

WASP7 Temperature and Fecal Coliform – Model Theory and User's Guide

RESEARCH AND DEVELOPMENT

WASP7 Temperature and Fecal Coliform – Model Theory and User's Guide

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

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ABSTRACT

The standard WASP eutrophication and toxicant modules use water temperature to determine rates of reactions that are influenced by temperature. In many cases there is not enough spatial and temporal water temperature data to adequately parameterize a water quality model. The WASP Temperature Module can be used to predict water column temperature based upon atmospheric conditions and heat exchange between the surface, subsurface and benthic layers of the water body. Furthermore, WASP has methods for transferring the predicted water temperatures to other WASP sub models via a transfer interface file.

This supplemental user manual documents the temperature and fecal coliform algorithms, including the kinetic equations, the additional model input and output, and a series of model verification tests.

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1 Introduction

The Water Analysis Simulation Program (WASP, Ambrose et al 1993) is a dynamic compartment modeling system that can be applied to a variety of water bodies. The flexibility afforded by WASP is unique. WASP permits the modeler to structure one, two, and three dimensional models; allows the specification of time-variable exchange coefficients, advective flows, waste loads and water quality boundary conditions.

One of the other unique advantages to WASP is its modular structure which permits tailoring structuring of the kinetic processes, all within the larger modeling framework without having to write or rewrite large sections of computer code. The two primary operational WASP models, TOXI5 and EUTRO5, are reasonably general and are intended to simulate two of the major classes of water quality problems: conventional pollution (involving dissolved oxygen, biochemical oxygen demand, nutrients and eutrophication) and toxic pollution (involving organic chemicals and sediment). In addition, kinetic models have been developed for mercury (MERC4, Martin 1992) and for simulation of metals in general (META4, Martin and Medine 1996).

One capability not available in any previous version of WASP is the capability of simulating water temperatures. Temperatures affect many of the kinetic rates in all versions of WASP and are often important in their own right. However, water temperatures are presently described (specified) as an input variable in all previous WASP versions. This version of WASP (Heat Module) has been developed to allow the dynamic simulation of processes affecting water temperatures, including surface heat exchange, ice formation and breakup. The temperature routines are based upon those in the U.S. Army Corps of Engineers CE-QUAL-W2 model (Hydraulics and Environmental Laboratories 1984, Cole and Buchak 1994). In addition, Heat Module allows the simulation of salinity, or total dissolved solids, coliform bacteria and two arbitrary materials, for a total of five state variables.

This manual is intended to describe the basic relationships used to predict variations in each of the five state variables simulated by Heat Module as well as describe the model input requirements. This manual is intended as supplement to the WASP manual (Ambrose et al 1993), and the reader is referred to that manual for a more complete description of WASP model theory and input requirements. In addition, the basic relationships used to predict temperature variations, as described in the following section, were taken from Cole and Buchak (1995).

2 Model Theory

2.1 General Mass Balance Equation

The basic equations solved by all versions of WASP are those based upon laws of conservation. The primary laws of conservation used in the development of water quality models include those for energy, mass and momentum. For example, the hydrodynamic models DYNHYD and RIVMOD are based upon conservation of momentum and water mass. Previous versions of WASP were based upon the conservation of water and constituent mass. The Heat Module model is also based upon conservation of water and constituent mass (for salinity, coliform bacteria, and the arbitrary constituents), as well as the law of conservation of energy, for heat transfer. These laws form the underlying principals of much of modern science and engineering as well as water quality modeling.

For all materials that act according to the laws of conservation, if some transformation or change occurs, the total amount of the material present after the change or transformation must be identical to that present before. For mass, in order to account for processes affecting the transformation the balance equation must account for material entering and leaving through direct and diffuse loading; advective and dispersive transport; and physical, chemical, and biological transformations. For a coordinate system where the x- and y-coordinates are in the horizontal plane and the z-coordinate is in the vertical plane, the mass balance equation around an infinitesimally small fluid volume is:

$$\begin{aligned} \frac{\partial C}{\partial t} = & -\frac{\partial}{\partial x}(U_x C) - \frac{\partial}{\partial y}(U_y C) - \frac{\partial}{\partial z}(U_z C) \\ & + \frac{\partial}{\partial x}\left(E_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(E_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(E_z \frac{\partial C}{\partial z}\right) \\ & + S_L + S_B + S_K \end{aligned}$$

where:

| | |
|--|---|
| C | = concentration of the water quality constituent, mg/L or g/m ³ |
| t | = time, days |
| U _x , U _y , U _z | = longitudinal, lateral, and vertical advective velocities, m/day |
| E _x , E _y , E _z | = longitudinal, lateral, and vertical diffusion coefficients, m ² /day |
| S _L | = direct and diffuse loading rate, g/m ³ -day |
| S _B | = boundary loading rate (including upstream, downstream, benthic, and |

$$\begin{array}{l} \text{atmospheric), g/m}^3\text{-day} \\ S_K = \text{total kinetic transformation rate; positive is source, negative is sink,} \\ \text{g/m}^3\text{-day} \end{array}$$

The mass balance equation as written above is based upon constituent concentrations, which refers to the mass of that dissolved or suspended in a given volume of water. Similarly, temperature may be considered a measure of the amount of heat energy contained in a volume of water, and the relationship between heat energy and temperature is given by:

$$H = V (\rho_w C_p T) = V C_h$$

where H is the heat content, C_p the specific heat of water (at a given pressure) and T the temperature, where the quantity in parenthesis may be considered the "concentration" of heat (C_h). Replacing the constituent concentration with the heat concentration in the above equation results in the heat balance equation, which is solved by Heat Module for water temperatures.

By expanding the infinitesimally small control volumes into larger adjoining "segments," and by specifying proper transport, loading, and transformation parameters, WASP implements a finite-difference form of equation (. The basic equation is applied to a set of expanded control volumes, or "segments," that together represent the physical configuration of the water body. The network may subdivide the water body laterally and vertically as well as longitudinally. Benthic segments can be included along with water column segments. If the water quality model is being linked to the hydrodynamic model, then water column segments must correspond to the hydrodynamic junctions. Concentrations of water quality constituents and temperatures are calculated within each segment. Transport rates of water quality constituents are calculated across the interface of adjoining segments.

2.2 Water Quality Kinetics

The balance relationship described in the previous section is solved by WASP for all state variables. The basic relationship is the same regardless of the state variable. Differences occur between WASP submodels in the number of state variables and the in the processes which are included in the total kinetic transformation rate (S_K) for each state variable. All versions of WASP share the same main program, which computes all terms except for S_K . That term is computed in a separate module (WASPB) which is specific to the submodel (EUTRO, TOXI, MERC, HEAT).

Heat Module allows simulation of five state variables: temperature, salinity or total dissolved solids, coliforms, and two arbitrary constituents. The terms included in the total kinetic transformation rate for each state variable are described below.

2.2.1 Temperature

The processes included in the total transformation rates for temperature include surface and bottom heat exchange. Surface heat exchange is calculated by either a full heat balance or of through use of equilibrium temperatures and coefficients of surface heat exchange (Brady and Edinger, 1975). The surface heat budget is described below and is taken from Cole and Buchak (1994).

