelled mean interception (cm) for hist (1991-2020), nf (2030-2060), and ff (2070-2099), derived from all 6 climate model where a) RCP2.6, b) RCP4.5, and c) RCP8. Each data point represents the median (solid black line), the mean (blue diamond), the upper and lower quartiles, and the minimum and maximum values (whiskers; data plus/minus 1.5 interquartile range).

We found an increase in soil evaporation values by the end of the century for all the RCP scenarios (RCP2.6, RCP4.5, and RCP8.5) (data not shown). In the current time (hist), average soil evaporation is expected to be 8.1 -9.0 cm per year, while these values for the near and far future are around 8.1 -9.3 cm, and 8.2-9.7 cm per year, respectively.

Among the management methods, we found that afforestation reduced soil evaporation within a range of 9.2% (hist RCP2.6) to 14.2% (far future RCP8.5) for all three RCP scenarios.

On average, the SWAP model predicted decrease in interception with climate change for all the RCPs (Figure 6.4), although no clear trend was evident. Interception varied on average between 10.0 to 12.1 cm, between 9.9 to 12.4 cm and between 9.7 to 12.1 cm for the historical, near future and far future scenarios, respectively. The lowest interception was estimated by far future RCP8.5 (baseline - 9.7 cm per year) and the highest was

estimated by near future RCP8.5 (afforestation - 12.34 cm per year). Afforestation increased interception from 17.7% (near future RCP4.5) to 21.7% (far future RCP4.5) cm.

# Annex 7. Modelling results for CS12 (Čechtický, CZ)

Authors: Csilla Farkas (NIBIO), Antonín Zajíček, Štěpán Marval, Petr Fučík, (VÚMOP)

## 1. Experimental site and model setup

The Čechtický stream catchment case study is located in the Central Bohemian Region of the Czech Republic. The catchment area is about 72 km<sup>2</sup>, most of which is used as agricultural land (69%); cropland covers 59% of catchment area. Čechtický stream catchment is a part of the Želivka river basin with Švihov drinking water reservoir where persistent problems with unstable water quality (phosphorus, nitrogen, pesticides pollution) occur. The area is facing a threat of soil erosion on large field blocks, and endangered soil quality by dehumification, soil compaction, together with increasing periods of drought. There are dense tile drainage systems in this area which are prevailingly still functioning, but problems are increasing over time (technical status, failures, undue runoff, worsened water quality).

In 2015 a monitoring system, consisting of soil water content (3 locations) and drainage discharge (outlet) measurements in croplands was established. The locations correspond to three different slope categories and represent recharge, transport and discharge areas within the catchment. The area is covered with Haplic Cambisols characterised with silty loam texture in both the topsoil and the deeper soil layers.

In the OPTAIN project, the experimental plot that represents discharge areas at the outlet of a small stream was selected for field-scale modelling. The basic soil hydrophysical properties are presented in Table 7.1.

**Table 7.1.** Soil hydrophysical properties determined for the pilot field within the Čechtický catchment

Soil Horizon	HORIZONT	Soil layer (cm)	Humus content (%)	Bulk density (g/cm <sup>3</sup> )	Saturated water content (cm <sup>3</sup> /cm <sup>3</sup> )	Gravitational pores (cm <sup>3</sup> /cm <sup>3</sup> )	Non-capillary pores (cm <sup>3</sup> /cm <sup>3</sup> )	Capillary pores (cm <sup>3</sup> /cm <sup>3</sup> )	K <sub>sat</sub> (cm/day)
Ap	topsoil	0-20	0.9	1.62	31.50	6.19	16.43	10.24	35.0600
Bv	cambic horizon	20-40	0.3	1.60	21.72	9.61	22.12	12.51	67.7800
Bv/C	transitional horizon	41-65	0.3	NA	NA	NA	NA	NA	NA
C	soil forming material	below 65 cm	NA	NA	NA	NA	NA	NA	NA

## 2. Model calibration and validation

The periods from 2016 to 2018 and from 2019 to 2021 were used for model calibration and validation, respectively. The crop rotation during this period was rather mosaic, and could be represented in the model in a complex way (Table 7.2).

The one-level drainage unit, based on formula from Hooghoudt or Ernst (Kroes et al., 2017). Zero flux bottom boundary conditions were defined, as requested by the SWAP

model when using the drainage sub-routine. The initial conditions were defined from the measured soil water content data.

```

*Swap.swp - Notepad
File Edit Format View Help
*****
*** CROP SECTION ***
*****
* Part 1: Crop rotation scheme
* Switch for bare soil or cultivated soil
SWCROP = 1 ! 0 = Bare soil
          ! 1 = Cultivated soil
* Specify for each crop (maximum MACROP):
* INITCRP = type of initialisation of crop growth: emergence (default) = 1, sowing = 2 [-]
* CROPSTART = date of crop emergence [dd-mmm-yyyy]
* CROPEPEND = date of crop harvest [dd-mmm-yyyy]
* CROPNAME = crop name [A40]
* CROPFIL = name of file with crop input parameters without extension .CRP, [A40]
* CROPTYPE = growth module: 1 = simple; 2 = detailed, WOFOST general; 3 = detailed, WOFOST grass

      CROPSTART      CROPEPEND      CROPFIL      CROPTYPE
2016-05-01      2016-09-15      'MaizeS'      1
2016-09-30      2017-08-06      'WinterWheat' 1
2017-08-31      2018-04-04      'Ceral + GrassS' 1
2018-04-20      2018-08-15      'MaizeS'      1
2018-09-02      2018-11-15      'GrassS'      1
2019-03-22      2019-07-25      'PeaS'        1
2019-09-25      2020-08-14      'WinterWheat' 1
2020-08-15      2020-09-05      'WinterBarley' 1
2021-07-25      2021-12-31      'PeaS'        1
* End of table

      RDS = 100.0          ! Maximum rooting depth allowed by the soil profile, [1..5000 cm, R]
  
```

Figure 7.1. The crop rotation scheme for the Čechtický site during the calibration and validation periods.

