

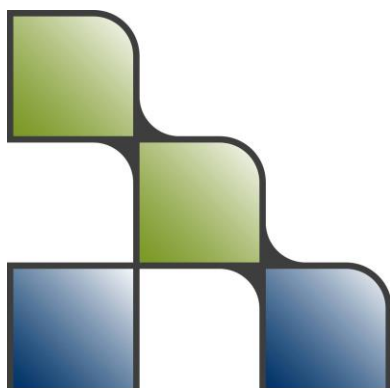
Reservoir module in SPHY

Implemented in SPHY v2.1

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1 Introduction

The Spatial Processes in HYdrology (SPHY) model is a state-of-the-art, easy to use, robust tool, that can be applied for operational as well as strategic decision support. The model has been successfully applied in several studies, including i) real-time soil moisture predictions to support irrigation management in lowland areas, ii) detailed climate change impact studies in snow and glacier-fed river basins, and iii) operational flow forecasting in mountainous catchments. SPHY has been developed by combining the best components of existing and well tested simulation models: HydroS (Droogers and Immerzeel, 2010), SWAT (Neitsch et al., 2009), PCR-GLOBWB (Sperna Weiland et al., 2012), SWAP (van Dam et al., 1997) and HimSim (Immerzeel et al., 2011). SPHY was developed with the explicit aim to simulate terrestrial hydrology at flexible scales, under various land use and climate conditions. SPHY is a spatially distributed leaky bucket type of model, and is applied on a cell-by-cell basis. The model is written in the Python programming language using the PCRaster (Karssenberget al., 2001; Karssenberget al., 2002; Karssenberget al., 2010) dynamic modelling framework. The model is available free-of-charge, and can be downloaded from the SPHY model website¹ or from GitHub².

Although most dominant hydrological processes were integrated in SPHY v2.0, the model was not yet capable of simulating reservoir inflow and outflow. A recent project in Vietnam focused on the simulation of reservoir inflow and outflow for several reservoirs that are located in the Red River Basin, using the SPHY model. Since SPHY v2.0 did not include the simulation of reservoir inflow and outflow, we have developed a reservoir module for the SPHY model. This module has been implemented in the most recent version of SPHY (v2.1). The objective of this report is therefore to introduce and describe the main features of the reservoir module. This report can be seen as an extension of the SPHY v2.0 user manual (Terink et al., 2014).

¹ <http://www.sphy-model.org/>

² <https://github.com/FutureWater/SPHY.git>



2 Concepts reservoir module

2.1 General

Depending on the availability and quality of reservoir data, the user has two options for simulating reservoir in- and outflow in the SPHY model, being i) a simple reservoir scheme, and ii) a more advanced reservoir scheme. The advanced reservoir scheme focuses on a target release, while the simple scheme calculates the outflow based on the actual and maximum reservoir storage. The reservoir schemes can be specified for each individual reservoir, meaning that simple and advanced reservoirs can exist independently from each other. The concepts of these schemes are described in the following two sections.

2.2 Simple reservoir scheme

Many studies have implemented reservoir operation schemes into large-scale hydrological models. Meigh et al. (1999) for example used a grid-based model and incorporated reservoir outflow using the following assumptions. For outflow regulation reservoirs, the outflow (Q_{out}) was proportional to the current storage (S_{act}) raised to the power of 1.5. For water storage reservoirs, any water released was used to meet demands and once the reservoir was filled, the outflow equaled the amount spilled (Hanasaki et al., 2006). A study by Döll et al. (2003) accounted for reservoir flow regulation (Hanasaki et al., 2006), and modified the equation of Meigh et al. (1999) to:

$$Q_{out} = k_r * S_{act} * \left(\frac{S_{act}}{S_{max}} \right)^{1.5}$$

with:

Q_{out}	=	reservoir outflow [m^3/d]
k_r	=	outflow coefficient [d^{-1}]
S_{act}	=	actual reservoir storage [m^3]
S_{max}	=	maximum reservoir storage [m^3]

This parametrization was developed for global lakes, but is also applied for reservoirs because of a lack of information on their management (Hanasaki et al., 2006). For this reason this reservoir outflow equation was implemented in the SPHY model, and is referred to as the simple reservoir scheme hereafter. The outflow coefficient (k_r) is generally used as a calibration parameter. An example of the reservoir inflow, outflow and storage is illustrated in Figure 1 for the simple reservoir scheme.