2.2.1.1 Surface Heat Exchange

The source and sink term for heat includes loadings from external sources, such as thermal discharges, as well as heat exchange across the air-water interface. The sources and sinks term for water temperature due to surface heat exchange may be written as

$$\frac{\partial V T}{\partial t} /_{exchange} = \frac{H_n A_s}{\rho C_p}$$

where V is volume (m^3), A_s is surface area (m^2), T is temperature ($^{\circ}C$), t is time, ρ the density of water ($997 \text{ Kg } m^{-3}$ at $25^{\circ}C$), C_p is its specific heat ($4179 \text{ J Kg}^{-1} ^{\circ}C^{-1}$ at $25^{\circ}C$), and H_n (Watts m^{-2}) is the net thermal energy flux. The net thermal energy flux includes the effects of a number of processes. The net thermal energy flux (H_n , Watts m^{-2}), may be expressed as

Term-by-term surface heat exchange is computed as:

$$H_n = H_s + H_a + H_e + H_c - (H_{sr} + H_{ar} + H_{br})$$

where

| | | |
|----------|---|--|
| H_n | = | the net rate of heat exchange across the water surface, $W m^{-2}$ |
| H_s | = | incident short wave solar radiation, $W m^{-2}$ |
| H_a | = | incident long wave radiation, $W m^{-2}$ |
| H_{sr} | = | reflected short wave solar radiation, $W m^{-2}$ |
| H_{ar} | = | reflected long wave radiation, $W m^{-2}$ |
| H_{br} | = | back radiation from the water surface, $W m^{-2}$ |
| H_e | = | evaporative heat loss, $W m^{-2}$ |
| H_c | = | heat conduction, $W m^{-2}$ |

In Heat Module, the surface heat exchange processes depending on water surface temperatures are

computed using previous time step data and are therefore lagged from transport processes by the model time step. The short wave solar radiation (H_s) is either measured directly or computed from sun angle relationships and cloud cover. The long wave atmospheric radiation is computed from air temperature and cloud cover or air vapor pressure using Brunt's formula.

Water surface back radiation is computed from:

$$H_{br} = \varepsilon \sigma^* (T_s + 273.15)^4$$

Where

$$\begin{aligned} \varepsilon &= \text{emissivity of water, } 0.97 \\ \sigma^* &= \text{Stephan-Boltzman constant, } 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \\ T_s &= \text{water surface temperature, } ^\circ\text{C} \end{aligned}$$

Evaporative heat loss is computed as:

$$H_e = f(W) (e_s - e_a)$$

where

$$\begin{aligned} f(W) &= \text{evaporative wind speed function, } \text{W m}^{-2} \text{ mm Hg}^{-1} \\ e_s &= \text{saturation vapor pressure at the water surface, } \text{mm Hg} \\ e_a &= \text{atmospheric vapor pressure, } \text{mm Hg} \end{aligned}$$

Evaporative heat loss depends on air temperature and dew point temperature or relative humidity. Surface vapor pressure is computed from the surface temperature for each surface segment.

Surface heat conduction is computed as:

$$H_c = C_c f(W) (T_s - T_a)$$

where

$$\begin{aligned} C_c &= \text{Bowen's coefficient, } 0.47 \text{ mm Hg } ^\circ\text{C}^{-1} \\ T_a &= \text{air temperature, } ^\circ\text{C} \end{aligned}$$

Short wave solar radiation penetrates the surface and decays exponentially with depth according to Bear's Law:

$$H_s(z) = (1 - \beta) H_s e^{-\eta z}$$

Where

| | | |
|----------|---|---|
| $H_s(z)$ | = | short wave radiation at depth z , $W m^{-2}$ |
| β | = | fraction absorbed at the water surface |
| η | = | extinction coefficient, m^{-1} |
| H_s | = | short wave radiation reaching the surface, $W m^{-2}$ |

In the equilibrium temperature approach, a temperature is computed at which the net surface exchange is equal to zero. The linearization of the net heat balance and this definition of the equilibrium temperature allows the net rate of surface heat exchange, H_n , to be expressed as:

$$H_n = -K_{aw} (T_w - T_e)$$

where

| | | |
|----------|---|--|
| H_n | = | rate of surface heat exchange, $W m^{-2}$ |
| K_{aw} | = | coefficient of surface heat exchange, $W m^{-2} EC^{-1}$ |
| T_w | = | water surface temperature, EC |
| T_e | = | equilibrium temperature, EC |

Seven separate heat exchange processes are summarized in the coefficient of surface heat exchange and equilibrium temperature. The linearization used in obtaining equation (has been examined in detail by Brady, et al. (1968), and Edinger et al. (1974).

2.2.1.2 Sediment Heat Exchange

Sediment heat exchange with water is generally small compared to surface heat exchange and has often been neglected. However, investigations on several reservoirs have shown the process must be included to accurately reproduce hypolimnetic temperatures primarily because of the reduction in numerical diffusion (Cole and Buchak 1994). The formulation used to compute bottom heat transfer is similar to that used in the equilibrium temperature approach for surface exchange:

$$H_{sw} = -K_{sw} (T_w - T_s)$$

Where:

| | | |
|----------|---|---|
| H_{sw} | = | rate of sediment/water heat exchange, $W m^{-2}$ |
| K_{sw} | = | coefficient of sediment/water heat exchange, $W m^{-2} EC^{-1}$ |
| T_w | = | water temperature, EC |

T_s = sediment temperature, EC

Cole and Buchak (1994) indicated that values of $7 \times 10^{-8} \text{ W m}^{-2} \text{ EC}^{-1}$ for K_{sw} have been used in previous applications and that average yearly air temperature is a good estimate of T_s .

2.2.1.3 Ice Cover

Ice formation can affect the heat balance, mixing characteristics, and water quality in lakes and reservoirs. For example, once a lake freezes over, sensible heat losses and evaporation nearly cease and net radiation is strongly outward, resulting in more or less steady ice growth during early winter months (Lerman 1978). In addition, other processes which are often negligible during ice-free periods, such as heat flux from the bottom, become important in the heat cycle. Ice essentially shields the lake against wind mixing and retards light penetration, depending upon the thickness of the ice and snow cover. Surface reaeration is also retarded during periods of ice cover and in many shallow eutrophic lakes anoxic conditions often occur following long periods of ice and snow cover and may result in winter fish kills.

Ice cover is described to the eutrophication submodel of WASP. Heat Module computes ice cover, based on relationships included in the CE-QUAL-W2 model (Cole and Buchak 1994). The ice model is based on an ice cover with ice-to-air heat exchange, conduction through the ice, conduction between underlying water, and a "melt temperature" layer on the ice bottom (Cole and Buchak 1994, Ashton, 1979). The overall heat balance for the water-to-ice-to-air system is:

$$\rho_i L_f \frac{\Delta h}{\Delta t} = h_{ai} (T_i - T_e) - h_{wi} (T_w - T_m)$$

where

| | | |
|---------------------|---|--|
| ρ_i | = | density of ice, $kg \text{ m}^{-3}$ |
| L_f | = | latent heat of fusion of ice, $J \text{ kg}^{-1}$ |
| $\Delta h/\Delta t$ | = | change in ice thickness (h) with time (t), $m \text{ sec}^{-1}$ |
| h_{ai} | = | coefficient of ice-to-air heat exchange, $W \text{ m}^{-2} \text{ EC}^{-1}$ |
| h_{wi} | = | coefficient of water-to-ice heat exchange through the melt layer, $W \text{ m}^{-2} \text{ EC}^{-1}$ |
| T_i | = | ice temperature, EC |
| T_{ei} | = | equilibrium temperature of ice-to-air heat exchange, EC |
| T_w | = | water temperature below ice, EC |
| T_m | = | melt temperature, $0EC$ |

The ice-to-air coefficient of surface heat exchange, h_{ai} , and its equilibrium temperature, T_{ei} , are computed the same as for surface heat exchange in Edinger, et al. (1974) because heat balance of the thin, ice surface water layer is the same as the net rate of surface heat exchange presented previously.

