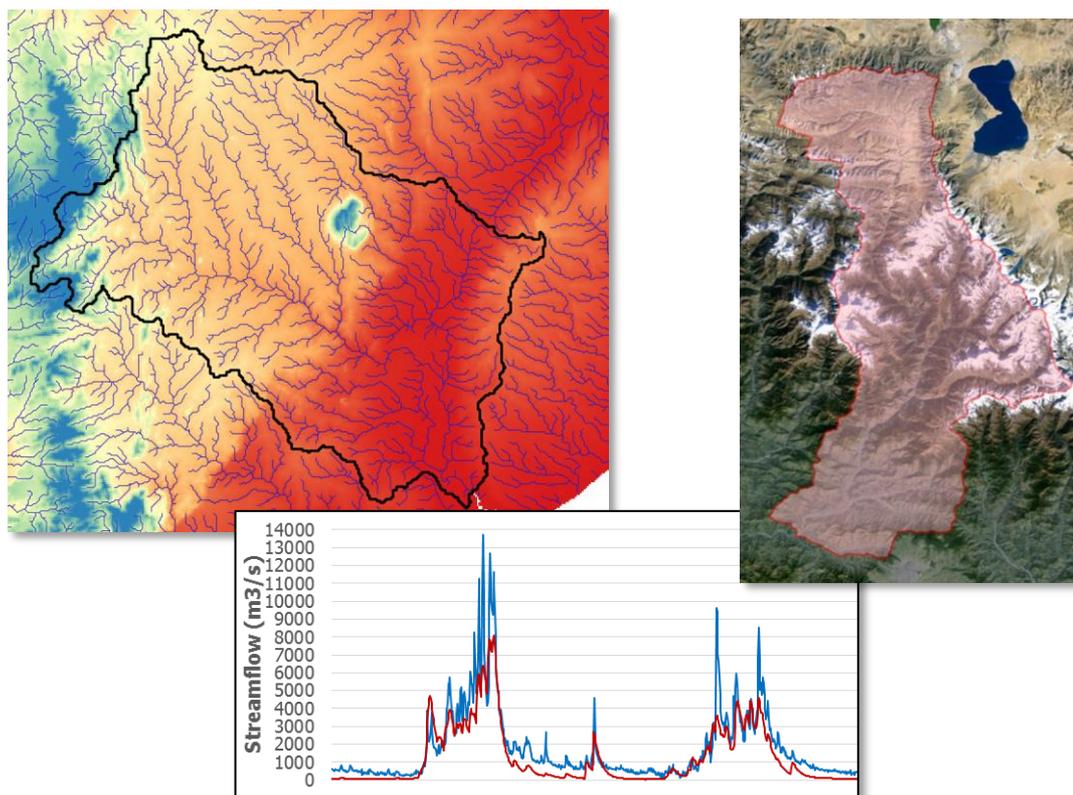


SPHY: Spatial Processes in Hydrology

Case-studies for training

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- NUFFIC⁶

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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/>

⁵ <http://www.rvo.nl/>

⁶ <https://www.nuffic.nl/en>



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1 Introduction

The Spatial Processes in Hydrology (SPHY) model (Terink et al., 2015, 2015a) is a hydrological modeling tool suitable for a wide range of water resource management applications. SPHY is a state-of-the-art, easy to use, robust tool, that can be applied for operational as well as strategic decision support. The SPHY modeling package is available in the public domain and only uses open source software. SPHY is developed by FutureWater in cooperation with national and international clients and partners. Key features of the SPHY model can be summarized as:

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

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

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

In order to learn to work with the SPHY model we have developed several case-studies which can be found in this manual. The applications of these case-studies vary from snow- and glacier fed river basins (Trisuli River Basin, Nepal) in the Himalayas to a large river basin in Mozambique (Pungwe River Basin) to a trans-boundary sub-basin in Vietnam and China (Tuyen Quang sub-basin). The objective of this manual is to teach people to work with the SPHY model using these orographically different case-studies.

Please note that each of these case-studies may require different versions of the SPHY model source code, and may or may not use the SPHY model GUIs. The compatibility and required software and data are specified in the first 2 sections of each case-study.

The model source code is in the public domain (open access) and can be obtained from the SPHY model website free of charge (www.sphy-model.org). The peer-reviewed open-access publication of the SPHY model can be found at <http://www.geosci-model-dev.net/8/2009/2015/gmd-8-2009-2015.pdf> (Terink et al., 2015).



2 Trisuli River Basin, Nepal

2.1 Model and GUI compatibility

This case-study has been developed using:

- [SPHY model v2.0](#) (Terink et al. (2015, 2015a))
- [SPHY model GUI \(SphyPlugin\) v1.0](#) (Terink et al. (2015c))

Currently, the SPHY model GUI (v1.0) is only compatible with SPHY model v2.0. Therefore, it is recommended to do this case-study using these versions of the model and the GUI.

This case-study is setup to work with the SPHY model GUI (v1.0). It does NOT use the SPHY model preprocessor (SphyPreProcess) (Terink et al., 2015c), and therefore it is required to create model input data manually. This is well described in the following sections. If it is not clear how to create model input data, then more information can be found in Section 5 from Terink et al. (2015a). Of course you can redo this case-study using the SphyPreProcess GUI and analyze the differences in the obtained results.

2.2 Downloads and installation

In order to do the Trisuli River Basin case-study it is required to download and install the following data and software:

- [SPHY model v2.0 source code](#) (see Section 4.2.4 of Terink et al. (2015a))
- [SPHY model GUI \(SphyPlugin\) v1.0](#) (see Section 2.3 of Terink et al. (2015c))
- [Trisuli River Basin case-study dataset](#)

Login credentials that are required to download software and data from the SPHY model website can be obtained using the link below:

<http://www.sphy.nl/software/download-sphy/>

2.3 Introduction

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.



