Rivers and lakes

Basic assumptions

The HYPE model can contain two types of rivers, local stream and main river, and two types of lakes, local lakes and outlet lakes (Figure 1). Local and main rivers are present in all subbasins and the length of each is calculated as the square root of the subbasin area. The length of the watercourses can be given as input. The river can be a SLC class and is then given an area, but rivers can also be one-dimensional (i.e. no fraction of the subbasin area are occupied by the river and no precipitation added to the river). All local runoff is entering the local river. Local lakes (ilake) receive a portion of the local runoff. The flow leaving the local river (including flow from local lake) goes to the main river of the same subbasin. If there are upstream subbasins their flow is added to the local flow when both flows flow into the main river. Outlet lakes (olake) receive the outflow from the main river, i.e. all upstream and local flows.

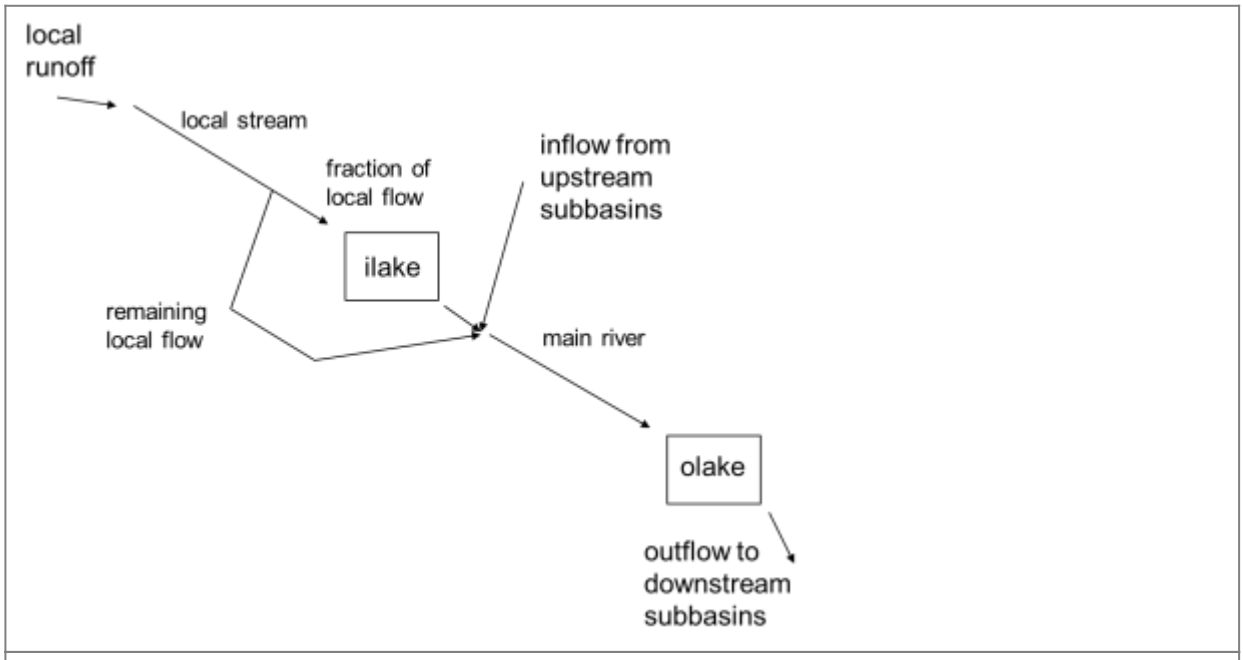


Figure 1: Schematic representation of streams and lakes i HYPE, and the link between them.

The two lake types are separate classes. The lake classes have characteristics such as land use and soil type, which are defined together with the other classes' characteristics (in GeoClass.txt). Precipitation, atmospheric deposition and evaporation of rivers and lakes are calculated first, while river flow and inflow, transformation processes and the outflow of the lakes is calculated thereafter. Lakes and rivers are calculated in the model's routing part after all classes are calculated for the subbasin.

An outlet lake can be part of a larger lake. It is then called a lake basin. Lake basins are olakes in nearby subbasins. Outlet lakes that are not lake basins are referred to below as simple outlet lakes.

A simple outlet lake has a threshold. The outflow ends if the water level drops below the threshold. Lake mean depth below the threshold is specified in GeoData.txt or LakeData.txt as *lake_depth* in meters. Lake depth can also be set by parameters, i.e general parameter *gldepo* or olake region parameter *olldepth*. The threshold is also the the water level of the lake at the start of a simulation. The current water level is denoted as *wlm* in Fig. 2. For printing, the outlet lake water level (output

variable *wcom*) is calculated in meters and you can set a reference level (*w0ref*) in LakeData.txt to get the same height system as any observations of the lake's water level. The lake's *w0ref* is added to the water level above the threshold. HYPE assumes the lake has vertical sides in the calculations, thus the observed variation may be larger than the simulated variation. It is therefore possible to adjust the output *wcom* for the actual amplitude of the regulation volume (*wamp*). This will make the simulated and recorded water stage comparable below the threshold for a regulated lake.

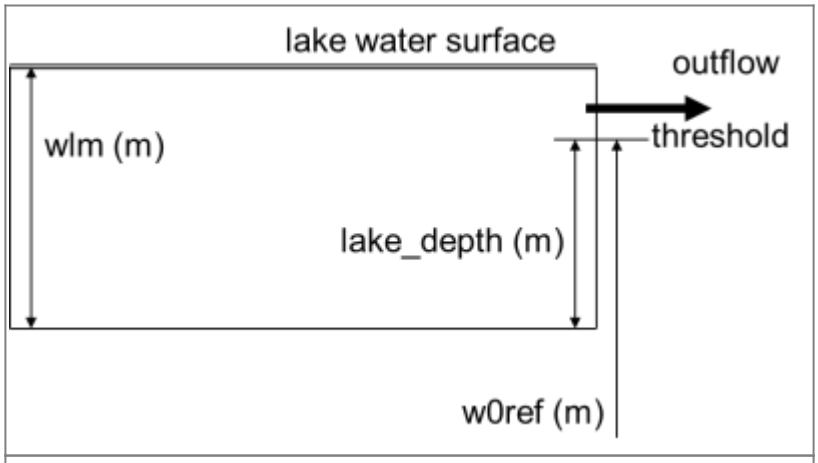


Figure 2: An outlet lake with some variables.

A local lake also has a threshold depth that is used as start value. The depth is given by general parameter *gldepi* and is then the same for all the local lakes, or by ilake region parameter *illdepth*. It is measured in meters. A percentage of flow from the local stream flows into the local lake. The rest of the local flow runs directly to main river watercourse.