The coefficient of water-to-ice exchange, h_{wi} , depends on turbulence and water movement under ice and their effect on melt layer thickness. It is a function of water velocity for rivers but must be

empirically adjusted for reservoirs.

Ice temperature in the ice-heat balance is computed by equating the rate of surface heat transfer between ice and air to the rate of heat conduction through ice:

$$h_{ai} (T_i - T_{ei}) = \frac{-k_i(T_i - T_m)}{h}$$

where

$$k_i = \text{molecular heat conductivity of ice, } W m^{-1} EC^{-1}$$

When solved for ice temperature, T_i , and inserted in the overall ice-heat balance, the ice thickness relationship becomes:

$$\frac{\rho_i L_f \Delta h}{\Delta t} = \frac{(T_M - T_{ei})}{\frac{h}{k_i} + \frac{1}{h_{ia}}} - h_{wi} (T_w - T_m)$$

from which ice thickness can be computed for each longitudinal segment. Heat from water to ice transferred by the last term is removed in the water temperature transport computations.

Variations in the onset of ice cover and seasonal growth and melt over the waterbody depend on locations and temperatures of inflows and outflows, evaporative wind variations over the ice surface, and effects of water movement on the ice-to-water exchange coefficient. Ice will often form in reservoir branches before forming in the main pool and remain longer due to these effects.

A second, more detailed algorithm for computing ice growth and decay has been developed for CEQUAL-W2 (Cole and Buchak 1994) and is included in Heat Module. The algorithm consists of a series of one-dimensional, quasi steady-state, thermodynamic calculations for each time step. It is similar to those of Maykut and Untersteiner (1971), Wake (1977) and Patterson and Hamblin (1988). The detailed algorithm provides a more accurate representation of the upper part of the ice temperature profile resulting in a more accurate calculation of ice surface temperature and rate of ice freezing and melting.

The ice surface temperature, T_s , is iteratively computed at each time step using the upper boundary condition as follows. Assuming linear thermal gradients and using finite difference approximations, heat fluxes through the ice, q_i , and at the ice-water interface, q_{iw} , are computed. Ice thickness at time t , $\theta(t)$, is determined by ice melt at the air-ice interface, $\Delta\theta_{ai}$, and ice growth and melt at the ice-water interface, $\Delta\theta_{iw}$. The computational sequence of ice cover is presented below.

Initial ice formation. Formation of ice requires lowering the surface water temperature to the freezing point by normal surface heat exchange processes. With further heat removal, ice begins to form on the water surface. This is indicated by a negative water surface temperature. The negative water surface temperature is then converted to equivalent ice thickness and equivalent heat is added to the heat source and sink term for water. The computation is done once for each segment beginning with the ice-free period:

$$\theta_0 = \frac{-T_{wn} \rho_w C_{pw} h}{\rho_i L_f}$$

where

| | | |
|------------|---|--|
| θ_0 | = | thickness of initial ice formation during a time step, m |
| T_{wn} | = | local temporary negative water temperature, EC |
| h | = | layer thickness, m |
| ρ_w | = | density of water, $kg\ m^{-3}$ |
| C_{pw} | = | specific heat of water, $J\ kg^{-1}\ EC^{-1}$ |
| ρ_i | = | density of ice, $kg\ m^{-3}$ |
| L_f | = | latent heat of fusion, $J\ kg^{-1}$ |

Upper air-ice interface flux boundary condition and ice surface temperature approximation: The ice surface temperature, T_s , must be known to calculate the heat components, H_{br} , H_e , H_c , and the thermal gradient in the ice since the components and gradient all are either explicitly or implicitly a function of T_s . Except during the active thawing season when ice surface temperature is constant at 0 EC, T_s must be computed at each time step using the upper boundary condition. The approximate value for T_s is obtained by linearizing the ice thickness across the time step and solving for T_s .

$$q_i = K_i \frac{T_f - T_s(t)}{\theta(t)}$$

$$H_{sn} + H_{an} - H_{br} - H_e - H_c + q_i = \rho_i L_f \frac{d\theta_{ai}}{dt}, \quad \text{for } T_s = 0^\circ C$$

$$T_s^n \approx \frac{\theta^{n-1}}{K_i} \left[H_{sn}^n + H_{an}^n - H_b T_{rs}^n - H_e T_s^n - H_c T_s^n \right]$$

where

| | | |
|----|---|---|
| Ki | = | thermal conductivity of ice, $W m^{-1} EC^{-1}$ |
| Tf | = | freezing point temperature, EC |
| n | = | time level |

Absorbed solar radiation by the water under the ice. Although the amount of penetrated solar radiation is relatively small, it is an important component of the heat budget since it is the only heat source to the water column when ice is present and may contribute significantly to ice melting at the ice-water interface. The amount of solar radiation absorbed by water under the ice cover may be expressed as:

$$H_{ps} = H_s (1 - ALB_i) (1 - \beta_i) e^{-\gamma_i \theta(t)}$$

where

| | | |
|------------------|---|--|
| Hps | = | solar radiation absorbed by water under ice cover, $W m^{-2}$ |
| Hs | = | incident solar radiation, $W m^{-2}$ |
| ALB _i | = | ice albedo |
| β_i | = | fraction of the incoming solar radiation absorbed in the ice surface |
| γ_i | = | ice extinction coefficient, m^{-1} |

Ice melt at the air-ice interface. The solution for Ts holds as long as net surface heat exchange, Hn(Ts), remains negative corresponding to surface cooling, and surface melting cannot occur. If Hn(Ts) becomes positive corresponding to a net gain of heat at the surface, qi must become negative and an equilibrium solution can only exist if Ts > Tf. This situation is not possible as melting will occur at the surface before equilibrium is reached (Patterson and Hamblin, 1988). As a result of quasi-steady approximation, heat, which in reality is used to melt ice at the surface, is stored internally producing an unrealistic temperature profile. Stored energy is used for melting at each time step and since total energy input is the same, net error is small. Stored energy used for melting ice is expressed as:

$$\rho_i C_{pi} \frac{T_s(t)}{2} \theta(t) = \rho_i L_f \Delta \theta_{ai}$$

where

| | | |
|---------------|---|---|
| Cpi | = | specific heat of ice, $J kg^{-1} EC^{-1}$ |
| θ_{a1} | = | ice melt at the air-ice interface, m^{-1} |

Formulation of lower ice-water interface flux boundary condition. Both ice growth and melt may

occur at the ice-water interface. The interface temperature, T_f , is fixed by the water properties. Flux of heat in the ice at the interface therefore depends on T_f and the surface temperature T_s through the heat flux q_i . Independently, heat flux from the water to ice, q_{iw} , depends only on conditions beneath the ice. An imbalance between these fluxes provides a mechanism for freezing or melting. Thus,

$$q_i - q_{iw} = \rho_i L_f \frac{d\theta_{iw}}{dt}$$

where

θ_{iw} = ice growth/melt at the ice-water interface

The coefficient of water-to-ice exchange, K_{wi} , depends on turbulence and water movement under the ice and their effect on melt layer thickness. It is known to be a function of water velocity for rivers and streams but must be empirically adjusted for reservoirs. The heat flux at the ice-water interface is:

$$q_{iw} = h_{wi} (T_w(t) - T_f)$$

where

T_w = water temperature in the uppermost layer under the ice, *EC*

Finally, ice growth or melt at the ice-water interface is:

$$\Delta\theta_{iw}^n = \frac{1}{\rho_i L_f} \left[K_i \frac{T_f - T_s^n}{\theta^{n-1}} - h_{wi} (T_w^n - T_f) \right]$$