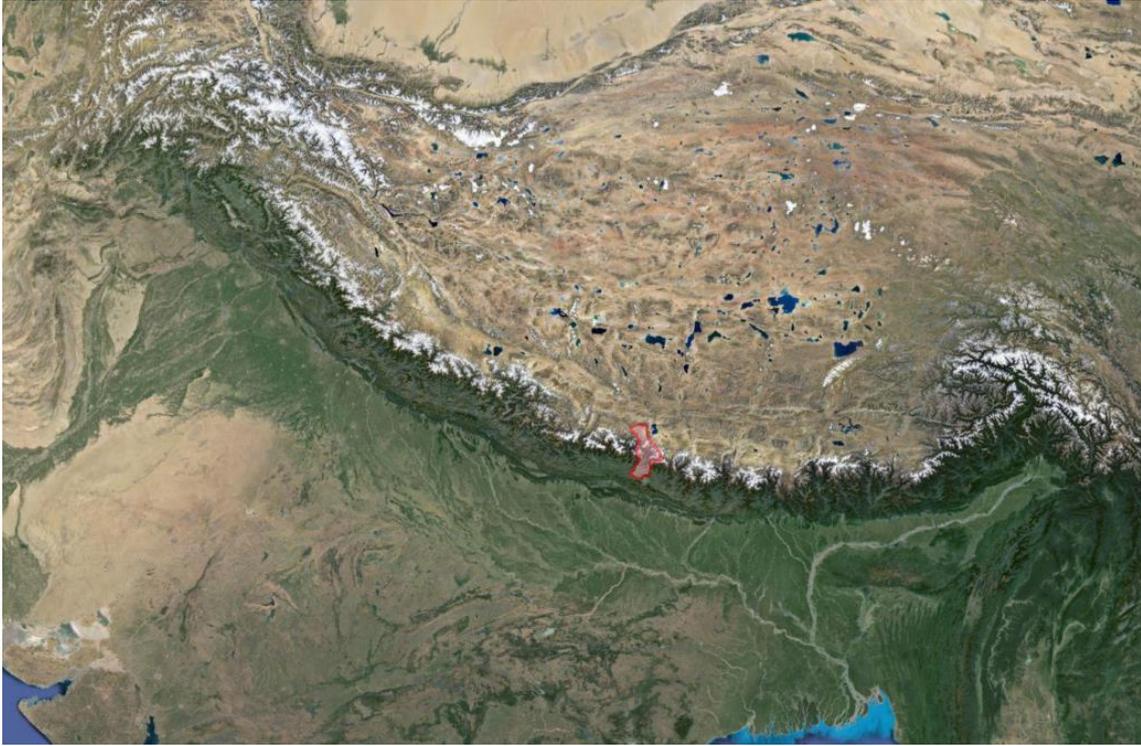


Figure 1: The location of the Trisuli basin.

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 detailed information on how to use the SPHY interface to accomplish the steps discussed in this tutorial, please refer to Terink et al. (2015c).

2.4 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 **input** directory to the **SPHY2.0\input** directory.

Subsequently start QGIS. From the **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 2: 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 1: 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:

Q1: Which parts of the basin are highest and which parts are the lowest?

Q2: 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.

2.5 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 2: 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.

Q3: Why is this map included? You can look it up in the theoretical part of the manual.

From the **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:

Q4: What is the maximum annual precipitation, and in which area does this occur?

Q5: What is the minimum annual precipitation, and in which area does this occur?

Q6: What is the mean precipitation for the entire basin, and for the sub-catchments of the Kyangjin and Betrawati discharge stations?



2.6 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 Terink et al. (2015, 2015a).

Usually these data are not readily available. However, maps with soil types are often available, and pedo-transfer 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 **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 **soil** directory is a lookup table 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 **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 lookup table, using the change directory (`cd`) command:

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

and press “Enter”.

Now type the following command:

```
pcrcalc root_field.map = lookupscale(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 lookup tables 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.

Q7: 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.

2.7 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:

Q8: What would happen to the delay in baseflow when the “*alphaGw*” parameter is increased?

2.8 Land use

Open the “*Land use*” tab in the SPHY interface. In the “*Land use map*” field select **luse.map** from the **SPHY2.0\input** 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 3: 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:

Q9: How is the potential evapotranspiration calculated from the reference evapotranspiration?

Q10: Why is the actual evapotranspiration not equal to the potential evapotranspiration?

2.9 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 **SPHY2.0\input** 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:

- Q11: How large is the area covered by glaciers in the Trisuli basin?
- Q12: What percentage of the total basin area is this?
- Q13: What percentage of the catchment upstream of Betrawati station is covered with glaciers?
- Q14: 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:

- Q15: How does a degree-day melt model work and what inputs does it need?
- Q16: Why is the degree-day-factor for debris-free glaciers larger than for debris-covered glaciers?
- Q17: What other factors than air temperature influence the actual melt rate of glacier ice?

2.10 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:

- Q18: Our model run will start at 1 January 2006. Is the initial snow storage realistic?
- Q19: What will be the consequences for the simulated discharge during the first year?
- Q20: 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 Terink et al. (2015a) 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.

2.11 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:

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

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:

- Try to repair the ldd using the *lddrepair* command
- 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.

2.12 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 4: 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*”.

2.13 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.



2.14 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.

2.15 Model calibration

2.15.1 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.

Q21: 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 **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 5: SPHY model output.

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

Q22: Why is the contribution of glacier melt larger at Kyangjin station than at Betrawati station?

Q23: During which months peaks the glacier melt? Why?

Q24: During which months peaks the snow melt? Why?

Q25: During which months peaks the rainfall-runoff? Why?

Q26: How would you rate the correlation of the observed and simulated flow?

2.15.2 Water balance

In **runoff_Trisuli.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)		

Q27: 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)		

Q28: Why is the difference between $P+M$ and $Q+ET$ still not equal to 0?



2.15.3 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.

Q29: 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 smoothed 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.

- Q30: Which parameters have most influence on change in discharge during January?
 Q31: Answer the same question for the three other months.
 Q32: Which parameters have most influence on the total discharge?
 Q33: 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 6: 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.

- Q34: How could you validate the performance of your calibrated model?



2.16 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 **SPHY2.0\input** 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:

- Q35: How does the total amount of runoff generated in the entire basin change between the baseline and the climate change run?
- Q36: 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?
- Q37: Does the amount of glacier melt generated in the Trisuli basin increase or decrease?
- Q38: 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?
- Q39: Do the areas where snow melt is generated change?
- Q40: Can you see shifts in snow melt when comparing the hydrographs at Betrawati station for the baseline and climate change run?
- Q41: How much does the amount of rainfall- runoff change in the basin?



3 Pungwe River Basin, Mozambique

3.1 Model and GUI compatibility

This case-study has been developed using:

- [SPHY model v2.0](#) (Terink et al., 2015, 2015a)
- [SPHY model GUI \(SphyPlugin\) v1.0](#) (Terink et al. (2015c))

Currently, the SPHY model GUI (v1.0) is only compatible with SPHY model v2.0. Therefore, it is recommended to do this case-study using these versions of the model and the GUI.

This case-study is setup to work with the SPHY model GUI (v1.0). It does NOT use the SPHY model preprocessor (SphyPreProcess) (Terink et al., 2015c), and therefore it is required to create model input data manually. This is well described in the following sections. If it is not clear how to create model input data, then more information can be found in Section 5 from Terink et al. (2015a). Of course you can redo this case-study using the SphyPreProcess GUI and analyze the differences in the obtained results.

3.2 Downloads and installation

In order to do the Pungwe River Basin case-study it is required to download and install the following data and software:

- [SPHY model v2.0 source code](#) (see Section 4.2.4 of Terink et al. (2015a))
- [SPHY model GUI \(SphyPlugin\) v1.0](#) (see Section 2.3 of Terink et al. (2015c))
- [Pungwe River Basin case-study dataset](#)

Login credentials that are required to download software and data from the SPHY model website can be obtained using the link below:

<http://www.sphy.nl/software/download-sphy/>

NOTE: since the SphyPlugin v1.0 GUI was originally developed to work with glacier-fed river basins only, a small modification needs to be done in the GUI template file. If you have installed the SPHY model GUI correctly, then you will find a folder

C:\Users\XXXXX\.qgis2\python\plugins\SphyPlugin\config

on your hard disk, with **XXXXX** being the username of the computer. Within this folder you find the file: **sphy_config_template.cfg**. Edit this file with a text editor (e.g. notepad, see Figure 3). Change the values of 1 (red boxes) to 0, and finally save the file. After this step has been completed you are ready to use the GUI for this case-study.