Using parameters, you can divide the lake into two parts, one with faster flows (FLP) and one with slower flows (SLP) (Figure 3). This function is used for the simulation of nutrients to simulate stratification, strangulation or other phenomena that may limit the mixing of a lake. With this feature, the flows through the lake follow the schedule below. The split is determined by the parameter *deeplake*, which is the fraction of the lake's initial volume SLP, the remaining (varying) volume in the lake is the FLP. The parameter *fastlake* determines where the outflow will be coming from. Default is that outflow is taken from the slow lake part. Increasing *fastlake* will let the FLP contribute to outflow. *Fastlake* equal to one gives the maximum contribution of FLP, and the outflow will be taken proportionally from the two lake parts according to their volume.

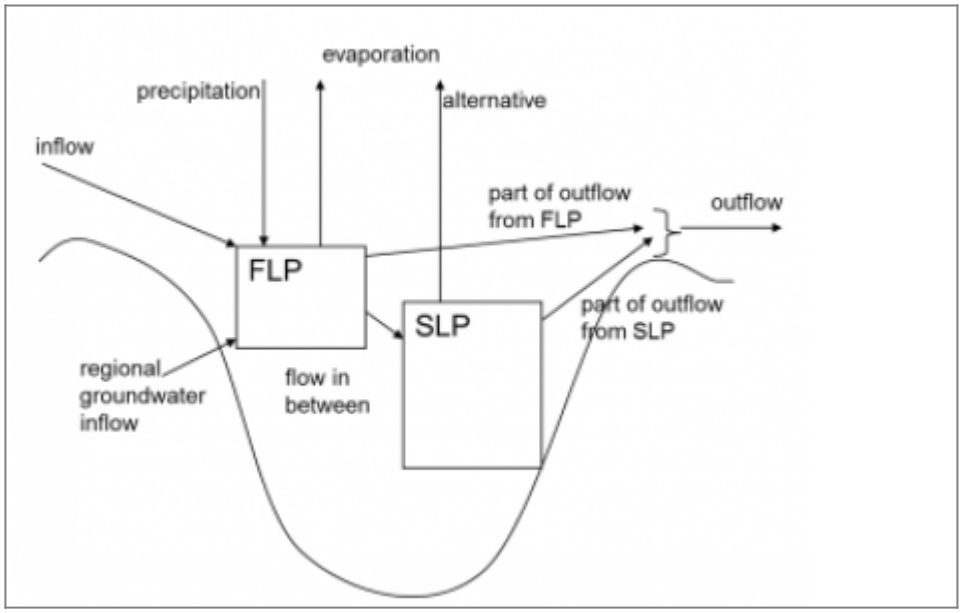


Figure 3: Division of a lake in two parts and water flows regarding lake.

The streams may have a delay and an attenuation of the flow. The former shifts the peaks, but leaves them otherwise untouched, while the attenuation both delays and smooths out peaks. The streams have a dead volume in which the residence time of solutes is increased relative to the water and the concentration smoothed out further over time.

Links to relevant modules in the code

Modules (file)	Procedures
modelmodule (model_hype.f90)	initiate_model_state
	initiate_model
surfacewater_processes (sw_proc.f90)	calculate_landarea_riverlength
	calculate_outflow_from_outlet_lake
	remove_outflow_from_lake
	calculate_flow_within_lake
	calculate_branched_flow
npc_surfacewater_processes (npc_sw_proc.f90)	set_lake_slowwater_maxvolume

Rivers

Common rivers processes

Precipitation

Daily precipitation is added to the river if it has an area (is a class) and a new concentration is calculated. Precipitation is divided between river water in damping box and queue according to the respective volumes.

Evaporation

If the river has an area (is a class), it evaporates and a new concentration is calculated. Normally the river area is constant over time, but with parameters can a reduction of riverarea be simulated for low volume/flow. The reduced river area is also used for heat exchange calculations.

$$frac_{area} = \begin{cases} 0 & x \leqslant 0 \\ \left(1 + \frac{\left(x - fraxe\right)}{\left(fraxe - fraxm\right)}\right) \times \left(\frac{x}{fraxe}\right)^{\frac{x}{\left(x - fraxm\right)}} & 0 < x < fraxe \\ 1 & x \geqslant fraxe \end{cases}$$

The parameters *fraxe* and *fraxm* are general, and *fraxe* is (minimum) mean river depth (m) where fractional river area = 1 and *fraxm* is mean river depth (m) where the slope of the fractional river area has its maximum (must be in the range between 0 and *fraxe*).

Pure delay

The delay in the watercourse (*transtime*) in days is determined by the length of the watercourse (*rivlen*) and the water's maximum velocity (*rivvel*). The maximum velocity is a general parameter with unit *m/s*. The delay in the local river is dependent on subbasin size, as stream length calculated from its area. The delay is a pure translation. The delay is divided into whole days (*ttday*) and parts of the day (*ttpart*).

$$transtime = \frac{rivlen}{rivvel \times 8.64 \times 10^4}$$

$$ttday = INT\left(transtime\right)$$

$$ttpart = transtime - REAL\left(ttday\right)$$

The inflow of the river is stored in two arrays (*riverq* and *riverc*) until it is time for it to flow out of the river stretch. The outflow is weighted by using the parts of the time step (*ttpart*) that are to flow out during the time step.

```
transq = (1-ttpart)*riverq(ttday) + ttpart*riverq(ttday+1)
IF(transq>0)THEN
  transc = ((1-ttpart)*riverq(ttday)*riverc(ttday) +
             ttpart*riverq(ttday+1)*riverc(ttday+1)) / transq
ELSE
  transc = 0.
ENDIF
```

After the calculation of outflow the values in the arrays are shifted forward one time step.

Delay and attenuation

If the delay in the watercourse also includes a damping of the peaks then only part of the delay is considered as translation, while the rest of the delay lies in damping. The translation is calculated first and then the flow goes through a linear box that creates attenuation. The parameter damp indicates how much of the delay that will occur in the attenuation box (or damping box), and translation time is reduced accordingly. Otherwise the translation is calculated in the same manner as above.

$$totaltime = \frac{rivlen}{rivvel \times 8.64\ \ 10^4}$$

$$transtime = \left(1 - damp\right) \times totaltime$$

The result from the translation of water (*transq* and *transc*) flows into the attenuation box, which is

assumed to be completely mixed. The delay time in the box (*kt*) is recalculated to a corresponding recession coefficient (*riverrc*). The recession coefficient (*riverrc*) used to calculate the outflow from the box (*dampq*) is a function of volume in the box (*riverbox*).

$$kt = damp \times totaltime$$

$$riverrc = 1. - kt + kt \times e^{-1/kt}$$

$$dampq = riverrc \times riverbox$$

The delay in the attenuation box is at the centre of gravity of the flow (not the tip) and is not calculated exactly (see Derivation of the equation of recession in the attenuation box below). Therefore there may be a difference in a peak delay between the use of pure delay and delay with damping, although the maximum velocity is set to the same value. In the case of damping the max velocity parameter *rivvel* may be approximated.

