WASP8 Macro Algae - Model Theory and User's Guide

Supplement to Water Analysis Simulation Program (WASP) User Documentation

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Introduction

Phytoplankton (floating plants) are commonly included as state variables in water quality models, such as WASP, both because they impact dissolved oxygen and material cycling in water bodies and because excessive phytoplankton and benthic algal populations are of environmental concern. However, in many waterbodies other forms of algae and/or true plants are of equal or greater importance. These may include benthic algae (macroscopic or microscopic), submersed or floating macroscopic algae (macroalgae) and true plants, the macrophytes (from makros meaning large and phyton, plant). The impact of these organisms is proportional to their abundance and productivity, which is in turn, impacted by waterbody characteristics, and the capability of estimating changes in that abundance and productivity using models such as WASP is important for environmental management.

The macroalgae and macrophytes represent a large and taxonomically diverse assemblage of organisms as do the phytoplankton. However, these groups can often be characterized in mathematical models based on their shared physiological and ecological characteristics rather solely their taxonomy. For example, these organisms can be characterized by the zones in which they live in the water column, size and shape, whether associated with a surface or are free floating, and other characteristics. The growth of these phototrophs is also impacted by temperature, light and nutrients. Their growth consumes nutrients and produces oxygen and they also excrete cell contents and die, recycling dissolved and particulate organic matter to the waterbodies carbon and nutrient pools.

The purpose of this submodel is to extend upon the previously developed benthic algal model (Martin, Ambrose and Wool 2006) to add the capability of simulating floating surface and subsurface and submersed macroalgae and some forms of macrophytes, those that obtain nutrients from the water column and not rooted in the sediments. Although applicable to some microscopic algae and macrophytes, for convenience hereafter the model will collectively be referred to as the macroalgae model. As stated above, more generally, the Macro Algal model is designed to simulate groups of phototrophic organisms with the following characteristics:

- Are capable of luxury uptake of nutrients, requiring simulation of internal nutrient concentrations
- Commonly have optimal growth at certain conditions of light, temperature and salinity
- May have a maximum density or carrying capacity.
- For submersed (non-rooted) forms
  - Do not move with the water current, except under extreme conditions (scoured)
  - While attached to the benthos, may grow through the water column, so the light reaching them is impacted by the bed or canopy height.
  - They self-shade, impacting their growth and that of other phototrophs within and below the bed or canopy
- For free-floating forms
  - Are strongly impacted by hydrodynamics, but are not expected to be transported at the same rate as the current velocities due to drag
  - Self-shade, impacting their growth and that of other phototrophs

WASP Background

WASP is based on a box model approach, or unstructured grid, and may be applied in 1, 2 or three dimensional mode. The hydraulic transport information is typically generated using a hydrodynamic model which is provided to WASP in a hydrodynamic linkage file. WASP then solves the transport equation (shown as the 3-D transport equation below), to which loading and source/sink terms are added specific to the model type (toxics, eutrophication, etc.) and model state variables. For some state variables (e.g. benthic algae and in this model submersed macroalgae) there is no water column transport.

The following sections will focus on the source/sink term. The source/sink term for the existing model state variables will be presented, with discussion of how they are modified, where necessary, to accommodate the macroalgal state variables.

Note that since an external linkage is used between hydrodynamics and water quality, there is no direct mechanism available in WASP for feedback between the submersed or floating macroalgae and the hydrodynamic model. Therefore, in the proposed approach includes only the feed-forward impacts of hydrodynamics on the SAVs. Potential modifications to the hydrodynamic model for feedback mechanisms are described in Gruber and Kemp (2010).

Dissolved and Suspended Materials

For dissolved or suspended materials, the 3-D transport equation is

Equation 1

$$\frac{\partial (C)}{\partial t} = -\frac{\partial (uC)}{\partial x} - \frac{\partial (vC)}{\partial y} - \frac{\partial (wC)}{\partial z} + \frac{\partial}{\partial x}\left[\frac{\partial (D_x C)}{\partial x}\right] + \frac{\partial}{\partial y}\left[\frac{\partial (D_y C)}{\partial y}\right] + \frac{\partial}{\partial z}\left[\frac{\partial (D_z C)}{\partial z}\right] \pm \frac{\mathbf{W}}{\mathbf{V}} + \frac{\mathbf{S_o}}{\mathbf{V}}$$

Where C is the concentration (g m^{-3}); u, v and w the velocities in the x, y, and z direction, respectively (m day^{-1}); D_x, D_y and D_z are turbulent diffusion coefficients (m^2 day^{-1}); W is an external load (g day^{-1}), S_o is a source/sink term (g m^{-3} day^{-1}) and V is volume (m^3).

WASP8 State Variables

The WASP8 eutrophication module presently includes the following state variables, several of which can have multiple forms :

- Water Temperature
- Ammonia Nitrogen
- Nitrate Nitrogen
- Dissolved Organic Nitrogen
- Inorganic Phosphate
- Dissolved Organic Phosphorus
- Inorganic Silica
- Dissolved Organic Silica
- CBOD (ultimate; maximum of 5 forms)
- Dissolved Oxygen

- Detrital Carbon
- Detrital Nitrogen
- Detrital Phosphorus
- Detrital Silica
- Total Detritus
- Salinity or TDS
- Inorganic Solids (maximum of 10 forms)
- Phytoplankton (maximum of 5 forms)
- pH
- Alkalinity
- MacroAlgae (maximum of 3 forms)
- MacroAlgae-N (maximum of 3 forms)
- MacroAlgae-P (maximum of 3 forms)
- Bacteria (maximum of 5 forms)

A generalized relationship between these state variables are illustrated in Figure 1.

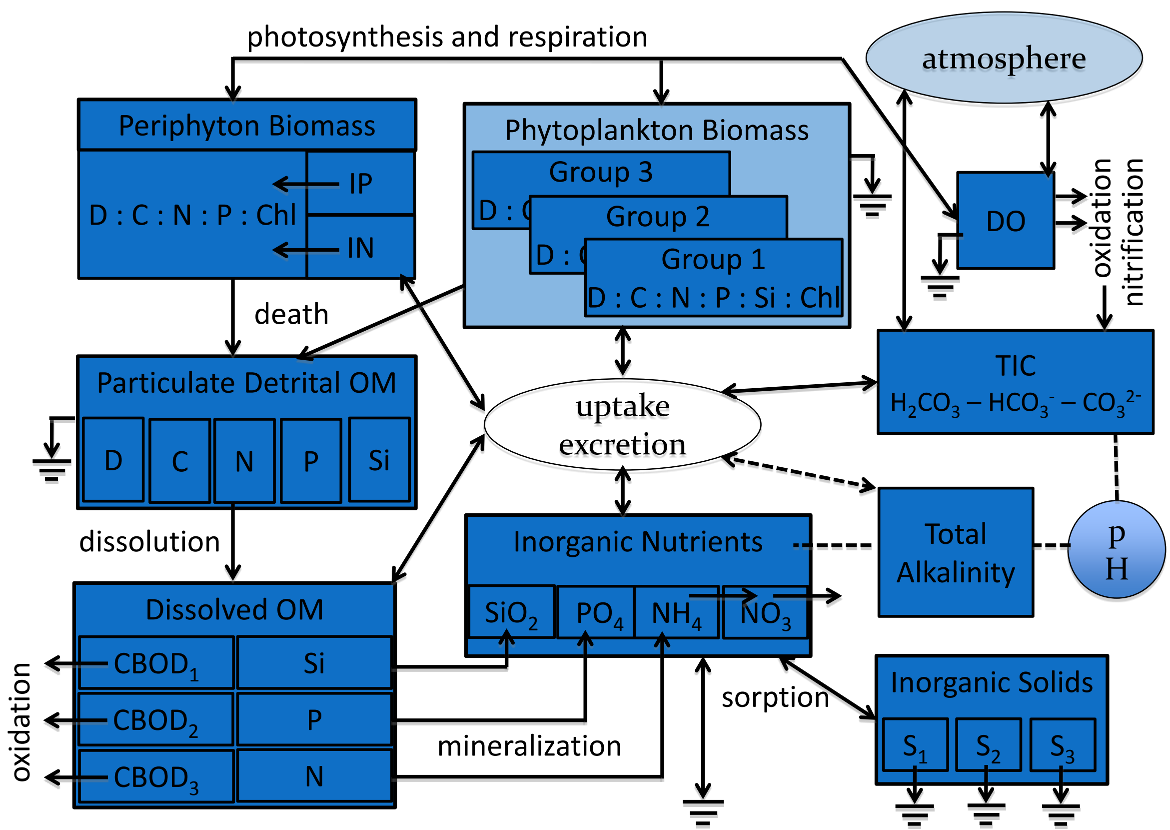

Figure 1. WASP8 Eutrophication Model

Light and Heat

WASP allows several mechanisms for including impacts of light and heat, from direct specification, to prediction, to obtaining the information for the hydrodynamic linkage. Similarly to hydrodynamics, water quality impacts mixing and light penetration which can in turn impact heat exchange. The impact of water quality state variables on light water column penetration, reflected in the light extinction coefficient, is included in the eutrophication model (existing and macroalgal).

