

## The Solids Module

### 1. Introduction

Suspended and benthic solids are important components of water quality. Excess suspended solids concentrations can harm fish directly through direct mortality or by reducing their growth rate and resistance to disease. High concentrations increase light attenuation and surface heating. Consequent reductions in light affect algal growth rates and the abundance of food available to fish. Excess silts can blanket benthic spawning areas and damage invertebrates. Organic deposits can reduce dissolved oxygen levels, causing an imbalance in natural biota.

Solids affect conventional water quality through sorption of nutrients. Sorption reduces dissolved  $\text{NH}_4$  and  $\text{PO}_4$  fractions, reducing nitrification and algal uptake and growth. Particulate nutrient fractions are removed from the water column by deposition, and returned by erosion and resuspension.

Likewise, solids affect the fate of potential toxicants, including organic chemicals and nano chemicals. Sorption reduces their dissolved fraction and bioavailability, and deposition removes them from the water column, attenuating some peak loading events. Net deposition stores chemical in sediments for long periods. Pore water diffusion and resuspension return chemicals to the water column between loading events. Large flood events scour significant amounts of sediment and chemical from the upper sediment to the water column. Burial below bioturbation depth potentially sequesters chemical from biota.

The WASP8 modeling system supports two separate models – Advanced Eutrophication and Advanced Toxicant. The appropriate model is chosen in the Data Set section of the user interface. The solids module is an independent set of routines along with associated Constants, Parameters, and Time Functions. It is implemented as a unit within each of these models.

Like other state variables Solids are transported between segments by advection and dispersion. In addition, Solids can settle through the water column, deposit to the surface benthic (i.e., sediment) layer, erode and resuspend back to the water column, and bury to lower benthic layers. These solids transport processes are described below. Using the Solids Option in the Constants section, Solids Transport group, you can choose either the descriptive option (0) or one of the process based solids transport options (1 or 2) for each Solid system. These options are described in sections below.

## 2. Solids Systems

WASP8 can simulate up to 10 different Solids systems, each representing a discrete size range and density. You must choose how many solids types to simulate, and then specify their characteristic sizes and densities. Table 1 gives characteristic size ranges for different classes of solids. Table 2 gives typical densities.

*Table 1 - Particle size classification*

| Size Range               | Wentworth Name   | Common Name |
|--------------------------|------------------|-------------|
| < 1 $\mu\text{m}$        | colloid          | mud         |
| 1.0 – 3.9 $\mu\text{m}$  | clay             | mud         |
| 3.9 – 62.5 $\mu\text{m}$ | silt             | mud         |
| 62.5 - 125 $\mu\text{m}$ | very fine sand   | sand        |
| 125 - 250 $\mu\text{m}$  | fine sand        | sand        |
| 0.25 – 0.5 mm            | medium sand      | sand        |
| 0.5 – 1 mm               | coarse sand      | sand        |
| 1 – 2 mm                 | very coarse sand | sand        |
| 2 – 4 mm                 | granule          | gravel      |
| 4 – 64 mm                | pebble           | gravel      |
| 64 – 256 mm              | cobble           | gravel      |
| > 256 mm                 | boulder          | gravel      |

*Table 2 - Particle densities*

| Substance                   | Density [g/mL] |
|-----------------------------|----------------|
| Organic matter (dry weight) | 1.27           |
| Siliceous minerals          | 2.65           |
| Garnet sands                | 4.0            |

The Solids to be simulated are specified in the Systems section. Each row is an independent model system. You can enter new rows by clicking the ‘Insert’ button or by setting the cursor to the bottom row and pressing the down arrow on your keyboard. To specify a solids variable, double click a cell in the System Type column, then select “SOLID”. A default name is provided in the System Name column. You can specify a more descriptive name by double clicking a cell in that column.

Particle densities are also specified in the Systems section. The Density column is preset to 1.0 g/mL, the nominal density of water. If you do not specify an alternate density for a Solids system, WASP8 will reset the particle density to 2.65 g/mL.

The characteristic particle diameter for each Solid is specified in the Constants section, Solids Transport group. If you do not specify particle diameter for a solids system, WASP8 will assign a default value of 0.025 mm, which is characteristic of silt.

### 3. Water Body Compartments

WASP8 model networks are composed of spatially-discrete segments, or compartments. Detailed network segmentation is best generated using special WASP builder software linked to GIS platforms such as BASINS. Simple networks can be specified directly in the WASP8 user interface.

Each segment is represented by a row in the Segments section of the interface. Segments can come in four types:

- Surface Water
- Subsurface Water
- Surface Benthic
- Subsurface Benthic

These are specified in the Segment Type column.

The Transport Mode determines how advective transport through each segment is calculated. This is covered in the WASP8 Advective Flow document.

For networks with vertical discretization, you must map segments vertically using the Segment Below column. The default setting is “None,” which indicates there is no model segment immediately below the current segment. To specify a segment below, double click in the cell and select the proper segment from a pick list. WASP8 will internally map the segments arranged in vertical columns.