Additional smoothing of dead volume

A dead volume (*deadriver*) can be used to get extra equalization of concentrations in the watercourse. Then the outflow equation for the attenuation box (*riverbox*) is:

$$dampq = riverrc \times \left(riverbox - deadriver \right)$$

In this case, the initial value of the attenuation box is equal to the dead volume. Inflows into the box are mixed with the entire volume. At present this represents a dilution of the concentration since the initial value of concentration in the box is zero. At present the estimated dead volume as dependent on the upstream area (inkluding the area of the subbasin itself. Depth is calculated from the parameter *dead* (*deadl* or *deadm*, m^2/km^2) and the upstream area (km^2), the width is assumed to be 10 times the depth and the river length (*m*) is estimated to be the root of the subbasin's area unless it is set among the input data. This gives the dead volume:

$$deadriver = dead \times upparea \times rivlen$$

Dead volume can be used even without suppression of water (*damp = 0*).

Derivation of the equation of recession in the attenuation box

The continuous-time equation for the change in volume *S* in a reservoir is:

$$\frac{dS}{dt} = i\left(t\right) - q\left(t\right)$$

where *i(t)* is influx and *q(t)* is outflow. If we assume that the outflow is proportional to the volume we get another expression for the change in *S*. *k* is in the unit of time.

$$q\left(t\right) = \frac{1}{k} \ S,$$

$$\frac{dS}{dt} = k \frac{dq}{dt}$$

Combining these two equations gives a first degree equation that can be solved using the method of "integrating factor":

$$\frac{dq}{dt} + \frac{1}{k} q = \frac{i}{k},$$

$$\frac{d e^{t/k} q}{dt} = \frac{i}{k} e^{t/k},$$

$$q\left(t\right) = \frac{1}{k} \int i\left(t\right) e^{\tau - t/k} d\tau$$

In our case, we have a constant influx during a time steps of length 1 day. Assume that the influx during a time steps are *I* and the outflow *Q*. These flows are thus the equivalent discrete flows.

Because *I* is constant during the time step (*i(t) = I*) *Q* can be calculated. Define $y\left(t\right) = e^{\frac{t}{k}} q\left(t\right)$ and integrate the second equation above, from 0 to t (*t = 1*, one time step).

$$\int_{y\left(0\right)}^{y\left(t\right)} \frac{dy}{dt} d\tau = \int_0^t \frac{i\left(\tau\right)}{k} e^{\tau/k} d\tau,$$

$$y\left(t\right) - y\left(0\right) = \frac{I}{k} \int_0^t e^{\tau/k} d\tau = I \left(e^{t/k} - 1 \right)$$

$$e^{t/k} q\left(t\right) - q\left(0\right) = I \left(e^{t/k} - 1 \right)$$

$$q\left(t\right) = q\left(0\right) e^{-t/k} + \left(1 - e^{-t/k} \right)$$

Calculate *Q* for time step (the mean of *q(t)*) and replace the outflow with the volume.

$$Q = \frac{\int_0^1 q\left(t\right) dt}{\int_0^1 dt} = \int_0^1 q\left(0\right) e^{-t/k} + I \left(1 - e^{-t/k} \right) dt$$

$$= q\left(0\right) \int_0^1 e^{-t/k} dt + I \int_0^1 1 - e^{-t/k} dt$$

$$=q\left(0\right)\times\left(\begin{array}{c}\\ \\ \end{array}k\left(e^{-1/k}-1\right)\right)+I\left(1-0\right)-I\left(\begin{array}{c}\\ \\ \end{array}k\left(e^{-1/k}-1\right)\right)$$

$$=I\left(e^{-1/k}-1\right)\left(kI-kq\left(0\right)\right)$$

$$Q=\left(I+\left(e^{-1/k}-1\right)\right)\left(kI-S\left(0\right)\right)$$

Recession coefficient is defined as the proportion of outflow after an inflow pulse. It is therefore calculated here as $r=Q/I$ under the assumption that the starting volume can be neglected, *s(0)=0*.

$$r=\frac{Q}{I}=1+\left(e^{-1/k}-1\right)\times k$$

For a real flow the volume can of course not be neglected in this way and the relationship is only approximate.

Bank-full flow

Bank-full flow is used for erosion of particulate phosphorus in rivers (see Sedimentation). It is approximated by the second highest daily flow during the last year.

Local river

The local river has a length equal to the square root of the subbasin area. Subbasin runoff forms the inflow to the local river. The flow in the local river is delayed and attenuated as described above. Of the resulting flow from the stream a constant percentage goes to the local lake, and the rest directly to the main river.

Main river

A main river is present in all subbasins. The length is equal to the square root of the subbasin area, if it is not specified in GeoData.txt. In areas without incoming water from upstream there is still a main river, but it receives only local river flow after the local lake. In subbasins with upstream incoming water, the flow to the main river will be the sum of outflow from the local lake, the proportion of flow in the local river not flowing into the local lake and the water from upstream.

The return flow from an aquifer is added to the inflow of the main river.

The flow in the main river is delayed and attenuated as described above. The resulting effluent from the river flows to the outlet lake or to the next subbasin if there is no outlet lake.

Inflow from upstream subbasins

In GeoData.txt it is given to which subbasin(s) the (main) outflow from each subbasin flows. The upstream flow enters the main river of the downstream subbasin. Inflow into the main river of a subbasin is calculated by adding outflows from upstream areas. Concentrations are flow-weighted by their relative share.

Links to relevant modules in the code

Modules (file)	Procedures	Sections
modelmodule (model_hype.f90)	initiate_model_state	rivers
	initiate_model	
	initiate_model	local river
		main river
surfacewater_processes (sw_proc.f90)	add_precipitation_to_river	precipitation
	calculate_river_evaporation	evaporation
	translation_in_river	pure delay
	calc_qbank	bank-full flow
	update_qbank	

Lakes

Common lake processes

Precipitation

Daily precipitation is added to the lake and a new concentration is calculated. Lakes are assumed to be completely mixed if the parameter *deeplake* is not set to a value greater than zero.

Evaporation

The lake is assumed to evaporate and a new concentration calculated.

Outflow with rating curve

The rating curve is used for calculation of outflow above a threshold at several occasions.

$$q\left(t\right)=k\times\left(w\left(t\right)-w_0\right)^p$$

In the program the equation is solved with linearization (Lindström, 2016). For rating curve exponent equal to one, the solution is exact, while for other exponent an approximation is used.

