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WASP7 Benthic Algae - Model Theory and User's Guide

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WASP7 Benthic Algae - Model Theory and User's Guide

Supplement to Water Quality Analysis Simulation Program (WASP) User Documentation

Robert B. Ambrose, Jr., P.E.
U.S. EPA, Office of Research and Development
National Exposure Research Laboratory
Ecosystems Research Division
Athens, Georgia

James L. Martin, Ph.D., P.E.
Mississippi State University
Starkville, Mississippi

Tim A. Wool
U.S. EPA, Region 4
Water Management Division
Atlanta, Georgia

U.S. Environmental Protection Agency
Office of Research and Development
Washington, DC 20460

NOTICE

ABSTRACT

The standard WASP7 eutrophication module includes nitrogen and phosphorus cycling, dissolved oxygen-organic matter interactions, and phytoplankton kinetics. In many shallow streams and rivers, however, the attached algae (benthic algae, or periphyton, attached to submerged substrates) are often of greater importance than phytoplankton. These attached plants affect water quality in various ways, and their impact must often be considered in order to properly evaluate riverine water quality conditions.

An advanced WASP7 eutrophication module has been developed to handle streams and rivers with bottom algae. This supplemental user manual documents the new bottom algae algorithms, including the kinetic equations, the additional model input and output, and a series of model verification tests.

This advanced WASP7 module, named "periphyton," includes the standard WASP7 eutrophication algorithms, and incorporates bottom algae, with three additional state variables: bottom algal biomass, bottom algal cell nitrogen, and bottom algal cell phosphorus. Bottom algae are not subject to advective and dispersive transport. Sources and sinks include nutrient uptake, growth, nutrient excretion, death, and respiration. Nutrient uptake rates are driven by concentrations of inorganic nitrogen and phosphorus in the water column and within algal cells, and are controlled by cell minimum and half-saturation parameters. Biomass growth is computed from a maximum zero or first-order rate constant that is adjusted internally by water temperature, bottom light intensity, internal nutrient concentrations, and maximum carrying capacity. Nutrient excretion, death, and respiration are represented by first-order, temperature dependent rates. Growth, respiration, and death rates affect other model state variables, including dissolved oxygen and nutrients. The algorithms for predicting bottom algal biomass and nutrient concentrations are based upon the periphyton routines included in the QUAL2K model (Chapra 2005).

To run the WASP7 periphyton module, the user must supply initial concentrations of algal biomass and cell nitrogen and phosphorus content by segment. In addition, some model parameters, time functions, and constants must be specified. A new spatially-variable parameter represents the fraction of bottom area suitable for growth. Standard WASP7 parameters and time functions representing water temperature and incident light intensity are used. A periphyton constant group was added, with 27 new rate constants and coefficients that must be specified.

The WASP7 periphyton module adds 8 new output variables to the standard eutrophication output available for examination in the post-processor. Simulated algal biomass per unit area of substrate is expressed both on a dry weight basis and as chlorophyll *a*. Internal cell nitrogen and phosphorus values are expressed as fractions of total biomass and as ratios with chlorophyll *a*. Finally, calculated light and nutrient growth limitation factors are provided.

Table of Contents

List of Figures

List of Tables

1 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 populations are of environmental concern. However, in many shallow streams and rivers it is the attached algae (benthic algae, or periphyton, attached to submerged substrates) that are often of greater importance. These attached plants affect water quality in various ways, and their impact must often be considered in order to properly evaluate riverine water quality conditions. Though the term "periphyton" includes both bottom algae and associated detritus and bacteria, in this document "benthic algae" and "periphyton" are used to designate the algal community attached to bottom rocks and stable sand surfaces.

As with phytoplankton, periphyton growth is impacted by temperature, light and nutrients. The growth of periphyton consumes nutrients and produces oxygen. Periphyton, like phytoplankton, also excrete cell contents and die, recycling dissolved and particulate organic matter to the stream's carbon and nutrient pools. While the modeling approaches used for phytoplankton and periphyton are similar, periphyton differ from phytoplankton in a number of fundamental ways, as illustrated in Figure 1 :

- Periphyton do not move with the water current, as do phytoplankton,
- Periphyton typically dwell on or near the bottom, so are not impacted by the average light in the water column but the light reaching the bottom (substrate).
- Periphyton are limited by the amount of substrate available for growth.
- There is typically a maximum density for attached plants.

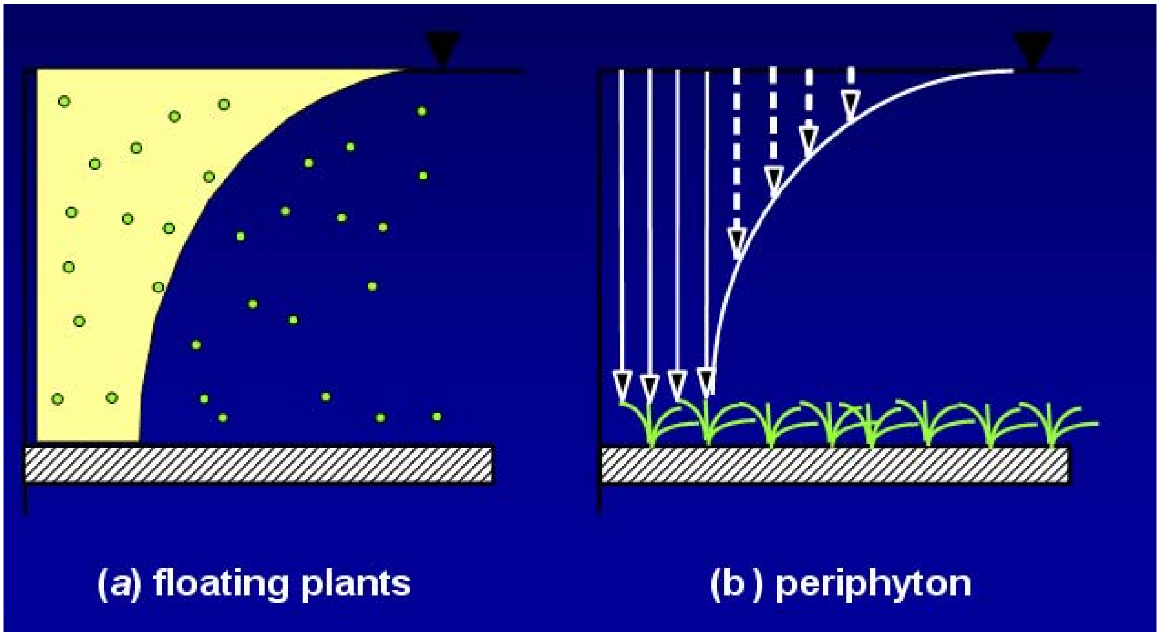


Figure 1 Phytoplankton and Periphyton

The importance of periphyton and need for incorporation of periphyton routines into the WASP modeling framework has long been recognized. Because of the impact of periphyton on water quality, Chapra (1997) suggested that eutrophication frameworks should include both phytoplankton and periphyton. As a result of the need to simulate either or both phytoplankton and periphyton in the WASP framework, studies were initiated to review available routines, select the routine(s) and then incorporate periphyton routines into WASP. For incorporation of periphyton routines into WASP, two periphyton models were reviewed: the Jackson River periphyton model developed by HydroQual (HydroQual 2003, reviewed by Martin 2003) and the periphyton routines incorporated into the QUAL2K model (Chapra 2003). The QUAL2K routines were ultimately selected and incorporated into WASP7. The more detailed HydroQual routines may be incorporated in part or in whole in later versions.

2 Background

WASP7 includes two eutrophication modules. The standard module (Ambrose, et al., 1993, Wool et al., 2001) includes the following state variables:

- Ammonia
- Nitrate
- Orthophosphate
- Phytoplankton
- Detrital carbon
- Detrital nitrogen
- Detrital phosphorus
- CBOD type 1
- CBOD type 2
- CBOD type 3
- Dissolved Oxygen
- Dissolved Organic Nitrogen
- Dissolved Organic Phosphorus
- Salinity
- Inorganic Solids

The advanced stream eutrophication module incorporates bottom algae, with the following additional state variables:

- Bottom algae biomass
- Internal cell nitrogen
- Internal cell phosphorus

The relationship between WASP state variables is illustrated in Figure 2.

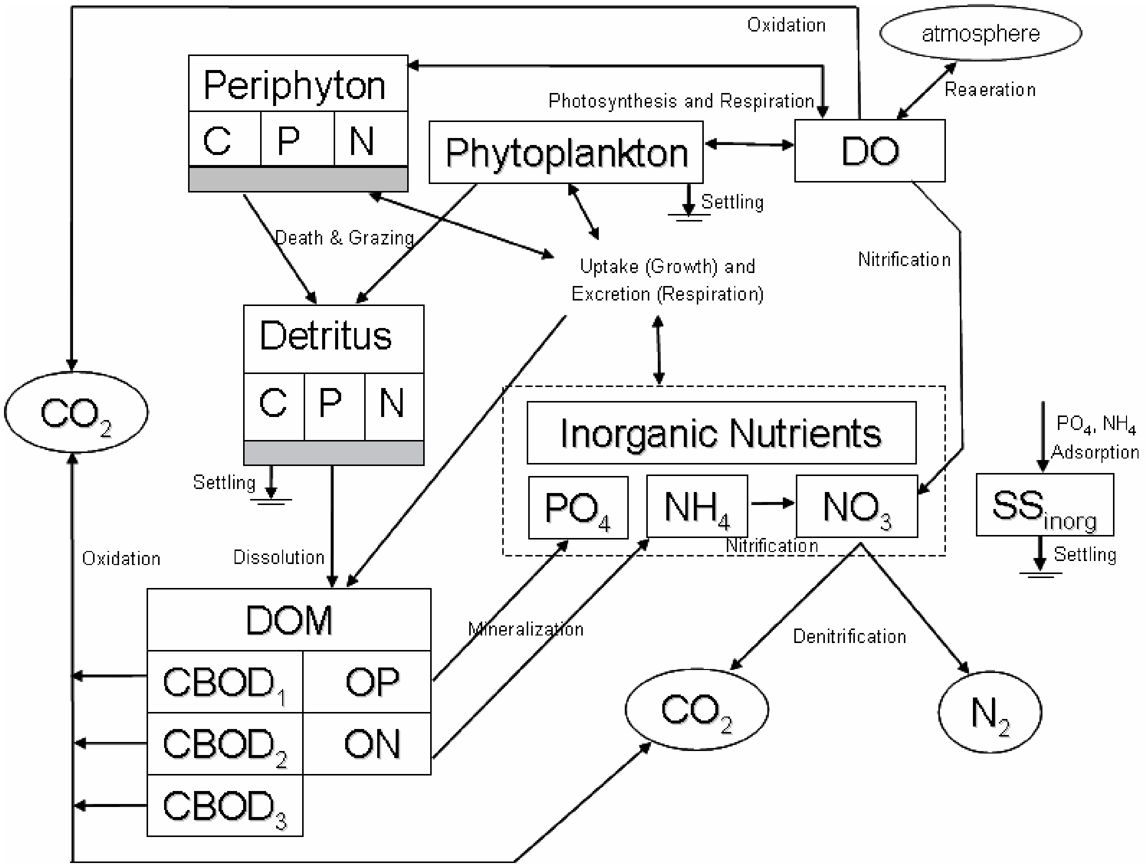


Figure 2 WASP Version 7 Eutrophication Kinetics

Each of the above state variables is represented using a general mass balance equation of the form of:

accumulation = ± advective transport ± diffusive transport + external load ± sources/sinks.

where accumulation is the rate of change in the mass of the constituent and sources/sinks result from reactions and transfer mechanisms. Periphyton state variables do not move with the flow of water, and their mass balance equations are reduced to:

accumulation = ± sources/sinks.