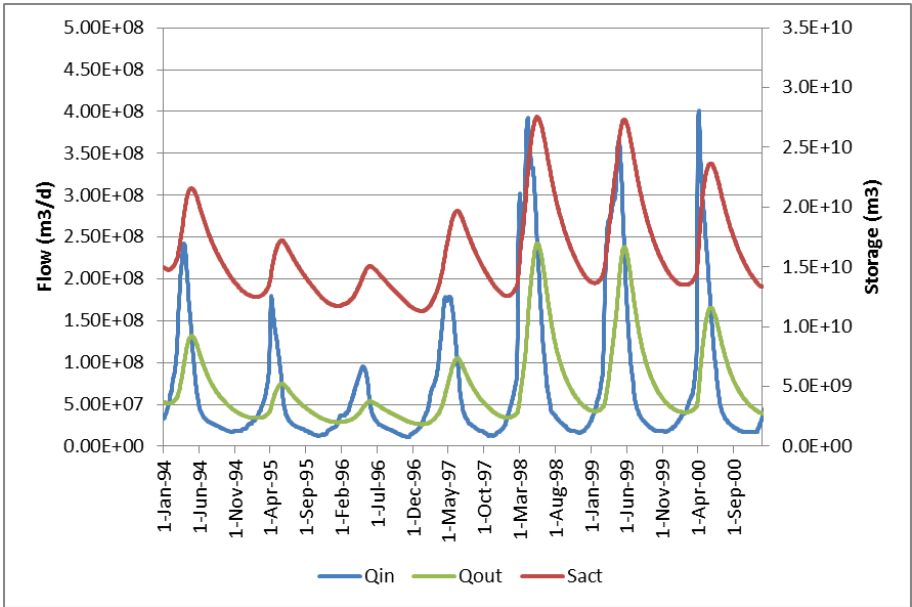


Figure 1: Example of reservoir inflow (Qin), outflow (Qout), and storage (Sact) as modelled by the simple reservoir scheme.

2.3 Advanced reservoir scheme

If reservoir management information is available, then it is recommended to use the advanced reservoir scheme. This scheme uses the same approach as is implemented in the SWAT model (Neitsch et al., 2009). Within the advanced reservoir scheme the user can define a target reservoir release volume, which is season dependent. The user can define two different seasons per year, being a flood and dry season respectively. The target releases that need to be defined are the MAX_FLOW (maximum flow) for the flood season, and the DEM_FLOW (demand flow) for the dry season.

In case of floods it is important to have a large storage capacity available. Therefore, the model tries to release the maximum amount of water from the reservoir during the flood season. The maximum amount of water that can be released depends on the user defined MAX_FLOW, the actual reservoir storage, and the maximum amount of water that is available between the emergency spillway and principal spillway. During the dry season, the model aims to keep the reservoir filled in order to have water available for its water users downstream. During this season, the reservoir outflow depends on the user defined DEM_FLOW (demand flow), the actual reservoir storage, and the maximum amount of water that is available between the emergency spillway and principal spillway. Reservoir outflow for both seasons is thus calculated as:

$$Q_{out} = F * \left(\frac{S_{act}}{RES_{evol} - RES_{pvol}} \right)$$

- with: Q_{out} = reservoir outflow [m^3/d]
- F = target release, being either MAX_FLOW or DEM_FLOW [m^3/d]
- S_{act} = actual reservoir storage [m^3]
- RES_{evol} = reservoir storage capacity at emergency spillway [m^3]
- RES_{pvol} = reservoir storage capacity at principal spillway [m^3]



An example of the reservoir inflow, outflow and storage is illustrated in Figure 2 for the advanced reservoir scheme.