Local lake (ilake)

The local lake has an initial volume which is determined by its area and threshold depth. The lake depth is determined by model parameters (*gldepi* or *illdepth*)).

The inflow to the lake is a percentage of the flow in the local stream. The percentage is determined by the percentage of the subbasin area that drain to the lake. This percentage can be given as a fraction in GeoData.txt (*icatch*) for each subbasin with an internal lake, or be given by a regional parameter *ilicatch*, or be given by a general parameter *gicatch*. If not set at all the default value is 1, i.e. the local river runs through the loacal lake. The flow from the local river is added to the lake. The lake water is assumed completely mixed if *deeplake = 0*.

Water outflow is calculated with the universal rating curve using general or region specific model parameters.

Simple outlet lake or dam (olake)

Inflow

The outlet lake receives both local runoff and inflow from upstream areas via the main river. An outlet lake may receive inflow from regional groundwater flow.

Outflow with universal rating curve

If the water level (*wlm*) is higher than the threshold (*lake_depth*) the outflow is calculated with the following equation:

$$outflow=\begin{cases}0 & ,\ for\ \ wlm<lake_{depth}\\ gratk\times uparea^{grata}\times ratcorr\times\left(wlm-lake_{depth}\right)^{gratp} & ,\ for\ \ grata>0\\ gratk\times ratcorr\times\left(wlm-lake_{depth}\right)^{gratp} & ,\ for\ \ grata=0\end{cases}$$

gratk, *gratp* and *grata* are general parameters that apply to all lakes in the model application. *ratcorr* is parameter region dependent model parameter for adjusting *gratk* to different regions. The upstream area (*uparea*, km^2) is included in the equation if parameter *grata* is >0. If the water level is

below the threshold then the outflow is zero.

Outflow with specific rating curve

In LakeData.txt a specific rating curve may be set instead of the general parameters. This is done by setting the *rate* and *exp* larger than zero in LakeData.txt.

$$outflow = rate \times \left(wlm\text{-}lake_{depth} \right)^{\exp}$$

Regulated lake

A simple regulation routine can be given in LakeData.txt for selected outlet lakes. There are two main versions of regulations. The first determine a (constant) production flow between the lake threshold and a lower water stage. The second determine different rating curves for two production periods.

Production flow

The regulated outflow is independent of water level (*wlm* (*m*)) between the threshold (*w0=lake_depth*) and a minimum water level (*wmin*). For this interval the production flow (*qprod*) is used. Production flow may depend on time of year and the water level. The minimum water stage is not really a water stage, but is calculated from the regulation volume (*regvol*) and the lake (surface) area. Thus it does not consider the area changing with depth.

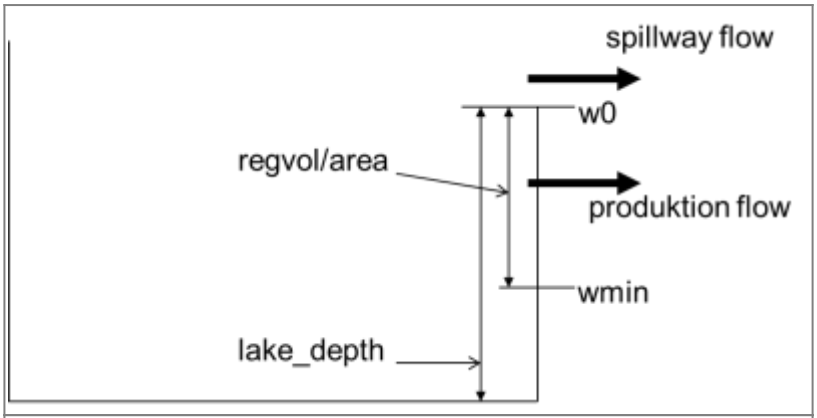


Figure 4: Illustration of regulation flow and variables.

For water levels above the threshold, the flow is calculated with a rating curve (typically flow through spillways) or all the water is discharged, but it is at least equal to the production flow (*qprod*). Compiled together as one equation, the outflow from a regulated lake is:

$$outflow = \begin{cases} MAX\left(rate \times \left(wlm - wo\right)^{\exp}, qprod\right) & , for \quad wlm > wo, rate > 0 \\ MAX\left(\frac{\left(wlm - wo\right) \times 1000}{qunitfactor}, qprod\right) & , for \quad wlm > wo, rate \leqslant 0 \\ MIN\left(qprod, \frac{\left(wlm - wmin\right) \times 1000}{qunitfactor}\right) & , for \quad wmin < wlm < wo \\ 0 & , for \quad wlm < wmin \end{cases}$$

Input variables *rate, exp, qprod, regvol, w0, qamp* and *qpha* can be found in LakeData.txt. The variable *wmin* is calculated by the program from *regvol* and lake area:

$$wmin = wo \square \frac{regvol \times 1000000}{area}$$

Production flow can have two different values during the year, which depends on the day of the year. This is determined by the input variables *qprod1, qprod2, datum1* and *datum2*. Regulation period 1 between *datum1* and *datum2* has production flow *qprod1*, while the rest of the year has production flow *qprod2*. Not setting the dates gives the same production flow the whole year (*qprod1*). Production flow can alternatively be made to vary sinusoidal over the years, with a peak in December, when power output is normally high, and a minimum in June. This is done with the input variable *qamp*. If you want a different seasonal variation set *qpha* (default = 102).

$$qprod = qprod \times \left(1. + qamp \times \sin\left(\frac{2 \times \pi \times \left(daymo + qpha\right)}{365}\right)\right)$$

In addition, the production flow is reduced from this level when there is a low water level in the dam. The flow will then be reduced linearly from full production flow for that time of year when water level is over the limit (*limqprod* (percentage of volume)) to zero when no water is left in the dam over *wmin* level.

Two rating curves

Regulated outflow can also be calculated from different rating curves for the regulation periods. The rating curve parameters are the specific rate and exponent of is lacking the general rate and exponent.

$$q\left(t\right)=k\times\left(w\left(t\right)-w_0\right)^p$$

Rating curve threshold (*w0*) determined by input variable *w0ref* is used for regulation period 1, while the rating curve threshold is changed for regulation period 2. The shift is determined by input variable *deltaw0*:

$$wo=woref+deltawo$$

Dams of specific purpose

In addition to regulated lakes (described above), dams in HYPE can instead be regulated by a specific purpose. Dams are then governed by the main purpose of the dam, e.g. hydropower, flood control. The rules of calculating the outflow of the dam then depends on the specified purpose of each dam. The outlet lakes that are regulated by a specified purpose is given in DamData.txt. A dam without defined purpose may use the methods given in previous sections (and be defined in LakeData.txt).

