HEC-RAS 2D Sediment Workshop: Model Calibration and Sensitivity

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US Army Corps of Engineers®

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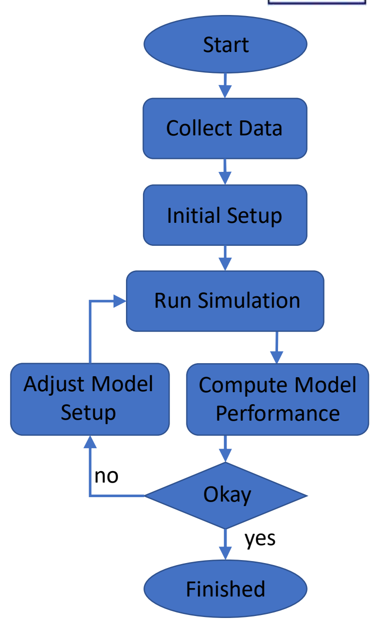
Model Calibration

- Defined as determining a unique set model **parameters** and **formulations** that provide a good description of a system behavior
- Goal and methods will depend on study requirements and data available
- In sediment transport modeling, calibration is generally limited by data and therefore model uncertainty is address with sensitivity analysis



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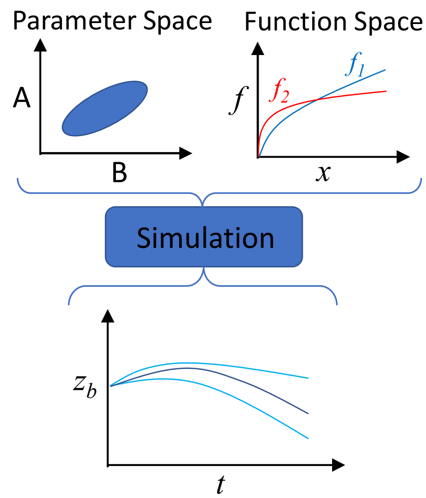
Sensitivity Analysis

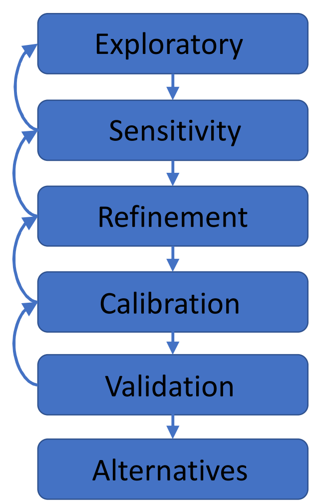
- Defined as the analysis of how uncertainty in model input parameters and formulations produce uncertainty in model output
- Generally required to address parameter and structural/formulation uncertainty in sediment modeling



Modeling Stages

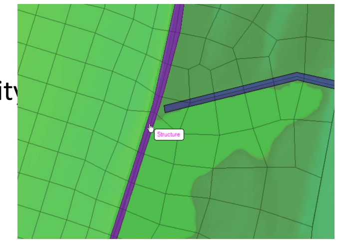
- Modeling stages tend to overlap
- **Iterative** and **incremental** process

1. Exploratory: Determine reasonable initial model setup
2. Sensitivity: Determine what model parameters need to be calibrated or varied to estimate model uncertainty
3. Refinement: Improve the model setup in preparation for calibration runs
   - Adjust mesh resolution, domain extent, number of grain classes, model parameters, etc.
   - Larger emphasis on comparison with measurements
4. Calibration: Determine optimal model setup to match physical system
5. Validation: Confirm calibration setup works for other time periods
6. Alternatives Analysis: Study system responses to proposed changes



Hydraulics Calibration

- Quality of hydraulics model much more important when simulating sediment transport
- Sediment models more sensitive to issues with
  - Boundary conditions, initial conditions, terrain, roughness, mesh quality, etc.
- Water levels can be calibrated with very coarse meshes by adjusting the Manning's n
  - Be weary of models calibrated with water levels only
- **Capacity Only** sediment models can be run on relatively coarse meshes,
- **Mobile bed** models require accurate velocity/shear stresses with higher resolution compared to models designed only for capturing water levels
- **Spatially variable roughness** very important
- If velocity data is not available, perform a **grid convergence on concentration capacity profiles** to determine an appropriate initial grid resolution for a mobile bed sediment model



