

Model description of PCDitch

Version 2.0



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Model description of *PCDitch*

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1 Process description

1.1 Nomenclature

The model variables have been named according to an easy-to-read system of nomenclature, so that the type, unit and meaning of a variable can be derived directly from its name. This system is used throughout this chapter and in the model code. The basic system is as follows:

type + element + process + component + layer (+ suffix)

- State variables: s + element + compartment + layer (+ 0)
(state) (D/P/N/O₂) (IM/Det/PO₄/NH₄/Phyt/etc.) (W/S) (-/IC)
- Processes (fluxes): t/w + element + process + compartment + layer
(flux) (D/P/N/O₂) (Set/Min/etc.) (IM/Det/PO₄/NO₃/Phyt/etc.) (W/S)

The abbreviations are listed here:

Substances, elements:

D- = dry weight
P- = phosphorus
N- = nitrogen
O₂- = oxygen
Q- = water flow
L- = light
Tm = temperature
Chla, Ch- = chlorophyll-a

Layers:

-W = water column
-S = sediment top layer
-T = total

Components:

-IM = inorganic matter
-Det = detritus
-Hum = humus
-PO₄ = phosphate
-NH₄ = ammonium
-NO₃ = nitrate
-Diss = (total) dissolved
-AIM = adsorbed onto inorganic matter
-Phyt = (total) phytoplankton
-OM = total organic matter
-Tot = total
-Veg = total vegetation
-Elod = rooted submerged angiosperms
(Elodeids)
-Char = Characeans
-Cera = non-rooted submerged angiosperms
-Lemn = non-rooted, floating plants (Lemnids)
-Nymp = floating-leaved plants (Nymphaeids)
-Helo = emergent plants (helophytes)

Processes:

Load = external loading
Dil = dilution
Ev = evaporation

Outfl = surface outflow

Inf = infiltration / seepage

Eros = erosion

Set = settling, sedimentation

Resus = resuspension

Bur = burial

Dif = diffusion

Nitr = nitrification

Denit = denitrification

Sorp = ad-/desorption

Min = mineralization

Upt = uptake (of nutrients)

Ass = assimilation

Prod = production

Cons = consumption

Eges = egestion

Resp = respiration (DW)

Excr = excretion (nutrients)

Graz = grazing

Mort = natural mortality

Loss = phytoplankton grazing loss

Man = management, mowing

Dred = dredging

Tran = total transport flux

Abio = total flux from abiotic module

Prim = total flux from algae module

Bed = total flux from vegetation module

Ext = total external flux (for mass balance)

Prefixes:

s- = state variable

s...0 = initial value of state variable

d- = derivative

t- = transfer per area [g/m²/d]

w- = transfer per volume of
water [g/m³/d]

v- = volume change per area [m/d]

r- = (dynamical) ratio [gA/gB]

o- = concentration [mg/l]

a- = other auxiliary

c- = constant (general)
 k- = rate constant [d-1]
 h- = half-saturation constant
 f- = fraction [-]
 b- = derived constant
 u- = (derived) input variable, or derived constant
 m- = measurement, read variable
 i-, j- = counters (integers)
 n- = numbers (integers)
 kd- = partitioning coefficient (used in sorption equations) $[(\text{gX/gDW}) / (\text{gX/m}^3)] = [\text{m}^3/\text{g}]$

Suffixes:

-Max = maximum

-Min = minimum
 -In = incoming
 -Bot = bottom
 -mg = in milligrammes
 -Sp = specific ("per unit of biomass")

Other abbreviations:

-Fun- = function, dependence
 -C(o)r- = corrected, modified
 -Iso- = adsorption isotherm
 -Ext- = extinction
 -V- = velocity [m/d]
 -Mu- = growth rate [d-1]
 -Carr- = carrying capacity, maximum biomass [gDW/m² or gDW/m³]
 -Secchi = transparency, Secchi depth [m]

1.2 Model structure

1.2.1 General structure and components

The model describes a homogeneous and well mixed linear water system, like a ditch. The model comprises both the water column and the sediment top layer, with the most important biotic and abiotic components. Spatial differences within the ditch are not taken into account. Moreover, the model can be used in a spatial setting, in conjunction with the water transport model DUFLOW (STOWA, 1998, 1999). This allows for modeling a network of ditches.

This model description is based on *PCDitch* version 1.24 (Janse 2005). The model structure is made flexible so that the user may lump, split or leave out certain groups of algae and water plants, but the default configuration is described here.

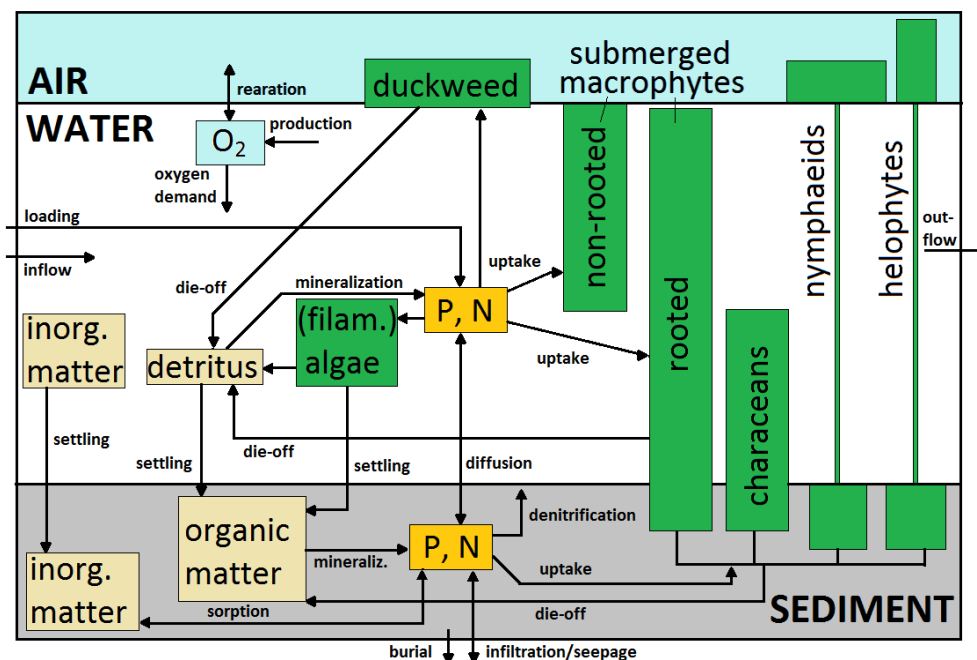


Figure 1: PCDitch model structure

The competition between the plant groups is mainly determined, in the model, by the factors light, temperature, N and P and - for algae and possibly duckweed – in- and outflow. Duckweed, algae and non-rooted submerged plants are confined to the water column for their nutrient uptake, while helophytes take nutrients from the sediment only and rooted submerged plants are able to use both pools. Duckweed, the nymphaeids and the helophytes hamper the growth of submerged plants by light interception at the water surface.

Mathematically, the model is composed of a number of coupled differential equations, one for each state variable, as listed in Table 1. The structure of the ditch model is shown in Figure 1. All biota are modelled as functional groups. Besides mass fluxes, the model also contains some 'empirical' or indirect relations between components. The water depth (*sDepthW*) is a state variable, while the thickness of the sediment top layer (*cDepthS*) is assumed constant (default 0.1 m). Both layers are considered as well mixed. All components in the water are modelled as concentrations [g/m^3], in the sediment as the amounts in the top layer [g/m^2]. The overall nutrient cycles for N and P are described as completely closed (except for external fluxes such as in- and outflow and denitrification). This was done by modelling most components in three elements (as indicated by the 'shadowed' blocks in the pictures), viz. dry-weight (abbreviated as D), nitrogen (N) and phosphorus (P). Inorganic carbon (CO_2) is not explicitly modelled. The nutrient-to-dry-weight ratios are thus variable. The total mass balances per element are dynamically checked during the calculations.

'Day' was chosen as a uniform time unit for all processes (but the simulation time can be chosen as variable); however, the relevant time scale for the output is about weeks to 1 month.

Table 1: State variables in PCDitch.. Abbreviations: *s*- = state variable, *D* = dry-weight, *P* = phosphorus, *N* = nitrogen, O_2 = oxygen

| Description | Unit | As dry-weight (D) | As phosphorus (P) | As nitrogen (N) | As oxygen (O_2) |
|--------------------------------|---------------------------|-------------------|----------------------------|--|----------------------------|
| Water depth | [m] | sDepthW | | | |
| Abiotic comp. in water column: | | | | | |
| Inorganic matter | [g/m^3] | sDIMW | - | - | - |
| Detritus (org. matter) | [g/m^3] | sDDetW | sPDetW | sNDetW | - |
| Inorg. nutrients | [g/m^3] | - | sPO ₄ W, sPAIMW | sNH ₄ W, sNO ₃ W | - |
| Oxygen | [g/m^3] | - | - | - | sO ₂ W |
| Abiotic comp. in sediment: | | | | | |
| Inorganic matter | [g/m^2] | sDIMS | - | - | - |
| Org. matter: humus | [g/m^2] | sDHumS | sPHumS | sNHumS | - |
| Org. matter: detritus | [g/m^2] | sDDetS | sPDetS | sNDetS | - |
| Inorg. nutrients | [g/m^2] | - | sPO ₄ S, sPAIMS | sNH ₄ S, sNO ₃ S | - |
| Oxygen | [g/m^2] | - | - | - | sO ₂ S |
| Algae: | | | | | |
| Phytoplankton | [g/m^3] | sDPhytW | sPPhytW | sNPhytW | - |
| Settled Phytoplankton | [g/m^2] | sDPhytS | sPPhytS | sNPhytS | |
| Vegetation: | | | | | |
| Submerged, rooted | [g/m^2] | sDElod | sPElod | sNElod | - |
| Charophytes | [g/m^2] | sDChar | sPChar | sNChar | - |
| Submerged, non-rooted | [g/m^2] | sDCera | sPCera | sNCera | - |
| Floating (duckweed) | [g/m^2] | sDLemn | sPLemn | sNLe mn | - |
| Nymphaeids | [g/m^2] | sDNymp | sPNymp | sNNymp | - |
| Helophytes | [g/m^2] | sDHelo | sPHelo | sNHelo | - |

1.2.2 List of differential equations

The differential equations are listed per compartment. The naming conventions explained in §1.1 are applied: state variables are denoted by *s*-, derivatives by *d*-, other variables by *a*-, concentrations by *o*-, and processes by *t*- (if expressed per area) or *w*- (if expressed per volume). The listed processes are described in detail in the next paragraphs.

The transport processes are typeset in the normal way, the *abiotic and microbial processes (as well as burial and dredging)* in *italics*, the **algal processes in bold** and the **macrophyte processes in bold italics**.

a. Water depth

$$dDepthW = (uQ_{in} - cQ_{inf} - uQ_{ev} - uQ_{out}) / 1000 + vDeltaW + vDredDepthW$$

|| Water depth [m/d]

= inflow – infiltration – evaporation – outflow + burial correction + dredging

b. Organic and inorganic matter

$$dDIMW = uDLoadIM/sDepthW - wDDilIM + (uDerosIMW - tDSetIM + tDResusIM) / sDepthW - aRelDeltaW * sDIMW$$

|| Inorganic matter in water [gD/m³/d]

= loading – dilution + erosion – settling + resuspension – burial correction

$$dDDetW = uDLoadDet/sDepthW - wDDilDet (- tDSetDet + tDResusDet) / sDepthW - wDMinDetW + \mathbf{wDMortPhytW} + (tDMortVegW + tDEgesBird) / sDepthW - aRelDeltaW * sDDetW$$

|| Detritus in water [gD/m³/d]

$$dPDetW = uPLoadDet/sDepthW - wPDilDet (- tPSetDet + tPResusDet) / sDepthW - wPMinDetW + \mathbf{wPMortPhytDetW} + (tPMortVegDetW + tPEgesBirdDet) / sDepthW - aRelDeltaW * sPDetW$$

|| Detritus in water [gP/m³/d]

$$dNDetW = uNLoadDet/sDepthW - wNDilDet (- tNSetDet + tNResusDet) / sDepthW - wNMinDetW + \mathbf{wNMortPhytDetW} + (tNMortVegDetW + tNEgesBirdDet) / sDepthW - aRelDeltaW * sNDetW$$

|| Detritus in water [gN/m³/d]

= loading - dilution - settling + resuspension - mineralisation + algal mortality + part of macrophyte mortality in water + birds egestion – burial correction

$$dDIMS = uDerosIMS + tDSetIM - tDResusIM - tDBurIM - tDDredNetIMS$$

|| Sediment inorg. matter [gD/m²/d]

= erosion + settling – resuspension – burial – dredging

$$dDHumS = uDerosOM + fRefrDetS * tDMinDetS - tDMinHumS - tDBurHum - tDDredNetHumS$$

|| Sediment humus [gD/m²/d]

$$dPHumS = uPErosOM + fRefrDetS * tPMinDetS - tPMinHumS - tPBurHum - tPDredNetHumS$$

|| Sediment humus [gP/m²/d]

$$dNHumS = uNErosOM + fRefrDetS * tNMinDetS - tNMinHumS - tNBurHum - tNDredNetHumS$$

|| Sediment humus [gN/m²/d]

= erosion + humification – mineralisation – burial – dredging

$$dDDetS = tDSetDet - tDResusDet - tDMinDetS - tDBurDet - tDDredDetS + \mathbf{tDMortPhytS} + \mathbf{tDMortVegS}$$

|| Sediment detritus [gD/m²/d]

$$dPDetS = tPSetDet - tPResusDet - tPMinDetS - tPBurDet - tPDredDetS + \mathbf{tPMortPhytDetS} + \mathbf{tPMortVegDetS}$$

|| Sediment detritus P [gP/m²/d]

$$dNDetS = tNSetDet - tNResusDet - tNMinDetS - tNBurDet - tNDredDetS + \mathbf{tNMortPhytDetS} + \mathbf{tNMortVegDetS}$$

|| Sediment detritus [gN/m²/d]

= settling – resuspension - mineralisation - burial - dredging + sed. algal mortality + macrophyte mortality in sed.

c Inorganic nutrients

$$dPO4W = uPLoadPO4/sDepthW - wPDilPO4 + cPBackLoad / sDepthW + wPMinDetW - wPSorpIMW + (tPDifPO4 + tPResusPO4 - tPInfPO4W) / sDepthW - wPUptPhyt + wPExcrPhytW + wPMortPhytPO4W + (- tPUptVegW + tPExcrVegW + tPMortVegPO4W + tPEgesBirdPO4) / sDepthW - aRelDeltaW * sPO4W$$

|| PO₄ in water [gP/m³/d]

= loading - dilution + background loading + mineralisation – sorption + diffusion from sediment + resuspension - infiltration - algal uptake + algal excretion + part of algal mortality - macrophyte uptake from water + macrophyte excretion in water + part of macrophyte mortality + egestion by birds – burial correction

$$dPAIMW = uPLoadAIM/sDepthW - wPDilAIM + (tPResusAIM - tPSetAIM) / sDepthW + wPSorpIMW - aRelDeltaW * sPAIMW$$

|| Adsorbed P in water [gP/m³/d]

= loading - dilution + resuspension - settling + sorption – burial correction

$$dPO4S = tPInfPO4W - tPInfPO4S + (1.0-fRefrDetS) * tPMinDetS + tPMinHumS - tPSorpIMS - tPResusPO4 - tPDifPO4 - tPDifGroundPO4 - tPChemPO4 - tPBurPO4 + tPExcrPhytS + tPMortPhytPO4S - tPUptVegS + tPExcrVegS + tPMortVegPO4S$$

|| PO₄ in pore water [gP/m²/d]

= infiltration from water - infiltration to groundwater + detritus and humus mineralisation – sorption – resuspension - diffusion to water and groundwater - immobilisation - burial + excretion and part of mortality of sed. algae - macrophyte uptake from sediment + macrophyte excretion in sediment + part of macrophyte mortality

$$dPAIMS = tPSetAIM - tPResusAIM + tPSorpIMS - tPBurAIM - tPDredAIMS$$

|| Adsorbed P in sediment [gP/m²/d]

= settling – resuspension + sorption – burial – dredging

$$dNH4W = uNLoadNH4/sDepthW - wNDilNH4 + cNBackLoad / sDepthW + wNMinDetW - wNNitrW - tNInfNH4W / sDepthW + (tNDifNH4 + tNResusNH4) / sDepthW - wNUptNH4Phyt + wNExcrPhytW + wNMortPhytNH4W - (tNUptNH4VegW + tNExcrVegW + tNMortVegNH4W + tNEgesBirdNH4) / sDepthW - aRelDeltaW * sNH4W$$

|| ammonium in water [gN/m³/d]

= loading - dilution + background loading + mineralisation – nitrification in water - infiltration + diffusion from sediment + resuspension - algal uptake + algal excretion + part of algal mortality - macrophyte uptake from water + macrophyte excretion in water + part of macrophyte mortality + egestion by birds – burial correction

$$dNO3W = uNLoadNO3/sDepthW - wNDilNO3 + wNNitrW - wNDenitW + (tNDifNO3 + tNResusNO3 - tNInfNO3W) / sDepthW - wNUptNO3Phyt - tNUptNO3VegW / sDepthW - aRelDeltaW * sNO3W$$

|| Nitrate in water [gN/m³/d]

= loading - dilution + nitrification in water – denitrif. in water + diffusion from sediment + resuspension – infiltration - algal uptake - macrophyte uptake from water – burial correction

$$dNH4S = tNInfNH4W - tNInfNH4S + (1.0-fRefrDetS) * tNMinDetS + tNMinHumS - tNResusNH4 - tNDifNH4 - tNDifGroundNH4 - tNNitrS - tNBurNH4 + tNExcrPhytS + tNMortPhytNH4S - tNUptNH4VegS + tNExcrVegS + tNMortVegNH4S$$

|| Pore water ammonium [gN/m²/d]

= infiltration from water - infiltration to groundwater + detritus and humus mineralisation – resuspension - diffusion to water and groundwater - nitrification in sediment - burial + excretion and part of mortality of sed. algae - macrophyte uptake from sediment + macrophyte excretion in sediment + part of macrophyte mortality

$$dNO3S = tNInfNO3W - tNInfNO3S + tNNitrS - tNDenitS - tNResusNO3 - tNDifNO3 - tNDifGroundNO3 - tNBurNO3 - tNUptNO3VegS$$

|| Pore water nitrate [gN/m²/d]

= infiltration from water - infiltration to groundwater + nitrification in sed. - denitrification in sed. – resuspension - diffusion to water and groundwater - burial - macrophyte uptake from sediment

d Dissolved oxygen

$$dO_2W = wO_2Inflow - wO_2Outfl + tO_2Aer / sDepthW - wO_2MinDetW - wO_2NitrW - (tO_2MinDetS + tO_2NitrS) / sDepthW + wO_2ProdPhyt - wO_2RespPhytW + wO_2UptNO_3Phyt + (tO_2ProdVegW - tO_2RespVegW + tO_2UptNO_3VegW) / sDepthW - aRelDeltaW * sO_2W$$

|| oxygen in water [gO₂/m³/d]

= inflow - outflow + reaeration - mineralisation - nitrification - sediment oxygen demand + algal production - algal respiration + nitrate uptake by algae + macrophyte production - macrophyte respiration + nitrate uptake by macrophytes – burial correction

e. Algae / phytoplankton

$$dDPhytW = uDLoadPhyt/sDepthW - wDDilPhyt + wDAssPhyt - wDRespPhytW - wDMortPhytW (- tDSetPhyt + tDResusPhyt) / sDepthW - WDLossPhyt - aRelDeltaW * sDPhytW$$

|| Algae in water column [gD/m³/d]

= loading -dilution +production -respiration - mortality - settling + resuspension – grazing - burial corr.

$$dPPhytW = uPLoadPhyt/sDepthW - wPDilPhyt + wPUptPhyt - wPExcrPhytW - wPMortPhytW (- tPSetPhyt + tPResusPhyt) / sDepthW - WPLossPhyt - aRelDeltaW * sPPhytW$$

|| Algae in water column [gP/m³/d]

= loading - dilution + uptake – excretion – mortality – settling + resuspension – grazing – burial corr.

$$dNPhytW = uNLoadPhyt/sDepthW - wNDilPhyt + wNUptPhyt - wNExcrPhytW - wNMortPhytW (- tNSetPhyt + tNResusPhyt) / sDepthW - WNLossPhyt - aRelDeltaW * sNPhytW$$

|| Algae in water column [gN/m³/d]

