

Memo

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Subject
WI TO27: Wetland vegetation modeling with DWAQ and LAVegMod, version 4

1 Introduction

Emergent wetland vegetation and submerged aquatic vegetation are influenced by abiotic and biotic conditions, but vegetation can also influence its environment by, among other things, changing water quality and sediment accretion. In the WI project emergent and submerged vegetation are included in the Barataria and Breton Sound DWAQ model to provide a more holistic understanding of how the planned diversions will act upon water quality and sediment accretion. This note describes how the available modeling tools will be used and what formulations will be implemented in DWAQ for vegetation modeling. The definition and calculation of output parameters needed as input for DFLOW concerning vegetation flow resistance and soil strength are not dealt with in the present document.

In this document the focus is on the emergent wetland vegetation to be simulated on the basis of DWAQ's VEGMOD module. The submerged vegetation will be dealt with using DWAQ's SAV module.

2 Available modeling tools and required modification

The available modeling tools include LAVegMod (UL Lafayette) and the VEGMOD module of DWAQ.

LAVegMod simulates the annual emergent and submerged vegetation coverage based on abiotic conditions delivered by other models. LAVegMod will be used to provide vegetation coverage as input to DWAQ, which in turn can provide abiotic conditions (salinity, water level, etc.) to LAVegMod. LAVegMod will be coupled to DWAQ offline with (multi-) year intervals. A previous note briefly describes LAVegMod and the envisaged modeling approach.

DWAQ simulates water and sediment quality as well as primary producers including phytoplankton, submerged vegetation and terrestrial emergent vegetation. It comprises many modules that describe an extensive array of processes: from reaeration to processes that determine the fate of heavy metals, and from algae competition to the transport of substances in the sediment. However, the present terrestrial vegetation module VEGMOD only partially

provides the formulations needed to simulate emergent wetland vegetation according to the requirements of the present project.

The VEGMOD module was developed to simulate the effects of mortality due to drowning (inundation) and re-growth of terrestrial vegetation (grasses, shrubs, trees) on water quality in water systems such as man-made reservoirs. The module can simulate up to 9 species of emergent vegetation, the biomass of which is distributed among five compartments (foliage, branches, stems, big roots, fine roots; see Figure 1). The design of the module is generic. Algorithms are present for the uptake of nutrients from sediment layers as well as for the release of organic detritus into water and sediment layers. Given VEGMOD's original purpose only the most essential formulations for growth and mortality have been included:

- The growth rate is based on age, a minimum and maximum biomass and nutrient limitation. Growth rates decrease more and more when the actual biomass closes in on the maximum biomass. When that maximum biomass is reached, the growth rate is reduced to zero. The seasonal variation of biomass is not considered.
- Mortality sets in after an inundation period only and the rate is defined as a fraction of the total biomass per day (a switch is present that allows for mortality during growth). When the sediment is exposed to the air again, the vegetation can grow anew.