```

sphy_config_template - Notepad
File Edit Format View Help
*****
# CONFIGURATION FILE BELONGING TO SPHY. MODEL CHANGES CAN BE DONE IN THIS FILE. THIS FILE
# CAN BE USED TO CHANGE MODEL INPUT, SET PARAMETERS, MODEL OUTPUT, AND TURN ON/OFF MODULES
#
# THE SPATIAL PROCESSES IN HYDROLOGY (SPHY) MODEL IS DEVELOPED AND OWNED BY FUTUREWATER.
# AUTHOR: W. Terink
# DATE LATEST CHANGE: 15-04-2014
# VERSION 2.0
*****
# SPHY enables the user to turn/off certain modules. The flags below can be used to turn on/off
# these modules (1=on, 0=off)
*****
[MODULES]
# Glacier melt processes module. This automatically turns on the snow module as well.
GlacFLAG = 1
# Snow module. If the glacier melt processes module is turned on, then this is also turned on
# automatically. If the glacier melt processes module is turned off, then you may turn this on
# if you want to incorporate snow melt and accumulation.
SnowFLAG = 1
# Routing module. If streamflow routing should be included, then this should be turned on. If
# this is turned on, then the reservoir module should be switched off.

```

Figure 3: Modifying the modules section of the sphy_config_template.cfg.

3.3 Introduction

The Pungwe basin covers 30.970 km², stretching out from the Zimbabwean highlands to its outlet to the Indian Ocean. The average elevation of the basin is 416 m.a.s.l., but the elevation ranges from 2427 m.a.s.l to sea level. During this tutorial we will explore the input data for Pungwe that feeds into SPHY, get the model running, and explore the model output.



Figure 4: The location of the Pungwe basin.

For the Pungwe basin, we will set up the SPHY model for a five year period from 1 January 2005 to 31 December 2009. For this period we will set up SPHY at a daily time step, and with 1000 x 1000 m spatial resolution (grid cell size). All maps used in this tutorial are in the WGS 84



/ UTM zone 36S projection (EPSG:32736). In this tutorial, each step to setup the model is discussed. If you need more technical background information to perform a certain step, please refer to the general SPHY v2.0 manual (Terink et al., 2015a).

3.4 Create new project and set general settings

Start by creating the **input** and **output** directories in the **SPHY** directory. Move the contents of the **data\input** directory into the **SPHY\input** directory.

Subsequently start QGIS. Now open the SPHY plugin by clicking the SPHY Model button (see Figure 5) in QGIS. Click “New Project” and save your new project in the **SPHY** directory. Name the project **Pungwe_v1.cfg** or another appropriate filename. Then, in the SPHY interface, go to the tab “*General Settings*”.

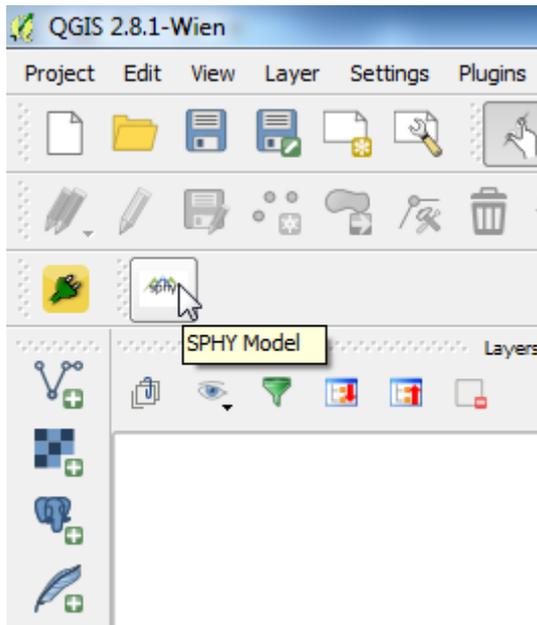


Figure 5: Opening the SPHY plugin inside QGIS.

From the **data\other_layers** directory, add **landsat8_july2015.tif** to the QGIS layer canvas. This is a Landsat 8 satellite image containing the Pungwe basin, and can be used as a reference background in QGIS. Landsat 8 is a satellite that makes high-resolution images (30m) and passes over the Pungwe Basin every 16 days.

In the part “*Folder selection*”, select the **SPHY** 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 2005 until 31 December 2009.

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 Pungwe case study model, we use the WGS 84 UTM 36 South projection, which has EPSG code 32736.

In the part “*Catchment settings*”, select the appropriate maps from the **SPHY\input** directory, as indicated in the table below. Each layer you add through the interface will automatically be added to the QGIS layer canvas. 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 (see Figure 6).

Table 7: General settings: Catchment settings.

Catchment settings	
Clone map	clone.map
DEM map [MASL]	dem.map
Slope map [-]	slope.map
Stations map	locations.map

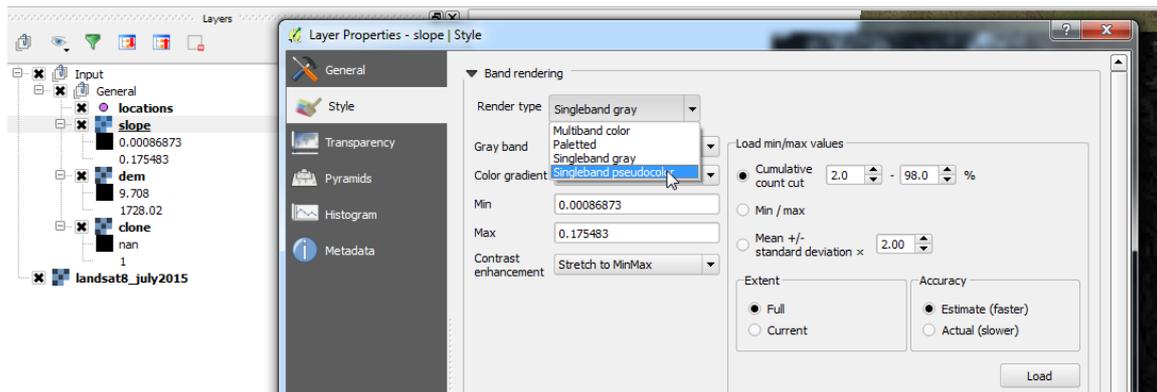


Figure 6: Example of changing the layout of a layer in QGIS.

Have a look at each of these four maps in QGIS. Answer the following questions:

- Q1: Which parts of the basin are highest and which parts are the lowest?
 Q2: Which parts of the basin have the steepest slopes, and which parts are more flat?

A number of locations are defined in the file **locations.map**. As you open it in the SPHY interface, it is automatically converted to the shapefile **locations.shp**. Some of these locations correspond with actual flow measurement stations, while others are the outlet points of sub-basins. Add the shapefiles **flowstations.shp** and **subbasins_weap.shp** from **data\other_layers** to the QGIS canvas.

- Q3: Which IDs in the locations.shp layer are flow measurement stations, and which are outlet points of sub-basins?

Save your model setup every once in a while by clicking the “Save” button in the top row of the SPHY interface.

3.5 Climate

Have a look at the contents of the **SPHY\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 **tair0000.001** until **tair0001.826**, where the extension of “.001” corresponds with the first day of simulation and “1.826” with day 1826.



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

Table 8: Meteorological forcing map-series.

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

In the part “*Meteorological parameters*” select **latitude.map** from the **SPHY\input** directory for “*Latitude zones*”. Leave the value for the “*Solar constant*” unchanged.

