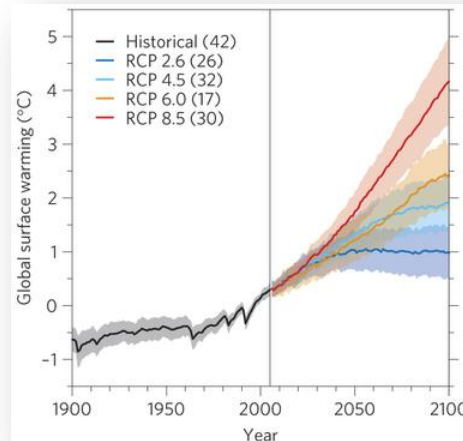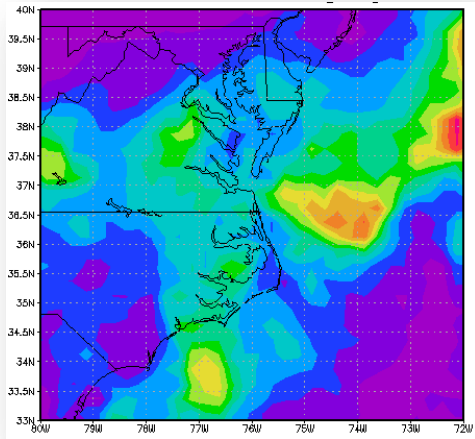# SPHY: Spatial Processes in Hydrology

Advanced training: input data, sensitivity analysis, model calibration, and scenario analyses

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- International Centre for Integrated Mountain Development (ICIMOD[1]);
- European Space Agency (ESA[2]);
- Asian Development Bank (ADB[3]);
- World Bank[4];
- Rijksdienst voor Ondernemend Nedeland (RVO[5])
- NUFFIC[6]

We are very grateful to these organizations that made the development of the SPHY model possible. We hope to continue to collaborate with these organizations in the future in order to further develop and improve the SPHY model and its interfaces.

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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 (Terink et al., 2015) 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:

- Trisuli River Basin, Nepal;
- Pungwe River Basin, Mozambique;
- Tuyen Quang sub-basin, Vietnam/China.

Before continuing with this more "advanced" training it is recommended to have finished one or more of these case-studies. The case-studies manual (Terink et al., 2015d) can be found at http://www.futurewater.nl/wp-content/uploads/2015/12/SPHY_case_studies.pdf. The case-studies will teach you the basic understandings of the SPHY model, like e.g. data preparation and formats, changing model parameters, and analyzing model output.

The learning objectives of this advanced SPHY training manual are:

- Refine your model using local and/or public domain data sets;
- Know how to perform a sensitivity analysis with the SPHY model and calibrate your model;
- Use the SPHY model for scenario analyses (applications):
  - Impact of climate change;

- - Impact of land use change.
- Use the SPHY model in operational mode for forecasting (e.g. Flood-Early-Warning).

Since the use of SPHY is educated in developing countries, the technical language used in this manual is "low-level" to make it accessible to everyone who is interested in using and applying this model.

2 Checklist

Before starting with this more advanced training it is i) required to have some basic understanding of the SPHY model, ii) have the required software packages installed, and iii) have a basic SPHY model with input maps already prepared on your PC (e.g. using the preprocessor). Read the sections below and check if you meet the requirements to proceed with this manual.

2.1 Basic SPHY model knowledge

The SPHY model has been developed by FutureWater. All information with respect to the SPHY model can be found on the SPHY model website: www.sphy-model.org. Make sure you:

- Have read and understand the SPHY model theory (Terink et al., 2015): http://www.geosci-model-dev.net/8/2009/2015/gmd-8-2009-2015.pdf;
- Know how to prepare SPHY model input data and run the model (Terink et al., 2015a): http://www.futurewater.nl/wp-content/uploads/2015/12/SPHY_manualV6.pdf;
- Know how to work with the SPHY model Graphical User Interface (GUI) (Terink et al., 2015c): http://www.futurewater.nl/wp-content/uploads/2015/12/SPHY_GUIs.pdf;
- Performed one or more of the SPHY model case-studies (Terink et al., 2015d): http://www.futurewater.nl/wp-content/uploads/2015/12/SPHY_case_studies.pdf.

2.2 Software installation

If you have not yet installed the SPHY model and its dependencies, then you can obtain the software from: http://www.sphy.nl/download-sphy/. Check the bullets below to make sure you have installed all required software packages / databases:

- Details about the required software packages and how to install them can be found in Chapter 4 of: http://www.futurewater.nl/wp-content/uploads/2015/12/SPHY_manualV6.pdf;
- Installation of the SPHY model Graphical User Interfaces (GUIs) is described separately in: http://www.futurewater.nl/wp-content/uploads/2015/12/SPHY_GUIs.pdf;
- Case-study databases can be downloaded from: http://www.sphy.nl/tutorials/.

2.3 Basic model for your basin of interest

You likely already have a basic SPHY model with input data prepared on your PC using either the training manuals or by participating in one of our SPHY trainings. If this is not the case, then:

1. Define your river basin;
2. Create SPHY model input using:
    a. SPHY model preprocessor GUI, database (only for Mozambique and Nepal) and own local data   OR
    b. PCRaster command functions in the *Command Prompt* using Chapter 5 of http://www.futurewater.nl/wp-content/uploads/2015/12/SPHY_manualV6.pdf and local data.

3 Refine your model

This chapter helps you to improve your model using the "best" data sources available for your basin of interest. Especially in developing countries it can be difficult to have access to high-quality model input data. It is well-known that measurements for meteorological (precipitation and temperature) and hydrological (discharge) variables in these regions are sparse, contain errors and/or missing values, and are often measured on a few locations only. For these countries it may therefore be an option to use public domain data sources often obtained through remote sensing techniques.

3.1   General workflow for refining your model

Generally we propose the following procedure for creating the "best" model input data:

1. Obtain as much local data possible for your basin of interest:
   a. Land use maps (GIS shapefile(s));
   b. Station data:
      i. Locations (latitude, longitude, elevation);
      ii. Discharge data (average daily values);
      iii. Precipitation data (daily sums);
      iv. Temperature data (daily maximum, minimum and average).
2. Perform data quality checks:
   a. Land use maps: based on expert knowledge or cross-validation with remotely sensed land use products (see Section 3.3);
   b. Stations data:
      i. Locations:
         1. Are discharge stations located in the river network, and correct branch / tributary?
         2. Is location of precipitation / temperature station correct, or has it been moved to another location?
      ii. Discharge data:
         1. Check for missing values. Why are they missing? Is a NaN value 0 discharge, or is it an empty record?
         2. Can you fill gaps in the discharge using records from a nearby discharge station? Check if there is a relation between station A and station B;
         3. Make time-series plots of your data. Do you see anything strange? If so, then remove these records or fill with plausible numbers.
      iii. Precipitation data:
         1. Check for missing values. Why are they missing? Is a NaN value 0 precipitation, or is it an empty record?
         2. Make scatterplots of cumulative precipitation records of station A versus station B. If both stations are more or less ok, then there should be a straight line. An offset indicates that there is something wrong with one of the stations;
         3. Can you fill gaps based on records from a nearby station? If there is a relation with a nearby station (see step 2 above), then you likely can use this relation to fill the gaps;

4. Make a time-series plot of your precipitation data. Do you see anything strange? If so, then remove these records or fill with plausible numbers.

iv. Temperature data:

1. Check for missing values. Why are they missing? For temperature you could use temperature from previous or next day to fill a missing record;
2. Is the maximum temperature always higher than the average?
3. Is the minimum temperature always lower than the average?
4. Is it true that stations located at higher elevations measure lower temperatures compared to stations located at lower elevations?
5. Make time-series plots of minimum, average, and maximum temperature. Do you see any strange things?

3. Convert local data to SPHY model input maps (for details see Section 3.2) and Chapter 5 of http://www.futurewater.nl/wp-content/uploads/2015/12/SPHY_manualV6.pdf;
4. Run the SPHY model with these local data sources;
5. Make a water balance to check:
   a. If the basin and/or sub-basin average precipitation, actual evapotranspiration, and discharge are correct;
   b. If the change in storage for a multiyear simulation is close to zero:

   $$dS = P - ETa - Q = \text{small number}$$

   with: dS   = change in storage
          P   = precipitation
          ETa   = actual evapotranspiration
          Q   = discharge

6. Check bias between observed and simulated streamflow: is there an over- or underestimation? If bias is too large, then you are overestimating your average discharge. This can be due to too much precipitation or too little evapotranspiration. In this case you may need to improve your meteorological input data or land use data. This can be achieved by:
   a. Correcting your local data or;
   b. Using public domain data sources (remote sensing, Section 3.3);
   c. Using a combination of local data and remote sensing.
7. Check for seasonality in simulated discharge and compare this with the observed discharge. If there is a small offset, then this can be correct later during sensitivity analysis and model calibration.

3.2 Local data sources

3.2.1 Land use

The SPHY model preprocessor uses the GlobCover2009 (Defourny et al., 2007) land use product. The land use in SPHY basically affects the evapotranspiration flux. SPHY model parameters related to land use are the crop factor (Kc) and root depth (first soil layer). If you have your own land use data, and thus are not using the GlobCover2009 product from the database, then you should follow these steps:

1. Classify your land use classes into numerical classes ranging from 1 to x, with x being the total number of classes;

2. Make a *.tbl file where you relate each land use class to a crop factor. You can use http://www.kimberly.uidaho.edu/water/fao56/fao56.pdf to find suitable crop factors for your land use classes;
3. Rasterize your land use classes shapefile in QGIS to the model extent and resolution. Details on how to achieve this can be found in Chapter 5 of http://www.futurewater.nl/wp-content/uploads/2015/12/SPHY_manualV6.pdf.
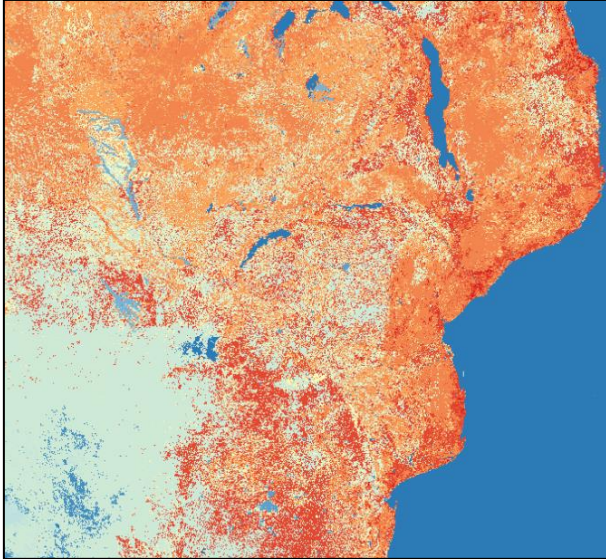
Figure 1: Part of GlobCover2009 domain included in the Southeast Africa database for the SPHY model.