Constituent Reactions and Kinetics

The eutrophication state variables for WASP are tabulated above. This section will briefly describe the constituent kinetic reactions included in the source and sink term (So, Equation 1).

Phytoplankton (up to 5 forms)

Equation 2

$$S_{phyto} = (\text{PhytoPhoto} - \text{PhytoResp} - \text{PhytoDeath} - \text{PhytoSettl})\,\text{C}_{\text{phyto}}$$

where phytoplankton increase due to photosynthesis and are lost via respiration, death and settling.

Detritus (as C, N and P)

Equation 3

$$S_{mo} = r_{da}\ \text{PhytoDeath} + r_{da}\ \text{BotAlgDeath} + r_{da}\ \text{MaroAlgDeath} - \text{DetrDiss} - \text{DetrSettl}$$

which includes production of detrital C, N and P from the death of phytoplankton and benthic algae and the loss due to settling and dissolution. Similarly, a term will be added for the source of detritus do to the death of macroalgae.

CBOD (up to five forms)

Equation 4

$$S_{CBOD} = \text{Decomposition-Oxidation-a}_{\text{dn}}\text{denitrification-settling}$$

which includes decomposition and oxidation of CBODU, along with losses due to denitrification and settling

Dissolved Organic Nitrogen

Equation 5

$$S_{no} = r_{na}\text{PhytoDeath} + q_{0N}\ \text{BotAlgDeath} + q_{0N,M}\ \text{MacroAlgDeath} - \text{ONHydr}$$

which includes the production of organic N by death of phytoplankton and benthic algae and loss due to hydrolysis.

Ammonia Nitrogen

Equation 6

$$S_{na} = \text{DONHydr} + r_{na}\ \text{PhytoResp} - \text{Nitrif} + \text{BotAlgExN} \\ - r_{na}P_{ap}\ \text{PhytoPhoto} - P_{ab}\ \text{BotAlgUpN}$$

where ammonia nitrogen increases due to organic nitrogen hydrolysis, phytoplankton respiration/excretion and bottom plant excretion. It is lost via nitrification and plant photosynthesis:

Nitrate Nitrogen

Equation 7

$$S_{ni} = \text{Nitrif} - \text{Denitr} - r_{na}(1-P_{ap})\,\text{PhytoPhoto} - (1-P_{ab})\,\text{BotAlgUptakeN}$$

where nitrate nitrogen increases due to nitrification of ammonia. It is lost via denitrification and plant photosynthesis.

Dissolved Organic Phosphorus

Equation 8

$$S_{po} = r_{pa}\text{PhytoDeath} + q_{0P}\,\text{BotAlgDeath} - \text{OPHydr}$$

which includes the production of organic P by death of phytoplankton and benthic algae and loss due to hydrolysis.

Inorganic Phosphorus

Equation 9

$$S_{pi} = \text{DOPHydr} + r_{pa}\text{PhytoResp} + \text{BotAlgExP} - r_{pa}\text{PhytoPhoto} - \text{BotAlgUpP} - \text{IPSettl}$$

which includes increases due to organic phosphorus hydrolysis, phytoplankton respiration/excretion and bottom plant excretion. It is lost via plant photosynthesis and settling of sorbed forms (e.g. such as on iron oxyhydroxides).

Dissolved Oxygen

Equation 10

$$S_o = r_{oa}\text{PhytoPhoto} + r_{oa}\text{BotAlgPhoto} - r_{oc}\text{FastCOxid} - r_{on}\text{NH4Nitr} - r_{oa}\text{PhytoResp} - r_{oa}\text{BotAlgResp} + \text{OxReaer}$$

where dissolved oxygen increases due to plant photosynthesis. It is lost via fast CBOD oxidation, nitrification and plant respiration. Depending on whether the water is undersaturated or oversaturated it is gained or lost via reaeration.

Total Inorganic Carbon

Equation 11

$$S_{cT} = r_{cco}\text{FastCOxid} + r_{cca}\text{PhytoResp} + r_{cca}\text{BotAlgResp} - r_{cca}\text{PhytoPhoto} - r_{cca}\text{BotAlgPhoto} + \text{CO2Reaer},$$

where total inorganic carbon concentration increases due to fast carbon oxidation and plant respiration. It is lost via plant photosynthesis. Depending on whether the water is undersaturated or oversaturated with CO_2, it is gained or lost via reaeration.

Alkalinity (Alk)

As summarized in Table 1 the present model accounts for changes in alkalinity due to several mechanisms

Table 1. Processes in WASP impacting alkalinity

Process	Utilize	Create	Alkalinity change
Nitrif	NH4	NO3	Decrease
Denitr	NO3		Increase
OPHydr		SRP	Decrease
ONHydr		NH4	Increase
PhytoPhoto	NH4		Decrease
	NO3		Increase
	SRP		Increase
PhytoResp		NH4	Increase
		SRP	Decrease
PhytoUpN	NH4		Decrease
	NO3		Increase
PhytoUpP	SRP		Increase
PhytoExcrN		NH4	Increase
PhytoExcrP		SRP	Decrease
BotAlgUpN	NH4		Decrease
	NO3		Increase
BotAlgUpP	SRP		Increase

pH

Computed from changes in alkalinity and TIC

Inorganic Solids

Up to three forms of inorganic solids can be simulated in WASP, and modeled both in the bed and water column. Sediment transport processes include settling and resuspension of both cohesive and non-cohesive sediments.

Sediment Diagenesis

WASP includes a model of sediment diagenesis, based on Di Toro (2001). The model receives fluxes of particulate organic matter (C, N and P) from the water column, separated into different G classes representing reactivity. The model then predicts sediment oxygen demands, releases of DIN and DIP from sediments along with methane and sulfides.

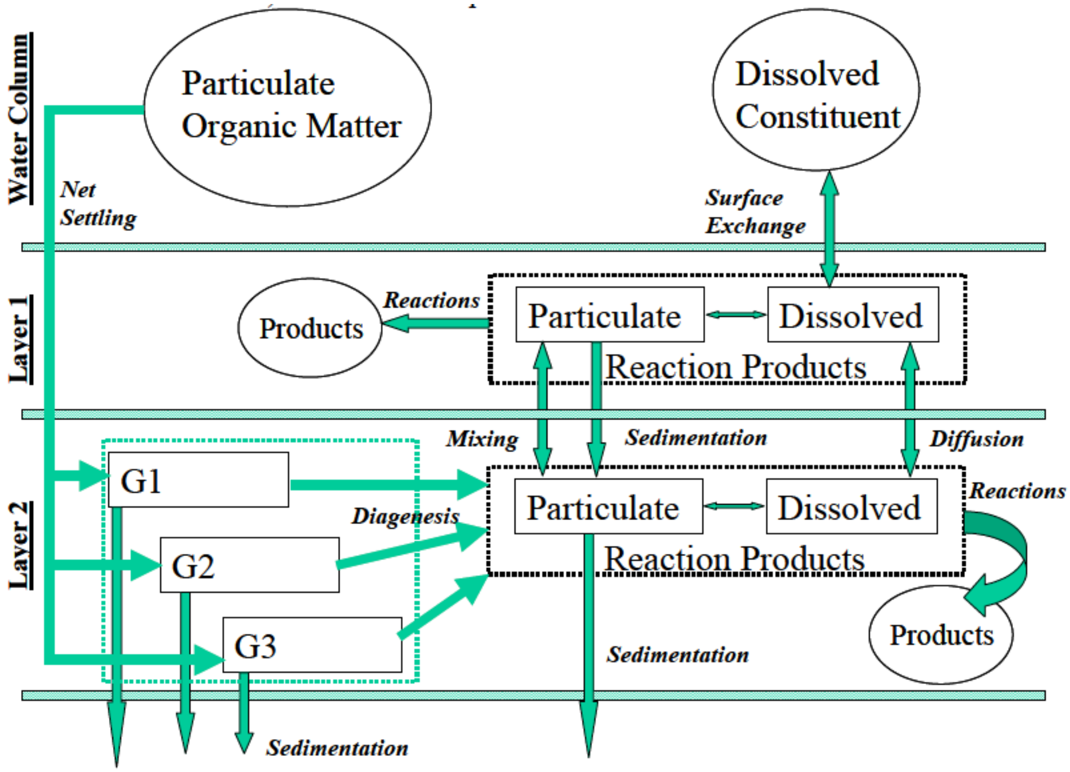

Figure 2. Structure of WASP sediment diagenesis model

Macroalgae Model Algorithms

Forms simulated

Macroalgae and macrophytes represent diverse and complex assemblages of autotrophs. Macroalgae generally refers to macroscopic forms of algae (not true plants) found in brackish water. They may be attached to hard substrates, free-floating or epiphytic. Macrophytes may include algae or true plants and are commonly distinguished based on the habit in which they grow, and may be benthic, submersed, floating or emergent (Martin 2013). Macrophytes may also be rooted, and derive nutrients from the water column and sediments. Macrophytes may also vary in their leaf structure, and include canopy-forming species (e.g. *Myriophyllum sibiricum*) or meadow-forming species (e.g., *Chara canescens*; *Zostera*, *Halodule* and *Thalassia* sp., Figure 3).

macroalgae on tidal flats

floating macroalgae in a closed lagoon

seagrass

Ruppia sp., a type of brackish water SAV (

Figure 3. Examples of primary producer groups found in tidal flats, shallow and deep water habitat types in estuaries (from Sutula et al. 2011).

