

SPHY v2.0: Spatial Processes in Hydrology

Model theory and SPHY interface (v1.0) manual

December 2014



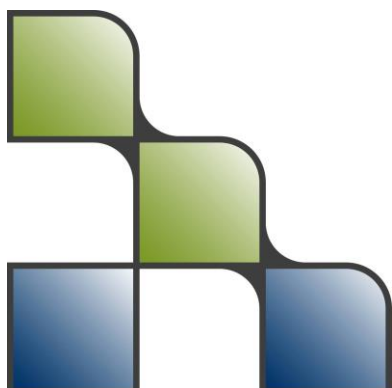
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¹ <http://www.icimod.org/>

² <http://www.esa.int/ESA>

³ <http://www.adb.org/>

⁴ <http://www.worldbank.org/>



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1 Introduction

The number and diversity of water-related challenges are large and are expected to increase in the future. Even today, the ideal condition of having the appropriate amount of good-quality water at the desired place and time, is most often not satisfied (Biswas and Tortajada, 2010; Droogers and Bouma, 2014). It is likely that climate variability and change will intensify food insecurity by water shortages (Wheeler and Braun, 2013), and loss of access to drinking water (Rockström et al., 2012). Current and future water related challenges are location and time specific and can vary from impact of glacier dynamics (Immerzeel et al., 2011), economic and population growth (Droogers et al., 2012), floods, or extended and more prolonged droughts (Dai, 2011), amongst others.

In response to these challenges hydrologists and water resources specialists are developing modeling tools to analyze, understand and explore solutions to support decision makers and operational water managers. Despite difficulties to connect the scientific advances in hydrological modeling with the needs of decision makers and water managers, progress has been made and there is no doubt that modeling tools are indispensable in what is called good “water governance” (Droogers and Bouma, 2014; Liu et al., 2008).

The strength of models is that they provide output on ultimate high temporal and spatial resolutions, and for difficult to observe sub-processes (Bastiaanssen et al., 2007). The most important aspect of applying models, however, is in their use to explore different scenarios expressing, for example, possible effects of changes in population and climate on the water cycle (Droogers and Aerts, 2005). Such kinds of scenarios are often referred to as projections. Models are also applied at the operational level to explore interventions (management scenarios) to be used by water managers and policy makers. Examples of this are changes in reservoir operation rules, water allocation between sectors, investment in infrastructure such as water treatment or desalination plants, and agricultural and irrigation practices. In other words: models enable hydrologists and water managers to change focus from a re-active towards a pro-active approach.

The number of existing hydrological models is probably in the tens of thousands (Droogers and Bouma, 2014). Some existing model- overviews cover a substantial amount of models: IRRISOFT (Irrisoft 2014): 114, USGS (USGS, 2014): 110, EPA (EPA, 2014): 211, USACE (HEC 2014): 18. Interesting is that in groundwater modelling ModFlow is the de-facto standard tool to use. For hydrological models such a standard is lacking, although the SWAT model is increasingly becoming popular (Neitsch et al., 2009).

Traditionally, hydrologists have put a strong emphasis on streamflow analysis and forecasting, while ignoring other hydrological processes. Typical examples are the so-called distributed model inter-comparison projects (DMIP) which have been undertaken over the last decade (Smith et al., 2004; Smith et al., 2012). DMIP, and similar initiatives (Moreda et al., 2006; Khakbaz et al., 2012), have analyzed the capacity of models to reproduce observed streamflow. It is however clear that the need of decision makers and managers goes far beyond streamflow only. The notion that not only water in streams is relevant, but a better understanding of the full hydrological cycle is required, has led to the popular division of “blue” and “green” water (Falkenmark and Rockström, 2010). Moreover, there is a clear need that not only rainfall-runoff processes are relevant, but an integrated approach encompassing processes as glacier and snowmelt, evapotranspiration, reservoirs, changes in land cover and land use should be better integrated in our models (Bell et al., 2014; Liu et al., 2008). Finally, the linkage with satellite



remote sensing data has been shown to be very relevant to increase accuracy and usefulness of hydrological models, especially in data scarce areas (Droogers and Kite, 2002; Ines et al., 2006; Kite and Droogers, 2000).

Based on the discussions above, there is clear a need for a hydrological model that combines the strengths of existing modelling approaches such that: (i) most relevant hydrological processes are integrated, (ii) setup is modular in order to switch on/off irrelevant processes and thus decreases model run-time, (iii) it can relatively easily be adjusted and applied, (iv) it can easily be linked to remotely sensed data, and (v) it can be applied for operational as well as strategic decision support.

Over the last couple of years FutureWater has developed the Spatial Processes in Hydrology (SPHY) model and improved its usefulness by applying the model in various research projects. SPHY has been developed using the best available components resulting in a simulation model that is i) flexible in scaling, ii) includes cryosphere, mountain hydrology, lowland hydrology and land surface processes, iii) is in the public domain, iv) can be linked to remote sensing, and v) it can be applied for operational as well as strategic decision support. Earlier versions of the SPHY model were only accessible to model experts, because it was developed and executed by modifying and running multiple python files and model configuration files. A user-friendly interface of the SPHY model was therefore lacking. In order to make the SPHY model available to a larger user-group world-wide, we have developed a Graphical User Interface (GUI) for the SPHY model that can be used inside QGIS.

The objectives of this manual are:

- Introduce and present the SPHY model (v2.0)
- Present the SPHY model (v2.0) theory and demonstrate some typical applications
- Provide the steps that are required to install the SPHY model as a standalone application, or as integrated in the SPHY model GUI
- Explain the use of the SPHY model GUI
- Learn how-to work with the SPHY model GUI by doing a case-study
- Learn how-to build a SPHY model for your own area of interest

The model executable and source code are in the public domain (open access) and can be obtained from the SPHY model website free of charge (www.sphy.nl).



2 Theory and applications

2.1 Model overview

2.1.1 Introduction

The SPHY model has been developed by combining the best components of existing and well tested simulation models: HydroS (Droogers and Immerzeel, 2010), SWAT (Neitsch et al., 2009), PCR-GLOBWB (Sperna Weiland et al., 2012), SWAP (van Dam et al., 1997) and HimSim (Immerzeel et al., 2011). SPHY was developed with the explicit aim to simulate terrestrial hydrology at flexible scales, under various land use and climate conditions. SPHY is a spatially distributed leaky bucket type of model, and is applied on a cell-by-cell basis. In order to minimize the number of input parameters, and avoid complexity and long model run-times, SPHY does not include energy balance calculations, and is therefore a water-balance based model. The main terrestrial hydrological processes are described in a physically consistent way so that changes in storages and fluxes can be assessed adequately over time and space. SPHY is written in the Python programming language using the PCRaster (Karssenberg et al., 2001; Karssenberg, 2002; Karssenberg et al., 2010; Schmitz et al., 2009; Schmitz et al., 2013) dynamic modelling framework.

An overview of the SPHY model concepts is shown in Figure 1. SPHY is grid-based and cell values represent averages over a cell, but sub-grid variability is taken into account. A cell can be glacier-free, partially glacierized, or completely covered by glaciers. The cell fraction not covered by glaciers consists of either land covered with snow or land that is free of snow. Land that is free of snow can consist of vegetation, bare soil, or open water. In order to distinct between land cover types at sub-grid level, SPHY calculates and stores the state variables as grid-cell averages. Sub-grid variability is mainly determined by the fractional vegetation coverage, which affects processes such as interception, effective precipitation, and potential evapotranspiration.

The land compartment is divided in two upper soil stores and a third groundwater store, with their corresponding drainage components: surface runoff, lateral flow and base flow. SPHY simulates for each cell precipitation in the form of rain or snow, depending on the temperature. Any precipitation that falls on land surface can be intercepted by vegetation and in part or in whole evaporated. The snow storage is updated with snow accumulation and/or snow melt. A part of the liquid precipitation is transformed in surface runoff, whereas the remainder infiltrates into the soil. The resulting soil moisture is subject to evapotranspiration, depending on the soil properties and fractional vegetation cover, while the remainder contributes in the long-term to river discharge by means of lateral flow from the first soil layer, and base flow from the groundwater reservoir.

Melting of glacier ice contributes to the river discharge by means of a slow and fast component, being (i) percolation to the groundwater reservoir that eventually becomes base flow, and (ii) direct runoff. The cell-specific runoff, which becomes available for routing, is the sum of surface runoff, lateral flow, base flow, snow melt and glacier melt.



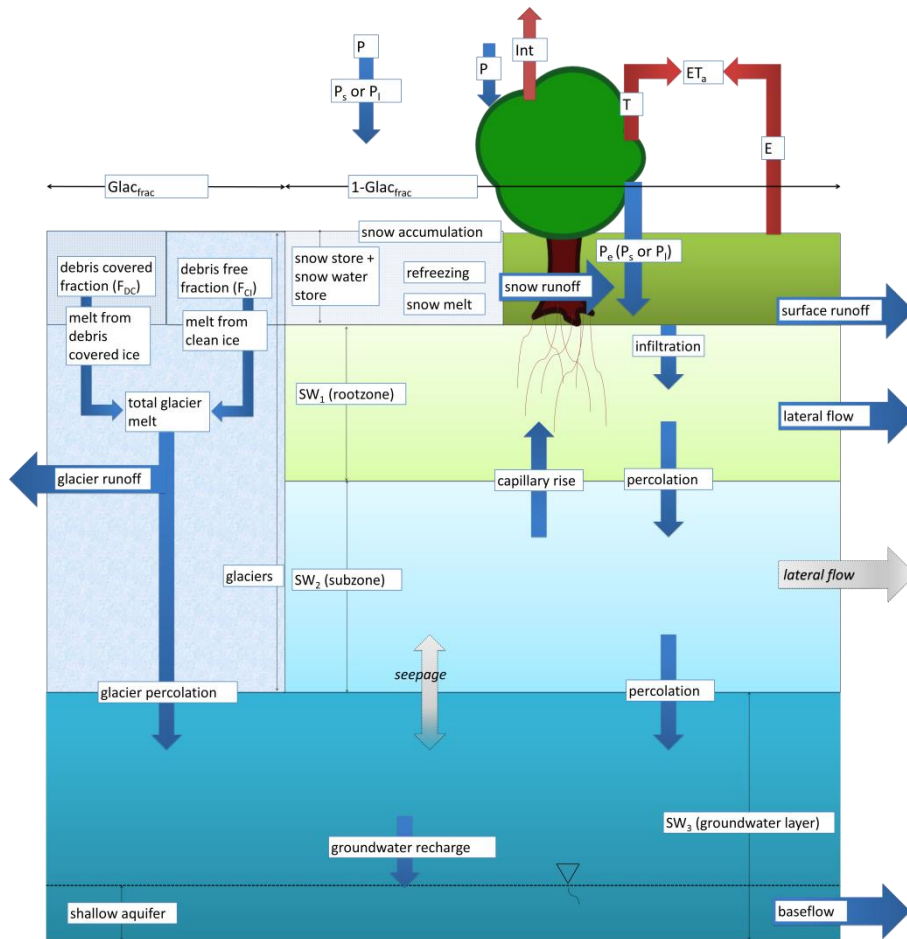


Figure 1: SPHY model concepts. Fluxes in grey (seepage and lateral flow) are only calculated if groundwater layer is switched off.

If no lakes are present, then the user can choose for a simple flow accumulation routing scheme: for each cell the accumulated amount of material that flows out of the cell into its neighboring downstream cell is calculated. This accumulated amount is the amount of material in the cell itself plus the amount of material in upstream cells of the cell. For each cell, the following procedure is performed: using the local drain direction network, the catchment of a cell is determined which is made up the cell itself and all cells that drain to the cell. If lakes are present, then the fractional accumulation flux routing scheme is used: depending on the actual lake storage, a fraction of that storage becomes available for routing and is extracted from the lake, while the remaining part becomes the updated actual lake storage. The flux available for routing is routed in the same way as in the simple flow accumulation routing scheme.

As input SPHY requires data on state variables as well as dynamic variables. For the state variables the most relevant are: Digital Elevation Model (DEM), land use type, glacier cover, reservoirs and soil characteristics. The main dynamic variables are climate data such as precipitation, temperature, reference evapotranspiration. Since SPHY is grid-based optimal use of remote sensing data and global data sources can be made. For example, the Normalized Difference Vegetation Index (NDVI) (Tucker, 1979; Carlson and Ripley, 1997; Myneni and Williams, 1994) can be used to determine the Leaf Area Index (LAI) in order to estimate the growth-stage of land cover. For setting-up the model data on streamflows are not necessary. However, to undertake a proper calibration and validation procedure flow data are required. The model could also be calibrated using actual evapotranspiration, soil moisture contents, or snow coverage.



The SPHY model provides a wealth of output data that can be selected based on the preference of the user. Spatial output can be presented as maps of all the hydrological processes. Maps often displayed as output include actual evapotranspiration, runoff generation (separated by its contributors), and groundwater recharge. These maps can be generated on daily base, but most users prefer to get those at monthly or annual aggregated time periods. Time-series can be generated for each location in the study area. Time-series often used are stream flow under current and future conditions, actual evapotranspiration and recharge to the groundwater.

2.1.2 Modules

SPHY enables the user to turn on/off modules that are not required. This concept is very useful if the user is studying hydrological processes in regions where not all hydrological processes are relevant. A user may for example be interested in studying irrigation water requirements in central Africa. For this region glacier and snow melting processes are irrelevant, and can thus be switched off. Another user may only be interested in simulating moisture conditions in the first soil layer, allowing the possibility to switch off the routing and groundwater modules. The advantages of turning off irrelevant modules are two-fold: (i) decrease model run-time, and (ii) decrease the amount of required model input data.

Figure 2 represents an overview of the six modules available: glaciers, snow, groundwater, dynamic vegetation, simple routing, and lake/reservoir routing. All modules can run independently from each other, except for the glacier module. If glaciers are present, then snow processes are relevant as well (Verbunt et al., 2003; Singh and Kumar, 1997), meaning that the snow module is turned on automatically if the glacier module is turned on. Since melting glacier water percolates to the groundwater store, the glacier module cannot run with the groundwater module turned off. For routing two modules are available, being (i) a simple flow accumulation routing scheme, and (ii) a fractional flow accumulation routing scheme used when lakes/reservoirs are present. The user has the option to turn off routing, or to choose between one of these two routing modules. All hydrological processes incorporated in the SPHY model are described in detail in the following sections.

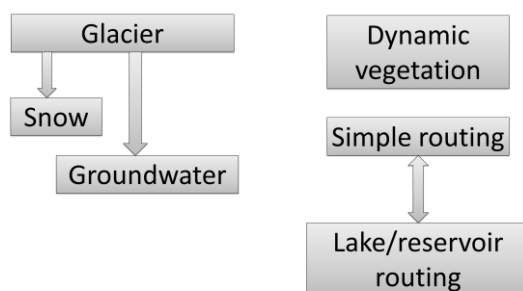


Figure 2: Modules of the SPHY model.

2.1.3 Dynamic vegetation module

SPHY allows the user to use the dynamic vegetation module in order to incorporate changing vegetation cover and corresponding rainfall interception. If this module is not used, then no rainfall interception is calculated and it is assumed that vegetation (land use) is static over time. This incorporates the use of a single crop coefficient for the calculation of the potential evapotranspiration throughout the entire simulation period. The calculation of the reference

evapotranspiration (ET_r), potential evapotranspiration (ET_p), and actual evapotranspiration (ET_a) is described in detail in Section 2.1.6.2 and Section 2.1.6.3.

2.1.3.1 Canopy storage

If the dynamic vegetation module is used, then SPHY simulates the impact of a dynamic vegetation cover using a time-series of the Normalized Difference Vegetation Index (NDVI) (Carlson and Ripley, 1997). The first step involves the calculation of the fraction photosynthetically active radiation (FPAR). The FPAR can be calculated using a relation between the NDVI and the FPAR, which was found by Peng et al. (2012) and described by Sellers et al. (1996), according to:

$$FPAR = \min \left(\frac{(SR - SR_{min})(FPAR_{max} - FPAR_{min})}{(SR_{max} - SR_{min})} + FPAR_{min}, 0.95 \right)$$

Equation 1.

with:

$$SR = \frac{1 + NDVI}{1 - NDVI}$$

Equation 2.

and $FPAR_{max}$ [–] and $FPAR_{min}$ [–] having values of 0.95 and 0.001, respectively. An FPAR of 0.95 is equivalent to the maximum LAI for a particular class, and an FPAR of 0.001 is equivalent to a minimum LAI. In order to calculate the FPAR, an NDVI time-series is required.

The second step is the calculation of the Leaf-Area-Index (LAI), which is eventually required to calculate the maximum canopy storage ($Scan_{max}$). According to Monteith (1973), the LAI for vegetation that is evenly distributed over a surface can be calculated using a logarithmic relation between the LAI and FPAR, according to:

$$LAI = LAI_{max} \cdot \frac{\log(1 - FPAR)}{\log(1 - FPAR_{max})}$$

Equation 3.

with LAI [–] the Leaf-Area-Index, and LAI_{max} [–] the maximum Leaf-Area-Index (vegetation type dependent). This means that the maximum and minimum LAI values are related to the maximum and minimum of FPAR. Table 1 shows the LAI_{max} values for a certain number of vegetation types.

For vegetation that is concentrated in clusters the linear relation from Goward and Huemmrich (1992) is often used. However, since SPHY is generally applied using grid cell resolutions between 250 m and 1 km, we can assume that the effect of having vegetation concentrated in clusters is neglectable. Therefore, the calculation of the LAI in SPHY is done using the logarithmic relation of Monteith (1973) (Equation 3).



Table 1: LAI_{max} values for different vegetation types (Sellers et al., 1996).

Vegetation type	LAI_{max} [-]
Broadleaf evergreen trees	7
Broadleaf deciduous trees	7
Mixed trees	7.5
Needleleaf evergreen trees	8
High latitude deciduous trees	8
Grass with 10 - 40% woody cover	5
Grass with <10% woody cover	5
Shrubs and bare soil	5
Moss and lichens	5
Bare	5
Cultivated	6

The next step involves the calculation of the maximum canopy storage ($Scan_{max}$ [mm]). Many different relations between S_{max} and the LAI can be found in literature depending on the vegetation type (de Jong and Jetten, 2010). The best results for crop canopies are shown by Kozak et al. (2007) and are archived by Von Hoyningen-Huene (1981) who derived the following relation between $Scan_{max}$ and the LAI:

$$Scan_{max} = 0.935 + 0.498LAI - 0.00575LAI^2$$

Equation 4.

Because of the agricultural focus in projects where SPHY has been applied, this relation has also been adopted in the SPHY model. Note that even with an LAI of zero, $Scan_{max}$ is still close to 1 mm.

2.1.3.2 Interception

Interception is calculated on a daily basis, and consists of the daily precipitation plus the intercepted water remaining in the canopy storage from the previous day. First of all the canopy storage is updated with the amount of precipitation of the current day:

$$Scan_t = Scan_{t-1} + P_t$$

Equation 5.

With $Scan_t$ [mm] the canopy storage on day t, $Scan_{t-1}$ [mm] the canopy storage on day t – 1, and P_t [mm] the amount of precipitation on day t. The portion of precipitation that cannot be stored in the canopy storage is known as precipitation throughfall, or effective precipitation, according to:

$$Pe_t = \max(0, Scan_t - Scan_{max,t})$$

Equation 6.

with Pe_t [mm] the effective precipitation on day t, and $Scan_t$ [mm] the canopy storage on day t. This equation shows that precipitation throughfall only occurs if the water stored in the canopy exceeds the maximum canopy storage. After the effective precipitation has been calculated, the canopy storage is updated as:



$$Scan_t = Scan_t - Pe_t$$

Equation 7.

The remaining amount of water stored in the canopy is available for interception, and the amount of water that will be intercepted depends on the atmospheric demand for open water evaporation. According to Allen et al. (1998), a value of 1.5 is generally taken for the atmospheric demand for open water evaporation, and is derived from the mean Kp (~0.65) between pan evaporation and the reference evapotranspiration (ET_r). If desired this value can easily be altered in the model code. The interception can now be calculated using:

$$Int_t = \min(1.5ET_r, Scan_t)$$

Equation 8.

with Int_t [mm] the intercepted water on day t, and $ET_{r,t}$ [mm] the reference evapotranspiration on day t. Finally, the canopy storage is updated by subtracting the interception:

$$Scan_t = Scan_t - Int_t$$

Equation 9.

2.1.4 Snow processes

For each cell a dynamic snow storage is simulated at a daily time step, adopted from the model presented by Kokkonen et al. (2006). The model keeps track of a snow storage, which is fed by precipitation and generates runoff from snow melt. Refreezing of snow melt and rainfall within the snowpack are simulated as well.

2.1.4.1 Snow and rainfall

Depending on a temperature threshold, precipitation is defined to fall in either solid or liquid state. Daily snow accumulation, which is defined as solid precipitation, is calculated as:

$$P_{s,t} = \begin{cases} Pe_t, & \text{if } T_{avg,t} \leq T_{crit} \\ 0, & \text{if } T_{avg,t} > T_{crit} \end{cases}$$

Equation 10.

with $P_{s,t}$ [mm] the snowfall on day t, Pe_t [mm] the effective precipitation on day t, $T_{avg,t}$ [°C] the mean air temperature on day t, and T_{crit} [°C] a calibrated temperature threshold for precipitation to fall as snow. The precipitation that falls as rain is defined as liquid precipitation, and is calculated as:

$$P_{l,t} = \begin{cases} Pe_t, & \text{if } T_{avg,t} > T_{crit} \\ 0, & \text{if } T_{avg,t} \leq T_{crit} \end{cases}$$

Equation 11.

with $P_{l,t}$ [mm] being the amount of rainfall on day t.



2.1.4.2 Snow melt, refreezing, and storage

To simulate snow melt, the well-established and widely used degree day melt modeling approach is used (Hock, 2003). The application of degree-day models is widespread in cryospheric models and is based on an empirical relationship between melt and air temperature. Degree-day models are easier to set up compared to energy-balance models, and only require air temperature, which is mostly available and relatively easy to interpolate (Hock, 2005). Using a degree-day modeling approach, the daily potential snow melt is calculated as follows:

$$A_{pot,t} = \begin{cases} T_{avg,t} \cdot DDF_s, & \text{if } T_{avg,t} > 0 \\ 0, & \text{if } T_{avg,t} \leq 0 \end{cases}$$

Equation 12.

with $A_{pot,t}$ [mm] the potential snow melt on day t , and DDF_s [$\text{mm } ^\circ\text{C}^{-1}\text{d}^{-1}$] a calibrated degree day factor for snow. The actual snow melt is limited by the snow store at the end of the previous day, and is calculated as:

$$A_{act,t} = \min(A_{pot,t}, SS_{t-1})$$

Equation 13.

with $A_{act,t}$ [mm] the actual snow melt on day t , and SS_{t-1} [mm] the snow store on day $[t - 1]$. The snow store from day $[t - 1]$ is then updated to the current day t , using the actual snow melt ($A_{act,t}$) and the solid precipitation ($P_{s,t}$). Part of the actual snow melt refreezes within the snow pack and thus does not runoff immediately. When temperature is below the melting point, melt water that has refrozen in the snow pack during $[t - 1]$ is added to the snow store as:

$$SS_t = \begin{cases} SS_{t-1} + P_{s,t} + SSW_{t-1}, & \text{if } T_{avg,t} < 0 \\ SS_{t-1} + P_{s,t} - A_{act,t}, & \text{if } T_{avg,t} \geq 0 \end{cases}$$

Equation 14.

with SS_t the snow store on day t , SS_{t-1} the snow store on day $[t - 1]$, $P_{s,t}$ the solid precipitation on day t , $A_{act,t}$ the actual snow melt on day t , SSW_{t-1} the amount of refrozen melt water on day $[t - 1]$. The units for all terms are in mm.

The capacity of the snow pack to refreeze snow melt is characterized by introducing a calibrated water storage capacity (SSC [$\text{mm} \cdot \text{mm}^{-1}$]), which is the total mm water equivalent of snow melt that can refreeze per mm water equivalent of snow in the snow store. The maximum of melt water that can refreeze (SSW_{max} [mm]) is thus limited by the thickness of the snow store:

$$SSW_{max,t} = SSC \cdot SS_t$$

Equation 15.

Then the amount of melt water stored in the snowpack, and that can refreeze in the next time-step, is calculated as:



$$SSW_t = \begin{cases} 0, & \text{if } T_{avg,t} < 0 \\ \min(SSW_{max,t}, SSW_{t-1} + P_{l,t} + A_{act,t}), & \text{if } T_{avg,t} \geq 0 \end{cases}$$

Equation 16.

with SSW_t the amount of melt water in the snow pack on day t , $SSW_{max,t}$ the maximum of melt water that can refreeze on day t , SSW_{t-1} the amount of refrozen melt water on day $[t - 1]$, $P_{l,t}$ the amount of rainfall on day t , and $A_{act,t}$ the actual snow melt on day t . The units of all terms are in mm.

The total snow storage (SST [mm]) consists of the snow store and the melt water that has refrozen within it, according to:

$$SST_t = (SS_t + SSW_t) \cdot (1 - GlacF)$$

Equation 17.

with $(1 - GlacF)$ [–] the gridcell fraction not covered with glaciers. In SPHY it is therefore assumed that snow accumulation and melt can only occur on the grid cell fraction determined as land surface. Snow falling on glaciers is incorporated in the glacier module.

2.1.4.3 Snow runoff

Runoff from snow (SRO [mm]) is generated when the air temperature is above melting point and no more melt water can be refrozen within the snow pack, according to:

$$SRO_t = \begin{cases} A_{act,t} + P_{l,t} - \Delta SSW, & \text{if } T_{avg,t} > 0 \\ 0, & \text{if } T_{avg,t} \leq 0 \end{cases}$$

Equation 18.

with ΔSSW [mm] the change in melt water stored in the snowpack according to:

$$\Delta SSW = SSW_t - SSW_{t-1}$$

Equation 19.

2.1.5 Glacier processes

Since the SPHY model usually operates at a spatial resolution between 250 m and 1 km, the dynamics of glaciers such as ice flow cannot be resolved explicitly. Therefore glaciers in SPHY are considered as melting surfaces which can completely or partly cover a grid cell.

2.1.5.1 Glacier melt

Glacier melt is calculated with a degree day modeling approach as well (Hock, 2005). Because glaciers covered with debris melt at different rates than debris-free glaciers (Reid et al., 2012), a distinction can be made between different degree day factors for both types. The daily melt from debris free glaciers (A_{CI} [mm]) is calculated as:



$$A_{CI,t} = \begin{cases} T_{avg,t} \cdot DDF_{CI} \cdot F_{CI}, & \text{if } T_{avg,t} > 0 \\ 0, & \text{if } T_{avg,t} \leq 0 \end{cases}$$

Equation 20.

with DDF_{CI} [$\text{mm } ^\circ\text{C}^{-1}\text{d}^{-1}$] a calibrated degree day factor for debris free glaciers and F_{CI} [–] is the fraction of debris free glaciers within the fractional glacier cover ($GlacF$) of a grid cell. The daily melt from debris covered glaciers (A_{DC} [mm]) is calculated in a similar way, but with a different degree day factor:

$$A_{DC,t} = \begin{cases} T_{avg,t} \cdot DDF_{DC} \cdot F_{DC}, & \text{if } T_{avg,t} > 0 \\ 0, & \text{if } T_{avg,t} \leq 0 \end{cases}$$

Equation 21.

where DDF_{DC} [$\text{mm } ^\circ\text{C}^{-1}\text{d}^{-1}$] is a degree day factor for debris covered glaciers and F_{DC} [–] is the fraction of debris covered glaciers within the fractional glacier cover of a grid cell. The total glacier melt per grid cell (A_{GLAC} [mm]) is then calculated by summing the melt from the debris-covered and debris-free glacier types and multiplying by the fractional glacier cover, according to:

$$A_{GLAC,t} = (A_{CI,t} + A_{DC,t}) \cdot GlacF$$

Equation 22.

2.1.5.2 Glacier runoff

In SPHY a fraction of the glacier melt percolates to the ground water while the remaining fraction runs off. The distribution of both is defined by a calibrated glacier melt runoff factor ($GlacROF$ [–]) which can have any value ranging from 0 to 1. Thus the generated runoff GRo [mm] from glacier melt is defined as:

$$GRo_t = A_{GLAC,t} \cdot GlacROF$$

Equation 23.

2.1.5.3 Glacier percolation

The percolation from glacier melt to the groundwater (G_{perc} [mm]) is defined as:

$$G_{perc,t} = A_{GLAC,t} \cdot (1 - GlacROF)$$

Equation 24.

The glacier water that percolates to the groundwater is added to the water percolating from the soil water from the non-glaciered part of the grid cell (Sections 2.1.6.1 and 2.1.6.7) which will then recharge the groundwater.

When SPHY is run for future scenarios the fractional glacier cover in a grid cell changes according to a parameterization for glacier changes at river basin scale. This parameterization estimates the changes of a river basin's glacier extent as a function of the glacier size distribution in the basin and projected temperature and precipitation. This parameterization was



developed specifically for inclusion in large scale hydrological models and is described in detail in Lutz et al. (2013).