3.2.2 *Soils*

The SPHY model requires physical soil property maps, which are often not provided in local soil maps. If you have maps with percentages of clay, silt, sand, organic carbon content, and bulk density, then you can use the pedo-transfer functions (De Boer, 2015) to calculate the hydrologic soil properties as required by the SPHY model. A link to a report on how to calculate these properties is shown below:

http://www.futurewater.nl/wp-content/uploads/2015/05/HiHydroSoil-A-high-resolution-soil-map-of-hydraulic-properties.pdf

After having calculated these soil properties you end up with a shapefile for each hydrologic soil property. To be useful for the SPHY model you need to rasterize these shapefiles to the model extent and resolution. Details on how to achieve this can be found in Chapter 5 of http://www.futurewater.nl/wp-content/uploads/2015/12/SPHY_manualV6.pdf. You should end up with the following soil maps:
- Field capacity rootzone;
- Saturated content rootzone;
- Permanent wilting point rootzone;
- Wilting point rootzone;
- Saturated hydraulic conductivity rootzone;
- Field capacity subzone;
- Saturated content subzone;
- Saturated hydraulic conductivity rootzone.
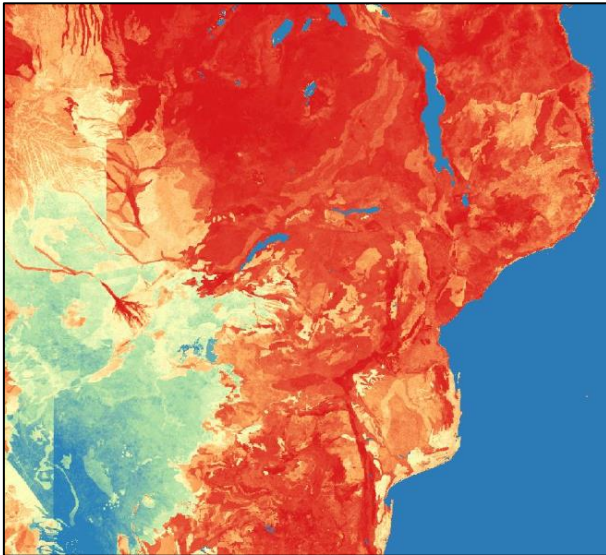
Figure 2: Field capacity soil map included in the Southeast Africa database for the SPHY model.

3.2.3   Precipitation

Having access to local precipitation data is very valuable because this data is not always included in remotely sensed precipitation products. Therefore we recommend using local precipitation data as much as possible. Make sure you have done the quality checks as indicated in Section 3.1. After having checked the quality of your precipitation data, and corrected where necessary, you can use the SPHY model preprocessor to create the precipitation input maps. This is clearly described in Section 3.7 of http://www.futurewater.nl/wp-content/uploads/2015/12/SPHY_GUIs.pdf. Make sure that you use the following format for the station location table:

Table 1: Format of location csv-file, containing 5 stations. Elevation units are in MASL. Coordinates need to be provided in latitude (lat) and longitude (lon). Names can be dummy values.

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

Precipitation data should be in the following format:

Table 2: Format of precipitation data csv-file, containing data for 5 stations. Precipitation units are in mm.

	A	B	C	D	E	F	G
1	DATE	1	2	3	4	5	
2	1-1-2001	3.705587	8.238709	0.083706	1.491564	4.100707	
3	2-1-2001	6.226049	9.936424	9.843851	5.403994	9.781127	
4	3-1-2001	7.443758	2.375468	0.037047	3.484891	9.984137	
5	4-1-2001	5.354188	1.177539	4.462445	3.151409	9.384312	
6	5-1-2001	5.286025	2.827377	7.729253	2.454813	3.210216	
7	6-1-2001	6.601565	6.876879	7.381467	7.911656	9.889859	
8	7-1-2001	6.210354	3.882653	1.280547	5.159928	1.423997	
9	8-1-2001	2.758112	7.243028	9.836882	0.265866	4.557234	

3.2.4 Temperature

Having access to local temperature data is very valuable because this data is hard to find in public domain data sources. Therefore we recommend using local temperature data as much as possible. Make sure you have done the quality checks as indicated in Section 3.1. After having checked the quality of your temperature data, and corrected where necessary, you can use the SPHY model preprocessor to create the temperature input maps. This is clearly described in Section 3.7 of http://www.futurewater.nl/wp-content/uploads/2015/12/SPHY_GUIs.pdf. For the station location table you should use the format as shown in Table 1. Temperature data should be in the format as shown in the table below:

Table 3: Format of temperature data csv-file, containing data for 5 stations. The order is from left to right: average, maximum, minimum temperature. Units of temperature are degrees Celsius.

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

3.2.5 Discharge

Observed discharge data is not used as input to your model but to compare your simulated discharge with. This data is almost impossible to find using public data sources. Without having local discharge data it is very hard to evaluate the performance of your model. Another option would be to calibrate your model on simulated evapotranspiration patterns. However, this requires measurements of evapotranspiration, which are even more difficult to obtain. Conceptual hydrological models normally use one observed discharge time-series to calibrate their model on. With spatially distributed models, like e.g. the SPHY model, it makes more sense to calibrate the model for several discharge measurement locations.
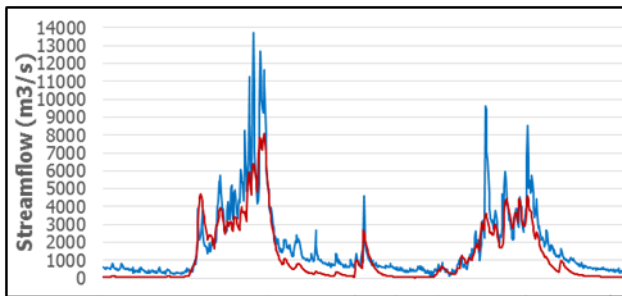
Figure 3: Example of simulated versus observed streamflow.

The number and locations of discharge measurements you want to calibrate for depends on your model objective; if you are interested in evaluating the effect of certain practices (e.g. land use change) in specific sub-basins, then you likely want to calibrate each of these sub-basins separately. If you are only interested in the discharge at the basin outlet, then you do not need to calibrate each sub-basin separately. You can decide for yourself for how many discharge stations you want to calibrate your model. Depending on your model objective you may wish to calibrate on monthly discharge instead of daily discharge. Details about model calibration and sensitivity analysis can be found in Section 0.

After having performed the quality checks on your local discharge data you need to match the period of discharge measurements with the period of available precipitation and temperature records; i.e. it makes no sense to run the model for a period for which discharge measurements are not available.

3.3 Public domain data sources

If local data cannot be found for your basin of interest, then you may find a suitable public domain data source using the sections below.

3.3.1 Land use

If you prefer to use one of the public domain land use data sources shown below, then it is required to rasterize them to the model extent and resolution. Follow step 3 from Section 3.2.1 to complete this.

3.3.1.1 GlobCover2009

The SPHY model preprocessor uses the GlobCover2009 product (Defourny et al., 2007) as source for land use data. Currently only Southeast Africa and the Hindu Kush Himalayan region are included in the preprocessor database. You can download original GlobCover2009 land use data for other regions in the world from: http://due.esrin.esa.int/page_globcover.php. You also can find this data in the folder: ***public_domain_data\Globcover_2009***
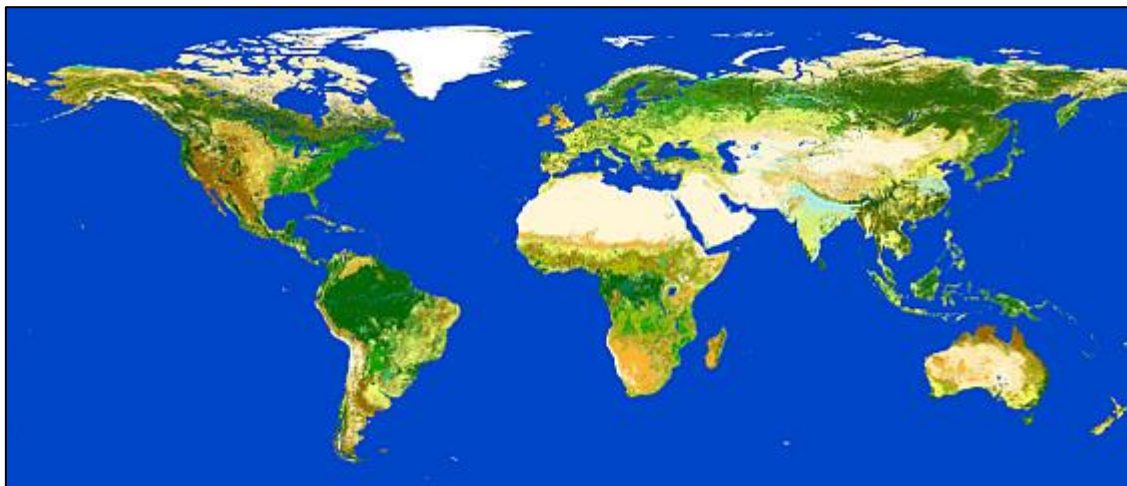
Figure 4: Regions for which GlobCover2009 land use data is available (Defourny et al., 2007).

GlobCover is an ESA initiative which began in 2005 in partnership with JRC, EEA, FAO, UNEP, GOFC-GOLD and IGBP. The aim of the project was to develop a service capable of delivering global composites and land cover maps using as input observations from the 300 m MERIS sensor on board the ENVISAT satellite mission. GlobCover2009 land use data is available at a 300 m spatial resolution.

3.3.1.2 CCI-LC

CCI-LC has been developed by the European Space Agency (ESA) and other partners, and contains 3-epoch series of global land cover maps at 300 m spatial resolution, where each epoch covers a 5-year period (2008-2012, 2003-2007, 1998-2002). The entire 2003-2012 MERIS Full and Reduced Resolution (FR and RR) archive was used as input to generate a 10-

year 2003-2012 global land cover map. This 10-year product has then served as a baseline to derive the 2010, 2005 and 2000 maps using back- and up-dating techniques with MERIS and SPOT-Vegetation time series specific to each epoch.

Details about this product can be found at: http://www.esa-landcover-cci.org/?q=node/164
A viewer is available at: http://maps.elie.ucl.ac.be/CCI/viewer/index.php
This product is available in the folder: **public_domain_data\ESA_CCI**

3.3.2   Soils - HiHydroSoil

Since local soil maps of good quality are often not available, global soil maps with a lower resolution are used. Furthermore soil maps do not include information about soil hydraulic properties, which are of importance, e.g. for hydrological modelling, erosion assessment and crop yield modelling. Therefore a Global Soil Map of Hydraulic Properties was created from soil data of the Harmonized World Soil Database by Droogers (2011). Since 2011 more soil data has become available and calculation algorithms have been improved, which made it possible to create a global soil map 'SoilGrids1km' with a higher resolution and improved accuracy (Hengl et al., 2014). However, SoilGrids1km does not include soil hydraulic properties (such as pF and Kh relationships) needed for hydrological modeling. De Boer (2015) describes the derivation of soil hydraulic properties from SoilGrids1km to create the HiHydroSoil map. The Harmonized World Soil database (HWSD) is used to fill missing data in the SoilGrids1km.

The SPHY model preprocessor uses this HiHydroSoil (De Boer, 2015) as data source to create the hydrological soil input maps for SPHY. HiHydroSoil is only included in the preprocessor databases for Southeast Africa and the Hindu Kush Himalayan region. For other regions use the link below to download the HiHydroSoil soil data:

HiHydroSoil data can be downloaded from the FutureWater ftp:
ftp://95.97.194.183:22/PUBLIC_SHARED_DATA/HiHydroSoil/

> *User: guest01*
> *Password: FW.guest012_*

A link to the report describing this dataset can be found here: http://www.futurewater.nl/wp-content/uploads/2015/05/HiHydroSoil-A-high-resolution-soil-map-of-hydraulic-properties.pdf

Finally you need to resample these soil maps to your model extent and resolution. Details on how to achieve this can be found in Chapter 5 of http://www.futurewater.nl/wp-content/uploads/2015/12/SPHY_manualV6.pdf.

3.3.3   Precipitation

Precipitation data is available through several public domain data sources, being either gauge based, satellite based (remote sensing), or a combination of both. Below we provide you with a number of well-known public domain data sources for precipitation. Each of these data sources have their pros and cons in terms of i) area coverage, ii) spatial resolution, iii) temporal resolution, iv) period covered, v) and user-friendliness of data format.

