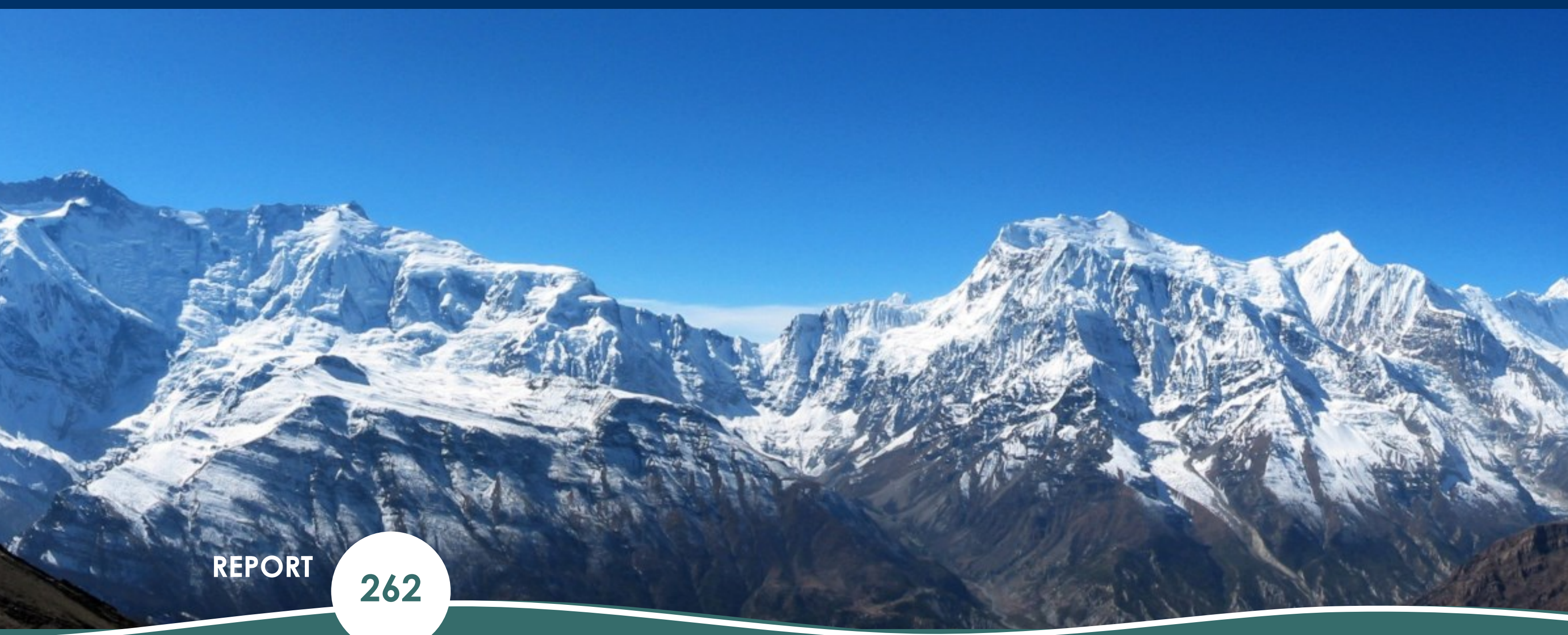
Technical Manual - SPHY: Spatial Processes in Hydrology

QGIS SPHY Plugin v3.1



REPORT 262

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Technical Manual - SPHY: Spatial Processes in Hydrology

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FutureWater

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- European Space Agency (ESA[2]);
- Asian Development Bank (ADB[3]);
- World Bank[4];
- Rijksdienst voor Ondernemend Nedeland (RVO[5])
- NUFFIC[6]

We are grateful to these organizations for enabling us to develop the SPHY model. We hope to continue collaborating with these organizations in the future to further develop and improve the SPHY model and its interfaces. We thank Jil van Etten, Matias Hernandez and Jisca Schoonhoven, who were the first users of QGIS plugin version 3.1, for their contribution to this report and debugging the code.

[1] http://www.icimod.org/
[2] http://www.esa.int/ESA
[3] http://www.adb.org/
[4] http://www.worldbank.org/
[5] http://www.rvo.nl/
[6] https://www.nuffic.nl/en

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1 Introduction

1.1 Background

The Spatial Processes in Hydrology (SPHY) model (https://sphymodel.com/) is a hydrological modeling tool suitable for a wide range of water resource management applications. SPHY is a state-of-the-art, easy-to-use, and robust tool that can be applied for operational and strategic decision support. The SPHY modeling package is available in the public domain and uses only open-source software. SPHY was developed by FutureWater in cooperation with national and international clients and partners. The key features of the SPHY model are as follows:

- Robust scientific basis
- Combines strength of existing de facto hydrological models
- Modular setup in order to switch on/off irrelevant processes for computation efficiency
- Wide range of applicability in terms of regions, climates, modeling purposes, spatial and temporal scales
- Performs under data scarcity
- Linkable to remote sensing data
- Easy adjustment and application
- Graphical User Interfaces (GUIs) for QGIS
- Open source

The SPHY model has been applied and tested in various studies, ranging from real-time soil moisture predictions in flat lands to operational reservoir inflow forecasting applications in mountainous catchments, irrigation scenarios in the Nile Basin, and detailed climate change impact studies in the snow- and glacier-melt-dominated Himalayan region. Typical examples of SPHY applications are as follows:

- Climate change impact and adaptation
- Water and energy
- Operational services
- Irrigation management
- Snow- and glacier fed river basins

The SPHY model was initially created in Python and utilizes a configuration file that allows users to adjust inputs, outputs, and parameter settings. This coded design makes the SPHY model accessible only to individuals with programming expertise. To address this issue, a QGIS Graphical User Interface (GUI) was built to broaden its accessibility to a global audience. The SPHY model GUI simplifies the process of building a model, selecting inputs and outputs, executing the model, and examining results using only a button click in a user-friendly interface.

The purpose of this manual is to introduce and provide comprehensive information about the GUI developed for the SPHY model within QGIS, which is entirely free and publicly accessible. This manual includes instructions for installing the required software, a detailed overview of the SPHY model preprocessor, and the SPHY model itself. The model's source code is open-access and can be freely obtained from the SPHY model. The peer-reviewed open-access publications of the SPHY model are available at https://sphymodel.com/publications/ .

1.2 Reading guide

The document is structured to serve both as a reference and step-by-step practical manual.

- **Section 2** describes the installation process of the SPHY QGIS plugin and preprocessor, including the required software and how to activate the tools within the QGIS.

- **Section 3.1** introduces the top-level interface and how to manage SPHY model projects.

- **Section 3.2** guides users through the SPHY preprocessor, including area selection, module setup, basin delineation, station creation, and meteorological forcing generation.

- **Section 3.3** explains the SPHY model plugin in detail, covering the model configuration, input data selection, parameter settings, model execution, and visualization of results.

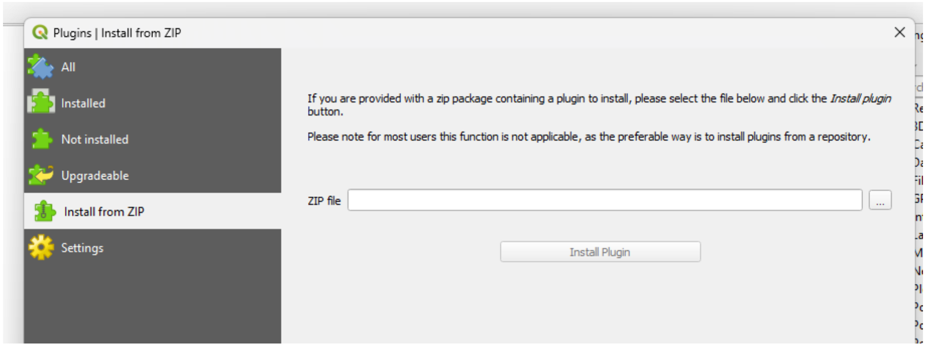
- **Section 4** provides the main references supporting the SPHY model and its development, while the appendices summarize required input/output variables and available regional datasets.

Readers can follow the sections sequentially when building a new SPHY model from scratch or consult individual subsections for support with specific tasks.

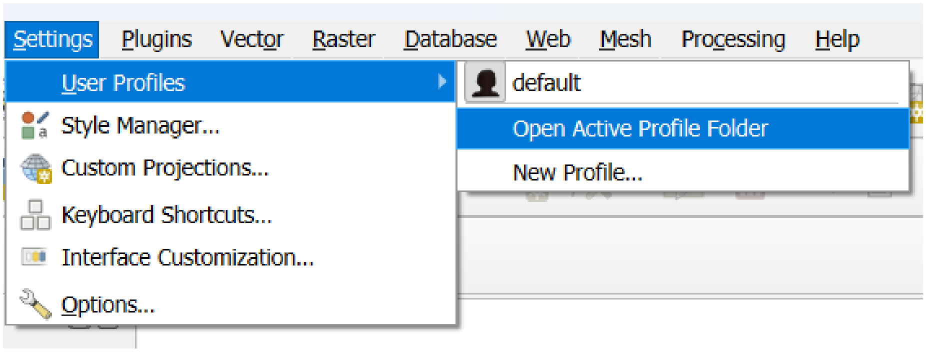
2 Installation of the SPHY v3.1 QGIS plugin

The code of the SPHY plugin is hosted in https://github.com/FutureWater/SphyPlugin
Installation process is the common one when you install any plugin in QGIS:

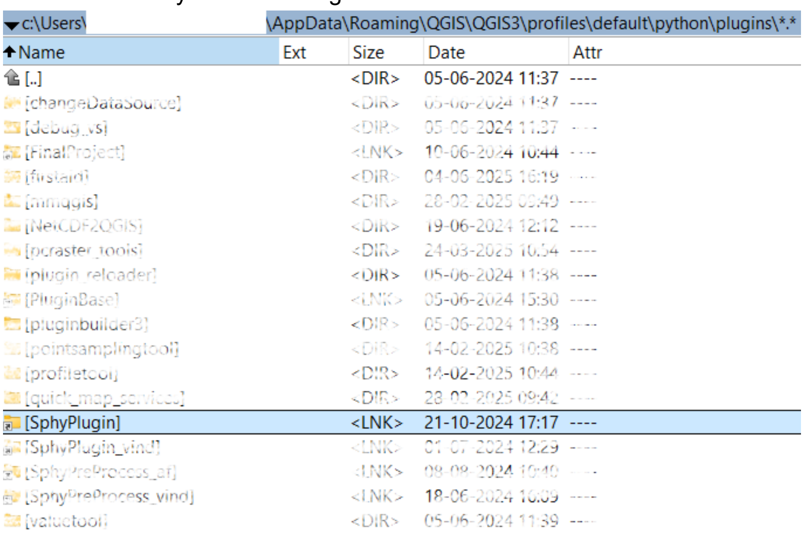
1. Download the code as zip from the repository – delete the “-main” suffix that is automatically added as default downloaded name.
2. Then go to the option Plugins → Manage and Install Plugins → Install from ZIP



3. Open the QGIS Active Profile folder by following these steps:

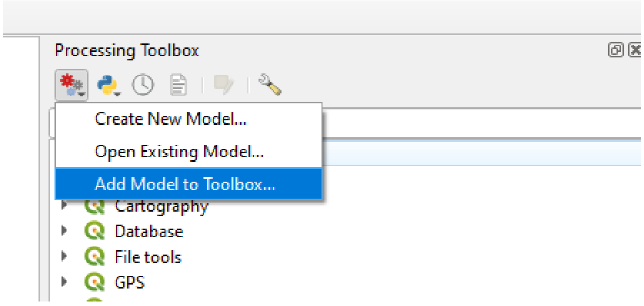


It will open a folder similar to C:\Users\XXX\AppData\Roaming\QGIS\QGIS3\profiles\default
Then navigate to python → plugins and make sure you get the name of the folder without the “-main” suffix. Sometimes when unzipping it keeps the original name even after changing it.
You should see your SPHYPlugin folder:

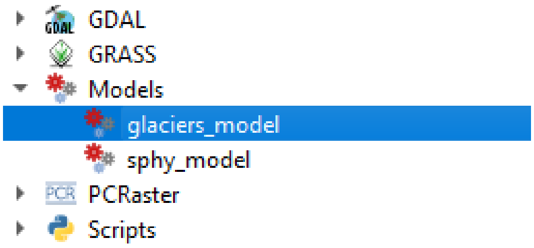


4. Make sure the glaciers model is already imported into the processing toolbox.

The glaciers model is a file called glaciers_model.model3 inside the SphyPlugin/aux_scripts folder. This file is the processing model that performs the chain of algorithms that are needed to compute glaciers csv table. This model has to be added to the QGIS Toolbox as follows:



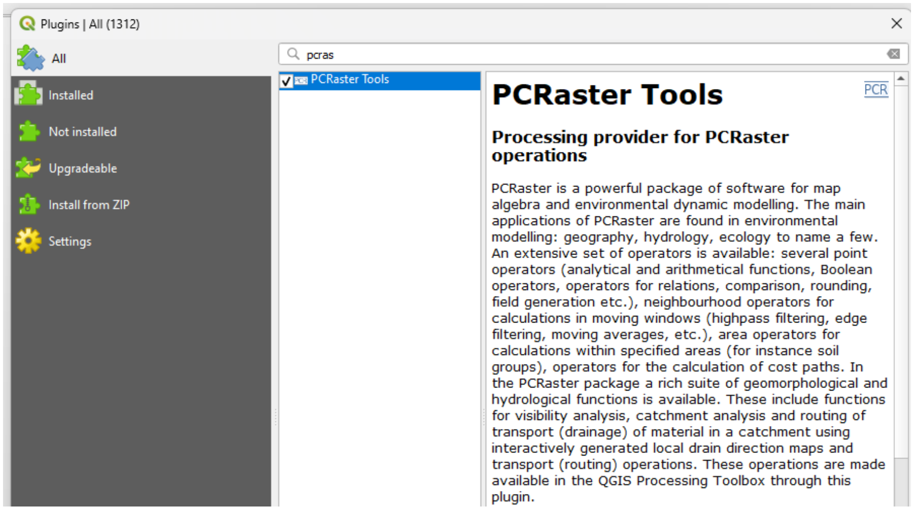
Once imported, it will appear on the toolbox:



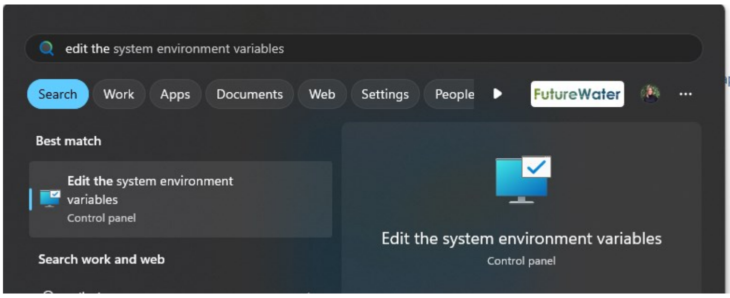
Once followed these steps, the plugin should appear in the toolbar:

This plugin has been developed using the latest QGIS LTR version that was available at the moment of the plugin development: **3.34.9**. The python version is **3.12.4**. It should work in later versions too.

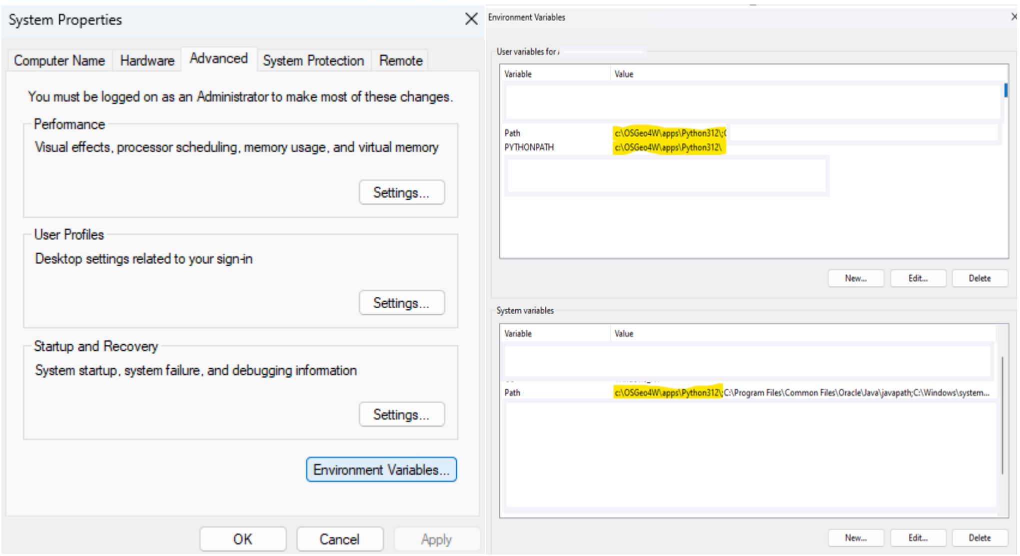
5. The PCRaster plugin must be installed separately. For that, we look for it in the Plugins management menu:



6. The last step is to modify the system properties and make the variables PATH and PYTHONPATH to point to the python interpreter of QGIS. If the QGIS was installed using OSGEO, this path is the following: c:\OSGeo4W\apps\Python312\
We have to look for the following setting:

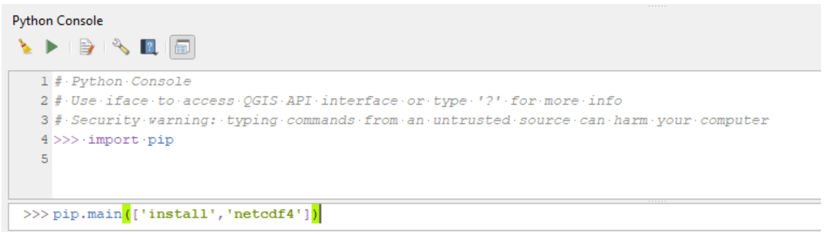


Then click on the Environment Variables and make sure to add this path is on the yellow locations:



7. If the error that a certain package is missing pops up, from the python console of QGIS:

- Import pip
- pip.main([‘install’,’package_name’]) this can happen with the netCDF4 library



3 SPHY v3.1 QGIS plugin

3.1 Top menu

To start the use of the plugin, launch the SPHY QGIS plugin by clicking the SPHY plugin button on the QGIS toolbar. If this is your first time using the interface, your registry settings will be empty, and no previous projects will be listed. The interface is shown in Figure 1, with three options available on the top menu and the following buttons:

- New Project
- Open Project
- Save As

The three buttons are explained in the following subsections.

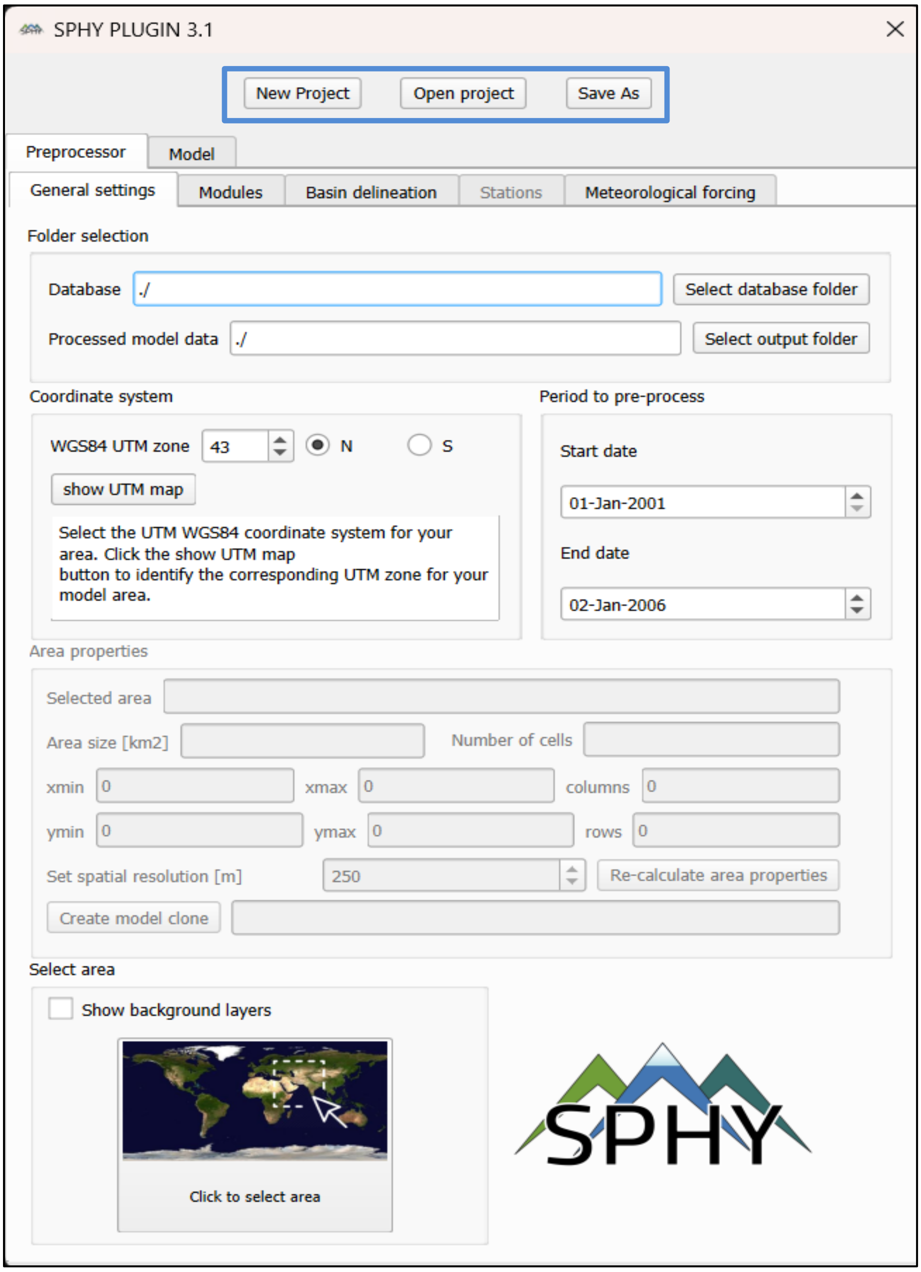


Figure 1. Overview of the SPHY model top menu (buttons in the blue box).

