Nitrogen and phosphorus processes in rivers and lakes

HYPE simulates concentration of inorganic nitrogen (IN), organic nitrogen (ON), soluble reactive phosphorus (SP) and particulate phosphorus (PP) in discharge and other surface waters. As output also the total nitrogen (TN) and phosphorus (TP) concentration can be had. In addition total suspended sediments (TS) can be simulated. It consists of the sum of suspended sediments (SS) and algae (AE) simulated concentrations.

Basic assumptions

Transformations of nutrients take place in lakes and rivers. For lakes, the whole water volume take part. For rivers, which hold delayed water in a queue and in the damping box, the processes is performed only in the damping box.

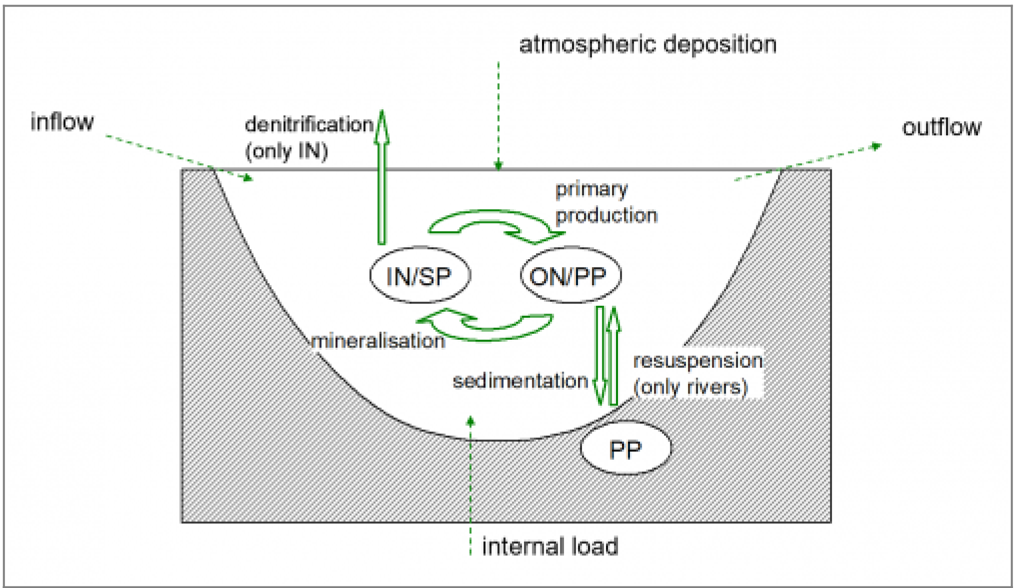

Figure 1: Sources and sinks of nitrogen and phosphorus in surface waters.

The processes of denitrification, primary production and mineralization have been implemented for both rivers and lakes. For particulate phosphorus (PP) there is an exchange with the river sediments. The rivers dimensions are used in the calculation of these processes. The width and depth of the watercourse are calculated from a number of empirical equations (for more information on these equations see “Modelling phosphorus transport and retention in river networks” by Jörgen Rosberg).

$$velocity = 10^{vel1} \times meanflow^{vel2} \times \left(\frac{flow}{meanflow} \right)^{vel3}$$

$$width = 10^{width1} \times \left(\frac{flow}{velocity} \right)^{width2 + width3 \times log10 \left(\frac{flow}{velocity} \right)}$$

$$depth = \frac{\left(\frac{flow}{velocity}\right)}{width}$$

where *vel1-vel3* and *width1-width3* are lake region dependent parameters, *flow* is the flow of water in the watercourse (*m3/s*) and *meanflow* is a 365-day rolling average flow. The river's width is limited by the dead volume width and a parameter *maxwidth*. The rivers length is estimated at square root of catchment area or is given as input. The watercourses **bottom area** is calculated as the length times the width, where the maximum of the above-calculated width and dead volume width is used. The bottom area is used for the nutrient processes. If the river is a class and thus has a defined class area, the class area is used to estimate the bottom area instead.