Q4: 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 two maps show the annual precipitation sums for 2006 and 2007 as calculated from the daily precipitation forcing map-series. As you will likely notice a warning message will be shown in the QGIS canvas (Figure 7). This means that there is no Coordinate Reference System (CRS) defined for these maps. Remember that the CRS for the Pungwe is EPSG:32736 (see Section 3.4). Now set the CRS for these two maps by selecting both layers and press the right mouse button (Figure 8). Then select the correct CRS by typing the EPSG number in the filter box and press “OK” (Figure 9). This procedure has to be performed every time this message appears.

Click right on these layers and choose “*properties*”, and view the metadata. Now answer the following questions for these two years:

Q5: What is the maximum annual precipitation in both years, and in which area does this occur?

Q6: What is the minimum annual precipitation in both years, and in which area does this occur?

Q7: What is the mean precipitation in 2006 and 2007 for the entire basin?

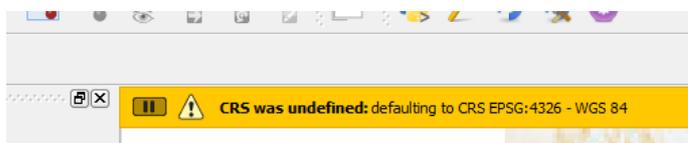


Figure 7: CRS was undefined message.

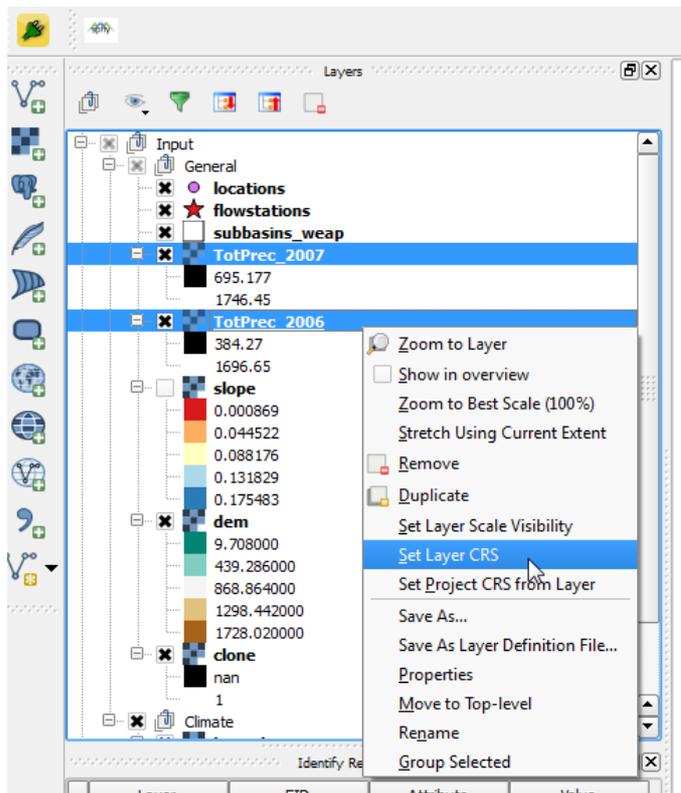


Figure 8: Setting a layer's CRS.

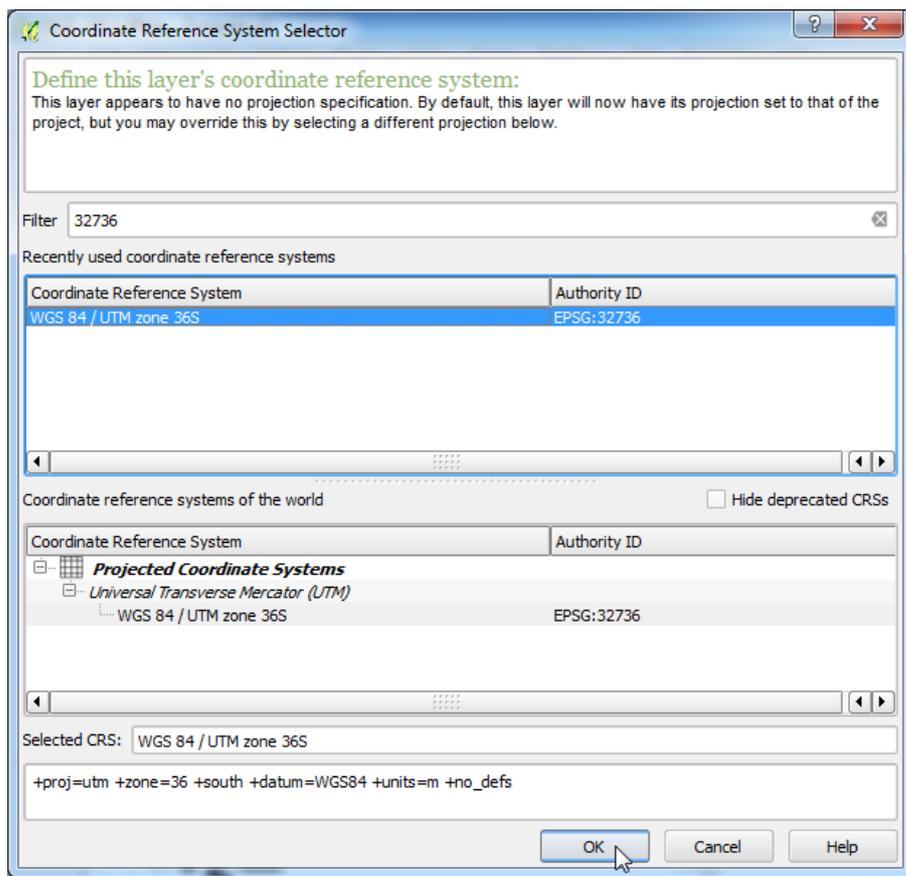


Figure 9: Selecting the CRS for a layer.



3.6 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 the SPHY v2.0 manual.

Usually these data are not readily available. However, maps with soil types are often available, and pedo-transfer functions (Nemes et al., 2001; Keshavarzi et al. 2010) are available to assign physical soil parameters to soil types. For the Pungwe model we use a new global soil map, the SoilGrids 1km dataset which is freely available (<http://soilgrids.org/>, Hengl et al., 2014). Now click the “select map” buttons to select the required soil maps (8 maps total).

Q8: Describe for each of these soil parameters how they are defined and how you expect that they will influence the behavior of water in the soil. Hint: have a look at Figure 2 of Terink et al., (2015a).

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

Q9: What effect do you expect a larger root zone depth to have on the surface runoff that is generated in the basin?

Q10: What is capillary rise?

3.7 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:

Q11: What would happen to the baseflow recession curve when the “alphaGw” parameter is increased?

3.8 Land use

Open the “Land use” tab in the SPHY interface. In the “Land use map” field select **globcover.map** from the **SPHYinput** directory. This land use map is derived from the Globcover 2009 dataset (http://due.esrin.esa.int/page_globcover.php). The Globcover map has the following legend:



Table 9: Land use classes.

Value	Class
11	Post-flooding or irrigated croplands (or aquatic)
14	Rainfed croplands
20	Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)
30	Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)
40	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)
50	Closed (>40%) broadleaved deciduous forest (>5m)
60	Open (15-40%) broadleaved deciduous forest/woodland (>5m)
70	Closed (>40%) needleleaved evergreen forest (>5m)
90	Open (15-40%) needleleaved deciduous or evergreen forest (>5m)
100	Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)
110	Mosaic forest or shrubland (50-70%) / grassland (20-50%)
120	Mosaic grassland (50-70%) / forest or shrubland (20-50%)
130	Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)
140	Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens / mosses)
150	Sparse (<15%) vegetation
160	Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) - Fresh or brackish water
170	Closed (>40%) broadleaved forest or shrubland permanently flooded - Saline or brackish water
180	Grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water
190	Artificial surfaces and associated areas (Urban areas >50%)
200	Bare areas
210	Water bodies
220	Permanent snow and ice

Q12: What are the major land use types in the Pungwe basin according to the Globcover map?

To each of the land use types a “crop coefficient” (K_c) is assigned, which is used to calculate the potential evapotranspiration from the reference evapotranspiration in the SPHY model. The K_c 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:

Q13: How can you calculate potential evapotranspiration from reference evapotranspiration? What happens to the potential evapotranspiration when K_c is increased?

Q14: The actual evapotranspiration can be lower than the potential evapotranspiration. Can you think of a reason why this can happen?

Q15: Instead of using a K_c lookup table per land use type, how could the K_c input to the model be improved?

3.9 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. Such a map is called a Local Drainage Direction map (LDD). It is usually



derived from a Digital Elevation Model (DEM). Select **Idd.map** from the **SPHY\input** as LDD input.

A good way to test if an LDD map is correct is to calculate for each cell how many cells are upstream. You can do this using the PCRaster command *accuflux*. Go to the command line window by clicking the Windows Start button and typing “*cmd*” in the search bar. Go to the **SPHY\input** folder in the Command line window and type:

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

Add the newly generated **accuflux.map** to the QGIS canvas by selecting the file and dragging it into the canvas. The outlet point of the Pungwe basin can be found in **other_layers\outlet_pungwe.shp**. Select this shapefile and drag it into the QGIS canvas. Now check if the stream network is complete, and all branches are connected to the outlet point.

Q16: How many grid cells drain to the outflow point according to **accuflux.map**?

Q17: How much is this in km²?

If the LDD map is correct, then again go to the Windows Command line window and enter the following command to construct a map of the Pungwe catchment:

```
pcrcalc catchment.map = catchment(Idd.map, outlet.map)
```

The **outlet.map** file used in the command above is a gridded version of the **outlet_pungwe.shp**. This command creates a catchment for the area upstream of the **outlet.map** using the flow direction network (**Idd.map**). Now go to the “General Settings” tab of the interface, and select the **catchment.map** as the “Sub-basins map” by clicking the “*Select map*” button. Finally check if the Pungwe catchment is calculated correctly.

3.10 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. The **locations.map** is used for this.

Set the following settings in this tab in the interface:



Table 10: Report options.

Variable/flux	Report frequency
Baseflow runoff	Annual, Monthly
ETa	Annual
Rain runoff	Annual, Monthly
Precipitation	Annual, Time-series output: Daily
Rainfall	Annual
Root zone drainage	Annual, Monthly
Routed base-flow runoff	Time-series output: Daily
Routed rain runoff	Time-series output: Daily
Routed total runoff	Time-series output: Daily
Surface runoff	Annual, Monthly
Total runoff	Annual

Also check the option “*Report mm fluxes for basin averages*”. This option allows the reporting of basin average fluxes in mm for the sub-basin areas upstream of each location in **locations.map**.

3.11 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 **SPHY\output** directory, where all output files are written. Note that there are different types of output files. There are maps with time steps indicated in the file name, and there are time-series, stored as **.csv** files.

3.12 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 **locations.shp** 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 [m3/s]*”, and then click “*Show time-series*”. Then click on the point locations of some of the stations in the QGIS canvas. An image pops up with the simulated routed total runoff for each time step (Figure 10).



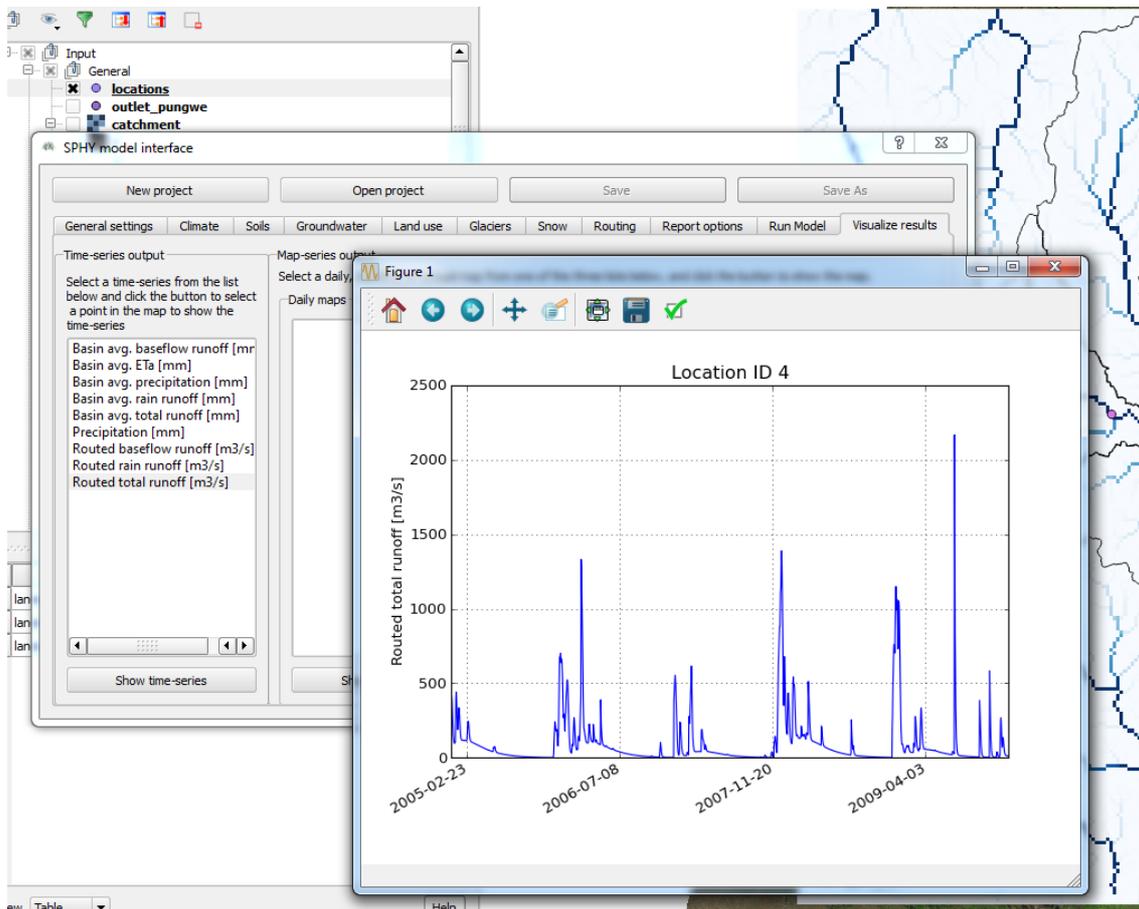


Figure 10: Example of visualization for Time-series output.

Close the graphs and add the annual map “*Total runoff [mm], 2006*” 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.

3.13 Model calibration

3.13.1 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.

Q18: Revisit the Groundwater 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 stations E65 (Pungue em E.N.102), E72 (Nhazónia em J.E. da Costa) and E651 (Púngoè em EN1 Ponte Gorongosa) station to calibrate the model.

Open **SPHY_results.xlsx** in Microsoft Excel. The first sheet of this file contains the daily measured discharge records at the three stations. These data are already plotted in the respective graphs.

From the **SPHY\output** directory, copy the data in **QAIIDTS.csv** to a separate Excel sheet. This file contains the daily routed total runoff that SPHY has computed for the different points in **locations.shp**. Remember from the **locations.shp** that there are 17 stations defined for the Pungwe River Basin. The first column in **QAIIDTS.csv** contains the simulation dates, running from 01-Jan-2005 through 31-Dec-2009. The next columns represent the routed total runoff calculated by the SPHY model for each station ID. This means column 2 corresponds with station ID1, column 3 corresponds with station ID2, etc.

Locate the three flow stations in **QAIIDTS.csv** and paste the simulated streamflow time series in the spreadsheet.

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.

As you will notice, there is an unlikely peak in discharge in July 2009, which is in the middle of the dry season. This does not correspond with the difference between modeled and observed flow during the rest of the time-series.

Q19: What could cause this problem? How could you solve it?

When the input has been corrected, run the model again. Before running the model make sure that you have closed all *.csv files (e.g. QAIIDTS.csv) that are open. After the model run has been completed, fill the following table:

Table 11: SPHY model output.

Average discharge 2005-2009	E65	E72	E651
Observed discharge (m3/s)			
Simulated discharge (m3/s)			

Q20: How would you rate the correlation of the observed and simulated flow?

3.13.2 Water balance

In **SPHY_results.xlsx**, now also fill the columns for precipitation and evapotranspiration in the “*water_balance*” sheet, using output files **PrecSubBasinTSS.csv** and **ETaSubBasinTSS.csv**. The conversion from SPHY simulated streamflow in m3/s to mm/d is done automatically in the Excel sheet in the columns F, M, and T. Use these values to fill the table below for the year 2006:



Table 12: SPHY water balance.

2006	E65	E72	E651
Precipitation P (mm/yr)			
Discharge Q (mm/yr)			
Actual evapotranspiration ET (mm/yr)			
Difference $P - Q - ET$ (mm/yr)			

Q21: Why is $Q + ET$ not equal to P ?

3.13.3 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.