2.1.6 Soil water processes

2.1.6.1 Soil water balances

The soil water processes in SPHY are modelled for three soil compartments, being (i) the first soil layer (rootzone), (ii) second soil layer (sub-soil), and (iii) third soil layer (groundwater store). The water balance of the first soil layer is:

$$SW_{1,t} = SW_{1,t-1} + Pe_t - Ea_t - RO_t - LF_{1,t} - Perc_{1,t} + Cap_t$$

Equation 25.

with $SW_{1,t}$ and $SW_{1,t-1}$ the water content in the first soil layer on day t and $[t - 1]$, respectively, Pe_t the effective precipitation on day t , Ea_t the actual evapotranspiration on day t , RO_t the surface runoff on day t , $LF_{1,t}$ the lateral flow from the first soil layer on day t , $Perc_{1,t}$ percolation from the first to the second soil layer on day t , Cap_t capillary rise from the second to the first soil layer on day t . The second soil layer water balance is:

$$SW_{2,t} = SW_{2,t-1} + Perc_{1,t} - Perc_{2,t} - Cap_t$$

Equation 26.

with $SW_{2,t}$ and $SW_{2,t-1}$ the water content in the second soil layer on day t and $[t - 1]$, respectively, and $Perc_{2,t}$ percolation from the second to the third soil layer on day t . The third soil layer water balance is given as:

$$SW_{3,t} = SW_{3,t-1} + Gchrg_t - BF_t$$

Equation 27.

with $SW_{3,t}$ and $SW_{3,t-1}$ the water content in the third soil layer on day t and $[t - 1]$, respectively, $Gchrg_t$ groundwater recharge from the second to the third soil layer on day t , and BF_t baseflow on day t . If the glacier module is used, then groundwater recharge consists of percolation from the second soil store and percolated glacier melt, otherwise only percolation from the second soil store is taken into account.

The user can opt to run SPHY without the third (groundwater) soil layer. This may be desirable if the user for example is mainly interested in simulating soil moisture conditions in the rootzone, instead of evaluating e.g. the contribution of baseflow to the total routed river flow. In that case only the two upper soil compartments are used where the bottom boundary of soil layer two is controlled by a seepage flux (pos. outward), and instead of baseflow from the third soil layer, water leaves the second soil layer through lateral flow. With the groundwater module turned off, the water balance for the second soil layer is:

$$SW_{2,t} = SW_{2,t-1} + Perc_{1,t} - LF_{2,t} - Cap_t - Seep$$

Equation 28.



with $LF_{2,t}$ lateral flow from the second soil layer, and Seep seepage in or out of the second soil layer (pos. is outgoing). The units for all water balance terms are mm.

2.1.6.2 Reference and potential evapotranspiration

Various methods exist to calculate the reference evapotranspiration (ET_r). From the many existing methods, the FAO-56 application of the Penman-Monteith equation (Allen et al., 1998) has been most widely used, and can be considered as a sort of standard (Walter et al., 2001). Despite the good physical underlying theory of this method, its major drawback is its relatively high data demand. The Penman-Monteith equation requires air temperature, wind speed, relative humidity, and solar radiation data. In many regions around the world (e.g. Africa), these data are not readily measured at meteorological stations, and therefore not suitable. Another well-known method to calculate the ET_r is the Hargreaves method (Hargreaves and Samani, 1985). Droogers and Allen (2002) showed that in many regions around the globe, the Hargreaves and Penman-Monteith method showed comparable results. A lack of meteorological data brought (Hargreaves and Samani 1985) to derive the modified Hargreaves equation that is only based on the average, minimum, and maximum daily air temperature. For this reason, this equation has also been implemented in the SPHY model, according to:

$$ET_r = 0.0023 \cdot 0.408 \cdot Ra(T_{avg} + 17.8) \cdot TD^{0.5}$$

Equation 29.

with $RA [MJm^{-2}d^{-1}]$ the extraterrestrial radiation, $T_{avg} [^{\circ}C]$ the average daily air temperature, and $TD [^{\circ}C]$ the temperature range, defined as the difference between the daily maximum and minimum air temperature. The constant 0.408 is required to convert the radiation to mm evaporation equivalents, and RA can be obtained from tables (Allen et al. 1998) or equations using the day of the year and the latitude of the area of interest.

According to Allen et al. (1998), the ET_r is the evapotranspiration rate from a reference surface, not short of water. The reference surface is a hypothetical grass reference crop with specific characteristics. The potential evapotranspiration ET_p has no limitations on crop growth or evapotranspiration from soil water and salinity stress, crop density, pests and diseases, weed infestation or low fertility. Allen et al. (1998) determined the ET_p by the crop coefficient approach, where the effect of various weather conditions are incorporated into ET_r , and the crop characteristics in the crop coefficient (Kc), using:

$$ET_{p,t} = ET_{r,t} \cdot Kc$$

Equation 30.

with $ET_{p,t} [mm]$ the potential evapotranspiration on day t , $ET_{r,t} [mm]$ the reference evapotranspiration on day t , and $Kc [-]$ the crop coefficient. The effect of both crop transpiration and soil evaporation are integrated into the Kc .

If the dynamic vegetation module in SPHY is not used, then the user can opt to use a single constant Kc throughout the entire simulation period or use a time-series of crop coefficients as model input. However, vegetation is generally very dynamic throughout the year, and therefore it is not very realistic to use a single constant Kc throughout the entire simulation period. It is



therefore more realistic to use a time-series of crop coefficients as model input, or use the dynamic vegetation module instead. This can be adjusted according to the user's preferences.

In the dynamic vegetation module the K_c is scaled throughout the year using the NDVI and the maximum and minimum values for K_c , which are crop specific. These values for K_c can easily be obtained from Allen et al. (1998). Then the K_c is calculated using:

$$K_c = K_{c_{min}} + (K_{c_{max}} - K_{c_{min}}) * \frac{(NDVI - NDVI_{min})}{(NDVI_{max} - NDVI_{min})}$$

Equation 31.

with $NDVI_{max}$ [–] and $NDVI_{min}$ [–] the maximum and minimum values for the NDVI (vegetation type dependent). Using this approach in SPHY to calculate the K_c dynamically using the NDVI as input shows the strong linkage with the use of remote sensing data as input to improve model accuracy.

2.1.6.3 Actual evapotranspiration

Evapotranspiration refers to both the transpiration from vegetation and the evaporation from soil or open water. Some models especially focusing on Plant-Water-Atmosphere processes, like e.g. SWAP (van Dam et al., 1997; Noory et al., 2011), calculate the evaporation and transpiration fluxes separately. For these kind of models it is relevant to calculate these fluxes separately, because these models generally focus on 1-dimensional flow processes on a very small spatial scale (1 farm field) where sufficient field data, that is required for the calculation of soil evaporation, is generally available.

At a wet soil, the soil evaporation is equal to its potential evaporation rate. As soon as the soil becomes drier the hydraulic conductivity decreases as well. The requirement of the soil water content as well as the hydraulic conductivity at multiple depths (van Dam et al., 1997) shows the amount of data detail that is required to calculate the soil evaporation separately from the plant transpiration.

SPHY does not calculate the evaporation and transpiration fluxes separately for several reasons. The first reason is that SPHY is generally applied on larger spatial scales where these data are simply not available. The second reason is because the process of soil evaporation generally starts after wetting of the soil, or in other words, after a precipitation event. These precipitation events occur normally within the time frame of one day, and have a duration varying from minutes to hours. Since SPHY runs on a daily temporal resolution, the sub-daily occurrence of precipitation events and sub-daily wetting of soil is not accounted for. The third reason is that SPHY is a spatially distributed model that allows the user to define different crop coefficients (K_c) spatially. As was mentioned in Section 2.1.6.2, the K_c accounts for both the crop transpiration and soil evaporation. Therefore, the user can choose to use a K_c specifically for bare soil (0.15-0.20, (Allen et al., 1998)) on locations where bare soil is the dominant land use. The additional use of the dynamic vegetation module accounts for a varying vegetation cover, meaning that the role of evaporation becomes more dominant as soon as vegetation cover decreases.

Many limiting factors (e.g. salinity stress, water shortage, water excess, diseases) can cause a reduction in potential evapotranspiration (ET_p), resulting in the actual evapotranspiration rate



(ET_a). Since SPHY is a water-balance model, SPHY only accounts for stresses related to water shortage or water excess. If there is too much water in the soil profile, then the plant is unable to extract oxygen (Bartholomeus et al., 2008). The calculation of evapotranspiration reduction due to water excess (oxygen stress) is quite complex and requires a vast amount of parameters that is generally not available for the spatial scale that SPHY is applied on. Therefore, SPHY uses an evapotranspiration reduction parameter ($ETred_{wet}$) that has a value of 0 if the soil is saturated, and otherwise it will have a value of 1. This parameter is used in the following equation to calculate the actual evapotranspiration:

$$ET_{a,t} = ET_{p,t} \cdot ETred_{wet} \cdot ETred_{dry}$$

Equation 32.

with $ET_{a,t}$ [mm] the actual evapotranspiration on day t, $ET_{p,t}$ [mm] the potential evapotranspiration on day t, and $ETred_{wet}$ and $ETred_{dry}$ being the reduction parameters for water excess and water shortage conditions, respectively. The $ETred_{dry}$ is calculated using the Feddes equation (Feddes et al., 1978), which assumes a linear decline in rootwater uptake if the water pressure head drops below a critical value. This critical value can be determined using the soil water retention curve (pF-curve), which relates the soil type to its water binding capacity. This binding capacity is a suction force, and is often expressed in cm negative water column. The pF is simply calculated as:

$$pF = \log_{10}(-H)$$

Equation 33.

with H [-cm] the water column. Soils that are at field capacity generally have a pF of 2, meaning -100 cm of water column, and soils that are at permanent wilting point have a pF of 4.2, or -16000 cm of water column. The permanent wilting point is often referred to as the point where the crop dies. In SPHY it is assumed that the linear decline in rootwater uptake starts at a pF of 3 (-1000 cm water column). Therefore, the $ETred_{dry}$ [-] is calculated as:

$$ETred_{dry,t} = \frac{SW_{1,t} - SW_{1,pF4.2}}{SW_{1,pF3} - SW_{1,pF4.2}}$$

Equation 34.

with $ETred_{dry,t}$ [-] the reduction in rootwater uptake due to water shortage on day t, $SW_{1,t}$ [mm] the actual soil water content in the first soil layer on day t, and $SW_{1,pF3}$ [mm] and $SW_{1,pF4}$ [mm] the soil water content in the first soil layer at pF3 and pF4, respectively. $ETred_{dry}$ can therefore have values ranging between zero and one, where a value of one represents optimal plant growing conditions, and zero means no rootwater uptake at all. Finally, $ETred_{dry}$ is used in Equation 32 to calculate ET_a .

2.1.6.4 Surface runoff

Within the field of hydrology two types of surface runoff can be distinguished: Hewlettian (Hewlett, 1961) and Hortonian (Beven, 2004; Corradini et al., 1998) runoff. Hewlettian runoff is often referred to as saturation excess overland flow, while Hortonian runoff is also known as infiltration excess overland flow. Hewlettian runoff occurs when the soil is saturated, and more



rainfall is added, resulting in direct surface runoff. Hortonian runoff occurs when the rainfall intensity exceeds the infiltration capacity of the soil: during wetting of the soil, the soil infiltration capacity decreases over time, and if at a certain moment the rainfall intensity exceeds the soil infiltration capacity, surface runoff occurs.

Since the SPHY model runs on a daily time-step, the model does not account for sub-daily variability in rainfall intensities, meaning that Hortonian runoff processes can be considered as less important. For this reason SPHY uses the Hewlettian runoff concept to calculate surface runoff. Surface runoff is calculated from the first soil layer:

$$RO = \begin{cases} SW_1 - SW_{1,sat}, & \text{if } SW_1 > SW_{1,sat} \\ 0, & \text{if } SW_1 \leq SW_{1,sat} \end{cases}$$

Equation 35.

with RO [mm] surface runoff, SW_1 [mm] the water content in the first soil layer, and $SW_{1,sat}$ [mm] the saturated water content of the first soil layer.

2.1.6.5 Lateral flow

Lateral flow is substantial in catchments with steep gradients and soils with high hydraulic conductivities (Beven, 1981; Beven and Germann 1982; Sloan and Moore 1984). In SPHY it is assumed that only the amount of water exceeding field capacity can be used for lateral flow. Therefore, first the drainable volume of water (excess water) needs to be calculated:

$$W_{l,exc} = \begin{cases} SW_l - SW_{l,fc}, & \text{if } SW_l > SW_{l,fc} \\ 0, & \text{if } SW_l \leq SW_{l,fc} \end{cases}$$

Equation 36.

with $W_{l,exc}$ [mm] the drainable volume of water from soil layer l, SW_l [mm] the water content in soil layer l, and $SW_{l,fc}$ [mm] the field capacity of soil layer l. According to Sloan and Moore (1984), the lateral flow at the hillslope outlet can be calculated as:

$$LF_l^* = W_{l,excfrac} \cdot v_{lat,l}$$

Equation 37.

with LF_l^* [mm] lateral flow from soil layer l, $W_{l,excfrac}$ [–] the drainable volume of water as fraction of the saturated volume, and $v_{lat,l}$ [mm · d⁻¹] the flow velocity at the outlet. In SPHY, the drainable volume as fraction of the saturated volume is calculated as:

$$W_{l,excfrac} = \frac{W_{l,exc}}{SW_{l,sat} - SW_{l,fc}}$$

Equation 38.

The velocity of flow at the outlet, $v_{lat,l}$ [mm · d⁻¹], depends on both the saturated hydraulic conductivity $K_{sat,l}$ [mm · d⁻¹] and the slope of the hill slp [–], and is defined as:



$$v_{lat,l} = K_{sat,l} \cdot slp$$

Equation 39.

The slope (slp) in SPHY is calculated for each cell as the increase in elevation per unit distance. According to Neitsch et al. (2009), only a fraction of lateral flow will reach the main channel on the day it is generated if the catchment of interest is large with a time of concentration is greater than 1 day. This concept is also implemented in the SPHY model, and uses a lateral flow travel time $TT_{lag,l}$ [d] to lag a portion of lateral flow release to the channel:

$$LF_l = (LF_l^* + LF_{l,t-1}^*) \cdot \left(1 - \exp\left[\frac{-1}{TT_{lag,l}}\right]\right)$$

Equation 40.

with LF_l [mm] the amount of lateral flow entering the channel on a given day, LF_l^* [mm] the lateral flow (Equation 37) generated within the cell on a given day, $LF_{l,t-1}^*$ [mm] the lateral flow lagged from the previous day. SPHY assumes the lateral flow travel time to be dependent on the field capacity $SW_{l,fc}$ [mm], saturated content $SW_{l,sat}$ [mm], and the saturated conductivity $K_{sat,l}$ [mm · d⁻¹], according to:

$$TT_{lag,l} = \frac{SW_{l,sat} - SW_{l,fc}}{K_{sat,l}}$$

Equation 41.

A larger lateral flow travel time will result in a smoother streamflow hydrograph.

2.1.6.6 Percolation

If the groundwater module is used, then water can percolate from the first to the second soil layer and from the second to the third soil layer. If the user decides to run SPHY without the groundwater module, percolation only occurs from the first to the second soil layer. In SPHY water can only percolate if the water content exceeds the field capacity of that layer, and the water content of the underlying layer is not saturated. A similar approach has been used in the SWAT model (Neitsch et al., 2009). The water volume available for percolation to the underlying layer is calculated as:

$$W_{l,exc} = \begin{cases} 0, & \text{if } SW_l \leq SW_{l,fc} \text{ or } SW_{l+1} \geq SW_{l+1,sat} \\ SW_{l+1,sat} - SW_{l+1}, & \text{if } SW_l - SW_{l,fc} > SW_{l+1,sat} - SW_{l+1} \\ SW_l - SW_{l,fc}, & \text{else} \end{cases}$$

Equation 42.

with $W_{l,exc}$ [mm] the drainable volume of water from layer l , SW_l [mm] the water content in layer l , $SW_{l,fc}$ [mm] field capacity of layer l , SW_{l+1} [mm] the water content in layer $[l + 1]$, and $SW_{l+1,sat}$ [mm] the saturated water content of layer $[l + 1]$. Only a certain amount of $W_{l,exc}$ will percolate to the underlying soil layer, depending on the percolation travel time $TT_{perc,l}$ [d]. This approach follows the storage routing methodology, which is also implemented in the SWAT model (Neitsch et al., 2009):



$$w_{l,perc} = W_{l,exc} \cdot \left(1 - \exp \left[\frac{-1}{T T_{perc,l}} \right] \right)$$

Equation 43.

with $w_{l,perc}$ [mm] the amount of water percolating to the underlying soil layer. The travel time for percolation is calculated in the same way as the travel time for lateral flow (Equation 41).

2.1.6.7 Groundwater recharge

Water that percolates from the second to the third soil layer will eventually reach the shallow aquifer. This process is referred to as groundwater recharge hereafter. If the glacier module is used as well, then also glacier melt that percolates contributes to the groundwater recharge. Groundwater recharge often does not occur instantaneous, but with a time lag that depends on the depth of the groundwater table and soil characteristics. SPHY uses the same exponential decay weighting function as proposed by Venetis (1969) and used by Sangrey et al. (1984) in a precipitation groundwater response model. This approach has also been adopted in the SWAT model (Neitsch et al. 2009), using:

$$Gchrg_t = \left(1 - \exp^{\frac{-1}{\delta_{gw}}} \right) \cdot w_{2,perc} + \exp^{\frac{-1}{\delta_{gw}}} \cdot Gchrg_{t-1}$$

Equation 44.

with $Gchrg_t$ [mm] and $Gchrg_{t-1}$ [mm] the groundwater recharge on day t and $t - 1$, respectively. δ_{gw} [d] is the delay time and $w_{2,perc}$ [mm] is the amount of water that percolates from the second to the third layer on day t . It is very difficult to measure δ_{gw} , and therefore this is a calibration parameter in the SPHY model.

2.1.6.8 Baseflow

After groundwater recharge has been calculated, SPHY calculates baseflow which is defined as the flow going from the shallow aquifer to the main channel. Baseflow only occurs when the amount of water stored in the third soil layer exceeds a certain threshold (BF_{thresh}) that can be specified by the user. Baseflow calculation in SPHY is based on the steady-state response of groundwater flow to recharge (Hooghoudt, 1940) and the water table fluctuations that are a result of the non-steady response of groundwater flow to periodic groundwater recharge (Smedema and Rycroft, 1983). The SWAT model (Neitsch et al., 2009) assumes a linear relation between the variation in groundwater flow (baseflow) and the rate of change in water table height, according to:

$$\frac{dBF}{dt} = 10 \cdot \frac{K_{sat}}{\mu L_{gw}^2} \cdot (Gchrg - BF) = \alpha_{gw} \cdot (Gchrg - BF)$$

Equation 45.

with BF [mm] the groundwater flow (baseflow) into the main channel on day t , K_{sat} [mm d⁻¹] the hydraulic conductivity of the shallow aquifer, μ [–] the specific yield of the shallow aquifer, L_{gw} [m] the distance from the subbasin divide for the groundwater system to the main channel, $Gchrg$ [mm] the amount of groundwater (Equation 44) recharge entering the shallow aquifer on



day t , and α_{gw} [–] is the baseflow recession coefficient. Equation 45 can be integrated and rearranged to calculate baseflow, according to:

$$BF_t = \begin{cases} 0, & \text{if } SW_3 \leq BF_{thresh} \\ BF_{t-1} \cdot \exp^{-\alpha_{gw}} + Gchrg_t \cdot (1 - \exp^{-\alpha_{gw}}), & \text{if } SW_3 > BF_{thresh} \end{cases}$$

Equation 46.

with BF_t [mm] the baseflow into the channel on day t , and BF_{t-1} [mm] the baseflow into the channel on day $t - 1$. Since this equation has proven its success in the SWAT model (Neitsch et al., 2009) throughout many applications worldwide, this equation has been adopted in the SPHY model as well.

The baseflow recession coefficient (α_{gw}) is an index that relates the baseflow response to changes in groundwater recharge. Lower values for α_{gw} therefore correspond to areas that respond slowly to groundwater recharge, whereas higher values indicate areas that have a rapid response to groundwater recharge. The baseflow recession coefficient is generally used as a calibration parameter in the SPHY model, but a good first approximation of this coefficient can be calculated using the number of baseflow days (Neitsch et al., 2009):

$$\alpha_{gw} = \frac{2.3}{BFD}$$

Equation 47.

with BFD [d] the number of baseflow days, which is defined as the number of days required for baseflow recession to decline.

2.1.7 Streamflow routing

After calculating the different runoff components, the cell specific total runoff ($QTot$) is calculated by summarizing these different runoff components. Depending on the modules being switched on, the different runoff components are i) rain runoff (RRo), ii) snow runoff (SRo), iii) glacier runoff (GRo), and iv) baseflow (BF). If the groundwater module is not used, then baseflow is calculated as being the lateral flow from the second soil layer. Rainfall runoff is the sum of surface runoff (RO, Section 2.1.6.4) and lateral flow from the first soil layer (LF_1 , Section 2.1.6.5). Then $QTot$ is calculated according to:

$$QTot = RRo + SRo + GRo + BF$$

Equation 48.

with $QTot$ [mm] the cell specific total runoff, RRo [mm] rainfall runoff, SRo [mm] snow runoff, GRo [mm] glacier runoff, and BF [mm] being baseflow from the third soil layer or laterateral flow from the second soil layer. In order to obtain river discharge, $QTot$ needs to be routed through a flow direction network. SPHY allows the user to opt between the use of a simple routing scheme (Section 2.1.7.1), or a more complex routing scheme (Section 2.1.7.2) that involves the calculation of lake outflow through $Q(h)$ -relations. Both methods require a flow direction network map, which can be obtained by delineating a river network using PCRaster or GIS software in combination with a Digital Elevation Model (DEM).



2.1.7.1 Routing

In hydrology streamflow routing is referred to as being the transport of water through an open channel network. Since open-channel flow is unsteady, streamflow routing often involves the solving complex partial differential equations. The St. Venant equations (Brutsaert, 1979; Morris and Woolhiser, 1980) are often used for this, but these have high data requirements related to the river geometry and morphology, which is unavailable for the spatial scale SPHY is generally applied on. Additionally, solving these equations require the use of very small time steps, which results in large model calculation times. Other models, such as e.g. SWAT (Neitsch et al., 2009), use the Manning equation (Manning, 1989) to define the rate and velocity of river flow in combination with the variable storage (Williams, 1975) or Muskingum (Gill, 1978) routing methods to obtain river streamflow. But also the Manning equation requires river bed dimensions, which are generally unknown on the spatial scale that SPHY generally is applied on.

Therefore, SPHY calculates for each cell the accumulated amount of water that flows out of the cell into its neighboring downstream cell. This can easily be obtained by using the *accuflux* PCRaster built-in function. If only the *accuflux* function would be used, then it is assumed that all the specific runoff generated within the catchment on one day will end up at the most downstream location within one day, which is not plausible. Therefore, SPHY implements a flow recession coefficient (kx [–]) that accounts for flow delay, which can be a result of channel friction. Using this coefficient, river flow in SPHY is calculated using the three equations shown below:

$$QTot_t^* = \frac{QTot_t \cdot 0.001 \cdot A}{24 \cdot 3600}$$

Equation 49.

$$Q_{accu,t} = \text{accuflux}(F_{dir}, QTot_t^*)$$

Equation 50.

$$Q_{rout,t} = (1 - kx) \cdot Q_{accu,t} + kx \cdot Q_{rout,t-1}$$

Equation 51.

with $QTot_t^*$ [m^3s^{-1}] the specific runoff on day t , $QTot_t$ the specific runoff in mm on day t , A [m^2] the grid cell area, $Q_{accu,t}$ [m^3s^{-1}] the accumulated streamflow on day t , without flow delay taken into account, $Q_{rout,t}$ [m^3s^{-1}] the routed streamflow on day t , $Q_{rout,t-1}$ [m^3s^{-1}] the routed streamflow on day $t - 1$, F_{dir} the flow direction network, and kx [–] the flow recession coefficient. kx has values ranging between zero and one, where values close to zero correspond to a fast responding catchment, and values approaching one correspond to a slow responding catchment.

The user can opt to rout each of the four streamflow contributors separately, which may be useful if one wants to evaluate for example the contribution of glacier melt or snow melt to the total routed runoff. However, this increases model run-time substantially, because the *accuflux* function, which is a time consuming function, needs to be called multiple times depending on the number of flow contributors to be routed.



2.1.7.2 Lake/reservoir routing

Lakes or reservoirs present within a catchment act as natural buffer, resulting in a delayed release of water from these water bodies. SPHY allows the user to choose a more complex routing scheme if lakes/reservoirs are located in their basin of interest. The use of this more advanced routing scheme requires a known relation between lake outflow and lake level height (Q(h)-relation) or lake storage. If this relation is unknown, it is not possible to use the lake/reservoir routing scheme.

To use this routing scheme, SPHY requires a nominal map with cells identified as lakes each have a unique ID, while the non-lake cells have a value of zero. If SPHY is run in operational mode, then the user can supply a boolean map with True for cells that have measured lake levels and False for lake cells that do not have measured lake levels.

The user can choose between four different relations to calculate the lake outflow from the lake level height or lake storage, being: i) an exponential relation, ii) a first-order polynomial function, iii) a second-order polynomial function, and iv) a third-order polynomial function. In order to let SPHY know which relation to use, the user needs to supply a map with a value of one for lake cells using an exponential relation, a value of two for lake cells that use a first-order polynomial function, a value of three for lake cells that use a second-order polynomial function, a value of four for lake cells that use a third-order polynomial function, and a zero for the non-lake cells. Correspondingly, the user needs to supply maps containing the coefficients used in the different functions.

The lake/reservoir routing scheme simply keeps track of the actual lake storage, meaning that an initial lake storage should be supplied. Instead of the simple accuflux function described in the previous section, the lake/reservoir routing scheme uses the PCRaster functions *accufractionstate* and *accufractionflux*. The *accufractionflux* calculates for each cell the amount of water that is transported out of the cell, while the *accufractionstate* calculates the amount of water that remains stored in the cell. For non-lake cells the fraction that is transported to the next cell is always equal to one, while the fraction that is transported out of a lake/reservoir cell depends on the actual lake storage. Each model time-step the lake storage is updated by inflow from upstream. Using this updated storage, the lake level and corresponding lake outflow can be calculated using one of the four relations mentioned before. The lake outflow can then be calculated as a fraction (Q_{frac} [-]) of the actual lake storage. Instead of using Equation 50, the Q_{frac} is then used in Equation 52 and Equation 53 to calculate the streamflow and updated storage, respectively:

$$Q_{accu,t} = accufractionflux(F_{dir}, S_{act,t}, Q_{frac,t})$$

Equation 52.

$$S_{act,t+1} = accufractionstate(F_{dir}, S_{act,t}, Q_{frac,t})$$

Equation 53.

with $S_{act,t}$ [m^3] and $S_{act,t+1}$ [m^3] the actual storage and updated storage to be used in the next time-step, respectively, and $Q_{accu,t}$ [$m^3 d^{-1}$] the accumulated streamflow on day t. Since Q_{frac} is always equal to one for the non-lake cells, the *accufractionflux* function becomes equal to the *accuflux* function used in the previous section. This actually means that for the river network the



same routing function from Section 2.1.7.1 is used, and that Equation 52 and Equation 53 only apply to lake/reservoir cells.

In order to account for non-linearity and slower responding catchments, the same k_x coefficient is used again. This involves applying Equation 51 as a last step after Equation 52 and converting the units from m^3d^{-1} to m^3s^{-1} . Since the accufractionflux and accufraction state functions are more complex to compute, the use of these functions increases model run-time.

2.2 Applications of SPHY in snow and glacier-fed river basins

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, to irrigation scenarios in the Nile Basin, to detailed climate change impact studies in the snow-glacier-rain dominated the Himalayan region. Typical examples of SPHY applications in snow and glacier-fed river basins are shown below.

SPHY is being used in large Asian river basins with significant contribution of glacier- and snow melt to the total flow (Immerzeel et al., 2012; Lutz et al., 2012; Lutz et al., 2014). The major goals of these applications are two-fold:

- Assess the current hydrological regimes at high-resolution; e.g. assess spatial differences in the contributions of glacier melt, snow melt and rainfall-runoff to the total flow
- Quantify the effects of climate change on the hydrological regimes in the future and how these affect the water availability

Rivers originating in the high mountains of Asia are considered to be the most melt-water dependent river systems on Earth (Schaner et al., 2012). In the regions surrounding the Himalayas and the Tibetan Plateau large human populations depend on the water supplied by these rivers (Immerzeel et al., 2010). However, the dependency on melt water differs strongly between river basins as a result of differences in climate and differences in basin hypsometry (Immerzeel and Bierkens, 2012). Only by using a distributed hydrological modelling approach that includes the simulation of key hydrological and cryospheric processes, and inclusion of transient changes in climate, snow cover, glaciers and runoff, appropriate adaptation and mitigation options can be developed for this region (Sorg et al., 2012). The SPHY model is very suitable for such an approach, and has therefore been widely applied in the region.

