EXAMPLE OF SEDIMENT TRANSPORT MODELING IN A RIVER USING HEC-RAS

A. I. Stamou, NTUA, January 2019

Sediment modeling using HEC-RAS

- ✓ It models sediment transport.
- ✓ It can route sediment and adjust channel cross-sections in response to sediment dynamics.
- ✓ It couples sediment transport computations with quasi-unsteady hydraulics that is used only in sediment studies.

EXAMPLE

Calculate the change of bed elevation in a river for a period of 7 days for the data that are shown below.

<u>RIVER DATA</u>

Geometry	Trapezoidal -
Bottom width	4.50 m
Height	15.00 m
Side slope (hor/ver)	1/10 -
Top width	7.50 m
Length	300.0 m
Slope	0.0005 -
Flow rate	50.00 m^3/s
Manning	0.030
Temperature	20.0 ^oC

<u>SEDIMENT DATA</u>

Material – Gradation curve; Coarse sand

Fine sand (0.5 mm): 0 % and Coarse sand (1.0 mm): 100 %

Sediment Transport Function: Yang

Equation for calculating fall velocity: Rubey

Bed sorting method: Thomas

Mobile bed channels=1; Max (erosion) depth=3.0 m

Rating Curve for Upstream Cross Section

For flow rate= 1 m^3/s -> Sediment load = 24 t/day

For flow rate= 50 m^3/s -> Sediment load = 2000 t/day

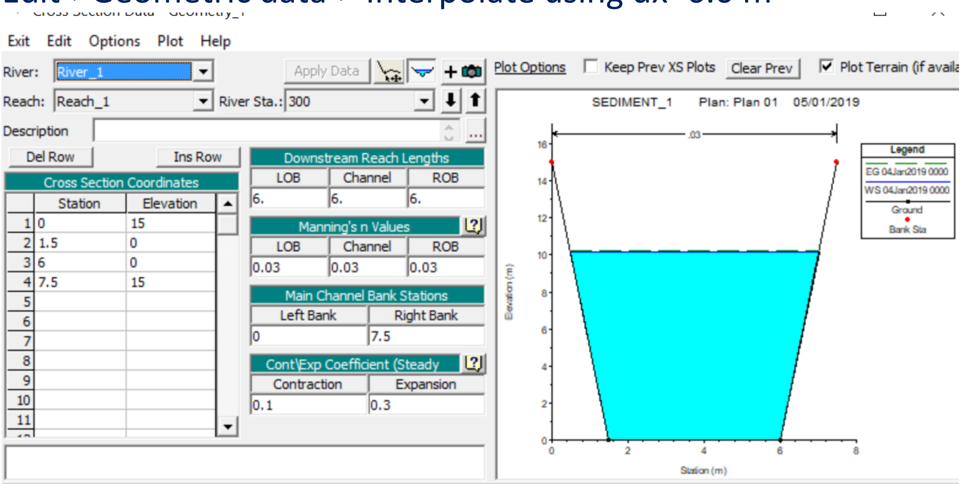
STEPS OF THE CALCULATION PROCEDURE

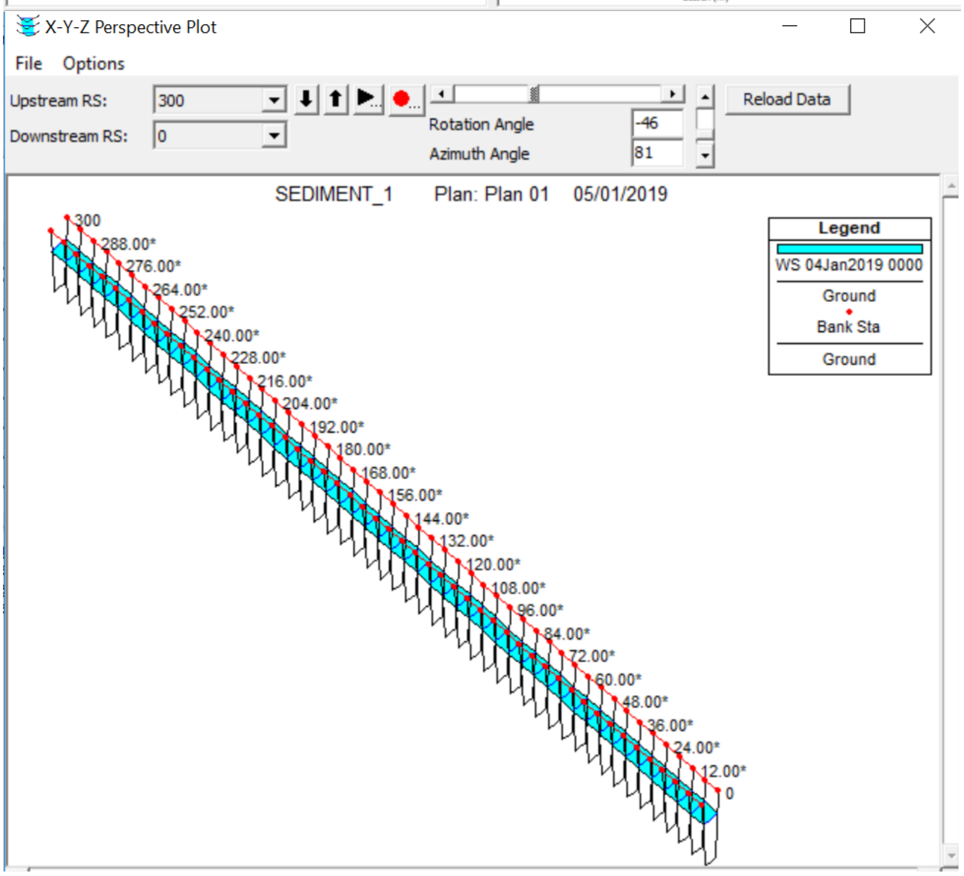
New project: **SEDIMENT_1**

Step 1: Construction of the geometry – Geometric Data

River Reach->River_1->Reach_1

Edit->Geometric data-> Interpolate using dx=6.0 m

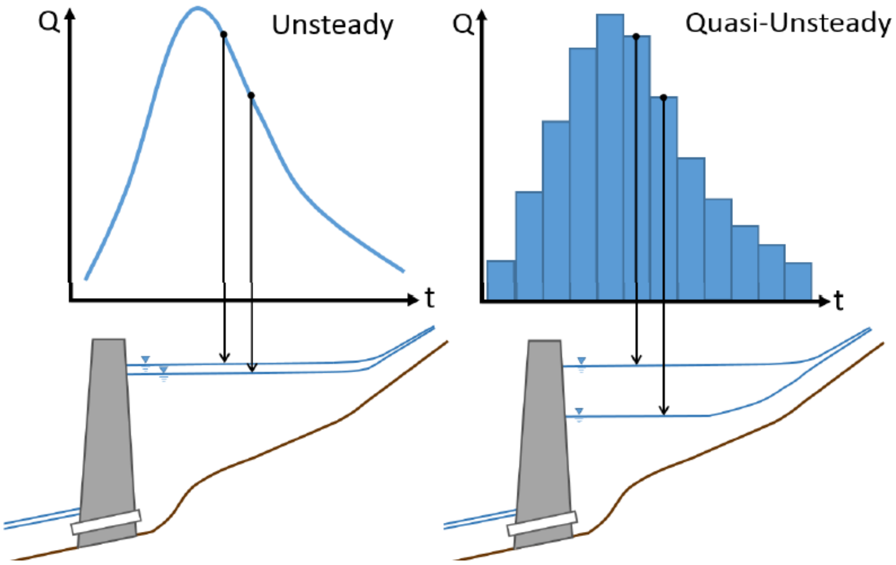