2.2.1.4 Density

Water densities are affected by variations in temperature and solids concentrations given by :

$$\rho = \rho_T + \Delta\rho_s$$

where

ρ = density, $kg\ m^{-3}$

$$\begin{aligned}\rho_T &= \text{water density as a function of temperature, } kg\ m^{-3} \\ \Delta\rho_S &= \text{density increment due to solids, } kg\ m^{-3}\end{aligned}$$

A variety of formulations have been proposed to describe water density variations due to temperatures. The following relationship is used in Heat Module (Cole and Buchak 1994, Gill, 1982):

$$\begin{aligned}\rho_{T_w} &= 999.8452594 + 6.793952 \times 10^{-2} T_w \\ &\quad - 9.095290 \times 10^{-3} T_w^2 + 1.001685 \times 10^{-4} T_w^3 \\ &\quad - 1.120083 \times 10^{-6} T_w^4 + 6.536332 \times 10^{-9} T_w^5\end{aligned}$$

The affect of dissolved solids, expressed as either salinity or total dissolved solids, on density is also included. Density effects due to TDS is given by Ford and Johnson (1983):

$$\Delta\rho_{TDS} = (8.221 \times 10^{-4} - 3.87 \times 10^{-6} T_w + 4.99 \times 10^{-8} T_w^2) \Phi_{TDS}$$

where

$$\Phi_{TDS} = \text{TDS concentration, } g\ m^{-3}$$

and for salinity (Gill, 1982):

$$\begin{aligned}\Delta\rho_{sal} &= (0.824493 - 4.0899 \times 10^{-3} T_w + 7.6438 \times 10^{-5} T_w^2 \\ &\quad - 8.2467 \times 10^{-7} T_w^3 + 5.3875 \times 10^{-9} T_w^4) \Phi_{sal} \\ &\quad + (-5.72466 \times 10^{-3} + 1.0227 \times 10^{-4} T_w \\ &\quad - 1.6546 \times 10^{-6} T_w^2) \Phi_{sal}^{1.5} + 4.8314 \times 10^{-4} \Phi_{sal}^2\end{aligned}$$

where

$$\Phi_{sal} = \text{salinity, } kg\ m^{-3}$$

2.2.2 Salinity

Salinity or tidal dissolved solids are treated in Heat Module as conservative materials. That

$$\frac{\partial VS}{\partial t} /_{kinetics} = 0$$

is, the sources and sink term for this state variable may be written as

where V is volume (m³), S the salinity or total dissolved solids concentration (Kg m⁻³ or g m⁻³, respectively), and t is time. The selection of whether this state variable is salinity or total dissolved solids is determined by the user's specification of the waterbody type (salt or fresh water).

2.2.3 Coliform Bacteria

Coliform bacteria are commonly used as an indicator of pathogen contamination. Safety standards and criteria for drinking and recreational purposes are based upon coliform concentrations. Predictions of coliform bacteria are important because of their impact on recreation and water supply. The rate equation for coliforms is:

$$\frac{\partial C_{col}}{\partial t} = -K_{col} \theta^{(T-20)} C_{col}$$

where

| | | |
|-----------|---|---|
| K_{col} | = | coliform mortality, day ⁻¹ |
| θ | = | temperature factor (Q10) |
| T | = | water temperature, EC |
| C_{col} | = | coliform concentration, g m ⁻³ |

The Q10 formulation arises from a doubling of the reaction rate with each 10EC increase in temperature.

2.2.4 Arbitrary Constituents

Two arbitrary constituents have been included in Heat Module. They may be used to represent conservative materials (such as tracers) or any constituent that degrades at a first order rate. The equation for each of the arbitrary constituents is:

$$\frac{\partial C_{arb}}{\partial t} = -K_{arb} \theta^{(T-20)} C_{arb}$$

where

| | | |
|------------------|---|--|
| K_{arb} | = | decay rate of the arbitrary constituent, day^{-1} |
| θ | = | temperature factor (Q10) |
| T | = | water temperature, $^{\circ}\text{C}$ |
| C_{arb} | = | concentration, g m^{-3} |

3 Model Input

The data required to support the application of a model of the thermal, fecal coliform and arbitrary constituent modules include initial conditions (segment parameters, environmental time functions and kinetic constants. Each of these is briefly described in the sections below.

3.1 Model Parameters

Parameters are spatially-variable characteristics of the water body. The definition of the parameters will vary, depending upon the structure and kinetics of the systems comprising each model. The input format, however, is constant. The number of parameters that is specified must be input for each segment. Figure 1 and Figure 2 illustrate where the user would define and enable segment specific parameters. If a segment parameter is not defined by the user it is considered to be inactive.

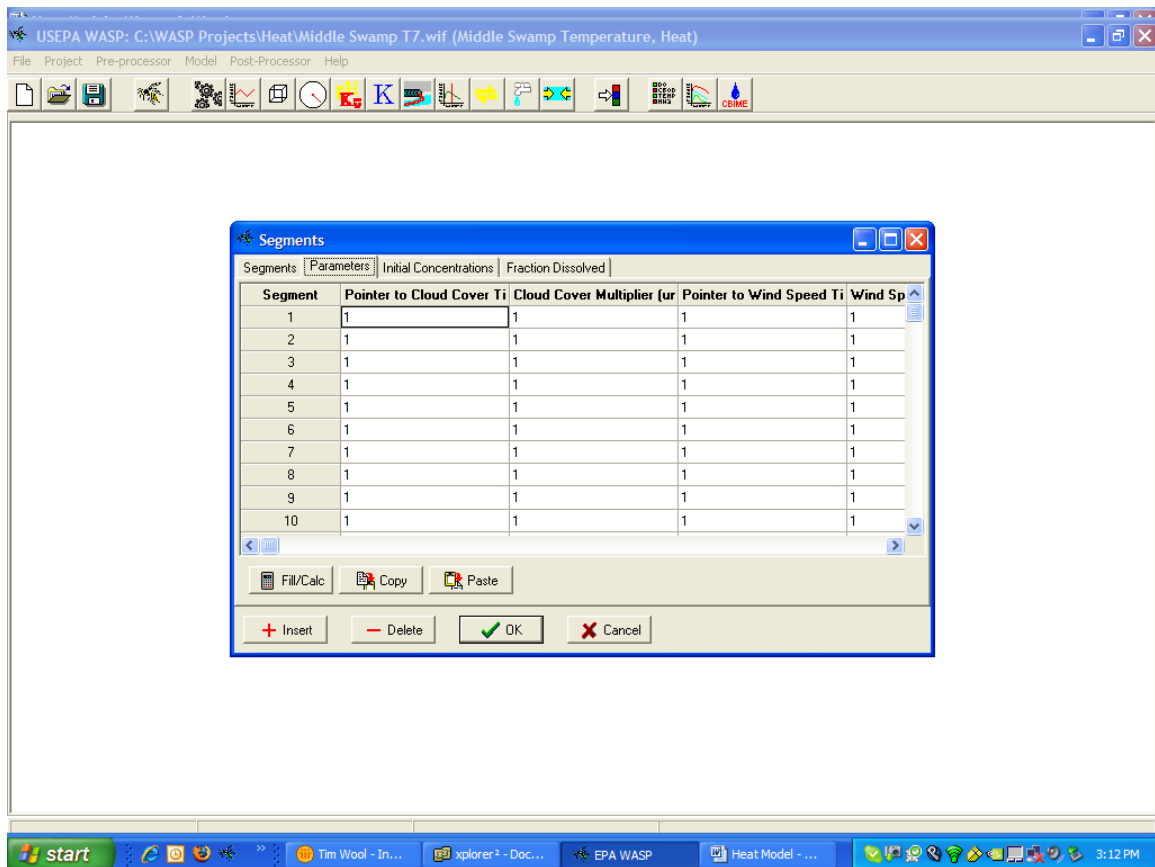


Figure 1 Segment Parameters for Temperature Module

Not only does the user have to define the segment specific parameters, the user must enable the parameter and adjust the scale factor if need be.