3.1.1 New project

A SPHY model project always involves a SPHY model configuration file (*.cfg)

This configuration file contains the SPHY model configuration, and is the same file used when running SPHY as a standalone application.

If the New project button is clicked, the user is asked where to save the new project and provides a filename (XXXX.cfg) for the project. You can choose any filename, except “sphy_config.cfg”. If a current SPHY model project is open in QGIS, it will be asked to save the current project first before creating a new project. It is mandatory to save a new project on the same disk where the SPHY model source code is installed. Otherwise, an error will occur.

After creating a new project, the map canvas will be emptied, and the GUI will look as shown in Figure 2. The user can fill in the different tabs.

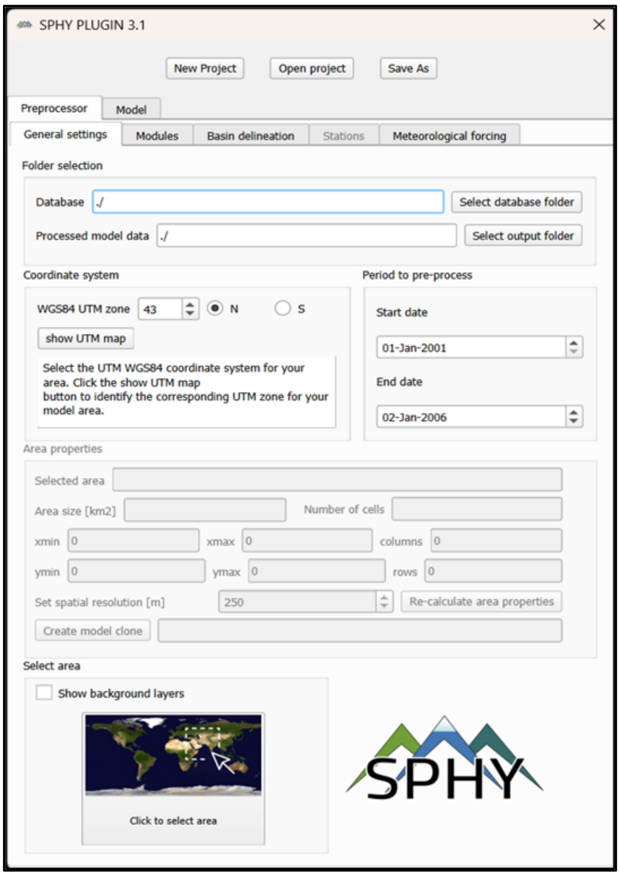


Figure 2. SPHY model interface after creating a new project.

3.1.2 Open project

Opening an existing project allows you to continue with a previous SPHY model interface project. By clicking the Open project button, you will be asked to select a *.cfg project file to be opened. If a current SPHY model project is open in QGIS, it will be asked to save the current project first before opening another project. Opening an existing project results in the QGIS canvas being cleared. All model settings present in the *.cfg file will be added to the SPHY model GUI. Your SPHY model interface can now look comparable to that in Figure 3.

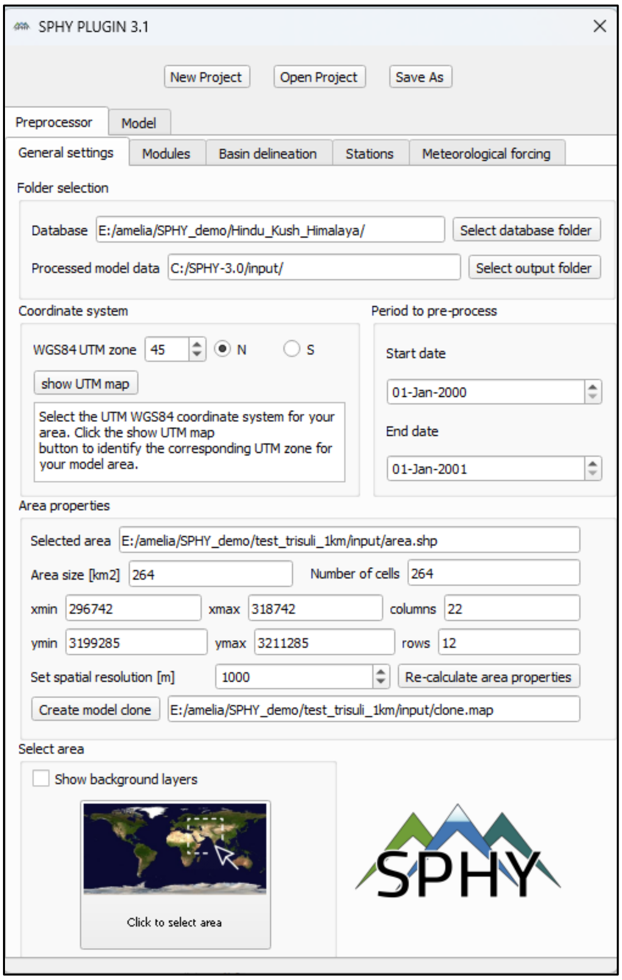


Figure 3. Example of SPHY model interface after opening an existing project.

3.1.3 Save As

The GUI allows you to save your SPHY model project. After clicking on the Save or Save As buttons, they become unavailable until something is changed (e.g., a parameter setting) in the GUI. This implies that these buttons are also indicators of recent changes in the interface. As soon as you change/modify something in the GUI, these buttons become available again. It should be noted that running the model automatically saves the SPHY model project before it is executed. This accounts for all GUI model settings to be saved in the *.cfg file and to run the model with these GUI settings.

The Save and Save As buttons save the GUI settings to the *.cfg file. The Save As button allows you to save the SPHY model project under another filename. This may be useful if one needs to study the effect of a parameter change without losing the previous model's run settings and output.

3.2 Preprocessor menu

3.2.1 Overview

The SPHY model preprocessor interface consists of a tab widget containing five tabs (Figure 4). The user must complete these tabs in the order in which they appear from left to right. The steps required for each tab are explained in the following subsections.

The current version of the SPHY model preprocessor GUI is only compatible with the Hindu Kush-Himalaya database (Appendix 2), more datasets will likely be added in the future. This means that this dataset can only be used to preprocess SPHY inputs for this region. It is possible for users to construct their own datasets.

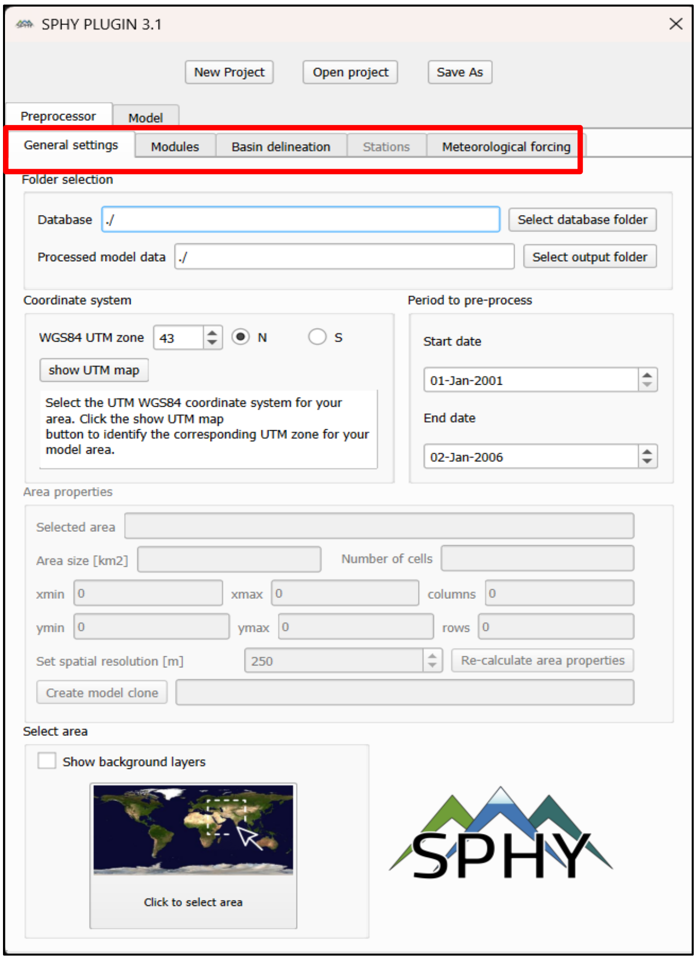


Figure 4. Overview of the SPHY model top menu (buttons in the blue box) and the preprocessor tab consisting of five menus (red box).

3.2.2 General settings

Folder selection

After starting a new project, the user must first select the folder in which the database can be found. This folder contains the **metadata.cfg** file of the corresponding database. Figure 5 shows the structure of the folder in the Hindu Kush-Himalaya database. Select this folder or the folder from another database by clicking the *Select database folder* button.

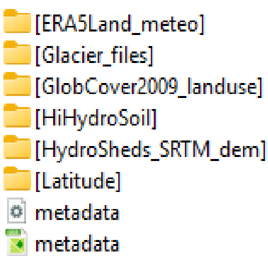


Figure 5. Example of the structure of the Hindu Kush-Himalaya database.

The database contains a set of folders with different input datasets such as land use, soil properties, surface elevation, glacier data, and meteorological forcing. The accompanying metadata file enables the SPHY plugin to read the data into QGIS to generate SPHY input layers. This file is not required to be modified by the user.

The second step involves creating a folder on the hard disk where the processed model input data is created. A logical folder name would be **\input**, and it should be created inside your SPHY model source folder, for example, **C:\SPHY3.1**. **Make sure that this path does not contain special characters or spaces**. As a first step, the SPHY code must be downloaded from Github and unzipped. Now, select the created folder by clicking the *Select output folder* button.

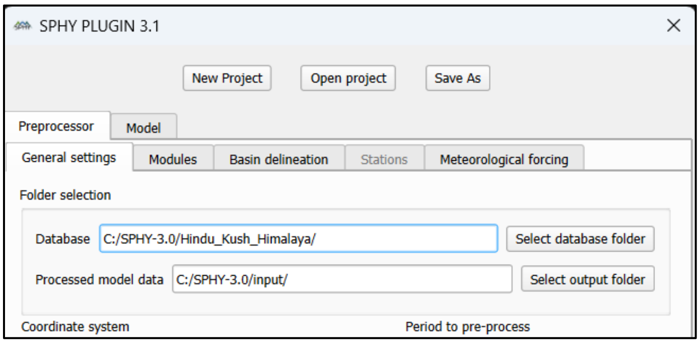


Figure 6. Completed folder selection part of the SPHY model preprocessor tab.

Coordinate system

The next step is to define the project Coordinate Reference System (CRS). Because the SPHY model was developed to work with a WGS84 UTM zone CRS, the UTM zone needs to be specified for the area of interest. If you do not know in which UTM zone your area of interest is located, click *the Show UTM map* button. This pops up an image containing the UTM zones. After defining the UTM zone for the area of interest, the spinbox can be used to set the value and the radio button to specify north (N) or south (S).

Period to pre-process

The start and end dates of the pre-processing period (later simulation period) must be specified for the GUI to create a meteorological forcing dataset. You must ensure that the selected period is covered by the database (Appendix 2). If you decide to use your own station data to create meteorological forcing data then you must ensure that the selected period is covered by the data specified in your *. CSV files.

3.2.3 Area selection

After completing the *General settings* you can go to the *Area selection* tab (Figure 7). This part of the GUI is most important because it defines the extent and spatial resolution of the area of interest. If no area has been previously selected, it is time to select the area of interest by dragging a rectangle. For better orientation, it is possible to show the standard background layer by checking the *Show background layers* checkbox (Figure 8). This background layer contains the Countries and Shaded Relief layers from OpenTopoMap. You can instead add your own background dataset if desired.

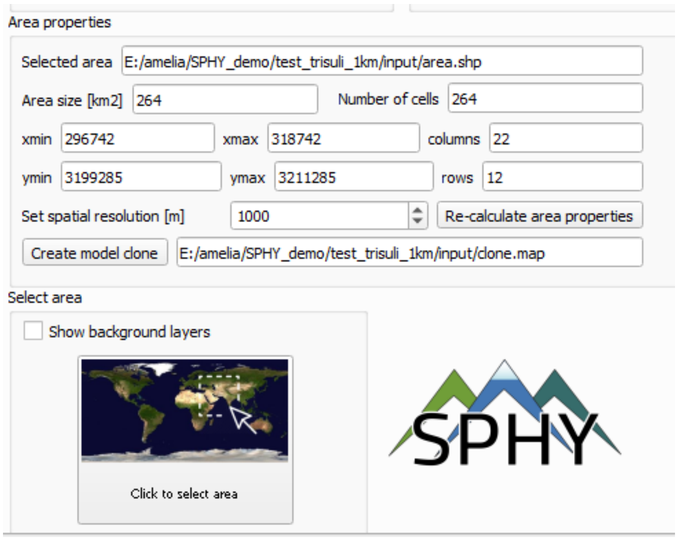


Figure 7. Overview of the Area selection tab

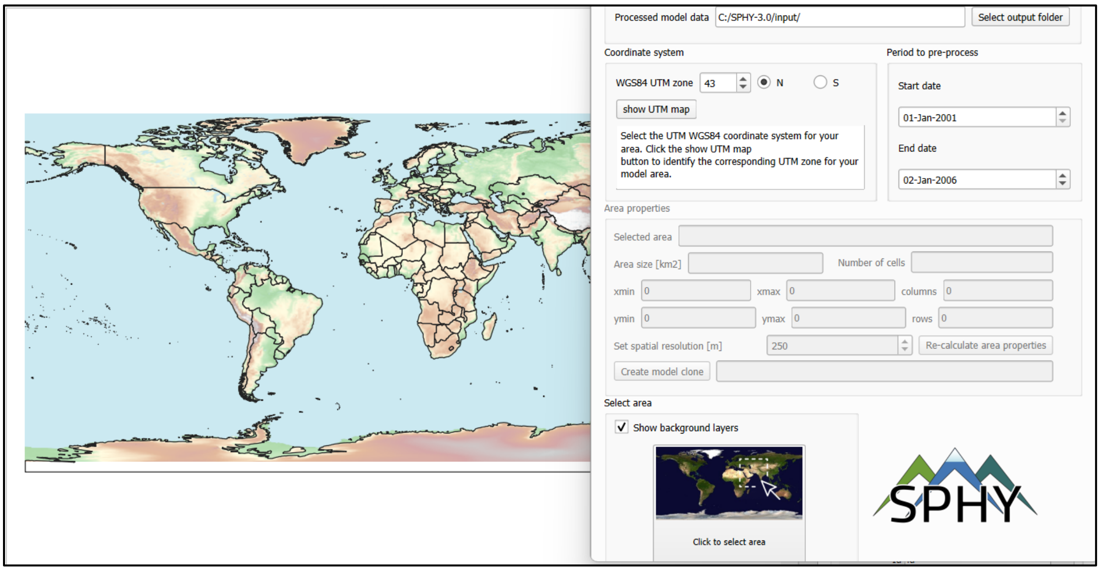


Figure 8. Standard background layer.

Select your area of interest by clicking on the *Click to select area* button. This temporarily hides the GUI, allowing the user to drag the rectangle. After dragging a rectangle for the area of interest, a red rectangle is shown, and the GUI is shown again with the *area properties* filled in (Figure 9). If the selected area is too large in combination with the model resolution, a warning that hints at choosing a coarser spatial resolution will appear.

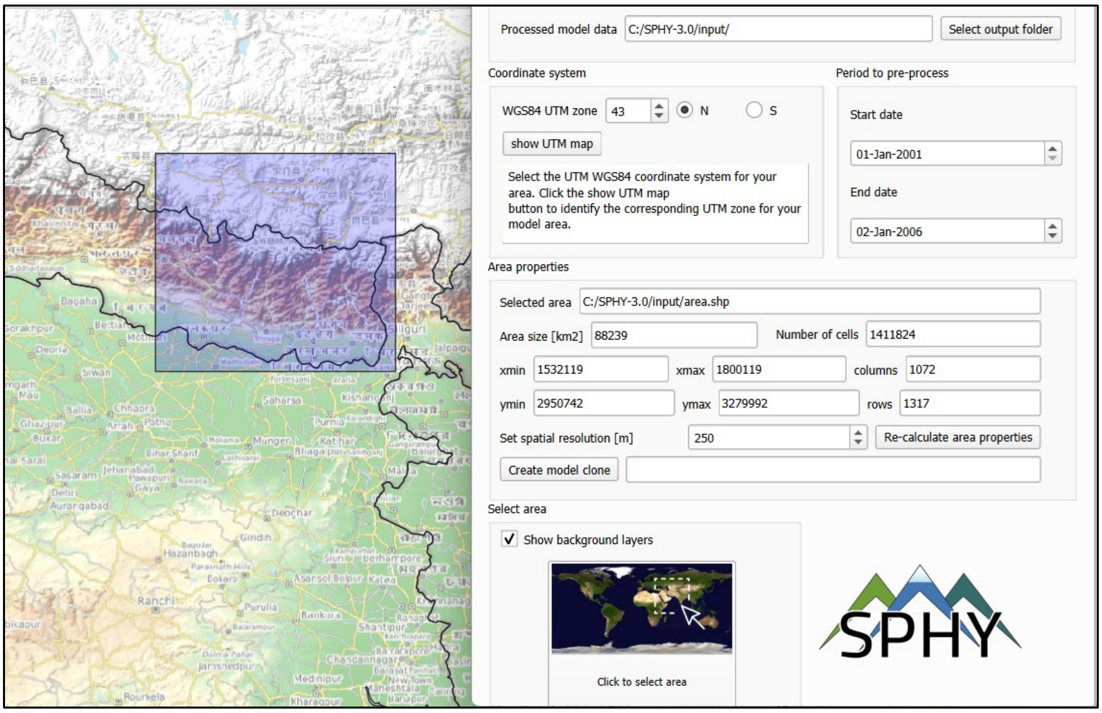


Figure 9. Selecting your area of interest.

You can change the model resolution under *Set spatial resolution [m]*. Each time you change the value in this box you need to click the *Re-calculate area properties* button. If you are happy with the selected area and its properties, finish this step by clicking the *Create model clone* button. After finalizing this step, your GUI may look like that in Figure 10.

You can always return to this tab of the GUI later if you are unsatisfied with the result and want to re-select or fine-tune your area of interest.

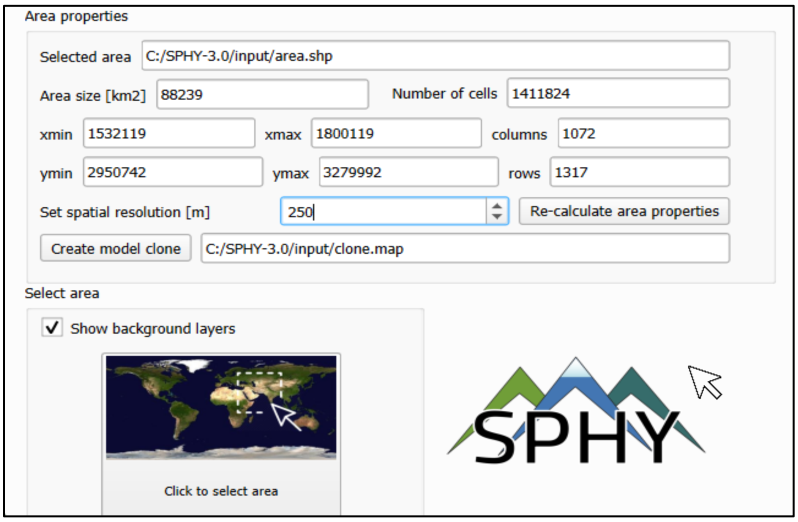


Figure 10. Finalizing the Area selection tab.

3.2.4 Modules

The next tab in the GUI is the *Modules* tab. In this tab you need to select the SPHY model modules for which you want to create input data. The input maps that are created are shown in the *Maps to process* log window. If no modules are selected, the 12 standard SPHY maps, as shown in Figure 11, are created by default. After selecting one or more modules more maps that need to be processed are shown in log window (Figure 12)

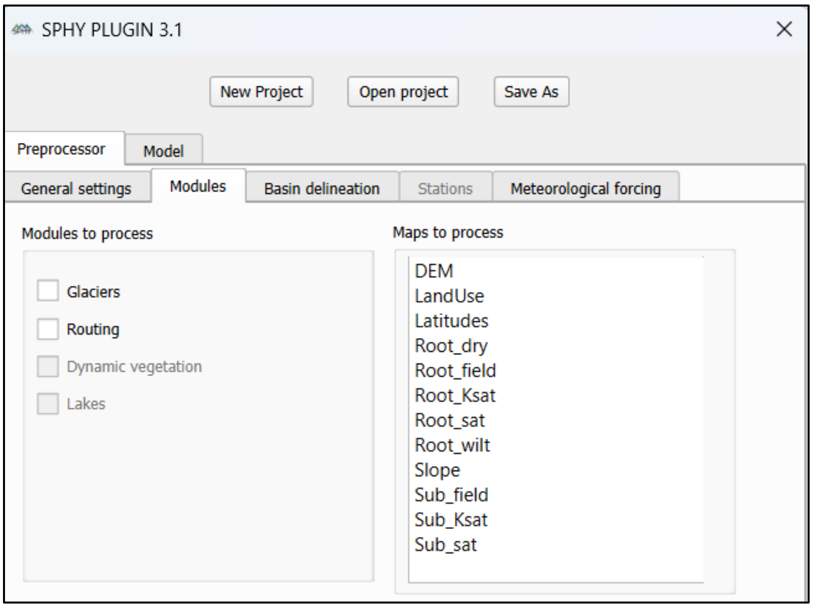


Figure 11. Overview of the Modules tab.