*The water column* – The water column is composed of Surface Water and Subsurface Water segments linked by advective flow paths and dispersive exchanges.

*The sediment bed* – Sediment beds are layers composed of Surface Benthic and Subsurface Benthic segments arranged in vertical stacks beneath a water column segment. Each segment is defined by its bulk density, porosity, cohesiveness and organic content. In WASP8, these properties are not specified directly, but are a product of the individual solids systems simulated along with their properties.

It is important to specify realistic initial concentrations for solids in benthic segments. The initial total solids concentration in a benthic segment [mg/L, or g/m<sup>3</sup>] is used to set the reference bulk density [g/mL] and porosity [L<sub>w</sub>/L]. As described in Section 8, the solids mass balance preserves reference bulk densities and porosities for benthic segments as individual solids are added or removed. Initial concentrations are specified in the Segments section, Initial Conditions group.

A benthic segment is considered “non-cohesive” or “cohesive” depending on whether the fraction of clay and silt-size solids (those less than 0.10 mm) exceeds the specified critical fraction. You can specify the “Critical cohesive sediment fraction, above which bed acts cohesively” in the Constants section, Solids Transport group. The default value is 0.2. In cohesive beds, clay and silt particles are eroded together as a unit. In non-cohesive beds, each particle class is eroded separately.

#### 4. Stream Sedimentation Regimes

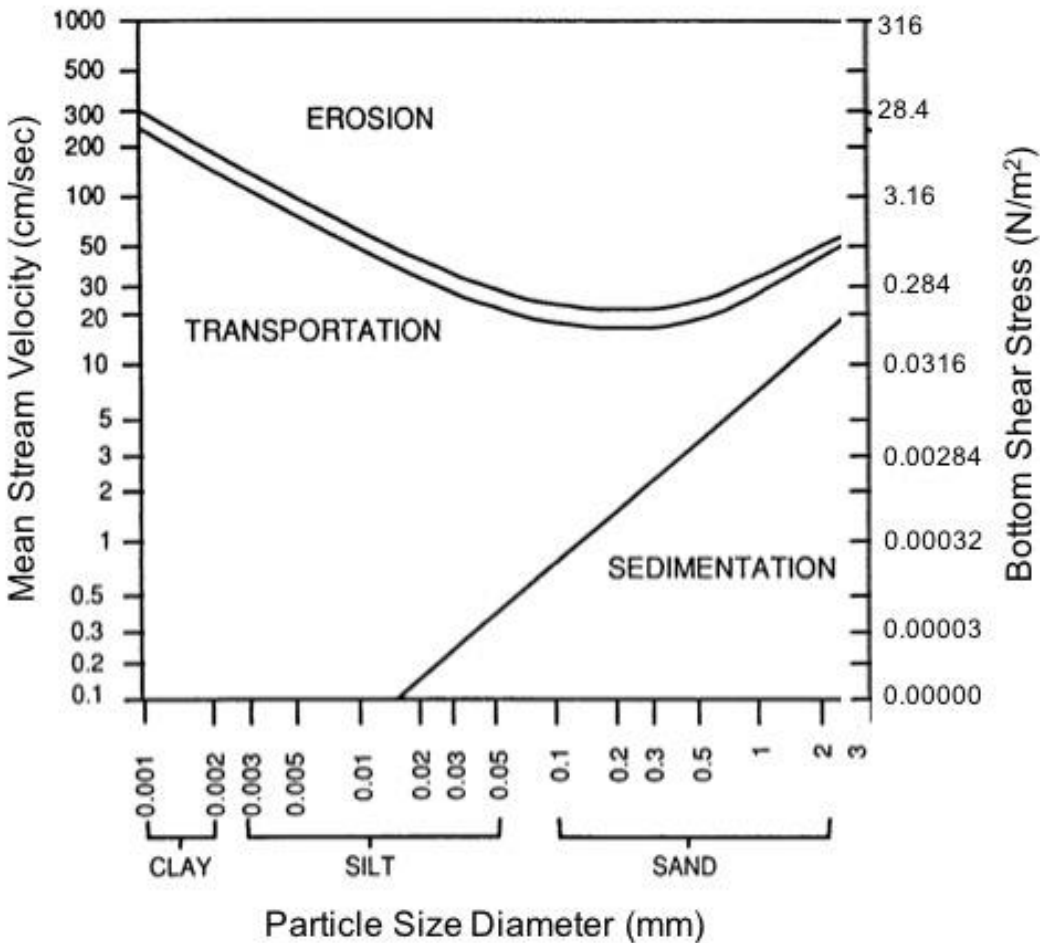
The transport of solids in surface waters is governed to a large degree by particle size and stream velocity (or bottom shear stress).

Figure 1 is a portion of the classic Hjulström-Sundborg Diagram, which provides rough guidance on the net transport regimes for different particle sizes subject to a range of stream velocities (the original diagram extended beyond sand to gravel, pebbles, cobble, and boulders). The diagram was constructed by Filip Hjulström in his 1935 dissertation “The River Fyris,” then modified by Åke Sundborg in 1956.