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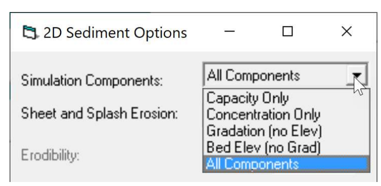
Data Collection

- Additional hydraulic data such as current velocities
- Repeat bathymetry
  - Use reference lines and polygons
  - Careful comparing point data
  - Use **Bed Elev (no Grad)** to "precondition" model
- Bed gradations
  - Can be very noisy
  - Careful interpolating raw data
  - Often better to compute representative bed gradations and then use the **Gradation (no Elev)** to "precondition" the bed gradations
- Concentrations and Transport Rates
  - Careful comparing point concentrations to depth-averaged concentrations
  - Better to compare total-load transport rates



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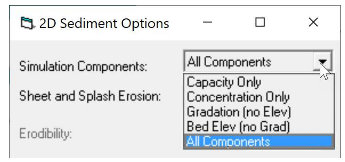
Model Parameters and Settings

- For initial guess with common sense, experience, and recommended guidance based on hydraulic and sediment conditions
- Narrow down appropriate setup with **Exploratory** and **Sensitivity Analysis**
- Start simple and slowly add complexity
- Iterative process
- Stay **Open Minded**
  - Don’t be afraid of trying things
  - Unexpected results are common
- Develop **hypothesis** for model changes
  - Investigate unexpected behavior or results
- Model accuracy determined by project decision thresholds
  - No deposition allowed vs. max 10 ft of deposition
  - Question if any improved accuracy will change the project outcome
- Keep it real (sediment modeling is very uncertain)



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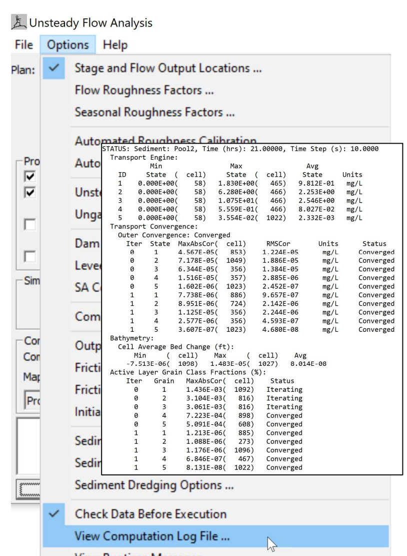
Inspection/Review of Model Output and Logging

- Global Mapping Output
  - Start heavy (lots of output at small intervals)
  - Decrease as mesh size and simulation window length increase
  - Inspect/explore variables such as shear stress, capacities, concentrations, bed fractions, etc.
- Time series
  - Inspect time series at boundary conditions, reference points, lines, and areas
- Computation Log File
  - Verify model setup
  - Check model convergence



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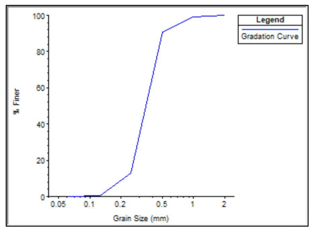
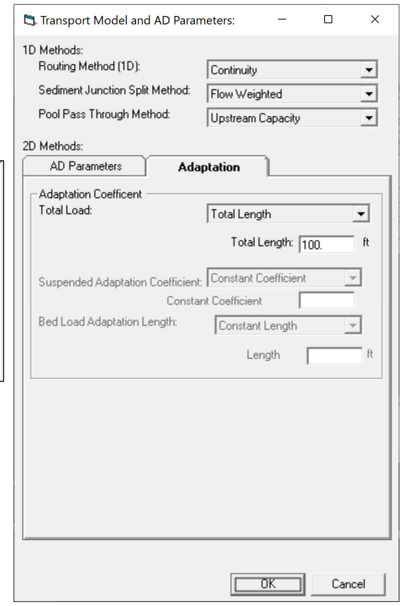
Calibration Parameters and Settings: Noncohesives