Save: **Geometry_1**

Step 2: Quasi-Unsteady Flow

2.1 Unsteady vs. quasi-unsteady flow analysis (Gibson et al., 2017)



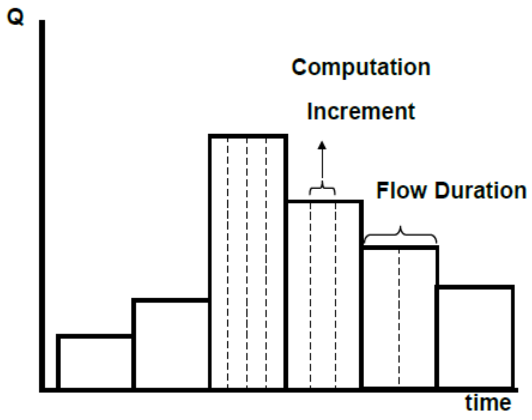
Unsteady flow

- ✓ It conserves water volume, making reservoir models much more viable, especially mid-model reservoirs and even reservoir cascades.
- ✓ It connects sediment transport to the unsteady flow model.

Quasi-unsteady flow

- ✓ It is often an acceptable sediment transport simplification.
- ✓ It does not conserve flow, which can distort results in systems with substantial storage (see Figure).
- ✓ It does not retain any hydrologic "memory" of previous time steps.
- ✓ It computes water volumes that are not contingent on the volume from previous times step; therefore, water can move in and out of storage without physical constraints. <u>Use small dt's (can improve in some cases).</u>
- ✓ It can compute egregious water surface changes in n systems with significant storage, particularly reservoirs (see Figure).
- ✓ It can also distort hydraulics in large river models - which are common 1D applications – immediately enforcing the upstream flow throughout the reach, instead of routing it.
- ✓ It is more stable; unsteady models can be unstable.
- ✓ It does not require specialized expertise like unsteady flow modelling that usually requires skilful trouble shooting by experienced practitioners.
- ✓ It is easier to use (e.g. movable cross-sections).
- ✓ It can be faster under certain conditions.