As indicated previously, while titled the Macro Algal model, this WASP submodel is not targeted to a specific group of aquatic phototrophs. Rather the submodel extends the capabilities of WASP to include phytoplankton, benthic algae (which can be microalgae or macroalgae) and either floating or submersed non-rooted macroscopic phototrophs. The formulations describing growth and death of these organisms are similar to those for phytoplankton (Wool et al. 2011) and the benthic algae model (Martin et al. 2006), which this model replaces. However, where the organisms occur in the water column impacts model formulations. For example, while growth of benthic organisms is impacted by light reaching the bottom, for submersed forms it depends upon the height to which the organisms grow. Also, benthic and submersed forms, unless detached such as during high bottom shear events, are not transported in the water column while floating forms may be. Benthic, surface floating, subsurface floating, and submersed forms are simulated in this submodel, with the specific form simulated selected by the user.

Table 2. MacroAlgal Characteristic Option

Form Options	Form	Transported	Applicable Light
1	Top Floating	Yes	Light at top of water column
2	Subsurface Floating	Yes	Depth averaged light
3	Submersed canopy forming	No	Light at top of canopy
4	Benthic mats	No	Bottom Light

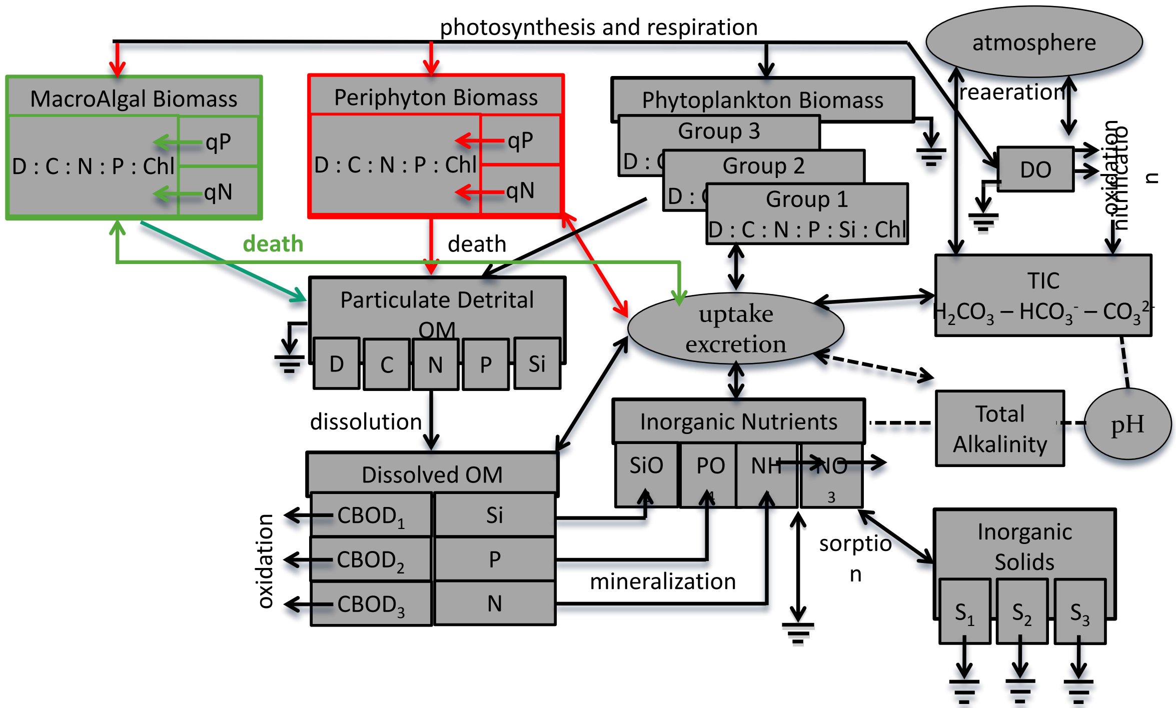

Figure 4. State Variables and Processes in Modified Model

Specific forms of aquatic phototrophs sharing characteristics described by the formulations provided below may be simulated using this submodel by judicious selection of model options and specification of model constants and coefficients appropriate for those forms. The formulations and coefficients are provided below as well as representative values, where appropriate, from the original WASP benthic algae model (Martin et al. 2006) for comparison.

Transport

Constituent transport in WASP is based on the three –dimensional advection and diffusion equation to which constituent source and sink terms are added:

Equation 12

$$\frac{\partial C}{\partial t} = -\frac{\partial U_x C}{\partial x} + \frac{\partial}{\partial x}\left(E_x \frac{\partial C}{\partial x}\right) - \frac{\partial U_y C}{\partial y} + \frac{\partial}{\partial y}\left(E_y \frac{\partial C}{\partial y}\right) - \frac{\partial U_z C}{\partial z} + \frac{\partial}{\partial z}\left(E_z \frac{\partial C}{\partial z}\right) \pm Sources \;\; and \;\; Sinks$$

where C is concentration (g/m^3), U is the velocity (m/s) in the x,y and z dimension and E (m2/s) the rate of dispersion in the x,y, and z dimension. In WASP, this equation is integrated over specified volumes resulting in

Equation 13

$$\frac{d(VC)}{dt} = \sum Q_{in} C_{in} - \sum Q_{out} C + \sum \frac{EA_i}{L_i}(C_i - C) \pm \textbf{sources/sinks}$$

where V is the segment volume (m3), Q the flowrate (m3/s), E the rate of dispersion (m2/s), A the area and L the mixing length for segment i.

The above equations are applied to all constituents simulated in WASP8, where the advection and dispersion terms are typically derived from the application of a hydraulic model (hydrostatic or hydrodynamic) in one-two or three-dimensions. One exception in previous versions of WASP are the benthic algae, which are assumed attached to the bottom and not transported.

Scour

In this version of WASP8 four forms of macroalgae are simulated, two associated with the bottom and two floating. For submersed and benthic algae, the assumption is that they are attached and therefore not transported with the water column transport. One exception is where the velocities are great enough such that the submersed and benthic forms become detached or are scoured from the bottom. In this version of the model an enhanced death rate due to scour is computed based on a specified a maximum velocity that the macroalgae can withstand (U_{max}) which is compared to the average velocity of a model segment. If the velocity is greater that the specified maximum then a fraction of the total biomass would be scoured (f_{scour}). It is further assumed that the scour is a somewhat explosive, rather than continuous event, and impacted by the time the macroalgae have had time to recover from a previous scour event ($T_{recovery}$, days). That is once a scour event is initiated a time counter is set to zero and then incremented with time

Equation 14

$$\begin{aligned}
&if \quad U > U_{max} \ then \\
&\quad if\,(Time <= T_{recovery})\,MacAlgaeDeath_{scour} = 0 \\
&\quad if\,(Time > T_{recovery})\,MacAlgaeDeath_{scour} = f_{scour}\ a_{MA}
\end{aligned}$$

That fraction lost to scour would then be a source term for detritus or floating algae (Note, this algorithm is not yet implemented).

Drag

Floating plants and macroalgae are subject to advective transport computed from Equation 13 with the exception that some floating algae and dense subsurface mats are assumed to place a drag on the advective transport. It is assumed that the drag is relatively constant so that it can be represented by a user specified coefficient representing the fraction of the advective transport applicable to macroalage.

Equation 15

$$Q_{MA} = f_{drag} Q_n$$

where f_{drag} is a flow attenuation coefficient and Q_n the net flow through a segment interface. If $f_{drag} = 0$, then the macroalgae will not be transported via advection.

