



OPTAIN

Optimal Strategies to Retain Water and Nutrients

D2.3: Participatory modelling settings and standardised guidelines for parameterisation of measures

SWAT+ and SWAP retention measure implementation handbook

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Summary

The deliverable D2.3 of the OPTAIN project introduces a framework and scale specific guidelines for the parameterization of Natural/Small Water Retention Measures (NSWRM) in modelling approaches. More specifically, it provides a detailed translation of NSWRM into parameters and design approaches for the application in the SWAT+ (catchment scale) and SWAP (field-scale) models, which were selected as the main modelling tools in the OPTAIN project. This document can also be considered as an extension of the well-known Conservation Practice Modelling Guide for SWAT and APEX (Waidler et al., 2011), which is frequently used by the SWAT modelling community for testing the effectiveness of conservation practices. However, besides of conservation practices, the report focuses mainly on NSWRMs, and how they can be implemented in SWAT+, the new and restructured version of SWAT. Analogously, the NSWRM parameters are also described for the SWAP model, which is addressing the field-scale. Compared to previous NSWRM modelling approaches, this methodology enables the setting of NSWRM parameters in the two selected models to improve the description of the related hydrological and hydrochemical processes.

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Abbreviations

COCOA	Contiguous Object COnnectivity Approach
CS	Case Study
CTD	Controlled Tile Drainage
CW	Constructed Wetland
DEM	Digital Elevation Model
DT	Decision Table
ERD	Entity-Relationship Diagram
HRU	Hydrological Response Unit
HRT	Hydraulic Retention Time
GIS	Geographic Information System
NSWRM	Natural/Small Water Retention Measure
NWRM	Natural Water Retention Measure
RTU	Routing Unit
SWAT	Soil & Water Assessment Tool
SWAP	Soil Water Atmosphere Plant
WCR	Wetland-Catchment Ratio
WLCS	Water Level Control Structure
WRT	Water Residence Time
WP	Work Package

1. Introduction

OPTAIN aims to increase the knowledge and understanding of the multiple benefits that spatially targeted combinations of Natural / Small Water Retention Measures (NSWRM) have on the management of small agricultural catchments across continental, Pannonian and boreal biogeographical regions of Europe, and on the conditions under which they perform most effectively. Two models are used in OPTAIN to assess the environmental impact of individual measures in the landscape.

The main model in OPTAIN is the Soil and Water Assessment Tool Plus (SWAT+), which will be used to test the effectiveness of individual measures at the catchment scale. SWAT+ is a public domain model jointly developed by the USDA Agricultural Research Service (USDA-ARS) and Texas A&M AgriLife Research, part of The Texas A&M University System. SWAT+ is a small watershed to river basin-scale model to simulate the quality and quantity of surface and ground water and predict the environmental impact of land use, land management practices, and climate change. SWAT is widely used in assessing soil erosion prevention and control, non-point source pollution control and regional management in watersheds.

The second model that will be applied in OPTAIN is SWAP (**S**oil-**W**ater-**A**tmosphere-**P**lant), which is used to obtain control data and to model the effectiveness of NSWRMs at the field scale. The calibration and scenario analyses results will be cross-validated with those of the catchment-scale models. SWAP simulates the transport of water, solutes and heat in the vadose zone in interaction with the vegetation development. The model employs the Richards equation including root water extraction to simulate soil moisture movement in variably saturated soils. Root water extraction can be simulated with macroscopic and microscopic concepts. SWAP includes a detailed module on macro-porous flow in clay and peat soils. For solute transport SWAP considers the basic processes convection, dispersion, adsorption and decomposition. Moreover, SWAP generates soil water fluxes for detailed chemical transport models as PEARL for pesticides, ANIMO for nutrients and ORCHESTRA for heavy metals. SWAP simulates soil heat flow taking into account actual heat capacities and thermal conductivities. In addition to prescribed top boundary conditions, the generic crop growth module WOFOST is incorporated to simulate leaf photosynthesis and crop growth. The soil moisture, heat, solute and plant growth modules exchange status information to account for all kind of interactions. An extensive test protocol ensures the numerical code quality of SWAP. The source code is well structured, and available on the SWAP site.

This deliverable 2.3 (D2.3) presents the output of the OPTAINs task 2.3 '*Participatory modelling settings and standardised guidelines for parameterisation of measures*'. The purpose of D2.3 is therefore to introduce the guidelines for the parameterization of NSWRM to be applied in the models. These guidelines are of a high importance for the project, since they provide a translation of the NSWRM design and description parameters into the modelling options and approaches. For greater comprehensiveness and ease of clarity of this document, some descriptions of the NSWRM are taken from the deliverable D2.1 (Lemann et al., 2022).

In this document, the individual NSWRM and the related parametrization guideline is presented in the following structure:

- i. A short description of the NSWRM, with a link to the NWRM catalogue (nwrn.eu). The NSWRM description is taken from the NWRM catalogue, the OPTAIN deliverable D2.1 or assembled by the authors of D2.3 in case the measure is not yet described in the NWRM catalogue (e.g. controlled drainage)
- ii. List of the NSWRM that will be considered by the OPTAIN case studies, with links to the OPTAIN documentation in WOCAT.
- iii. Measure design in reality – a brief explanation of the principles and design of the measure in practice.
- iv. Design parameters – a commented list of the NSWRM main design parameters.
- v. SWAT+ model implementation - Option A – COCOA; Option B – Default (Conventional). A brief description is provided, with specified advantages (pros) and disadvantages / limitations (cons). Each NSWRM and related SWAT+ parametrization is provided with a scheme (entity-relationship diagram for the SWAT+ model input files) and a table of the parameters.

Analogously, this structure is applied for the parametrization of the NSWRM for the SWAP model.

1.1. Overview of case studies and measures to be modelled

The OPTAIN project is carried out in 14 case studies across Continental (7), Pannonia (3) and Boreal (4) biogeographical regions of Europe including one Pannonia-Continental cross-border case. All case studies (CS) represent small catchments (4.5-250 km²) dominated by agricultural land use but cover a wide range of soil-climatic zones and agricultural systems. The distribution of case studies reflects well on the share of agricultural land within the different H2020 focus regions. With the help of OPTAINs stakeholder groups, each CS has identified and selected several NSWRM to be modelled on catchment or field scale, due to the environmental problems or preferences.



Fig. 1: OPTAIN case studies per biogeographical region.

Table 1: OPTAIN case studies.

Case study nr	Case country	Case name	Bio-region	Size [km ²]	Problems with
1	Germany	Schwarzer Schöps	Continental	136	P losses, floods and droughts
2	Switzerland	Petite Glâne	Continental	101	P losses and droughts
3a	Hungary	Csorsza	Pannonia	21	P losses and floods
3b	Hungary	Felso-Valicka	Pannonia	21	P losses and floods
4	Poland	Upper Zglowiaczka	Continental	78	P losses, N losses, floods and droughts
5	Austria/ Slovenia	Pesnica	Continental	137	Floods and droughts
6	Slovenia/ Hungary	Kebele/ Kobiljski potok	Continental/ Pannonia	247	P losses, N losses, floods, and droughts
7	Belgium	La Wimbe	Continental	128	Floods and droughts
8	Lithuania	Dotnuvele	Boreal	176	P losses and N losses
9	Italy	Cherio	Continental	153	N losses, floods and droughts
10	Norway	Hobøl	Boreal	56	P losses, N losses and floods
11	Hungary	Tetves	Pannonia	117	P losses and floods
12	Czech Rep.	Čechtický	Continental	72	P losses, N losses and floods
13	Latvia	Deviete	Boreal	254	P losses, N losses and floods
14	Sweden	Sävjaån Headwaters	Boreal	125	P losses, floods and droughts

For the purpose of this deliverable D2.3, the selected NSWRM, were merged into several representative groups of measures with analogous characteristics, as depicted in Figure 2. These groups, separated in structural and management-related measures, are further described from the SWAT+ and SWAP application perspective.

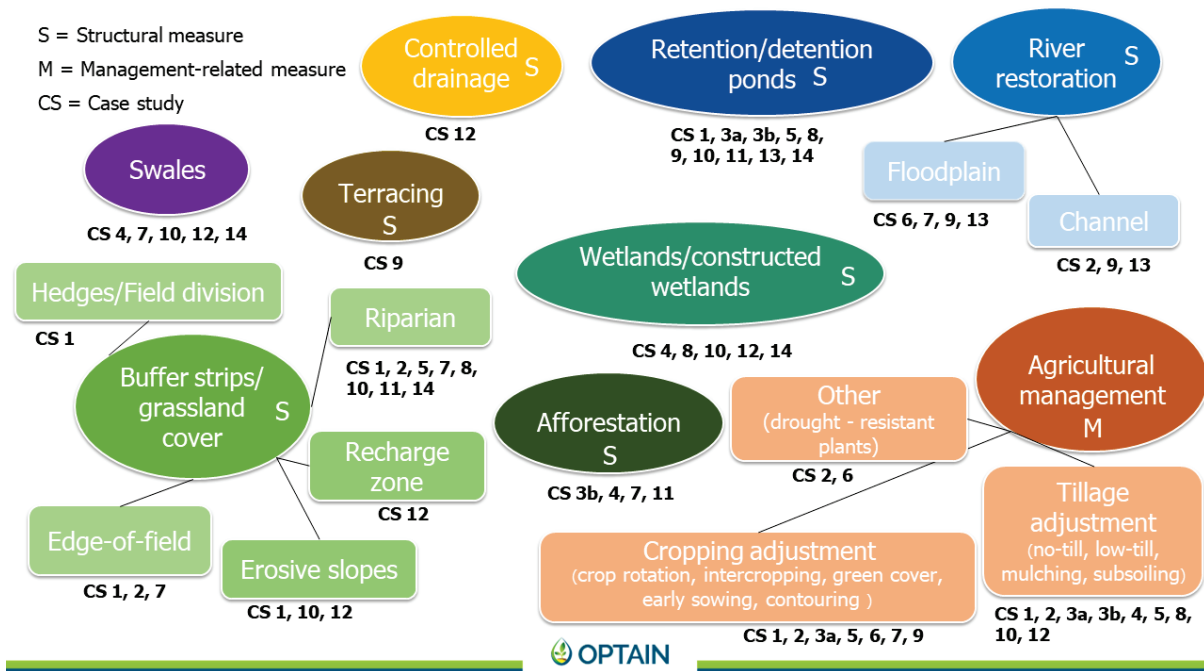


Fig. 2: Overview of measures to be modelled.

1.2. Proposed SWAT+ modelling concepts: Spatial object connectivity (COCOA) vs. default routing

The catchment scale case studies in OPTAIN will use SWAT+ for the simulation of effects of NSWRM at the catchment scale. SWAT+ is a fundamentally restructured version of the Soil and Water Assessment Tool (SWAT). In contrast to the rather rigid model structure of the previous version of SWAT (SWAT2012), the SWAT+ model setups consist of spatial objects that represent the land areas, channels, reservoirs, aquifers, and other components of a watershed system. Spatial objects can be mutually connected to enable different types of fluxes between them, such as surface runoff, lateral flow, and groundwater recharge. The introduction of spatial objects and their connectivity is a substantial improvement and allows a flexible representation of hydrological catchment systems.

Yet the model setup process with the QSWAT+ v2.2 GIS interface (such model setups or the model setup process is referred to as conventional in the following) is still based on concepts that were established for SWAT2012 model setups. Thus, the conventional model setup procedure with QSWAT+ does not take full advantage of the flexibility of the model in configuring a watershed. The smallest spatial land phase unit that has a spatial reference in such a conventional setup is the routing unit (RTU). RTUs usually contain multiple hydrological response units (HRUs), which lump areas with the same land use, soil and similar slope in a unit without a spatial reference. Thus, HRUs usually aggregate areas in an RTU which are scattered across the landscape, and which are not connected.

In OPTAIN, the spatial scale of interest is the field scale. The catchment scale model applications are used to investigate the sum of field scale effects (introduced by NSWRMs) at the catchment scale. Thus, conventional model setups, which strongly

aggregate the landscape at the scale of interest, may be inappropriate to evaluate the implementation of NSWORMs. Consequently, a new approach for SWAT+ model setup is being developed in OPTAIN that can represent features in the landscape at the field scale and accounts for the connectivity between land phase objects (HRUs). With this approach each individual landscape feature in a land cover layer needs to be a contiguous spatial unit and is eventually considered as a unique object in the SWAT+ model setup. Contiguous units are here defined as in itself contained areas with clearly defined borders to neighbouring units (which is different to the fragmented representation of the landscape with conventional model setups). The connectivity between contiguous objects is calculated based on terrain properties which are calculated with a raster DEM.

This **contiguous object connectivity** approach is abbreviated as COCOA in the following document.

When the different spatial configurations of SWAT+ model setups are initiated conventionally in QSWAT+ or with COCOA, they lead to a different representation of NSWORMs. Different landscape representations within SWAT are not necessarily a novel concept. Also for SWAT2012 approaches were documented to implement a hillslope discretization in order to simulate the retention behaviour of grassland and filter strips for runoff from e.g. more erosion prone areas (see e.g. <https://swat.tamu.edu/media/69422/Appendix-B.pdf>). Yet, this modification in a model setup was rarely implemented, as it requires substantial manual modifications in input files. COCOA aims to automatize these modifications in the model setup process.

Although we aim to define agricultural fields as unique and separated HRUs also in conventional SWAT model setups, the representation of the landscape is still rather abstract in such model setups, as the connectivity between land units is not accounted for at all. Therefore, spatial structural measures can only be implemented in an abstract way and measures are usually represented by changes of model parameter values that impact the hydrological processes of interest. Parameter values often do not have a clear physical reference and are empirical and abstract instead. Yet, literature values may be available for most of the model parameters that represent certain measures.

COCOA represents the landscape with greater detail. In such a setup, spatial structural measures (and potential locations of measures) are represented by unique spatial objects (see Figure 3). The implementation of a measure (e.g., the transformation of an agricultural area to a retention area) is then for example represented by a transformation in the land use of the respective spatial object. The effectiveness of the measure in such a model setup is then strongly impacted by the connectivity between the spatial objects and the retention properties of a certain land use.

COCOA is under development (as of August 2022) and its more in-depth description is underway as a part of the ongoing OPTAIN deliverable D2.2 “Modelling protocols”, which is due in October 2022. Thus, its implementation in all 14 OPTAIN catchment scale case studies is not guaranteed, partly due to a high degree of detail that is required for the input data (not available in all CSs), but also due to the potential problems (while developing new ideas), which would not make COCOA a better option after all. Therefore, for the implementation of spatial structural NSWORMs both options

COCOA (option A) and 'conventional' (option B) are addressed and described in the following document.

For COCOA, it is necessary that all measures, which are going to be modelled in later scenario simulations, are represented as unique polygons in the land use map. Such an extended land use map must be used as input for setting up the SWAT+ models (see Fig. 3).

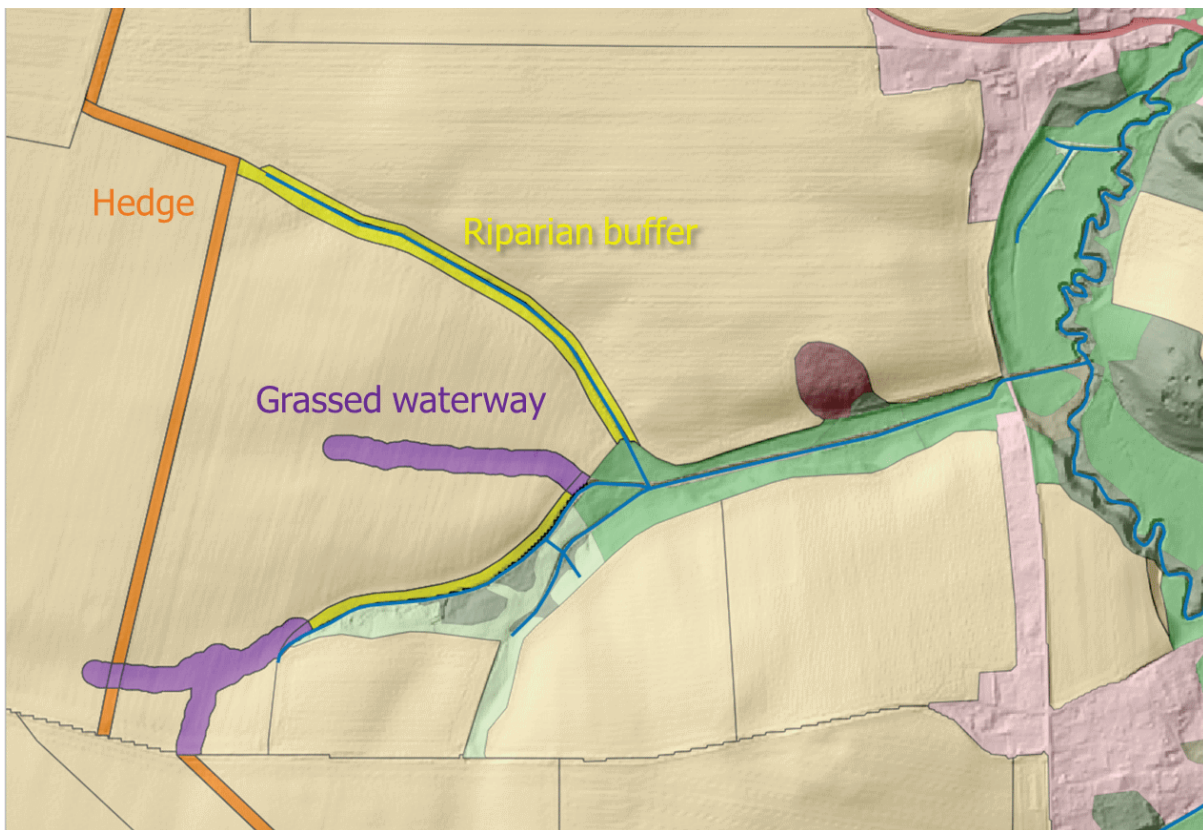


Fig. 3: Land use map including potential water and nutrient retention measures (hedges, grassed waterways, riparian buffer). For COCOA, it is necessary that all measures, which are going to be modelled in later scenario simulations, are represented as unique polygons in the land use map. Such an extended land use map must be used as input for setting up the SWAT+ model.

1.3. Farm management scheduling - decision tables and fixed management

While structural measures mainly affect the connectivity of objects, the management-related measures mainly address the agricultural and land operations and practices. In SWAT+ such agricultural operations (planting/sowing, harvesting, fertilisation, irrigation, tillage, etc.) can be scheduled and executed by using a “fixed” date (or Heat Unit value), or via decision tables. Both methods have pros and cons and are described in the following section.

Fixed Management

Fixed land-use management is described in detail in the SWAT+ I/O documentation (<https://swatplus.gitbook.io/docs/user/editor/inputs/land-use-management>).

Pros:

- If the actual dates are known, then the setup is more realistic.
- The modeller decides when the operation takes place, more certainty.
- Model management setup does not change from simulation to simulation, less uncertainty.

Cons:

- Cannot be used in scenarios for future simulations.
- If exact dates are unknown, then the actual management might be misrepresented.
- For accurate representation, it has to be developed for every field/region/HRU, which might be overwhelming or impossible for large areas.

Decision tables

Decision tables (DT) are a precise yet compact way to model complex rule sets and their corresponding actions. Decision tables, like flowcharts and if-then-else and switch-case statements, associate conditions with actions to perform, but in many cases do so in a more elegant way. The use of DTs in SWAT+ is described in the SWAT+ I/O documentation (<https://swatplus.gitbook.io/docs/user/editor/inputs/decision-tables>).

Pros:

- Can be constructed for multiple operations.
- Can be used to schedule future operations based on past conditions (i.e. future fertilisation based on past soil tests).
- Can be used if the information on the system is limited.
- Can be randomised over the entire catchment.
- Management for big areas can be represented in a single DT.
- Very flexible approach.
- Can be used for simulations of future management.

Cons:

- Requires some knowledge of algorithm theory (or systems thinking) to develop representative DTs.
- If no suitable conditions are detected, the operation might not trigger or trigger during a sub-optimal time/date.
- Management operations with a random factor might trigger during different times/dates during separate simulations.

DTs can be used to represent such management and structural measures, of which many correspond to OPTAIN measures illustrated in Fig. 2:

Land Use and Management – called from HRU object

- Plant/harvest – Single summer crop, 2-year rotation summer crops, single winter crop, detailed 5 crop rotation, hay and forest cuttings, etc.
- Irrigation – unlimited and multiple sources. Can't use the channel as source since it is flowing water, no rights – first simulated, first serve.
- Controlled drainage.

- Grazing – winter and summer examples.
- Fertiliser – spring side dressing, stress test, etc.
- Tillage – fall plough, spring plough, mulch till, no till, etc.
- Curve number (CN2) update.

Land Use Scenarios – called from outside routing loop

- Change entire land use.
- Change HRU fractions.
- Change P factor – terracing, contouring, strip cropping, etc.
- Installation of structures – install tile.
- Surface runoff vulnerability index and scenarios.

Reservoir Release – called from reservoir object

- Demand based release.
- Direct withdrawal for water rights object.
- Direct withdrawal for HRU.

Water Diversions – currently (August 2022) can be modelled using a separate water rights object (wro).

2. Structural measures

Structural measures are physical or bio-technical constructions / land works to reduce or avoid possible impacts of quick or elevated runoff (both overland flow and subsurface drainage runoff), floods, soil erosion and related pollution entry into water bodies, settlements, roads, or other immovable property. They cover engineered interventions, such as reservoirs or drainage water management approaches to more natural solutions like wetlands and river restorations. For OPTAIN, we include also grassing and afforestation in the structural measures, as related to the SWAT+ modelling setting; see Table 2.

Table 2: Grouping of structural measures containing categories from nwrn.eu.

Group of measure in OPTAIN	Measure in the nwrn.eu catalogue	Specific measures in OPTAIN
Buffer strips/grassland cover	F01 - Forest riparian buffer	Riparian buffer
	A02 - Buffer strips and hedges	Edge-of-field filter strips
		Hedges/Field division
	Not defined	Grassland cover - Arable land, Recharge zone
Not defined	Grassland cover - Erosive slopes	
Retention/detention ponds	N01 - Basins and ponds	Retention/detention ponds
River restoration	N03 - Floodplain restoration and management	River restoration - Floodplain
	N04 - Re-meandering	
	N05 - Stream bed re-naturalization	River restoration - Channel
Afforestation	F02 - Maintenance of forest cover in headwater areas	Afforestation
	F03 - Afforestation of reservoir catchments	
	F05 - Land use conversion	
Wetlands	N02 - Wetland restoration and management	Wetlands/Constructed wetlands
Controlled drainage	Not defined	Controlled drainage
Terracing	A10 Traditional terracing	Terracing

2.1. Buffer strips - Riparian buffers

F01 Forest riparian buffer

<http://nwrn.eu/measure/forest-riparian-buffers>

Riparian buffers are treed areas alongside streams and other water bodies. While most commonly associated with set asides following forest harvest, riparian buffers can also be found in urban, agricultural and wetland areas. By preserving a relatively undisturbed area adjacent to open water, riparian buffers can serve a number of functions related to water quality and flow moderation. The trees in riparian areas can efficiently take up excess nutrients and may also serve to increase infiltration. Riparian buffers serve to slow water as it moves off the land. This can decrease sediment inputs to surface waters (NWRM, 2019).