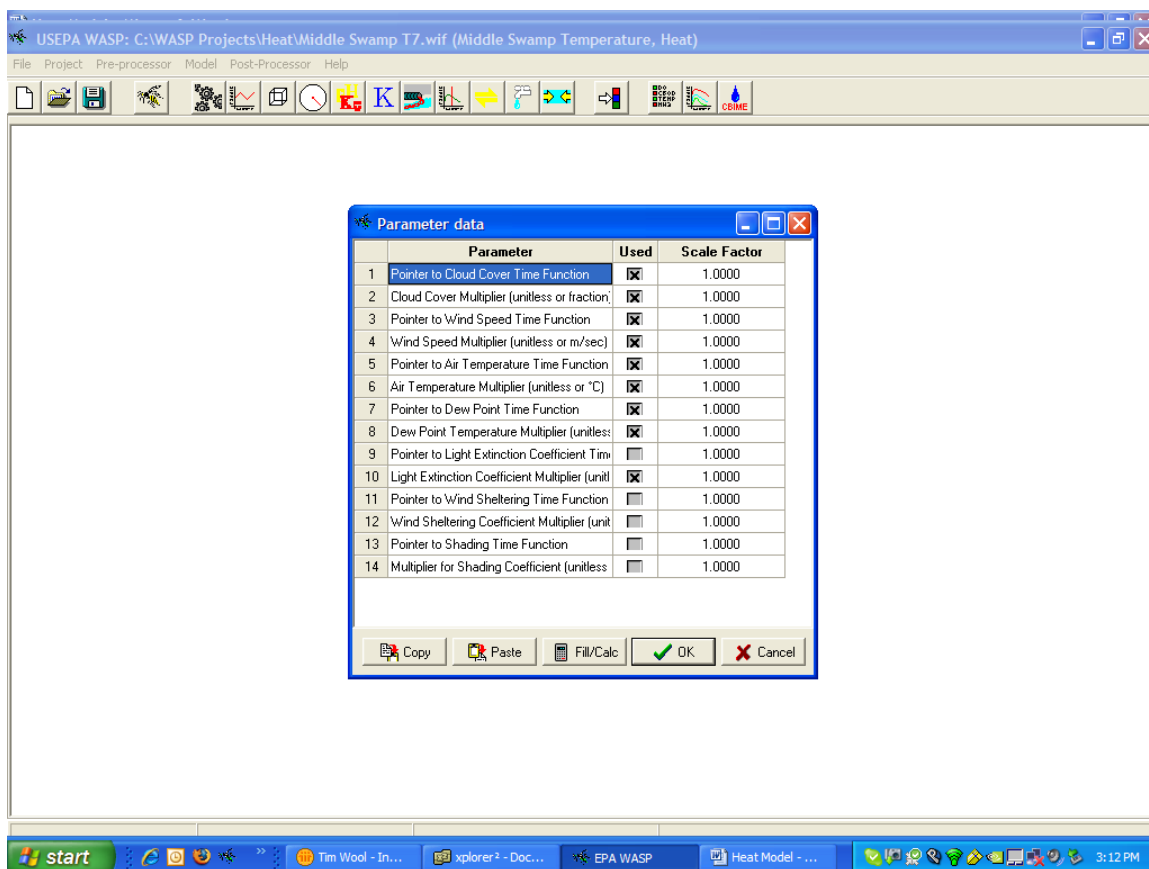


Figure 2 Enabling and Scaling Segment Parameters for Temperature Module

Table 1 provides a detailed description of the segment parameters that are available for the heat module.

Table 1 Description of Segment Parameters for Temperature Module

| Name | Description |
|---|--|
| Pointer to Cloud Cover Time Function | Flag designating the time-variable cloud cover function to be used for the segment. The four cloud cover time functions are defined by the user in the Environmental Time Function Data Entry Screen |
| Cloud Cover Multiplier (unitless or fraction) | Segment clouds cover multiplier. Cloud Cover varies over space and can be either actual cloud cover (as a percent of clear sky) or a normalized function, depending on the way the user defines the time function. |
| Pointer to Wind Speed Time Function | Flag designating the time-variable wind speed function to be used for the segment. The four wind speed functions are defined the Environmental Time Function Data Entry Screen. |
| Wind Speed Multiplier (unitless or m/sec) | Segment wind speed multiplier. Wind speed varies over space and can be either wind speed (m/sec) or a normalized function, depending on the way the user defines the time function. |

| | |
|---|--|
| Pointer to Air Temperature Time Function | Flag designating the time-variable air temperature function to be used for the segment. The air temperature functions are defined the Environmental Time Function Data Entry Screen. |
| Air Temperature Multiplier (unitless or °C) | Segment air temperature multiplier. Air Temperature varies over space and can be either air temperature (°C) or a normalized function, depending on the way the user defines the time function. |
| Pointer to Dew Point Time Function | Flag designating the time-variable dew point temperature function to be used for the segment. The dew point temperature functions are defined the Environmental Time Function Data Entry Screen. |
| Dew Point Temperature Multiplier (unitless or °C) | Segment dew point temperature multiplier. Segment Dew Point Multiplier varies over space and can be either the dew point temperature (°C) or a normalized function, depending on the way the user defines the time function. |
| Wind Sheltering Coefficient Multiplier (unitless or fraction) | Segment wind sheltering coefficient multiplier (a fraction, from 0 to 1). The wind sheltering coefficient varies over space and can be either an actual sheltering coefficient or a normalized function, depending on the definition. |
| Pointer to Wind Sheltering Time Function | Pointer designating the time variable wind sheltering coefficient to be used for segment. This coefficient is used to adjust the effects of the wind. Its physical basis is that surrounding terrain often shelters the waterbody so that observed winds taken from meteorological stations are not the effective winds reaching the waterbody. Since prevailing wind direction and vegetative cover vary with time, the user has the option to vary the wind sheltering coefficient with time as well as space. The four sheltering coefficients time functions available are defined in the Environmental Time Function Data Entry Screen. |
| Light Extinction Coefficient Multiplier (unitless or 1/m) | Segment extinction coefficient multiplier (m^{-1}). Light Extinction varies over space and can be either an actual extinction coefficient or a normalized function, depending on the definition. |

3.2 Model Constants

The definition of the constants will vary, depending upon which state variables you elect to use in the temperature module. The kinetic constants screen in the WASP interface breaks the available constants down into three separate constant groups.