3.3.3.1   Global Surface Summary of the Day – GSOD

GSOD is a gauge based dataset containing meteorological variables (precipitation, mean temperature, maximum temperature, etc.) for more than 9000 stations worldwide. GSOD is derived from The Integrated Surface Hourly (ISH) dataset. The ISH dataset includes global data

obtained from the USAF Climatology Center, located in the Federal Climate Complex with NCDC. The latest daily summary data are normally available 1-2 days after the date-time of the observations used in the daily summaries. An overview of GSOD station locations is shown in Figure 5. If you plan to use GSOD data, then check for the units that are used because they are generally in Fahrenheit for temperature and inches for precipitation. Therefore you may need to convert them to be useful for the SPHY model.
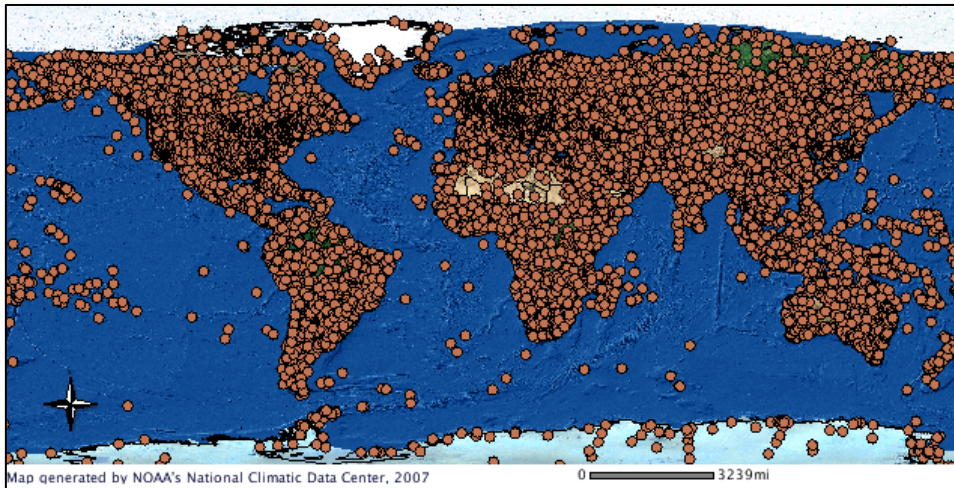
Figure 5: Overview of GSOD station locations (NOAA, National Climatic Data Center, 2007).

Details about GSOD can be found at: https://data.noaa.gov/dataset/global-surface-summary-of-the-day-gsod.

A viewer for selecting and downloading GSOD meteorological data is available at: https://gis.ncdc.noaa.gov/maps/ncei/cdo/daily.

Another option is to download the data from: http://www7.ncdc.noaa.gov/CDO/cdoselect.cmd?datasetabbv=GSOD&resolution=40

3.3.3.2   CHIRPS v2.0

Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) is a 30+ year quasi-global rainfall dataset (Funk et al., 2015). CHIRPS was created in collaboration with scientists at the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center in order to deliver reliable, up to date, and more complete datasets for a number of early warning objectives (such as trend analysis and seasonal drought monitoring). Spanning 50°S-50°N (and all longitudes), starting in 1981 to near-present, CHIRPS incorporates 0.05° resolution (~5 km) satellite imagery with in-situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring. As of February 12th, 2015, version 2.0 of CHIRPS is complete and available to the public.

Early research focused on combining models of terrain-induced precipitation enhancement with interpolated station data. More recently, new resources of satellite observations such as gridded satellite-based precipitation estimates from NASA and NOAA have been leveraged to build high resolution (0.05°) gridded precipitation climatologies. When applied to satellite-based precipitation fields, these improved climatologies can remove systematic bias, a key technique in the production of the 1981 to near-present CHIRPS dataset. The creation of CHIRPS has

supported drought monitoring efforts by the USAID Famine Early Warning Systems Network (FEWS NET).
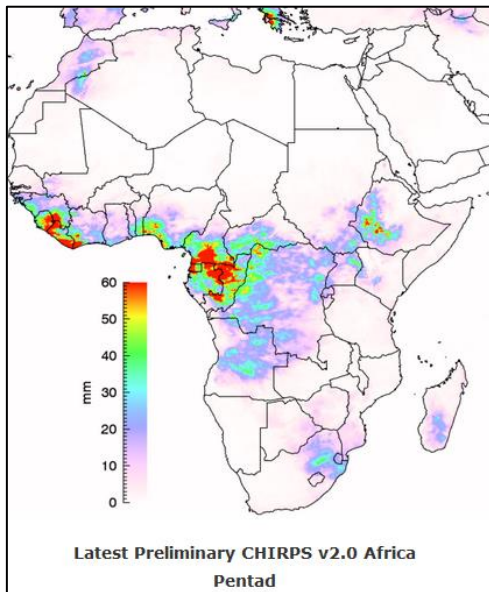
Figure 6: Snapshot of CHIRPS v2.0 precipitation data for Africa (http://chg.geog.ucsb.edu/data/chirps/#plus8).

Details about CHIRPS can be found at: http://chg.geog.ucsb.edu/data/chirps/#plus8.

CHIRPS v2.0 data can be downloaded from:
ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRPS-2.0/

You can download precipitation data with the following options:
- Domain: Africa or World.
- Temporal resolution: daily or monthly.
- Spatial resolution: 0.05 degrees (~5 km) or 0.25 degrees (~25 km).
- Data format: Bil or GTiff.
- 1 January 1981 up till now.

CHIRPS v2.0 is also available as zip-file in the *public_domain_data\CHIRPS2.0* folder for the period 1981-2015. Unzipping this zip-file results in GeoTiff files for daily precipitation on a spatial resolution of 0.05 degrees (~ 5km) for the period 1 January 181 through 31 December 2015. These files can be processed using *process_CHIRPS.xlsx* and *process_CHIRPS.py*. Before you can process CHIRPS v2.0 into PCRaster files for your model extent and resolution you need to have installed the *openpyxl* python package. This can be installed following steps 1-4 from Section 5.1.4.1.

Now open the *process_CHIRPS.xlsx* file and go to the *chirps* sheet (Figure 7). Do not change the name of this file or worksheet because this leads to errors when processing the CHIRPS precipitation data. It is also not allowed to change any cells, except for the orange marked cells. In this sheet you can change the values according to:
- INPUT / OUTPUT DIRECTORIES: set here the directories where your unzipped CHIRPS GeoTiff files can be found and where your processed CHIRPS precipitation data should be created;
- START / END DATE: set here the first and last date of your processing period;

- MODEL PROPERTIES: set here the Coordinate Reference System (CRS, EPSG code), model resolution, and coordinates of your model extent;
- NAME FORMAT FOR PRECIPITATION FORCING: set here the name format of the precipitation file format to be used for the PCRaster files.

	A	B	C	D	E	F	G
1		**INPUT / OUTPUT DIRECTORIES**					
2		*Input directory download CHIRPS GeoTiff files*	e:\Active\2016-010_NUFFIC_ARA-Sul\public_domain_data\CHIRPS2.0\				
3		*Output directory processed CHIRPS precipitation data*	e:\Active\2016-010_NUFFIC_ARA-Sul\public_domain_data\CHIRPS2.0\output\				
4							
5							
6		**START / END DATE**			**NAME FORMAT FOR PRECIPITATION FORCING**		
7		*Start year for CHIRPS processing*	1981		*Precipitation*	prec	
8		*Start month for CHIRPS processing*	1				
9		*Start day for CHIRPS processing*	1				
10							
11		*End year for CHIRPS processing*	1981				
12		*End month for CHIRPS processing*	1				
13		*End day for CHIRPS processing*	31				
14							
15							
16		**MODEL PROPERTIES**					
17		*EPSG Coordinate Reference System*	32736				
18		*Model resolution [m]*	250				
19		*Xmin [m]*	42216				
20		*Xmax [m]*	67216				
21		*Ymin [m]*	7604720				
22		*Ymax [m]*	7629720				
23							
24							
25				= fields that can be changed / filled in			
26							
27							

Figure 7: CHIRPS processing settings sheet in process_CHIRPS.xlsx.

After this sheet has been completed you can save and close *process_CHIRPS.xlsx*. Then open *process_CHIRPS.py* with a text editor (e.g. notepad) and change the path that links to the location of the *process_CHIRPS.xlsx* file (red box, Figure 8).

```
process_CHIRPS.py
1    import os, subprocess, openpyxl, datetime, glob
2
3    #-Read Excel file with settings
4    Excel_file = 'e:/Active/2016-010_NUFFIC_ARA-Sul/public_domain_data/CHIRPS2.0/process_CHIRPS.xlsx'
5    wb = openpyxl.load_workbook(Excel_file)
6    sheet = wb.get_sheet_by_name('chirps')
```
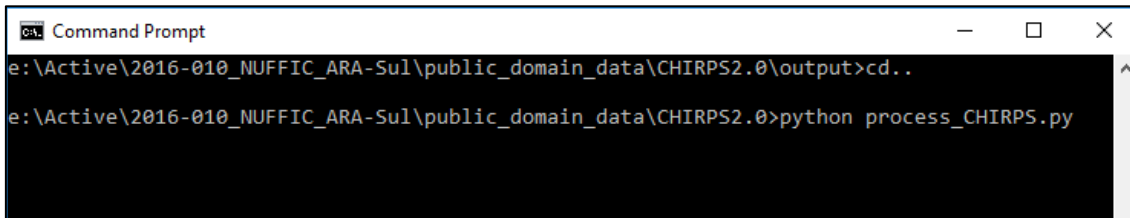
Figure 8: Changing the Excel_file location path in the process_CHIRPS.py file.

Now follow the steps below to convert the CHIRPS GeoTiff files into PCRaster precipitation files for your model extent and resolution:

1. Open a cmd prompt and go to the *public_domain_data\CHIRPS2.0* folder;
2. Type *python process_CHIRPS.py* in the cmd prompt and hit enter ();
3. Depending on the number of years, model extent, and resolution, it may take some time before processing is finished. If processing is finished successfully, then you will see the message: *CHIRPS v2.0 precipitation was created successfully!*

Figure 9: Processing CHIRPS using the process_CHIRPS.py script.

3.3.3.3   FEWS RFE2.0 precipitation

Beginning January 1, 2001 RFE 2.0[1] replaced RFE 1.0 as the operational CPC Africa rainfall algorithm. Along with a dramatically reduced processing time, the new algorithm gives increased accuracy and enhanced code portability. The output domain is 20W-55E, 40S-40N with a 0.1 degree resolution and daily temporal resolution, and each day's time scale is 6Z-6Z.

More information about this dataset can be found at:
http://www.cpc.noaa.gov/products/fews/data.html.

The SPHY model preprocessor uses FEWS RFE2.0 data as data source for precipitation. The database of the preprocessor contains this data for Southeast Africa for the period January 2001 through 31 December 2001 on a spatial resolution of 0.1 degrees (~10 km) and daily temporal resolution. FEWS RFE2.0 precipitation data can be downloaded using the link below:

http://earlywarning.usgs.gov/fews/datadownloads/Continental%20Africa/Dekadal%20RFE

Data can be downloaded in BIL format. CHIRPS v2.0 is an updated and improved precipitation product compared to FEWS RFE2.0, and is therefore recommended to use.

3.3.3.4   Global Precipitation Mission (GPM)

The Global Precipitation Measurement (GPM) mission is an international network of satellites that provide the next-generation global observations of rain and snow to advance our understanding of Earth's water and energy cycle, improve forecasting of extreme events, and provide accurate and timely information to directly benefit. The GPM mission concept builds on the success of the Tropical Rainfall Measuring Mission (TRMM), a joint NASA and JAXA satellite launched in 1997 that measures precipitation over tropical and subtropical regions, from approximately 35° north latitude (e.g., the Mediterranean Sea) to 35° south latitude (e.g., the southern tip of South Africa). The highest spatial resolution available is 5 km. Temporal resolutions range from 3-hourly to daily.

Observations from the GPM constellation, combined with land-surface data, will improve:
- Weather forecast models;
- Climate models;
- Integrated hydrologic models of watersheds;
- Forecasts of hurricanes, landslides, floods, and droughts.