For application in this region, SPHY was setup at a 1 km spatial resolution using a daily time-step, and forced with historical air temperature (T_{avg} , T_{max} , T_{min}) and precipitation data, obtained from global and regional datasets (e.g. APHRODITE (Yatagai et al., 2012), Princeton (Sheffield et al., 2006), TRMM (Gopalan et al., 2010)) or interpolated WMO station data from a historical reference period. For this historical reference period SPHY was calibrated and validated using observed streamflow. For the future period, SPHY was forced with downscaled climate change projections obtained from General Circulation Models (GCMs), as available through the Climate Model Intercomparison Projects (e.g. CMIP3 (Meehl et al., 2007), CMIP5 (Taylor et al., 2012)), and which were used as basis for the Assessment Reports prepared by the Intergovernmental Panel on Climate Change (IPCC).

In Central Asia, SPHY was successfully applied in a study for the Asian Development Bank (ADB, 2012; Immerzeel et al., 2012; Lutz et al., 2012), which focused on the impacts of climate



change on water resources in the Amu Darya and Syr Darya river basins. SPHY was used to quantify the hydrological regimes in both basins, and subsequently to project the outflow from the upstream basins to the downstream areas by forcing the model with an ensemble of 5 CMIP3 GCMs. The SPHY model output fed into a water allocation model that was setup for the downstream parts of the Amu Darya and Syr Darya river basins.

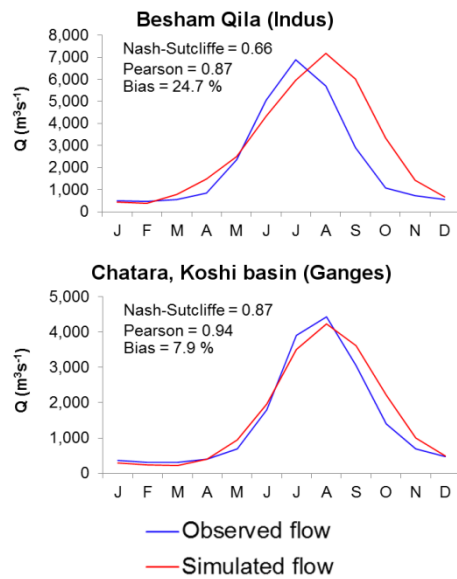


Figure 3: Average annual observed and SPHY-simulated flow 1998-2007 for major discharge measurement locations at Besham Qila in the Indus basin (upper panel) and Chatara in the Ganges basin (lower panel) (after Lutz et al., 2014).

In the Himalayan Climate Change Adaptation Programme (HICAP), led by the International Centre for Integrated Mountain Development (ICIMOD), SPHY has been successfully applied in the upstream basins of the Indus, Ganges, Brahmaputra, Salween and Mekong rivers (Lutz et al., 2013, 2014). In this study the hydrological regimes of these five basins have been quantified and the calibrated and validated model (Figure 3) was forced with an ensemble of eight GCMs to create water availability scenarios until 2050. SPHY allowed the assessment of current and future contribution of glacier melt and snow melt to total flow (Figure 4), and how total flow volumes and the intra-annual distribution of river flow will change in the future.

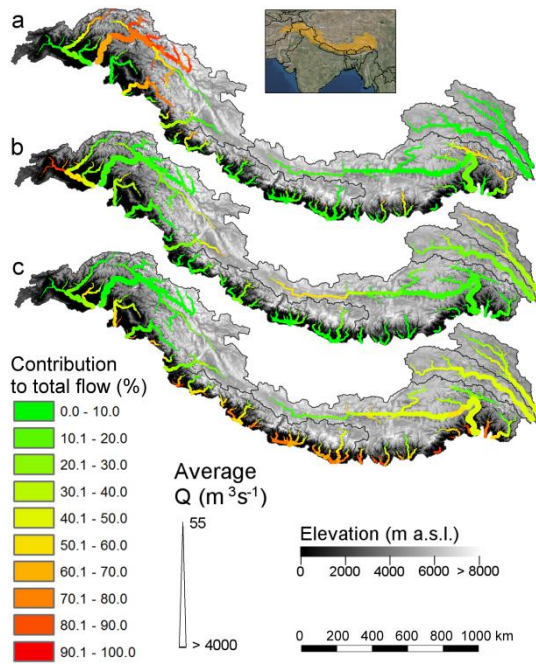


Figure 4: The contribution of glacier melt (a), snow melt (b), and rainfall (c) to the total flow for major streams in the upstream basins of the Indus, Ganges, Brahmaputra, Salween and Mekong during 1998-2007 (after Lutz et al., 2014).



3 Installation of SPHY

SPHY can be either be installed as i) a stand-alone application, where the user can run the model throughout the command prompt, or as ii) a an integrated application in QGIS, where the model can be run using a Graphical User-Interface (GUI). This GUI has been developed as a plugin in QGIS¹, and has the advantage that changing the model input and output, as well as changing model parameters, is more clear and user-friendly. Furthermore, the use of the GUI allows you to store and visualize your model input and output in the user-friendly and world-wide used QGIS Geographical Information System (GIS), which is in the public domain.

This chapter describes the installation of the various software packages that are required to use the SPHY model both as a stand-alone application and as an integrated application in QGIS.

3.1 Installing SPHY as a stand-alone application

In order to install SPHY as a stand-alone application it is required to have a PC with a windows operating system. Windows versions of 7 and higher are supported by the GUI, meaning that Windows XP is not compatible. The software packages that are required to run the SPHY model as stand-alone application are:

1. Python 2.7.6, 32-bit
2. Numpy 1.8.0, 32-bit
3. PCRaster 4.0, 32-bit
4. SPHY v2.0 source code

These packages need to be installed in the same order as shown above, and the installation of the each package is described in the following sections.

3.1.1 *Python 2.7.6 32-bit*

SPHY requires the installation of the Python² programming language. PCRaster has been developed using the 2.7.6 version of Python. Since SPHY has been developed using the 32-bit version of PCRaster 4.0, it is required to install the 32-bit version of Python 2.7.6, which can be downloaded from the internet using the link below:

<https://www.python.org/ftp/python/2.7.6/python-2.7.6.msi>

After downloading Python it can be installed by double clicking the downloaded file. During installation it will be asked where to install Python. You can choose any location that you prefer. As an example to be used in this manual, we have installed Python in the folder:

c:\Python27\

A final installation step includes setting the environmental variables. In order to do this, follow the steps below:

1. Go to start, then control panel, and type environment in the top-right search window.
2. Click on "Edit the system environmental variables".
3. Click "Environmental Variables" in the bottom-right of this window (Figure 5).
4. Under system variables, select the Path variable and click "Edit" (Figure 6).

¹ <http://www.qgis.org/en/site/>

² <https://www.python.org/>



5. In order let your system know the existence of your Python installation, it is required to add your Python installation folder to the “Path” system variable. This is shown in Figure 7 for our case, which was the c:\Python27 installation folder. It is important to have a semicolon between the system variables.
6. Finally, click OK and OK again in order to complete the installation of Python.

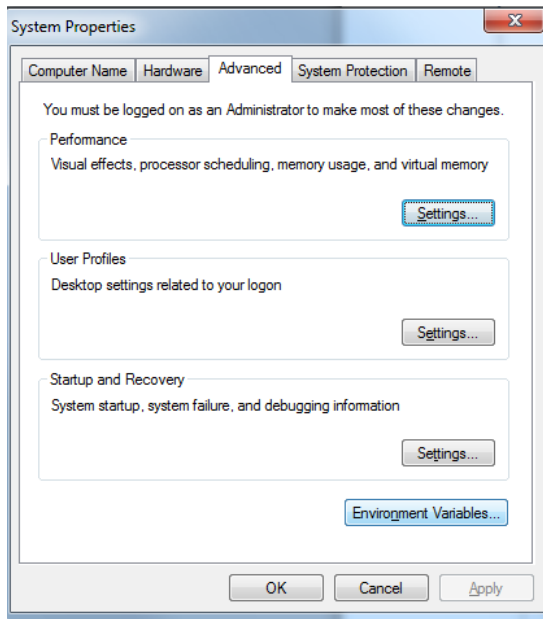


Figure 5: System properties to set Environmental Variables.

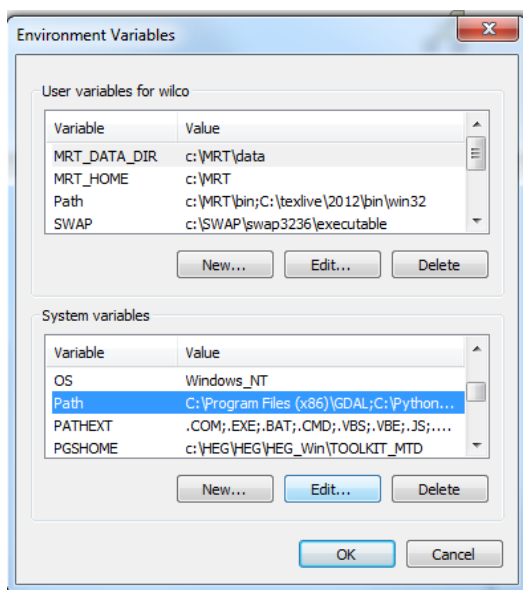


Figure 6: Setting the Path variable.

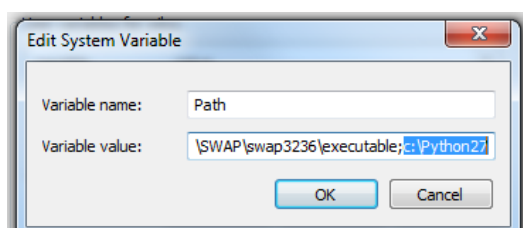


Figure 7: Adding the Python27 installation folder to the Path system variables.



3.1.2 Numpy 1.8.0 32-bit

Numpy stands for Numerical Python, and is a fundamental package for scientific computing with Python. It has especially been developed to work with raster data (arrays), which is also the basis of the PCRaster dynamic modelling framework in which SPHY has been developed.

SPHY requires a Numpy version that works with the 32-bit version of Python 2.7.6, which is Numpy 1.8.0 32-bit. This package can be downloaded using the link below:

<http://sourceforge.net/projects/numpy/files/NumPy/1.8.0/numpy-1.8.0-win32-superpack-python2.7.exe/download>

After downloading the Numpy package, it can be installed by double-clicking on the downloaded file. If Python 2.7.6 has been installed correctly in the previous step, then the Python installation folder will be found automatically during the installation of Numpy. In our example case this folder was c:\Python27\ (see example Figure 8).

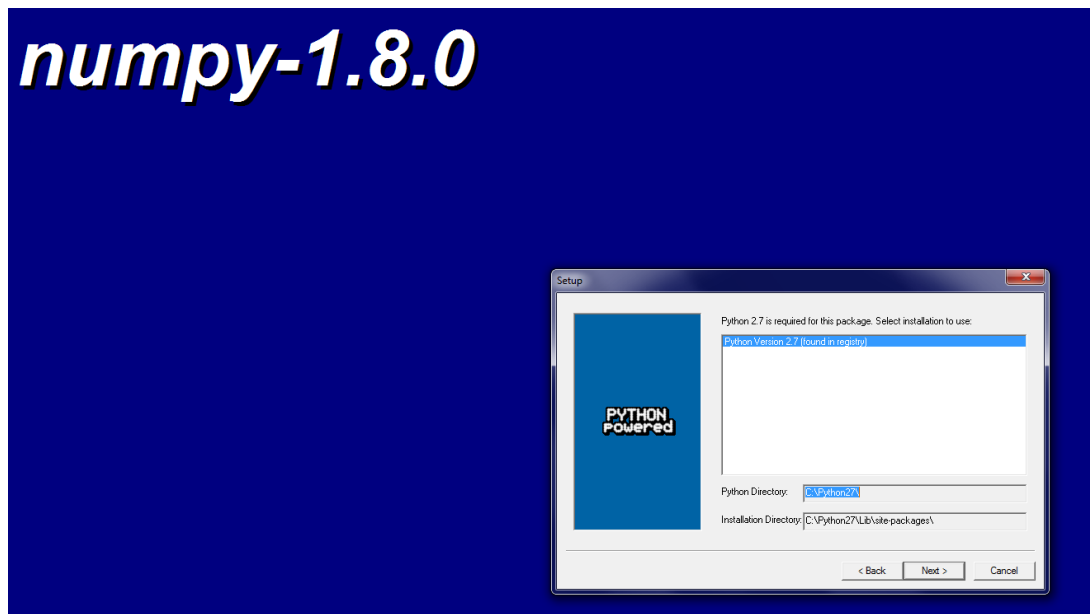


Figure 8: Illustration of selecting the Python installation folder during installation of the Numpy package.

3.1.3 PCRaster 4.0 32-bit

SPHY is written in the Python programming language using the PCRaster (Karssenberg et al., 2001; Karssenberg, 2002; Karssenberg et al., 2010; Schmitz et al., 2009, 2013) dynamic modelling framework. PCRaster¹ has been developed at Utrecht University. PCRaster is targeted to the development and deployment of spatio-temporal environmental models. It allows users to develop their own simulation models for applications in environmental sciences, such as e.g. hydrology, ecology, geography, etc.

SPHY v2.0 is based on the 32-bit system architecture, and therefore requires the 32-bit PCRaster 4 version. SPHY v2.0 has been built and thoroughly tested using PCRaster 4.0.0,

¹ <http://pcraster.geo.uu.nl/>

and it is therefore recommended to download and install this stable version of PCRaster. More information about this version of PCRaster can be found at the link below:

<http://pcraster.geo.uu.nl/pcraster-4-0-0/>

In order to install PCRaster 4.0.0, it is mandatory to have successfully installed Python 2.7.6 and Numpy 1.8.0 during the previous two steps (Section 3.1.1 and 3.1.2). To install PCRaster 4.0.0 you need to perform the following steps:

1. Download the PCRaster version using this link:
http://sourceforge.net/projects/pcraster/files/PCRaster/4.0.0/pcraster-4.0.0_x86-32.zip/download?use_mirror=heanet
2. Create a new folder on your hard disk where you prefer to install PCRaster. For example: c:\Program Files (x86)\PCRaster40\
3. Unzip the contents of the file downloaded under 1) to this folder
4. To let your system recognize the existence of PCRaster, the Environmental Variables need to be updated again. The steps to get to your system Environmental Variables are shown in Section 3.1.1, steps 1-4.
5. It is now required to add the “bin” directory of the extracted PCRaster package to the “Path” system variable (Figure 9). In our example it is the folder: c:\Program Files (x86)\PCRaster40\bin\
6. Click OK.
7. The next step involves setting the PYTHONPATH environment variable. In the same system variables window check the existence of a PYTHONPATH variable. If it exists, then edit the variable by adding the path (Figure 10) of the Python directory of the extracted PCRaster package, which is in our example:

c:\Program Files (x86)\PCRaster40\python\

Otherwise click “New” to create it, and add PYTHONPATH as Variable name, and add the Python directory folder as the Variable value.

8. Click OK and OK to complete the installation of PCRaster.
9. The successful installation of PCRaster can be tested as follows:
 - a. Open a command prompt
 - b. Type *pcrcalc*
 - c. You should see the command prompt view as is shown in Figure 11
10. To test the combination of PCRaster and Python:
 - a. Open a command prompt
 - b. Type *python*
 - c. This opens the Python interactive console
 - d. Type *import pcraster*
 - e. If no errors are shown, then installation has been completed successfully.

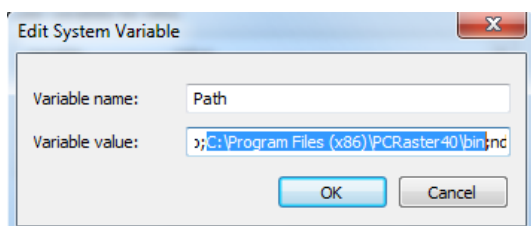


Figure 9: Adding the PCRaster bin folder to the Path system variables.



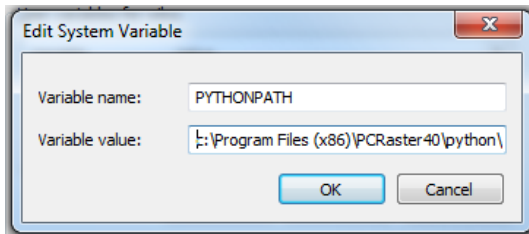


Figure 10: Editing or creating the PYTHONPATH variable for the PCRaster package.

```

C:\Users\wilco>pcrcalc
pcrcalc Dec 4 2013 (win32/msvc)
USAGE: pcrcalc [options] "expression"
or pcrcalc [options] -f scriptFile
( or #! : pcrcalc -F [options] + )
other flags:
s # : set seed (integer > 0) for random generator
      default is based on current time
b f : overrule script bindings
i : update timeseries files at end of each timestep
r f : set run directory
d f : debug mode, check MU creation on assignment
      comparing against clone or areamap boolean mask
c : strict Case significant filename check (Unix portability)
p : print profile information
n : optimize with areamap MU compression
l : use less memory but more temporary disk storage
t : test argument substitution

C:\Users\wilco>

```

Figure 11: Command prompt view of testing a successful installation of PCRaster after entering the *pcrcalc* command.

3.1.4 SPHY v2.0 source code

The SPHY v2.0 source code can be obtained from FutureWater. The source code is available as a zip-file (SPHY2.0.zip) and needs to be extracted to a folder on your hard drive. In our case we created the folder c:\SPHY and unzipped the contents of SPHY2.0.zip to this folder. After unzipping the contents of SPHY2.0.zip to a folder of your preference, installation has been completed successfully.

3.2 Installing SPHY as an integrated application in QGIS

In order to install SPHY as an integrated application in QGIS, all the steps under Section 3.1 have to be conducted first. Then the following additional packages should be installed:

1. QGIS 2.4.0 Chugiak, 32-bit
2. Matplotlib library
3. SPHY model interface plugin

The installation of these packages is described in detail in the following sections.

3.2.1 QGIS 2.4.0 Chugiak, 32-bit and Matplotlib

The 32-bit version of QGIS 2.4.0 Chugiak can be downloaded from:



The downloaded file (osgeo4w-setup-x86.exe) involves the OSGeo4W network installer that can be used to install QGIS, as well as other OSGeo packages. In order to install QGIS 2.4.0 32-bit, follow the steps below:

1. Double click on the file "osgeo4w-setup-x86.exe"
2. In the window that pops up, select Advanced Install and click Next
3. Choose install from Internet and click Next
4. Select a root directory where you want to install QGIS (Figure 12) and click Next. In our case we chose the folder: c:\OSGeo4W
5. Select a temporary folder (Figure 13) where you want the temporarily installation files to be downloaded and click Next. This is only required for the installation of QGIS, and can be removed after installation of QGIS.
6. Select Direct Connection and click Next
7. Choose the default download site and click Next
8. In the next window you need to select the packages to install (Figure 14). Type *qgis* in the search field and select Desktop (+)
9. Select the following packages to install (all should be version 2.4.0):
 - a. *qgis*: QGIS Desktop
 - b. *qgis-full*: QGIS Full Desktop package
10. Additionally, the Matplotlib¹ package should be installed. Type *matplotlib* in the search field (Figure 15) and select Libs (+)
11. Then select to install the matplotlib: Python plotting package. It is recommended to install version 1.2.
12. Finally, click Next to complete the installation of both QGIS 2.4.0 and Matplotlib.

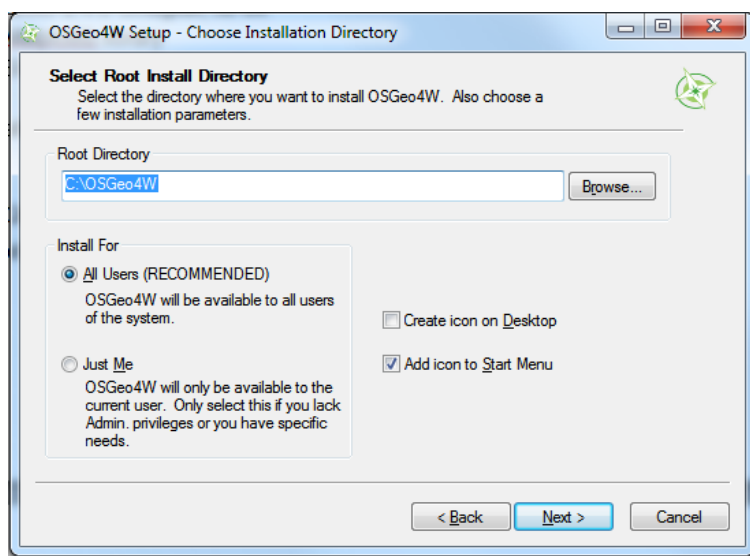


Figure 12: Setting the root directory where to install QGIS.

¹ <http://matplotlib.org/>



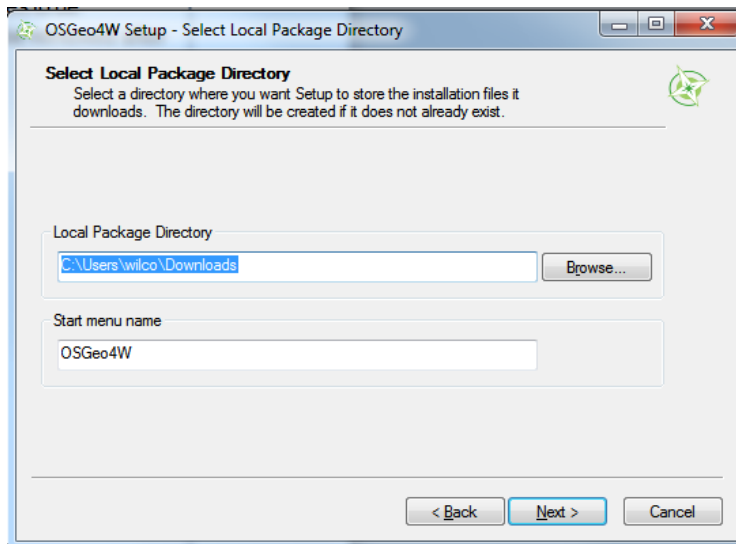


Figure 13: Setting the local package directory for QGIS installation files.

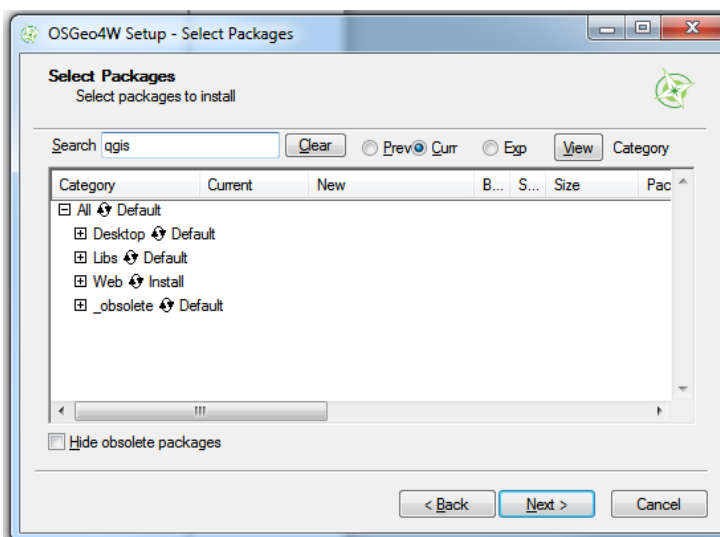


Figure 14: Selecting the QGIS package to install from the OSGeo4W install menu.

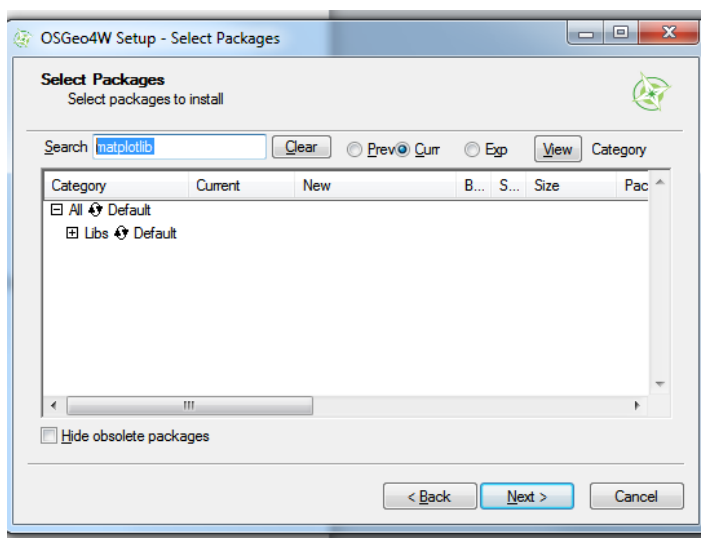


Figure 15: Selecting the Matplotlib package to install from the OSGeo4W install menu.

3.2.2 SPHY model interface plugin

A Graphical User-Interface (GUI) has been developed for the SPHY model. This interface has been developed in QGIS and Python, and can be added as plugin into QGIS. The SPHY model GUI (plugin) is available as zip file: SphyPlugin.zip.

3.2.2.1 Installing the plugin

In order to use the SPHY model GUI inside QGIS, it is only required to extract the contents of this zip-file into the QGIS Python plugins directory. Generally, this directory is located on the following location on your hard disk:

c:\Users\XXXX\.qgis2\python\plugins\

where XXXX should be replaced by the name of the PC user. In my case, this folder is:

c:\Users\wilco\.qgis2\python\plugins\

After unzipping the contents of SphyPlugin.zip into this folder, the installation of the interface has been completed, and you can continue to Section 3.2.2.2.

If you don't see a .qgis2 folder under the c:\Users\XXXX\ folder, then it is very likely that you have never installed other plugins in QGIS before. This can easily be solved by starting QGIS and then select the Plugins menu and subsequently Manage and Install Plugins (Figure 16).

Then in the window that pops up (Figure 17) you should select under Settings:

- Show also experimental plugins
- Show also deprecated plugins

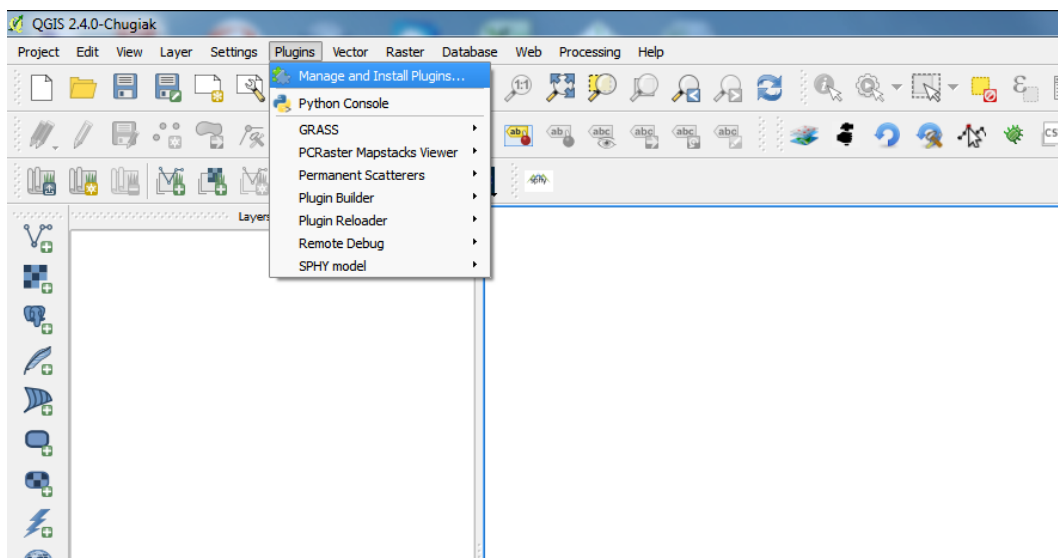


Figure 16: Activating the plugins folder for the first-time use in QGIS.

After completion of these steps you should be able to see the folder structure:

c:\Users\XXXX\.qgis2\python\plugins\



To complete installation of the SPHY model interface, unzip the contents of SphyPlugin.zip into this folder.