The water temperature (T_w) is used in some of the process calculations. It is calculated through weighting the air temperature (*T*) and yesterday's water temperature. The weighting constant (similar to moving average period) T_{wdays} is set to 20 days for rivers and is by default 5 days for lakes. For lakes a depth dependent T_{wdays} can also be used. Then the weighting constant is set to the equivialent days of the lake's depths up to a maximum (*maxpar*, a parameter) plus 5 days. Note that the water temperature can fall below $0^{\circ}C$.

$$T_w = \left(1 - \frac{1}{T_{wdays}}\right) \times T_w + \frac{1}{T_{wdays}} \times T$$

$$T_{wdays} = \begin{cases} MIN\left(MAX\left(lake_{depth}, 5\right), 5 + maxpar\right) & lake \\ 20 & river \end{cases}$$

Alternatively the water temperature calculated as a tracer (called T2) may be used. This model option is set in info.txt.

Links to file reference

Symbol	Parameter/Data	File
	rivlen, loc_rivlen	GeoData.txt
vel1, vel2, vel3	*rivvel1, rivvel2, rivvel3*	par.txt
width1, width2, width3	*rivwidth1, rivwidth2, rivwidth3*	
	deadl, deadm, maxwidth	
maxpar	*laketemp*	
$lake_{depth}$	*lake_depth*	GeoData.txt or LakeData.txt or DamData.txt
	gldepo, olldepth, gldepi, illdepth	par.txt

Links to relevant procedures in the code

Modules (file)	Procedures
npc_surfacewater_processes (npc_sw_proc.f90)	substance_processes_in_river
	substance_processes_in_lake
	river_characteristics
surfacewater_processes (sw_proc.f90)	calculate_water_temperature
	set_water_temperature

Nutrient sources

The basic nutrient sources of rivers and lakes are the inflow from upstream catchment area. For local rivers the inflow is the sum of the runoff from land. For internal lakes, the inflow is a fraction of the local river flow. For main rivers, the inflow is the flow from local catchment (local river and internal lake) and the flow from upstream subbasins. For outlet lakes the inflow is the flow from the main river.

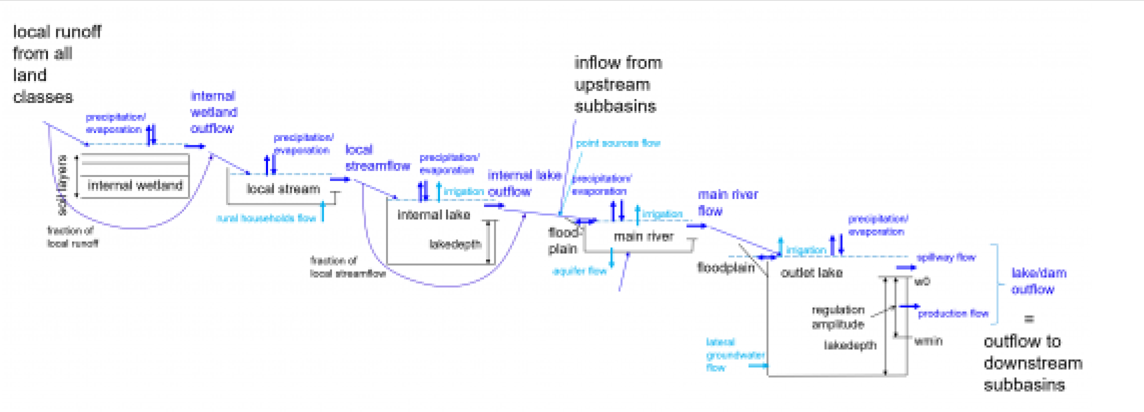

Figure 2: Schematic representation of water flows and storages in a subbasin of HYPE.

Other nutrient sources can be additional inflow to the surface waters through water transfers, regional grundwater flow and aquifer flow.

Deposition

Atmospheric deposition is added to lakes and rivers that have a class area. Deposition is described here.

Rural household diffuse source

Rural household diffuse source can be a source to local rivers. It can alternatively be added to the soil of some or all land classes, or be divided between the two recievers. It is described in detail under Nutrient sources to land.