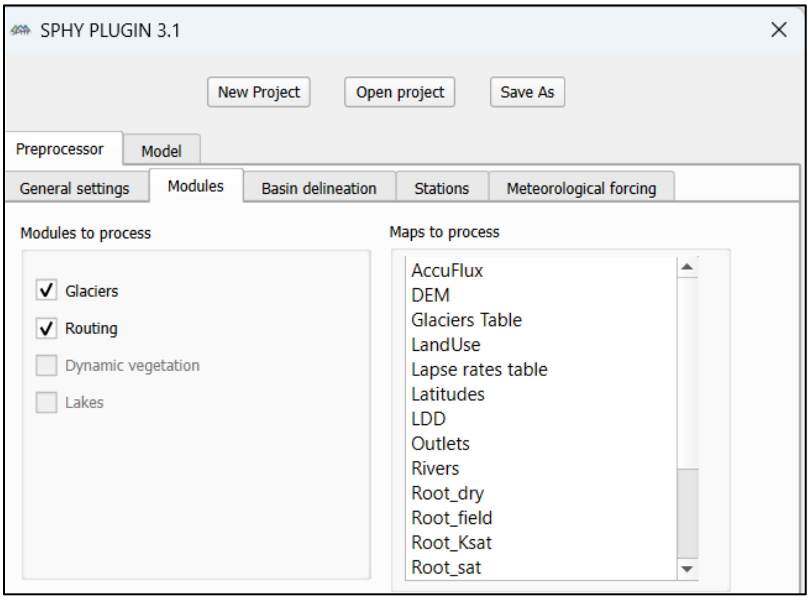


Figure 12. Selecting multiple modules to process and create input maps for other modules.

If you finish selecting the required modules, click the *Create initial maps* button to begin processing these maps. This may take some time, depending on the extent, spatial resolution, and number of modules selected. During processing of the input maps, the *Process log* window of the *Modules* tab looks like Figure 13. After each map is processed it will automatically be added to the QGIS canvas. After processing has been completed the message *"Processing is finished"* will appear. The colors/layout of each layer can be changed by clicking the right mouse button on the layer and then pressing on *Properties*.

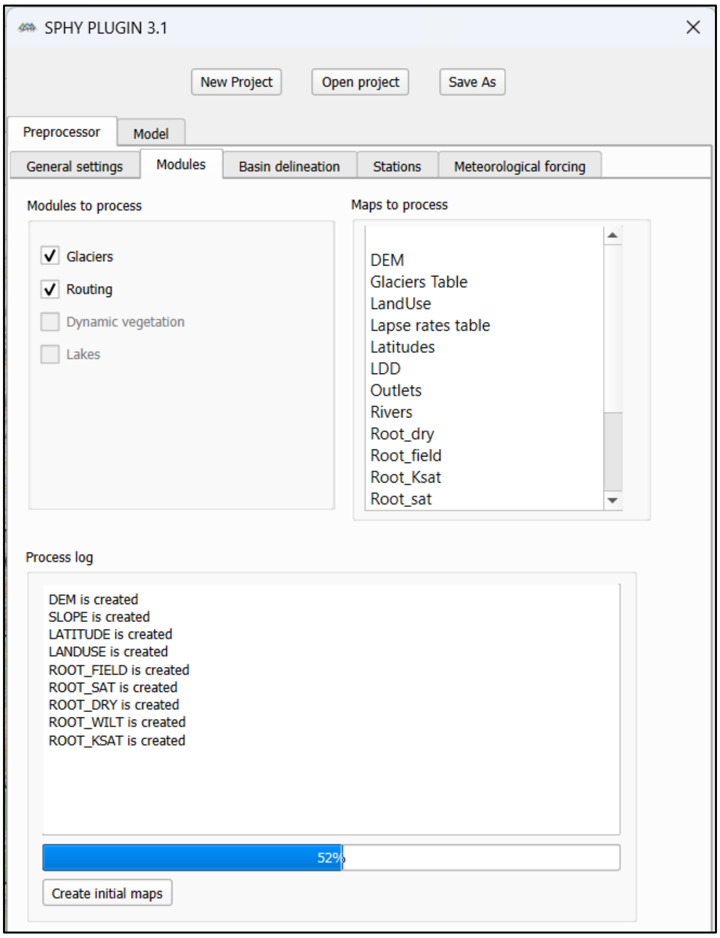


Figure 13. Processing the initial maps in the Modules tab.

If you are satisfied with the processed maps, continue to the next tab. This next tab is *Basin delineation* (Section 3.2.5) if you have selected the *Routing* module. If this module has not been selected, then the *Basin delineation* tab is inactive, and you can continue to the *Stations* (Section 3.2.6) tab. If you do not need the SPHY model to report time-series output, then you also can skip the *Stations* tab and move on to the *Meteorological forcing* tab (Section 3.2.7).

3.2.5 Basin delineation

The next step involves delineating your river basin. Note that this step is only required if the routing module has been selected from the *Modules* tab. An overview of the *Basin delineation* tab is shown in Figure 14. Before you can delineate your basin, you need to have an **outlets.shp** shapefile representing the outlet(s) of your basin(s). If you do not have this file, you can create it using QGIS, following the steps below:

1. Create a new shapefile layer by clicking the *New Shapefile Layer* button (Figure 15).
2. Make sure you select *Point* as *Type* in the window that pops-up (Figure 16) and that you select the correct CRS (see Section 3.2.3).
3. Click *Ok*.
4. Give it the name **outlets.shp** and save it. It is recommended to save this file under the *Processed model data* folder (**/input**) you have set in Section 3.2.1. After saving this layer it will appear on the QGIS map canvas (Figure 17).
5. Now start editing this layer by clicking the *Toggle Editing* button (Figure 18). Make sure that the *outlets* layer is selected before clicking this button.
6. Now start adding the outlets by clicking the *Add Feature* button (Figure 19).

7. Make sure you can accurately determine the location of the river network. This can be achieved by examining the *accuflux* layer and choosing an appropriate color layout. Now start adding one or more outlets to this layer by clicking on the desired locations of your river network (Figure 20). Each time you click on a location, you need to enter a different value. Start with 1 and continue numbering until the number of outlets you desire.
8. Figure 21 shows an example of having 3 outlets added to the **outlets.shp** layer. The attribute table can be shown by right-clicking on this layer and then *Open Attribute Table*.
9. If you are finished with adding outlets you can click again on the *Toggle Editing* button (Figure 18). Next, click *Save* to save your edits to the **outlets.shp** layer. Now you are finished with creating an outlet(s) layer shapefile.

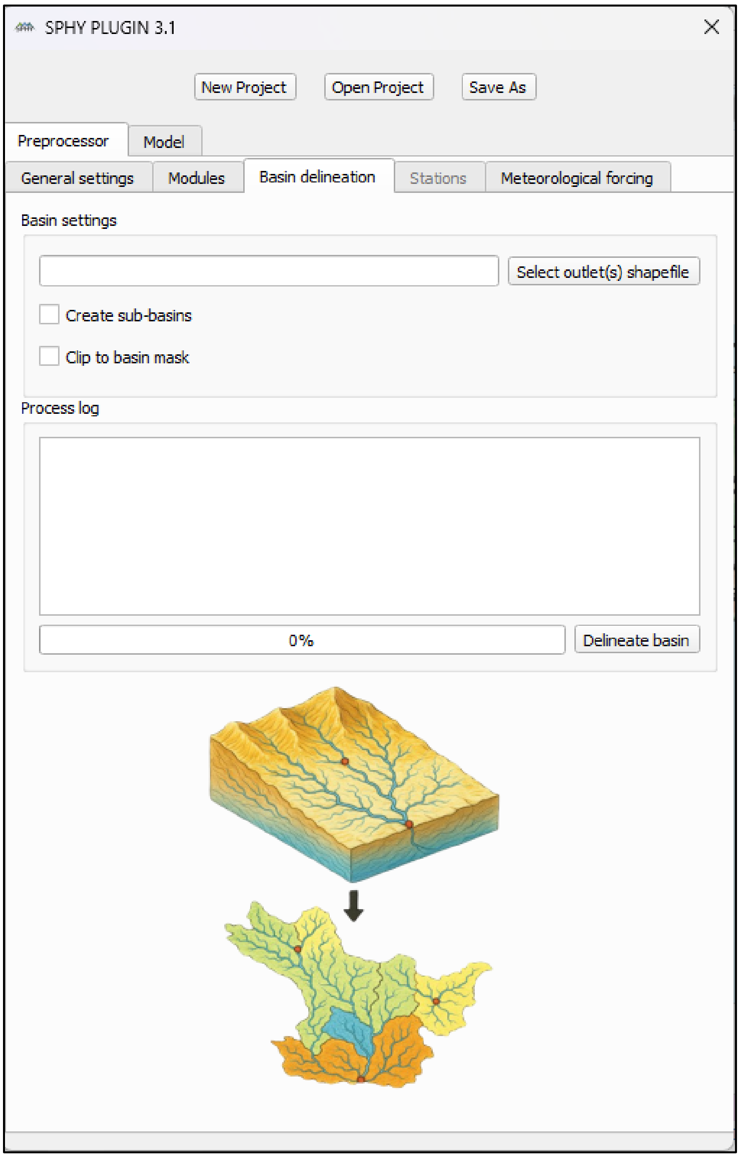


Figure 14. Overview of the Basin delineation tab.

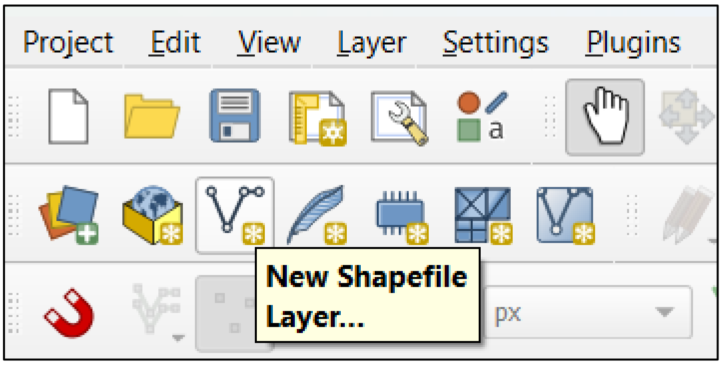


Figure 15. Creating a new shapefile layer.

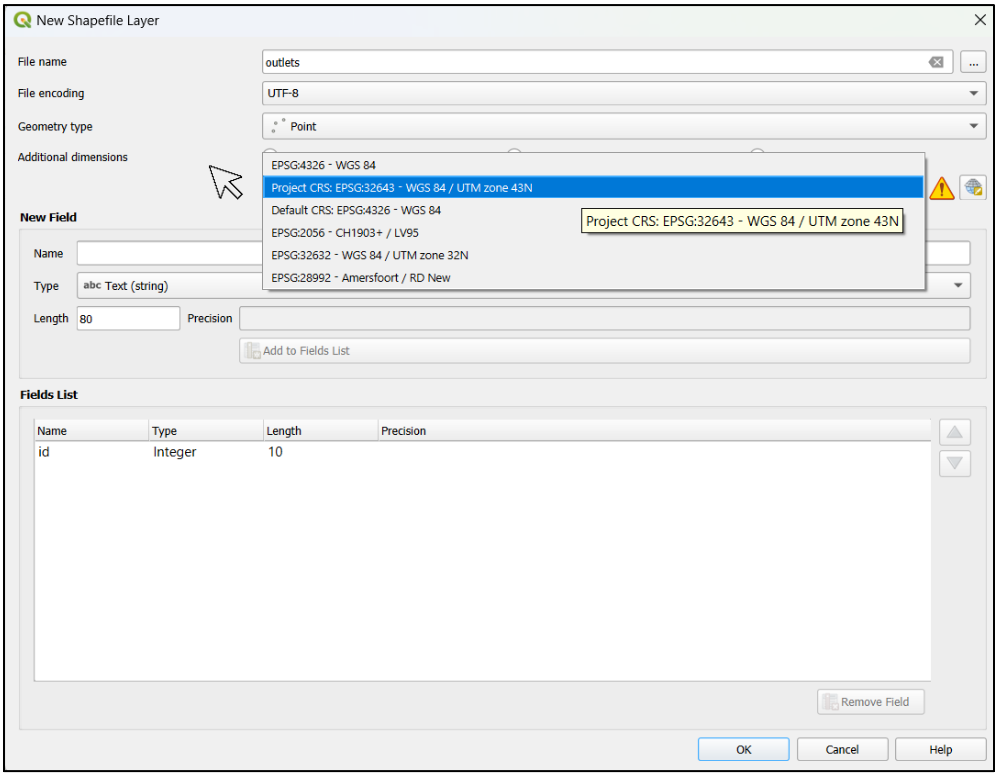


Figure 16. Setting the properties of the new Shapefile.

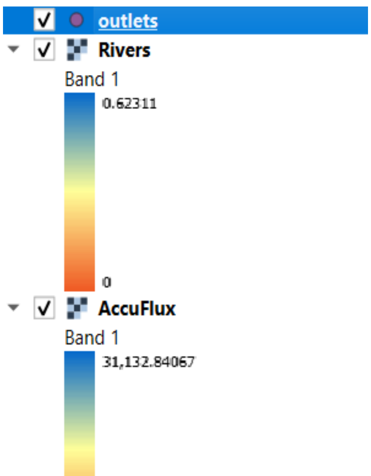


Figure 17. outlets.shp in the layers overview.

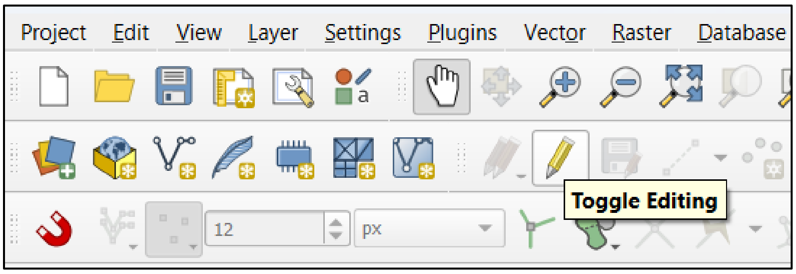


Figure 18. Editing a layer in QGIS.

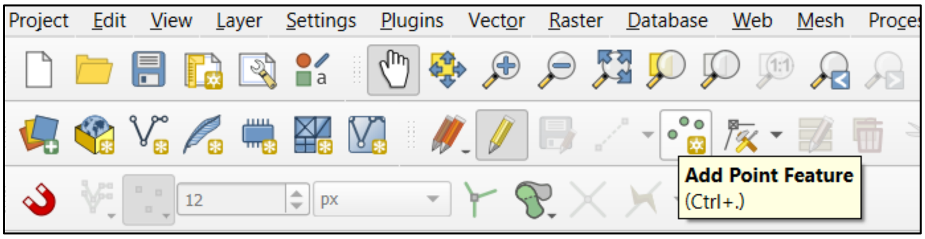


Figure 19. Adding features in QGIS.

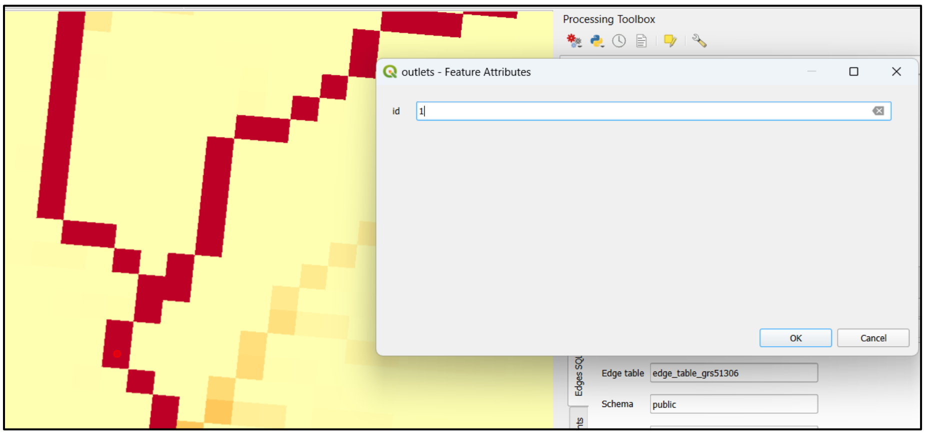


Figure 20. Adding outlets to the outlets.shp layer in QGIS.

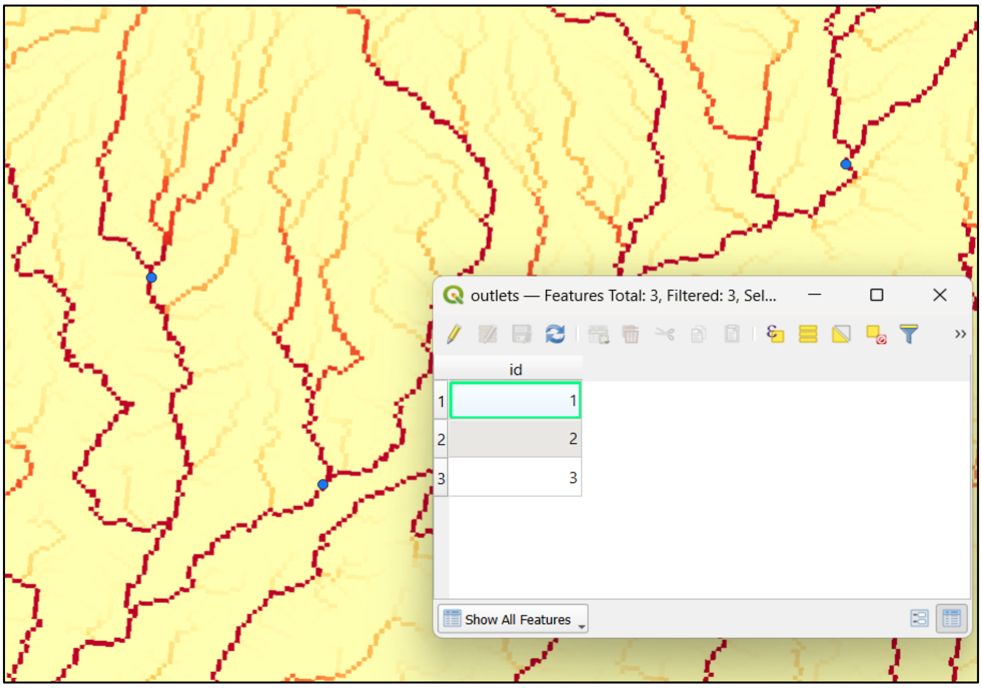


Figure 21. Example of 3 outlets that have been added to the outlets.shp layer.

Two additional options are now available for delineating the basin (Figure 22):

- Clip to basin mask: all SPHY model input maps will be clipped to the extent of your delineated basin. This results in smaller input map sizes and reduced model runtime.
- Create sub-basins: sub-basins are created for outlets located inside the basin outline of the most downstream outlet.

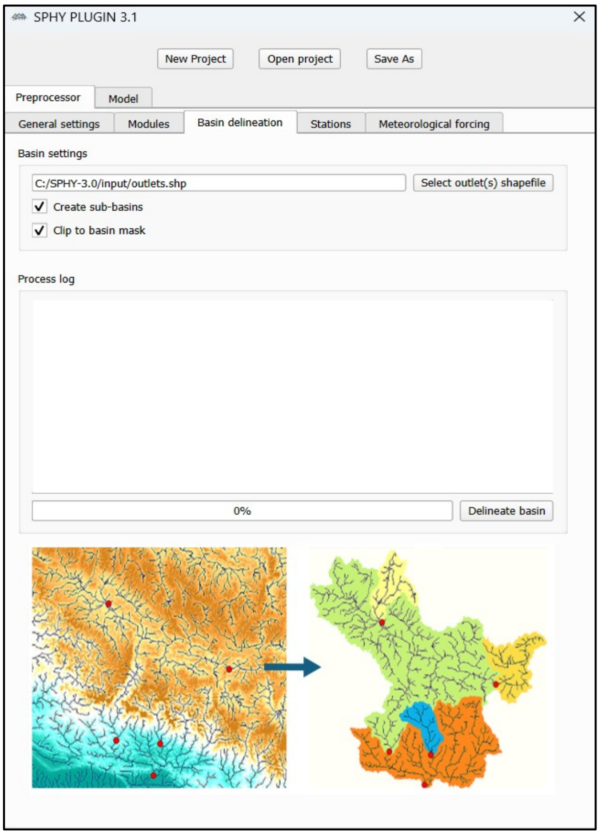


Figure 22. Overview of the Basin delineation tab with the outlet(s) shapefile selected.

Select or de-select these options and click *Delineate basin* to start the basin delineation. Basin delineation may take some time, and during delineation, several maps will be removed and added to the QGIS map canvas.

Note that the *Delineate basin* button has become inactive if you have selected the *Clip to basin mask* option. This means that you can only redo basin delineation after returning to the *Modules* tab and click the *Create initial maps* button again. Alternatively, you may start over with the *Area selection* tab if you are not happy with the results of the delineated basin(s).

3.2.6 Stations

An overview of the *Stations* tab is shown in Figure 23. This tab creates a **stations.map** file used by the SPHY model to report the time-series outputs. In order to create this file, you need to have a **stations.shp** shapefile, and place it in your **/input** folder. If you do not have this file, then you need to create it by following the same steps as done for the **outlets.shp** file (Section 3.2.5) but now naming it **stations.shp** instead of **outlets.shp**. For the stations it is not mandatory to place them on the river network if you are interested in other fluxes besides river flow.

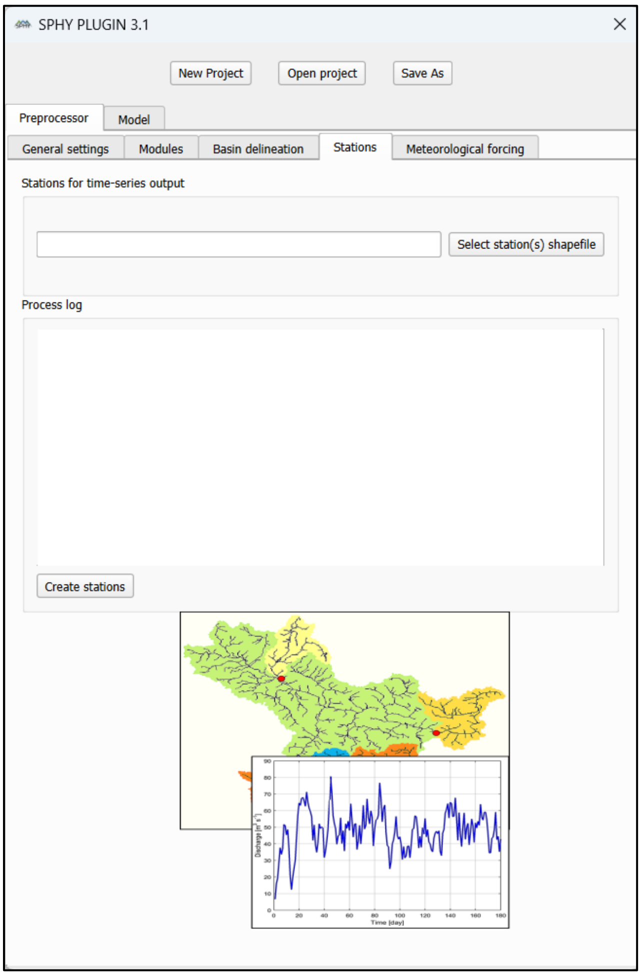


Figure 23. Overview of the Stations tab.