Sources and sinks for periphyton include growth, death, and respiration. Growth is computed from a maximum rate that is then modified based upon available light and internal nutrients. Unlike phytoplankton, bottom light rather than average water column light is used in the computation of growth. Rates of death and respiration are temperature dependent. Rates of growth, respiration, and death impact other model state variables including dissolved oxygen and nutrients.

The algorithms for predicting variations in detrital and periphyton concentrations were based upon routines included in the QUAL2K model (Chapra 2005). The kinetic formulations provided in the following text were taken largely from the QUAL2K

(Chapra 2005) documentation. Here, source/sink terms are denoted by "*S*" and are in g/d. Areal rates (e.g., fluxes) [g/m^2-d] are denoted by "*F*" and are used to calculate benthic algal source/sink terms. Volumetric rates [g/m^3-d] are denoted by "*R*" and are used to calculate source/sink terms for most WASP variables. Volumetric rates are the product of areal rates and active surface area divided by segment volume. Rate constants are denoted by "*k*" and are in units of d^{-1}. Mass units are qualified by D, C, N, P, and A, which refer to dry weight, carbon, nitrogen, phosphorus, and chlorophyll *a*, respectively.

3 Development of Equations

3.1 Bottom algal biomass (a_b)

Bottom algae, a_b, is represented as total biomass per unit area of available substrate [gD/m^2]. Bottom algal biomass increases due to photosynthesis and decreases with respiration and death:

$$S_{ab} = \left(F_{Gb} - F_{Rb} - F_{Db}\right) A_b \tag{1}$$

where S_{ab} is the total source/sink of algal biomass [gD/d], F_{Gb} is the photosynthesis rate [gD/m^2-d], F_{Rb} is the respiration loss rate [gD/m^2-d], F_{Db} is the death rate [gD/m^2-d], and A_b is the bottom substrate surface area [m^2].

3.1.1 Photosynthesis

Two options are available to represent the bottom algal photosynthesis rate, F_{Gb} [gD/m^2-d]. The first option is a temperature-corrected, zero-order maximum rate attenuated by nutrient and light limitation (simplied from Rutherford et al., 2000):

$$F_{Gb} = F_{Gb20}\ \phi_{Tb}\ \phi_{Nb}\ \phi_{Lb} \tag{2}$$

where F_{Gb20} is the maximum photosynthesis rate at 20 °C [gD/m^2-d], ϕ_{Tb} is the photosynthesis temperature correction factor [dimensionless], ϕ_{Nb} is the bottom algae nutrient attenuation factor [dimensionless number between 0 and 1], and ϕ_{Lb} is the bottom algae light attenuation coefficient [dimensionless number between 0 and 1].

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

$$F_{Gb} = k_{Gb20}\ \phi_{Tb}\ \phi_{Nb}\ \phi_{Lb}\ \phi_{Sb}\ a_b \tag{3}$$

where k_{Gb20} is the maximum photosynthesis rate constant at 20 °C [d^{-1}], ϕ_{Sb} is the bottom algae space attenuation coefficient [dimensionless number between 0 and 1], and other terms are as defined above.

Temperature Effect. An Arrhenius model is employed to quantify the effect of temperature on bottom algae photosynthesis:

$$\phi_{Tb} = \theta_{Gb}^{T-20} \tag{4}$$

where θ_{Gb} is the photosynthesis temperature coefficient [dimensionless].

Nutrient Limitation Effect. Nutrient limitation of the photosynthesis rate is dependent on intracellular nutrient concentrations using a formulation originally developed by Droop (1974):

$$\phi_{Nb} = \min\left[\left(1 - \frac{q_{0N}}{q_N}\right), \left(1 - \frac{q_{0P}}{q_P}\right)\right] \tag{5}$$

where q_N and q_P are cell quotas of nitrogen [mgN/gD] and phosphorus [mgP/gD], respectively, and q_{0N} and q_{0P} are 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 are state variables calculated by WASP. Their mass balance equations are described in a later section.

Light Limitation Effect. Light limitation is determined by the amount of photosynthetically-active radiation (PAR) reaching the bottom of the water column. This quantity is computed with the Beer-Lambert law evaluated at the bottom of the river:

$$I(H) = I(0)e^{-k_e H} \tag{6}$$

where *I(H)* is light intensity at depth *H* below the water surface [Ly/d], *I(0)* is light intensity just below the water surface [Ly/d], *H* is depth [m], and k_e is the light extinction coefficient [d^{-1}].

Three models are used to characterize the impact of light on bottom algae photosynthesis. Substituting the above formulation into these models yields the following formulas for the bottom algae light attenuation coefficient:

<u>Half-Saturation Light Model:</u>

$$\phi_{Lb} = \frac{I(0)e^{-k_e H}}{K_{Lb} + I(0)e^{-k_e H}} \tag{7}$$

<u>Smith's Function:</u>

$$\phi_{Lb} = \frac{I(0)e^{-k_e H}}{\sqrt{K_{Lb}^2 + \left(I(0)e^{-k_e H}\right)^2}} \tag{8}$$

Steele's Equation:

$$\phi_{Lb} = \frac{I(0)e^{-k_e H}}{K_{Lb}} e^{\left(1 + \frac{I(0)e^{-k_e H}}{K_{Lb}}\right)} \quad (9)$$

where K_{Lb} is the appropriate bottom algae light parameter for each light model.

Space Limitation Effect. Bottom algal densities are limited by their carrying capacity, or maximum density. Space limitation of the first-order growth rate is modeled as a logistic function:

$$\phi_{Sb} = 1 - \frac{a_b}{a_{b\max}} \quad (10)$$

where a_{bmax} is the bottom algae carrying capacity, or maximum density [gD/m^2].

3.1.2 Losses

Bottom algal biomass decreases due to respiration and death.

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

$$F_{Rb} = k_{Rb20}\ \theta_{Rb}^{T-20}\ a_b \quad (11)$$

where k_{Rb20} is the bottom algae respiration rate constant at 20 °C [d^{-1}] and θ_{Rb} is the bottom algae respiration temperature coefficient [dimensionless].

Death. Bottom algal death is also represented using first-order, temperature-corrected kinetics:

$$F_{Db} = k_{Db20}\ \theta_{Db}^{T-20}\ a_b \quad (12)$$

where k_{Db20} is the bottom algae death rate constant at 20 °C [d^{-1}] and θ_{Db} is the bottom algae death temperature coefficient [dimensionless].

3.2 Bottom Algal Cell Nutrients (q_N, q_P)

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

$$q_N = 10^3 \frac{IN_b}{a_b} \quad (13)$$

$$q_P = 10^3 \frac{IP_b}{a_b} \tag{14}$$

where qN and qP are cell quotas [mgN/gD or mgP/gD], IN_b is intracellular nitrogen concentration [gN/m^2], IP_b is 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 bottom algal cells [g/d] are controlled by uptake, excretion, and death:

$$S_{bN} = \left(F_{UNb} - F_{ENb} - F_{DNb}\right) A_b \tag{15}$$

$$S_{bP} = \left(F_{UPb} - F_{EPb} - F_{DPb}\right) A_b \tag{16}$$

where F_{UNb} and F_{UPb} are uptake rates for nitrogen and phosphorus by bottom algae [gN/m^2-d and gP/m^2-d], F_{ENb} and F_{EPb} are the bottom algae cell excretion rates [gN/m^2-d and gP/m^2-d], and F_{DNb} and F_{DPb} are loss rates from bottom algae death [gN/m^2-d and gP/m^2-d].

The N and P uptake rates depend on both external and intracellular nutrient concentrations as in Rhee (1973):

$$F_{UNb} = 10^{-3} \rho_{mN} \left(\frac{NH_4 + NO_3}{K_{sNb} + NH_4 + NO_3}\right)\left(\frac{K_{qN}}{K_{qN} + (q_N - q_{0N})}\right) a_b \tag{17}$$

$$F_{UPb} = 10^{-3} \rho_{mP} \left(\frac{PO_4}{K_{sPb} + PO_4}\right)\left(\frac{K_{qP}}{K_{qP} + (q_P - q_{0P})}\right) a_b \tag{18}$$

Where NH_4, NO_3, and PO_4 are external water concentrations of ammonium N, nitrate N, and phosphate P [mgN/L and mgP/L], ρ_{mN} and ρ_{mP} are the maximum uptake rates for nitrogen and phosphorus [mgN/gD-d and mgP/gD-d], K_{sNb} and K_{sPb} are half-saturation constants for external nitrogen and phosphorus [mgN/L and mgP/L], K_{qN} and K_{qP} are 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:

$$F_{ENb} = k_{Eb20}\, \theta_{Eb}^{T-20}\, q_N\, a_b\, 10^{-3} \tag{19}$$

$$F_{EPb} = k_{Eb20}\, \theta_{Eb}^{T-20}\, q_P\, a_b\, 10^{-3} \tag{20}$$

where k_{Eb20} is the bottom algae cell excretion rate constant at 20 °C [d^{-1}] and θ_{Eb} is the bottom algae excretion temperature coefficient [dimensionless].

The internal N and P loss rates from benthic algal death are the product of the algal death rate, F_{Db} [gD/m^2-d], and the cell nutrient quotas:

$$F_{DNb} = F_{Db}\ q_N\ 10^{-3} \tag{21}$$
$$F_{DPb} = F_{Db}\ q_P\ 10^{-3} \tag{22}$$

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

In the following sections, volumetric rate terms "R_s" [g/m^3-d] are used in place of the corresponding periphyton areal rate, or flux terms "F_s" [g/m^2-d]. Volumetric rates are calculated from areal rates as follows:

$$R_s = F_s\left(A_b / V\right) \tag{23}$$

where "s" denotes the appropriate subscripts, A_b is the active surface area [m^2], and V is the segment volume [m^3].