Details about GPM can be found at: https://www.nasa.gov/mission_pages/GPM/main/index.html

TRMM data can be downloaded from: https://pmm.nasa.gov/data-access/downloads/trmm
GPM data can be downloaded from: https://pmm.nasa.gov/data-access/downloads/gpm

---

[1] http://www.cpc.noaa.gov/products/fews/RFE2.0_tech.pdf

Precipitation data can also be downloaded and viewed from:
http://giovanni.gsfc.nasa.gov/giovanni/. This portal also allows for downloading other meteorological and hydrological products.

3.3.4   Temperature

We only provide a gauge based temperature product here, which is the Global Summary of the Day (GSOD). Since this data source can also be used for precipitation, check Section 3.3.3.1 for more details.

4 Sensitivity analysis and model calibration

4.1 General

Sensitivity analysis (what-if analysis) is a brainstorming technique used to determine how projected model performance is affected by changes in the inputs. Sensitivity is generally measured as the response of an output variable to a change in an input parameter, with larger output response changes corresponding to larger sensitivities. It evaluates how different parameters influence a predicted output. Sensitivity analysis is often used to compare different scenarios and their potential outcomes based on changing conditions. Parameters identified in sensitivity analysis that influence predicted outputs are generally used to calibrate a model.

4.2 Sensitivity analysis

4.2.1 Objective

The main objective of the sensitivity analysis is to understand the contribution of the model parameters to the physical processes in the hydrological system. This exercise will help the users to identify the most sensitive parameter(s) and eventually help the model calibration process. At the end of this exercise the trainees will have better understanding of the model parameters.

4.2.2 Methodology

The model will be run with fixed initial values and thereafter will be regarded as the reference model run. The parameters will be changed one at a time and compared with reference model run each time. So, the effect of change in each parameter will be reflected to simulated discharge.

Note: For this exercise the output variable taken is the simulated discharge. Alternatively, this exercise can be done for other output variables such as simulated snow cover, evaporation etc.

Select **01-01-2005** as your starting day and **31-12-2007** as end day for the simulation from the *General setting tab* in GUI. Change the parameter values in the GUI corresponding to the values shown in the Table 4. Make sure to output the daily time series of *Routed total runoff (m3/s)* in the Report option tab in GUI. Now run the model and open the *QAllDTS.csv* from the output folder. Copy the discharge time series in to the *simulation* work sheet of the *Sensitivity analysis.xls* as your reference run.

Table 4: Initial values for the reference model run.

Parameters	Initial Value
rootdepthflat	400
subdepthflat	1600
gwdepth	3000
gwsat	300
deltagw	3
alphagw	0.5
kx	0.5

Now fill the **Parameter_Set** worksheet in the same excel file. The first parameter set is already done in the worksheet. Try to tabulate the other parameter sets. Make sure you follow the same convention as followed in the worksheet (1st increase by 50% and then decrease by 50%). After completing the table, again run the model with changed parameter values. So, the 1st model run will be with increased value of **rootdepthflat** from 400 to 600 and keeping all the other parameters the same.

After the end of each run, copy the simulated outflow in the subsequent columns of the simulation worksheet. The average values at the top of the table will be automatically populated. The right side of the sheet has parameter sensitivity graphs. The average annual and 1st quarter of the year (Jan, Feb and Mar) sensitivity analysis have already been done for the reference run. Make new graphs for the other three quarters of the year. Compare your results and make a ranking matrix for the parameters. Ranks are assigned based on the absolute differences; assign 1 for the highest difference and so on.

Answer these questions:
1. Which parameter is the most sensitive on annual basis?
2. Is this different for the seasons? If so, why do you think this is different?
3. Which season(s) is/are the most important for your modelling objectives and why?
4. Select the 4 most sensitive parameters to be used for calibration;
5. Now we have performed the sensitivity analysis focusing on discharge only. Which parameters do you think has the largest impact on simulated actual evapotranspiration?

4.3   Model calibration

Model calibration is the process of selecting suitable values for model parameters such that the hydrological behavior of a catchment can be simulated closely to the real situation. The goal of model calibration is to "optimize" the model so that the simulated variable resembles the observed variable as close as possible.

4.3.1   Objective and overview

Most calibration approaches use an objective function. Many objective functions are available for model calibration. For this training we propose to use the "minimization of error between observed and simulated outputs". The variable to calibrate for can be discharge, evaporation, snow cover etc. The calibration process depends on the availability of observed data, and in most cases we have observed discharge records for one or more locations within the river basin. The calibration process is also dependent on the time-step, like e.g. sub-daily, daily, weekly, and monthly. The time-step selection depends on the model objective; i.e. if the model is calibrated for flood forecasting then it would be wise to have hourly time-steps, but for reservoir operations weekly or monthly calibrations can be sufficient.

The calibration process can be either manual or automatic. In practice, however, it is often a combination of the two. Manual calibration relies on the modeler's knowledge; being familiar with the SPHY model concepts and river basin characteristics allows you to speed-up the calibration process by manual adjusting the model parameters, and going through the trial-and-error process more efficiently. Through automatic calibration the model is forced to run with either a predefined or random set of initial parameter values. The advantages of automatic calibration are to i) speed-up (in terms of computational efficiency) the calibration process and ii) end up with a better optimized model. For this training we use the manual calibration approach.

Generally, the calibration is terminated after you have achieved a state where the goodness of fit (GoF) cannot be improved more substantially. GoF is a numerical measure for the difference between the simulated model output and the observations. A popular GoF for hydrological studies is the Nash-Sutcliffe Efficiency (NSE) criterion, which gives the proportion of the variance of the data explained by the model. Other GoF objective functions are Root-Mean-Square-Error (RMSE), correlation coefficient (R^2) and bias. Table 5 shows the ranges and best values for the GoF.

Table 5: Objective functions and their best values.

Indicators	Range	Best Value
NSE	(- ∞ to 1)	1
R2	(0 to 1)	1
RMSE	(0 to ∞)	0
Bias	(- ∞ to ∞)	0

4.3.2   Methodology

The first step of the calibration is to identify the parameter(s) that you are going to optimize. After having performed the sensitivity analysis (Section 4.2) it is assumed that you have good knowledge on the most sensitive parameters. A ***Calibration and Validation.xlsx*** Excel template has been provided to you. The first calibration step is to make a worksheet with all parameters to be used and track the values of parameters you are changing for each run. Open the ***Runs*** worksheet from the excel file and check the parameters to be used for the calibration. If you think that there are other parameters that can be calibrated, add them to the table. The start- and end period for calibration will be **01-01-2005** and **12-31-2007.** You may change this if you want to calibrate for a different period. Follow the steps below to calibrate your model:

1. Start the calibration with parameter set 1, and fill them in the table;
2. Copy the simulated flow data from the output file and put them in the ***Calibration*** sheet under the subsequent column. Copy the observed data from your study basin to the subsequent column;
3. Calculate the Mean, NSE, Bias and R^2 value;
4. Check the hydrograph by comparing the observed values with the simulated values;
5. Check the model performance on a monthly time scale;
6. Calculate the water balance (it's already covered in the previous training). Think about the parameter(s) that will affect the water balance. Change the parameter value(s) from the model GUI and run the model. Make sure that you write down the values for the next simulation in "Runs" worksheet. Run the model with 20 different parameter sets;
7. Calibration is an iterative process and can take some effort. Practically, there is no end to the calibration process; it depends on the modeler's perception. You can stop the model calibration once you think that you have done enough to emulate the real physical processes.

5 SPHY model applications

A calibrated hydrological model enables you to evaluate the impact of i) certain measures (e.g. land use change), ii) socio-economic developments (e.g. population increase), and iii) climate change, on the dynamics (discharge, evapotranspiration, infiltration, flooding, etc.) of a river basin. These impact evaluation studies are often referred to as scenario analyses, and serve as a tool to support policy and decision makers in their decision making.

Hydrological models are also used in operational mode to forecast river discharge, soil moisture contents, irrigation water requirements and seasonal reservoir inflow. This information is useful for operational water managers, like e.g. reservoir operators and farmers. A hydrological model in operational mode can also provide useful information for Flood-Early-Warning Systems.

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. An overview of SPHY model applications can be found at: http://www.sphy.nl/applications/.

This chapter focuses on three typical applications for which the SPHY model has been used, being:
- Climate change
- Land use change
- Forecasting

The data provided for these three applications is "synthetic", and is therefore not suitable for use in real studies. These data sets have been created for the purpose of this training only.

5.1 Climate change

5.1.1 Representative Concentration Pathways

Since the release of Intergovernmental Panel on Climate Change's fifth Assessment Report, four representative concentration pathways (RCPs) have been defined as a basis for long-term and near-term climate modeling experiments in the climate modeling community (van Vuuren et al., 2011). The four RCPs together span the range of radiative forcing values for the year 2100 as found in literature, from 2.6 to 8.5 Wm^{-2} (Table 6). Climate modelers use the time series of future radiative forcing from the four RCPs for their climate modeling experiments to produce climate scenarios. The development of the RCPs allowed climate modelers to proceed with experiments in parallel to the development of emission and socio-economic scenarios (Moss et al., 2010). The four selected RCPs were considered to be representative of the literature, and included one mitigation scenario (RCP2.6), two medium stabilization scenarios (RCP4.5/RCP6) and one very high baseline emission scenario (RCP8.5) (van Vuuren et al., 2011).

Since the four RCPs are considered to be representative of radiative forcing that can be expected by 2100, each of them should theoretically be considered with equal probability to be included in climate change impact studies. However, in climate change impact studies there is usually a trade-off in how many RCPs and how many climate models can be included within the available time and resources, whilst at the same time having the ability of producing robust and

reliable results. Figure 10 shows the global average change in surface temperature for the 4 RCPs.

Table 6: Description and visualization of the four representative concentration pathways (RCPs) (van Vuuren et al., 2011).

RCP	Description
RCP8.5	Rising radiative forcing pathway leading to 8.5 Wm^2 (~1370 ppm CO_2eq) by 2100
RCP6	Stabilization without overshoot pathway to 6 Wm^2 (~850 ppm CO_2eq) at stabilization after 2100
RCP4.5	Stabilization without overshoot pathway to 4.5 Wm^2 (~650 ppm CO_2eq) at stabilization after 2100
RCP2.6	Peak in radiative forcing at ~3 Wm^2 (~490 ppm CO_2eq) before 2100 and then decline (the selected pathway declines to 2.6 Wm2 by 2100
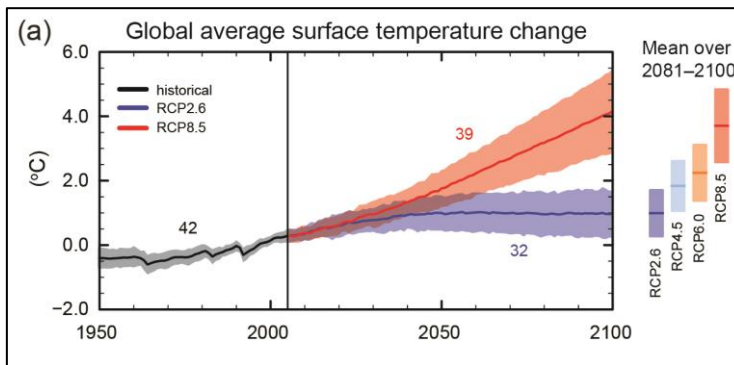
Figure 10: Global average change in surface temperature for the 4 RCPs.
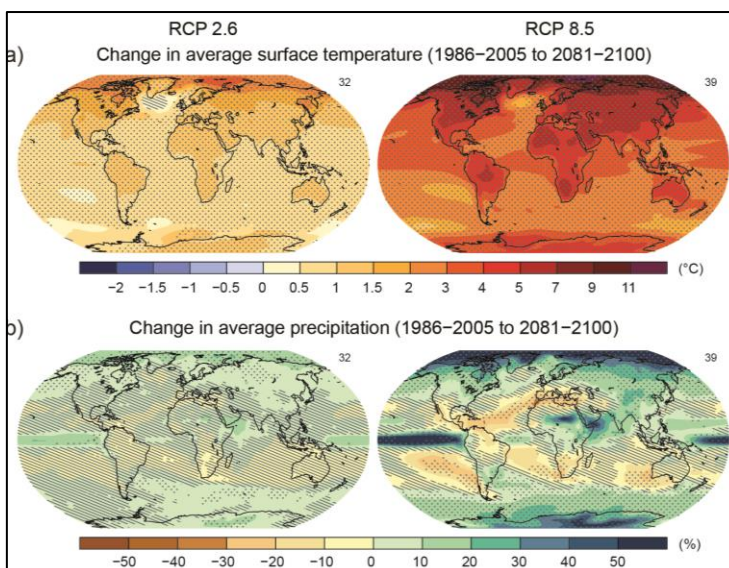
Figure 11: Global changes in average surface temperature and precipitation for the period 2081-2100 for RCP 2.6 and RCP 8.5.