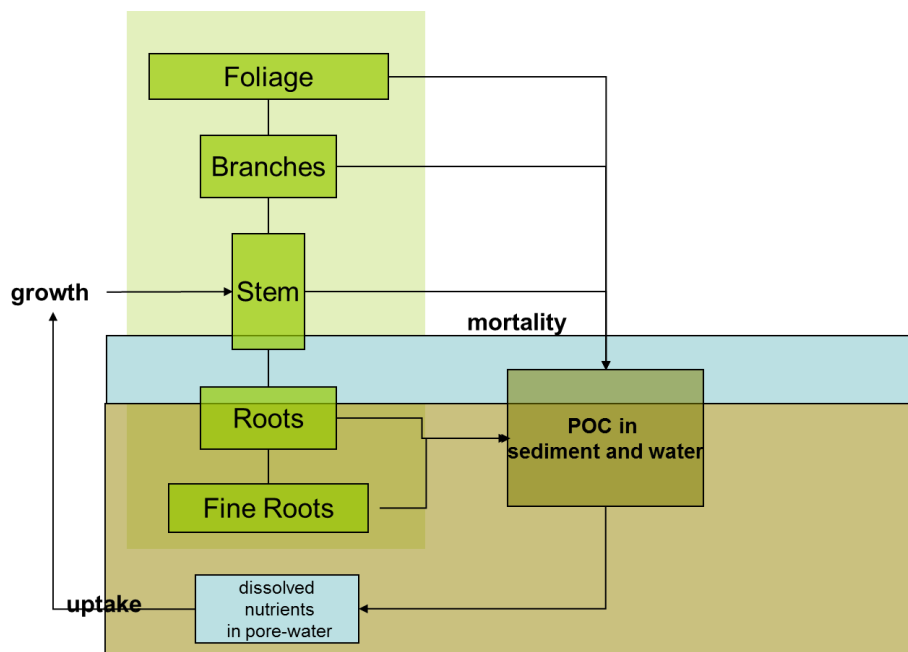


Figure 1: The structure of vegetation biomass and processes in VEGMOD.

Using VEGMOD in its present form brings along some issues. The calculation of vegetation growth based on age is an unnecessary complication for herbaceous wetland vegetation that develops on a seasonal basis, and the biomass of which is reset yearly. This resetting of the vegetation biomass could potentially violate the mass conservation constraint of DWAQ, and therefore provisions have to be made to prevent this. Moreover, a reduction of nutrient uptake towards zero when approaching maximum biomass is not realistic. In reality, nutrients are still taken up for growth to compensate for losses due to various mortality processes. Wetland vegetation induced by inundation is incidental in the Baratara and Breton Sound basins, whereas the mortality due to senescence and herbivory by Nutria results in the continuous turn-over of biomass into detritus. And finally, the distribution of biomass among the various aboveground and belowground compartments is fixed in VEGMOD, whereas for the wetland vegetation this needs to depend on nutrient availability.

With some adaptations of VEGMOD, its infrastructure can be preserved while the above mentioned issues are solved. One of the concepts used in DWAQ's phytoplankton-detritus zooplankton-zoobenthos grazing module CONSBL gives the key to the adaptations needed. CONSBL uses a so-called 'forcing function' approach. The user needs to specify the biomass of filter feeders as varying over a year. Based on this biomass the grazing rate on phytoplankton and detritus is simulated. Whenever the nutrient availability is insufficient to sustain the specified biomass development, the filter feeder biomass in the model is corrected. A lower sustainable biomass is assumed in the model in that case. This type of biomass modeling prevents the violation of mass conservation. It is therefore proposed to replace VEGMOD's present growth formulation with a growth formulation as used in CONSBL, for which age information is not needed. This formulation strives for a seasonally varying target biomass, that takes into account the effect of nutrient availability on the distribution of target biomass among the aboveground and belowground compartments. Furthermore, because the herbaceous wetland vegetation species considered lack woody parts, only the "foliage" and "fine roots" compartments in VEGMOD are used. The compartments "branches", "stems" and "big roots" are not used.

However, the substitution of the growth formulation as such does not solve the issue of nutrient uptake when the vegetation is approaching its maximum biomass. This is because growth and mortality need to occur at the same time, as in reality. Combining them in the way this is done in CONSBL can solve this. When combined, the first order decay approach of mortality and the growth formulation based on a biomass forcing function leads to nutrient uptake even when biomass is at its maximum: the forcing function with a target biomass will compensate the biomass loss due to mortality. This approach works similarly when biomass starts to decline due to the (same) forcing function: the extra mortality and hence growth compensation, leads to some generation of biomass and thus nutrient uptake.

To make the method presented above work, the calculation order is important: First, mortality needs to be calculated to "make room" for growth. Next, the available nutrients must be calculated to have to right amount of nutrients available for vegetation growth. Then growth can be calculated in agreement with the stock of available nutrients, followed by nutrient uptake. In the text below, however, the formulation of growth and nutrient uptake will be described before mortality and detritus formation as this seems the natural order.