- Sediment transport function
  - Transport scaling function
  - Modifying transport function coefficients more difficult
- Incipient motion
  - Hiding and exposure
  - Mobility factor
- Bed gradation
  - Only calibrate within bounds of measurements or reasonable limits
- Adaptation parameters
- Load Correction Factor
- Diffusion Coefficient





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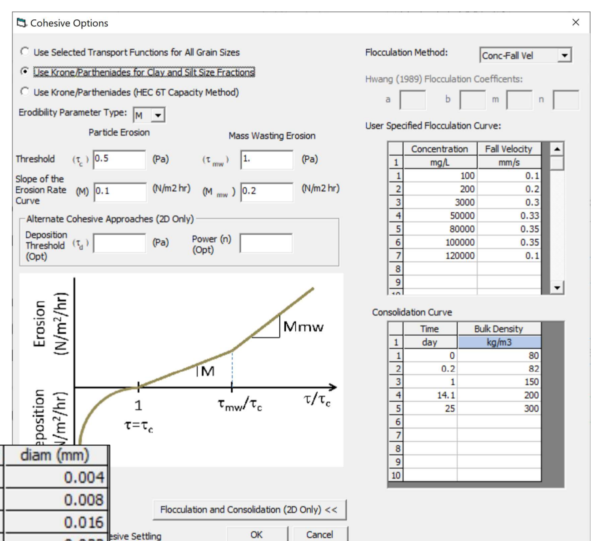
Calibration Parameters and Settings: Cohesives

- Cohesive Erosion rates
- Threshold shear stresses
- Deposition threshold
- Excess shear exponent n
- Bed gradation
  - Only calibrate within bounds of measurements or reasonable limits
- Flocculation
  - Can vary by orders of magnitude
  - Free settling velocity not sensitive
- Bed layering and
- Use 1 or 2 cohesive grain classes!



	Class	diam (mm)
1	Clay	0.004
2	VFM	0.008
3	FM	0.016
4	MM	0.032
5	CM	0.0625

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Noncohesive Erosion and Deposition of Suspended Load

- Near-bed Model

$$D_s = \omega_s c_b$$

$$E_s = \omega_s c_{b*}$$

ω_s: Fall velocity [L/T]

c_b : Near-bed concentration [M/L^3]

c_{b*} : Near-bed conc. capacity [M/L^3]

- Near-bed concentration and capacity difficult to estimate for depth-averaged models
- Values vary by several orders of magnitude
- Very few equations for near-bed concentration capacity
- Near-bed concentration capacity is very difficult to measure

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Noncohesive Erosion and Deposition of Suspended Load

- Relating near-bed values to depth-averaged values

$$c_b = \alpha_c C \qquad c_{b*} = \alpha_{s*} C_*$$

- Inserting into deposition and erosion rates

$$D = \alpha_s \omega_s C \qquad E = \alpha_{s*} \omega_s C_*$$

- Depth-average concentrations can easily be computed and are readily available

$$\alpha_s \approx \alpha_{s*}$$

$$\therefore D_s - E_s = \alpha_s \omega_s \left(C - C_* \right)$$

α_s : Adaptation coefficient (correction factor R_{cp}) [-]

α_{s*} : Adaptation coefficient under equilibrium conditions [-]

ω_s: Fall velocity [L/T]

C : Depth-averaged concentration [M/L^3]

C_* : Depth-averaged capacity [M/L^3]

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Noncohesive Erosion and Deposition of Suspended Load

- In fact, under equilibrium conditions defined as

$$D_s - E_s = 0$$

and the computed coefficients

$$\alpha_s \neq \alpha_{s*}$$

then

$$C \neq C_*$$

which is obviously incorrect

- This why forcing $\alpha_c = \alpha_{c*}$ is a good approximation

α_s : Adaptation coefficient (correction factor R_{cp}) [-]