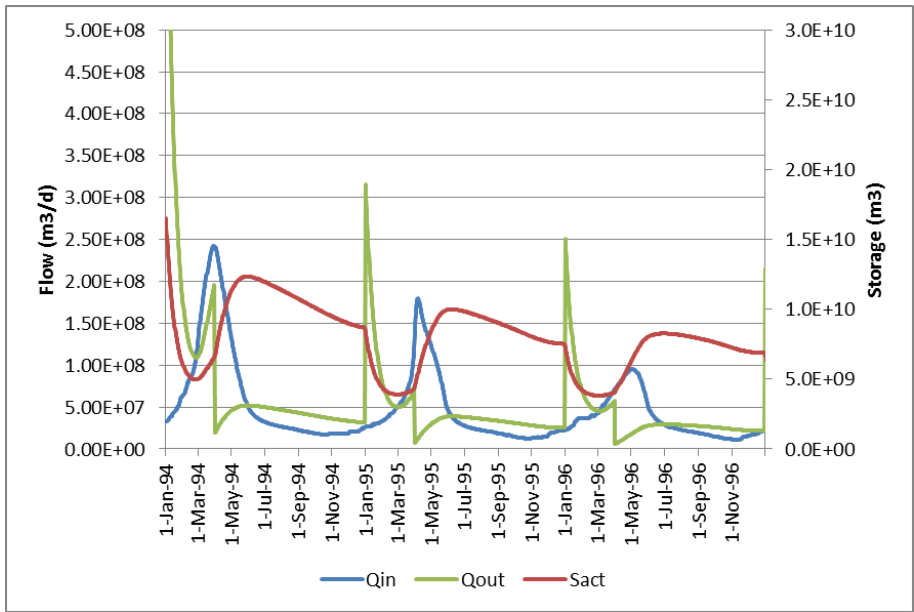


Figure 2: Example of reservoir inflow (Qin), outflow (Qout), and storage (Sact) as modelled by the advanced reservoir scheme.



3 SPHY model configuration

3.1 Input

In order to implement the reservoir module in SPHY, some changes have been made to the configuration file. First of all the user needs to turn on the reservoir module by setting the ResFLAG variable to 1 (Figure 3).

```
#####
# 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.
RoutFLAG = 1
# Lakes module. If lakes are located in your basin, and the Q(h)-relations are known,
# then this can be turned on to implement a more advanced routing scheme. If this module is
# turned on, then the routing module should be switched off.
LakeFLAG = 1
# Reservoirs module. This module can be used to model reservoir inflow, outflow, and storage. A
# simple or advanced reservoir operation schedule can be selected for each individual reservoir.
# If this module is turned on, then the routing module should be switched off.
ResFLAG = 1
# Dynamic vegetation module. This module allows to vary the crop factor (Kc) over the year. This
# can be done by using ndvi values, or by inserting a user defined kc time-series. If this
# module is not used, then the Kc will be constant for each crop.
DynVegFLAG = 0
```

Figure 3: Enabling the reservoir module in the SPHY configuration file.

After the reservoir module has been switched on, the user needs to define the reservoir map, tables and parameters (Figure 4). The following map and table are mandatory:

- Nominal map with unique values for each reservoir
- Reservoir scheme function and storage lookup table

If there are for example three reservoirs in the basin of interest, then the user needs to create a nominal map with 3 reservoir cells, having values from 1 to 3. For each of these reservoirs, the user needs to specify whether it should be modelled as a simple or advanced reservoir, and its initial storage volumes. These values are set in a lookup table file (*.tbl), which should be created by the user. In the example of Figure 5 two reservoirs are included for which reservoir 1 is modelled as a simple reservoir, and reservoir 2 is modelled as an advanced reservoir. Note that the SPHY configuration file only contains the format of how the lookup table should be created. The actual lookup table should be created as a separate file. The header should not be included in the lookup table, meaning that the first line should start with the -99 value.




```

*****
# Define reservoir maps and parameters. The RESERVOIR module only has to be filled in if
# this module is used. Otherwise it can be left empty.
*****

[RESERVOIR]

# RESERVOIR ID MAP. Nominal map with a unique id number specifying each reservoir in the basin. Zero values
# for non-reservoir cells
ResId = reservoir.map

# RESERVOIR FUNCTION AND STORAGE LOOKUP TABLE. Create a table file containing the reservoir function to be
# used (simple or advanced) and the initial storage volumes (Mm3) for each reservoir that can be found in
# the ResId map. Format should be as shown below. The first line should not be in the table file and
# the # marks should be removed:
# ID #Simple or advanced [1,2] #Stor_init [Mm3] #RainRA_init [Mm3] #SnowRA_init [Mm3] #GlacRA_init [Mm3] #BaseRA_init [Mm3]
# -99 1 2 3 4 5 6
# 1 1 value1 value2 etc etc etc
# 6 2 etc etc etc etc etc etc
ResFuncStor = res_id.tbl

# SIMPLE RESERVOIR PARAMETERS. Create a lookup table file containing the parameters to be used for the
# reservoirs that should be modeled as simple reservoir (Hanasaki et al (2006), which are defined in
# the table shown above. Format should be as shown below. The first line should not be in the table file and
# the # marks should be removed:
# ID #Kr #Smax [Mm3]
# -99 1 2
# 1 value1 value2
# etc etc etc
ResSimple = simple_reservoir.tbl

# ADVANCED RESERVOIR PARAMETERS. Create a lookup table file containing the parameters to be used for the
# reservoirs that should be modeled as advanced reservoirs, using a target release, which are defined in
# the table shown above. Format should be as shown below. The first line should not be in the table file and
# the # marks should be removed:
# ID #RES_EVOL [Mm3] #RES_PVOL [Mm3] #MAX_FLOW [Mm3/d] #DEM_FLOW [Mm3/d] #FLOOD_start [d] #FLOOD_end [d]
# -99 1 2 3 4 5 6
# 6 value1 value2 etc etc etc etc etc
ResAdv = advanced_reservoir.tbl