For the soft calibration of the SWAP model the rswap package was used, and manual calibration was applied. Figure 7.2 shows the measured and modelled soil water contents for the calibration period.



Figure 7.2. Modelled vs. observed soil water contents in the 10, 20, 30 and 40 cm layers at the Cechtnicky experimental site. Red and light blue colours indicate under- and overestimation, respectively.

The PBIAS, and the Index of Agreement (d), assessing the model's performance along with its associated layers, are presented in Table 7.2.

**Table 7.2.** SWAP model performance statistics for the Čechtický pilot site

Soil layer	Calibration period		Validation period	
	d	PBIAS	d	PBIAS
10 cm	0.71	-1.5	0.70	0.4
20 cm	0.65	-8.1	0.66	9.0
30 cm	0.81	-18.2	0.52	20.1
40 cm	0.76	4.5	0.57	5.0

According to the performance statistics, the model calibration can be considered as good for the 40 cm layer, and satisfactory for the 10 and 20 cm layers. The calibration was difficult for the 30 and 40 cm layers, as no observed initial conditions were available from the starting date of the simulation. This resulted in a strong overestimation of the soil water content during the first period when observed data were available.

Four different management scenarios were applied in the Čechtický catchment, as presented in Table 7.3. The same abbreviations are used in the following figures to represent the results.

**Table 7.3.** Measures applied for Čechtický pilot field (CS12)

Management Scenario Abbreviation	Explanation
Base	Baseline
Mgt1	Reduced tillage
Mgt2	Shifting from cropland to grassland
Mgt3	Afforestation
Mgt4	Introducing drought tolerant crops

For scenario analyses, we run the SWAP model for six climate models for three RCP scenarios (Chapter 2, Table 2.5) along with the baseline and four management scenarios (Table 7.3). A total of 90 simulations were run for the period from 1991 to 2099 in a daily step. The results were evaluated for three different time periods: historical (1991-2022), near future (2030-2060) and the far future (2070-2099).

The NSWORMs were implemented in the SWAP model following the recommendations of the OPTAIN NSWORMs implementation handbook (Marval et al., 2022) as follows:

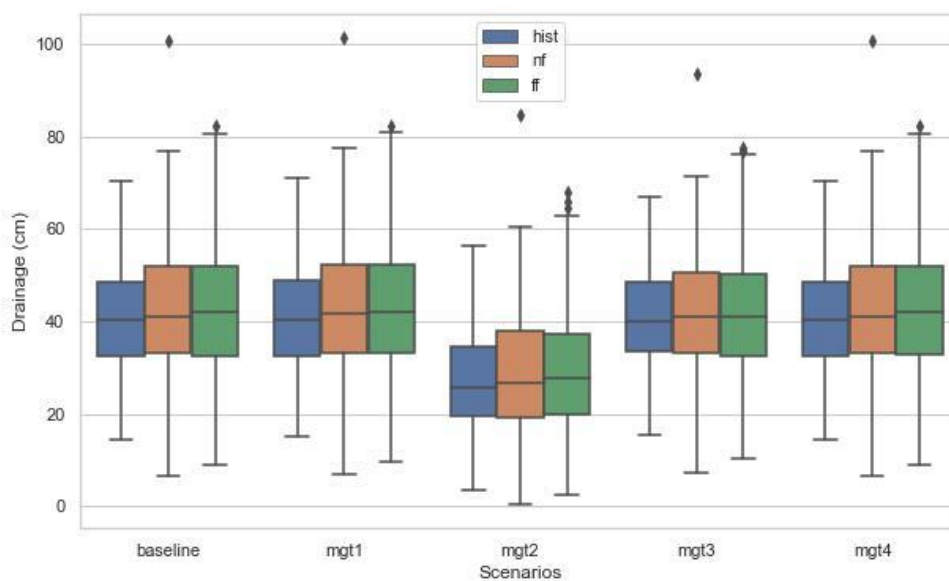
- *Reduced tillage (Mgt1)* was implemented by changing the soil hydraulic parameters; the saturated water content, saturated hydraulic conductivity and

residual water content were increased, and the bulk density was decreased (see Chapter 3, Table 3.5 for details).

- **Shifting to grassland (Mgt2)** was implemented by changing the arable land to grassland.
- **Afforestation (Mgt3)** was implemented by changing the arable land into deciduous forest.
- The effects of growing **drought tolerant crops (Mgt4)** was tested by increasing the drought tolerance of the winter wheat and maize crops grown in the area as described by Marval et al. (2022). Thus, we changed the parameters of the plant stress response function (Annex 4, Figure 4.2) as described in Chapter 3, Table 3.5.

### 3. Effectiveness of selected in-field NSWORMs under present and future climate conditions

We evaluated the effect of various NSWORMs on changes in water balance elements (drainage outflow, evaporation from soil surface, transpiration (which equals to plant water uptake) and soil water storage, interception and surface runoff under present and various future climate conditions. Selected results are shown in Figures 7.3 – 7.6.



**Figure 7.3.** Boxplots of modelled mean yearly drainage outflow (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060), and far future (ff, 2070-2099) periods.