= loading - dilution + uptake – excretion – mortality – settling + resuspension – grazing – burial corr.

$$dDPhytS = tDSetPhyt - tDResusPhyt - tDMortPhytS - tDRespPhytS - tDDredPhytS$$

|| Settled algae [gD/m²/d]

= settling – resuspension – mortality – respiration or excretion - dredging

$$dPPhytS = tPSetPhyt - tPResusPhyt - tPMortPhytS - tPExcrPhytS - tPDredPhytS$$

|| Settled algae [gP/m²/d]

= settling – resuspension – mortality – respiration or excretion - dredging

$$dNPhytS = tNSetPhyt - tNResusPhyt - tNMortPhytS - tNExcrPhytS - tNDredPhytS$$

|| Settled algae [gN/m²/d]

= settling – resuspension – mortality – respiration or excretion - dredging

f. Water plants

These equations are defined for the plant groups Elod, Cera, Char, Lemn, Nymf and Helo.

$$dDVeg = tDProdVeg - tDRespVeg - tDMortVeg (\pm tDMigrVeg) - tDGrazBird - tDManVeg - tDDredVeg$$

|| Macrophytes [gD/m²/d]

= production - respiration - mortality (± migration) - bird grazing – mowing – dredging

$$dPVeg = tPUptVeg - tPExcrVeg - tPMortVeg (\pm tPMigrVeg) - tPGrazBird - tPManVeg - tPDredVeg$$

|| Macrophytes [gP/m²/d]

= uptake – excretion - mortality (± migration) - bird grazing – mowing – dredging

$$dNVeg = tNUptVeg - tNExcrVeg - tNMortVeg (\pm tNMigrVeg) - tNGrazBird - tNManVeg - tNDredVeg$$

|| Macrophytes [gN/m²/d]

= uptake – excretion - mortality (± migration) - bird grazing – mowing – dredging

g. Total mass balances

Total fluxes [g per m² ditch per day]:

$$tDExtTotT = uDLoad - wDOutflTot * sDepthW - tDBurTot + cDErosTot - wDMinDetW * sDepthW - (1.0 - fRefrDetS) * tDMinDetS - tDMinHumS + (wDAssPhyt - wDRespPhytW) * sDepthW - tDRespPhytS + tDMigrVeg + tDProdVeg - tDRespVeg - tDManVeg - tDAssVegBird - tDDredNetTot$$

|| Total dry-weight mass balance [gD/m²/d]

$$tPExtTotT = uPLoad - wPOutflTot * sDepthW + cPBackLoad - tPBurTot + uPErosOM - tPChemPO4 - tPInfPO4S - tPDifGroundPO4 + tPMigrVeg - tPManVeg - tPAssVegBird - tPDredNetTot$$

|| Total P mass balance [gP/m²/d]:

$$\begin{aligned}
tNExtTotT = & uNLoad - wNOutflTot * sDepthW + cNBackLoad - tNBurTot + uNErosOM - tNDenitS - \\
& wNDenitW * sDepthW - tNInfNH4S - tNInfNO3S - tNDifGroundNO3 - tNDifGroundNH4 + tNMigrVeg \\
& - tNManVeg - tNAssVegBird - tNDredNetTot \\
\parallel & \text{Total N mass balance [gN/m}^2\text{/d]}
\end{aligned}$$

1.2.3 Coupling of dry-weight and nutrient cycles

An important feature of the present model is the basically independent modelling of the carbon cycle (expressed as dry weight D), the nitrogen (N) and the phosphorus (P) cycle. This feature allows for a variable stoichiometry (P/D and N/D ratio) of organisms and organic matter and makes sure that there is a closed cycle for all modelled substances at any time. In many existing food web models, this feature is not adequately dealt with, often without mentioning it. In all models of the 'Di Toro-type' for instance (Di Toro et al. 1971, 1975, Thomann 1977, Di Toro & Matystik 1980), with phytoplankton chlorophyll, zooplankton C, detritus P and inorganic P as state variables, no closed phosphorus cycle is possible whatsoever, unless the P/C ratios of all compartments are equal (Aldenberg & Peters 1988). Jørgensen (1980) developed a multi-unit model (dry weight, C, N and P) with variable ratios between them, but also in this model no systematic differences in ratios between compartments can be achieved, because the underlying ecological and physiological mechanisms which are responsible for those differences, are not included. Therefore, in steady state, all P/C ratios would become equal. In any model with basically different P/C ratios between compartments, one or more of the P/C ratios should be dynamical to maintain a closed P balance. This approach is followed in *PCDitch*, also for the N/C ratios, and is applied to macrophytes, algae, detritus and sediment humus (see Table 1). These model compartments thus have a variable stoichiometry, while their nitrogen and phosphorus cycle is closed. The stoichiometric ratios are simply calculated as (with r- being the prefix for ratios):

$$\begin{aligned}
rPDComp &= sPComp / sDComp && \text{P/D ratio of component 'Comp' [gP/gD]} \\
rNDComp &= sNComp / sDComp && \text{N/D ratio of component 'Comp' [gN/gD]}
\end{aligned}$$

For macrophytes and algae, only the equations for growth/nutrient uptake, respiration/excretion and assimilation/egestion are really different for dry-weight or nutrients. In this way, their nutrient ratios may change during the model run. The nutrient ratio of detritus may vary because it is a mixture of many sources, mainly algae and macrophytes after they die off. All other processes, such as settling, mortality and mineralisation, are described similar for nutrients as for dry-weight, and do not influence the ratios:

$$\begin{aligned}
tPProcess &= rPDComp * tDProcess \\
tNProcess &= rNDComp * tNProcess
\end{aligned}$$

The only purpose of tripling these equations is to close the nutrient cycles. The model is thus much less complex than it may seem at first sight from the list of differential equations. For a quick impression of the model, it should be sufficient to have a look at the dry-weight differential equations as well as the equations for PO_4 , NH_4 and NO_3 .

Mass balance check

Please note that the cycles of all four elements are considered as closed within the system, apart from external fluxes. These are: external input and outflow, infiltration, burial, erosion, denitrification (for N), precipitation (for P) and migration. As dissolved carbon is not modelled, in contrast to dissolved N and P, growth and respiration by algae and macrophytes and decomposition, expressed as dry-weight, are considered as external fluxes as well. The corresponding nutrient processes of uptake and excretion are internal fluxes.

The external fluxes are reflected in the total mass balance equations. These consist of four additional differential equations, one for each element D, P and N, describing the mass crossing the system boundaries. This amount should equal the difference between the total amount present in the system, i.e. the sum of all biotic and abiotic components, and the initial amount. This can be checked any time during the simulation. The mass balance equations are similar for P, N and D. The 'mass balance errors' $[g/m^2]$ for each element should be smaller than the accuracy of the integration method.

The mass balance equations (for P) look like:

| | |
|--|---|
| $uPTotT0$ | initial P amount in the system [gP/m ²] |
| $aPTotT$ | total P amount in system [gP/m ²] |
| $tPExtTotT$ | sum of P fluxes entering or leaving system [gP/m ² /d] |
| $sPExtTotT = INTEG(tPExtTotT, uPTotT0)$ | total P amount that has entered or left system [gP/m ²] |
| $aPError = aPTotT - sPExtTotT$ | P mass balance error [gP/m ²] |

1.2.4 Software implementation

The *PCDitch* model code is originally developed in ACSL/Math and has a modular structure. The processes have been gathered in the following modules (### stands for the version number, i.e. 2.0):

- *main module* ('PCDi###.csl'): definition of the model components, initialisation, differential equations and overall mass balances, as well as burial and dredging.
- *transport module* ('PCDTran###.csl'): external transport of water and substances.
- *abiotic and microbial module* ('PCDAbio###.csl'): physical and chemical processes, water-sediment exchange, mineralisation processes.
- *algal module* ('PCDPrim###.csl'): growth and loss processes of phytoplankton.
- *vegetation module* ('PCDBed###.csl'): growth and loss processes of macrophytes.

PCDitch has been implemented in different platforms:

- ACSL/Math v. 11.8 (MGA, 2002)
- DUFLOW v. 3.8.3 (STOWA, 2006)
- PCSHELL-C++ (Osiris v. 3.01) (NIOO, 2012)
- PCSHELL-R v. 1.0 (NIOO/WUR, 2012)

PCDitch is a 0-D model in all platforms, except for DufLOW where *PCDitch* is implemented in a 1-D way, which means that the ditch has a horizontal dimension. The transport module is not included in the DUFLOW version, since DufLOW arranges the external transport of water and substances and the *PCDitch* model code is only implemented for the internal processes in the ditch. Table 2 gives additional information on the platforms in which *PCDitch* can be run.

In the PCSHELL-C++ platform (Osiris), the *PCDitch* code is stored in an Excel workbook, with different worksheets for the state variables, parameters, initial values and model equations. The model equations are coded in a universal 'Esperanto' language, which allows easy translation to other languages (C++, ACSL, Duprol) as required by the different platforms. The translator programme is written in Visual Basic and is incorporated in the Excel workbook as a macro. This approach facilitates model development, in a way that code adjustments are automatically translated to the languages required by the different platforms.

Table 2: The platforms in which *PCDitch* can be run

| platform | description | PCDitch code | default integrator |
|----------------------|--|--------------|--|
| PCShell-C++ (Osiris) | C++ scripts to run <i>PCDitch</i> , using the I/O settings defined in an Excel workbook | C++ | Runge-Kutta-Cash-Karp (5th order) (to solve ode's) |
| PCShell-R | R scripts to run <i>PCDitch</i> , using the I/O settings defined in an Excel workbook | C++ | 'vode' (from R-package DeSolve) (to solve ode's) |
| ACSL | ACSL script to run <i>PCDitch</i> , using the I/O settings defined in the ACSL code and in .txt files | ACSL | Runge-Kutta-Fehlberg (5th order) (to solve ode's) |
| DufLOW | 1-D hydrodynamic model. <i>PCDitch</i> is implemented as a process library. The transport part of <i>PCDitch</i> is taken over by DufLOW | DUPROL | implicit numerical scheme (to solve pde's) |

1.3 Transport processes and water depth

Transport and loading

One of the basic processes in a ditch is the inflow and outflow of water with dissolved and particulate substances. The following mass balance is kept for each component in the water column:

$$\begin{aligned} dCV/dt &= V dC/dt + C dV/dt \\ dC/dt &= Q_{in}/V * (C_{in} - C) - Q_{out}/V * (C_{out} - C) \\ dV/dt &= Q_{in} - Q_{out} \end{aligned}$$

As C_{out} equals C for all outflows except evaporation (where the outflow concentration is zero), the differential equation for concentration reduces to:

$$dC/dt = Q_{in}/V * C_{in} - (Q_{in} - Q_{ev})/V * C \quad \text{or} \quad dC/dt = L/V - (Q_{in} - Q_{ev})/V * C$$

where Q_{in} is the sum of all water inflows and C_{in} the weighted average of the concentrations of the component in those inflows. The product $Q_{in} * C_{in}$ is the external loading, L . Note that the dilution effect on the concentration is caused by the water *inflow*, not by the outflow. In the model, the water volume is represented by the water depth since the model has no horizontal awareness and therefore applies to 1 m² of surface area. Water flows are in [mm/d] (so, for practical reasons, a factor 1000 is introduced to convert from mm to m) and loadings are in [g m⁻² d⁻¹].

Evaporation is by default described as a sinusoid; instead, it may be read in from a file.

$$uQE_{ev} = cQE_{evAve} - cQE_{evVar} * \cos(2.0 * \pi * (Time + 10 - cTimeLag) / 365) \quad [\text{mm/d}]$$

The minimum is thus found at $cTimeLag$ days after the shortest day of the year. The ‘time lag’ is chosen the same as the one for the water temperature (see below). In the Dutch situation, the average evaporation is about 1.5, the amplitude about 1.3 mm/d.

The resulting transport equations are, with PO₄ as an example:

$$wPTranPO4W = uPLoadPO4 / sDepthW - wPDilPO4 \quad \text{PO}_4 \text{ transport flux [gP/m}^3\text{/d]}$$

in which:

$$\begin{aligned} uPLoadPO4 & \quad \text{external PO}_4 \text{ loading [gP/m}^2\text{/d]} \\ sDepthW & \quad \text{water depth [m]} \\ wPDilPO4 &= ukDil * sPO4W \quad \text{dilution of PO}_4 \text{ [gP/m}^3\text{/d]} \\ ukDil &= (uQIn - uQE_{ev}) / 1000 / sDepthW \quad \text{dilution rate [d}^{-1}\text{]} \end{aligned}$$

These loading and dilution equations apply (*mutatis mutandis*) to the following components in the water column: dissolved nutrients (PO₄, NH₄ and NO₃), oxygen, IM, adsorbed P, detritus and phytoplankton. So not for water plants; possible migration of water plants, which is only possible in the model for duckweed, is defined separately and discussed in §1.6.8.

The total P load, N load and water inflow should be supplied by the user, either as time-series, as constants or as summer- and winter-averages. Evaporation values may be supplied as a time-series or approximated as a sinusoid function. In case of constants or seasonal averages, the fraction of the load entering in dissolved form (PO₄, resp. NH₄ and NO₃) and bound in phytoplankton should be given as well; the remainder is in detrital form. Algal and detrital nutrient loading are converted to dry-weight loading by means of fixed conversion factors. External input of IM should be given as input concentrations [g/m³].

Water depth

The water depth is a state variable. It may vary due to two causes: ‘at the top’ (due to water level changes) or ‘at the bottom’ (due to sedimentation or dredging). The differential equation is:

$$dDepthW = vTranDepthW + vDeltaW + vDredDepthW \quad \text{change in water depth [m/d]}$$

in which:

$$\begin{aligned} vTranDepthW &= (uQin - uQev - uQout) / 1000 && \text{water level change [m/d]} \\ vDeltaW &&& \text{water depth change by sedimentation [m/d]} \\ vDredDepthW &&& \text{water depth change due to dredging [m/d]} \end{aligned}$$

Water level changes occur if water inflow and outflow + evaporation are not equal. This happens only if the user supplies a separate time-series for the outflow rate Q_{out} [mm/d]. The user should check that time-series of inflow and outflow together reflect a realistic picture of the water level around the year.

The second contribution to (slow) changes in water depth is (net) sedimentation. Dredging can be explicitly modelled as well, which is an important process in ditches. Both processes are discussed in §1.4.3 (‘burial’) and §1.4.4 (‘dredging’).

Note on the DUFLOW implementation

In the DUFLOW implementation of the model, the transport processes (i.e. the transport of the state variables defined as of type ‘WATER’ in DUFLOW) are calculated by DUFLOW itself and are thus left out from the model code. This has been done by excluding the transport module at the DUPROL translation step.

Infiltration and seepage

Infiltration is defined as a water flux from the surface water to the groundwater, via the sediment top layer. If applicable, it is assumed that dissolved substances (PO_4 , NH_4 and NO_3) are transported with it: dissolved nutrients from the water column enter the pore water, while pore water nutrients are lost to the deeper groundwater. The opposite situation is seepage, a flux of water with dissolved nutrients from the groundwater via the upper sediment layer to the water column.

The infiltration / seepage rate cQ_{Inf} is expressed in [mm/d]; a positive value means infiltration, a negative one seepage, zero is none. With the infiltration, the surface water outflow rate can be calculated, by extracting the infiltration rate from the dilution rate:

$$ukOutfl = (uQIn - uQEv - cQInf) / 1000 / sDepthW \quad \text{surface outflow rate [d}^{-1}\text{]}$$

The nutrient infiltration fluxes are described as (with PO_4 as an example, analogous to NH_4 and NO_3); in case of infiltration ($cQ_{Inf} > 0$):

$$\begin{aligned} tPInfPO4W &= cQInf / mmPerm * sPO4W && \text{PO}_4 \text{ infiltration from water to pore water [gP/m}^2\text{/d]} \\ tPInfPO4S &= cQInf / mmPerm * oPO4S && \text{infiltration of interstitial PO}_4 \text{ to groundwater [gP/m}^2\text{/d]} \end{aligned}$$

In case of seepage ($cQ_{Inf} < 0$), where a user-defined groundwater concentration $cPO4Ground$ [gP/m³] is used :

$$\begin{aligned} tPInfPO4S &= cQInf / mmPerm * cPO4Ground && \text{seepage of groundwater PO}_4 \text{ to pore water [gP/m}^2\text{/d]} \\ tPInfPO4W &= cQInf / mmPerm * oPO4S && \text{seepage of interstitial PO}_4 \text{ to water column [gP/m}^2\text{/d]} \end{aligned}$$

Background loading

Direct loading on the water surface, e.g. by atmospheric deposition, is defined separately in the model, apart from the transport processes. Average values for The Netherlands around 1990 approximate 0.0003 gP/m²/d and 0.009 gN/m²/d. Ever since the atmospheric deposition has decreased (RIVM).

Erosion

Apart from loading via inflowing water, an input of soil material by erosion can be defined, which is directly added to the pools of organic and inorganic matter. A total erosion flux ($cDErosTot$ [g/m²/d]) is defined, plus the organic fraction ($fDOrgSoil$ [-]) and the P and N fractions in it ($cPDSoilOM$ and $cNDSoilOM$). The parameters are taken from the soil composition in the surroundings. The inorganic matter is divided in an instantly sedimentating part ($fSedErosIM$ [-]) and the remainder that is suspended in the water column. The organic matter goes to the sediment humus pool.

$$\begin{aligned} uDErosIM &= (1.0 - fDOrgSoil) * cDErosTot && \text{IM input from banks [gD/m}^2\text{/d]} \\ uDErosIMS &= fSedErosIM * uDErosIM && \text{IM input to sediment from banks [gD/m}^2\text{/d]} \\ uDErosIMW &= uDErosIM - uDErosIMS && \text{IM input to water column from banks [gD/m}^2\text{/d]} \\ uDErosOM &= fDOrgSoil * cDErosTot && \text{organic matter input from banks [gD/m}^2\text{/d]} \end{aligned}$$

The corresponding organic P and N fluxes are defined as $cPDSoilOM$ resp. $cNDSoilOM$ times the D flux.

Direct sediment N loading by artificial fertilizer

It sometimes happens that ditches receive a direct loading of artificial fertilizer, due to spill or drift during the application of fertilizer on the adjacent fields. Although measures have now been taken to avoid this, the option to include it has remained in the model, to allow for historical or scenario runs:

$$\begin{aligned} tNH4LoadS &= fNH4LoadS * cNLoadS && \text{NH}_4 \text{ load to sediment by artificial fertilizer [gN/m}^2\text{/d]} \\ tNO3LoadS &= cNLoadS - tNH4LoadS && \text{NO}_3 \text{ load to sediment by artificial fertilizer [gN/m}^2\text{/d]} \end{aligned}$$

1.4 Abiotic and microbial processes

1.4.1 Organic and inorganic components and initialisation

Water column

The abiotic components in the water column are: inorganic matter, detritus, adsorbed P and dissolved PO₄, NH₄ and NO₃. It is assumed that the dissolved fractions are available for primary production. Humus is neglected in the water column, as it is assumed to settle quickly.