Dams are characterised by their regulation volume (*regvol*) between a minimum water stage (*wmin*) and the spill threshold (*w0*). The minimum water stage is not a real a water stage, but is calculated from the regulation volume (*regvol*) and the dam (surface) area. Thus it does not consider the area changing with depth. Below the minimum water level (*wmin*) no outflow occur.

For dams a preferred production flow is calculated (see below). This is released if the dam in within the regulation volume, but no more water than to the minimum threshold is released. If instead the water level of the dam is above the threshold *w0*, the spillway equation (rating curve) is used. The outflow is the maximum of the spillway equation and the preferred production flow.

Input variables *rate, exp, regvol, qamp* and *qpha* is given in DamData.txt.

General preferred production flow

For all dams the general preferred production flow is calculated from input data on the dam. The flow that is preferred to be released from the dam today is then adjusted depending on purpose. The general production flow (*qprod*) may be constant or vary between two values per year. This is determined by the input variables *qprod1, qprod2, datum1* and *datum2*. Regulation period 1 between *datum1* and *datum2* has production flow *qprod1*, while the rest of the year has production flow *qprod2*. Not setting the dates gives the same production flow the whole year (*qprod1*). IF *qprod1* is not given *qprod* is estimated from the yearly average inflow of the dam, which is given as input data.

The production flow may be reduced from this level when there is a low water level in the dam. The flow will be reduced linearly from full production flow for that time of year when water level is over the limit (*limqprod* (percentage of volume)) to zero when no water is left in the dam over *wmin* level.

1 - Irrigation dam and 2 - Water supply dam

Dams of these purposes uses the general perferred production flow as it is.

3 - Flood control dam

The flood control dam will try to stay empty and ready to delay large inflows. The preferred production flow is calculated from the inflow of the day (*Qinftoday*) for low inflow and water stages, but set higher than the inflow for high flows and water levels. The maximum flow (*qthresh*, the threshold flow) is determined from input data (*Qinf* is average inflow to dam for each month) and a general parameter (*kthr*), while the water level threshold (*wthres*) is determined by a general parameter (*klow*) for the fraction of the regulation depth.

$$qthresh = kthr \times MAX\left(Qinf\right)$$

$$wthresh = wo - klow \times \left(wo - wmin\right)$$

If the current inflow is larger than the threshold inflow (*qthresh*), the maximum allowable discharge is released:

$$qprod = qthresh$$

If the current inflow is less than the threshold inflow (*qthresh*) and the current water level is lower than the threshold level (*wthresh*), the inflow is released from the dam:

$$qprod = Qinftoday$$

If the water level is above the threshold (*wthresh*), more water is released than inflow in an attempt to empty the dam. The factor multiplied by inflow (*krel*) is a general parameter:

$$qprod = MIN\left(krel \times Qinftoday, qthresh\right)$$

4 - Hydropower dam

Dams for hydropower uses the general preferred production flow, but it may be adjusted with a seasonal factor. The factor is sinusoidal over the year, with a peak in December, when power output is normally high, and a minimum in June. This is done with the input variable *qamp*. If you want a different seasonal phase set *qpha* to another value (default = 102).

$$qprod = qprod \times \left(1 + qamp \times \sin\left(\frac{2 \times \pi \times \left(daymo + qpha\right)}{365}\right)\right)$$

Outlet lake with two outlets

An outlet lake that is not part of a lake composed of lakebasins, may have two defined outlets in LakeData.txt. The outlets can be divided into different outlet types depending on method for determining the outflow. HYPE will define an outlet's type based on variables present in LakeData.txt.

Below the defining (necessary) variables are given for each outlet type.

Outlet types

1. An outlet with outflow as production flow (only). The production flow can be determined by constants for different seasons or with a sinus adjustment; see **Production flow** above. Defining variables in LakeData.txt: *regvol*, (*rate*=0, *maxQprod*=0, *minflow*=0)

2. An outlet with outflow as production flow (same as type 1), but with an allowed (higher) maximum production flow. If the outflow from the other outlet is above zero, part of that flow will be sent through this outlet as part of production flow instead. Defining variables in LakeData.txt: *regvol*, *maxQprod*.

3. Rating curve determined outflow with constant threshold. Defining variables in LakeData.txt: *rate* (*deltaw0*=0, *regvol*=0, *maxQprod*=0)

4. Rating curve determined outflow with constant threshold relative to the threshold of the first outlet. This type is only used for the second outlet. Defining variables in LakeData.txt: *rate*, *w0ref* (*regvol*=0, *deltaw0*=0)

5. Flow determined by production flow below the threshold, and by a rating curve above the threshold. This could be production and overflow from a hydropower plant that goes too the same downstream subbasin. Defining variables in LakeData.txt: *regvol*, *rate* (*maxQprod*=0, *minflow*=0)

6. An outlet with outflow as production flow determined by different rating curves for different seasons; see **Two rating curves** above. Defining variables in LakeData.txt: *rate*, *deltaw0* (*regvol*=0, *maxQprod*=0)

7. An outlet with outflow as production flow determined by two rating curves (same as type 6), but with an allowed (higher) maximum production flow. If the outflow from the other outlet is above zero, part of that flow will be sent through this outlet as part of production flow instead. Defining variables in LakeData.txt: *rate*, *deltaw0*, *maxQprod* (*regvol*=0)

8. An outlet with outflow as minimum flow. The minimum flow is determined same as production flow by constants for different seasons or with a sinus adjustment. Defining variables in LakeData.txt: *regvol*, *minflow* (*rate*=0, *maxQprod*=0)

9. Minimum flow determined by a production flow below the threshold. In addition overflow is determined by a rating curve above the threshold. This could be a minimum environmental flow together with overflow. Defining variables in LakeData.txt: *regvol*, *rate*, *minflow* (*maxQprod*=0).

10. An outlet with outflow determined from a time series in Xobs (dwtr). This type is only used for the second outlet. Defining variables in LakeData.txt: *obsflow*=1

Combinations of outlet types

Examples of common combinations of outlets:

- A hydropower plant with an estimated average production flow and a spill overflow at high water levels are simulated by combining production flow (outlet type 1) with rating curve determined

overflow (outlet type 3).

- Same as above a hydropower plant with production flow in one branch and overflow in another (outlet type 3), but in this case the maximum allowed production is assumed higher than the average production (outlet type 2). This means that if overflow is calculated due to high water level, part of that flow is lead to the powerplant and through production to the first branch.

- A hydropower plant where the production flow and spill goes to the same downstream subbasin (outlet type 5), but where a second spill outlet goes to another subbasin (outlet type 4).

- A hydropower plant with production flow in one branch (outlet type 1), and a minimum (environmental) flow plus overflow outlet in the old river course that goes to another subbasin (outlet type 9).