Table 3 Transport and Scour Options

Variable	Value	Ex. Value from Benthic Algal Model	Description	Reference
U_{max}		NA	Maximum velocity beyond which scour is initiated (m/s) for submersed macroalgae	
f_{scour}		NA	Fraction of submersed Macroalgae biomass scoured in a single event	
$T_{recovery}$		NA	Recovery time (days) following a scour event below which no additional scour will occur	
f_{drag}		NA	Drag coefficient for floating Macroalgae (fraction of advective transport)	

Macroalgal Reactions and Kinetics

Macroalgal biomass stoichiometry

For this submodel, macroalgae are represented as total biomass (dry-weight) per unit area of available substrate (gD/m^2). The model requires that the stoichiometry be specified in order to compute relationships with other state variables and model output variables in the form of

Equation 16

$$r_{xy} = \frac{\text{gX}}{\text{gY}}$$

for relationships between dry weight (D), chlorophyll, nitrogen (N), phosphorus (P), and oxygen (O_2) production. User input is required for the following:

Table 4. Constants for stoichiometry

Variable	Value	Ex. Value from Benthic Algal Model	Description	Reference
ADC		2.5	Macroalgae D:C Ratio (mg D/mg C)	
ANC		0.18	Macroalgae N:C Ratio (mg N/mg C)	
APC		0.025	Macroalgae P:C Ratio (mg P/mg C)	
AChlC		0.025	Macroalgae Chl a:C Ratio (mg Chl/mg C)	
ROC		2.69	Macroalgae O2:C Production (mg O_2/mg C)	

Macroalgal biomass (a_{MA})

Macroalgae, a_{MA} (g-dw m^{-2}) are represented as total biomass per unit area of available surface area (gD/m^2). Macroalgal biomass would increase due to photosynthesis and decrease with respiration and death:

Equation 17

$$S_{MA} = (F_{GMA} - F_{RMA} - F_{DMA})\, A_{MA}\, f_{sub}$$

where S_{MA} = the total source/sink of macroalgal biomass [g/day], F_{GMA} is the photosynthesis rate [g/m^2-day], F_{RMA} is the respiration loss rate [g/m^2-day], F_{DMA} is the death rate [g/m^2-day], and A_{MA} is the surface area [m^2].

The f_{sub} is not an actual computational term but is used here to reflect the specific forms simulated, so is specific to the form of macroalgae:

- Surface floating macroalage; These forms use light at the surface so growth is also restricted to surface segements
- Floating subsurface macroalage: These macroalgae can occur anywhere in the water column where light and nutrients are available.
- Submersed macroalgae: For submersed forms, the height of the bed or canopy is presently not simulated but is specified by the user. Using this option, macroalgae are assumed not to occur above the canopy height. Therefore, for model segments in the vertical water column above the specified canopy height the rates of change (sources and sinks) are assumed to be zero (f_{sub} = 0). As WASP makes no assumption as to the shape of a segment a parameter is provided for the fraction of the bottom area of any segment that is available as a substrate for the growth of submersed macroalgae.
- Benthic macroalgae: For these algae, they are assume to occur on the bottom of a segment. As WASP makes no assumption as to the shape of a segment a parameter is provided for the fraction of the bottom area of any segment that is available as a substrate for the growth of benthic macroalgae.

The complete sexual and asexual reproductive cycle for macroalgae is not simulated in this version of WASP8. To some degree mimic those patterns it is assumed that some algal concentrations persist under all conditions which can provide a seed concentration for future growth. That concentration is specified by the user (MacAlg_seed) and if specified the concentration of macroalgae (a_{MA}) is not allowed to go below that minimum concentration.

Equation 18

$$a_{MA} \geq a_{MA,seed}$$

Photosynthesis

As in the periphyton model (Martin et a. 2006) two options are available for the photosynthesis rate, F_{GMA} [gD/(m^2-d)]. The first option is a temperature-corrected zero-order maximum rate attenuated by nutrient and light limitation:

Equation 19

$$F_{G,MA} = F_{G,MA,20}\ \varphi_{T,MA}\ \varphi_{N,MA}\ \varphi_{L,MA}\ \varphi_{Sal,MA}$$

where $F_{GMA,20}$ = the maximum photosynthesis rate at 20 °C [gD/(m^2-d)], $\varphi_{T,MA}$ = photosynthesis temperature correction factor [dimensionless], $\varphi_{N,MA}$ = bottom algae nutrient attenuation factor [dimensionless number between 0 and 1], $\varphi_{L,MA}$ = the bottom algae light attenuation coefficient [dimensionless number between 0 and 1] and $\varphi_{Sal,MA}$ = salinity preference attenuation factor for marine macroalgae [dimensionless number between 0 and 1].

The second option uses a first-order, temperature-corrected rate constant, attenuated by nutrient, light, and space limitation:

Equation 20

$$F_{G,MA} = k_{G,MA,20}\ \varphi_{T,MA}\ \varphi_{N,MA}\ \varphi_{L,MA}\varphi_{Sal,MA}\ \varphi_{S,MA}\, a_{MA}$$

where $k_{G,MA,20}$ = the maximum photosynthesis rate constant at 20C [day^{-1}], $\varphi_{Sb,MA}$= the bottom algae space attenuation coefficient [dimensionless number between 0 and 1], a_{MA} the macroalgal concentration (g-dw m^{-2})and other terms are as defined above.

There is considerable variability in the literature on maximum growth rates, as would be expected give the diverse assemblage of organisms making up macroalgae and macrophytes. An additional complexity in the literature is the diverse rates specified and measures of concentration, making comparisons difficult between individual studies. Representative rates are provided in Table 5.

Table 5. Model Constants for growth

Variable	Value	Ex. Value from Benthic Algal Model	Description	Form	Source

Macro_GrowthOption	0 = Zero Order; 1 = First Order		Growth Option	NA	
Macro_KGAF ($F_{GMA,20}$)	0.4-0.45	9	Maximum growth rate (day^{-1})	Ulva macroalgae in Venice lagoon	Trancoso et al. 2005

Temperature Effect

Two options are implemented to modify the maximum growth rate due to temperature based on a user specified option (MacAlg_Temp_Opt). The first option is a modified Arrhenius model is employed to quantify the effect of temperature on bottom algae photosynthesis:

Equation 21

$$\varphi_{\mathrm{T,MA}} = \theta_{MA}^{\mathrm{T-20}}$$

where Θ is a coefficient and T temperature (°C). An alternative formulation (MacAlg_Temp_Opt = 2) is (Cerco and Cole 1994),

Equation 22

$$\varphi_{\mathrm{T,MA}} = e^{-\kappa_1 (T - T_{opt})^2} \qquad T \le T_{opt}$$

$$\varphi_{\mathrm{T,MA}} = e^{-\kappa_2 (T - T_{opt})^2} \qquad T > T_{opt}$$

where T_{opt} is the optimal temperature and κ_1 and κ_2 are shape parameters (that determine the shape of the relationship of growth to temperature below and above the optimal temperature, respectively.

Table 6. Temperature related model constants

Constant	Value	Value from Benthic Algal Model	Description	Reference
MacAlg_Temp_Opt			Temperature Option, if = 1 then use theta formulation; if = 2 then use optimal formulation	
Macro_TKGAF		1.07	Temp Coefficient for Macro Algal Growth	
MacAlg_Topt		NA	Optimal Temperature for Macro Algal Growth (oC)	
MacAlg_KAPPA1		NA	Shape parameter for below optimal temperatures for Macro-algae	

MacAlg_KAPPA2		NA	Shape parameter for above optimal temperatures for Macro-algae	

Nutrient Limitation Effect

Nutrient limitation of the photosynthesis rate in macroalgae is assumed dependent on intracellular nutrient concentrations (luxury uptake) as with the periphyton model (Martin et al. 2006).

A typical method for computing nutrient limitation is based on a formulation originally developed by Droop (1974) and referred to as Droop kinetics:

Equation 23

$$\varphi_{N,MA} = \min\left[\left(1-\frac{q_{oN}}{q_N}\right),\left(1-\frac{q_{oP}}{q_P}\right)\right]$$

where q_N and q_P = the cell quotas of nitrogen [mgN/gD] and phosphorus [mgP/gD], respectively, q_{0N} and q_{0P} = the minimum cell quotas of nitrogen [mgN/gD] and phosphorus [mgP/gD], respectively. The minimum cell quotas are the levels of intracellular nutrient at which growth ceases. Nutrient cell quotas for macroalgae are state variables calculated by WASP.

Table 7. Nutrient related constants

Constant	Value	Ex. Value from Benthic Algal Model	Description	Reference
Macro_CellQuotaMinN		7.2	Minimum Cell Quota of Internal Nitrogen for Macro Algal Growth (mgN/gDW)	
Macro_CellQuotaMinP		1	Minimum Cell Quota of Internal Phosphorus for Macro Algal Growth (mgP/gDW)	

Light Limitation Effect

For floating macroalage, the light available for growth is the light at the top of a water column segments. For other forms, the available light is computed at the depth at which they grow. The available light for growth of plant species in WASP8 is based upon available surface light (PAR) which is then attenuated exponentially through the water column using Beer-Lambert law, based on a light extinction coefficient (k_e, m^{-1}) which is used to compute light at the top and bottom of each vertical water column segment:

Equation 24

$$I = I_a \exp(-k_e\ z)$$

where I_a is the specified incident light intensity during daylight hours just below the surface, for a surface water segment, or the light at the top of the segment for sub-surface water segments and z is the depth of the segment (m). As described in the following section, the light may represent a daily average or include values over the diel cycle.