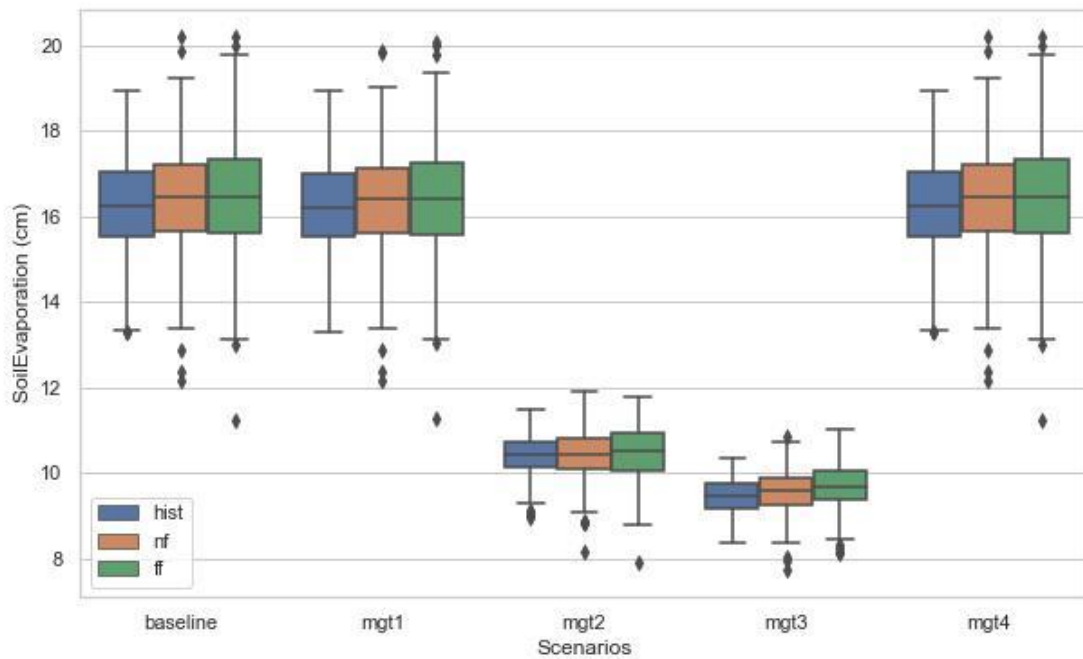


Figure 7.4. Boxplots of modelled mean yearly soil evaporation (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060), and far future (ff, 2070-2099) periods.

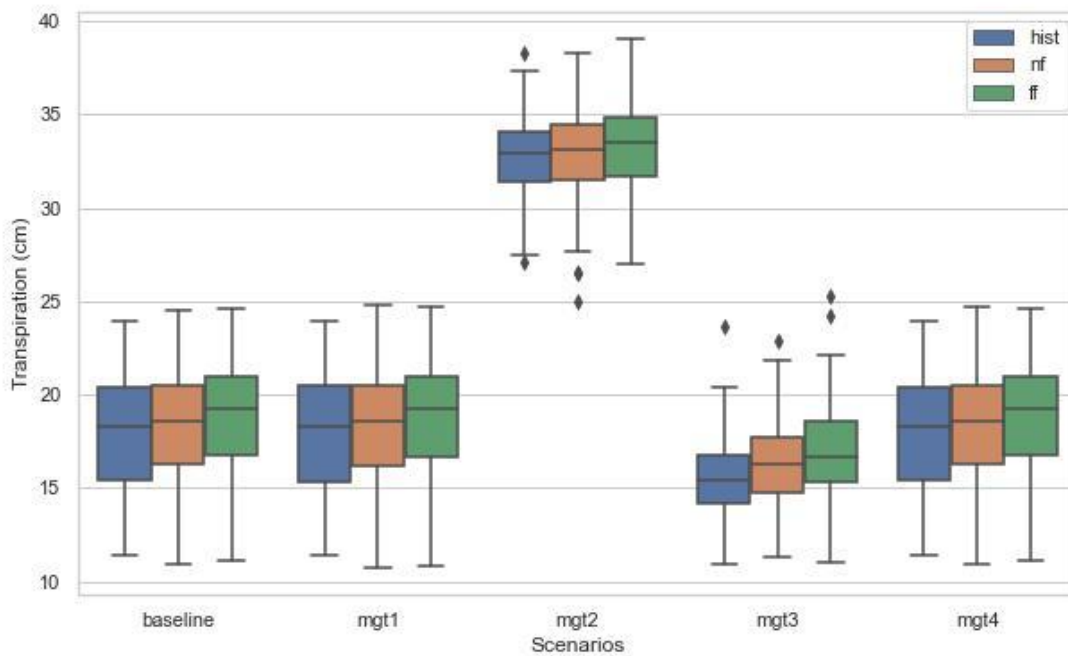
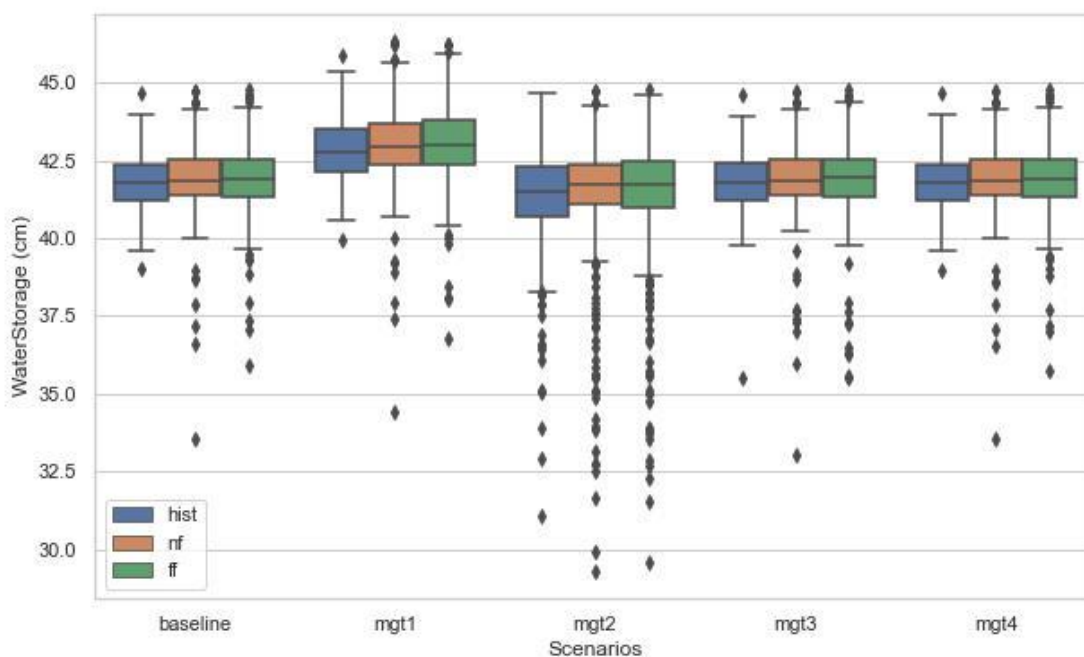


