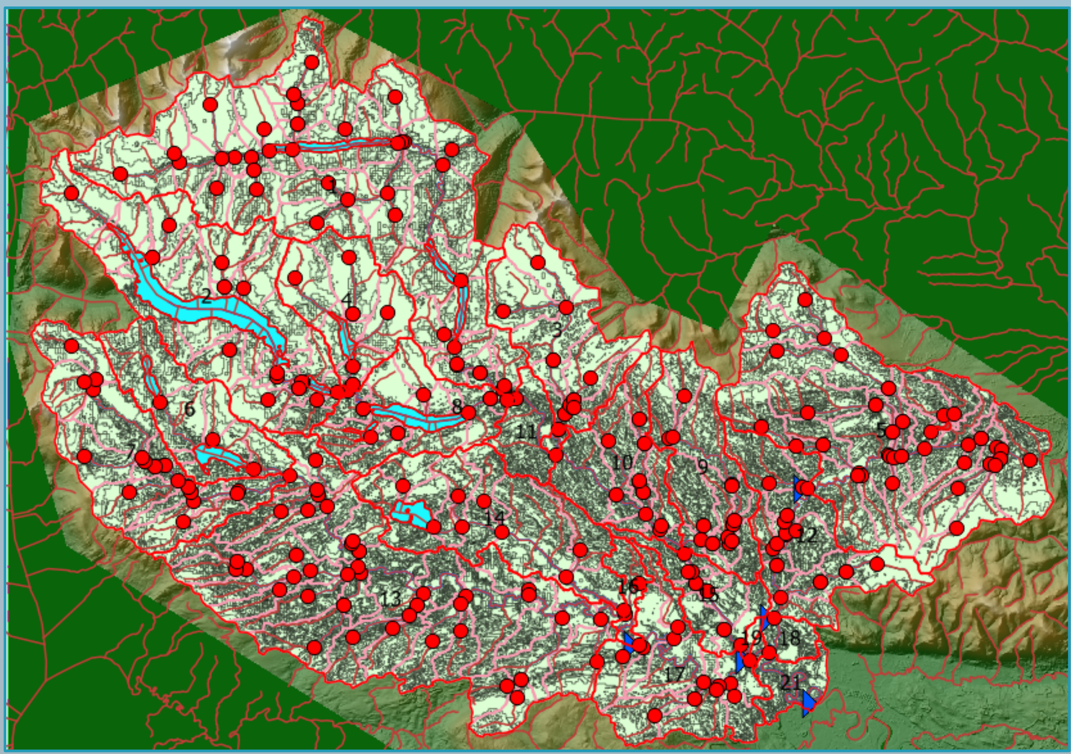

Deliverable D3.3:

The MERLIN modelling workflow to assess the biophysical and economic impact of freshwater ecosystem restoration at catchment scale

www.project-merlin.eu

Imprint

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MERLIN Key messages

1. Freshwater ecosystems in Europe are increasingly under threat due to climate change, land-use intensification, and biodiversity loss –posing serious risks to critical ecosystem services.
2. Restoration of freshwater ecosystems is essential for achieving EU policy goals, including the European Green Deal and the Biodiversity Strategy, while enhancing ecological resilience and sustainability.
3. The MERLIN modelling workflow, developed under Work Package 3, provides a structured, scalable approach to assess both biophysical and economic impacts of restoration across Europe.
4. Based on the open-source SWAT+ tool, the workflow integrates ecohydrological modelling with ecosystem service analysis and socio-economic valuation to support evidence-based decision-making.
5. It uses harmonised, EU-wide publicly available datasets, making it applicable even in data-scarce regions and adaptable to both local and continental scales.
6. The tool simulates a wide array of restoration measures –including wetland rewetting, riparian buffers and floodplain reconnection –offering insights into ecosystem service trade-offs and synergies.
7. A distinguishing feature of the MERLIN workflow is its capacity to conduct a monetary valuation of restoration benefits and improved policy alignment.
8. This user-friendly, step-by-step guidance is designed for a wide audience – from field practitioners to policymakers – and supports various technical skill levels.
9. Early implementation shows the workflow's flexibility and potential to improve restoration planning, with opportunities for enhanced accuracy through integration of local, high-resolution data.

MERLIN Executive Summary

Freshwater ecosystems across Europe are under increasing pressure due to climate change, intensive land use, and widespread biodiversity loss. These ecosystems –including streams, rivers, lakes, wetlands and peatlands – play a vital role in maintaining ecological integrity and delivering critical ecosystem services (ES) such as water purification, flood and drought regulation, and carbon sequestration. Restoration of these ecosystems is essential not only for ecological health but also for meeting key European policy goals, such as those set forth in the European Green Deal and the EU Biodiversity Strategy. **However, planning effective and scalable restoration interventions requires robust, data-driven tools that can simulate their outcomes, and assess both their ecological and socio-economic impacts**.

The MERLIN project directly addresses this need through its Work Package 3 (WP3). This deliverable introduces the **MERLIN modelling workflow: a structured and scalable approach designed to assess the biophysical and economic impacts of freshwater ecosystem restoration across Europe**. Built around the open-source Soil and Water Assessment Tool Plus (SWAT+), the workflow integrates ecohydrological modelling with ecosystem service evaluation and socio-economic valuation. The goal is to enable evidence-based, spatially explicit restoration planning that can be applied from small catchments to continental scales.

The MERLIN workflow uses harmonised, EU-wide publicly available datasets – such as digital elevation models, land use, soil maps and climate data – making it applicable even in data-scarce regions. It simulates a broad range of restoration measures, including wetland and peatland rewetting, riparian buffer implementation, floodplain reconnection, and river channel restoration. **Outputs include indicators that serve as a basis for understanding trade-offs and synergies in ecosystem services under different restoration scenarios**.

A unique strength of the MERLIN modelling workflow is its integration of socio-economic analysis through Natural Capital Accounting (NCA) and Cost-Benefit Analysis (CBA). This allows users not only to quantify ecological benefits but also to **assign monetary value to restoration impacts, thus supporting policy alignment, stakeholder engagement, and financing strategies**. The workflow equips decision-makers to explore restoration trade-offs, identify optimal intervention points, and justify investments based on long-term ecosystem service gains.

This guidance document presents the modelling workflow in a user-friendly, step-by-step format that accommodates varying levels of technical expertise. It covers software setup, data preparation, model configuration, calibration, scenario simulation, and both biophysical and economic valuation. Each step is illustrated with practical examples to facilitate understanding and application. **By structuring the workflow in this way, the MERLIN team has ensured that a broad range of users– including environmental agencies, NGOs, consultants, academics, and government planners – can implement and benefit from the tool**.

Initial implementation of the workflow across European landscapes has demonstrated its flexibility and scalability. While it performs effectively with EU-level datasets, its accuracy and relevance can be further enhanced through integration with local, high-resolution data when available. **Nonetheless, even in areas with limited data, the workflow provides valuable insights and supports strategic planning**.

In summary: the **MERLIN modelling workflow represents a significant advancement in ecological restoration planning.** By uniting ecohydrological modelling, ecosystem service quantification, and socio-economic evaluation in a replicable and adaptable framework, it offers a powerful tool to support Europe's transition toward resilient, nature-based freshwater systems. Its broad applicability, scientific robustness, and policy relevance make it a cornerstone for transformative restoration efforts in alignment with Europe's sustainability agenda.

Content

1 Introduction

1.1 Background

Freshwater-related ecosystems across Europe are under increasing pressure from climate change, land-use intensification, and biodiversity loss. Restoration of these ecosystems presents a key opportunity to enhance ecological resilience, restore natural functions, and deliver multiple ecosystem services such as water purification, flood and drought mitigation, climate regulation, and carbon sequestration. However, to effectively design and implement restoration strategies, practitioners and policymakers require robust, scalable tools that can simulate and quantify the benefits of such interventions.

Work Package 3 (WP3) of the MERLIN (Mainstreaming Ecological Restoration of freshwater-related ecosystems in a Landscape context: Innovation, upscaling and transformation) project addresses this challenge by developing a modelling workflow capable of assessing the bio-physical and economic impacts of freshwater ecosystem restoration across Europe. This workflow applies a process-based, eco-hydrological modelling approach using the modelling tool SWAT+ (Soil and Water Assessment Tool) that is an open-source software. The modelling workflow enables users to simulate a wide range of restoration measures and evaluate their impacts on a set of ecosystem services (ES) to inform the planning of where and how to restore freshwater ecosystems to optimize restoration benefits. The modelled ES include carbon sequestration, nutrient regulation, flood and drought risk reduction, and agricultural productivity. The input data for the modelling is completely based on harmonized, **publicly available data at the EU level**, allowing it to be implemented also in data-scarce regions and applied across multiple spatial scales, from small catchments to the whole of Europe.

Crucially, the modelling workflow is designed for broad applicability, supporting future restoration efforts across diverse geographic and policy contexts. Its outputs, including GIS layers, scenario results, and valuation data, will also inform stakeholder engagement and capacity-building activities.

An important part of the workflow comprises a socio-economic assessment component to evaluate restoration benefits from a stakeholder and policy perspective. This includes monetizing ecosystem service impacts through Natural Capital Accounting (NCA), helping to carry out Cost-Benefit Analysis (CBA), identifying financing incentives, policy synergies, and potential trade-offs between restoration goals.

In summary, the (hereinafter) **MERLIN modelling workflow** developed under WP3 provides a structured approach to simulate restoration scenarios, assess ecosystem service outcomes, and evaluate the socio-economic benefits of restoration strategies to inform planning of freshwater restoration projects. It serves as both a technical tool for analysts and a strategic resource for decision-makers, allowing users to explore the opportunities of different restoration approaches in a spatially explicit and evidence-based manner.

1.2 Contribution to European Green Deal Goals

This workflow aligns with the ambitions of the European Green Deal, particularly regarding climate action, biodiversity enhancement, and sustainable land and water management. By enabling data-driven assessments of restoration outcomes, it strengthens the scientific foundation for investment in nature-based solutions and supports the mainstreaming of ecological restoration across sectors.

1.3 Overview of the guidance document and targeted audience

The guidance document introduces the MERLIN modelling workflow in a clear, step-by-step format—starting from software installation and data preparation through simulation and analysis to socio-economic valuation. Each step is accompanied by practical examples to support users of varying technical backgrounds. The final product is a replicable and adaptable workflow that promotes integration between biophysical modelling and socio-economic evaluation.

This guidance is intended for a wide audience, including environmental agencies, NGOs, restoration practitioners, academic researchers, consultants, and public administrators. Whether users are conducting field-level implementation or developing national restoration strategies, the workflow offers practical tools to inform decisions, demonstrate benefits, and enhance the long-term sustainability of freshwater restoration initiatives.

The following sections of this document provide a comprehensive guide to applying the MERLIN modelling workflow in practice. **Section 2** outlines the prerequisites for effective implementation, including recommended software and technical skills, hardware requirements, and expected time investments based on user expertise. The core of the document, **Section 3**, presents the modelling workflow in seven detailed steps. It begins with **Step 1**, which covers the installation of essential software tools such as QGIS, QSWAT+, SWAT+ Editor, Python, and R. **Step 2** guides users through data collection and preparation, including sourcing and organizing key spatial and environmental datasets like digital elevation models, stream networks, land cover, soil maps, and weather data. **Step 3** focuses on project setup within the SWAT+ environment, addressing watershed delineation, Hydrological Response Unit (HRU) creation, and model configuration. **Step 4** details model calibration using observed data and optimization algorithms, ensuring accurate simulation of hydrological and ecological processes. In **Step 5**, users apply various restoration scenarios—such as peatland and wetland rewetting, riparian buffer establishment, floodplain reconnection, and channel restoration—to explore their effects on ecosystem functions. **Step 6** connects model outputs to ecosystem services, analysing biophysical indicators and integrating socio-economic data to evaluate restoration benefits. Finally, **Step 7** introduces valuation techniques for monetizing ecosystem services, including methods for assessing water purification, flood risk reduction, climate regulation, and drought mitigation. **Section 4** captures the key technical and conceptual challenges encountered throughout the development process, offering solutions and recommendations for future users. **Section 5** concludes with reflections on the workflow's relevance, usability, and potential to support large-scale, impact-oriented freshwater restoration efforts across Europe.

2 Prerequisites

2.1 Recommended skills of the users

To effectively use the tools described in the MERLIN Cookbook, users should have intermediate to advanced knowledge in the following software areas:

- QGIS and QSWAT+:
  - Familiarity with Geographic Information Systems (GIS), especially QGIS.
  - Ability to work with maps and geographic layers, including shapefiles and raster files
- R and RStudio:
  - Basic programming knowledge in R
- Skills in running scripts and managing packages like R-SWAT
- Python (Optional but Recommended):
  - Competence in installing and managing Python packages using pip
- Basic skills in running Python scripts (although a comprehensive guidance is provided in this guidance)
- SWAT+ Editor:
  - Basic understanding of how the SWAT+ editor operates to modify parameters and run hydrological simulations

2.2 Hardware requirement

To ensure optimal performance while working with the specified tools, users are recommended to have hardware that meets at least the following specifications:

- Processor:
  - Minimum: Quad-core processor (e.g., Intel Core i5 or equivalent)
  - Recommended: 8-core processor for running simulations and parallel calibrations efficiently
- RAM:
  - Minimum: 8 GB
  - Recommended: 16 GB or more to handle large projects in QGIS and complex simulations in SWAT+
- Storage:
  - Minimum of 50 GB free space to store project data, maps, climate databases, and simulation results
- Operating System:
  - Windows 10 or later (required for specific installations, such as the Microsoft Store version of Python) (can run on other operating systems, such as Linux or MacOS, mind the differences in commands to run Python and different file paths structures).
- Graphics Card:
  - Integrated: Sufficient for QGIS and SWAT+ (Integrated is enough)
  - Dedicated: Recommended for more efficient map processing
- Internet Connection:
  - Required for downloading software, additional databases, and receiving tool updates
- Extra:
  - Access to a computational cluster would be optimal to improve drastically time efficiency when calibrating the models

2.3 Time dedication to complete the modelling workflow: Make it depend on background/level of expertise in modelling

The time required to complete the MERLIN modelling workflow depends on the user's background, particularly their experience with spatial analysis and hydrological modelling. However, practical applications show that the workflow is both efficient and accessible, even for those with limited modelling experience.

For example, in a real-world implementation, a user with a Master's degree and strong expertise in GIS—but no prior experience in eco-hydrological modelling—was able to complete the core modelling tasks for the Bzura River Basin (Poland) in approximately 7 hours. This time covered software setup, data preparation, model configuration, and scenario simulation. (Note: model calibration was included only in terms of setup, as full calibration can take several days.)

In comparison, a member of the MERLIN development team with extensive SWAT+ experience completed the same tasks in about 6 hours.

This small time difference—just one hour—highlights the usability and efficiency of the MERLIN modelling workflow. Its step-by-step guidance, seamless software integration, and practical examples help flatten the learning curve, enabling effective use by a wide range of users. Whether environmental practitioners, consultants, planners, or researchers, users can implement the workflow with confidence, regardless of their modelling background.

3 The MERLIN modelling workflow Step-by-Step

This section provides a complete and structured walkthrough of the MERLIN modelling workflow. Each step is explained in detail, from software installation to model setup, execution, and result evaluation. The guide is designed to be followed sequentially, ensuring that users — regardless of prior experience — can carry out each stage of the modelling process successfully.

3.1 Software installation

In this section, we detail the software needed to successfully complete the workflow, as well as recommendations for downloading and installing the appropriate versions. We strongly suggest using the latest versions of all tools to ensure compatibility and access to the newest features. Below we list the software requirements to follow this guide, providing a link to download each of them as well as the suggested order:

1. **QGIS LTR**: Although version 3.22 was used in our workflow, we recommend installing the most recent long-term release of QGIS for Windows (Download from here).
2. **QSWAT+, SWAT+ Editor and SWAT+ rev**: Version 3.0.3 of QSWAT+, 3.0.8 of SWAT+ Editor and 61.0.1 of SWAT+ were used in our workflow, the current latest SWAT+ release. We recommend always downloading and installing the latest version, following the official installation guide available on the SWAT+ website (Download from here).
3. **R, R Studio, and R-SWAT: To use R-SWAT, we recommend installing the latest version of R (Download from here) and RStudio (Download from here) and following the instructions provided by the author to properly install R-SWAT** (Available here).
4. **Python and PIP**: The latest version of Python can be installed through the Microsoft Store on Windows. To install PIP, the user can follow the steps provided here.
5. **FileZilla**: We recommend installing the latest version of FileZilla (Download from here)

3.2 Data collection

In this section, we describe the data required to build the hydrological model. This includes spatial datasets such as topography, land use, soil types, and river networks, as well as climate and hydrological records. Proper data collection ensures that the modelling process can proceed without interruptions or inconsistencies.

3.2.1 Data structuring

To organize all input files clearly and consistently, we propose the following folder structure:

- **0-Model**: Here, the user should save the different models for the given basin

- **1-Delineate_watershed**: Here, the user should save the DEM, the river network shapefile, the outlets/gouging stations shapefile, and the lakes shapefile.
- **2-Create_HRUs**: Here, the user should save the Soil map and the Corine Land cover shapefile
- **3-Weather_data**: Here, the user should save the Weather data for the basin
- **4-Outputs:** Here, the user should store the SQLite output files from the different restoration simulations

3.2.2 Data collection & processing

This section provides step-by-step instructions for downloading, processing, and preparing spatial datasets in **QGIS**. It covers key data sources, including **Digital Elevation Models (DEM), Stream Networks, Lakes, Land Use, Soil Maps, and Weather Data**. Instructions include **importing, clipping, reprojecting, and exporting** data to ensure consistency for further analysis.

The required data is:

Digital elevation model (DEM)

- Download and Import DEM Data:

1. Access the area of interest data from the **Eurostat digital elevation model** (access here).
2. Use the interactive map to select and download the data by clicking the rectangle(s) that cover your study area.

- Import and process in QGIS

1. Open the downloaded raster(s) in QGIS. If you have multiple raster tiles, merge them into a single layer.
2. Clip and Reproject the Layer:
   - Clip the layer to fit the case study zone (by using the *Clip Raster by extent* tool).
   - Reproject the layer to EPSG 3035 (by using the *Wrap (reproject)* tool).
3. Save the final files in the **"1-Delineate_watershed"** folder

Stream Network

- Download and import Stream Network

1. Download and Import River Network Data
2. Access the area of interest data from the Copernicus EU Hydro River Network Database (access here).
3. Download the relevant file for your area of interest.
4. Note: Other available river shapefiles, such as HydroRIVERS, ECRINS, or CCM, can also be used.

- Import and Process in QGIS

1. Open **QGIS** and import the downloaded file (when asked, import only **HYDRO/River_Net_l** layer).

- Export the Layer

2. **Export the layer**: Save it for further use, ensuring it is in the correct projection (**EPSG 3035**).
3. Save the final files in the **"1-Delineate_watershed "** folder.

Inlets/outlets shapefile

The inlets/outlets shapefile contains points where there will be a channel separation in the model, but it might not always be necessary. These are the cases where it is necessary:

- ***Channel restoration*** will be simulated in a restoration scenario. Since only target channels will be restored, a point at the beginning and end of each restoration area is needed, so SWAT+ channels will be delineated accordingly. The model needs to include ***point source discharges*** from wastewater treatment plants, since point sources are only created at the beginning of a channel.
- Only a section of the basin is simulated (e.g., the Danube in the Romanian case study), and therefore, we need the point of the upstream location at which we have observed streamflow data to input into the model.
- Optional ***streamflow calibration*** will be performed. The locations of the gauging stations must be included in the shapefile.

→ Optionally, the location of the ***basin outlet***. It can be manually drawn during the model set-up in QSWAT+, but it can also be provided in the inlet/outlet shapefile.

The steps to create the inlets/outlets shape files are the following:

→ Create a vector point shapefile

4. Create a **vector point shapefile** with the following fields, all type Integer:
    a. ID
    b. RES
    c. INLET
    d. PTSOURCE

→ Add point data

5. The attribute table should be populated as follows:
    a. **ID:** sequential ID, must be unique for each point.
    b. **INLET, RES, and PTSOURCE:** the different combinations for these fields will determine the type of object that will be created.
        i. **1, 0, 1:** This combination will create a point source. Use this option for most cases.
        ii. **1, 0, 0:** This combination will create an inlet. Use this option when only parts of the basin are simulated, to locate the point where upstream streamflow data will be input, and the basin delineated from this point forward.
        iii. **0, 0, 0:** This combination will create an outlet. Use this option only for the basin outlet.
6. Save the final file in the **"1-Delineate_watershed "** folder.

Lakes

The integration of lakes in the model depends on the characteristics of the case study basin. If the proportion of lake areas in the basin is significant (e.g., based on expert criteria), this step should be followed.

→ Download and Import Data

1. Access the **Copernicus EU Hydro River Network Database** (access here).
2. Download the relevant file for your area of interest.

→ Process in QGIS

1. Open **QGIS** and import the downloaded file (when asked, import only **HYDRO/InlandWATER** layer).

→ Use CORINE Land Cover Data

1. Open the **CORINE Land Cover Map** in QGIS (refer to the **Land Use Land Cover** section for download instructions).

→ Apply Zonal Statistics for Water Classification

1. Use the **"Zonal Statistics"** tool in QGIS to extract statistics from the CORINE land cover map based on the **polygon of interest**.
2. Specify:
3. HYDRO/InlandWATER-selected polygons as the zones.
4. CORINE Land Cover Map as the raster layer.
5. Choose **"Majority"** as the statistic to calculate.
6. Apply a filter to retain only polygons where most pixels fall into the **WATER** category (**values 40 to 44**).

→ Save the Final Layer

1. Select the new layer, create the attribute **"RES"**, and set its value to **2**.
2. Save the new file in the **"1-Delineate_watershed "** folder.

Land Use and Land Cover

→ Download CORINE Land Cover Data

1. Visit the WateriTech webpage (access here).
2. Locate the “Land Cover Maps” section.
3. Download all files related to CORINE Land Cover Map (raster map + lookup table).