The light extinction coefficient (k_e) is computed for each water column segment from either a base input (model parameter and time function, $k_{e,P}$) to which the impact of phytoplankton self-shading may be added based on the computed chlorophyll concentration and a user specified multiplier (M_{chl}) and exponent ($E_{xp,chl}$) . Alternatively, the extinction coefficient is based on an input background coefficient ($K_{e,b}$)to which the impacts of attenuation due to DOC, inorganic suspended solids (ISS) and phytoplankton chlorophyll are added based on computed concentrations and user-specified coefficients.

Equation 25

$$k_{e,1} = k_{e,P} + M_{CHL} C_{CHL}^{\;E_{xp,chl}}$$

or

$$k_{e,1} = k_{e,b} + k_{e,DOC} C_{DOC} + C_{ISS} * C_{ISS} + M_{CHL} C_{CHL}^{\;E_{xp,chl}}$$

In addition to self-shading by phytoplankton, self -shading by floating or submersed macrophytes or macroalgae can impact available light for plant growth. For example, Krause-Jensen et al. (1996) found that light declined exponentially in dense algal mats of *Chaetomorpha linum*, and that the irradiance was reduced to 10% of surface irradiance at approximately 4.0 cm depth into the mats. The impact of macroalgae on the light extinction coefficient is computed from

Equation 26

$$K_{\mathrm{e,MacroAlgae}} = K_{e,MA} a_{\mathrm{MA}} \frac{\mathrm{A}}{\mathrm{V}}$$

where $K_{e,MA}$ is a light extinction multiplier ($m^3 m^{-1}$ g-dw^{-1}), a_{MA} the macroalgal concentration (g-dw m^{-2}), A is surface area (m^2) and V segment volume (m^3).

If floating macroalgae are present, the light extinction coefficient computed for macroalgae (Equation 26) is added to the above relationship (Equation 25) to compute the total light extinction coefficient (k_e)

Equation 27

$$k_{e,2} = k_{e,P} + M_{CHL} C_{CHL}^{\;E_{xp,chl}} + K_{e,MA} a_{\mathrm{MA}} \frac{\mathrm{A}}{\mathrm{V}}$$

or

$$k_{e,2} = k_{e,b} + k_{e,DOC} C_{DOC} + C_{ISS} * C_{ISS} + M_{CHL} C_{CHL}^{\;E_{xp,chl}} + K_{e,MA} a_{\mathrm{MA}} \frac{\mathrm{A}}{\mathrm{V}}$$

where the subscripts ($k_{e,1}$ and $k_{e,2}$) are used to distinguish between the two formulations.

Similarly, for the impacts of submersed macroalgae, (Figure 5), the available light is impacted by the height of the canopy which for this model refers to the average height to which the growth extends from the bottom of the waterbody (Figure 5), which is a user specified value (constant MacAlg_Bed_H). If the top of the canopy is above the top of the segment, then the total light extinction coefficient, including the impact of self-shading, is computed from Equation 27. However, if the canopy only partially extends into the segment, then a weighted light extinction coefficient is computed. For example, the light at the bottom of the segment (I) for the case with or without macroalgae can be computed from the light reaching the top of the segment (I_O), the depth (z) and either

Equation 28

$$I = I_a \exp(-k_{e,1}\ z) \quad OR \quad = I_a \exp(-k_{e,2}\ z)$$

For the case where the canopy does not extend through the water column segment, as illustrated for segment 2 in Figure 5, then the light at the bottom is computed from

Equation 29

$$I = I_a \exp(-k_{e,1}\ z_1) \exp(-k_{e,2}\ z_2)$$

so that the total light extinction can be computed from a depth-weighted average of the two, as in

Equation 30

$$I = I_a \exp(-\,k_{e,2,1} z2,_1) \exp(-k_{e,2,2}\ z_{2,2}) = I_o \exp\left[\left(\frac{z2,_1\, k_{e,2,1} + z_{2,2} k_{e,2,2}}{z_{2,1} + z_{2,2}}\right)\left(z_{2,1} + z_{2,2}\right)\right]$$

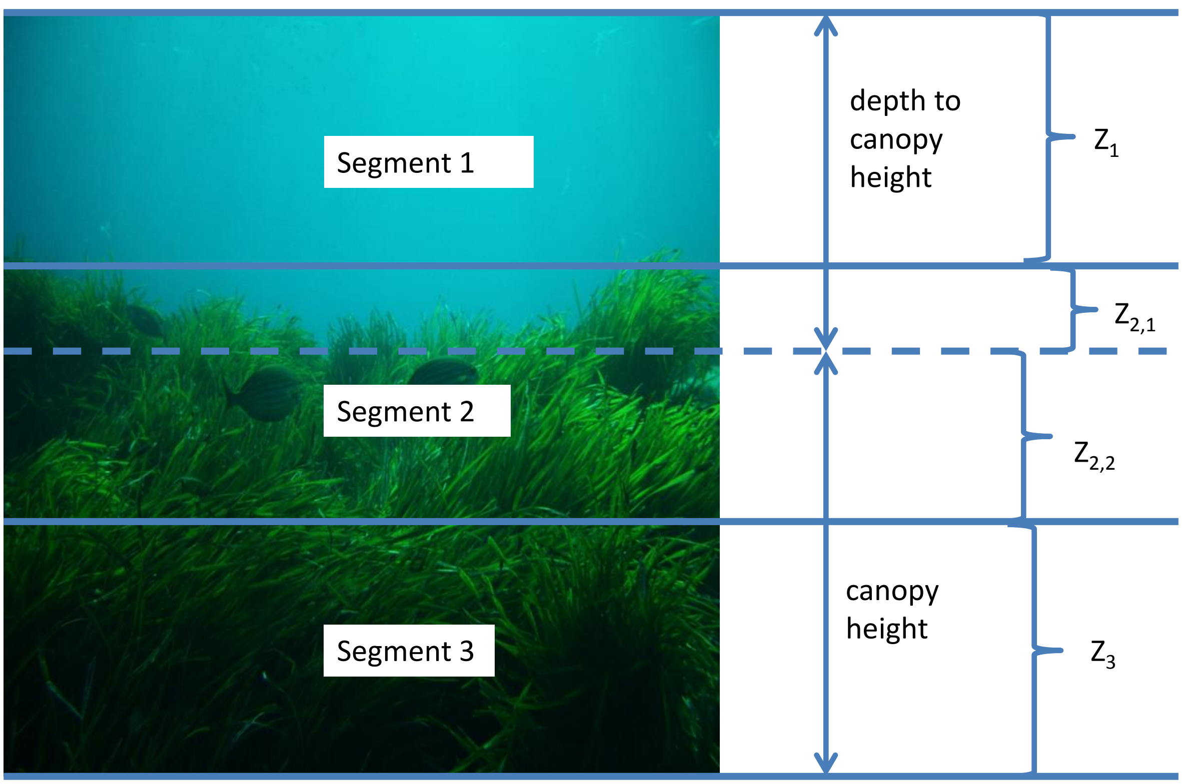

Figure 5. Conceptualization of canopy height impact on light computation

Table 8. Constants for light

Constant	Value	Ex. Value from Benthic Algal Model	Description	Reference
MacAlg_Shade		NA	Macro Algal Self shading coefficient ($m^3 m^{-1}$ g-dw^{-1})	
MacAlg_Bed_H		NA	macroalgal bed height (m, used if MacAlg_SYS=2)	

Impact of Light on Macroalgae

The preceding section described the impacts of macroalgae shading on light, impacting other phototrophs. The light available for growth for macrophytes is computed:

- For surface macroalgae (type 1) the light at the top of a surface segement
- For floating macroalgae from available surface light averaged over the water column, based on Equation 27.
- for submersed macroalgae, from light at the top of the canopy (computed from the total water depth and specified bed or canopy height and light extinction coefficient from Equation 25),
- For benthic algae, the light reaching the bottom

The Macroalgal model, similarly to the WASP phytoplankton model, incorporates the framework developed by Di Toro (1971) and by Smith (1980), extending upon a light curve analysis by Steele (1962), for formulating the impact of light on macroalgal growth. The formulations account for both supersaturating light intensities and light attenuation through the water column. There are two alternative formulations for computing the impact of light, depending on whether the user enters daily average light or the model computes diel variations in light (model parameters and time functions). In the first, light is integrated (averaged) over the segment depth and day length, where f is the faction of the day that is light and f is input as a model time function. For diel light option, where light is input or computed within a day, light is averaged only over depth.