α_{s*} : Adaptation coefficient under equilibrium conditions [-]

C : Depth-averaged concentration [M/L^3]

C_* : Depth-averaged capacity [M/L^3]

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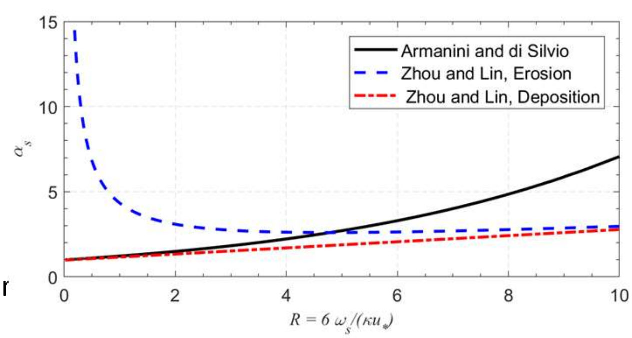
Suspended-load Adaptation Coefficient

- Armanini and di Silvio (1986)
  - Approximate analytical integration of the pure vertical 2D advection-diffusion equation with "gradient" near-bed BC
- Zhou and Lin (1998)
  - Approximate analytical integration of the pure vertical 2D advection-diffusion equation with "concentration" BC for erosion and "gradient" BC for deposition



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Bed-load Adaptation

- Bed-load exchange models are typically formulated as

$$D_b - E_b = \frac{1}{L_b}\left(q_b - q_{b*}\right)$$

- Adaptation length is a measure of the distance it takes for the load to reach equilibrium
- Methods
  - Constant L_b
  - Depth-dependent $L_b = f_{bL} h \quad f_{bL} \approx 7.3$

L_b : Bed-load adaptation length [L]

q_b : Actual bed-load transport rate [M/L/T]

q_{b*} : Bed-load transport capacity [M/L/T]

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Total-load Adaptation Length

- Adaptation approach (Wu 2000)

$$D_t = \alpha_t \omega_s C_t \qquad E_t = \alpha_t \omega_s C_{t*}$$

- Total-load Adaptation Coefficient
  - Constant Adaptation Length

$$\alpha_t = \frac{hU}{L_t \omega_s}$$

  - Weighted Bed- and Suspended-lengths

$$\alpha_{tk} = r_{sk}\alpha_{sk} + (1 - r_{sk})\frac{hU}{L_b \omega_{sk}}$$

α_t : Total-load adaptation coefficient [-]

L_t : Total-load adaptation length [L]

C_t : Total-load concentration [M/L^3]

C_{t*} : Total-load capacity [M/L/T]

r_s : Ratio of suspended-load to total-load [-]

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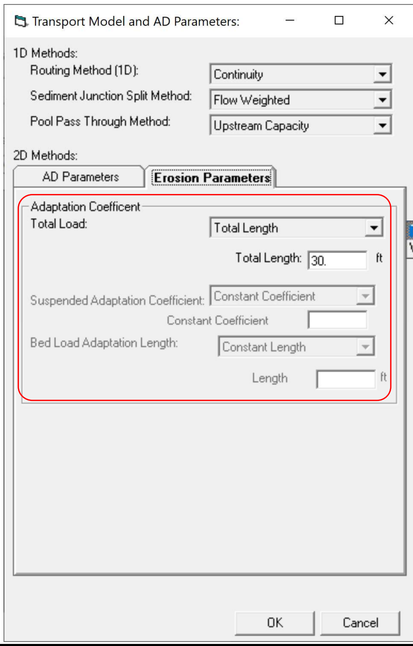
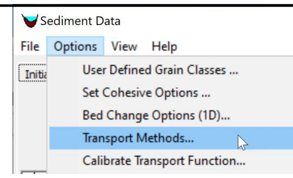
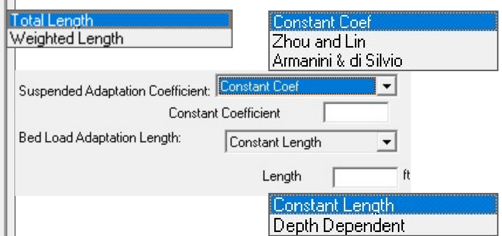
Adaptation Parameters