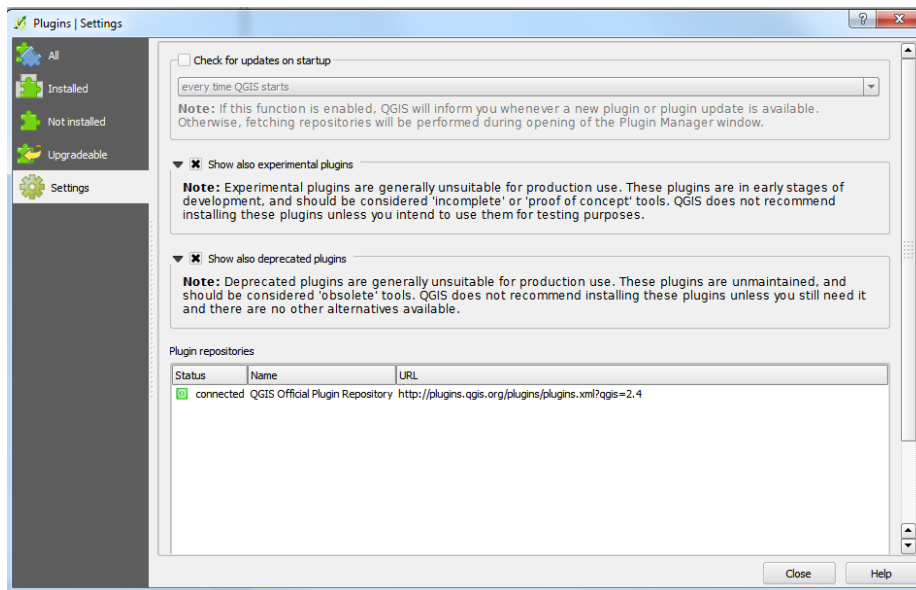


Figure 17: Selecting the experimental and deprecated plugins options in the QGIS plugin settings menu.

3.2.2.2 Activating the SPHY model interface in QGIS

The last step before you can use the SPHY model GUI involves activating the plugin inside QGIS. In order to complete this, follow the steps below:

1. Start QGIS and then select the Plugins menu and subsequently Manage and Install Plugins (Figure 16).
2. Type *SPHY* in the Search bar and select the SPHY model plugin that shows up (Figure 18).
3. Click Close to close the Plugins menu.
4. If installation and activation has been successful, then the SPHY model interface logo (button) has been added to the toolbar (Figure 19).

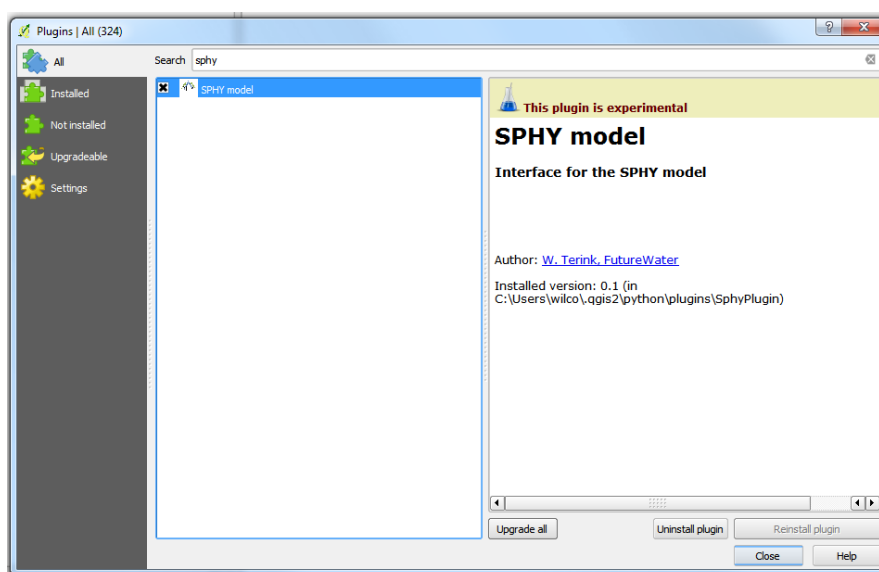


Figure 18: Activating the SPHY model plugin inside QGIS.



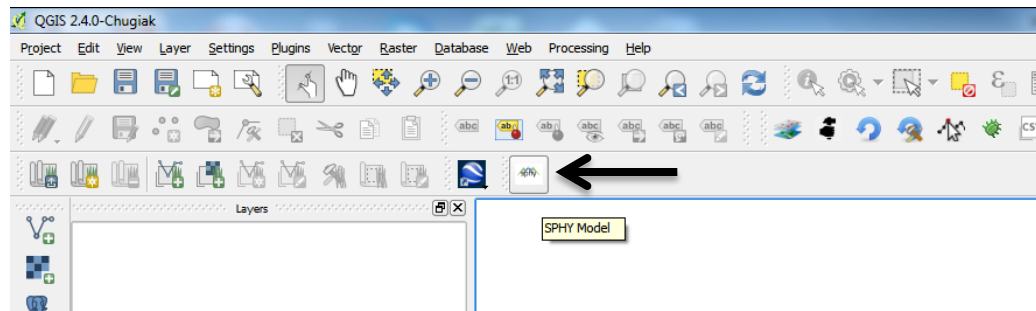


Figure 19: SPHY model interface button.

You now can start using the interface by clicking the SPHY model interface button. The use of this interface is described in detail in the next Section.



4 SPHY model Graphical User-Interface v1.0

4.1 Overview

4.1.1 Introduction to the GUI

The SPHY model GUI has been developed with the goal to make the use of the SPHY model more user-friendly, and thus more applicable to a larger user-group world-wide. Using the SPHY model GUI has several advantages above the use of SPHY as stand-alone application:

- Easy creation of new projects, and opening/modifying existing projects.
- Quick overview of all your SPHY model settings.
- Easy to select model input and output, and to modify model parameters.
- Default parameter values and parameter ranges prevent the use of physically wrong parameters values.
- Model output reporting options can be easily managed.
- The model can be executed inside the GUI, meaning that command line execution is history. A progress bar shows model execution progress.
- Visualization of the model in- and output can be done inside QGIS. This provides the user with a clear overview of the maps that are used as model input. Model output can be added as spatial map, or can be analyzed using time-series plots.
- The GUI uses the registry, meaning that your last project (settings) will be saved and loaded upon the next time you continue to work with your model (project).

The SPHY model interface consists of a top menu with four buttons and a tab widget that contains 11 tabs (Figure 20). The use of the top menu buttons will be explained in detail in Section 4.3. When working on a SPHY model project, the user has to 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 has to complete these tabs in the order they appear: from left to right. The last steps always are running the model and thereafter visualizing the model results. The use of each of these tabs is described in detail in the Sections 4.4 through 4.14. The effect of changing parameter settings is only briefly described in Sections 4.4 through 4.14. For a detailed description of parameters and theory, we refer to the Theoretical section of this manual (Section 2). A detailed overview of the model input and output can be found in Appendix 1.

If it is the first time you use the SPHY model GUI, then please first read Section 4.1.2 before continuing with the other sections.



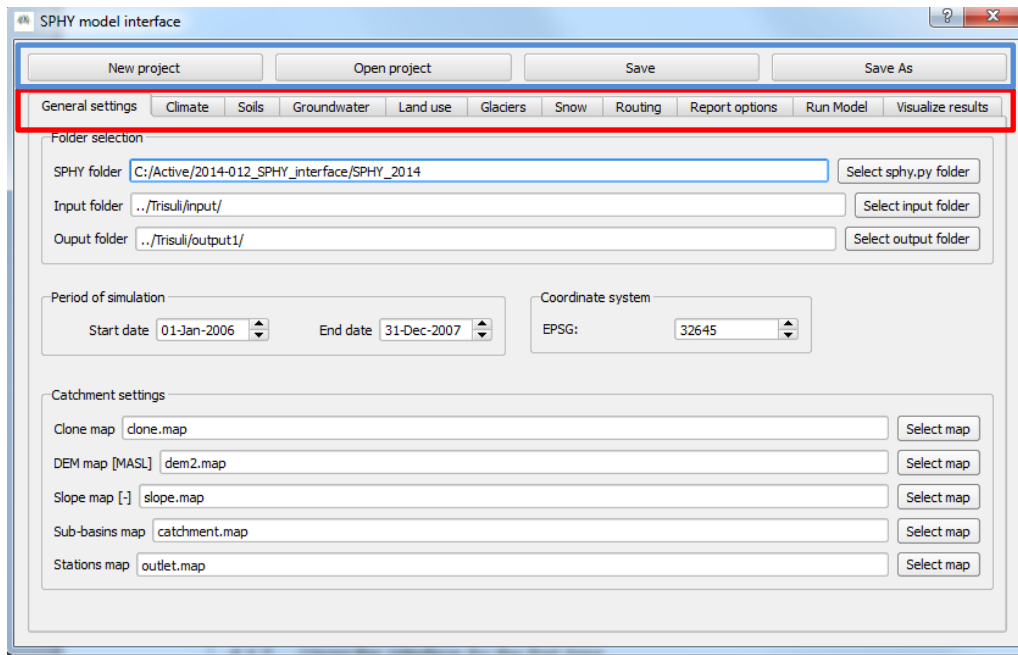


Figure 20: Overview of the SPHY model interface top menu (buttons in blue box) and a tab widget, consisting of 11 tabs (red box).

4.1.2 Using the interface for the first time

The SPHY model GUI is always **started** by clicking the SPHY model interface button (Figure 19). Since it is the first time you use the interface, the registry settings will be empty. This means no previous SPHY projects can be found by the interface. If this is the case, then the interface looks like Figure 21. The only options available are:

- New project
- Open project

The New project button logically asks the user to save a new SPHY model project, whereas the Open project button asks the user to open an existing SPHY model project. After one of these options has been selected, the tabs will be activated such that the user can go through these tabs to complete model setup.



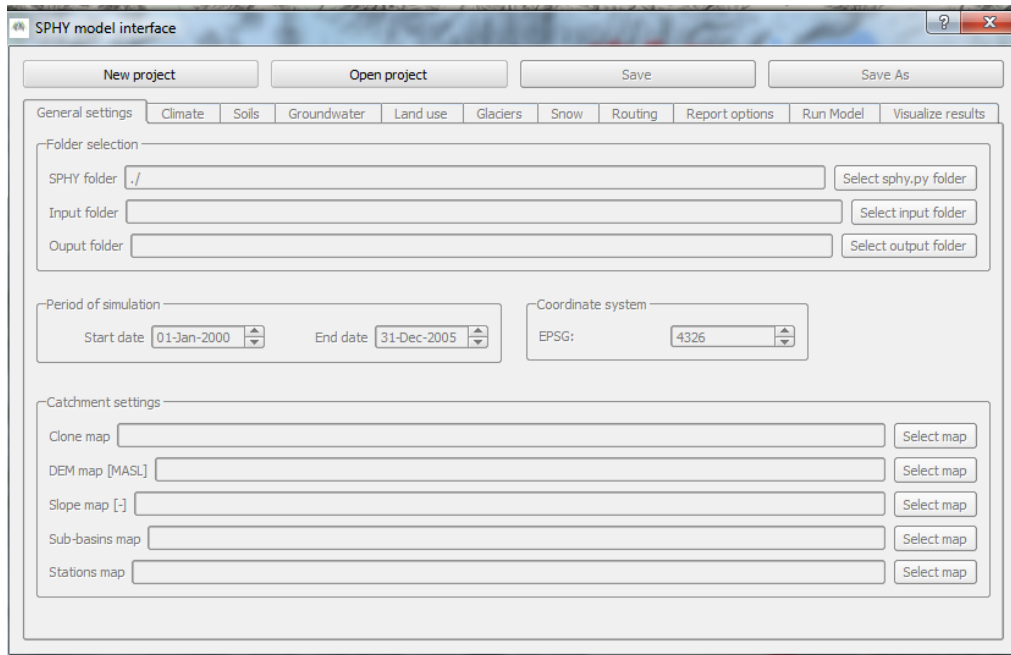


Figure 21: SPHY model interface for first-time use.

4.1.3 Editing the SPHY model configuration file outside the GUI

The current version of the SPHY model GUI (version 1.0) is the first version that has been developed. It therefore does not include all SPHY model settings that are included in SPHY v2.0. This version of the SPHY model GUI has especially been developed to be applicable in glaciated river basins. However, the user is still able to change model settings that cannot be done throughout the GUI. This can be done by editing the SPHY model configuration file (*.cfg) that is created when creating a New project (see Section 4.3.1).

4.2 Map canvas layers and GUI interaction

4.2.1 Interaction with the map canvas

During model setup in the GUI, the QGIS map canvas will be extended with more and more layers that are added by setting model input maps and evaluating model output maps. The user can modify layer legends to its own preferences, because this does not have an effect on the model results. You are also free to add additional layers or remove layers from the QGIS map canvas. Both actions will not affect model results; because the maps that are used in the model are always shown in the text lines in the GUI (see for example the catchment settings in Figure 26). If you select a model input map in the GUI, this map will automatically be added to the QGIS map canvas. If this layer name already existed in the map canvas, then it will be overwritten with the new selected layer.

4.2.2 Map canvas layout

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 22. The Input layer groups correspond with the GUI tab widgets that need to be completed by the user during Section 4.4 through Section 4.14. The Output layer groups are built during the last step of the GUI: Visualize results.

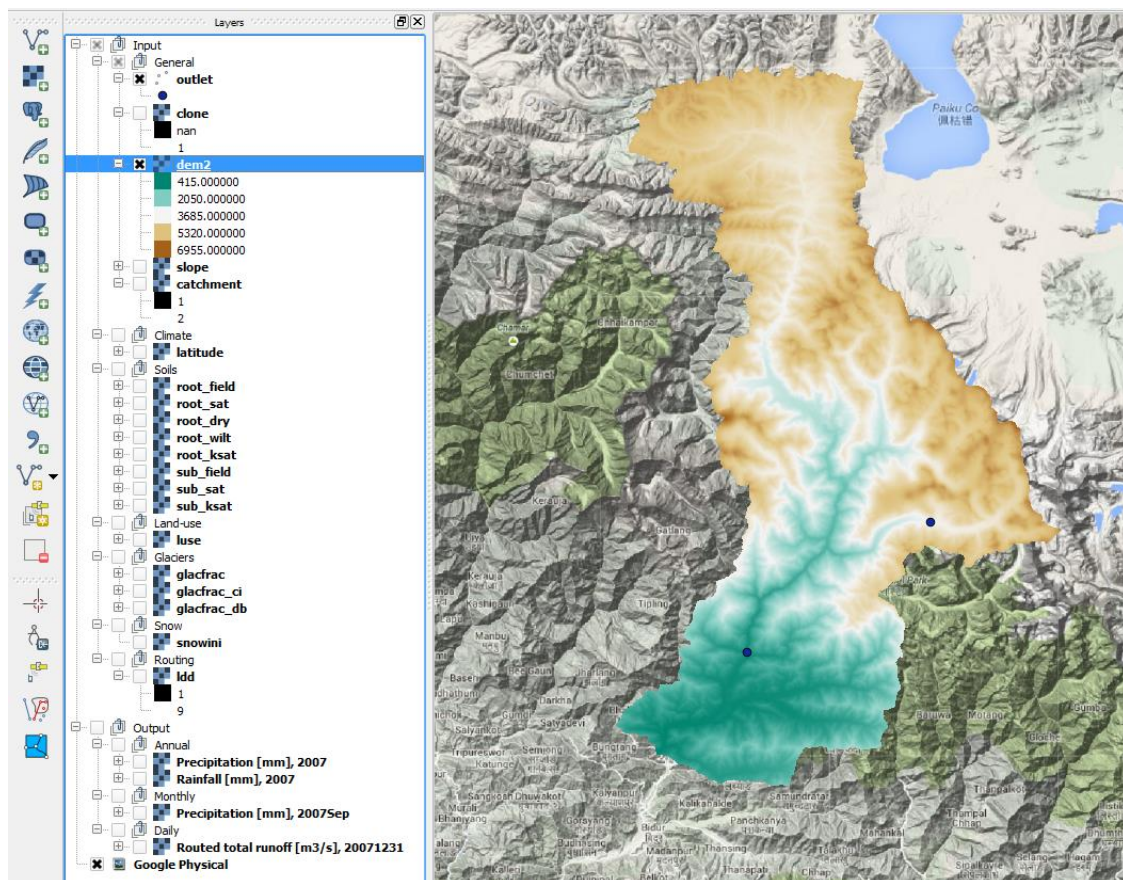


Figure 22: Example of map canvas groups and layers layout.

4.2.3 Setting a background layer

As can be seen from Figure 22, a Google Physical background has been added to the canvas. Background layers in QGIS, such as the Google Physical background layer, are available as plugins. The Google Physical background layer, together with layers as OpenStreetMap, Bing maps and other Google maps, are part of the OpenLayers plugin. This plugin can be installed and activated in a similar way as the SPHY model plugin was activated (see Figure 16, Figure 18, and Section 3.2.2.2). You can search for this plugin by typing google in the search window (Figure 23). Then select the OpenLayersPlugin and click Install plugin and after installation click



Close. You are now able to set any background map from the OpenLayersPlugin you like (Figure 24).

It should be noted that setting and viewing a background layer requires an internet connection. Because of the continuous connection with internet, the use of background layers may slow down processes such as panning and zooming inside QGIS.

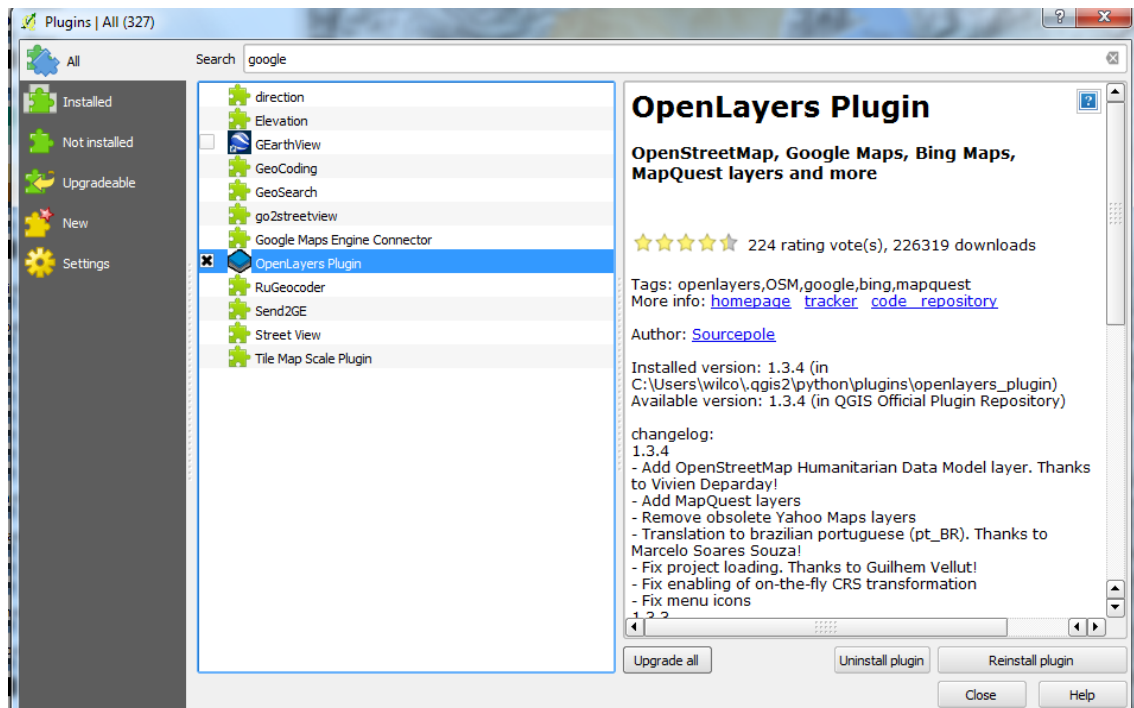


Figure 23: Activating the OpenLayers Plugin in QGIS.

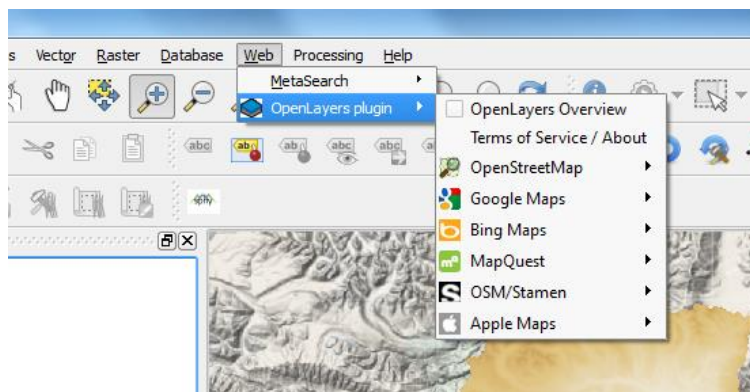


Figure 24: OpenLayers plugin in the QGIS menu.

4.3 Top menu buttons

4.3.1 New project

A SPHY model project always involves two files, being the SPHY model configuration file (*.cfg) and the SPHY model project file (*.qgs). The *.cfg file contains the SPHY model configuration, and is the same file that is used when running SPHY as a standalone application. The *.qgs is a QGIS project file, and contains the layers and map canvas view settings.



If the New project button is clicked, then the user is asked where to save the new project and to provide a filename (XXXX.cfg) for the project. You can choose any filename, except “sphy_config.cfg”. If a current SPHY model project was open in QGIS, then it will be asked to save the current project first before creating a new project. It is mandatory to save the new project to the same disk where the SPHY model source code has been installed (Section 3.1.4). Otherwise an error will occur.

After creating a new project, the map canvas will be emptied and the GUI looks like Figure 25. The user may now continue completing the different tabs.

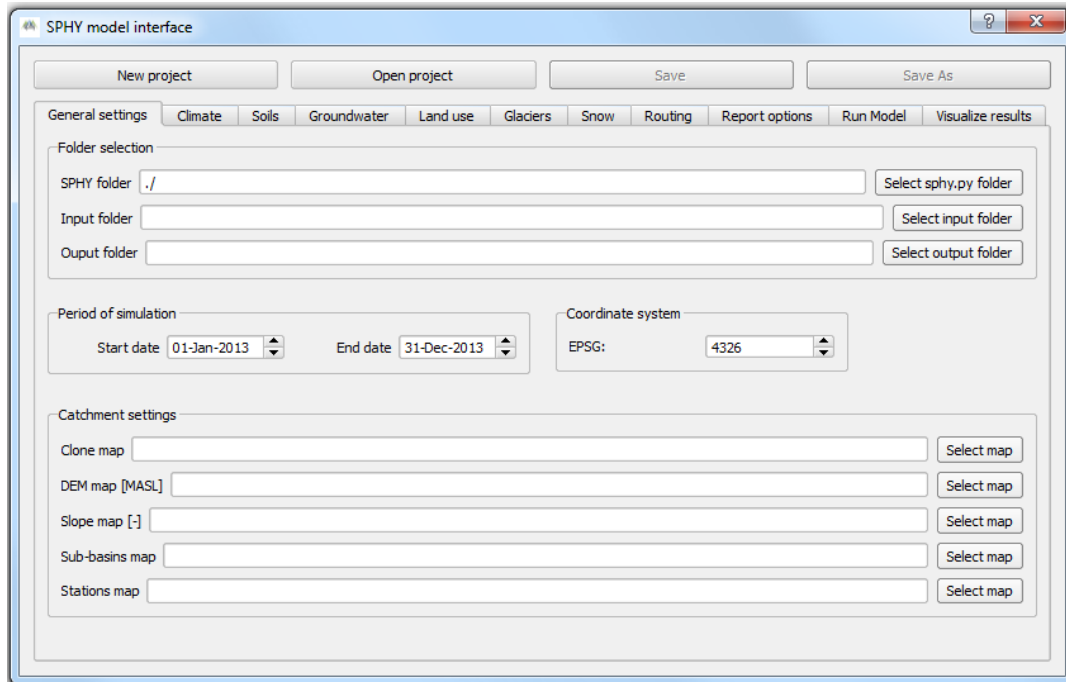


Figure 25: SPHY model interface after creating a new project.

4.3.2 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 was open in QGIS, then it will be asked to save the current project first before opening another project. Opening an existing project results in the QGIS canvas to be cleared, and the layers present in the *.qgs file to be added to the canvas. All model settings present in the *.cfg file will be added to the SPHY model GUI. Your SPHY model interface could now look something comparable to Figure 26.



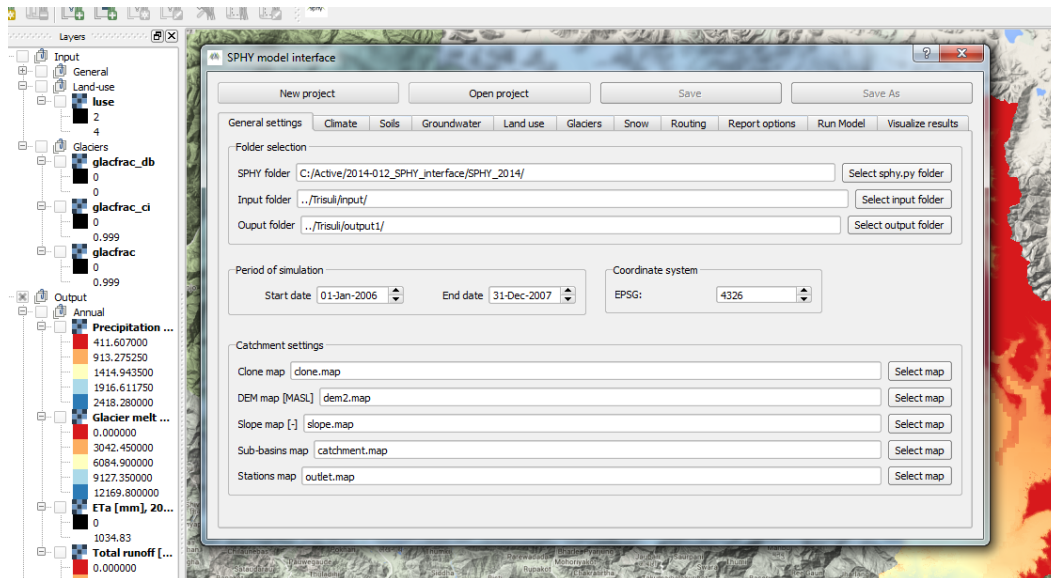


Figure 26: Example of SPHY model interface after opening an existing project.

4.3.3 Save and Save As

The GUI allows you to save your SPHY model project. After clicking the Save or Save As buttons, these buttons will become unavailable (see Figure 26) until you change something (e.g. a parameter setting) in the GUI. This means these buttons are also an indicator of recent changes to the interface. As soon as you change/modify something in the GUI, these buttons will become available again. It should be noted that running the model automatically results in saving your SPHY model project before the model 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 and the map canvas layers and view settings to the *.qgs file. The Save As button allows you to save the SPHY model project under another filename. This may be useful if you need to study for example the effect of a parameter change without losing your previous model run settings and output.

4.4 General settings

4.4.1 Folder selection

Figure 27 shows an overview of the General settings tab. As soon as you start a new project, the folder selection settings should be completed first. If this is not set correctly, then errors will show up. First of all, the GUI needs to know where your SPHY model source code is located. By clicking the Select sphy.py folder 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 28. As was mentioned in Section 4.3.1, it is mandatory to have the SPHY model source code on the same disk as your SPHY model interface project.

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

The output folder is the location where all the model output will be saved during execution of the model. The model output data in this folder will be parsed to the Visualize results tab, which

allows you to select certain output to be added to the map canvas. This is described in detail in Section 4.14.

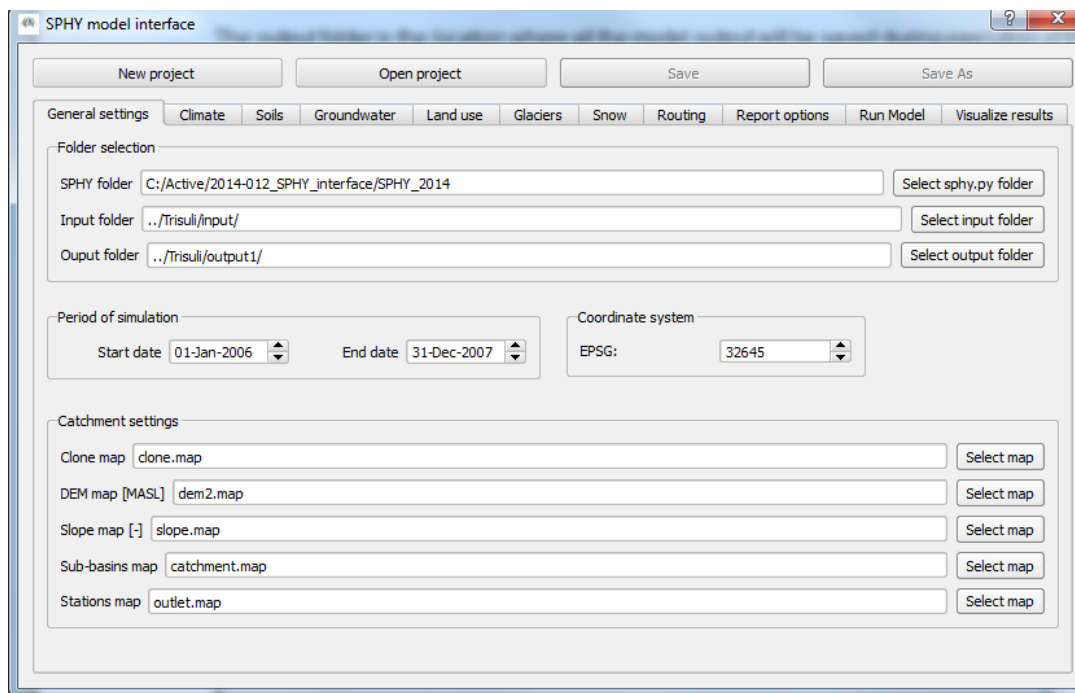


Figure 27: Overview of the General settings tab.