Daily averaged light option

Equation 31

$$\varphi_{\mathrm{L,MA}} = \frac{ef}{K_e D}\left[\exp\left\{-\frac{I_a}{I_s}\exp\left(-K_e D\right)\right\} - \exp\left(-\frac{I_a}{I_s}\right)\right]$$

Diel variations in light

Equation 32

$$\varphi_{\mathrm{L,MA}} = \frac{e}{K_e D}\left[\exp\left\{-\frac{I_a}{I_s}\exp\left(-K_e D\right)\right\} - \exp\left(-\frac{I_a}{I_s}\right)\right]$$

where:

e = 2.718

I_a = the average incident light intensity during daylight hours just below the surface, or diel light ly/day

I_s = the saturating light intensity of the macroalgal group, ly/day

I = incident solar radiation, ly/day

f = fraction of day that is daylight, unitless

D = depth of the water column or model segment, m

K_e = total light extinction coefficient, m^{-1}

Space Limitation Effect

Macroalgal densities are limited by their carrying capacity, or maximum density. Space limitation of the first-order growth rate can be modeled as a logistic function (Madden and Kemp (1996):

Equation 33

$$\varphi_{S,MA} = 1 - \left(\frac{a_{MA}}{a_{MA,\max}}\right)^2$$

where $a_{MA,max}$ is the macroalgae carrying capacity [g_D/m^2]. Note that this formulation differs from that in the original WASP periphyton model (Martin et al. 2006) in that the term is squared.

Table 9. Constants for carrying capacity

Constant	Value	Ex. Value from Benthic Algal Model*	Description	Reference
MacroAlgMax		NA	Macro Algal Carrying Capacity for First Order Model (g D/m²)	

* Benthic algal model using a different formulation, not squared

Salinity Effect

Salinity impacts on macroalgae can include increases in mortality with increases in salinity for fresh water species, while for marine organisms there is commonly an optimal salinity and growth declines at higher and lower values. Similarly to temperature, the impact of salinity is computed from

Equation 34

$$\varphi_{\text{Sal,MA}} = e^{-\kappa_1 (S - S_{opt})^2} \qquad \text{S} \le S_{opt}$$

$$\varphi_{\text{Sal,MA}} = e^{-\kappa_2 (S - S_{opt})^2} \qquad \text{S} > S_{opt}$$

where S is salinity, S_{opt} is the optimal salinity and κ_1 and κ_2 are shape parameters (that determine the shape of the relationship of growth to salinity below and above the optimal salinity, respectively.

Table 10. Constants for impacts of salinity

Constant	Value	Ex. Value from Benthic Algal Model	Description	Reference
MacAlg_Salinity_Tol		NA	if = 0, not considered, if = 1 then salt water optimal model, 2 fresh water	
MacAlg_SSat		NA	salinity at which algal mortality is half maximum value for fresh water species	
MacAlg_Sopt		NA	Optimal Salinity for marine Macro_algal Growth (ppt)	
MacAlg_Smin		NA	Minimum Salinity for marine Macro_algal Growth (ppt)	
MacAlg_SMax		NA	Maximum Salinity for marine Macro_algal Growth (ppt)	

Losses

Macroalgal biomass decreases with respiration and death.

Respiration.

Bottom algal respiration is represented using first-order temperature- corrected kinetics:

Equation 35

$$\textbf{MacroAlgResp} = k_{r,MA}(T)\; a_{MA}$$

where $k_{r,MA}(T)$ = temperature-dependent bottom algae respiration rate [/d].

Death

Bottom algal death is represented using first-order temperature-corrected kinetics. In addition, for fresh-water species, the death rate may be enhanced due to the impact of salinity:

Equation 36

$$\textbf{MacroAlgDeath} = \left(k_{d,MA}(T) + k_{d,sal,MA}\left(\frac{S}{S+Ks}\right)\right) a_{MA} + f_{scour}\ a_{MA}$$

where $k_{d,MA}(T)$ = the temperature-dependent macroalgal death rate [/d], $K_{d,sal,MA}$ is a salinity-dependent macroalgal death rate[/d] for fresh water species, S is salinity (g/m^3) and K_S the salinity (g/m^3) at which algal mortality is half the maximum value for fresh water species. An additional contribution to death is scour when velocities exceed a specified threshold as computed using Equation 14.

Equation 37

$$\textbf{MacroAlgGrazing} = k_{GR,MA}\ a_{MA}$$

Table 11. Constants related to mortality and excretion

Constant	Value	Ex. Value from Benthic Algal Model	Description	Reference
Macro_KREAF		0.31	Macro Algal Respiration Rate Constant (1/day)	
Macro_TKREAF		1.07	Temperature Coefficient for Macro Algal Respiration	
kMacroAlgExcr		0.09	Internal Nutrient Excretion Rate Constant for Macro Algae (1/day)	
TMacroAlgExcr		1.07	Temperature Coefficient for Macro Algal Nutrient Excretion	
Macro_KDEAF		0.01	Macro Algae Death Rate Constant (1/day)	
Macro_TKEAF		1.07	Temperature Coefficient for Macro Algal Death	
Macro_Algal_SalTox		NA	Macro Algae Salinity Enhanced Death Rate Constant (1/day)	

MacAlg_Graze		NA	grazing rate on macroalgae (1/day)	
MacAlg_Salinity_Tol		NA	if = 0, not considered, if = 1 then salt water optimal model, 2 fresh water toxicity model	
MacAlg_SSat		NA	salinity at which algal mortality is half maximum value for fresh water species	

Macroalgae Cell Nutrients (q_N, q_P)

Intracellular nutrient concentrations, or cell quotas, represent the ratios of the intracellular nutrient to the macroalgal dry weight:

Equation 38

$$q_N = 10^3 \frac{IN_{MA}}{a_{MA}}$$
$$q_P = 10^3 \frac{IP_{MA}}{a_{MA}}$$

where IN_{MA} = intracellular nitrogen concentration [gN/m^2] and IP_{MA} = intracellular phosphorus concentration [gP/m^2], and 10^3 is a units conversion factor [mg/g].

The total source/sink terms for intracellular nitrogen and phosphorus in macroalgal cells [g/day] are controlled by uptake, excretion, and death:

Equation 39

$$S_{MA,N} = \left(F_{UN,MA} - F_{EN,MA} - F_{DN,MA}\right) A_{MA}$$
$$S_{MA,P} = \left(F_{UP,MA} - F_{EP,MA} - F_{DP,MA}\right) A_{MA}$$

where $F_{UN,MA}$ and $F_{UP,MA}$ = uptake rates for nitrogen and phosphorus by macroalgae (gN/m^2-d and gP/m^2-d), $F_{EN,MA}$ and $F_{EP,MA}$ = the macroalgae cell excretion rates (gN/m^2-d and gP/m^2-d), and FDNb and FDPb = loss rates from macroalgae death (gN/m2-d and gP/m2- d).

The N and P uptake rates depend on both external and intracellular nutrients as in (Rhee1973):

Equation 40

$$F_{UN,MA} = 10^{-3}\left(\frac{NH_4 + NO_3}{K_{sN,MA} + NH_4 + NO3}\right)\left(\frac{K_{qN}}{K_{qN} + (q_N - q_{ON})}\right) a_{MA}$$
$$F_{UP,MA} = 10^{-3}\left(\frac{PO_4}{K_{sP,MA} + PO_4}\right)\left(\frac{K_{qP}}{K_{qP} + (q_P - q_{OP})}\right) a_{MA}$$

and mgP/gMA-d], $K_{sN,MA}$ and $K_{sP,MA}$ = half-saturation constants for external nitrogen and phosphorus [mgN/L and mgP/L], K_{qN} and K_{qP} = half-saturation constants for intracellular nitrogen and phosphorus [mgN/gD and mgP/gD], and 10^{-3} is a units conversion factor [g/mg]. Note that nutrient uptake rates fall to half of their maximum values when external nutrient concentrations decline to the half-saturation constants, or when excess internal nutrient concentrations rise to the internal half-saturation constants.

The internal N and P excretion rates are represented using first-order temperature- corrected kinetics:

Equation 41

$$F_{EN,MA} = K_{E,MA,20}\theta_{E,MA}^{T-20} q_N a_{MA} 10^{-3}$$
$$F_{EP,MA} = K_{E,MA,20}\theta_{E,MA}^{T-20} q_P a_{MA} 10^{-3}$$

where k_{EMA20} = bottom algae cell excretion rate constant at 20 ^oC [day^{-1}] and $\Theta_{E,MA}$ = bottom algae excretion temperature coefficient [dimensionless].

The internal N and P loss rates from macroalgal death are the product of the algal death rate and the cell nutrient quota:

Equation 42

$$F_{DN,MA} = F_{D,MA} q_N 10^{-3}$$
$$F_{DP,MA} = F_{D,MA} q_P 10^{-3}$$

where 10^{-3} is a units conversion factor [g/mg].

In the following sections, volumetric rate terms “R_S” [g/m^3-day] are used in place of the corresponding macroalgal areal rate terms “F_S” [g/m^2-day]. Volumetric rates are calculated from areal rates as follows:

Equation 43

$$R_S = F_S\left(\frac{A_{MA}}{V}\right)$$

where “*s*” denotes the appropriate subscripts, A_{MA} is the active surface area [m^2], and V is the segment volume [m^3].