Point sources

Point sources are primarily added to the main river of a subbasin. For tracer T1 there is a possibility to instead add point sources at different locations of the surface water in the subbasins; to local river, to internal lake, to main river or to outlet lake.

Denitrification

Denitrification, a sink for inorganic nitrogen in lakes and rivers, is a function of the bottom area, the IN concentration (*conc*) in water volume, water temperature (T_w) and a rate parameter. The dependence on concentration is formulated as a half saturation equation. In the concentration function, the half saturation parameter (par_{half}) is a general parameter, but it was in earlier HYPE versions a constant equal to 1.5 mg/L. Denitrification (*denitr*, *kg/day*) is limited to a maximum of 50% of the available IN pool.

$$tmpfcn = \begin{cases} 0 & T_w < 0 \\ \frac{T_w}{5} \times 2^{\frac{T_w - 20}{10}} & 0 < T_w < 5 \\ 2^{\frac{T_w - 20}{10}} & else \end{cases}$$

$$concfcn = \frac{conc}{conc + par_{half}}$$

$$denitr = MIN\left(0.5 \times INpool, par_{den} \times area \times concfcn \times tmpfcn\right)$$

The bottom area (*area*) is equal to the lake area for lakes, and watercourse width multiplied by the length for rivers (see above). The rate parameter (par_{den}) depend on the water body. Local and main rivers have general parameters (*denitwrl, denitwrm*), while lakes in addition to use a general parameter (*denitwl*) can have lake specific values.

Links to file reference

Symbol	Parameter/Data	File
par_{half}	*hsatINw*	par.txt
par_{den}	*denitwrl, denitwrm*	
	denitwl	par.txt or LakeData.txt

Links to relevant procedures in the code

Modules (file)	Procedures
npc_surfacewater_processes (npc_sw_proc.f90)	substance_processes_in_river
	substance_processes_in_lake
	denitrification_water

Primary production and mineralization

Primary production in lakes and rivers is a source of organic nitrogen and particulate phosphorus and a sink for inorganic nitrogen and soluble reactive phosphorus in the model. The reverse is true for mineralization. The processes are modelled together and only one is active at the time. Primary production and mineralization are controlled by two temperature functions. The first (*tmpfcn1*) is solely dependent on the water temperature (T_w). It simulates the increased activity at warmer temperatures. The second (*tmpfcn2*) governs the relationship between primary production and mineralization and determines which one dominates. Net primary production is highest in spring (northern hemisphere) and changes into net mineralization when the temperature *T10* is less than the temperature *T20* in autumn. These two temperatures are calculated as the average water temperature of 10 and 20 days.

$$tmpfcn1 = \frac{T_w}{20.}$$

$$tmpfcn2 = \frac{\left(T10 - T20\right)}{5.}$$

$$tmpfcn = tmpfcn1 \times tmpfcn2$$

The primary production and mineralization processes are also governed by long-term average concentrations of modelled total phosphorus (*TP*) in the lake or watercourse through a concentration function (*TPfcn*) with the general half saturation parameter *hsatTP*. The half saturation parameter was in earlier HYPE versions a constant equal to 0.05 mg/L. If phosphorus is not modelled a long-term average total phosphorus concentration as a lake region dependent parameter (*tpmean*) is used. A limiting concentration (*lim*) can be set, and then the long-term average concentration is reduced before using it in the concentration function.

$$TPfcn = \frac{TP - lim}{\left(TP - lim\right) + hsatTP}$$

The estimated production/mineralization (*minprodNpot*, kg / day) is the potential transformation, and may be limited by the availability of nutrients. Only 50% of the available IN the pool (at the primary production) or 50% of the ON-pool (for mineralization) can be transformed. The potential phosphorus conversion (*minprodPpot*) is calculated in the same way, but with its own parameter (*wprodp*) and a factor for phosphorus/nitrogen ratio (*NPratio* = 1/7.2). Similarly, there is a restriction against transforming maximum 50% of the SP and PP pools. The parameters *wprodn* and *wprodp* is generic or can be specified for each lake. The area is equal to lake area for lakes and bottom area for rivers (width multiplied by the length of the watercourse, see Basic assumptions, or if the river is a class, the class' area). The water depth (*depth*) is the lake depth, and for the river the depth calculated above.