3.3 External Inorganic Nutrients

External inorganic nutrients, found in the water column around the benthic algae, include ammonia nitrogen, NH_4 [mgN/L], nitrate nitrogen, NO_3 [mgN/L], and orthophosphate, PO_4 [mgP/L]. Bottom algae affect these nutrient concentrations by cell uptake and cell excretion. The source/sink terms in the inorganic nutrient mass balance equations include the following benthic algal terms:

$$S_{NH4b} = \left[\left(R_{ENb} + R_{DNb}\right)\left(1 - f_{ONb}\right) - R_{UNb}\ P_{NH4b}\right]V \tag{24}$$
$$S_{NO3b} = -\left[R_{UNb}\ \left(1 - P_{NH4b}\right)\right]V \tag{25}$$
$$S_{PO4b} = \left[\left(R_{EPb} + R_{DPb}\right)\left(1 - f_{OPb}\right) - R_{UPb}\right]V \tag{26}$$

where f_{ONb} and f_{OPb} are the cell nutrient organic fractions [dimensionless number between 0 and 1] and P_{NH4b} is the benthic algae 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:

$$f_{ONb} = \frac{\left(ANC / ADC\right)}{q_N\, 10^{-3}} \tag{27}$$

$$f_{OPb} = \frac{\left(APC / ADC\right)}{q_P\, 10^{-3}} \tag{28}$$

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 benthic algae for ammonium as a nitrogen source. P_{NH4b} is calculated from NH_4 and NO_3 concentrations:

$$P_{NH4b} = \frac{NH_4 \times NO_3}{(K_{hnxb} + NH_4)(K_{hnxb} + NO_3)} + \frac{NH_4 \times K_{hnxb}}{(NH_4 + NO_3)(K_{hnxb} + NO_3)} \tag{29}$$

where K_{hnxb} is the preference coefficient of bottom algae for ammonium [mgN/L].

3.4 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:

$$S_{mCb} = R_{Db}\ ADC^{-1}\,V \tag{30}$$

$$S_{mNb} = R_{DNb}\ f_{ONb}\,V \tag{31}$$

$$S_{mPb} = R_{DPb}\ f_{OPb}\,V \tag{32}$$

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

$$S_{DONb} = R_{ENb}\ f_{ONb}\,V \tag{33}$$

$$S_{DOPb} = R_{EPb}\ f_{OPb}\,V \tag{34}$$

3.5 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 indirect effects of organic matter on dissolved oxygen are covered in the WASP6 user manual, and will be documented in a WASP7 supplement on dissolved oxygen. The production of oxygen by periphyton is given by the following equation:

$$S_{O2Peri} = \left(R_{Gb} \frac{ROC}{ADC} + R_{Gb} \frac{ANC}{ADC} (1 - P_{NH4b}) \left(\frac{3}{2} \times \frac{32}{14} \right) - R_{Rb} \frac{ROC}{ADC} \right) V \tag{35}$$

where R_{Gb} is the periphyton growth rate [gD/m^3-d], R_{Rb} is the periphyton respiration rate [gD/m^3-d], *ROC* is oxygen to carbon ratio, 32/12 [gO_2/gC], *ADC* is periphyton dry mass to carbon ratio [gD/gC], and *ANC* is periphyton nitrogen to carbon ratio [gN/gC]. The first term gives the production of oxygen during photosynthesis. The third term gives the consumption of oxygen by respiration. The second term represents the evolution of oxygen with the reduction of nitrate to ammonium. It is based on the following reaction:

$$2\,NO_3 \rightarrow 2\,NH_4 + 3\,O_2 \tag{36}$$

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

4 Bottom Algae Model Inputs

The data required to support the application of a model of periphyton include initial conditions (for total biomass, cell nitrogen, and cell phosphorus), model parameters, and reaction constants and coefficients. Each of these is briefly described in the sections below.

4.1 Initial Conditions and Model Parameters

Initial conditions are required for bottom algal biomass [gD/m^2], cell nitrogen quota [mgN/gD], and cell phosphorus quota [mgP/gD]. If initial conditions are not specified for cell N and P in a segment with bottom algal biomass, WASP will initialize these variables to the minimum cell quotas specified in the constants section 4.3. Boundary conditions are not required for bottom algae variables.

The initial conditions can be based on measurements or estimated by modeling. The modeling estimations are typically based on steady state or quasi-dynamic calculations. Estimates of initial periphyton biomass can also be made using direct measurements or artificial substrate studies. If the periphyton biomass is estimated in units other than ash free dry weight (e.g. carbon or chlorophyll *a*) it will be necessary to convert the units using some representative stoichiometry. The following representation is suggested as a first approximation (Redfield et al. 1963, Chapra 1997, Chapra 2005),

$$100\,\mathrm{gD} : 40\,\mathrm{gC} : 7200\,\mathrm{mgN} : 1000\,\mathrm{mgP} : 1000\,\mathrm{mgA} \tag{37}$$

where gX is mass of element X [g] and mgY is mass of element Y [mg]. It should be noted that chlorophyll *a* is the most variable of these quantities with a range of approximately 500-2000 mgA (Laws and Chalup 1990, Chapra 1997).

4.2 Model Parameters and Time Functions

To implement bottom algae simulations, segment-specific values for the bottom substrate surface area A_b are required for equation 1. In WASP the plan surface area of a model segment A_{surf} is computed by dividing the computed volume by the computed depth. Only a fraction of this area, however, may provide adequate substrate. Alternatively, in some reaches, the substrate (such as rocks) may provide more available area for growth than is represented by the plan area. To account for the effects of available substrate, the spatially-variable parameter f_{AS} was added to WASP representing the fraction of bottom area in each segment providing suitable substrate for growth (parameter 23). The user must specify segment-specific values for f_{AS}, and the model will compute the available substrate area A_b as the product of f_{AS} and A_{surf}. If no substrate fraction is specified for a segment, the value defaults to 0 and no bottom algae will be supported.

Bottom algal simulations also require the specification of parameters and time functions representing temperature and light. An example is provided in Figure 3.

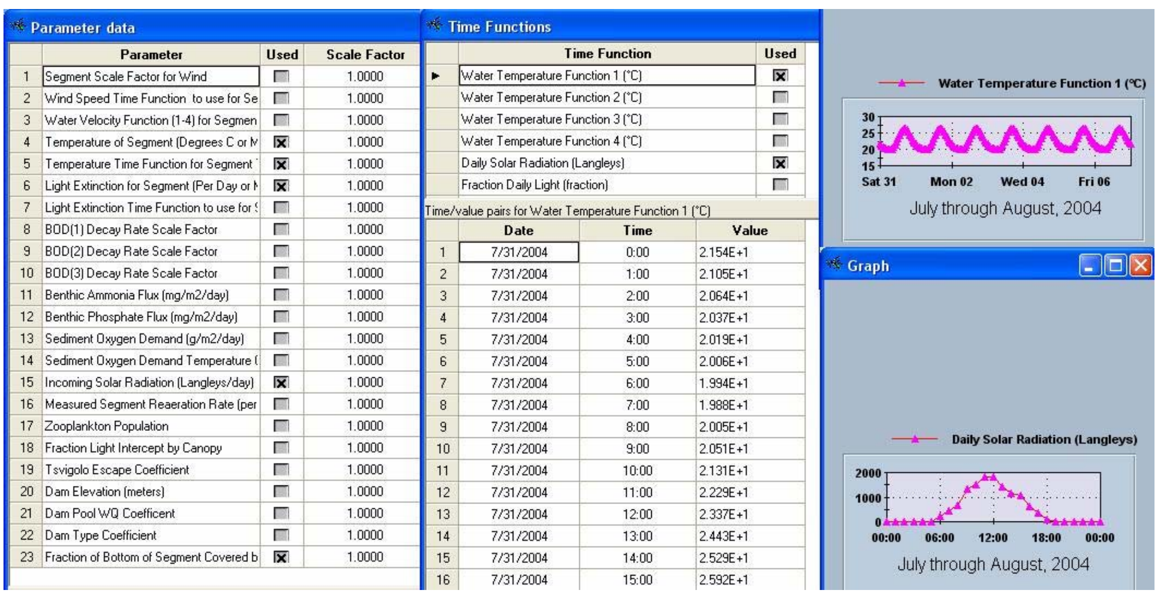
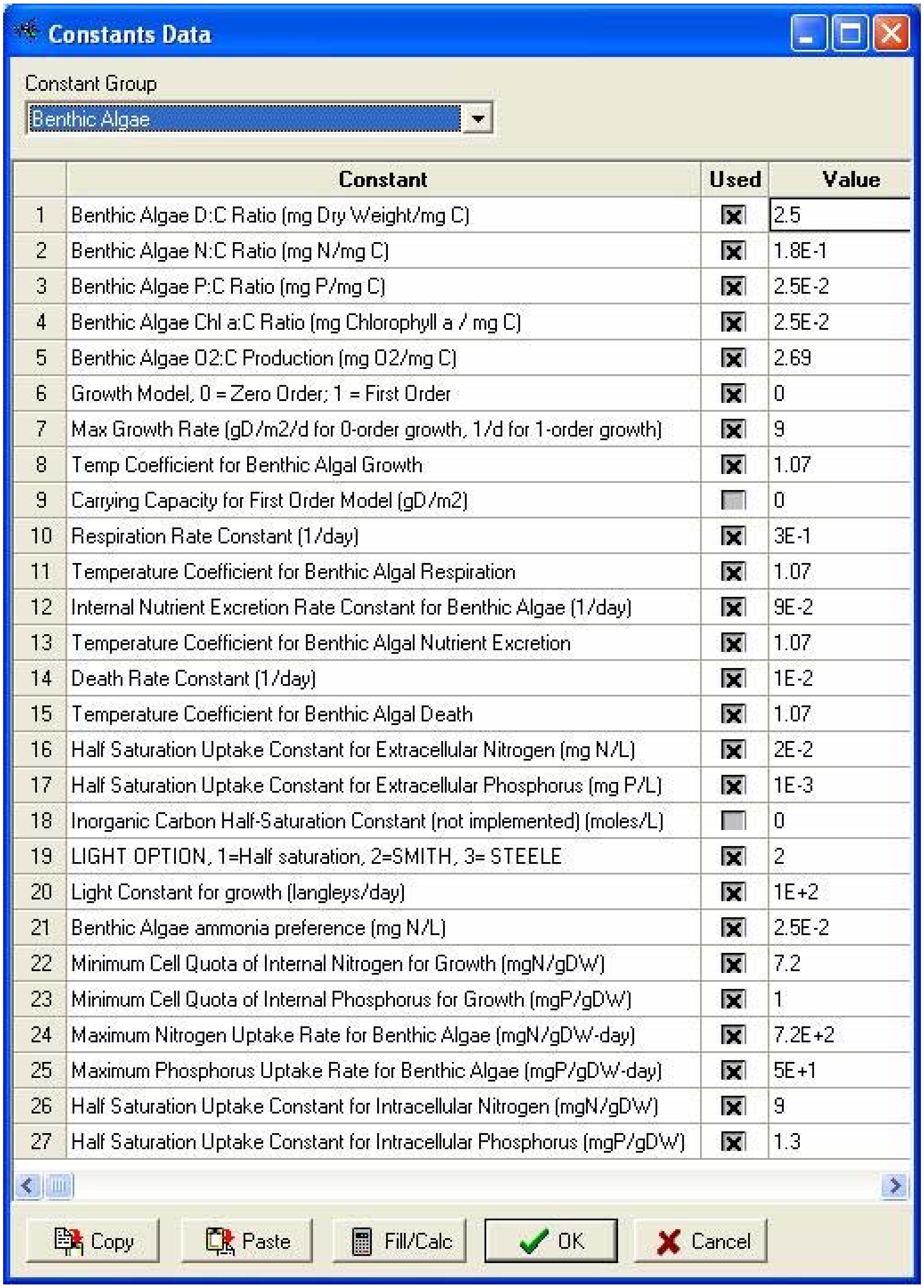


Figure 3 Model Parameters and Time Functions

4.3 Model Constants and Reaction Coefficients

Several kinetic constants and reaction coefficients control benthic algal dynamics. The WASP7 model constants related to bottom algae are listed Figure 4. The correspondence between the QUAL2K constants and the WASP7 constants is provided in Figure 5.