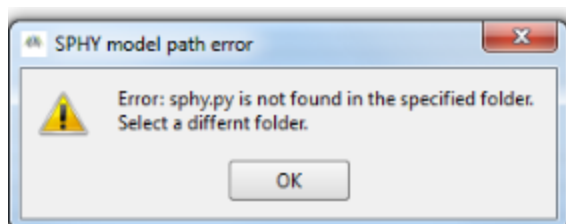


Figure 28: Error message indicating that no sphy.py can be found in the selected folder.

4.4.2 Period of simulation

The period of simulation allows you to change the start and end date of your simulation. It should be noted that the start date always has to correspond with the first climate forcing file (*.001). Setting the end date is an interesting option if the user only wants to model/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 input is correctly set before executing the entire period of 20 years, which can take a long time.

4.4.3 Coordinate system

In order to present the model input and output map correctly in the QGIS map canvas, you need to specify the coordinate system of your area of interest. The coordinate system has to be specified in EPSG. You can search for the corresponding EPSG number on this website:

<http://spatialreference.org/ref/epsg/>

The default coordinate system used in the SPHY model GUI is WGS 84. This corresponds with EPSG:4326. It is important to specify the coordinate system at the beginning of your SPHY model project, and keep this coordinate system throughout the SPHY model project. If you change the coordinate system halfway your project, then maps will not align in QGIS.



4.4.4 Catchment settings

The catchment settings basically define the shape and orography of your river basin. The user has to select five spatial maps that define the basin of interest. Table 2 provides an overview of these maps. Each of these 5 maps can be selected and added to the map canvas by clicking the Select map button. After clicking this button you will be referred to the Input folder that has been set under Section 4.4.1. Within this folder you are asked to select the map of interest and to click on Open to add the map to the GUI and the QGIS map canvas. This is illustrated in Figure 29 for the DEM map.

After these 5 maps have been set, the user can continue with the next tap: Climate.

Table 2: Catchment settings maps.

Map name	Description
Clone map	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.

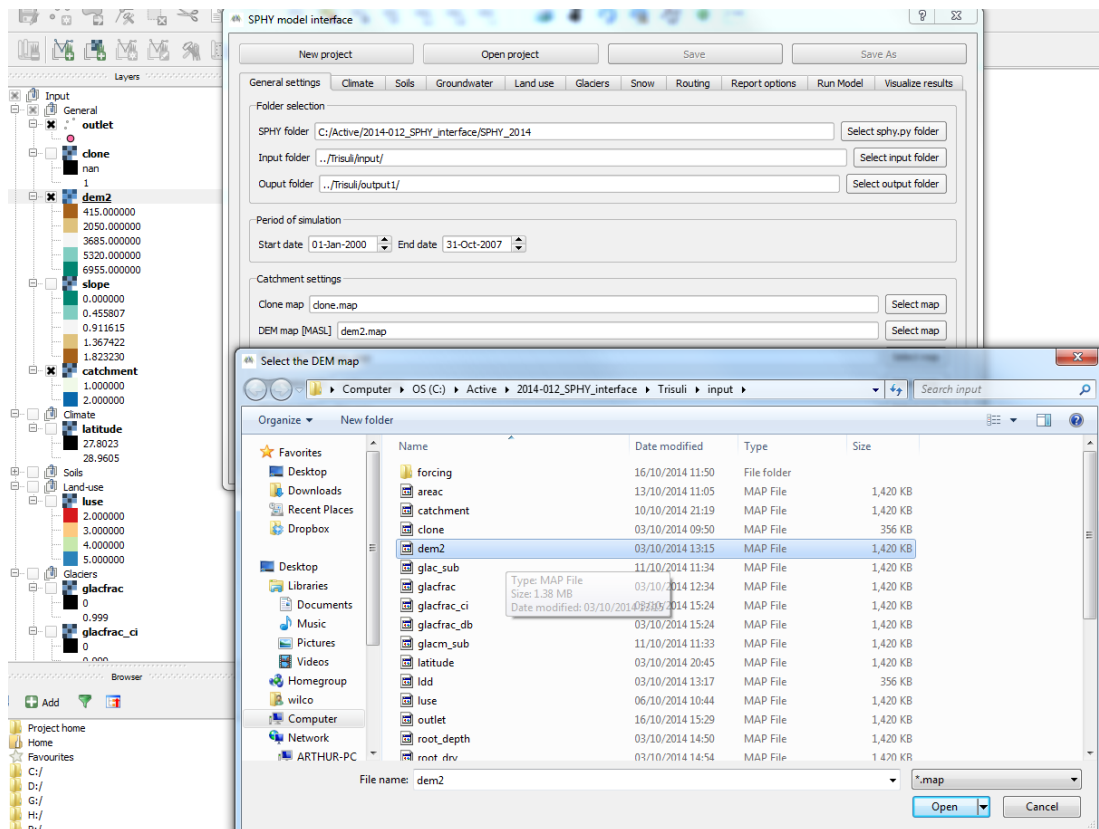


Figure 29: Selecting a DEM map in the catchment settings.

4.5 Climate

4.5.1 Meteorological forcing map-series

Figure 30 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 temperature.

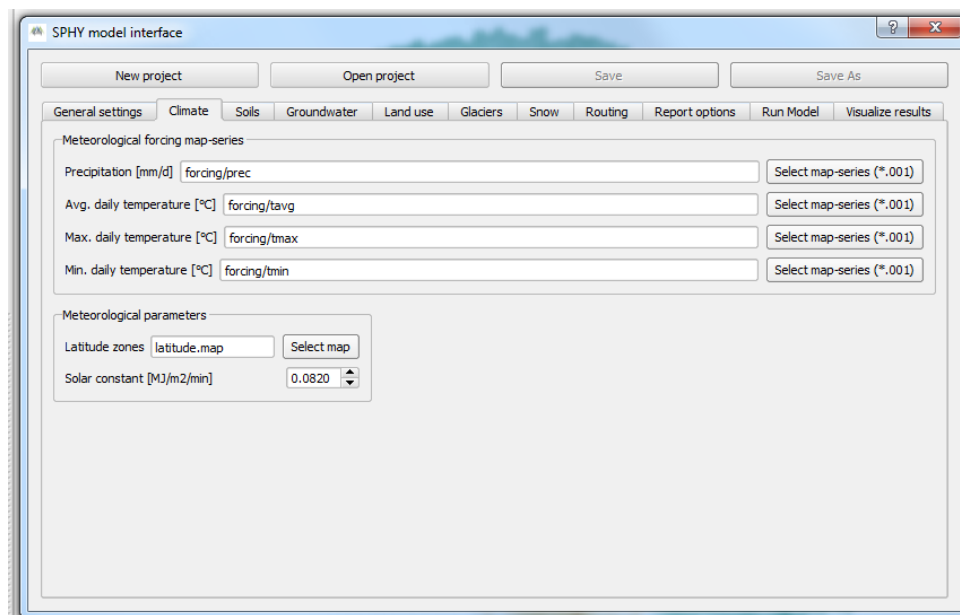


Figure 30: Overview of the Climate tab.



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 the *.001 extension, corresponding with the start date of your model simulation period. The format of each individual forcing file should have eight characters before the dot, and 3 characters after the dot. If your model has for example 3542 time-steps, then your first precipitation forcing file could 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 of this is shown in Figure 31. It can be seen that the meteorological forcing is inside another folder ("forcing") within the Input folder. This can be done 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 30 shows that the "forcing" folder will just be added before the variable name.

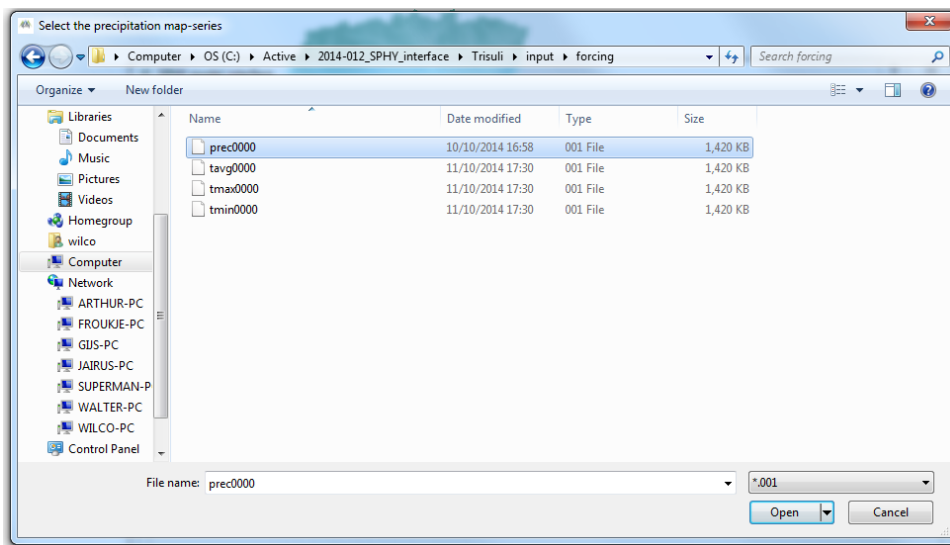


Figure 31: Selecting the precipitation map-series.

4.5.2 Meteorological parameters

The second part of the Climate tab involves setting the parameters for calculating the terrestrial radiation, which is eventually used in the Hargreaves method to calculate the reference evapotranspiration. To calculate the terrestrial radiation the user needs to select a map with latitude zones. This map can be select by clicking 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 needs to provide a single floating number for the solar constant. The default value of $0.0820 \text{ MJ m}^{-2} \text{ min}^{-1}$ is generally applicable for most areas world-wide, but may be changed if needed.

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

4.6 Soils

4.6.1 Rootzone physical maps

An overview of the Soils tab is shown in Figure 32. The rootzone physical maps refer to the physical soil properties of the first soil layer, where the subzone physical maps refer to the second soil layer's physical properties. 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 regarding these processes can be found in the Theoretical section of this manual (Section 2). 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 the Select map buttons. It is important to check that the cell values should increase from permanent wilting point to wilting point to field capacity, and with saturated content having the highest cell values.

Figure 33 shows an example of a field capacity map for the rootzone, showing more details in the upstream part than the downstream part.

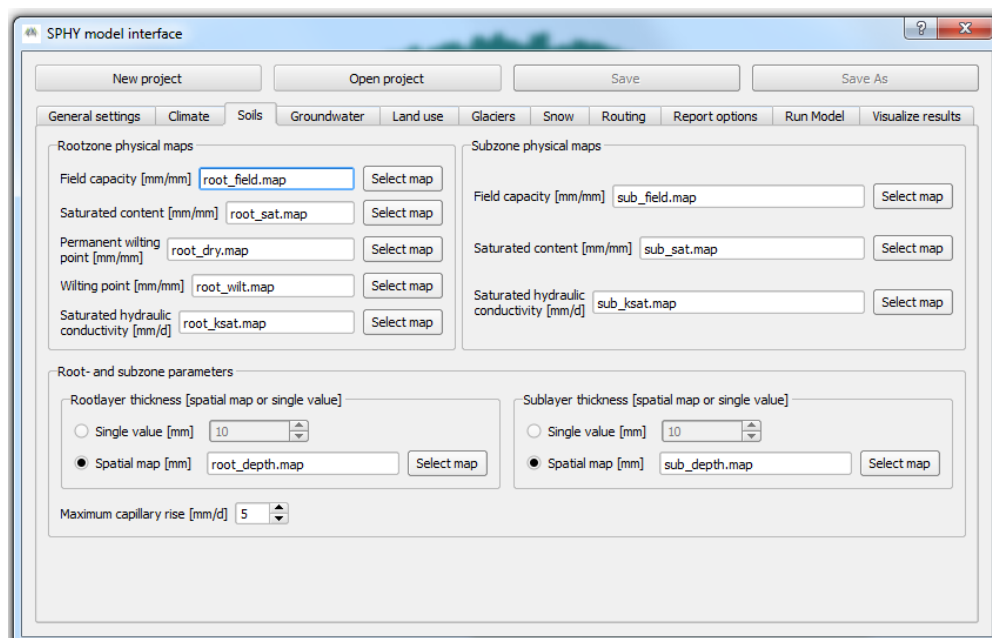


Figure 32: Overview of the Soils tab.



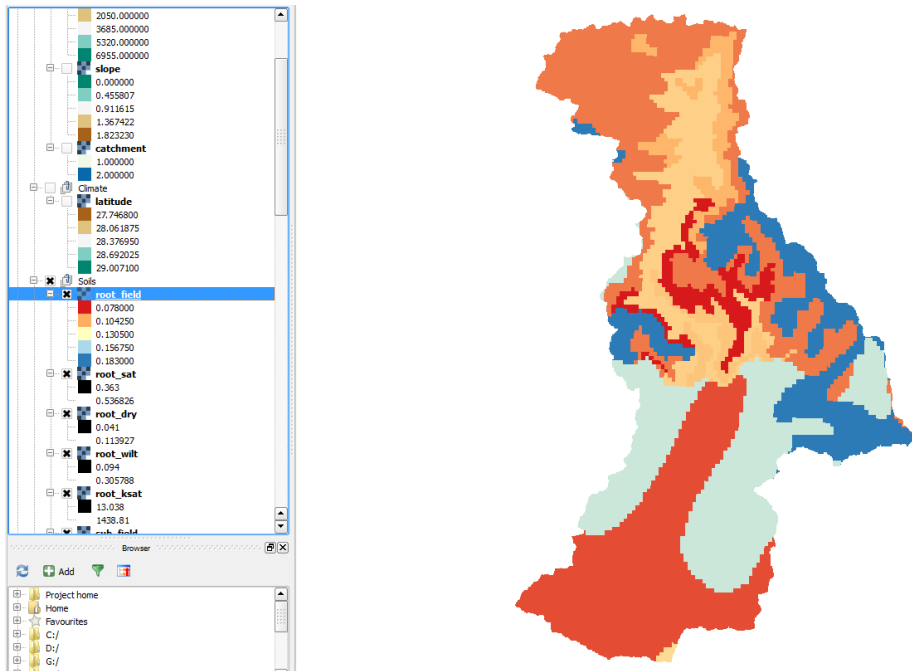


Figure 33: Example of rootzone field capacity map.

4.6.2 Subzone physical maps

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 for the field capacity map.

4.6.3 Root- and subzone parameters

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 to provide a spatial map with a spatially distributed soil depth over the entire basin. In Figure 32 we chose to select a spatially distributed soil depth map for both the root- and subzone. 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 settings in the Soils tab the user can continue with the next tab: Groundwater.



4.7 Groundwater

4.7.1 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 34. The left part contains the volume settings and the right 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, then this value is taken as homogeneous for the entire catchment. Using a spatial map can be useful to differentiate between different groundwater volume settings spatially in your basin.

The following three groundwater volume settings have to be provided:

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

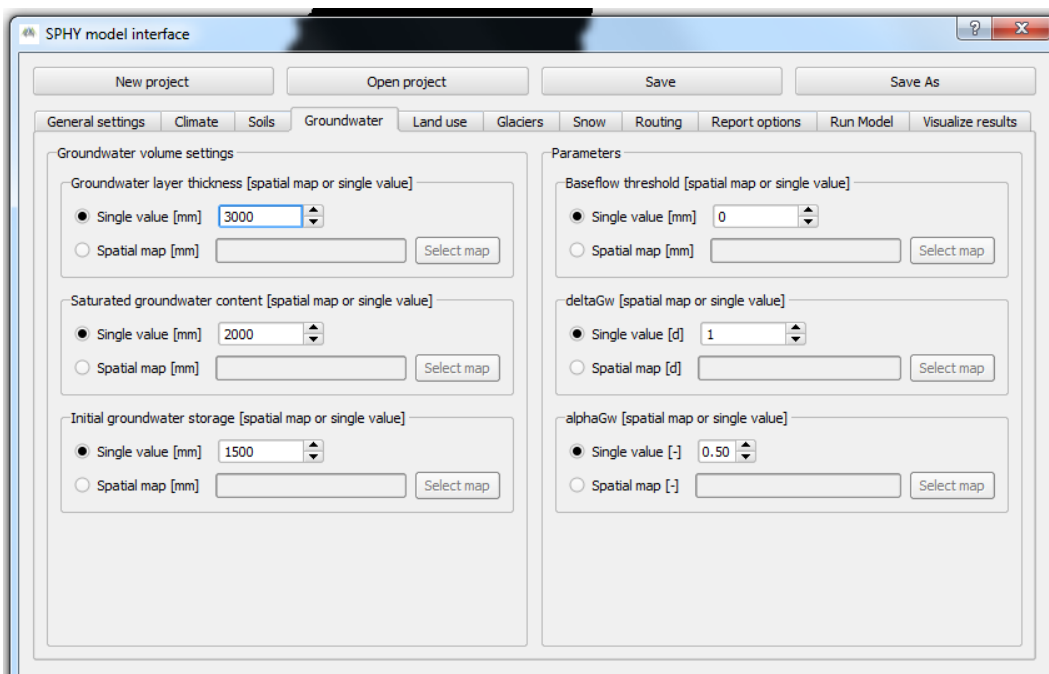


Figure 34: Overview of the Groundwater tab.

Spatial maps can be selected and added to the GUI by clicking the Select map button. It is required that the groundwater layer thickness is higher than or equal to the saturated groundwater content, and that the initial groundwater storage is equal to or smaller than the saturated groundwater content.

It should be noted that if you choose a small or zero initial groundwater storage, it may take a long time before baseflow occurs. Therefore, it is recommended to have substantial initial groundwater storage in order to have baseflow.

4.7.2 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 opt for a single value or a spatial map for each of the three parameters. If a single value is chosen, then this value is taken as homogeneous for the entire catchment. Otherwise, a spatially distributed map may be chosen.

If during 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. For this it is required to set a value or single map for the baseflow threshold parameter. It is required to have a baseflow threshold value that is lower than the saturated groundwater content.

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 ranges between 0 and 1. More details regarding the groundwater processes can be found in the Theoretical section of this manual (Section 2).

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

4.8 Land use

Figure 35 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 has to 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 which 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 36.

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 37 shows an example of the format of a crop coefficients lookup table that corresponds with the land use map of Figure 36.



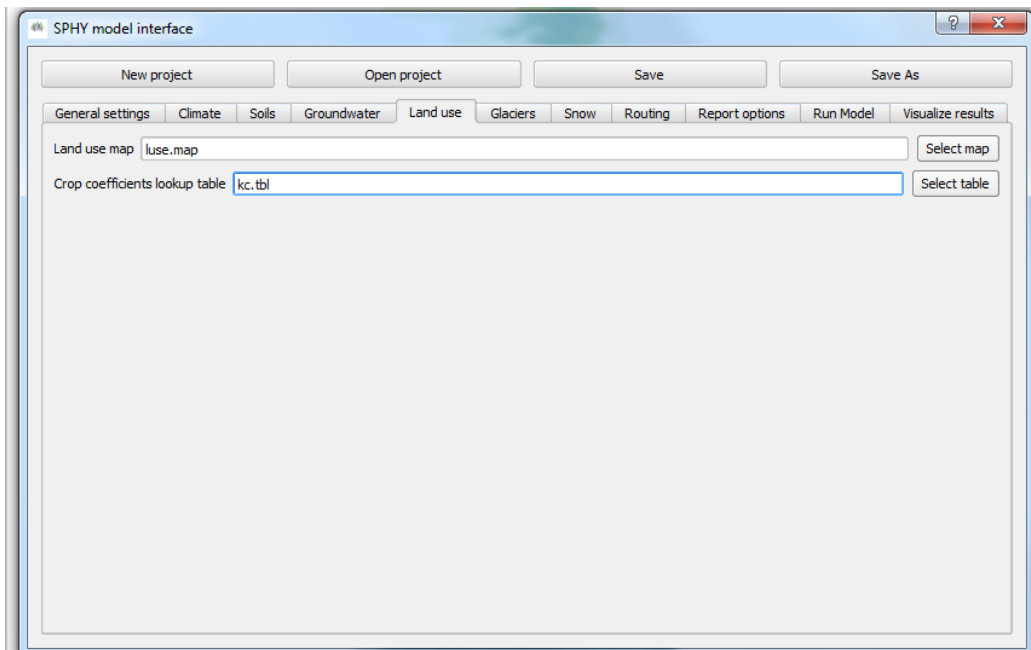


Figure 35: Overview of the Land use tab.

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

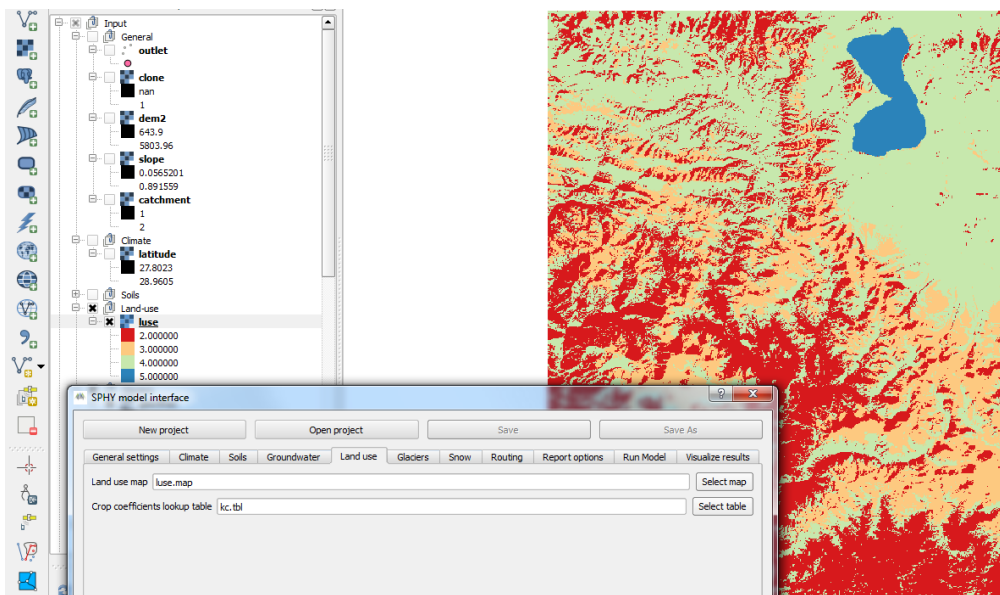


Figure 36: Example of a land use map with four land use classes.

kc.tbl		
1	2	1.2
2	3	0.5
3	4	1.0
4	5	1.0
5		

Figure 37: Example of crop coefficients lookup table in Notepad++.



4.9 Glaciers

An overview of the settings in the Glaciers tab is shown in Figure 38. A distinction has been made between glacier fraction settings and the setting of glacier degree-day-factors.

4.9.1 Glacier fraction settings

In the glacier fraction settings the user has to select the following three spatial maps:

- Initial glacier fraction [-]
- Clean ice glacier fraction [-]
- Debris covered glacier fraction [-]

These maps can be selected and added to the canvas by clicking the Select map button. The initial glacier fraction map defines for each cell the fraction that is covered by glaciers. Values for this map can range between zero and one. An example of a glacier fraction map is shown in Figure 39.

The clean ice and debris covered glacier fraction maps define for each cell the fraction covered by clean ice and debris covered glaciers, respectively. Values of these maps range between zero and one, and the sum of the fractions covered by clean ice and debris covered glaciers should always equal one.

The screenshot shows the 'SPHY model interface' window with the 'Glaciers' tab selected. The interface includes buttons for 'New project', 'Open project', 'Save', and 'Save As'. Below these are tabs for 'General settings', 'Climate', 'Soils', 'Groundwater', 'Land use', 'Glaciers', 'Snow', 'Routing', 'Report options', 'Run Model', and 'Visualize results'. The 'Glaciers' tab contains two main sections: 'Glacier fraction settings' and 'Glacier degree-day-factors'. The 'Glacier fraction settings' section has three rows, each with a label, a text input field, and a 'Select map' button. The first row is 'Initial glacier fraction [-]' with 'glacfrac.map' in the field. The second row is 'Clean ice glacier fraction [-]' with 'glacfrac_ci.map' in the field. The third row is 'Debris covered glacier fraction [-]' with 'glacfrac_db.map' in the field. Below these is a section for 'GlacF [spatial map or single value]' with a radio button for 'Single value [-]' set to '0.90' and a 'Select map' button. The 'Glacier degree-day-factors' section has two rows, each with a radio button for 'Single value [mm degree-1 day-1]' and a 'Select map' button. The first row is for 'DDFDG [spatial map or single value]' with a value of '2.00'. The second row is for 'DDFG [spatial map or single value]' with a value of '7.00'.

Figure 38: Overview of the Glaciers tab.

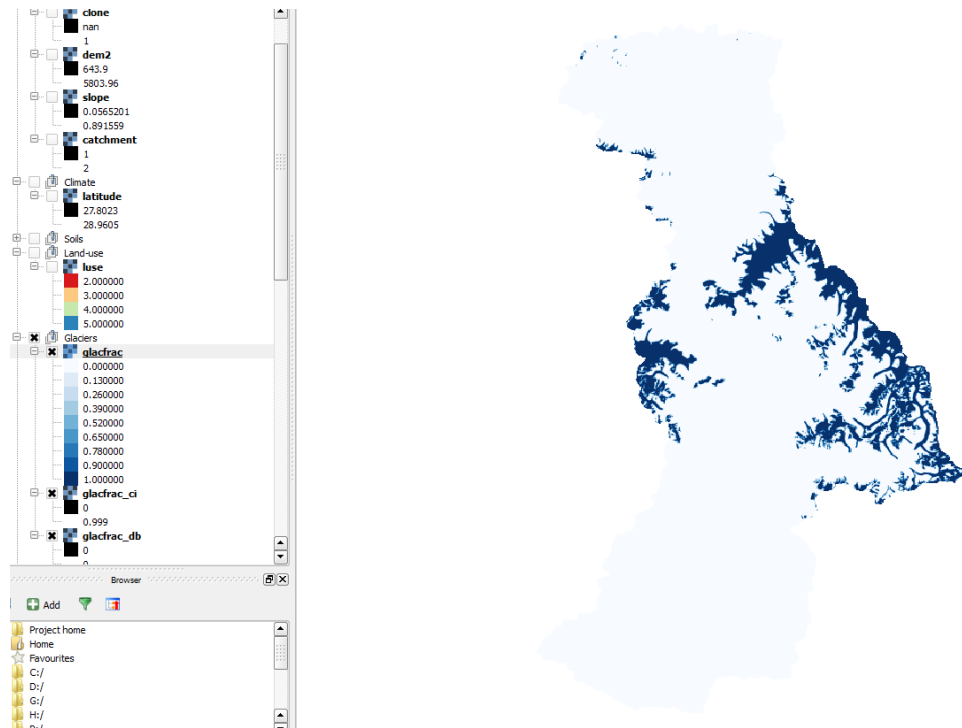


Figure 39: Example of glacier fraction map.

The glacier melt runoff factor (GlacF) differentiates between the amount of glacier melt that results in direct runoff and the amount of glacier melt that percolates to the groundwater. The default value is 0.90, and values range between zero and one. The user can opt to choose a spatially distributed value for GlacF, or to choose a single value that is applied homogeneously over the entire catchment.

4.9.2 Glacier degree-day-factors

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

The user can opt to choose a single value that results in a homogeneous degree-day-factor for the entire basin, or to 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.

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

4.10 Snow

An overview of the snow tab is shown in Figure 40. A distinction has been made between snow storage settings and snow parameters that affect the melting of snow.

4.10.1 Snow storage

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

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



SnowIni defines for each cell the amount of initial snow storage. The user can either provide a single value that is applicable as 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.