Transport equation

$$\frac{\partial}{\partial t}\left(\frac{hC_{tk}}{\beta_{tk}}\right)+\nabla\cdot(hUC_{tk})=\nabla\cdot(\varepsilon_{tk}h\nabla C_{tk})+E_{tk}-D_{tk}$$



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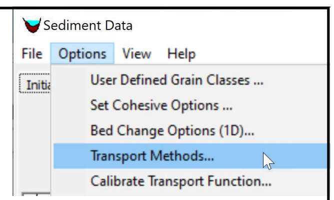
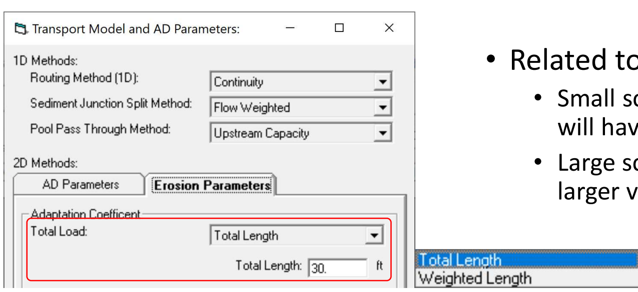
Total-load Adaptation Length





- Related to space time scales
  - Small scale high-resolution models will have a smaller value
  - Large scale coarse models will have a larger value

▪ Increasing
  - ► Decreases bed change
  - ► Smooths bathymetry
  - ► Improves stability

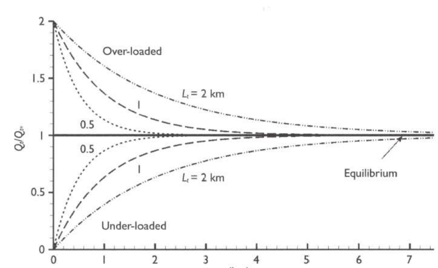


Figure 5.6 Sediment discharge profiles in non-equilibrium transport model.

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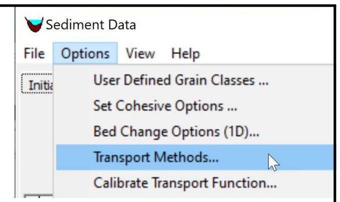
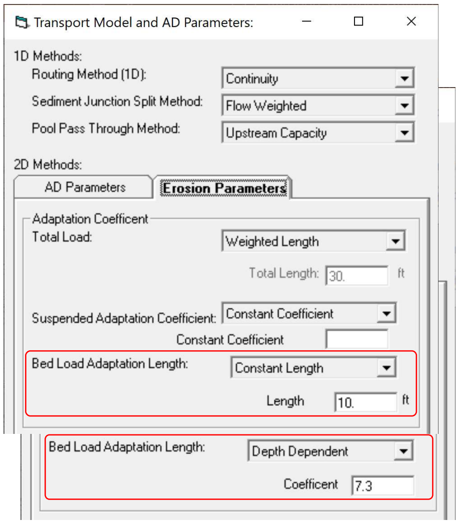
Bed-Load Adaptation Length





- Constant length
  - Most robust
  - Easiest to calibrate
  - Less accurate
- Depth-dependent
  - Less robust
  - Harder to calibrate
  - More accurate