Listed below are the three constant groups with a description of each kinetic constant. Figure 3 illustrates the kinetic constant data entry screen for global constants. To switch between the constant groups, chose using the drop down picklist. Note the user is specifies the values for the constants, but also needs to check the “Used” radio button. Failing to check this box will keep the interface for sending this information to the model.

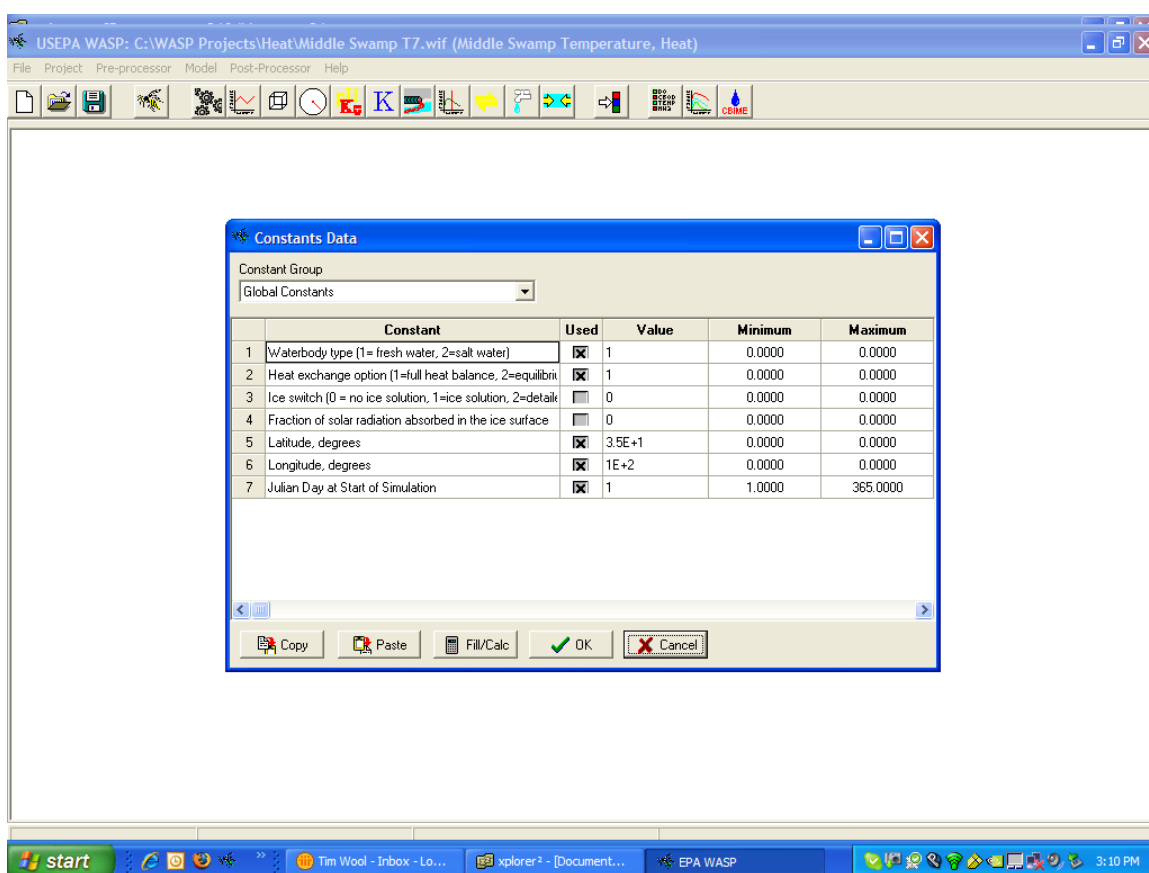


Figure 3 Global Constants for the Temperature Module

Table 2 provides a list of the kinetic constants for the global constants group.

Table 2 Global Constants for Heat Module of WASP

| | Constant |
|---|---|
| 1 | Waterbody type (1= fresh water, 2=salt water) |
| 2 | Heat exchange option (1=full heat balance, 2=equilibrium temperature) |
| 3 | Ice switch (0 = no ice solution, 1=ice solution, 2=detailed ice solution) |
| 4 | Fraction of solar radiation absorbed in the ice surface |
| 5 | Latitude, degrees (Used of the Solar Radiation Generator) |
| 6 | Longitude, degrees (Used of the Solar Radiation Generator) |
| 7 | Julian Day at Start of Simulation (Used of the Solar Radiation Generator) |

Figure 4 illustrates the kinetic constants for the temperature prediction module. Note the user specifies the values for the constants, but also needs to check the “Used” radio button. Failing to check this box will keep the interface for sending this information to the model.

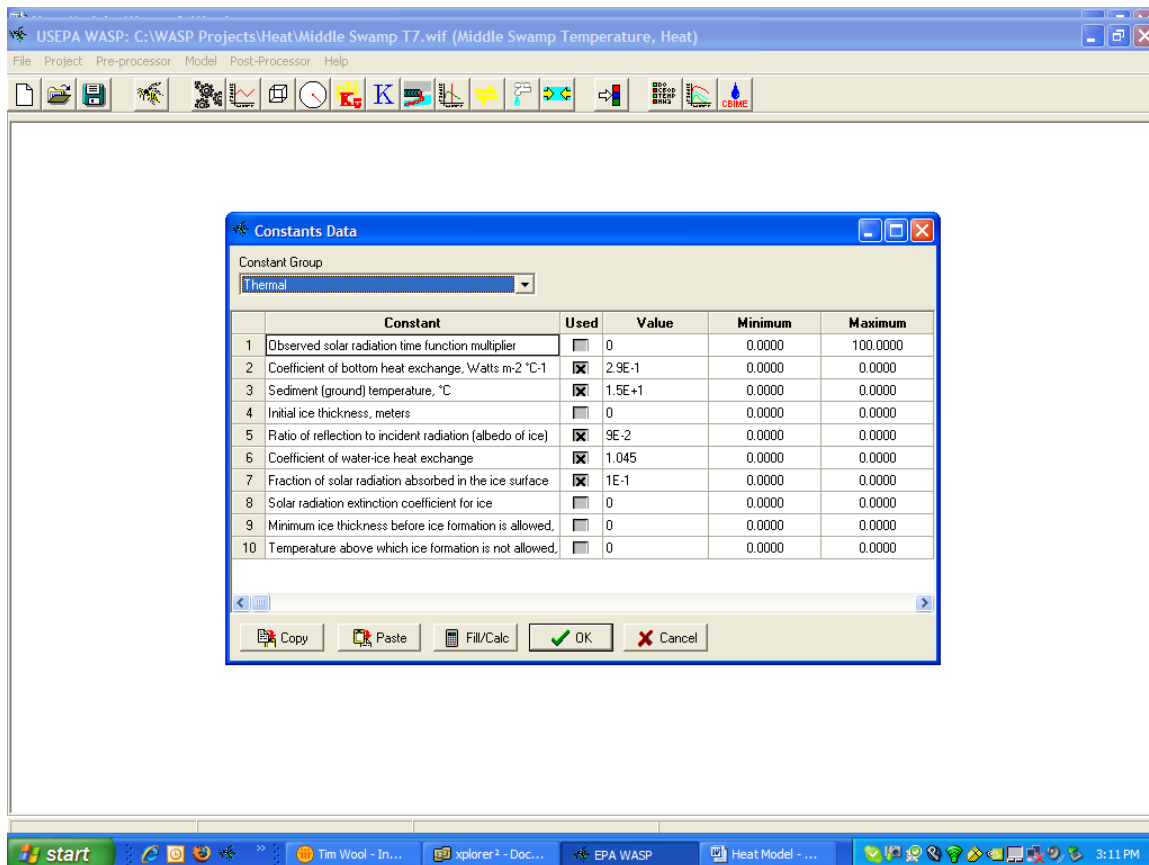


Figure 4 Constants for Temperature Calculation

The kinetic constants that are defined by the user to predict water temperature are presented in Table 3.