The top curve in the diagram gives the minimum velocity required to erode a particle from the sediment bed. Below this critical velocity for erosion, the bottom shear stress is not sufficient to move a particle from the sediment bed, and it will tend to remain in place. Above this critical velocity, a particle will begin to move and be picked up into suspension.

The bottom curve gives the minimum velocity required for a particle to remain in suspension without depositing. Above this critical velocity for deposition, the bottom shear stress prevents a settling particle from transferring to the underlying sediment bed. Below this critical velocity, a settling particle that encounters the bed will tend to remain in the bed.

Figure 1 - Stream Sedimentation Regimes



## 5. Descriptive Solids Transport

If default Solids Option 0 is chosen for a Solid system, then WASP8 will apply segment-specific settling and resuspension velocities as specified in the Parameter Data section, Solids group. Settling is the movement of a solid from a water column segment to the underlying water column segment. Deposition is the transfer of a solid from a water column segment to the underlying surface benthic segment. Resuspension is the transfer of a solid from a surface benthic segment to the overlying water column segment. Solids burial is calculated internally based on mass balance calculations for total solids within the benthic segments. This is described in Section 8 below.

*Settling and Deposition* – The Solids Settling Velocity  $w_s$  [m/day] should be specified for settling or deposition from each water column segment. WASP multiplies  $w_s$  by the

solids concentration in the segment [ $\text{g}/\text{m}^3$ ] to obtain the solids flux [ $\text{g}/\text{m}^2\text{-day}$ ] to the segment below. Note that the deposition velocity for a solid is generally a fraction of the characteristic settling velocity for that solid, as described in the *Deposition* subsection in Section 6. In WASP8, Solids Transport constants can be specified to make deposition dependent on shear stress. For Solids Option 0, the default values for these deposition constants are set so that specified settling velocities will be used for deposition.

Note that settling and deposition velocities can be quite high for size classes ranging from coarse silts and above, causing severe numerical burdens. In cases when settling removes more than 0.1% of a solid from a water column segment during the calculation time step, WASP8 uses an analytical solution described in Appendix 1. This solution calculates  $C^*$  [ $\text{g}/\text{m}^3$ ], the average solid concentration during the time step. This concentration is used in the WASP8 solution for settling and advection out of the segment during the time step.

*Resuspension* – The Solids Resuspension Velocity  $w_R$  [ $\text{m}/\text{day}$ ] should be specified for resuspension from each surface benthic segment. WASP multiplies  $w_R$  by the solids concentration in the segment [ $\text{g}/\text{m}^3$ ] to obtain the solids flux [ $\text{g}/\text{m}^2\text{-day}$ ] to the segment above.

## 6. Process Based Solids Transport

If Solids Option 1 or 2 is chosen for a Solid system, then WASP8 will use a set of solids constants along with process-based equations to calculate dynamic settling, deposition, erosion, resuspension velocities. While settling is a function only of particle size and density, deposition, erosion, and resuspension are functions of bottom shear stress. Erosion and resuspension also depend on whether the sediment bed is acting cohesively or noncohesively. Solids burial is calculated internally based on mass balance calculations for total solids within the benthic segments. This is described in Section 8 below.

*Bottom Shear Stress* – Flowing water exerts a shear stress  $\tau_b$  [ $\text{N}/\text{m}^2$ ] on the benthic surface layer. WASP8 uses Darcy–Weisbach expression for the grain-related bottom shear stress (skin friction) that is a function of the average water velocity,  $u$  [ $\text{m}/\text{sec}$ ] and water density  $\rho_w$  [ $\text{kg}/\text{m}^3$ ]:

$$\tau_b = \frac{\rho_w f u^2}{8}$$

$f$  is the Darcy–Weisbach friction factor, estimated by:

$$f = \frac{0.24}{\log^2(12 H/k_s)}$$

where  $H$  is water depth [ $\text{m}$ ],  $D_{50}$  is median sediment grain size [ $\text{m}$ ], and  $k_s$  is the equivalent roughness height [ $\text{m}$ ], calculated as  $3D_{50}$ , or  $0.01H$ , whichever is larger. Note

that for a bed of medium sand (0.5 mm) or finer in streams greater than 5 cm deep,  $f$  assumes a constant value of 0.0253. With values of  $\rho_w$  close to 998, the bottom shear stress simplifies to:

$$\tau_b = 3.16 u^2$$

**Settling** – Settling is the movement of solids down through the water column. WASP8 calculates the settling velocity  $w_s$  [m/sec] for each solid using the van Rijn (1984) method. This is a set of equations based on mean particle diameter  $D_s$  [m], particle density  $\rho_s$  [kg/m<sup>3</sup>], water density  $\rho_w$  [kg/m<sup>3</sup>], and absolute viscosity  $\mu$  [kg/m-sec]:

$$\frac{W_s}{\sqrt{g'D}} = \begin{cases} \frac{R_d}{18} & D \leq 100 \mu\text{m} \\ \frac{10}{R_d} \left( \sqrt{1 + 0.01 R_d^2} - 1 \right) & 100 \mu\text{m} < D \leq 1000 \mu\text{m} \\ 1.1 & D > 1000 \mu\text{m} \end{cases}$$

where  $R_d$  is the sediment particle densimetric Reynolds number:

$$R_d = \frac{D_s \sqrt{g'D_s}}{\mu / \rho_w}$$

and

$$g' = g \left( \frac{\rho_s}{\rho_w} - 1 \right)$$

where  $g$  is the acceleration of gravity, 9.807 [m/sec<sup>2</sup>]. For  $D_s < 100 \mu\text{m}$  (very fine sands and smaller), the van Rijn expression reduces to Stokes Law:

$$w_s = \frac{D_s^2}{18 \mu} g (\rho_s - \rho_w)$$

For  $D_s > 1000 \mu\text{m}$  (very coarse sands and larger), and particle density of 2650 kg/m<sup>3</sup>, the van Rijn expression simplifies to:

$$w_s = 4.425 \sqrt{D_s}$$

In the model initialization phase, WASP8 calculates the characteristic settling velocity for each simulated solid using the input particle densities and diameters along with nominal values for water viscosity (0.001 kg/m-sec) and water density (1000 kg/m<sup>3</sup>).

*Deposition* – Deposition is the movement of solids from the water column to the surficial benthic (or sediment) bed. In noncohesive deposition, the settling of individual solids particles is attenuated by the shear stress from water flow. WASP8 calculates the deposition velocity  $w_D$  [m/sec] for each solid as the product of its settling velocity,  $w_s$ , and the probability of deposition upon contact with bed,  $\alpha_D$ :

$$w_D = w_s \times \alpha_D$$

where  $\alpha_D$  is a function of bottom shear stress  $\tau_b$  as well as the lower and upper critical shear stress thresholds  $\tau_{cD1}$  and  $\tau_{cD2}$ . Using a formulation by Krone (1963),  $\alpha_D$  is equal to 1 for  $\tau_b < \tau_{cD1}$ , and equal to 0 for  $\tau_b > \tau_{cD2}$ . Within the critical shear stress range,  $\alpha_D$  varies from 1 to 0 as bottom shear stress rises from  $\tau_{cD1}$  to  $\tau_{cD2}$  in a roughly linear fashion:

$$\alpha_D = \left( \frac{\tau_{cD2} - \tau_b}{\tau_{cD2} - \tau_{cD1}} \right)^{\gamma_D}$$

where  $\tau_{cD1}$  and  $\tau_{cD2}$  are in [N/m<sup>2</sup>], and  $\gamma_D$  is a dimensionless exponent. For the default  $\gamma_D$  of 1.0, the interpolation function is linear.

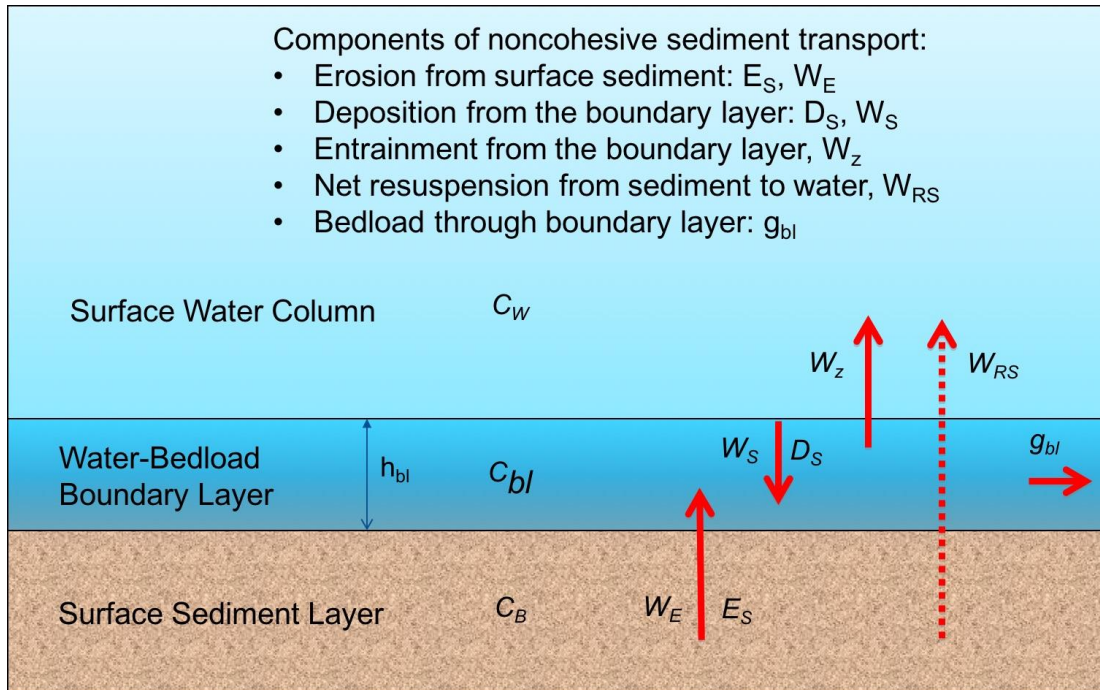
These three constants are input for each solid in the Constants section, Solids Transport group. The lower critical shear stress for deposition is generally considered to be close to 0.0 N/m<sup>2</sup>, while the upper critical shear stress for deposition is in the range of 0.01 - 0.2 N/m<sup>2</sup>, depending on particle size (smaller particles have lower values for  $\tau_{cD2}$  as shown by the lower curve in