Riparian buffer (Source: http://en.wikipedia.org/wiki/Riparian_buffer)

The following specific example measures are contained in the group buffer strips - riparian buffers.

- **Forest riparian buffers** (7 Belgium - La Wimbe)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6167
- **Forest riparian buffers** (11 Hungary – Tetves)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6204
- **Grassed Riparian buffer strips** (1 Germany - Schwarzer Schöps)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6258
- **Riparian forest** (2 Switzerland - Petite Glâne)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6248/

Riparian buffers are also proposed as grassed or shrubby. This type of riparian buffer is a subset of measure A02 Buffer strips and hedges in the nwrn.eu catalogue (see chapter 2.2), as they are mainly proposed on agricultural land. For the purposes of D.2.3, the basic design parameters for grassed banks are given below.

2.1.1. Measure design in reality

Riparian buffers are designed and implemented with a certain width (tbd in each CS) and length on cropland or intensive grassland along the stream network.

The width of the forested riparian buffer is proposed to vary from 2 (very narrow) to 50 m (more in specific cases) on each bank. For grassed or shrubland riparian buffers on agricultural land, the width is recommended between 5 - 15 m depending on the degree of watercourses protection.

It is measured from the flow line (as a line in the model - shp layer). The width of the riparian buffers could be set according to several empirical approaches related to design precipitation / runoff, slope, length, soil hydrologic group and land use of the adjacent land. For easier proposals and with a relation to subsidies, it is recommended to use one of the above specified range of values and to confirm those values by local actors.

2.1.2. Design parameters

- forested riparian buffers width - between 10 and 50 m
- grassed riparian buffers width - between 5 and 15 m
- vegetation cover (forest, grass, shrubland)
- detailed information on designing the forested riparian buffers are provided in the following linked document (particularly in ch. VIII. Design Guidance): [Individual NWRM - forest riparian buffers](#)

2.1.3. SWAT+ model implementation

Option A – COCOA

The potential buffer area along a channel is defined as a unique spatial unit in the generation of the land use layer. With the developed model setup process this unit will become a unique object in the SWAT+ model setup. The initial land use for this unit will be defined the same as the land use of the agricultural field to which this area initially belongs (see Fig. 3).

The implementation of the measure is performed by changing the land use and management from an agricultural land use to extensive grassland, woodland, or wetland forest (with the respective management), depending on the intended type of riparian buffer.

The initial and the alternative land use/management combinations should be predefined in the landuse.lum file. The land use change is performed by changing the 'lu_mgt' in the file hru-data.hru for the respective spatial units from the initial land use label to the one that represents the buffer strip. Fig. 4 additionally shows all links to input files where parameterizations have to be defined for the initial and the alternative land use configuration. These parameterizations eventually affect the simulated hydrological processes and the nutrient transport in the SWAT+ simulations.

Pros:

- The model setup can account for the actual location and dimensions of the measure.
- The water balance will be simulated for the updated land use and can therefore also account for an increased evapotranspiration of e.g. forest land use.
- The retention effect is accounted for by the land use parameters and the routing between units and does not require additional empirical literature parameter values.

Cons:

- The input data preparation requires a manual implementation of potential measure locations (see example in Fig. 4).
- Potential measure locations add spatial units to the model setup and increase the simulation time.
- The simulation of the status quo can be affected by the split of a single field into the remaining field area and the potential measure location and can thus affect the simulation outputs.

- The link between large fields and small buffer strip areas may not be appropriately represented by the SWAT+ model (e.g. budgeting of water balance components in the small unit when adding large volumes of water, water that can potentially pass through the measure without residing there).

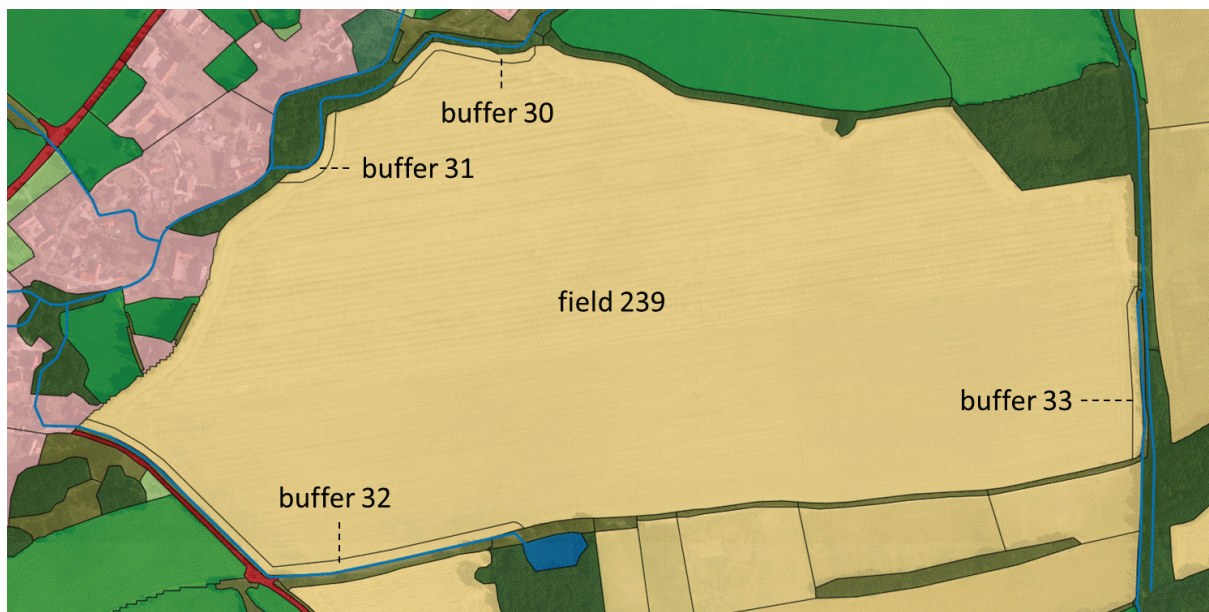


Fig. 4: Example for including riparian buffers in the land-use map for the option A (preparation must be done before HRU definition!). Here, field 239 contains four potential areas to implement riparian buffers (buffers 30 to 33). All those delineated buffers will remain with the management of field 239 in calibration and status quo simulations. In the scenario case, however, these objects will undergo a land cover/management change.

Option B – Default

The agricultural land use of the field is defined in the landuse.lum to which the respective HRU points in the hru-data.hru file. In the parametric default approach, the main land use with its parametrization (e.g., cn2 or ov_mann) remain unchanged with the implementation of a buffer strip. The buffer strip will be added to an HRU by adding a measure in the column 'vfs'. This can be done by either a) changing the label in the landuse.lum when the measure is implemented, which then points to the measure in the file filterstrip.str or by b) initialising the measure in the default configuration and setting the value of the 'flag_fs' to 1 when the measure should be activated and reset it to 0 when removing the buffer strip.

Pros:

- The land use map that is implemented in the model setup does not require additional work. The measure does not have to be considered in the initial land use layer.
- It is easy to implement the measure by activating a predefined parametrization.
- A potential measure location does not add spatial units in the model setup and does therefore not increase simulation time.
- The parametric implementation can make use of existing literature values that empirically assessed the effect of buffer strips.

Cons:

- The evapotranspiration does not change, as the effect of land use change on water balance components is not accounted for in the simulations (parametric approach).
- The spatial reference of the measure cannot be clearly defined. The measure will be represented as a fraction of the lumped HRU area.
- It may be challenging to translate the measure design parameters into model parameters, although literature values exist.
- The effect of a measure is defined by empirical parameters. Literature parameter values can vary and thus can impose large uncertainties on the simulated effect of this measure.
- The measure should be placed only in floodplain HRUs. Depending on the width of the floodplain, the parametrization may also be assigned to HRU areas which are actually not adjacent to a channel.

Options for modelling riparian buffers are summarised in Fig 5. Table 3 describes the input variables required for modelling the measure.

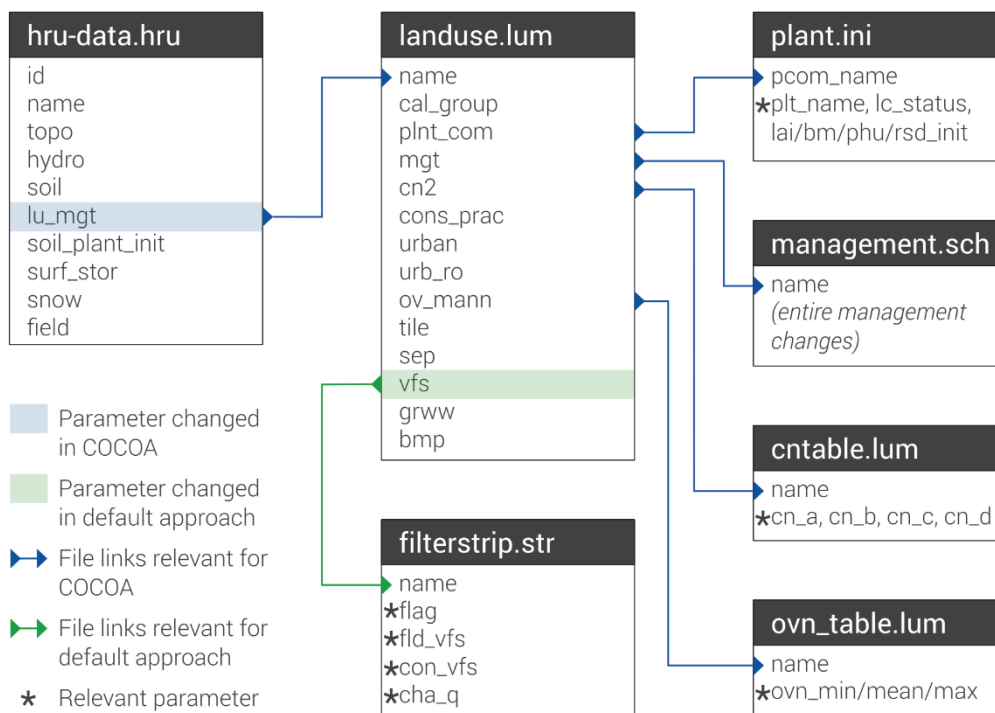


Fig. 5: Entity-Relationship Diagram for the SWAT+ model input files for the implementation of riparian buffers. The blue and green highlighted input file values will be changed in the COCOA and the conventional model setup to implement riparian buffers, respectively. The links refer to input files that are required to parameterize the NSWRM. Parameters that express the measure are indicated by an asterisk.

Table 3: Definition of the model parameters that are used to parameterize riparian buffers in the Option A (COCOA) and option B (conventional).

Option A (COCOA)	
hru-data.hru	
Parameter	Definition
lu_mgt	The pointer to the land use and management file is a foreign key referencing name in landuse.lum.
landuse.lum	
Parameter	Definition
name	The name of the land use and management record is a primary key referenced by lu_mgt in hru-data.hru. All names in the landuse.lum file must be unique.
plnt_com	The pointer to the plant community file is a foreign key referencing the primary key name in plant.ini.
mgt	The pointer to the management schedule file is a foreign key referencing the primary key in name management.sch.
cn2	The pointer to the Curve Number database file is a foreign key referencing the primary key in name cntable.lum.
ov_mann	The pointer to the overland Manning's n database is a foreign key referencing the primary key in name ovn_table.lum.
plant.ini	
Parameter	Definition
pcom_name	The name of the plant community is a primary key referenced by plnt_com in landuse.lum. All names in the plant.ini file must be unique.
plt_name	The plant name is a foreign key referencing the primary key name in plants.plt.
lc_status	Land cover status at start of simulation (n - Plant not growing, y - Plant growing).
lai_init	Initial leaf area index.
bm_init	Initial plant biomass.
rsd_init	Initial residue cover.
cntable.lum	
Parameter	Definition

cn_a to cn_d	Curve number for hydrologic soil group A - D.
ovn_table.lum	
Parameter	Definition
ov_min/mean/max	This is the value that is used by the model. The ovn_min and ovn_max values are included in the file to help users stay within reasonable ranges during calibration.
Option B (default)	
landuse.lum	
Parameter	Definition
vfs	The pointer to the filter strip file is a foreign key referencing the primary key name in filterstrip.str.
filterstrip.str	
Parameter	Definition
flag_fs	Flag for the simulation of filter strips (1/0 - active/inactive).
fld_vfs	Ratio of field area to filter strip area (unitless). Ranges from 0 to 300 with values from 30-60 being most common. Default value is 10.
con_vfs	Fraction of the HRU which drains to the most concentrated ten percent of the filter's strip area. Runoff generated upslope a filter strip is not uniformly distributed across the entire length of the strip. Ten percent of the filter strip can receive between 0.25 and 0.75 of the runoff from the entire field. Default value is 0.5.
cha_q	This parameter defines the fraction of the flow within the most concentrated 10% of the filter strip that is fully channelized. Flow that is fully channelized is not subject to filtering or infiltration effects. Default value is 90.

2.2. Buffer strips - Edge-of-field filter strips

A02 Buffer strips and hedges

<http://nwrn.eu/measure/buffer-strips-and-hedges>

The measure in the nwrn.eu catalogue defined as A02 Buffer strips and hedges describes measures called Edge-of-field filter strips (this section) and Hedges/Field division (section 2.3.).

Buffer strips are areas of natural vegetation cover (grass, bushes or trees) at the margin of fields, arable land, transport infrastructures and water courses. They can have several different configurations of vegetation found on them varying from simply grass to combinations of grass, trees, and shrubs. Due to their permanent vegetation, buffer strips offer good conditions for effective water infiltration and slowing surface flow; they therefore promote the natural retention of water. They can also significantly reduce the amount of suspended solids, nitrates and phosphates originating from agricultural run-off. Buffer strips can be sited in riparian zones, or away from water bodies as field margins, headlands or within fields (e.g., beetle banks). Hedges across long, steep slopes may reduce soil erosion as they intercept and slow surface run-off water before it builds into a damaging flow, particularly where there is a margin or buffer strip alongside (NWRM, 2019).



Flowering strip (Source: <https://www.bee-safe.eu/articles/bee-series/flowering-strips/>)

The following specific example measures are contained in the group buffer strips - edge-of-field filter strips.

Edge-of-field filter/Flower strips (1 Germany - Schwarzer Schöps)

https://qcat.wocat.net/en/wocat/technologies/view/technologies_6264

2.2.1. Measure design in reality

- Edge-of-field buffer strip
- Grassed buffer of a certain width (tbd in CS) on cropland or intensive grassland.

The width of the edge-of-field buffer strip is proposed to be between 5 – 30 m. The width could be set according to several empirical approaches (Graziosi, Faullkner, 2016, Prosser, Karssies, 2001), related to design precipitation / runoff slope, length, and land use of the adjacent land. For easier proposal and with a relation to subsidies, it is recommended to use the above mentioned values. Edge-of-field filter strips are very similar to the riparian buffer measure defined above. The main difference is that there is no requirement to locate filter strips near watercourses and they are most often designed as grassed.

In the final design, the Edge-of-field filter/Flower strips should be sized with respect to the agricultural equipment on the cultivated land (width of the agricultural machinery).

2.2.2. Design parameters

- Width
- vegetation cover (forest, grass, shrubland, flowers)

2.2.3. SWAT+ model implementation

Option A – COCOA and option B - default

While a field division with a buffer strip the implementation of a hedge row or a riparian buffer is usually done in a specific location in the landscape, edge-of-field filter strips are often implemented along the entire perimeter of an agricultural field. From a model setup perspective, it is reasonable to consider potential locations for larger individual units in the landscape as unique objects in a model setup. In contrast, considering all potential edge-of-field filter strips as individual objects in a model setup will result in a large number of small objects. This adds computational costs but may also introduce issues in the modelling of the water cycle or nutrient transport when routing between large fields and thin edge-of-field units.

Thus, independent of the connectivity approach that is used in a model setup, edge-of-field filter strips will be implemented with a parametric approach. The agricultural land use of the field is defined in the landuse.lum to which the respective HRU points in the hru-data.hru file. In the parametric approach, the edge-of-field filter strip will be added to an HRU by adding a measure in the column 'vfs'. This can be done, by either changing the label in the landuse.lum when the measure is implemented, which then points to the measure in the file filterstrip.str or by initialising the measure in the default configuration and setting the value of the 'flag_fs' to 1 when the measure should be activated and reset it to 0 when removing the buffer strip.

Pros:

- The land use map that is implemented in the model setup, it does not require additional work. The measure does not have to be considered in the initial land use layer.
- It is easy to implement the measure by activating a predefined parametrization.
- A potential measure location does not add spatial units in the model setup and does therefore not increase simulation time.
- The parametric implementation can make use of existing literature values that empirically assessed the effect of filter strips.
- The spatial reference of the measure is along the entire perimeter of a field. Thus, small scale topographic features do affect the parametric representation of the measure less, than compared to e.g. single landscape features where the representation of their location in the landscape would be more relevant.

Cons:

- The evapotranspiration does not change, as the effect of land use change on water balance components is not accounted for in the simulations
- It may be challenging to translate the measure design parameters into model parameters, although literature values may exist.

- The effect of a measure is defined by empirical parameters. Literature parameter values can vary and thus can impose large uncertainties on the simulated effect of this measure.

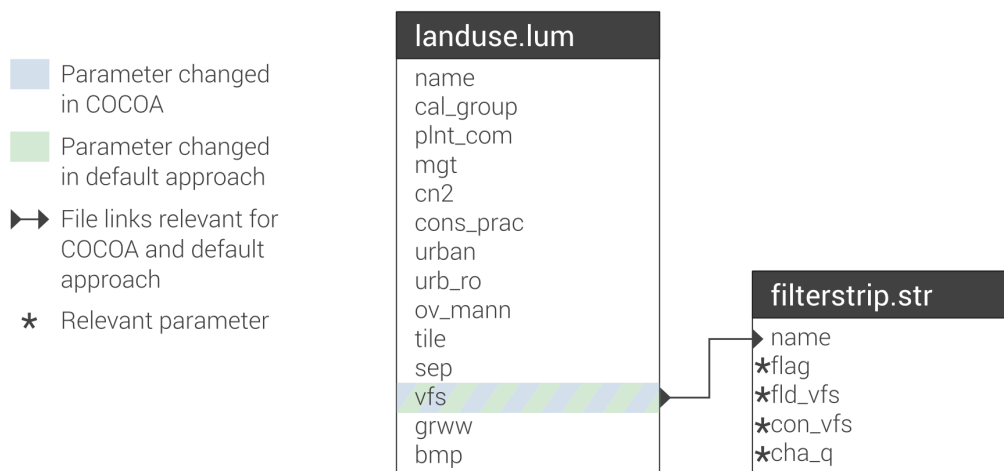


Fig. 6: Entity-Relationship Diagram for the SWAT+ model input files for the implementation of edge-of-field filter strips. The blue/green highlighted input file value will be changed in the COCOA and the conventional model setup to implement filter strips. The link refers to the filterstrip.str input file that is used to parameterize the NSWRM. Parameters that express the measure are indicated by an asterisk.

Table 4: Definition of the model parameters that are used to parameterize Edge-of-field filter in the Option A (COCO A) and option B (conventional).

Option A (COCO A) and Option B (default)	
landuse.lum	
Parameter	Definition
vfs	The pointer to the filter strip file is a foreign key referencing the primary key name in filterstrip.str.
filterstrip.str	
Parameter	Definition
flag_fs	Flag for the simulation of filter strips (1/0 - active/inactive).
fld_vfs	Ratio of field area to filter strip area (unitless). Ranges from 0 to 300 with values from 30-60 being most common. Default value is 10.
con_vfs	Fraction of the HRU which drains to the most concentrated ten percent of the filter's strip area. Runoff generated upslope a filter strip is not uniformly distributed across the entire length of the strip. Ten percent of the filter strip can receive between 0.25 and 0.75 of the runoff from the entire field. Default value is 0.5.
cha_q	This parameter defines the fraction of the flow within the most

	concentrated 10% of the filter strip that is fully channelized. Flow that is fully channelized is not subject to filtering or infiltration effects. Default value is 90.
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2.3. Buffer strips - Hedges/Field division

Also known as rustic hedges or living hedges, hedgerows are fences formed by plants, often set in rows, and made up of a wide variety of local species. These trees, shrubs, bushes, subshrubs and other plants of various kinds may be left to grow freely on the land or be subject to regular maintenance. These plant formations, which surround agricultural plots, come with many advantages (some examples wind, water erosion, etc.), not least the fact that they harbour a particularly rich biodiversity and related connectivity.



Hedges in agricultural land
(Source: <https://ptes.org/hedgerow/>)

The following specific example measures are contained in the group buffer strips - hedges/field division.

- **Hedgerows to subdivide larger fields** (1 Germany - Schwarzer Schöps)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6263
- **Slope subdivision through a field seam (A04 Strip cropping along contours)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_1670/

2.3.1. Measure design in reality

In the OPTAIN project, hedgerows are understood as any boundary line of trees or shrubs over 20 m long and less than 5 m wide at the base on cropland or intensive grassland. Hedgerows are placed along contour lines and divide larger fields into more or less equal parts. Hedges across long, steep slopes reduce soil erosion as they intercept and slow surface run-off water before it builds into a damaging flow, particularly where there is a margin or buffer strip alongside. This includes 'classic' shrubby hedgerows, lines of trees, shrubby hedgerows with trees and very gappy hedgerows (where each shrubby section may be less than 20 m long, but the gaps are less than 20 m). Connection to other semi-natural habitats is recommended, assuming good cultivability for farmers (availability and size of soil block).

The field division is carried out at field spots risky by overland flow and erosion. Recommended width of the grass strip for dividing the fields is between 5 - 30 m.

2.3.2. Design parameters

- width
- length
- buffer area/cropland area ratio
- land cover specification

2.3.3. References for detailed design

- **A02 Buffer strips and hedges**
<http://nwrn.eu/measure/buffer-strips-and-hedges>

2.3.4. SWAT+ model implementation

Option A - COCOA

The potential location of a field division by a buffer strip or a hedge row is defined as a unique spatial unit in the generation of the land use layer. With the developed model setup process this unit will become a unique object in the SWAT+ model setup. Through the division of a large agricultural field with this measure, the field polygon will also be split in two or more unique units. The initial land use of all split units will be defined the same as the land use of the initial agricultural field to which these areas initially belonged.