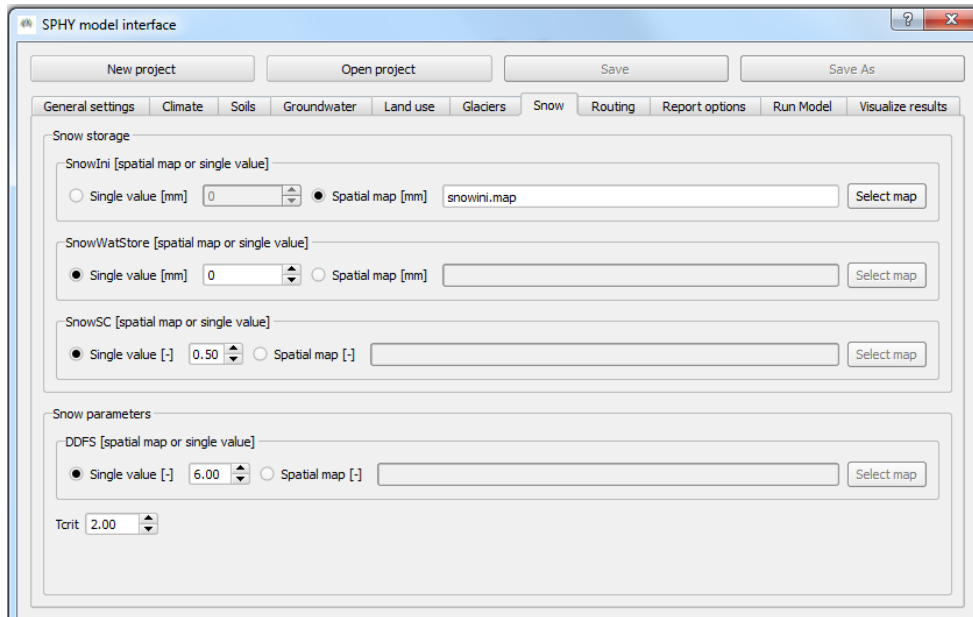


Figure 40: Overview of the Snow tab.

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

4.10.2 Snow parameters

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

- DDFS [mm degree⁻¹ 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 choose 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 if precipitation falls as snow or as rain. If the average daily air temperature is higher than Tcrit, then precipitation will fall as rain. Otherwise,

precipitation will fall as snow. Only a single value can be supplied here, and the default value for T_{crit} is set to 2 °C.

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

4.11 Routing

Settings in the Routing tab affect the way streamflow routing is performed and how streamflow routing is reported as model output. An overview of the Routing tab is shown in Figure 41.

4.11.1 Recession coefficient and flow direction

The recession coefficient affects the velocity in which 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. You can opt to choose either a spatially distributed recession coefficient map or 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 42. A flow direction map needs to be prepared by the user, and is based on the DEM. The flow direction map contains for each cell a number that defines the direction of streamflow. The numbers and their corresponding directions are shown in Figure 43.

The screenshot shows the 'SPHY model interface' window with the 'Routing' tab selected. The interface includes a top menu bar with 'New project', 'Open project', 'Save', and 'Save As'. Below this is a tabbed interface with 'General settings', 'Climate', 'Soils', 'Groundwater', 'Land use', 'Glaciers', 'Snow', 'Routing', 'Report options', 'Run Model', and 'Visualize results'. The 'Routing' tab is active, displaying settings for 'Recession coefficient [spatial map or single value]', 'Flow direction', and 'Initial values [spatial map or single value]'. The 'Recession coefficient' section has a radio button for 'Single value [-]' set to 0.40 and a 'Spatial map [-]' option with a 'Select map' button. The 'Flow direction' section has a text field 'ldd.map' and a 'Select map' button. The 'Initial values' section contains five sub-sections: 'Routed total runoff', 'Routed snow runoff', 'Routed rainfall runoff', 'Routed glacier runoff', and 'Routed baseflow runoff'. Each sub-section has a radio button for 'Single value [m3/s]' set to 0.00 and a 'Spatial map [m3/s]' option with a 'Select map' button. The 'Routed rainfall runoff' section has a 'Spatial map [m3/s]' option that is currently selected.

Figure 41: Overview of the routing tab.





Figure 42: Example of flow direction map.

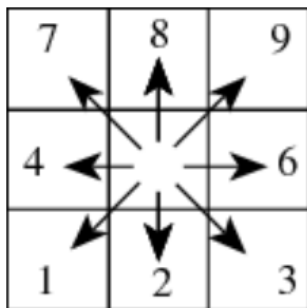


Figure 43: Values indicating the direction of flow in the flow direction map.

4.11.2 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]

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, it may be that you are interested in using results from a previous model as starting point for a new model

run. In that case you may provide the routed runoff of the last time-step of your previous model run as initial value for 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.

Routing of the individual streamflow components (rainfall runoff, baseflow runoff, snow runoff, and glacier runoff) is more time-consuming than only routing the total runoff. 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. This is also illustrated in Figure 41, where all routed runoff components will be calculated, except for the routed rainfall runoff.

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.

4.12 Report options

Figure 44 represents an overview of the Report options tab. Within this section of the GUI you need to specify for each variable if you want this to be reported as model output yes or no. The left side of this section shows a list with all the variables that can be reported as model output.

The right side of this section shows the options for the model output settings, which are divided into:

- Map-series output
- Time-series output
- Report mm fluxes for basin averages



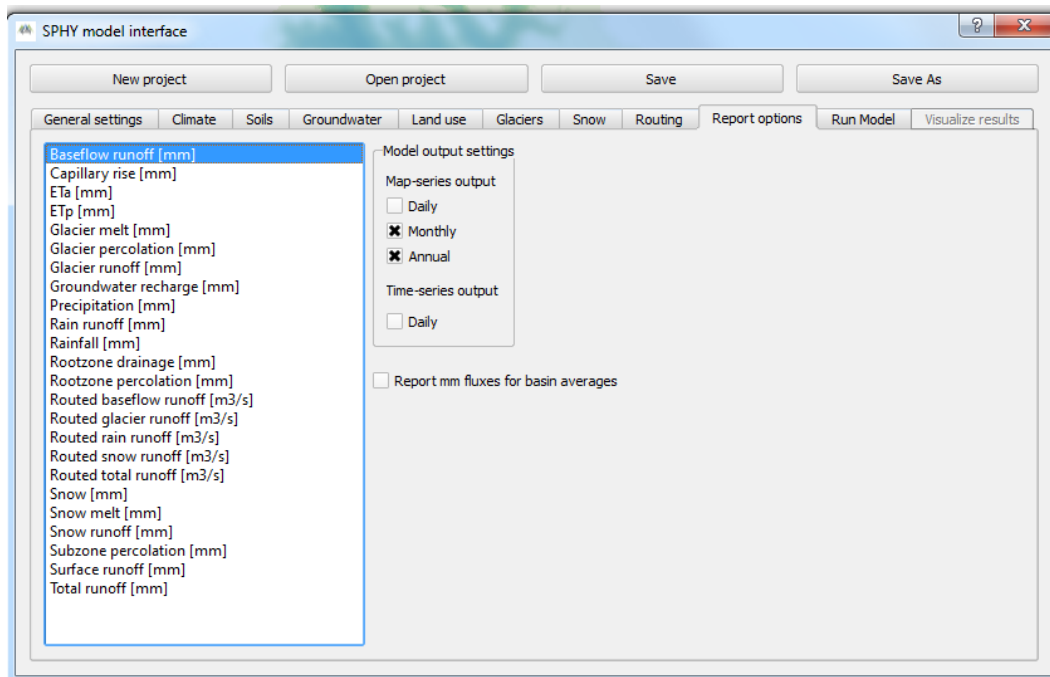


Figure 44: Overview of the Report options tab.

Under map-series output you can specify whether you want output maps to be reported on a daily, monthly, or annual basis. In the example above it can be seen that baseflow runoff is reported on both a monthly and annual basis.

Additionally, you may be interested in plotting time-series for certain variables on locations defined in the Stations map under Catchment settings. If this is required, then you need to check the Daily box under the Time-series output option.

Another interesting option is to report mm fluxes for basin averages. It is often more useful to analyze fluxes in mm than comparing fluxes in m^3/s . The “Report mm fluxes for basin averages” calculates for the areas upstream of your locations, which are defined in your Stations map, basin average fluxes in mm. This calculation will only be done for the in- and outgoing fluxes, which are: precipitation, actual evapotranspiration, glacier melt, routed snow runoff, routed rain runoff, routed glacier runoff, routed baseflow runoff, and routed total runoff.

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

4.13 Running the model

Figure 45 provides an overview of the Run Model tab. Before running the model you need to specify your environmental settings, which are setting the PATH of the PCRaster bin folder and selecting the python executable (python.exe).

The PCRaster bin PATH can be found under the PCRaster installation folder (see Section 3.1.3). This folder can be selected by clicking the Select path button.

The python executable can be found under the Python installation folder (see Section 3.1.1), and can be selected by clicking the Select python.exe button.



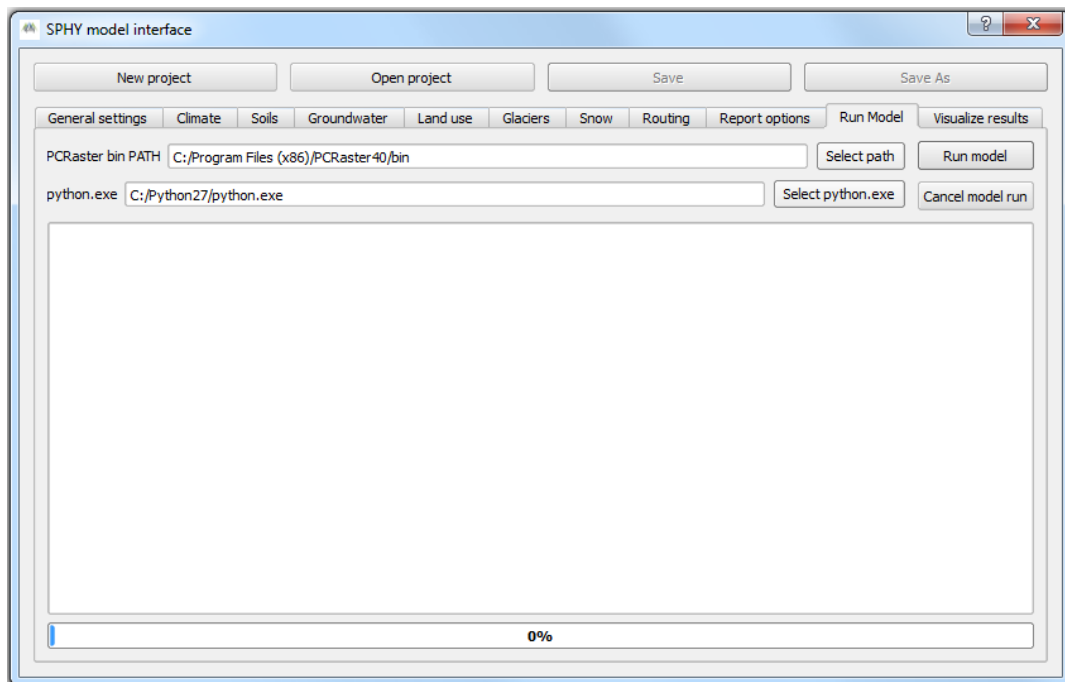


Figure 45: Overview of the Run Model tab.

After setting these environmental settings you can 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 46. Model run can be canceled anytime by pressing the Cancel model run button. If this is done, then previous model output will NOT be overwritten. Figure 47 shows an example of the log screen output of a cancelled model run.

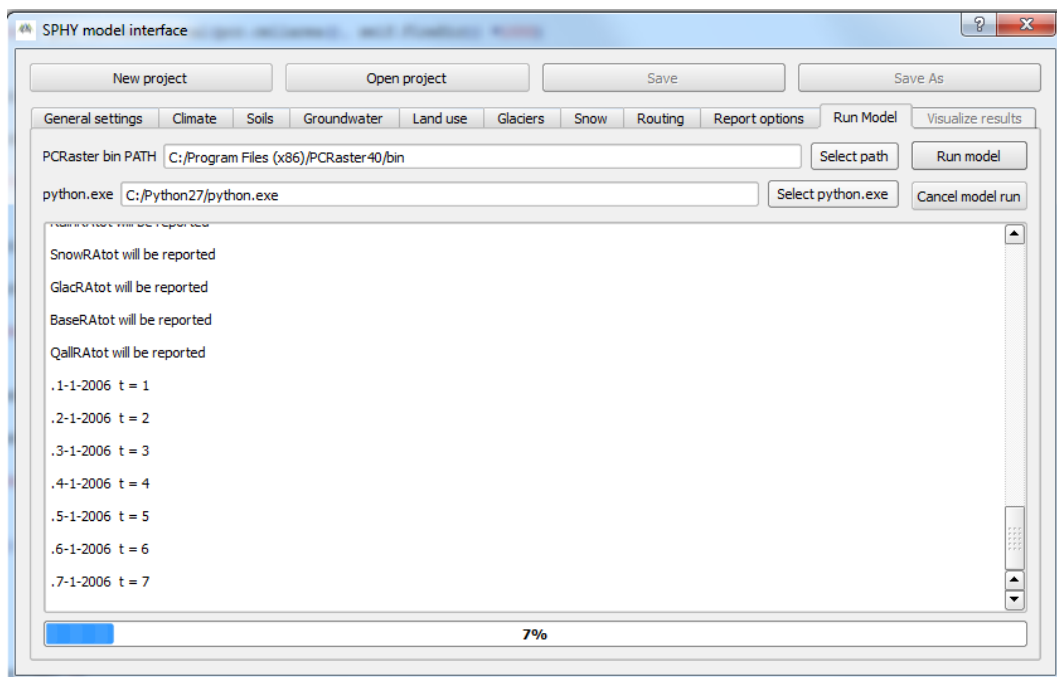


Figure 46: Example of log screen output during model run.



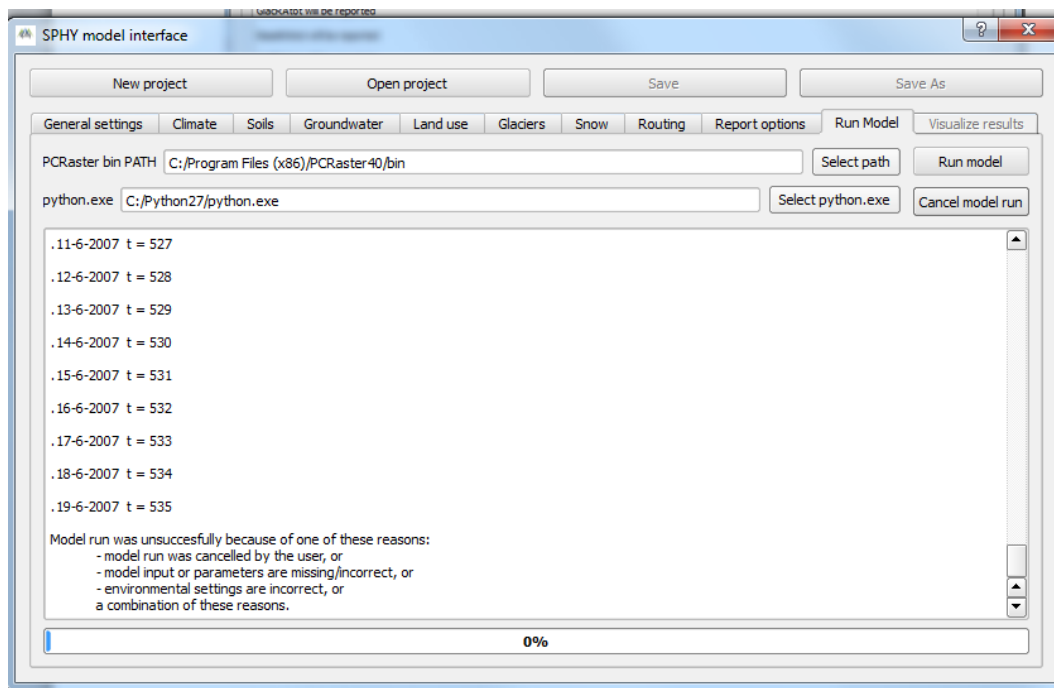


Figure 47: Example log screen output of cancelled model run.

If an error occurs after the Run model button has been clicked, then a screen similar to that of Figure 47 will be shown. In that case you need to check your model input/parameters, environmental settings, or a combination of these.

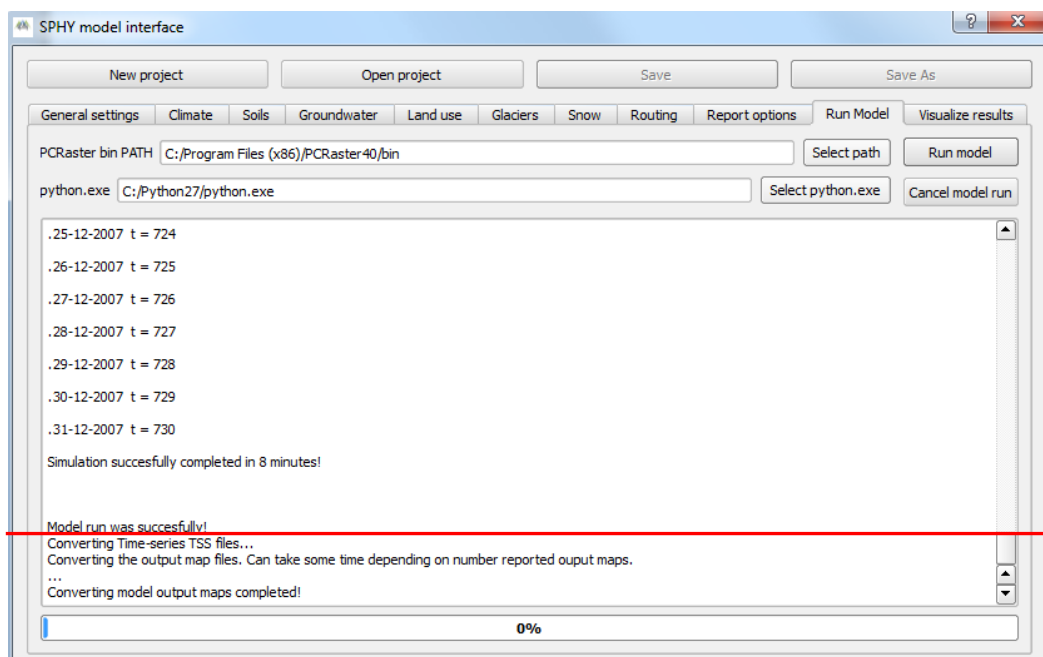


Figure 48: Example log screen output of successful model run.

If your model run was successful, then a screen similar (without red line) to Figure 48 will be shown. The text “Model run was successfully!” indicates that model execution was successfully.

At this stage you still can click the Cancel model run to prevent previous model output to be overwritten. Otherwise the GUI continues with converting model output (part below red line) to 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 in order to analyze model output.

4.14 Visualizing model output

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 49. 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 has been made between time-series output (left list widget) and map-series output (three right list widgets). Map-series output has been split into three separate list widgets, being i) daily maps, ii) monthly maps, and iii) annual maps.

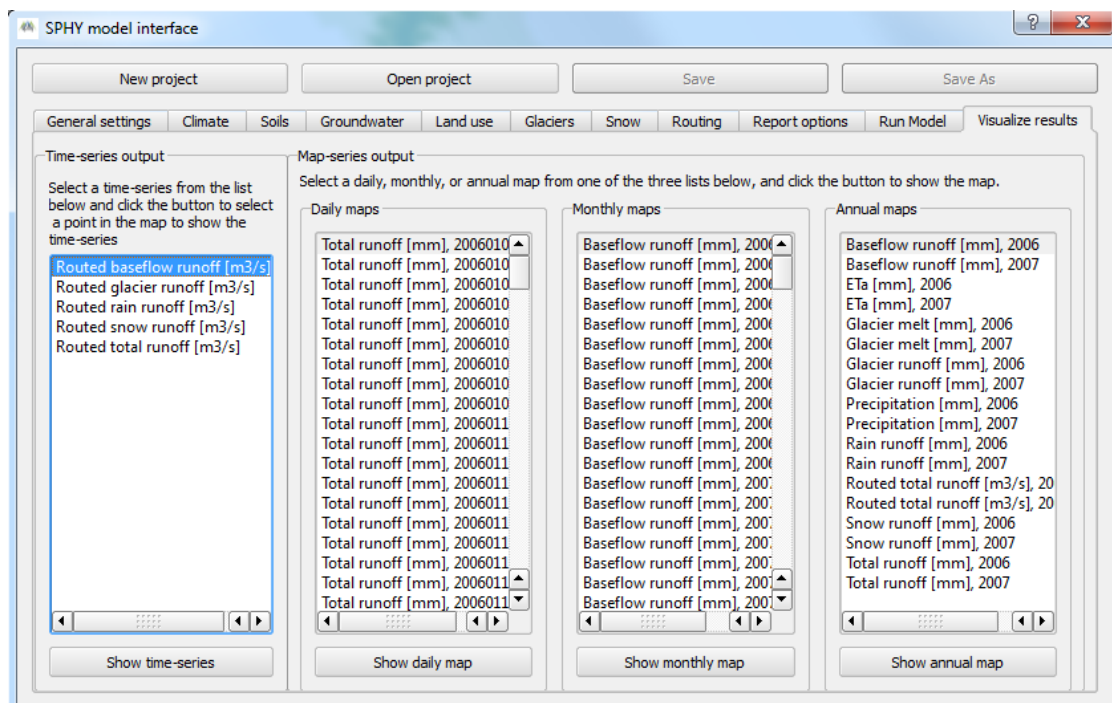


Figure 49: Overview of Visualize results tab.

4.14.1 Time-series output

Time-series plots can be shown for the locations that are defined in the Stations map in the General settings tab (Section 4.4.4). In order to show a time-series plot you need to:

1. Select the variable of interest from the list (in Figure 49 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 50).
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 51).



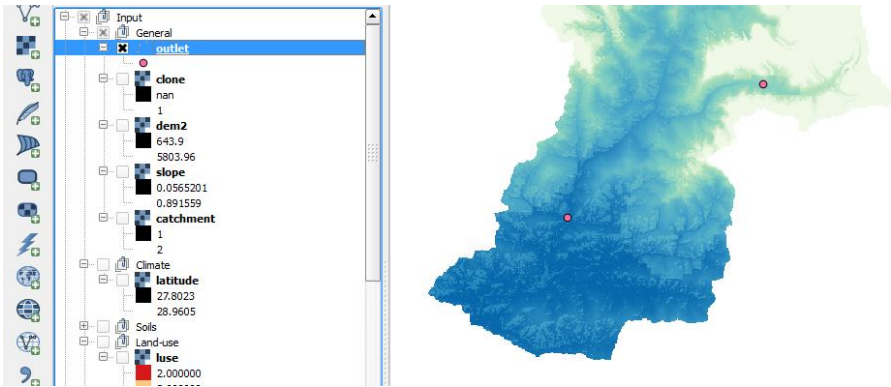


Figure 50: Setting the Stations map layer (outlet) as active layer.

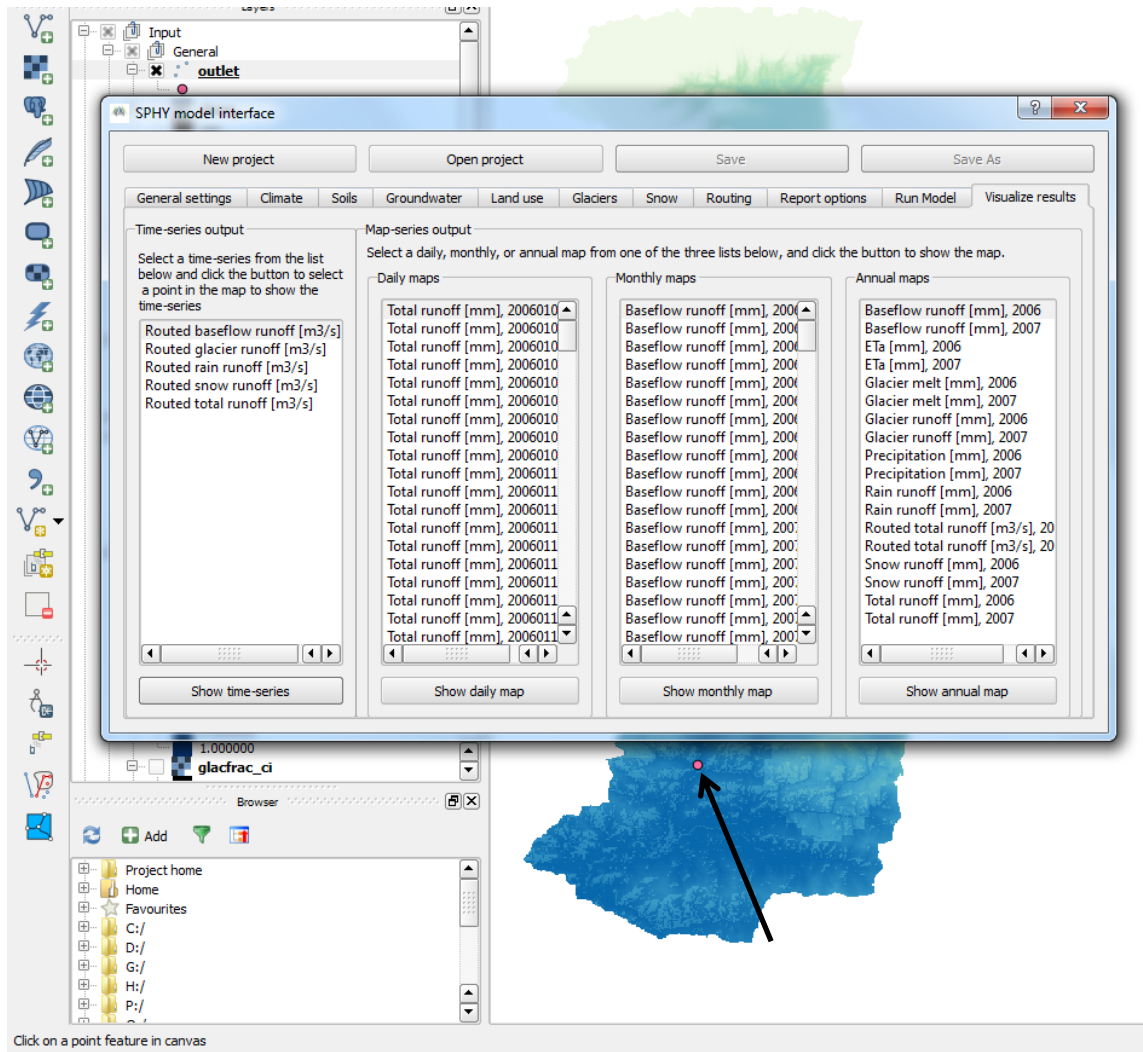


Figure 51: Click on a point feature in the canvas to show a time-series.

After completing step 4 a time-series plot will be shown (Figure 52). The buttons shown inside the red box allow you to zoom in and zoom out of your graph, pan through the graph, change axis and label settings, and save your graph to an image file.

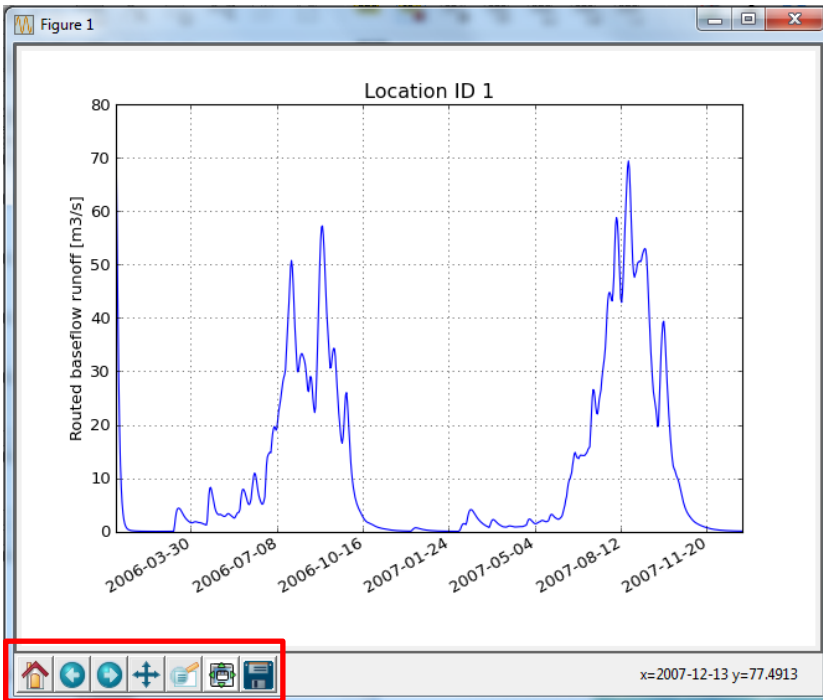


Figure 52: Example of time-series plot.

4.14.2 Map-series output

Showing map-series output is more straightforward than the plotting of 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 press 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 existed in the group, then this layer will be overwritten with the new selected map layer. Figure 53 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.