Table 3 Temperature Kinetic Constants for Heat Module of WASP

| | Constant |
|---|---|
| 1 | Observed solar radiation time function multiplier |
| 2 | Coefficient of bottom heat exchange, Watts m ⁻² °C ⁻¹ |
| 3 | Sediment (ground) temperature, °C |
| 4 | Initial ice thickness, meters |
| 5 | Ratio of reflection to incident radiation (albedo of ice) |
| 6 | Coefficient of water-ice heat exchange |
| 7 | Fraction of solar radiation absorbed in the ice surface |
| 8 | Solar radiation extinction coefficient for ice |
| 9 | Minimum ice thickness before ice formation is allowed, meters |

| | |
|----|--|
| 10 | Temperature above which ice formation is not allowed, °C |
|----|--|

Table 4 illustrates the kinetic constants for the fecal coliform state variable. Note the user specifies the values for the constants, but also needs to check the “Used” radio button. Failing to check this box will keep the interface for sending this information to the model.

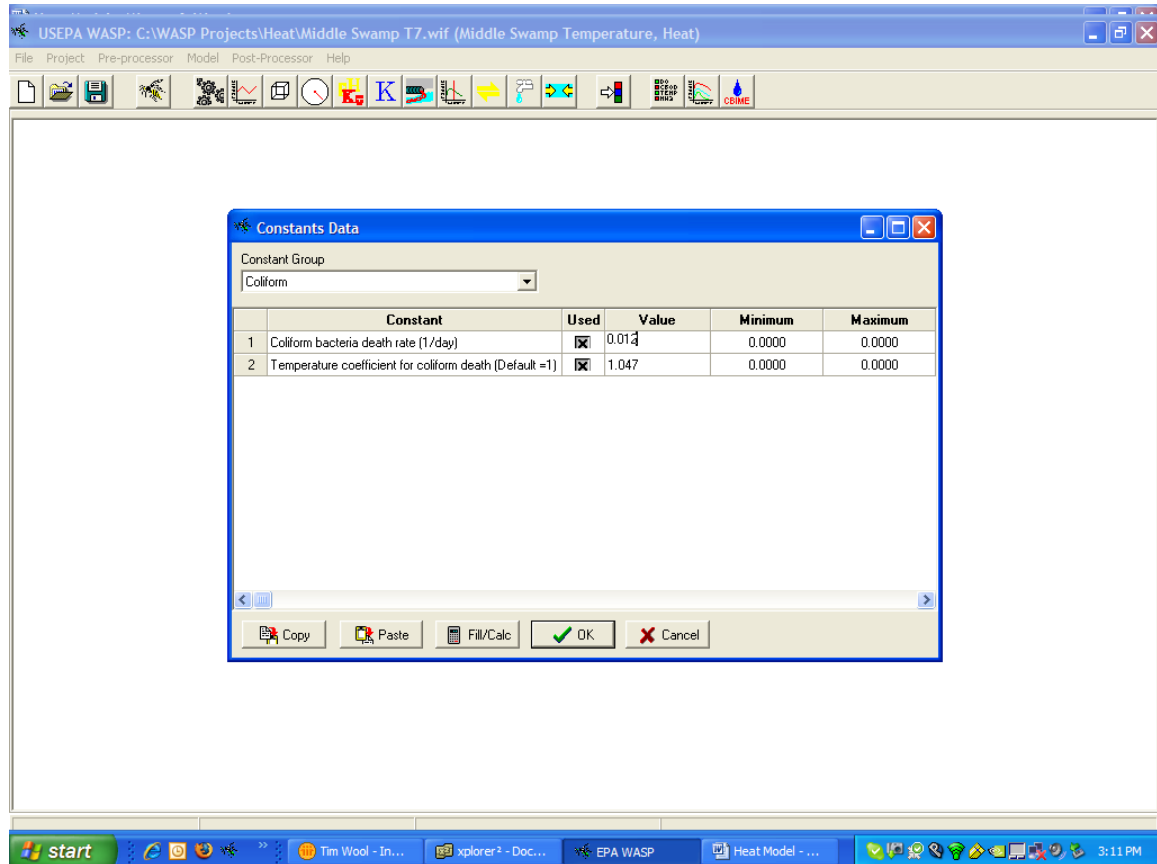


Figure 5 Constants for Fecal Coliform Calculation

The kinetic constants that are defined by the user to predict fecal coliform fate are presented in Table 4

Table 4 Fecal Coliform Kinetic Constants

| | Constant |
|---|---|
| 1 | Coliform bacteria death rate (1/day) |
| 2 | Temperature coefficient for coliform death (Default =1) |

3.3 Kinetic Time Functions

The definition of the kinetic time functions will vary depending upon the structure and the kinetics of the systems comprising each model. Listed below are the 21 time functions available in Heat Module. All of the time functions operate in conjunction with a parameter "pointer" in segment parameter definition (Section 3.1). Figure 6 illustrates the environmental time function user entry screen for WASP. Note the user selects which time functions will be considered and must check the "used" radio button for the information to be passed to the model. For each time function being defined the user must provide a time series of data (Figure 7).