→ Process in QGIS

1. Clip and Reproject the Layer:
    a. Clip the layer to fit the case study zone (by using the *Clip Raster by extent* tool).
    b. Reproject the layer to EPSG 3035 (by using the *Wrap (reproject)* tool).
2. Save the processed layer in the "2-Create_HRUs" folder.

→ In case of conducting peatland rewetting simulation

1. Create a vector layer and draw the polygons over the areas to be restored
2. Use the **Rasterize** tool to convert this layer into a raster. Use the value “49” as a “fixed value to burn”
3. Apply the **r.patch** tool of the GRASS GIS 7 toolkit available in QGIS to create a composite raster layer. Make sure that the raster layers to be patched together are the peatland restoration areas layer and the CORINE Land Cover Map, in that order.
4. Modify the **land use lookup table** (CSV file) to be used in QSWAT+ by changing “36,WETL” (wetland) to “36,PEAT” (peatland), and also add “49,BSVG” (barren or sparsely vegetated).

→ In case of conducting riparian buffer simulation

1. Create a vector layer and draw the polygons over the areas that will be “filtered” by the riparian buffer
2. Use the **Rasterize** tool to convert this layer into a raster. Use the value “49” as a “fixed value to burn”
3. Apply the **r.patch** tool of the GRASS GIS 7 toolkit available in QGIS to create a composite raster layer. Make sure that the raster layers to be patched together are the peatland restoration areas layer and the CORINE Land Cover Map, in that order.
4. Modify the **land use lookup table** by adding “49,FSTP” (generic agriculture filter strip) or “50,FSTP” in the case you are also simulating peatland restoration.

Soil Map

→ Download OpenLand Soil Data

1. Visit the **WateriTech** webpage (access here).
2. Locate the **“Soil Maps”** section.
3. Download all files related to **OpenLand Soil Map** (raster map + lookup table + usersoil).

→ Process in QGIS

1. Clip and Reproject the Layer:
    a. Clip the layer to fit the case study zone (by using the *Clip Raster by extent* tool).
    b. Reproject the layer to EPSG 3035 (by using the *Wrap (reproject)* tool).
2. Save the processed layer in the "2-Create_HRUs" folder.

Floodplains

→ A floodplain raster map is only required for the restoration scenarios of ***riparian buffer*** and ***floodplain reconnection***. The QSWAT+ interface also provides options to delineate the floodplain. Therefore, the user can choose between the options of using an existing and generalizable floodplain layer or creating one from the delineation options from QSWAT+. In the case of the former:

1. Access the area of interest data from the **Copernicus EU Riparian Zones** (access here).
2. Download the Riparian zones layer of the area of interest.
3. Open the downloaded layer in QGIS and **Clip and Reproject the Layer** by using the ***Clip*** and ***Reproject*** tools
4. Reclass all the values to “1” by using the ***Reclassify by Table*** QGIS tool
5. Save the processed layer in the "**2-Create_HRUs**" folder.

Weather Data

→ Request and Download Data

1. Access the **WaterWebTools** tool (https://www.wwt-platform.com/bgis/f774824d-5c0e-44e3-b6a0-46d4d107ccd3access here).
2. Use the tool's interface and guide to **define the area of interest**.
3. Provide the **location name** and a valid **email address** for data delivery.
4. Specify the **desired date range** (ensure it matches the model's timeframe, including warm-up).

Important: ERA5 data can be downloaded through Open Meteo. WateriTech has developed a tool that allows you to download ERA5 data from Open Meteo and convert this directly to SWAT+ format through the WaterWebTools portal (https://www.wwt-platform.com/bgis/f774824d-5c0e-44e3-b6a0-46d4d107ccd3). Download for free is currently restricted to one year. Alternatively, ERA5 data can also be downloaded directly from Open Meteo or from the original Climate Data Store using an Application Program Interface (CDS API). Downloading and formatting the ERA5 data from Open Meteo or CDS into SWAT+ format requires some programming skills.

→ Receive and Save the Data

1. Click **"Request"** to submit the data request.
2. Wait for the confirmation email.
3. Download the provided **zip file** containing the data.
4. Save the extracted data in the **"3-Weather_data"** folder.

Nutrient inputs: Atmospheric deposition

→ Download the data

1. Access to the **Co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe** website to download the modelled air depositions. Latest reported yearly in NetCDF format (access here).

To process this data into SWAT+ format, first, we will need to use a template file that has to be downloaded from the SWAT+ Editor after importing the weather data. Therefore, before continuing to process the atmospheric deposition data, first build the model up to section 3.3.4, until you reach the step to download **"atmo-weather-station-map.csv"**.

→ Create points and extract N variables information

1. Open the .nc download file in QGIS. Select only the following rasters, changing the project CRS **EPGS 4326**:
   a. DDEP_OXN_m2Grid
   b. DDEP_RDN_m2Grid
   c. WDEP_OXN
   d. WDEP_RDN
   e. WDEP_PREC
2. Create a vector point layer with the locations of the weather stations using the file downloaded in section 3.3.4. Use **Add delimited text layer** and select the file **"atmo-weather-station-map.csv"**, making sure that the coordinates are correctly defined using CRS **EPGS 4326.**
3. Add the following fields (Real) to the atmo-weather-station-map attribute table: nh4_rf, no3_rf, nh4_dry, no3_dry, and pcp.
4. Use the **v.what.rast** tool of the GRASS GIS 7 toolkit available in QGIS to sample raster values to the new fields:
   a. nh4_rf: WDEP_RDN
   b. no3_rf: WDEP_OXN
   c. nh4_dry: DDEP_RDN_m2Grid
   d. no3_dry: DDEP_OXN_m2Grid
   e. pcp: WDEP_PREC

5. The units of dry and wet deposition or oxidized and reduced nitrogen sampled from the rasters are in mg/m^2. However, SWAT+ uses kg/ha for dry deposition and mg/L for wet deposition. Therefore, use the **Field Calculator QGIS** tool to update the fields with the correct units.
   a. Considering that *pcp* is the precipitation in mm, *nh4_rf* and *no3_rf* need to be divided by *pcp*.
   b. *nh4_dry* and *no3_dry* need to be divided by 100.
6. Delete all fields in the attribute table except *nh4_rf*, *no3_rf*, *nh4_dry*, and *no3_dry*.
7. Export this vector as CSV to prepare the SWAT+ Atmospheric deposition files

→ Prepare files in SWAT+ format

1. Open the provided template file **"atmo_avgannual.csv"**. Replace the columns *nh4_rf*, *no3_rf*, *nh4_dry*, and *no3_dry* with the values in the CSV from the previous step. Then populate the columns *month* and *year* with 0, and the column *name* with unique names (e.g., atmo_1, atmo_2, etc). Save the file.
2. Open the original **"atmo-weather-station-map.csv"** file you downloaded from the Editor in Excel. Copy the same station names (e.g., atmo_1, atmo_2, etc) to the column *atmo_station*. Save the file.

Nutrient inputs: Urban wastewater

→ Download the data

1. Access to the European Environment Agency Datahub portal, to download the Urban Waste Water Treatment Directive on reported data about urban waste water treatment plants. Download both the Treatment plants (access here) and discharge points (access here) geopackages.

→ Gather the UWWT relevant data on nutrient discharge

1. Load the WWTP location (**UWWTD_TreatmentPlants.gpkg**) and the discharge point location (**UWWTD_DischargePoints.gpkg**) to QGIS.
2. **Join Attributes by Field Value**. Use the discharge points as the input layer and the WWTP as the input later 2. Table field and Table field 2 should be **"uwwCode"**, and the Join type should be **"Take attributes of the first matching feature only (one-to-one)"**.
3. Select the discharge points of WWTPs within the case study basin
4. The relevant data to extract are on these attributes:
5. uwwWasteWaterTreated: Mean annual volume of wastewater treated in m^3/year.
6. uwwNDischargeMeasured: Annual load of N in tons/year.
7. uwwPDischargeMeasured: Annual load of P in tons/year.
8. Calculated (uwwNDischargeCalculated and uwwPDischargeCalculated) or estimated (uwwNDischargeEstimated and uwwPDischargeEstimated) loads could also be used instead if measured data is not available. If none of these variables have value, you could try to extrapolate discharge loads from uwwLoadEnteringUWWTP variable (organic biodegradable load of the urban wastewater entering the treatment plant), which is typically expressed in population equivalents, or exclude this WWTP from the model. If you cannot find or extrapolate discharged volumes, also exclude them from the model.

→ Prepare files in SWAT+ format

For each WWTP discharge, SWAT+ needs daily volume (in m^3) and loads (in kg N or P), so the database values should be converted to the corresponding units. Therefore, divide the volume by 365, and for the N and P loads, multiply by 1000 and divide by 365. Note that SWAT+ differentiates between different forms of nitrogen (organic N, nitrate, ammonia, and nitrogen oxide) and phosphorus (organic and mineral/soluble P). However, since the database accounts for total N and total P, we will assume that all nitrogen will be nitrate and all the phosphorus will be mineral/soluble phosphorus.

The final formatting into SWAT+ format will be continued during the project set-up, as a template file for point sources has to be exported from the Editor, modified, and then imported again (see section 3.3.4).

Evapotranspiration and Soil Water Content

Evaporation and soil water data can be used to calibrate the SWAT+ model.

→ Access and Request GLEAM Data

1. Go to the **GLEAM data webpage** (access here).
2. Navigate to the **"Downloads"** section.
3. Provide your **email address** to receive the necessary information for data retrieval.

→ Receive Login Credentials

1. Check your **email** for the login details, which should include:
2. Protocol
3. Host
4. Port
5. Username & Password
6. Use these credentials to **access the data repository**.

→ Download Data Using FileZilla

1. Open **FileZilla** and enter the **Host, Port, Username, and Password** in the fields at the top of the window.

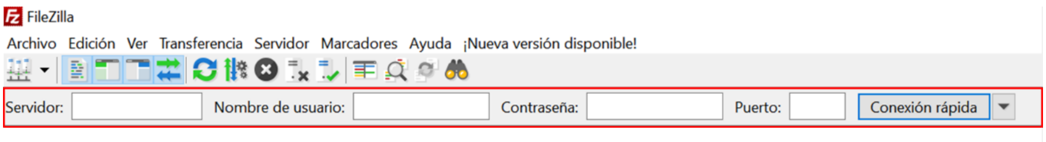

Figure 1. Evapotranspiration and Soil Water Content (1)

2. Navigate to the **data directory** on the right side of the window.

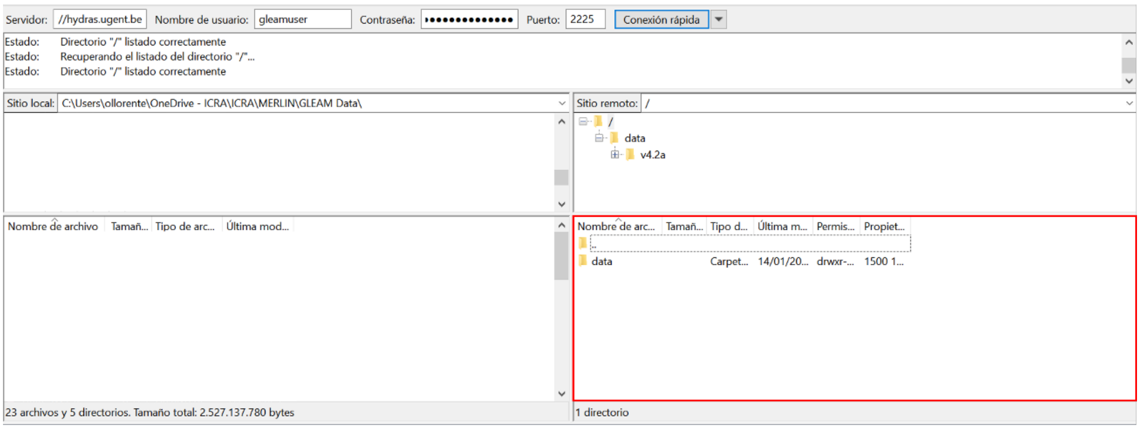

Figure 2. Evapotranspiration and Soil Water Content (2)

3. Locate and **download the monthly data** to your computer.
4. Open the .nc download file in QGIS, using CRS **EPGS 4326.**
5. Clip any of the available raster layers with ***Clip raster by mask layer***, using the downloaded DEM layer as a mask.
6. Convert the selected raster cells to points using ***raster pixel to points***
7. Use the ***Add geometry attributes*** tool to create a new vector points layer with "long" and "lat" attributes
8. Export the resulting vector layer as a .csv named "gleamdata.csv"
9. Save the "gleamdata.csv" in the same folder as the "PrepareObservations.py" Script and the "requirements.txt" file (which you will find in the MERLIN GitHub repository)
10. Open the script and select the date range. Use the same range that you will use in the 3.4.3 section. You may want to wait for that section before doing this step (Figure 3).

```python
import pandas as pd
import xarray as xr
import numpy as np
import os
import glob

# ==== DEFINE DATE RANGE (start and end) ====
start_date = '2001-01-01'  # Change as needed (format: 'YYYY-MM-DD')
end_date = '2011-12-31'    # Change as needed (format: 'YYYY-MM-DD')

# Directory containing the .nc files
nc_directory = 'E'  # Change this path if needed

# Load the points file with `id_conca = 1`
points_df = pd.read_csv('gleamdata.csv')
```

Figure 3. Evapotranspiration and Soil Water Content (3)

11. Open a Windows terminal inside the folder of both the script and the data by typing “cmd” in the path finder and pressing Enter (Figure 4).

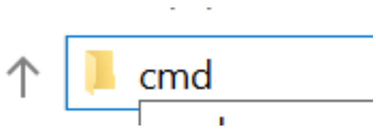

Figure 4. Evapotranspiration and Soil Water Content (4)

12. In the terminal, type the following command to install all the necessary Python libraries: “pip install -r requirements.txt” (Figure 5).

```
Símbolo del sistema
Microsoft Windows [Versión 10.0.19045.5608]
(c) Microsoft Corporation. Todos los derechos reservados.

C:\Users\ollorente>pip install -r requirements.txt
```

Figure 5. Evapotranspiration and Soil Water Content (5)

13. After installing the libraries, type the final command to run the Python script: “python PrepareObservations.py” or “python3 PrepareObservations.py” (Figure 6) to get the resulting file with the evapotranspiration filtered observations (which will be needed for the 3.4.4 step):

```
C:\Windows\System32\cmd.exe
Microsoft Windows [Versión 10.0.19045.5608]
(c) Microsoft Corporation. Todos los derechos reservados.

C:\Users\ollorente\ICRA\EU MERLIN - WP3_upscaling\SWAT+\D3_3_files>python PrepareObservations.py
```

Figure 6. Evapotranspiration and Soil Water Content (6)

3.3 Project set-up

The project set-up phase establishes the foundational structure of the model, integrating spatial data and configuring the watershed to enable accurate simulation of hydrological and ecological processes.

Replace the *swatplus_datasets.sqlite* file from the installation folder (SWAT → SWATPlus → Datasets) with the one provided in the [MERLIN GitHub repository](). This sqlite includes several modifications needed to simulate some of the restoration measures of the MERLIN project.

3.3.1 Creating a New Project:

Figure 7 illustrates the steps to create a new project and initiate watershed delineation using **QSWAT+ in QGIS**.

1. **Open QSWAT+**: Click on the **QSWAT+** icon in the toolbar to launch the plugin (Step 1).
2. **Create a New Project**: In the **QSWAT+ 3.0.3** window, select **"New Project"** and click **OK** to create a new project, define the desires parent directory and project name. (Step 2).
3. **Delineate the Watershed**: In the main **QSWAT+** interface, select **"Step 1: Delineate Watershed"** to begin defining the watershed area (Step 3).

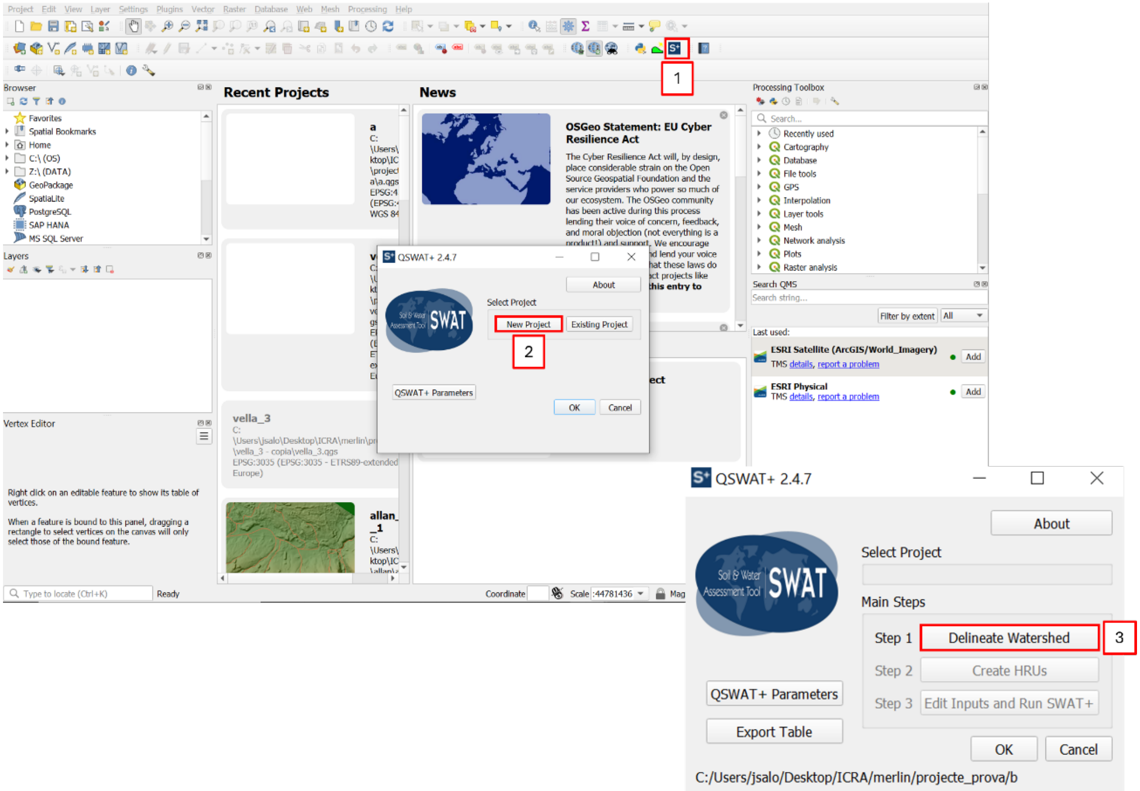

Figure 7. Creating a New Project

3.3.2 Watershed Delineation in QSWAT+

Figure 8 shows the process of setting up **watershed delineation** in **QSWAT+** by selecting a **DEM (Digital Elevation Model)** and configuring various inputs. The highlighted steps are as follows:

1. **Select the DEM File** – The **Digital Elevation Model (DEM)** file is loaded to define the terrain for watershed delineation. (Step **1**)
2. **Burn in Existing Stream Network** – This option ensures that the stream network is incorporated into the DEM to better represent actual hydrological features. (Step **2**)
3. **Select the Stream Network File** – A **shapefile** containing the stream network is loaded to define the river system. (Step **3**)
4. **Create Streams** – Threshold values for **channel and stream** delineation are set, which determine the extension of the stream network. The smaller they are, the more detailed the network will be. We recommend using the default values (provided by QSWAT+) unless there is a specific need (e.g., the stream network does not reach a lake near the headwaters, and the threshold needs to be reduced so it does). Clicking **"Create streams"** generates the stream network based on these thresholds, and it can be repeated multiple times until you have the desired stream network. IMPORTANT: Consider that this step may take a while to complete, it is not hanging, it just needs time as it is processing.(Step **4**)

5. **Use an Inlets/Outlets Shapefile** – This option enables the use of a **shapefile** with inlets and outlets, ensuring correct watershed outlet placement. (Step **5**)
6. **Select the Inlets/Outlets File** – A shapefile with **outlet locations** is provided to guide watershed delineation. Might not be a necessary step (see section 3.2.2).
7. **Draw outlet** – Select the outlet point at the downstream end of your watershed simply by clicking on it. An outlet (blue triangle) will be drawn. This may not be necessary if the basin outlet has already been included in the inlets/outlets shapefile (see section 3.2.2).
8. **Create Watershed** – Clicking **"Create watershed"** initiates the watershed delineation process using the provided inputs. (Step **8**)
9. **Add Lakes Shapefile** – If the study area contains lakes, a **lake shapefile** can be added to refine hydrological modelling. (Step **9**)
10. **Confirm and Run the Process** – Clicking **"OK"** finalizes the setup and runs the watershed delineation. (Step **10**)