Between 1996 and the release of the IPCC's fifth assessment report in 2013 (IPCC, 2013), the IPCC used a different set of future scenarios, combining main demographic, economic and technological driving forces with future greenhouse gas emissions. These scenarios were used in some of the literature cited in this thesis. An extensive description of the scenarios can be found in the IPCC's special report on emission scenarios (IPCC, 2000).

5.1.2   Types of climate models

Climate is modeled at different spatial scales. General Circulation Models (GCMs) are used to simulate global climate and operate at spatial resolutions ranging from ~100 km^2 to ~250 km^2. Regional Climate Models (RCMs) can be used to simulate regional climate at a typical resolution of ~10-50 km. Hydrological models usually require higher spatial resolution climate data compared to what is provided by the GCMs. For this reason climate data from GCMs is generally downscaled to the higher resolution used by the hydrological model, using either statistical or dynamic downscaling techniques. These techniques are rather complex, and are therefore not part of this training manual.

The current state-of-the-art GCMs are organized in the fifth Coupled Model Intercomparison Project (CMIP5) archive (Taylor et al., 2012), which was used as a basis by the IPCC for the generation of its fifth Assessment Report. A similar effort to organize the output from RCMs is the CORDEX framework (Giorgi et al., 2009). The earlier CMIP3 (Meehl et al., 2007) archive is the main archive used for studies prior to the release of the CMIP5 archive.

5.1.3   Downloading and viewing climate data

Because of the complexity of dynamic and statistical downscaling it is out of scope for this training manual. However, we like to share some links that allows you to view, download and process climate data. The portal below aims to support climate change impact modelers, impact and adaptation consultants, as well as anyone interested in using climate change data:

https://climate4impact.eu/impactportal/general/index.jsp

Another very interesting portal is the KNMI Climate Explorer:

https://climexp.knmi.nl/start.cgi?id=someone@somewhere

With the KNMI Climate Explorer you can upload a time-series of precipitation or temperature data. These time-series will then be converted into a time-series representing a possible future climate. This option is very interested in combination with the SPHY model preprocessor, because it allows you to create future time-series of X station locations, which can then finally be converted into climate input maps required by the SPHY model.

5.1.4   Case-study

For this case study two options are available to create future climate data.

5.1.4.1   Climate data processing: option A

This approach to process climate data is rather simplistic, assuming changes in precipitation and temperature per month that are equal for each year. In reality these changes may differ between years, but also spatially.

In the **Applications\climate_change** folder you will find the files and folders as shown in Figure 12. Before you can do this case-study you need to install the Python package **openpyxl**.

An internet connection is required for this. It may also be required to install **pip**. Follow the steps below to install these 2 packages:

1. Open a cmd prompt and go to the climate change application folder;
2. Type **python get-pip.py**   (Figure 13)
3. Add the scripts folder where pip is installed to your PATH environment. The scripts folder is normally located under **c:\Python27\Scripts**
4. Install openpyxl by typing **pip install openpyxl** in the cmd prompt (Figure 14).
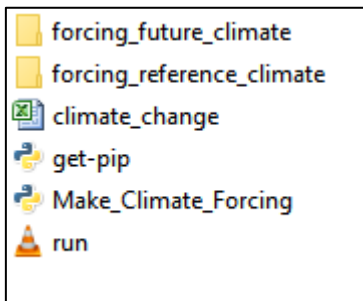
Figure 12: Files and folders in the climate change application folder.
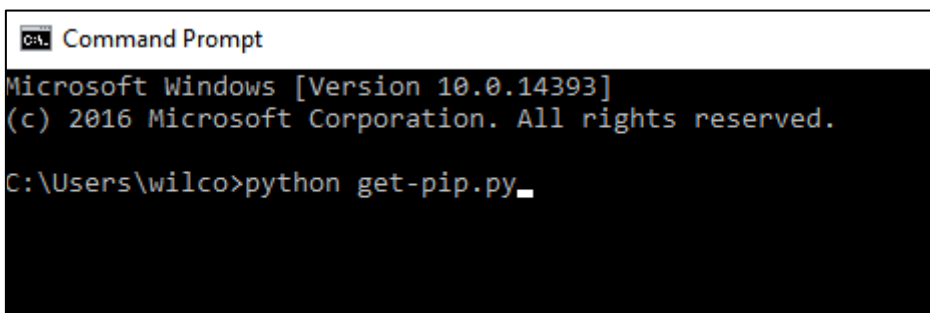
Figure 13: Install pip using the cmd.
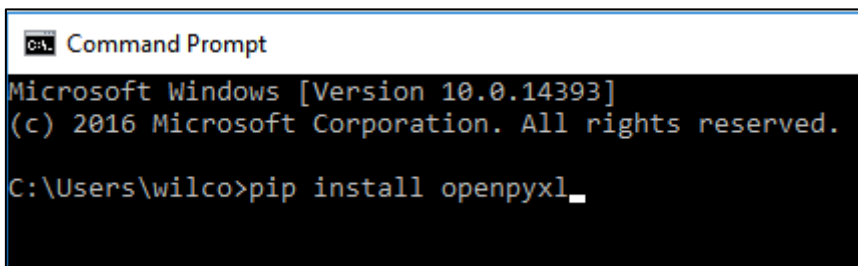
Figure 14: Install openpyxl using the cmd.

Now open the **climate_change.xlsx** file and go to the **climate_change_setting** sheet (Figure 15). Do not change the name of this file or worksheet because this leads to errors when processing the climate data. It is also not allowed to change any cells, except for the orange marked cells. In this sheet you can change the values according to:

- INPUT / OUTPUT DIRECTORIES: Set here the directories where your reference climate data can be found and where your future climate data should be created;
- START / END DATE: Set here the first and last date of your reference climate data;
- PRECIPITATION AMD TEMPERATURE CHANGE PER MONTH: Here you can enter the expected changes in climate per month for precipitation (%) and temperature (degrees Celsius);
- NAME FORMAT FOR FORCING FILES: set here the name format of the climate variables as used in the PCRaster file names of your reference climate data set; e.g. if

the file format for average temperature is *tavg0000.001*, then the name format should be *tavg*. If it is *tair0000.001*, then it should be *tair*.

	A	B	C	D	E	F	G	H
1		**INPUT / OUTPUT DIRECTORIES**						
2		*Input directory reference climate:*	e:\Active\2016-010_NUFFIC_ARA-Sul\Applications\climate_change\forcing_reference_climate\					
3		*Output directory future climate:*	e:\Active\2016-010_NUFFIC_ARA-Sul\Applications\climate_change\forcing_future_climate\					
4								
5								
6		**START / END DATE**			**NAME FORMAT FOR FORCING FILES**			
7		*Start year climate data*	2005		*Precipitation*	prec		
8		*Start month climate data*	1		*Mean temperature*	tair		
9		*Start day climate data*	1		*Maximum temperature*	tmax		
10					*Minimum temperature*	tmin		
11		*End year climate data*	2009					
12		*End month climate data*	12					
13		*End day climate data*	31					
14								
15		**PRECIPITATION AND TEMPERATURE CHANGE PER MONTH**						
16		*Month*	*delta P [%]*	*delta T [degrees Celsius]*				
17		1	10	0.5				
18		2	15	0.5				
19		3	20	0.5				
20		4	0	1				
21		5	0	2				
22		6	-5	1.5				
23		7	-10	1.5				
24		8	-20	1.5				
25		9	-15.3	0.5				
26		10	5	0.5				
27		11	5	0.5				
28		12	10	0.5				
29								
30								
31				= fields that can be changed / filled in				
32								

Figure 15: Climate change setting sheet in climate_change.xlsx.

You can use your own expertise, scientific literature, technical reports, or internet resources to fill in plausible values for changes in precipitation and temperature as a result of climate change. Save the file after you have completed filling in all orange cells.

Now open the ***Make_Climate_Forcing.py*** file with a text editor and change the location path (red box Figure 16) to the location where your ***climate_change.xlsx*** can be found. Save your edits and close this file.
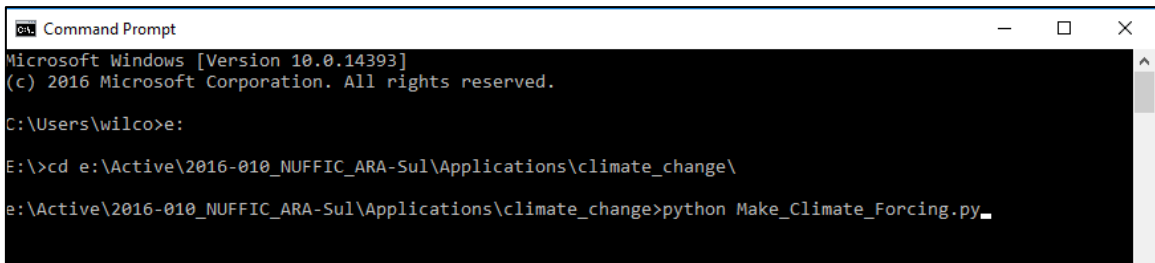
```
import openpyxl, datetime, os
import subprocess


#-Read Excel file with settings
Excel_file = 'e:/Active/2016-010_NUFFIC_ARA-Sul/Applications/climate_change/climate_change.xlsx'
wb = openpyxl.load_workbook(Excel_file)
sheet = wb.get_sheet_by_name('climate_change_setting')
```

Figure 16: Changing the Excel_file location path in the Make_Climate_Forcing.py file.

Now follow the steps below to create a climate data set for your future climate using the reference climate data set and monthly changes from the Excel sheet:
4. Open a cmd prompt and go to the climate change application folder;
5. Type ***python Make_Climate_Forcing.py*** in the cmd prompt and hit enter (Figure 17);
6. *Depending on the number of years of your reference climate data set it may take some time before processing is finished. If processing is finished successfully, then you will see the message: Climate data was created successfully!*

Figure 17: Processing climate data using the Make_Climate_Forcing.py script.