Figure 1). For Solids Options 1 and 2, the default values for  $\tau_{cD1}$  and  $\tau_{cD2}$  are set to 0.0 and 0.2 N/m<sup>2</sup>. For Solids Option 0, they are set to 10 and 20 N/m<sup>2</sup> so that under all reasonable conditions, deposition is set to the specified settling velocity.

*Noncohesive Erosion* – Noncohesive erosion is the detachment of solids particles from the surface benthic sediment into a mobile boundary layer. Resuspension is the transport of the solids particles from the mobile layer into the water column (Figure 2). In non-cohesive benthic segments, all solids particles are subject to noncohesive erosion and resuspension. In cohesive benthic segments, only sands and larger particles (greater than 0.1 mm diameter) are subject to noncohesive erosion and resuspension.



Figure 2 - Noncohesive erosion and resuspension



In WASP8, erosion velocity and flux are calculated for each particle size class using either the van Rijn or the Roberts formulation (Solids option 1 or 2). These are based on particle diameter and density, the bottom shear stress, and the critical shear stress for erosion.

The van Rijn erosion algorithm (Solids Option 1) calculates a non-dimensional quantity,  $E$ , which is the ratio of the gross erosion to gross deposition rate. The erosion velocity, then, is the product of  $E$  and the settling velocity:

$$w_E = E \times w_S$$

The van Rijn non-dimensional  $E$  is given by:

$$E = 0.015 \gamma_E \frac{D_s}{k_s} R_d^{-0.2} \tau_*^\eta$$

where  $\gamma_E$  is a user-specified multiplier that defaults to 1.0,  $D_s$  is the median particle size [m],  $k_s$  is the roughness height [m],  $R_d$  is the sediment particle densimetric Reynolds number (defined above),  $\eta$  is a user-specified exponent that defaults to 1.5, and  $\tau_*$  is the non-dimensional shear stress:

$$\tau_* = \frac{\tau_b - \tau_{cE}}{\tau_{cE}} \quad \tau_b \geq \tau_{cE}$$

$$\tau_* = 0 \quad \tau_b < \tau_{cE}$$

where  $\tau_b$  is the bottom shear stress [N/m<sup>2</sup>] and  $\tau_{cE}$  is the critical shear stress for erosion:

$$\tau_{cE} = \gamma_{cE} (\rho_s - \rho_w) g D_s \theta_{cE}$$

where  $\gamma_{cE}$  is a user-specified multiplier that defaults to 1.0 and  $\theta_{cE}$  is the non-dimensional Shields parameter, which is calculated by the Brownlie (1981) fit to the Shields curve:

$$\theta_{cE} = 0.22 R_d^{-0.6} + 0.06 \times 10^{-7.7 R_d^{-0.6}}$$

The critical velocity for erosion  $u_{cE}$  [m/sec], is the velocity that produces  $\tau_{cE}$ :

$$u_{cE} = \sqrt{8 \tau_{cE} / \rho_w f}$$

In WASP8, you can calibrate van Rijn noncohesive erosion by specifying values for the following constants in the Solids Transport group: shear stress exponent for noncohesive resuspension,  $\eta$  (default = 1.5); critical shear stress multiplier for noncohesive resuspension,  $\gamma_{cE}$  (default = 1.0), and shear stress multiplier for noncohesive resuspension,  $\gamma_E$  (default = 1.0).

Eroded solids in the mobile boundary layer may be transported along the sediment bed by bed load, or to the water column by resuspension.

The Roberts erosion algorithm (Solids Option 2) calculates erosion velocity  $w_E$  [m/sec] for each particle size class as a function of bottom shear stress  $\tau_b$  [N/m<sup>2</sup>] and bulk density  $\rho_B$  [kg/m<sup>3</sup>]:

$$w_E = \gamma_E A \rho_B^m \tau_b^n$$

where  $\gamma_E$  is a user-specified multiplier that defaults to 1.0. The fitting coefficients  $A$ ,  $m$ , and  $n$  were determined experimentally for different particle sizes from fine silt (less than 5.7  $\mu$ m) to coarse sand (greater than 1.25 mm). In WASP8, you can calibrate the Roberts erosion rate by specifying a value for the shear stress multiplier for noncohesive resuspension,  $\gamma_E$  (default = 1.0) in the Solids Transport group.