Table 12. Constants related to excretion of internal nutrients

Constant	Value	Ex. Value from Benthic Algal Model	Description	Reference

kMacroAlgExcr		0.09	Internal Nutrient Excretion Rate Constant for Macro Algae (1/day)	
TMacroAlgExcr		1.07	Temperature Coefficient for Macro Algal Nutrient Excretion	
kMacroAlgUNmax		720	Maximum Nitrogen Uptake Rate for Macro Algae (mgN/gDW-day)	
kMacroAlgUPmax		50	Maximum Phosphorus Uptake Rate for Macro Algae (mgP/gDW-day)	
Macro_KQN		9	Half Saturation Uptake Constant for Macro Algal Intracellular Nitrogen (mgN/gDW)	
Macro_KQP		1.3	Half Saturation Uptake Constant for Macro Algal Intracellular Phosphorus (mgP/gDW)	

External Inorganic Nutrients

External inorganic nutrients include ammonia nitrogen, [NH_4, mgN/L], nitrate nitrogen, [NO_3, mgN/L], and orthophosphate, [PO_4, mgP/L]. Macroalgae affect these nutrients by cell uptake and cell excretion. The source/sink terms in the inorganic nutrient equations include the following macroalgal terms:

Equation 44

$$S_{NH4,MA} = \left[\left(R_{EN,MA} + R_{DN,MA}\right)\left(1 - f_{ON,MA}\right) - R_{UN,MA} P_{NH4,MA}\right] V$$
$$S_{NO3,MA} = -\left[R_{UN,MA}\left(1 - P_{NH4,MA}\right)\right] V$$
$$S_{PO4,MA} = \left[\left(R_{EP,MA} + R_{DP,MA}\right)\left(1 - f_{OP,MA}\right) - R_{UP,MA}\right] V$$

where $f_{ON,MA}$ and $f_{OP,MA}$ are the cell nutrient organic fractions [dimensionless number between 0 and 1] and $P_{NH4,MA}$ is the macroalgae ammonia preference factor [dimensionless number between 0 and 1]. The cell nutrient organic fractions are calculated as ratios of the stoichiometric nutrient fraction to the total cell nutrient fraction:

Equation 45

$$f_{ON,MA} = \frac{\left(ANC / ADC\right)}{q_N 10^{-3}}$$
$$f_{OP,MA} = \frac{\left(APC / ADC\right)}{q_P 10^{-3}}$$

Where ANC, APC, and ADC are specified stoichiometric nitrogen to carbon, phosphorus to carbon, and dry weight to carbon ratios [gN/gC, gP/gC, and gD/gC], q_N and q_P are the calculated total cell nitrogen and phosphorus cell quotas [mgN/gD and mgP/gD], and 10^{-3} is a units conversion factor [g/mg]. Whenever the calculated cell nutrient fractions fall below the specified stoichiometric nutrient fractions, the nutrient organic fractions are set to 1.0.

The ammonia preference factor reflects the preference of macroalgae for ammonium as a nitrogen source. P_{NH4b} is calculated from NH4 and NO3 concentrations:

Equation 46

$$P_{NH3} = \frac{NH_4 * NO_3}{(K_{hnx,MA} + NH_4) * (K_{hnx,MA} + NO_3)} + \frac{NH_4 * K_{knx,MA}}{(NH_4 + NO_3) * (K_{hnx,MA} + NO_3)}$$

where $K_{hnx,MA}$ = preference coefficient of bottom algae for ammonium [mgN/L].

Table 13. Ammonia preference and recycling constants

Constant	Value	Ex. Value from Benthic Algal Model	Description	Reference
Macro_KHNXF		.025	Macro Algae ammonia preference (mg N/L)	
Macro_FON_excr		0	Fraction of Macro Algae Recycled to Organic N	
Macro_FOP_excr		0	Fraction of Macro Algae Recycled to Organic P	

External Organic Matter

External organic matter includes particulate and dissolved forms. Particulate organic matter is derived from algal death, and is transformed to dissolved organic matter by bacterial dissolution. Dissolved organic matter is further mineralized to inorganic forms.

WASP7 simulates detrital carbon, nitrogen, and phosphorus [mgC/L, mgN/L, and mgP/L], dissolved organic nitrogen [mgN/L], and dissolved organic phosphorus [mgP/L]. WASP7 also simulates three forms of dissolved organic carbon in terms of their oxygen equivalents (i.e., $CBOD_i$ in mgO_2/L). These carbonaceous variables are formed only by detrital dissolution, and are not linked directly to algal cell excretion or death.

Bottom algae affect the particulate detrital C, N, and P pools by death:

Equation 47

$$S_{mC,MA} = R_{D,MA} ADC^{-1} V$$
$$S_{mN,MA} = R_{DN,MA} f_{ON,MA} V$$
$$S_{mP,MA} = R_{DP,MA} f_{OP,MA} V$$

Bottom algae affect the dissolved organic N and P pools by cell excretion:

Equation 48

$$S_{DON,MA} = R_{EN,MA} f_{ON,MA} V$$
$$S_{DOP,MA} = R_{EP,MA} f_{OP,MA} V$$

Dissolved Oxygen

Bottom algae affect dissolved oxygen levels directly through photosynthesis and respiration, and indirectly through the production of detrital organic carbon, which is subsequently dissolved and oxidized.

The direct effects are given by the following equation:

Equation 49

$$SO2, MA = \left(R_{G,MA} \frac{ROC}{ADC} + R_{G,MA} \frac{ANC}{ADC} \left(1 - PNH_{MA}^{4}\right) \left(\frac{3}{2} * \frac{32}{14} \right) - R_{R,MA} \frac{ROC}{ADC} \right) V$$

The first term gives the production of oxygen during photosynthesis. The third term gives the consumption of oxygen with respiration. The second term represents the evolution of oxygen with the reduction of nitrate to ammonium. It is based on the following reaction:

Equation 50

$$2NO_3 \rightarrow 2NH_4 + 3O_2$$

in which 3 moles of oxygen are produced when 2 moles of nitrate are reduced. The term 32/14 coverts this molar ratio to the mass ratio of gO_2/gN.

Table 14. Summary of Macroalgal Kinetic Constants (continued)

Variable	Description
MacAlg_OPT	if =1 then floating forms, transported (QBY, RBY = 0) if =2 then submersed forms, not transported (QBY, RBY = 1) and using light at top of specified bed height, if = 4 then benthic and not transported, used for comparison with benthic algal routines
Macro_ADC	Macroalgae D:C Ratio (mg D/mg C)
Macro_ANC	Macroalgae N:C Ratio (mg N/mg C)
Macro_APC	Macroalgae P:C Ratio (mg P/mg C)
Macro_AChlC	Macroalgae Chl a:C Ratio (mg Chl/mg C)
Macro_ROC	Macroalgae O2:C Production (mg O2/mg C)
Macro_Umax	Maximum tolerable velocity (U_{max}), or threshold velocity for scour (m/s), submersed species
Macro_fscour	Fraction of macroalgae scoured where $U>U_{max}$, submersed species
Macro_fdrag	Reduction factor for advection due to drag (floating species)
Macro_GrowthOption	Macroalgal Growth Model, 0 = Zero Order; 1 = First Order
Macro_KGAF	Macroalgae Max Growth Rate (gD/m2-day, or 1/day)
MacAlg_Temp_Opt	if = 1 then use theta formulation; if = 2 then use optimal formulation
Macro_TKGAF	Temp Coefficient for Macroalgal Growth
MacAlg_Topt	Optimal Temperature for Macroalgal Growth (øC)
MacAlg_KAPPA1	Shape parameter for below optimal temperatures for Macroalgae
MacAlg_KAPPA2	Shape parameter for above optimal temperatures for Macroalgae
MacroAlgMax	Macroalgal Carrying Capacity for First Order Model (g D/m2)
Macro_KREAF	Macroalgal Respiration Rate Constant (1/day)
Macro_TKREAF	Temperature Coefficient for Macroalgal Respiration
kMacroAlgExcr	Internal Nutrient Excretion Rate Constant for Macroalgae (1/day)
TMacroAlgExcr	Temperature Coefficient for Macroalgal Nutrient Excretion
Macro_KDEAF	Macroalgae Death Rate Constant (1/day)
Macro_TKEAF	Temperature Coefficient for Macroalgal Death
MacAlg_Salinity_Tol	if = 0, not considered, if = 1 then salt water optimal model, 2 fresh water
MacAlg_SSat	salinity at which algal mortality is half maximum value for fresh water species
MacAlg_Sopt	Optimal Salinity for marine Macroalgal Growth (ppt)
MacAlg_Smin	Minimum Salinity for marine Macroalgal Growth (ppt)
MacAlg_SMax	Maximum Salinity for marine Macroalgal Growth (ppt)