Figure 7.5. Boxplots of modelled mean yearly transpiration (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060), and far future (ff, 2070-2099) periods.



**Figure 7.6.** Boxplots of modelled mean yearly water storage (cm) for historical (hist, 1991-2020), near future (nf, 2030-2060), and far future (ff, 2070-2099) periods.

The SWAP modelling results for the Čechtický pilot site can be summarised as follows:

- The calibration of the model was moderately successful. The model performed generally well on yearly time scale (as indicated by PBIAS) for all the layers except 30 cm, but the index of agreement and visual evaluation showed that the soil water content dynamics were less satisfactory modelled in the upper 20 cm layer.
- Considerable - up to 40% - reduction in drainage outflow compared to the baseline were shifting from intensive (cropland) to extensive (grassland, Mgt2) land management practices under present and future climate conditions. The other management practices did not show any valuable changes in drainage outflow.
- Reduced tillage resulted in a slight increase in soil water storage but had no effect on the other water balance elements.
- Generally, grassland (Mgt2) had the most significant effect on soil water regime for both the historical and the future periods, resulting in a strong - up to 40% and 36 %, respectively - decrease in drainage outflow and in soil evaporation. The strongest - with up to 90% increase - impact of grassland was found on transpiration (or plant water uptake).
- Afforestation (Mgt3) also reduced evaporation from the soil surface substantially compared to other management scenarios and showed a slight reduction effect on transpiration and soil water storage.

## 4. References

Kroes, J.G., van Dam, J.C., Bartholomeus, R.P., Groenendijk, P., Heinen, M., Hendics, R.F.A., Mulder, H. M., Supit, I. and van Walsum, P.E.T. 2017. SWAP version 4. Theory description and user manual. Wageningen Environmental Research, Rep. No. 2780. [www.swap.alterra.nl/Documents/Kroes\\_etal\\_2017\\_SWAP\\_version\\_4\\_ESG\\_Report\\_2780.pdf](http://www.swap.alterra.nl/Documents/Kroes_etal_2017_SWAP_version_4_ESG_Report_2780.pdf)

Marval, S., Fucik, P., Čerkasova, N., Schürz, C., Strauch, M., Witing, F., Piniewski, M., Plunge, S., Farkas, C., Weiland, S., Krzeminska, D. and Lemann, T. 2022. SWAT+ and SWAP water retention measure implementation handbook. Deliverable D2.3 EU Horizon 2020 OPTAIN Project, Grant agreement No. 862756

# Annex 8. Auxiliary materials

## 1. Spatial matching

- **Case 2:** No monitored field exists within the SWAT+ catchment. In this case, the HRUs used for cross-validation are identified using the following scheme:

*Step 1.* Find the soil classes used for SWAP modelling: SOILswap = GLU, LV, PZ

*Step 2.* Finding the SOILswap classes within the *soils.sol* file of the SWAT+ model setup.