2.2 Time steps (HEC Reference manual; Chapter 13)



Flow Duration (FD)

- ✓ Coarsest time step
- ✓ Flow, stage, temperature and sediment are constant.

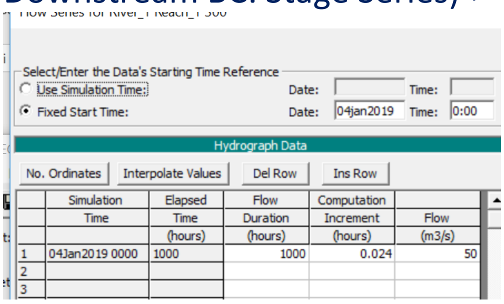
Computational Increment (CI)

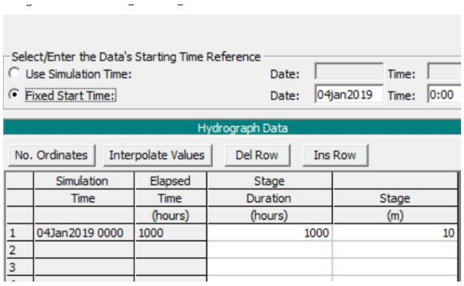
- ✓ Primary quasi-unsteady hydraulic and sediment time step.
- ✓ Subdivides FD.
- ✓ Bed geometry and hydrodynamics are updated after each CI.
- ✓ When cross sections change (especially rapidly) hydraulic parameters that depend on sediments also change. This may lead to unreasonable deposition or erosion and thus may cause instability; <u>the model may crash!</u>

Bed Mixing Time Step (BMTS)

- ✓ Composition of bed mixing layers (active, cove, inactive) is updated during BMTS, since it can evolve very quickly during each CI.

Upstream BC: Flow Series (only)-> We use FD=1000 h and CI=0.024 h
Downstream BC: Stage Series)-> We use same FD and <u>Stage=10.0 m</u>





Note: We can use variable FD
Small at high flow rates and high for low flow rates!

Temperature=20°C
Save: **Quasi_Unsteady_1**

Step 3: Sediment Data

3.1 Sediment continuity – Exner equation (HEC Reference Manual; Chapter 13)

$$(1-\lambda_P)B\frac{\partial \eta}{\partial t} = -\frac{\partial Q_s}{\partial x}$$

where:

- B = channel width
- η = channel elevation
- λ_p = active layer porosity
- t = time
- x = distance
- Q_s = transported sediment load

Like most continuity equations, the Exner equation simply states that the difference between sediment entering and leaving a control volume must be stored or removed from storage. The unique feature of the Exner equation is that sediment storage is stored in the bed in a multi-phase mixture with water, requiring porosity to translate mass change into volume change. The Exner equation translates the difference between inflowing and outflowing loads into bed change, eroding or depositing sediment.

HEC-RAS solves the sediment continuity equation by computing a sediment transport capacity for control volume ($Q_{s\text{-}out}$) associated with each cross section, comparing it to the sediment supply ($Q_{s\text{-}in}$) entering the control volume from the upstream control volume or loacal sources (e.g. lateral sediment loads). If capacity is greater than supply, HEC-RAS satisfies the deficit by eroding bed sediments. If supply exceeds capacity, HEC-RAS deposits the sediment surplus.