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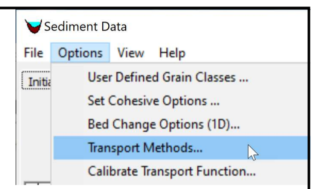
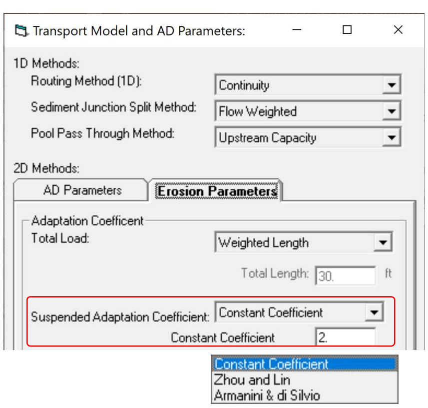
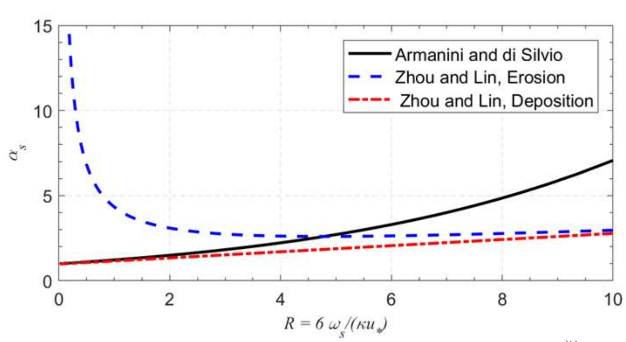
Suspended-Load Adaptation Coefficient





$$\alpha_s \approx 0.5 - 5$$

- Calibration parameter
- Many processes are lumped into parameter



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Discussion

- Total-load adaptation length
  - Use for single mode transport (e.g. well sorted fine sand)
  - At least 1-2x cell size
- Weighted bed and suspended load lengths
  - Use for mixed mode transport (e.g. poorly sorted sediments)
  - Try different formulations for suspended and bed-load adaptation parameters

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Concentration Definition

- **Depth-averaged**

$$\hat{C}_{tk} = \frac{1}{h}\int_0^h c_{tk}\,dz \qquad q_{tk} = \beta_t U h \hat{C}_{tk} \qquad \beta_t = \frac{1}{Uh\hat{C}_{tk}}\int_0^h u c_{tk}\,dz$$

  - Coefficient for transport (advection term)
  - **Used in HEC-RAS 1D**
- **Velocity weighted** (Einstein definition)

$$C_{tk} = \frac{1}{Uh}\int_0^h u c_{tk}\,dz \qquad q_{tk} = UhC_{tk}$$

  - Simpler formula for transport (advection term)
  - **Used in HEC-RAS 2D**
  - Coefficient in temporal term

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Total-load Transport Equation

- Unsteady Advection-Diffusion Coefficient

$$\underbrace{\frac{\partial}{\partial t}\left(\frac{hC_{tk}}{\beta_{tk}}\right)}_{\text{Temporal or Storage}}+\underbrace{\nabla\cdot\left(h\mathbf{U}C_{tk}\right)}_{\text{Advection}}=\underbrace{\nabla\cdot\left(\boldsymbol{\varepsilon}_{tk}h\nabla C_{tk}\right)}_{\text{Diffusion}}+\underbrace{E_{tk}}_{\text{Erosion}}-\underbrace{D_{tk}}_{\text{Deposition}}$$

k : Grain class
h : Water depth
C_{tk} : Total-load concentration
β_{tk} : Total-load correction factor
$\mathbf{U}$: Current velocity
$\boldsymbol{\varepsilon}_{tk}$: Total-load diffusion coefficient
E_{tk} : Total-load erosion rate
D_{tk} : Total-load deposition rate

- Simulating total-load instead of separate bed- and suspended-loads reduces computational costs because it requires half as many transport equations

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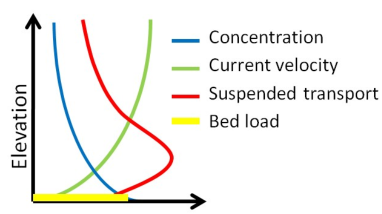
Load-Correction Factors