After creating the **stations.shp** shapefile, click the *Select station(s) shapefile* button and select the **stations.shp** shapefile. Finally press the *Create stations* button to create the **stations.map** file. This process typically runs quickly. As a result, a *stations.map* will appear in your /input folder. Now move on to the *Meteorological forcing* tab.

3.2.7 Meteorological forcing

Within this tab (Figure 24) you need to specify which meteorological forcing variables you want to create for the SPHY model:

- Precipitation
- Temperature (average, maximum, and minimum)

If you have created your own forcing data manually, you can skip this section. If not, start by selecting the variable(s) that you need to process (precipitation and/or temperature). After this step you need to tell the GUI where to find the data for your forcing variable. This can either be database based, or based on user-defined station data. For more information regarding the source of the database forcing data, refer to Appendix 2. Both precipitation and temperature data are interpolated using bilinear[7] interpolation.

The example in Figure 25 shows that both precipitation and temperature forcing will be created using the GUI, whereas precipitation data will be based on the database and temperature data will be based on user-defined station data. If you select to use station data, then you need to select a station location CSV-file and a station data CSV-file. It is important that the number of stations in the location file match the number of stations in the data file. The required CSV file format is shown in Figure 26 to Figure 28. Ensure that the selected forcing period to process is covered by the database and/or user-defined station data. Finally, click the *Create forcing* button to start creating the forcing data. This may take a while depending on the length of the period to process, and the extent and spatial resolution of your selected area. During processing, the GUI may appear similar to that shown in Figure 29. After this step has been completed, all SPHY model input data are processed.

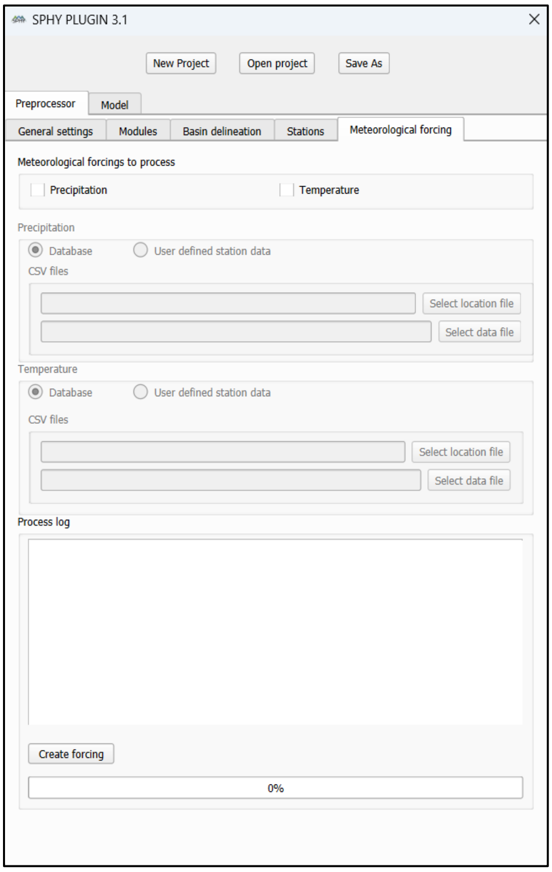


Figure 24. Overview of the Meteorological forcing tab.

[7] https://en.wikipedia.org/wiki/Bilinear_interpolation

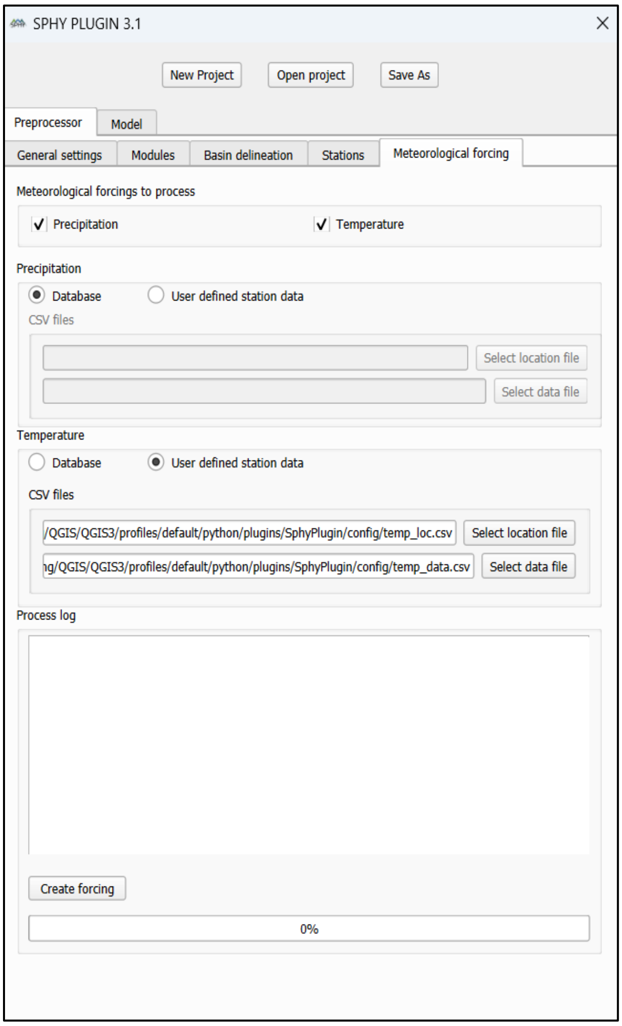


Figure 25. Setting the options in the Meteorological forcing tab, using precipitation data from the database and temperature data from user-defined stations.

	A	B	C	D	E
1	ID	Name	Lat	Lon	Elevation
2	1	sdf	30.05	82.84	4455
3	2	sdc	28.16	84.91	4200
4	3	sdf	29.08	84.42	2000
5	4	sdc	28.76	82.81	5000
6	5	sdf	29.2	83.7	3000

Figure 26. Format of location CSV-file, containing 5 stations. Elevation units are in MASL. Coordinates need to be provided in latitude (lat) and longitude (lon). Names can be dummy values.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	DATE	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
2	01/01/2001	3.705587	8.238709	0.083706	1.491564	4.100707	5.705587	10.23871	2.083706	3.491564	6.100707	2.705587	7.238709	-0.91629	0.491564	3.100707
3	02/01/2001	6.226049	9.936424	9.843851	5.403994	9.781127	8.226049	11.93642	11.84385	7.403994	11.78113	5.226049	8.936424	8.843851	4.403994	8.781127
4	03/01/2001	7.443758	2.375468	0.037047	3.484891	9.984137	9.443758	4.375468	2.037047	5.484891	11.98414	6.443758	1.375468	-0.96295	2.484891	8.984137
5	04/01/2001	5.354188	1.177539	4.462445	3.151409	9.384312	7.354188	3.177539	6.462445	5.151409	11.38431	4.354188	0.177539	3.462445	2.151409	8.384312
6	05/01/2001	5.286025	2.827377	7.729253	2.454813	3.210216	7.286025	4.827377	9.729253	4.454813	5.210216	4.286025	1.827377	6.729253	1.454813	2.210216
7	06/01/2001	6.601565	6.876879	7.381467	7.911656	9.889859	8.601565	8.876879	9.381467	9.911656	11.88986	5.601565	5.876879	6.381467	6.911656	8.889859
8	07/01/2001	6.210354	3.882653	1.280547	5.159928	1.423997	8.210354	5.882653	3.280547	7.159928	3.423997	5.210354	2.882653	0.280547	4.159928	0.423997
9	08/01/2001	2.758112	7.243028	9.836882	0.265866	4.557234	4.758112	9.243028	11.83688	2.265866	6.557234	1.758112	6.243028	8.836882	-0.73413	3.557234

Figure 27. Format of precipitation data CSV-file, containing data for 5 stations. Precipitation units are in mm.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	DATE	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	
2	1-1-2001	3.705587	8.238709	0.083706	1.491564	4.100707	5.705587	10.23871	2.083706	3.491564	6.100707	2.705587	7.238709	-0.91629	0.491564	3.100707	
3	2-1-2001	6.226049	9.936424	9.843851	5.403994	9.781127	8.226049	11.93642	11.84385	7.403994	11.78113	5.226049	8.936424	8.843851	4.403994	8.781127	
4	3-1-2001	7.443758	2.375468	0.037047	3.484891	9.984137	9.443758	4.375468	2.037047	5.484891	11.98414	6.443758	1.375468	-0.96295	2.484891	8.984137	
5	4-1-2001	5.354188	1.177539	4.462445	3.151409	9.384312	7.354188	3.177539	6.462445	5.151409	11.38431	4.354188	0.177539	3.462445	2.151409	8.384312	
6	5-1-2001	5.286025	2.827377	7.729253	2.454813	3.210216	7.286025	4.827377	9.729253	4.454813	5.210216	4.286025	1.827377	6.729253	1.454813	2.210216	

Figure 28. Format of temperature data CSV-file, containing data for 5 stations. The order is from left to right: average, maximum, minimum temperature. Units of temperature are degrees Celsius.

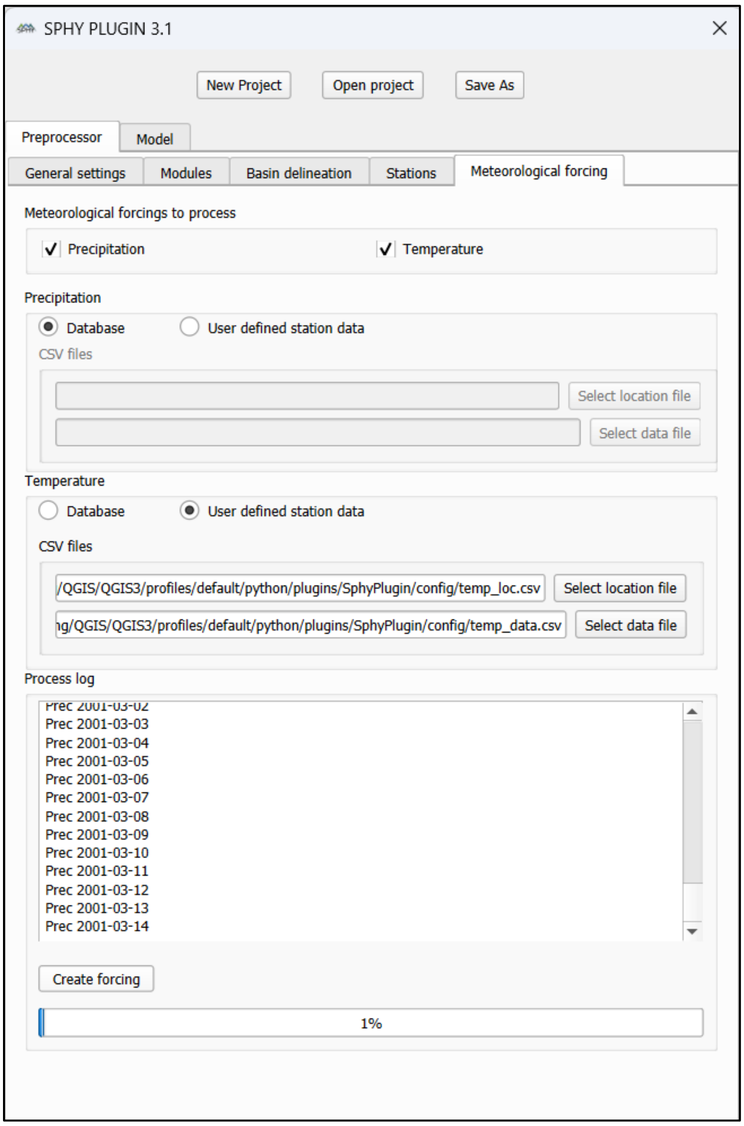


Figure 29. Processing of meteorological forcing data.

3.3 Model menu

3.3.1 Overview

The SPHY model menu consists of 11 tabs (Figure 30). When working on a SPHY model project, the user must go through the individual tabs and complete the required information, which can be related to model input maps, parameter values, reporting options, running the model, and visualizing results. The user must complete these tabs in the order in which they appear from left to right. The last steps are running the model and thereafter visualizing the model results. The use of each tab is described in the following subsections. For a detailed description of the parameters and theory, refer to the SPHY manual. Appendix 1 provides a detailed overview of the model inputs and outputs. **Please note that not all configuration parameters of the plugin are editable from the QGIS interface**, as it is a simplified version of the model configuration. Advanced users might want to modify the configuration file itself, outside the QGIS interface.

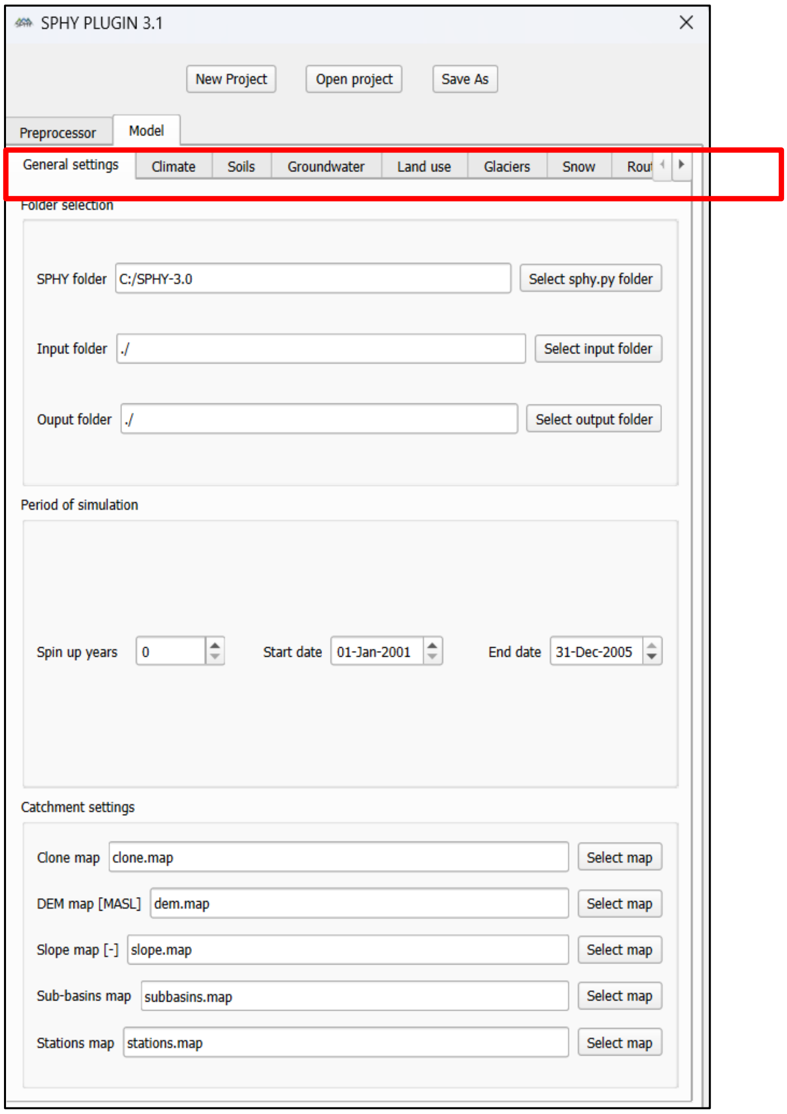


Figure 30. Overview of the SPHY model plugin consisting of 11 tabs (red box).

<u>Interaction with the map canvas</u>

During the model setup in the GUI, the QGIS map canvas is extended with an increasing number of layers that are added by setting model input maps and evaluating model output maps. The user can modify the layer legends to their own preferences because this does not influence the model results. You are also free to add or remove additional layers from the QGIS map canvas.

<u>Map canvas layout</u>

The map canvas is built using several layer groups. At the beginning of each new project the map canvas is empty. The layer groups are built after model map layers have been selected and added to the canvas. The layer group layout is shown below:

- Input
    - General
    - Climate
    - Soils
    - Land-use
    - Glaciers
    - Snow
    - Routing
- Output
    - Annual
    - Monthly
    - Daily

An example of this layer group (with layers) layout is shown in Figure 31.

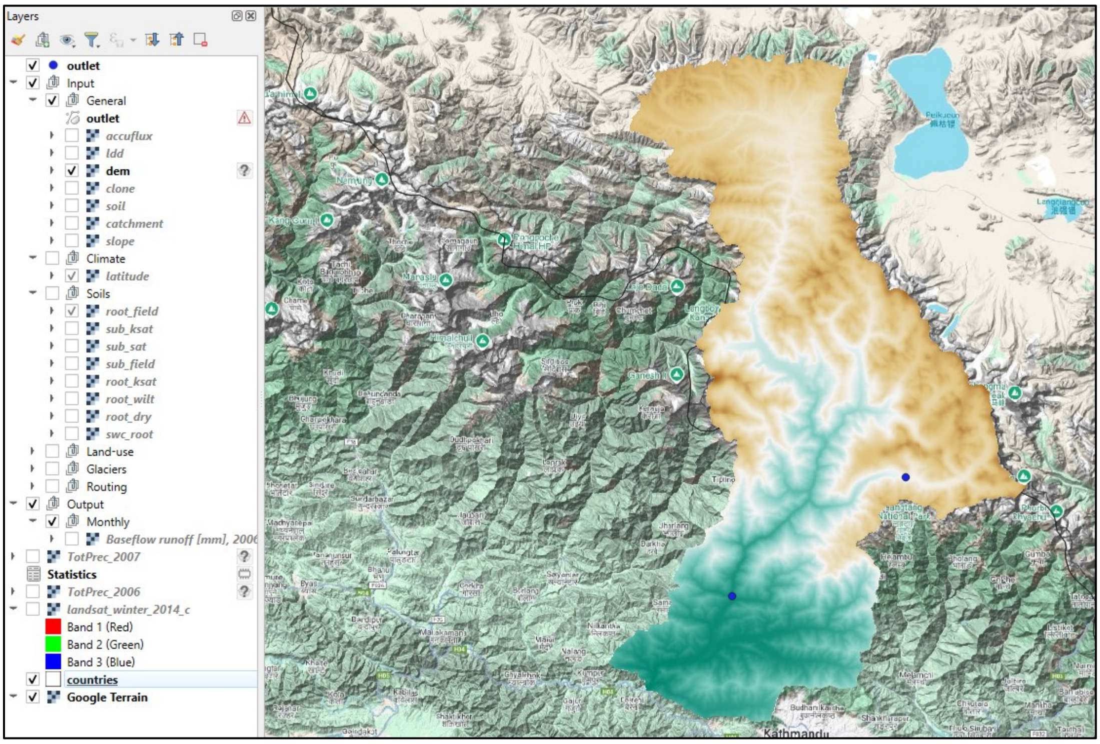


Figure 31. Example of map canvas groups and layers layout.

3.3.2 General settings

Folder selection

Figure 32 shows an overview of the General settings tab. As soon as you start a new project and run the preprocessor steps, the folder selection settings should be completed first. If this is not set correctly, errors will appear. First, the GUI must know the path of the SPHY model's source code (where the sphy.py script is located). By clicking on the *Select sphy.py folder* button, you are asked to select the folder in which the sphy.py file can be found. If you select a folder in which no sphy.py file can be found, then you will receive a notification as is shown in Figure 33.

The next step is to set your SPHY model input and output folders. The input and output folders must be on the same disk as the SPHY model source code because these folders are used as relative paths in the model. All the model input data (maps, tables, etc.) that are used to set up the model in the GUI should be located inside the input folder.

The output folder is the location where all model outputs are saved during the execution of the model. Ideally, you create this folder within your SPHY folder, in the same directory as the **/input** folder. You can just call it **/output**. The model output data in this folder are parsed to the Visualize results tab, which allows the selection of a certain output to be added to the map canvas.

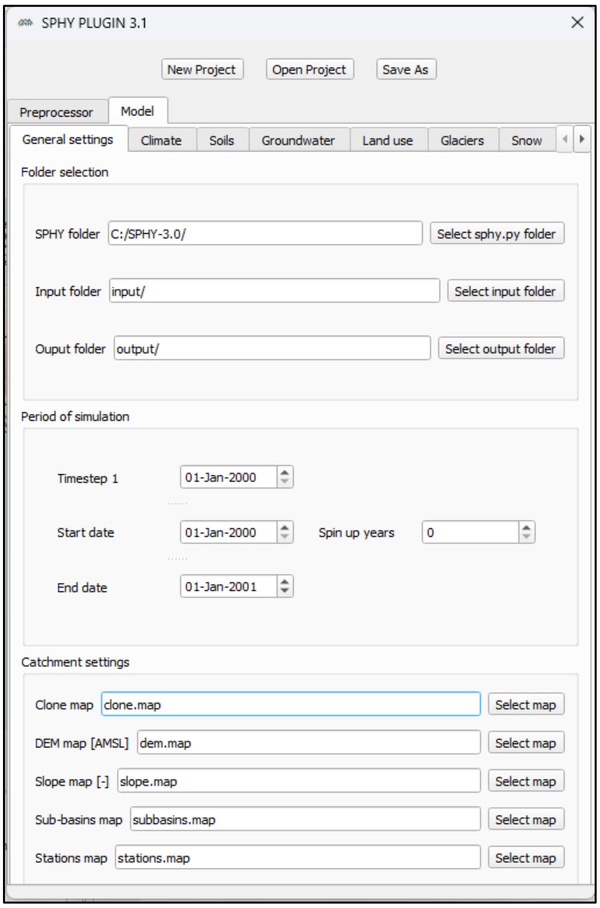


Figure 32. Overview of the General settings tab.