3.2 Sediment transport capacity (HEC Reference manual; Chapter 13)

RHS of the Exner equation = Sediment gradient along a control volume

$$\frac{\partial Q_s}{\partial x} = Q_{s,in} - Q_{s,out}$$

$Q_{s,in}$ = easy to calculate

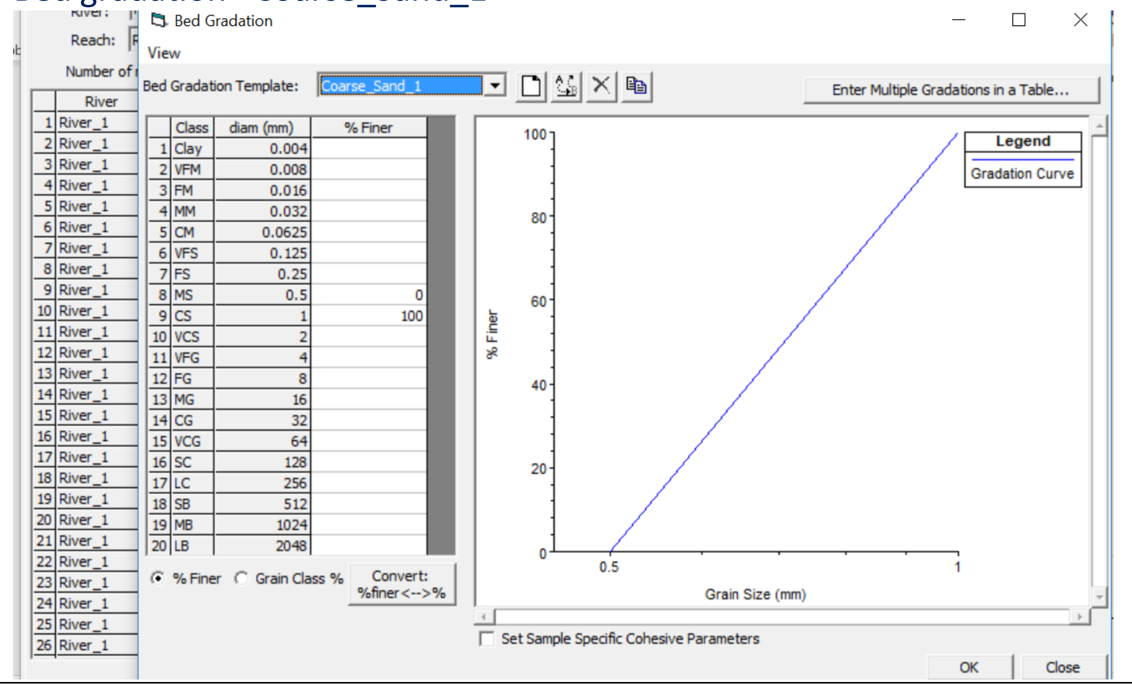
$Q_{s,out}$ = more difficult to calculate; it is a complex function of hydrodynamics and sediment properties

Sediment transport capacity of the control volume = maximum sediment can be transported by grain sizes

3.3 Grain sizes (HEC Reference Manual; Chapter 13) – Define/Edit bed gradation

- ✓ Sediment material is divided in multiple grain classes.
- ✓ Default: 20 grain classes.

Bed gradation= Coarse_Sand_1



3.4 Sediment Transport Potential – Sediment Transport Functions (STFs)

- ✓ SFT: An empirical equation that simply translates hydrodynamics into transport.
- ✓ Majority of STFs: Were developed for a single grain class.
- ✓ In HEC-RAS: There are 8 STFs; we need to choose the one of similar gradation; see Appendix E of the Manual.
- ✓ HEC-RAS firstly computes transport potential to each grain class and then calculates transport capacity multiplying by the percentage of each calls in the bed.

3.5 Example: Yang; see Hydraulic Reference Manual Appendix E-20

Yang Sediment Transport Function

by Yang, from ASCE Journal of Hydraulics, Oct 1973, Dec 1984

Input Parameters

Temperature, F	T = 55	Average Velocity, ft/s	V = 5.46
Kinematic viscosity, ft²/s	ν = 0.00001315	Discharge, ft³/s	Q = 5000
Hydraulic Radius, ft	R = 10.68	Unit Weight water, lb/ft³	γ_w = 62.385
Slope,	S = 0.0001		
Meidan Particle Diamter, ft	d_{si} = 0.00232		
Specific Gravity of Sediment		s = 2.65	

Constants

Acceleration of gravity, ft/s² g = 32.2

Solution

Shear Velocity, ft/s,

$$u_* = \sqrt{g \cdot R \cdot S} \qquad u_* = 0.185$$

Particle Fall Velocity, ft/s,

Use Rubey's equation, Vanoni p. 169

$$F_1 = \sqrt{\frac{2}{3} + \frac{36 \cdot \nu^2}{g \cdot d_{si}^{\ 3} \cdot (s-1)}} - \sqrt{\frac{36 \cdot \nu^2}{g \cdot d_{si}^{\ 3} \cdot (s-1)}}$$

F_1 = 0.725

$$\omega = F_1 \cdot \sqrt{(s-1) \cdot g \cdot d_{si}} \qquad \omega = 0.255$$

Shear Reynold's Number,

$$R_s = \frac{u_* \cdot d_{si}}{\nu} \qquad R_s = 32.717$$

Critical Velocity, ft/s,

E-20

$$V_{cr} = \begin{cases} \omega \cdot \left(\dfrac{2.5}{\log\left(\dfrac{u_* \cdot d_{si}}{\nu}\right) - 0.06} + 0.66 \right) & \text{if } 0 < R_* < 70 \\ (\omega \cdot 2.05) & \text{if } R_* \geq 70 \end{cases}$$