```

Figure 4: Setting the reservoir map, tables and parameters.

```

# RESERVOIR FUNCTION AND STORAGE LOOKUP TABLE. Create a table file containing the reservoir function to be
# used (simple or advanced) and the initial storage volumes (Mm3) for each reservoir that can be found in
# the ResId map. Format should be as shown below. The first line should not be in the table file and
# the # marks should be removed:
# ID #Simple or advanced [1,2] #Stor_init [Mm3] #RainRA_init [Mm3] #SnowRA_init [Mm3] #GlacRA_init [Mm3] #BaseRA_init [Mm3]
# -99 1 2 3 4 5 6
# 1 1 value1 value2 etc etc etc
# 2 2 etc etc etc etc etc etc

```

Figure 5: Creating the reservoir function and storage lookup table.

Depending of what type of reservoirs should be modelled (simple or advanced), the next step is to complete the parameter sections about the simple and/or advanced reservoirs. The corresponding simple or advanced reservoir section only needs to be completed if these types of reservoirs are present in the basin of interest.

For the simple reservoirs the user needs to create a lookup table containing the reservoir ID, the outflow coefficient (k_r), and the maximum reservoir storage (S_{max}). The format of this table is shown in Figure 6. Again the header should be ignored in the creation of this table, meaning that the table should start with the value -99.

```

# ID #Kr #Smax [Mm3]
# -99 1 2
# 1 value1 value2
# etc etc etc

```

Figure 6: Creating the simple reservoir parameters lookup table.

For the advanced reservoirs the user needs to create a lookup table containing the reservoir ID, the reservoir storage capacity at the emergency spillway (RES_{evol}), the reservoir storage capacity at the principal spillway (RES_{pvol}), the target release during the flood season (MAX_FLOW), the target release during the dry season (DEM_FLOW), and the start



(FLOOD_start) and end day (FLOOD_end) of the flood season. For the latter two, the user needs to specify a day number in the year [1-365]. The format of this table is shown in Figure 7. Again the header should be ignored in the creation of this table, meaning that the table should start with the value -99.

# ID	#RES_EVOL [Mm3]	#RES_PVOL [Mm3]	#MAX_FLOW [Mm3/d]	#DEM_FLOW [Mm3/d]	#FLOOD_start [d]	#FLOOD_end [d]
# -99	1	2	3	4	5	6
# 2	value1	value2	etc	etc	etc	etc

Figure 7: Creating the advanced reservoir parameters lookup table.

3.2 Output

The reporting options as shown in Figure 8 have been added to the configuration file to allow the reporting of lake and reservoir water balances. With flags (1=Yes, 0=No) the user can specify whether the SPHY model needs to write the reservoir inflow, outflow, and storage as output. Additionally, also the entire basin storage (for each cell) can be written as output, which may be a useful option if the final output is needed as initial condition for a new model run.

```
##### ONLY FOR LAKE AND/OR RESERVOIR MODULE #####
# FLAG TO REPORT LAKE WATER BALANCE (inflow, outflow, and storage) (1=Y, 0=N)
Lake_wbal = 1
# FLAG TO REPORT RESERVOIR WATER BALANCE (inflow, outflow, and storage) (1=Y, 0=N)
Res_wbal = 1
# REPORT TOTAL STORAGE (only D or F options are logical)
TotStor_mapoutput = D
TotStor_TSoutput = NONE
TotStor_fname = TotS
# REPORT STORAGE FROM RAINFALL (only D or F options are logical)
RainStor_mapoutput = D
RainStor_TSoutput = NONE
RainStor_fname = RainS
# REPORT STORAGE FROM SNOW RUNOFF (only D or F options are logical)
SnowStor_mapoutput = D
SnowStor_TSoutput = NONE
SnowStor_fname = SnowS
# REPORT STORAGE FROM GLACIER RUNOFF (only D or F options are logical)
GlacStor_mapoutput = D
GlacStor_TSoutput = NONE
GlacStor_fname = GlacS
# REPORT STORAGE FROM BASEFLOW RUNOFF (only D or F options are logical)
BaseStor_mapoutput = D
BaseStor_TSoutput = NONE
BaseStor_fname = BaseS
#####
```

Figure 8: Define output options for the reservoir module.



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