The implementation of the measure is performed by changing the land use and management from an agricultural land use to extensive grassland, woodland, or wetland forest (with the respective management), depending on the intended type of riparian buffer.

The initial and the alternative land use/management combinations should be predefined in the landuse.lum file. The land use change is performed by changing the 'lu_mgt' in the file hru-data.hru for the respective spatial units from the initial land use label to the one that represents the buffer strip. Fig. 3 additionally shows all links to input files where parameterizations must be defined for the initial and the alternative land use configuration. These parameterizations eventually affect the simulated hydrological processes and the nutrient transport in the SWAT+ simulations.

Pros:

- The model setup can account for the actual location and dimensions of the measure.
- The water balance will be simulated for the updated land use and can therefore also account for an increased evapotranspiration of e.g. forest land use.
- The retention effect is accounted for by the land use parameters and the routing between units and does not require additional empirical literature parameter values.

Cons:

- The input data preparation requires a manual implementation of potential measure locations (see example in Fig. 3).
- Potential measure locations add spatial units to the model setup and increase the simulation time.
- The simulation of the status quo can be affected by the split of a single field into the remaining field area and the potential measure location and can thus affect the simulation outputs.
- The link between large fields and small buffer strip areas may not be appropriately represented by the SWAT+ model (e.g., budgeting of water balance components)

in the small unit when adding large volumes of water, water that can potentially pass through the measure without residing there).

Option B – Default

In the parametric default approach, the main land use with its parametrization (e.g. `cn2` or `ov_mann`) remain unchanged. The buffer strip will be added to an HRU by adding a measure in the column 'vfs'. This can be done by either changing the label in the `landuse.lum` when the measure is implemented, which then points to the measure in the file `filterstrip.str`, or by initialising the measure in the default configuration and setting the value of the 'flag_fs' to 1 when the measure should be activated and reset it to 0 when removing the buffer strip/

Pros:

- The land use map that is implemented in the model setup, does not require additional work. The measure does not have to be considered in the initial land use layer.
- It is easy to implement the measure by activating a predefined parametrization.
- A potential measure location does not add spatial units in the model setup and does therefore not increase simulation time.
- The parametric implementation can make use of existing literature values that empirically assessed the effect of buffer strips.

Cons:

- The evapotranspiration does not change, as the effect of land use change on water balance components is not accounted for in the simulations (parametric approach).
- The spatial reference of the measure cannot be clearly defined. The measure will just be represented as a fraction of the lumped HRU area.
- It may be challenging to translate the measure design parameters into model parameters, although literature values may exist.
- The effect of a measure is defined by empirical parameters. Literature parameter values can vary and thus can impose large uncertainties on the simulated effect of this measure.

Options for modelling buffers strips and hedge rows are summarised in Fig 7 and in Tab. 5 describes the input variables required for modelling the measure.

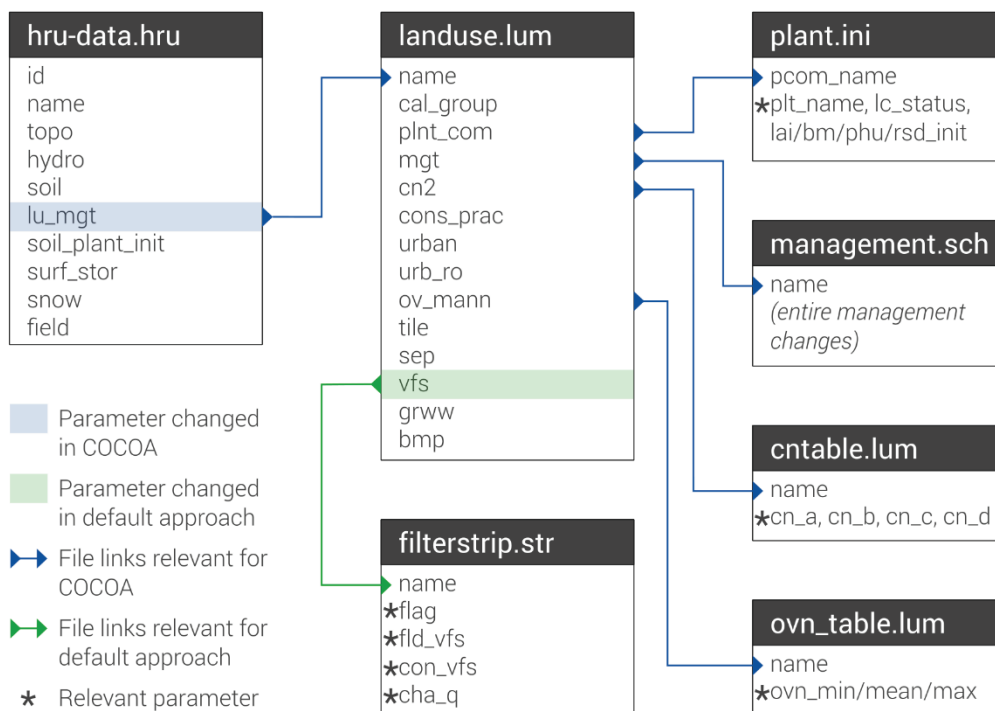


Fig. 7: Entity-Relationship Diagram for the SWAT+ model input files for the implementation of buffer strips and hedge rows. The blue and green highlighted input file values will be changed in the COCOA and the conventional model setup to implement buffers, respectively. The links refer to input files that are required to parameterize the NSWRM. Parameters that express the measure are indicated by an asterisk.

Table 5: Definition of the model parameters that are used to parameterize hedges in the Option A (COCO A) and option B (conventional).

Option A (COCO A)	
hru-data.hru	
Parameter	Definition
lu_mgt	The pointer to the land use and management file is a foreign key referencing name in landuse.lum.
landuse.lum	
Parameter	Definition
name	The name of the land use and management record is a primary key referenced by lu_mgt in hru-data.hru. All names in the landuse.lum file must be unique.
plnt_com	The pointer to the plant community file is a foreign key referencing the primary key name in plant.ini.
mgt	The pointer to the management schedule file is a foreign key referencing the primary key in name management.sch.

cn2	The pointer to the Curve Number database file is a foreign key referencing the primary key in name cntable.lum.
ov_mann	The pointer to the overland Manning's n database is a foreign key referencing the primary key in name ovn_table.lum.
plant.ini	
Parameter	Definition
pcom_name	The name of the plant community is a primary key referenced by plnt_com in landuse.lum. All names in the plant.ini file must be unique.
plt_name	The plant name is a foreign key referencing the primary key name in plants.plt.
lc_status	Land cover status at start of simulation (n - Plant not growing, y - Plant growing).
lai_init	Initial leaf area index.
bm_init	Initial plant biomass.
rsd_init	Initial residue cover.
cntable.lum	
Parameter	Definition
cn_a to cn_d	Curve number for hydrologic soil group A - D.
ovn_table.lum	
Parameter	Definition
ov_min/mean/max	This is the value that is used by the model. The ovn_min and ovn_max values are included in the file to help users stay within reasonable ranges during calibration.
Option B (default)	
landuse.lum	
Parameter	Definition
vfs	The pointer to the filter strip file is a foreign key referencing the primary key name in filterstrip.str.
filterstrip.str	
Parameter	Definition

flag_fs	Flag for the simulation of filter strips (1/0 - active/inactive).
fld_vfs	Ratio of field area to filter strip area (unitless). Ranges from 0 to 300 with values from 30-60 being most common. Default value is 10.
con_vfs	Fraction of the HRU which drains to the most concentrated ten percent of the filter's strip area. Runoff generated upslope a filter strip is not uniformly distributed across the entire length of the strip. Ten percent of the filter strip can receive between 0.25 and 0.75 of the runoff from the entire field. Default value is 0.5.
cha_q	This parameter defines the fraction of the flow within the most concentrated 10% of the filter strip that is fully channelized. Flow that is fully channelized is not subject to filtering or infiltration effects. Default value is 90.

2.4. Grassland cover - erosive slope

Grassed waterways are areas planted with grass or other permanent vegetative cover where water usually concentrates as it runs off a field. They can be either natural or man-made channels. Grass in the waterway slows the water, supports infiltration, reduce gully erosion and aid in trapping sediment.



Grassed waterway (source: Jane Thomas, Integration and Application Network ian.umces.edu/media-library)

The following specific example measures are contained in the group grassland cover - erosive slope.

- **Grassed waterways (1 Germany - Schwarzer Schöps)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_5935
- **Grassed waterways (10 Norway – Hobøl)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6169
- **Grassed waterway (talweg) (12 Czech Rep. – Čechtický)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6243

2.4.1. Measure design in reality

Grassed waterways are usually proposed for carrying the maximum runoff for a 10- year recurrence interval period. The size of the waterway depends upon the expected runoff. As the catchment area of the waterway increases towards the outlet, the expected runoff is calculated for different reaches of the waterway and used for design purposes. The waterway is to be given greater cross-sectional area towards the outlet as the amount of water gradually increases towards the outlet.

2.4.2. Design parameters

- Manning's roughness coefficient
- Sediment transport coefficient defined by user
- Depth
- Width
- Length
- Slope

2.4.3. References for detailed design

- **Estimation of Direct Runoff from Storm Rainfall**
<https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17752.wba>
- **Lesson 27 Grassed Waterways**
<http://www.jnkv.org/PDF/17042020105115introduction%20and%20design%20of%20grass%20ed%20waterways.pdf>

- **Manning's roughness coefficient**
<https://www.agric.wa.gov.au/water-management/mannings-roughness-coefficient#ManT2>
- **Sizing Grassed Waterways**
http://www.pfra.ca/doc/Erosion%20Control%20and%20Drainage/Sizing%20Grassed%20Waterways_EN.pdf

2.4.4. SWAT+ model implementation

Option A - COCOA

The potential location for the implementation of a grassed waterway is defined as a unique spatial unit in the generation of the land use layer. The delineation of the spatial unit in the landscape must account for the terrain properties of the field where the measure should be implemented. The polygon must be placed in the flow path of potential concentrated flow in the field and should also include the side slopes of an erosive channel that may already be visible in a field. The delineation is key to result in adequate values for the terrain properties of the separated spatial units (the remaining field area and the potential area for the grassed waterway).

The separated units in the land cover map become separate land objects in the SWAT+ model setup. The initial land use parameterization of the potential location of the grassed waterway is defined by the land use of the remaining field area. The implementation of the measure is performed by changing the land use and management from an agricultural land use to extensive grassland.

The initial and the alternative land use/management combinations should be predefined in the landuse.lum file. The land use change is performed by changing the 'lu_mgt' in the file hru-data.hru for the respective spatial units from the initial land use label to the one that represents the extensive grassland land use of the grassed waterway. Fig. 8 additionally shows all links to input files where parameterizations have to be defined for the initial and the alternative land use configuration. These parameterizations eventually affect the simulated hydrological processes and the nutrient transport in the SWAT+ simulations.

Pros:

- The model setup can account for the actual location and dimensions of the measure.
- The water balance will be simulated for the updated land use and can therefore also account for an increased evapotranspiration of e.g., forest land use.
- The retention effect is accounted for by the land use parameters and the routing between units and does not require additional empirical literature parameter values.

Cons:

- The input data preparation requires a manual implementation of potential measure locations (see example in Fig. 3).
- The delineation of the measure and the definition of the measure dimensions require great knowledge of the terrain.

- The terrain properties of the land units of the model setup can be sensitive to the delineation of the measure.
- Potential measure locations add spatial units to the model setup and increase the simulation time.
- The link between large fields and small grassed areas may not be appropriately represented by the SWAT+ model (e.g., budgeting of water balance components in the small unit when adding large volumes of water, water that can potentially pass through the measure without residing there).

Option B – Default

Grassed waterways were added as a measure in SWAT+. Waterways are treated as trapezoidal channels with 8:1 side slope (a very gentle “bank” slope – e.g. one meter height on eight meters length). The deposition of sediment and organic nutrients is calculated in the same manner as in SWAT+ subbasin tributary channels. The primary user inputs are waterway width and length.

In the parametric default approach, the main land use with its parametrization (e.g., `cn2` or `ov_mann`) remain unchanged. The grassed waterway will be implemented in an HRU by adding a measure in the column ‘`grww`’ in the input file `landuse.lum`. This can be done, by either changing the label in the `landuse.lum` when the measure is implemented, which then points to the measure in the file `filterstrip.str` or by initialising the measure in the default configuration and setting the value of the ‘`flag_grww`’ to 1 when the measure should be activated and reset it to 0 when removing the buffer strip.

Pros:

- The land use map that is implemented in the model setup, it does not require additional work. The measure does not have to be considered in the initial land use layer.
- It is easy to implement the measure by activating a predefined parametrization.
- A potential measure location does not add spatial units in the model setup and does therefore not increase simulation time.
- The parametric implementation can make use of existing literature values that empirically assessed the effect of grassed waterways.

Cons:

- The evapotranspiration does not change, as the effect of land use change on water balance components is not accounted for in the simulations (parametric approach).
- The spatial reference of the measure cannot be clearly defined. The measure will be represented as a fraction of the lumped HRU area.
- It may be challenging to translate the measure design parameters into model parameters, although literature values may exist.
- The effect of a measure is defined by empirical parameters. Literature parameter values can vary and thus can impose large uncertainties on the simulated effect of this measure.

Options for the modelling of grassed waterways are summarised in Fig 8. Table 6 describes the input variables required for modelling the measure.

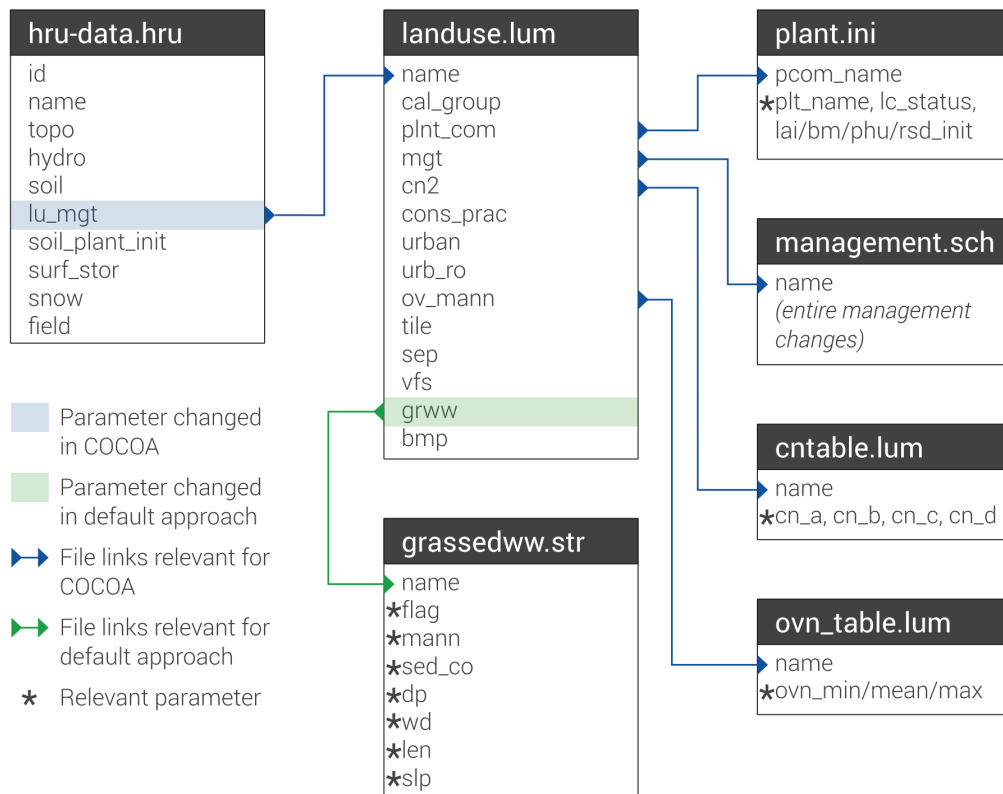


Fig. 8: Entity-Relationship Diagram for the SWAT+ model input files for the implementation of grassed waterways. The blue and green highlighted input file values will be changed in the COCOA and the conventional model setup to implement grassed waterways, respectively. The links refer to input files that are required to parameterize the NSWRM. Parameters that express the measure are indicated by an asterisk.

Table 6: Definition of the model parameters that are used to parameterize grassed waterways in the Option A (COCO) and option B (conventional).

Option A (COCO)	
hru-data.hru	
Parameter	Definition
lu_mgt	The pointer to the land use and management file is a foreign key referencing name in landuse.lum.
landuse.lum	
Parameter	Definition
name	The name of the land use and management record is a primary key referenced by lu_mgt in hru-data.hru.. All names in the landuse.lum file must be unique.
plnt_com	The pointer to the plant community file is a foreign key referencing the primary key name in plant.ini.

mgt	The pointer to the management schedule file is a foreign key referencing the primary key in name management.sch.
cn2	The pointer to the Curve Number database file is a foreign key referencing the primary key in name cntable.lum.
ov_mann	The pointer to the overland Manning's n database is a foreign key referencing the primary key in name ovn_table.lum.
plant.ini	
Parameter	Definition
pcom_name	The name of the plant community is a primary key referenced by plnt_com in landuse.lum. All names in the plant.ini file must be unique.
plt_name	The plant name is a foreign key referencing the primary key name in plants.plt.
lc_status	Land cover status at start of simulation (n - Plant not growing, y - Plant growing).
lai_init	Initial leaf area index.
bm_init	Initial plant biomass.
rsd_init	Initial residue cover.
cntable.lum	
Parameter	Definition
cn_a to cn_d	Curve number for hydrologic soil group A - D.
ovn_table.lum	
Parameter	Definition
ov_min/mean/max	This is the value that is used by the model. The ovn_min and ovn_max values are included in the file to help users stay within reasonable ranges during calibration.
Option B (default)	
landuse.lum	
Parameter	Definition
vfs	The pointer to the filter strip file is a foreign key referencing the primary key name in filterstrip.str.

filterstrip.str	
Parameter	Definition
flag_grww	Flag for the simulation of grassed waterway (1/0 - active/inactive).
mann	Manning's n for grassed waterway. Value mwidthanning's n for grassed waterway can receive between 0.001 - 0.5. Default value is 0.1.
sed_co	Sediment transport coefficient. Value sediment transport coefficient for grassed waterway can receive between 0.0 - 1.0. Default value is 0.01.
dp	Depth of grassed waterway. Value depth for grassed waterway can receive between 0.0 - 10.0. Default value is 10.0. The value is entered in metres.
wd	Width of grassed waterway. Value width for grassed waterway can receive between 0.0-1000.0. Default value is 1 000.0. The value is entered in metres.
len	Length of grassed waterway. Value length for grassed waterway can receive between 0.0-10 000.0. Default value is 10 000.0. The value is entered in kilometres (km).
slp	Slope of grassed waterway. Value slope for grassed waterway can receive between 0.0 - 1.0. Default value is 1.0. The value is entered like ratio length and high in metres (m/m).

2.5. Grassland cover - Grassing arable land/targeted in recharge area

Grassing targeted in recharge area is a measure intended to slow down the subsurface water runoff and transport of pollution by tile drainage, coming from these sites. Recharge areas contain shallow soils with low water and nutrient retention potential. I.e., soils that enable rapid infiltration and transport of solutes through the soil profile into tile drains / groundwater. These areas are often hydrologically connected to land drainage, which then transports large amounts of pollution (N, pesticides) from land to waters. By grassing of arable land in the recharge area, the input of N and pesticides is lower, consumption/decomposition of N is higher and all-season.

The following specific example measures are contained in the group grassland cover - grassing arable land/targeted in recharge area.

- **Grassing targeted into Recharge area** (A01 Meadows and pastures)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_5934
- **Green cover of arable land (6 Slovenia / Hungary -Kebele- Kobiljski potok)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6238

2.5.1. Measure design in reality

In areas with the presence of tile drainage and also in parts of the field blocks with more than 50% of shallow, permeable soils in the recharge area. The design (grassed shape) should to a certain extent take into account also the options for machinery access and cultivability.

2.5.2. Design parameters

- Area
- Grass type (for Manning ´s roughness setting)
- Soil infiltration conditions (categorized)

2.5.3. SWAT+ model implementation

From a modelling perspective the implementation of a grassland cover in the recharge area of a field must consider two aspects: i) A specific part of a field block or an arable landscape must be converted to grassland land use. ii) As the measure has a focus on the retention of drainage water, the connectivity of tile flow from the arable area into the recharge area in the SWAT model setup will be relevant.

Option A - COCOA

The identified recharge area in the landscape is delineated as a unique spatial unit in the generation of the land use layer. The delineation of the spatial unit in the landscape must account for the terrain properties of the field where the measure should be implemented. The polygon must be placed in the recharge area where concentrated flow from the upland arable area would route surface and subsurface flow. The

delineation is key to result in adequate values for the terrain properties of the separated spatial units (the remaining field area and the potential area for the grassed waterway).

The separated units in the land cover map become separate land objects in the SWAT+ model setup. The initial land use parameterization of the potential location of the grassed recharge area is defined by the land use of the remaining arable land. The implementation of the measure is performed by changing the land use and management from an agricultural land use to extensive grassland and by additional modifications in the routing of tile flow from the drained arable upland area into the now grassed recharge area.

The initial and the alternative land use/management combinations should be predefined in the landuse.lum file. The land use change is performed by changing the 'lu_mgt' in the file hru-data.hru for the respective spatial units from the initial land use label to the one that represents the extensive grassland land use of the grassed recharge area. In the initial model setup without a grassed recharge area the drained arable land will route its tile flow to its receiving channel. With the measure in place tile flow is routed into the grassed recharge area where the water will be further routed into the receiving waters and the groundwater. The changes in the routing are performed in the 'rout_unit.con'. For each spatial land unit (routing unit) the connections to other spatial objects (with object type (obj_typ) and object id (obj_id)) are defined. The different flow types (hyd_typ, e.g., total, surface, lateral, tile flow, etc.) and their fractions (frac) to the other spatial objects are defined here. For the spatial unit of the drained arable land the connection of the tile flow to the channel object will be changed to then route into the grassed recharge area.

Fig. 9 shows all links to input files where parameterizations have to be defined for the initial and the alternative land use configuration. These parameterizations eventually affect the simulated hydrological processes and the nutrient transport in the SWAT+ simulations.

Pros:

- The model setup can account for the actual location and dimensions of the measure.
- The measure can be represented with a great degree of detail (apportionment of land areas, connectivity of tile flow, etc.)
- The water balance will be simulated for the updated land use and can therefore also account for changed evapotranspiration and the soil water budget due to the additionally routed tile flow.
- The retention effect is accounted for by the land use and soil parameters and the routing between units and does not require additional empirical literature parameter values.