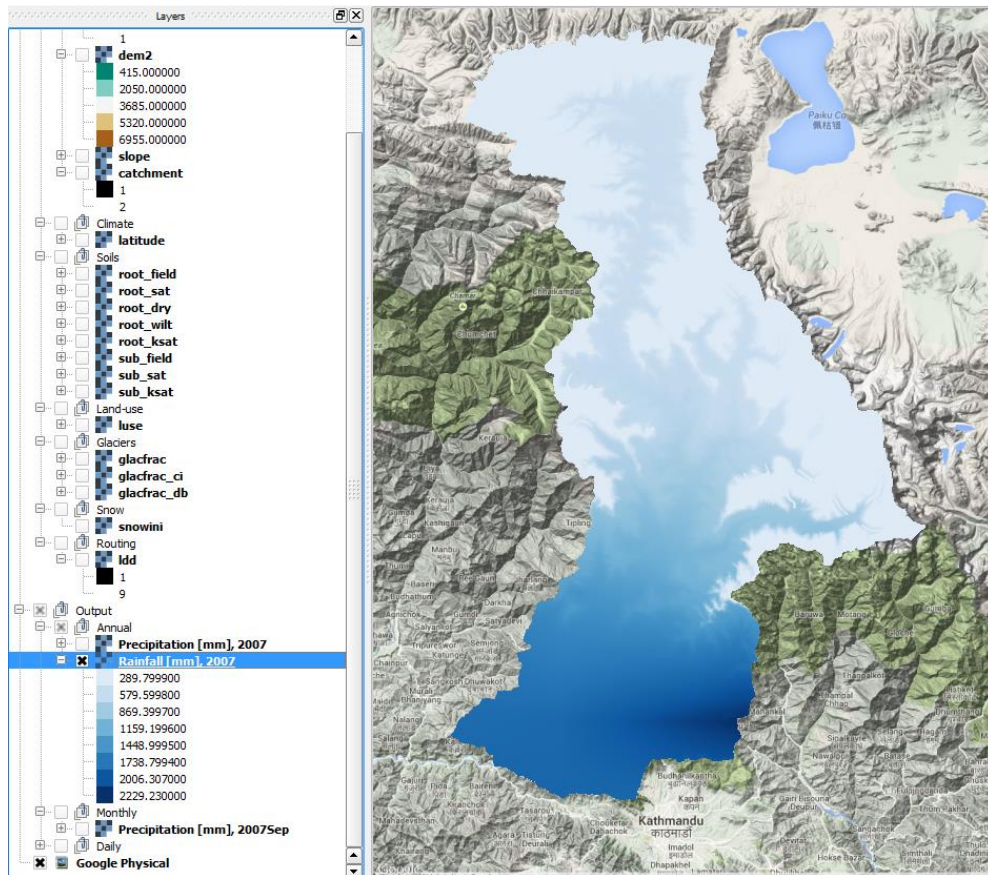


Figure 53: Example of annual rainfall map that has been added to the map canvas.

5 Case-study: Trisuli River Basin, Nepal

The model setup and interpretation of model results is illustrated with a case study for the Trisuli river basin in Nepal. The Trisuli basin covers 144.056 km² ranging from the Tibetan Plateau in the North to Kathmandu in the South. The average elevation of the basin is 3747 m a.s.l., but the elevation ranges from 6955 to 415 m a.s.l. During this tutorial we will explore the input data for Trisuli that feeds into SPHY, get the model running, and explore the model output.

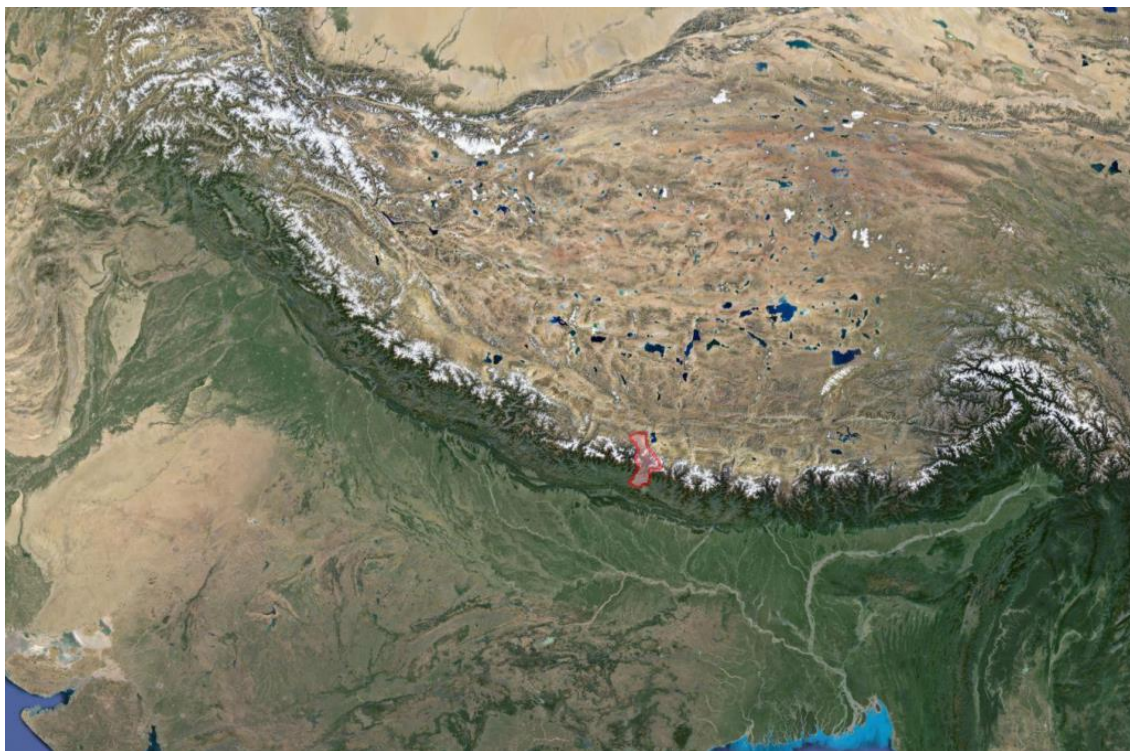


Figure 54: The location of the Trisuli basin.

For the Trisuli basin, we will setup the SPHY model for two years: 2006 and 2007. For this period we will setup SPHY at a daily time step, and with 200 x 200 m spatial resolution (grid cell size). All maps used in this tutorial are in the WGS 84 / UTM zone 45N projection. In this tutorial, each step to setup the model is discussed. For more technical information on how to use the SPHY interface to accomplish the steps discussed in this tutorial, please refer to Chapter 4.

5.1 Create new project and set general settings

Start by creating the **input** and **output** directories in the **SPHY2.0** directory. Subsequently copy the contents of the **data\input** directory to the **SPHY2.0\input** directory.

Subsequently start QGIS. From the **data\other_layers** directory, add **landsat_winter_2014_c.tif** to the QGIS layer canvas. This is a LandSat satellite image containing the Trisuli basin, and can be used as a reference background in QGIS.





Figure 55: Trisuli basin

Now open the SPHY plugin. Click “New Project” and save your new project in the **SPHY2.0** directory. Name the project **Trisuli_v1.cfg** or another appropriate filename. Then, in the SPHY interface, go to the tab “General Settings”.

In the part “Folder selection” select the **SPHY2.0** directory as “SPHY folder” and select the **input** and **output** directories which you just created as “Input folder” and “Output folder”.

In the part “Period of simulation”, set the “Start date” and “End date” of the simulation, from 1 January 2006 until 31 December 2007.

In the part “Coordinate System”, you need to specify the coordinate system of your area of interest. The coordinate system has to be specified in EPSG. You can search for the corresponding EPSG number on this website: <http://spatialreference.org/ref/epsg/>. For the Trisuli case study model, we use the WGS 84 UTM 45 North projection, which has EPSG code 32645.

In the part “Catchment settings”, select the appropriate maps from the **SPHY2.0\input** directory, as indicated in the table below.

Table 3: General settings: Catchment settings

Catchment settings	
Clone map	clone.map
DEM map [MASL]	dem.map
Slope map [-]	slope.map
Sub-basins map	catchment.map
Stations map	outlet.map

Each layer you add through the interface will automatically be added to the QGIS layer canvas.

Have a look at each of these maps in QGIS. If you wish, you can change the individual layer's legend by double-clicking on the layer's name in the "Layers" window and adjust settings under the "Style" tab. Answer the following questions:

Which parts of the basin are highest and which parts are the lowest?

Which parts of the basin have the steepest slopes, and which parts are more flat?

Note that two point locations are defined, which are coinciding with locations where the actual discharge is measured in the Trisuli basin. The upstream location is Kyangjin station and the downstream station is Betrawati station. The sub-basins map shows the catchments of each of these stations. Save your model setup every once in a while by clicking the "Save" button in the top row of the SPHY interface.

5.2 Climate

Have a look at the contents of the **SPHY2.0\input\forcing** directory. This directory contains daily input maps (map-series) for precipitation, mean temperature, maximum temperature and minimum temperature. The filenames have a strict numbering format. For example the mean temperature maps have the format **tavg0000.001** until **tavg0000.730**.

In the SPHY-interface go to the "Climate" tab. In the part for "Meteorological forcing map-series", select the appropriate map-series from the **SPHY2.0\input\forcing** directory:

Table 4: Meteorological forcing map-series

Meteorological forcing map-series	
Precipitation [mm/d]	prcc
Avg. daily temperature [°C]	tavg
Max. daily temperature [°C]	tmax
Min. daily temperature [°C]	tmin

In the part "Meteorological parameters" select **latitude.map** from the **SPHY2.0\input** directory for "Latitude zones". Leave the value for the "Solar constant" unchanged.

The map with latitude zones defines the latitude values for all grid cells in the model. Why is this map included? You can look it up in the theoretical part of the manual.

From the **data\other_layers** directory add **TotPrec_2006.map** and **TotPrec2007.map** to the QGIS canvas. These maps show the annual precipitation sums for 2006 and 2007 as calculated from the daily precipitation forcing map-series. Now answer the following questions for 2006 and 2007:

What is the maximum annual precipitation, and in which area does this occur?

What is the minimum annual precipitation, and in which area does this occur?

What is the mean precipitation for the entire basin, and for the subcatchments of the Kyangjin and Betrawati discharge stations?



5.3 Soil

Go to the “Soils” tab in the SPHY interface. In the parts for “*Rootzone physical maps*” and “*Subzone physical maps*” input maps need to be provided for different physical soil parameters for a topsoil layer and a subsoil layer separately. These parameters are required for model calculations for evaporation, infiltration and surface runoff generation, as described in detail in Section 2.1.6

Usually these data are not readily available. However, maps with soil types are often available, and pedotransfer functions [e.g. *Nemes et al.*, 2001; *Keshavarzi et al.*, 2010] are available to assign physical soil parameters to soil types. For the Trisuli model we use a global soil type map, the Harmonized World Soil Database (HWSD, [FAO/IIASA/ISRIC/ISSCAS/JRC, 2012]).

Add **soil.map** from the **SPHY2.0\input** directory to the QGIS canvas. This map has the soil types in the Trisuli basin according to the HWSD. The numerical values correspond to the categorized soil types legend of the HWSD.

HWSD_soil_data.xlsx in the **data\soil** directory contains a table with the values of the soil parameters coupled to each soil type. We now want to generate a map for each physical soil parameter using the soil types map and the table with physical soil parameter values. To do this we can use the PCRaster command line functions.

The file **root_field.tbl** in the **data\soil** directory is a lookuptable containing the first column of the **HWSD_soil_data** spreadsheet (soil type) and the sixth column (field capacity of the rootzone). Copy **soil.map** from the **SPHY2.0\input** directory to the **data\soil** directory. Now open the command line by clicking the Windows Start button, then type **cmd**, and press enter. Navigate to the directory containing the soil type map and the lookuptable, using the change directory (**cd**) command:

```
cd c:\...enter_path_to_directory_here...\data\soil
```

and press “Enter”.

Now type the following command:

```
pcrcalc root_field.map = lookupscalar(root_field.tbl, soil.map)
```

A new file was created (**root_field.map**) giving the values of the rootzone field capacity for each grid cell. Copy this file to the **SPHY2.0\input** directory.

In the SPHY interface, select the new map at the field for “*Field capacity*” in the part for “*Rootzone physical maps*”. The added map will be added to the QGIS canvas.

Now create the lookuptables for the other soil parameters yourself and use them to create maps of the other soil parameters. Subsequently copy them to the **SPHY2.0\input** directory and select them in the SPHY interface.

Describe for each of these soil parameters how they are defined and how they influence the behavior of water in the soil.



In the SPHY interface, in the part for “*Root- and subzone parameters*”, maps with the approximate rootzone depth and subsoil depth are included. Alternatively a single value can be set. Leave these settings unchanged as well and do the same for the value for maximum capillary rise.

5.4 Groundwater

Open the “*Groundwater*” tab in the SPHY interface. The left part contains the groundwater volume settings. Here you can set values for the groundwater layer thickness, saturated groundwater content and initial groundwater storage for the first time step. Often, the values of these groundwater volumes are unknown and values are usually calibrated, using observed stream flow. The values you choose here will mainly affect the generation and delay of baseflow. In the right part, three parameters can be set, which are also related to groundwater. Also these values are usually unknown and need to be calibrated. For now, leave the default values. Answer the following question using the theoretical part of the manual:

What would happen to the delay in baseflow when the “*alphaGw*” parameter is increased?

5.5 Land use

Open the “*Land use*” tab in the SPHY interface. In the “*Land use map*” field select **luse.map** from the **SPHY2.0input** directory. This land use map is derived from the LandSat 8 image we have seen before. Four different land use types have been classified:

Table 5: Land use classes

Land use classes		
2	Forest	Kc = 1.2
3	Snow and ice	Kc = 0.5
4	Bare soil	Kc = 1.0
5	Water	Kc = 1.0

To each of these land use types a “crop coefficient” (Kc) is assigned, which is used to calculate the potential evapotranspiration from the reference evapotranspiration in the SPHY model. The Kc values are stored in a lookup table, similar as the data for the physical soil parameters. Select this lookup table (kc.tbl) from the input directory. Now answer the following question using the theoretical part of the manual:

How is the potential evapotranspiration calculated from the reference evapotranspiration?
Why is the actual evapotranspiration not equal to the potential evapotranspiration?

5.6 Glaciers

Open the “*Glaciers*” tab in the SPHY interface. The part on “*Glacier fraction settings*” is used to define the glaciated areas and distinguish debris-covered and debris-free glaciers. In the field with the “*Initial glacier fraction*”, add **glacfrac.map** from the **SPHY2.0input** directory. The map is added to the QGIS canvas.



This map was calculated from the ICIMOD glacier inventory [Bajracharya and Shrestha, 2011]. For every grid cell, a fractional glacier cover between 0 and 1 is calculated. You can see this when you zoom in to the glaciers in QGIS. For example, when only half of a 200 x 200 m grid cell is covered by glaciers, that grid cell has value 0.5 assigned.

The glacier fraction is further divided in debris-covered glaciers and debris-free glaciers, to enable the use of different melt rates in SPHY. Add **glacfrac_ci.map** from the **SPHY2.0\input** directory in the field for “*Clean ice glacier fraction*” and **glacfrac_db.map** in the field for “*Debris covered glacier fraction*”. The distinction of debris covered and debris free glaciers was done manually using the Landsat 8 scene. Now answer the following questions:

How large is the area covered by glaciers in the Trisuli basin?
What percentage of the total basin area is this?
What percentage of the catchment upstream of Betrawati station is covered with glaciers?
What percentage of the catchment upstream of Kyangjin station is covered with glaciers?

In the part “*Glacier degree-day-factors*” you can assign melt factors for the debris covered glaciers (DDFDG) and debris free glaciers (DDFG). These parameters are usually calibrated. They are based on the relation between air temperature and melt. For now, leave the default values. Answer the following questions:

How does a degree-day melt model work and what inputs does it need?
Why is the degree-day-factor for debris-free glaciers larger than for debris-covered glaciers?
What other factors than air temperature influence the actual melt rate of glacier ice?

5.7 Snow

Open the “*Snow*” tab in the SPHY interface. “*SnowIni*” is the initial snow storage at the first time step. In the “*SnowIni*” part you can assign the snow storage (mm water equivalent) at the beginning of the model run. You can assign a single value, which is the same for all grid cells, or a spatial map, where you can assign different initial snow storages for each grid cell. For now, leave this setting at default (0 mm single value). This means that there is no snow storage at the beginning of the model run. Answer the following questions:

Our model run will start at 1 January 2006. Is the initial snow storage realistic?
What will be the consequences for the simulated discharge during the first year?
How could you create a more accurate initial snow storage?

“*SnowWatStore*” is the initial amount of water that is refrozen in the snow pack and “*SnowSC*” is a parameter that determines how much refrozen water the snow pack can store. Leave these parameters at their default values for now.

Draw a diagram showing how all snow-related processes in SPHY interact. Use the theoretical part of the manual for your reference.

“*DDFS*” is a degree-day-factor for snow melt, assigned to determine how fast snow melts. This is a calibration parameter. You can provide a single value or a spatial map to have spatial variation in the melt factor. Similarly as for glacier ice, this degree-day model is based on the relation between air temperature and melt.



"*Tcrit*" is the temperature threshold to define if precipitation falls as snow or rain. Leave it unchanged for now.

5.8 Routing

Open the "*Routing*" tab in the SPHY interface. The "*Recession coefficient*" is used to determine how fast water travels from the grid cell where it is generated to the downstream cells. This parameter is also used to calibrate the model. For now a single value is set as default. The "*Flow direction*" map is an important part of the model, indicating for each grid cell in which direction it drains. Using this map, the water can be directed from each grid cell towards the basin's outflow point. This map is usually derived from a Digital Elevation Model (DEM).

Create a new directory named **workdir**. Copy **dem.map** from the **SPHY2.0\input** directory to **workdir**. Open the command prompt and navigate to **workdir**, using the change directory (cd) command:

```
cd c:\...enter path to directory here...\workdir
```

First, we fill the sinks in the DEM to avoid that pits are generated in the depression in the DEM, which hamper the water to flow to the basin's outlet. This is done using PCRaster's [lddcreatedem](#) command. Type:

```
pcrcalc demfil.map = lddcreatedem(dem.map,1000,1e31,1e31,1e31)
```

To create a flow direction map (or local drain direction (LDD)), you can use the PCRaster command [lddcreate](#). Type the following command:

```
pcrcalc ldd.map = lddcreate(demfil.map,1000,9999999,9999999,9999999)
```

Add the newly created **ldd.map** to the QGIS canvas. You can see the draining directions of the grid cells. A good way to test if the LDD map is correct is to calculate for each grid cell how many cells are upstream, to highlight the stream network. You can do this using the PCRaster command [accuflux](#). Type:

```
pcrcalc accuflux.map = accuflux(ldd.map,1)
```

Add the newly generated **accuflux.map** to the QGIS canvas. Check if the stream network is complete, and all branches are connected to the outlet point.

If the generated LDD is not entirely correct and not all streams are connected toward the downstream outlet point, this happens because during the creation of the LDD map, pits have been generated where depressions in the landscape are present. More details on the LDD generation can be found in the PCRASTER online manual. There are multiple ways to overcome the problem of pit generation:

- Test different values for the parameters in the lddcreate command
- Remove pits manually by changing the values for those cells.



- Use a map with the streams present in your study area and “burn” them into the DEM to force the other cells to drain in into them.

When you have a correct LDD map, copy **ldd.map** from **workdir** to the **SPHY2.0\input** directory.

5.9 Report options

Open the tab “*Report options*” in the SPHY interface. In this tab you can set for each flux and variable calculated in SPHY if and how often it is reported during a model run. Map-series can be written at daily, monthly and annual time step or a combination of these. Time-series at point locations can be written at a daily time-step.

Set the following settings in this tab in the interface:

Table 6: Report options

Variable/flux	Report frequency
Baseflow runoff	Annual, Monthly
ETa	Annual
Glacier melt	Annual, Time-series output: Daily
Glacier runoff	Annual, Monthly
Rain runoff	Annual, Monthly
Precipitation	Annual, Time-series output: Daily
Rainfall	Annual
Rootzone drainage	Annual, Monthly
Routed base-flow runoff	Time-series output: Daily
Routed glacier runoff	Time-series output: Daily
Routed rain runoff	Time-series output: Daily
Routed snow runoff	Time-series output: Daily
Routed total runoff	Time-series output: Daily
Snow	Annual,
Snow runoff	Annual, Monthly
Surface runoff	Annual, Monthly
Total runoff	Annual

Also check the option “*Report mm fluxes for basin averages*”.

5.10 Run Model

Now it is time to do the first model run. Open the Run Model tab in the SPHY interface. Select the paths to the PCRaster **bin** directory (most probably: **C:/Program Files (x86)/PCRASTER4/bin**) and Python 2.7 executable (most probably: **C:/Python27/python.exe**). Then click the “*Run model*” button, and the model run is started.

When the run is finished browse to the **SPHY2.0\output** directory, where all output files are written. Note that there are different types of output files. There are maps with the year and month indicated in the file name, and there are timeseries, stored as **.csv** files.



5.11 Visualize results

In the SPHY interface, open the last tab: “*Visualize results*”. In the first column you see all time-series output. In the other three columns you see the map-series output, categorized for daily maps, monthly maps, and annual maps.

In QGIS, place the outlet point layer on top of the other layers, and make sure the layer is selected in the “*Layers*” window. In the “*Visualize results*” tab in the SPHY interface, click “*Routed total runoff*”, and then click “*Show time-series*”. Then click on the point location of the Betrawati station in the QGIS canvas. An image pops up with the simulated routed total runoff for each time step at Betrawati station.

Close the graphs and add the annual map with the total runoff in 2007 by selecting it in the SPHY interface and clicking “*Show annual map*”. If you wish, adjust the legend in QGIS. You can add other maps in the same way.

5.12 Model calibration

5.12.1 Discharge time-series

Using the “*Visualize results*” tab, look at all different outputs to get an idea of what data you have available. As already mentioned in the previous sections, many of the tabs we visited during model setup contain parameters that require values, but these values are not always known in advance. Some of the parameters can be measured in the field, others can be approximated with values found in scientific literature, or they can be calibrated.

Revisit the Groundwater, Glaciers, Snow and Routing tabs. How could each of these parameters be calibrated, and what data would you need to do that?

For this tutorial, we will use discharge measurements at Betrawati Station and Kyangjin station to calibrate the model.

Open **runoff_Trisuli.xlsx** from the **data\runoff** directory in Excel or another spreadsheet program. This file contains the daily measured discharge records at Betrawati and Kyangjin stations, each on a separate sheet. The first column shows the dates from 1 January 2006 until 31 December 2007. The second column shows the observed discharge in m^3/s .

For both stations, derive the catchment areas and fill this number in field B2 in the spreadsheets. Note that, once you filled in the catchment area, the third column will be also filled with the values of the observed discharge converted from m^3/s to mm.

From the **SPHY2.0\output** directory, copy the data in **QGLACSubBasinTSS.csv**, to the column for QGLAC in **runoff_Trisuli.xlsx**. In the .csv file, the first column is the date, the second column is the simulated runoff (mm) at Betrawati, and the third column is the simulated runoff (mm) at Kyangjin. In the same way, copy the data for discharge from snow melt, baseflow and rainfall-runoff from the corresponding .csv files to **runoff_Trisuli.xlsx**. When you have filled the columns, you will notice that the data is plotted in the graphs that are included in the spreadsheet file. You are able to see the difference between the observed and simulated



discharge, and the contribution of glacier melt, snow melt, rainfall-runoff and baseflow to the total flow.

Using this model output, fill the following table:

Table 7: SPHY model output

	Betrawati	Kyangjin
Observed discharge (mm/yr)		
Simulated discharge (mm/yr)		
Glacier melt contribution (%)		
Snow melt contribution (%)		
Rainfall contribution (%)		
Baseflow contribution (%)		

Why is the contribution of glacier melt larger at Kyangjin station than at Betrawati station?

During which months peaks the glacier melt? Why?

During which months peaks the snow melt? Why?

During which months peaks the rainfall-runoff? Why?

How would you rate the correlation of the observed and simulated flow?

5.12.2 Water balance

In **runoff_Trissuli.xlsx**, now also fill the columns for precipitation (PREC) and evapotranspiration (ET), using the outputfiles **PrecSubBasinTSS.csv** and **ETaSubBasinTSS.csv**. Then fill the table below using the output from this model run:

	Betrawati	Kyangjin
Precipitation P (mm/yr)		
Discharge Q (mm/yr)		
Actual evapotranspiration ET (mm/yr)		
Difference P – Q – ET (mm/yr)		

Why is $Q + ET$ not equal to P ?

In SPHY, glaciers are static entities generating melt water, but they are not mass conserving, e.g.: the precipitation falling on their surface is excluded from the water balance. In fact, the precipitation calculated for the subbasins in the outputfiles is calculated for the non-glaciated fraction only. This mean that the glacier melt can be considered as an input to the water balance. Recalculate the water balance using the glacier melt as an additional input to the water balance:

	Betrawati	Kyangjin
Precipitation P (mm/yr)		
Glacier Melt M (mm/yr)		
Discharge Q (mm/yr)		
Actual evapotranspiration ET (mm/yr)		
Difference P + M – Q – ET (mm/yr)		

Why is the difference between $P+M$ and $Q+ET$ still not equal to 0?



5.12.3 Sensitivity analysis

To improve the model performance, we need to tune some of the model parameters. Before we start changing parameters, we will do a simple sensitivity analysis for the most important model parameters to see how changes in each of the model parameters will affect the model results. In the table below, most important parameters are listed, for which we will test their sensitivity for the discharge at Betrawati station. First, fill the column for initial discharge in 2007. We will analyse the discharge changes for 4 different months in 2007, equally distributed over the year, to be able to see also which parameter has effect on the flows in which part of the year. The filled column will serve as a 'baseline' to which we are going to look how the model results change when adjusting parameters.

Before you start the analysis, try to reason which parameters will be most sensitive and how this could be different for different parts of the year. Write down your expectations.

Now do a series of model runs, each time changing one parameter and leaving the others the same as the baseline. First change the parameter by setting the parameter at 50% of its initial value. Then for the next run set the parameter at 150% of its initial value. After each model run, write in the table how the average discharge during each of the four months in 2007 changes. Also write down how the hydrograph has changed after each model run. Did the distribution of flow over the year change, did low flows increase or decrease? Is the hydrograph getting smoothened or does it show more spikey patterns?

Parameter	Initial Value	Initial Q 2007 (mm/day)	ΔQ (%) for parameter value 50%	ΔQ (%) for parameter value 150%
Soil				
Rootlayer thickness (mm)	300	Jan:		
		Apr:		
		Jul:		
		Oct:		
Sublayer thickness (mm)	700	Jan:		
		Apr:		
		Jul:		
		Oct:		
Groundwater				
deltaGW	3	Jan:		
		Apr:		
		Jul:		
		Oct:		
alphaGW	0.05	Jan:		
		Apr:		
		Jul:		
		Oct:		
Glaciers and Snow				
DDFDG	2	Jan:		
		Apr:		
		Jul:		
		Oct:		
DDFG	6	Jan:		
		Apr:		
		Jul:		
		Oct:		
DDFS	5	Jan:		
		Apr:		



		Jul:		
		Oct:		
Routing				
Recession coefficient	0.50	Jan:		
		Apr:		
		Jul:		
		Oct:		

When finished, plot your results. Make a plot with ΔQ on the y-axis and the change in parameter value (%) on the x-axis, and plot for all parameters in the same plot.

Which parameters have most influence on change in discharge during January? Answer the same question for the three other months.

Which parameters have most influence on the total discharge?

Are the findings in line with your expectations?

Now think carefully how you would change the parameter values to improve your model results, and then do another model run with the parameter values you suggest.

A commonly accepted criterion to indicate how well a model is able to simulate observations is the Nash-Sutcliffe model efficiency coefficient (NSE [Nash and Sutcliffe, 1970]). The NSE is defined as:

$$NSE = 1 - \frac{\sum_{t=1}^T (Q_o^t - Q_m^t)^2}{\sum_{t=1}^T (Q_o^t - \bar{Q}_o)^2}$$

where \bar{Q}_o is the mean of observed discharges, and Q_m is modeled discharge. Q_o^t is observed discharge at time t.

Assess the performance of your last model run, by calculating the Nash-Sutcliffe model efficiency for the daily values in 2007. The table below provides an indication of how the model performance can be characterized by the Nash-Sutcliffe efficiency.

Table 8: Description of fit linked to Nash-Sutcliffe model efficiency coefficient (Adapted from [Foglia et al., 2009])

Fit	Nash-Sutcliffe efficiency
Observed mean is a better predictor than the model	<0
Insufficient	0- 0.2
Sufficient	0.2-0.4
Good	0.4-0.6
Very good	0.6-0.8
Excellent	>0.8

Adjust your model parameters and do additional model runs until you are satisfied with the model's performance.

During this tutorial, we are not going to do a complete validation of the calibrated model. How could you validate the performance of your calibrated model?



5.13 Climate Change

Hydrological models are very useful to assess the impacts of climate change for water resources. We are now going to use the calibrated model to assess the hydrological changes in the Trisuli basin for a hypothetical climate change scenario assuming that the daily air temperature increases by 3 °C and daily precipitation increases by 20%.

To do this, first save the project under a new name: Click the “Save As” button in the top row of the SPHY interface. Give the new project for example the name: **Trisuli_CC_v1.cfg**.

We will leave all parameters unchanged, except for the climate input and glaciers map. Open the “*Climate*” tab in the user interface and select other meteorological forcing map-series. These are located in the **SPHY2.0/input/forcing_cc** directory.