3 Formulations

The emergent vegetation biomass is modeled in VEGMOD according to:

$$\frac{\Delta BM}{\Delta t} = Rgr - Rm \quad (1)$$

Where:

- BM = the total aboveground and belowground biomass ($\text{gC}\cdot\text{m}^{-2}$)
- t = time step (d^{-1})
- Rgr = the net growth rate ($\text{gC}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)
- Rm = the mortality rate ($\text{gC}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)

The net growth is gross growth minus respiration as forced by imposed biomass but limited by the available nutrients. Mortality is defined as the loss of live vegetation biomass due to natural senescence, herbivory and inundation.

3.1 Coupling LAVegMod to DWAQ

The coupling of LAVegMod and DWAQ concerns the passing of information about vegetation composition expressed as spatial distribution. However, because the calculated vegetation coverage in LAVegMod is expressed in % area and DWAQ simulates biomass in gC/m^2 , a conversion of units is needed for the initial species composition in DWAQ:

$$BM_{act,i} = fa_i \times \left(\frac{BM_{dm,i}}{dmc_i} \right) / 100 \quad (2)$$

Where:

- BM_{act} = actual total aboveground and belowground biomass of a vegetation species in a grid cell (gC/m^2)
- i = index of vegetation species
- fa_i = percentage of area coverage (%)
- BM_{dm} = the initial total biomass (i.e. 1st of January) in the grid cell (gDM/m^2 in the model, tDM/ha for biomass input data)
- dmc = dry matter carbon ratio (gDM/gC)

This biomass is distributed among the biomass compartments of VEGMOD. For the herbaceous wetland species, the number of plant compartments is reduced from 5 to 2 (see above). The aboveground and belowground biomasses are derived from the total initial biomass by multiplication with fractions. The initial total biomass $BM_{dm,i}$ is allocated according to input parameters $fr2BM_i$ (foliage compartment) and $fr5BM_i$ (fine roots compartment).

At the reset of vegetation coverage (not the very first modeling year, but every succeeding modeling year) the mass conservation constraint of DWAQ could be violated. This can be caused by:

- The introduction of a species in specific grid cells: according to LAVegMod the vegetation composition has changed and a “new” species is added to a grid cell. Because of the mass conservation constraint, DWAQ should not create biomass

from nothing. This issue can be dealt with by having all species in all grid cells at all times, and to allocate a small default biomass (for instance 0.1 gC/m²) to each species. If LAVegMod doesn't predict a species in a specific grid cell, its default initial biomass does not change and growth will not occur in this grid cell. When LAVegMod predicts the presence of this species in this grid cell, it will start to grow from the small default biomass.

- The disappearance of a species: when a species was present in the foregoing year, it is likely to have some biomass left at the end of the year, both above and below ground. According to LAVegMod, the species has disappeared, but DWAQ is burdened with "left over" biomass. The forcing function concept solves this issue by gradually reducing the above and below ground biomass of this species to the small default biomass (the 0.1 gC/m² mentioned above).
- A reduction or increase of the percent coverage by a species: This requires the redistribution of biomass of this species over larger or smaller areas, e.g. the area proportional decrease or increase of its biomass per m². The redistribution leads to a biomass per m² (much) lower or higher than the target biomass at the beginning of a year. The mortality and growth rates should be fast enough to establish target biomass within a period as short as possible. Additional provisions can be made for temporarily enhanced/reduced growth or mortality, avoiding numerical instabilities by too large nutrient fluxes.

3.2 Biomass growth

Growth is based on establishing a target total biomass BM_{for} , which is obtained from target biomass time series for all model species (gC/m²)¹. Such time series are imposed as model input (preferred option because this is adequate and provides flexible biomass forcing; see the example in Figure 2). In DWAQ the forced biomass of a species is scaled for its percentage coverage, i.e. if this is 40%, the target biomass is set at 40% of the imposed target biomass (gC/m²) known from field data.