$V_{cr} = 0.606$

Log of Concentration,

$$\log C_t = \begin{cases} \left[5.435 - 0.286 \cdot \log\left(\dfrac{\omega \cdot d_{si}}{\nu}\right) - 0.457 \cdot \log\left(\dfrac{u_*}{\omega}\right) \ldots \\ + \left(1.799 - 0.409 \cdot \log\left(\dfrac{\omega \cdot d_{si}}{\nu}\right) - 0.314 \cdot \log\left(\dfrac{u_*}{\omega}\right)\right) \cdot \log\left(\dfrac{V \cdot S}{\omega} - \dfrac{V_{cr} \cdot S}{\omega}\right) \right] & \text{if } d_{si} < 0.00656 \quad \text{Sand} \\ \left[\left(6.681 - 0.633 \cdot \log\left(\dfrac{\omega \cdot d_{si}}{\nu}\right) - 4.816 \cdot \log\left(\dfrac{u_*}{\omega}\right)\right) \ldots \\ + \left(2.784 - 0.305 \cdot \log\left(\dfrac{\omega \cdot d_{si}}{\nu}\right) - 0.282 \cdot \log\left(\dfrac{u_*}{\omega}\right)\right) \cdot \log\left(\dfrac{V \cdot S}{\omega} - \dfrac{V_{cr} \cdot S}{\omega}\right) \right] & \text{if } d_{si} \geq 0.00656 \quad \text{Gravel} \end{cases}$$

$\log C_t = 1.853$

Concentration, ppm

$$C_t = 10^{\log C_t}$$

$C_t = 71.284$

Sediment Discharge, lb/s

$$G = \frac{\gamma_w \cdot Q \cdot C_t}{1000000}$$

$G = 22.235$

Sediment Discharge, tons/day

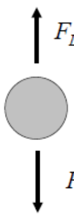
$$G_s = \frac{86400}{2000} \cdot G$$

$G_s = 961$

3.6 Fall Velocity

- ✓ <u>Very important!</u>
  Sediment particle starts to suspend when
  bed-level shear velocity -> fall velocity
  Sediment remains in suspension when
  vertical component of bed-level turbulence > fall velocity
  Also: depends on shape factor (sf)
- ✓ Calculation: Gravitational Force=Drag Force

$$F_D = \frac{1}{2}\pi\rho c_D\left(\frac{D}{2}\right)^2 v_s^2$$



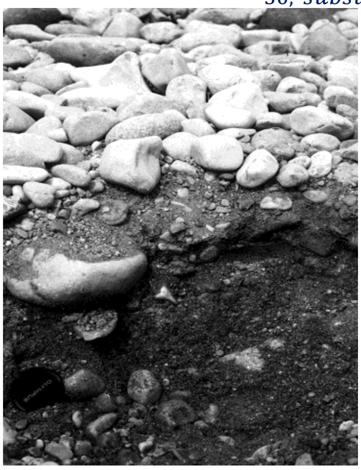
$$F_g = \frac{4}{3}\pi\rho R g\left(\frac{D}{2}\right)^3$$

- ✓ In HEC-RAS: There are 3 methods to select.

3.7 Bed Sorting Method

- ✓ STFs compute transport potential without accounting for what's available. The bed sorting method (mixing / armoring method) keeps track of bed gradation that HEC-RAS uses to compute specific transport capacities and simulate armoring process which regulates supply, i.e. it takes into account the there is a potential supply limitation as a result of bed mixing processes.
- ✓ Armoring occurs when the bed surface of gravel-bed rivers is coarsened relative to the sub-surface.
- ✓ Degree of armoring can be described by the armor ratio

Armor ratio= $\frac{D_{50,surface}}{D_{50,\ subsurface}}$ >1 when armoring present.



Wilcock (2005)

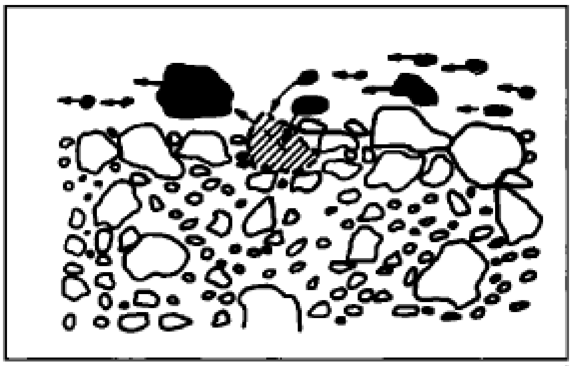


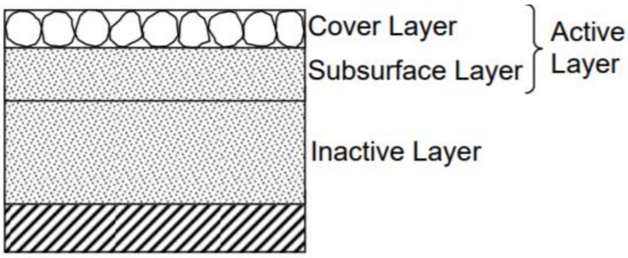
Fig. 10. Schematization of vertical winnowing of fine particles.