	A	B	C	D	E	F	G	H	I	J	K	L	
1	soils.sol:	written	by	SWAT+	editor	v2.1.0	on	#####	16:26	for	SWAT+	rev.60.5.4	
2	<b>name</b>	<b>nly</b>	<b>hyd_grp</b>	<b>dp_tot</b>	<b>anion_exc</b>	<b>perc_crk</b>	<b>texture</b>	<b>dp</b>	<b>bd</b>	<b>awc</b>	<b>soil_k</b>	<b>carbon</b>	
3	ANT	2	D	500	0.5	0.5	sandy_loam						
6	ARD	4	C	1000	0.5	0.5	loamy_sand						
32	GLU	3	C	1000	0.5	0.5	silt_loam						
33		250	1.28	0.19	8.1	3.9		23	55.9	21.1	9	0.2	0.3
34		550	1.47	0.18	12.4	1.6		10	51.2	38.8	10	0.2	0.3
35		1000	1.7	0.19	9	0.6		11	40.6	48.4	9	0.2	0.3
39	HUM	1	D	250	0.5	0.5	silt_loam						
40		250	0.33	0.35	40	25		52.9	30	17.1	13	0.2	0.1
41	LV	4	C	1000	0.5	0.5	silt_loam						
42		250	1.37	0.18	3.4	2.2		16	74.4	9.6	10	0.2	0.3
43		550	1.61	0.15	7.9	0.7		15	75.2	9.8	10	0.2	0.4
44		700	1.74	0.21	5.9	0.3		18	69.1	12.9	10	0.2	0.4
45		1000	1.82	0	3.7	0.1		18	69.1	12.9	10	0.2	0.4
46	Mon	2	D	500	0.5	0.05	sandy_loam						
53	PZ	3	C	1000	0.5	0.5	loamy_sand						
54		250	1.23	0.24	34.9	3		4	16.4	79.6	10	0.2	0.1
55		350	1.56	0.19	16.9	0.6		6	20	74	10	0.2	0.2
56		1000	1.7	0.08	11	0.2		6	20	74	11	0.2	0.2
57	RG	2	D	450	0.5	0.45	clay_loam						
58		250	1.61	0.15	11.7	2		30	37.8	32.2	10	0.2	0.2
59		450	1.61	0.18	15.6	0.4		7	17.3	75.7	10	0.2	0.2
60	SDd	1	D	150	0.5	0.25	sandy_loam						

Figure 8.1. Highlighting the soil classes, used in the SWAP model setup within the SWAT+ setup.

**Step 3a.** Listing all the HRUs having PZ soil type from the *hru-data.hru*

hru-data last modified by CS10 workflow @ section X and edited with SWATfa R 2.0.5 on 2024-02-01 00:42:50.497045									
id	name	topo	hydro	soil	lu_mgt	soil_plant_init	surf_stor	snow	field
1862	hru1862	topohru1862	hyd1862	PZ	a_105f_4_lum_1862_1	spi_hru1862	null	snow001	null
2169	hru2169	topohru2169	hyd2169	PZ	a_110f_3_drn_lum_2169_1	spi_hru2169	null	snow001	null
2583	hru2583	topohru2583	hyd2583	PZ	a_128f_3_lum_2583_1	spi_hru2583	null	snow001	null
2585	hru2585	topohru2585	hyd2585	PZ	a_129f_2_lum_2585_1	spi_hru2585	null	snow001	null
3970	hru3970	topohru3970	hyd3970	PZ	rnbg_lum	spi_hru3970	null	snow001	null
3975	hru3975	topohru3975	hyd3975	PZ	rnbg_lum	spi_hru3975	null	snow001	null
5898	hru5898	topohru5898	hyd5898	PZ	a_019f_4_lum_5898_1	spi_hru5898	null	snow001	null
5922	hru5922	topohru5922	hyd5922	PZ	a_210f_1_lum_5922_1	spi_hru5922	null	snow001	null
6104	hru6104	topohru6104	hyd6104	PZ	rnbg_lum	spi_hru6104	null	snow001	null
6208	hru6208	topohru6208	hyd6208	PZ	frst_lum	spi_hru6208	null	snow001	null
6209	hru6209	topohru6209	hyd6209	PZ	utrn_lum	spi_hru6209	null	snow001	null
6210	hru6210	topohru6210	hyd6210	PZ	frst_lum	spri_hru6210	null	snow001	null

Figure 8.2. Highlighting the HRUs with SOILswap soil classes within the SWAT+ setup

Step 3b. Selecting HRUs; soil type: PZ; land use: agriculture, file: *hru-data.hru*

hru-data last modified by CS10 workflow @ section X and edited with SWATfa R 2.0.5 on 2024-02-01 00:42:50.497045

id	name	topo	hydro	soil	lu_mgt	soil_plant_init	surf_stor	snow	field
1862	hru1862	topohru1862	hyd1862	PZ	a_105f_4_lum_1862_1	spi_hru1862	null	snow001	null
2169	hru2169	topohru2169	hyd2169	PZ	a_110f_3_drn_lum_2169_1	spi_hru2169	null	snow001	null
2583	hru2583	topohru2583	hyd2583	PZ	a_128f_3_lum_2583_1	spi_hru2583	null	snow001	null
2585	hru2585	topohru2585	hyd2585	PZ	a_129f_2_lum_2585_1	spi_hru2585	null	snow001	null
5898	hru5898	topohru5898	hyd5898	PZ	a_019f_4_lum_5898_1	spi_hru5898	null	snow001	null
5922	hru5922	topohru5922	hyd5922	PZ	a_210f_1_lum_5922_1	spi_hru5922	null	snow001	null

Soils.sol | SWAP\_soil | hru\_data | **hru-data.hru** | ... (+) | < | >

Figure 8.3. Selecting the HRUs with SOILswap soil classes and agricultural land use units within the SWAT+ setup

Step 4. Finding the management schedule of HRU=1862, using SWAT+ file *management.sch*; lu\_mgt = a\_105f\_4\_lum\_1862\_1