The total biomass as resulting from growth only is calculated for each species as follows:

When $BM_{for} \geq BM_{act}$

$$BM_{unl,i} = BM_{act,i} * (1 + G_{act,i} * \Delta t) \quad (3)$$

$$G_{act,i} = acg_i \times G_i^{20} \times kg_i^{(T-20)} \quad (4)$$

Where:

acg = acceleration factor for growth (-)

BM_{act} = the total biomass calculated at t-1 (gC/m²)

¹ **NOTE:** Biomass is composed of aboveground and belowground biomass that have different features and affect the water-sediment system in different ways. Aboveground biomass has a distinct annual cycle of biomass increase and decrease, and influences the flow velocity of the water and the settling velocity of sediment. Belowground biomass has a different seasonal growth pattern, and living roots intertwined with dead roots affect the soil strength e.g. the erosion of sediment.

- BM_{for} = the target total biomass (gC/m²)
- BM_{unl} = maximum total biomass after time step Δt , solely based on its growth rate (gC/m²)
- G_{act} = first order growth rate (d⁻¹)
- G^{20} = first order growth rate at 20°C (d⁻¹)
- kg = temperature coefficient of growth (-)
- T = daily average air temperature (°C)
- Δt = time step (d)
- i = index for the vegetation species

NB: The temperature dependency may not be needed for biomass growth forcing, but it has been included here to stay close to the generic approach of rate constants in DWAQ.

The acceleration factor acg_i can be used to speed up growth towards the winter target biomass for emerging species. The value is equal to 1.0 if the ratio of biomass resulting from standard growth and the target biomass is lower than a minimum value ($MnBR_i$), which is an input parameter.

When the calculated $BM_{unl,i}$ is larger than $BM_{for,i}$ than $BM_{unl,i}$ is set equal to $BM_{for,i}$. When the calculated $BM_{unl,i}$ is smaller than $BM_{for,i}$ than $BM_{unl,i}$ prevails.

The availability of nutrients N and P affects the distribution of biomass among aboveground and belowground biomasses. Depending on the local availability of nutrients in the soil/sediment bed the aboveground and belowground biomasses $ABM_{unl,i}$ and $BBM_{unl,i}$ (output parameters) can be derived from the total biomass $TBM_{unl,i}$ using an allocation ratio determined for the presently available nutrients. This ratio follows from a biomass allocation model with an optimization algorithm to be developed by LSU Lafayette (Scott Duke-Sylvester). The algorithm needs to define available nutrients as they are defined in the DWAQ model (see section 3.3). The aboveground/belowground biomass ratio BMr_i is determined from lookup tables linking the ratio to the concentration of available nutrients, or from formulations if the results of the optimization algorithm can be described by these formulations. Preferably, the availability of nutrients should be evaluated over a period of a week rather than for each computational timestep in DWAQ (in the order of 10 minutes).

The nutrient uptake fluxes need to be corrected for the change of the aboveground/belowground biomass ratios compared to the previous timestep, because the aboveground and belowground biomasses have different nutrient stoichiometry (see the next section).

Moreover, if vegetation growth is limited by nutrients (N, P or S), the now calculated growth rate is too large and is to be reduced. For simplicity the biomasses of all present species are corrected in the same way, proportional to the stock of the limiting nutrient:

$$BM_{lim,i} = BM_{unl,i} * \left(\frac{nut_{av}}{nut_{need}} \right) \quad (5)$$

Where:

- BM_{lim} = the total biomass of a species after time step Δt corrected for nutrient limitation (gC/m²)

BM_{unl} = the total biomass of a species after time step Δt prior nutrient limitation correction (gC/m^2)
 nut_{av} = the available quantity (stock) of the limiting nutrient for all species (N,P,S g/m^2)
 nut_{need} = the required quantity of the limiting nutrient based on BM_{unl} for all species (N,P,S g/m^2).

If the nutrient ratio is larger than 1.0 BM_{lim} is equal to BM_{unl} . The resulting biomass rate for growth ($\text{gC/m}^2/\text{d}$) is:

$$Rgr_i = \frac{BM_{lim,i} - BM_{act,i}}{\Delta t} \quad (6)$$

Nutrient limitation might induce a change of nutrient stoichiometry of both the aboveground and belowground biomasses. In the model this phenomenon and the pertinent transfer of nutrients from roots (nutrient-rich rhizomes) to foliage is ignored. A provision for such a transfer should be considered if this simplification would lead to an unacceptable growth limitation for aboveground biomass.