	Constant	Used	Value
1	Benthic Algae D:C Ratio (mg Dry Weight/mg C)	X	2.5
2	Benthic Algae N:C Ratio (mg N/mg C)	X	1.8E-1
3	Benthic Algae P:C Ratio (mg P/mg C)	X	2.5E-2
4	Benthic Algae Chl a:C Ratio (mg Chlorophyll a / mg C)	X	2.5E-2
5	Benthic Algae O2:C Production (mg O2/mg C)	X	2.69
6	Growth Model, 0 = Zero Order; 1 = First Order	X	0
7	Max Growth Rate (gD/m2/d for 0-order growth, 1/d for 1-order growth)	X	9
8	Temp Coefficient for Benthic Algal Growth	X	1.07
9	Carrying Capacity for First Order Model (gD/m2)		0
10	Respiration Rate Constant (1/day)	X	3E-1
11	Temperature Coefficient for Benthic Algal Respiration	X	1.07
12	Internal Nutrient Excretion Rate Constant for Benthic Algae (1/day)	X	9E-2
13	Temperature Coefficient for Benthic Algal Nutrient Excretion	X	1.07
14	Death Rate Constant (1/day)	X	1E-2
15	Temperature Coefficient for Benthic Algal Death	X	1.07
16	Half Saturation Uptake Constant for Extracellular Nitrogen (mg N/L)	X	2E-2
17	Half Saturation Uptake Constant for Extracellular Phosphorus (mg P/L)	X	1E-3
18	Inorganic Carbon Half-Saturation Constant (not implemented) (moles/L)		0
19	LIGHT OPTION, 1=Half saturation, 2=SMITH, 3= STEELE	X	2
20	Light Constant for growth (langleys/day)	X	1E+2
21	Benthic Algae ammonia preference (mg N/L)	X	2.5E-2
22	Minimum Cell Quota of Internal Nitrogen for Growth (mgN/gDW)	X	7.2
23	Minimum Cell Quota of Internal Phosphorus for Growth (mgP/gDW)	X	1
24	Maximum Nitrogen Uptake Rate for Benthic Algae (mgN/gDW-day)	X	7.2E+2
25	Maximum Phosphorus Uptake Rate for Benthic Algae (mgP/gDW-day)	X	5E+1
26	Half Saturation Uptake Constant for Intracellular Nitrogen (mgN/gDW)	X	9
27	Half Saturation Uptake Constant for Intracellular Phosphorus (mgP/gDW)	X	1.3

Figure 4 Model Constants for Benthic Algae

The stoichiometric coefficients (constants 1-4) reflect the measured or assumed stoichiometry of benthic algal organic matter. They correspond to variables ADC, ANC, and APC in the treatment on page 8. The following organic matter representation is suggested as a first approximation (Redfield et al. 1963, Chapra 1997):

100 gD : 40 gC : 7200 mgN : 1000 mgP

The terms D, C, N, P, and A refer to dry weight, carbon, nitrogen, phosphorus, and chlorophyll *a*, respectively. These values are then combined to determine stoichiometric ratios [gX / gY]. For example, the amount of organic phosphorus that is released due to the death of periphyton expressed in carbon units is:

$$APC = \frac{1000\left[mgP\right]\times 10^{-3}\left[gP/mgP\right]}{40\left[gC\right]} = 0.025\left[\frac{gP}{gC}\right] \tag{38}$$

The stoichiometric ratio for oxygen production and consumption (ROC, constant 5) is based upon a typical chemical reaction for plant photosynthesis (P) and respiration (R) assuming that ammonia is used as a substrate (Chapra 1997):

$$106CO_2 + 16NH_4^+ + HPO_4^{2-} + 108H_2O \underset{R}{\overset{P}{\rightleftarrows}} C_{106}H_{263}O_{110}N_{16}P_1 + 107O_2 + 14H^+$$

so that the stoichiometric ratio in Figure 4 is determined by (Chapra 2003):

$$ROC = \frac{107\left[mole\,O_2\right]\times 32\left[g\,O_2/mole\,O_2\right]}{106\left[mole\,C\right]\times 12\left[g\,C/mole\,C\right]} = 2.69\left[\frac{g\,O_2}{g\,C}\right] \tag{39}$$

Periphyton growth (equations 2-9) is computed from a maximum growth rate (constant 7) that is modified by the impacts of temperature (constant 8), light (constants 19, 20), and the ratios of cell nutrient concentration to minimum cell quota (constants 22, 23). The impact of light on periphyton is computed using the quantity of light reaching the bottom of a WASP segment. The maximum growth rate is typically on the order of 30 g/m^2-d, with a range of 10-100. The nutrient half-saturation constants tend to be higher than in phytoplankton by a factor of 10 to 100 (Chapra, personal communication).

Bottom algal biomass declines with respiration and death (equations 11-12). Rates are calculated from first-order, 20 °C rate constants (constants 10, 14) and temperature coefficients (constants 11, 15). Typical values of the respiration rate constant are on the order of 0.1 d^{-1} with a range of 0.05-0.2. Death rate constants have typical values of 0.05 d^{-1} with ranges of 0.01-0.5. Death rates during sloughing events could be greater (Chapra, personal communication).

Cell nutrient concentrations are controlled by uptake, excretion, and death rates (equations 15-22). Ambient nutrient uptake is a function of the maximum uptake rate (constants 24, 25), the external nutrient half-saturation constants (constants 16, 17), and the internal nutrient half-saturation constants (constants 26, 27). Excretion is calculated from a first-order, 20 °C rate constant and a temperature coefficient (constants 12, 13).

Microsoft Excel - Q2K-WASP Test Input.xls

	A	B	C	D	G	H
8	***Stoichiometry:***				to WASP7.1	
9	Carbon	40	gC	gC	2.500	gD/gC
10	Nitrogen	7.2	gN	gN	0.180	gN/gC
11	Phosphorus	1	gP	gP	0.025	gP/gC
12	Dry weight	100	gD	gD	0.025	gA/gC
13	Chlorophyll	1	gA	gA		
14	***Inorganic suspended solids:***					
15	Settling velocity	0.3	m/d	v_i		
16	***Oxygen:***					
17	Reaeration model	Internal				
18	Temp correction	1.024		θ_a		
19	Reaeration wind effect	None				
20	O2 for carbon oxidation	2.69	gO_2/gC	r_{oc}	2.69	gO2/gC
21	O2 for NH4 nitrification	4.57	gO_2/gN	r_{on}		
22	Oxygen inhib model CBOD oxidation	f saturation				

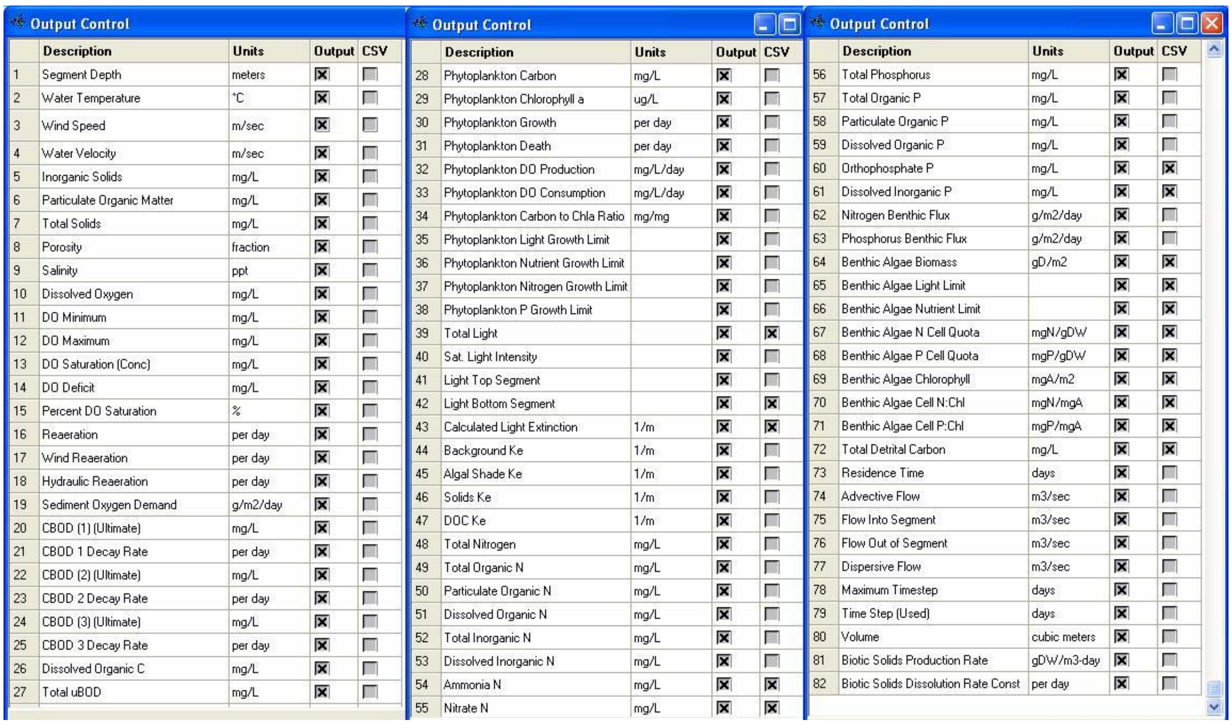
Headwater | Rates | Temperature | Light | WASP-SS