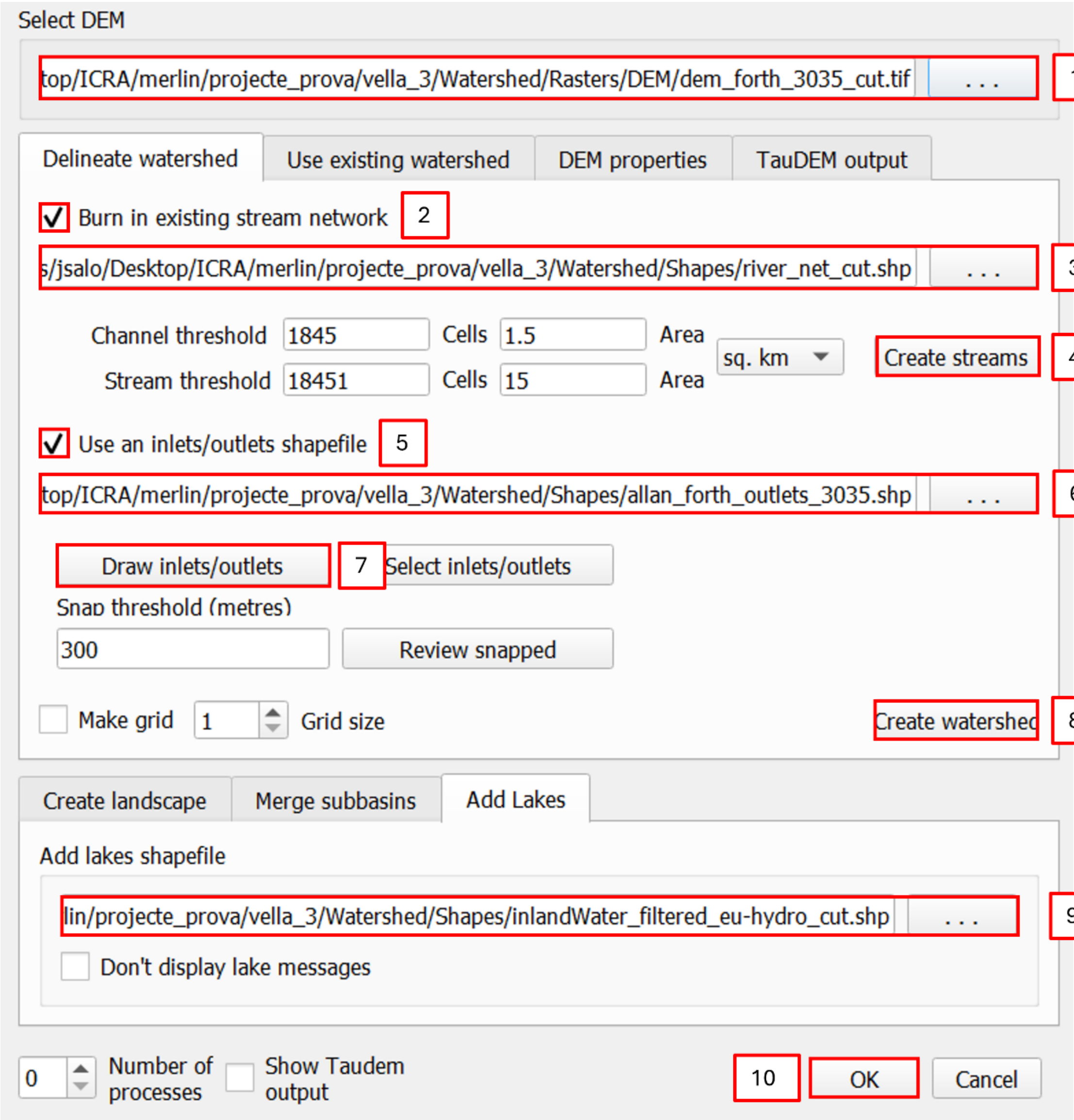

Figure 8. Watershed Delineation in QSWAT+

3.3.3 Creating HRUs in QSWAT+

Figure 9 illustrates the process of creating **Hydrological Response Units (HRUs)** in **QSWAT+** by defining land use, soil, and slope parameters. Below are the key steps shown:

1. **Select the Land Use Map** – A **raster file** containing land use classifications is chosen to define different land cover types. (Step **1**)

2. **Select the Soil Map** – A **raster file** with soil data is loaded to define soil properties within the watershed. (Step **2**)
3. **Select Land Use and Soil Tables** – Select the corresponding **lookup** ("DSOLMap_database_lookup.csv") and **usersoil** ("DSOLMap_database.csv") tables. (Step **3**)
4. **Select Plant Table** – Import the *plant_merlin.csv* table from the MERLIN GitHub repository. (Step **4**)
5. **Define Slope Bands** – Custom **slope categories** are inserted to differentiate terrain features. Introduce "2" and then press insert to add this band, add "8" and press insert to also add this band, unless the project will have a floodplain, in which case it might not be necessary since there will already be a separation between upland and floodplain. (Step **5**)
6. **Select floodplain map** – If the model involves simulating restoration measures related to the floodplain, a floodplain map is required. To be able to select it from the drop-down menu, first, the raster file must be copied into the project folder → Watershed → Rasters → Landscape → Flood. IMPORTANT: Note that you might need to close and reopen the window for it to detect the floodplain file.(Step **6**)
7. **Generate Full HRUs Shapefile** – This option ensures that the **HRU shapefile** is created for further analysis. (Step **7**)
8. **Read and Process Data** – Clicking **"Read"** starts processing the HRUs using the selected land use, soil, and slope information. (Step **8**)

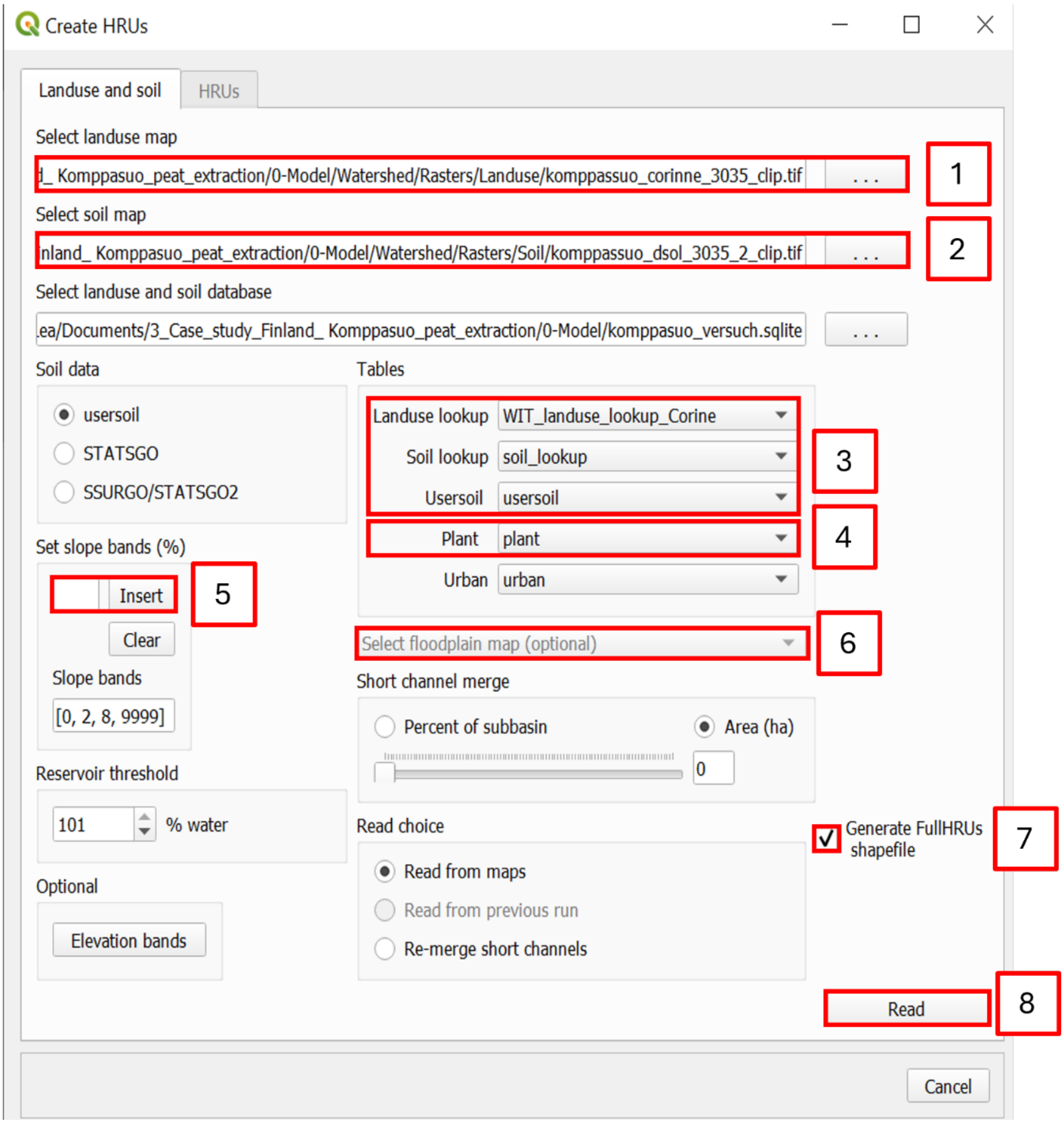

Figure 9. Creating HRUs in QSWAT+ (1)

Figure 10 shows the process of **defining and filtering Hydrological Response Units (HRUs)** in **QSWAT+** before finalizing their creation. The key steps highlighted are:

1. **Filter HRUs by Area** – The option **"Filter by area"** is selected, meaning that HRUs will be created based on a defined minimum area threshold. This helps remove very small HRUs that may not significantly impact the hydrological model.
2. **Set the Area Threshold** – The threshold value is set to **0**, meaning that no HRUs will be removed based on size. This ensures that all HRUs are considered in the analysis.
3. **Create HRUs** – Clicking **"Create HRU"** finalizes the process, generating the HRU dataset based on the selected filtering criteria.

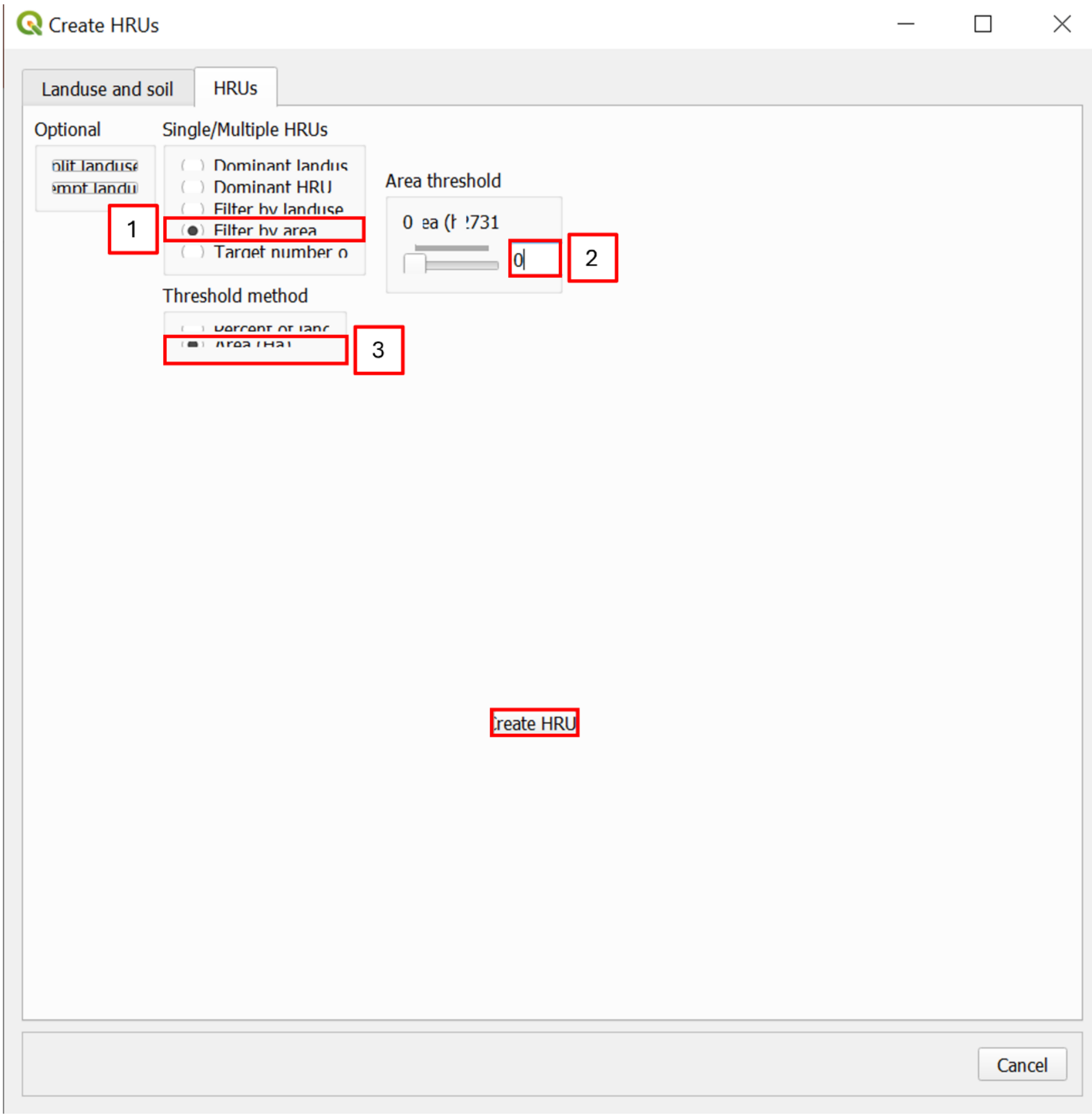

Figure 10. Creating HRUs in QSWAT+ (2)

3.3.4 Edit inputs and run SWAT+

Import project to the SWAT+ Editor

Figure 11 shows the steps to **open the project** in the **SWAT+ Editor**. The highlighted steps are:

1. Open the SWAT+ Editor – Click on "Step 3: Edit Inputs and Run SWAT+". This will open the SWAT+ Editor. (Step 1)
2. Import project – Since this is the first time opening the project in the Editor, it needs to be imported. Click on "Start". (Step 2)

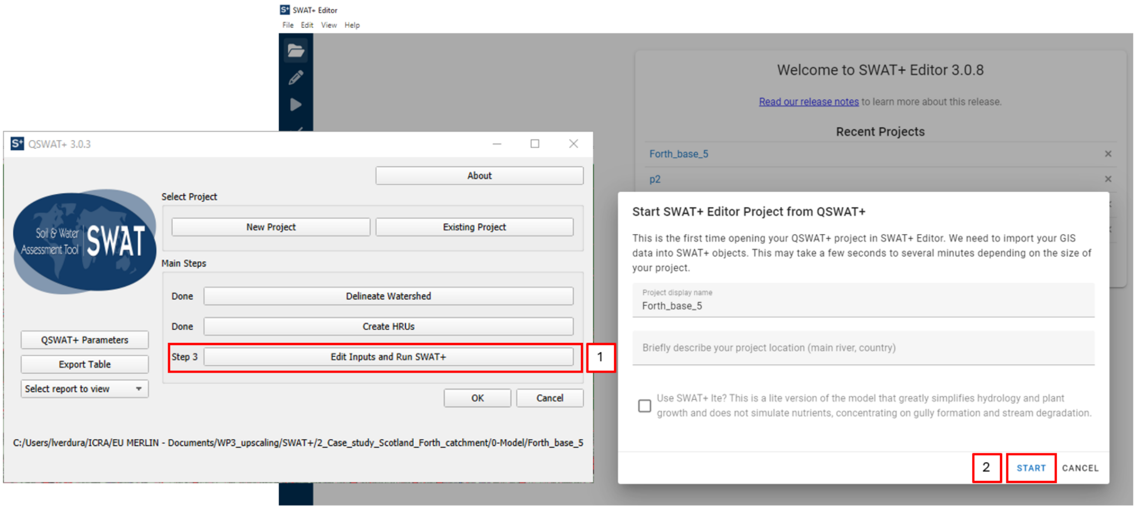

Figure 11. Edit inputs and Run SWAT+ (1)

Opening an Existing Project in SWAT+ Editor

Once the project has already been imported into the SWAT+ Editor, you can open it whenever directly from the editor. If your project is not shown below **"Recent Projects"**, you can follow Figure 12 to open it.

1. **Open Another Project** – In the **SWAT+ Editor** interface, click on **"Open another project"** to load an existing project. (Step **1**)
2. **Browse for the Project File** – In the Open project selection window, click on the folder icon and locate the project **SQLite database file**, located in the project directory. (Step **2**)
3. Select the SQLite Database File – Select the SQLite (.sqlite) file corresponding to the project. (Step 3)
4. Open project – Click "Open". (Step 4)
5. Do not reimport watershed data – Select the option "No, continue to Editor". (Step 5)

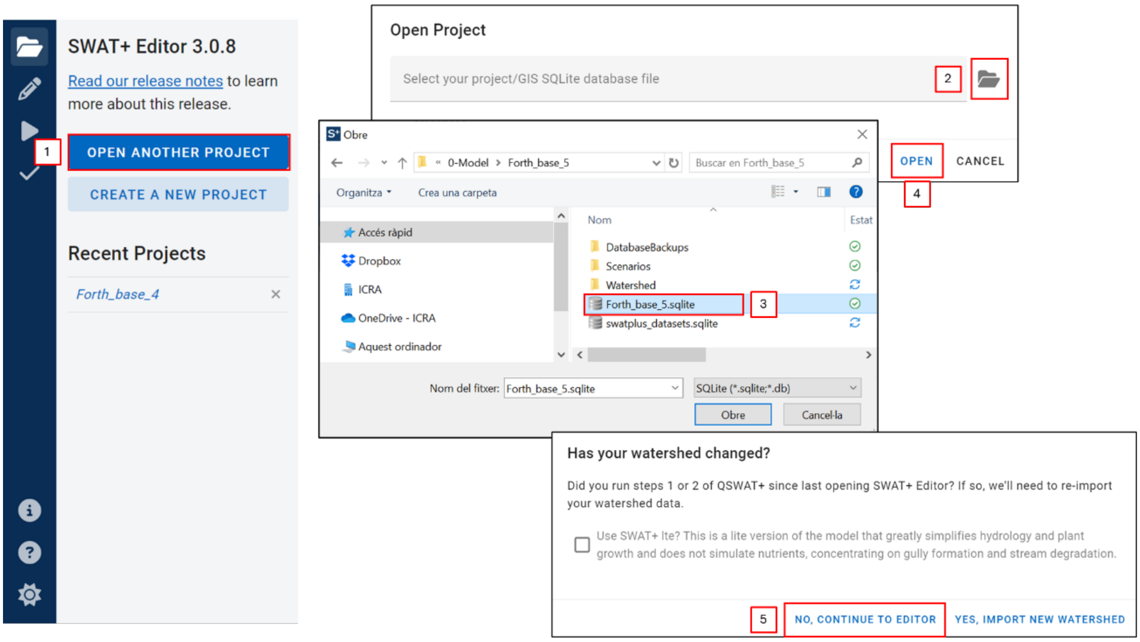

Figure 12. Edit inputs and Run SWAT+ (2)

Importing Weather Generator Data in SWAT+

Figure 13 illustrates the process of **importing weather generator data** into the **SWAT+ Editor** to define climate conditions for the model. The steps highlighted are:

1. **Open the Climate Menu** – Navigate to the **"Climate"** section in the left panel and select **"Weather Generator"**. (**Step 1**)

2. **Access the Import Menu** – Click on the **Weather Generator** tab to open the import interface. (**Step 2**)
3. Import data – Click on "Import Data". (Step 3)
4. **Select Data Format** – Choose **"Database"** as the data format for importing weather generator data. (**Step 4**)
5. **Set Database File** – Ensure that the Database File is **"swatplus_wgn.sqlite"**. If you downloaded it when installing the SWAT+ Editor, it should already be selected by default. If not, locate and select it. (**Step 5**)
6. **Specify the Table Name** – Enter the table name **"wgn_cfsr_world"**, which contains pre-defined weather generator data. (**Step 6**)
7. **Check Observed Weather Data** – Enable the **"Check if you are using observed weather data"** option to ensure the model correctly integrates actual climate records. (**Step 7**)
8. **Start the Import Process** – Click **"Import Data"** to begin importing the weather generator data into SWAT+. (**Step 8**)

This process ensures that climate inputs are correctly set up, enabling SWAT+ to simulate hydrological and meteorological conditions accurately.

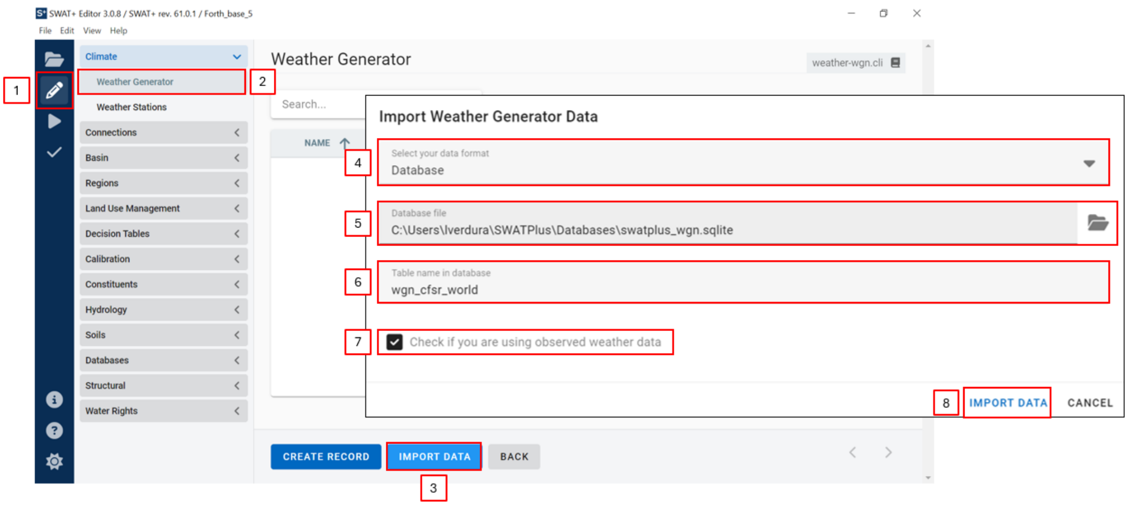

Figure 13. Edit inputs and Run SWAT+ (3)

Importing Observed Weather Data in SWAT+

Figure 14 illustrates the process of **importing observed weather data** into **SWAT+ Editor**, which is essential for running climate-based simulations. The key steps shown are:

9. **Copy the Weather Data into the TxtInOut** – Copy the weather data that was previously downloaded (should be in the model folder > 3-Weather data) into the **TxtInOut** folder (project folder → Scenarios → Default → TxtInOut). Now it should contain weather input files such as precipitation (.pcp), temperature (.tem), solar radiation (.slr), wind speed (.wnd), and humidity (.hmd), as well as master files (.cli). (Step **0**)
10. **Access the Weather Stations Menu** – Navigate to the **"Climate"** section in the left panel and select **"Weather Stations"** to manage weather inputs. (**Step 1**)
11. **Open the Import Data Window** – Click **"Import Data"** to begin the process of loading observed weather data. (**Step 2**)
12. **Select Data Format** – Choose **"SWAT+"** as the data format, ensuring compatibility with SWAT+ formatted weather files. (**Step 3**)
13. **Browse for the Weather Data Directory** – Select the folder where the observed weather data files were previously stored (TxtInOut). It should already be selected by default. (**Step 4)**.
14. **Start the Import Process** – Click **"Import Data"** to begin importing the observed weather data into SWAT+. (**Step 5**)

This step ensures that **real-world climate data is correctly integrated into the SWAT+ model**, allowing for more accurate hydrological simulations.