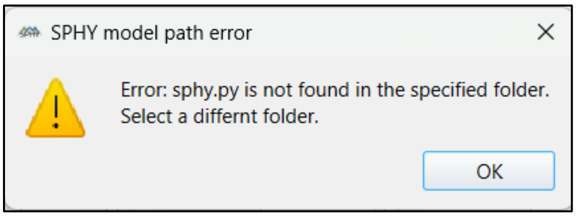


Figure 33. Error message indicating that no sphy.py can be found in the selected folder.

Period of simulation

The simulation period can be customized by setting the desired start and end dates for the model run. It should be noted that Timestep 1 always corresponds to the first climate forcing file (*.001). Start date must be larger than Timestep 1. Setting the end date is an interesting option if the user only wants to model or study, for example, the first year out of a period of 20 years of data. This may be used to check if all the model inputs are correctly set before executing the entire period of 20 years, which can take a long time.

Catchment settings

To define the geographical characteristics of the basin(s) of interest, the user must select five spatial maps that define the basin of interest. Table 1 provides an overview of these maps. Each of these five maps can be selected and added to the map canvas by clicking on the Select Map button. After clicking this button, refer to the input folder that has been set under Section 3.2.1. Within this folder, you are asked to select the map of interest and click on Open to add the map to the GUI and QGIS map canvas. This is illustrated in Figure 34 for DEM map (dem.map).

Table 1. Catchment settings maps.

Map name	Description
Clone map	Boolean mask of catchment. Defines the basin for cells being True.
DEM map [MASL]	Digital Elevation Model. Defines for each cell the elevation in Meters Above Sea Level [MASL].
Slope map [-]	Defines for each cell the slope [-], based on the DEM.
Sub-basins map	Map with cells belonging to the same sub-basin having the same unique ID. Used for calculation of sub-basin fluxes in mm.
Stations map	Nominal map with unique IDs for cells identified as being a location where time-series output is required. Non-station cells have zero value.

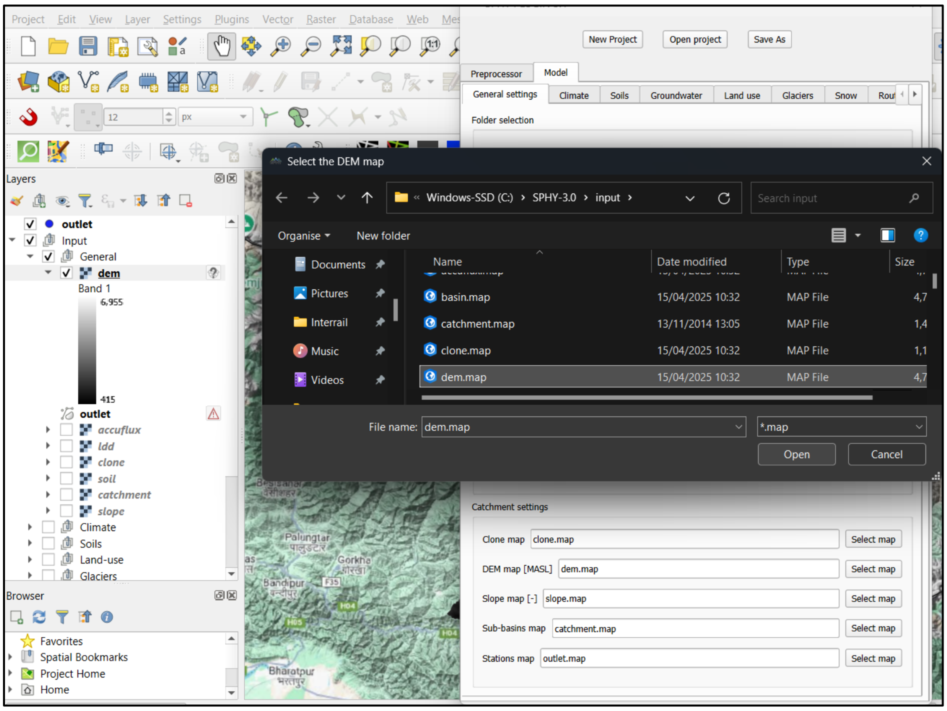


Figure 34. Selecting a DEM map in the catchment settings.

After these five maps have been set, the user can continue with the next tap, Climate.

3.3.3 Climate

<u>Meteorological forcing map-series</u>

Figure 35 provides an overview of the Climate tab. In this tab, the user has to specify the model forcing input map series containing precipitation and the average, maximum, and minimum daily temperatures.

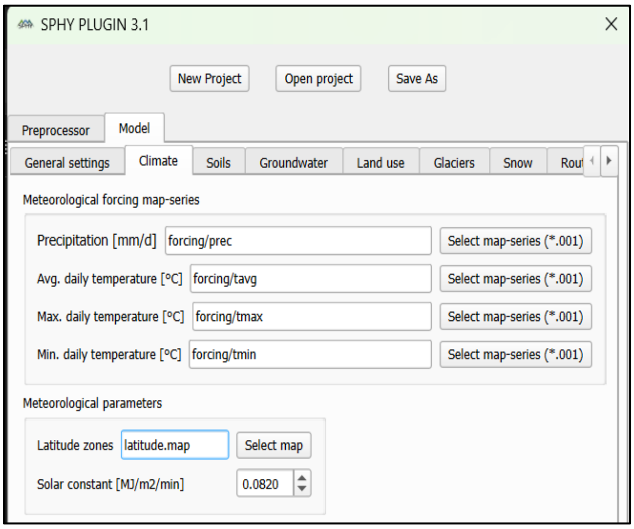


Figure 35. Overview of the Climate tab.

A map series in SPHY consists of a spatial map for each time-step in the model. This means that if your model has 365 daily time-steps, then you also need 365 maps of climate forcing for each of the four forcing variables.

A map series in PCRaster always starts with a *.001 extension, corresponding to the start date of the model simulation period. Each individual forcing file should have eight characters before the dot and three characters after the dot. If your model has 3542 time-steps, then your first precipitation forcing file can look like

prec0000.001

and your last precipitation forcing file:

prec0003.542

After clicking the Select map-series (*.001) button for each of the four climate variables, the user will be asked to select the first map of the meteorological forcing map-series. An example is shown in Figure 48. It can be seen that the meteorological forcing is inside another folder ("forcing") within the Input folder. This can be performed without any issues as long as the folder is created inside the input folder, meaning that the input folder will always be the *parent* folder of all model input data. Figure 36 shows that the "forcing" folder is added before the variable name.

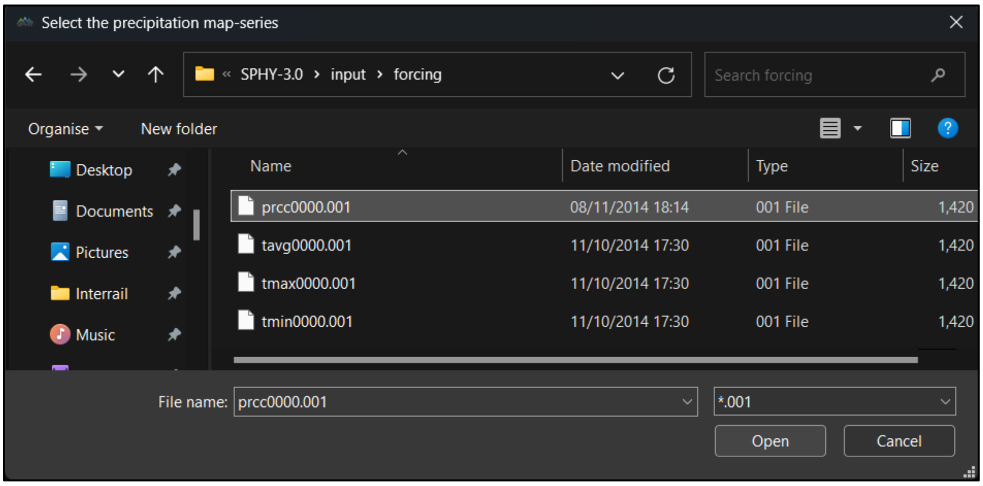


Figure 36. Selection of the precipitation map series.

<u>Meteorological parameters</u>

The second part of the Climate tab involves setting the parameters for calculating terrestrial radiation, which is eventually used in the Hargreaves method to calculate the reference evapotranspiration. To calculate terrestrial radiation, the user needs to select a map with latitude zones. This map can be selected by clicking on the *Select Map* button. After selecting the latitude zones map, this map will be added as a layer to the map canvas.

Additionally, the user must provide a single floating number for the solar constant. The default value of 0.0820 MJ m^{-2} min^{-1} is generally applicable for most areas worldwide but may be changed if needed.

After completion of the Climate tab, the user can continue with the Soils tab.

3.3.4 Soils

<u>Rootzone physical maps</u>

An overview of the Soils tab is shown in Figure 37. The rootzone physical maps refer to the physical soil properties of the first soil layer, where the subzone physical maps refer to the physical properties of the second soil layer. The settings in this tab significantly affect soil water processes in the root- and subzone, such as e.g. lateral flow, surface runoff, percolation, and evapotranspiration. Details of these processes can be found in Terink et al. (2015a). The user needs to select the following five rootzone physical maps:

- Field capacity [mm/mm]
- Saturated content [mm/mm]
- Permanent wilting point [mm/mm]
- Wilting point [mm/mm]
- Saturated hydraulic conductivity [mm/d]

These maps can be selected and added to the map canvas by clicking on the Select map buttons. It is important to check that the cell values should increase from the permanent wilting point to the wilting point to field capacity, with saturated content having the highest cell values.

Figure 38 shows an example of a field capacity map for the rootzone, showing more details in the upstream part than the downstream part.

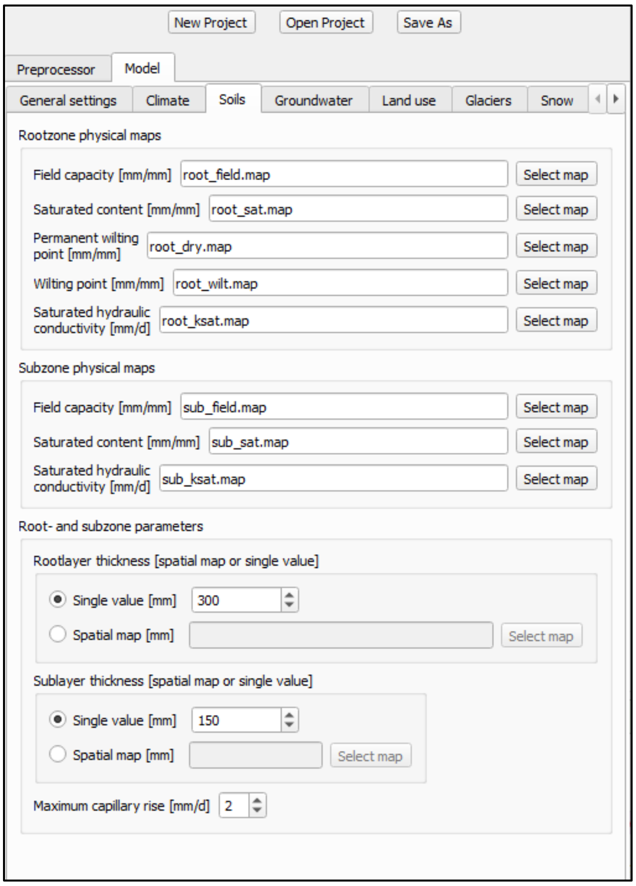


Figure 37. Overview of the Soils tab.

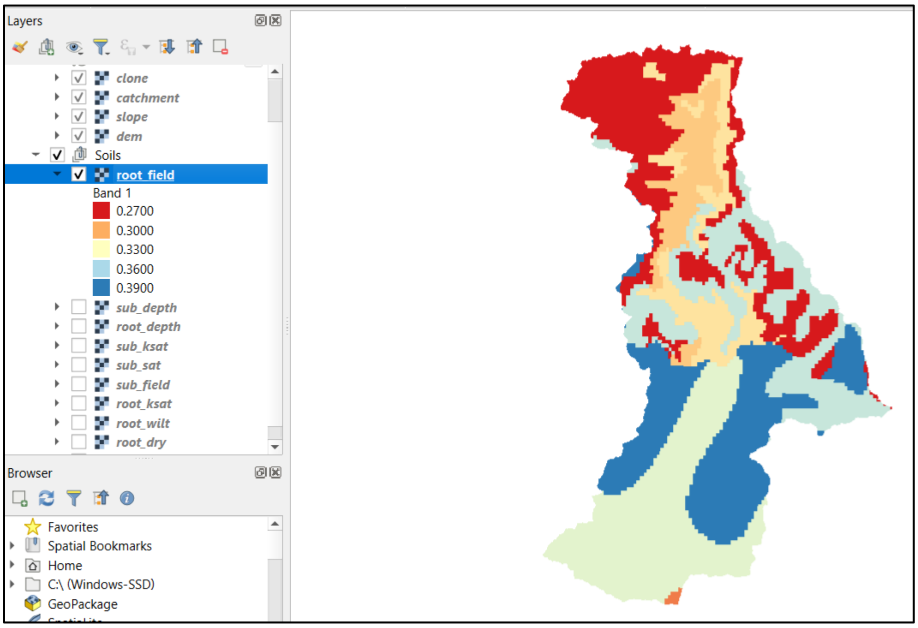


Figure 38. Example of rootzone field capacity map.

<u>Subzone physical maps</u>

For the subzone physical maps, the user has to select the following three maps:

- Field capacity [mm/mm]
- Saturated content [mm/mm]
- Saturated hydraulic conductivity [mm/d]

These maps can be selected and added to the map canvas by clicking the Select map buttons. For the subzone physical maps, it is important to check that the cell values of the saturated content map are higher than those of the field capacity map.

<u>Root- and subzone parameters</u>

The last section of the Soils tab involves setting the soil layer thickness for both the root- (left part) and subzone (right part). The user can opt to provide a homogeneous rootzone and/or subzone soil depth for the entire basin or provide a spatial map with a spatially distributed soil depth over the entire basin. We selected a spatially distributed soil depth map for both the root and subzones. These maps can be selected and added to the canvas by clicking the Select map button.

If you prefer to have a homogeneous soil depth for the entire basin, then a default value of 500 mm for the rootzone, and 1500 mm for the subzone are good values to start with.

The final setting in the Soils tab involves setting a value for the maximum capillary rise. This value affects the maximum amount of water that can travel from the subzone to the rootzone on a daily basis due to evapotranspiration demand.

After completing all the settings in the Soils tab, the user can continue with the next tab: Groundwater.

3.3.5 Groundwater

Groundwater volume settings

The settings in the groundwater tab substantially affect groundwater recharge and baseflow. An overview of the groundwater tab is shown in Figure 39. The upper part contains the volume settings, and the below part involves setting three parameters.

In the groundwater volume settings, the user can opt to provide a single value or a spatial map for each setting. If a single value is chosen, this value is considered homogeneous for the entire catchment. Using a spatial map can be useful for spatially differentiating between different groundwater volume settings in the basin.

The following three groundwater volume settings have to be provided:

- Groundwater layer thickness [mm]
- Saturated groundwater content [mm]
- Initial groundwater storage [mm]

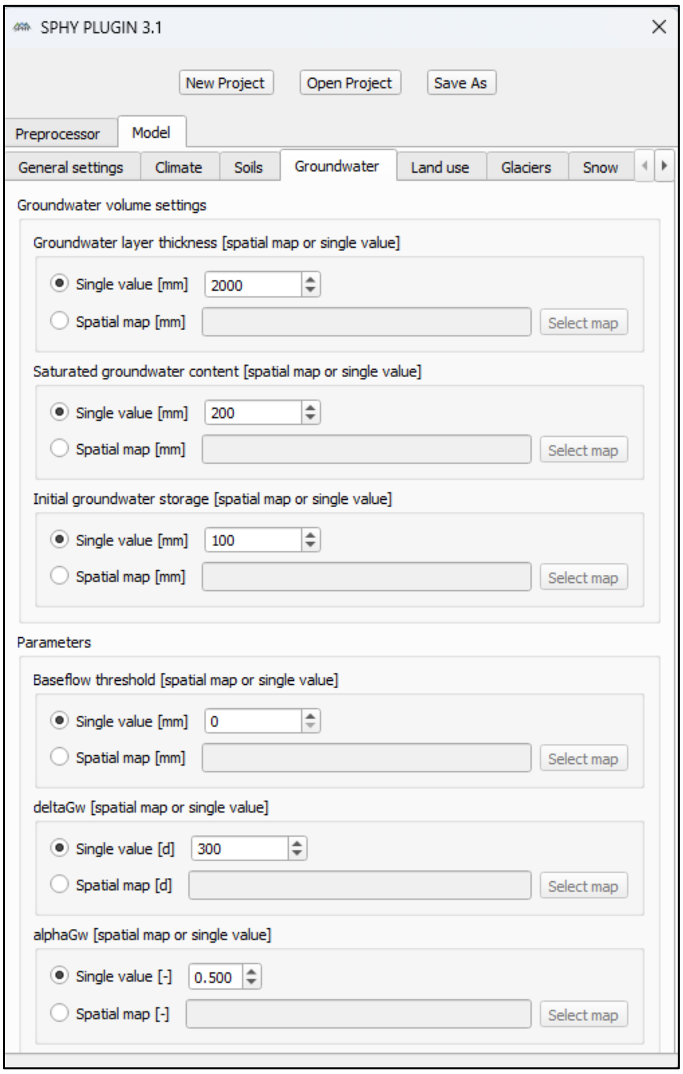


Figure 39. Overview of the Groundwater tab.

Spatial maps can be selected and added to the GUI by clicking the Select map button. The groundwater layer thickness should be greater than or equal to the saturated groundwater content, and the initial groundwater storage should be equal to or less than the saturated groundwater content.

It should be noted that if a small or zero initial groundwater storage is chosen, it may take a long time for baseflow to occur. Therefore, substantial initial groundwater storage is recommended to achieve an early baseflow.

Groundwater parameters

The parameter settings mainly affect the groundwater recharge and baseflow release from the third soil layer (groundwater layer). The parameters that need to be set are:

- Baseflow threshold [mm]
- deltaGw [d]
- alphaGw [-]

The user can choose a single value or spatial map for each of the three parameters. If a single value is chosen, this value is considered homogeneous for the entire catchment. Otherwise, a spatially distributed map can be chosen.

If, during the model simulation, the actual groundwater content is below the baseflow threshold parameter, then no baseflow occurs. The default value for the baseflow threshold is set to zero, meaning that baseflow always occurs. The user may choose to have baseflow only if the actual groundwater content is above a certain threshold. To achieve this, it is necessary to set a value or a single map for the baseflow threshold parameter. A baseflow threshold value lower than the saturated groundwater content is required.

deltaGw affects the duration of the percolated water from the second to the third layer to reach the groundwater store, and alphaGw affects the baseflow recession curve. The default value for deltaGw is 1 day, and for alphaGW 0.5. deltaGw can have values from 1 to many days, and alphaGw can range between 0 and 1. More details regarding the groundwater processes can be found in Terink et al. (2015a).

After completing all settings in the Groundwater tab the user can continue with the next tab: Land use.

3.3.6 Land use

Figure 40 provides an overview of the Land use tab. Settings in the Land use tab affect the calculation of the potential evapotranspiration. In this tab, the user must select a land use map and a lookup table containing crop coefficients for each land use class.

The land use map is a nominal map with land use classes than can be selected and added to the map canvas by clicking the Select map button. An example of a land use map that has been selected and added to the canvas is shown in Figure 41.

A table with a crop coefficient for each land use class defined in the land use map can be added to the GUI by clicking the Select table button. After clicking this button you will be asked to select a *.tbl file inside the Input folder. Figure 42 shows an example of the format of a crop coefficients lookup table that corresponds with the land use map of Figure 41.

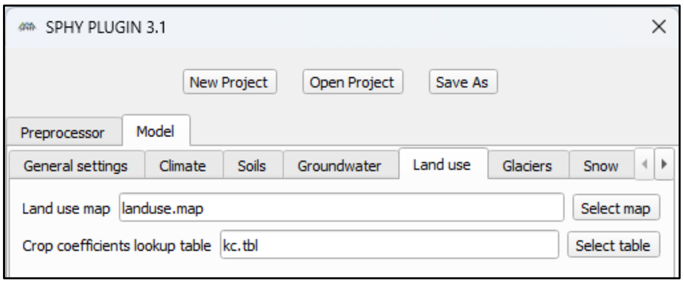


Figure 40. Overview of the Land use tab.

After completion of the settings in the Land use tab the user can continue with the next tab: Glaciers.

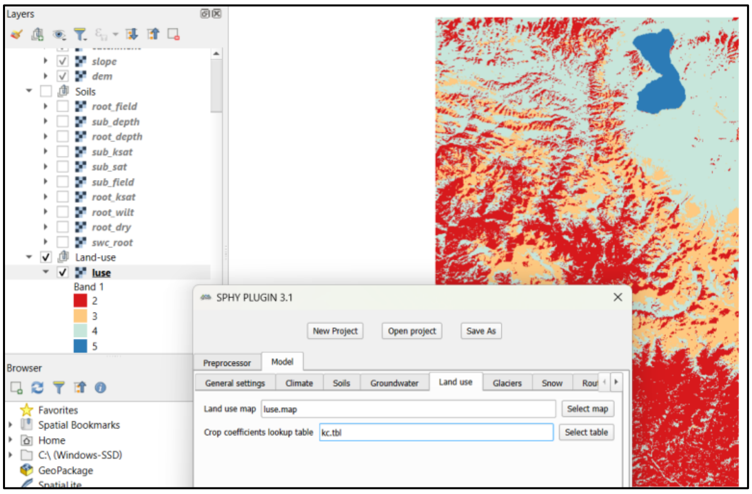


Figure 41. Example of a land use map with four land use classes.

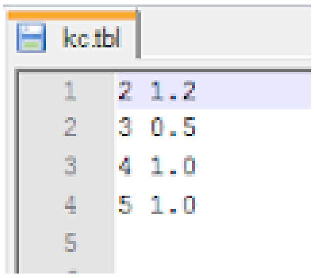


Figure 42. Example of crop coefficients lookup table in Notepad++.

3.3.7 Glaciers

An overview of the settings in the Glaciers tab is shown in Figure 43. A distinction has been made between glacier settings and the setting of glacier degree-day-factor.