To do this, have a look at the “*calibration*” sheet in **SPHY_results.xlsx**. In the table below, most important parameters are listed, for which we will test their sensitivity for the discharge at **E65** station. The initial simulated discharge in mm/d (results from Section 3.13.2) is already shown in column D (SPHY Q (mm/d) run 1). The observed discharge in mm/d is already shown in column C.

We will analyze 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. For Kc, only change the values of the three main land use types in the basin. You can use the “*calibration*” sheet to look at the results by following these steps:

1. Open **QTOTSubBasinTSS.csv** (contains total routed runoff in mm/d);
2. Copy the values from column B (represents station E65) to the **SPHY_results.xlsx** file to the “*calibration*” sheet in column E;
3. Copy the values from column E to the blue column O.
4. Analyze the results from the tables which are shown next to column O

After each model run, write in the table below 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 smoothed 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)	400	Jan:		
		Apr:		
		Jul:		
		Oct:		
Maximum capillary rise (mm/d)	3	Jan:		
		Apr:		
		Jul:		
		Oct:		
Land use				
Crop factor (-)	<i>see kc.tbl</i>	Jan:		
		Apr:		
		Jul:		
		Oct:		
Groundwater				
deltaGW	60	Jan:		
		Apr:		
		Jul:		
		Oct:		
Routing				
Recession coefficient	0.60	Jan:		
		Apr:		
		Jul:		
		Oct:		

Q22: 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 looking at the Nash-Sutcliffe values at E65 in the “*calibration*” sheet for the different years. The table below provides an indication of how the model performance can be characterized by the Nash-Sutcliffe efficiency.

Table 13: 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. Save the best model configuration as **Pungwe_calibrated.cfg**.

Q23: What year has the worst model performance? Can you think of a reason why the model does not perform well in this year?

Q24: 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?

If time permits, create a new Excel sheet and use your calibrated model to evaluate the contribution of rainfall-runoff (**RTotDTS.csv**) and baseflow (**BTotDTS.csv**) to streamflow.



3.14 Scenario simulations

3.14.1 Strategic decision support: climate change scenario

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 Pungwe basin for a hypothetical climate change scenario for 2050. We assume that precipitation during the wet season increases 10%, and during the dry season decreases with 10%. Also, daily temperatures are increased with 2 °C for the entire year.

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: **Pungwe_CC_v1.cfg**.

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

Create new output directory named **output_cc** in the **SPHY** directory. In the “General settings” tab, select this folder as “Output folder”.

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

Q25: How does the total amount of runoff generated in the entire basin change between the baseline and the climate change run?

Q26: How do the contributions of rainfall-runoff and base flow change for the entire basin?

3.14.2 Operational decision support: flood prediction using weather forecast

Besides strategic decision support for water resource planning, SPHY can also support short-term management decisions such as flood mitigation measures. Based on a hypothetical forecast of temperature and rainfall in the forthcoming week, we are now going to evaluate whether a flood is likely to happen.

Set the climate forcing in the SPHY interface to the files located in **SPHY/input/forcing_fp**. If you locate this folder in Windows Explorer, you will see that there are now only 7 daily maps available per parameter. Set the starting date of the SPHY model run to today’s date and the end date as 7 days from now. Enter **flood_location.map** as the stations map. This location is now equal to the E651 flow station, but of course any desired spot could be chosen. Leave all other model parameters unchanged.

Run your calibrated model and paste the streamflow results in the “flood_prediction” tab of the **SPHY_Results.xlsx**. A rating curve (Q vs. h relation) can be used to compute water levels from discharges simulated by SPHY. A hypothetical rating curve is provided in the sheet that relates discharge at point E651 to water level.

Q27: What is the appropriate flood warning level for this location for the coming week?



4 Tuyen Quang sub-basin, Vietnam/China

4.1 Model and GUI compatibility

This case-study has been developed using SPHY model v2.1. This version of the SPHY model differs from version 2.0 such that it includes a reservoir module. This module is described in Terink et al., 2015b.