Growth can be inhibited at all during inundation. The growth rate can be set equal to zero during inundation as is done in present VEGMOD.

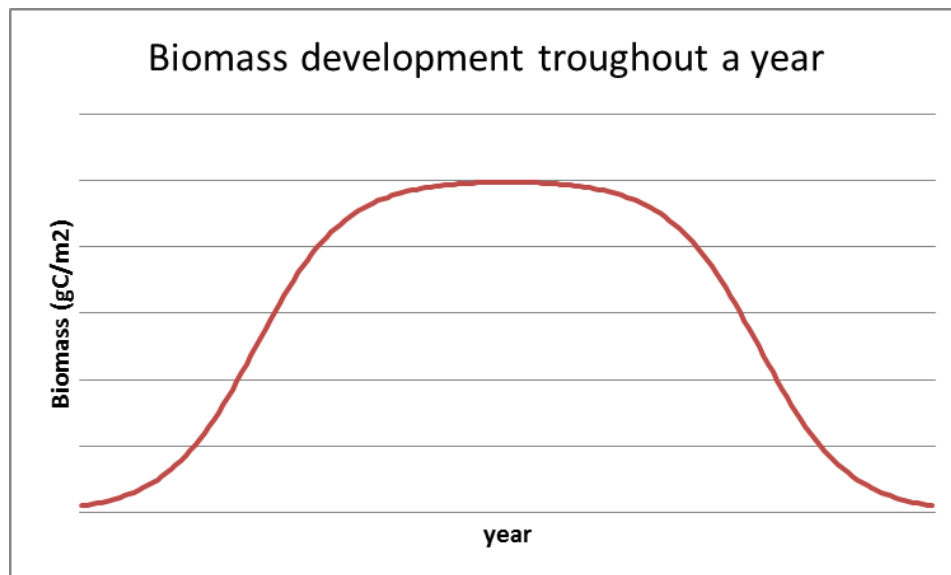


Figure 2: Example of a biomass forcing function (gC/m^2) over a year.

3.3 Nutrient uptake

The nutrient uptake and the stocks of available nutrients can be calculated in the same way as already implemented in VEGMOD. Nutrients (N, P and S) are taken up by vegetation from the sediment within rooting depth, whereas carbon is taken up from the atmosphere. The total uptake rates are computed using vegetation species and biomass compartment specific carbon

to nutrient ratios. The total uptake rates are distributed among the sediment layers within rooting depth proportional to the quantities of the nutrients available in the layers (grid cells). The nutrient uptake rates result from:

$$Rnup_{lin} = fn_{ln} * \Delta BM * \sum_{j=1}^2 \frac{\left(\frac{fb_{ij}}{vn_{lij}}\right)}{H} \quad (7)$$

$$Rnup_{tot,l} = \sum_{i=1}^7 (\sum_{n=1}^{nr} (Rnup_{lin})) \quad (8)$$

Where:

- fb* = fraction of biomass in a compartment (-)
- fn* = fraction of total available nutrient in a layer (-)
- H* = sediment layer thickness (-)
- Rnup* = uptake rate of nutrients in all compartments (gN/P/S.m⁻³.d⁻¹)
- Rnup_{tot}* = total uptake rate of nutrients in all compartments (gN/P/S.m⁻³.d⁻¹)
- vn* = carbon nutrient ratio in vegetation biomass (gC.gN/P/S⁻¹)
- ΔBM = the change in total biomass over a time step (g N/P/S .m⁻² .d⁻¹)
- i* = index for the vegetation species
- j* = index for biomass compartments (2= foliage and 5 = fine roots)
- l* = index for nutrient (1=nitrogen, 2=phosphorus, 3=sulphur)
- n* = index for a sediment layer

As mentioned above, the uptake fluxes need to be corrected for changing biomass fractions *fb*. The correction entails a comparison of the quantities of nutrients in the biomasses from the previous timestep for the old and the new biomass fractions. The differences must be added to or subtracted from the fluxes calculated with equations 7 and 8.