- Total-load Correction Factor

$$\beta_{tk}=\frac{1}{r_{sk}/\beta_{sk}+(1-r_{sk})/\beta_{sk}}$$

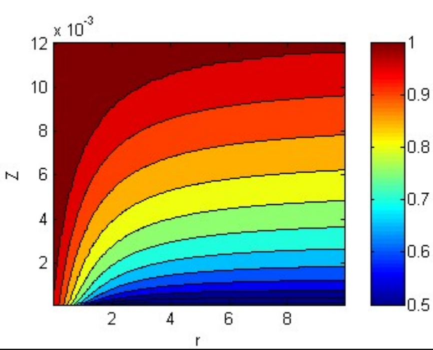
- Suspended-load

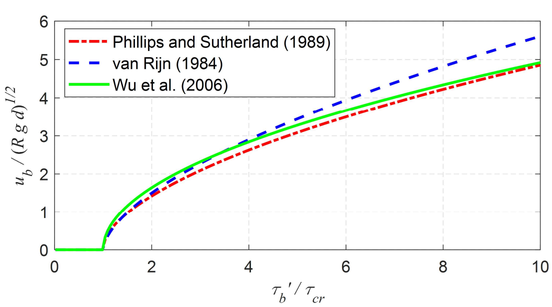
$$\beta_{sk}=\frac{\int_0^h uc_k dz}{UC_k}$$



- Bed-load

$$\beta_{bk}=\frac{u_{bk}}{U}$$





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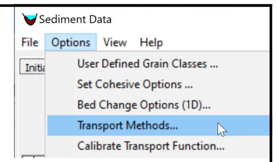
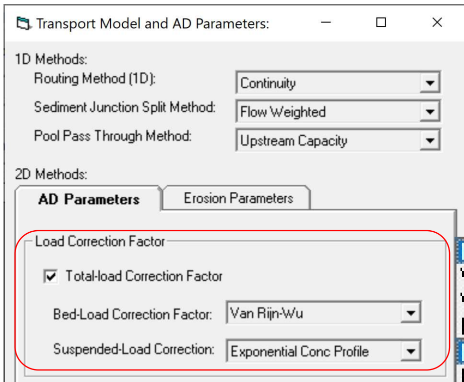
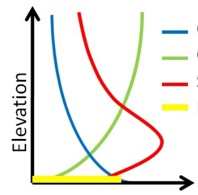
Total-Load Correction Factor







Transport equation

$$\frac{\partial}{\partial t}\left(\frac{hC_{tk}}{\beta_{tk}}\right)+\nabla\cdot(h\boldsymbol{U}C_{tk})=\nabla\cdot\left(\varepsilon_{tk}h\nabla C_{tk}\right)+E_{tk}-D_{tk}$$

$$\beta_{tk}=\frac{1}{r_{sk}/\beta_{sk}+(1-r_{sk})/\beta_{bk}}$$

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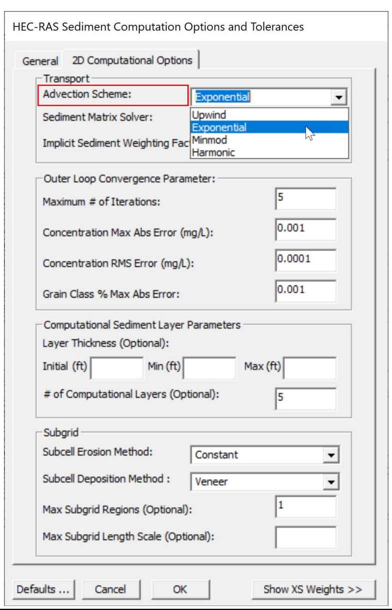
Advection Scheme



- Upwind
  - Most stable (and diffusive)
  - First order and Linear (no iterations)
- Exponential (Patankar 1980)
  - Based on 1D steady solution of Advection-Diffusion Equation
  - First Order and linear (no iterations)
- Minmod (Roe 1985)
  - TVD Flux Limiter
  - Second Order
  - Non-linear (requires iterations)
- Harmonic (van Leer 1977)
  - TVD Flux Limiter
  - Second Order
  - Non-linear (requires iterations)