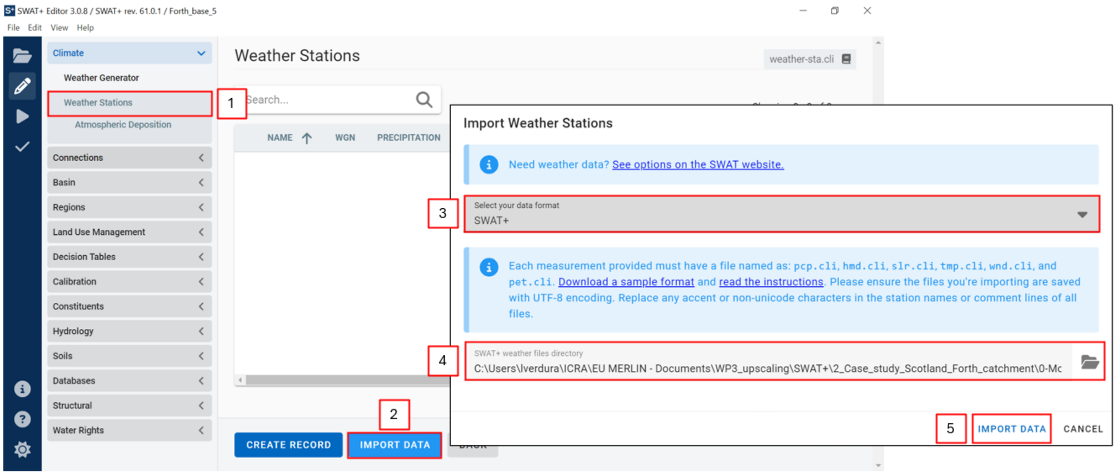

Figure 14. Edit inputs and Run SWAT+ (1)

Import Atmospheric Deposition Data in SWAT+

Figure 15 illustrates the process of **importing atmospheric deposition data** into the **SWAT+ Editor**. The key steps shown are:

1. Access the Atmospheric Deposition Menu – Navigate to the "Climate" section in the left panel and select "Atmospheric Deposition". (Step 1)
2. **Download the weather station mapping template** – Click **"Import Data"** and then **"Export template file"**. Save this **"atmo-weather-station-map.csv"** file to your computer. As mentioned before, this is necessary before continuing with the atmospheric deposition data processing, so after downloading it, refer to 3.2.2 to continue processing the original atmospheric deposition dataset. (**Step 2**)
3. **Select the "Atmospheric deposition file"** – After finishing processing the data and converting it into SWAT+ format, click on the folder icon besides **"Atmospheric deposition file"** and select the CSV **"atmo_acgannual.csv"**. (**Step 3**)
4. Select the "Atmospheric deposition to weather station mapping file" – Click on the folder icon besides "Atmospheric deposition to weather station mapping file" and select the CSV "atmo-weather-station-map.csv". (Step 4)
5. **Start the Import Process** – Click **"Import Data"** to import the atmospheric deposition data into SWAT+. (**Step 5**)

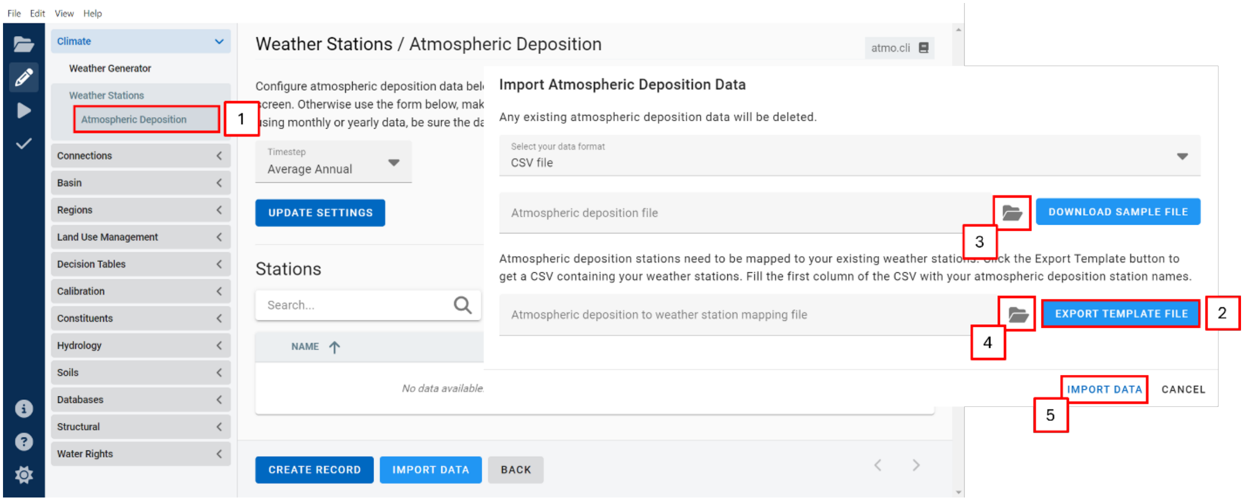

Figure 15. Edit inputs and Run SWAT+ (4)

Add inlet and point source WWTP discharge data

Figure 16 illustrates the process of **adding inlet and WWTP discharge data in point sources** in SWAT+.

1. Access the Point Sources / Inlets Menu – Navigate to the "Connections" section in the left panel and select "Point Sources / Inlets". (Step 1)

2. Determine if the model has an inlet, that is, if only part of the river basin is simulated, and thus the inlet is a point in the stream network where we have observed streamflow. This observed streamflow will be used as an input while SWAT+ simulates the processes downstream to that point. If that is the case, identify which point source represents the inlet by looking at its ID in the **"Pt sources and reservoirs"** shapefile. For example, if the ID is 2, the equivalent object in the Editor will have a name such as pt002. Once identified, click on the edit icon beside the name and change the "Time Step" drop-down menu from "Constant" to **"Daily"** (or **"Monthly"**, depending on the timestep of the observed streamflow data). **"Save Changes"** and then go **"Back"**. (**Step 2**).
3. **Export point source template** – Click **"Import/Export"** and then **"Export Data"**. This will download a file called **"recall.csv"**, which contains the data for all point sources in the model. If the model also has an inlet, as mentioned in the previous section, another file with a name like **"ptXXX.csv"** will also be downloaded (where XXX is the point source id). (**Step 3**)
4. **Populate "recall.csv"** and (if present) **"ptXXX.csv**" accordingly. For the **inlet** file, input the volume of water in m^3 (column flo) that enters for each timestep for the entire time series. For the point source file, identify the **point sources** that include a WWTP discharge using the **"Pt sources and reservoirs"** shapefile, whose ID corresponds to the name in **"recall.csv"** (see step 2 below for more detail in how to link them). The point coordinates might not be exactly the same, so a **"Join Attributes by Nearest"** could help if there are too many WWTP to do it manually. Then, in the **"recall.csv"** file, for each WWTP, add the daily volume in m^3 (column flo), the daily load of nitrate in kg N (column no3), and the daily load of mineral phosphorus in kg P (column solp). See section 3.2.2 for data processing. (**Step 4**).
5. **Import modified files** – Click **"Import/Export"** again and select the directory that contains the file(s) that you modified. Then click **"Import Data"**. (**Step 5**)

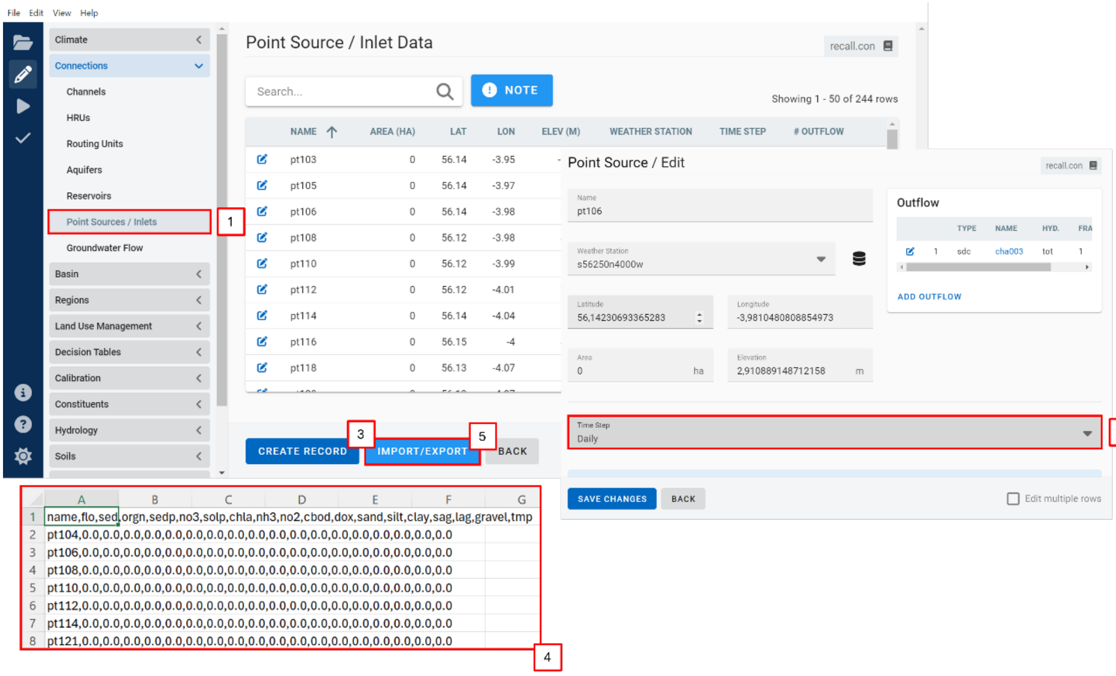

Figure 16. Edit inputs and Run SWAT+ (5)

Change the water routing method

Figure 17 illustrates the process of **changing the water routing method** in SWAT+. This step is only necessary if the model will include the simulation of floodplain reconnection. In all other cases, the default water routing method can be used.

1. **Access the Codes Menu** – Navigate to the **"Basin"** section in the left panel and select **"Codes"**. (**Step 1**)
2. Change the water routing method – From the drop-down menu of "Water routing method", select "1-Muskingum method". (Step 2)
3. Save changes – Click on "Save changes". (Step 3)

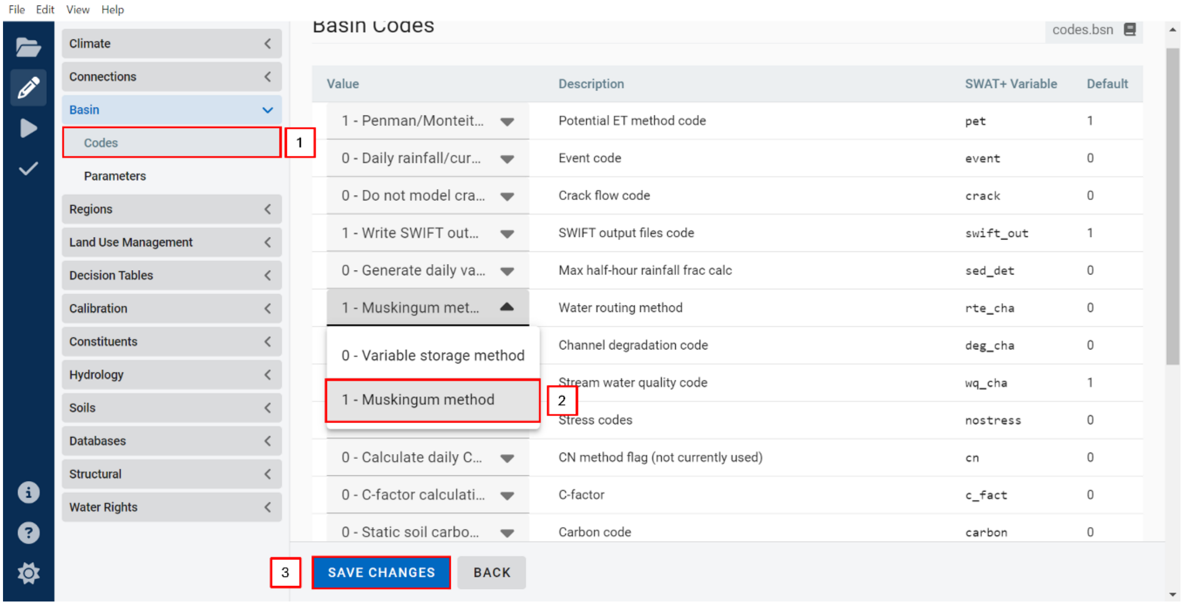

Figure 17. Edit inputs and Run SWAT+ (6)

Agriculture crop rotation

For the agriculture land uses included in the WateriTech land use map (agrl and agrr), a management schedule with a decision table to simulate annual planting and harvesting has already been created by default. However, if the model includes the land use fstp (to simulate the restoration of riparian vegetation using filter strips), the management schedule for this land use must be manually added. Figure 18 illustrates this process of **adding the plant and harvest management schedule** for the land use **"fstp"**, if it exists, into SWAT+.

1. **Check if "fstp" exists** - Navigate to the **"Land Use Management"** section in the left panel and then select **"Land Use Management"**. Search if the land use **"fstp"** exists. If not, skip this section. (**Step 1**)
2. Access the Management Schedules Menu – Navigate to the "Land Use Management" section in the left panel and select "Management Schedules". (Step 2)
3. Create a new management schedule – Click "Create record" and name it "fstp_rot". (Step 3)
4. **Add crop rotation** – From the drop-down menu below **"Add a decision table"** select **"crop rotation"**. Then select **"plant and harvest for continuous summer crop"** from the new drop-down menu that will appear below and click on **"Configure & Add"**. (**Step 4**)
5. **Configure the decision table** – Select **"fstp"** from the plant drop-down menu and then click **"Save"**. (**Step 5**)
6. Save management schedule – Click "Save Changes" and then "Back". (Step 6)
7. Edit land use – Go back to "Land Use Management" and edit "fstp_lum". (Step 7)
8. Assign management schedule to land use – From the "Management Schedule" drop-down menu, select "fstp_rot" and then "Save changes". (Step 8)

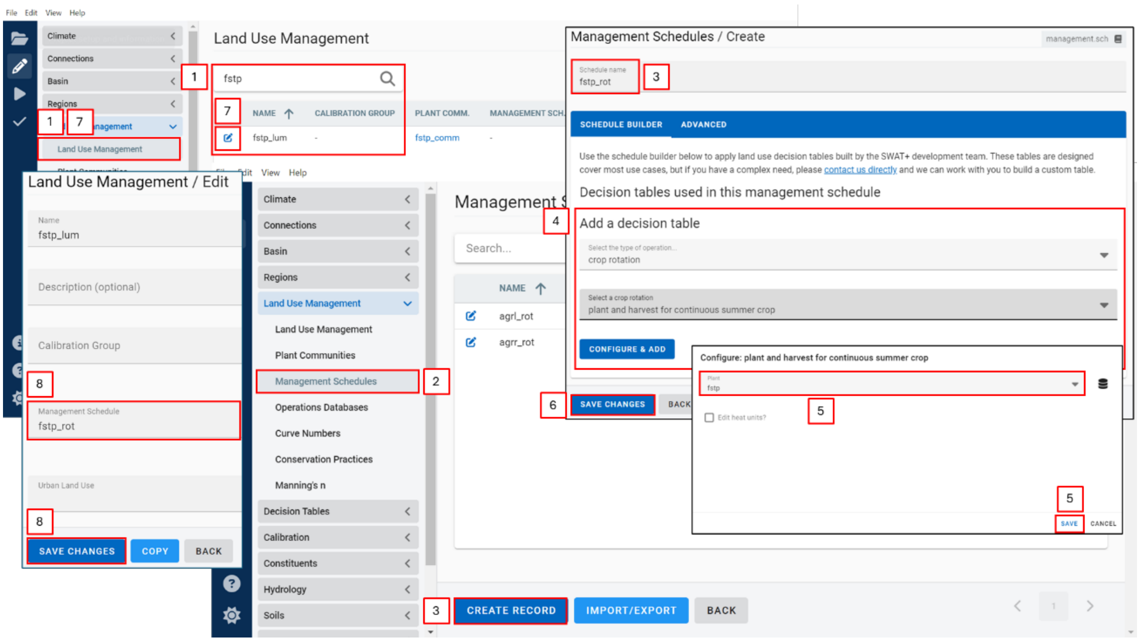

Figure 18. Edit inputs and Run SWAT+ (7)

Nutrient inputs: Grazing

Figure 19 illustrates the process of **adding grazing** into SWAT+ if the land use **"past"** (pasture) exists. The key steps shown are:

1. **Check if "past" exists** - Navigate to the **"Land Use Management"** section in the left panel and then select **"Land Use Management"**. Search if the land use **"past"** exists. If not, skip this section. (**Step 1**)
2. Access the Management Schedules Menu – Navigate to the "Land Use Management" section in the left panel and select "Management Schedules". (Step 2)
3. Create a new management schedule – Click "Create record" and name it "past_rot". (Step 3)
4. **Add grazing** – From the drop-down menu below **"Add a decision table"** select **"grazing"**. Then select **"summer grazing"** from the new drop-down menu that will appear below and click on **"Configure & Add"**. (**Step 4**)
5. **Configure the decision table** – If local data/knowledge is available, configure the decision table parameters (day of year to start and end grazing, biomass threshold to avoid overgrazing) accordingly. Otherwise, use the default values and click **"Save…"** → **"Save changes for only this schedule"**. (**Step 5**)
6. Save management schedule – Click "Save Changes". (Step 6)
7. Edit land use – Go back to "Land Use Management" and edit "past_lum". (Step 7)
8. Assign management schedule to land use – From the "Management Schedule" drop-down menu, select "past_rot" and then "Save changes". (Step 8)

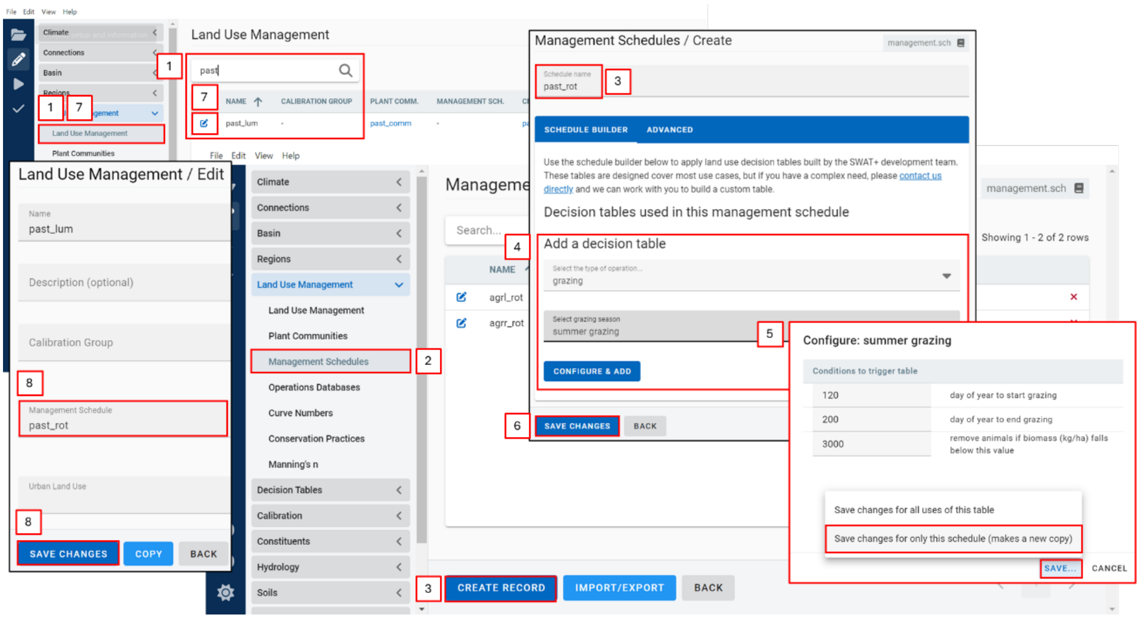

Figure 19. Edit inputs and Run SWAT+ (8)

Nutrient inputs: Fertilization

Figure 20 illustrates the process of **adding fertilization** into SWAT+ for agricultural land uses (agrl, agrr, and/or fstp). The key steps shown are:

1. Access the Management Schedules Menu – Navigate to the "Land Use Management" section in the left panel and select "Management Schedules". (Step 1)
2. **Add the fertilization schedule** – For each of the management schedules for agricultural land uses present in the model (agrl_rot, agrr_rot, and/or fstp_rot), edit them by clicking on the icon beside the name. (**Step 2**)
3. From the drop-down menu below **"Add a decision table"** select **"fertilizer"**. Then select **"fertilizer stress test"** from the new drop-down menu that will appear below and click on **"Configure & Add"**. (**Step 3**)
4. **Configure the decision table** – If local data/knowledge is available, configure the decision table accordingly. Otherwise, use the default values and click on **"Save…" → "Save changes for only this schedule".** (**Step 4**)
5. Save the management schedule – Click "Save changes" and then "Back". (Step 5).