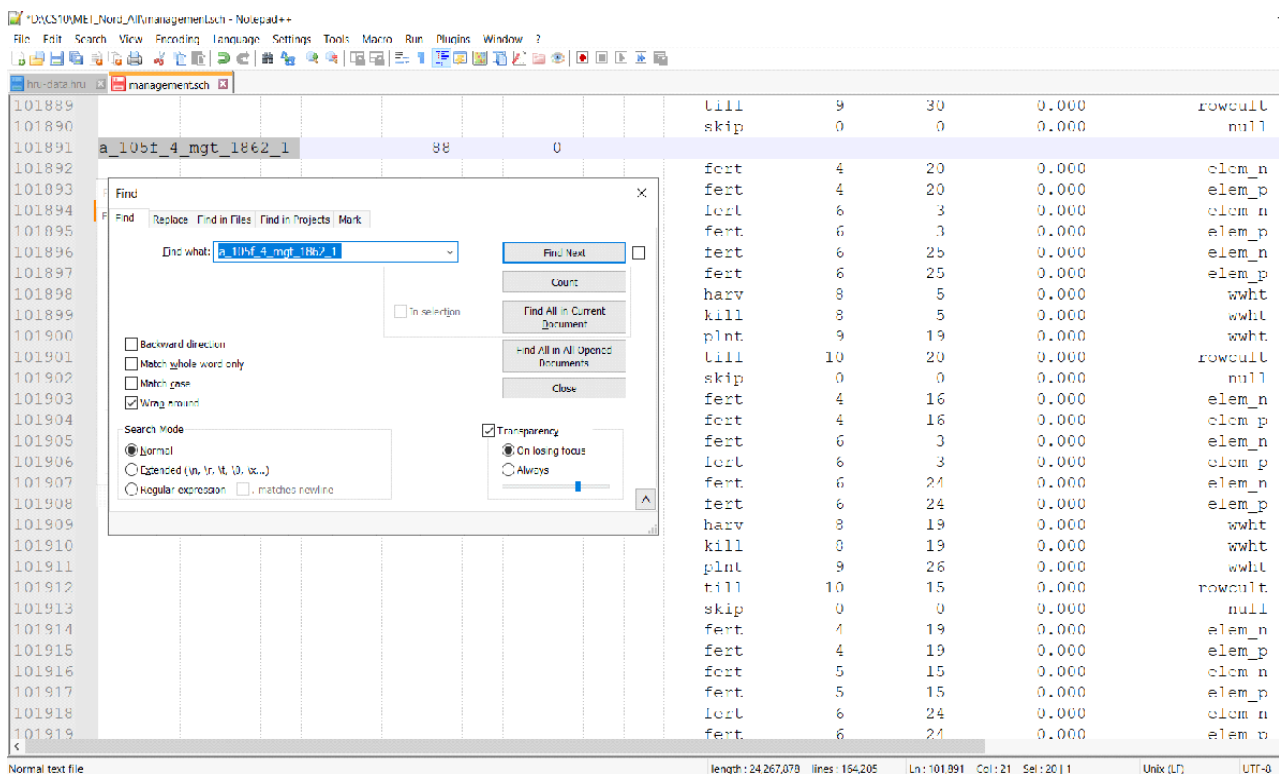


Figure 8.4. Finding the management schedule/crop rotation for the HRU, selected for cross-validation

Note, that instead of "a\_105f\_4\_lum\_1862\_1", the search within *management.sch* was performed for a\_105f\_4\_mgt\_1862\_1

**Step 5.** Matching the SWAT+ crop rotations with the crop rotations for SWAP executions (Figure 8.5)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1					hru_data.hru					management.sch							
2					plant.ini		plant.ini		management.sch	2011	2012	2013	2014	2015	2016	2017	2018
3	SWAT+	input	file	WATme	at												
7		1862	hru1862	GLU	a_105f_4_lum	wwht			a_105f_4_mgt	wwht	wwht	wwht	wwht	wwht	wwht	wwht	wwht
8		2169	hru2169	GLU	_110f_3_rn_1_lum	wwht			_110f_3_rn_1_mgt	wwht	wwht	wwht	wwht	wwht	wwht	wwht	wwht
9		2583	hru2583	GLU	a_128f_3_lum	barl	oats	wwht	a_128f_3_mgt	barl	oats	wwht	oats	oats	barl	wwht	ba
10		2585	hru2585	GLU	a_129f_2_lum	oats	swht	barl	a_129f_2_mgt	oats	swht	barl	oats	swht	barl	oats	sw
11		5898	hru5898	GLU	a_019f_4_lum	wwht			a_019f_4_mgt	wwht	wwht	wwht	wwht	wwht	wwht	wwht	ww
12		5922	hru5922	GLU	a_210f_1_2_lum	wwht			a_210f_1_2_mgt	wwht	wwht	wwht	wwht	wwht	wwht	wwht	ww
14	SWAP runs	1	GLU			wwht rotation											
15		2	GLU			summer crops and wwht rotation											
16		3	GLU			summer crops rotation											

**Figure 8.5.** Identifying typical crop rotations, simulated by the SWAT+ model for SOILswap soil classes

**Step 6.** For the example case, HRUs **1862** (wwh rotation), **2583** (summer crops and wwht rotation and 2585 (summer crop rotation) could be selected for cross-validation.

## 2. SWAP and SWAT+ output files used for cross-validation

The SWAP output file *\*.bal* (Figure 8.6) incorporates most of the soil water balance elements evaluated in yearly time step within the cross-validation of the two models (see Table 2.7, Chapter 2).

```

results.bal - Notepad
File Edit Format View Help
* Project: REF_CONV
* File content: overview of actual water and solute balance components
* File name: results.bal
* Model version: Swap 4.0.1
* Generated at: 2024-06-10 03:42:46

Period : 1981-01-01 until 1981-12-31
Depth soil profile : 100.00 cm

Water storage
Final : 29.38 cm
Initial : 40.49 cm
=====
Change -11.12 cm

Water balance components (cm)

In Out
=====
Rain + snow : 53.57 Interception : 2.66
Runon : 0.00 Runoff : 0.00
Irrigation : 0.00 Transpiration : 32.40
Bottom flux : -16.24 Soil evaporation : 13.39
Crack flux : 0.00
Drainage level 1 : 0.00
=====
Sum : 37.33 Sum : 48.45