	A	B	C	D	G	H
74	***Bottom Algae:***				WASP7.1	
75	Growth model	Zero-order			Zero-order	
76	Max Growth rate	300	$mgA/m^2/d$ or /d	C_{gb}	30	gD/m2-d
77	Temp correction	1.07		θ_{gb}	1.07	
78	First-order model carrying capacity	1500	mgA/m^2	$a_{b,max}$	150	gD/m2
79	Respiration rate	0.1	/d	k_{rb}	0.1	
80	Temp correction	1.07		θ_{rb}	1.07	
81	Excretion rate	0.09	/d	k_{eb}	0.09	/d
82	Temp correction	1.07		θ_{db}	1.07	
83	Death rate	0.05	/d	k_{db}	0.05	/d
84	Temp correction	1.07		θ_{db}	1.07	
85	External nitrogen half sat constant	100	ugN/L	k_{sPb}	0.1	mgN/L
86	External phosphorus half sat constant	40	ugP/L	k_{sNb}	0.04	mgP/L
87	Inorganic carbon half sat constant	1.30E-05	moles/L	k_{sCb}	1.30E-05	moles/L
88	Light model	Smith			Smith	
89	Light constant	135	mgO^2/L	K_{Lb}	135	Ly/day
90	Ammonia preference	25	ugN/L	k_{hnxb}	0.025	mgN/L
91	Subsistence quota for nitrogen	0.72	mgN/mgA	q_{0N}	7.2	mgN/gD
92	Subsistence quota for phosphorus	0.1	mgP/mgA	q_{0P}	1	mgP/gD
93	Maximum uptake rate for nitrogen	72	mgN/mgA/d	ρ_{mN}	720	mgN/gD-d
94	Maximum uptake rate for phosphorus	5	mgP/mgA/d	ρ_{mP}	50	mgP/gD-d
95	Internal nitrogen half sat constant	0.9	mgN/mgA	K_{qN}	9	mgN/gD
96	Internal phosphorus half sat constant	0.13	mgP/mgA	K_{qP}	1.3	mgP/gD

Figure 5 Conversion of constants from QUAL2K to WASP7.1

5 Bottom Algae Model Outputs

Output variables from the algal water quality module are listed in Figure 6. Variables checked in the "Output" box will be available to the WASP7 graphical post-processing software. For each variable with a checked "CSV" box, WASP7 will produce a separate comma-delimited file containing output for all segments and all output times. In this example, checked CSV output variables are related directly or indirectly to the benthic algal simulation.



Output Control

	Description	Units	Output	CSV
1	Segment Depth	meters	X	
2	Water Temperature	°C	X	
3	Wind Speed	m/sec	X	
4	Water Velocity	m/sec	X	
5	Inorganic Solids	mg/L	X	
6	Particulate Organic Matter	mg/L	X	
7	Total Solids	mg/L	X	
8	Porosity	fraction	X	
9	Salinity	ppt	X	
10	Dissolved Oxygen	mg/L	X	
11	DO Minimum	mg/L	X	
12	DO Maximum	mg/L	X	
13	DO Saturation (Conc)	mg/L	X	
14	DO Deficit	mg/L	X	
15	Percent DO Saturation	%	X	
16	Reaeration	per day	X	
17	Wind Reaeration	per day	X	
18	Hydraulic Reaeration	per day	X	
19	Sediment Oxygen Demand	g/m2/day	X	
20	CBOD (1) (Ultimate)	mg/L	X	
21	CBOD 1 Decay Rate	per day	X	
22	CBOD (2) (Ultimate)	mg/L	X	
23	CBOD 2 Decay Rate	per day	X	
24	CBOD (3) (Ultimate)	mg/L	X	
25	CBOD 3 Decay Rate	per day	X	
26	Dissolved Organic C	mg/L	X	
27	Total uBOD	mg/L	X	
28	Phytoplankton Carbon	mg/L	X	
29	Phytoplankton Chlorophyll a	ug/L	X	
30	Phytoplankton Growth	per day	X	
31	Phytoplankton Death	per day	X	
32	Phytoplankton DO Production	mg/L/day	X	
33	Phytoplankton DO Consumption	mg/L/day	X	
34	Phytoplankton Carbon to Chla Ratio	mg/mg	X	
35	Phytoplankton Light Growth Limit		X	
36	Phytoplankton Nutrient Growth Limit		X	
37	Phytoplankton Nitrogen Growth Limit		X	
38	Phytoplankton P Growth Limit		X	
39	Total Light		X	X
40	Sat. Light Intensity		X	
41	Light Top Segment		X	
42	Light Bottom Segment		X	X
43	Calculated Light Extinction	1/m	X	X
44	Background Ke	1/m	X	
45	Algal Shade Ke	1/m	X	
46	Solids Ke	1/m	X	
47	DOC Ke	1/m	X	
48	Total Nitrogen	mg/L	X	
49	Total Organic N	mg/L	X	
50	Particulate Organic N	mg/L	X	
51	Dissolved Organic N	mg/L	X	
52	Total Inorganic N	mg/L	X	
53	Dissolved Inorganic N	mg/L	X	
54	Ammonia N	mg/L	X	X
55	Nitrate N	mg/L	X	X
56	Total Phosphorus	mg/L	X	
57	Total Organic P	mg/L	X	
58	Particulate Organic P	mg/L	X	
59	Dissolved Organic P	mg/L	X	
60	Orthophosphate P	mg/L	X	X
61	Dissolved Inorganic P	mg/L	X	X
62	Nitrogen Benthic Flux	g/m2/day	X	
63	Phosphorus Benthic Flux	g/m2/day	X	
64	Benthic Algae Biomass	gD/m2	X	X
65	Benthic Algae Light Limit		X	X
66	Benthic Algae Nutrient Limit		X	X
67	Benthic Algae N Cell Quota	mgN/gDW	X	X
68	Benthic Algae P Cell Quota	mgP/gDW	X	X
69	Benthic Algae Chlorophyll	mgA/m2	X	X
70	Benthic Algae Cell N:Chl	mgN/mgA	X	X
71	Benthic Algae Cell P:Chl	mgP/mgA	X	X
72	Total Detrital Carbon	mg/L	X	X
73	Residence Time	days	X	
74	Advective Flow	m3/sec	X	
75	Flow Into Segment	m3/sec	X	
76	Flow Out of Segment	m3/sec	X	
77	Dispersive Flow	m3/sec	X	
78	Maximum Timestep	days	X	
79	Time Step (Used)	days	X	
80	Volume	cubic meters	X	
81	Biotic Solids Production Rate	gDW/m3-day	X	
82	Biotic Solids Dissolution Rate Const	per day	X	

Figure 6 Output Variables for Eutrophication – Bottom Algae Module

Output variables 64 – 71 are directly related to the benthic algae. Algal biomass per unit area of substrate is expressed both on a dry weight basis (64) and as chlorophyll *a* (69). Internal cell nitrogen and phosphorus concentrations are expressed as fractions of total biomass (67 and 68) and as ratios with chlorophyll *a* (70 and 71). Finally, the calculated light and nutrient growth limitation factors are provided (65 and 66).

Many other water quality variables will be of interest when calibrating a benthic algae model. Those directly affecting benthic algal nutrients and biomass include bottom light (42), ammonia nitrogen (54), nitrate nitrogen (55), and orthophosphate phosphorus (60). Variables that are directly affected by benthic algae include ammonia and phosphate, detrital carbon (72), particulate organic nitrogen (50), particulate organic phosphorus (58), dissolved organic nitrogen (51), dissolved organic phosphorus (59), and dissolved oxygen (10). Users are encouraged to explore patterns and relationships among these variables to better understand the dynamics controlling water quality in their water body.

6 References

Ambrose, R.B., Jr., T.A. Wool, and J.L. Martin. 1993. The Water Quality Analysis Simulation Program, WASP5; Part A: Model Documentation. Internal Report Distributed by USEPA Center for Exposure Assessment Modeling, U.S. Environmental Protection Agency, Athens, GA, June, 1993.

Chapra, S.C. 1997. *Surface Water-Quality Modeling*, McGraw-Hill, New York, New York, 844 pp.

Chapra, S.C. 2003. QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality (Beta Version): Documentation and Users Manual. Civil and Environmental Engineering Dept., Tufts University, Medford, MA.

Chapra, S.C. and G.J. Pelletier. 2004. QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality, Version 1.3: Documentation and Users Manual. Civil and Environmental Engineering Dept., Tufts University, Medford, MA.

Droop, M.R. 1974. The Nutrient Status of Algal Cells in Continuous Culture. *J. Mar. Biol. Assoc. UK*. 54:825-855.

HydroQual. 2003. "Development and Calibration of the Jackson River Periphyton Model," Prepared for MEAD-WESTVACO Corporation. HydroQual Project No: WEST0092, June, 2003.

Laws, E. A. and M.S. Chalup. 1990. A Microalgal Growth Model. *Limnol. Oceanogr.* 35(3):597-608.

Martin, J. L. 2003. “Review of the HydroQual Jackson River Periphyton Model," Contract report prepared for Tetra Tech, Inc., Atlanta, GA.

Redfield, A.C., B.H. Ketchum, and F.A. Richards. 1963. The Influence of Organisms on the Composition of Seawater, in *The Sea*, M.N. Hill, ed. Vol. 2, pp. 27-46, Wiley-Interscience, NY.

Rhee, G-Y. 1973. A Continuous Culture Study of Phosphate Uptake, Growth Rate, and Polyphosphate in *Scenedesmus sp*. *J. Phycol*. 9:495-506.

Rutherford, J.C., M.R. Scarsbrook, and N. Broekhuizen. 2000. Grazer Control of Stream Algae: Modeling Temperature and Flood Effects. *J. Environ. Eng.* 126(4):331-339.

Wool, T.A., R.B. Ambrose, and J. L. Martin. 2001. “The Water Analysis Simulation Program, User Documentation for Version 6.0,” Distributed by USEPA Watershed and Water Quality Modeling Technical Support Center, Athens, GA.

7 Appendix 1: Model Verification Tests

Model verification tests were designed to assure that the equations are implemented correctly in the model code. In this section, analytical solutions are derived for cell nitrogen, cell phosphorus, and algal biomass concentrations under steady-state conditions. WASP7 simulations were run for 2 months under steady flow, temperature, and light conditions until simulated concentrations reached steady state. The simulated results were then compared to the analytical solutions.

7.1 Development of Equations

First, we solved for total biomass. Setting the source/sink term S_{ab} to 0 in equation 1 gives the controlling steady-state equation:

$$F_{Gb} - F_{Rb} - F_{Db} = 0 \tag{40}$$

Substituting the kinetic expressions for growth (using the zero-order model with the Smith light formulation), respiration, and death developed in Section 3.1 into equation 40, the following equation is derived for bottom algal biomass density:

$$a_b = \frac{F_{Gb20}\ \theta_{gb}^{T-20} \times \min\left[\left(1 - \frac{q_{0N}}{q_N}\right), \left(1 - \frac{q_{0P}}{q_P}\right)\right] \times \left(\frac{I(0)e^{-k_e H}}{\sqrt{K_{Lb}^2 + \left(I(0)e^{-k_e H}\right)^2}}\right)}{k_{Rb20}\ \theta_{Rb}^{T-20} + k_{Db20}\ \theta_{Db}^{T-20}} \tag{41}$$

This equation gives the steady-state algal biomass density [gD/m^2] as a function of cell N and P content, a set of reaction constants, and ambient environmental conditions, including light intensity just below the water surface, water temperature, and depth.