- A lake with two outlets with flow determined by a rating curve for each of them (may have different threshold also) are simulated by a combination of outlet type 3 and 4.

Many other combinations can be used, but not all outlet types are natural to combine. The following are not allowed:

Outlet 1	Outlet 2
1	2, 4
2	1, 2, 4, 7, 8, 10
3	5, 9
4	all
5	3, 9
6	4
7	2, 4, 7, 8, 10
8	2, 4, 7-9
9	3-5, 8, 9
10	all

Change of branched flow after updating total flow

After calculating the outflow from the two outlets, which is done separately, the total outflow could be higher than the volume above the threshold. In this case the outflow will be reduced. When updating the total outflow from a lake with two outlets aginst observed total flow, the flow in respective branch has to be adjusted too. Depending on the outlet types this is done by different methods.

Lakes with a clear defined division between production flow and spill branch is handled so that production flow takes priority. For outlets with a maximum production flow, flow are diverted into this branch up to the maximum value and the rest into the other branch. For other lakes with a clear defined division between production flow and spill branch, the same method is applied but with the current production flow as the maximum value. For lakes with a minimum flow in one branch the minimum flow is given highest priority. Second priority is given to the production flow of the other branch (if any). At last the remaining flow is given to the branch for spill (outlet type 9) or the non minimum flow branch (outlet type 8). For the rest of the outlet type combinations the new flows are changed to be proportional to the old flows.

Outlet lake (olake) as a lake basin

An olake can be part of a larger lake. It is then called a lake basin of the larger lake. Lake basins are treated differently if they are located within the lake or if they are the last one, i.e. the one with the lake outflow.

Inflow

A lake basin can get local inflow from upstream areas and from the regional groundwater. Inflow works in the same way as for a simple olake (see above).

Flow between lake basins

Flow through a lake divided into lake basins occurs only in one direction according to the *maindown* (and possibly *branchdown*), no two-way exchange between lake basins is implemented. For upstream lake basins that run into another lake basin, all the water above the threshold is drained. The threshold of the lake (same as last lake basin) is used, not any internal threshold between lake basins. If the lake water level (*wlm*) is higher than the threshold (*w0* or *wmin*) outflow is obtained.

Outflow of lake composed of lake basins

For the last lake basin outflow is estimated by a rating curve, either a specific equation or with the general equation, or by regulation routine. Since all the water (above threshold) in the lake (from all lake basins) accumulates in the last lake basin the water level cannot be used directly, but it is recalculated to calculate the outflow from the lake. The last lake basin water level (*wlm*) is scaled by the subbasin lake area (*area*) to the whole lake area (*lakearea*). If the calculated lake water level (*wlake*) is higher than the threshold (*wthresh*) the outflow is estimated by the rating curve.

```
wlake = (wlm – wthresh) * area / lakearea + wthresh
outflow = rate * (wlake – wthresh)**exp
```

The threshold may be changing over the year as described in Section Two rating curves above. If the water level is below the threshold then the outflow is zero or if the production flow regulation is used there is production flow. See Section Production flow above. Production flow is also applied on the recalculated water stage.

Initalisation of lake volume

Unless a starting state is given from a file, the lakes start the simulation filled with water to their outflow threshold. That means for ilakes and simple olakes a water level equal to *lake_depth*. Dams are filled to the dam's maximum elevation (equal to *lake_depth*), except for flood control dams which are initializied with an empty regulation volume.

For lakes with outflow determined by a rating curve, the water level of the lake will be higher than the outflow threshold level. The equilibrium level will depend on the size of the inflow and the outflow

rating curve parameters. Depending on the residence time of water in the lake it may take time for this level to be established, and until then the outflow of the lake will be simulated lower than it should be. Thus a spin-up time is needed for a model simulation.

Links to relevant modules in the code

Modules (file)	Procedures	Sections
surfacewater_processes (sw_proc.f90)	calculate_potential_evaporation	evaporation
	calculate_actual_lake_evaporation	
	average_flow_rating_curve	ouflow with rating curve
	calculate_ilake_outflow	local lake
	calculate_outflow_from_outlet_lake	simple outlet lake
		outlet lake as a lakebasin
		outlet lake with two outlets
	set_general_rating_k	simple outlet lake
	calculate_olake_waterstage	outlet lake as a lakebasin
	calculate_branched_flow	outlet lake with two outlets
	calculate_branched_flow_new	
modelmodule (model_hype.f90)	initiate_model	local lake

References

Lindström, G., 2016. Lake water level for calibration of the S-HYPE model, Hydrology Research 47.4:672-682. doi: 10.2166/nh.2016.019.

Floodplains

Floodplains may be simulated adjacent to a main river or outlet lake. Floodplain is a land area close to the surface water that may be temporary flooded. Water may flow from the surface water to the floodplain and back. The floodplain is a part (*fpf*) of the classarea of the main river or the lake. The lake/river surface area is the rest of the classarea. The floodplain is flooded when the water in the river or lake reaches above a certain threshold. The water on the floodplain may return to the river lake or may be trapped when the water level of the floodplain sink.

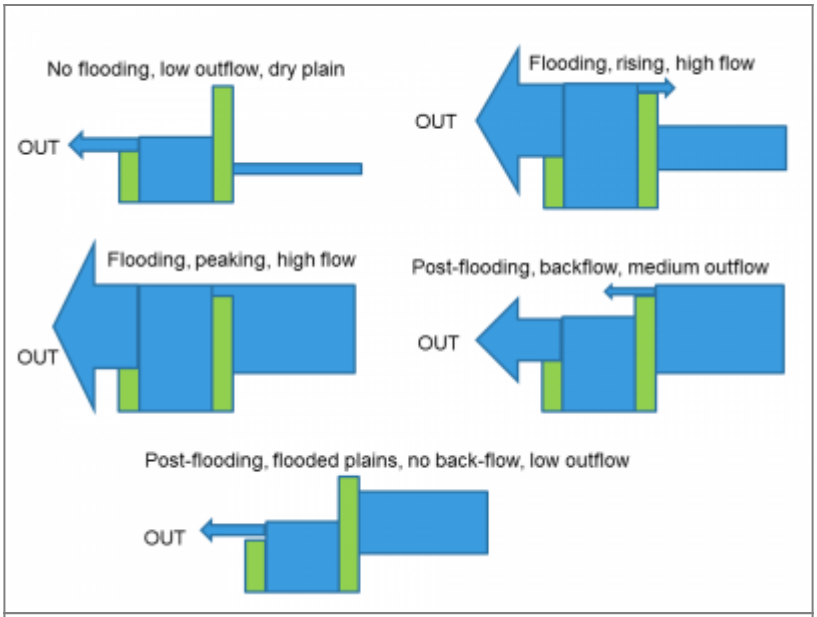


Figure 7: Five possible scenarios of flooding.