These components should be **initialised** as concentrations, as well as the initial P/D and N/D ratios of the detritus. Adsorbed P, usually a minor component in the water column, is initialised at 0 gP/m³; adsorption is calculated, however, during the run. Derived variables in the water column are defined as:

DW variables:

$$\begin{aligned} oDPhytW &= sDPhytW && \text{total phytoplankton [gD/m}^3\text{]} \\ oDOMW &= sDDetW + oDPhytW && \text{organic seston [gD/m}^3\text{]} \\ oDSestW &= oDOMW + sDIMW && \text{total seston [gD/m}^3\text{]} \end{aligned}$$

P variables:

$$\begin{aligned} oPPhytW &= sPPhytW && \text{total phytoplankton [gP/m}^3\text{]} \\ oPOMW &= oPPhytW + sPDetW && \text{org.seston P, without adsorbed [gP/m}^3\text{]} \\ oPSestW &= oPPhytW + sPDetW + sPAIMW && \text{total seston P (incl. adsorbed) [gP/m}^3\text{]} \\ oPInorgW &= sPO4W + sPAIMW && \text{inorganic P in water [gP/m}^3\text{]} \\ oPTotW &= oPSestW + sPO4W && \text{total P in water (excl. vegetation) [gP/m}^3\text{]} \end{aligned}$$

N variables:

$$\begin{aligned} oNDissW &= sNO3W + sNH4W && \text{SRN in water [gN/m}^3\text{]} \\ oNPhytW &= sNPhytW && \text{total phytoplankton [gN/m}^3\text{]} \\ oNOMW &= oNPhytW + sNDetW && \text{org.seston N [gN/m}^3\text{]} \\ oNSestW &= oNOMW && \text{total seston N [gN/m}^3\text{]} \\ oNkjW &= oNSestW + sNH4W && \text{kjeldahl N in water [gN/m}^3\text{]} \\ oNTotW &= oNkjW + sNO3W && \text{total N in water (excl. vegetation) [gN/m}^3\text{]} \end{aligned}$$

Nutrient ratios:

| | |
|-----------------------------|-------------------------------------|
| $rPDIMW = sPAIMW / sDIMW$ | P adsorbed to IM in water [gP/gD] |
| $rPDDetW = sPDetW / sDDetW$ | P/D ratio of water detritus [gP/gD] |
| $rNDDetW = sNDetW / sDDetW$ | N/D ratio of water detritus [gN/gD] |
| $rPDOMW = oPOMW / oDOMW$ | P/D ratio of org.seston [gP/gD] |

Sediment

The sediment top layer consists of particulate matter and a pore water fraction with as dissolved nutrients PO_4 , NH_4 and NO_3 . The particulate matter consists of inorganic ('IM') and organic ('OM') matter. The inorganic matter (sand or clay particles) does not take part in the biological cycling, but forms the basic structure of the sediment and determines its P adsorption capacity. The organic matter (usually given as fraction ash-free dry-weight, AFDW) has been split into refractory ('humus', abbreviated as 'Hum') and degradable OM or 'detritus' ('Det'). Detritus is the organic matter that takes part in the biological cycling while its nutrients become available again at a time scale of months. The humus component may break down at a very slow rate, comparable the decomposition rate of peat. For simplicity, detritus is modelled as one component, although it may originate from various sources. Organic matter can also be expressed in carbon units by means of a fixed ratio, $cCPerDW$ (default 0.4 gC/gD).

The thickness of the top layer, $cDepthS$ [m], is considered as fixed, with a default value of 0.1 m, following Lijklema (1993) and other models. This layer is assumed to contain all the nutrients taking part in the present nutrient cycle, thus being important for the water quality and bioproduction. Net increase of sediment material is counteracted in the model by *burial* of a small layer of sediment, equally thick as the layer that had been added to it. This process of 'sediment dilution' may change the composition of the sediment top layer and may constitute a nutrient sink (Lijklema, 1993). The burial calculation is given below.

Similar to the water column, inorganic phosphorus comprises dissolved P in the pore water and adsorbed P. Inorganic nitrogen comprises nitrate and ammonium in the pore water; the sum of these is called $NDiss$. Please note that all water fractions are expressed as concentrations [g/m³], while the pore water fractions are expressed on an areal base [g/m²]. Elemental units are used (so, g N- NO_3 and not g NO_3). The amounts are converted to concentrations in the pore water by dividing by the porosity and the sediment depth.

Initially, the dry-weight fraction, the fraction organic matter, the detritus fraction and the lutum fraction (= particles <16 μ) in the top layer, are given by the user. Data may be derived from measurements, databases or estimates. These values are used to calculate the initial amounts, in [g/m²], of the sediment components, the initial bulk density of the sediment, and the porosity: the water content of the sediment on a volume base [m³ water / m³ sediment]. To avoid unnecessary complexity, the porosity is further considered as constant. The porosity is used in various equations, such as the calculation of nutrient concentrations in the pore water, as well as diffusion fluxes and resuspension (see below).

| | |
|-----------|---|
| $fDTotS0$ | initial dry-weight fraction [g solid / g sediment] |
| $fDOrgS0$ | initial fraction organic matter [g AFDW / g solid] |
| $fLutum$ | fraction lutum (= particles <16 μ) in the inorganic matter [g/g] |
| $fDDetS0$ | initial fraction detritus of the organic matter [g/g] |

The solid density of the organic and inorganic fractions are taken as constant:

| | |
|-----------|--|
| $cRhoOM$ | solid density of organic matter [g/m ³ solid] |
| $cRhoIM$ | solid density of inorganic matter [g/m ³ solid] |
| $cRhoWat$ | density of water = $1.0 \cdot 10^6$ [g/m ³] |

Default values for these solid densities are $1.4 \cdot 10^6$ [g/m³ solid] for OM and $2.5 \cdot 10^6$ [g/m³ solid] for IM (Hendriks, 1991). Jørgensen (1991) gives values of 1.3 (1.2-1.4) for organic matter, 1.95 (1.7-2.2) for clay soil and 1.7 (1.4-2.0) for sandy soil (all $\cdot 10^6$ [g/m³ solid]).

$$\begin{aligned}
bRhoSolidS0 &= fDOrgS0 * cRhoOM + (1 - fDOrgS0) * cRhoIM && \text{initial average density of solid material [g/m}^3 \text{ solid]} \\
bPorS &= (1.0 - fDTotS0) * bRhoSolidS0 / cRhoWat / (fDTotS0 + (1.0 - fDTotS0) * bRhoSolidS0 / cRhoWat) && \text{porosity [m}^3 \text{ water/m}^3 \text{ sediment]} \\
bPorCorS &= bPorS ** (bPorS + 1.0) && \text{sediment porosity, corrected for tortuosity [-]} \\
bRhoTotS0 &= bRhoSolidS0 * (1.0 - bPorS) && \text{initial sediment bulk density [g solid/m}^3 \text{ sediment]}
\end{aligned}$$

Based on the initial sediment bulk density, the initial values of the state variables are calculated:

$$\begin{aligned}
bDTotS0 &= bRhoTotS0 * cDepthS && \text{initial total dry-weight in top layer [gD/m}^2 \text{]} \\
sDHumS0 &= (1.0 - fDDetS0) * fDOrgS0 * bDTotS0 && \text{initial humus in top layer [gD/m}^2 \text{]} \\
sDDetS0 &= fDDetS0 * fDOrgS0 * bDTotS0 && \text{initial detritus in top layer [gD/m}^2 \text{]} \\
sDIMS0 &= bDTotS0 - sDHumS0 - sDDetS0 && \text{initial inorganic matter in top layer [gD/m}^2 \text{]}
\end{aligned}$$

Also the initial amounts of nutrients should be given by the user, in the form of P and N fractions in the organic matter [gP/gD and gN/gD], dissolved NH_4 and NO_3 and a fraction inorganic P [gP/gD]; the latter is divided in an adsorbed fraction *sPAIMS* (usually the bulk) and dissolved PO_4 . It is important, though not always easy, to start with good estimates of all these initial values. It is recommended that these are derived from actual measurements. The default values are listed here.

$$\begin{aligned}
sNH4S0 &= 0.02 && \text{initial dissolved N-NH}_4 \text{ in interstitial water [gN/m}^2 \text{]} \\
sNO3S0 &= 0.002 && \text{dissolved N-NO}_3 \text{ in interstitial water [gN/m}^2 \text{]} \\
cPDDet0 &= 0.0025 && \text{initial P fraction in detritus [gP/gD]} \\
cNDDet0 &= 0.025 && \text{initial N fraction in detritus [gN/gD]} \\
cPDHum0 &= 0.005 && \text{initial P fraction in humus [gP/gD]} \\
cNDHum0 &= 0.05 && \text{initial N fraction in humus [gN/gD]} \\
sPHumS0 &= cPDHum0 * sDHumS0 && \text{initial sediment humus [gP/m}^2 \text{]} \\
sNHumS0 &= cNDHum0 * sDHumS0 && \text{initial sediment humus [gN/m}^2 \text{]} \\
sPDetS0 &= cPDDet0 * sDDetS0 && \text{initial sediment detritus [gP/m}^2 \text{]} \\
sNDetS0 &= cNDDet0 * sDDetS0 && \text{initial sediment detritus [gN/m}^2 \text{]}
\end{aligned}$$

To comply with measurements, inorganic P is initialised as a fraction of the sediment dry-weight [gP/gD], and divided in an adsorbed (the bulk) and a dissolved part by a fixed fraction. (We refrained from an initialisation based on an ‘inverse’ Langmuir equation, which was considered as unnecessarily complex.)

$$\begin{aligned}
fPInorgS0 &= 0.0005 && \text{initial inorg. P fraction in sed. [gP/gD]} \\
fPAdsS0 &= 0.99 && \text{initial adsorbed fraction of inorg. P in sed. [-]} \\
sPAIMS0 &= fPAdsS0 * fPInorgS0 * bDTotS0 && \text{P adsorbed into inorg. matter in sediment [gP/m}^2 \text{]} \\
sPO4S0 &= (1.0 - fPAdsS0) * fPInorgS0 * bDTotS0 && \text{initial amount of dissolved P in sediment [gP/m}^2 \text{]}
\end{aligned}$$

Besides, a number of **derived variables** (total N, total P, etc.) are calculated because these variables are useful output and/or used in process equations. These are, for the sediment (recall that the prefix *o-* stands for concentration [g/m³]):

DW variables:

$$\begin{aligned}
aDTotS &= sDIMS + sDHumS + sDDetS && \text{total sediment (excl. biota) [g/m}^2 \text{]} \\
aRhoTotS &= aDTotS / cDepthS && \text{bulk density of sediment [g solid/m}^3 \text{ sediment]} \\
aRhoSolidS &= (sDIMS * cRhoIM + (sDHumS + sDDetS) * cRhoOM) / aDTotS && \text{average solid density [g/m}^3 \text{ solid]} \\
afDTotS &= 1.0 / (1.0 + bPorS / (1.0 - bPorS) * cRhoWat / aRhoSolidS) && \text{sediment dry-weight fraction [g solid/g sediment]} \\
afDOrgS &= (sDHumS + sDDetS) / aDTotS && \text{total organic fraction of sediment DW [-]} \\
afDDetS &= sDDetS / (sDHumS + sDDetS) && \text{detrital fraction of sediment organic DW [-]} \\
afDetTotS &= sDDetS / (sDIMS + sDHumS + sDDetS) && \text{detrital fraction of total sediment DW [-]}
\end{aligned}$$

P variables:

| | |
|---|---|
| $aPInorgS = sPO4S + sPAIMS$ | inorganic P in sediment [gP/m ²] |
| $aPTotAvailS = sPDetS + aPInorgS + aPPhytS$ | total P in sediment (excl. humus,vegetation) [gP/m ²] |
| $aPTotS = aPTotAvailS + sPHumS$ | total P in sediment (excl. vegetation) [gP/m ²] |
| $afPInorgS = aPInorgS / aDTotS$ | fraction inorganic P in sediment [gP/gD] |
| $afPTotS = aPTotS / aDTotS$ | total P fraction in sediment [gP/gD] |
| $afPO4S = sPO4S / aPTotAvailS$ | fraction dissolved P in sediment [-] |
| $oPO4S = sPO4S / cDepthS / bPorS$ | conc. dissolved P in interstitial water [gP/m ³] |

N variables:

| | |
|---|--|
| $aNDissS = sNH4S + sNO3S$ | total dissolved N in pore water [gN/m ²] |
| $aNkjAvailS = sNDetS + aNPhytS + sNH4S$ | kjeldahl N in sediment, excl. humus [gN/m ²] |
| $aNkjS = aNkjAvailS + sNHumS$ | kjeldahl N in sediment [gN/m ²] |
| $aNTotAvailS = aNkjAvailS + sNO3S$ | total N in sediment, excl. humus [gN/m ²] |
| $aNTotS = aNkjS + sNO3S$ | total N in sediment [gN/m ²] |
| $afNInorgS = aNDissS / aDTotS$ | fraction inorganic N in sediment [gN/gD] |
| $afNTotS = aNTotS / aDTotS$ | total N fraction in sediment [gN/gD] |
| $oNO3S = sNO3S / cDepthS / bPorS$ | conc. dissolved N-NO ₃ in interstitial water [gN/m ³] |
| $oNH4S = sNH4S / cDepthS / bPorS$ | conc. dissolved N-NH ₄ in interstitial water [gN/m ³] |
| $oNDissS = aNDissS / cDepthS / bPorS$ | dissolved N conc. in sediment [gN/m ³] |

Nutrient/DW ratios:

| | |
|-----------------------------|--|
| $rPDIMS = sPAIMS / sDIMS$ | adsorbed P on sediment IM [gP/gD] |
| $rPDHumS = sPHumS / sDHumS$ | P content of sediment OM [gP/gD] |
| $rNDHumS = sNHumS / sDHumS$ | N content of sediment OM [gN/gD] |
| $rPDDetS = sPDetS / sDDetS$ | P content of sediment detritus [gP/gD] |
| $rNDDetS = sNDetS / sDDetS$ | N content of sediment detritus [gN/gD] |

Overview of processes

The following abiotic and microbial processes are incorporated in *PCDitch* and will be discussed here:

- sedimentation (for IM and detritus) and resuspension (IM, detritus and nutrients) (§1.4.2)
- burial (IM, humus, detritus and nutrients) (§1.4.3)
- dredging (§1.4.4)
- mineralisation (detritus and humus) (§1.4.5)
- nitrification (NH₄) (§1.4.5)
- denitrification (NO₃) (§1.4.5)
- sorption (PO₄) and immobilisation (PO₄ in sediment) (§1.4.6)
- diffusion (nutrients and O₂) (§1.4.7)
- reaeration (O₂) (§1.4.8)

The formation of detritus or dissolved nutrients related to the mortality of phytoplankton and macrophytes are not discussed here but are discussed in the paragraphs on algae and macrophytes (§1.5 and §1.6). Concerning nitrogen, adsorption and atmospheric release of NH₄ are neglected, as well as nitrogen fixation by algae, water plants or bacteria.

1.4.2 Sedimentation and resuspension

In *PCDitch* the resuspension is by default set to zero, contrary to *PCLake* where detritus, phytoplankton, IM and AIM are subjected to resuspension. Settling is not affected by the wind like, contrary to *PCLake*. Settling (sedimentation) is defined only for the small-sized particles, i.e. the lutum fraction of IM and detritus, as well as phytoplankton. The sandy fraction of IM and humus particles are neglected, as they are assumed to settle down within a time scale of hours, shorter than the scope of the model.

Settling is modelled by a commonly used first-order equation. The settling velocity is different for the different seston components. The settling of IM is also made dependent on its lutum content. All settling

velocities are slightly influenced by temperature as well ($\Theta = 1.01$) to account for the effect on the viscosity of water. The maximum settling rates are different for the different seston components: IM, detritus and phytoplankton.

$$\begin{aligned}
 tDSetIM &= cVSetIM * cThetaSet^{Tm-20} * SQRT(fLutumRef / fLutum) * sDIMW && \text{settling of IM [gD/m}^2\text{/d]} \\
 tDSetDet &= cVSetDet * cThetaSet^{Tm-20} * sDDetW && \text{settling of detritus [gD/m}^2\text{/d]} \\
 tDSetPhyt &= cVSetPhyt * cThetaSet^{Tm-20} * sDPhytW && \text{settling of phytoplankton [gD/m}^2\text{/d]}
 \end{aligned}$$

The corresponding P and N fluxes are calculated as the dry-weight flux times the actual P/D and N/D ratios:

$$\begin{aligned}
 tPSetAIM &= sPAIMW / sDIMW * tDSetIM && \text{settling of P adsorbed to inorg. matter [gP/m}^2\text{/d]} \\
 tPSetDet &= rPDDetW * tDSetDet && \text{settling of detritus [gP/m}^2\text{/d]} \\
 tNSetDet &= rNDDetW * tDSetDet && \text{settling of detritus [gN/m}^2\text{/d]} \\
 tPSetPhyt &= rPDPhytW * tDSetPhyt && \text{settling of phytoplankton [gP/m}^2\text{/d]} \\
 tNSetPhyt &= rNDPhytW * tDSetPhyt && \text{settling of phytoplankton [gN/m}^2\text{/d]}
 \end{aligned}$$

1.4.3 Burial

In order to keep a fixed sediment thickness and closed nutrient cycles at the same time, a process of burial is defined. A net increase of sediment material is counteracted in the model by burial of a small layer of sediment, equally thick as the layer that had been added to it. This material is considered as buried in the deeper sediment and lost from the system. This thickness is calculated from the derivatives (excluding burial itself) of the three sediment components ($tDIMS$, $tDHumS$ and $tDDets$) (Van Drecht, pers. comm.):

$$vDeltaS = (tDIMS / cRhoIM + (tDHumS + tDDetS) / cRhoOM) / (1.0 - bPorS)$$

'sediment turnover depth' [m/d]

If the sediment turnover depth is positive, the burial fluxes ('Bur') of the three components are:

$$\begin{aligned}
 tDBurIM &= ((tDHumS + tDDetS) + (cRhoOM / cRhoIM) * tDIMS) / && \text{IM burial [gD/m}^2\text{/d]} \\
 &\quad ((sDHumS + sDDetS) / sDIMS + cRhoOM / cRhoIM) && \\
 tDBurOM &= (sDHumS + sDDetS) / sDIMS * tDBurIM && \text{OM burial [gD/m}^2\text{/d]} \\
 tDBurDet &= sDDetS / (sDHumS + sDDetS) * tDBurOM && \text{detritus burial [gD/m}^2\text{/d]} \\
 tDBurHum &= tDBurOM - tDBurDet && \text{humus burial [gD/m}^2\text{/d]}
 \end{aligned}$$

and the total burial loss is:

$$tDBurTot = tDBurIM + tDBurOM$$

total burial loss [gD/m²/d]

The corresponding nutrient fluxes are calculated according to the actual ratios and concentrations in the sediment, following the assumption of a mixed layer. For dissolved nutrients the equation is (with PO_4 as an example):

$$tPBurPO4 = sPO4S * (vDeltaS / cDepthS)$$

PO_4 burial [gP/m²/d]

Settled phytoplankton is assumed not to be buried. 'Negative burial', e.g. if resuspension temporarily exceeds sedimentation, does not occur in *PCDitch*, since the resuspension is zero by default.

Effect on water depth

A net rise of the sediment layer ($vDeltaS$ [m/d]) as described above, is reflected in a decrease of the water depth, defined as $vDeltaW$ [m/d]. This effect on the water depth may be partly counteracted by consolidation, which is not modelled. A switch parameter (*ConstDepth*), with the value 0 or 1, is available in the model to switch off the effect of burial on the water depth. If this effect is not switched off, then the relative water depth change due to sediment turnover and dredging is:

$$aRelDeltaW = (vDeltaW + vDredDepthW) / sDepthW \quad \text{water depth change [d}^{-1}\text{]}$$

This (potential) volume change does not affect the *amounts* of dissolved and particulate substances in the water column, but it does affect their *concentrations*. Their derivatives are therefore corrected for this water volume change; *e.g.*:

$$dPO4W = \dots - aRelDeltaW * sPO4W \quad \text{change in SRP concentration [gP/m}^3\text{/d]}$$

1.4.4 Dredging

In ditches, burial is an important process and implies that most ditches are dredged every 5 to 10 years to maintain the water depth and thus ensure their hydrological function. In *PCDitch* it is possible to include periodical dredging of the ditch every *x* years (given by the parameter *cDredInterval* [y]). A part of the sediment, including the water plants and the settled algae, is then removed, to re-establish a user-defined water depth (*cDepthRef*). A dredging efficiency *fEffDred*, default 0.95 [-], can be set, which applies to all model components that are affected by dredging, except for duckweed, which has a separate dredging efficiency (*fEffDredLemn*). The material removed is replaced by 'clean' soil material. Also, the length of the dredging period (*cLengDred* [d]) can be set, which effects the dredging rate:

$$\begin{aligned} akDredDepth &= (LOG(cDepthRef / aDepthStart)) / cLengDred && \text{deepening rate by dredging [d}^{-1}\text{]} \\ akDred &= (- LOG(1.0 - fEffDred)) / cLengDred && \text{removal rate by dredging [d}^{-1}\text{]} \\ akDredLemn &= (- LOG(1.0 - fEffDredLemn)) / cLengDred && \text{duckweed removal rate [d}^{-1}\text{]} \end{aligned}$$

The water depth change by dredging is:

$$vDredDepthW = akDredDepth * sDepthW \quad \text{deepening by dredging [m/d]}$$

The removal rate due to dredging is calculated as (e.g. for sediment detritus, and analogous for other sediment components (AIM, IM and Hum), water plants and settled algae)

$$tDDredDetS = akDred * sDDetS \quad \text{sed. detritus removal [gD/m}^2\text{/d]}$$

1.4.5 Mineralisation, nitrification, denitrification and their effect on oxygen conditions

Mineralisation

Following many other water quality models, the mineralisation of detritus has been described as simple as possible, by means of a first order, temperature dependent, rate. The temperature dependency follows the Arrhenius' equation: the rate increases exponentially with temperature.