<u>Glacier settings</u>

In glacier settings, the user must select a glacier CSV file and three spatial maps:

- Glaciers.CSV
- Model ID [-]
- Glacier ID [-]
- Glacier fraction [-] (can also be a single value)

These inputs can be selected and added to the canvas by clicking the Select table and select map buttons. The glaciers.csv file contains the columns GLAC_ID, MOD_ID, MOD_H, U_ID, GLAC_H, ICE_DEPTH, DEBRIS and FRAC_GLAC. The GLAC_ID and MOD_ID columns match the glacier ID and model ID maps. The model ID map is a grid that numbers cells from 1 to n from the top left to the bottom right. The glacier ID map contains glacier IDs from the Randolph Glacier Inventory, an example of which is shown in Figure 44.

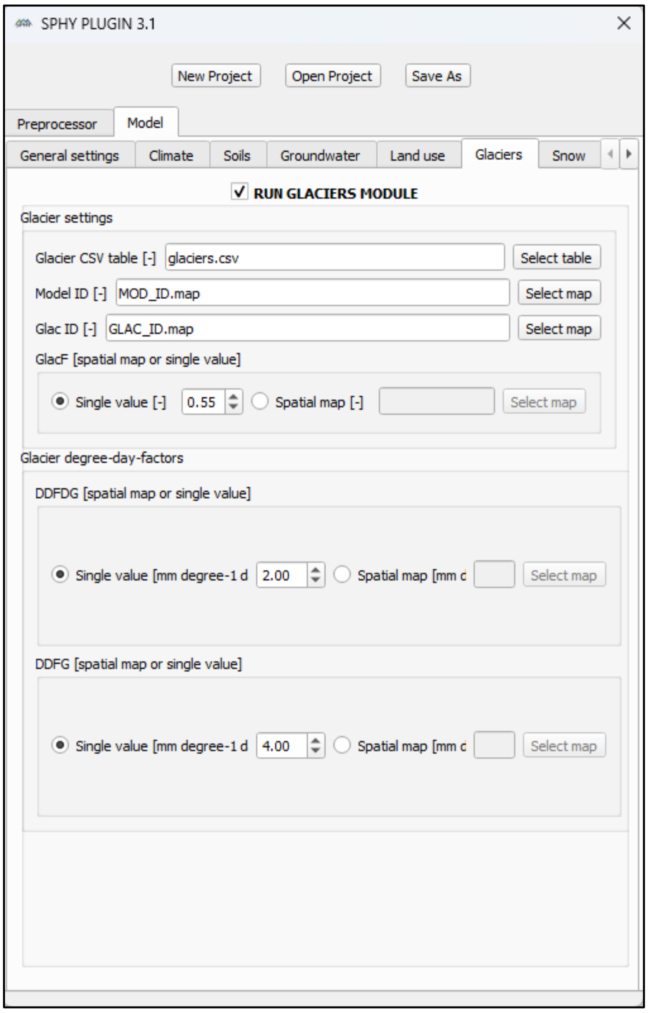


Figure 43. Overview of the Glaciers tab.

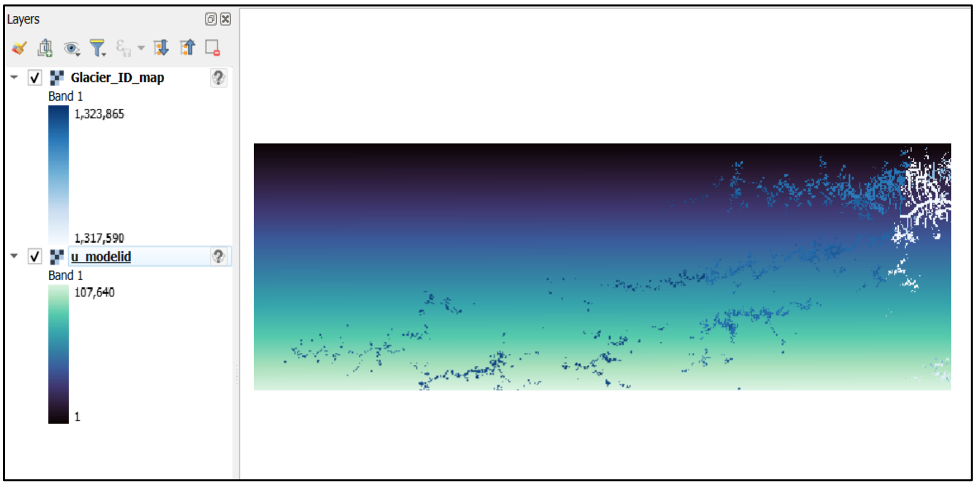


Figure 44. Example of model ID and glacier ID maps.

The glacier melt runoff factor (GlacF) differentiates between the amount of glacial melt that results in direct runoff and the amount of glacial melt that percolates into groundwater. The default value is 0.55, and the values range from zero to one. The user can choose a spatially distributed value for GlacF or a single value that is applied homogeneously over the entire catchment.

<u>Glacier degree-day-factors</u>

The degree-day factors for debris-covered glaciers (DDFDG) and clean ice-covered glaciers (DDFG) define the amount of glacial melt per day as a result of the average daily air temperature. Because different melting rates may apply to these two types of glaciers, two parameters must be set here.

The user can choose a single value that results in a homogeneous degree-day-factor for the entire basin or choose a map with a spatially distributed degree-day-factor. The maps can be selected and added to the canvas by clicking the Select map button.

The glaciers model that was run in order to get glaciers.csv, GLAC_ID.map and MOD_ID.map is also available as a standalone processing model that can be executed outside the SPHY Plugin interface. In your Processing Toolbox → Models → Glaciers Model, if you double click, you can see the interface of the model itself (Figure 45).

If you have created your own inputs, you can use this processing model in order to process them.

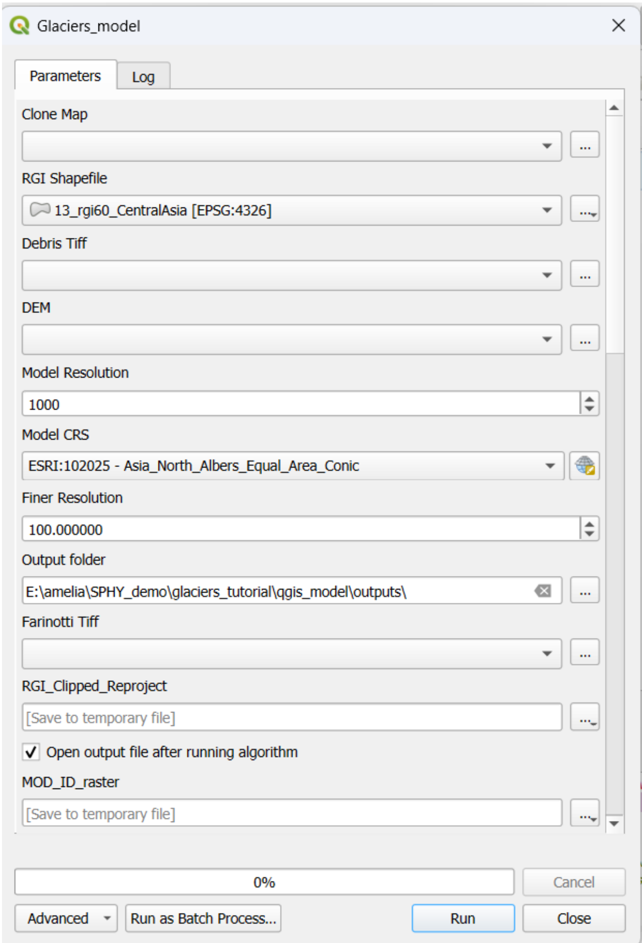


Figure 45. Glaciers model interface

After completion of all the settings in the Glacier tab you may continue with the next tab: Snow

3.3.8 Snow

An overview of the Snow tab is shown in Figure 46. A distinction has been made between snow storage settings and snow parameters that affect snow melting.

<u>Snow storage</u>

Within the snow storage section, the user needs to define the following three settings:

- SnowIni [mm]
- SnowWatStore [mm]
- SnowSC [-]

SnowIni defines the initial amount of snow storage for each cell. The user can either provide a single value that is applicable as a homogeneous value to the entire basin, or provide a spatially distributed initial snow storage map. The map can be selected and added to the canvas by clicking the Select map button.

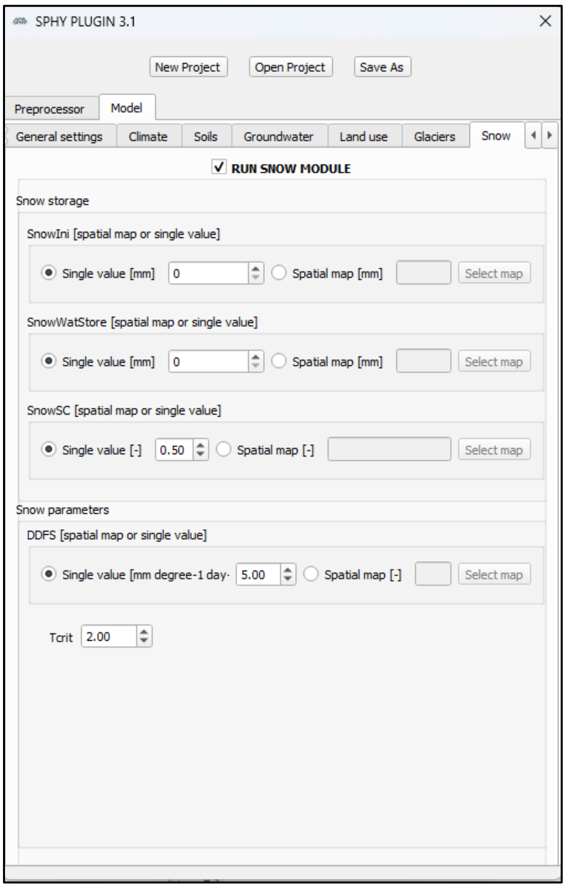


Figure 46. Overview of the Snow tab.

SnowWatStore defines the amount of melt water stored in the snowpack for each cell. This value can never be higher than the initial snow storage (SnowIni). The user can choose to either provide a single value for the entire basin, or provide a spatially distributed SnowWatStore map. The map can be selected and added to the canvas by clicking the Select map button.

The maximum amount of melt water stored in the SnowWatStore map that can refreeze is defined by setting SnowSC. Values for SnowSC range between zero and one, and the default value is set to 0.5. Users can choose a single value that is homogeneous for the entire catchment or choose a spatially distributed SnowSC map. This map can be selected and added to the map canvas by clicking the Select map button.

Snow parameters

The final step in this section involves setting the snow parameters that affect the melting and accumulation of snow:

- DDFS [mm degree day^{-1}]
- Tcrit [°C]

The degree-day factor for snow (DDFS) defines the potential snow melt per day as a result of the average daily air temperature. The user can either select a spatially distributed DDFS map or a single value that is applicable to the entire basin. The default value for DDFS is set to 6 mm $degree^{-1}$ day^{-1}.

The temperature threshold (Tcrit) defines whether the precipitation falls as snow or rain. If the average daily air temperature is higher than Tcrit, then the precipitation will fall as rain. Otherwise, precipitation falls as snow. Only a single value can be supplied here, and the default value for Tcrit is set to 2 °C. After the completion of all the settings in the Snow tab, you may continue with the next tab: Routing.

3.3.9 Routing

Settings in the Routing tab affect the way streamflow routing is performed and how streamflow routing is reported as the model output. An overview of the Routing tab is shown in Figure 47.

Recession coefficient and flow direction

The recession coefficient affects the velocity at which the water is transported downstream through the delineated river network. Values for the recession coefficient range between zero and one, and the default value is set to 0.40. One can choose either a spatially distributed recession coefficient map or a single value that is applicable to the entire basin. A recession coefficient map can be selected and added to the map canvas by clicking the Select map button.

For the flow direction you need to select a map by clicking the Select map button. After selecting a flow direction map this map will be added to the map canvas. An example of a flow direction map is shown in Figure 48. A flow direction map needs to be prepared by the user, and is based on the DEM. The flow direction map contains a number that defines the streamflow direction for each cell. The numbers and corresponding directions are shown in Figure 49.

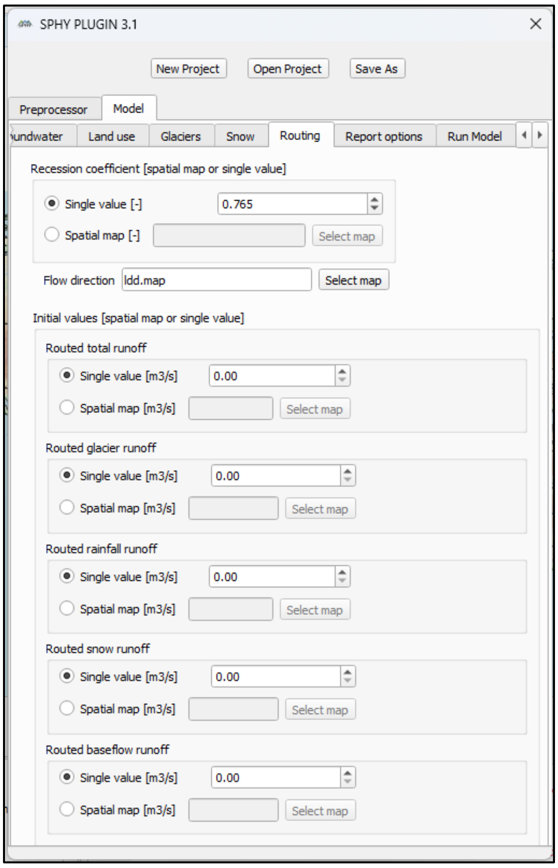


Figure 47. Overview of the routing tab.

Figure 48. Example of flow direction map.

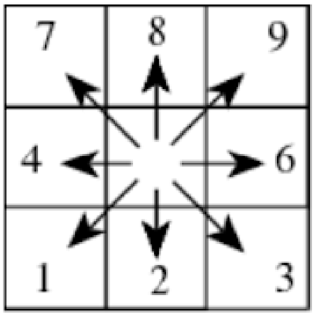


Figure 49. Values indicating the direction of flow in the flow direction map.

Initial values

The initial values that need to be set are:

- Routed total runoff [m^3/s]
- Routed rainfall runoff [m^3/s]
- Routed baseflow runoff [m^3/s]
- Routed snow runoff [m^3/s]
- Routed glacier runoff [m^3/s]

The routed total runoff is the sum of the individual routing components, which are the last four items shown above. The default values for all routing components are set to zero. However, you may be interested in using results from a previous model as a starting point for a new model run. In this case, the routed runoff of the last time-step of the previous model run is the initial value for the routed runoff of the current model run.

For each of the routed runoff components you may choose to either provide a single value that is applicable to the entire basin, or to provide a spatially distributed map with routed runoff. Maps are selected and added to the map canvas by clicking the Select map buttons.

The routing of individual streamflow components (rainfall runoff, baseflow runoff, snow runoff, and glacier runoff) is more time-consuming than routing total runoff alone. If you are only interested in routing the total runoff, then it is possible to not compute the routing of the individual routing components. This can be achieved selecting the spatial map option for the routing component that you do not want to be calculated and leave the corresponding field blank.
After completion of all the settings in the Routing tab you are finished with setting all the model input maps and parameters. The next step involves setting the model output options in the Report options tab.

3.3.10 Report options

Figure 50 represents an overview of the Report options tab. Within this section of the GUI you can choose two different options for reporting: basic and custom. Basic reporting will provide you the following variables and time aggregations:

- Precipitation: daily, monthly, monthly sums and yearly maps. Daily timeseries for the stations selected, if any.
- Water balance: daily timeseries for the stations selected if any.
- Reference evapotranspiration: monthly, long-term average monthly sums and yearly maps. Daily timeseries for the stations selected, if any.
- Actual evapotranspiration: monthly, long-term average monthly sums and yearly maps. Daily timeseries for the stations selected, if any.
- Total Runoff: monthly, long-term average monthly sums and yearly maps. Daily timeseries for the stations selected, if any.
- Rootzone Storage: monthly and long-term monthly average maps.

- Subsoil Storage: monthly and long-term monthly average maps.
- Groundwater Storage: monthly and long-term monthly average maps.

If the Custom Reporting option is selected, you will get an empty **reporting.csv** table in your input folder and it has to be manually filled, specifying the desired outputs and their time aggregation. This procedure is explained in detail in the SPHY Model manual.

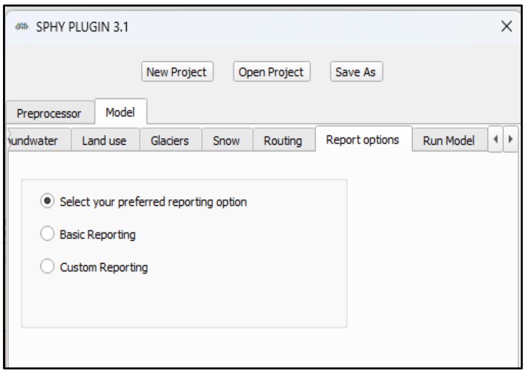


Figure 50. Overview of the Report options tab.

After the reporting options have been set you can continue with the next tab: Run Model

3.3.11 Running the model

Figure 51 provides an overview of the Run Model tab. You are now ready to run the model by pressing the Run model button. During model execution the command line output will be reported in the log screen as is shown in Figure 52. The model run can be canceled at any time by pressing the Cancel model run button. If this is done, the previous model output will not be overwritten. Figure 53 shows an example of the log-screen output of a cancelled model run.

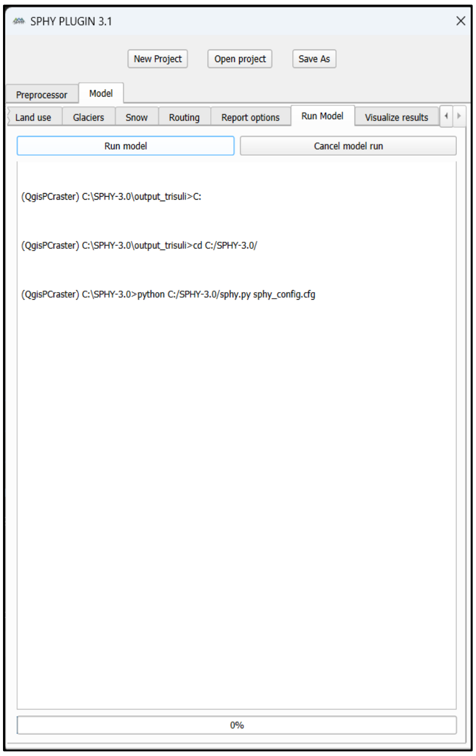


Figure 51. Overview or the Run Model tab.

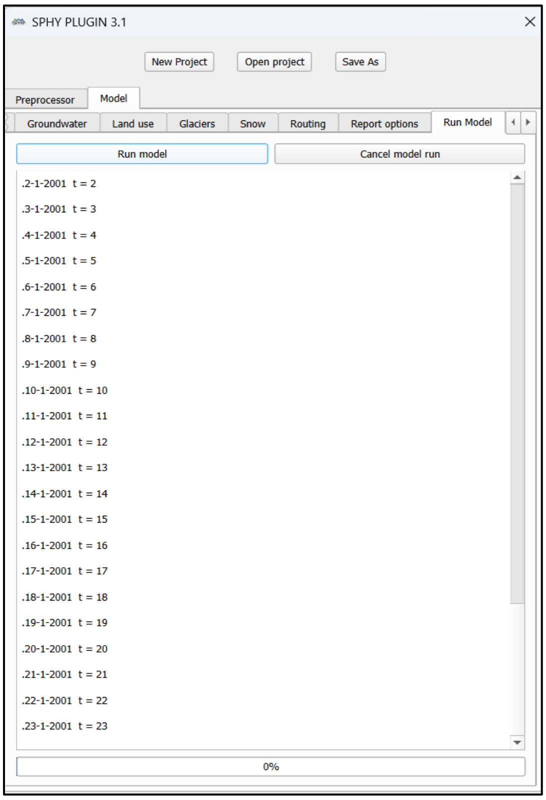


Figure 52. Example of log screen output during model run.

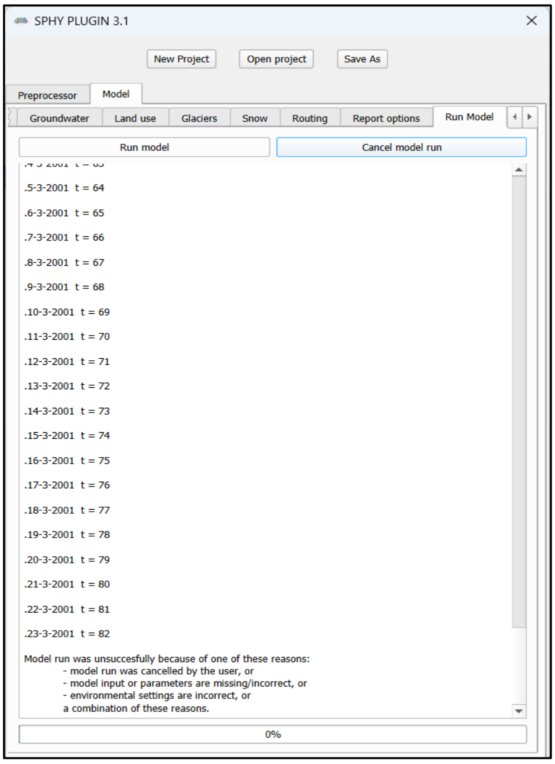


Figure 53. Example log screen output of cancelled model run.

If an error occurs after the Run model button has been clicked, then the concrete error will be shown in text. In this case, you need to check your model input/parameters, environmental settings, or a combination of these.

If your model run was successful, then a screen similar to Figure 54 will be shown. The text "Model run was successfully!" indicates that model execution was successful.