Cons:

- The input data preparation requires a manual implementation of potential measure locations (see example in Fig. 3).
- The delineation of the measure and the definition of the measure dimensions require great knowledge of the terrain.

- The terrain properties of the land units of the model setup can be sensitive to the delineation of the measure.
- Changes in the water routing is highly error prone and has to be implemented with great care.
- Potential measure locations add spatial units to the model setup and increase the simulation time.
- The link between large fields and small grassed areas may not be appropriately represented by the SWAT+ model (e.g. budgeting of water balance components in the small unit when adding large volumes of water, water that can potentially pass through the measure without residing there).

Option B – Default

SWAT+ does not offer a parametric approach for the implementation of this measure. Hence, in a conventional model setup, changes in the routing may be required as they are described for the option A above. Yet, the advanced user may adopt such strategy to represent such measure in the model:

- Target only floodplain HRUs where the measure will be modelled.
- Initiate an HRU division in the floodplain area using DTs.
- Initiate land-use change for divided HRUs (using DTs).
- If necessary, remove or alter tile drains, management, and other practices (using DTs).

Pros:

- Mimics the parametric approach by changing the land-use fractions.

Cons:

- Untested approach in SWAT+: A proper representation of this measure may be difficult or even infeasible with a parametric approach.
- Requires advanced knowledge of the model and setup.
- Needs manual manipulation of model setup files (lsu_unit.ele and rout_unit.ele). Alteration via the interfaces is not available (as of August, 2022).

Options for the modelling of grassed recharge areas are summarised in Fig 9. Tab. 7 describes the input variables required for modelling the measure.

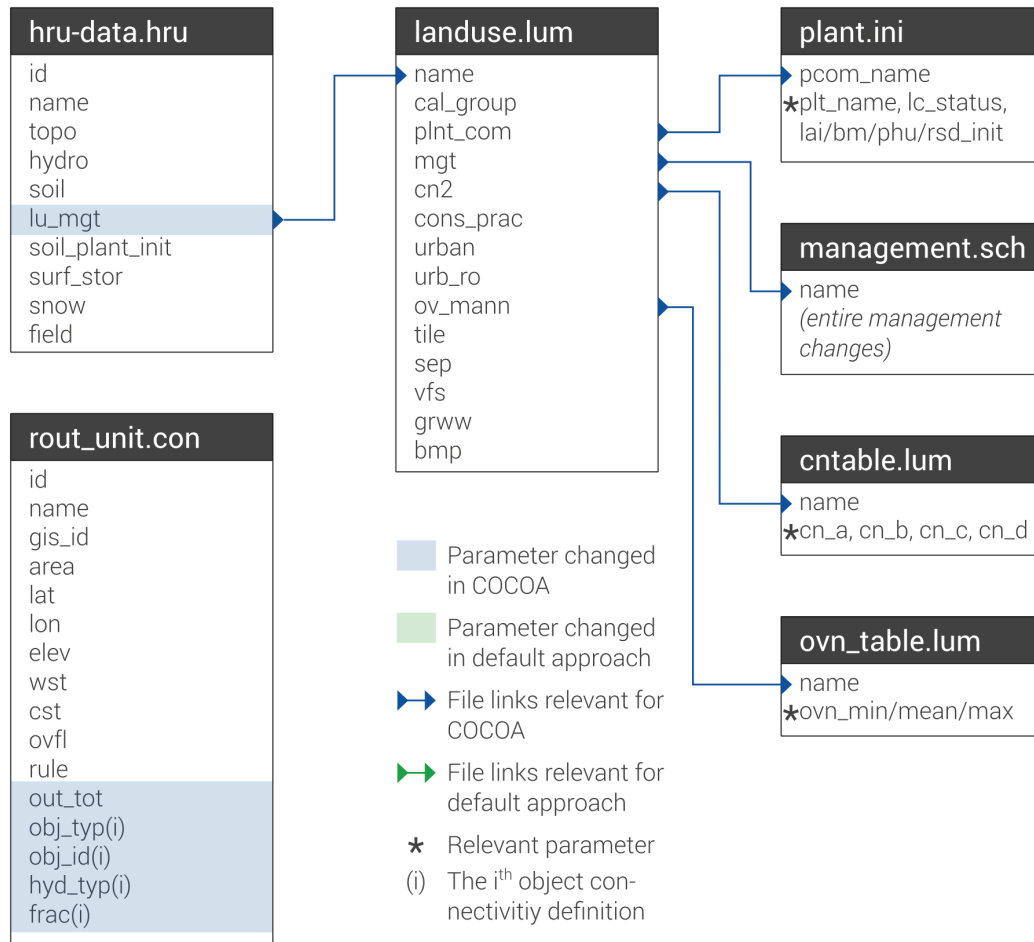


Fig. 9: Entity-Relationship Diagram for the SWAT+ model input files for the implementation of grassed recharge areas. The blue highlighted input file values will be changed in the COCOA model setup to implement grassed recharge areas. The links refer to input files that are required to parameterize the NSWRM. Parameters that express the measure are indicated by an asterisk.

Table 7: Definition of the model parameters that are used to parameterize grassed recharge areas.

Option A (COCO A)	
hru-data.hru	
Parameter	Definition
lu_mgt	The pointer to the land use and management file is a foreign key referencing name in landuse.lum.
landuse.lum	
Parameter	Definition
name	The name of the land use and management record is a primary key referenced by lu_mgt in hru-data.hru. All names in the landuse.lum file must be unique.

plnt_com	The pointer to the plant community file is a foreign key referencing the primary key name in plant.ini.
mgt	The pointer to the management schedule file is a foreign key referencing the primary key in name management.sch.
cn2	The pointer to the Curve Number database file is a foreign key referencing the primary key in name cntable.lum.
ov_mann	The pointer to the overland Manning's n database is a foreign key referencing the primary key in name ovn_table.lum.
plant.ini	
Parameter	Definition
pcom_name	The name of the plant community is a primary key referenced by plnt_com in landuse.lum. All names in the plant.ini file must be unique.
plt_name	The plant name is a foreign key referencing the primary key name in plants.plt.
lc_status	Land cover status at start of simulation (n - Plant not growing, y - Plant growing).
lai_init	Initial leaf area index.
bm_init	Initial plant biomass.
rsd_init	Initial residue cover.
cntable.lum	
Parameter	Definition
cn_a to cn_d	Curve number for hydrologic soil group A - D.
ovn_table.lum	
Parameter	Definition
ov_min/mean/max	This is the value that is used by the model. The ovn_min and ovn_max values are included in the file to help users stay within reasonable ranges during calibration.
rout_unit.con	
Parameter	Definition
out_tot	Total number of outgoing hydrographs. Default value is 1, maximum value is 12. The next four columns (obj_typ, obj_id, hyd_typ, frac) are repeated for each outgoing hydrograph.

obj_typ	Type of the receiving object (string). <table border="1" data-bbox="485 237 858 465"> <thead> <tr> <th data-bbox="485 237 655 271">Code</th> <th data-bbox="655 237 858 271">Definition</th> </tr> </thead> <tbody> <tr> <td data-bbox="485 271 655 304">hru</td> <td data-bbox="655 271 858 304">HRU</td> </tr> <tr> <td data-bbox="485 304 655 338">hlt</td> <td data-bbox="655 304 858 338">HRU-lte</td> </tr> <tr> <td data-bbox="485 338 655 371">ru</td> <td data-bbox="655 338 858 371">Routing Unit</td> </tr> <tr> <td data-bbox="485 371 655 405">aqu</td> <td data-bbox="655 371 858 405">Aquifer</td> </tr> <tr> <td data-bbox="485 405 655 439">cha</td> <td data-bbox="655 405 858 439">Channel</td> </tr> <tr> <td data-bbox="485 439 655 472">res</td> <td data-bbox="655 439 858 472">Reservoir</td> </tr> </tbody> </table>	Code	Definition	hru	HRU	hlt	HRU-lte	ru	Routing Unit	aqu	Aquifer	cha	Channel	res	Reservoir
Code	Definition														
hru	HRU														
hlt	HRU-lte														
ru	Routing Unit														
aqu	Aquifer														
cha	Channel														
res	Reservoir														
obj_id	ID of the receiving object.														
hyd_typ	Type of hydrograph that is sent to the receiving object.														
frac	Fraction of hydrograph sent to the receiving object.														

2.6. Retention/detention ponds

In the nwrn.eu catalogue, retention and detention ponds are described in the following three categories.

N01 Basins and ponds

<http://nwrn.eu/measure/basins-and-ponds>

Detention basins and ponds are water bodies storing surface run-off. A detention basin is free from water in dry weather flow conditions, whereas a pond (e.g., retention ponds, flood storage reservoirs, shallow impoundments) contains water during dry weather, and is designed to hold more when it rains.

U10 Detention Basins

<http://nwrn.eu/measure/detention-basins>

Detention basins are vegetated depressions designed to hold runoff from above situated areas and allow the settling of sediments and associated pollutants. Stored water may be slowly drained to a nearby watercourse, using an outlet control structure to control the flow rate. Detention basins do not generally allow infiltration: see U12 for infiltration basins. Detention basins can provide water quality benefits through physical filtration to remove solids/trap sediment, adsorption to the surrounding soil or biochemical degradation of pollutants. Detention basins are landscaped areas that are dry except in periods of heavy rainfall, and may serve other functions (e.g., recreation), hence have the potential to provide ancillary amenity benefits. They are ideal for use as laying fields, recreational areas, or public open space. They can be planted with trees, shrubs, and other plants, improving their visual appearance, and providing habitats for wildlife (NWRM, 2019).



Detention pond

(Source: <http://archive.inside.iastate.edu/2008/0703/rain.shtml>)

U11 Retention Ponds

<http://nwrn.eu/measure/retention-ponds>

Retention ponds are ponds or pools designed with additional storage capacity to attenuate surface runoff during rainfall events. They consist of a permanent pond area with landscaped banks and surroundings to provide additional storage capacity during rainfall events. They are created by using an existing natural depression, by excavating a new depression, or by constructing embankments. Existing natural water bodies should not be used due to the risk that pollution events and poorer water quality might disturb/damage the natural ecology of the system. Retention ponds can provide both storm water attenuation and water quality treatment by providing additional storage capacity to retain runoff and release this at a controlled rate. Ponds can be designed to control runoff from all storms by storing surface drainage and releasing it slowly once

the risk of flooding has passed. Runoff from each rain event is detained and treated in the pond. The retention time and still water promotes pollutant removal through sedimentation, while aquatic vegetation and biological uptake mechanisms offer additional treatment. Retention ponds have good capacity to remove urban pollutants and improve the quality of surface runoff (NWRM, 2019).



Retention pond

(Source: <https://stormwater.pca.state.mn.us>)

The following specific example measures are contained in the group retention/detention ponds:

- **Retention or detention ponds** (1 Germany - Schwarzer Schöps)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6265
- **Basins and Ponds** (5 Austria / Slovenia – Pesnica)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_5933
- **Water storage reservoirs** (9 Italy – Cherio)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6254
- **Water retention areas along the river** (9 Italy – Cherio)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_5931
- **Water Level Adjustment Threshold** (13 Latvia – Deviete)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_5937

2.6.1. Measure design in reality

A **detention pond** is designed to hold water for a short period of time before allowing the water to discharge to a nearby stream. Detention ponds control peak flows of runoff, help improve water quality, reduce transportation of nutrient loads, and lessen the effects of erosion. Between rain events, a detention pond looks like a large, grassy low area. When it rains, the pond fills with water. They hold water for 48-72 hours to allow sediment and pollutants to settle out. Because they detain water for a brief time before allowing it to flow out, detention ponds are also called dry ponds.

- Pond with a certain volume (capacity, m³); surface area (m²); at a certain location.
- Location at the end of the erosive thalwegs; only at the larger ones.
- The pond volume remains empty (the absence of a permanent pool of water).

A **retention pond**, on the other hand, maintains a permanent pool of water throughout the year. They remove pollutants by allowing sediment to settle as water slowly moves from one end of the pond to the other and through biological uptake, as plants absorb excess nutrients. Retention ponds frequently have smaller pools, plants, and a wetland area. Wet pond water levels can increase dramatically as a result of rainstorms, like dry ponds. Because they retain water for a longer time, retention ponds are also called wet ponds.

- Pond with a certain volume (capacity, m³); surface area (m²); at a certain location.
- Generally, at the most vulnerable sites, directly connected to streams, municipalities, close to the municipalities.

2.6.2. Design parameters

- Pond area/drainage area ratio.
- Water retention time under average conditions / N-year water runoff periodicity.

2.6.3. References for detailed design

- **Retention ponds**
<http://nwrn.eu/measure/retention-ponds>
- **Measures for water protection and nutrient reduction**
https://wrs.se/wp-content/uploads/2014/03/Owenius_Measures-for-water-protection_Baltic-Compass_2011.pdf
- **Stormwater Pond Design, Construction and Sedimentation**
<https://www.clemson.edu/extension/water/stormwater-ponds/problem-solving/construct-repair-dredge/index.html>

2.6.4. SWAT+ model implementation

From a modelling perspective the implementation of detention basin/retention pond must consider two aspects. i) Surface runoff that - due to the terrain concentrates - has to be collected by a storage volume and ii) has to be released to a receiving water body. The runoff peak is dampened because of the retention in the water storage.

Option A - COCOA

A potential area in the landscape/terrain where surface runoff accumulates (and maybe even a potential depression is already in place) has to be identified. The identified potential location in the landscape is delineated as a unique spatial unit in the generation of the land use layer. The polygon must be placed in the recharge area where concentrated flow from the upland area would route surface and subsurface flow. A proper delineation is key as it affects the fractions of surface runoff that is routed through the spatial unit, and which eventually influences the volume of water which the retention/detention basin receives.

The potential location of the detention basin/retention pond becomes a unique land object in the SWAT+ model setup. The initial land use parameterization of the potential location of the detention basin/retention pond is defined by the initial land use of the potential location.

Detention basins

A detention pond is best represented by a wetland area. Wetland objects can simulate plant growth like other HRU objects and can store and release water based on rules as a reservoir does. A wetland object is, unlike a reservoir, an HRU object. Thus, to implement a detention pond, the initial land use of the discretized land object is changed, and a wetland is added to this HRU object. Additionally, the routing of the water from the wetland has to be modified. The water that leaves the wetland is no longer routed to the neighbouring land units but will be routed from the wetland to a receiving stream water body.

The initial land unit is defined in the hru-data.hru file. Its connectivity to other land objects is given with the file rout_unit.con. The land use change is performed by pointing to an alternative land use in the landuse.lum (similar to other measures above). The initial land object is replaced by a connectivity to the receiving channel in the rout_unit.con. In order to control the release of the wetland, release rule sets can be defined in the file res_rel.dtl to which the variable 'rel' will point to.

Retention ponds

In the case of a retention pond the implementation of the measure is performed by replacing the initial land object and its routing with a reservoir object that receives the same surface water fluxes as the initial object, but which has a changed connectivity for its water and nutrient emissions. Also, in the case of a reservoir the water that leaves the reservoir is no longer routed to the neighbouring land units, but will be routed from to a receiving stream water body. As the new object is now a reservoir and not an HRU or RTU object anymore, the routing to the receiving water is defined in the reservoir.com file.

The initial land unit is defined in the hru-data.hru file. Its connectivity to other land objects is given with the file rout_unit.con. With the introduction of the reservoir object in the model setup, the land object and its connectivity are removed from the model setup and replaced by the new reservoir object. The new reservoir object is defined in the file reservoir.res. The connectivities of the land objects that sent water fluxes to the initial land object are changed to now send the respective water fractions to the reservoir object. The new reservoir object will be connected to a channel in the stream network to which it releases the collected water fluxes. In order to control the release of the reservoir, release rule sets can be defined in the file res_rel.dtl to which the variable 'rel' will point to.

Pros:

- The model setup can account for the actual location and dimensions of the measure.
- The measure can be represented with a great degree of detail (land area which is apportioned to pond and not available for other land use anymore, connectivity with local catchment area of the pond, release to receiving channel)
- If e.g. a detention pond is combined with a grassland area the water balance will be simulated for the updated land use and can therefore also account for changed evapotranspiration and the soil water budget
- The retention effect is accounted for by influx of the local catchment of the reservoir and the release rules of the reservoir

Cons:

- The input data preparation requires a manual implementation of potential measure locations.

- The delineation of the measure and the definition of the measure dimensions require great knowledge of the terrain.
- The final location and dimension of the potential pond area polygon in the land use layer can have a strong effect on the calculation of the local catchment of this polygon and eventually affect the connectivities of water fluxes between land objects and the pond area.
- Potential measure locations add spatial units to the model setup and increase the simulation time.

Option B - Default

Detention and retention ponds can be simulated using either a pond object or a wetland. The nutrient settling and uptake is simulated in the same way, as is the water release. The main difference between the two representations is that the wetland is considered a land-use object, part of an HRU (meaning that certain management can be assigned to this object), whereas a pond is a separate spatial object that only holds and, if applicable, releases water to the next downstream channel/object.

Detention basins or ponds can be represented as HRUs that allow water to be stored on the surface. SURF_STOR column in the hru-data.hru file points to the wetland file. The pointer to the wetland file is a foreign key referencing the name in wetland.wet. The wetland.wet file (and associated files, i.e., hydrology.wet) should be changed to hold the information about the pond. The stored water will be released whenever the water volume exceeds the normal storage volume of the wetland.

Pros:

- Simple and flexible way to parametrise.
- Can be done after the initial model setup.
- Management operations can be assigned to the HRUs (i.e., to remove grass cover).
- Presence of vegetation is modelled: nutrients can be uptaken by the vegetation.

Cons:

- Proper parameterization requires some GIS calculations (i.e., fraction of HRU).
- Routing has to be adjusted to enable a realistic representation.
- Has to be placed in areas with impermeable soils.
- All adjustments are done on an HRU-level, which does not account for an actual position or a specific location within a watershed.
- Seepage parameters must be adjusted to restrict water loss through the bottom of the wetland.
- Sediment and nutrient processes modelled in ponds and wetlands are identical, they use a simplistic mass balance approach.

Retention ponds have to be modelled as a pond object. Pond outflow is calculated as a function of target storage. The target storage varies based on flood season and soil water content. The pond object and its location have to be predefined in the model initiation phase.

Pros:

- Easy setup when the initial location is known.
- Parameters can be adapted to represent the exact conditions.

Cons:

- Seepage parameters have to be adjusted to allow water loss through the bottom of the pond.
- Has to be pre-defined during the project setup.
- Difficult to implement mid-simulation, although possible using DTs
- Sediment and nutrient processes modelled in ponds and wetlands are identical, they use a simplistic mass balance approach.

2.7. Afforestation

In the nwrn.eu catalogue, Afforestation are described in the following three categories.

F03 Afforestation of reservoir catchments

<http://nwrn.eu/measure/afforestation-reservoir-catchments>

Planting trees in reservoir catchments can have both positive and negative effects. Afforestation of previously bare or heavily eroded areas can control soil erosion, thereby mitigating the silting of the reservoir and improving water quality. Water quality can also be improved if precipitation is able to infiltrate into forest soils before flowing to the reservoir. These potential improvements in water quality need to be balanced against the possibility that less precipitation will be available for reservoir recharge due to the potentially greater interception and evapotranspiration associated with forests. Studies have indicated a decrease of water yield after afforestation of the catchment and with the increase of forest age. Forests in reservoir catchments should typically not be managed for timber production but maintained in as close to a natural state as possible as the fertilization and ground disturbance associated with intensive forest management can have negative impacts on reservoir water quality. Increased acidification and eutrophication after afforestation with conifer species have also been reported. Use of long-lived native deciduous tree species for afforestation instead of fast-growing conifers or eucalypts is likely to bring enhanced biodiversity benefits while minimizing water loss (NWRM, 2019).



Lučina water reservoir (Source: <https://cs.wikipedia.org>)

F05 Land use conversion

<http://nwrn.eu/measure/land-use-conversion>

Land use conversion is a general term for large scale geographic change. Afforestation is one such land conversion in which trees are planted on previously non-forested areas. Afforestation may occur deliberately or through the abandonment of marginal agricultural land. Depending on the tree species planted and the intensity of forest management, afforestation may have more or less environmental benefits. The NWRM related benefits include potentially enhanced evapotranspiration associated with growing forests and better water holding capacity associated with forest soils. The greatest environmental benefits are probably associated with planting of indigenous broadleaves and low intensity forestry. Plantation forestry with exotic species is likely to be less beneficial to the environment. It should be mentioned that afforestation in dry

areas can cause or intensify water shortage. Even though afforestation may reduce available water supply at local scale, forest cover increases water supply regionally and globally, in particular through the intensification of the water cycle (NWRM, 2019).



*Afforestation of a hill
(Source: Gebhard Schueler's
presentation, NWRM Workshop 1)*

F02 Maintenance of forest cover in headwater areas

<http://nwrn.eu/measure/maintenance-forest-cover-headwater-areas>

Headwaters are the source areas for rivers and streams, crucial for sustaining the structure, function, productivity and complexity of downstream ecosystems. They are vital to hydrologic cycling as they are one of the main areas where precipitation contributes to surface and groundwater. Headwaters are typically less intensively used than downstream areas. In many headwater areas, extensive agriculture, forests or other semi-natural land cover types predominate. Forests in headwater areas have a beneficial role for water quantity and quality. Creating or maintaining forest cover in headwater catchments is a widely used practice in many major cities including New York, Istanbul and Singapore, as these cities are reliant on headwater forests for drinking water provisioning. Forest soils generally have better infiltration capacity than other land cover types and may act as a “sponge”, slowly releasing rainfall. In areas of high relief, afforestation of headwater catchments can contribute to slope stabilization and may reduce the risks associated with landslides. On the other hand, afforestation of headwaters in dry areas may lead to reduction of water yield (NWRM, 2019).

The following specific example measures are contained in the group afforestation:

- **Maintenance of forest cover in headwaters** (7 Belgium - La Wimbe)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_5925
- **Afforestation of reservoir catchments** (4 Poland - Upper Zgłowiaczka)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6255

2.7.1. Measure design in reality

Afforestation is the establishment of a forest or stand of trees (forestation) in an area where there was no previous tree cover. The establishment of new woodlands and forests on agricultural land is carried out to protect the environment: protection of soil erosion, enhancement of water retention and water quality, limiting greenhouse gas emissions, supporting carbon sequestration, and biodiversity. Sites proposed for afforestation may also meet the minimum timber productivity, if the main forest function is expected to be wood output.