*Noncohesive Resuspension* – Noncohesive resuspension is the transport of the solids particles from the mobile layer or from the surface benthic segment into the water column (Figure 2). Eroded particles move in the boundary layer as bed load below the critical shear stress for resuspension,  $\tau_{cRS}$  [N/m<sup>2</sup>].

$$\tau_{cRS} = 0.1 \frac{(4 w_s 100 / D_*)^2}{\rho_w / 1000}$$

where  $w_s$  is the settling velocity [m/sec],  $\rho_w$  is the water density [kg/m<sup>3</sup>], and  $D_*$  is the non-dimensional particle diameter, given by

$$D_* = \left[ \frac{\left( \frac{\rho_s - \rho_w}{\rho_w} \right) g}{\nu^2} \right]^{1/3} D_s$$

When bottom shear stress exceeds  $\tau_{cRS}$ , particles are entrained from the mobile boundary layer and resuspension begins. The net resuspension velocity  $w_R$  is given by:

$$w_R = f_{RS} \times w_E$$

where  $f_{RS}$  is the fraction of the noncohesive erosion that is entrained to suspension, given by:

$$\begin{aligned} f_{RS} &= 0 & \tau_b &< \tau_{cRS} \\ f_{RS} &= \frac{\ln(u_*/w_s) - \ln(u_{*cRS}/w_s)}{\ln(4) - \ln(u_{*cRS}/w_s)} & \tau_b &\geq \tau_{cRS} \\ f_{RS} &= 1 & u_* &\geq 4w_s \end{aligned}$$

where  $u_*$  is shear velocity [m/sec],  $u_{*cRS}$  is critical shear velocity for resuspension [m/sec], and  $w_s$  is particle settling velocity [m/sec]. The shear velocity and critical shear velocity are given by:

$$\begin{aligned} u_* &= \sqrt{\tau_b / \rho_w} \\ u_{*cRS} &= \sqrt{\tau_{cRS} / \rho_w} \end{aligned}$$

*Noncohesive Bed Load* – Bed load is the transport of noncohesive solids particles downstream through the mobile layer (Figure 2). Bed load begins when the bottom shear stress exceeds the critical shear stress for erosion,  $\tau_{cE}$ . Most eroded particles are redeposited back to the surface sediment layer. The bed load flux per unit width,  $g_{bl}$  [g/m-sec] is given by the van Rijn expression:

$$g_{bl} = \alpha_{bl} \rho_s u h \left( \frac{D_{50}}{h} \right)^{1.2} M_e^\eta$$

where  $\alpha_{bl}$  is a fitted coefficient,  $u$  is stream velocity [m/sec],  $h$  is depth [m],  $\eta$  is a fitted exponent, and  $M_e$  is given by:

$$M_e = \frac{u - u_{cE}}{\sqrt{\left( \frac{\rho_s - \rho_w}{\rho_w} \right) g D_{50}}}$$

where  $u_{cE}$  is the critical velocity for erosion, given in the previous section.

van Rijn calibrated the bed load flux equation to measured transport data (van Rijn, 2007), yielding  $\alpha_{bl} = 15$  and  $\eta = 1.5$ . In WASP8,  $\alpha_{bl}$  is given by:

$$\alpha_{bl} = 15 \times vBLmult$$

where  $vBLmult$  is the calibration multiplier for bed load flux (default = 1.0) and  $\eta$  is set to  $vRNonCohExp$ , the shear stress exponent for noncohesive resuspension (default = 1.5). Both are specified in the Constants section, Solids Transport group.

*Cohesive Resuspension* – Cohesive erosion is the detachment and transfer of a thin layer of cohesive sediment from the surface benthic sediment to the water column. All cohesive solids in the eroded layer are transferred at the erosion velocity,  $w_E$  [m/sec].

A commonly-used expression for cohesive erosion flux [g/m<sup>2</sup>-sec] is the following excess shear stress power law formulation (Lick et al., 1994):

$$E_{coh} = f_{coh} M \tau_*^n$$

where  $M$  is the shear stress multiplier [g/m<sup>2</sup>-sec],  $n$  is the shear stress exponent,  $f_{coh}$  is the fraction of the surface bed that is cohesive, and  $\tau_*$  is the excess shear stress [N/m<sup>2</sup>]:

$$\begin{aligned} \tau_* &= \frac{\tau_b - \tau_{cE}}{\tau_{cE}} & \tau_b &\geq \tau_{cE} \\ \tau_* &= 0 & \tau_b &< \tau_{cE} \end{aligned}$$

where  $\tau_b$  is the bottom shear stress [N/m<sup>2</sup>] and  $\tau_{cE}$  is the critical shear stress for erosion [N/m<sup>2</sup>].