In the water (for DDet, analogous for PDet and NDet):

$$wDMinDetW = kDMinDetW * cThetaMin^{Tm-20} * sDDetW \quad \text{mineralization rate of detritus [gD/m}^3\text{/d]}$$

In the sediment (for DDet, analogously for PDet and NDet):

$$tDMinDetS = kDMinDetS * cThetaMin^{Tm-20} * sDDetS \quad \text{mineralization rate of detritus [gD/m}^2\text{/d]}$$

The rates may differ for water and sediment, because the mechanisms may be different: usually mainly aerobic mineralisation takes place in the water (except for very polluted situations), in contrast to the sediment where there is a variety of electron acceptors in absence of oxygen. During mineralisation, the nutrients in the detritus are released as PO₄ or NH₄, while the dry-weight is assumed to be lost from the system. PO₄ and NH₄ are added to the pore water pool.

Denitrification

Denitrification is an important process by which nitrogen is lost from the system. It comprises the transformation of nitrate into volatile substances like molecular nitrogen, which is lost into the atmosphere. It occurs when nitrate is used as elektron acceptor for mineralisation of organic matter. The process is thus anaerobic and needs the presence of both organic carbon and nitrate. As it is a microbial process, it is temperature-dependent (Van Luin, 1997; Soetaert et al., 1995).

In *PCDitch*, denitrification is coupled to the anaerobic part of the mineralisation process. The nitrate dependency is described as a sigmoid function, with a half-saturation value estimated at 1-2 gN-NO₃/m³. Soetaert et al. (1995) report a value of 0.4 g/m³ for Michaelis-Menten kinetics.

In the water:

$$wNDenitW = NO3PerC * molNmolC * cCPerDW * sNO3W^{**2.0} / (hNO3Denit^{**2.0} + sNO3W^{**2.0})$$

denitrification flux [gN/m³/d]

In the sediment:

$$tNDenitS = NO3PerC * molNmolC * cCPerDW * oNO3S^{**2.0} / (hNO3Denit^{**2.0} + oNO3S^{**2.0})$$

denitrification flux [gN/m²/d]

The process normally is significant in the sediment layer only, but it may also play a role in the water column if the oxygen concentration drops to a very low value.

Nitrification

Nitrification is a microbial process involving the transformation of ammonium to nitrate. Obviously, this process is aerobic. It is modelled as a first order function of the ammonium concentration, dependent on temperature and corrected for the oxygen conditions. The nitrification constant is assumed to be much higher in the sediment than in the water as it is assumed that the density of nitrifying bacteria is higher. The corresponding oxygen consumption is calculated using a conversion factor of 2 mol O₂ per mol NH₄⁺ and the ratio of molecular weights.

$$uFunTmNitr = cThetaNitr^{** (uTm-20)}$$

temperature dependence [-]

In the water:

$$aCorO2NitrW = sO2W^{**2.0} / (hO2Nitr^{**2.0} + sO2W^{**2.0})$$

oxygen dependence of nitrif. [-]

$$wNNitrW = kNitrW * uFunTmNitr * aCorO2NitrW * sNH4W$$

nitrification flux [gN/m³/d]

$$wO2NitrW = O2PerNH4 * molO2molN * wNNitrW$$

O₂ flux due to nitrif. [gO₂/m³/d]

In the sediment:

$$tNNitrS = afOxySed * kNitrS * uFunTmNitr * sNH4S$$

nitrification flux [gN/m²/d]

$$tO2NitrS = O2PerNH4 * molO2molN * tNNitrS$$

O₂ flux due to nitrif. [gO₂/m²/d]

Oxygen

The oxygen consumption related to the mineralisation fluxes are calculated by means of two conversion factors, O₂/C and C/D, and corrected for the available oxygen concentration (as the oxygen consumption stops if the oxygen concentration is very low). In the water column, where the oxygen concentration is modelled dynamically, we followed the common Michaelis-Menten-type correction used in classical (Streeter & Phelps) biological oxygen demand (BOD) models:

$$aCorO2BOD = sO2W / (hO2BOD + sO2W)$$

BOD correction in water at low oxygen conc. [-]

$$wO2MinDetW = molO2molC * cCPerDW * aCorO2BOD * wDMinDetW$$

O₂ flux due to miner. [gO₂/m³/d]

with:

$$hO2BOD = 1.0$$

half-sat. oxygen conc. for BOD [gO₂/m³]

$$molO2molC = 32/12$$

ratio of mol.weights [gO₂/gC]

$$cCPerDW = 0.4$$

C content of organic matter [gC/gD]

The variable *aCorO2BOD* is also used in the equations for denitrification, nitrification and phosphorus adsorption in the water column (see below).

In the **sediment**, the oxygen conditions are modelled by an equilibrium equation, as the time scale of the oxygen dynamics in the sediment is that small (order of minutes) that a dynamic description is not useful (Lijklema, 1993). Following Lijklema (1993) and other models (Smits & Van der Molen, 1993; Asaeda & Van Bon, 1997; cf also Van Straten, 1982), the thickness of the aerobic sediment layer is described as a function of the oxygen concentration in the water, the oxygen diffusion rate and the sediment oxygen demand *per volume* of sediment:

$$aDepthOxySed = (2.0 * sO2W * akO2DifCor / tSOD) ** 0.5 \quad \text{oxygen penetration depth [m]}$$

with:

$$akO2DifCor = kO2Dif * uFunTmDif * cTurbDifO2 * bPorCorS \quad \text{O}_2 \text{ diffusion coefficient [m}^2\text{/d]}$$

$$tSOD = (molO2molC * cCPerDW * (1.0 - fRefrDetS) * tDMinDetS + O2PerNH4 * molO2molN * kNitrS * uFunTmNitr * sNH4S) / cDepthS \quad \text{sediment oxygen demand [gO}_2\text{/m}^3\text{/d]}$$

in which:

$$molO2molN = 32/14 \quad \text{ratio of mol.weights [gO}_2\text{/gN]}$$

$$molNmolC = 14/12 \quad \text{ratio of mol.weights [gN/gC]}$$

$$kO2Dif = 2.6D-5 \quad \text{mol. O}_2 \text{ diffusion constant [m}^2\text{/d]}$$

$$cThetaDif = 1.02 \quad \text{temperature coefficient for diffusion [1/e}^{oC}\text{]}$$

$$cTurbDifO2 = 2.0 \quad \text{bioturbation factor for O}_2 \text{ diffusion [-]}$$

$$bPorCorS = bPorS^{(bPorS + 1)} \quad \text{corrected porosity [-] (see §1.4.7)}$$

$$kNitrS = 1.0 \quad \text{nitrification rate constant in sediment [d}^{-1}\text{]}$$

$$cThetaNitr = 1.08 \quad \text{temperature coefficient of nitrification [1/e}^{oC}\text{]}$$

$$O2PerNH4 = 2.0 \quad \text{mol O}_2 \text{ used per mol NH}_4^+ \text{ nitrified [-]}$$

$$cDepthS = 0.1 \quad \text{sediment depth [m]}$$

The sediment oxygen demand (SOD) is thus estimated as the sum of the main potential oxygen-demanding processes, i.e. the mineralisation of organic matter and the nitrification of NH₄ to NO₃. This allows to relate the size of the aerobic layer to the amount of degradable organic matter and to allow for seasonal variation (aerobic layer is smaller in summer than in winter). This formulation, although a bit pragmatic in nature, results in a thickness of a few millimeters to centimeters, which is reasonably in line with observations in ditch sediments.

The thickness of the aerobic layer is divided by the (fixed) thickness of the sediment top layer to get the ‘proportion aerobic sediment’:

$$afOxySed = aDepthOxySed / cDepthS \quad \text{proportion aerobic sediment [-]}$$

It is assumed that this proportion of the mineralisation occurs aerobically; the oxygen consumption is again based on the conversion factors O₂/C and C/D:

$$tO2MinDetS = molO2molC * cCPerDW * afOxySed * (1.0 - fRefrDetS) * tDMinDetS \quad \text{oxygen consumption by mineralisation in sediment [gO}_2\text{/m}^2\text{/d]}$$

It is assumed that a small part *fRefrDetS* [-] (default 0.15) of the decomposed material in the sediment is transformed into humus. The humus component itself may be subject to (further) mineralisation if exposed to oxygen, although at a very low rate *kDMinHum* in the order of 10⁻⁵ [d⁻¹] (Hendriks, 1991):

$$tDMinHumS = kDMinHum * uFunTmMinS * afOxySed * sDHumS \quad \text{decomposition of upper sediment humus [gDW/m}^2\text{/d]}$$

and analogous equations for N and P in humus. The same variable *afOxySed* is used in the equations for denitrification, nitrification and phosphorus adsorption in the sediment, processes that are highly dependent on the oxygen conditions.

This description is a simplification to avoid the – rather complicated and calculation time consuming – description of several sediment layers, with vertical transport between them, as is done in many sediment models (e.g. Smits & Van der Molen, 1993). Typically, going from top to bottom, one encounters a small aerobic layer, a small denitrification layer, a sulphate reduction layer and a methanogenic layer, depending on the type of elektron acceptor for mineralisation. The formulation in *PCDitch* is based on an ‘aerobic fraction’ of the sediment top layer for those processes where this is needed, maintaining the assumption of a mixed top layer as far as possible, without defining exact ‘layers’. Arguments in favour of this approach are the fact that, in shallow surface waters, the sediment top layer is often disturbed, and the observation that aerobic and anaerobic processes are not always neatly located in layers but rather in intertwined ‘hot spots’ (e.g. Van Luin, 1997).

1.4.6 Sorption and immobilization of phosphorus

Sorption

Dissolved P may adsorb onto inorganic matter, especially when this consists of clay. This process acts as a 'buffer' for the availability of phosphorus for primary production. It is assumed that the adsorbed fraction is in reversible chemical equilibrium with the dissolved state. Although also adsorption of P onto organic matter has been described in some cases (e.g. Rijkeboer et al., 1991), this process is neglected in the model. The sorption process is defined in the model as an instantaneous, reversible binding of phosphorus to an adsorbent. In reality, it might be a lumped process involving a variety of different chemical processes, while in some cases, a part of the phosphorus binding might be explained by the activity of detritus-bound bacteria.

The equilibrium value is determined by the adsorption isotherm, defined as the relation between the dissolved P concentration and the amount of adsorbed P per gram adsorbent [gP/gD] at equilibrium. The total amount of adsorbed P, expressed as [gP/m²] in the sediment or [gP/m³] in the water, thus equals the product of the relative adsorption (as given by the isotherm) and the amount of adsorbent.

For the relative adsorption, the generally used Langmuir isotherm is used, which is a Monod-type equation. The relation is about linear at low phosphorus concentrations, while at higher concentrations, the curve flattens and approaches a maximum. The isotherm is defined by the maximum adsorption capacity, *bPAdsMax* [gP/gD] and the affinity *aKPAds* [gP/m³]. The affinity equals the reciprocal half-saturation value, which is the quotient of the maximum adsorption and the initial slope. The use of a linear adsorption isotherm would simplify the model, but is allowed only for substances always present in low concentrations, like micropollutants. Phosphorus concentrations in sediments can easily be so high that the maximum adsorption capacity is reached. This maximum mainly depends on the iron and aluminium contents of the adsorbent, as these are the main adsorbing elements (e.g. Lijklema, 1980). The adsorption is influenced by a number of environmental conditions, like the redox conditions and the pH: only oxidised forms of iron adsorb phosphorus. This is modelled by means of the aerobic fraction of the layer. The entire water column is in general aerobic, whereas the thickness of the aerobic sediment layer is often restricted to 1-2 mm. In mathematical terms, these relations are expressed as follows:

In the water:

$$\begin{aligned}
 aPAdsMaxW &= cRelPAdsD + aCorO2BOD * cRelPAdsFe * fFeDIM + cRelPAdsAl * fAlDIM \\
 &\quad \text{max. P adsorption per g inorg. matter in water [gP/gD]} \\
 aKPAdsW &= (1.0 - fRedMax * (1.0 - aCorO2BOD)) * cKPAdsOx \\
 &\quad \text{P adsorption affinity, corrected for redox conditions [m}^3\text{/gP]} \\
 aPIsoAdsW &= aPAdsMaxW * aKPAdsW * sPO4W / (1.0 + aKPAdsW * sPO4W) \\
 &\quad \text{P adsorption isotherm onto inorg. matter in sediment [gP/gD]} \\
 aPEqIMW &= aPIsoAdsW * sDIMW \\
 &\quad \text{equilibrium conc. [gP/m}^3\text{]} \\
 wPSorpIMW &= kPSorp * (aPEqIMW - sPAIMW) \\
 &\quad \text{sorption flux in water [gP/m}^3\text{/d]}
 \end{aligned}$$

In the sediment:

$$\begin{aligned}
 aPAdsMaxS &= cRelPAdsD + afOxySed * cRelPAdsFe * fFeDIM + cRelPAdsAl * fAlDIM \\
 &\quad \text{max. P adsorption per g inorg. matter in sediment [gP/gD]} \\
 aKPAdsS &= (1.0 - fRedMax * (1.0 - afOxySed)) * cKPAdsOx \\
 &\quad \text{P adsorption affinity, corrected for redox conditions [m}^3\text{/gP]} \\
 aPIsoAdsS &= aPAdsMaxS * aKPAdsS * oPO4S / (1.0 + aKPAdsS * oPO4S) \\
 &\quad \text{P adsorption isotherm onto inorg. matter in sediment [gP/gD]} \\
 aPEqIMS &= aPIsoAdsS * sDIM \\
 &\quad \text{equilibrium amount [gP/m}^2\text{]} \\
 tPSorpIMS &= kPSorp * (aPEqIMS - sPAIMS) \\
 &\quad \text{sorption [gP/m}^2\text{/d]}
 \end{aligned}$$

with:

| | |
|--------------|---|
| $cRelPAdsD$ | max. P adsorption per gram dry-weight [gP/gD] |
| $cRelPAdsFe$ | max. P adsorption per gram iron [gP/gFe] |
| $cRelPAdsAl$ | max. P adsorption per gram aluminium [gP/gAl] |
| $fFeDIM$ | iron content of IM [gFe/gD] |
| $fAlDIM$ | aluminium content of IM [gAl/gD] |
| $afOxySed$ | proportion aerobic sediment [-] |

Immobilisation

The model provides the option of defining a maximum PO_4 concentration, $cPO4Max$ [gP/m³], in the interstitial water, above which phosphorus is lost by irreversible chemical immobilisation. The equation is:

$$tPChemPO4 = \text{MAX}(0.0, kPChemPO4 * (oPO4S - cPO4Max)) \quad \text{chem. loss of interstitial P [gP/m}^2\text{/d]}$$

in which $kPChemPO4$ [d⁻¹] is a rate constant which is set at 0.03 (Bril, 1996) and the maximum P concentration is set at 1 gP/m³.

1.4.7 Diffusion across the sediment-water interface

Dissolved inorganic phosphorus, ammonium and nitrate can move from the pore water to the water column by diffusion across the sediment-water interface. The diffusion fluxes can be upward (defined as positive in the model) or downward (negative). In most cases, however, phosphorus and ammonium diffuse upward, whereas nitrate diffuses downward. Upward diffusion means *release* of nutrients from the sediment.

The fluxes depend on the concentration gradient between the two compartments, which is approximated in the model by the difference in concentration divided by the diffusion distance, $aDepthDif$ [m], defined at half the thickness of the modelled sediment layer. The equation for phosphorus is (analogous to the equations for ammonium and nitrate):

$$tPDifPO4 = kPDifPO4 * uFunTmDif * cTurbDifNut * bPorCorS * (oPO4S - sPO4W) / aDepthDif$$

diffusion flux of dissolved P from sediment to water [gP/m²/d]

in which:

| | |
|------------------------------------|---|
| $kPDifPO4$ | diffusion constant of dissolved P [m ² /d] |
| $cThetaDif$ | temperature parameter [(e ^{°C}) ⁻¹] |
| $cTurbDifNut$ | bioturbation factor [-] |
| $aDepthDif = 0.5 * cDepthS$ | diffusion distance [m] |
| $bPorCorS = bPorS * (bPorS + 1.0)$ | sediment porosity, corrected for tortuosity [-] |

The latter equation includes a correction factor for the diffusion path in the sediment. This equation is used in stead of the usual formulation of porosity divided by the squared tortuosity, a parameter which is mostly unknown. The molecular diffusion constant is 6.2·10⁻⁵ m²/d for PO₄, 8.6·10⁻⁵ m²/d for NO₃ and 11.2·10⁻⁵ m²/d for NH₄.

1.4.8 Reaeration

Reaeration, the diffusion of oxygen across the water surface, is proportional to the oxygen deficit with respect to the saturation concentration, which is temperature dependent (Rich, 1973, ref. in Portielje & Lijklema, 1995):

$$uO2Sat = 14.652 - 0.41022 * Tm + 7.991 \cdot 10^{-3} * Tm^2 - 7.7774 \cdot 10^{-5} * Tm^3$$

oxygen saturation concentration [gO₂/m³]

$$tO2Reaer = kReaer * (uO2Sat - sO2W) * uFunTmReaer * uFunLemnReaer$$

reaeration flux of O₂ into the water [gO₂/m²/d]

with

$$aFunLemnAer = MAX(0.0, 1.0 - (kLemnAer * sDLemn))$$

hampering of reaeration by duckweed [-]

As can be seen, reaeration is assumed to be hampered by duckweed (Marshall, 1981; Portielje & Lijklema, 1995). The reaeration constant $kReaer$ [m/d] depends on the temperature (Tm) and the wind speed ($uVWind$). The temperature influence is described as an exponential function with a 'theta' of 1.024 [1/e^{°C}] (Downing & Truesdale, 1955). The wind influence is described using the empirical relation derived by Banks & Herrera (1977):

$$kReaer = 0.727 * uVWind^{0.5} - 0.371 * uVWind + 0.0376 * uVWind^2$$

reaeration coefficient [m/d]

The model uses by default a constant wind speed of 5 m/s, giving a reaeration constant of 0.71 [m/d], but it is possible to use a measured time-series of the wind speed.

1.5 Phytoplankton

1.5.1 Overview

The phytoplankton comprises in reality both planktonic, epiphytic and filamentous species, the latter often being dominant in biomass. For simplicity, in *PCDitch* they have been lumped into one group (which may be split if desired, however), abbreviated as 'Phyt'. Phytoplankton is considered to be homogeneously distributed over the water column ('PhytW'). The phytoplankton may settle to form benthic algae ('PhytS'). The settling rate is user defined and is unaffected by wind or flow velocity. It is assumed that the settled phytoplankton is not active any more (no uptake and production), that respiration goes on, and that the mortality rate is higher.