Curran & Tan (2010)

✓ Armoring process (Hanson & Koutsunis)

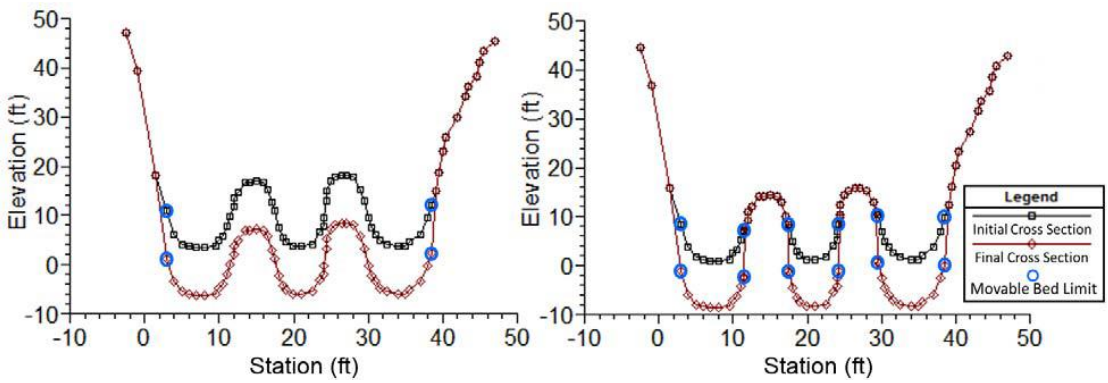
1) Flow develops shear stresses less than required to move large particles, but large enough to move fines.
2) Flow entrains fine particles, winnowing them from bed surface.
3) Coarse layer forms, sheltering fine grains (precluding erosion).
4) Coarse layer increases resistance to entrainment.

✓ In HEC-RAS 3 methods; in all methods two layers: active and inactive. Exner 5: to compute bed sorting mechanisms.

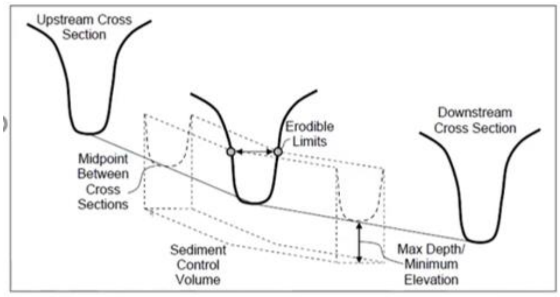


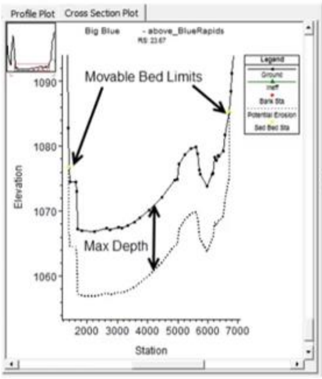
✓ Bed coarsening is simulated by removing fines initially from a thin cover layer. During each time step, the composition of this cover layer is evaluated and if, according to a rough empirical relationship, the bed is partially or fully armored, the amount of material available to satisfy excess capacity can be limited.

3.8 Movable Bed Limits (multiple) and Maximum Depth (Gibson et al., 2017)



Multi-channel erosion simulated with a single set of movable bed limits (left) and multiple movable bed limits (right). The multiple movable bed limits restrict erosion (or all bed change, if specified) to the channels (e.g. for vegetated inter-channel islands).