Cell N and P content can be solved by setting the source/sink terms S_{bN} and S_{bP} equal to 0 in equations 15 and 16. The resulting equations control cell nitrogen and phosphorus concentrations under steady-state conditions:

$$F_{UNb} - F_{ENb} - F_{DNb} = 0 \tag{42}$$

$$F_{UPb} - F_{EPb} - F_{DPb} = 0 \tag{43}$$

Substituting in the rate expressions for these fluxes (equations 17-22) and simplifying results in the following:

$$\rho_{mN}\left(\frac{NH_4 + NO_3}{K_{sNb} + NH_4 + NO_3}\right)\left(\frac{K_{qN}}{K_{qN} + (q_N - q_{0N})}\right) - k_{Eb20}\ \theta_{Eb}^{T-20}\ q_N\ -\ k_{Db20}\ \theta_{Db}^{T-20}\ q_N = 0 \tag{44}$$

$$\rho_{mP}\left(\frac{PO_4}{K_{sPb} + PO_4}\right)\left(\frac{K_{qP}}{K_{qP} + (q_P - q_{0P})}\right) - k_{Eb20}\ \theta_{Eb}^{T-20}\ q_P\ -\ k_{Db20}\ \theta_{Db}^{T-20}\ q_P = 0 \tag{45}$$

These equations can be rearranged into the quadratic form:

$$a_1\, q_N^2 + b_1\, q_N + c_1 = 0 \qquad (46)$$

$$a_2\, q_P^2 + b_2\, q_P + c_2 = 0 \qquad (47)$$

where:

$$a_1 = 1 \qquad (48)$$

$$a_2 = 1 \qquad (49)$$

$$b_1 = K_{qN} - q_{0N} \qquad (50)$$

$$b_2 = K_{qP} - q_{0P} \qquad (51)$$

$$c_1 = -\,\rho_{mN}\left(\frac{NH_4 + NO_3}{K_{sNb} + NH_4 + NO_3}\right)\left(\frac{K_{qN}}{k_{Eb20}\,\theta_{Eb}^{T-20} + k_{Db20}\,\theta_{Db}^{T-20}}\right) \qquad (52)$$

$$c_2 = -\,\rho_{mP}\left(\frac{PO_4}{K_{sPb} + PO_4}\right)\left(\frac{K_{qP}}{k_{Eb20}\,\theta_{Eb}^{T-20} + k_{Db20}\,\theta_{Db}^{T-20}}\right) \qquad (53)$$

The solutions to these quadratic equations are:

$$q_N = \frac{-b_1 \pm \sqrt{b_1^2 - 4\,a_1\,c_1}}{2\,a_1} \qquad (54)$$

$$q_P = \frac{-b_2 \pm \sqrt{b_2^2 - 4\,a_2\,c_2}}{2\,a_2} \qquad (55)$$

These equations give the steady-state cell nutrient content as a function of external nutrient concentrations, a set of reaction constants, and water temperature. The external nutrient concentrations will depend on upstream flow and boundary concentrations, as well as the segment volume. Substituting the values for q_N and q_P from equations 54 and 55 into equation 41 gives the value for bottom algal biomass density at steady-state.

7.2 Verification Test Results

For verification testing, a single reach was set up with a depth of 0.5 m and a volume of 5000 m^3. The advective flow was set to 50,000 m^3/d, giving a hydraulic residence time of 0.1 days. With this large through-flow, ambient nutrient concentrations will remain close to the specified upstream boundary concentrations.

The first verification test is based on the kinetic coefficients in Table 1. Temperature was set at a constant value of 22.63 °C. Incident light was set at a constant value of 519 Ly/d, and the light extinction coefficient was set to 0.1 m^{-1}. In WASP, light just below the water surface is set to 90% of incident light to account for reflectance. In WASP, boundary concentrations for NH_4, NO_3, and PO_4 were set to 0.1 mg/L, 1 mg/L, and 0.1

mg/L, respectively, resulting in calculated ambient concentrations of 0.072, 0.930, and 0.088 mg/L, respectively. These concentrations were used to drive the analytical solutions for cell nutrient content and biomass density.

Table 1 Kinetic coefficients for bottom algae.

No.	Constant	Value
1	Benthic Algae D:C Ratio (mg Dry Weight/mg C)	2.5
2	Benthic Algae N:C Ratio (mg N/mg C)	0.18
3	Benthic Algae P:C Ratio (mg P/mg C)	0.025
4	Benthic Algae Chl a:C Ratio (mg Chlorophyll a / mg C)	0.025
5	Benthic Algae O2:C Production (mg O2/mg C)	2.69
6	Growth Model, 0 = Zero Order; 1 = First Order	0
7	Max Growth Rate (gD/m2/d for 0-order growth, 1/d for 1-order growth)	30
8	Temp Coefficient for Benthic Algal Growth	1.07
9	Carrying Capacity for First Order Model (gD/m2)	0
10	Respiration Rate (1/day)	0.1
11	Temperature Coefficient for Benthic Algal Respiration	1.07
12	Internal Nutrient Excretion Rate Constant for Benthic Algae (1/day)	0.09
13	Temperature Coefficient for Benthic Algal Nutrient Excretion	1.07
14	Death Rate (1/day)	0.05
15	Temperature Coefficient for Benthic Algal Death	1.07
16	Half Saturation Uptake Constant for Extracellular Nitrogen (mg N/L)	0.1
17	Half Saturation Uptake Constant for Extracellular Phosphorus (mg P/L)	0.04
18	Inorganic Carbon Half-Saturation Constant (not implemented) (moles/L)	0
19	LIGHT OPTION, 1=Half saturation, 2=SMITH, 3= STEELE	2
20	Light Constant for growth (langleys/day)	135
21	Benthic Algae ammonia preference (mg N/L)	0.025
22	Minimum Cell Quota of Internal Nitrogen for Growth (mgN/gDW)	7.2
23	Minimum Cell Quota of Internal Phosphorus for Growth (mgP/gDW)	1
24	Maximum Nitrogen Uptake Rate for Benthic Algae (mgN/gDW-day)	720
25	Maximum Phosphorus Uptake Rate for Benthic Algae (mgP/gDW-day)	50
26	Half Saturation Uptake Constant for Intracellular Nitrogen (mgN/gDW)	9
27	Half Saturation Uptake Constant for Intracellular Phosphorus (mgP/gDW)	1.3

The first month's output from this WASP7 verification simulation is illustrated in Figure 7, Figure 8, and Figure 9. At the end of the first month, calculated variables were close to steady-state conditions. A comparison of these simulated variables after 4 months with the analytical solutions is provided in Table 2. WASP7 deviates from the analytical solutions by 0.05% for total biomass, and 0.01% or less for cell nutrients and limitation factors.

The second verification run tested WASP7 output under low temperature and low light conditions. Temperature and incident light intensity were reduced by a factor of 4 to 5.7 °C and 130 Ly/d, and the model was re-run. Table 3 shows WASP7 deviating from the analytical solutions by 0.1% or less. Because of the low temperature conditions, the WASP7 solution was probably not quite to steady-state.

The third verification run tested WASP output under high temperature and high light conditions. Temperature and incident light intensity were increased by 50% to 34 °C and