As stated before, phytoplankton is modelled in three elements: dry-weight (D), P and N. The specific nutrient contents of the algae are modelled dynamically; nutrient uptake and production are modelled as separate processes. The nutrient-to-dry-weight ratios are simply given by:

$$rPDPhyt = sPPhyt / sDPhyt$$

P/D ratio [gP/gD]

$$rNDPhyt = sNPhyt / sDPhyt$$

N/D ratio [gN/gD]

The biomass of phytoplankton in the water column is described by the following differential equations:

$$dDPhytW/dt = production - respiration - mortality - settling - grazing \pm transport$$

[gD/m³/d]

$$dPPhytW/dt = uptake - excretion - mortality - settling - grazing \pm transport$$

[gP/m³/d]

$$dNPhytW/dt = uptake - excretion - mortality - settling - grazing \pm transport$$

[gN/m³/d]

For the settled algae (expressed in [g/m²]):

$$dDPhytS/dt = - respiration - mortality + settling - grazing$$

[gD/m²/d]

$$dPPhytS/dt = - excretion - mortality + settling - grazing$$

[gP/m²/d]

$$dNPhytS/dt = - excretion - mortality + settling - grazing$$

[gN/m²/d]

The algal processes thus are (see Figure 2):

- nutrient uptake (§1.5.2)
- production (§1.5.3)
- respiration and nutrient excretion (§1.5.4)
- settling and resuspension (§1.5.5)
- natural mortality (§1.5.5)
- grazing loss (§1.5.5)

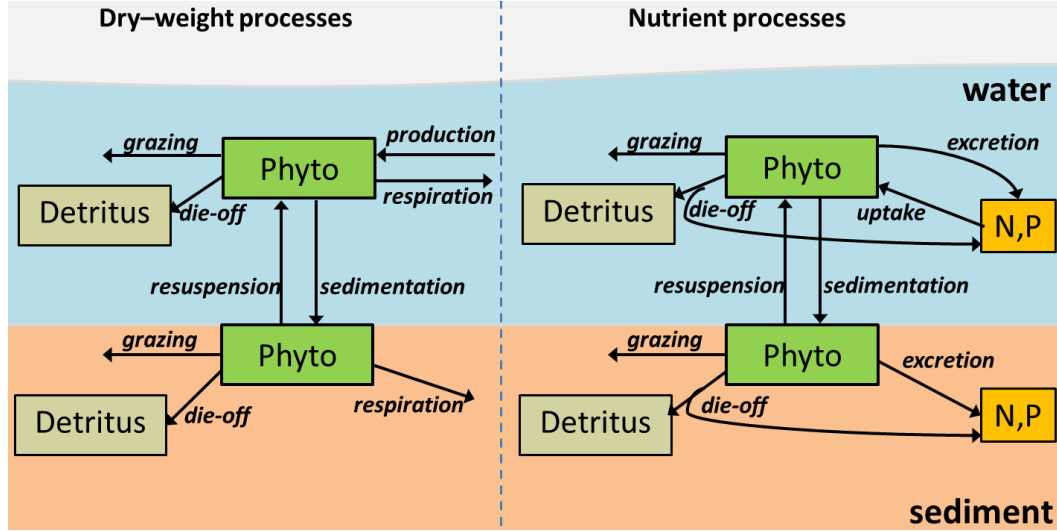


Figure 2: Phytoplankton processes

1.5.2 Nutrient uptake

The modelling of the nutrient uptake is worked out here for *phosphorus*. The specific phosphorus uptake rate, that is the uptake rate per unit of biomass, is dependent on both the nutrient demand of the phytoplankton, defined by its actual nutrient content, and the availability of dissolved phosphorus in its environment. This is modelled as follows.

The *maximum* specific uptake rate is dependent on the actual nutrient content of the algae, the P/D ratio. If this ratio is low (close to the minimum value), the maximum uptake rate is high (close to the intrinsic maximum rate at the current temperature), while the rate drops to near-zero if the P/D ratio is close to its maximum value:

$$aVP_{UptMaxCorPhyt} = cVP_{UptMaxPhyt} * uFunTmPhyt * \frac{cPD_{PhytMax} - rPD_{Phyt}}{cPD_{PhytMax} - cPD_{PhytMin}}$$

maximum P uptake rate [gP/gD/d]

with $cPD_{PhytMin}$ [gP/gD] and $cPD_{PhytMax}$ [gP/gD] the minimum and maximum phosphorus content of the plants, respectively.

The temperature function is modelled as an optimum curve, implemented as a Gaussian function, defined by an optimum temperature $cTmOpt$ and is normalized to 1.0 at the reference temperature of 20 °C:

$$uFunTmPhyt = EXP(-0.5/cSigTmPhyt^2 * ((uTm - cTmOptPhyt)^2 - (cTmRef - cTmOptPhyt)^2))$$

temperature function of phytoplankton group [-]

The specific uptake rate is then described as a modified Monod-type function of the SRP concentration. The modification means that the phosphorus *affinity*, the slope of the curve when SRP is close to zero, is taken as

constant for all values of V_{\max} , in accordance with experimental data (Riegman & Mur, 1984). The specific uptake rate is:

$$aVPUptSpecW = aVPUptMaxCorSpec * \frac{sPO4W}{\frac{aVPUptMaxCorSpec}{cAffPUptSpec} + sPO4W}$$

specific P uptake rate [gP/gD/d]

This formulation implies that the half-saturating SRP concentration is not a constant, but is depending on V_{\max} :

$$ahPUptPhyt = aVPUptMaxCorPhyt / cAffPUptPhyt \quad \text{half-saturating SRP concentration [gP/m}^3\text{]}$$

The resulting P uptake flux is the product of the specific uptake rate and the biomass:

$$tPUptPhyt = aVPUptPhyt * sDPhytW \quad \text{P uptake flux [gP/m}^3\text{/d]}$$

The uptake of *nitrogen* is modelled in the same way, with one extra feature, namely the form in which nitrogen is taken up, as nitrate or as ammonium. It is assumed that the plants have a strong preference for ammonium, because this is energetically more advantageous. The N uptake rates are based on total SRN in the water, and are then divided over the two N fractions according to the preference equation taken from the EPA WASP4 model (Ambrose et al., 1988). The fraction of the N uptake absorbed as ammonium, $afNH_4UptPhytW$ [-], equals:

$$afNH_4UptPhytW = \frac{sNH_4W * sNO_3W}{(ahNUptPhyt + sNH_4W) * (ahNUptPhyt + sNO_3W)} + \frac{sNH_4W * ahNUptPhyt}{(sNH_4W + sNO_3W) * (ahNUptPhyt + sNO_3W)}$$

ammonium uptake fraction [-]

This equation only states that nitrogen is absorbed preferably as ammonium. Only when the ammonium concentration drops to low values, the plants switch to nitrate as main nitrogen source. A technical advantage of this preference function is that it requires no extra parameters. The relation between internal nutrient content and growth rate is described in the next paragraph.

1.5.3 Production

By production (or growth) is meant increase in biomass. It is expressed in [g/m²/d]. Growth respiration (photorespiration) is included in the definition, but maintenance respiration (dark respiration) is not; this is described as a separate process (see §1.5.4). In the model, the production is a function of the following factors:

- maximum growth rate (defined at 20 °C)
- water temperature
- day length
- light interception at the water surface
- under-water light climate (extinction coefficient)
- P content (P/D ratio) of the phytoplankton, representing P limitation
- N content (N/D ratio) of the phytoplankton, representing N limitation

Maximum growth rate

The *maximum growth rate* is the maximum increase in biomass per gram total phytoplankton biomass per day, on an exponential base: $D(t) = EXP(cMuMax * t)$. The maximum growth rate is defined at a temperature of 20 °C.

Temperature

The temperature function is already described in §1.5.2: an optimum curve, implemented as a Gaussian function, defined by an optimum temperature $cTmOpt$ and normalized to 1.0 at the reference temperature of 20 °C:

$$uFunTmPhyt = EXP(-0.5/cSigTmPhyt^2 * ((uTm - cTmOptPhyt)^2 - (cTmRef - cTmOptPhyt)^2))$$

temperature function of phytoplankton [-]

Light function

The limitation factor for under-water light is modelled as a Monod-type P-I curve, integrated over the depth trajectory in which the phytoplankton grows, and averaged over 24 hours (Jørgensen, 1980). Light attenuation with increasing depth in the water column is described by the well known Lambert-Beer law:

$$aLPAR(z) = uLPAR(0) * EXP(- aExtCoef * z)$$

light intensity at depth z [W/m² PAR]

with:

$$uLPAR(0) = LOut * fPAR * (1 - fRefl)$$

light intensity just under water surface [W/m² PAR]

in which $LOut$ [W/m²] is the light intensity above the water surface, $fPAR$ [-] the fraction photosynthetically active radiation, 0.48, $fRefl$ [-] the fraction reflected at the surface (about 0.1) and $aExtCoef$ [m⁻¹] the extinction coefficient. The extinction coefficient is the sum of the background extinction (the extinction of the water itself and dissolved substances) and the contributions of inorganic matter, detritus, algae and submerged water plants:

$$aExtCoef = cExtWat + aExtIM + aExtDet + aExtPhyt + aExtVeg$$

extinction coefficient [m⁻¹]

The contributions of the different components to the extinction are linearly related to their concentrations or submerged biomass density, the proportionality constant being the specific extinction, $cExtSpPhyt$ [m²/g]. For example:

$$aExtPhyt = cExtSpPhyt * sDPhytW$$

contribution of phytoplankton to extinction coefficient [m⁻¹]

The contribution of submerged vegetation is based on the submerged shoots (see §1.6.4):

$$aExtVeg = cExtSpVeg * aDSubVeg / sDepthW$$

contr. of submerged vegetation to extinction coef. [m⁻¹]

In general, the specific extinction of macrophytes is much less than that of phytoplankton. To reduce complexity, the extinction coefficient is based on the total biomass present in the water column, assuming that the biomass is homogeneously distributed within the water column. This assumption might introduce a small inaccuracy in some cases regarding the light intensity encountered by certain vegetation, but the total light absorption in the entire water column is exactly the same with or without this simplification.

The extinction coefficient without the contribution of the water plants is called $aExtCoefOpen$ [m⁻¹]. This variable is used for conversion to Secchi depth, because the Secchi depth is usually measured in open water:

$$aSecchi = MIN(sDepthW, aPACoef / aExtCoefOpen)$$

Secchi depth [m]

with $aPACoef$ [-] the Poole-Atkins coefficient, which depends, in a certain range, negatively on the concentration of organic matter (= the sum of algae and detritus) in the water, $oDOMW$ [gD/m³]. The slope parameter is called $hPACoef$:

$$aPACoef = cPACoefMin + (cPACoefMax - cPACoefMin) * hPACoef / (hPACoef + oDOMW)$$

Poole-Atkins coefficient [-]

The Secchi depth is merely an additional output variable of the model; calculations of production are based on the extinction coefficient itself.

The light limitation on the phytoplankton growth is implemented in two different ways:

- assuming light inhibition (Steele equation)
- neglecting light inhibition (Lehman light function)

The user can choose which implementation is to be used. Accounting for photo-inhibition at high light intensities, the light limitation function is based on the Steele equation:

$$aLLimPhyt = EXP(1.0) / (aExtCoef * sDepthW) * (EXP(- aLPARBot / (cLOptRefPhyt * uFunTmPhyt)) - EXP(- uLPAR0 / (cLOptRefPhyt * uFunTmPhyt)))$$

light limitation function [-]

with $cLOptRef$ the optimum light intensity [W/m^2]. Neglecting light inhibition, the light limitation function is described by an integral function based on a Monod-type production curve (Lehman light function):

$$aLimPhyt = 1.0 / (aExtCoef * sDepthW) * LOG((1.0 + uLPAR0 / uhLPhyt) / (1.0 + aLPARBot / uhLPhyt))$$

light limitation function [-]

with:

$$\begin{aligned} uLPAR0 & \text{light at the water surface [W/m}^2 \text{ PAR]} \\ aLPARBot &= uLPAR0 * EXP(- aExtCoef * sDepthW) \text{light at the bottom [W/m}^2 \text{ PAR]} \\ uhLPhyt &= hLRefPhyt * uFunTmPhyt \text{half saturating light intensity at current temp. [W/m}^2 \text{ PAR]} \end{aligned}$$

Both light limitation functions include a ‘self-shading’ effect, as the extinction coefficient is partly dependent on the phytoplankton concentration itself.

Like the maximum growth rate, also the half-saturating light intensity is dependent on the temperature. This implies that temperature has only little impact as long as the in situ light intensity is very low. This generally found phenomenon can be explained by the fact that in this range, photochemical reactions predominate, while at light saturation, the rate is determined by enzymatic reactions (e.g. Wetzel, 1983, p. 354). This permits the plants to grow also in winter, when both light and temperature are low.

Averaging the production over the day takes places in a very simplified way, by multiplying the growth rate with the day length, $ufDay$ [-], which is calculated according to a cosine function (with $Time$ = time in days):

$$ufDay = 0.5 - 0.3 * COS(2\pi * (Time + 10) / 365)$$

day length [h/24h]

The combined growth rate equation, including the influence of temperature and light, based on the entire biomass [d^{-1}], is described as:

$$aMuTmLPhyt = ufDay * (1.0 - afCovSurfVeg) * aLLimPhyt * uFunTmPhyt * cMuMaxPhyt$$

growth rate at current light and temp. [d^{-1}]

Nutrient limitation

Nutrient limitation is modelled by means of the well-known Droop equation (see for instance Riegman & Mur, 1984), which describes the dependence of the growth rate on the nutrient content of algae. The growth rate rapidly increases above the minimum content. For phosphorus, the equation is:

$$aPLimPhyt = \left(1.0 - \frac{cPDPhytMin}{rPDPhyt} \right) * \frac{cPDPhytMax}{cPDPhytMax - cPDPhytMin}$$

Droop function (P) for the phytoplankton growth rate [-]

with $cPDPhytMin$ [gP/gD] and $cPDPhytMax$ [gP/gD] the minimum and maximum phosphorus content of the cells, respectively. The equation for nitrogen is analogous.

It is assumed that the *minimum* of the nutrient equations determines the growth rate (Liebig's law of the minimum), and that the nutrient limitation is multiplicative with the light reduction function:

$$\begin{aligned} aNutLimPhyt &= MIN [aPLimPhyt, aNLimPhyt] && \text{nutrient limitation function [-]} \\ aMuPhyt &= aNutLimPhyt * aMuTmLPhyt && \text{growth rate [d}^{-1}\text{]} \end{aligned}$$

Besides in dry-weight or nutrients, algal biomass may also be expressed as the concentration of chlorophyll-*a*. The chlorophyll-*a* content of the phytoplankton, a derived variable in the model, is assumed to be variable, being higher in case of a more severe light limitation (Riegman, 1985):

$$rChDPhyt = cChDPhytMax - (cChDPhytMax - cChDPhytMin) * aLLimPhyt$$

chlorophyll-*a*/DW ratio [g/g]

1.5.4 Respiration and nutrient excretion

In general, respiration can be divided in growth respiration (or photorespiration), which is related to growth, and maintenance respiration (also called 'dark respiration'), which denotes the energy required for maintenance. In *PCDitch*, only maintenance respiration is explicitly modelled, because growth respiration is incorporated implicitly in the growth rate. The maintenance respiration is modelled as a temperature dependent first order process and is modelled identically for the water and the sediment algae:

$$\begin{aligned} ukDRespTmPhyt &= kDRespPhyt * uFunTmPhyt && \text{maintenance respiration rate at current temp. [d}^{-1}\text{]} \\ tDRespPhyt &= ukDRespTmPhyt * sDPhyt && \text{maintenance respiration flux [gD/m}^3\text{/d]} \end{aligned}$$

Together with the respiration fluxes, nutrient fluxes are defined, called 'excretion'. It is assumed that they are proportional to the dry-weight fluxes if the nutrient content of the cells is high, but are relatively lower if the nutrient content is low: saving of sparse nutrients. The excretion process is modelled as follows (and similar for the settled algae):

$$wPExcrPhytW = (2.0 * rPDPhytW) / (cPDPhytMax + rPDPhytW) * rPDPhytW * wDRespPhytW$$

P excretion of phytoplankton [gP/m³/d]

1.5.5 Settling, resuspension, mortality and grazing

Settling of phytoplankton is already discussed in §1.4.2. It is described as a first-order process, the rate being the user-defined settling velocity [m/d], corrected for the water temperature and divided by the water depth. Resuspension of sediment algae has been set to zero in *PCDitch*.

Natural mortality is also described as a first-order process, where the mortality rates for the settled algae are assumed to be higher than for algae in the water column:

$$\begin{aligned} wDMortPhytW &= kMortPhytW * sDPhytW && \text{mortality of phytoplankton [g/m}^3\text{/d]} \\ tDMortPhytS &= kMortPhytS * sDPhytS && \text{mortality of settled phytoplankton [g/m}^2\text{/d]} \end{aligned}$$

Grazing of phytoplankton is described as first-order process and is approximated by a user-defined loss constant (*kLossPhyt*) which is corrected for the water temperature:

$$wDLossPhyt = kLossPhyt * uFunTmLoss * sDPhytW$$

grazing loss of phytoplankton [gD/m³/d]

The grazing loss constant is set to zero or a low value, because filamentous algae that are often dominant in ditches are not heavily grazed. The corresponding P and N fluxes for phytoplankton loss by grazing and mortality are calculated as the dry-weight flux times the actual P/D and N/D ratios.

1.6 Water plants

1.6.1 Functional groups

PCDitch describes six functional groups of water plants. The definition of the plant groups is primarily based on the layer(s) in which they grow and the layer(s) from which they take up nutrients. The classification into 16 growth forms given by Den Hartog & Segal (1964) and Den Hartog & Van der Velde (1988) has been used as a template. Several groups were lumped, while others were left out because they are not common in ditches. Free-floating (e.g. duckweed) and submerged plants were of course included; the latter were split into rooted and a non-rooted group, with charophytes (also rooted) as macro-algae as a special group. Helophytes (emergent plants) and floating-leaved plants (Nymphaeids) are included because of their role in the nutrient household and light interception. In practice, the natural succession to helophytes is impeded by regular ditch management. The groups are defined by the relative size of emergent, floating, submerged and root fractions, and their vertical distribution. The number and the definition of the plant groups have been made flexible. The default configuration and their characteristics are:

- Submerged plants, divided into:
 - Rooted submerged angiosperms (abbreviated as '*Elod*'). This group comprises the elodeid and potamid growth forms. Assumed to fill the entire water column, nutrient uptake from both water and sediment. Root fraction set to 0.1 in summer, 0.6 in winter.
 - Charophytes ('*Char*'). Confined to the lower half of the water column. Root fraction set to 0.05 in summer, 0.1 in winter. They were distinguished because of their special character as macro-algae.
 - Non-rooted submerged angiosperms ('*Cera*'). Canopy-formers, confined to the upper half of the water column. Nutrient uptake from the water only.
- Non-rooted, floating plants: duckweed ('*Lemn*'). This group includes floating fern (*Azolla*) as well. Nutrient uptake from the water only.
- Rooted plants with floating or emergent leaves
 - Floating-leaved plants: Nymphaeids ('*Nymp*'). Nutrient uptake from the sediment, root fraction set to 0.75 in summer, 0.95 in winter.
 - Emergent plants: helophytes ('*Helo*'). Nutrient uptake from the sediment, root fraction set to 0.5 in summer, 0.8 in winter.

Each group is defined by the fractions of the biomass that are present in the sediment (the roots), in the water column (submerged part), on the water surface (the floating part), and above the water (the emergent part). Their sum is, of course, always 1.0. Optionally, the submerged fraction (if existing) can be assumed homogeneously distributed over the water column, or restricted to only a part of it. For the current model with six plant groups, these parameters are summarized in Table 3.

Table 3: Parameters that define the six water plant groups in *PCDitch*

| parameter | Elod | Char | Cera | Lemn | Nymp | Helo |
|---------------------------------|--------------|------------|------------|---------|---------|---------|
| fRoot summer | 0.1 | 0.05 | 0 | 0 | 0.75 | 0.5 |
| fRoot winter | 0.6 | 0.1 | 0 | 0 | 0.95 | 0.8 |
| <i>proportion of shoots:</i> | | | | | | |
| emergent | 0 | 0 | 0 | 0 | 0 | 1 |
| floating | 0 | 0 | 0 | 1 | 1 | 0 |
| submerged | 1 | 1 | 1 | 0 | 0 | 0 |
| distribution of submerged parts | water column | lower half | upper half | n.appl. | n.appl. | n.appl. |

1.6.2 General aspects

As stated before, macrophytes are modelled in three elements: dry-weight (D), P and N, always expressed in [g/m²]. For comparison with field data, the biomass values are also converted to cover percentages by means

of a fixed conversion factor, with a maximum of 100 % cover. Most processes are modelled in the same way for each plant group, although with distinct parameter values. The overall differential equations are (where the vegetation is denoted by ‘Veg’, which can be replaced by Elod, Char, Cera, Lemn, Nymf and Helo):

For biomass:

$$dDVeg/dt = tDProdVeg - tDRespVeg - tDMortVeg \pm tDMigrVeg - tDGrazBird \quad [gD/m^2/d]$$

(= production - respiration - mortality \pm migration - bird grazing)

For nutrients:

$$dPVeg/dt = tPUptVeg - tPExcrVeg - tPMortVeg \pm tPMigrVeg - tPGrazBird \quad [gP/m^2/d]$$

$$dNVeg/dt = tNUptVeg - tNExcrVeg - tNMortVeg \pm tNMigrVeg - tNGrazBird \quad [gN/m^2/d]$$

(= uptake - excretion - mortality \pm migration (- bird grazing))

By modelling the vegetation in three units, the specific nutrient contents of the plants are modelled dynamically, which allows for a dynamic stoichiometry. Hence, nutrient uptake and production are modelled as separate processes, equally to the phytoplankton. The nutrient-to-dry-weight ratios are simply given by:

$$rPDVeg = sPVeg / sDVeg \quad \text{P/D ratio of vegetation } [gP/gD]$$

$$rNDVeg = sNVeg / sDVeg \quad \text{N/D ratio of vegetation } [gN/gD]$$

These ratios refer to the plant as a whole; no distinction is made between different parts of the plant, like roots or leaves. It is assumed that the nutrients are distributed homogeneously over the whole plant (instantaneous reallocation). The biomass is divided in an under-ground part (roots) (*afRootVeg*) and an above-ground part (shoots) (*afShootVeg*), and it is assumed that the latter is homogeneously divided over the water column. Hence, the modelled vegetation mimicks plants with overwintering parts.