The set of cohesive constants can be specified for each solid in the Constants section, Solids Transport group. The shear stress multiplier varies between 0.1 – 100 [g/m<sup>2</sup>-sec], with a default value of 5. The shear stress exponent varies between 1.6 – 4, with a default value of 3. The critical shear stress for erosion varies between 0.5 – 8 [N/m<sup>2</sup>], with a default value of 2.

The shear stress multiplier, exponent, and the critical shear stress for erosion can vary spatially in a water body. You can input different values for these for each surface benthic segment in the Parameter Data, Solids group. If a nonzero value is specified for a segment, then that value is used rather than the constant.

## 7. Biotic Solids Production and Dissolution

Biotic solids include living algae and non-living detritus. The WASP8 eutrophication model simulates the growth, settling and death of phytoplankton and macro algae, with the subsequent production, settling, and dissolution of detritus. The total dry weight of these biotic solids components is added to the inorganic solids concentrations to produce total suspended solids in water column segments.

In the WASP8 toxicant model, one or more of the solids variables can be characterized as biotic. For solid “i” the net production rate  $R_{prod,i}$  [g/m<sup>3</sup>-day] is given by:

$$R_{prod,i} = (R_{p,seg} + R_{p,t}) \times \theta_{prod}^{T-20}$$

where  $R_{p,seg}$  is the spatially-variable Biotic Solids Net Production Rate [g/m<sup>3</sup>-day] specified in the Parameters section, Solids group;  $R_{p,t}$  is the time-variable Biotic Solids Net Production Rate [g/m<sup>3</sup>-day] specified in the Time Functions section, and  $\theta_{prod}$  is the temperature correction coefficient, specified in the Constants section, Solids Transport group.

Similarly, the dissolution rate constant  $k_{diss,i}$  [1/day] is given by:

$$k_{diss,i} = (k_{d,seg} + k_{d,t}) \times \theta_{diss}^{T-20}$$

where  $k_{d,seg}$  is the spatially-variable Biotic Solids Dissolution Rate Constant [1/day] specified in the Parameters section, Solids group;  $k_{d,t}$  is the time-variable Biotic Solids Dissolution Rate Constant [1/day] specified in the Time Functions section, and  $\theta_{diss}$  is the temperature correction coefficient, specified in the Constants section, Solids Transport group.

The dissolution rate  $R_{diss,i}$  [g/m<sup>3</sup>-day] is the product of its dissolution rate constant [1/day] and its concentration [g/m<sup>3</sup>]:

$$R_{diss,i} = k_{diss,i} \times S_i$$

The inorganic residue of biotic solid “i” dissolution will be added to solid “j” if the user specifies the Ash Dry Weight Residue and the Residue Solid Identification Number in the Constants section, Solids Transport group. The organic carbon fraction of biotic solid “i” dissolution will be added to DOC “k” if the user specifies the Organic Carbon Fraction and Dissolution Product DOC Identification Number in the Constants section, Solids Transport group.

## 8. Solids Burial

As described in Section 3, the benthic sediment below each water column reach can be divided into one or more layers. The initial total solids concentration in each benthic segment [mg/L, or g/m<sup>3</sup>] is used to set its reference bulk density [g/mL] and porosity [L<sub>w</sub>/L]. Driven by deposition, erosion (including resuspension and bed load), growth, and dissolution fluxes, WASP8 conducts a solids mass balance in these layers. There are two options in the Dataset screen – Static (constant volumes) and Dynamic (constant densities). We strongly recommend using the Dynamic option, described below. In this option, you must also set the benthic time step  $DT_B$  in the Dataset screen. The default value is 1 day.

*Surface Benthic Layer* – The surface benthic layer is active. When solids are deposited, it accumulates volume and depth. When solids are eroded, it loses volume and depth. Except as noted below, the initial reference bulk density and porosity are maintained.

If there are no subsurface benthic layers, then deposition causes the surface layer to accumulate depth and volume indefinitely. There is no net burial. Erosion reduces the depth and volume until it reaches 5% of the initial values. No further erosion is allowed.

If there are underlying subsurface benthic layers, then the surface layer volume and depth are reset to their initial reference values each benthic time step. The amounts reset correspond to either net burial ( $V_{B1}$  and  $d_{B1}$ ) or net erosion ( $V_{E1}$  and  $d_{E1}$ ).

Under depositional conditions, the surface benthic segment buries  $V_{B1}$  and  $d_{B1}$  to the first subsurface benthic segment each benthic time step. The solids and pollutant concentrations in the buried volume are also passed downward. The burial velocity  $w_{B1}$  [m/sec] from the surface benthic segment is

$$w_{B1} = d_{B1} / DT_B$$

Note that burial velocity is reported in the model output in units of [cm/year]. The burial fluxes from the surface layer for solids and pollutants are:

$$F_{B1,k} = C_{k,1} \times w_{B1}$$

where  $C_{k,1}$  is the concentration of constituent 'k' in the surface benthic layer [g/m<sup>3</sup>], and  $F_{B1,k}$  is the burial flux [g/m<sup>2</sup>-sec] from the surface benthic layer.