778 Ly/d, and the model was re-run. Table 4 shows WASP7 deviating from the analytical solutions by 0.05% or less.

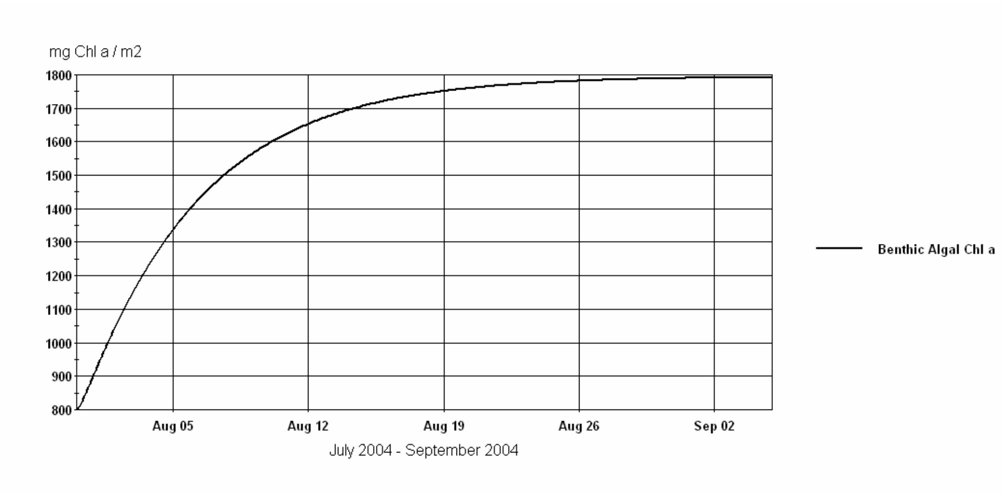


Figure 7 WASP7 Simulation of Benthic Algal Density

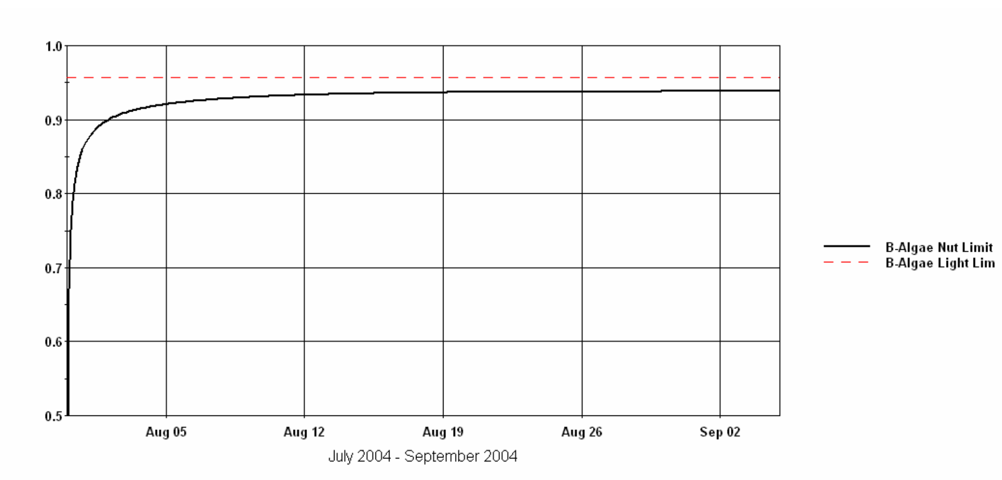


Figure 8 WASP7 Calculated Nutrient and Light Limitation

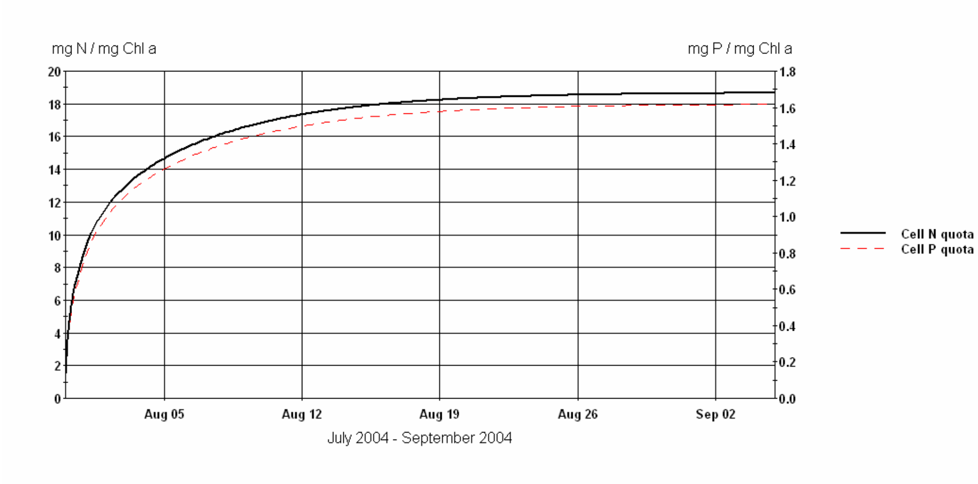


Figure 9 WASP7 Simulation of Cell Nutrient Content

Table 2 Comparison of WASP7 with analytical solutions – base test conditions

Variable	Analytical Solution	WASP7 Solution	Relative Error
Nutrient Limitation Factor	0.9382	0.9382	0.0000
Light Limitation Factor	0.9568	0.9568	0.0001
Total Biomass, mgA/m^2	1795	1794	-0.0005
Cell Nitrogen, mgN/mgA	18.68	18.68	0.0001
Cell Phosphorus, mgP/mgA	1.619	1.619	0.0000

Table 3 Comparison of WASP7 with analytical solutions – low temperature & light

Variable	Analytical Solution	WASP7 Solution	Relative Error
Nutrient Limitation Factor	0.9659	0.9659	0.0000
Light Limitation Factor	0.6351	0.6354	0.0005
Total Biomass, mgA/m^2	1227	1226	-0.0010
Cell Nitrogen, mgN/mgA	33.34	33.31	-0.0010
Cell Phosphorus, mgP/mgA	2.932	2.930	-0.0007

Table 4 Comparison of WASP7 with analytical solutions – high temperature & light

Variable	Analytical Solution	WASP7 Solution	Relative Error
Nutrient Limitation Factor	0.9064	0.9065	0.0001
Light Limitation Factor	0.9801	0.9801	0.0000
Total Biomass, mgA/m^2	1777	1776	-0.0003
Cell Nitrogen, mgN/mgA	12.65	12.65	0.0004
Cell Phosphorus, mgP/mgA	1.069	1.069	0.0005

The fourth verification run tested WASP output under low nutrient conditions. In WASP, incoming ammonia, nitrate, and phosphate boundary concentrations were reduced by a factor of 100, resulting in calculated ambient concentrations of 0.1 μg/L, 1.2 μg/L, and 0.3 μg/L, respectively. These concentrations were used in the analytical solutions for cell nutrient content and cell biomass density. Table 5 shows WASP7 deviating from the analytical solutions by 0.05% for biomass, 0.1% for cell nitrogen, and 0.05% for cell phosphorus, the limiting nutrient. The WASP nutrient limitation term differs from the analytical solution by 0.1% in this simulation.

Table 5 Comparison of WASP7 with analytical solutions – low nutrients

Variable	Analytical Solution	WASP7 Solution	Relative Error
Nutrient Limitation Factor	0.3541	0.3545	0.0012
Light Limitation Factor	0.9568	0.9568	0.0001
Total Biomass, mgA/m^2	678	679	0.0005
Cell Nitrogen, mgN/mgA	2.14	2.14	0.0008
Cell Phosphorus, mgP/mgA	0.155	0.155	0.0005

The fifth verification run tested WASP output under base temperature and light conditions, but with a different set of rate constants (Table 6). The maximum growth rate was reduced to 9 gD/m^2-d, while the respiration rate was increased to 0.3 d^{-1} and the death rate was reduced to 0.01 d^{-1}. The half-saturation constants for extracellular nitrogen and phosphorus were reduced to 0.02 and 0.001 mg/L, and the Smith light constant was reduced to 100 Ly/d. The model was re-run, with results summarized in Table 7. With lower growth and higher respiration rates, biomass declined by more than a factor of 6 from the base simulation, while the lower death rate caused cell nutrient concentrations to increase. WASP7 deviates from the analytical solutions by less than 0.06%.

Table 6 Alternate kinetic coefficients for bottom algae

No.	Constant	Value
1	Benthic Algae D:C Ratio (mg Dry Weight/mg C)	2.5
2	Benthic Algae N:C Ratio (mg N/mg C)	0.18
3	Benthic Algae P:C Ratio (mg P/mg C)	0.025
4	Benthic Algae Chl a:C Ratio (mg Chlorophyll a / mg C)	0.025
5	Benthic Algae O2:C Production (mg O2/mg C)	2.69
6	Growth Model, 0 = Zero Order; 1 = First Order	0
7	Max Growth Rate (gD/m2/d for 0-order growth, 1/d for 1-order growth)	9
8	Temp Coefficient for Benthic Algal Growth	1.07
9	Carrying Capacity for First Order Model (gD/m2)	0
10	Respiration Rate (1/day)	0.3
11	Temperature Coefficient for Benthic Algal Respiration	1.07
12	Internal Nutrient Excretion Rate Constant for Benthic Algae (1/day)	0.09
13	Temperature Coefficient for Benthic Algal Nutrient Excretion	1.07
14	Death Rate (1/day)	0.01
15	Temperature Coefficient for Benthic Algal Death	1.07

16	Half Saturation Uptake Constant for Extracellular Nitrogen (mg N/L)	0.02
17	Half Saturation Uptake Constant for Extracellular Phosphorus (mg P/L)	0.001
18	Inorganic Carbon Half-Saturation Constant (not implemented) (moles/L)	0
19	LIGHT OPTION, 1=Half saturation, 2=SMITH, 3= STEELE	2
20	Light Constant for growth (langleys/day)	100
21	Benthic Algae ammonia preference (mg N/L)	0.025
22	Minimum Cell Quota of Internal Nitrogen for Growth (mgN/gDW)	7.2
23	Minimum Cell Quota of Internal Phosphorus for Growth (mgP/gDW)	1
24	Maximum Nitrogen Uptake Rate for Benthic Algae (mgN/gDW-day)	720
25	Maximum Phosphorus Uptake Rate for Benthic Algae (mgP/gDW-day)	50
26	Half Saturation Uptake Constant for Intracellular Nitrogen (mgN/gDW)	9
27	Half Saturation Uptake Constant for Intracellular Phosphorus (mgP/gDW)	1.3

Table 7 Comparison of WASP7 with analytical solutions – alternate rate constants

Variable	Analytical Solution	WASP7 Solution	Relative Error
Nutrient Limitation Factor	0.9582	0.9582	0.0001
Light Limitation Factor	0.9756	0.9756	0.0000
Total Biomass, mgA/m^2	271	271	0.0003
Cell Nitrogen, mgN/mgA	23.82	23.83	0.0005
Cell Phosphorus, mgP/mgA	2.390	2.391	0.0006

7.3 Model Comparison Test

Further testing of the new WASP7 formulation was conducted by comparing case study results with QUAL2K. This is a hypothetical case study with no observed data. A single reach with 4 computational elements was set up in QUAL2K. An equivalent 4 segment network was set up with WASP7. Each segment and computational element had a depth of 0.5 m and a volume of 5000 m^3. The advective flow was set to 1 m^3/sec, giving a hydraulic residence time of 83 minutes per segment. Upstream boundary concentrations for NH_4, NO_3, and PO_4 were set to 0.1 mg/L, 1 mg/L, and 0.1 mg/L, respectively. Model constants and coefficients from Table 6 were used in this test. A diel temperature function (Figure 10) was specified with a daily average equal to 22.63 °C to match the previous analytical solutions.

Setting up comparable incident solar radiation in the two models proved to be problematic, since QUAL2K calculates light internally. The site location of 42.5 N, 72 W was specified, and the simulation date was set to August 5. The WASP7 diel light function, illustrated in Figure 10, averages 519 Ly/d, with a peak of 1830, which is typical of clear skies at 40 N during late summer. The light function in Figure 10 is adjusted for surface reflectance loss, which is assumed to be 10%.

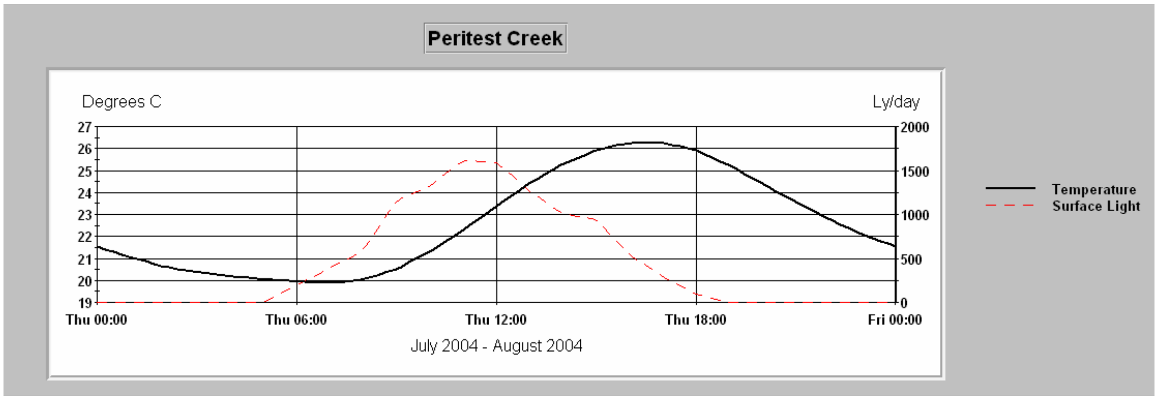


Figure 10 WASP Diel Temperature and Light Functions

Starting with nutrient and biomass initial conditions of zero, QUAL2K was run for a period of 60 days to assure a steady-state initial solution. WASP7 was run for 28 days with initial benthic algal densities set to 10 gD/m^2. Algal densities and cell nutrient concentrations converged to a repeating diel solution within 3 to 4 weeks.