Seasonality is modelled in a simplified way by assuming a high root fraction in the winter period and a low one during the growing season (see Table 3). The switch between both values in spring and autumn mimicks germination, allocation and reallocation processes, which are not explicitly modelled. It is assumed that allocation of biomass to the shoots in spring starts when the water temperature exceeds a certain value (default 10 °C). The biomass is then gradually (default in 15 days) redistributed over roots and shoots until the summer ratio is reached. The opposite takes in place at a predefined day in autumn, default mid-September, except for duckweed (Mid-October). These functions have been designed as part of a sinusoid to make the transition fluently. The second seasonal aspect is a temporarily enhanced mortality in autumn (see §1.6.6).

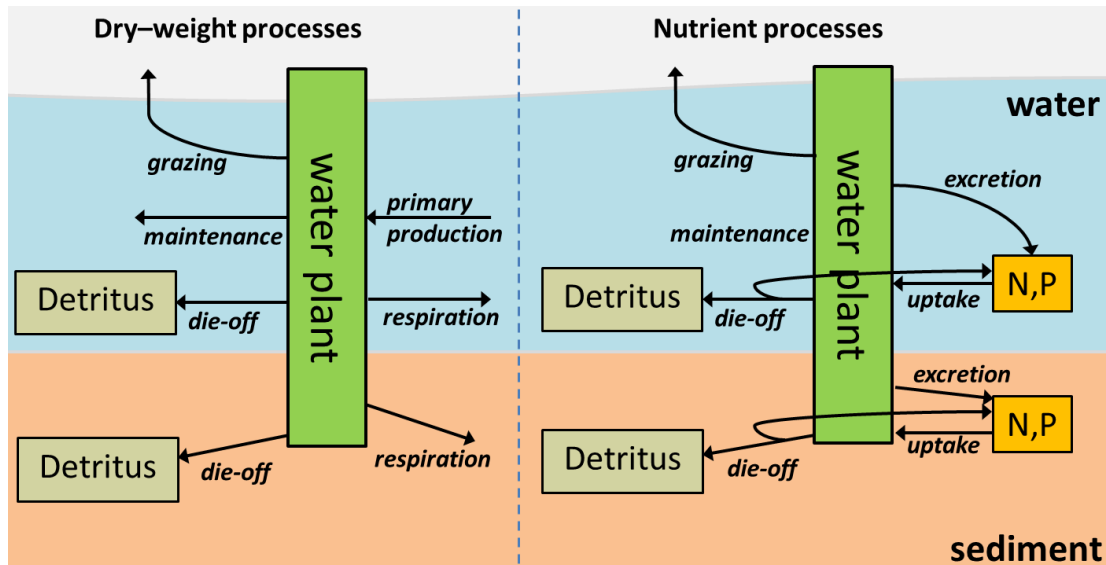


Figure 3: Macrophyte processes

The modelled processes, which will be described in the next paragraphs, are (see *Figure 3*):

- nutrient uptake (§1.6.3)
- production (§1.6.4)
- respiration and nutrient excretion (§1.6.5)
- mortality (§1.6.6)
- grazing by birds (§1.6.7)
- migration (§1.6.8)
- vegetation management (mowing and dredging) (§1.6.9)

1.6.3 Nutrient uptake

Nutrient uptake and production are modelled grossly analogously to the phytoplankton. Because of specific differences (as macrophytes have root and shoot fractions), the processes are described again. It is assumed that macrophytes can take nutrients both from the water and from the pore water. The modelling of the nutrient uptake is first illustrated for phosphorus. The specific phosphorus uptake rate, that is the uptake rate per unit of biomass, is dependent on both the nutrient demand of the vegetation, defined by its actual nutrient content, and the availability of dissolved phosphorus in its environment. This is modelled as follows.

The *maximum* specific uptake rate is dependent on the actual nutrient content of the plants, the P/D ratio. If this ratio is low (close to the minimum value), the maximum uptake rate is high (close to the intrinsic maximum rate at the current temperature), while the rate drops to near-zero if the P/D ratio is close to its maximum value:

$$aVPUptMaxCorVeg = cVPUptMaxVeg * cQ10ProdVeg^{0.1^*(Tm-20)} * \frac{cPDVegMax - rPDVeg}{cPDVegMax - cPDVegMin}$$

maximum P uptake rate [gP/gD/d]

with $cPDVegMin$ [gP/gD] and $cPDVegMax$ [gP/gD] the minimum and maximum phosphorus content of the plants, respectively. The specific uptake rate is then described as a modified Monod-type function of the SRP concentration. The modification means that the phosphorus *affinity*, the slope of the curve when SRP is close to zero, is taken as constant for all values of V_{max} , in accordance with experimental data (Riegman & Mur, 1984). The specific uptake rate is calculated separately for uptake from the water and from the sediment pore water, as the SRP concentrations in both compartments will often markedly differ. The specific uptake rate from the *water* is:

$$aVPUptVegW = aVPUptMaxCorVeg * \frac{sPO4W}{\frac{aVPUptMaxCorVeg}{cAffPUptVeg} + sPO4W}$$

specific P uptake rate by shoots [gP/gD/d]

This formulation implies that the half-saturating SRP concentration is not a constant, but is depending on V_{max} :

$$ahPUptVeg = aVPUptMaxCorVeg / cAffPUptVeg \quad \text{half-saturating SRP concentration [gP/m}^3\text{]}$$

The resulting P flux from the water is the product of the specific uptake rate and the biomass of the submerged and floating parts:

$$tPUptVegW = aVPUptVegW * (aDSubVeg + aDFloatVeg) \quad \text{P uptake from water [gP/m}^2\text{/d]}$$

In the same way, the specific uptake rate from the *sediment* is:

$$aVPUptVegS = aVPUptMaxCorVeg * \frac{oPO4S}{\frac{aVPUptMaxCorVeg}{cAffPUptVeg} + oPO4S}$$

specific P uptake rate by roots [gP/gD/d]

The P uptake from the pore water is the product of this rate and the root biomass:

$$tPUptVegS = aVPUptVegS * aDRootVegS \quad \text{P uptake from pore water [gP/m}^2\text{/d]}$$

The total P uptake is the sum of water and sediment uptake:

$$tPUptVeg = tPUptVegW + tPUptVegS \quad \text{total P uptake by the plant group [gP/m}^2\text{/d]}$$

This formulation results in most phosphorus being absorbed from that compartment (water or sediment pore water) where it is most available, which is usually the pore water. Many other authors found that aquatic macrophytes take up the greater part of their nutrients from the sediment (e.g. Carignan, 1982; Moss, 1988). The formulation used here has the same effect, but is more robust within the framework of the nutrient cycle in *PCDitch* than the empirical equation derived by Carignan (1982), which can be used as an alternative.

The uptake of *nitrogen* is modelled in the same way, with one extra feature, namely the form in which nitrogen is taken up, as nitrate or as ammonium. It is assumed that the plants have a strong preference for ammonium, because this is energetically more advantageous. The N uptake rates are based on total SRN in the water resp. pore water, and are then divided over the two N fractions according to the preference equation taken from the EPA WASP4 model (Ambrose et al., 1988). For the shoots, the fraction of the N uptake absorbed as ammonium, $afNH_4UptVegW$ [-], equals:

$$afNH_4UptVegW = \frac{sNH_4W * sNO_3W}{(ahNUptVeg + sNH_4W) * (ahNUptVeg + sNO_3W)} + \frac{sNH_4W * ahNUptVeg}{(sNH_4W + sNO_3W) * (ahNUptVeg + sNO_3W)} \quad \text{ammonium uptake fraction [-]}$$

and the ammonium fraction [-] of the N uptake by the roots:

$$afNH_4UptVegS = \frac{oNH_4S * oNO_3S}{(ahNUptVeg + oNH_4S) * (ahNUptVeg + oNO_3S)} + \frac{oNH_4S * ahNUptVeg}{(oNH_4S + oNO_3S) * (ahNUptVeg + oNO_3S)} \quad \text{ammonium uptake fraction [-]}$$

These equations are analogous to the one for phytoplankton and state a preference for ammonium uptake. Only when the ammonium concentration drops to very low values, the plants switch to nitrate as main nitrogen source. A technical advantage of this preference function is that it requires no extra parameters. The relation between internal nutrient content and growth rate is described in the next paragraph.

1.6.4 Production

By production (or growth) is meant increase in biomass. It is expressed in [g/m²/d]. Growth respiration (photorespiration) is included in the definition, but maintenance respiration (dark respiration) is not; this is described as a separate process (see §1.6.5). In the model, the production is a function of the following factors:

- maximum growth rate (defined at 20 °C)
- water temperature
- light interception at the water surface (for submerged and floating plants)
- under-water light climate (extinction coefficient) (for submerged plants only)
- P content (P/D ratio) of the plants, representing P limitation
- N content (N/D ratio) of the plants, representing N limitation
- carrying capacity (maximum abundance of a plant)

Maximum growth rate

The *maximum growth rate* is the maximum increase in biomass per gram total plant biomass per day, on an exponential base: $D(t) = EXP(cMuMax * t)$. The root fraction (if present) does not contribute to the production. The maximum growth rate is defined at a temperature of 20 °C. In the literature, values between about 0.05 and 0.5, sometimes up to 1.0 [d⁻¹] are given, depending on the plant species. The lowest rates are found among the nymphaeids and helophytes, while many submerged plants and also duckweeds show rates in the range of 0.2 - 0.4 [d⁻¹]. These values are lower than those of most phytoplankton species.

Temperature

The effect of *temperature* (symbol: T_m) has been modelled by an exponential function (comparable to the well-known Arrhenius equation). It is based on the commonly used Q_{10} value (symbol: $cQ_{10}Prod$), that is the factor by which the growth rate increases due to a 10 °C temperature increase.

$$uMuMaxTmVeg = cMuMaxVeg * cQ_{10}ProdVeg^{0.1 * (T_m - 20)} \quad \text{max. growth rate at current temp. [d}^{-1}\text{]}$$

Actually, this relation only applies within a certain temperature range; most species have an optimum temperature, above which the growth rate decreases again. In stead of applying some kind of optimum curve, which have the disadvantage of using parameters which are less easy to derive from experimental data, we mimicked an optimum function by applying a similar temperature function for the maintenance respiration, but with a higher Q_{10} (symbol: $cQ_{10}Resp$). Typical Q_{10} values are between 1.5 and 2.5 for the production, and 2.0 - 3.0 for the respiration, depending on the plant species.

Light function

The *light function* applies to the submerged growing plants, not to floating or emergent plants who are assumed to be subjected to all available sun light. The formulation is made up of two parts, viz. the light interception by surface coverage, and the limitation factor for under-water light. The fraction of the daylight intercepted at the water surface is calculated from the biomass of the floating, floating-leaved and emergent plants, with a maximum of 100 %. For the duckweeds, a single layer of fronds determines the percentage light interception. The equation is, per plant group:

$$afCoverSurfVeg = MIN[1.0, MAX[aDFloatVeg / cDLayerVeg, aDEmergVeg / (fEmergVeg * cDCarrVeg)]]$$

fraction of water surface covered by vegetation [-]

The total fraction of the water surface covered by plants, $afCoverSurfVeg$ [-], is the sum of the fractions for each group, with a maximum of 1.0 (= 100 %). This part of the water area does not contribute to the submerged production.

It is assumed that the production of the floating and floating-leaved plants is hampered by light interception by the emergent plants. The limitation factor for under-water light is modelled as a Monod-type P-I curve, integrated over the depth trajectory in which the plants grow, and averaged over 24 hrs. (Jørgensen, 1980). Light attenuation with increasing depth (Lambert-Beer law) and extinction coefficient are described already in the phytoplankton section. It is assumed that only the shoots are the productive part. The light limitation of the production is calculated as:

$$aLLimShootVeg = fEmergVeg + fFloatVeg * (1.0 - afCovEmergVeg) + bfSubVeg * (1.0 - afCovSurfVeg) * 1.0 / (aExtCoef * sDepthW) * LN((1.0 + aLPAR1Veg / uhLVeg) / (1.0 + aLPAR2Veg / uhLVeg))$$

light function of growth, based on shoot fraction [-]

with:

$$aLPAR1Veg = uLPAR0 * EXP(- aExtCoefOpen * uDepth1Veg)$$

light at top of vegetation layer [W/m² PAR]

$$aLPAR2Veg = aLPAR1Veg * EXP(- aExtCoef * (uDepth2Veg - uDepth1Veg))$$

light at bottom of vegetation layer [W/m² PAR]

$$uhLVeg = hLRefVeg * uFunTmProdVeg$$

half-saturating light for vegetation production at current temp. [W/m² PAR]

For the default assumption that the macrophytes are homogeneously distributed over the depth, this function equals the Lehman function which assumes that there is no photo-inhibition on the primary production.

Like the maximum growth rate, the half-saturating light intensity is dependent on the temperature. This implies that temperature has only little impact as long as the in situ light intensity is very low. This generally found phenomenon can be explained by the fact that in this range, photochemical reactions predominate, while at light saturation, the rate is determined by enzymatic reactions (e.g. Wetzel, 1983, p. 354). This permits the plants to grow also in winter, when both light and temperature are low.

Averaging the production over the day takes places, as for phytoplankton, by multiplying the growth rate with the day length, $ufDay$ [-]. The combined growth rate equation, including the influence of temperature and light, based on the entire biomass [d^{-1}], is described as:

$$aMuTmLVeg = ufDay * bfShootVeg * aLLimShootVeg * uFunTmProdVeg * cMuMaxVeg$$

max. growth rate at current temp. and light [g prod./g total biomass/d]

Hence, the growth rate of submerged plants [d^{-1}] depends on the temperature, the under-water light climate, the covered fraction of the water surface ($afCoverSurfVeg$ [-]) and the day length ($ufDay$ [-]). Only the shoot fraction ($afShoot$ [-]) contributes to the production.

Nutrient limitation

Nutrient limitation is, analogous to phytoplankton, modelled by means of the Droop equation (see for instance Riegman & Mur, 1984), which describes the dependence of the growth rate on the nutrient content of the plants. The growth rate rapidly increases above the minimum content. For phosphorus, the equation is:

$$aFunPPProdVeg = \left(1.0 - \frac{cPDVegMin}{rPDVeg} \right) * \frac{cPDVegMax}{cPDVegMax - cPDVegMin} \quad \text{Droop function (P) for growth rate [-]}$$

with $cPDVegMin$ [gP/gD] and $cPDVegMax$ [gP/gD] the minimum and maximum phosphorus content of the plants, respectively. The equation for nitrogen is analogous. It is assumed that the minimum of both equations determines the growth rate (Liebig's law of the minimum), and that, for submerged plants, the nutrient limitation is multiplicative with the light reduction function:

$$aNutLimVeg = MIN [aPLimVeg, aNLimVeg] \quad \text{nutrient reduction function [-]}$$

$$aMuVeg = aNutLimProdVeg * aMuTmLVeg \quad \text{growth rate [d}^{-1}\text{]}$$

Density dependence

Finally, the description of the growth rate is combined with a density-dependent correction. The assumption is that other factors than the ones explicitly modelled (*i.e.* phosphorus, nitrogen, light and temperature) might be limiting for the plant density that could maximally be achieved in a certain environment. This maximum biomass is expressed as the *carrying capacity*. This parameter appears in the logistic growth equation which is generally used in animal population models, and which is adapted here for vegetation. The general equation is:

$$\frac{dx}{dt} = r \cdot x \cdot \left(1 - \frac{x}{K} \right) = r \cdot x - \frac{r}{K} \cdot x^2 \quad \text{logistic growth equation}$$

with r the intrinsic rate of increase and K the maximum biomass. The quadratic term in the equation represents the feedback caused by the (non-modelled) density-dependent factors. For water plants, one should primarily think of competition for *space*, and possibly for carbon dioxide. In general, the intrinsic rate of increase is the maximum growth rate minus the 'inevitable losses': respiration and mortality. Specifically for water plants, the 'inevitable growth limitations', *i.e.* temperature and light limitation, have been included in the definition of the growth rate, while the 'inevitable losses' have been defined as the sum of the respiration rate corrected for temperature, and the minimum mortality rate (see next paragraphs).

The intrinsic increase rate r , in our nomenclature $akDIncrVeg$, is defined as:

$$akDIncrVeg = aMuTmLVeg - ukDRespTmVeg - bkMortVeg \quad \text{intrinsic net increase rate of vegetation [d}^{-1}\text{]}$$

and the correction term $tDEnvVeg$ ("Env" is an abbreviation for "Environment") equals:

$$tDEnvVeg = akDIncrVeg / aDCarrVeg * sDVeg^2 \quad \text{logistic correction of vegetation [gD/m}^2\text{/d]}$$

The correction term $tDEnvVeg$ is divided between a reduction of the production and an increase of the mortality (Traas & Aldenberg, 1992). The partitioning is based on the degree of growth limitation (including nutrient limitation). This formulation leads to a correct handling of all mass fluxes, without a need for an extra parameter. Other assumptions are possible and might be more plausible, however. The production reduction is described as:

$$tDEnvProdVeg = aNutLimVeg * aLLimProdVeg * ufDay * tDEnvVeg \quad \text{logistic correction of production [gD/m}^2\text{/d]}$$

The total production flux (per plant group) and the submerged production are:

$$\begin{aligned} tDProdVeg &= aMuVeg * sDVeg - tDEnvProdVeg && \text{vegetation production flux [gD/m}^2\text{/d]} \\ tDProdSubVeg &= ufSubVeg * tDProdVeg && \text{submerged production [gD/m}^2\text{/d]} \end{aligned}$$

The remainder of the environmental correction is added to the mortality (see §1.6.6):

$$tDEnvMortVeg = tDEnvVeg - tDEnvProdVeg \quad \text{logistic correction of mortality [gD/m}^2\text{/d]}$$

1.6.5 Respiration and nutrient excretion

In general, respiration can be divided in growth respiration (or photorespiration), which is related to the plant's growth, and maintenance respiration (also called 'dark respiration'), which denotes the energy required for maintenance. Only maintenance respiration is explicitly modelled, because growth respiration is incorporated implicitly in the growth rate. The maintenance respiration is modelled as a temperature dependent first order process. The respiration rate of a plant species is often correlated with its maximum growth rate and, consequently, differs among species. An exponential temperature function is used, based on the Q_{10} value, the temperature interval that causes a doubling of the rate. This Q_{10} value is in general higher than the one for growth. Together, this leads to an optimum curve for the net growth rate.

$$ukDRespTmVeg = kDRespVeg * cQ10RespVeg^{0.1*(Tm-20)} \quad \text{maintenance respiration rate at current temperature [d}^{-1}\text{]}$$

$$tDRespVeg = ukDRespTmVeg * sDVeg \quad \text{maintenance respiration flux of vegetation [gD/m}^2\text{/d]}$$

Together with the respiration fluxes, nutrient fluxes are defined, called 'excretion'. It is assumed that they are proportional to the dry-weight fluxes if the nutrient content of the cells is high, but are relatively lower if the nutrient content is low: saving of sparse nutrients. The excretion process is modelled like this:

$$tPExcrVeg = (2.0 * rPDVeg) / (cPDVegMax + rPDVeg) * rPDVeg * tDRespVeg \quad \text{P excretion by vegetation [gP/m}^2\text{/d]}$$

The P and N excretion fluxes are partitioned between sediment and water column according to the root/shoot ratio of the plant group:

$$\begin{aligned} tPExcrVegS &= fRootVeg * tPExcrVeg && \text{P excretion by roots [gP/m}^2\text{/d]} \\ tPExcrVegW &= tPExcrVeg - tPExcrVegS && \text{P excretion by shoots [gP/m}^2\text{/d]} \end{aligned}$$

1.6.6 Mortality

In general, the natural mortality of water plants is low during spring and summer, and increases in autumn. The factors responsible for this increased mortality are only poorly understood. Decreasing day length probably is one of the triggers, others might be temperature changes, ageing of leaves, or investment in the formation of overwintering structures. Because the causal relationships between these factors are poorly known, a simple phenomenological approach was chosen to model the mortality. In spring and summer, a first-order equation is used with a low mortality constant ($kMortVegSum$ [d^{-1}]). At a certain, predefined date ($cDayWinVeg$), default mid-September, the same day as the reallocation starts, the mortality rate is increased, and the vegetation dies off until a certain fraction ($fWinVeg$ [-]) of the biomass is left over. This surviving fraction is available again at the start of the next growing season. (This is not completely true, because production and respiration will not stand still completely during winter). The start and length of the "autumn period", as well as the surviving fraction, can be defined by the user. They may, of course, differ among plant groups. The equations are:

```

IF (Day.LT. cDayWinVeg) THEN
    bkMortVeg = kMortVegSum                low mortality constant [ $d^{-1}$ ]
ELSE
    IF (Day.LT. cDayWinVeg + cLengMort) THEN
        bkMortVeg = - LOG(fWinVeg) / cLengMort    high mortality constant (autumn) [ $d^{-1}$ ]
    ELSE
        bkMortVeg = kMortVegSum                low mortality constant [ $d^{-1}$ ]
    ENDIF
ENDIF
ENDIF

```

The mortality is always extended with the environmental correction $tEnvMortVeg$, as explained above:

$$tEnvMortVeg = tEnvVeg - tEnvProdVeg \quad \text{logistic correction of mortality [gD/m}^2\text{/d]}$$

The total mortality flux then is:

$$tDMortVeg = bkMortVeg * sDVeg + tEnvMortVeg \quad \text{total mortality flux [gD/m}^2\text{/d]}$$

The corresponding N and P mortality fluxes are proportional to the dry-weight fluxes. To account for autolysis, it is possible to define a fraction of the nutrients ($fDissMortVeg$) released directly in dissolved form (as PO_4 or NH_4). The remainder of the mortality flux, the particulate fraction, is divided between the suspended detritus (a small part, $fDetWMortVeg$, of the shoot mortality) and the sediment detritus (the remainder). This seems reasonable, as a relatively large proportion of died leaves etc. will settle to the bottom quite fast.