The available nutrients are defined as follows: available nitrogen is the sum of the bulk concentrations (g/m³ wet sediment/soil) of ammonium-N (NH₄) and nitrate-N (NO₃), available phosphorus is the sum of the bulk concentrations of dissolved phosphate-P (PO₄) and adsorbed phosphate-P (AAP), available sulphur is the sum of the bulk concentrations of dissolved sulphate-S (SO₄) and dissolved sulphide-S (SUD). The quantities of available nutrients are calculated from the nutrient concentrations in the sediment layers within rooting depth. When not enough nutrients are available to sustain potential growth, the growth is reduced proportionally (see above). In order to avoid numerical errors when all available nutrient would be depleted the maximum fraction of the available nutrients that can be taken up in a time step can be made smaller than 1.0 by means of input parameter *VBFrMaxU*.

3.4 Biomass mortality

Mortality decreases the vegetation biomass and transfers living vegetation to particulate detritus fractions. The mortality due to inundation can be simulated in the same way as done in present VEGMOD, as a first order decay starting after a lag time (input parameter). However, the model must be extended with a critical water depth that must be exceeded before mortality starts. If this critical water depth (input parameter) is smaller than the threshold depth for “running dry”, inundation time will start counting when the actual water depth exceeds the threshold. If the

critical water depth is larger than the threshold depth, inundation time will start counting when the actual water depth exceeds the critical water depth.

The mortality due to senescence and herbivory is calculated as follows:

$$BM_{mor,i} = BM_{act,i} \times (1 - Ms_i \times \Delta t - Mi_i \times \Delta t) - Mgr_i \times \Delta t \quad (9)$$

$$Ms_i = acm_i \times Ms_i^{20} \times km_i^{(T-20)} \quad (10)$$

Where:

- acm = acceleration factor for senescence mortality (-)
- TBM_{mor} = the total biomass at the end of timestep Δt due to mortality ($gC \cdot m^{-2}$)
- Δt = time step (d)
- Mgr = mortality rate due to herbivory ($gC/m^2/d^{-1}$)
- Mi = first order mortality rate due to inundation (d^{-1})
- Ms = first order mortality rate due to senescence (d^{-1})
- Ms^{20} = first order mortality rate due to senescence at 20 °C (d^{-1})
- km = temperature coefficient of mortality due to senescence (-)
- T = air temperature (°C)

As argued above the actual biomass may be much higher than the target biomass after a reset of vegetation composition at the beginning of a new year simulation in winter. In order to speed up mortality to establish target biomass as soon as possible the following procedure is implemented. If the ratio of biomass $BM_{mor,i}$ resulting from standard mortality and the target biomass $BM_{for,i}$ is higher than a maximum value ($MxBR_i$), the mortality rate is increased using an input multiplier acm_i larger than 1.0.

The resulting total mortality biomass rate ($gC/m^2/d$) is :

$$Rm_i = \frac{BM_{mor,i} - BM_{act,i}}{\Delta t} \quad (11)$$

After all mortality calculations, the $BM_{act,i}$ that is used in the growth calculation is set equal to $BM_{mor,i}$. This biomass tends to be lower than the imposed $BM_{for,i}$, which allows for growth in parallel with mortality, the need for which was explained before.

3.5 Detritus release

Two biomass compartments are used for the herbaceous wetland vegetation, the foliage compartment for aboveground biomass and the fine roots compartment for belowground biomass. In present VEGMOD detritus from the foliage goes to the water layers and detritus from the roots to the sediment layers. The detritus release rates are species specific and computed by the specific carbon to nutrient ratios of a species and the fraction of biomass allocated to a water or sediment layer. This fraction is derived from vegetation height and rooting depth. The release rate of detritus (R_{det}) is described by:

$$Rdet_{klij} = \frac{fh_i * fd_{kij} * fb_{ij} * D_{BM_{veg,i}}}{vn_{lij} * H} \quad (12)$$