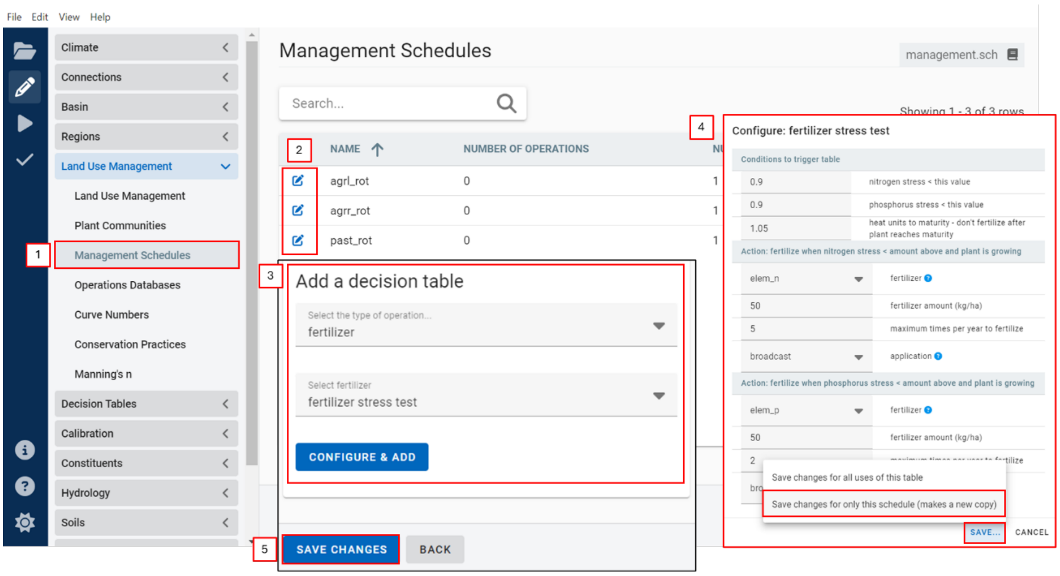

Figure 20. Edit inputs and Run SWAT+ (9)

Customize files to write in SWAT+

Figure 21 illustrates the process of **customizing which files the model will write/use** from the **SWAT+ Editor** before running the model. The highlighted steps are:

1. **Access the Simulation Settings** – Click on the **Run SWAT+** menu in the left panel to configure the model's run period. (**Step 1**)
2. Customize files to write – Click "Choose where to write input files" and then "Advanced: Customize files to write…". (Step 2)
3. **Use calibration.cal file** – Scroll down to row **"chg"** and then click on the "none" of the second column and select **"provide my own calibration.cal"**. This file will include the parameter changes that will account for calibration, and will be generated in section 3.4, but this step will ensure that, if available, the model will use it. Click on **"Save and close"**. (**Step 3**)

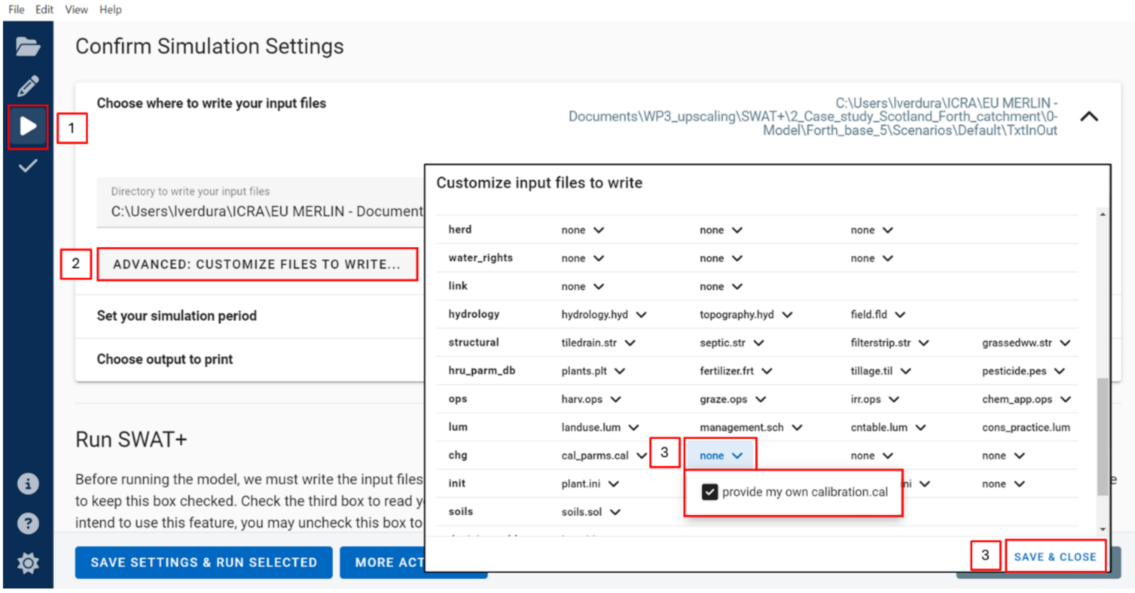

Figure 21. Edit inputs and Run SWAT+ (10)

Setting the Simulation Period in SWAT+

Figure 22 illustrates the process of **defining the simulation period** in the **SWAT+ Editor** before running the model. The highlighted steps are:

1. **Define the Simulation Period** – Make sure your **simulation dates** (including the warm-up period, which we recommend setting to **5 years**) fall within the dates in your observed weather files (**Step 1**).
2. **Set Start and End Dates** – The **starting and ending dates** of the simulation can be manually adjusted. For example, if you need to calibrate and assess outputs from **2000 – 2022**, despite having weather data until September 10, 2023, the starting date should be left at 01/01/1995 (to account for the additional **5 years** of warm-up), but the ending date should be modified to 31/12/2022. Any dates outside the available weather data range will rely on **simulated weather** instead of on the observed data provided (**Step 2**).

This step ensures that **the simulation is based on actual recorded climate data**, preventing errors caused by missing or extrapolated weather information.

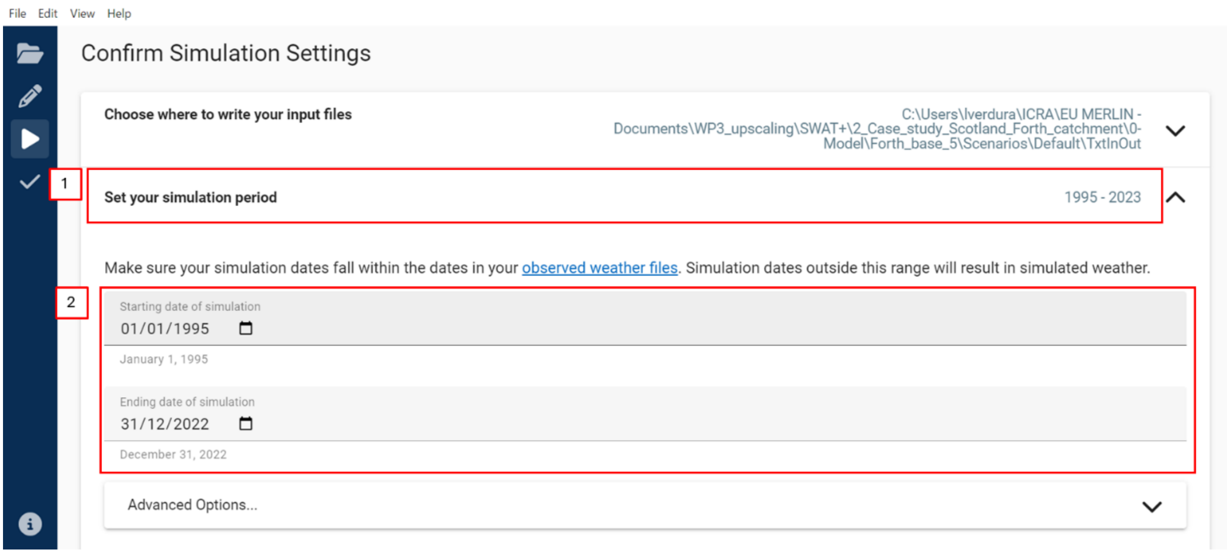

Figure 22. Edit inputs and run SWAT+ (11)

Configuring Output Settings and Warm-up Period in SWAT+

Figure 23 shows the configuration of **output options** and the **warm-up period** in the **SWAT+ Editor**, an important step before running the model. Here's what each step does:

1. Choose output to print – Click "Choose output to print". (Step 1)
2. **Define the warm-up period** – The warm-up period defines how many initial years of the simulation will be skipped in the output. These years are used to stabilize model conditions. In this case, **5 years** are set as a warm-up, meaning output will begin from the sixth simulation year. (**Step 2**)
3. **Select outputs to be written** – The user can select the different outputs and the timestep at which these will be printed (**Daily, Monthly, Yearly, or Average**). For compatibility with the ecosystem services plugins, select at least the following outputs, although others can also be selected if desirable. (**Step 3**)
    a. **Model Components - Channel**: Daily, Monthly, and Average
    b. **Model Components - Reservoir**: Monthly and Average
    c. **Nutrient Balance - Landscape Unit**: Monthly and Average
    d. **Water Balance - Landscape Unit**: Monthly and Average
    e. **Plant Weather - Landscape Unit**: Monthly and Average
    f. **Losses - Landscape Unit**: Monthly and Average

This configuration ensures that the model only prints **relevant and necessary results** and that it excludes the **warm-up period** to avoid distortions in the analysis.

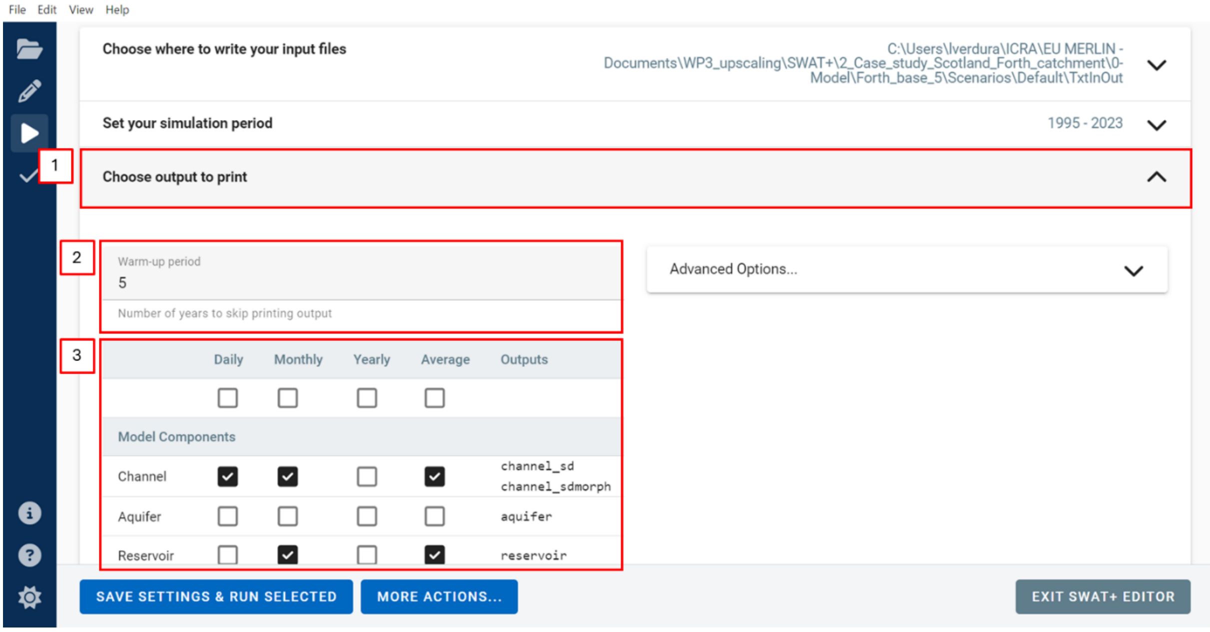

Figure 23. Edit inputs and Run SWAT+ (12)

Write SWAT+ input files in the TxtInOut

Once the model setup is complete, this step allows you to write the necessary input files in the TxtInOut folder (project folder → Scenarios → Default → TxtInOut), as seen in Figure 24.

1. Configure Run SWAT+ options – Check only the box “Write input files”. (Step 1)
2. **Write input files** – click on **“Save settings & run selected”**. This will write all the input files in the TxtInOut folder. (**Step 2**)
3. **Locate the SWAT+ executable** – Locate the *rev61.0.1_64rel.exe* executable in the SWAT+ Editor installation folder. You can easily access it by clicking on the folder icon besides **“Run SWAT+ rev. 61.0.1”**, or we also provided it with the Github files. (**Step 3**)
4. **Copy the SWAT+ executable** – Copy the *rev61.0.1_64rel.exe* executable to the TxtInOut folder. This last two steps are not completely necessary, as we will run SWAT+ using the Editor (section 3.6.2), but we recommend also copying the executable as then the model can easily be executed if needed by double-clicking on it from the TxtInOut folder. (**Step 4**)

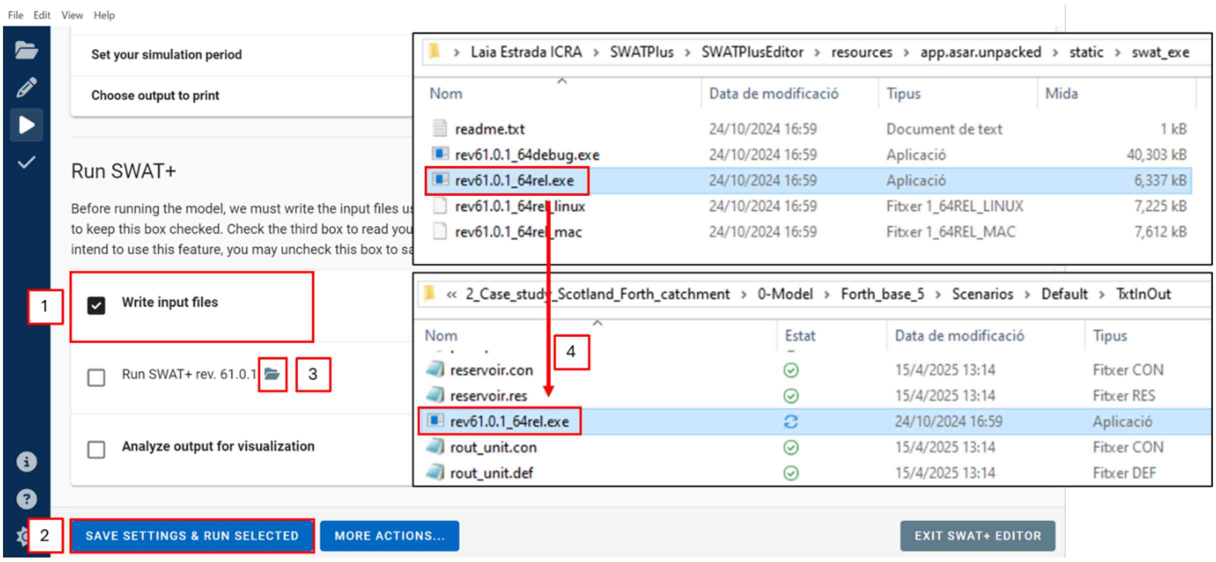

Figure 24. Edit inputs and Run SWAT+ (13)

3.4 Calibration

The main purpose of the calibration phase is to achieve a basin-wide, balanced representation of hydrological dynamics by adjusting key model parameters to fit SWAT+ outputs to globally available hydrology datasets such as GLEAM, ensuring realistic simulation performance even in data-scarce regions.

Open RSWAT

Figure 25 shows the commands that are needed to open the RSWAT graphical interface:

```
> library(RSWAT)
> showRSWAT()
```

Figure 25. Calibration (1)

General Settings – Linking a SWAT+ Project in R-SWAT and Parameters

Before starting the calibration or sensitivity analysis in R-SWAT, it is necessary to define a few key settings. This step links your **SWAT+ model** to R-SWAT and ensures that all required files are correctly located. Follow these steps as shown in Figure 26:

1. **Access the "General setting" section** – In the left-hand menu of R-SWAT, click on **"1. General setting"** to open the configuration panel. (Step 1)
2. **Select project type** – In the dropdown at the top, select **"SWAT+"** as the project type. This tells R-SWAT to expect the SWAT+ structure and file formats. (Step 2)
3. **Set the working folder** – Define the **working folder**, which is the directory where R-SWAT will save results and intermediate files. It is recommended to create a dedicated folder within your model directory (e.g., a folder named "Calibration" inside the project folder). (Step 3)
4. **Link the TxtInOut folder** – In the **TxtInOut folder** field, select the path to the TxtInOut directory generated during the SWAT+ setup in QSWAT+. This folder contains all the input files needed to run the model. (Step 4)
5. **Select the SWAT+ executable** – Click the button to browse and select the **SWAT+ executable** file (usually named something like revxx_xxrel.exe). This file is needed to run the SWAT+ model during calibration. This file is typically located in the **SWAT+ installation folder**, as specified in the previous step. We have also already provided the executable *rev61.0.1_64.rel.exe*. (Step 5)
6. **Load the parameter file** – Finally, load the **cal_params.cal file**, which contains the list of parameters in SWAT+ that can be calibrated. This file is found in the TxtInOut folder. (Step 6)

Once all these paths are correctly defined, R-SWAT will be ready to run the model and begin the calibration or sensitivity analysis process. Make sure all folders and files exist and are correctly formatted before proceeding to the next step.

Figure 26. Calibration (2)

3.4.1 General Settings – Parameter sampling and calibration algorithm

The first step of the calibration process is defining which SWAT+ parameters will be considered. For each case study, we performed a sensitivity analysis, considering 24 SWAT+ parameters based on literature and expert knowledge. Based on the results of the sensitivity analysis, we have selected only those which are sensitive at least in one of the case studies, and we recommend using them to calibrate any model.

Figure 27 shows the setup for this process:

1. **Open the "Parameter Sampling" Section** – In the left panel, click on **"2. Parameter sampling"** to open the configuration window. (Step 1)
2. **Define the Parameters to Be Calibrated** – In the parameter table, you must enter the list of SWAT+ parameters to be included in the calibration or sensitivity analysis. (Step 2). We recommend using the 15 parameters that we have listed in Table 1, do not modify this list unless you are certain of the implications.
3. Choose the Sampling Approach - From the dropdown menu, select "Sensi_Cali_(uniform_Latin_Hypercube_Sampling)" as the method. (Step 3)
4. **Define the Number of Iterations**- In the field below the method selection, enter the number of iterations or parameter combinations to simulate. We recommend setting it to 2000. (Step 4).

Table 1. Calibration parameters

Parameter	Change	Min	Max
awc.sol	relative	-1	5
bd.sol	relative	-0.5	0.5
canmx.hru	absolute	0	20
esco.hru	absolute	0	1
epco.hru	absolute	0	1
evrch.bsn	absolute	0.5	1
k.sol	relative	-1	5
latq_co.hru	absolute	0	1
lat_ttime.hru	absolute	0	180
perco.hru	absolute	0	1
revap_co.aqu	absolute	0.02	0.2
snomelt_tmp.hru	absolute	-5	5
snomelt_max.hru	absolute	1.5	8
snomelt_min.hru	absolute	1.5	8
z.sol	relative	-0.5	0.5

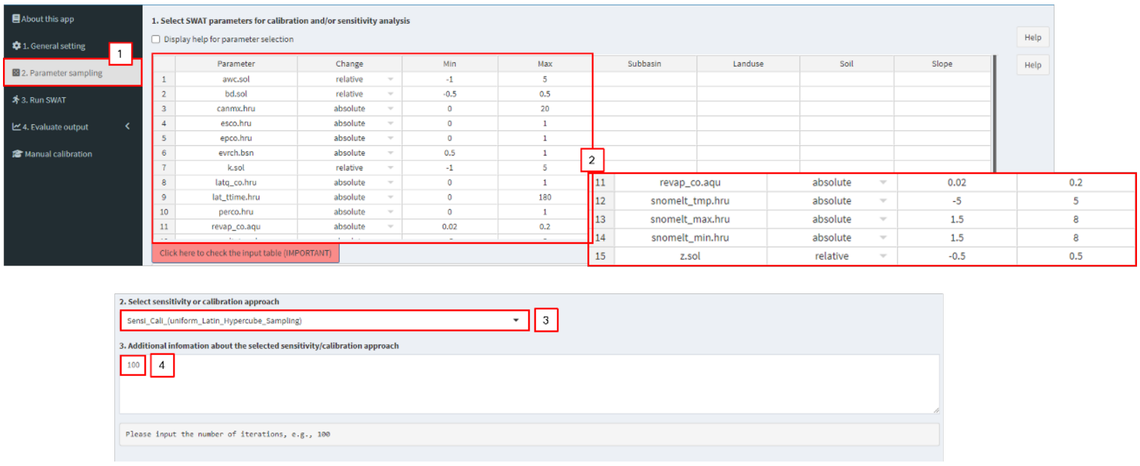

Figure 27. Calibration (3)

3.4.2 Running the SWAT+ Model in R-SWAT

Figure 28Figure 28 shows how to **run the SWAT+ model using the parameter sets** generated in the previous step.

Follow the instructions below and use the same configuration shown, unless you know exactly why you should change something.

1. **Open the "Run SWAT" section** – From the left menu, click on **"3. Run SWAT"**. This section is where you control how the model is run. (Step 1)
2. **Define model outputs for extraction** – This is where you tell R-SWAT which output file and variable to use for evaluating model performance. Use exactly the following configuration:
    a. **FileType:** Select basin_wb_mon.txt from the dropdown. (Step 2)
    b. **FileName:** Write or confirm the name is basin_wb_mon.txt. This file contains monthly water balance results at the basin level. (Step 3)
    c. **Column:** Write 15. This refers to the column that contains the variable of interest (usually discharge or flow). (Step 4)
    d. **Reach_Unit:** Define it as "1". Since we are working at the basin scale, the whole basin acts as a unique reach. (Step 5)

Do not change these settings unless you are working with different output files or analysing other components (e.g., a subbasin or HRU). For this guide, we will always work at the basin level.