1.6.7 Grazing by birds

Optionally, grazing of the vegetation by herbivorous birds can be included. The birds are considered as an 'external' component and are not modelled dynamically. The user can define the bird density and, if applicable, the period of the year that they are present in the ditch. It is assumed that a fixed amount per bird is consumed, with a fixed assimilation efficiency. A Monod factor is included to ensure that no more is eaten than is there. The egested part returns as detritus, the assimilated part is considered as lost from the system. When birds are present, the biomass loss due to grazing is:

$$tDGrazVegBird = cPrefVegBird * sDVeg / (hDVegBird + sDVeg) \\ * cBirdsPerha / m2Perha * cDGrazPerBird \quad \text{biomass loss due to grazing of birds [gD/m}^2\text{/d]}$$

1.6.8 Migration

The only plant group that really migrates is that of the duckweeds ("Lemn"). Because these plants are freely floating on the water surface, they can be moved into or out of the ditch by the water flow. The migration of duckweeds is also affected by wind. On the other hand, obstructions like small dams hamper the migration. The

local situation may thus result in a complicated pattern of migration of duckweeds, which can only be simulated using a network approach. In the current zero-dimensional model, the process is approximated by an outward migration rate, coupled to the outflow rate of dissolved and suspended substances, $ukOut$ [d⁻¹], but corrected for an 'obstruction factor' $fObstrLemn$ [-]:

$$kMigrLemn = (1 - fObstrLemn) * ukOut \quad \text{migration rate of duckweeds [d}^{-1}\text{]}$$

Furthermore, a small migration flux, transport of plant biomass into or out of the ditch, has been assigned to all plant groups, mainly for computational reasons: it prevents state variables from approaching zero and thereby slowing down the model calculations. The migration constant $kMigrVeg$ has been chosen arbitrarily at the low rate of 10⁻⁵ d⁻¹ and the external plant density $cDVegIn$ at 1.0 gD/m². The general equation is (for D; the equations for P and N are analogous):

$$tDMigrVeg = kMigrVeg * (cDVegIn - sDVeg) \quad \text{vegetation migration [gD/m}^2\text{/d]}$$

1.6.9 Vegetation management

Both dredging and mowing can be applied in *PCDitch*. Mowing applies only to macrophytes. Dredging also applies to the sediment and is already discussed in §1.4.4. Optionally, management (mowing) of the vegetation can be defined once or twice a year, for example in autumn which is common practice in most ditches. The mowing efficiency can be defined separately for 'helophytes and nymphaeids', 'duckweed' and the remaining submerged water plants. By default the mowing efficiency is 40% for duckweed and 80% for the other plants. The length of the mowing ($cLengMan$ [d]) can be defined over which the mowing removal rate is spread, such that the mowing efficiency is reached at the end of the mowing period:

$$tDManVeg = LN(1.0 - fManVeg) / cLengMan * sDVeg \quad \text{water plant removal by mowing [gD/m}^2\text{/d]}$$

2 Parameter listing

The next table lists all the default model parameters with their units for *PCDitch* (version 2.0). A distinction is made in process parameters, conversion factors, input factors, initial values and configuration settings. The last three categories are case-specific.

Configuration settings

BeginTime [0] day ; begintime
 ConstDepth [1] - ; if 1 water depth kept constant by daily dredging
 ReadTemp [0] - ; if 1 use measured time-series of temperature otherwise sinus
 ReadLOut [0] - ; if 1 use measured time-series of light otherwise sinus
 ReadVWind [0] - ; if 1 use measured time-series of wind speed otherwise constant
 YearZero [0] year ; calender year of start year
 InitCalc [0] - ; if 1 calculate initial values
 InclTran [0] - ; if 1 use transportmodule (in DufLOW transport module can not be used)
 ReadQIn [0] - ; if 1 use measured time-series of water inflow otherwise constant
 ReadQOut [0] - ; if 1 use measured time-series of water outflow otherwise constant
 ReadQEv [0] - ; if 1 use measured time-series of evaporation otherwise constant
 ReadPLoad [0] - ; if 1 use measured time-series of P loading otherwise constant
 ReadNLoad [0] - ; if 1 use measured time-series of N loading otherwise constant
 ReadNutFrac [0] - ; if 1 use measured time-series of loading with diff nutrient fractions
 ReadPLoadPhyt [0] - ; if 1 use measured time-series of P phytoplankton loading otherwise constant
 ReadDLoadDet [0] - ; if 1 use measured time-series of DDet loading otherwise constant
 ReadDLoadIM [0] - ; if 1 use measured time-series of DIM loading otherwise constant
 UseSeasonLoad [0] - ; if 1 use different inflow and loading for summer and winter periods
 UsePulseLoad [0] - ; if 1 use a pulse-wise nutrient loading

Optional input tables

mQIn [0] mm/day ; use measured time-series of inflow
 mQOut [0] mm/day ; use measured time-series of outflow
 mQEv [0] mm/day ; use measured time-series of evaporation
 mPLoad [0] gP/m²/day ; use measured time-series of P loading
 mPLoadPO4 [0] gP/m²/day ; use measured time-series of PO₄ loading
 mPLoadOrg [0] gP/m²/day ; use measured time-series of loading P bound to organic matter
 mPLoadPhytTot [0] gP/m²/day ; use measured time-series of P loading algal input
 mNLoad [0] gN/m²/day ; use measured time-series of N loading
 mNLoadNH₄ [0] gN/m²/day ; use measured time-series of NH₄ loading
 mNLoadNO₃ [0] gN/m²/day ; use measured time-series of NO₃ loading
 mNLoadOrg [0] gN/m²/day ; use measured time-series of loading N bound to organic matter
 mDLoadDet [0] gDW/m²/day ; use measured time-series of Detritus loading
 mDLoadIM [0] gDW/m²/day ; use measured time-series of loading of DW of inorganic matter

Initial values

fDTotS0 [0.3] gDW/g_{sediment} ; initial dry-weight fraction in sediment
 fDOrgS0 [0.1] gOM/gDW ; initial organic fraction of sediment DW
 fDDetS0 [0.1] dDet/gOM ; initial detritus fraction of sediment organic matter
 fPInorgS0 [0.0005] gP/gDW ; initial inorganic P fraction in sediment
 fPAdsS0 [0.99] gP_{Ads}/gP_{IM} ; initial adsorbed fraction of inorganic P in sediment
 cPDDet0 [0.0025] gP/gDW ; initial P fraction in detritus
 cNDDet0 [0.025] gN/gDW ; initial N fraction in detritus
 cPDHum0 [0.005] gP/gDW ; initial P fraction in humus
 cNDHum0 [0.05] gN/gDW ; initial N fraction in humus
 cPDPhyt0 [0.01] gP/gDW ; initial P fraction in phytoplankton
 cNDPhyt0 [0.1] gN/gDW ; initial N fraction in phytoplankton
 cPDElod0 [0.002] gP/gDW ; initial P fraction in Elodeids

cNDElod0 [0.02] gN/gDW ; initial N fraction in Elodeids
 cPDChar0 [0.002] gP/gDW ; initial P fraction in Characeans
 cNDChar0 [0.02] gN/gDW ; initial N fraction in Characeans
 cPDCera0 [0.002] gP/gDW ; initial P fraction in Ceratophyllids
 cNDCera0 [0.02] gN/gDW ; initial N fraction in Ceratophyllids
 cPDLe mn0 [0.005] gP/gDW ; initial P fraction in Lemnaceae
 cNDLe mn0 [0.05] gN/gDW ; initial N fraction in Lemnaceae
 cPDNyp0 [0.002] gP/gDW ; initial P fraction in Nymphaeids
 cNDNyp0 [0.02] gN/gDW ; initial N fraction in Nymphaeids
 cPDHelo0 [0.002] gP/gDW ; initial P fraction in helophytes
 cNDHelo0 [0.02] gN/gDW ; initial N fraction in helophytes

Input factors

cQInf [0] mm/day ; infiltration rate
 cPBackLoad [0] gP/m²/day ; Background P loading
 cNBackLoad [0] gP/m²/day ; Background N loading
 cNLoadS [0] gN/m²/day ; N fertilizer to sediment
 fNH4LoadS [0.5] - ; NH₄ fraction of N fertilizer to sediment
 cPO4Ground [0.1] gP/m³ ; PO₄ concentration in groundwater
 cNH4Ground [1] gN/m³ ; NH₄ concentration in groundwater
 cNO3Ground [0.1] gN/m³ ; NO₃ concentration in groundwater
 cQIn [30] mm/day ; standard water inflow if not measured
 cQInSum [30] mm/day ; summer water inflow if not measured
 cQInWin [30] mm/day ; winter water inflow if not measured
 cDepthWMax [3] m ; maximum water depth
 cQInExtraAprill [0] mm/day ; extra water inflow at start of summer
 cQInExtraOctl [0] mm/day ; extra water inflow at start of winter
 cQOutExtraAprill [0] mm/day ; extra water outflow at start of summer
 cQOutExtraOctl [0] mm/day ; extra water outflow at start of winter
 cQEvAve [1.5] mm/day ; average evaporation
 cQEvVar [1.3] mm/day ; variation in evaporation
 cPLoad [0.02] gP/m²/day ; P loading if not measured
 cPLoadSum [0.02] gP/m²/day ; summer P loading if not measured
 cPLoadWin [0.02] gP/m²/day ; winter P loading if not measured
 fPO4In [0.8] - ; fraction PO₄ in input (if PO₄ input not measured)
 fPhytInWin [0.001] - ; minimum algal fraction in organic P input
 fPhytInSum [0.002] - ; maximum algal fraction in organic P input
 cNLoad [0.2] gN/m²/day ; N loading
 cNLoadSum [0.2] gN/m²/day ; summer N loading
 cNLoadWin [0.2] gN/m²/day ; winter N loading
 cNPLoadMeas [7] gN/gP ; N/P loading if P is measured and N not
 cNPPhytIn [7] gP/gDW ; N/P ratio of algal input
 cNPDetIn [7] gP/gDW ; N/P ratio of detrital input
 fNH4DissIn [0.5] - ; NH₄ fraction of dissolved N load (if NH₄ not measured)
 cNDPhytIn [0.07] gN/gDW ; N/day ratio of algal input
 cNDDetIn [0.07] gN/gDW ; N/P ratio of detrital input
 cDIMIn [10] gDW/m³ ; inorganic matter concentration in inflow water
 cO2In [5] gO₂/m³ ; O₂ concentration in inflow water
 cDredInterval [9999000] year ; dredging interval
 cDredStart [9999000] year ; first dredging year (should be n times cDredInterval)
 cDepthRef [1E-33] m ; reference water depth for dredging
 cLengDred [10] day ; length of dredging period
 fEffDred [0.95] - ; dredging efficiency (<10)
 fEffDredLemn [0.5] - ; dredging efficiency for duckweed (<10)
 cFetch [0] m ; wind fetch
 cTmAve [12] oC ; average water temperature

cTmVar [10] °C ; annual temperature variation
 cTimeLag [40] day ; time lag for temperature
 cVWind [5] m/s ; average wind speed needed to calculate reaeration
 cLDayAve [10000000] J/m²/day ; annual average radiation
 cLDayVar [8000000] J/m²/day ; annual variation in radiation
 cfDayAve [0.5] - ; average day length
 cfDayVar [0.2] - ; annual variation in day length
 fRefl [0.2] - ; the fraction photosynthetically active radiation reflected at the surface
 fPAR [0.48] - ; fraction photosynthetically active radiation (PAR)
 cDayManVeg1 [-9999000] day ; first mowing day (default non-existent)
 cDayManVeg2 [-9999000] day ; second mowing day (259 = 16 Sep)
 fManVeg [0.8] - ; fraction removed by management for submerged plants
 fManLemn [0.4] - ; fraction of Lemnaceae removed by management
 fManHelo [0.8] - ; fraction of helophytes and Nymphaeids removed by management
 cLengMan [10] day ; length of mowing period
 cYearStartBirds [0] year ; first year of birds presence
 cDayStartBirds [46] day ; yearly first day of birds presence
 cDayEndBirds [288] day ; yearly last day of birds presence
 cBirdsPerha [0] n/ha ; number of birds per ha
 cDGrazPerBird [45] gDW/coot/day ; daily grazing of birds
 hDVegBird [5] gDW/m² ; half-sat vegetation biomass for birds grazing
 fDAssBird [0.5] - ; birds assim efficiency
 fDissEgesBird [0.25] - ; fraction dissolved nutrient of coot egestion
 cDErosTot [10] gDW/m²/day ; DW input by erosion

Abiotic parameters

Light extinction

cExtWat [0.5] m⁻¹ ; background extinction
 cExtSpDet [0.15] m²/gDW ; specific extinction detritus
 cExtSpIM [0.05] m²/gDW ; specific extinction inert matter
 cExtSpPhyt [0.25] m²/gDW ; specific extinction phytoplankton

Sediment

fDOrgSoil [0.1] - ; fraction soil organic matter
 cPDSoilOM [0.001] gP/gDW ; P/DW ratio of soil organic matter
 cNDSoilOM [0.01] gN/gDW ; N/DW ratio of soil organic matter
 cDepthS [0.1] m ; sediment depth
 fLutum [0.1] - ; lutum content of inorganic matter
 fFeDIM [0.01] gFe/gDW ; Fe content of inorganic matter
 fAlDIM [0.01] gAl/gDW ; Al content of inorganic matter
 cCPerDW [0.4] gC/gDW ; C content of organic matter
 cRhoIM [2500000] g/m³_solid ; density of sediment inorganic matter
 cRhoOM [1400000] g/m³ ; density of sediment detritus

Reaeration

cAerRoot [0.727] - ; reaeration coefficient for sqrt(VWind)
 cAerLin [-0.371] s/day ; reaeration coefficient for Vwind
 cAerSquare [0.0376] - ; reaeration coefficient for Vwind²
 cThetaAer [1.024] 1/e^{°C} ; temperature coeff for reaeration (Downing & Truesdale 1955)
 kLemnAer [0.01] m²/gDW ; Reaeration reduction coeff for duckweed

Sedimentation

fSedErosIM [0.95] - ; instantly sedimentating fraction of inorganic matter
 cVSetIM [1] m/day ; maximum sedimentation velocity of inert organic matter
 cVSetDet [0.25] m/day ; maximum sedimentation velocity of detritus

cThetaSet [1.01] 1/e^oC ; temperature parameter of sedimentation

Resuspension

cSuspRef [0.5] - ; reference suspended matter function
 cSuspMin [6.1] - ; minimum value of logistic empirical suspended matter function
 cSuspMax [25.2] - ; maximum value of logistic empirical suspended matter function
 cSuspSlope [2.1] - ; slope of logistic empirical suspended matter function
 hDepthSusp [2] - ; half sat value of depth in logistic empirical suspended matter function
 cFetchRef [1000] m ; reference fetch
 fLutumRef [0.2] - ; reference lutum fraction of sediment
 kVegResus [0.01] m²/gDW ; resuspension reduction per g vegetation
 kResusPhytMax [0.25] day⁻¹ ; maximum resuspension of phytoplankton
 cResusPhytExp [-0.379] (gDW/m²/day)⁻¹ ; coefficient for phytoplankton resuspension

Diffusion

kPDifPO4 [0.000072] m²/day ; mol PO4 diffusion constant
 kNDifNO3 [0.000086] m²/day ; mol NO3 diffusion constant
 kNDifNH4 [0.000112] m²/day ; mol NH4 diffusion constant
 kO2Dif [0.000026] m²/day ; mol O2 diffusion constant
 cThetaDif [1.02] 1/e^oC ; Temperature coefficient for diffusion
 fDepthDifS [0.5] - ; nutrient diffusion distance as fraction of sediment depth
 cTurbDifNut [5] - ; bioturbation factor for diffusion
 cTurbDifO2 [5] - ; bioturbation factor for diffusion

Sorption

kPSorp [0.05] day⁻¹ ; P sorption rate constant (not too high -> model speed)
 cRelPAdsD [0.00003] gP/gDW ; maximum P adsorption per g DW
 cRelPAdsFe [0.065] gP/gFe ; maximum P adsorption per g Fe
 cRelPAdsAl [0.134] gP/gAl ; maximum P adsorption per g Al
 cKPAdsOx [0.6] m³/gP ; P adsorption affinity at oxidized conditions
 fRedMax [0.9] - ; maximum reduction factor of P adsorption affinity
 coPO4Max [2] gP/m³ ; maximum SRP concentration in pore water
 kPChemPO4 [0.03] day⁻¹ ; chemical PO4 loss rate

Microbial parameters

Mineralization

cTmRef [20] oC ; reference temperature
 fRefrDetS [0.15] - ; refractory fraction of sediment detritus
 cThetaMinW [1.07] - ; exponential temperature constant of mineralization in water
 kDMinDetW [0.01] day⁻¹ ; decomposition constant of detritus
 hO2BOD [1] gO2/m³ ; half-sat oxygen conc for BOD
 cThetaMinS [1.07] - ; exponential temperature constant of sediment mineralization
 kDMinDetS [0.002] day⁻¹ ; decomposition constant of sediment detritus
 kDMinHum [0.00001] day⁻¹ ; maximum decomposition constant of humic material

Denitrification

hNO3Denit [2] gN/m³ ; quadratic half-sat NO3 concentration for denitrification
 NO3PerC [0.8] - ; mol NO3 denitrified per mol C mineralised

Nitrification

kNitrW [0.1] day⁻¹ ; nitrification rate constant in water
 kNitrS [1] day⁻¹ ; nitrification rate constant in sediment
 cThetaNitr [1.08] 1/e^oC ; temperature coefficient of nitrification
 O2PerNH4 [2] - ; mol O2 used per mol NH4⁺ nitrified
 hO2Nitr [2] gO2/m³ ; half-sat O2 concentration for nitrification in water