Create new output directory named **output_cc** in the **SPHY2.0** directory. In the “*General settings*” tab, select this folder as “*Output folder*”. Create a new glacier map, assuming that all glaciers in the basin have retreated by 50%. You can do this by changing **glacfrac.map**. Open the command line window and browse to the **SPHY2.0input** directory. Type

```
pcrcalc glacfrac_cc.map = glacfrac.map * 0.5
```

Then under the “*Glaciers*” tab in SPHY interface, select the new map as “*Initial glacier fraction*”. Think carefully which maps and time-series you want to report, also keeping in mind the questions stated below. Save the project and run the model.

When the run is finished analyse the output and investigate how the hydrology has changed, by looking at time-series of discharge and discharge contribution at Betrawati and Kyangjin stations and compare spatial maps of the baseline run and climate change run. Answer the following questions:

How does the total amount of runoff generated in the entire basin change between the baseline and the climate change run?

How do the contributions of glacier melt, snow melt, rainfall-runoff and baseflow change for the entire basin, the catchment of Betrawati station, and the catchment of Kyangjin station?

Does the amount of glacier melt generated in the Trisuli basin increase or decrease?

Can you see shifts in the peak of snow melt when comparing snow melt maps of different months for the baseline and climate change run?

Do the areas where snow melt is generated change?

Can you see shifts in snow melt when comparing the hydrographs at Betrawati station for the baseline and climate change run?

How much does the amount of rainfall- runoff change in the basin?



6 Build your own SPHY-model

To setup SPHY for your own area of interest, you will need to create the same model inputs as for the Trisuli case-study. They can be created using own data you have available for your area of interest. You will need the PCRaster command line functions and GIS software, like the open source QGIS.

6.1 Select projection extent and resolution

Because all calculations in SPHY are metric, you will need to project your data in a metric coordinate system. For example for the Trisuli basin, we chose the WGS84 UTM Zone 45 North projection. Define the minimum and maximum x and y values in the projection that you have chosen that cover the entire area you want to model. Then, define the spatial resolution of your model. The choice of resolution will be a tradeoff of the resolution of your input data, computation resources availability, number of runs you intend to do and required detail for your modelling purpose. For your reference, the model for the Trisuli case study has an extent of 150 x 97 km². For this model the spatial resolution is 200x200 m, and thus the model contains ~350.000 grid cells. Running this model at a daily time step for 2 years takes about 15 minutes.

Create a new directory structure for the new model, including an **input** and an **output** directory.

6.2 Clone map

You will need to define a 'clone' map, which is a map in PCRaster format, with the model extent and resolution. This map is used as 'template' for the model. You can create a clone map using PCRaster's [mapattr](#) command.

In the command line type:

```
mapattr clone.map
```

You will enter a menu, where you can set the clone map's properties:

```

ca. Command Prompt - mapattr clone.map
creation of map: clone.map

number of rows      : *NOT SET*
number of columns   : *NOT SET*
data type           : boolean
cell representation : small integer
projection           : y increases from bottom to top
x upperleft corner  : 0.0
y upperleft corner  : 0.0
cell length         : 1.0
angle (degrees)     : 0.0
file id             : 0

ACTIONS: keyboard-keys=action
Enter=Select; ArrowDown,j=LineDown ArrowUp,k=LineUp;
q=Quit; u=UndoLastEdit;

```

Figure 56: Command line menu for clone creation

Change the settings of the number of rows, number of columns, check if the y values in your model projection increase from bottom to top or from top to bottom, define the x and y values of the upperleft corner of your model's extent, and define the cell length (spatial resolution).

When all is set, press "q" to quit and then press "y" to confirm the map creation. Then open the newly created map in QGIS to check if the map has the correct extent.

6.3 DEM and Slope

Use your own DEM or otherwise download the HydroSheds DEM [Lehner *et al.*, 2006] from internet. You will need to project your DEM in the model's projection and resample the DEM to model resolution and extent. In QGIS you can use the Warp tool to do reproject the raster under Raster → Projections → Warp (Reproject):

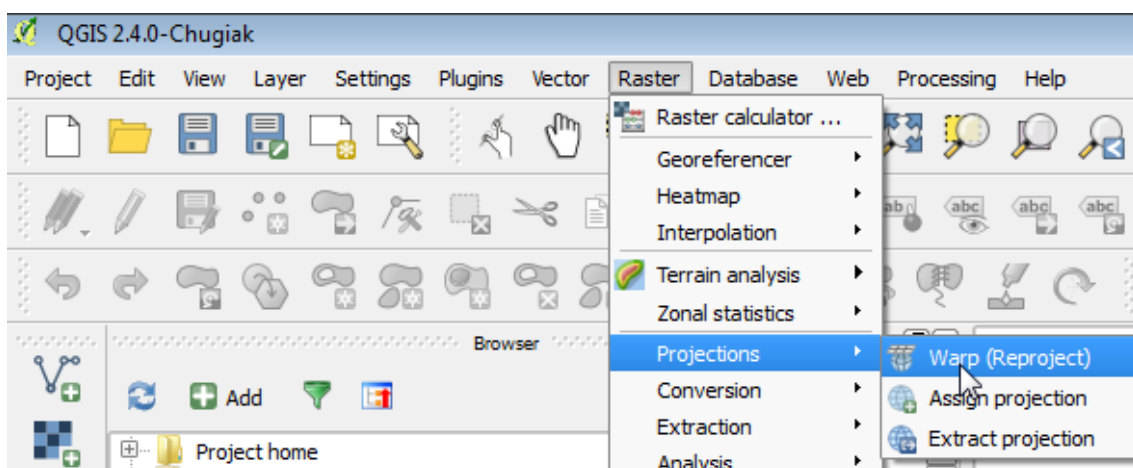


Figure 57: Warp tool

Subsequently you can resample the reprojected grid to model resolution and extent using the "r.resamp.interp" tool under Processing Toolbox → GRASS commands → r.resamp.interp



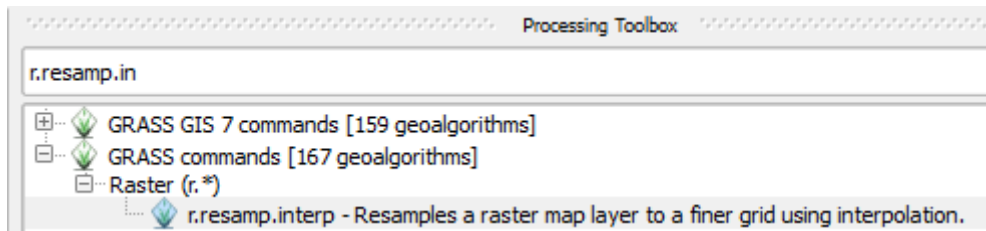


Figure 58: GRASS Resample tool

In the tool's dialog box, select the extent and cellsize from the clone map. Then convert the resampled grid to ASCII format using the Translate function under Raster → Conversion → Translate (Convert Format). When defining the output file, select “Arc/Info ASCII Grid (*.asc)” as file type.

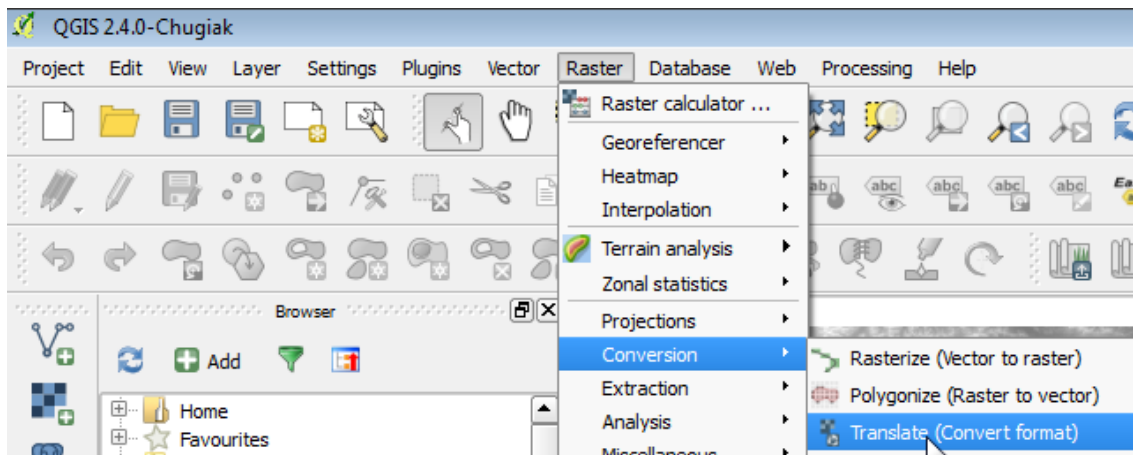


Figure 59: Translate tool (convert raster format)

After you did this you should have a file named **dem.asc** at the same resolution and extent as the clone map. Before you can use the clone map in combination with the **dem.asc** map, you need to convert the boolean clone map into a scalar clone map. This can be done using the following command:

```
pcrcalc clonefile_out = scalar(clonefile_in)
```

You need to provide the correct map filenames for the *clonefile_out* (e.g. **clonescalar.map**) and *clonefile_in* (e.g. **clone.map**) maps. The next step is to convert this ASCII grid to a PCRaster **.map** file. You can use the [asc2map](#) command for that, which has the following format:

```
asc2map -a --clone clonefile asciifile_in mapfile_out
```

Use the command line to navigate to the directory containing **clone.map** and **dem.asc** and type:

```
asc2map -a --clone clone.map dem.asc dem.map
```

Now you should have the DEM in the model resolution and extent and in PCRaster format.

The slope map can be derived from the DEM using the [slope](#) command. Type:



```
pcrcalc slope.map = slope(dem.map)
```

6.4 Delineate catchment and create local drain direction map

During the Trisuli case study, you generated a local drain direction map for each grid cell from the DEM. You can now use the DEM you created in the previous section to generate a local drain direction (LDD) map for your own model area.

First, fill the sinks in the DEM to avoid that pits are generated in the depression in the DEM, which hamper the water to flow to the basin's outlet. This is done using the `lddcreatedem` command in PCRaster. Type:

```
pcrcalc demfil.map = lddcreatedem(dem.map, 1000, 1e31, 1e31, 1e31)
```

To create a flow direction map (or local drain direction (LDD)), you can use the `pcraster` command `lddcreate`. Type the following command:

```
pcrcalc ldd.map = lddcreate(demfil.map, 1000, 99999999, 99999999, 99999999)
```

A good way to test if the LDD map is correct is to calculate for each cell how many cells are upstream. You can do this using the `pcraster` command `accuflux`. Type:

```
pcrcalc accuflux.map = accuflux(ldd.map, 1)
```

Add the newly generated `accuflux.map` to the QGIS canvas. Check if the stream network is complete, and all branches are connected to the outlet point.

If the generated LDD is not entirely correct and not all streams are connected toward the downstream outlet point, this happens because during the creation of the LDD map, pits have been generated where depressions in the landscape are present. More details on the LDD generation can be found in the PCRASTER online manual. There are multiple ways to overcome the problem of pit generation:

- Test different values for the parameters in the `lddcreate` command
- Remove pits manually by changing the values for those cells.
- Use a map with the streams present in your study area and “burn” them into the DEM to force the other cells to drain in into them.

6.5 Preparing stations map and sub-basins.map

To prepare a stations map it is easiest to use a vector file with the point locations (for example a shapefile), to a PCRaster grid (.map file). You can create a new shapefile with points in QGIS under Layer → New → New Shapefile layer:



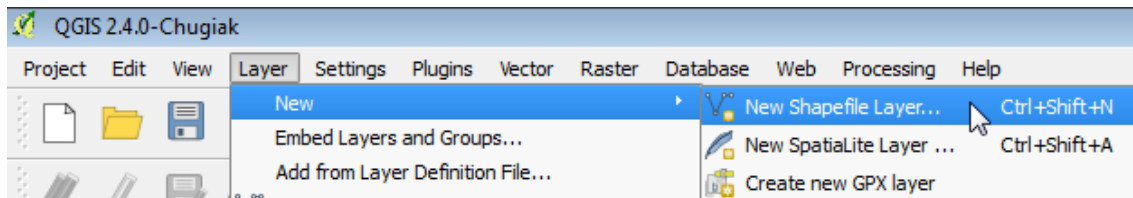


Figure 60: Create new shapefile layer

Tip: You can easily check if your points are located in the stream network by showing the **accuflux.map** under the shapefile.

Subsequently convert this shapefile to raster using the “*v.to.rast.value*” tool in QGIS under Processing Toolbox → GRASS commands → vector.

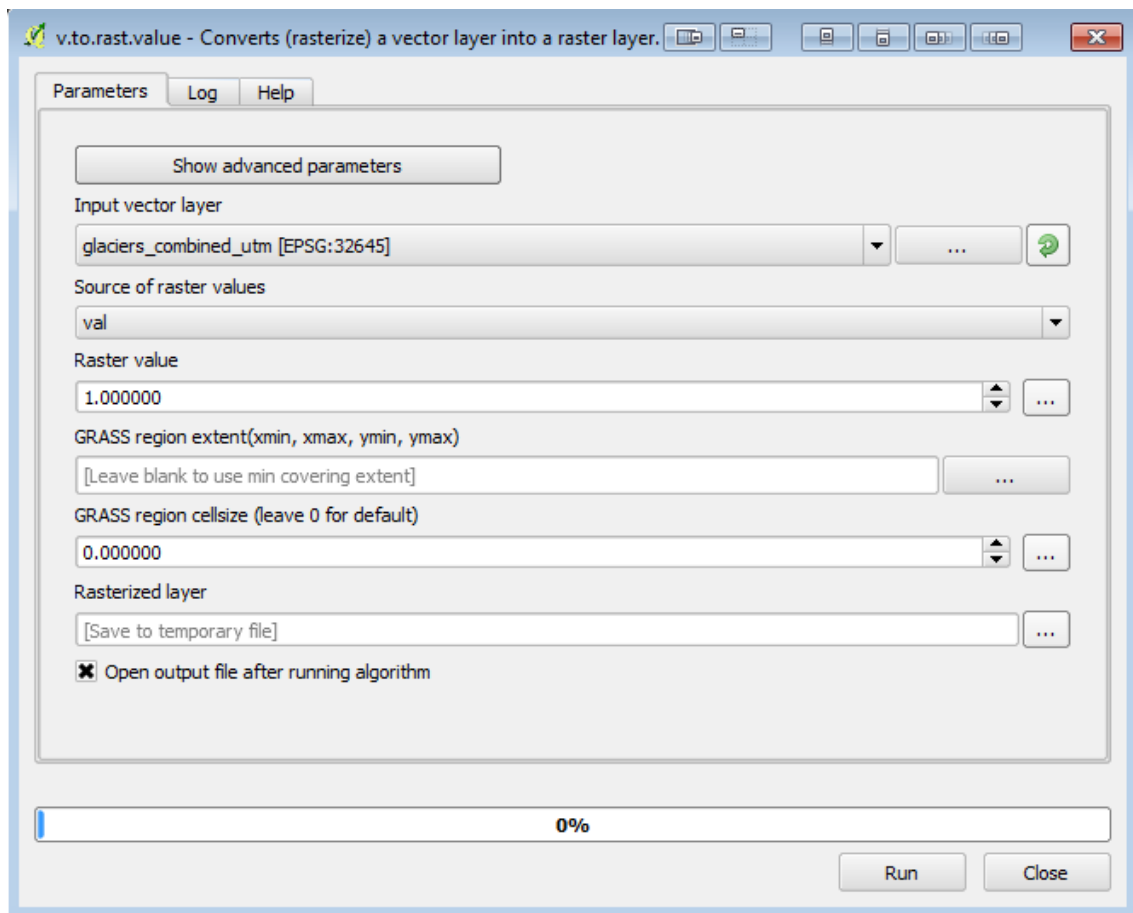


Figure 61: GRASS convert vector to raster tool

Make sure you convert to the same extent and resolution as your clone map, and save the file as ASCII grid. Then use the “*asc2map*” command to convert the ASCII grid to PCRaster grid. Name the resulting file **outlet.map**.

You can use **outlet.map** and **ldd.map** to delineate the catchments of the points in outlet.map. Use the [subcatchment](#) command for that:

```
pcrcalc catchment.map = subcatchment(ldd.map, outlet.map)
```


6.6 Glacier fraction map

The glacier fraction map can be calculated from a vector file with glacier outlines. In QGIS from the Processing toolbox, select the “*v.to.rast.value*” tool like in the previous section.

Select your glacier outlines as vector input layer and convert it to raster at the same extent of the clone map. Set the cellsize at a lower value than your model resolution. For example, if your model cell size is 200 m, select 20 m for the converted raster.

The “*nodata*” values need to be reclassified to zeros. To do this use SAGA’s Reclassify tool from the Processing toolbox. You can easily find it by typing Reclassify in the search field.

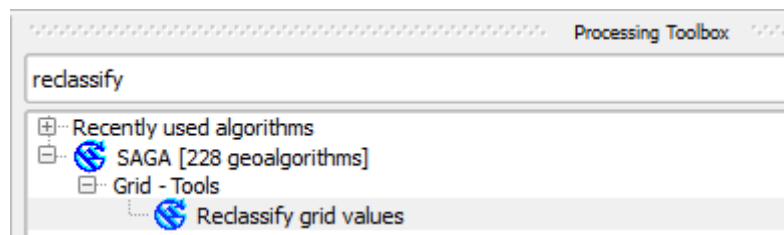


Figure 62: Reclassify tool

In the dialog box set all values to 0.0, and set “*replace no data values*” to “*Yes*”, set “*new value for no data values*” to 0.0 and set “*replace other values*” to “*No*”. Select an output filename and click “*Run*”.



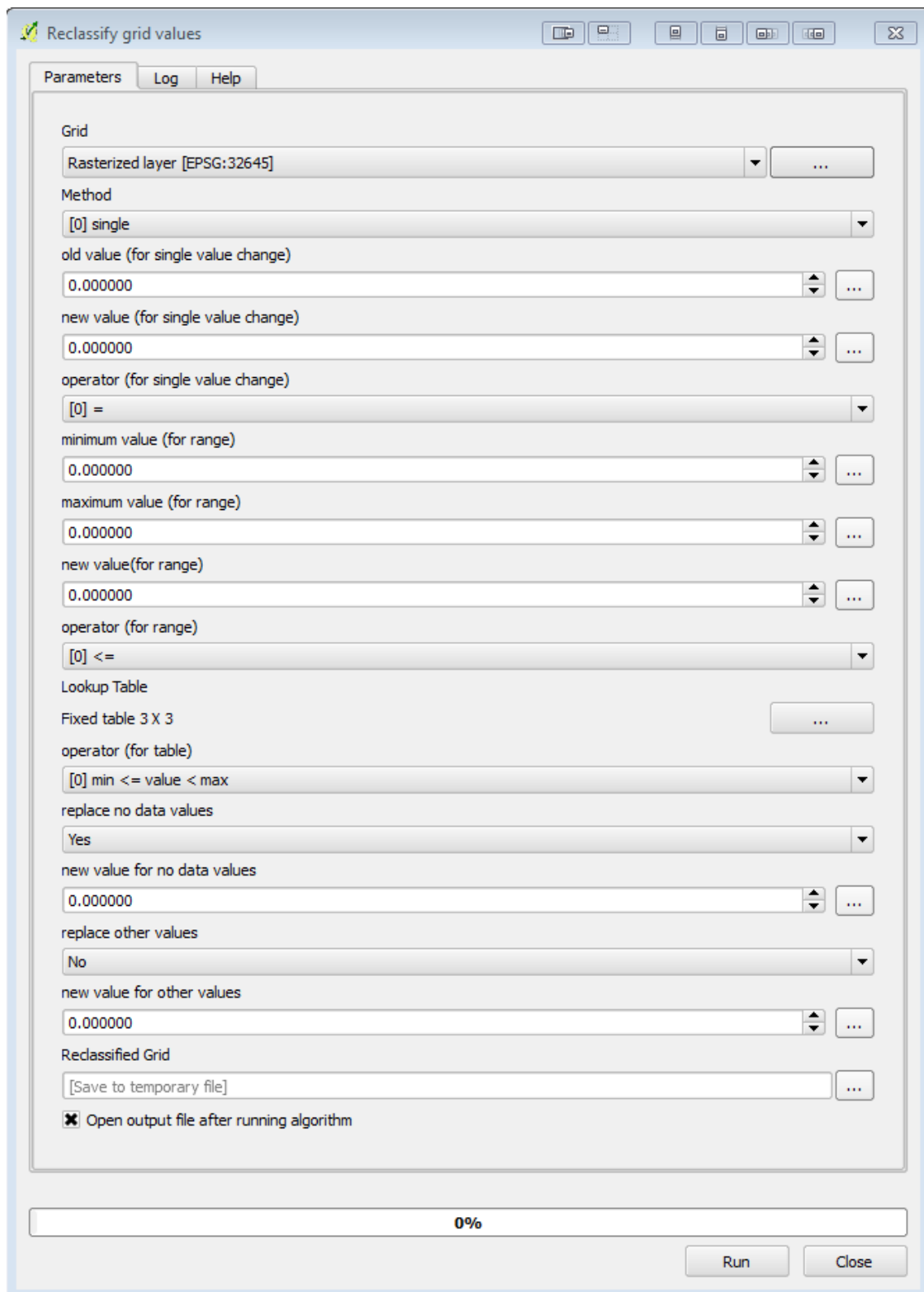


Figure 63: Reclassify tool dialog box

Now we aggregate the fine resolution grid with glaciers to the model resolution. This can be done using the “*r.resamp.stats*” tool selected under Processing Toolbox → GRASS commands → Raster → *r.resamp.stats*.

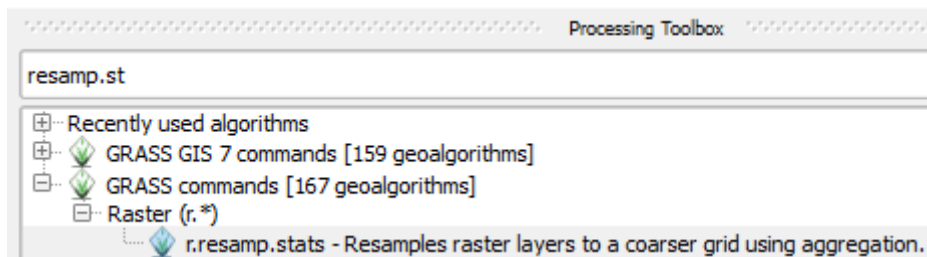


Figure 64: GRASS aggregation tool

In the dialog box, set the fine resolution glacier grid as input raster layer and choose aggregation method “*average*”. Import the processing extent from the clone map and set the cell size to the model resolution (in the screenshot below it is 200m as in the example of the Trisuli case study).

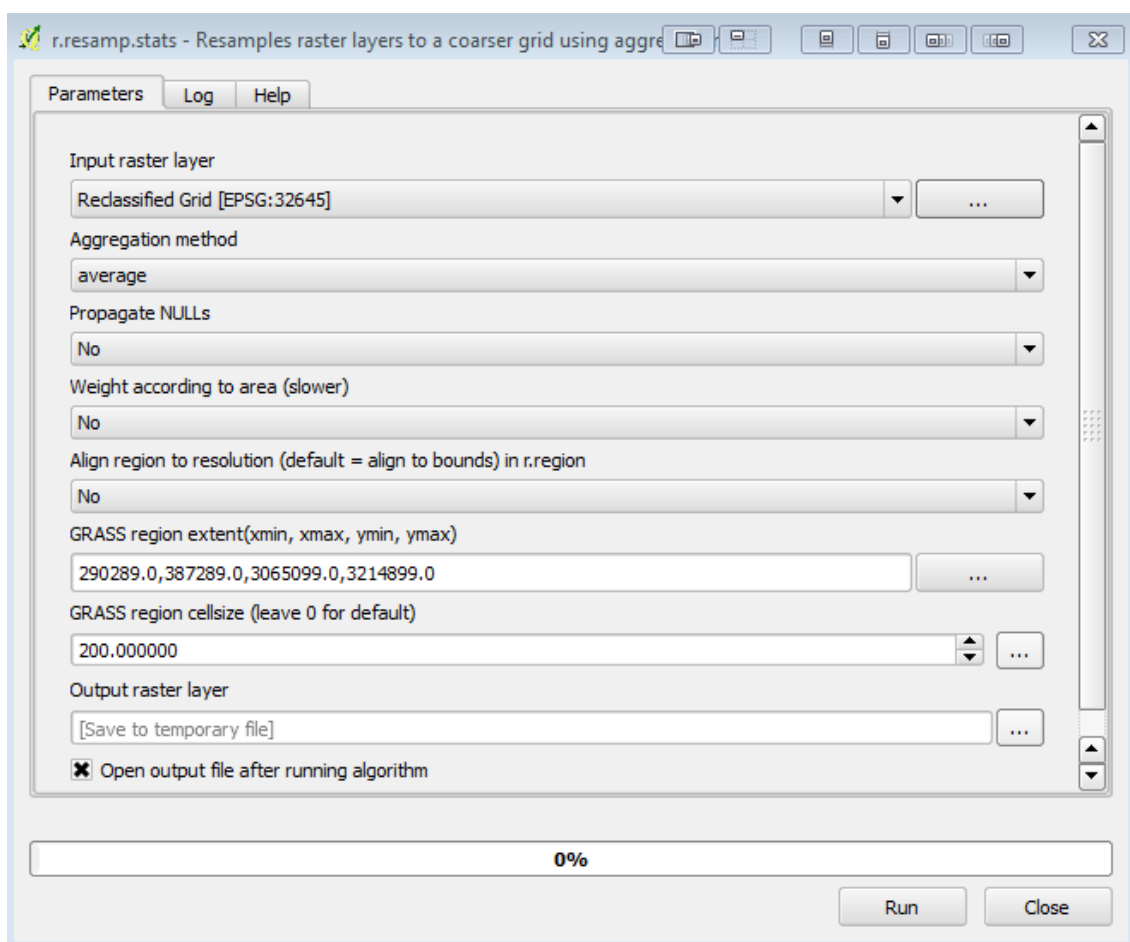


Figure 65: GRASS aggregation tool dialog box

The resulting grid can be saved as ASCII grid and then converted to PCRaster map using the “*asc2map*” command.

If you want to specify also the debris-covered and clean ice fractions, follow the same procedure as described above for the outlines of the debris-covered parts and the outlines of the clean ice parts. In the end do the following step for both glacier surface types:

Multiply the resulting fractional grid with the glacier fraction map to make sure the surface type is expressed as a fraction of the fractional glacier cover. For example if a cell has a fractional



glacier cover of 0.5 and half of that is debris-free and the other half is debris-covered, then the resulting maps for fractional debris-free and fractional debris-covered should have value 0.5 both (and not 0.25). The results can be tested by summing the map of fractional debris-free and fractional debris-covered. For all grid cells that have a value larger than 0 in the glacier fraction map, the sum of fractional debris-free and fractional debris-covered maps should be equal to 1.

6.7 Other static input maps

Similar as the DEM, you can reproject and resample other input data and convert them to PCRaster format maps using the reprojection and resampling functions in QGIS and the `asc2map` command in the command line. Use this approach to create other static input maps. Note that different data types are used for PCRaster maps. You can convert maps from one data type to another using the command line functions `Boolean()`, `nominal()`, `ordinal()`, `scalar()`, `directional()` or `ldd()`. For example to convert the Boolean type clone map to a scalar map, type:

```
pcrcalc clonescalar.map = scalar(clone.map)
```

Table 9: Data types used in SPHY. Source: PCRaster online manual

data type	description attributes	domain	example
boolean	boolean	0 (false), 1 (true)	suitable/unsuitable, visible/non visible
nominal	classified, no order	$-2^{31} \dots 2^{31}$, whole values	soil classes, administrative regions
ordinal	classified, order	$-2^{31} \dots 2^{31}$, whole values	succession stages, income groups
scalar	continuous, linear	$-10^{37} \dots 10^{37}$, real values	elevation, temperature
directional	continuous, directional	0 to 2 pi (radians), or to 360 (degrees), and -1 (no direction), real values	aspect
ldd	local drain direction to neighbour cell	1...9 (codes of drain directions)	drainage networks, wind directions

6.8 Meteorological forcing map series

Meteorological forcing map-series are series of input maps with the time step indicated in each filename. The filenames have a strict format with 8 characters before a dot (.), and three characters behind the dot. For example the average temperature maps can have the format **tavg0000.001**, **tavg0000.002**, etc. To generate forcing data you have two options:

- 1) interpolate point station data to grids at the model extent and resolution, and convert to PCRaster grid format.
- 2) resample existing gridded meteorological dataproducts to model extent and resolution and convert to PCRaster grid format.

Depending on the number of time steps in your model you will probably need to write a script to batch this process and repeat it automatically for multiple time steps. A script like this can be created in any scripting language like for example Python or R.



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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 10 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 11.

Table 10: 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 37)	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 42 and Figure 43)	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 11: 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