Currently, the SPHY model GUI (v1.0) is only compatible with SPHY model v2.0. Therefore, this case-study does NOT work with the SPHY model GUI (SphyPlugin).

This case-study does NOT use the SPHY model preprocessor (SphyPreProcess) (Terink et al., 2015c), and therefore it is required to create some model input data manually. This is well described in the following sections. If it is not clear how to create model input data, then more information can be found in Section 5 from Terink et al. (2015a).

4.2 Downloads and installation

In order to do the Tuyen Quang sub-basin case-study it is required to download and install the following data and software:

- [SPHY model v2.1 source code](#) (Terink et al. (2015b))
- [Tuyen Quang sub-basin case-study dataset](#)

Login credentials that are required to download software and data from the SPHY model website can be obtained using the link below:

<http://www.sphy.nl/software/download-sphy/>

4.3 Introduction

Area of interest is the Tuyen Quang sub-basin (Figure 11). This sub-basin of the Red River extends across the Vietnamese-Chinese border. This training focuses on the period 2002-2003, before construction of the Na Hang dam.

This case-study describes the steps required to build a SPHY model of the area using the sample dataset provided. In particular, it focuses on analysis of model results and calibration using river discharge measurements and satellite-derived evapotranspiration (ET) maps. This case-study also explains how the SPHY reservoir module can be used to analyze the impact of the construction of reservoirs on downstream flow conditions.



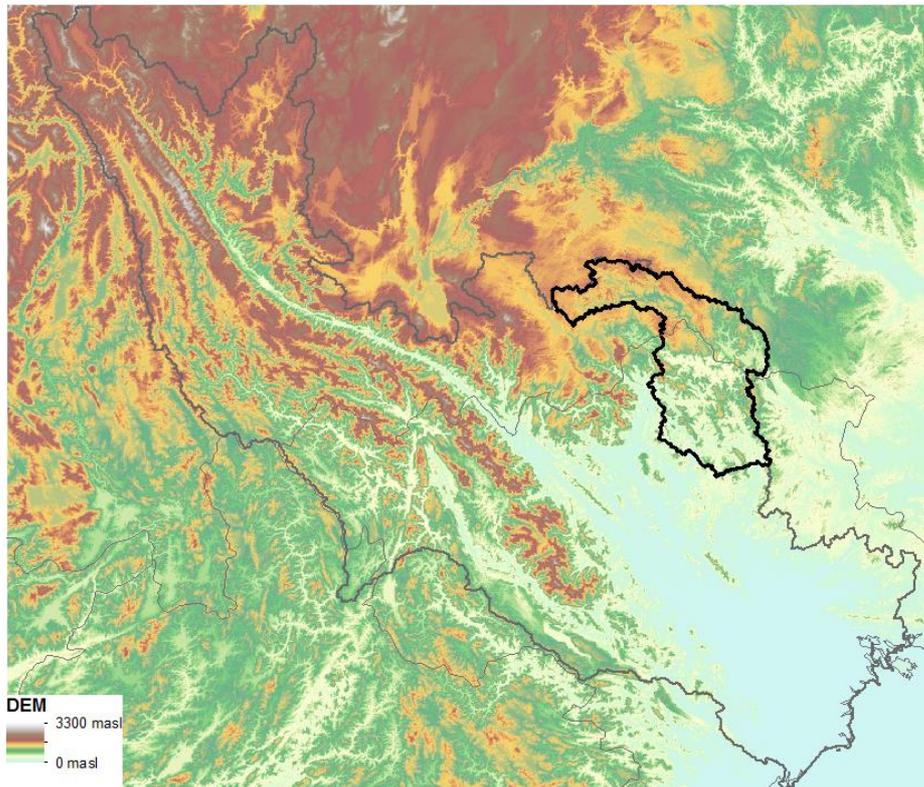


Figure 11: Location of the Tuyen Quang sub-basin within the Red River basin.

4.4 General settings

As an ordinary user, you will only need to make changes to the configuration file (**sphy_config.cfg**). You can open this file in a text editor (e.g. Notepad). In the *MODULES* section of the config file, the user specifies the modules that are relevant for the study area (as described in Terink et al. (2015a), Section 2.2). Under *DIRS*, you can specify the location of input and output files, and *TIMING* lists modeling period. The model is typically run on a daily time step. For now, these sections can be left unchanged.

As you browse further through the .cfg file, you will see the full list of inputs needed by the SPHY model. SPHY inputs can be raster maps, lookup tables or constant values. For this tutorial, input maps are already provided. The various files to which the .cfg file refers can be found in the directory **input**. The format of the files is .map, which is the PCRaster type of raster file. It is directly compatible with most common GIS software packages, such as ArcGIS and Quantum GIS.

All input files should have the same extent and cell size for the model to run correctly. The files in the **input\forcing** directories are dynamical inputs, thus they are different for every time step. The extension of these files is the time step for which they are valid, with day 001 being the starting date of the period specified in the .cfg file.

4.5 Input data

For the sake of this training, most input data has already been prepared for the Tuyen Quang area. You can find the sources of these data in Table 14. Of course, suitable data sources will be different for each study area and other sources can be used for feeding SPHY.



Table 14: Main SPHY input parameters with their sources for the Tuyen Quang area.

Parameter	Source	Link
Precipitation	TRMM	http://mirador.gsfc.nasa.gov/
Temperature (min, mean, max)	GSOD	https://data.noaa.gov/dataset/global-surface-summary-of-the-day-gsod
NDVI	MODIS	https://ladsweb.nascom.nasa.gov/
DEM	SRTM	http://srtm.csi.cgiar.org/
Soil properties	ISRIC	http://soilgrids.org
Land use	Globcover	http://due.esrin.esa.int/page_globcover.php

Now open some of the .map files provided and explore the properties of the Tuyen Quang area. Answer the following questions:

- Q1: What is the area of the catchment?
Q2: What is the average elevation of the catchment?
Q3: What is the maximum and minimum elevation within the catchment?
Q4: Which part of the catchment has the steepest slopes?

Some input data still needs to be created manually. 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). It should be specified in the *ROUTING* section of the config file. As you now have the PCRaster modelling framework installed on your computer, we can use this software to derive the flow direction map (see <http://pcraster.geo.uu.nl/pcraster/4.0.0/doc/manual/index.html> for further documentation on PCRaster functions).

Create a new directory named **workdir**. Copy **dem_500m_tq.map** from the **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_500m_tq.map, 1e31, 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, 1e31, 1e31, 1e31, 1e31)
```