Common floodplain processes

The water level of the floodplain and the extent of the flooded area (a_{plain}, m^2) are calculated from the volume (vol_{plain}, m^3), maximum area (a_{max}) and water level at maximum areal extent (fym, m). The actual water level will be compared to the equlibrium water level to determine the water exchange. The equilibrium water level is the water level we would have if water was evenly distributed in the lake and the floodplain. It is solved from a second degree equation.

$$wl_{plain} = \sqrt{\frac{vol_{plain} \times fym \times 2}{a_{max}}}$$

$$a_{plain} = \frac{wl_{plain} \times a_{max}}{fym}$$

$$a_{max} = fpf \times classarea$$

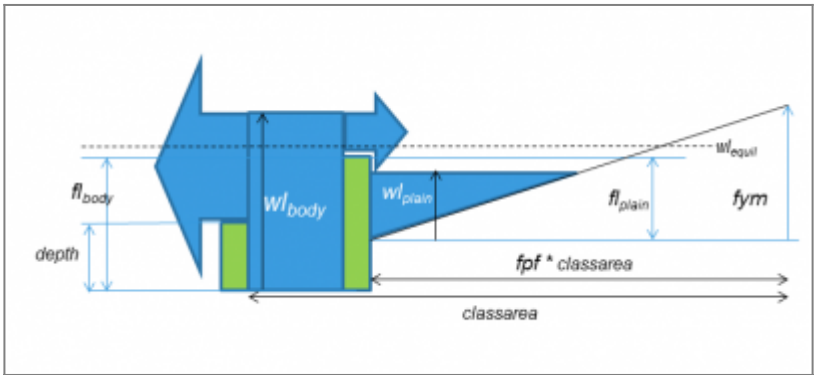


Figure 8: Illustration of floodplain variables of a lake.

The exchange of water between lake (or river) and floodplain is determined by the respective water levels (wl_{body} and wl_{plain}), the equilibrium water level (wl_{equil}) and the thresholds between the water bodies (fl_{body}/fl_{plain}). If the water level is over the threshold and higher than the water level of the floodplain the flow from water body to floodplain is:

$$q = rc_{bodyToPlain} \times MIN\left(\left(wl_{lake} - fl_{body}\right) - wl_{equil}, \left(wl_{lake} - fl_{body}\right)\right)$$

If the floodplain water level is over the threshold and higher than the water level of the water body the flow from floodplain to body is similarly:

$$q = rc_{plainToBody} \times MIN\left(\left(wl_{plain} - fl_{plain}\right) - wl_{equil}, \left(wl_{plain} - fl_{plain}\right)\right)$$

Floodplain water level (wl_{plain}) and degree of flooded area ($\frac{a_{plain}}{a_{\max}}$) are possible to print out from a simulation with an outlet lake or main river with floodplain.

Simple floodplain model

The simple floodplain model simulates precipitation on the floodplain and evaporation from the flooded water, in addition to the exchange of water between the river or lake and the flood plain. All precipitation on the floodplain is contributing to flooded water.

Floodplain model with soil routines

The floodplain model with soil routines is calculating all soil flows for the non-flooded part of the floodplain. The runoff from the floodplain soil goes to the flooded water, and not to the local stream as it does for ordinary land classes. Precipitation and evapotranspiration is calculated for the flooded water and the non-flooded soil. For the soil part, snow, infiltration and surface runoff, percolation, tile drainage and groundwater runoff is calculated as for an ordinary soil. Infiltration from the flooded water to the soil may occur. Regional groundwater percolation is only calculated for the flooded part together with percolation from the river.

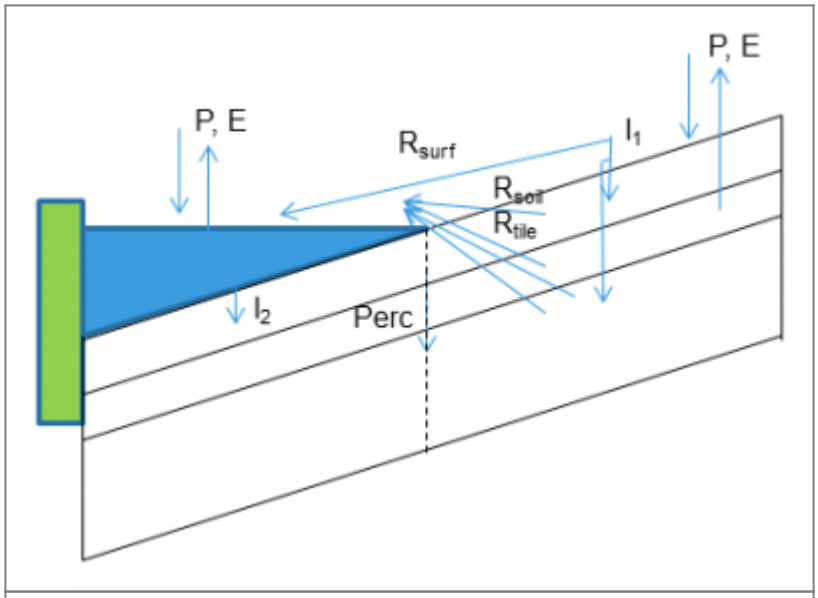


Figure 9: Illustration of floodplain soil flows.

Connected floodplains

It is possible for flooded floodplains to limit the water flow from upstream rivers and lakes. This is determined based on the water levels in the floodplains, a higher water level of a downstream floodplain compared to a upstream floodplain may reduced the flow from the upstream compartment (main river or outlet lake) to the downstream compartment (main river or outlet lake). The damming flow is calculated as the flow to reach equilibrium water level between the two floodplains. The relative level of the two floodplains location is determined based om the classes average elevation and thresholds or given as indata separately. The function of connecting floodplains works within a subbasin or between connected subbasins. This floodplain features may be used together with the **Floodplain model with soil routines**.