3. **Select date range** – Set the simulation period to match the period for which you have observed data, setting a **start** and **end** date. These dates must fall within the simulation period you defined in SWAT+ (and must exclude the warm-up period). If your observed data uses different dates, adjust them accordingly. (Step 6)
4. **Select number of parallel runs (threads)** – Use the slider to set the number of threads to 12. This defines how many simulations R-SWAT will run at the same time. If your computer has fewer than 12 cores, you can reduce this number, but 12 is ideal if your system allows it. (Step 7)
5. **Run the model** – Click the blue button **"Click here to run SWAT"** to start the simulations. R-SWAT will begin running the model for each parameter set and save the outputs for evaluation. IMPORTANT: Take into consideration that this step may take days to finish as it will run a huge number of SWAT+ simulations. (Step 8)

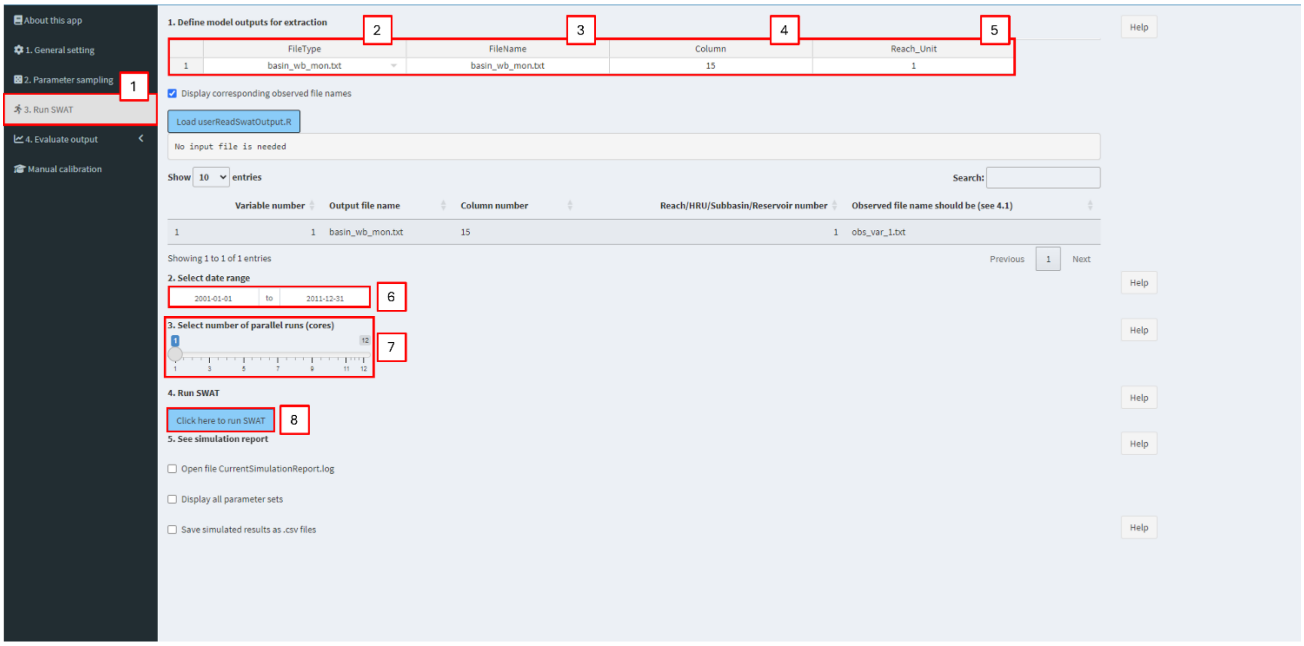

Figure 28. Calibration (4)

3.4.3 Evaluate Calibration – Objective Function

After running the model, the next step is to evaluate its performance by comparing simulated results with observed data. This is done by calculating an objective function, which gives a numerical value to show how well the model fits the observations.

Unless otherwise instructed, follow exactly the setup described below and illustrated in Figure 29.

1. **Open the "Objective Function" Section** – From the left panel, expand **"4. Evaluate output"** and click on **"4.1 Objective function"**. This will open the settings for computing model performance. (Step 1)
2. **Select the Objective Function** – In the dropdown list, choose **NSE** (Nash-Sutcliffe Efficiency) as the objective function. You can choose any other metric, but NSE is one of the most widely used objective function in hydrology, measuring how closely the simulated values match the observed values. A NSE of 1 indicates a perfect match, while NSE below 0 indicates that the mean of the observed data is a better predictor than the model. NSE > 0.5 is considered acceptable, while NSE > 0.7 is considered good. (Step 2).
3. **Load the Observed Data File** – Click on the blue button **"Please select observed data file(s)"** and select the file containing your observed data (The file named "obs_var_1.txt from the 3.2.2 step, the GLEAM data). This file should:
    a. Have the **same date range** used in the Run SWAT step (excluding warm-up)
    b. Be formatted correctly according to R-SWAT's requirements.

The model will only evaluate correctly if the observed data file matches the simulation dates and output type exactly. (Step 3)

4. **Calculate the Objective Function** – Once the observed data file is loaded, click on **"Click here to calculate objective function"**. R-SWAT will now compare each parameter set's simulation output against the observed data and calculate the NSE value for each one. (Step 4)

This completes the **first evaluation of model performance** and prepares you for sensitivity analysis or further calibration.

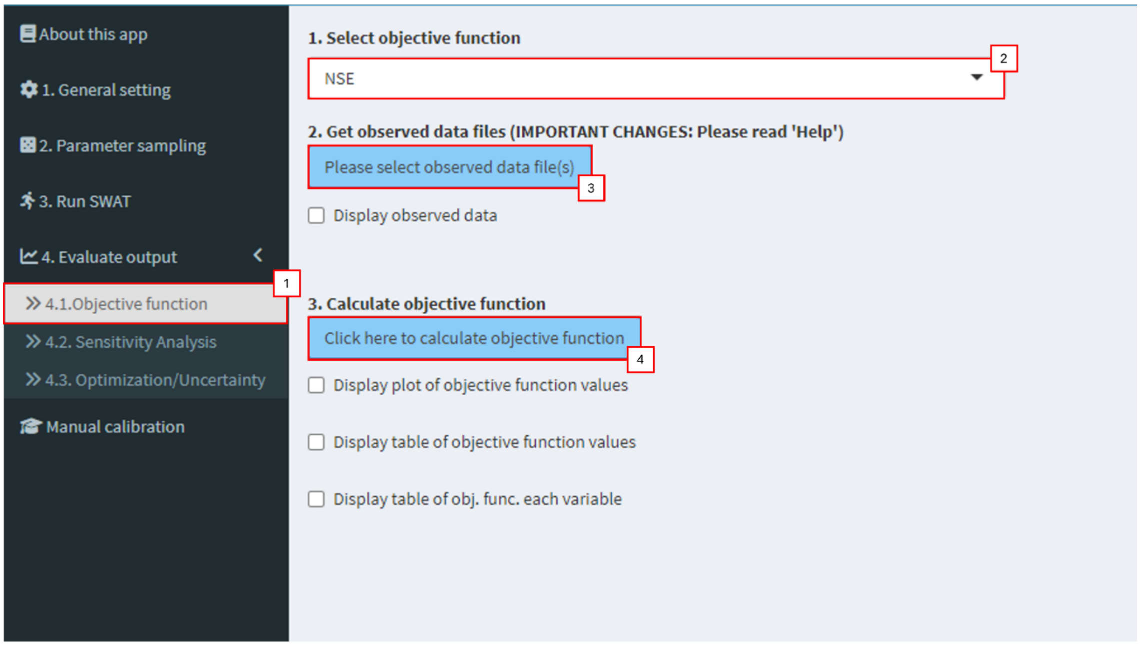

Figure 29. Calibration (5)

3.4.4 Evaluate Calibration – Create calibration.cal file

The final step is to generate the "calibration.cal" file, which will contain the calibrated parameter values. As illustrated in Figure 30, follow the next steps:

1. Display the Objective Function Table – Check the option "Display table of objective function values." (Step 1)
2. **Identify the Best Simulation** – Each row corresponds to one simulation. The simulation with the **highest objCalibration** value (e.g., 0.24 in this example) is typically the best-performing one. (Step 2)
3. **Copy the values of the parameters for the best simulation** – There is a column for each parameter (in this case a test with only 8 parameters) and the value of each parameter for each simulation. Copy the values of each parameter for the best simulation (There is also an option to export to CSV or Excel). (Step 3)
4. **Locate and modify the "calibration.cal" file** – Inside the calibration directory (defined earlier), there will be a directory named "TxtInOut_1", inside this directory locate the "calibration.cal" file and modify the values of the "chg_val" column according to the values of the best simulation. (Step 4)
5. **Copy "calibration.cal" to the original TxtInOut** – Copy the modified "calibration.cal" to the original TxtInOut folder (project folder → Scenarios → Default → TxtInOut). (Step 5)
6. **Copy the TxtInOut folder** – Make a copy of the TxtInOut folder and rename it "TxtInOut_inputs". (Step 6)

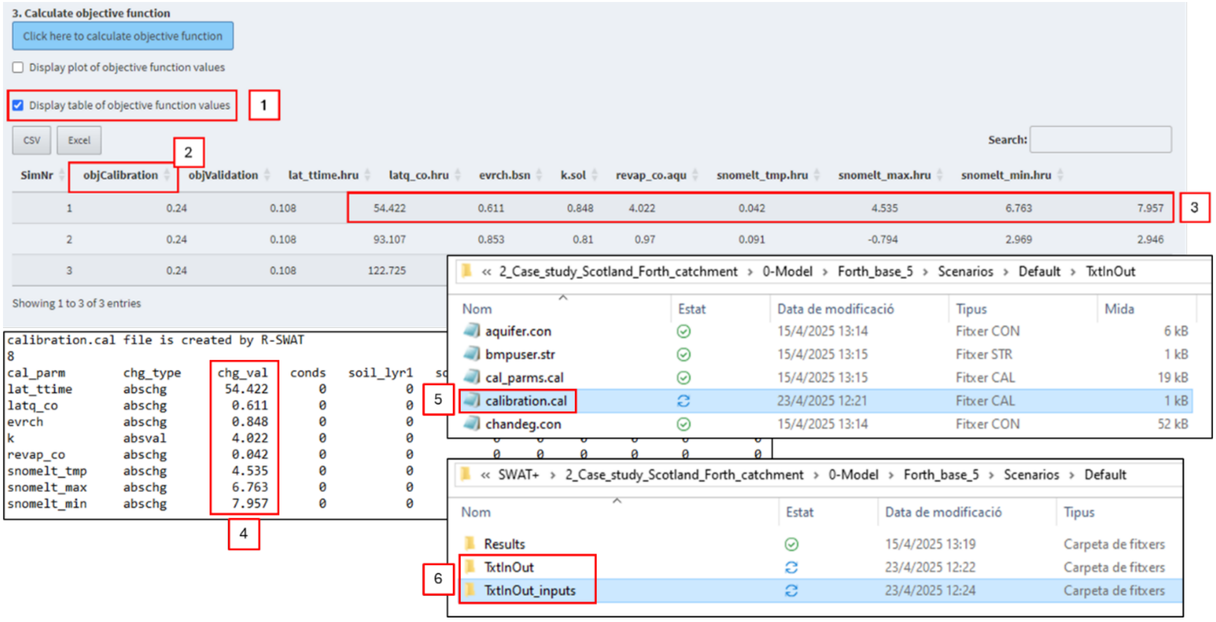

Figure 30. Calibration (6)

3.5 Simulation of restoration measures

This section outlines the procedures used to simulate the restoration measures considered in the MERLIN project within the SWAT+ modelling framework. The restoration actions are implemented by modifying specific model inputs in a copy of the calibrated default scenario to avoid overwriting baseline conditions. The actions simulated include **peatland rewetting**, **wetland rewetting**, **riparian buffer establishment**, **floodplain reconnection**, and **stream channel restoration**. These measures represent a range of interventions in different freshwater ecosystem types applied in selected MERLIN restoration case studies; the Forth (UK), Danube (Romania), Sorraia (Portugal), Kampinos (Poland), and Komppasuo (Finland).

Each type of restoration is represented in SWAT+ through targeted changes to land use classifications, hydrological parameters, and structural connectivity, depending on the nature of the intervention. For instance, rewetting peatlands and wetlands requires redefining land cover and, in the case of wetlands, associating HRUs with wetland-specific hydrological objects. Riparian buffer establishment is simulated through the inclusion of vegetated filter strips along watercourses, while floodplain reconnection is achieved by enabling overbank flow and linking channels with their adjacent routing units. Channel restoration is modelled by adjusting parameters such as Manning's roughness coefficient and sinuosity to reflect more natural fluvial dynamics.

While restoration scenarios could be set up directly in the SWAT+ Editor, to avoid overwriting the default scenario and making it easier to compare baseline with scenario simulations, we recommend creating new scenarios by duplicating the TxtInOut and directly modifying the input files to define restoration scenarios. That is the reason why in the previous section, after adding the "calibration.cal" file to the TxtInOut, we created a copy of **TxtInOut_inputs** to easily use as a backup copying folder. This way, even after we run the baseline scenario in the TxtInOut folder (section 3.6.2), we will still have a copy containing only the inputs files to easily copy into new folders/scenarios, since output files can be of large size, and we do not need to copy them for new scenarios.

3.5.1 Peatland rewetting

The restoration measure of peatland rewetting is simulated in SWAT+ by changing the land use of the target HRUs from barren or sparsely vegetated (bsvg) to peatland (peat). To identify these target HRUs, use QGIS and the shapefile **"Actual HRUs (hrus2)"**. Their ID is the value in the column **"HRUS"**.

If the land use peat is already present in the model, the following file from the TxtInOut must be edited:

→ *hru-data.hru*. For the target HRUs, change "bsvg_lum" to "peat_lum" in the lu_mgt column.

```
hru-data.hru: written by SWAT+ editor v3.0.8 on 2025-04-15 13:14 for SWAT+ rev.61.0.1
     id  name                topo           hydro         soil          lu_mgt        lu_mgt
      1  hru0001             topohru0001    hyd0001       DSOLMap_1413  bsvg_lum      peat_lum
      2  hru0002             topohru0002    hyd0002       DSOLMap_1413  bsvg_lum      peat_lum
      3  hru0003             topohru0003    hyd0003       DSOLMap_1413  bsvg_lum      peat_lum
      4  hru0004             topohru0004    hyd0004       DSOLMap_1884  bsvg_lum      peat_lum
      5  hru0005             topohru0005    hyd0005       DSOLMap_1884  bsvg_lum      peat_lum
      6  hru0006             topohru0006    hyd0006       DSOLMap_1452  bsvg_lum      peat_lum
      7  hru0007             topohru0007    hyd0007       DSOLMap_1452  bsvg_lum      peat_lum
      8  hru0008             topohru0008    hyd0008       DSOLMap_1416  bsvg_lum      peat_lum
      9  hru0009             topohru0009    hyd0009       DSOLMap_1413  rngb_lum      rngb_lum
     10  hru0010             topohru0010    hyd0010       DSOLMap_1413  rngb_lum      rngb_lum
```

Figure 31. Simulation of restoration measures (1)

Although it may not be the case, if the land use peat was not previously present in the model, the following files must also be edited:

→ *landuse.lum* – Add a row with the following information. You can also copy it from the example file *peat_landuse.lum*.

name	cal_group	plnt_com	mgt	cn2	cons_prac	urban
peat_lum	null	peat_comm	null	wood_p	up_down_slope	null

urb_ro	ov_mann	tile	sep	vfs	grww	bmp
null	forest_med	null	null	null	null	null

→ *plant.ini* – Add two rows with the following information. You can also copy it from the example file *peat_plant.ini*.

pcom_name	plt_cnt	rot_yr_ini	plt_name	lc_status	lai_init	bm_init
peat_comm	1	1				
			peat	y	2	50000
			phu_init	**plnt_pop**	**yrs_init**	**rsd_init**
			0	0	1	10000

3.5.2 Wetland rewetting

The restoration measure of wetland rewetting is similar to peatland rewetting, but the only difference is that HRUs with the land use wetland (wetl) also require a wetland object to be defined, and the original land use of target HRUs could be any. If the land use wetl is already present in the model, the following files must be edited:

→ *hru-data.hru* – For the target HRUs, change "xxxx_lum" to "wetl_lum" in the lu_mgt column. In the surf_stor column, change "null" to "wet#", where # is the HRU's numerical id. Note that the number must be the same as the one in the columns name, topo and hydro, with zeroes in front of the id if necessary. For example, if the model has thousands of HRUs, for the HRU with id 9 in the surf_stor column you must write "wet0009", while the HRU with id 10 will be "wet0010" and the HRU with id 1234 will be "wet1234".

```
hru-data.hru: written by SWAT+ editor v3.0.8 on 2025-04-15 13:14 for SWAT+ rev.61.0.1
     id  name          topo         hydro     soil          lu_mgt    soil_plant_init  surf_stor   lu_mgt    surf_stor
      1  hru0001       topohru0001  hyd0001   DSOLMap_1413  peat_lum  soilplant1       null        peat_lum  null
      2  hru0002       topohru0002  hyd0002   DSOLMap_1413  peat_lum  soilplant1       null        peat_lum  null
      3  hru0003       topohru0003  hyd0003   DSOLMap_1413  peat_lum  soilplant1       null        peat_lum  null
      4  hru0004       topohru0004  hyd0004   DSOLMap_1884  peat_lum  soilplant1       null        peat_lum  null
      5  hru0005       topohru0005  hyd0005   DSOLMap_1884  peat_lum  soilplant1       null        peat_lum  null
      6  hru0006       topohru0006  hyd0006   DSOLMap_1452  peat_lum  soilplant1       null        peat_lum  null
      7  hru0007       topohru0007  hyd0007   DSOLMap_1452  peat_lum  soilplant1       null        peat_lum  null
      8  hru0008       topohru0008  hyd0008   DSOLMap_1416  peat_lum  soilplant1       null        peat_lum  null
      9  hru0009       topohru0009  hyd0009   DSOLMap_1413  rngb_lum  soilplant1       null        wetl_lum  wet0009
     10  hru0010       topohru0010  hyd0010   DSOLMap_1413  rngb_lum  soilplant1       null        wetl_lum  wet0010
     11  hru0011       topohru0011  hyd0011   DSOLMap_1413  rngb_lum  soilplant1       null        wetl_lum  wet0011
     12  hru0012       topohru0012  hyd0012   DSOLMap_1884  rngb_lum  soilplant1       null        rngb_lum  null
```

Figure 32. Simulation of restoration measures (2)

→ *wetland.wet* – Add a row for each of the target HRUs with the following information:

id	name	init	hyd	rel	sed	nut
(sequential id)	wet#	initwet1	hydwet#	wetland	sedwet1	nutwet1

where wet# is the name in the surf_stor column of the hru-data.hru file, and hydwet# must have the same number as wet#. Following the previous example, for "wet0009" you must also write "hydwet0009". The sequential id refers to the wetland object id (different from the HRU id). For example, if in the wetland.wet file there already were 19 objects and three more needed to be added, their ids would respectively be 20, 21, and 22.

wetland.wet: written by SWAT+ editor v3.0.8 on 2025-04-15 13:14 for SWAT+ rev.61.0.1

id	name	init	hyd	rel	sed	nut
1	wet0159	initwet1	hydwet0159	null	sedwet1	nutwet1
2	wet0553	initwet1	hydwet0553	null	sedwet1	nutwet1
3	wet0554	initwet1	hydwet0554	null	sedwet1	nutwet1
4	wet1646	initwet1	hydwet1646	null	sedwet1	nutwet1
5	wet1647	initwet1	hydwet1647	null	sedwet1	nutwet1
6	wet1884	initwet1	hydwet1884	null	sedwet1	nutwet1
7	wet2052	initwet1	hydwet2052	null	sedwet1	nutwet1
8	wet2053	initwet1	hydwet2053	null	sedwet1	nutwet1
9	wet2342	initwet1	hydwet2342	null	sedwet1	nutwet1
10	wet2436	initwet1	hydwet2436	null	sedwet1	nutwet1
11	wet3089	initwet1	hydwet3089	null	sedwet1	nutwet1
12	wet3611	initwet1	hydwet3611	null	sedwet1	nutwet1
13	wet3777	initwet1	hydwet3777	null	sedwet1	nutwet1
14	wet4234	initwet1	hydwet4234	null	sedwet1	nutwet1
15	wet6189	initwet1	hydwet6189	null	sedwet1	nutwet1
16	wet6479	initwet1	hydwet6479	null	sedwet1	nutwet1
17	wet6480	initwet1	hydwet6480	null	sedwet1	nutwet1
18	wet7333	initwet1	hydwet7333	null	sedwet1	nutwet1
19	wet7334	initwet1	hydwet7334	null	sedwet1	nutwet1
20	wet0009	initwet1	hydwet0009	null	sedwet1	nutwet1
21	wet0010	initwet1	hydwet0010	null	sedwet1	nutwet1
22	wet0011	initwet1	hydwet0011	null	sedwet1	nutwet1

Figure 33. Simulation of restoration measures (3)

→ *hydrology.wet* – Add a row for each of the target HRUs with the following information:

name	hru_ps	dp_ps	hru_es	dp_es	k
hydwet#	0.1	20	0.25	100	0.01
	evap	**vol_area_co**	**vol_dp_a**	**vol_dp_b**	**hru_frac**
	0.7	1	1	1	0.5

hydrology.wet: written by SWAT+ editor v3.0.8 on 2025-04-15 13:14 for SWAT+ rev.61.0.1

name	hru_ps	dp_ps	hru_es	dp_es	k	evap	vol_area_co	vol_dp_a	vol_dp_b	hru_frac
hydwet0159	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet0553	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet0554	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet1646	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet1647	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet1884	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet2052	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet2053	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet2342	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet2436	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet3089	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet3611	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet3777	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet4234	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet6189	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet6479	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet6480	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet7333	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet7334	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet0009	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet0010	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000
hydwet0011	0.10000	20.00000	0.25000	100.00000	0.01000	0.70000	1.00000	1.00000	1.00000	0.50000

Figure 34. Simulation of restoration measures (4)

Similarly to peatland rewetting, even though it may not be the case, if the land use wetl was not previously present in the model, the following files must also be edited:

→ *landuse.lum* – Add a row with the following information. You can also copy it from the example file *wetl_landuse.lum*.