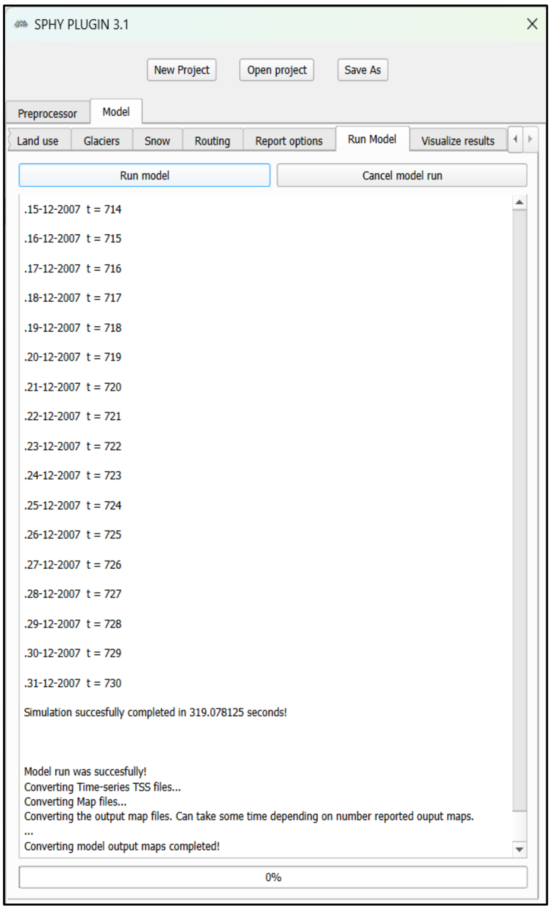


Figure 54. Example log screen output of a successful model run.

At this stage, the Cancel model run can still be clicked to prevent the previous model output from being overwritten. Otherwise, the GUI continues to convert the model output into a suitable output format. Converting the model output may take a long time, depending on the length of the model simulation period and the settings in the Report options tab. The line with the three dots (…) indicates that the GUI is still working to convert the output.

After the line "Converting model output maps completed!" is shown, you can continue to the Visualize results tab to analyze the model output.

3.3.12 Visualizing results

If model execution has been completed successfully, then the Visualize results tab will become available. An overview of the Visualize results tab is shown in Figure 55. If no model run has been performed yet, or if nothing was reported in the Report options tab, then the list widgets in this tab will be completely empty.

A distinction was made between the time-series output (left list widget) and map-series output (three right list widgets). The map-series output is split into three separate list widgets: i) daily maps, ii) monthly maps, and iii) annual maps.

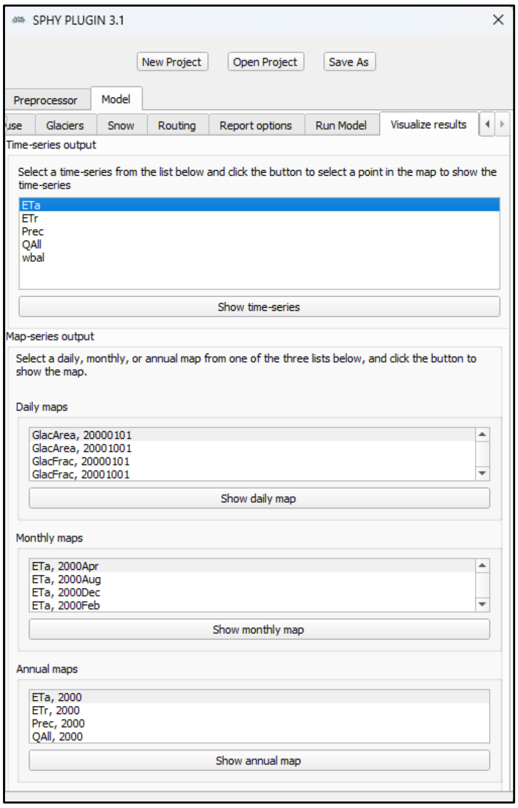


Figure 55. Overview of Visualize results tab.

Time-series output

Time-series plots can be shown for the locations that are defined in the Stations map in the General settings tab. To show a time-series plot you need to:

1. Select the variable of interest from the list (in Figure 55 the “Routed baseflow runoff [m3/s]” is the selected variable).
2. Make sure that the Stations map layer (outlet) is selected in the map canvas (Figure 56).
3. Click the Show time-series button.
4. Finally, click on one of the points in the canvas that is part of your Stations map layer (Figure 57).

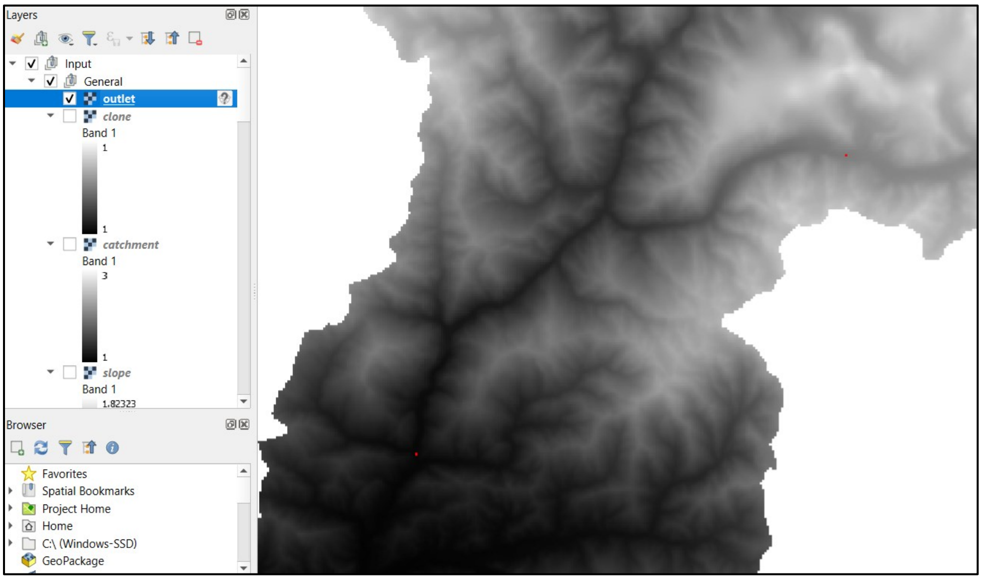


Figure 56. Setting the Stations map layer (outlet) as active layer.

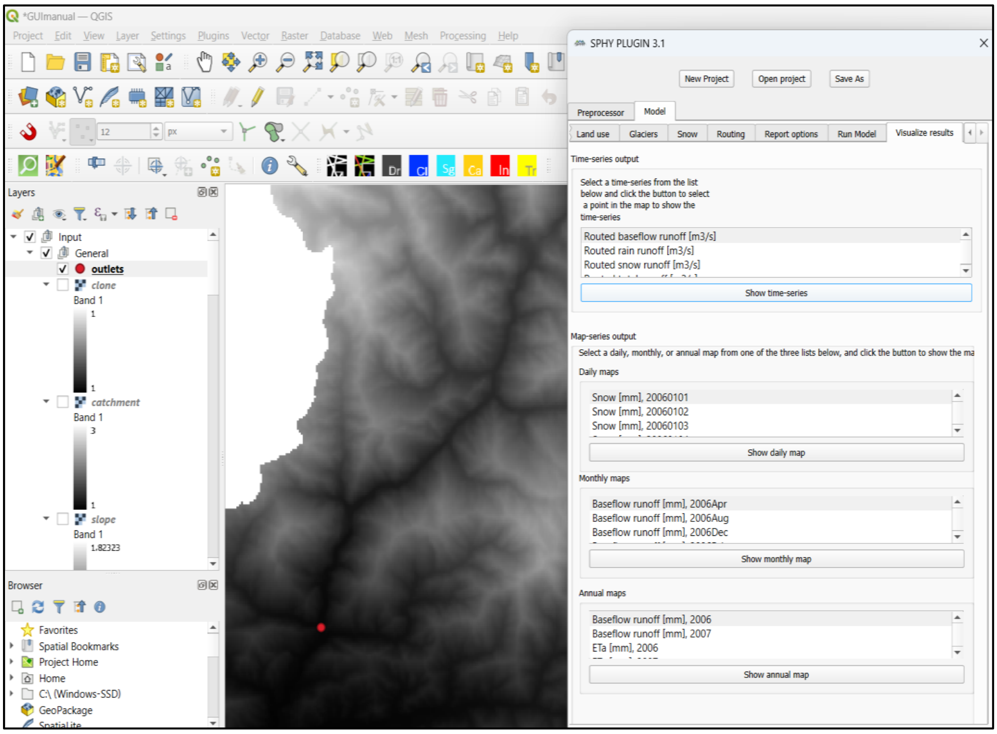


Figure 57. Click on a point feature in the canvas to show a time-series.

After completing Step 4, a time-series plot is shown (Figure 58). The buttons shown inside the red box allow you to zoom in and zoom out of your graph, pan through the graph, change axes, and label settings, and save your graph to an image file.

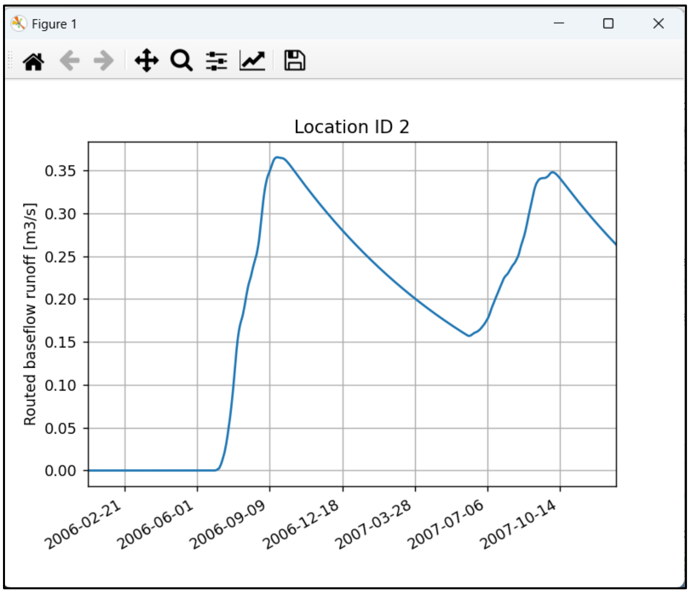


Figure 58. Example of time-series plot.

<u>Map-series output</u>

Showing map-series output is more straightforward than plotting the time-series. An output map (daily, monthly, or annual) can be added to the canvas by selecting the map of interest from the list widget and subsequently pressing the Show XXX map button at the bottom of the list widget, with XXX being daily, monthly, or annual.

Within the QGIS map canvas three layer groups are defined within the Output group layer, being:

- Daily
- Monthly
- Annual

The selected map output will be inserted as a new layer in one of these groups. If the layer name already exists in the group, this layer will be overwritten with the newly selected map layer. Figure 59 shows an example of adding an annual rainfall map to the map canvas. Since it is an annual map, it will be inserted inside the Output – Annual layer group.

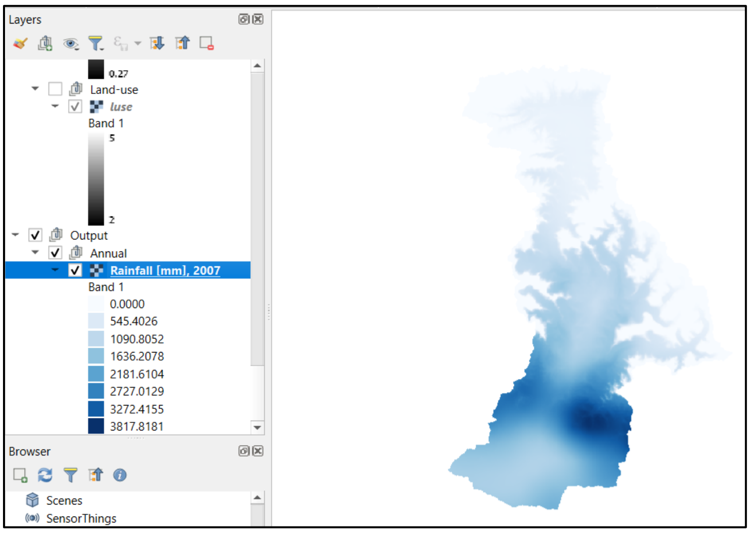


Figure 59. Example of annual rainfall map that has been added to the map canvas.

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Appendix 1: Input and Output

This appendix provides an overview of the input that is required by the SPHY model, and the output that can be reported by the SPHY model. It should be noted that the current version of the SPHY model GUI (version 1.0) does not support the interaction with all the input that can be specified in the SPHY model configuration file (*.cfg). This will be implemented in future versions of the GUI. Table 2 specifies the model input that can be specified in the current version of the SPHY model GUI. An overview of the output that can be reported by the model is shown in Table 3.

Table 2. Overview of SPHY model input.

Map or parameter name	Interface tab	Spatial map [SM], single value [SV], or table [TB]	For maps: Boolean [BO], Nominal [NO], Scalar [SC], Directional [DI]. For single value: Integer [IN] or Float [FL]	Units
Clone map	General settings	SM	BO	[-]
DEM map	General settings	SM	SC	[MASL]
Slope map	General settings	SM	SC	[-]
Sub-basins map	General settings	SM	NO	[-]
Stations map	General settings	SM	NO	[-]
Precipitation	Climate	SM	SC	[mm/d]
Avg. daily temperature	Climate	SM	SC	[°C]
Max. daily temperature	Climate	SM	SC	[°C]
Min. daily temperature	Climate	SM	SC	[°C]
Latitude zones	Climate	SM	SC	[latitude]
Solar constant	Climate	SV	FL	[MJ/m^2/min]
Field capacity	Soils	SV	SC	[mm/mm]
Saturated content	Soils	SV	SC	[mm/mm]
Permanent wilting point	Soils	SV	SC	[mm/mm]
Wilting point	Soils	SV	SC	[mm/mm]
Saturated hydraulic conductivity	Soils	SV	SC	[mm/d]
Rootlayer thickness	Soils	SM, SV	SC IN	[mm]
Sublayer thickness	Soils	SM, SV	SC IN	[mm]
Maximum capillary rise	Soils	SV	IN	[mm]
Groundwater layer thickness	Groundwater	SM, SV	SC IN	[mm]

Saturated groundwater content	Groundwater	SM, SV	SC IN	[mm]
Initial groundwater storage	Groundwater	SM, SV	SC IN	[mm]
Baseflow threshold	Groundwater	SM, SV	SC IN	[mm]
deltaGw	Groundwater	SM, SV	SC IN	[d]
alphaGw	Groundwater	SM, SV	SC FL	[-]
Land use map	Land use	SM	NO	[-]
Crop coefficients lookup table (see example Figure 54)	Land use	TB	FL	[-]
Initial glacier fraction	Glaciers	SM	SC	[-]
Clean ice glacier fraction	Glaciers	SM	SC	[-]
Debris covered glacier fraction	Glaciers	SM	SC	[-]
GlacF	Glaciers	SM, SV	SC FL	[-]
DDFDG	Glaciers	SM, SV	SC FL	[mm/°C/d]
DDFG	Glaciers	SM, SV	SC FL	[mm/°C/d]
SnowIni	Snow	SM, SV	SC IN	[mm]
SnowWatStore	Snow	SM, SV	SC IN	[mm]
SnowSC	Snow	SM, SV	SC FL	[-]
DDFS	Snow	SM, SV	SC FL	[mm/°C/d]
Tcrit	Snow	SV	FL	[°C]
Recession coefficient	Routing	SM, SV	SC FL	[-]
Flow direction (see example Figure 59 and Figure 60)	Routing	SM	DI	[-]
Routed total runoff	Routing	SM, SV	SC FL	[m^3/s]
Routed rainfall runoff	Routing	SM, SV	SC FL	[m^3/s]
Routed baseflow runoff	Routing	SM, SV	SC FL	[m^3/s]
Routed snow runoff	Routing	SM, SV	SC FL	[m^3/s]
Routed glacier runoff	Routing	SM, SV	SC FL	[m^3/s]

Table 3: Overview of SPHY model output (Report options tab).

Output variable	Spatial map [SM] or time-series [TS]	Output frequency: daily [D], monthly [M], or annual [A]	Units	Option to report sub-basin average flux in mm: yes [Y] or no [N].
Baseflow runoff	SM, TS	D, M, A	mm	N
Capillary rise	SM, TS	D, M, A	mm	N
ETa	SM, TS	D, M, A	mm	Y
ETp	SM, TS	D, M, A	mm	N
Glacier melt	SM, TS	D, M, A	mm	Y
Glacier percolation	SM, TS	D, M, A	mm	N
Glacier runoff	SM, TS	D, M, A	mm	N
Groundwater recharge	SM, TS	D, M, A	mm	N
Precipitation	SM, TS	D, M, A	mm	Y
Rain runoff	SM, TS	D, M, A	mm	N
Rainfall	SM, TS	D, M, A	mm	N
Rootzone drainage	SM, TS	D, M, A	mm	N
Rootzone percolation	SM, TS	D, M, A	mm	N
Routed baseflow runoff	SM, TS	D, M, A	m^3/s	Y
Routed glacier runoff	SM, TS	D, M, A	m^3/s	Y
Routed rain runoff	SM, TS	D, M, A	m^3/s	Y
Routed snow runoff	SM, TS	D, M, A	m^3/s	Y
Routed total runoff	SM, TS	D, M, A	m^3/s	Y
Snow	SM, TS	D, M, A	mm	N
Snow melt	SM, TS	D, M, A	mm	N
Snow runoff	SM, TS	D, M, A	mm	N
Subzone percolation	SM, TS	D, M, A	mm	N
Surface runoff	SM, TS	D, M, A	mm	N
Total runoff	SM, TS	D, M, A	mm	N

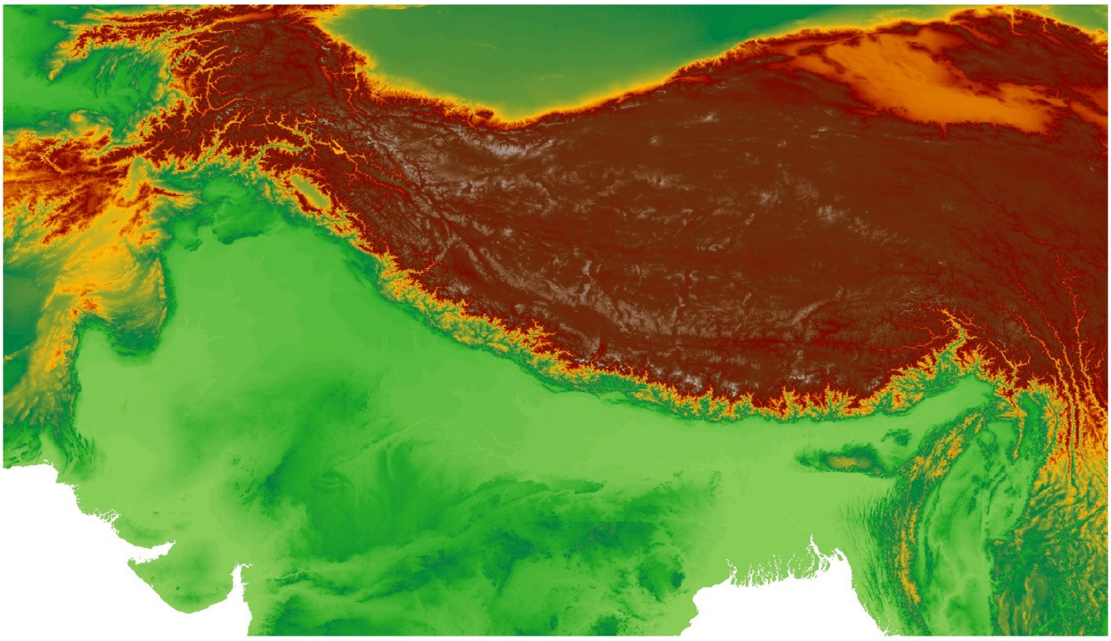
Appendix 2: Hindu Kush-Himalaya database

Database extent:
Xmin: 65.00
Xmax: 100.0
Ymin: 20.0
Ymax: 40.0

HydroSheds SRTM DEM

The included Digitial Elevation Model (DEM) is the USGS HydroSheds hydrologically conditioned DEM (Lehner et al., 2006). The data is based on the SRTM DEM and public available through http://hydrosheds.cr.usgs.gov. The specific product included is "Hydrologically conditioned elevation". This product is available divided in 5°x5° tiles. Parts of the tiles have been mosaicked to generate the DEM.

Data format and size	GeoTiff 2.35 GB			
Values	Elevation in meters above sea level			
Projection	Geographic (LAT/LON) WGS1984 (EPSG:4326)			
Spatial resolution	3 arc-second (~90 meter at the equator)			
Extent (dd):	xmin: 65.00	xmax: 100.00	ymin: 20.00	ymax: 40.00

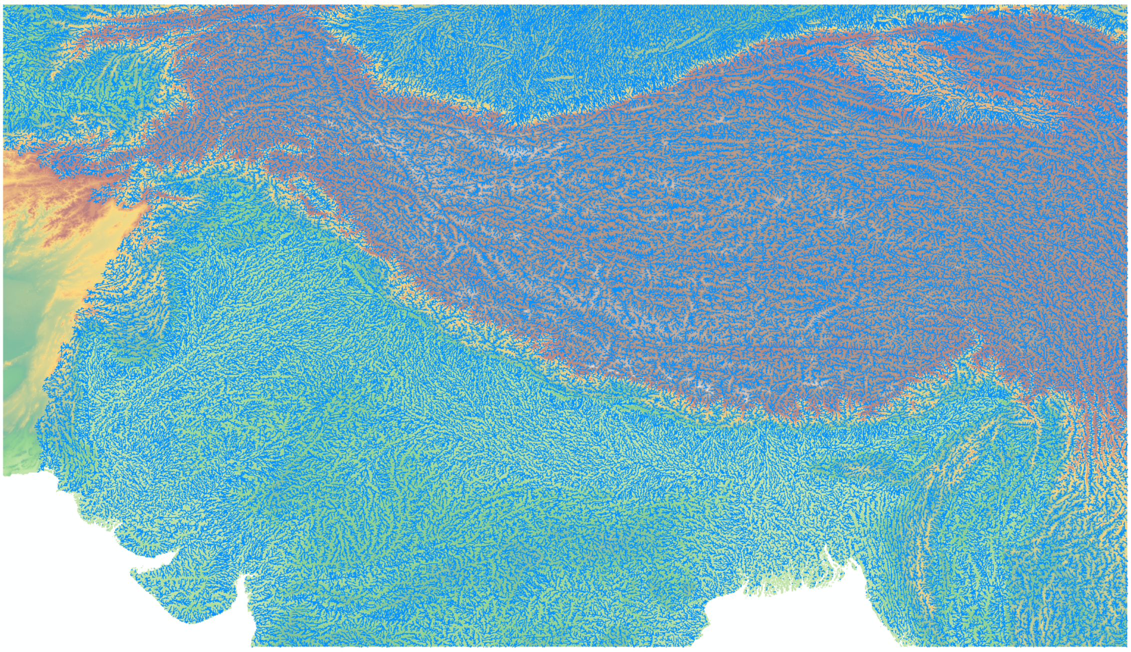


HydroSheds DEM included in the Hindu Kush-Himalaya database.