The criteria and principles for agricultural land afforestation are mainly based on soil and terrain characteristics of farmland. Usually, afforestation is recommended (and favoured in subsidies - in some countries) on steeper slopes (7° and more or 12° and more) and/or on waterlogged soils, shallow / stony soils or at sites with less fertile soils, unsuitable for farming. Recommended (and higher subsidised) are the tree species which are site-natural. Among the major reasons for the afforestation of agricultural and other non-forest soils are the following: improving the economics compared to fallow land, soil erosion control, water management conditions, influence on microclimate, enhancement of biodiversity (locally or by connection of these sites), the recreational use of landscape, use of anthropogenically affected soils, areas after mining raw materials.

2.7.2. Design parameters

- Area
- Land cover specification

2.7.3. References for detailed design

- **Environmental Requirements for Afforestation**
www.agriculture.gov.ie/forests-service
- **Afforestation and reforestation as adaptation opportunity**
<https://climate-adapt.eea.europa.eu/metadata/adaptation-options/afforestation-and-reforestation-as-adaptation-opportunity>

2.7.4. SWAT+ model implementation

Option A – COCOA and option B - default

Afforestation is represented in a SWAT+ model setup by a land use conversion from any initial land use to a forest land use. The major difference between COCOA and the default approach is that in a COCOA setup each land object has a local catchment (i.e. that other land objects route into the respective land unit), while only floodplain units in a conventional QSWAT+ model setup receive water from upland HRUs. Thus, a land use change in a COCOA model setup also affects the water fluxes from other land objects on their way to a receiving water, while in the conventional setup a land use change in an upland HRU would only affect its own water balance and the water flux to a possible floodplain and the receiving channel.

The implementation of the measure is in both model setup procedures performed by changing the land use and management from the initial land use to a forest land use (with the respective management).

The initial and the alternative land use/management combinations should be predefined in the landuse.lum file. The land use change is performed by changing the 'lu_mgt' in the file hru-data.hru for the respective spatial units from the initial land use label to the one that represents the buffer strip. Fig. 10 additionally shows all links to input files where parameterizations have to be defined for the initial and the alternative land use configuration. These parameterizations eventually affect the simulated hydrological processes and the nutrient transport in the SWAT+ simulations.

Pros of COCOA connectivity:

- The model setup can account for the actual location and dimensions of the measure.
- The implementation accounts for the connectivity with the surrounding local catchment of the respective land unit.
- The retention effect due to the updated forest land use on fluxes from other land objects is accounted for with COCOA.

Cons of COCOA:

- The link between large and small land units may not be appropriately represented by the SWAT+ model (e.g. budgeting of water balance components in the small unit when adding large volumes of water).

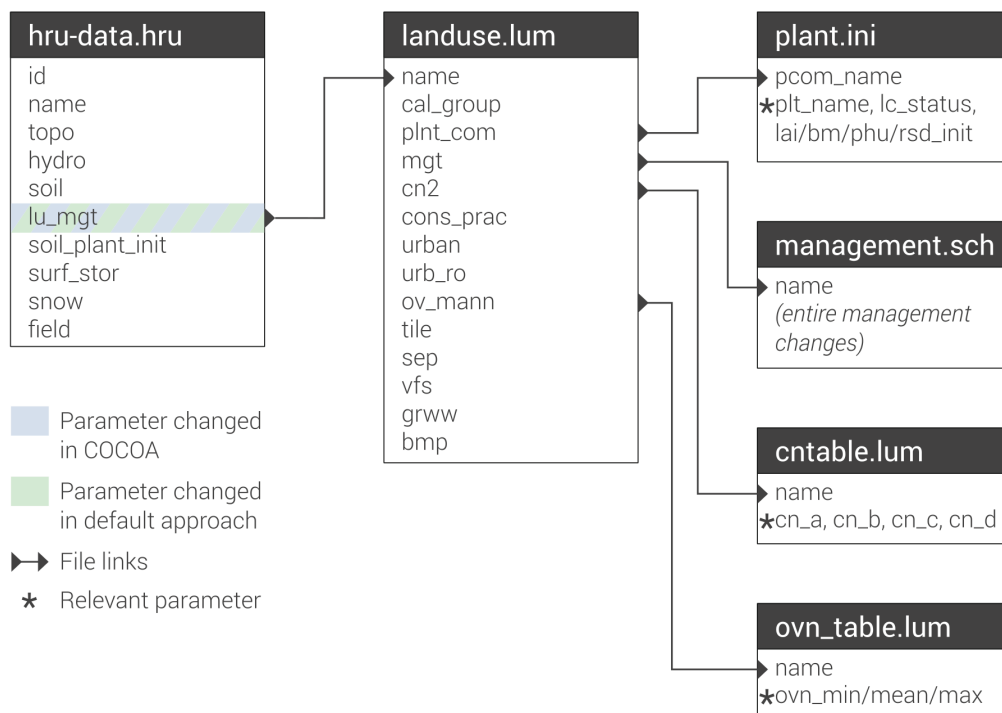


Fig. 10: Entity-Relationship Diagram for the SWAT+ model input files for the implementation of afforested areas. The green/blue highlighted input file value will be changed in the COCOA and default model setup to perform the land use change. The links refer to input files that are required to parameterize the NSWRM. Parameters that express the measure are indicated by an asterisk.

Table 8: Definition of the model parameters that are used to parameterize afforested areas.

Option A (COCOA)	
hru-data.hru	
Parameter	Definition
lu_mgt	The pointer to the land use and management file is a foreign key referencing name in landuse.lum.
landuse.lum	
Parameter	Definition
name	The name of the land use and management record is a primary key referenced by lu_mgt in hru-data.hru. All names in the landuse.lum file must be unique.
plnt_com	The pointer to the plant community file is a foreign key referencing the primary key name in plant.ini.
mgt	The pointer to the management schedule file is a foreign key referencing the primary key in name management.sch.
cn2	The pointer to the Curve Number database file is a foreign key referencing the primary key in name cntable.lum.
ov_mann	The pointer to the overland Manning's n database is a foreign key referencing the primary key in name ovn_table.lum.
plant.ini	
Parameter	Definition
pcom_name	The name of the plant community is a primary key referenced by plnt_com in landuse.lum . All names in the plant.ini file must be unique.
plt_name	The plant name is a foreign key referencing the primary key name in plants.plt.
lc_status	Land cover status at start of simulation (n - Plant not growing, y - Plant growing).
lai_init	Initial leaf area index.
bm_init	Initial plant biomass.
rsd_init	Initial residue cover.
cntable.lum	
Parameter	Definition

cn_a to cn_d	Curve number for hydrologic soil group A - D.
ovn_table.lum	
Parameter	Definition
ov_min/mean/max	This value is used by the model. The ovn_min and ovn_max values are included in the file to help users stay within reasonable ranges during calibration.

2.8. River restoration - Floodplain

N03 Floodplain restoration and management

<http://nwrn.eu/measure/floodplain-restoration-and-management>

A floodplain is the area bordering a river that naturally provides space for the retention of flood and rainwater. Floodplain soils are generally very fertile, and they have often been dried-out to be used as agricultural land. Floodplains in many places have also been separated from the river by dikes, berms or other structures designed to control the flow of the river. They have also been covered by legacy sediments. Major floodplains roles have thus been lost, due to land drainage, intensive urbanization and river channelization. The objective is to restore them, their retention capacity and ecosystem functions, by reconnecting them to the river. Restoring the floodplain roles requires measures such as:

- modification of the channel,
- removing of the legacy sediment
- creation of lakes or ponds in the floodplain
- new/modification of agricultural practices,
- afforestation, etc.
- plantation of native grasses, shrubs & trees
- creation of grassy basins and swales
- wetland creation
- invasive species removal
- riparian buffer installation & development (NWRM, 2019).



Natural flood prevention (Photo: Goran Šafarek)

The following specific example measure is contained in the group river restoration – floodplain.

- **Maintenance of forest cover in headwaters** (7 Belgium - La Wimbe)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_5925

2.8.1. Measure design in reality

River restoration activities for the floodplain are linked to the channel restoration. It includes changes of floodplain land use (e.g. from cropland to wet meadows), removal / elimination of land drainage and creation of small depressions along the stream.

2.8.2. Design parameters

- Floodplain area and land use

2.8.3. References for detailed design

- **Floodplain Restoration Principles**
<https://seas.umich.edu/ecomgt/pubs/wetlands/hennepin/2.4.PDF>
- **The Danube River Basin Floodplain Restoration**

https://www.interregdanube.eu/uploads/media/approved_project_output/0001/48/b63e8d1b6639ec3c230c2ef9ba3f129f1188406a.pdf

2.8.4. SWAT+ model implementation

Option A – COCOA and option B - default

With both proposed approaches option A - COCOA and option B - default it is only possible to mimic changes of fluxes from the land phase to the channel due to a floodplain restoration. Any effects on the flow in the case of a floodplain inundation cannot be modelled with the current version of SWAT+, but could be modelled if SWAT+ is coupled with a hydrodynamic model, which would be a major effort. Thus, any changes in the floodplain land phase will not affect the flow in the channel. For both approaches option A - COCOA and option B - default, a restoration of the floodplain will mostly be modelled with a change in the land use of floodplain land units or HRUs.

In a SWAT+ model setup that was generated with COCOA all land units are unique spatial objects in the model setup. A river restoration can therefore be represented by a land use change of land units which are directly connected to a channel.

In a conventional model setup, the user has the option to define upland and floodplain landscape units, where the upslope area (HRUs) drains into the downslope HRUs. GIS tools, such as QSWAT+, provide the flexibility to choose a method of creating floodplain areas, or using a custom floodplain area map (see QSWAT+ manual for more details: <https://swatplus.gitbook.io/docs/user/qswat+>). This step, however, is part of the initial model setup. To create a different floodplain area, the modeller has to either: i) reassign each individual HRU from upland to floodplain area with respective aquifer and routing information, or ii) re-create the model using a different floodplain map. Either of these methods require a manual adjustment to the model, with no automatic procedure available.

Possible land use changes that mimic the effects of a floodplain restoration (at least from the land side) can be a transformation of arable or pasture land to forested shrubland or forests. The representation of this measure is then comparable to an implementation of riparian buffers (see section 2.1). Also, a transformation to wetland forests is a potentially possible approach. For this approach, part of the spatial land units/HRUs have to become wetlands to allow storage of water. To use this approach, refer to the “wetlands” part of this document.

Pros:

- Good representation of reduced influx of water and nutrients into the receiving waters is possible in both approaches.

Cons:

- Inundation of floodplain and effects of the floodplain on the flow dynamics cannot be represented.

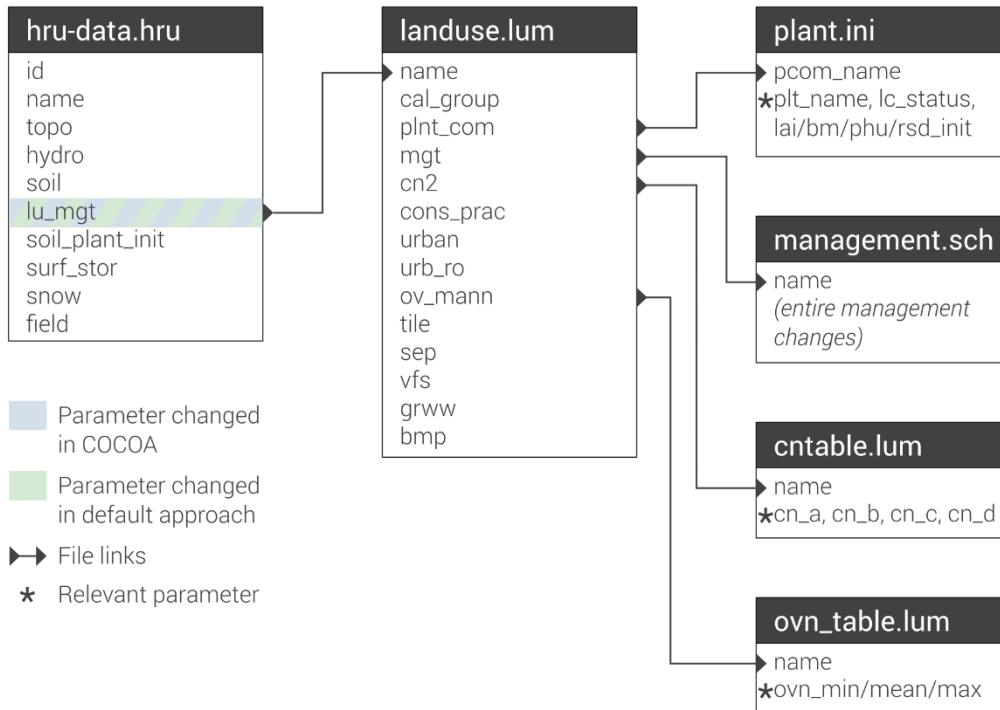


Fig. 11: Entity-Relationship Diagram for the SWAT+ model input files for the implementation of floodplains through land use change. The green/blue highlighted input file value will be changed in the COCOA and default model setup to perform the land use change. The links refer to input files that are required to parameterize the NSWRM. Parameters that express the measure are indicated by an asterisk.

Table 9: Definition of the model parameters that are used to parameterize floodplains.

Option A (COCO A)	
hru-data.hru	
Parameter	Definition
lu_mgt	The pointer to the land use and management file is a foreign key referencing name in landuse.lum.
landuse.lum	
Parameter	Definition
name	The name of the land use and management record is a primary key referenced by lu_mgt in hru-data.hru.. All names in the landuse.lum file must be unique.
plnt_com	The pointer to the plant community file is a foreign key referencing the primary key name in plant.ini.
mgt	The pointer to the management schedule file is a foreign key referencing the primary key in name management.sch.
cn2	The pointer to the Curve Number database file is a foreign key

	referencing the primary key in name cntable.lum.
ov_mann	The pointer to the overland Manning's n database is a foreign key referencing the primary key in name ovn_table.lum.
plant.ini	
Parameter	Definition
pcom_name	The name of the plant community is a primary key referenced by plnt_com in landuse.lum. All names in the plant.ini file must be unique.
plt_name	The plant name is a foreign key referencing the primary key name in plants.plt.
lc_status	Land cover status at start of simulation (n - Plant not growing, y - Plant growing).
lai_init	Initial leaf area index.
bm_init	Initial plant biomass.
rsd_init	Initial residue cover.
cntable.lum	
Parameter	Definition
cn_a to cn_d	Curve number for hydrologic soil group A - D.
ovn_table.lum	
Parameter	Definition
ov_min/mean/max	This is the value that is used by the model. The ovn_min and ovn_max values are included in the file to help users stay within reasonable ranges during calibration.

2.9. River restoration - Channel

N04 Re-meandering

<http://nwrn.eu/measure/re-meandering>

A river meander is a U-form taken by the river, allowing it to decrease water velocity. In the past, rivers have been straightened by cutting off meanders. Many rivers in northern and Western Europe have been straightened and channelized to, for example, facilitate log floating and/or speed up the drainage of water and control/limit the river bed movements. Channelizing was also a way to gain land for cultivation. River re-meandering consists in creating a new meandering course or reconnecting cut-off meanders, therefore slowing down the river flow. The new form of the river channel creates new flow conditions and very often also has a positive impact on sedimentation and biodiversity. The newly created or reconnected meanders also provide habitats for a wide range of aquatic and land species of plants and animals (NWRM, 2019).



Watercourse revitalisation (source: <https://www.dotace.nature.cz/galerie-oparteni/?arrangementId=39&pictureId=205>)

N05 Stream bed re-naturalization

<http://nwrn.eu/measure/stream-bed-re-naturalization>

Streambed (or riverbed) represents the floor of the river, including each riverbank. In the past, riverbeds were artificially reconstructed with concrete or big stones, therefore modifying flows and decreasing fauna habitat and vegetation diversity. Those modifications were aiming at flood prevention or supporting changes of agricultural practices for example. This has led to uniformed flows in the rivers and often having the effect of reducing travel time along the river. Streambed re-naturalization consists in removing some concrete or inert constructions in the riverbed and on riverbanks, then replacing them with vegetation structures, in order to avoid these damages and restore biodiversity. The re-naturalization of riverbeds and banks could have a high impact on the erosion process. Stabilisation techniques are among the main measures to be implemented. The maximum impact is reached when the stabilisation technique restores the vegetation cover and the naturalness of the banks. Most of the time, techniques use plants for bank stabilization (NWRM, 2019).



River after renaturalization (source: <http://chandrashekharasandprints.wordpress.com/2012/05/11/restoring-an-urban-river-bed-to-its-natural-eco-system-a-singapore-experiment/>)

The following specific example measure is contained in the group river restoration – channel.

- **River bank stabilisation with natural materials** (9 Italy – Cherio)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6253

2.9.1. Measure design in reality

River restoration activities for the channel includes re-meandering of the straightened channels, making the riverbed shallower, removing the channel fortification, introduction of trees along the river.

2.9.2. Design parameters

- Channel routing,
- Channel length
- Channel slope
- Channel roughness

2.9.3. References for detailed design

- **Guidelines for Naturalized River Channel Design and Bank Stabilization**
<https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/2020-01/r-wd-06-37.pdf>
- **Streamflow naturalization methods: a review**
<https://www.diva-portal.org/smash/get/diva2:1507927/FULLTEXT01.pdf>

2.9.4. SWAT+ model implementation

A channel restoration usually modifies the course of the channel and therefore changes the configuration of the surrounding landscape of a channel. In a SWAT model setup the landscape units and the location of the channel is defined and fixed during the model setup processes. It is for example not possible to represent the effects on the surrounding landscape when a straight channel segment is restored into a meandering channel. Thus, the effects of a channel restoration on the surrounding land phase cannot be well represented.

Changes of channel properties through a channel restoration can be represented by changes in the channel parameters. A meandering of a channel for example would increase the flow length and reduce the channel slope. A restoration of the river bed might change the roughness of the riverbed or change the permeability of the riverbed and therefore the influx of ground water.

Channel objects are defined in the channel-lte.cha input file. Each channel points to an entry in the parameter input file hyd-sed-lte.cha which lists the hydromorphological parameters of each channel. Changes in these parameter values for restored channels can mimic some of the effects of the channel restoration.

Channel segments that are identified for implementation of one of these measures should ideally be single or multiple channels in SWAT+, but not parts of longer channels,

because the parameter values such as length, slope or roughness always refer to a specific channel.

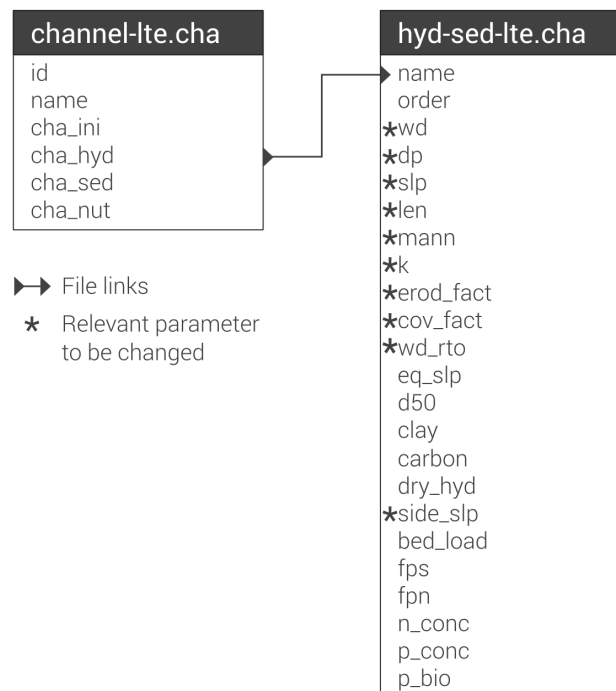


Fig. 12: Entity-Relationship Diagram for the SWAT+ model input files for the implementation of channel restoration. The links refer to input files that are required to parameterize the NSWRM. Parameters that express the measure and which are modified when the measure is implemented are indicated by an asterisk.

Table 10: Definition of the model parameters that are used to parameterize river channel restoration.

Option A (COCOA)	
channel-lte.cha	
Parameter	Definition
cha_hyd	The pointer to the channel hydrology and sediment file is a foreign key referencing name in hyd-sed-lte.cha.
hyd-sed-lte.cha	
Parameter	Definition
name	The name of the channel hydrology and sediment record is a primary key referenced by in hyd channellte.cha
wd	Channel width.
dp	Channel depth.
slp	Channel slope

len	Channel length
mann	Channel Manning's number.
k	Effective hydraulic conductivity of the channel alluvium.
erod_fact	Channel erodibility factor. A value of erod_fact = 1 indicates that there is no resistance to erosion. A value of erod_fact = 0 is suitable for non-erosive channels.
cov_fact	Channel cover factor. A value of cov_fact = 1 indicates that there is no vegetative cover on the channel. A value of cov_fact = 0 indicates that the channel is completely protected from erosion.
wd_rto	Width depth ratio.
side_slp	Channel side slope.

2.10. Swales

U04 Swales

<http://nwrms.eu/measure/swalesS>

Swales are broad, shallow, linear vegetated channels which can store or convey surface water (reducing runoff rates and volumes) and remove pollutants. They can be used as conveyance features to pass the runoff to the next stage of a treatment system (e.g. from one retention pond to another) and can be designed to promote infiltration where soil and groundwater conditions allow.

The promotion of settling is enhanced by the use of dense vegetation, usually grass, which promotes low flow velocities to trap particulate pollutants. In addition, check dams or berms can be installed across the swale channel to promote settling and infiltration. As a result, swales are effective in improving water quality of runoff, by removing sediment and particulate pollutants. In wet swales, the effectiveness is further enhanced by providing permanent wetland conditions on the base of the swale (NWRM, 2019).



Retention swale (source: <http://www.zabreh.cz>)

The following specific example measure is contained in the group swales.

- **Retention swale (U04 Swales)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6244

2.10.1. Measure design in reality

Swales should be designed to convey the peak flow of the 10-year storm without overtopping, which is calculated using the Rational Method. (e.g. Chin et al. 2019). The size of the swale depends upon the expected runoff. The swale is to be given greater cross-sectional area towards the outlet as the amount of water gradually increases towards the outlet.

- A very shallow “ditch”, channel; usually grassed,
- It is oriented almost along the contours with a certain (very gentle) slope, to slow down water flow and safely rout it to a certain place (grassed waterway, pond) or support water infiltration,
- It has a certain volume, width (3 - 6 m) and depth (0,3 – 0,8 m); Side Slopes 6:1 to 4:1.