Vegetation parameters

fDissMortVeg [0.25] - ; fraction dissolved nutrients from died plants
 cLengAllo [15] day ; duration of allocation and reallocation phase
 cLengMort [15] day ; duration of autumn mortality period

Elodeids

fRootElodSum [0.1] gDW_Root/gDW ; root fraction in growing season
 fRootElodWin [0.6] gDW_Root/gDW ; root fraction outside growing season
 fFloatElod [0] gDW_Floating/gDW_Shoot ; floating fraction of shoot
 fEmergElod [0] gDW_Emergent/gDW_Shoot ; emergent fraction of shoot
 fDepth1Elod [0] - ; maximum upper depth of submerged vegetation layer as fraction of water depth
 fDepth2Elod [1] - ; maximum lower depth of submerged vegetation layer as fraction of water depth
 cDLayerElod [0] gDW/m² ; biomass of a single layer floating leaves
 cCovSpElod [0.5] %_cover_per_gDW_Shoot/m² ; specific cover
 kMigrElod [0.00001] day⁻¹ ; vegetation migration rate
 cDElodIn [0.1] gDW/m² ; external vegetation density
 cTmInitElod [10] oC ; temperature for start of growing season
 cDCarrElod [500] gDW/m² ; maximum vegetation biomass
 cMuMaxElod [0.32] gDW/gDW_Shoot/day ; maximum growth rate of vegetation at 20oC
 cQ10ProdElod [1.2] - ; temperature quotient of production
 hLRefElod [32] W/m²_PAR ; half-sat light intensity at 20 oC
 cExtSpElod [0.01] m²/gDW ; specific ligh extinction
 kDRespElod [0.024] day⁻¹ ; dark respiration rate of vegetation
 cQ10RespElod [1.5] - ; temperature quotient of respiration
 cDayWinElod [259] day ; end of growing season (259 = 16 Sep)
 kMortElodSum [0.005] day⁻¹ ; vegetation mortality rate in Spring and Summer (low)
 fWinElod [0.2] - ; fraction of vegetation DW surviving in winter
 fDetWMortElod [0.5] - ; fraction of shoot mortality becoming water detritus
 cPrefElodBird [1] - ; edibility for birds
 cVPuptMaxElod [0.01] gP/gDW/day ; maximum P uptake capacity of vegetation at 20 oC
 cAffPUptElod [0.2] m³/gDW ; initial P uptake affinity vegetation
 cPDElodMin [0.0008] gP/gDW ; minimum P/D ratio vegetation
 cPDElodMax [0.0035] gP/gDW ; maximum P/D ratio vegetation
 cVNuptMaxElod [0.1] gN/gDW/day ; maximum N uptake capacity of vegetation at 20oC
 cAffNUptElod [0.2] m³/gDW ; initial N uptake affinity vegetation
 cNDElodMin [0.01] gN/gDW ; minimum N/D ratio vegetation
 cNDElodMax [0.035] gN/gDW ; maximum N/D ratio vegetation

Characaeans

fRootCharSum [0.05] gDW_Root/gDW ; root fraction in growing season
 fRootCharWin [0.1] gDW_Root/gDW ; root fraction outside growing season
 fFloatChar [0] gDW_Floating/gDW_Shoot ; floating fraction of shoot
 fEmergChar [0] gDW_Emergent/gDW_Shoot ; emergent fraction of shoot
 fDepth1Char [0.5] - ; maximum upper depth of submerged vegetation layer as fraction of water depth
 fDepth2Char [1] - ; maximum lower depth of submerged vegetation layer as fraction of water depth
 cDLayerChar [0] gDW/m² ; biomass of a single layer floating leaves
 cCovSpChar [0.5] %_cover_per_gDW_Shoot/m² ; specific cover
 kMigrChar [0.00001] day⁻¹ ; vegetation migration rate
 cDCharIn [0.1] gDW/m² ; external vegetation density
 cTmInitChar [10] oC ; temperature for start of growing season
 cDCarrChar [500] gDW/m² ; maximum vegetation biomass
 cMuMaxChar [0.22] gDW/gDW_Shoot/day ; maximum growth rate of vegetation at 20oC
 cQ10ProdChar [1.2] - ; temperature quotient of production
 hLRefChar [19] W/m²_PAR ; half-sat light intensity at 20 oC
 cExtSpChar [0.01] m²/gDW ; specific ligh extinction

kDRespChar [0.025] day⁻¹ ; dark respiration rate of vegetation
 cQ10RespChar [1.2] - ; temperature quotient of respiration
 cDayWinChar [259] day ; end of growing season (259 = 16 Sep)
 kMortCharSum [0.005] day⁻¹ ; vegetation mortality rate in Spring and Summer (low)
 fWinChar [0.9] - ; fraction of vegetation DW surviving in winter
 fDetWMortChar [0.5] - ; fraction of shoot mortality becoming water detritus
 cPrefCharBird [0.5] - ; edibility for birds
 cVPuptMaxChar [0.01] gP/gDW/day ; maximum P uptake capacity of vegetation at 20 oC
 cAffPUptChar [0.2] m3/gDW ; initial P uptake affinity vegetation
 cPDCharMin [0.0012] gP/gDW ; minimum P/D ratio vegetation
 cPDCharMax [0.0035] gP/gDW ; maximum P/D ratio vegetation
 cVNUptMaxChar [0.1] gN/gDW/day ; maximum N uptake capacity of vegetation at 20oC
 cAffNUptChar [0.2] m3/gDW ; initial N uptake affinity vegetation
 cNDCharMin [0.01] gN/gDW ; minimum N/D ratio vegetation
 cNDCharMax [0.035] gN/gDW ; maximum N/D ratio vegetation

Ceratophyllids

fRootCeraSum [0] gDW_Root/gDW ; root fraction in growing season
 fRootCeraWin [0] gDW_Root/gDW ; root fraction outside growing season
 fFloatCera [0] gDW_Floating/gDW_Shoot ; floating fraction of shoot
 fEmergCera [0] gDW_Emergent/gDW_Shoot ; emergent fraction of shoot
 fDepth1Cera [0] - ; maximum upper depth of submerged vegetation layer as fraction of water depth
 fDepth2Cera [0.5] - ; maximum lower depth of submerged vegetation layer as fraction of water depth
 cDLayerCera [0] gDW/m² ; biomass of a single layer floating leaves
 cCovSpCera [0.5] %_cover_per_gDW_Shoot/m² ; specific cover
 kMigrCera [0.00001] day⁻¹ ; vegetation migration rate
 cDCeraIn [0.1] gDW/m² ; external vegetation density
 cTmInitCera [10] oC ; temperature for start of growing season
 cDCarrCera [500] gDW/m² ; maximum vegetation biomass
 cMuMaxCera [0.21] gDW/gDW_Shoot/day ; maximum growth rate of vegetation at 20oC
 cQ10ProdCera [1.5] - ; temperature quotient of production
 hLRefCera [25] W/m²_PAR ; half-sat light intensity at 20 oC
 cExtSpCera [0.01] m²/gDW ; specific light extinction
 kDRespCera [0.024] day⁻¹ ; dark respiration rate of vegetation
 cQ10RespCera [2] - ; temperature quotient of respiration
 cDayWinCera [259] day ; end of growing season (259 = 16 Sep)
 kMortCeraSum [0.005] day⁻¹ ; vegetation mortality rate in Spring and Summer (low)
 fWinCera [0.1] - ; fraction of vegetation DW surviving in winter
 fDetWMortCera [0.5] - ; fraction of shoot mortality becoming water detritus
 cPrefCeraBird [0] - ; edibility for birds
 cVPuptMaxCera [0.01] gP/gDW/day ; maximum P uptake capacity of vegetation at 20 oC
 cAffPUptCera [0.2] m3/gDW ; initial P uptake affinity vegetation
 cPDCeraMin [0.0012] gP/gDW ; minimum P/D ratio vegetation
 cPDCeraMax [0.0035] gP/gDW ; maximum P/D ratio vegetation
 cVNUptMaxCera [0.1] gN/gDW/day ; maximum N uptake capacity of vegetation at 20oC
 cAffNUptCera [0.2] m3/gDW ; initial N uptake affinity vegetation
 cNDCeraMin [0.01] gN/gDW ; minimum N/D ratio vegetation
 cNDCeraMax [0.033] gN/gDW ; maximum N/D ratio vegetation

Lemnids

fObstrLemn [1] - ; obstructed fraction of Lemnaceae outflow
 fRootLemnSum [0] gDW_Root/gDW ; root fraction in growing season
 fRootLemnWin [0] gDW_Root/gDW ; root fraction outside growing season
 fFloatLemn [1] gDW_Floating/gDW_Shoot ; floating fraction of shoot
 fEmergLemn [0] gDW_Emergent/gDW_Shoot ; emergent fraction of shoot
 fDepth1Lemn [0] - ; maximum upper depth of submerged vegetation layer as fraction of water depth

fDepth2Lemn [0] - ; maximum lower depth of submerged vegetation layer as fraction of water depth
 cDLayerLemn [100] gDW/m² ; biomass of a single layer floating leaves
 cCovSpLemn [1] %_cover_per_gDW_Shoot/m² ; specific cover
 cMigrLemn [0.00001] day⁻¹ ; vegetation migration rate
 cDLemnIn [0.1] gDW/m² ; external vegetation density
 cTmInitLemn [10] oC ; temperature for start of growing season
 cDCarrLemn [575] gDW/m² ; maximum vegetation biomass
 cMuMaxLemn [0.4] gDW/gDW_Shoot/day ; maximum growth rate of vegetation at 20oC
 cQ10ProdLemn [2.5] - ; temperature quotient of production
 hLRefLemn [7.5] W/m²_PAR ; half-sat light intensity at 20 oC
 cExtSpLemn [0.01] m²/gDW ; specific ligh extinction
 kDRespLemn [0.03] day⁻¹ ; dark respiration rate of vegetation
 cQ10RespLemn [3] - ; temperature quotient of respiration
 cDayWinLemn [289] day ; end of growing season (289 = 16 Oct)
 kMortLemnSum [0.02] day⁻¹ ; vegetation mortality rate in Spring and Summer (low)
 fWinLemn [0.2] - ; fraction of vegetation DW surviving in winter
 fDetWMortLemn [0.8] - ; fraction of shoot mortality becoming water detritus
 cPrefLemnBird [0] - ; edibility for birds
 cVPuptMaxLemn [0.005] gP/gDW/day ; maximum P uptake capacity of vegetation at 20 oC
 cAffPUptLemn [0.02] m³/gDW ; initial P uptake affinity vegetation
 cPDLemnMin [0.004] gP/gDW ; minimum P/D ratio vegetation
 cPDLemnMax [0.026] gP/gDW ; maximum P/D ratio vegetation
 cVNuptMaxLemn [0.05] gN/gDW/day ; maximum N uptake capacity of vegetation at 20oC
 cAffNUptLemn [0.02] m³/gDW ; initial N uptake affinity vegetation
 cNDLemnMin [0.04] gN/gDW ; minimum N/D ratio vegetation
 cNDLemnMax [0.1] gN/gDW ; maximum N/D ratio vegetation

Nymphaeids

fRootNympSum [0.75] gDW_Root/gDW ; root fraction in growing season
 fRootNympWin [0.95] gDW_Root/gDW ; root fraction outside growing season
 fFloatNymp [1] gDW_Floating/gDW_Shoot ; floating fraction of shoot
 fEmergNymp [0] gDW_Emergent/gDW_Shoot ; emergent fraction of shoot
 fDepth1Nymp [0] - ; maximum upper depth of submerged vegetation layer as fraction of water depth
 fDepth2Nymp [0] - ; maximum lower depth of submerged vegetation layer as fraction of water depth
 cDLayerNymp [100] gDW/m² ; biomass of a single layer floating leaves
 cCovSpNymp [0.5] %_cover_per_gDW_Shoot/m² ; specific cover
 kMigrNymp [0.00001] day⁻¹ ; vegetation migration rate
 cDNympIn [0.1] gDW/m² ; external vegetation density
 cTmInitNymp [10] oC ; temperature for start of growing season
 cDCarrNymp [500] gDW/m² ; maximum vegetation biomass
 cMuMaxNymp [0.1] gDW/gDW_Shoot/day ; maximum growth rate of vegetation at 20oC
 cQ10ProdNymp [1.5] - ; temperature quotient of production
 hLRefNymp [25] W/m²_PAR ; half-sat light intensity at 20 oC
 cExtSpNymp [0.01] m²/gDW ; specific ligh extinction
 kDRespNymp [0.01] day⁻¹ ; dark respiration rate of vegetation
 cQ10RespNymp [2] - ; temperature quotient of respiration
 cDayWinNymp [259] day ; end of growing season (259 = 16 Sep)
 kMortNympSum [0.005] day⁻¹ ; vegetation mortality rate in Spring and Summer (low)
 fWinNymp [0.333] - ; fraction of vegetation DW surviving in winter
 fDetWMortNymp [0.25] - ; fraction of shoot mortality becoming water detritus
 cPrefNympBird [0] - ; edibility for birds
 cVPuptMaxNymp [0.01] gP/gDW/day ; maximum P uptake capacity of vegetation at 20 oC
 cAffPUptNymp [0.2] m³/gDW ; initial P uptake affinity vegetation
 cPDNympMin [0.001] gP/gDW ; minimum P/D ratio vegetation
 cPDNympMax [0.0075] gP/gDW ; maximum P/D ratio vegetation
 cVNuptMaxNymp [0.1] gN/gDW/day ; maximum N uptake capacity of vegetation at 20oC

cAffNUptNymp [0.2] m3/gDW ; initial N uptake affinity vegetation
 cNDNympMin [0.01] gN/gDW ; minimum N/D ratio vegetation
 cNDNympMax [0.03] gN/gDW ; maximum N/D ratio vegetation

Helophytes

fRootHeloSum [0.5] gDW_Root/gDW ; root fraction in growing season
 fRootHeloWin [0.8] gDW_Root/gDW ; root fraction outside growing season
 fFloatHelo [0] gDW_Floating/gDW_Shoot ; floating fraction of shoot
 fEmergHelo [1] gDW_Emergent/gDW_Shoot ; emergent fraction of shoot
 fDepth1Helo [0] - ; maximum upper depth of submerged vegetation layer as fraction of water depth
 fDepth2Helo [0] - ; maximum lower depth of submerged vegetation layer as fraction of water depth
 cDLayerHelo [0] gDW/m2 ; biomass of a single layer floating leaves
 cCovSpHelo [0.05] %_cover_per_gDW_Shoot/m2 ; specific cover
 kMigrHelo [0.00001] day-1 ; vegetation migration rate
 cDHeloIn [0.1] gDW/m2 ; external vegetation density
 cTmInitHelo [10] oC ; temperature for start of growing season
 cDCarrHelo [2000] gDW/m2 ; maximum vegetation biomass
 cMuMaxHelo [0.1] gDW/gDW_Shoot/day ; maximum growth rate of vegetation at 20oC
 cQ10ProdHelo [1.5] - ; temperature quotient of production
 hLRefHelo [25] W/m2_PAR ; half-sat light intensity at 20 oC
 cExtSpHelo [0.01] m2/gDW ; specific ligh extinction
 kDRespHelo [0.01] day-1 ; dark respiration rate of vegetation
 cQ10RespHelo [2] - ; temperature quotient of respiration
 cDayWinHelo [259] day ; end of growing season (259 = 16 Sep)
 kMortHeloSum [0.005] day-1 ; vegetation mortality rate in Spring and Summer (low)
 fWinHelo [0.333] - ; fraction of vegetation DW surviving in winter
 fDetWMortHelo [0.25] - ; fraction of shoot mortality becoming water detritus
 cPrefHeloBird [0] - ; edibility for birds
 cVPuptMaxHelo [0.01] gP/gDW/day ; maximum P uptake capacity of vegetation at 20 oC
 cAffPUptHelo [0.2] m3/gDW ; initial P uptake affinity vegetation
 cPDHeloMin [0.001] gP/gDW ; minimum P/D ratio vegetation
 cPDHeloMax [0.0075] gP/gDW ; maximum P/D ratio vegetation
 cVNUptMaxHelo [0.1] gN/gDW/day ; maximum N uptake capacity of vegetation at 20oC
 cAffNUptHelo [0.2] m3/gDW ; initial N uptake affinity vegetation
 cNDHeloMin [0.01] gN/gDW ; minimum N/D ratio vegetation
 cNDHeloMax [0.03] gN/gDW ; maximum N/D ratio vegetation

Phytoplankton parameters

cPACcoefMin [1.5] - ; minimum Poole-Atkins coefficient
 cPACcoefMax [2.5] - ; maximum Poole-Atkins coefficient
 hPACcoef [3] g/m2 ; decrease constant for PA coefficient with DOMW
 cSecchiPlus [0] m ; maximum Secchi depth above water depth
 cEuph [1.7] - ; constant to convert Secchi depth to euphotic depth
 cCovSpPhyt [2] %/gDW/m2 ; specific coverage
 cTmOptLoss [25] oC ; optimum tempearture for grazing
 cSigTmLoss [13] oC ; temperature constant of grazing(sigma in Gaussian curve)
 fDissMortPhyt [0.2] - ; soluble nutrient fraction of died phytoplankton
 fDissLoss [0.25] - ; dissolved nutrient fraction of grazing loss
 cMuMaxPhyt [1.9] day-1 ; maximum growth rate phytoplankton
 cTmOptPhyt [25] oC ; optimum temperature of phytoplankton
 cSigTmPhyt [15] oC ; temperature constant phytoplankton(sigma in Gaussian curve)
 UseSteelePhyt [0] - ; if 1 use Steele function (light inhibition) if use Lehman function (no light inhibition)
 hLRefPhyt [10.2] W/m2 ; half-sat PAR for phytoplankton at 20 oC(Lehman function)
 cLOptRefPhyt [1000] W/m2 ; optimum PAR at 20 oC (Steele function)
 cChDPhytMin [0.01] gChl/gDW ; minimum chlorophyll/C ratio phytoplankton
 cChDPhytMax [0.02] gChl/gDW ; maximum chlorophyll/C ratio phytoplankton

kDRespPhyt [0.1] day⁻¹ ; maintenance respiration constant phytoplankton
 kLossPhyt [0] - ; grazing loss rate for phytoplankton
 kMortPhytW [0.01] day⁻¹ ; mortality constant of phytoplankton in water
 cVSetPhyt [0.1] m/day ; sedimentation velocity phytoplankton
 kMortPhytS [0.05] day⁻¹ ; mortality constant sed phytoplankton
 cVPUpMaxPhyt [0.01] gP/gDW/day ; maximum P uptake capacity of phytoplankton at 20 oC
 cAffPUptPhyt [0.2] m³/gDW ; initial P uptake affinity phytoplankton
 cPDPhytMin [0.002] gP/gDW ; minimum P/D ratio phytoplankton
 cPDPhytMax [0.015] gP/gDW ; maximum P/D ratio phytoplankton
 cVNUptMaxPhyt [0.07] gN/gDW/day ; maximum N uptake capacity of phytoplankton at 20 oC
 cAffNUptPhyt [0.2] m³/gDW ; initial N uptake affinity phytoplankton
 cNDPhytMin [0.02] gN/gDW ; minimum N/D ratio phytoplankton
 cNDPhytMax [0.1] gN/gDW ; maximum N/D ratio phytoplankton

General conversion factors

O2PerNO3 [1.5] - ; mol O2 formed per mol NO3- ammonified
 cDayApril1 [91] day ; April 1
 cDayOct1 [273] day ; October 1
 cLengChange [10] day ; length of season change
 DaysPerYear [365] day/y ; days per year
 TenDays [10] day ; ten days
 HoursPerDay [24] h/day ; hours per day
 SecsPerDay [86400] s/day ; secs per day
 mmPerm [1000] mm/m ; mm per m
 m2Perha [10000] m²/ha ; m² per ha
 mgPerg [1000] mg/g ; mg per g
 gPerkg [1000] g/kg ; g per kg
 gPerton [1000000] g/ton ; g per ton
 PerCent [0.01] % ; per cent
 NearZero [1E-33] - ; very small number used to avoid dividing by zero
 molO2molC [2.6667] gO₂/gC ; ratio of molar weights
 molO2molN [2.2857] gO₂/gN ; ratio of molar weights
 molNmolC [1.1667] gN/gC ; ratio of molar weights
 cRhoWat [1000000] g/m³ ; density of water
 Pi [3.14159265358979] - ; Pi