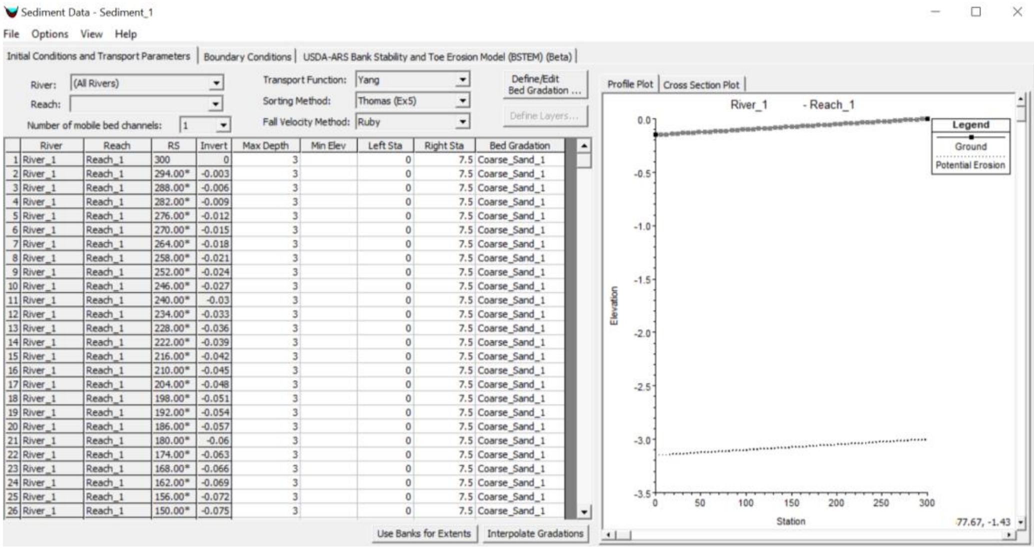


Initial conditions and transport parameters

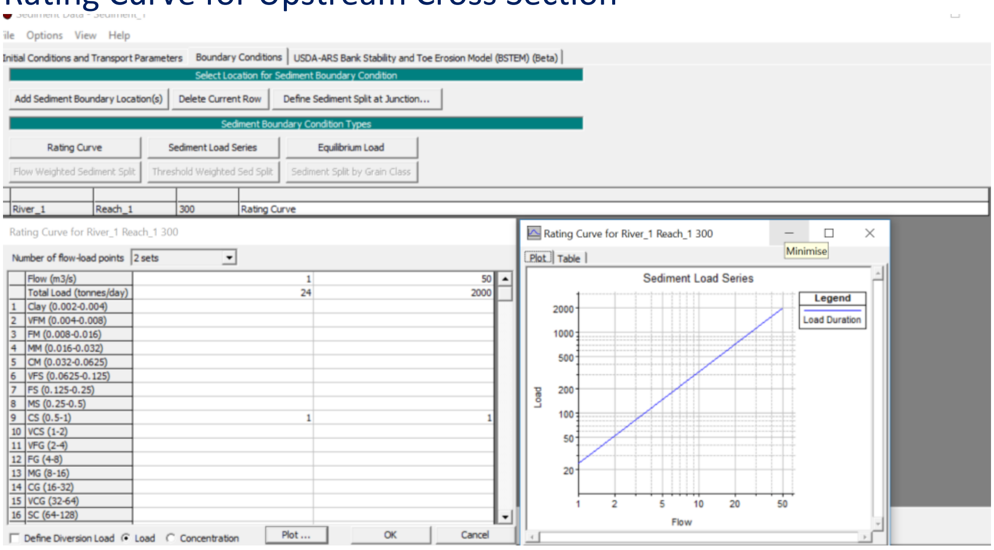
Mobile bed channels=1; Max (erosion) depth=3.0 m;

Transport function = Yang; Sorting method= Thomas;

Fall velocity method=Ruby;