Where:

- fb = fraction of biomass in a compartment (-)
- fd = fraction of biomass released into a specific detritus fraction (-)
- fh = fraction of biomass in a layer (-)
- H = water layer or sediment layer thickness (-)
- $Rdet$ = release rate of detritus (gC/N/P/S.m⁻³.d⁻¹)
- vn = carbon nutrient ratio in vegetation biomass (gC.gC/N/P/S⁻¹)
- k = index for detritus fraction (1=POX1, 2=POX2, 3=POX3)
- j = index for the nutrients (X=C,N,P or S)

The fractions fd for foliage and fine roots to organic detritus fractions POX1-3 are derived from input parameters in the existing VEGMOD module. The fractions of biomass in the two compartments fb are calculated from the aboveground and belowground biomasses in this case.

In order to obtain vertical distributions of the detritus release rates among water layers and sediment layers, the biomass compartments of each vegetation species are distributed virtually among the layers (grid cells) in each water-sediment column. Aboveground biomass of each cohort has a vegetation height. Below-ground biomass of each cohort has a rooting depth. Based on these parameters, the number of water layers and sediment layers involved in the distribution are determined. Water layers above vegetation height and sediment layers below rooting depth have zero biomass, and therefore zero detritus release.

The distribution of the detritus fluxes is determined from the total above-ground or the total below-ground biomass per m² using a distribution shape constant. The total above-ground and total below-ground biomass is derived from the total biomass of a vegetation cohort and the biomass fractions in the five compartments. When it is assumed that the vegetation is distributed uniformly over the water column and in the sediment. The shape constant is given by:

$$fh_i = \frac{BM_{act,p,i} * (z_{n+1} - z_n)}{BM_{act,i} * H_{max,i}} \quad \text{if } z_n > z_{max,i} \quad (13)$$

$$fh_i = \frac{BM_{act,p,i} * (z_{max,i} - z_n)}{BM_{act,i} * H_{max,i}} \quad \text{if } z_n < z_{max,i} \text{ and } z_{n+1} > z_{max,i} \quad (14)$$

Where:

- fh = fraction of biomass in a water or sediment layer (-)
- BM_{act} = above-ground or below-ground biomass (gC.m⁻²)
- z_{max} = water depth (positive) at vegetation height or sediment (negative) depth
- z = water depth (positive) or sediment depth (negative) at bottom of a layer (m)
- H_{max} = vegetation height (positive) or rooting depth (negative) (m)

When wetlands in the DWAQ model are not flooded, a thin residual water layer is maintained. The water quality processes are put on hold, but the settling of detritus continues, which means that eventually all detritus ends up in the sediment bed.

4 The implementation in DWAQ

DWAQ's existing VEGMOD sub-model already contains the code for:

- the administration of 9 vegetation species (substances for biomass), process coefficients and mass fluxes;
- nutrient uptake (correction needed!) and detritus release as distributed among water layers and sediment layers (vertical distribution of biomass);
- available nutrient stocks and nutrient limitation;
- mortality due to inundation.

The present functionality for the re-growth of terrestrial vegetation for reservoir inundation studies can be maintained as an option. We propose the following modification of DWAQ's processes library code. The new growth formulations can be implemented as a additional option (SwVEGMOD = 0 or 1), using the existing input and output parameters where appropriate. Where needed new input and output parameters are added.

Given the expected large computational burden of the Barataria and Breton Sound DWAQ model, an additional provision is implemented in the code to restrict the application of vegetation sub-models to those areas that actually have a vegetation cover. This is done by means testing the coverage percentage against a critical low value. If the percentage for a species is smaller the processes will be "short circuited" for this species, and fluxes will be set equal to zero. If in a segment all coverage percentages are smaller than the critical value vegetation will not develop in this segment.

Another possibility to reduce computational burden is to allow for a larger time step for the vegetation modules (6-24 hours) compared to the time step for the water quality processes (5-15 minutes), similar to the larger time step for the phytoplankton module BLOOM. Implementation of this is not yet foreseen.

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