Table 15. Summary of Macroalgal Kinetic Constants (completed)

Macro_KSNF	Macroalgal Half Saturation Uptake Constant for Extracellular Nitrogen (mg N/L)
Macro_KSPF	Macroalgal Half Saturation Uptake Constant for Extracellular Phosphorus (mg P/L)
Macro_SATF	Macroalgal Light Constant for growth (langleys/day)
Macro_KHNXF	Macroalgae ammonia preference (mg N/L)
Macro_CellQuota MinN	Minimum Cell Quota of Internal Nitrogen for Macroalgal Growth (mgN/gDW)
Macro_CellQuota MinP	Minimum Cell Quota of Internal Phosphorus for Macroalgal Growth (mgP/gDW)
kMacroAlgUNma x	Maximum Nitrogen Uptake Rate for Macroalgae (mgN/gDW-day)
kMacroAlgUPmax	Maximum Phosphorus Uptake Rate for Macroalgae (mgP/gDW-day)
Macro_KQN	Half Saturation Uptake Constant for Macroalgal Intracellular Nitrogen (mgN/gDW)
Macro_KQP	Half Saturation Uptake Constant for Macroalgal Intracellular Phosphorus (mgP/gDW)
Macro_FON_excr	Fraction of Macroalgae Recycled to Organic N
Macro_FOP_excr	Fraction of Macroalgae Recycled to Organic P
MacAlg_Seed	macroalgae seed or minimum concentration (gD/m^2)
MacAlg_Graze	grazing rate on macroalgae
MacAlg_Shear	detachment critical shear stress
MacAlg_Shade	Macroalgal Self shading coefficient (m^{3}m^{-1} g-dw^{-1})
MacAlg_Bed_H	Macroalgal bed height (m, used if MacAlg_SYS=2), submersed species

MacroAlgal Output

WASP 8 Multi-Algal Output Variables and Coefficients (not including Macroalgae)

The WASP multi-algal model output includes a variety of output values for not only predicted concentrations of model state variables but a series of derived values useful in the interpretation of the model predictions and the use of those predictions in environmental management. The multi-algal output was appended with output for macroalage. The exact output from the model is user selectable and output options include a binary model data (BMD) file which can be post-processed or CSV file for importing into Excel. There are presently 139 output values, as listed in the tables below. Each output is specified for each model segment at a frequency (print interval) specified by the user.

Table 16. WASP8 Multi-algal model output values (continued)

Name	Units
Volume	cubic meters
Flow Into Segment	m3/sec
Flow Out of Segment	m3/sec
Advective Flow	m3/sec
Dispersive Flow	m3/sec
Residence Time	days
Segment Depth	meters
Water Temperature	c
Segment Width	m
Water Velocity	m/sec
Maximum Timestep	days
Calculational Time Step Used	days
Total Dissolved Solids	mg/L
Salinity	PSU
Water Density	kg/L
Ammonia N	mg/L
Unionized Ammonia	mg/l
Nitrogen Benthic Flux	g/m2-day
Ammonia Settling Flux	g/m2
Nitrate N	mg/L
Dissolved Inorganic N	mg/L
Total Inorganic N	mg/L
Dissolved Organic N	mg/L
Particulate Organic N	mg/L
Total Organic N	mg/L
PON Settling Flux	g/m2
Total Nitrogen	mg/L
Dissolved Inorganic P	mg/L
Inorganic P Settling Flux	g/m2
Phosphorus Benthic Flux	g/m2-day
Total Inorganic P	mg/L

Dissolved Organic P	mg/L
Particulate Organic P	mg/L
Total Organic P	mg/L
Total Phosphorus	mg/L
POP Settling Flux	g/m2
Dissolved Inorganic Silica	mg/L
Inorganic Silica Flux	g/m2
Total Inorganic Silica	mg/L
Dissolved Organic Silica	mg/L
Particulate Organic Silica	mg/L
POSi Settling Flux	g/m2
Total Silica	mg/L
CBOD (Ultimate)	mg/L
CBOD Decay Rate	per day
Total CBOD	mg/L
Particulate Organic C	mg/L
Dissolved Organic C	mg/L
POC Settling Flux	g/m2
Dissolved Oxygen	mg/L
DO Diurnal Average	mg/L
DO Diurnal Minimum	mg/L
DO Diurnal Maximum	mg/L
DO Saturation (Conc)	mg/L
DO Deficit	mg/L
Percent DO Saturation	%
Reaeration rate constant	per day
Wind Reaeration rate constant	per day
Hydraulic Reaeration rate constant	per day
Sediment Oxygen Demand	g/m2-day
Total Phytoplankton Chlorophyll a	ug/L
Total Phytoplankton Biomass	mgDW/L
Total Phytoplankton C to Chla Ratio	mg/mg
Phytoplankton Carbon	mg/L
Phytoplankton Chlorophyll a	ug/L

Phytoplankton Growth Rate	per day
Phytoplankton Death Rate	per day
Phytoplankton Sat. Light Intensity	Ly/day
Phytoplankton Light Growth Limit	(0-1)
Phytoplankton Nutrient Growth Limit	(0-1)
Phytoplankton Nitrogen Growth Limit	(0-1)
Phytoplankton P Growth Limit	(0-1)
Phytoplankton Silica Growth Limit	(0-1)
Total Phytoplankton Net Growth Rate	1/day
Phytoplankton Settling Flux	g/m2
Benthic Algae Chlorophyll	mgA/m2
Benthic Algae Cell N:Chl	mgN/mgA
Benthic Algae Cell P:Chl	mgP/mgA
Bottom Algae Growth Rate Const	1/day
Bottom Algae Resp + Death Rate Const	1/day
Bottom Algae Net Growth Rate Const	1/day
Benthic Algae N Cell Quota	mgN/gDW
Benthic Algae P Cell Quota	mgP/gDW
Benthic Algae Biomass	gDW/m2
Benthic Algae Light Limit	(0-1)
Benthic Algae Nutrient Limit	(0-1)
Macro Algae Concentration per unit area, dry weight	gDW/m2
Macro Algae Concentration per unit volume, dry weight	gDW/m3
Macro Algae Chlorophyll concetration, ug/L	gChl/m3
Macro Algae Intracellular N concentration	gN/m2
Macro Algae Intracellular P Concentration	gP/m2
Macro Algae growth rate	gDW/m2-day
Macro Algae Internal Fraction N	NA
Macro Algae Internal Fraction P	NA
Macro Algae death rate	gDW/m3-day
Macro Algae death rate as N based on cell quota	gN/m3-day
Macro Algae death rate as P based on cell quota	gP/m3-day
Macro Algae N excretion rate	gN/m3-day
Macro Algae P excretion rate	gP/m3-day

Macro Algae growth rate	gDW/m3-day
Macro Algae growth rate	gC/m3-day
Macro Algae respiration rate	gDW/m3-day
Macro Algae respiration rate	gC/m3-day
Macro Algae uptake of external inorganic N as ammonia	gN/m3-day
Macro Algae uptake of external inorganic N as nitrate	gN/m3-day
Macro Algae uptake of external inorganic phosphorus	gP/m3-day
Total Inorganic Carbon	mg/L
pH	mol/L
Alkalinity	CaCo3 mg/L
pH (Selected Scale)	mol/kg
Solid Resuspension Velocity	m/day
Burial Velocity	cm/yr
Biotic Solids Production Rate	gDW/m3-day
Solids Settling Flux	g/m2
Solids	mg/L
Cobbles	mg/L
Total Detrital Settling Flux	g/m2
Total Solids	mg/L
Biotic Solids Dissolution Rate Const	per day
Particulate Organic Matter	mg/L
Bottom Shear Stress	N/m2
Calculated Light Extinction	1/m
Background Ke	1/m
Algal Shade Ke	1/m
Solids Ke	1/m
DOC Ke	1/m
Total Light	[W/m2]
Light Top Segment	[W/m2]
Light Bottom Segment	[W/m2]
Depth Averaged Ke	m
Total Light Ke at Bottom	Fraction
UV light at the Top of the segment	[W/m2]
PAR light at the Top of the segment [W/m2]	[W/m2]

IR light at the Top of the segment [W/m2]	[W/m2]
UV light at the bottom of the segment	[W/m2]
PAR light at the bottom of the segment [W/m2]	[W/m2]
IR light at the bottom of the segment [W/m2]	[W/m2]
Ice Thickness	m
Net Solar Radiation	W/m2
Daily Ave Net Solar Radiation	W/m2
Net Atmospheric Radiation	W/m2
Longwave Radiation	W/m2
Evaporation Heat Loss	W/m2
Conduction Heat Exchange	W/m2
Net Surface Heat Exchange	W/m2
Equilibrium Temperature	c
Coefficient of Heat Exchange	W/m2-C
Minimum Water Temperature	c
Maximum Water Temperature	c
Mean Water Temperature	c

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