5.1.4.2   Climate data processing: option B

It is not mandatory to use the Excel sheet and python script as shown above. You may wish to use the KNMI Climate Explorer as shown in Section 5.1.3 in combination with the SPHY model preprocessor. Follow the steps on the KNMI Climate Explorer website to i) upload your own meteorological station data, and ii) convert this to a likely future climate for each station. Finally, use the **Meteorological forcing** tab (Figure 18) from the preprocessor to make climate input maps for the SPHY model. Check Section 3.7 from http://www.futurewater.nl/wp-content/uploads/2015/12/SPHY_GUIs.pdf on how to achieve this.
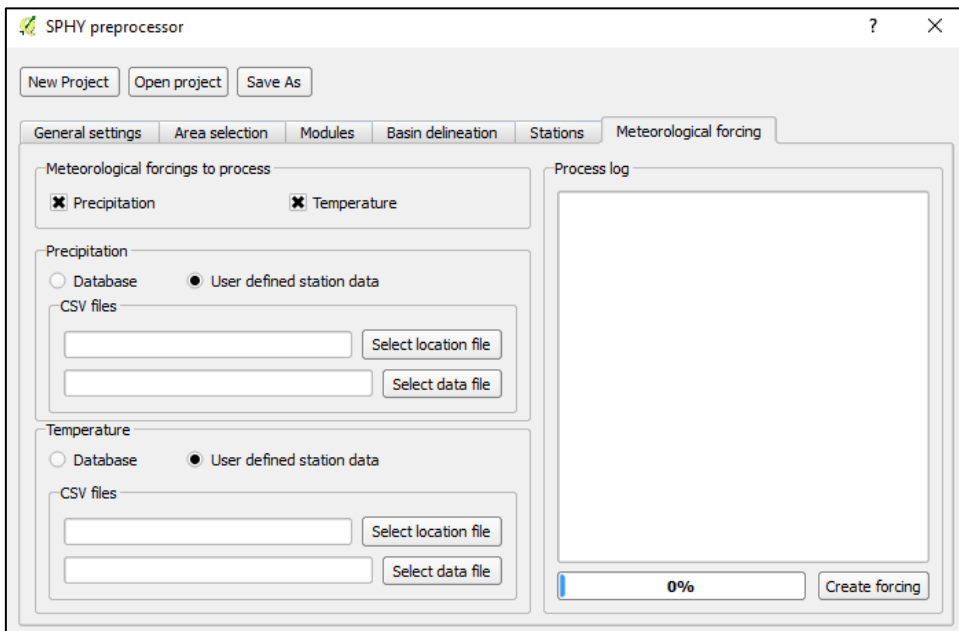
Figure 18: Set the location and data files for precipitation and temperature in the Meteorological forcing tab of the SPHY model preprocessor to create input maps for a future climate.

5.1.4.3   Running SPHY and analyzing results

Next you can use the SPHY model GUI to start a new project, or open an existing project and save it under a different name. Then make sure you select the future climate data for precipitation, average daily temperature, maximum daily temperature, and minimum daily temperature using the **Climate** tab from the SPHY model GUI (Figure 19).
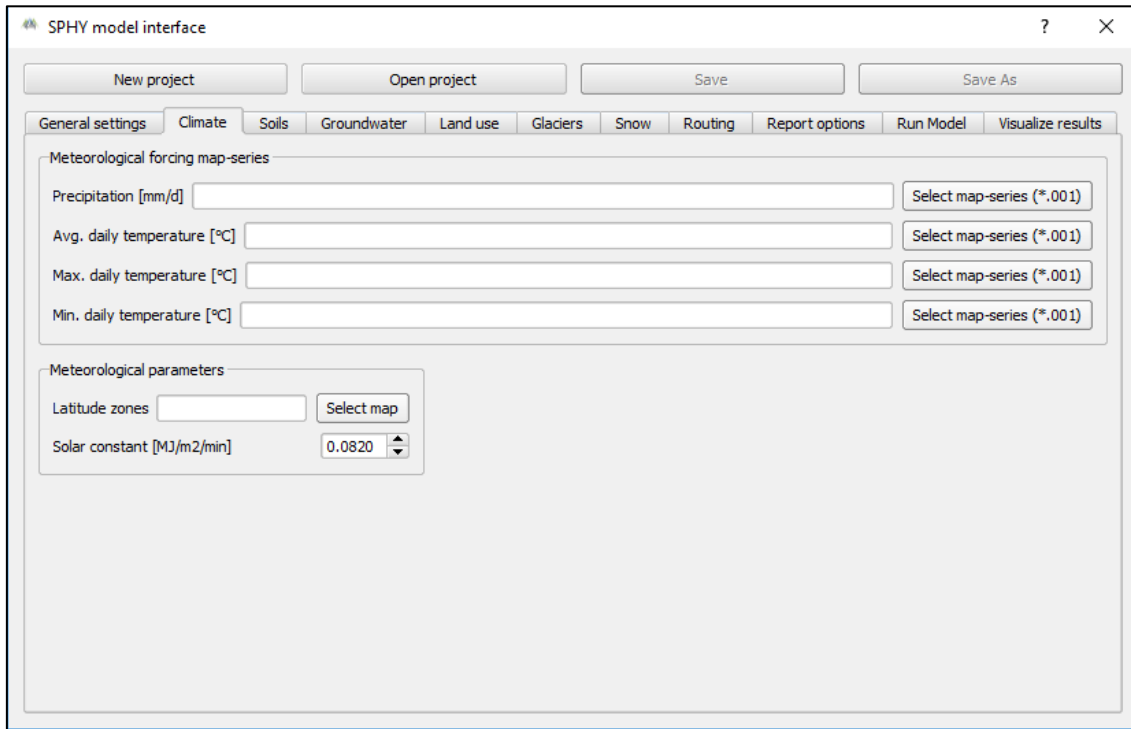
Figure 19: Setting the future climate data using the Climate tab in the SPHY model GUI.

Check the reporting options in the *Report options* tab to select the model output to be reported. Finally run the model.

After the model run has been completed open *climate_change.xlsx* and go to the *Results* sheet. This sheet provides you with a template that you can use to analyze the model results for the climate change run(s). You are free to extend this sheet to your preferences. Fill this sheet with your simulation results and try to answer the questions below:

1. How much is the annual basin average precipitation for my reference climate and future climate?
2. Make a graph with the monthly basin average precipitation for my reference climate and future climate;
3. Do the same for one particular sub-basin;
4. Which sub-basin experiences the largest increase in annual precipitation, and which sub-basin experiences the largest decrease in annual precipitation?
5. How much is the annual basin average actual evapotranspiration for my reference climate and future climate?
6. Make a graph with the monthly basin average actual evapotranspiration for my reference climate and future climate;
7. Do the same for one particular sub-basin;
8. Which sub-basin experiences the largest increase in annual actual evapotranspiration, and which sub-basin experiences the largest decrease in annual actual evapotranspiration?
9. How much is the annual basin average discharge for my reference climate and future climate?
10. Make a graph with the monthly basin average discharge for my reference climate and future climate;
11. Do the same for one particular sub-basin;

12. Which sub-basin experiences the largest increase in annual discharge, and which sub-basin experiences the largest decrease in annual discharge?
13. Make a water balance.
14. What can you say about extremes in terms of very high discharge or days with low discharge?
15. What would be your advice towards policy makers? Try to write one page (A4) with your main findings. What are the positive and negative effects of climate change?

5.2 Land use change

Due to socio-economic developments (e.g. population increase) in particular areas of your river basin, the use of land in these areas will change. Population increase for example requires the transformation of rural land into urban areas to build houses on. Because of population increase it is possible that 5% of the forested areas will turn into urban areas. The hydrological impact of this could be less surface infiltration, more surface runoff, and a reduction of the actual evapotranspiration. Another scenario could be the development of irrigated agriculture on locations where bare soil is the current land use. This will likely result in more evapotranspiration and reduced groundwater recharge. Another scenario could be the development of bench terraces to reduce erosion and surface runoff, and to increase surface infiltration.

Figure 20: Example of land use change where forest is removed.

For the purpose of this case study 3 land use scenarios have been developed:
1. All forest in your basin will be transformed into grass lands;
2. All bare soil in your basin will be transformed into irrigated agriculture;
3. Implementation of bench terraces.

All these cases use the *land_use_change.xlsx* file from the *Applications\land_use_change* folder. Each of the cases can be analyzed in a separate work sheet.

Figure 21: Bench terraces to reduce erosion and surface runoff, and to increase surface infiltration.

5.2.1 Forest to grass

This scenario assumes that all the forest in your river basin will be transformed into grass lands. In order to achieve this you need to follow the steps below:

1. Open your land use map in QGIS;
2. Check the land use class number(s) belonging to forest;
3. Check the land use class number belonging to the grass land use class;
4. Open a cmd prompt and go to the directory that contains your land use map;
5. Type ***pcrcalc x1.map = if(x2.map == y1, y2, x2.map)*** and hit enter. This command searches for the land use class belonging to forest, and assigns a new land use class number to it belonging to grass;

    With   x1 = name for new land use map;
                   x2 = name of original land use map;
                   y1 = land use class number belonging to forest;
                   y2 = land use class number belonging to grass.

6. Repeat step 5 for each forest type of land use class;
7. A change of land use may also affect the root depth of your soil. Grass has a shallower root depth compared to forest. Therefore we also need to change the thickness of the rootzone soil layer for locations where forest has been transformed into grass. This can be achieved by opening a cmd prompt and type:

    pcrcalc x1.map = if(x2.map == y1, y2, x3.map)
            With   x1 = name for new rootzone depth map;
                         x2 = name of original land use map;
                         y1 = land use class number belonging to forest;
                         y2 = rootzone depth for grass;
                         x3 = original rootzone depth map
    .

8. Repeat step 5 for each forest type of land use class;
9. Use the SPHY model GUI to start a new project, or open an existing project and save it under a different name;
10. Use the **Land use** tab from the SPHY model GUI (Figure 22) to select the new land use map;
11. Use the **Soils** tab from the SPHY model GUI (Figure 23) to select the new rootzone layer thickness map;
12. Check the reporting options in the ***Report options*** tab to select the model output to be reported;
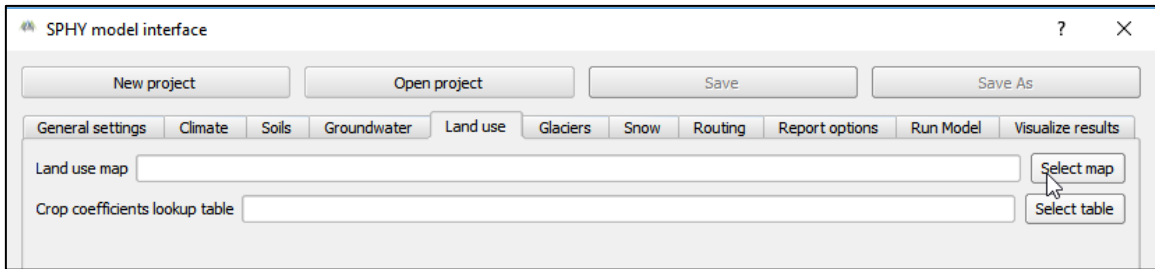13. Run the model;

14. Analyze the results.

Figure 22: Selecting a land use map using the Land use tab from the SPHY model GUI.
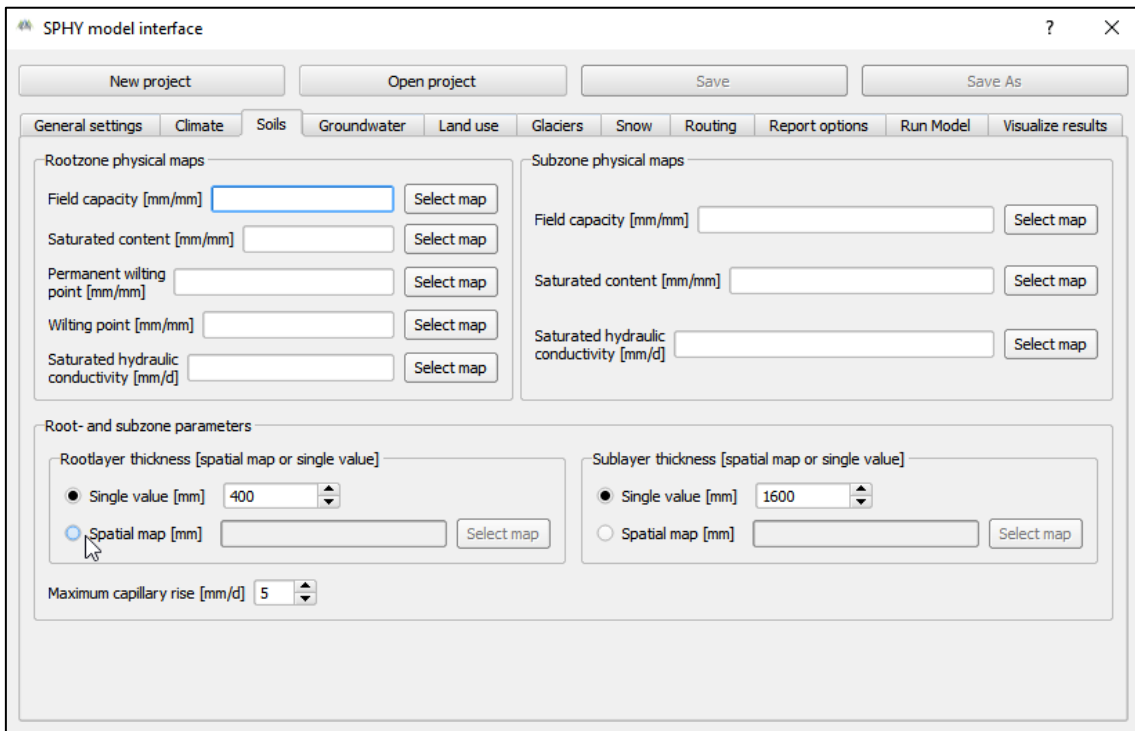

Figure 23: Selecting a new rootzone layer thickness map using the Soils tab from the SPHY model GUI.