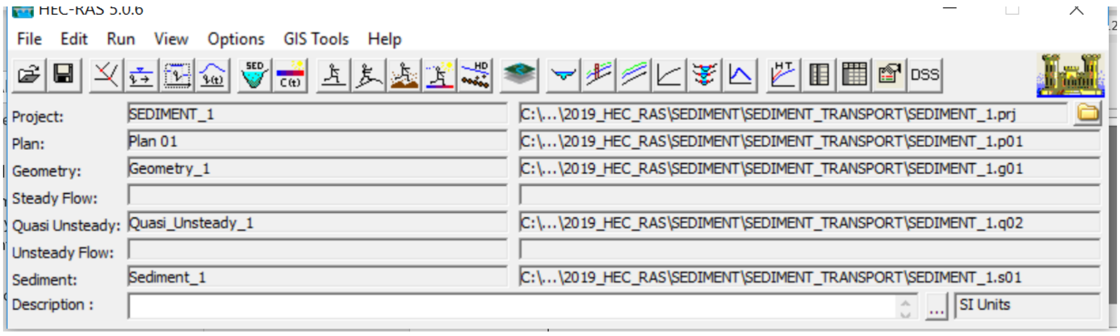


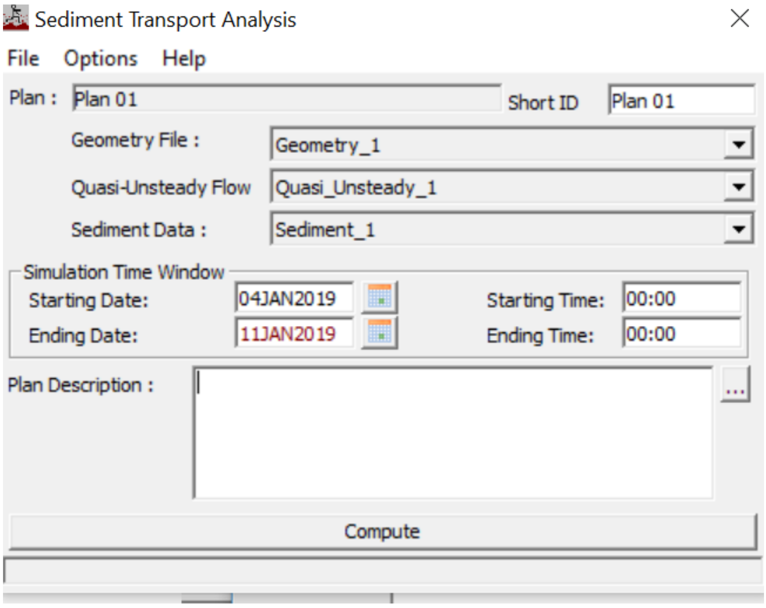
Rating Curve for Upstream Cross Section

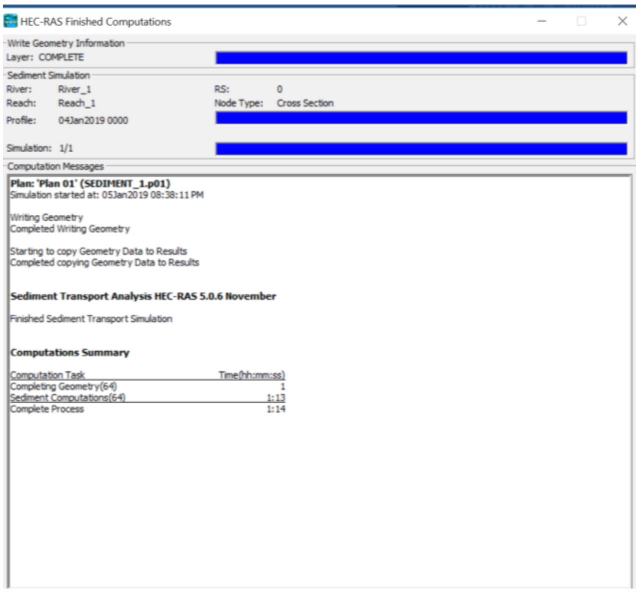


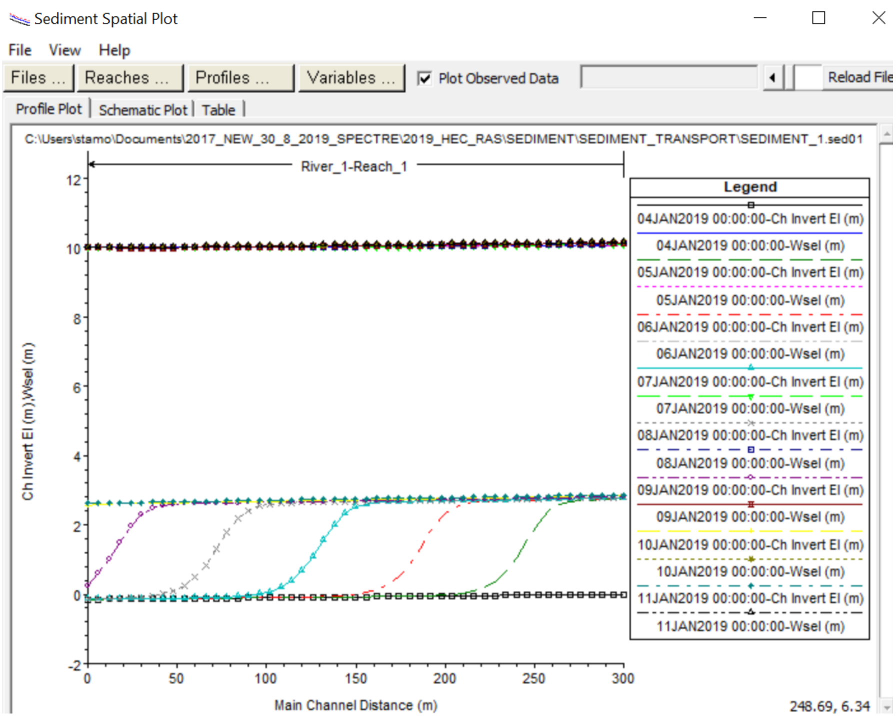
Save: **Sediment_1**

Step 4: Perform Sediment Transport Analysis for 7 days









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