Links to relevant modules in the code

Modules (file)	Procedures	Sections
surfacewater_processes (sw_proc.f90)	add_precipitation_to_floodplain	common floodplain processes
	calculate_floodplain_evaporation	
	calculate_floodplain_waterlevel	
	calculate_waterbody_floodplain_interflow	
	calculate_floodplain_volume	
	calculate_floodplain_equilibriumlevel	
	calculate_regional_floodplain_flows	connected floodplains
	calculate_two_floodplain_equilibriumlevel_dp	
	calculate_equilibrium_floodplain_level_eq1dp	
	calculate_equilibrium_floodplain_level_eq2dp	
	calculate_equilibrium_floodplain_level_eq3dp	
	calculate_interflow_between_floodplains2	
floodplain soilmodel (soilmodel4.f90)	soilmodel_4	simple floodplain model
		floodplain model with soil routines
		connected floodplains

Bifurcations

Outflow from a subbasin may flow in one or two directions. The main flow follows the main channel, which is the downstream subbasin described by the path given in GeoData.txt. If there is a bifurcation, the branch flow goes to another downstream subbasin. Any of the flows may go outside the model set-ups area, they are then no longer a concern of the model. There are three ways to determine the flow in the different channels. 1) The division of the total outflow is determined in BranchData.txt. 2) The outflow is calculated for two outlets separately and then divided into the channels. For the second alternative see Outlet lake with two outlets section above. 3) The demanded flow in the branch is prescibed. If the total flow is not enough to fulfil the need, less water goes into the branch. The main channel gets the rest of the total flow. For the first method the flow division into two channels by BranchData.txt is described by four parameters; *mainpart*, $maxQ_{main}$, $minQ_{main}$ and $maxQ_{branch}$, which is set in BranchData.txt. Zero values of the parameters mean they are not used. The main flow (*mainflow*) is calculated from the totalflow (q) as:

$$mainflow = \begin{cases} q & q \leqslant minQ_{main} \\ mainpart \square \left(q\text{-}minQ_{main} \right) + minQ_{main} & minQ_{main} < q \leqslant q_{thresh} \\ maxQ_{main} & q > q_{thresh}, q_{thresh} = \dfrac{maxQ_{main}\text{-}minQ_{main}}{mainpart} + minQ_{main} \\ q\text{-}maxQ_{branch} & q > q_{thresh}, q_{thresh} = \dfrac{maxQ_{branch}}{1\text{-}mainpart} + minQ_{main} \end{cases}$$

$$q_{thresh} = MIN \left(\frac{maxQ_{main}\text{-}minQ_{main}}{mainpart} + minQmain, \frac{maxQ_{branch}}{1\text{-}mainpart} + minQ_{main}, 0 \right)$$

The rest of the total flow goes in the branch. The following figures give some examples of parameter combinations.

- Serie 1: *mainpart* = 0.5, *minQmain* = 2, *maxQmain* = 10, *maxQbranch* = 0
- Serie 2: *mainpart* = 0.5, *minQmain* = 2, *maxQmain* = 0, *maxQbranch* = 5
- Serie 3: *mainpart* = 0.5, *minQmain* = 0, *maxQmain* = 10, *maxQbranch* = 0
- Serie 4: *mainpart* = 0, *minQmain* = 2, *maxQmain* = 0, *maxQbranch* = 5

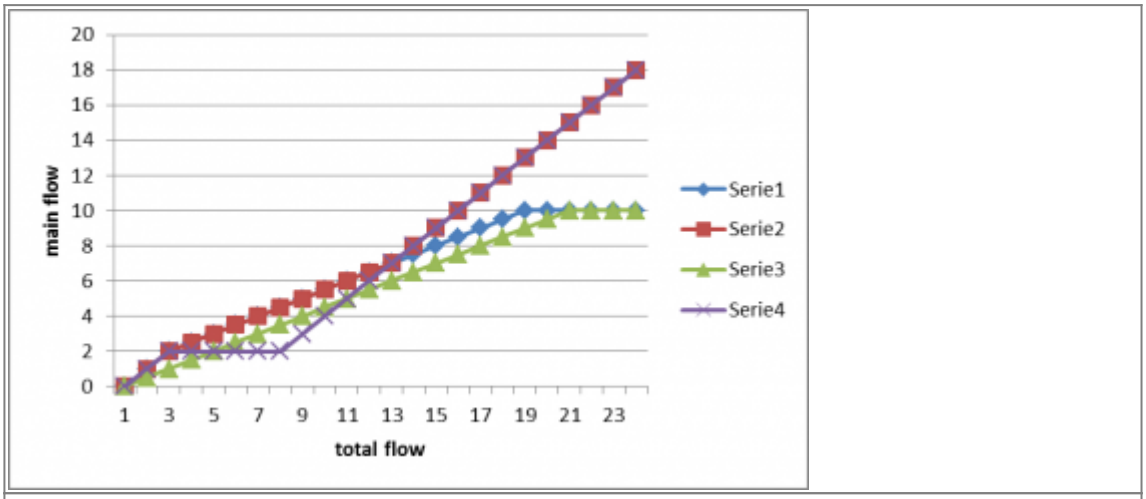


Figure 5: Main flow in relation to total flow for four different parameter combinations.

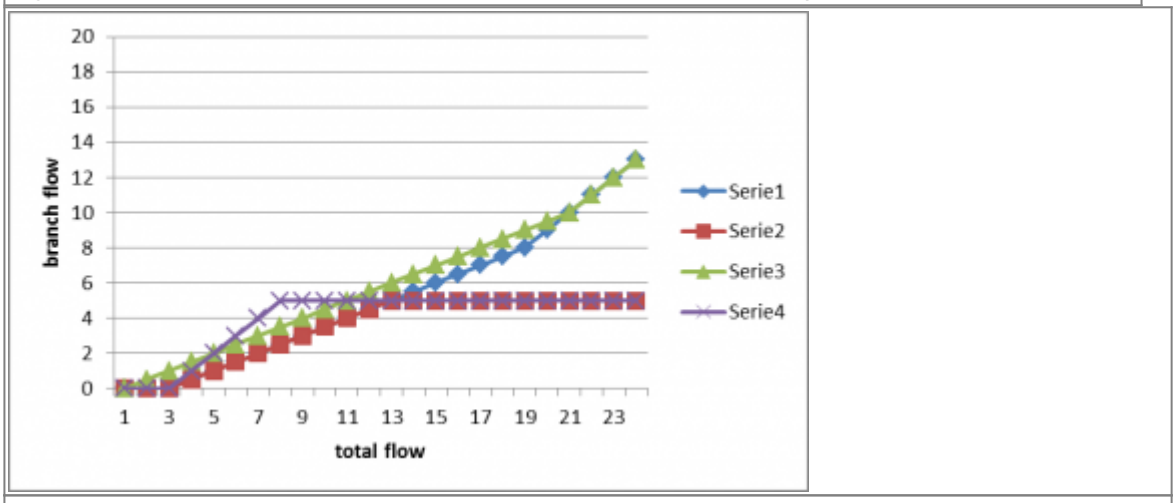


Figure 6: Branch flow in relation to total flow for four different parameter combinations.

Links to relevant modules in the code

Modules (file)	Procedures	Sections
surfacewater_processes (sw_proc.f90)	calculate_branched_flow	-
	calculate_branched_flow_new	-