name	cal_group	plnt_com	mgt	cn2	cons_prac	urban
wetl_lum	null	wetl_comm	null	wood_p	up_down_slope	null
urb_ro	**ov_mann**	**tile**	**sep**	**vfs**	**grww**	**bmp**
null	forest_med	null	null	null	null	null

→ *plant.ini* – Add two rows with the following information. You can also copy it from the example file *wetl_plant.ini*.

pcom_name	plt_cnt	rot_yr_ini	plt_name	lc_status	lai_init	bm_init	phu_init	plnt_pop	yrs_init	rsd_init
wetl_comm	1	1								
			wetl	y	2	50000	0	0	1	10000

Although highly improbable, there could also be the possibility that the model does not previously have any wetland land use, in which case the wetland.wet and hydrology.wet files will not exist within the TxtInOut, and the files must be created. We have provided some sample files to use as a template. Note that the first line in both files is not read by SWAT+ and therefore the header must be in line 2, and the actual data for each HRU must start in line 3. Moreover, the following files must also be edited/added:

→ *file.cio* – If the model has reservoirs/lakes, change the last two null values of line 6 (reservoir) to wetland.wet and hydrology.wet, respectively. If there are no reservoirs/lakes, all values in line 6 will be null and it should be changed to:

reservoir	initial.res	null	null	sediment .res	nutrients .res	null	wetland. wet	hydrolog y.wet

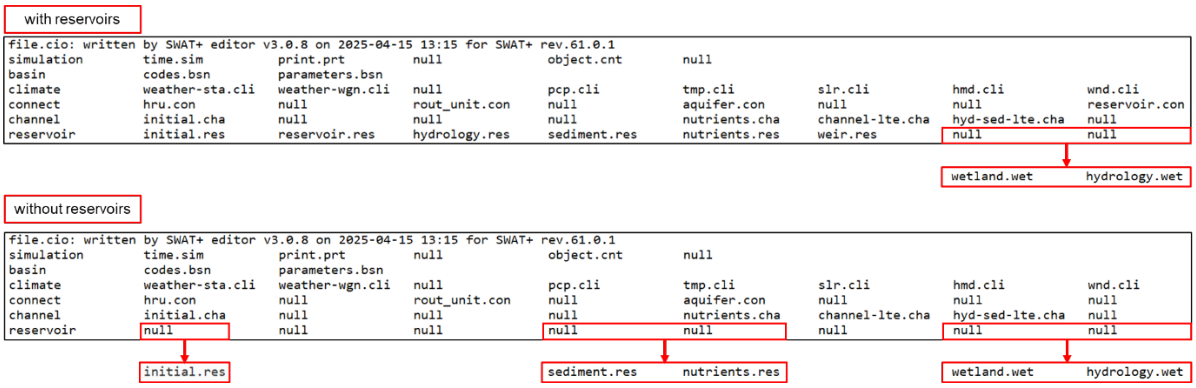

Figure 35. Simulation of restoration measures (5)

→ *initial.res* – If the model has reservoirs/lakes, this file will already exist and a row for initwet1 should be added. Otherwise, the file must be added to the TxtInOut, noting that the header must be in line 2 and the initwet1 values in line 3. We have provided an example *initial.res* file to copy the line/file.

name	org_min	pest	path	hmet	salt	description
initwet1	no_init	null	null	null	null	null

→ *sediment.res* – If the model has reservoirs/lakes, this file will already exist and a row for sedwet1 should be added. Otherwise, the file must be added to the TxtInOut, noting that the header must be in line 2 and the sedwet1 values in line 3. We have provided an example *sediment.res* file to copy the line/file.

name	sed_amt	d50	carbon	bd	sed_stl	stl_vel
sedwet1	1	10	0	0	1	1

→ *nutrients.res* – If the model has reservoirs/lakes, this file will already exist and a row for nutwet1 should be added. Otherwise, the file must be added to the TxtInOut, noting that the header must be in line 2 and the nutwet1 values in line 3. We have provided an example *nutrients.res* file to copy the line/file.

name	mid_start	mid_end	mid_n_stl	n_stl	mid_p_stl	p_stl	chla_co	secchi_co	theta_n	theta_p	n_min_stl	p_min_stl
nutwet1	5	10	5.5	5.5	10	10	1	1	1	1	0.1	0.01

Riparian buffer

To simulate the restoration of riparian vegetation in target HRUs we need to assign them a filter strip. As seen in section 3.2.2, we have already identified those HRU and assigned them a different land use (fstp) during the land use map processing. The following files from the TxtInOut need to be modified:

- *landuse.lum* – For "fstp_lum", change the value in column vfs from "null" to "field_border".

```
landuse.lum: written by SWAT+ editor v3.0.8 on 2025-04-24 10:33 for SWAT+ rev.61.0.1
name         cal_group   plnt_com      mgt        cn2     cons_prac  urban          urb_ro          ov_mann  tile   sep    vfs       vfs
wpas_lum          null  wpas_comm     null    pastg_g   cross_slope   null            null     bermudagrass  null   null   null      null
urld_lum          null       null     null      urban up_down_slope   urld  buildup_washoff  urban_asphalt  null   null   null      null
agrl_lum          null  agrl_comm agrl_rot rc_strow_g   cross_slope   null            null    convtill_res  null   null   null      null
rngb_lum          null  rngb_comm     null    brush_f up_down_slope   null            null  range_20cover  null   null   null      null
wetl_lum          null  wetl_comm     null     wood_p up_down_slope   null            null      forest_med  null   null   null      null
orcd_lum          null  orcd_comm     null   woodgr_g   cross_slope   null            null      shortgrass  null   null   null      null
urhd_lum          null       null     null      urban up_down_slope   urhd  buildup_washoff  urban_asphalt  null   null   null      null
fstp_lum          null  fstp_comm fstp_rot rc_strow_g   cross_slope   null            null    convtill_res  null   null   null  ->  field_border
frsd_lum          null  frsd_comm     null     wood_f up_down_slope   null            null      forest_med  null   null   null      null
frst_lum          null  frst_comm     null     wood_f up_down_slope   null            null      forest_med  null   null   null      null
frse_lum          null  frse_comm     null     wood_f up_down_slope   null            null    forest_heavy  null   null   null      null
agrr_lum          null  agrr_comm agrr_rot rc_strow_g   cross_slope   null            null    convtill_res  null   null   null      null
utrn_lum          null       null     null      urban up_down_slope   utrn  buildup_washoff  urban_asphalt  null   null   null      null
rnge_lum          null  rnge_comm     null    pastg_f up_down_slope   null            null    range_sparse  null   null   null      null
peat_lum          null  peat_comm     null     wood_p up_down_slope   null            null      forest_med  null   null   null      null
```

Figure 36. Simulation of restoration measures (6)

- *filterstrip.str* – For "field_border", change the value in column flag from 0 to 1.

```
filterstrip.str: written by SWAT+ editor v3.0.8 on 2025-04-24 10:43 for SWAT+ rev.61.0.1
name                    flag      fld_vfs       con_vfs       cha_q  description
field_border               0      0.10000       0.00300     0.20000  Field_border
high_engineered            0      0.10000       0.00100     0.05000  Highly_engineered_low_channelized

                        flag
                           1
                           0
```

Figure 37. Simulation of restoration measures (7)

3.5.3 Floodplain reconnection

To simulate the reconnection between stream and floodplain we will activate the SWAT+ functionality of overbank flow. The following files need to be modified/added:

- *codes.bsn* – Change the value for "i_fpwet" from 1 to 2.

```
codes.bsn: written by SWAT+ editor v3.0.8 on 2025-04-10 12:54 for SWAT+ rev.61.0.1
       pet_file           wq_file        pet      event      crack  swift_out    sed_det    rte_cha    deg_cha     wq_cha   nostress         cn
           null              null          1          0          0          1          0          1          0          1          0          0

         c_fact     carbon      lapse       uhyd    sed_cha  tiledrain     wtable     soil_p      gampt   atmo_dep   stor_max    i_fpwet     gwflow
              0          0          0          1          0          0          0          0          0          a          0          1          0

                                                                                                                              i_fpwet
                                                                                                                                    2
```

Figure 38. Simulation of restoration measures (8)

- *file.cio* – Change the first "null" value from row "link" to "chan-suf.lin".

```
file.cio: written by SWAT+ editor v3.0.8 on 2025-04-10 13:03 for SWAT+ rev.61.0.1
simulation      time.sim        print.prt       null            object.cnt
basin           codes.bsn       parameters.bsn
climate         weather-sta.cli weather-wgn.cli null            pcp.cli
connect         hru.con         null            rout_unit.con   null
channel         initial.cha     null            null            null
reservoir       initial.res     null            null            sediment.res
routing_unit    rout_unit.def   rout_unit.ele   rout_unit.rtu   null
hru             hru-data.hru    null
exco            null            null            null            null
recall          null
dr              null            null            null            null
aquifer         initial.aqu     aquifer.aqu
herd            null            null            null
water_rights    null            null            null
link            null            null

                chan-surf.lin
```

Figure 39. Simulation of restoration measures (9)

- *chan-surf.lin* – Create this file and add it to the TxtInOut, which links the target channels we want to reconnect to its respective floodplain. The file's structure is the following, but an example of the *chan-surf.lin* file is also available to use as a template.
    - Line 1 – Title, SWAT+ will not read it. It can be left blank.
    - Line 2 – Number of channels that connect to the floodplain.
- Line 3 – Header. The columns represent the following:
        - NUMB: channel id.
        - NAME: channel name.
        - NSPU: number of objects in the floodplain. In our case, it will always be 1, as the channel will connect to all HRUs in the floodplain (using the routing unit object).
- OBTYP: in our case, ru (routing unit).
        - OBTYP_N0: routing unit ID.
    - Line 4+ – Data for each channel that connects to the floodplain.

To populate the *chan-surf.lin* file, follow the steps from Figure 40.

1. Identify the ID and name of target channels in the TxtInOut file *chandeg.con*. Note that the ID in the attribute "Channel" in the shapefile rivs1.shp corresponds to the column "gis_id", but might not necessarily be the same as the actual channel ID in the TxtInOut. (Step 1)
2. Use the file *rout_unit.con* to determine the routing unit that each target channel connects to. The column "obj_id" corresponds to the channel ID, but multiple routing units can connect to the same channel. This is because one represents the upland and the other the floodplain, but in this case, we only need the floodplain ru, which will be the one with the lowest number in the column "out_tot". Once the floodplain ru for each target channel has been identified, the ID in the rtu column is the OBTYP_N0 value in *chan-surf.lin*. (Step 2)

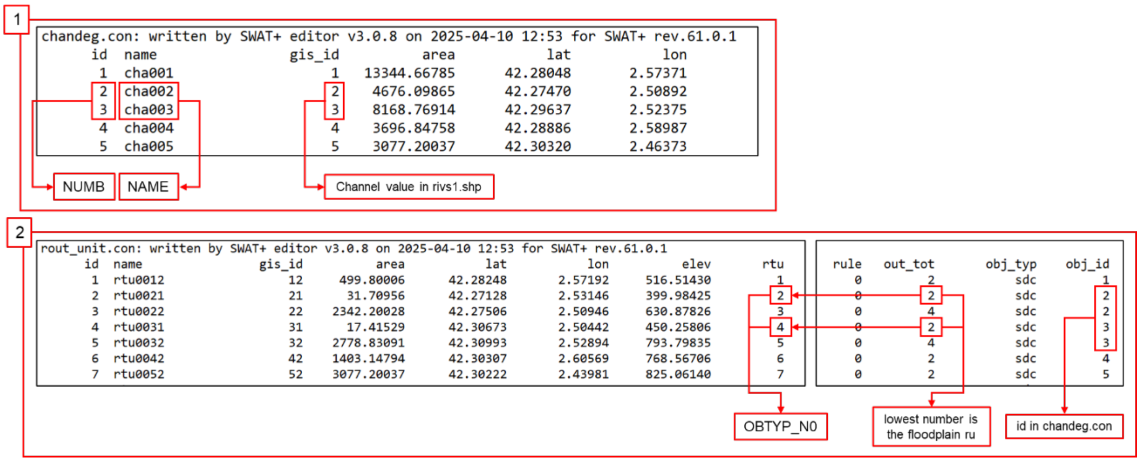

Figure 40. Simulation of restoration measures (10)

3.5.4 Channel restoration

The restoration of channels can be simulated in SWAT+ by increasing two key channel parameters: Manning's n roughness coefficient and sinuosity. Once the target channels to be restored are identified, we need to modify these parameters in the following file:

- *hyd-sed-lte.cha* – Manning's n and sinuosity are respectively in columns "mann" and "sinu". The value increase for each target channel is at the user's discretion; a larger increase implies the return to more natural conditions.

hyd-sed-lte.cha: written by SWAT+ editor v3.0.8 on 2025-04-15 13:14 for SWAT+ rev.61.0.1

name	order	wd	dp	slp	len	mann	k	erod_fact	cov_fact	sinu
hydcha001	1	6.56898	0.38478	0.03278	1.26550	0.05000	1.00000	0.01000	0.00500	1.05000
hydcha002	1	5.29141	0.33312	0.08654	0.64110	0.05000	1.00000	0.01000	0.00500	1.05000
hydcha003	1	4.53721	0.30066	0.02312	2.15750	0.05000	1.00000	0.01000	0.00500	1.05000
hydcha004	3	25.37041	0.94719	0.00088	3.86740	0.05000	1.00000	0.01000	0.00500	1.05000
hydcha005	2	21.33241	0.84381	0.00001	0.13770	0.05000	1.00000	0.01000	0.00500	1.05000
hydcha006	2	20.28176	0.81587	0.00225	0.26350	0.05000	1.00000	0.01000	0.00500	1.05000

Figure 41. Simulation of restoration measures (11)

3.6 Analysis of biophysical outputs related to ecosystem services

Understanding and quantifying the benefits of freshwater ecosystem restoration requires a clear link between the physical landscape processes simulated by models and the ecosystem services (ES) they support. Step 6 of the MERLIN modelling workflow focuses on this critical connection—bridging the outputs of the SWAT+ model with the ecosystem services, and ultimately linking these services to human well-being.

At the core of this step is the concept of the ecosystem services cascade ((Haines-Young & Potschin, 2010), which illustrates how the biophysical structures and processes of ecosystems—such as vegetation, soils, water, and their interactions—support ecosystem functions (e.g. water regulation, nutrient cycling), which in turn give rise to the ecosystem services that provide direct and indirect benefits to people. These benefits can be assessed in both non-monetary and monetary terms, depending on the available data and the intended use of the results in decision-making contexts (Figure 42).

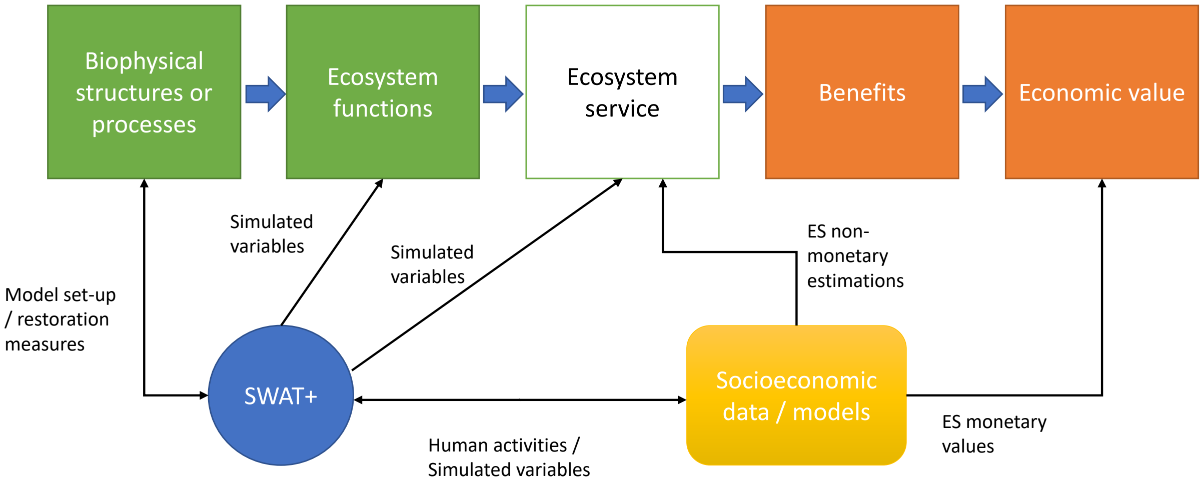

Figure 42. Interconnection between the ecosystem services cascade, the SWAT+ model, and socioeconomic data and models used in the development of the MERLIN modelling workflow.

The SWAT+ model is uniquely suited for this type of analysis. Its detailed simulation of landscape processes allows for the quantification of key variables related to ecosystem functions—such as streamflow, soil moisture, nutrient retention, erosion rates, and vegetation biomass. Some of these outputs, like reservoir water storage or crop yields, are already direct proxies for ecosystem services. Others require additional interpretation and integration with socio-economic data to assess their contribution to provisioning, regulating, or cultural ES.

In this step, users will explore how SWAT+ outputs can be mapped onto ES categories, how to select the most relevant simulated variables for each service, and how to complement these outputs with additional data and methods to derive meaningful indicators of ES provision.

3.6.1 MERLIN modelling workflow considered ecosystem services

Table 2 outlines the key ecosystem services (ES) that will be evaluated in the restoration scenarios for the MERLIN modelling workflow for the selected case studies. These services have been selected based on their relevance to both ecological integrity and human well-being. The selected services—**water purification**, **carbon sequestration**, **flood mitigation**, and **drought mitigation**—are considered core indicators of restoration success across diverse contexts. While other ES, such as erosion prevention, food production, and recreational opportunities, are also important for freshwater ecosystem restoration, they have not been included. For example, modelling food production or recreation would require additional data, assumptions, and model components that exceed the current scope and capacity of the MERLIN workflow. By concentrating on a core set of services that are broadly applicable and closely tied to hydrological and ecological processes, the workflow remains focused and efficient, while still capturing the primary benefits of restoration efforts.

Table 2 Selection of ecosystem services to be considered in the evaluation of the impact of the restoration scenarios for MERLIN modelling workflows

Ecosystem services	Description	Examples
Water purification	Natural ecosystems remove contaminants and pollutants from water, making it safer for human use and consumption. Focused on	Examples of ecosystems that provide water purification services include wetlands, forests, and riparian areas, which can filter pollutants and nutrients from agricultural and urban runoff, and

	nitrogen and phosphorus	reduce the risk of harmful algal blooms and waterborne diseases
Carbon sequestration	Natural ecosystems remove and store carbon dioxide from the atmosphere, helping to mitigate climate change and reduce the impacts of greenhouse gas emissions.	Examples of ecosystems that provide carbon sequestration services include forests, grasslands, and wetlands, which can store carbon in the form of plant biomass, soil organic matter, and other organic materials.
Flood mitigation	Ability of natural ecosystems to absorb and store excess water during periods of heavy precipitation, reducing the risk of flooding.	Examples of ecosystems that provide flood mitigation services include wetlands, floodplains, and forests, which can absorb and slow down the flow of water and provide natural barriers against storm surges and sea level rise.
Drought mitigation	Ability of natural ecosystems to maintain and regulate water availability during periods of low precipitation, helping to reduce the impacts of drought and water scarcity.	Examples of ecosystems that provide drought mitigation services include forests, grasslands, and wetlands, which can maintain soil moisture levels, regulate stream flow, and recharge groundwater resources.

Table 3 links each restoration action or ecosystem considered in the five MERLIN cases to the most relevant ES. This table provides a clear overview of how each restoration action aligns with the selected ES and highlights which ES should be prioritized when evaluating the socioeconomic impacts of restoration across different freshwater systems.

For peatland rewetting, carbon sequestration is one of the most relevant ES, due to the strong role of peatlands in storing carbon and reducing emissions when rewetted (Günther et al., 2020). Water purification, flood mitigation, and drought have a moderate relevance (Gatis et al., 2023). While peatlands contribute to nutrient retention and water regulation, their primary value lies in carbon storage.

Wetland rewetting shows a strong relevance to water purification, given wetlands' natural capacity to filter nutrients and sediments (Land et al., 2016). It also contributes moderately to carbon sequestration, flood mitigation, and drought mitigation, as wetlands can store carbon, reduce flood peaks, and maintain water availability during dry periods (Creed et al., 2022).

Riparian buffer restoration is especially important for water purification. This reflects the critical role riparian zones play in filtering agricultural runoff, trapping sediments and diluted nutrients, and improving water quality (Tsai et al., 2022). There are other ES related to riparian buffer restoration. However, Table 3 reflects only the ones that can be estimated based on SWAT+.

In the case of floodplain reconnection, flood mitigation is highly relevant. Water purification, carbon sequestration, and drought mitigation have some relevance, recognizing that reconnected floodplains can filter pollutants, store carbon in vegetation and soils, and support groundwater recharge to enhance drought resilience (Serra-Llobet et al., 2022).

Finally, for channel restoration, water purification and flood mitigation have some significance, acknowledging that restoring natural channel structure can slow water flow and support pollutant metabolization (Verdonschot & Verdonschot, 2023). However, its contributions to carbon sequestration and drought mitigation are either limited or cannot be assessed within the SWAT+ model.

Table 3: Linking each restoration action/ecosystem considered in MERLIN to the most relevant ecosystem services (ES)

Restoration actions	Ecosystem services			
	Water purification	Carbon sequestration	Flood mitigation	Drought mitigation
Peatland rewetting	▲	▲▲	▲	▲
Wetland rewetting	▲▲	▲	▲	▲
Riparian buffer	▲▲▲			
Floodplain reconnection	▲	▲	▲▲	▲
Channel restoration	▲		▲	

Note: The black triangles (▲) indicate the relevance or importance of that ES in relation to the restoration action. More triangles = higher relevance: ▲ = low/moderate relevance; ▲▲ = significant relevance; ▲▲▲ = very high relevance.