HydroSheds streams

HydroSheds has also stream lines available as derived from the hydrologically corrected DEM. The data is available as lines shapefile. The data is derived from the 15 arc seconds DEM.

Data format and size	Shapefile 40 MB			
Values	Line elements with ID and number of upstream cells			
Projection	Geographic (LAT/LON) WGS1984 (EPSG:4326)			
Extent (dd):	xmin: 65.00	xmax: 100.00	ymin: 20.00	ymax: 40.00

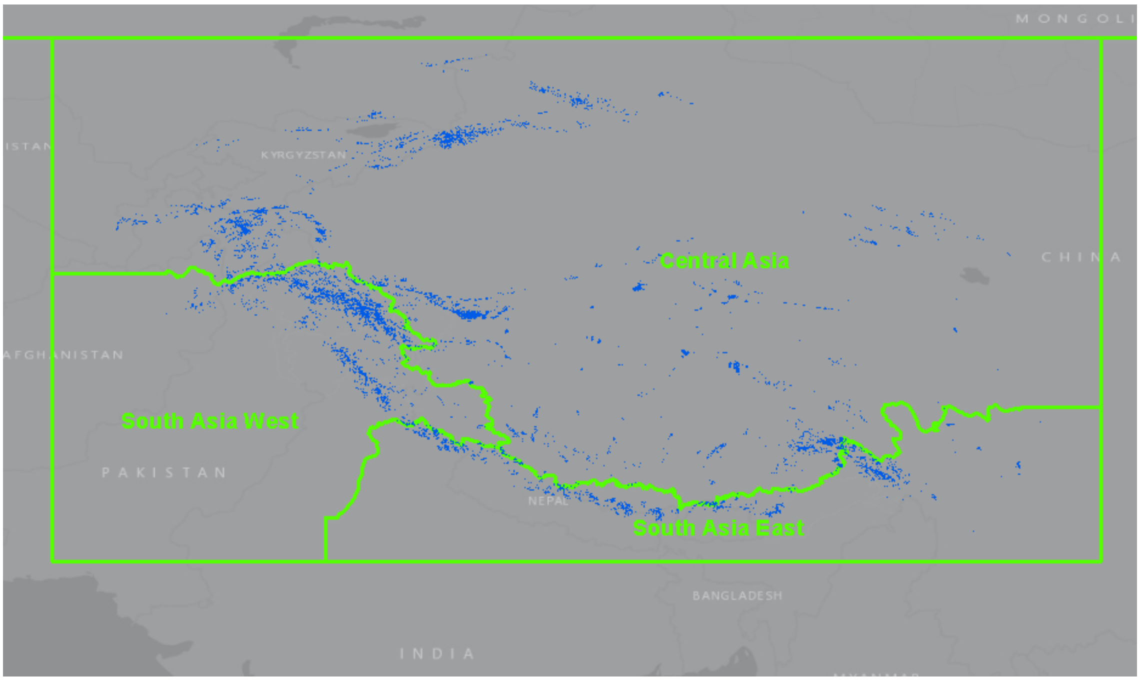


HydroSheds streams included in the Hindu Kush-Himalaya database.

Randolph Glacier Inventory (RGI v6.0)

The Randolph Glacier inventory (Pfeffer et al., 2014) is considered the most complete global glacier outlines inventory. The inventory is available online through GLIMS: http://www.glims.org/RGI/. Version 6.0 was released in July 2017. The outlines for Central Asia, South Asia West, South Asia East. These regions were available as separate shapefiles which have been merged into one shapefile.

Data format and size	Shapefile 120 MB
Values	Glacier outlines as polygons and glacier properties in attribute table
Projection	Geographic (LAT/LON) WGS1984 (EPSG:4326)

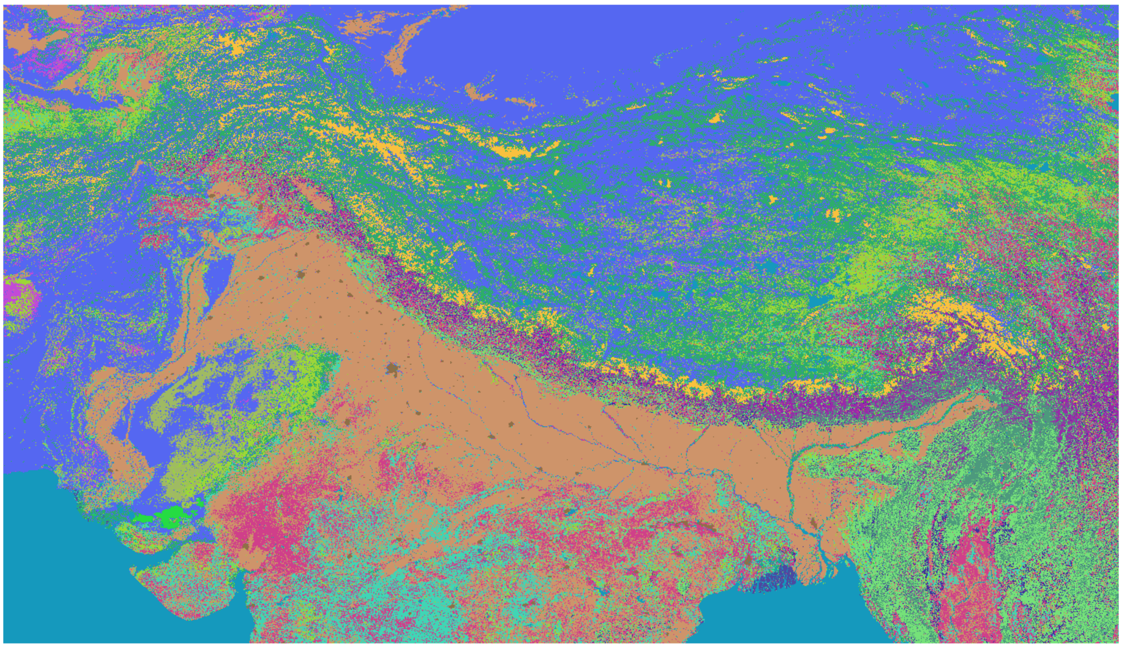


Randolph Glacier Inventory 4.0 glacier outlines (blue) included in Hindu Kush-Himalaya database. RGI regions are indicated by green polygons.

GlobCover Land use data

GlobCover (Defourny et al., 2007) is an ESA initiative which began in 2005 in partnership with JRC, EEA, FAO, UNEP, GOFC-GOLD and IGBP. The aim of the project was to develop a service capable of delivering global composites and land cover maps using as input observations from the 300m MERIS sensor on board the ENVISAT satellite mission. ESA makes available the land cover maps, which cover 2 periods: December 2004 - June 2006 and January - December 2009. The latter is included in the dataset. A quick scan comparing different available public domain global land use datasets shows that GlobCover is the most reliable at the moment.

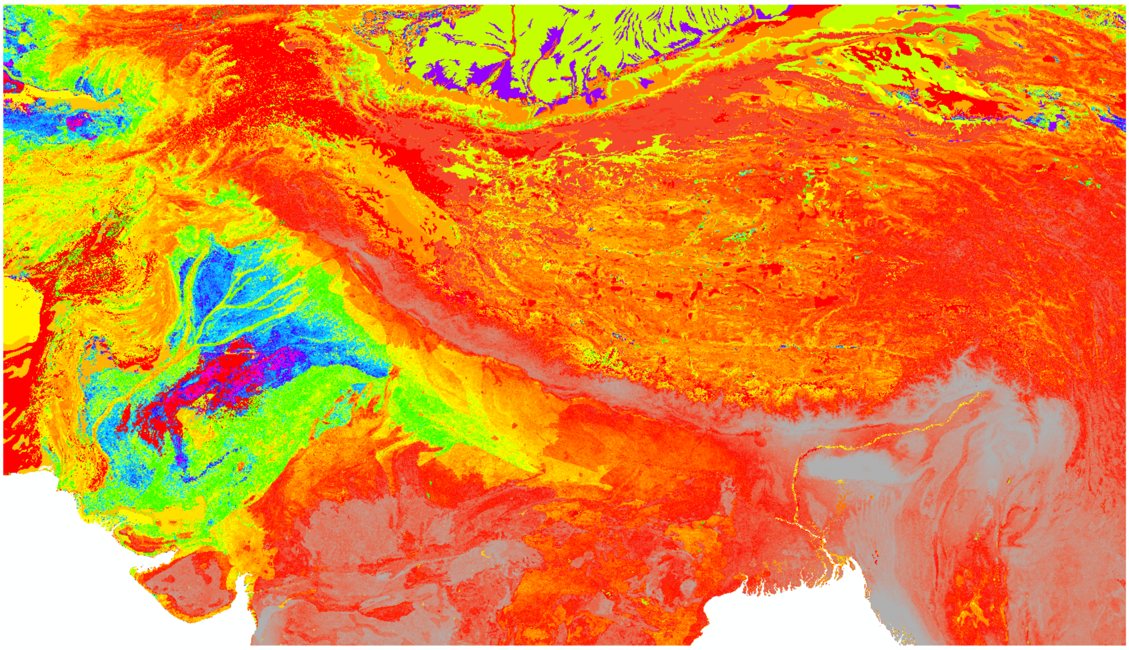
Data format and size	GeoTiff 86.5 MB			
Values	Land use classes (categorical as integer values)			
Projection	Geographic (LAT/LON) WGS1984 (EPSG:4326)			
Spatial resolution	300 meter			
Extent (dd):	xmin: 65.00	xmax: 100.00	ymin: 20.00	ymax: 40.00



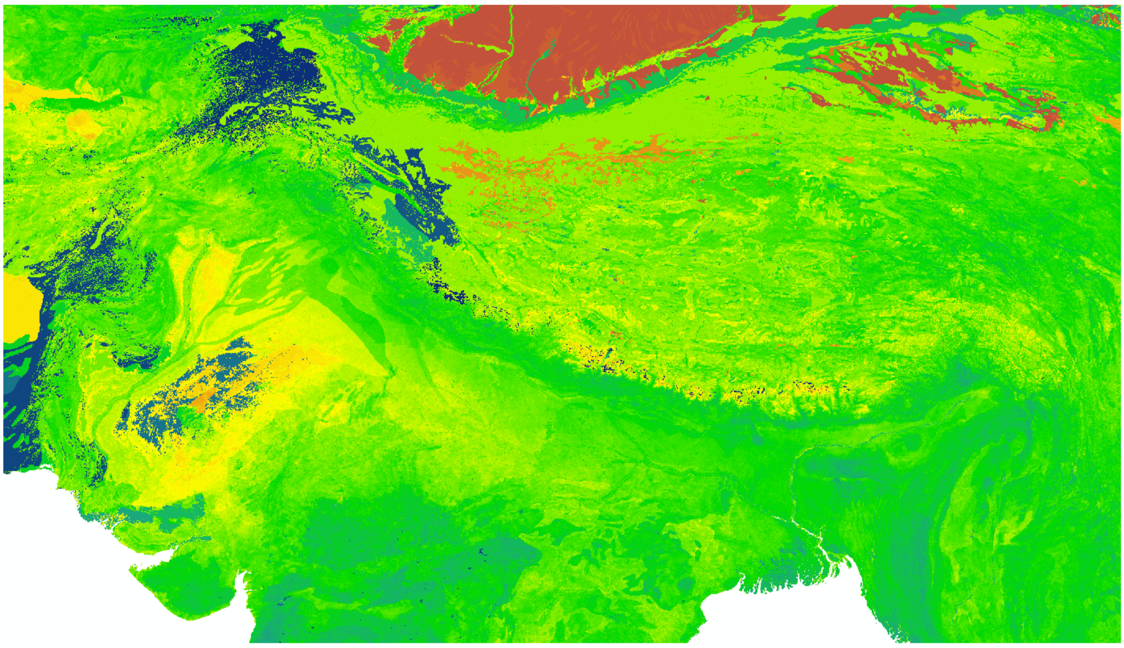
GlobCover domain included in the Hindu Kush-Himalaya database.

HiHydroSoil

FutureWater has developed a new global soil product containing quantitative hydrological properties, as required by most hydrological models, including SPHY (Terink et al., 2015a). This global physical soil properties product (HiHydroSoil) is based on the SoilGrids1km database. The Harmonized World Soil Database (HWSD) is used to fill missing data in the SoilGrids1km.
Pedotransfer functions are used to estimate physical soil properties from soil type. A detailed description of the HiHydroSoil product can be found in de Boer (2015).



HiHydroSoil saturated conductivity of the topsoil layer in the Hindu Kush-Himalaya database.



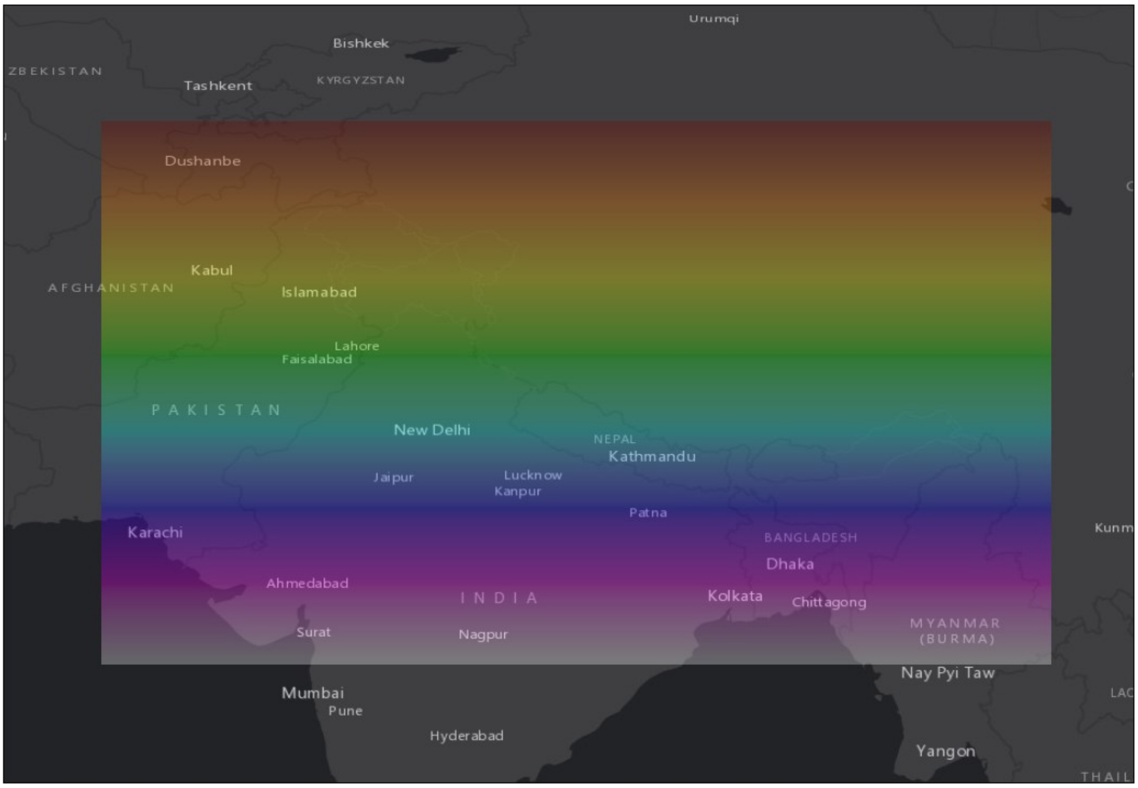
HiHydroSoil field capacity of the topsoil layer in the Hindu Kush-Himalaya database.

<table>
<tr><td>Data format and size</td><td colspan="4">8 x GeoTiff 39 MB</td></tr>
<tr><td>Values</td><td colspan="2">Top Soil
Saturated water content (WCSat (mm/mm))
Field capacity (pF2 (mm/mm))
Wilting point (pF3 (mm/mm))
Permanent wilting point (pF4.2 (mm/mm))
Saturated conductivity (Ksat (mm/day))</td><td colspan="2">Sub Soil
Saturated water content (WCSat, mm/mm)
Field capacity (pF2 (mm/mm))
Saturated conductivity (Ksat (mm/day))</td></tr>
<tr><td>Projection</td><td colspan="4">Geographic (LAT/LON) WGS1984 (EPSG:4326)</td></tr>
<tr><td>Spatial resolution</td><td colspan="4">0.0083° (~800m)</td></tr>
<tr><td>Extent (dd):</td><td>xmin: 65.00</td><td>xmax: 100.00</td><td>ymin: 20.00</td><td>ymax: 40.00</td></tr>
</table>

Latitude

SPHY requires each grid cell's latitude for the calculation of the reference evapotranspiration using the Modified-Hargreaves equation (Droogers and Allen, 2002). The latitude is derived for a 0.01° x 0.01° grid covering the dataset domain.

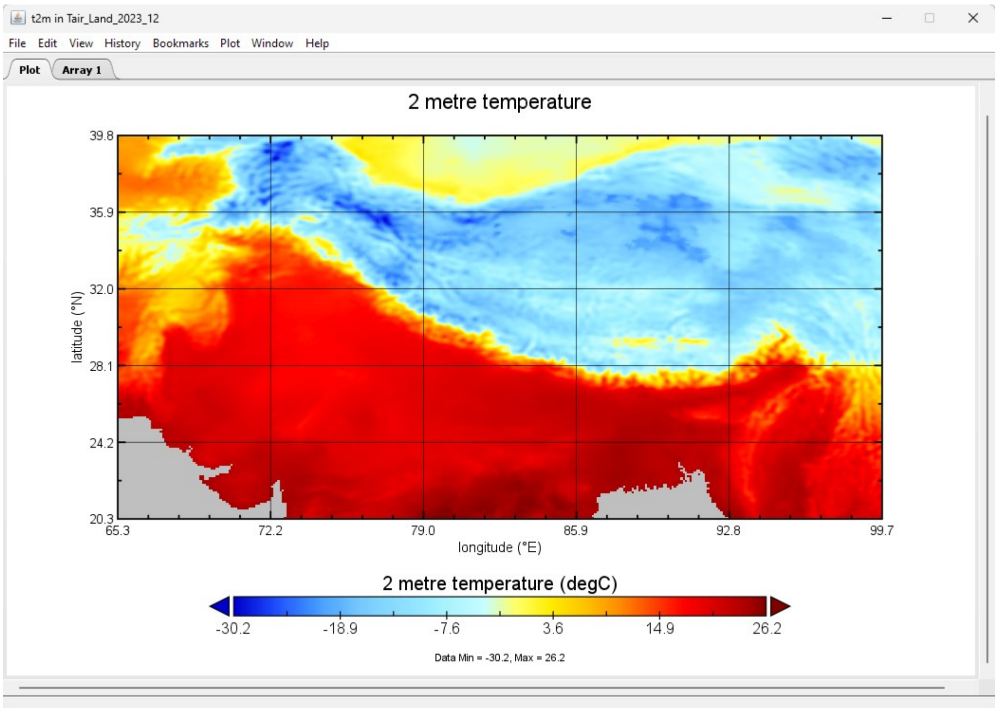
<table>
<tr><td>Data format and size</td><td colspan="4">GeoTiff 56 MB</td></tr>
<tr><td>Values</td><td colspan="4">Latitude values (LAT) in decimal degrees</td></tr>
<tr><td>Projection</td><td colspan="4">Geographic (LAT/LON) WGS1984 (EPSG:4326)</td></tr>
<tr><td>Spatial resolution</td><td colspan="4">0.01° (~1000m at the equator)</td></tr>
<tr><td>Extent (dd):</td><td>xmin: 65.00</td><td>xmax: 100.00</td><td>ymin: 20.00</td><td>ymax: 40.00</td></tr>
</table>



Latitude values for the Hindu Kush-Himalaya database.

Meteo Forcings (ERA5-Land)

The ERA5-Land meteorological data is clipped for the domain covering the Hindu Kush-Himalaya region, including the downstream basins of Indus, Ganges and Brahmaputra. The data only covers grid cells classified as land, grid cells located in the sea are not included.



Average air temperature grid from WFDEI for the Hindu Kush-Himalaya database.

Daily mean air temperature:

Data format and size	NetCDF (1 file per month) 8 MB			
Values	Daily mean air temperature (Celsius Degrees)			
Projection	Geographic (LAT/LON) WGS1984 (EPSG:4326)			
Spatial resolution	0.1°			
Extent (dd):	xmin: 65.00	xmax: 100.00	ymin: 20.00	ymax: 40.00
Time step	Daily			
Period covered	1 January 1980 – 31 December 2023			

Daily maximum air temperature:

Data format and size	NetCDF (1 file per month) 8 MB			
Values	Daily maximum air temperature (Celsius Degrees)			
Projection	Geographic (LAT/LON) WGS1984 (EPSG:4326)			
Spatial resolution	0.1°			
Extent (dd):	xmin: 65.00	xmax: 100.00	ymin: 20.00	ymax: 40.00
Time step	Daily (calculated as maximum from hourly data)			
Period covered	1 January 1980 – 31 December 2023			

Daily minimum air temperature:

Data format and size	NetCDF (1 file per month) 8 MB			
Values	Daily minimum air temperature (Celsius Degrees)			
Projection	Geographic (LAT/LON) WGS1984 (EPSG:4326)			
Spatial resolution	0.1°			
Extent (dd):	xmin: 65.00	xmax: 100.00	ymin: 20.00	ymax: 40.00
Time step	Daily (calculated as minimum from hourly data)			
Period covered	1 January 1981 – 31 December 2010			

Daily precipitation:

Data format and size	NetCDF (1 file per month) 8 MB			
Values	Total precipitation Precipitation (m)			
Projection	Geographic (LAT/LON) WGS1984 (EPSG:4326)			
Spatial resolution	0.1°			
Extent (dd):	xmin: 65.00	xmax: 100.00	ymin: 20.00	ymax: 40.00
Time step	Daily			
Period covered	1 January 1980 – 31 December 2023			