```

**Figure 8.6.** Example SWAP output file (\*.bal) with yearly sums of water balance elements



1	optainc10	hru_wb_yr.txt	SWAT+ Jan 11 2024										MODULAR Rev 2024.61.0									
2	jday	mon	day	yr	unit	gis_id	name	precip	snofall	snomlt	surq_gen	latq	waterysid	perc	et	econopy	eplant	esoil	surq_cont	cm	sw	
3								mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
4	365	12	31	2018	1	0	hru0001	576.760	101.527	100.308	128.780	131.391	260.171	3.825	313.512	18.899	270.295	24.318	128.794	82.319	19.	
5	365	12	31	2018	2	0	hru0002	576.760	101.527	100.308	127.578	135.288	262.866	3.498	311.586	18.899	268.358	24.329	127.593	82.188	19.	
6	365	12	31	2018	3	0	hru0003	576.760	101.527	100.308	1108.220	170.346	1278.566	7.437	353.978	18.903	310.626	24.449	1108.381	84.469	21.	
7	365	12	31	2018	4	0	hru0004	576.760	101.520	100.559	180.949	123.910	304.859	8.973	263.860	6.618	62.077	195.166	180.948	91.772	17.	
8	365	12	31	2018	5	0	hru0005	576.760	101.520	100.559	215.325	91.854	307.179	6.866	266.608	6.618	62.077	197.913	215.325	90.715	13.	
9	365	12	31	2018	6	0	hru0006	576.760	101.520	102.729	397.337	4.942	402.179	0.366	182.292	0.000	0.000	182.292	397.337	98.697	6.	
10	365	12	31	2018	7	0	hru0007	576.760	101.520	100.559	211.841	97.158	308.839	4.361	265.766	6.618	62.077	197.071	211.841	90.471	13.	
11	365	12	31	2018	8	0	hru0008	576.760	102.332	101.099	115.580	0.152	250.240	2.354	332.238	10.967	166.856	154.514	119.580	86.379	15.	
12	365	12	31	2018	9	0	hru0009	576.760	103.990	102.701	133.799	0.139	273.109	2.310	325.134	7.736	167.201	150.197	133.801	86.223	15.	
13	365	12	31	2018	10	0	hru0010	576.760	101.411	100.179	119.620	0.106	249.789	2.278	340.638	9.073	170.831	160.735	119.622	86.379	15.	

Figure 8.9. Example for SWAT+ output file (hru\_wb\_yr.txt) with yearly water balance elements

Below we give an example worksheet for calculating volumetric water contents from SWAT+ output file *SM\_22.out* (Chapter 2, Table 2.8). The workbook with all the formulas is available on [UFZ Cloud](#).

SM_22.out (for 1 specific HRU, name, type columns deleted)										st_mm_1	st_mm_2	st_mm_3	st_mm_4	st_mm_5	layer_2	layer_3	layer_4	upper 30 cm
										Soil water content, v%				Soil water content in m3 / m3				
										Soil layer 0-25 cm 25-55 cm 55-80 cm 80-100cm				Soil layer 0-25 cm 25-55 cm 55-80 cm 80-100cm				
jday	mon	day	yr	st_mm_1	st_mm_2	st_mm_3	st_mm_4	st_mm_5	mm	250	300	250	200	250	300	250	200	
1	1	1	2015	4.7	86.8	58.0	44.3	37.2	not used	34.7	19.3	17.7	18.6	0.35	0.19	0.18	0.19	
2	1	2	2015	4.7	87.9	58.6	44.3	37.2	not used	35.1	19.5	17.7	18.6	0.35	0.20	0.18	0.19	
3	1	3	2015	4.7	88.5	59.2	44.3	37.2	not used	35.4	19.7	17.7	18.6	0.35	0.20	0.18	0.19	
4	1	4	2015	4.7	89.1	59.7	44.3	37.2	not used	35.6	19.9	17.7	18.6	0.36	0.20	0.18	0.19	
5	1	5	2015	4.7	89.5	60.2	44.3	37.2	not used	35.8	20.1	17.7	18.6	0.36	0.20	0.18	0.19	

Figure 8.10. Converting the soil water content from mm (SWAT+ output) into volumetric water content (V%), required for cross-validation.

## Annex 9. Issues and implications

The implementation of the field-scale modelling work (Task 4.3) in OPTAIN is delayed compared to the original schedule for several reasons, which are listed below.

### 1. SWAP model bugs and upgrade

The team of Task 4.3 started the field-scale modelling work with the latest version of the selected model at that time – SWAP v4.0.1. The SWAP model was developed and is being maintained by scientists from the Wageningen University and Research (<https://www.swap.alterra.nl/>). During the implementation, a number of technical issues and minor errors (“bugs”) were found that caused delays in our work. These issues were mentioned and solutions were offered in the OPTAIN SWAP modelling protocol (Farkas et al., 2022). The main issues that were resolved were as follows:

1. Absence of parameters for the macropore routine in the example \*.swp file.
2. The model was not running with some of the example input files (user-defined soil input file, some of the crop input files etc.).
3. The structure of some input files (like the weather data in hourly resolution), were documented incorrectly in the official SWAP Technical Documentation (Kroes et al., 2017).
4. Model instability when using the macropore option.

As these issues were not properly documented, the field-scale modelling team spent time on solving these problems. Meanwhile, as described in sub-chapters 2.3, 2.5, 2.6 and 2.7, R-scripts were developed to facilitate the preparation and processing of the input data, the reference data quality check and model calibration. The R-scripts were adjusted to the V4.0.1 data structure.