Now open *land_use_change.xlsx* and go to the *forest to grass* work sheet. This sheet provides you with a template that you can use to analyze the model results for this land use change simulation. You are free to extend this sheet to your preferences. Fill this sheet with your simulation results and try to answer the questions below:

1. How much is the annual basin average actual evapotranspiration for my reference situation (forest) and land use change situation (forest to grass)?
2. Make a graph with the monthly basin average actual evapotranspiration for my reference situation and land use change situation;
3. Do the same for one sub-basin where a substantial area has been transformed from forest to grass;
4. How much is the annual basin average discharge for my reference situation (forest) and land use change situation (forest to grass)?
5. Make a graph with the monthly basin average discharge for my reference situation and land use change situation;
6. Do the same for one sub-basin where a substantial area has been transformed from forest to grass;

7. Analyze and show spatial maps of:
    a. Actual evapotranspiration
    b. Surface runoff
    c. Rootzone percolation
    d. Rootzone drainage
    e. Groundwater recharge
    f. Total runoff

    Analyze and show these maps for both the reference and land use change simulation;
8. Make a water balance;
9. If this land use change scenario would be part of a development plan, what would then be your advice towards policy makers? Try to write one page (A4) with your main findings, and provide arguments why this land use change is a positive or negative development.

5.2.2 Bare soil to irrigated agriculture

This scenario assumes that all bare soil in your river basin will be transformed into irrigated agriculture. If sufficient irrigation water is available, and other resources (e.g. nutrients) are not limited, then evapotranspiration from irrigated areas will be at the potential rate. Practically this means that we need to adjust the crop factor (Kc) for bare soil areas into a crop factor for irrigated agriculture. You can use *fao56.pdf* to search for suitable crop factors for irrigated agriculture.

Figure 24: Irrigated agriculture using a gated pipe supply system.

The current version of the SPHY model does not contain an irrigation module. This means that no irrigation water is supplied, and that the actual evapotranspiration rate is lower than the potential evapotranspiration rate due to water shortage. Implementing an irrigation module in SPHY is currently an ongoing model development. For the purpose of this training we therefore only change the crop factor. A robust approach to include irrigation water supply would be to add X mm of irrigation water to the precipitation input map-series, assuming that irrigation water comes from an external source outside your river basin.

Follow the steps below to change bare soil into irrigated agriculture:
1. Open your land use map in QGIS;
2. Check the land use class number belonging to bare soil;
3. Use fao56.pdf to find a suitable crop factor for irrigated agriculture;
4. Open the crop factor table (e.g. kc.tbl) with a text editor (Figure 25);
5. Change the crop factor of the bare soil land use class into the crop factor belonging to irrigated agriculture;

6. Use the SPHY model GUI to start a new project, or open an existing project and save it under a different name;
7. Use the **Land use** tab from the SPHY model GUI (Figure 22) to select your crop coefficient lookup table;
8. Check the reporting options in the **Report options** tab to select the model output to be reported;
9. Run the model;
10. Analyze the results.

```
kc.tbl
 1   14   0.6
 2   20   0.6
 3   30   0.6
 4   40   0.6
 5   50   0.5
 6   60   0.4
 7   90   0.6
 8   100  0.6
 9   110  0.6
10   120  0.6
11   130  0.5
12   140  0.5
13   150  0.4
14   180  0.6
15   190  0.2
16   200  0.2
17   210  0.5
18   220  0.2
```

Figure 25: Crop factor table (kc.tbl).

Now open **land_use_change.xlsx** and go to the **bare soil to irr. agriculture** work sheet. This sheet provides you with a template that you can use to analyze the model results for this land use change simulation. You are free to extend this sheet to your preferences. Fill this sheet with your simulation results and try to answer the questions below:

1. How much is the annual basin average actual evapotranspiration for my reference situation (bare soil) and land use change situation (irrigated agriculture)?
2. Make a graph with the monthly basin average actual evapotranspiration for my reference situation and land use change situation;
3. Do the same for one sub-basin where a substantial area has been transformed from bare soil to irrigated agriculture;
4. How much is the annual basin average discharge for my reference situation (bare soil) and land use change situation (irrigated agriculture)?
5. Make a graph with the monthly basin average discharge for my reference situation and land use change situation;
6. Do the same for one sub-basin where a substantial area has been transformed from bare soil to irrigated agriculture;
7. Analyze and show spatial maps of:
   a. Potential evapotranspiration
   b. Actual evapotranspiration
   c. Surface runoff
   d. Rootzone percolation
   e. Rootzone drainage
   f. Groundwater recharge
   g. Total runoff
   Analyze and show these maps for both the reference and land use change simulation;
8. Make a water balance;

9. If this land use change scenario would be part of a development plan, what would then be your advice towards policy makers? Try to write one page (A4) with your main findings, and provide arguments why this land use change is a positive or negative development.

5.2.3   Implementation of bench terraces

It turns out that erosion in your basin is a serious issue resulting in sedimentation of rivers and reservoirs, and loss of valuable agricultural land. In order to prevent this we think that the development of bench terraces will substantially i) reduce the amount of surface runoff, ii) increase infiltration, iii) increase groundwater recharge, and iv) increase the actual evapotranspiration. These effects are beneficial for both reservoir operators (more storage capacity) as well as farmers (increased crop yields). More details about bench terraces can be found at the FAO: http://www.fao.org/docrep/006/ad083e/AD083e07.htm.

An approach to analyze the bench terraces scenario with the SPHY model would be to reduce the slope of these areas. For this case-study we assume that the areas where bench terraces will be implemented will have a maximum slope of 1%. In order to implement this in SPHY we need to adjust the slope map:
1. Open the slope map in QGIS;
2. Open annual precipitation maps in QGIS, as simulated by the SPHY model;
3. Justify for yourself in which areas the development of bench terraces would have the most effect (steep slopes, high annual precipitation);
4. Change the slope in these areas to 1%:
    Hint: use a combination of PCRaster commands in the cmd promt to select the areas with steep slopes AND high annual precipitation. Check step 5 and 7 from Section 5.2.1.
5. Use the SPHY model GUI to start a new project, or open an existing project and save it under a different name;
6. Use the **General settings** tab from the SPHY model GUI (Figure 26) to change the slope map;
7. Check the reporting options in the *Report options* tab to select the model output to be reported;
8. Run the model;
9. Analyze the results.
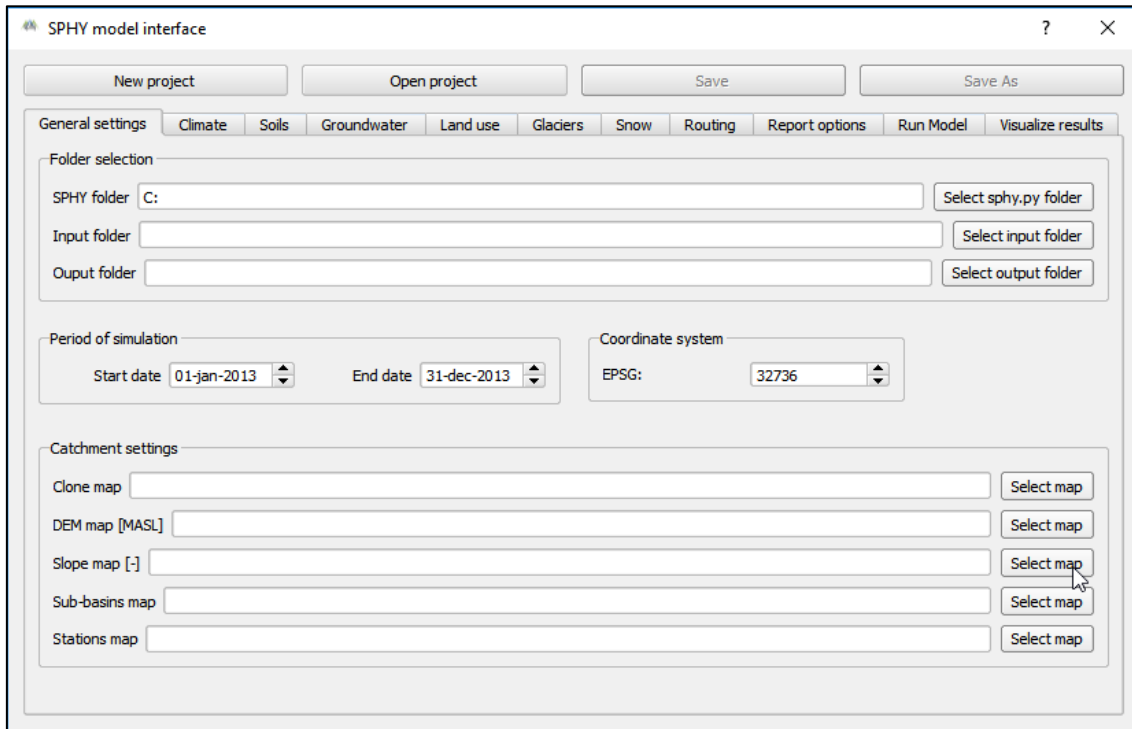
Figure 26: Changing the slope map in the SPHY model GUI.

Now open *land_use_change.xlsx* and go to the **bench terraces** work sheet. This sheet provides you with a template that you can use to analyze the model results for this land use change simulation. You are free to extend this sheet to your preferences. Fill this sheet with your simulation results and try to answer the questions below:

1. How much is the annual basin average actual evapotranspiration for my reference situation (no bench terraces) and land use change situation (bench terraces)?
2. Make a graph with the monthly basin average actual evapotranspiration for my reference situation and land use change situation;
3. Do the same for one sub-basin where a substantial area has been transformed into bench terraces;
4. How much is the annual basin average discharge for my reference situation (no bench terraces) and land use change situation (bench terraces)?
5. Make a graph with the monthly basin average discharge for my reference situation and land use change situation;
6. Do the same for one sub-basin where a substantial area has been transformed into bench terraces;
7. Analyze and show spatial maps of:
    a. Actual evapotranspiration
    b. Surface runoff
    c. Rootzone percolation
    d. Rootzone drainage
    e. Groundwater recharge
    f. Total runoff
    Analyze and show these maps for both the reference and land use change simulation;
8. Make a water balance;
9. If this land use change scenario would be part of a development plan, what would then be your advice towards policy makers? Try to write one page (A4) with your main

findings, and provide arguments why this land use change is a positive or negative development.

5.3 Forecasting

Besides strategic decision support for water resource planning, SPHY can also support short-term management decisions such as flood mitigation measures. In combination with a weather forecast for the coming 7-10 days you can use SPHY to simulate the expected discharge for the coming days. With this information you can check whether these discharges approach critical levels leading to floods.