3.6.2 Running SWAT+ and obtaining the SQLite output file of the SWAT+ restoration simulation

This subsection will detail how to run SWAT+ and obtain the SQLite output file for each restoration scenario using the SWAT+ Editor. An SQLite file is a lightweight, self-contained database that stores tabular data generated during model simulations. Specifically, it will contain all the relevant output files that we specified in section 3.3.4, concretely in the "Configuring Output Settings and Warm-up Period in SWAT+" subsection.

As indicated in section 3.5, each restoration scenario implemented with SWAT+ should be conducted in a separate copy of the **TxtInOut_inputs** folder. Each folder should be clearly named to reflect the type of restoration applied (e.g., **TxtInOut_fullpeatlandsrest**, which contains the output files of a simulation where all potentially restorable peatlands have been restored).

Run SWAT+ and create the SQLite output file

Figure 43 illustrates how to run SWAT+ from the SWAT+ Editor.

1. **Access the Simulation Settings** – Click on the **Run SWAT+** menu in the left panel to configure the model's run period. (**Step 1**)
2. **Define TxtInOut path** – Under **"Choose where to write your input files"**, ensure that the directory is set to the TxtInOut that you want to run. For the default scenario, the first time, this path is already set to the default TxtInOut folder. For scenarios, select the folders containing their respective modified TxtInOut files. (**Step 2**)
3. **Configure Run SWAT+ options** – Check only the boxes "**Run SWAT+ rev. 61.0.1"** and **"Analyze output for visualization"**. Note that it would also be possible to run SWAT+ directly from the TxtInOut folder (by double-clicking on the executable *rev61.0.1_64rel.exe*). In this case, only **"Analyze output for visualization"** should be selected.(**Step 3**)
4. **Execute SWAT+ and import outputs** – click on **"Save settings & run selected"**. This simulation will be executed, and the outputs will be imported into the SQLite file. (**Step 4**)
5. **Open the Results folder** – Once the execution and output import are done, click on **"Open Results Directory"**. This will open the folder where the SQLite output file **"swatplus_output.sqlite"** is written. (**Step 5**)
6. **Duplicate "swatplus_output.sqlite"** – Make a copy of the **"swatplus_ outputs.sqlite"** file, rename it accordingly to differentiate it from the other scenarios, and store it in the designated **4-Outputs** folder for future use, as when you repeat these steps to run/import the other scenarios, the **"swatlus_outputs.sqlite"** file will get rewritten. (**Step 6**)

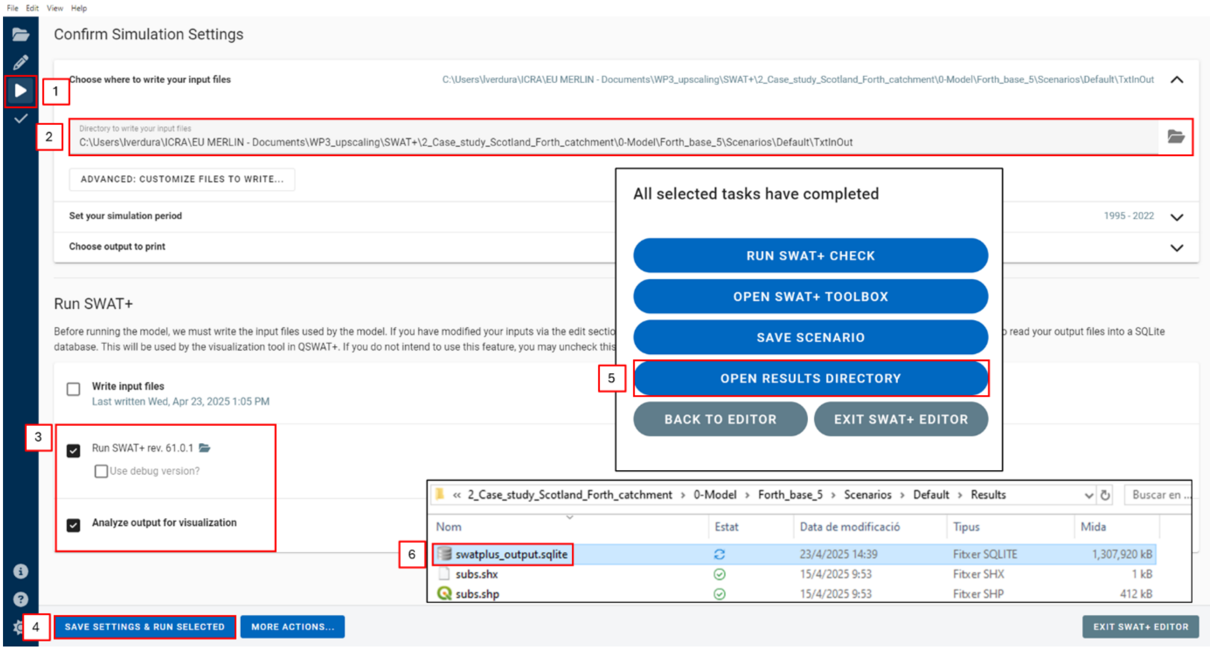

Figure 43. Analysis of biophysical outputs

3.6.3 Exploring the simulated biophysical results

To explore the results, that is, the SWAT+ output files and the biophysical variables relevant for ES assessment, we recommend using an SQLite browser such as **DB Browser for SQLite** (Download here).

As detailed in section 3.3.4, the selected output files that will be included in the SQLite are:

- Model Components - Channel: Daily (**channel_sd_day**), Monthly (**channel_sd_mon**) and Average (**channel_sd_aa**)
- Model Components - Reservoir: Monthly (**reservoir_mon**) and Average (**reservoir_aa**)
- Nutrient Balance - Landscape Unit: Monthly (**lsunit_nb_mon**) and Average (**lsunit_nb_aa**)
- Water Balance - Landscape Unit: Monthly (**lsunit_wb_mon**) and Average (**lsunit_wb_aa)**
- Plant and Weather - Landscape Unit: Monthly (**lsunit_pw_mon**) and Average (**lsunit_pw_aa)**
- Losses - Landscape Unit: Monthly (**lsunit_ls_mon**) and Average (**lsunit_ls_aa**)

The rationale behind selecting these specific output files is to capture the key biophysical variables relevant to the ecosystem services (ES) targeted in the MERLIN modelling workflow. For example:

- **channel_sd_day**: Includes the variable *flo_out* (flow out of the channel) in m^3/s at a daily timestep, which is useful for constructing hydrographs or estimating the return period of peak flows or base flows relevant for supporting the habitat services
- **channel_sd_mon**: Includes the variable *flo_out* (flow out of the channel) in m^3/s at a monthly timestep. Average concentration of pollutants can be calculated based on variables such as *no3_out* (nitrate nitrogen leaving the channel) or *solp_out* (soluble phosphorus leaving the channel), both in kg units.
- **reservoir_mon**: Contains variables such as *flo_in* (flow into the reservoir) in m^3/s at a monthly timestep, enabling assessments of water availability during dry periods.
- **lsunit_nb_mon**: Provides *fertn* (total nitrogen applied through fertilization) in kg/ha per month, which can be used to evaluate changes in nutrient loading.
- **lsunit_wb_mon**: Includes *perc* (percolation) in mm, representing groundwater recharge at a monthly timestep.
- **lsunit_pw_aa**: Captures *bioms* (total plant biomass) in kg/ha as an average, useful for estimating aboveground carbon sequestration.
- **lsunit_ls_mon**: Reports *sedorgp* (organic phosphorus transported via surface runoff) in kg/ha per month, applicable for analysing phosphorus retention in the landscape.

More details on these and the other available output variables in the selected files, or the other output files available and their corresponding variables, can be found in the **SWAT+ Documentation** website (access here). More information on the use of SWAT and SWAT+ output variables to assess the impact on ES provision of land and water management actions can be found in Francesconi et al. (2016) and Garcia (2023).

3.7 Monetary valuation of restoration benefits

The monetary valuation of restoration benefits translates ecosystem service outcomes into economic terms, helping to demonstrate the tangible value of restoration efforts. This section outlines methods for estimating the financial benefits of services such as water purification, flood and drought risk mitigation, and climate regulation. By combining SWAT+ outputs with socio-economic data and valuation methods, this step supports cost-benefit analysis and strengthens the case for investing in nature-based solutions.

3.7.1 Water purification

Water purification is an essential ecosystem service whereby natural ecosystems contribute to the removal of harmful substances—such as nitrogen and phosphorus—from water, thereby enhancing its quality and safety for human use and consumption and the ecosystems. This ES improves the quality of water sources that supply drinking water, thereby enhancing safety for human consumption and reducing the need for costly treatment.

As a core component of the MERLIN modelling workflow, the economic value of water purification can be assessed using the **S+WaterPurification** QGIS plugin. This plugin applies a valuation method based on replacement costs, developed from La Notte et al. (2017). Full methodological details are available in Deliverable 3.4.

Installation and application of the S+WaterPurification QGIS plugin

1. Open QGIS and click on the **Plugins** menu.
2. In the Not installed section, search for **S+WaterPurification** and click on "**Install Plugin**"
3. If correctly installed, a new menu bar will appear with the name **S+WaterPurification.** By clicking on it, two options are available: "**Channel Purification**" and "**Landscape Purification**". The former should be applied to quantify the impact of in-channel restorations. The latter for restoration actions conducted in other parts of the watershed (e.g., peatland rewetting, best management agricultural practices, etc.).
4. By clicking on **Landscape Purification,** the tool window will come up. The data requirements are:
    a. SWAT+ layers: The landscape units layer (lsus2) and channel layer (rivs1)
    b. SQLite files: One with the baseline scenario output tables and another with the restoration scenario output tables
    c. Parameters (default values):
        i. Actualization rate (no units),
        ii. Life expectancy (years)
        iii. Yearly operation maintenance cost (Euros/ha)

For the **Channel purification** tool, the required input data/values are the same, with the exception that the landscape units' layer is not required.

Once the tool has finished processing, a shapefile will be generated. **Landscape Purification** will provide a landscape units layer, and the **Channel purification** a channel layer (Figure 44). Both layers will include an additional field that indicates the annualised net present value of nutrient retention in total Euros.

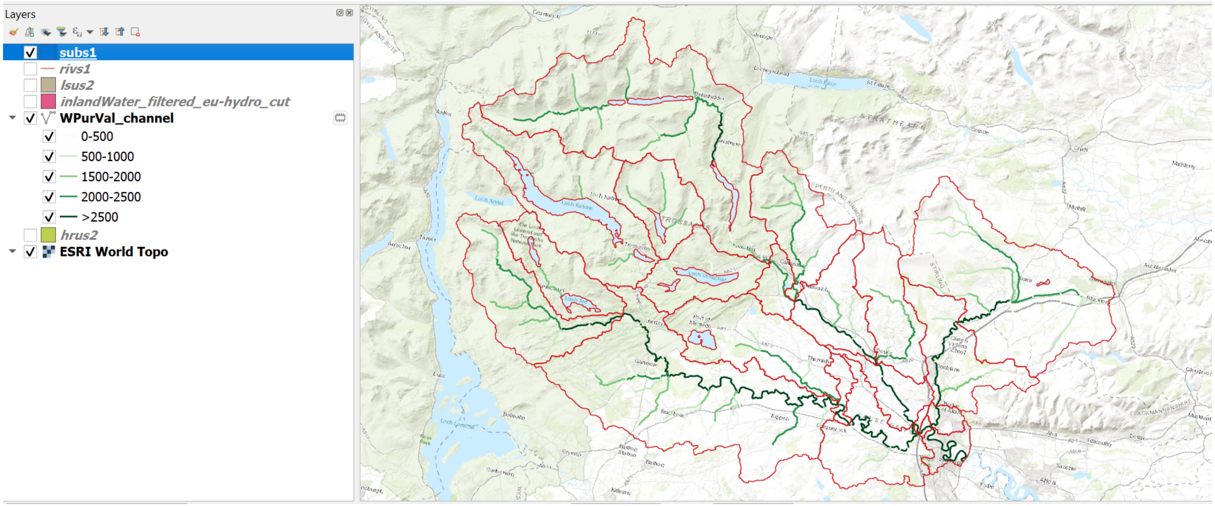

Figure 44. Result of the Channel purification tool for a large-scale channel restoration simulated in the Forth Basin (UK)

3.7.2 Flood risk mitigation

Flood risk mitigation ES is the contribution of the ecosystems to the absorption and retention of surplus water during periods of intense precipitation, thereby mitigating flood risks. As well as the previous, a QGIS plugin was developed to support the economic quantification of the impact of the restoration measures of the MERLIN modelling workflow. This is the **S+FloodRisk.** This plugin is methodologically based on the calculation of the average annual value of flood risk mitigation benefits through the calculation of the expected annual damage (EAD) (Dierauer et al., 2012)**.** Full methodological details are available in Deliverable 3.4.

Installation and application of the S+FloodRisk QGIS plugin

5. Open QGIS and click on the **Plugins** menu.
6. In the Not installed section, search for **S+FloodRisk** and click on "**Install Plugin**"
7. If correctly installed, a new menu bar will appear with the name **S+FloodRisk**. By clicking on it, two options are available: **"Damage units"** and **"Risk Mitigation"**. The former is required to create the Damage Units vector layer, which is needed to run the second tool.
8. By clicking on **Damage units,** the tool window will come up. The data requirements are:
    a. **SWAT+ layers**: The channel layer (rivs1)
    b. **Risk raster layers**: Minimum 3 and maximum 5 risk raster layers can be uploaded. These represent the annualised damage in Euros/m^2 calculated for a given flood event of return time T.
    c. Parameters:
        i. **Projection** (coordinate reference system, CRS). The default CRS is EPSG: 3035
        ii. **Channel distance selection**. The default is 250 meters from the SWAT+ channel layer. This parameter controls de selection of Damage Units to be used to calculate the EAD.
        iii. The **Damage units cell size** (in meters). No default value is provided. Smaller damage unit cells will make the results more precise, but computationally heavy. This size should not be smaller than the risk raster layer's pixel size.
        iv. The **Pixel size** (in meters). The risk raster layer's pixel size.
9. Once the Damage units vector layer has been created and stored safely (e.g., in the 4-outputs folder), click on the Risk Mitigation toolbar. The data requirements in this case are:
    a. **SWAT+ layers**: The channel layer (rivs1)
    b. **Administrative units layer**: This layer will be used as a basis to calculate EAD at the decided level. For instance, if EAD is preferred to be calculated at the municipality level, then a municipality limits layer should be selected. SWAT+ layers such as Subbasin could also be used instead.
    c. **Damage units layer** previously calculated

d. **SQLite files**: One with the baseline scenario output tables and another with the restoration scenario output tables

e. Parameters:

   i. **Return periods** of the risk map layers used in the previous step (A, B, C, E-optional, D-optional)

   ii. Field in the administrative units layer with unique identification values (**Admin_id**). A string value should be provided.

Once the tool **Risk Mitigation** has finished processing, a shapefile similar to the Administrative units layer will be generated, but with a EADD_sum field with the calculated EAD by administrative unit.

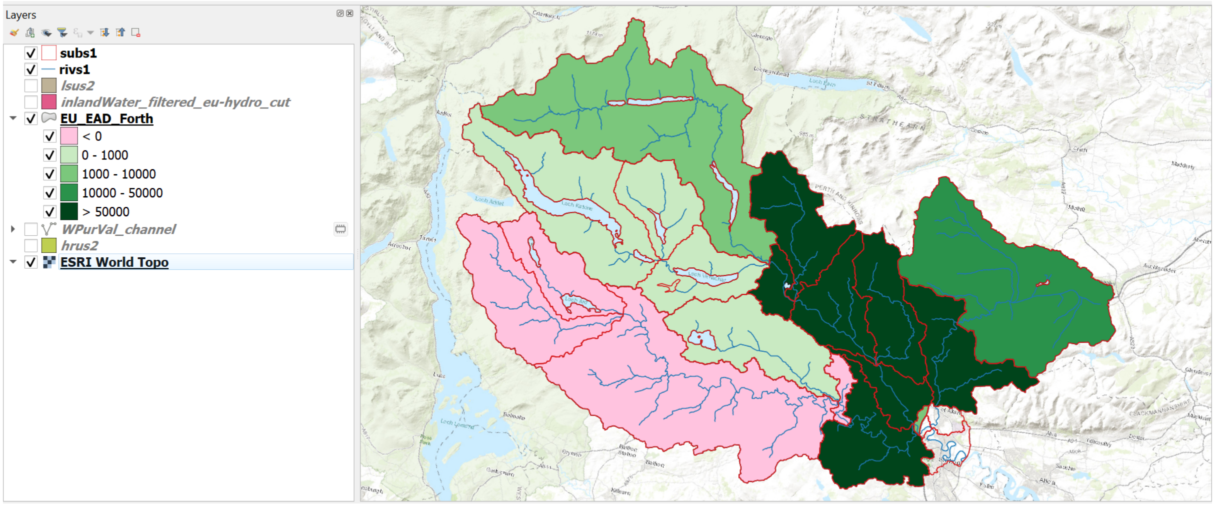

Figure 45. Result of the S+FloodRisk tool for a large-scale peatland restoration simulated in the Forth Basin (UK)

3.7.3 Global climate regulation

While SWAT+ does not directly model CO_2 emissions or sequestration in ecosystems, it provides land use data that can be combined with default CO_2 emission and sequestration factors per land use class to estimate the impact of restoration on global climate regulation—specifically, in terms of reduced emissions or increased sequestration. These benefits can then be monetized by applying a monetary value per ton of CO_2, based on estimates such as the social cost of carbon or carbon credit market prices. Deliverable 3.4 presents examples of how global climate regulation benefits are estimated and integrated into the cost-benefit analysis of MERLIN case studies.

3.7.4 Drought risk mitigation

SWAT+ enables the modelling of key indicators relevant to drought risk mitigation, such as reservoir and groundwater recharge, as well as hydraulic flows in channels (see Section 3.6.3). However, the monetary value of drought risk mitigation varies significantly depending on the hydrological context of the catchment—e.g. comparing north-western European to Mediterranean basins—and on the specific types of water use, such as for agriculture, water supply, hydropower, or navigation. These variations necessitate the use of context-specific valuation methods. As a result, the MERLIN modelling workflow does not include a universal approach for valuing drought risk mitigation. Instead, Deliverable 3.4 presents several valuation methods that can be applied alongside SWAT+ physical indicators to estimate drought risk mitigation benefits tailored to specific catchment and water use contexts.

4 Issues during development and solutions / Lessons learned

The development of the MERLIN modelling workflow encountered several challenges, primarily related to data availability, quality, and spatial resolution. To ensure consistent and comparable calibration across the diverse MERLIN case studies, the modelling team adopted a strategy cantered on modelled evapotranspiration data from GLEAM as the primary reference for hydrological calibration. GLEAM provides globally consistent, high-quality estimates of evapotranspiration, offering a robust and spatially comprehensive dataset that is particularly well suited for achieving reliable calibration in regions where observed hydrological data are limited or inconsistent. This approach enabled a more balanced, basin-wide representation of hydrological processes and allowed the modelling to deliver meaningful insights, even in data-scarce contexts.

This strategy proved more effective than relying solely on observed streamflow data from local gauging stations, which was the initial plan. Although daily streamflow data were collected for several sites, their quality varied significantly—some datasets contained errors, gaps, or inconsistent periods that compromised their reliability. Moreover, the underlying input data used to set up the SWAT+ model were primarily EU-wide datasets, which often lacked the spatial resolution necessary to match local hydrological conditions. This mismatch meant that, in many cases, the model could not be satisfactorily calibrated using streamflow observations alone, regardless of how parameters were adjusted.

Another challenge encountered during the development of the MERLIN modelling workflow was the attempted integration of water quality modelling, specifically the simulation of nitrogen and phosphorus dynamics. While initially part of the workflow design, this component had to be removed in most case studies due to a lack of reliable data on key nutrient sources, including both point and diffuse inputs. Except for atmospheric nitrogen deposition—available from EU datasets—critical input data were either missing or too inconsistent to support robust simulations. Including this component would have introduced considerable uncertainty without adding dependable results.

Despite these limitations, we consider that the MERLIN modelling workflow is a robust and valuable tool. It provides structured, quantitative insights into hydrological processes and supports the design and evaluation of restoration actions. While in some contexts it may be tempting to proceed without modelling, doing so risks overlooking important system dynamics. The adapted calibration approach using GLEAM ensures that the modelling can still produce credible outputs, making it a worthwhile component of project planning and assessment.

5 Conclusions

The MERLIN modelling workflow was developed to provide a structured, scalable approach for assessing the bio-physical and economic opportunities of freshwater ecosystem restoration that can be used across Europe to inform the prioritization and planning of restoration projects. By integrating hydrological modelling (SWAT+), ecosystem service analysis, and socio-economic valuation, the workflow supports evidence-based planning and decision-making aligned with the goals of the European Green Deal. It offers a practical, step-by-step guide—from data preparation and scenario simulation to valuation of ecosystem services—adaptable to diverse catchment contexts and user expertise levels. To demonstrate broad applicability, the workflow was implemented using EU-wide datasets, showing how restoration planning can be supported even in data-scarce regions. Where more detailed, site-specific data are available, they can and should be integrated to improve the accuracy and local relevance of the modelling outputs.

While the current version of the MERLIN modelling workflow represents a significant achievement, it is also clear that without ongoing support and development, its utility will quickly diminish. The modelling tools, datasets, and policy landscapes it relies on are evolving. New versions of the SWAT+ model are expected, offering improved features and compatibility. Additionally, the availability of high-resolution EU-wide datasets for both biophysical and socio-economic parameters is rapidly increasing, promising to enhance model accuracy and relevance. Emerging socio-economic models will further strengthen the valuation of restoration benefits, enabling more nuanced and robust cost-benefit analyses.

To ensure the long-term value and usability of the MERLIN modelling workflow, it is essential that efforts are made to maintain, update, and expand it—both technically and conceptually. This includes integrating future model versions, updating documentation and training materials, and ensuring that the workflow remains compatible with the latest data and policy priorities. With continued investment and adaptation, the MERLIN modelling workflow can serve as a cornerstone for advancing large-scale, evidence-based freshwater restoration in Europe and beyond.

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