Open the newly created **ldd.map** in your GIS software. 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(idd.map, 1)
```

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

When you have a correct LDD map, copy **idd.map** from **workdir** to the **input** directory. Add the reference to the ldd map in the config file at the right place.

4.6 Setting reporting options and running the model

With all input data specified in the .cfg file, it is now almost time to run the model. However, first you need to specify which outputs of the model you would like to save. This can be done in the final section of the .cfg file, *REPORTING*. Per output parameter, you can choose daily or monthly spatial maps, tables with time series, or no output at all. If you choose time series, these will be created for the locations of the *LOCATIONS MAP*. Currently, all reporting options are turned off.

Q5: Decide which model outputs you would like to save for analyzing model performance, and enter these reporting options in the .cfg file.

If all installation steps were successful and all input data is ready, the model can be run from the command line.

Q6: Run the model by going to the sphy model source code directory and type:

```
python sphy.py
```

4.7 Model calibration

4.7.1 Checking streamflow results

As our current goal is to calculate river flow, we need some observed streamflow data to determine the model performance. Bao Lac and Bac Me are two hydrological stations located in Tuyen Quang. The file **streamflow_TQ.xls** contains daily flow measured at these locations for the 2002-2003 period. The **flowstations_500m_tq.map** locations map contains the locations of Bao Lac and Bac Me. If you have specified a daily reporting of routed total runoff (Qall) in the .cfg file, then your SPHY run has created a time series file (.tss) of flow at these two stations. These time series can be compared with station measurements.

The Nash-Sutcliffe (NS) coefficient is a commonly used indicator for evaluating model performance. Table 15 links model performance to NS values (Foglia et al. 2009).



Table 15: NS coefficient values and corresponding qualification of model performance.

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

Another indicator of the model performance is the total amount of runoff generated on a yearly basis in comparison to measured totals.

Open the files **streamflow_TQ.xls** and **QalIDTS.tss**. Paste your daily SPHY results into the correct columns of the Excel file. You can now compare the measured and modeled curves and evaluate the NS value computed in the Excel file. Also, the total amount of runoff modelled and observed is calculated under “total runoff”.

Q7: How do you rate the current model performance?

4.7.2 Sensitivity analysis and calibration

To improve performance of the model, several SPHY input parameters can be altered. In this workshop we focus on two important calibration parameters: the recession coefficient K_x and the maximum crop factor ($K_{C_{max}}$).

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 0.70. You can opt to choose either a spatially distributed recession coefficient map or single value that is applicable to the entire basin.

The crop factor K_c is used to calculate potential evapotranspiration from reference evapotranspiration, and $K_{C_{max}}$ is the maximum value that can occur (under conditions of full vegetation cover). A spatial land use-dependent $K_{C_{max}}$ map is recommended, but for the sake of simplicity this tutorial works with a constant value.

Lookup K_x and $K_{C_{max}}$ in Chapter 2 of Terink et al. (2015a), and evaluate how they are used in the model formulas.

Q8: How would you expect these inputs to impact your streamflow results?

Now perform a series of model runs using the parameter values as shown in the table below to investigate the sensitivity of the model to K_x and $K_{C_{max}}$. Evaluate the results in the Excel file, and find the best performing combination.



Run no.	Kx	K _{Cmax}
1	0.7	1.5
2	0.5	1.5
3	0.9	0.5
4	0.9	1

Q9: Do the results match your expectations?

Q10: Can you think of any other calibration parameters that could improve your results?

4.7.3 Validating evapotranspiration results

Traditionally, hydrologists focus strongly on streamflow results for determining model performance. However, it is possible to get good streamflow results by having unrealistic inputs in terms of other parts of the water balance. SPHY can produce spatial maps of the full water balance, including evapotranspiration (ETa), soil water content and groundwater recharge. This enables you to compare these model results to validation data (if available).

Spatial ETa data are increasingly freely available online (e.g. the MOD16 product, <http://www.nts.gov/umt.edu/project/mod16>) and are very useful as a proxy for model performance in simulating the vegetation/soil/water processes. For this workshop, we provide energy balance-based ETa maps from USGS (Senay et al., 2013) which can be found in the **ETa_validation** folder.

Perform another SPHY run using your best SPHY configuration, but now also reporting monthly ETa maps. Using GIS software, compare the SPHY monthly ETa maps to the provided validation maps, in terms of spatial patterns and absolute values.

Q11: How do the simulated monthly ETa maps compare to the energy-based ETa maps?

4.8 Using the reservoir module

The SPHY v2.1 model has an improved module for simulating reservoir operations. The user can opt for a simple and advanced reservoir module, depending on the available input data. Have a look at Terink et al. (2015b) for detailed information about the new SPHY reservoir module.

A map of a hypothetical reservoir in the river is provided as **reservoir.map** in the **input** directory. You can view this map in GIS software to find out its location, which is upstream of Bac Me hydrological station. We are going to run the advanced reservoir option in SPHY to find out the impact of this reservoir on downstream river discharge.

For implementing reservoirs into the model, re-calibrating the model would be necessary as the regional hydrological system changes substantially when reservoirs are introduced. For the sake of time, we will not go through calibration again. However, the following exercises will demonstrate the principles of the SPHY reservoir module.



Table 16: Reservoir properties of a hypothetical reservoir in the study area.

Reservoir properties	Value
Initial storage (Mm3)	3000
Reservoir storage capacity at emergency spillway (Mm3)	6000
Reservoir storage capacity at principal spillway (Mm3)	1500
Maximum daily outflow (Mm3/d)	100
Demand flow (Mm3/d)	10
Start of the flood season (DOY)	166
End of the flood season (DOY)	258

Make the necessary adjustments in the SPHY config file to activate the reservoir module using **reservoir.map** as an input. Change Kx to 0.2. Also, create the necessary input tables to run the advanced reservoir modelling option, according to the properties provided in Table 16. Now run the model and plot the time series of inflow, outflow and storage in Excel.

- Q12: Can you explain what happens in terms of reservoir operation through time?
- Q13: Compare the new model results for Bac Me (upstream of the reservoir) and Bao Lac (downstream of the reservoir).
- Q14: If time permits, experiment further with the reservoir module by modifying the reservoir properties or introducing a new reservoir at a different location.



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