$$minprodNpot = wprodn \times TPfcn \times tmpfcn \times area \times depth$$

$$minprodPpot = wprodp \times TPfcn \times tmpfcn \times area \times depth \times NPratio$$

For simulations of total suspended sediments, algae is simulated as a component of the suspendend material. Nitrogen in algae is assumed to grow and decline with the same function as production and mineralisation of organic nitrogen. If nitrogen is simulated it uses the actual estimated production/mineralisation, but otherwise the potential production/mineralisation (*minprodNpot*) is used. The mineralisation of algae is limited to available amount, but the production is then unlimited.

Links to file reference

Symbol	Parameter/Data	File
	hsatTP, tpmean	par.txt
lim	*limsedPP*	
	wprodn, wprodp	par.txt or LakeData.txt

Links to relevant procedures in the code

Modules (file)	Procedures
npc_surfacewater_processes (npc_sw_proc.f90)	substance_processes_in_river
	substance_processes_in_lake
	production_mineralisation
	calculate_lake_tpmean
	calculate_river_tpmean

Sedimentation and Resuspension

Sedimentation in **lakes** is a sink for particulate phosphorus (PP) and organic nitrogen (ON), as well as for suspended sediments (SS), algae (AE), and silica in algae (AS). Sedimentation (sed_{lake}, *kg/timestep*) is calculated as a function of concentration (*conc*) in the lake and lake area (*area*, m^2). The sedimentation rate (par_{sed}, *m/timestep*) is given by parameters (*sedon*, *sedpp*, *sedss*, *sedae*,*sedsi*) which are generic, but can be specified for each lake. The concentration used in the equation may be reduced (*lim, mg/L*) by general parameters (*limsedON*, *limsedPP*, *limsedSS*), but not for AE (*lim*=0). No sedimentation occurs unless the concentration is above this limit.

$$sed_{lake} = par_{sed} \times \left(conc - lim \right) \times area \times 10^{-3}$$

The sedimentation is additionally limited by the amount of substance in the lake. If the lake is shallow or the sedimentation rate (sinking velocity) high, all substances in the lake may settle on the bottom.

In the **river** we simulate both sedimentation and resuspension. No particles are removed from the simulation by sedimentation. For the original model they are redistributed over time and can come back through resuspension. For the alternative model it is possible to resupend more particles than is previously settled. This double process is used for particulate phosphorus (PP) (described here) as well as for suspended sediments (SS) and tracers (T1). Particles in the sediments is collected in a pool (*sedimentpool, kg*).

For the **original model** the sediment pool will increase as particles from the water volume (*waterpool, kg*) settle at low water flows, and vice versa. At high water flow the sedimentation is lower and the resuspension higher, and more particles returns to the water. The net effect of these combined processes are given by the variable *sedresp*. It is governed by the current flow (*flow*) in relation to the bankful flow (*qbank*) and a general parameter *sedexp*. The net effect is determined by the sign of the variable (-1 <*sedresp* <1), and the variable size give the fraction of the pool that is transfered per day. The process will give either net sedimentation (*settl, kg/day*) or resuspension (*resusp, kg/day*).

$$sedresp = \max\left(-1., \min\left(1., \frac{qbank - flow}{qbank}^{sedexp} - \frac{flow}{qbank}^{sedexp}\right)\right)$$

$$settl = \begin{cases} sedresp \times waterpool & sedresp > 0 \\ 0 & sedresp < 0 \end{cases}$$

$$resusp = \begin{cases} -sedresp \times sedimentpool & sedresp < 0 \\ 0 & sedresp > 0 \end{cases}$$

where *flow* is the current river flow (*m3/s*) and *qbank* is the flow when river is filled to the brim. The latter flow is calculated as the second largest simulated flow in the last year. It is adjusted with a correction factor of 0.7 before use in the *sedresp* equation. The first alternative model is the same as the original model but the correction factor can be calibrated. It is given by general model parameter *qbank*.