2.10.2. Design parameters

- Channel depth
- Channel width
- Channel length

- Channel slope

2.10.3. References for detailed design

- **Design criteria for dry swale (grass swale)**
[https://stormwater.pca.state.mn.us/index.php?title=Design_criteria_for_dry_swale_\(grass_swale\)](https://stormwater.pca.state.mn.us/index.php?title=Design_criteria_for_dry_swale_(grass_swale))
- **Vegetated Swales**
<https://www.ncagr.gov/SWC/costshareprograms/CCAP/documents/Chapter8-VegetatedSwales.pdf>

2.10.4. SWAT+ model implementation

An implementation of swales with the option A - COCOA may be too complex and would require introducing many objects initially that will be activated with the measure implementation. In the scope of OPTAIN it is therefore infeasible to provide a generalised solution that can be implemented in all CSs. Therefore, swales will be represented only in a parametric way using the grassed waterway parametrization that was presented in section 2.4.4 option - B. This is as well the suggested way of implementation according to the SWAT+ model development team.

2.11. Constructed wetlands (CW)

According to the Convention on Wetlands (1971), a wetland is an area of marsh, fen, peatland, or water, whether natural or artificial, permanent, or temporary, with water that is static or flowing, fresh, brackish, or salt, including areas of marine water the depth of which at low tide does not exceed six metres. It provides water retention, biodiversity enhancement or water quality improvement. Wetland restoration and management can involve: technical, spatially large-scale measures (including the installation of ditches for rewetting or the cutback of dykes to enable flooding); technical small-scale measures such as clearing trees; changes in land-use and agricultural measures, such as adapting cultivation practices in wetland areas. They can improve the hydrological regime of degraded wetlands and generally enhance habitat quality. Creating artificial or constructed wetlands (CWs) in urban areas can also contribute to flood attenuation, water quality improvement and habitat and landscape enhancement (NWRM, 2019).



Wetland in a forest (Source: Gebhard Schueler's presentation, NWRM Workshop 1)

CWs share some basic principles of detention/retention basins (see section 2.6), but their primary goal is usually not flood water storage, but an improvement of water quality (e.g., sediment and nutrients). Therefore, they are typically placed in areas with high non-point source or point source water pollution.

The following specific example measures are contained in the group constructed wetlands (CW).

- **Wetland in Dotnuvėlė river basin** (8 Lithuania - Dotnuvele river basin)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_5996
- **Small constructed wetland** (10 Norway – Hobøl)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_5940
- **Wetland restoration and management** (4 Poland - Upper Zglowiaczka)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6267
- **Wetland** (7 Belgium - La Wimbe)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_5926
- **Constructed wetland on tile drainage** (12 Czech Rep. – Čechtický)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_5939
- **Phosphorus pond** (14 Sweden - Sävjaån Headwaters)
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6260

2.11.1. Measure design in reality

The design of a constructed wetland is recommended according to several criteria. One of the most used for sizing a wetland is the Wetland-Catchment Ratio (WCR). WCR is between 1-3%, for the intensive CWs then 0,2-0,25% (Hoffmann et al. 2020). Others are e.g., required Water Residence Time or Hydraulic Retention Time (WRT / HRT). HRT (hrs) = substrate porosity (%) * wetland volume (m³) / discharge (m³.hrs⁻¹). The depth of a wetland is usually between 0.8 – 1.4 m.

- CW with a certain volume (capacity, m³); surface area (m²); at a certain location.
- At the end of the erosive thalwegs; only at the big ones. A sedimentation object is needed to place prior to the wetland to catch the sediment and to not allow clogging the CW.
- Other allocations are - at the wet sites at the lowermost field parts, directly connected to streams, drainage ditches, tile drainage.
- Source of water for the CW should be carefully assessed to provide a permanent inflow of water, if the CW is intended to provide biodiversity enhancement

2.11.2. Design parameters

- CW volume
- CW water retention time

2.11.3. References for detailed design

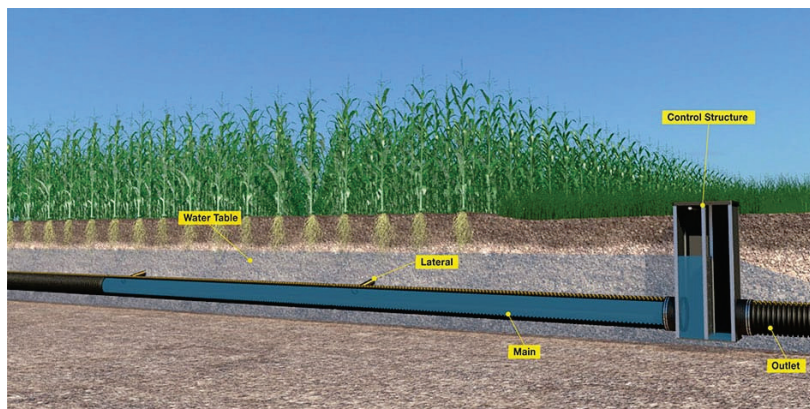
- **Handbook of constructed wetlands**
<https://www.epa.gov/sites/default/files/2015-10/documents/constructed-wetlands-handbook.pdf>
- **Constructed wetland guidelines**
<https://niwa.co.nz/freshwater-and-estuaries/management-tools/restoration-tools/constructed-wetland-guidelines>

2.11.4. SWAT+ model implementation

In SWAT+ a CW can be represented by wetlands - a part of the land object (HRU), which can store water. This process can be initiated by land use change (refer to section 2.7.4 for details on implementation). Another option is to use a pond object, which will store water and, if applicable, route it to the downstream channel. Refer to chapter 2.6 on retention/detention ponds for more details on possible implementation and differences between these approaches. Due to a stronger focus of CWs on water quality improvement compared to detention basins, it is also important to consider the nutrient and sediment settling rate parameters in SWAT+.

2.12. Controlled drainage

Controlled tile drainage (CTD) is a practice where drainage flow is retarded by water level control structure (WLCS). The purpose of CTD is to increase soil moisture by capillary rise of the regulated drainage water in the surrounding area. Drainage discharge in the CTD approach can be controlled by several WLCS types; basically, with adjustable or fixed WLCS placed either at drainage outlets, in manholes or directly on collective or conductive drains. Stop-gates in the WLCS can be adjusted throughout the year so the water can be close to the root level. During dry periods, water is retained in the soil profile. This reduces the overall drainage volume and supports self-cleaning processes (e.g. denitrification), thus reducing the amount of nutrients / pollutants leaving the land and improving the crop yields.



Controlled drainage (Source: <https://www.watertable.ag/best-practice/controlled-drainage/overall>)

The following specific example measures are contained in the group constructed wetlands (CW).

CTD has not been documented in the NSWRM catalogue yet. Nevertheless, there are several online sources with related descriptions and characteristics of this practice.

- **The Transforming Drainage Project**
<https://transformingdrainage.org/practices/controlled-drainage/>
- **The Water Table Project**
<https://www.watertable.ag/best-practice/controlled-drainage/>

2.12.1. Measure design in reality

CDT is designed and implemented by installation of WLCS to raise a shallow water table at various parts of drainage - in manholes, drainage outlets or at the drains themselves. The practice is generally and meaningfully applicable in tile-drained fields up to 3° slope, at middle textured to heavier soils. To design and delineate the WLCS, detailed information of tile drainage placement and characteristics is needed, as well as soil map, drainage extent and structure (manholes, outlets, etc.).

2.12.2. Design parameters

- Average change of shallow water table level (height of the WLCS)
- Area - range of drainage flow control

2.12.3. References for detailed design

- **Controlled Drainage – An Important Practice to Protect Water Quality That Can Enhance Crop Yields**
<https://content.ces.ncsu.edu/controlled-drainage>
- **Controlled Drainage**
<https://sswm.info/sswm-solutions-bop-markets/improving-water-and-sanitation-services-provided-public-institutions-0/controlled-drainage>

2.12.4. SWAT+ model implementation

In SWAT+, a controlled drainage system can be implemented at the HRU level using Decision Tables (DT), where the user should specify the conditions/rules on how the system should function. A detailed overview of the DTs is available on the SWATPlusEditor guide: <https://swatplus.gitbook.io/docs/user/editor/inputs/decision-tables>

An example of such DT is presented below:

name	conds	alts	acts	!open drains in spring and close after harvest - close in summer if low soil water and plant hu > 0.5									
control_drainage	6	4	4										
var	obj	obj_num	lim_var	lim_op	lim_const	alt1	alt2	alt3	alt4				
jday	hru	0	null	-	65.00000	=	-	-	-				!open drains on day 65
days_harv	hru	0	null	-	14.00000	-	>	-	-				!close drains 14 days after harvest
jday	hru	0	null	-	295.00000	-	=	-	-				!close drains on day 295
phu_plant	hru	0	null	-	0.50000	-	-	>	-				!plant heat units > 0.5 - check for summer closing
soil_water	hru	0	fc	*	0.50000	-	-	<	-				!sw < 0.5*fc - check for summer closing
phu_plant	hru	0	null	-	1.00000	-	-	-	>				!open when plant heat units > 1.0
act_typ	obj	obj_num	name	option	const	const2	fp	outcome					
drain_control	hru	0	open_spring	null	1.00000	1.00000	null	y	n	n	n		
drain_control	hru	0	close_fall	null	0.00000	1.00000	null	n	y	n	n		
drain_control	hru	0	close_summer	null	0.00000	1.00000	null	n	n	y	n		
drain_control	hru	0	open_summer	null	1.00000	1.00000	null	n	n	n	y		

Fig 13. Example of a Decision table, which executes the following operation: opens drains in spring and closes after harvest, closes in summer if low soil water and plant heat units are more than 0.5.

The DT action “drain_control” triggers the adjustment of drain depth for drainage water management, hence controlling the outflow.

For CT application in SWAT+ identification of fields/HRUs in which this measure is to be applied has to be made. Thus, it has to be taken into account that in the model setup CT should be applied in entire HRUs, and not in its parts.

2.13. Terracing

A10 Traditional terracing

<http://nwrn.eu/measure/traditional-terracing>

Traditional terraces consist of nearly level platforms built along contour lines of slopes, mostly sustained by stone walls, used for farming on hilly terrain. By reducing the effective slope of land, terracing can reduce erosion and surface run-off by slowing rainwater to a non-erosive velocity. This also increases the degree of infiltration and improves soil moisture. However, abandonment of traditional terracing can result in high levels of erosion and run-off due to the lack of maintenance of stone walls. Abandonment can also change the nature of local flora and fauna; this may not be beneficial, for example the spontaneous regeneration of vegetation can present a risk of wildfire spread on sloping land.

This measure focuses on existing or traditional terracing as it involves less disturbance of the terrain than modern terracing such as significant levelling or cutting using heavy machinery. As the measure is highly labour intensive and costly to implement, the focus of the measure would be in maintaining existing terracing rather than expansion.



Traditional terracing in montane area (Source: Gonzalo Delacámara's presentation, NWRM Workshop 1 (Spain))

The following specific example measure is contained in the group terracing.

Including the following NSWRM:

- **Hillside terraces and hillside terraces with dry stone walls (9 Italy – Cherio)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6252/

2.13.1. Measure design in reality

Terraced fields are traditionally built on pre-existing slopes, covering the area with flattened steps used in rainwater harvesting to grow crops, and provide ample soil moisture. The flat areas give way to soil conservation, allowing the nutrients in the soil to stay on the steps instead of running down the hills. As rainwater flows down the terrace fields, water-retaining walls act as a catch basin, preventing moisture and soil nutrients from trickling down the slopes. Crops such as maize, barley, and rice are among the crops planted in terrace fields, and terrace cultivation is most prevalent in parts of Asia, mostly in rice-growing countries and hilly terrains.

2.13.2. Design parameters

- Slope
- Width and height of a terrace
- Number / density of terraces within an area (field block)

2.13.3. References for detailed design

- **A Field Guideline on Bench Terrace Design and Construction**
<https://nrmdblog.files.wordpress.com/2016/04/bench-terrace-manual.pdf>
- **Terraces - Permaculture Design Course Handbook**
<https://treeyopermacultureedu.com/chapter-9-earth-working-and-earth-resources/terraces/>

2.13.4. SWAT+ model implementation

Terraces can be represented using the parametric approach in SWAT+. The terraces are a part of the conservation measures in SWAT+. Terraces are “installed” at the HRU-level as a management operation. The model then adjusts the p factor as a function of slope (relationship with the table cons_practice.lum is used to determine the level of adjustment). The user is referred to the land management guide: <https://swatplus.gitbook.io/docs/user/editor/inputs/land-use-management> for more details.

3. Management measures

Some measures of agricultural management are called conservation practices.. These activities are done by farmers aiming at:

- i. soil protection (decrease of overland flow and water erosion, decrease of pedocompaction, improvement of soil physical properties, structure and aggregate stability, enhancement of soil nutrient regime),
- ii. enhancement of water retention in soil (support of infiltration, decrease of evaporation),
- iii. maintaining crop yields (crop scheduling, proper fertilisation),
- iv. improvement of water quality coming from the fields (surface and subsurface runoff).

These conservation practices are done usually by various types of soil management (tillage or no-till approaches), crop rotations & management, fertilisation types, application & timing, and amounts. The management measures that are planned to be modelled in OPTAIN are listed in the following table.

Table 11. Management measures that are planned to be modelled in OPTAIN.

Group of measure in OPTAIN	Measure in the nwrn.eu catalogue	Specific measures in OPTAIN
Tillage adjustment (Soil management)	A06 No till agriculture	No till agriculture (Direct seeding)
	A07 Low till agriculture	Mulch seeding with permanent minimum tillage
		Low till agriculture
	A13 Mulching	Mulching
	Not defined	Subsoiling
Cropping adjustment	A03 Crop rotation	Crop rotation, strip cropping, contouring
	A05 Intercropping	Intercropping
	A08 Green cover	Green cover
	A09 Early sowing	Early sowing
Others	Not defined	Drought - resistant plants

3.1. Tillage adjustment - No till agriculture (Direct seeding)

A06 No till agriculture

<http://nwrn.eu/measure/no-till-agriculture>

Tillage is a mechanical modification of the soil. Intensive tillage can disturb the soil structure, thus increasing erosion, decreasing water retention capacity, reducing soil organic matter through the compaction and transformation of pores. No-till farming (also called zero tillage or direct drilling) is a way of growing crops or pasture from year to year without disturbing the soil through tillage. No-till is an agricultural technique which increases the amount of water that infiltrates into the soil and increases organic matter retention and cycling of nutrients in the soil. In many agricultural regions it can mitigate or even avoid soil erosion. The most powerful benefit of no-tillage is improvement of soil biological fertility, making soils more resilient.



Maize planted without tillage (Source: <http://www.commodityonline.com/news/zero-tilling--a-popular-alternative-farming-method-35479-3-35480.html>)

The following specific example measures are contained in the group no till agriculture (direct seeding).

- **Direct seeding (2 Switzerland - Petite Glâne)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_1007
- **Reduced tillage - no tillage in autumn (10 Norway – Hobøl)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_1245
- **No till agriculture (11 Hungary – Tetves)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6199
- **Direct seeding (12 Czech Rep. – Čechtický)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6245

3.1.1. Measure design in reality

- No-till is the practice of never tilling a field. Tilling every other year is called rotational tillage.
- In the case of no-till in the autumn, field cultivation is not carried out in the autumn season.
- No-till practice is applicable to all soil types except those prone to pedocompaction.
- No-till practice is usually implemented for cereals and intercrops, with eventual shallow stubble breaking / undermining every 3. or 4. year

3.1.2. Design parameters

- Area

3.1.3. References for detailed design

- **No till agriculture**
<http://nwrn.eu/measure/no-till-agriculture>
- **No-till Farmer website**
<https://www.no-tillfarmer.com/>

3.1.4. SWAT+ model implementation

Various tillage operations are modelled at an HRU-level in SWAT+. Fixed schedule setup, decision tables approach, or combination of both can be used to represent this measure (e.g. Ullrich and Volk, 2009). The user can refer to the SWATPlusEditor guide for more information on tillage operations and associated parameters: <https://swatplus.gitbook.io/docs/user/editor/inputs/land-use-management#operations-types>.

3.2. Tillage adjustment - Low till agriculture

A07 Low till agriculture

<http://nwrn.eu/measure/low-till-agriculture>

Low till agriculture, also known as conservation or reduced tillage, is applied to arable land. It consists of a combination of a crop harvest which leaves at least 30% of crop residue on the soil surface, during the critical soil erosion period and some surface work (low till). This slows overland flow, which reduces the amount of soil erosion and potentially leads to greater infiltration.



Crop planted in conservation tillage (Source: <http://uirig.altervista.org/naturaitaliana/viewpics.php?title=Contour+farming+and+conservation+tillage+protect+highly+erodi>)

The following specific example measures are contained in the group tillage adjustment - low till agriculture.

- **Low till agriculture (5 Austria / Slovenia – Pesnica)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_5494
- **Mulch seeding with permanent minimum tillage (1 Germany - Schwarzer Schöps)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6257

3.2.1. Measure design in reality

Minimum tillage optionally with mulching uses plant residues of the preceding crop to remain on the soil surface before and after seeding, thereby protecting the soil from erosion. A minimum (ploughless) soil cultivation is used to till the upper soil layer and create the seedbed. This practice is applicable at all soil types and for the majority of the field crops. A special practice is strip-till, applicable to maize (corn). In strip-till, the soil is tilled shallowly, just in the narrow seed band. The rest of the soil (between the rows) is covered with crop residues or planted with a winter intercrop.

3.2.2. Design parameters

- Area
- Mixing depth
- Mixing efficiency

3.2.3. References for detailed design

- **Advanced strip-till technology**
<https://www.vogelsang.info/index.php?eID=dumpFile&t=f&f=2845&token=928c934c9ad18f6340907514c174221843afa07c>
- **Strip-till cultivator**
<https://www.farmet.cz/en/strip-till-cultivator-strip-till>

3.2.4. SWAT+ model implementation

Fixed schedule setup, or decision tables approach, or a combination of both can be used to represent this measure. Tillage can be adjusted by changing the timing of the operation, the frequency or the plough type and tillage depth. The user can refer to the SWATPlusEditor guide for more information on tillage operations and associated parameters <https://swatplus.gitbook.io/docs/user/editor/inputs/land-use-management#operations-types>.

3.3. Mulching

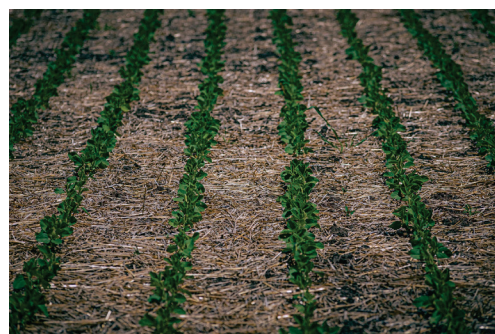
A13 Mulching

<http://nwrp.eu/measure/mulching>

Mulching as NWRP uses organic material (e.g., bark, wood chips, grape pulp, shell nuts, green waste, leftover crops, compost, manure, straw, dry grass, leaves etc.) to cover the surface of the soil. It may be applied to bare soil, or around existing plants. Mulches of manure or compost will be incorporated naturally into the soil by the activity of worms and other organisms. The process is used both in commercial crop production and in gardening, and when applied correctly can dramatically improve the capacity of soil to store water.

A mulch is a layer of material applied to the surface of an area of soil. Its purpose is any or all of the following:

- to conserve moisture,
- to improve the fertility and health of the soil,
- to reduce weed growth,
- to enhance the visual appeal of the area.



Mulching (Source: <https://www.ziva-puda.cz/opatreni-pro-pudu/Mulcovani>)

The following specific example measure is contained in the group.

- **Mulching (4 Poland - Upper Zglowiaczka)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6249/

3.3.1. Measure design in reality

In mulch tillage systems, more than 30% of the soil surface is left covered with residue after planting. Chisel plows, offset discs or modified moldboard plows are the common implement. Natural mulches include compost (including composted manure), crop residues, hay, straw, shrub and tree leaves and grass clippings. These feed the soil to varying extents, with the compost, hay and grass clippings doing it best. Pine needles, sawdust, wood chips, chopped bark and rock are additional natural mulch options (rather for gardens). Pine needles add acidity to the soil and should only be used when this won't create a pH problem but rather is desired (or at least tolerated) by plants that enjoy a lower pH. Very thick mulch can make it difficult for moisture to get through to the soil. "Too thick" varies with the type of mulch but be aware of that possible pitfall and check the soil itself when in doubt.

3.3.2. Design parameters

- Area
- Surface roughness

3.3.3. References for detailed design

- **A Farmer's Guide to Mulching | EcoFarming Daily**
<https://www.ecofarmingdaily.com/a-farmers-guide-to-mulching/>
- **Best Management Practices MULCH TILLAGE**
<http://www.omafra.gov.on.ca/english/environment/bmp/AF171.pdf>

3.3.4. SWAT+ model implementation

Mulching can be represented as a type of tillage in SWAT+. Fixed schedule setup, decision table approach, or combination of both can be used to represent this measure. The user can refer to the SWATPlusEditor guide for more information on tillage operations and associated parameters <https://swatplus.gitbook.io/docs/user/editor/inputs/land-use-management#operations-types>.

3.4. Subsoiling

Deep ploughing is the basic cultivation procedure restoring soil production efficiency. It consists in a partial or total cut off from the cane of the role belt and then reversed and crushed. The purpose of deep ploughing is primarily to improve the soil structure, give it efficiency, and accumulate the maximum amount of water from precipitation. Deep ploughing significantly reduces the population of pests, diseases, and weeds. The plough sole is the result of compaction of the arable layer by passing machines, but mainly ploughing at a constant depth. The sole is a barrier to the roots of many crops and a deep chilled frog can solve this problem. Maybe, provided that the profile is deep enough, and we will not cause this operation to draw the sterile soil necrosis on top. Compaction adversely affects air-water relations, clogging capillaries and reducing the amount of water available. The plough sole is characterised by lower air permeability, permeability and water capacity than the arable layer and deeper soil profile layers.



Subsoiling (ripping) operation (continuous MSP) on a former agricultural field in the Lower Mississippi Alluvial Valley, southern USA. The rig is spraying a band of herbicide over the ripped row. (Source: Photo by Ray Souter).

The following specific example measure is contained in the group subsoiling.

- **Subsoiling (4 Poland - Upper Zglowiaczka)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6250

3.4.1. Measure design in reality

Subsoiling is used to loosen the extremely compacted subsoil without uprooting the subsoil. Historically, it is associated with ploughing operations using scarifiers placed behind the individual ploughing bodies or in front of the first ploughing body. When scarifiers are placed behind all ploughing bodies, the compacted subsoil is disturbed throughout the plot. However, this method is economically very costly due to the increase in fuel consumption. At present, chisel cultivators or cultivators allowing the adjustment of different depths of individual types of working tools or their rows on the machine frame are used for targeted subsoiling.