Under erosional conditions, the surface benthic segment recruits  $V_{E1}$  and  $d_{E1}$  from the first subsurface benthic segment each benthic time step. The solids and pollutant concentrations in the subsurface volume  $C_{k,B2}$  are also passed 'upward' (actually, the surface benthic segment is moving downward). In subsurface benthic layers, the total solids are usually packed more tightly and so have higher bulk densities and lower porosities. To preserve mass and volume balance, the surface layer bulk density and porosity are recalculated each benthic time step. If erosion continues over time, the bulk density and porosity approach the values in the subsurface layer.

*Subsurface Benthic Layers* – Subsurface benthic layers are passive. Each benthic time step, mass is transported downward or upward through the subsurface layers depending on whether the surface benthic segment experiences depositional or erosional conditions.

Under depositional conditions, the first subsurface segment receives solids from the surface layer each benthic time step. If the subsurface segment has a higher bulk density, then the buried volume and depth ( $V_{B1}$  and  $d_{B1}$ ) are compressed to  $V_{B2}$  and  $d_{B2}$  and pore water is squeezed upward. The compressed volume  $V_{B2}$  is passed downward to the next benthic layer or out of the system. The solids and pollutant concentrations in

the subsurface volume  $C_{k,B2}$  are also passed downward to the next lower benthic segment through the bed, maintaining the initial bulk density and porosity.

Under erosional conditions, the surface segment receives volume  $V_{E1}$  from the first subsurface layer each benthic time step. Solids within this volume are also transferred upward. In turn, lower subsurface benthic layers transfer the eroded volume and solids concentrations to their overlying benthic layers. Erosion reduces the depth and volume of the bottom layer until it reaches 5% of its initial value. No further erosion of that layer is allowed. Further erosion then reduces the depth and volume of the next lowest benthic layer until it, too, reaches 5% of its initial value. If erosion continues, all benthic layers will eventually reach 5% of their initial values. At this point, no more erosion is allowed.

## Appendix 1: Analytical Solution for Settling

WASP8 normally uses a backward difference numerical solution technique. For each state variable, the concentration at beginning of a time step,  $C_0$ , is used in the transport and transformation equations. The time step,  $DT$ , is adjusted to maintain stability.

For coarse silts and sands, however, the high settling velocities could cause WASP8 to use vanishingly small time steps. In cases when settling removes more than 0.1% of a solid from a water column segment during the normal calculation time step, WASP8 uses the alternative analytical solution described here. This solution calculates  $C^*$ , the average solid concentration during the time step, which is applied in the solid settling and advection loss for the time step.

Balancing loading, advection, and settling, the analytical steady-state solution for a solid under prevailing conditions is:

$$C_{SS} = \frac{L}{Q + V w_S/d}$$

where  $L$  is the total loading of solid “i” [g/day] including external loadings, advection in, and resuspension;  $Q$  is the advective flow [ $m^3/day$ ],  $V$  is the segment volume [ $m^3$ ],  $d$  is the segment depth [m], and  $w_S$  is the settling or deposition velocity [m/day]. During the time step, the concentration will move from  $C_0$  toward  $C_{SS}$ .

For convenience, this equation can be rearranged:

$$C_{SS} = \frac{L/V}{X_{ks}}$$

where  $X_{ks}$  is the overall loss rate constant due to outflow plus settling [1/day]:

$$X_{ks} = \frac{Q}{V} + \frac{w_S}{d}$$

The first order attenuation equation is:

$$\frac{V dC}{dt} = L - \left( Q + \frac{V w_S}{d} \right) C$$

The solution for C as a function of time is:

$$C = C_0 + \frac{L/V}{X_{ks}} (1 - e^{-X_{ks} t})$$

$$C = C_0 + C_{SS} (1 - e^{-X_{ks} t})$$

Integrating this equation over DT gives:

$$\int_0^{DT} C dt = \left[ -\frac{1}{X_{ks}} (C_0 - C_{SS}) e^{-X_{ks} t} + C_{SS} t \right]_0^{DT}$$

evaluating the right-hand side at t = DT minus t=0 and rearranging terms gives:

$$\int_0^{DT} C dt = C_{SS} DT + \frac{1}{X_{ks}} (C_0 - C_{SS}) (1 - e^{-X_{ks} t})$$

The average concentration during DT is:

$$C^* = \frac{\int_0^{DT} C dt}{DT} = C_{SS} + \frac{1}{X_{ks} DT} (C_0 - C_{SS}) (1 - e^{-X_{ks} DT})$$

It is convenient to define  $X_{term}$ , which varies from close to 1 (for small DT or  $X_{ks}$ ) to 0 (for large DT or  $X_{ks}$ ):

$$X_{term} = \frac{1 - e^{-X_{ks} DT}}{X_{ks} DT}$$

so that:

$$C^* = C_0 X_{term} + C_{SS} (1 - X_{term})$$

The average concentration  $C^*$  varies from  $C_0$  at small time steps or loss rates to  $C_{SS}$  for large time steps or loss rates.