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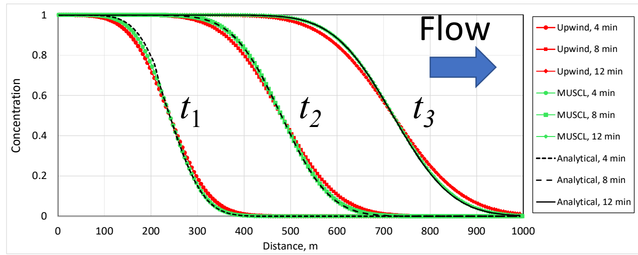
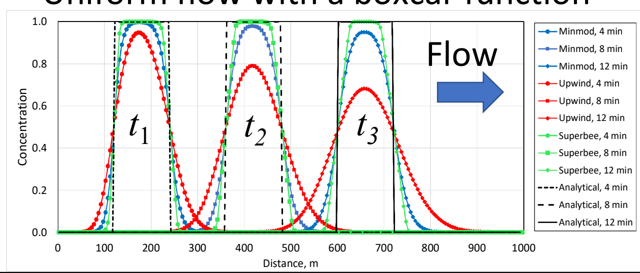
Verification: Advection and Diffusion

- Analytical Problems
  - Grid and time step convergence
  - Analysis of relative performance of difference schemes

Uniform flow with a step function



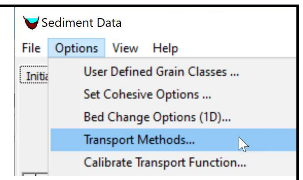
Uniform flow with a boxcar function

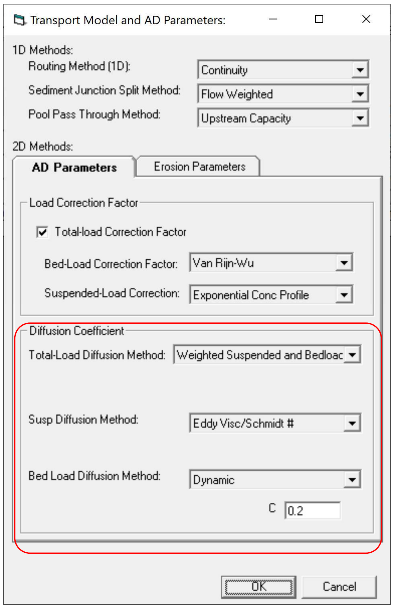


Advection Scheme Recommendations

- Default advection scheme is **Exponential**, which reduces to **Upwind** if no diffusion is included
- Never use **Upwind** scheme and **diffusion** at the same time as this will produce too much diffusion
- If model convergence is good, switch to **High-Resolution** (i.e. **Harmonic** and **Minmod**) schemes or better accuracy and compare
- If **High-Resolution** scheme results not significantly different, switch back to **Exponential** scheme
- Use suspended diffusion coefficient based on turbulent eddy viscosity

Diffusion Coefficient

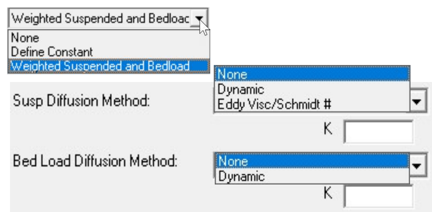




Transport equation

$$\frac{\partial}{\partial t}\left(\frac{hC_{tk}}{\beta_{tk}}\right)+\nabla\cdot(h\boldsymbol{U}C_{tk})=\nabla\cdot(\varepsilon_{tk}h\nabla C_{tk})+E_{tk}-D_{tk}$$

- Accounts for:
  - Turbulent mixing
  - Dispersion
- **Dynamic** requires a coefficient



$$\varepsilon_{sk}=K_s u_* h$$

$$\varepsilon_{bk}=K_B u'_* d_k$$

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Notes on Diffusion Coefficients

- More important for fine sediments
  - Coarse sediments interact more with the bed and net dispersion is dominated by bed storage effect
- More important for fine resolution models
  - Coarse resolution models have more numerical diffusion
- Recommendations
  - Total-load: Weighted approach
  - Suspended load: Eddy viscosity approach
  - Bed-load: Negligible

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Thank You!

HEC-RAS Website:
https://www.hec.usace.army.mil/software/hec-ras/

Online Documentation:
https://www.hec.usace.army.mil/confluence/rasdocs

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