3.4.2. Design parameters

- Area
- degree of soil compaction prior application of this technology

3.4.3. References for detailed design

- **Using Subsoiling To Reduce Soil Compaction**
<https://www.fs.fed.us/t-d/pubs/pdfpubs/pdf08342828/pdf08342828dpi72.pdf>
- **7 steps to successful subsoiling**
<https://www.fwi.co.uk/arable/land-preparation/soils/7-steps-to-successful-subsoiling>

3.4.4. SWAT+ model implementation

Various tillage operations, including deep-ploughing, are modelled at an HRU-level in SWAT+. Fixed schedule setup, or decision tables approach, or combination of both can be used to represent this measure. The user can refer to the SWATPlusEditor guide for more information on tillage operations and associated parameters <https://swatplus.gitbook.io/docs/user/editor/inputs/land-use-management#operations-types>.

3.5. Cropping adjustment - Crop rotation

A03 Crop rotation

<http://nwrp.eu/measure/crop-rotation>

Crop rotation is the practice of growing a series of dissimilar/different types of crops in the same area in sequential seasons. Judiciously applied (i.e. selecting a suitable crop), crop rotation can improve soil structure and fertility by alternating deep-rooted and shallow-rooted plants. In turn this can reduce soil erosion and increase infiltration capacity, thereby reducing downstream flood risk. It gives various benefits to the soil. A traditional element of crop rotation is the replenishment of nitrogen through the use of green manure in sequence with cereals and other crops. Crop rotation also mitigates the build-up of pathogens and pests that often occurs when one species is continuously cropped. However, as crop rotation has been traditionally practiced for agronomic reasons rather than to achieve environmental and water objectives, new practices may be required to ensure water retention benefits can be achieved.



Fields in crop rotation (USA) (Source: <http://www.conewagoinitiative.net/practices/farm/1296-2>)

A04 Strip cropping along contours

<http://nwrp.eu/measure/strip-cropping-along-contours>

Strip cropping is a method of farming used when a slope is too steep or too long, or otherwise, when one does not have an alternative method of preventing soil erosion. It alternates strips of closely sown crops such as hay, wheat, or other small grains with strips of row crops, such as corn, soybeans, cotton, or sugar beets. Strip cropping helps to stop soil erosion by creating natural dams for water, helping to preserve the strength of the soil. Certain layers of plants will absorb minerals and water from the soil more effectively than others. When water reaches the weaker soil that lacks the minerals needed to make it stronger, it normally washes it away. When strips of soil are strong enough to slow down water from moving through them, the weaker soil can't wash away like it normally would. Because of this, farmland stays fertile much longer. There is no available information on the extent of strip cropping in Europe. The practice has been widespread in North America as a means of mitigating soil erosion from wind and water.



Strip cropping along contour lines (UK) (Source: <http://www.britannica.com/EBchecked/media/149126/Contour-farming-and-strip-cropping-on-sloping-farmland>)

The following specific example measures are contained in the group crop rotation.

- **Crop rotation (6 Slovenia / Hungary .- Kebele- Kobiljski potok)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6239
- **Crop rotations (9 Italy – Cherio)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6251
- **Maize strip tillage (A04 Strip cropping along contours)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_1008/
- **Slope subdivision through a field seam (Switzerland - Petite Glâne)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_1670

3.5.1. Measure design in reality

Crop rotation simply focuses on rotating crops in a particular area so that no field (or only several ones) has the same crop in successive seasons. The main objective is to maintain soil pH and nutrients so that each crop species in every season can get the most out of the soil. Another important point is to avoid pests and diseases, i.e. to get a more resilient crop-soil system. There is no single crop rotation plan that applies to all farmers. The period of rotation may vary from a planting season to a few years or even longer periods. Crops can be rotated in a particular field depending upon a farmer's individual requirements, the type of soil, climate and environmental conditions, the markets for various crops and budget.

For example, some farmers may rotate two different crops, say corn and soybeans, in a single field for alternative years. Others might follow a more diverse plan where they rotate five or six crops in a field for several years. Listed below are some basic principles of crop rotation that would help you choose the right crop to plant on the right soil at the right time:

1. Crops with deep roots, such as carrot, should be followed by shallow rooted crops like wheat, rice, and corn. This allows for efficient and uniform use of nutrients from the soil.
2. Leguminous crops like pulses and alfalfa should be planted after non-leguminous or cereal crops, such as oats and rice. Legumes boost atmospheric nitrogen and organic content in the soil.
3. More exhaustive crops like sunflowers should be followed by restorative crops like pulses and legumes.
4. Avoid growing crops of the same family in succession as they serve as alternate hosts for pests and diseases, i.e. for example rapeseed only every four years on the same field; sugar beet only every 3 years.
5. Long duration crops should be succeeded by short duration crops.
6. Crops susceptible to soil borne pathogens and parasitic weeds should be grown after tolerant crops.
7. Crops that involve heavy irrigation and intensive labour should be grown after crops requiring less water and labour.

3.5.2. Design parameters

- Area
- Crop types scheduling

3.5.3. References for detailed design

- **CROP ROTATION GUIDE: PRINCIPLES AND BENEFITS**
<https://kg2.com.au/crop-rotation-guide-principles-and-benefits/>
- **Basics of Crop Rotation**
<https://www.sare.org/publications/crop-rotation-on-organic-farms/how-expert-organic-farmers-manage-crop-rotations/basics-of-crop-rotation/>

3.5.4. SWAT+ model implementation

Crop management and rotation can be implemented using fixed management scheduling or/and DTs. It is a standard operation in any SWAT/SWAT+ model setup. The user is referred to the Land Use Management guide: <https://swatplus.gitbook.io/docs/user/editor/inputs/land-use-management> and the Decision Table guide: <https://swatplus.gitbook.io/docs/user/editor/inputs/decision-tables> for more details on the implementation of crop rotations.

3.6. Cropping adjustment - Intercropping

A05 Intercropping

<http://nwrn.eu/measure/intercropping>

Intercropping is the practice of growing two or more crops in proximity. The most common goal of intercropping is to produce a greater yield on a given piece of land by making use of resources that would otherwise not be utilised by a single crop. Examples of intercropping strategies are planting a deep-rooted crop with a shallow-rooted crop, or planting a tall crop with a shorter crop that requires partial shade. Numerous types of intercropping, all of which vary the temporal and spatial mixture to some degree, have been identified: mixed intercropping, row cropping, relay cropping, etc.



Intercropped cereals with soybeans (Source: Gábor Ungvári's presentation, NWRM Workshop 1)

The following specific example measure is contained in the group intercropping.

- **Grain legumes intercropped with cereals & partners (2 Switzerland - Petite Glâne)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6235

3.6.1. Measure design in reality

Intercropping may pose a special problem for crop rotation. One fundamental principle of crop rotation is the separation of plant families in time. This is critical for management of diseases and, to a lesser extent, insects. If plants from two families are mixed in the same bed or field, however, achieving a substantial time lag before replanting either of those families may be difficult. Suppose, for example, that a farm grows an acre each of tomato, squash, broccoli, and mid-season lettuce. A simple rotation would put each of the crops in a different year, with a three-year interval before a crop is repeated on the same bed. If, however, the lettuce and tomato are grown together, crops would be separated by only a two-year interval, which may be insufficient to keep some diseases under control. Thus, intercropping requires extra care and effort in planning and maintaining a viable crop rotation.

3.6.2. Design parameters

- Area
- Intercrop specification / surface roughness - canopy characteristics and timing / scheduling

3.6.3. References for detailed design

- **Guidelines for Intercropping**
<https://www.sare.org/publications/crop-rotation-on-organic-farms/guidelines-for-intercropping/>
- **INTERCROPPING PRINCIPLES AND PRODUCTION PRACTICES**
<https://attra.ncat.org/wp-content/uploads/2019/05/intercrop.pdf?>

3.6.4. SWAT+ model implementation

Can be implemented via the fixed management scheduling or/and DTs by implementing crop communities (several crops grown at the same time). The user can refer to the SWATPlusEditor guide for more information on crop parametrisation and management <https://swatplus.gitbook.io/docs/user/editor/inputs/land-use-management#operations-types>. The associated databases are available at the same resource: <https://swatplus.gitbook.io/docs/user/editor/inputs/databases>

3.7. Cropping adjustment - Green cover / Catch crops

A08 Green cover

<http://nwrn.eu/measure/green-cover>

Green cover (including cover crops or catch crops) refers to crops planted in late summer or autumn, usually on arable land, to protect the soil, which would otherwise lie bare during the winter, against wind and water erosion. Green cover crops also improve the structure of the soil, diversify the cropping system, and mitigate the loss of soluble nutrients.



Orchard with green cover (Source: Gonzalo Delacámara's presentation, NWRM Workshop 1).

The following specific example measures are contained in the group green cover / catch crops.

- **Cover crops (1 Germany - Schwarzer Schöps)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_5929
- **Green cover in vineyard (3a Hungary - Csorsza)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6194
- **Intermediate Nitrate Trapping Crops (7 Belgium - La Wimbe)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6159
- **Grass (or stubble) on areas prone to flooding and erosion risk (10 Norway – Hobøl)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6170

3.7.1. Measure design in reality

There are no limitations for the use of catch crops. Preferably, the intercrops or catch crops are planted on erosion-prone parts of field blocks or at the sites with shallow soils, prone to rapid leaching and movement of nutrients and pesticides to soil and groundwater. The introduction of intercrops (preferably non-freezing) into crop rotations enable the use of residual soil mineral nitrogen for biomass production, thereby reducing nitrogen leaching by up to 30-40%.

3.7.2. Design parameters

- Area
- Cover crop specification /surface roughness - canopy characteristics and timing

3.7.3. References for detailed design

- **Cover, Catch and Companion Crops - Agricolgy**
https://www.agricology.co.uk/sites/default/files/Cover%20Crops-%20Final_1.pdf
- **Cover Crops, Soil Health Principles and Maximizing Yields**

<https://www.sare.org/resources/cover-crops-soil-health-principles-and-maximizing-yields/>

3.7.4. SWAT+ model implementation

Green cover can be implemented using fixed management scheduling and/or DTs. Green cover should be included in the rotation, after the harvest of the main crop in the rotation. More information on the land management is provided in the SWATPlusEditor documentation: <https://swatplus.gitbook.io/docs/user/editor/inputs/land-use-management>

When implementing the green cover, the cover plant has to be included in the plants.plt database, with associated parameters.

3.8. Early sowing

A09 Early sowing

<http://nwrms.eu/measure/early-sowing>

Early sowing refers to sowing up to six weeks before the normal sowing season. This allows for an earlier and quicker establishment of winter crops that can provide cover over winter and of a root network that leads to soil protection. The period in which the soil lies bare is shorter and, therefore, erosion and run-off are less significant and water infiltration is improved. Early sowing can also help to mitigate summer drought impacts on spring sown crops, in particular the extreme evapotranspiration rates of Mediterranean regions. However, early sown plants are frost sensitive; therefore, farmers run the risk of losing the crops because of the low temperatures. In northern countries, temperature in spring (March) can be adequate but the risk of frost is still serious until May. The low temperatures in northern countries may also delay crop establishment in spring crops resulting in an increased risk of soil erosion, avoiding cultivation, and retaining residues from preceding crops may be preferable. Therefore, early sowing may require specific tools (plastic tunnel covers, onsite greenhouse, etc.) and cannot be applied by all farmers for all crops. Early sowing of spring crops may also require different cultivation techniques (reduced tillage, controlled traffic farming) as soils are likely to be saturated before usual sowing times increasing the risk of soil compaction. Restrictions on early sowing of winter crops include the harvest date of the preceding crop (particularly root crops) which may be later in northern Europe. For both spring and winter crops, early sowing involves several trade-offs. For example, different pest and disease risks arise that might require changes in management.



Early sowed barley (India) (Source: <http://sowasia.org/sowing-seeds-early>)

The following specific example measure is contained in the group early sowing.

- **Early sowing (5 Austria / Slovenia – Pesnica)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6242/

3.8.1. Measure design in reality

Generally, and in practice, the early sowing approach is being planned and tailored by the farmers for the specific field crops according to the crop schedule and with a regard to the actual/seasonal meteorological situation, which may differ profoundly from year to year. As stated above and in the particular NWRM sheet, the early sowing may have some beneficial impacts as for soil protection, crop yield, improvement of soil water retention and the use of soil nutrients, however, the farmer should consider also the uncertainties and possible risks, related with the early sowing practices.

3.8.2. Design parameters

- Area
- Timing

3.8.3. References for detailed design

- **Ten tactics for early-sown canola**

<https://grdc.com.au/resources-and-publications/groundcover/groundcover-133-march-april-2018/ten-tactics-for-early-sown-canola>

- **Frost risk – manage wheat variety and sowing time**

<https://www.agric.wa.gov.au/frost/frost-risk-%E2%80%93-manage-wheat-variety-and-sowing-time?nopaging=1>

3.8.4. SWAT+ model implementation

Can be implemented via the fixed management scheduling and/or DTs by adjusting the planting dates. The user is referred to the Land Use Management guide: <https://swatplus.gitbook.io/docs/user/editor/inputs/land-use-management> and the Decision Table guide: <https://swatplus.gitbook.io/docs/user/editor/inputs/decision-tables> for more details on the implementation of early sowing.

3.9. Other - Drought-resistant plants

Drought-resistant plants are cultivated under this measure. These plants are so-called drought tolerant. Drought tolerance is the ability to which a plant maintains its biomass production during arid or drought conditions. Some plants are naturally adapted to dry conditions, surviving with protection mechanisms such as desiccation tolerance, detoxification, or repair of xylem embolism. Drought tolerant crops — like maize, cowpeas, and rice — have been bred through conventional plant breeding techniques or biotechnology and continue to grow and produce even when rains fail.



Mustard greens require far less water than some of their leafy cousins. (Source: Photography by Far700, Shutterstock)

The following specific example measure is contained in the group drought-resistant plants.

- **Drought - resistant plants (Switzerland - Petite Glâne)**
https://qcat.wocat.net/en/wocat/technologies/view/technologies_6272/

3.9.1. Measure design in reality

Due to the climate change it is obvious that drought-resistant plants (crops), i.e., the use particular crops or cultivars adapted to European growth conditions, is urgently needed, including grass for hay / pastures. The new cultivars shall have a shorter growing cycle (specifically for adaptation to North-West Europe), high yield potential under European growing conditions, and sufficient drought resistance. Also sowing and harvest dates may be altered to cope with warmer springs and higher temperatures – for example, sowing earlier and harvesting later could help to compensate for drought-related losses.

3.9.2. Design parameters

- Area
- Crop specification (canopy, grow + roots characteristics, yield)

3.9.3. References for detailed design

- **Drought resistant crops for the future**
https://pure.aber.ac.uk/portal/files/38047395/TA_Drought_resistant_crops.pdf
- **Ecological farming: Drought-resistant agriculture**
https://www.greenpeace.to/publications/Drought_Resistant_Agriculture.pdf

3.9.4. SWAT+ model implementation

Can be implemented via the fixed management scheduling or/and DTs by changing the plant-specific parameters in plants.plt. The user is referred to the Land Use Management guide: <https://swatplus.gitbook.io/docs/user/editor/inputs/land-use-management>, the Decision Table guide: <https://swatplus.gitbook.io/docs/user/editor/inputs/decision-tables>, and Databases: <https://swatplus.gitbook.io/docs/user/editor/inputs/databases> for more details on changing the crop parameters.

4. Designing measures in the field-scale SWAP model

The SWAP field-scale model, used in OPTAIN to perform precise soil water balance calculations for selected fields and cross-validate them with those obtained from the SWAT+ model runs is a profile-based model, with a spatial validity from profile to field scale. The spatial limitations of the SWAP model determine the measures that can be introduced in the model.

Table 12: Possibilities of incorporating the OPTAIN measures in the SWAP model

Group of measure in OPTAIN	Specific measure in OPTAIN	Incorporation in the SWAP model		
		direct	indirect	no
Structural measures				
Buffer strips/grassland cover	Riparian buffer			X
	Edge-of-field filter strips			X
	Hedges/Field division			X
	Arable land, Recharge zone			X
	Erosive slopes			X
Retention/detention ponds	Surface runoff, sediments			X
River restoration	Floodplain			X
	Channel			X
Afforestation	Afforestation	X		
Wetlands	Wetlands/Constructed wetlands			X
Management measures		direct	indirect	no
Tillage adjustment	No till agriculture (Direct seeding)/No tillage in autumn	X		
	Mulch seeding with permanent minimum tillage		X	
	Low till agriculture	X		
	Mulching		X	
	Subsoiling	X		
Terracing	Hillside terraces and hillside terraces with dry-stone walls			X
Cropping adjustment	Crop rotation	X		
	Intercropping		X	
	Green cover		X	
	Early sowing	X		
Others	Drought - resistant plants		X	

Table 12 gives an overview of the possibilities of accounting for the effects of various NSWORMs on water and solute transport in the SWAP model. Some measures can be introduced in the SWAP model directly, using specific parameters. The indirect way of incorporating an NSWORM in the SWAP model means that an expert assessment is needed to select the measure-specific parameters and estimate their changes when accounting for the effects of a particular measure. Apart from land use changes - afforestation in our case - structural measures cannot be incorporated in the field-scale soil hydrological models like SWAP.

In order to introduce a measure in the SWAP model, soil, crop or drainage parameters or their combinations have to be modified/adjusted. Figure 14 demonstrates the decision scheme on input file and parameter type selection, depending on the type of the measure.

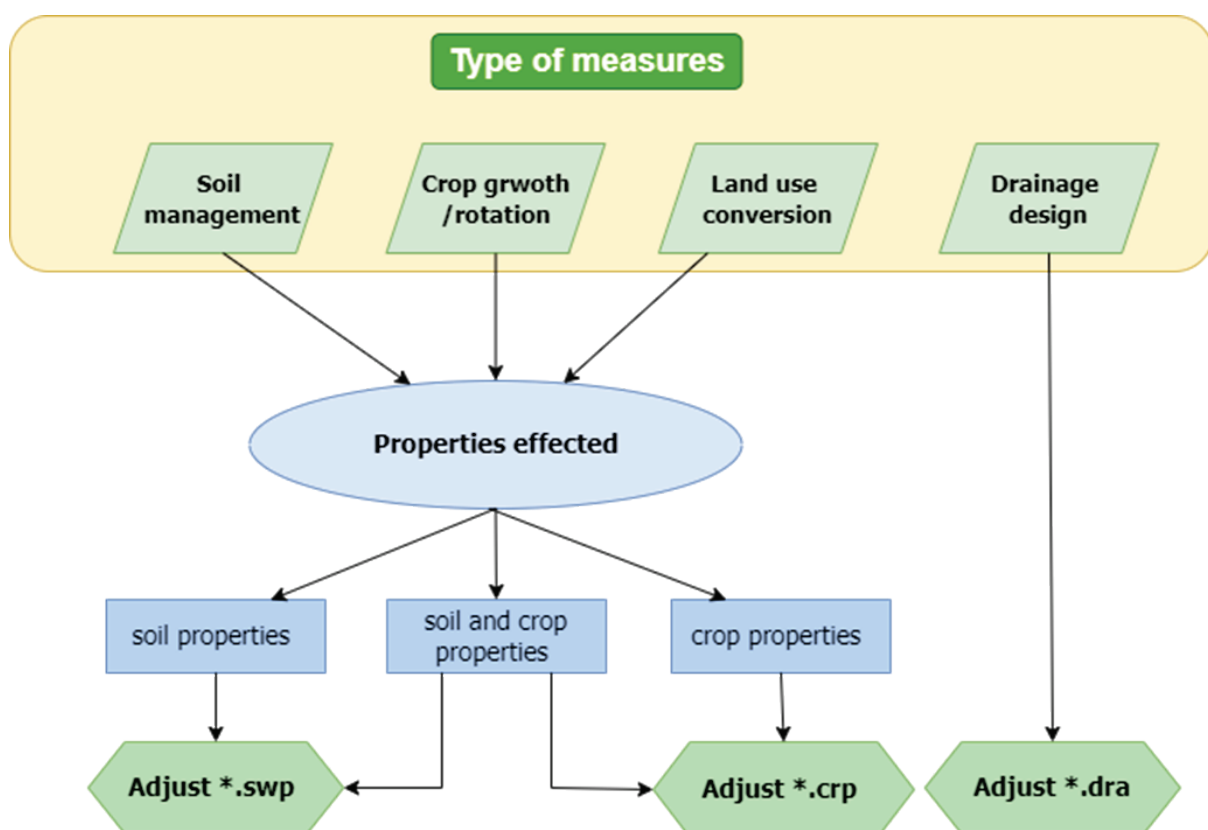


Figure 14: Decision scheme on input file selection for designing measures in the SWAP model.

In the following chapters we give a detailed overview of the parameters to be modified when introducing different measures in the model. For detailed description of the measures please see chapters 2 and 3.

4.1. Afforestation

As the SWAP model does not distinguish between different parts of the catchment but simulates water and nitrogen balance at a much smaller scale, structural measures related to afforestation (e.g. **F03**: Afforestation of reservoir catchments; **F05**: Land use conversion - afforestation) are introduced in the model identically.

To account for the short- and long-term consequences of afforestation, its direct and indirect effects on crop and soil properties have to be accounted for.

4.1.1. Design parameters - short-term effects

- Parameters, defining the vertical discretisation of the soil profile are to be changed, as, compared to grassland or agricultural crops, transpiration takes place from deeper soil layers.
- All the input parameters related to the thickness of the soil profile (e.g. initial soil moisture conditions) need to be adjusted accordingly.
- Parameters of the crop section (Figure 15) of the main SWAP file (*.swp) are to be changed.
- The crop file (*.crp), containing all the crop-related parameters is to be replaced with a relevant crop file for forests.
- Crop files for various forest types are provided on the OPTAIN cloud ([SWAP *.crp files for different forests](#)).

```

*** 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]
* CROPEND   = 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
  INITCRP  CROPSTART  CROPEND  CROPNAME  CROPFIL  CROPTYPE
    1      01-apr-2013  15-aug-2013  'Alfalfa'  'GrassSdry'  1
    1      01-sep-2013  15-mar-2014  'Alfalfa'  'GrassSdry'  1
    1      01-apr-2014  15-aug-2014  'Alfalfa'  'ForestHU'   1
* End of table
*****

```

Figure 15: Example data for the crop section of the main SWAP file.

4.1.2. SWAP model implementation

The main input files and model parameters that are used for modelling the possible direct and indirect effects of afforestation on soil water and nitrogen regime are listed in Tables 13 and 14, respectively.

Table 13: Definition of the model parameters that are used to parameterize the direct effects of afforestation.