Simulation results for the two models are illustrated in the following figures. Results are illustrated from midnight to midnight (hour 0 to 24 in QUAL2K, time 00:00 to 00:00 in WASP7). For the specified incident light, WASP7 reproduced the QUAL2K diel biomass trend well, with minimum and maximum values higher by 2.4% and 1.0%, respectively (Figure 11 and Figure 12). Cell nutrient dynamics were also reproduced well, with WASP7 exceeding QUAL2K by 4% for the diel minimum and 2.4% for the diel maximum (Figure 13 and Figure 14). Finally, the diel dissolved oxygen dynamics in Figure 15 and Figure 16 compare favorably. The small percentage differences could be due to slightly different model inputs, specifically including incident light. Nevertheless, this case study basically confirms that the new WASP7 benthic algae routines have been implemented correctly.

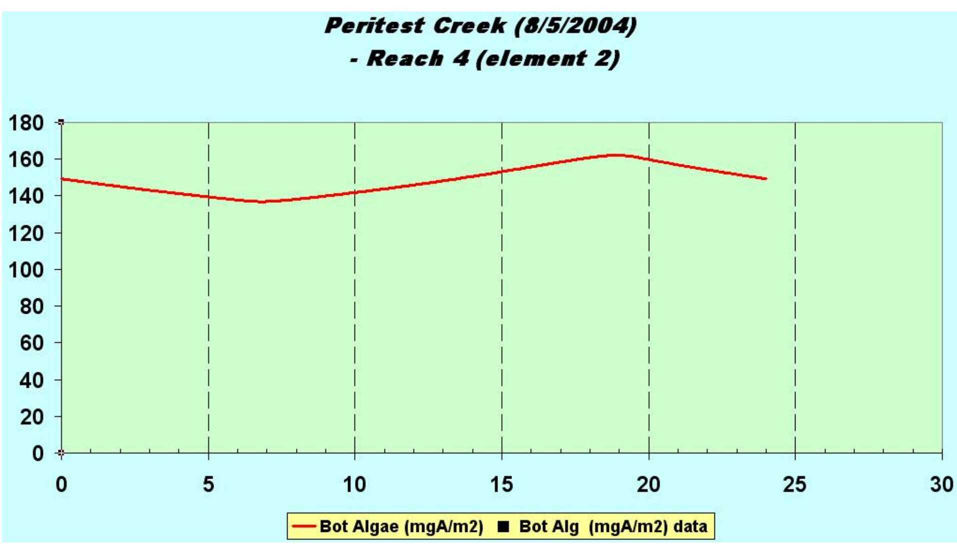


Figure 11 QUAL2K Periphyton Biomass Diel Results

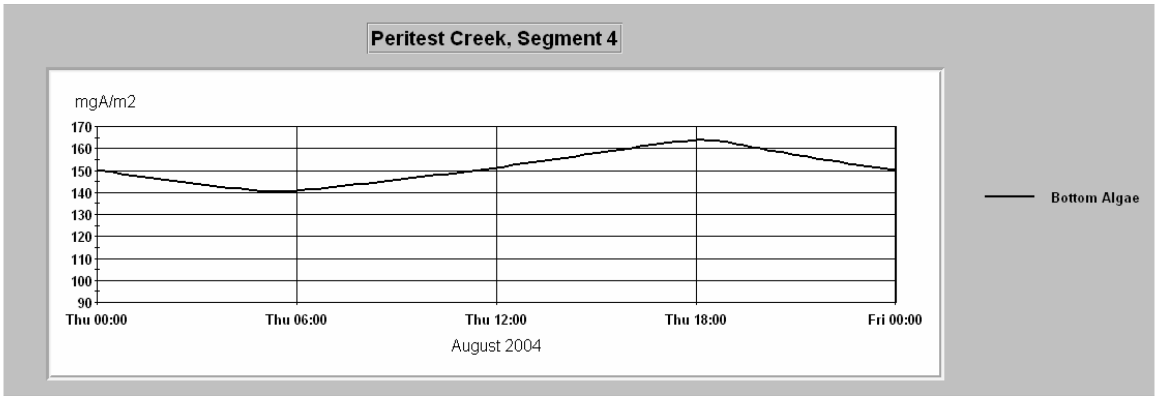


Figure 12 WASP7 Periphyton Biomass Diel Results

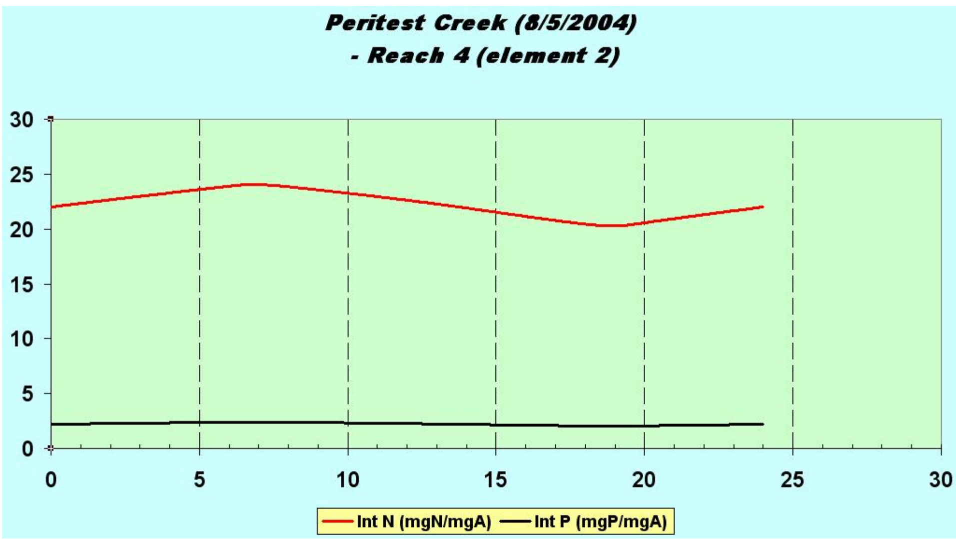


Figure 13 QUAL2K Cell Nutrient Diel Results

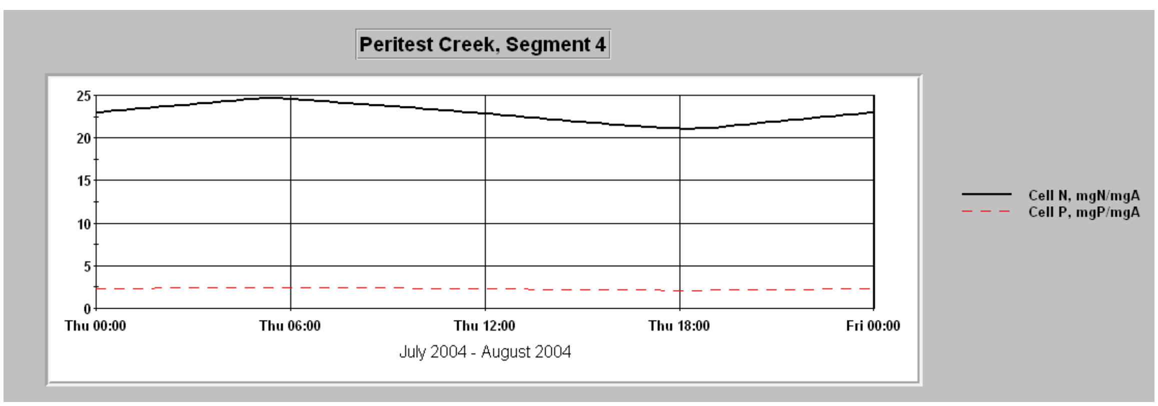


Figure 14 WASP7 Cell Nutrient Diel Results

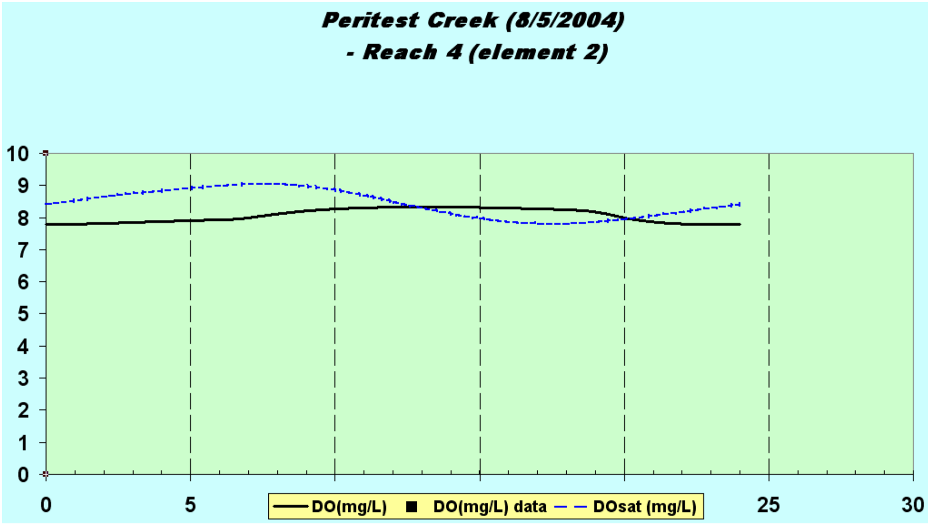


Figure 15 QUAL2K Diel Dissolved Oxygen Results

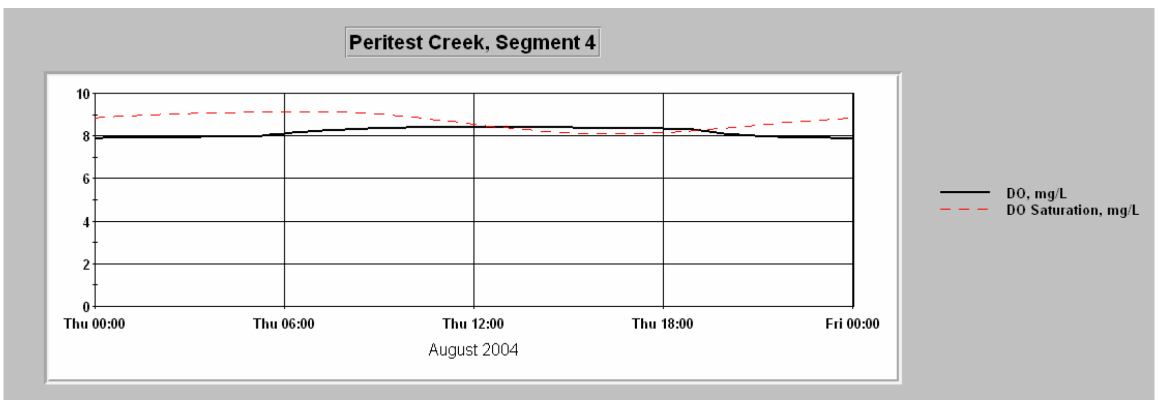


Figure 16 WASP7 Diel Dissolved Oxygen Results