The **second alternative model** is based on a simplified Bagnold equation (see Chapter on Sediment). It is used to simulate suspended sediment, and particulate phosphorus use it by exchanging the parameters for maximum sediment concentration (*spcon, spexp*) to parameters for maximum particulate phosphorus concentration (*suspconPP,suspexpPP*).

Links to file reference

Symbol	Parameter/Data	File
area	*slc_nn, area*	GeoData.txt
par_{sed}	*sedpp, sedon, sedss, sedsi*	par.txt or LakeData.txt
	sedae	par.txt
lim	*limsedON, limsedPP, limsedSS*	
	sedexp, qbank	
spcon,spexp	*suspconpp, suspexppp*	

Links to relevant procedures in the code

Modules (file)	Procedures
npc_surfacewater_processes (npc_sw_proc.f90)	substance_processes_in_river
	substance_processes_in_lake
	lake_sedimentation
	river_sedimentation_resuspension

Internal load

Lakes can leak phosphorus from the bottom e.g. release of phosphorus during oxygen deficiency or the mixing of the previously sedimented emissions. Internal load can be simulated for SP or PP or both fractions of phosphorus. With two parameters the release of PP or SP is obtained for a specific lake (*par_{prod}, m/d*). The load to the lake (*load, kg/day*) is calculated as a function of lake water temperature (T_w), average concentration of phosphorus in the lake (*TPfcn*) and lake area (*area*). *TPfcn* is currently not depending on simulated concentration as it is set to constant 0.1 mg/L.

$$load = \frac{par_{prod} \times TPfcn \times tmpfcn \times area}{1000}$$

$$tmpfcn = 0.86^{\left|T_w - 15\right|}$$

$$TPfcn = 0.1$$

Links to file reference

Symbol	Parameter/Data	File
par_{prod}	*prodPP, prodSP*	LakeData.txt

Links to relevant procedures in the code

Modules (file)	Procedures
npc_surfacewater_processes (np_sw_proc.f90)	substance_processes_in_lake
	internal_lake_load

Macrophyte uptake

For shallow waters in rivers and lakes macrophytes can grow and take up inorganic nutrients (IN and SP). The nutrients are lost to the model. Macrophyte uptake are controlled by a temperature function (*tmpfcn*) and a concentration function (*TPfcn*) for total phosphorus. The temperature function is composed of two parts; one exponential and one dependent on the water temperature (*Tw*) above the average temperature of the last twenty days (*T20*). The concentration function is the same half-saturation function as for production and mineralisation above.

$$tmpfcn = \frac{\left(\frac{Tw}{20}\right)^{0.3} \times \left(Tw - T20\right)}{5}, Tw > 0 \; and \; tempfcn > 0$$

The bottomarea (*fracarea*) that is shallower than a production depth (*proddep* set by general parameters) is assumed to be active with macrophyte uptake. The river or lake are for this purpose assumed to be decreasing linearly with depth until twice the average depth.

$$fracarea = \frac{proddep}{\left(\frac{2 \times vol}{area}\right)} \times area$$

The uptake (*upt*) is limited to maximum 50% of the available nutrients and the whole equation becomes:

$$upt = uptpar \times tmpfcn \times TPfcn \times fracarea$$

The uptake rate parameters (*uptpar*), different for IN and SP, are general. The process is similar to the modelled macrophyte uptake in wetlands.

Links to file reference

<table>
<tr><th>Symbol</th><th>Parameter/Data</th><th>File</th></tr>
<tr><td rowspan="2">uptpar</td><td>muptn, muptp</td><td>par.txt or LakeData.txt</td></tr>
<tr><td>muptnriv, muptpriv</td><td rowspan="2">par.txt</td></tr>
<tr><td>proddep</td><td>muptdep, muptdepriv</td></tr>
</table>

Links to relevant procedures in the code

<table>
<tr><th>Modules (file)</th><th>Procedures</th></tr>
<tr><td rowspan="2">npc_surfacewater_processes (np_sw_proc.f90)</td><td>substance_processes_in_lake</td></tr>
<tr><td>macrophyte_uptaked</td></tr>
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