Afforestation; short-term effects	
*.swp file, Crop section	
Parameter	Definition
INITCRP	type of initialisation of crop growth (suggested value -1)
CROPSTART	date of crop emergence [dd-mmm-yyyy]
CROPEND	date of crop harvest [dd-mmm-yyyy]
CROPNAME	crop name
CROPFIL	name of file with crop input parameters without extension. CRP
CROPTYPE	growth module
*.swp file, Vertical discretization of soil profile	
Parameter	Definition
ISUBLAY	number of sub layer, start with 1 at soil surface
ISOILLAY	number of soil physical layer, start with 1 at soil surface
HSUBLAY	height of sub layer
HCOMP	height of compartments in the sub layer
NCOMP	number of compartments in the sub layer
*.swp file, Soil water section	
Parameter	Definition
ZI	soil depth (if switch SWINCO = 1, otherwise neglected)
H	soil water pressure head (if switch SWINCO = 1, otherwise neglected)
RDS	maximum rooting depth
*.crp file. Crop development	
Parameter	Definition
LCC	Length of crop cycle (=366 for forest; switch IDEV = 1)
*.crp file. Light extinction	
Parameter	Definition
KDIF	extinction coefficient for diffuse visible light
KDIR	extinction coefficient for direct visible light

Afforestation; short-term effects	
*.crop file. Leaf area index OR soil cover fraction (driven by switch SWGC)	
Parameter	Definition
DVS	crop development stage (SWAP manual, Kroes et al., 2017)
LAI	leaf Area index as a function of DVS
SCF	soil cover fraction as a function of DVS
*.crop file. Crop factor OR crop height (driven by switch SWCF)	
Parameter	Definition
CF	crop factor as a function of DVS
CH	crop height as a function of DVS
ALBEDO	crop reflection coefficient
RSC	minimum canopy resistance
RSW	canopy resistance of intercepted water
*.crop file. Rooting depth	
Parameter	Definition
RD	rooting depth as a function of DVS
*.crop file. Soil water extraction by plant roots	
Parameter	Definition
HLIM1	no water extraction at higher pressure heads
HLIM2U	h below which optimum water extraction starts for top layer
HLIM2L	h below which optimum water extraction starts for sub layer
HLIM3H	h below which water uptake reduction starts at high Tpot
HLIM3L	h below which water uptake red. starts at low Tpot
*.crop file. Soil water extraction by plant roots	
Parameter	Definition

Afforestation; short-term effects	
HLIM4	no water extraction at lower pressure heads
ADCRH	level of high atmospheric demand
ADCRL	level of low atmospheric demand
*.crop file. Interception (switch SWINTER = 2)	
Parameter	Definition
T	time of the year
PFREE	free throughfall coefficient as a function of time
PSTEM	stem flow coefficient as a function of time
SCANOPY	storage capacity of canopy as a function of time
AVPREC	average rainfall intensity as a function of time
AVEVAP	average evaporation intensity during rainfall from a wet canopy as function of time
*.crop file. Root density distribution	
Parameter	Definition
RD	rooting depth
RDCTB	relative rooting density

4.1.3. Design parameters: long-term effects

- Parameters characterising surface properties related to water ponding and surface runoff.
- Soil hydraulic properties.
- Preferential flow due to macropores.

During a longer period, land use changes, including afforestation, have a strong effect on soil properties and surface conditions. Horel et al. (2015) provide a detailed overview of the findings related to short-term and long-term effects of land use changes on soil hydraulic properties. Bormann et al. (2007) suggest methods for estimating land use conversion induced changes in soil bulk density and soil hydraulic properties and evaluate the effects of these changes on water regime. These findings can be used to estimate the values of main parameters listed in Table 13. Suggested changes for some of the main parameters are given in Table 14.

4.1.4. SWAP model implementation

Table 14: Definition of the model parameters that are used to parameterize the indirect effects of afforestation.

Afforestation; long-term effects	
*.swp file, Ponding, runoff and runoff	
Parameter	Definition
PONDMX	minimum thickness for runoff
RSRO	drainage resistance for surface runoff
RSROEXP	exponent in drainage equation of surface runoff
*.swp file, Soil hydraulic functions	
Parameter	Definition
ORES	residual water content
OSAT	saturated water content
ALFA	parameter alfa of main drying curve
NPAR	parameter n
KSATFIT	fitting parameter Ksat of hydraulic conductivity function
KSATEXM	measured hydraulic conductivity at saturated conditions
BDENS	dry soil bulk density
*.swp file, Soil hydraulic functions - preferential flow due to macropores	
<p>Root growth of trees and their penetration in the deeper soil layers can lead to formation of soil macropores and corresponding preferential flow. The SWAP model is capable of describing this process via its macropore option, activated using the switch SWMACRO. The parameterisation of the macropore section, however, is recommended only for advanced SWAP users. Information on how changes in different parameters of the macropore section influence soil water balance elements and soil water content dynamics can be found on the OPTAIN cloud: SWAP_key_functions_parameters. Some key parameters are listed below.</p>	

Parameter	Definition
Z_ST	Depth of static macropores
VLMPSTSS	Volume of static macropores at the soil surface
*.swp file, Soil hydraulic functions - preferential flow due to macropores	
Parameter	Definition

Afforestation; long-term effects	
DIPOMI	Minimal diameter of soil polygons
DIPOMA	Maximal diameter of soil polygons
<p>Bio-pores from roots belong to the static macropores which are continuous and horizontally connected and go deep into the soil. Therefore the depth of these macropores can be adjusted with Z_ST. Furthermore static macropore volume has a great impact on the soil moisture content and on the preferential flow. The size of the minimal and maximal soil polygons define the horizontal distribution. (SWAP manual, Kroes et al., 2017)</p>	
<p>Additional information on root-induced changes of soil hydraulic properties can be found in the review paper of Lu et al. (2020).</p>	

Table 15: Changes in main selected parameters reported for specific land use changes (Bormann et al., 2007)

Afforestation; long-term effects	
*.swp file, Soil hydraulic functions	
Parameter	Relative change
OSAT	crops to forest: 30% increase
OSAT	grassland to forest: 20% increase
KSATFIT	crops to forest : 140% increase
KSATFIT	grassland to forest: 70% increase
BDENS	crops to forest : 15% decrease
BDENS	grassland to forest: 9% decrease

4.2. Tillage adjustment

In the OPTAIN project, five management measures related to tillage adjustments are studied (Table 13). Model parameters, effected by soil tillage systems are summarised in Table 16.

4.2.1. Design parameters

- Parameters characterising surface properties related to water ponding and surface runoff.
- Soil hydraulic properties.
- Preferential flow due to macropores.

4.2.2. SWAP model implementation

Model parameters that reflect the influence of soil tillage system on different surface, soil or crop properties are summarised in Table 16.

Table 16. Definition of the model parameters that are used to parameterize the effects of measures related to tillage adjustment.

Tillage adjustment	
*.swp file, Ponding, runoff and runon	
Parameter	Definition
PONDMX	minimum thickness for runoff
RSRO	drainage resistance for surface runoff
RSROEXP	exponent in drainage equation of surface runoff
*.swp file, Soil hydraulic functions	
Parameter	Definition
ORES	residual water content
OSAT	saturated water content
ALFA	parameter alfa of main drying curve
NPAR	parameter n
KSATFIT	fitting parameter Ksat of hydraulic conductivity function
KSATEXM	measured hydraulic conductivity at saturated conditions
BDENS	dry soil bulk density
RDS	maximum rooting depth
*.swp file, Soil hydraulic functions - preferential flow due to macropores	

Tillage adjustment

Soil tillage operations can lead to formation of soil macropores and corresponding preferential flow. The SWAP model is capable of describing this process via its macropore option, activated using the switch SWMACRO.

The parameterisation of the macropore section, however, is recommended only for advanced SWAP users. Information on how changes in different parameters of the macropore section influence soil water balance elements and soil water content dynamics can be found on the OPTAIN cloud: [SWAP_key_functions_parameters](#).

Some key parameters are listed below.

*.swp file, Soil hydraulic functions - preferential flow due to macropores

Parameter	Definition
Z_IC	Depth of internal catchment macropores
RZAH	Fraction of macropores ending at depth of A-horizon
POWM	Power M for frequency distribution curve of the internal catchment domain
DIPOMI	Minimal diameter of soil polygons
DIPOMA	Maximal diameter of soil polygons

Macropores due to tillage belong rather to the internal catchment macropores which are discontinuous and end in different depths. Therefore they lead to infiltration in the unsaturated soil. The depth of the macropores can be adjusted with Z_IC and the distribution of the different depths can be impacted with the parameter POWM. RZAH is especially used for simulating tillage operations as the parameter can indicate what part of the internal catchment macropores ends at the bottom of the A-horizon. Again DIPOMA and DIPOMI are used to define the horizontal distribution. (SWAP manual, Kroes et al., 2017)

Numerous studies have been published on the effects of soil conserving and conventional tillage systems on soil and crop properties and water regime (Horel et al., 2015; Castellini et al., 2019;). These studies can present contradictory results, because the effect of tillage operations strongly depends on the soil type and geographical conditions of the study area.

Within the OPTAIN project studies and literature reviews are being carried out to identify the site-specific tillage-induced changes in soil properties for all the case study areas. The SWAP model will further be parameterised accordingly.

Table 17: Examples of reported tillage-induced changes of SWAP parameters for no tillage (NT), low tillage (LT) and conventional tillage (CT) systems (See table 13 for parameter description).

Tillage adjustment - no tillage agriculture and low tillage agriculture				
*.swp file, Soil hydraulic functions				
Parameter	Type of tillage adjustment	Conditions	Relative change	Source
OSAT	shift from CT to NT	Loamy clay soil	-8%	Castellini et al., 2019
OSAT	shift from CT to NT	Clay soil	-8%	Castellini et al., 2019
OSAT	shift from CT to NT	Sandy soil	-6%	Osanyinpeju&Dada, 2018
OSAT	shift from CT to LT	Sandy soil	+19%	Osanyinpeju&Dada, 2018
OSAT	shift from CT to NT	Topsoil, Calcic Chernozem loam	-15%	Farkas et al., 2008
OSAT	shift from CT to LT	Subsoil, Calcic Chernozem loam	-6%	Farkas et al., 2008
OSAT	shift from CT to NT	Topsoil, Calcic Chernozem loam	+25%	Farkas et al., 2008
OSAT	shift from CT to LT	Subsoil, Calcic Chernozem loam	+19%	Farkas et al., 2008
ORES	shift from CT to NT	Loamy clay soil	-47%	Castellini et al., 2019
ORES	shift from CT to NT	Clay soil	-1%	Castellini et al., 2019
ORES	shift from CT to NT	Topsoil, Calcic Chernozem loam	+25%	Farkas et al., 2008
ORES	shift from CT to LT	Subsoil, Calcic Chernozem loam	+6%	Farkas et al., 2008
ORES	shift from CT to NT	Topsoil, Calcic Chernozem loam	+18%	Farkas et al., 2008
ORES	shift from CT to LT	Subsoil, Calcic Chernozem loam	+6%	Farkas et al., 2008
ALFA	shift from CT to NT	Loamy clay soil	+70%	Castellini et al., 2019
ALFA	shift from CT to NT	Clay soil	-1%	Castellini et al., 2019

Tillage adjustment - no tillage agriculture and low tillage agriculture				
*.swp file, Soil hydraulic functions				
Parameter	Type of tillage adjustment	Conditions	Relative change	Source
ALFA	shift from CT to NT	Topsoil, Calcic Chernozem loam	-90%	Farkas et al., 2008
ALFA	shift from CT to LT	Subsoil, Calcic Chernozem loam	+41%	Farkas et al., 2008
ALFA	shift from CT to NT	Topsoil, Calcic Chernozem loam	+40%	Farkas et al., 2008
ALFA	shift from CT to LT	Subsoil, Calcic Chernozem loam	+243%	Farkas et al., 2008
NPAR	shift from CT to NT	Loamy clay soil	-10%	Castellini et al., 2019
NPAR	shift from CT to NT	Clay soil	-32%	Castellini et al., 2019
NPAR	shift from CT to NT	Topsoil, Calcic Chernozem loam	+6%	Farkas et al., 2008
NPAR	shift from CT to LT	Subsoil, Calcic Chernozem loam	+1%	Farkas et al., 2008
NPAR	shift from CT to NT	Topsoil, Calcic Chernozem loam	-2%	Farkas et al., 2008
NPAR	shift from CT to LT	Subsoil, Calcic Chernozem loam	-2%	Farkas et al., 2008
BDENS	shift from CT to NT - topsoil	Eutric Fluvisols silt loam	+29%	Tebrügge & Düring, 1999
BDENS	shift from CT to NT - subsoil	Eutric Fluvisols silt loam	+28%	Tebrügge & Düring, 1999
BDENS	shift from CT to LT	Soil, sensitive to compaction	+18%	Roger-Estrade et al, 2015
BDENS	shift from CT to LT	Soil, not sensitive to compaction	+12%	Roger-Estrade et al, 2015
BDENS	shift from CT to NT	Sandy soil	+5%	Osanyinpeju&Dada, 2018
BDENS	shift from CT to LT	Sandy soil	-8%	Osanyinpeju&Dada, 2018

Tillage adjustment - no tillage agriculture and low tillage agriculture				
*.swp file, Soil hydraulic functions				
Parameter	Type of tillage adjustment	Conditions	Relative change	Source
BDENS	shift from CT to NT	Topsoil, Calcic Chernozem loam	+26%	Farkas et al., 2008
BDENS	shift from CT to LT	Subsoil, Calcic Chernozem loam	+1%	Farkas et al., 2008
BDENS	shift from CT to NT	Topsoil, Calcic Chernozem loam	-3%	Farkas et al., 2008
BDENS	shift from CT to LT	Subsoil, Calcic Chernozem loam	-6%	Farkas et al., 2008
KSATFIT	shift from CT to NT	Topsoil, Calcic Chernozem loam	-45%	Farkas et al., 2008
KSATFIT	shift from CT to LT	Subsoil, Calcic Chernozem loam	+13%	Farkas et al., 2008
KSATFIT	shift from CT to NT	Topsoil, Calcic Chernozem loam	+8%	Farkas et al., 2008
KSATFIT	shift from CT to LT	Subsoil, Calcic Chernozem loam	+18%	Farkas et al., 2008
KSATEXM	shift from CT to NT	Eutric Fluvisols silt loam	-84%	Tebrügge & Düring, 1999
KSATEXM	shift from CT to LT	Eutric Fluvisols silt loam	+5%	Tebrügge & Düring, 1999
KSATEXM	shift from CT to NT	Eutric Cambisol sand	-68%	Tebrügge & Düring, 1999
KSATEXM	shift from CT to LT	Eutric Cambisol sand	+18%	Tebrügge & Düring, 1999
KSATEXM	shift from CT to NT	Luvic Phaozem loam	-9%	Tebrügge & Düring, 1999
KSATEXM	shift from CT to LT	Luvic Phaozem loam	+4%	Tebrügge & Düring, 1999
KSATEXM	shift from CT to NT	Alfisol sand	-11%	Busari et al., 2015
KSATEXM	shift from CT to LT	Alfisol sand	+21%	Busari et al., 2015
KSATEXM	shift from CT to NT	Sandy soil	-10%	Osanyinpeju&Dada, 2018

Tillage adjustment - no tillage agriculture and low tillage agriculture				
*.swp file, Soil hydraulic functions				
Parameter	Type of tillage adjustment	Conditions	Relative change	Source
KSATEXM	shift from CT to LT	Sandy soil	+2%	Osanyinpeju&Dada, 2018
KSATEXM	shift from CT to NT	Silt loam	-61%	Lipiec et al., 2006.
KSATEXM	shift from CT to LT	Silt loam	-36%	Lipiec et al., 2006.

Tillage adjustment - no tillage agriculture and low tillage agriculture				
*.crp file, Crop properties				
Parameter	Type of tillage adjustment	Conditions	Relative change	Source
LAI (max)	from CT to NT shift	Loamy clay soil	-12%	Castellini et al., 2019
LAI (max)	shift from CT to NT	Clay soil	-32%	Castellini et al., 2019

In case of conventional tillage systems, subsoil compaction might occur. In this case the 5-8 cm thick soil below the depth of the tillage operation has to be handled separately (*.swp file, vertical discretization of the soil profile) and the compaction can be expressed via soil hydraulic properties in the *.swp file, by reducing OSAT and KSATFIT, KSATEXM and increasing BDENS (see tables 14 – 17 for the abbreviations).

4.3. Cropping adjustment

4.3.1. Design parameters

- parameters characterising the crop rotation scheme
- crop parameters

4.3.2. SWAP model implementation

In the SWAP model, the same parameters are used to incorporate crop rotation and early sowing (Table 18).

For *crop rotation*, the crop section of the *.swp file should be adjusted according to the rotation scheme. An example is given in Figure 16. The length of the crop cycle is to be revised as well.

Early sowing can easily be implemented by adjusting the CROPSTART parameter to the required sowing date. The length of the crop cycle is to be revised as well.

Table 18: Definition of the model parameters that are used to parameterize cropping adjustment - crop rotation and early sowing

Cropping adjustment - crop rotation and early sowing	
*.swp file, Crop section	
Parameter	Definition
INITCRP	type of initialisation of crop growth (suggested value -1)
CROPSTART	date of crop emergence [dd-mmm-yyyy]
CROPEND	date of crop harvest [dd-mmm-yyyy]
CROPNAME	crop name
CROPFIL	name of file with crop input parameters without extension .CRP
*.crp file. Crop development	
Parameter	Definition
LCC	Length of crop cycle

```

*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]
* CROPEND   = 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
  INITCRP   CROPSTART   CROPEND   CROPNAME   CROPFIL   CROPTYPE
    2      01-may-2016   15-sep-2016   'Maize'    'MaizeS'    1
    2      30-sep-2016   06-aug-2017   'Winter wheat' 'WinterCer1' 1
    2      31-aug-2017   04-apr-2018   'cereal+grass' 'GrassS'    1
    2      20-apr-2018   15-aug-2018   'Maize'    'MaizeS'    1
    2      02-sep-2018   15-nov-2018   'catchcr mustard' 'GrassS'    1
    2      22-mar-2019   15-jul-2019   'pea'      'PeaS'      1
    2      25-sep-2019   14-aug-2020   'Winter wheat' 'WinterCer1' 1
    2      15-aug-2020   05-sep-2020   'Winter barley' 'WinterCer1' 1
    2      25-jul-2021   31-dec-2021   'oil seed rape' 'OilSeeds'   1

* End of table
*****

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Figure 16. SWAP model crop rotation scheme for the Cernici (CZ) OPTAIN case study.

To introduce *intercropping*, the crop parameters should be adjusted so that they would represent both the crops in one value (Table 19). The SWAP model does not accept two parallel crops in time, so the incorporation of this measure needs expert-based solutions. The simple crop routine of the SWAP model handles the crop as a sophisticated water extractor; thus, it is not important for the model, how many crops in reality extract water from the different soil layers. What matters is the joint water demand from both the crops at time. Thus intercropping can be introduced as a water demand from seemingly one crop that in reality behaves as the association of the two crops.

Table 19: Definition of the model parameters that are used to parameterize cropping adjustment – intercropping.

Cropping adjustment - intercropping	
*.swp file, Crop section	
Parameter	Definition
INITCRP	type of initialisation of crop growth
CROPSTART	date of crop emergence [dd-mmm-yyyy] (choose the crop that is sown first)
*.swp file, Crop section	
Parameter	Definition

Cropping adjustment - intercropping	
CROPEND	date of crop harvest [dd-mmm-yyyy] (choose the crop that is harvested later)
CROPNAME	crop name
CROPFIL	name of file with crop input parameters without extension .CRP
*.crop file. Leaf area index OR soil cover fraction (driven by switch SWGC)	
Parameter	Definition
DVS	crop development stage (SWAP manual, Kroes et al., 2017)
LAI	leaf Area index as a function of DVS
SCF	soil cover fraction as a function of DVS (recommended for intercropping)
*.crop file. Crop factor OR crop height (driven by switch SWCF)	
Parameter	Definition
CF	crop factor as a function of DVS (for the crop association as a whole)
CH	crop height as a function of DVS (for the crop association as a whole)
ALBEDO	crop reflection coefficient (mutual for two crops)
RSC	minimum canopy resistance (for the crop association as a whole)
RSW	canopy resistance of intercepted water (for the crop association as a whole)
*.crop file. Rooting depth	
Parameter	Definition
RD	rooting depth as a function of DVS (for the crop association as a whole)
*.crop file. Soil water extraction by plant roots	
These parameters (Table 13) have to be defined considering the characteristics of the more stress-tolerant crop.	

4.4. Other measures: Drought - resistant pants

4.4.1. Design parameters

- crop parameters in general (might change slightly for drought-resistant crop genotypes)
- key parameters are those, defining the soil water extraction by plant roots

4.4.2. SWAP model implementation

Table 20: Definition of the model parameters that are used to parameterize drought-resistant plants.

Other measures: Drought-resistant plants	
*.swp file, Soil water section	
Parameter	Definition
RDS	maximum rooting depth
*.crp file. Crop development	
Parameter	Definition
LCC	Length of crop cycle
*.crp file. Light extinction	
Parameter	Definition
KDIF	extinction coefficient for diffuse visible light
KDIR	extinction coefficient for direct visible light
*.crop file. Leaf area index OR soil cover fraction (driven by switch SWGC)	
Parameter	Definition
DVS	crop development stage (SWAP manual, Kroes et al., 2017)
LAI	leaf Area index as a function of DVS
SCF	soil cover fraction as a function of DVS
*.crop file. Crop factor OR crop height (driven by switch SWCF)	
Parameter	Definition
CF	crop factor as a function of DVS
CH	crop height as a function of DVS
ALBEDO	crop reflection coefficient
RSC	minimum canopy resistance

Other measures: Drought-resistant plants	
RSW	canopy resistance of intercepted water
*.crop file. Rooting depth	
Parameter	Definition
RD	rooting depth as a function of DVS
*.crop file. Soil water extraction by plant roots (key parameters)	
Parameter	Definition
HLIM1	no water extraction at higher pressure heads
HLIM2U	h below which optimum water extraction starts for top layer
HLIM2L	h below which optimum water extraction starts for sub layer
HLIM3H	h below which water uptake reduction starts at high Tpot
HLIM3L	h below which water uptake red. starts at low Tpot
HLIM4	no water extraction at lower pressure heads
ADCRH	level of high atmospheric demand
ADCRL	level of low atmospheric demand
For drought-tolerant crops HLIM3H, HLIM3L and HLIM4 should be reduced. Hagyó (2009) in her PhD thesis adapted the SWAP model to semiarid grasslands. The HLIM4 values were so low for this specific grassland that the SWAP code limit was exceeded. Thus, in some cases incorporation of certain measures might require changes in the SWAP code to make the model run.	
*.crop file. Root density distribution	
Parameter	Definition
RD	rooting depth
RDCTB	relative rooting density

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