If you plan to use SPHY in operational mode for forecasting river discharge it is relevant that you have calibrated the SPHY model on daily basis for locations that are prone to flooding. For weather forecasts it is best to rely on the forecasts provided by the meteorological service in your country. If they do not provide these forecasts, then you can download weather forecasts for stations from the Weather Underground web portal: https://www.wunderground.com/. An overview of this portal is shown in Figure 27.
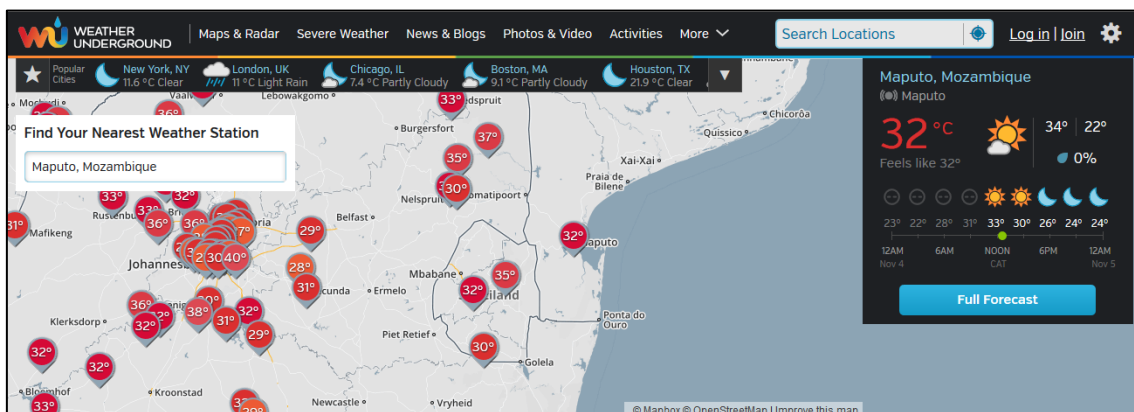

Figure 27: Weather Underground web portal for obtaining weather forecasts.

For this case-study it is required that you have access to meteorological forecasts from i) your meteorological service, or ii) Weather Underground, or iii) create some "dummy" values for a 7-day forecast.

As operational water manager your task for this case-study is to guarantee the safety of people living near flood prone areas in your river basin. In order to achieve this you are going to use the SPHY model to forecast river discharge for the coming 7 days for these critical locations. The start date of your forecasts will be the date of today. This means that you need to have a historical SPHY model run with simulations up to yesterday. This is required in order to have correct values for the initial conditions (rootzone content, subzone content, groundwater content, and river discharge). You also need to prepare spatial input maps with forecasted precipitation, and average, maximum, and minimum temperature. Follow the steps below to provide a forecast of river discharge for the coming 7 days, and if necessary, a flood-early-warning to the people living in flood-prone areas:

1. Run the SPHY model for a period of at least 2 years with yesterday as last simulation day. For this it is required that you have a calibrated SPHY model and that you have prepared meteorological input maps for this period for precipitation, and the average, maximum, and minimum temperature. These input maps can be prepared using the SPHY model preprocessor in combination with your observed station data;

2. Check if the files below can be found in the model output folder:
    a. RootWater_end.map
    b. SubWater_end.map
    c. GW_end.map
    d. Q_end.map
3. Setup a new SPHY model project and structure, or open an existing one and save it under a useful name;
4. Change the **Period of simulation** in the **General settings** tab of the SPHY model GUI. Set the start date to today's date, and the end date to 6 days from today;
5. Change the **Output folder** in the **General settings** tab of the SPHY model GUI to a folder where you want to save your forecasts;
6. If required, then change the **Stations map** in the **General settings** tab of the SPHY model GUI to match the locations for which you want to provide forecasts;
7. Change the **Initial groundwater storage** map in the **Groundwater** tab of the SPHY model GUI (Figure 28) to **GW_end.map** (resulting groundwater content of historic run);
8. Change the **initial routed total runoff** map in the **Routing** tab of the SPHY model GUI (Figure 29) to **Q_end.map** (last routed river discharge historic run);
9. Save your changes and close the SPHY model GUI;
10. Open the SPHY model configuration file with a text editor (e.g. notepad);
11. Set the maps for the initial rootwater and subwater content to **RootWater_end.map** and **SubWater_end.map**, respectively (Figure 30). Save your edits and close this file;
12. Open the SPHY model GUI;
13. Check the reporting options in the **Report options** tab to select the model output to be reported;
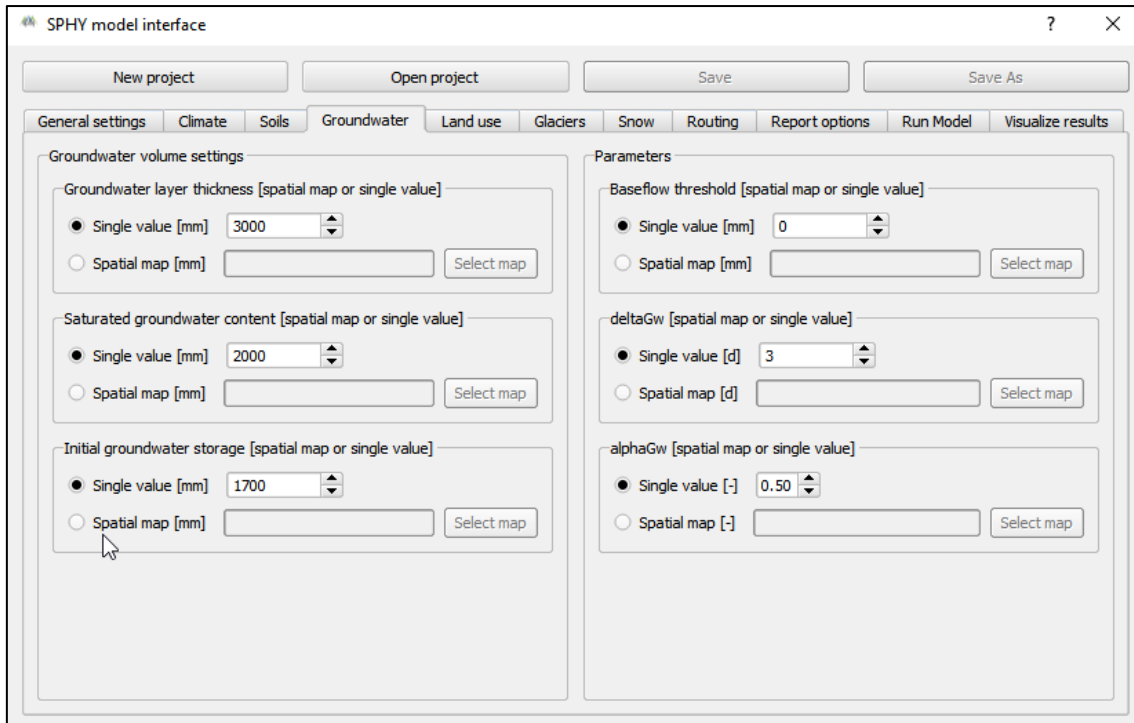14. Run the model;
15. Analyze the results.

Figure 28: Changing the initial groundwater storage in the SPHY model GUI.
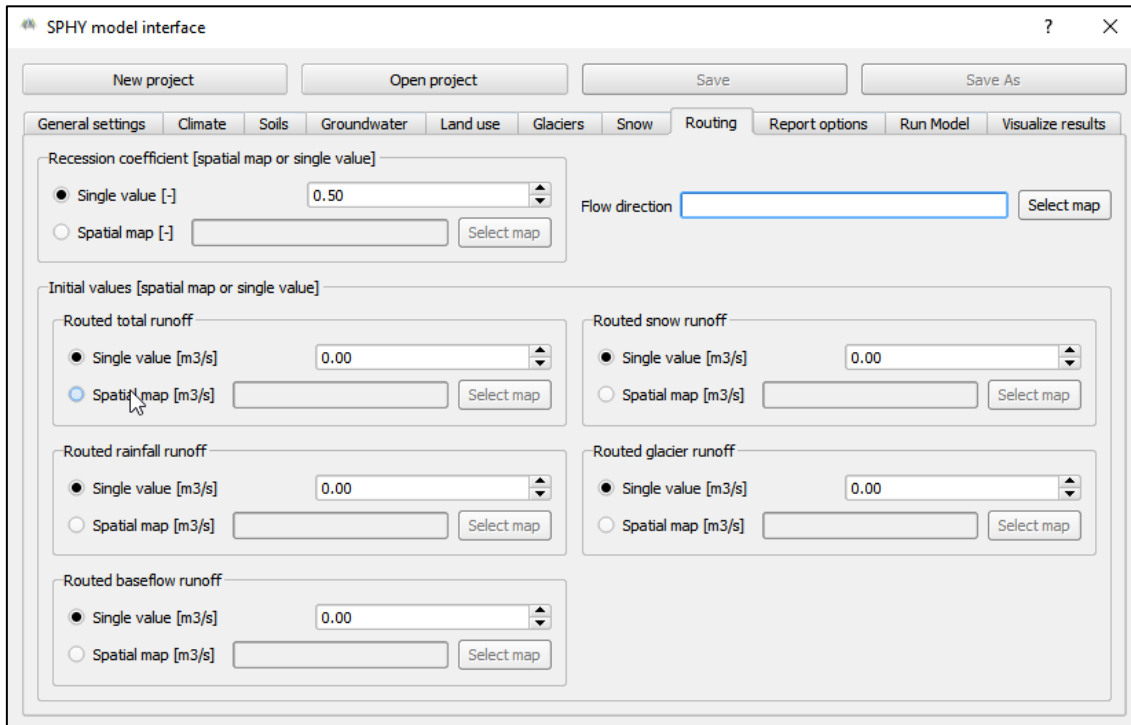
Figure 29: Changing the initial routed total runoff in the SPHY model GUI.

```
[SOIL_INIT]

# INITIAL ROOTWATER CONTENT (initial rootwater content (mm), if no value is supplied,
# then RootWater=field capacity rootzone). Can be map or single value.
RootWater       =
# INITIAL SUBSOIL WATER CONTENT (initial water content in subsoil (mm), if no value is supplied,
# then SubWater=field capacity subsoil). Can be map or single value.
SubWater        =
# INITIAL CAPILLARY RISE (initial capillary rise (mm). Can be map or single value.
CapRise         = 3
# INITIAL DRAINAGE ROOTZONE (initial drainage from rootzone (mm)). Can be map or single value.
RootDrain       = 3
# INITIAL DRAINAGE SUBSOIL (initial drainage from the subsoil (mm)). Can be map or single value.
# This can be left empty if the groundwater module is used, because then recharge to the gw will
# be calculated instead.
SubDrain        = 3
```

Figure 30: Changing the initial maps for RootWater and SubWater in the SOIL_INIT section of the SPHY model *.cfg file.

Now open *forecasting.xlsx* in the *Applications\forecasting* folder and go to the *Forecasting* work sheet. This sheet provides you with a template that you can use to analyze the forecasted discharge and provide an early warning if necessary. The template contains fields for 3 stations, which can be extended to include more stations. Copy the simulated discharge for each station in the table in the top left corner. If you have Q(h)-relations, then you can use them to calculate corresponding water levels for each station. Fill in critical discharge and water level values for each station (columns N and O) that normally lead to flooding. The Flood-Early-Warning table checks if the critical threshold for discharge or water level will be exceeded, and turns to a red cell if these levels become critical (Figure 31). Complete the tasks/questions below:

1. Check if a Flood-Early-Warning should be provided for the coming few days and do so accordingly.

2. How could you decrease the uncertainty of your forecasted discharge and thus increase the accuracy of your Flood-Early-Warning report?

Flood-Early-Warning			
Date	Station 1	Station 2	Station 3
4-11-2016	1	1	1
5-11-2016	0	1	1
6-11-2016	0	1	1
7-11-2016	0	1	1
8-11-2016	0	1	1
9-11-2016	0	1	1
10-11-2016	0	1	1

Figure 31: Example of Flood-Early-Warning table with red cells being days where the discharge or water levels are critical.

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