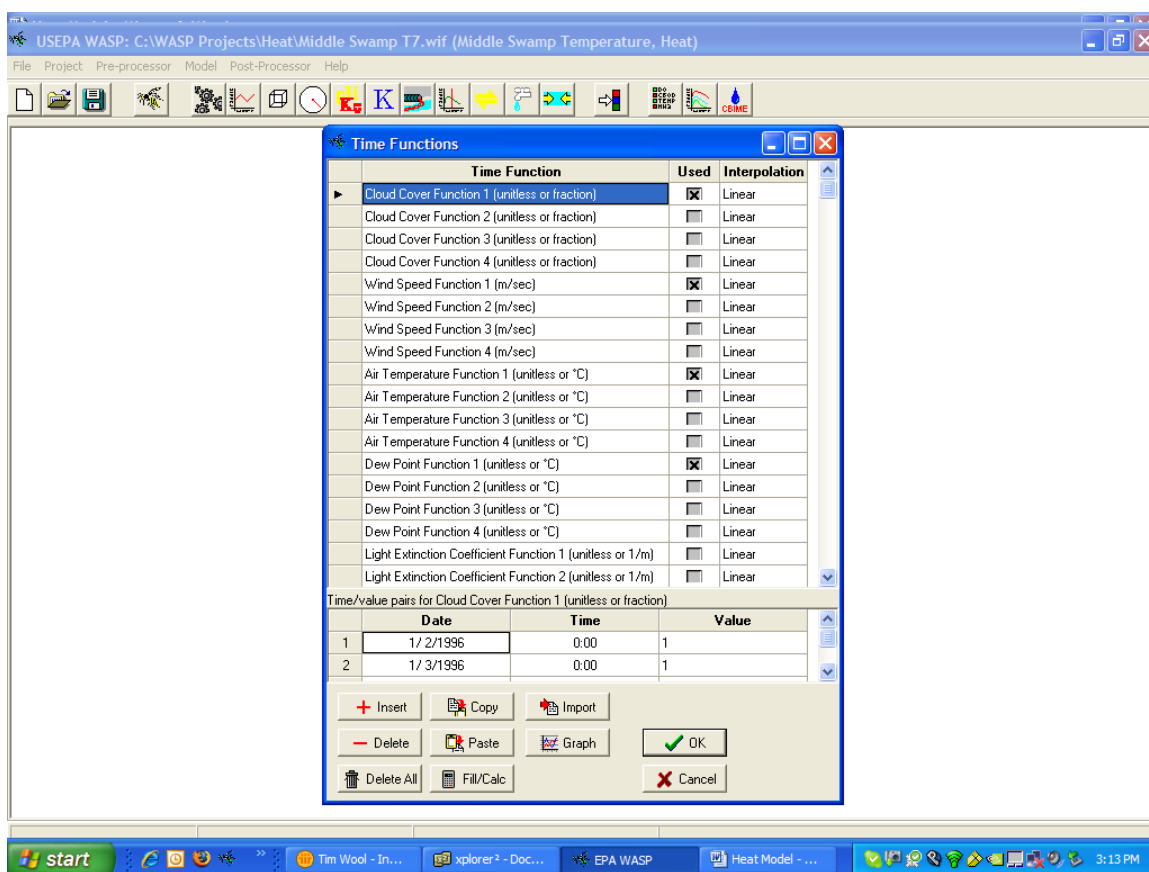


Figure 6 Kinetic Time Functions for Temperature Module

Brief descriptions of the environmental time functions are given in Table 4.

Table 5 Environmental Time Functions for the Temperature Module

| | Environmental Time Functions |
|----|---|
| 1 | Time-variable cloud cover function (1). Cloud Cover can be either a normalized function or an cloud cover (percent), depending upon the definition of the segment parameter multiplier |
| 2 | Time-variable cloud cover function (2), unitless or percent |
| 3 | Time-variable cloud cover function (3), unitless or percent |
| 4 | Time-variable cloud cover function (4), unitless or percent |
| 5 | Time-variable wind-speed function (1). Wind Speed can be either a normalized function or an actual wind speed (m sec^{-1}), depending upon the definition of the segment parameter multiplier. |
| 6 | Time-variable wind speed function (2), unitless or m sec^{-1} . |
| 7 | Time-variable wind speed function (3), unitless or m sec^{-1} . |
| 8 | Time-variable wind speed function (4), unitless or m sec^{-1} . |
| 9 | Time variable air temperature function (1). Air Temperature can be either a normalized function or an air temperature, depending upon the definition of the segment parameter multiplier. |
| 10 | Time-variable air temperature function (2), unitless or EC. |
| 11 | Time-variable air temperature function (3), unitless or EC. |
| 12 | Time-variable air temperature function (4), unitless or EC. |
| 13 | Time-variable dew point temperature function (1). Dew Point Temperature can be either a normalized function or a dew point temperature, depending upon the definition of the segment parameter multiplier. |
| 14 | Time-variable dew point temperature function (2), unitless or EC. |
| 15 | Time-variable dew point temperature function (3), unitless or EC. |
| 16 | Time-variable dew point temperature function (4), unitless or EC. |
| 17 | Time-variable extinction coefficient function (1). Light Extinction can be either a normalized function or an actual extinction coefficient in m^{-1} , depending upon the definition of the segment parameter multiplier. |

| | |
|----|--|
| 18 | Time-variable extinction coefficient function (2), unitless or m^{-1} . |
| 19 | Time-variable extinction coefficient function (3), unitless or m^{-1} . |
| 20 | Time-variable extinction coefficient function (4), unitless or m^{-1} . |
| 21 | Time-variable wind sheltering coefficient function. The Wind Sheltering Coefficient can be either a normalized function or an actual sheltering coefficient (0 to 1), depending upon the definition of the segment parameter multiplier. |

Time series

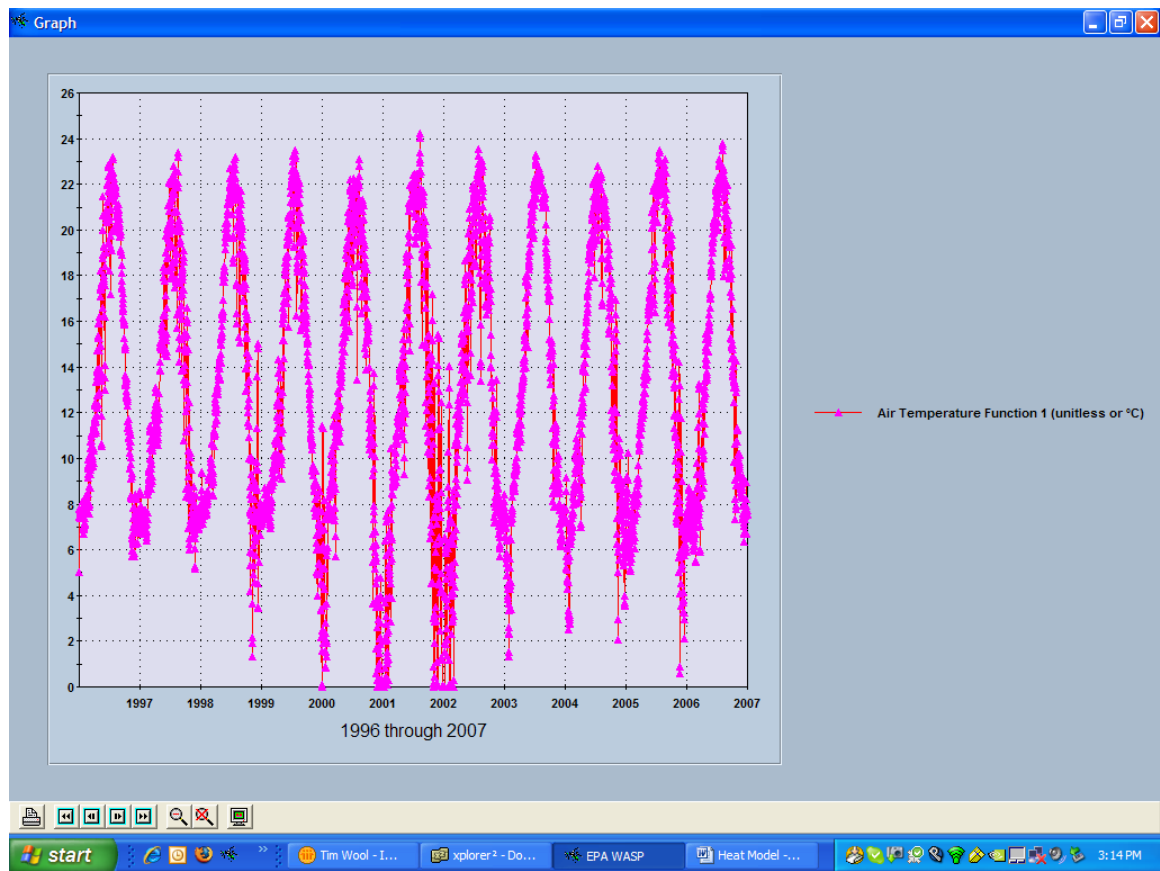


Figure 7 Time Series Definition for Temperature Module

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