In July 2022 a new SWAP version (4.2.0) was released. In this new version the developers solved all the problems found in SWAP v4.0.1, but they also slightly changed the structure of the input data, especially the meteorological input data. To avoid the technical issues and bugs, we decided to use the latest version of the model, so all the R-scripts had to be modified. Switching from one model version to another delayed the SWAP modelling work.

### 2. Development of new approaches

OPTAIN aims to standardise and harmonise its approaches across all the case study sites for both, SWAT+ and SWAP models, 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. However, the harmonised approach of OPTAIN across all case studies also led to an underestimated demand for support. This was particularly true for WP4 and all modelling related tasks.

The new approaches introduced within Task 4.3 (and listed in Chapter 2) facilitate the modelling work and its standardisation, but their development and testing are time

consuming. Note, that these approaches were not promised in the project proposal, but some of them (e.g., rswap, script for formatting weather input data) have already been used outside the project in a BSc and an MSc thesis.

The scripts and new approaches (e.g., using user-defined soil input data for representing stable root and earthworms' channels in the soil) will be made publicly available in the future and will be used outside the OPTAIN project.

### 3. Correction of climate scenario data

The OPTAIN deliverable D3.1, submitted in February 2022, included bias adjusted climate model simulations based on the ERA5-Land (Honzak and Pogačar, 2022), as indicated in the project proposal, and as agreed in the preliminary project phase. The product was a set of netCDF datasets for each CS, each containing time series of meteorological variables downscaled to the pilot sites that are used as SWAP climate forcing (temperature, precipitation, wind speed, radiation and relative humidity) and representing various RCP emission scenarios and EURO-CORDEX Regional Climate Models (RCMs). Testing this set of forcing data with the models in WP4 was not possible until the first model setups were ready (late 2022- early 2023).

During the test of the forcing data set, the bias-corrected climate simulations were compared with station data for CS2, CS4 and CS12. Large differences were found, especially for maximum temperature (up to 5 °C) and precipitation (overestimation by up to 30 % on mean annual basis). Based on the literature, which was unfortunately not available when selecting the reference dataset, the precipitation overestimation of ERA5 and ERA5-Land is a known problem (Bandhauer et.al, 2022; Gomis-Cebola et.al, 2023). In addition, it was found that this bias is much higher than the climate change signal for the end of the 21st century, which means that the climate change effects projected with SWAP and SWAT+ would be obscured by the ERA5-Land bias.

This required an urgent solution, and after discussion between WP3, WP4 and the coordinator, it was agreed that bias-corrected climate simulations 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 labour and time required as much as possible. Nevertheless, the entire process from identifying an issue to quality checking and approving the new dataset took about three months, which was of course not foreseen. The newly developed dataset was briefly described in the D3.1 addendum (Honzak, 2023).

### 4. Delay in the SWAT+ modelling work

In OPTAIN, the SWAP modelling work was planned to be accomplished in parallel with the SWAT+ modelling tasks (Task 4.4) to ensure a harmonised model setup, which serves as a basis for cross-validation of the two models. The delays in the SWAP modelling reported in the preliminary version of D4.4 therefore had a direct impact on the SWAT+ modelling 4.4.

To speed up this work, R-scripts and methods have been developed and tested to automatise the scenario analysis work to the highest extent possible.

Cross-validation was also affected and hindered by delays in the SWAT+ modelling, as only calibrated SWAT+ setups could be used for this purpose. As the Czech (CS12) and Lithuanian (CS8) case studies were not ready with their catchment model calibration and scenario analyses by the D4.4 reporting, the cross-validation for these pilot sites could not be completed by the time of this reporting but will be completed later and published in the joint publication dedicated to the OPTAIN models cross-validation work.

## 5. Data availability and quality in the case studies

In subsection chapter 2.5 we described the challenges with the soil water content records. The absence or poor quality of such data caused serious delays for some of the case studies. CS3a, CS10 and CS11 were impacted the most.

CS3a and CS11 (Hungary) reported delays in data analyses due to issues with the different soil moisture sensors, as the discontinued 5TM sensors were replaced with TEROS 12 sensors. The new sensors had to be calibrated for all the soil types. It was also found that the 5TMs could record much lower residual water contents compared to the new TEROS types. Unfortunately, these sensor replacements during the monitoring period resulted in missing data and a few percentages of change in the measured soil water values. The year 2022 was extremely dry at the Hungarian pilot sites, especially during the vegetation period; the catchment's stream dried out. This also resulted in a lowering of the groundwater table in the studied soil profiles and caused instability in the soil water content records.

CS10 (Norway) joined the field-scale modelling work on a voluntary basis. Soil water sensors were installed at five locations within the pilot catchment in 2021. The extreme precipitation events, however, caused water stagnation in the tube of the sensors, so a large part of the records had to be taken out of the analysis and calibration process. The time used for reinstalling the probes and collecting data for having long enough data series for model calibration contributed strongly to the delay in the CS10 field-scale modelling work.

## 6. COVID

The implications of the COVID-19 pandemic led to several obstacles for OPTAIN in general, but also specifically for WP4 and the work related to deliverable D4.3. 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 3 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 D4.3 have occurred from activities that are indirectly related to modelling (e.g. COVID induced delays in stakeholder engagement activities and data acquisition). This also led to the fact that not all processes of the case studies were running in parallel, which challenged OPTAINs harmonised approach and intensified the requirements for supervision/guidance.