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

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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 quasiunsteady 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.

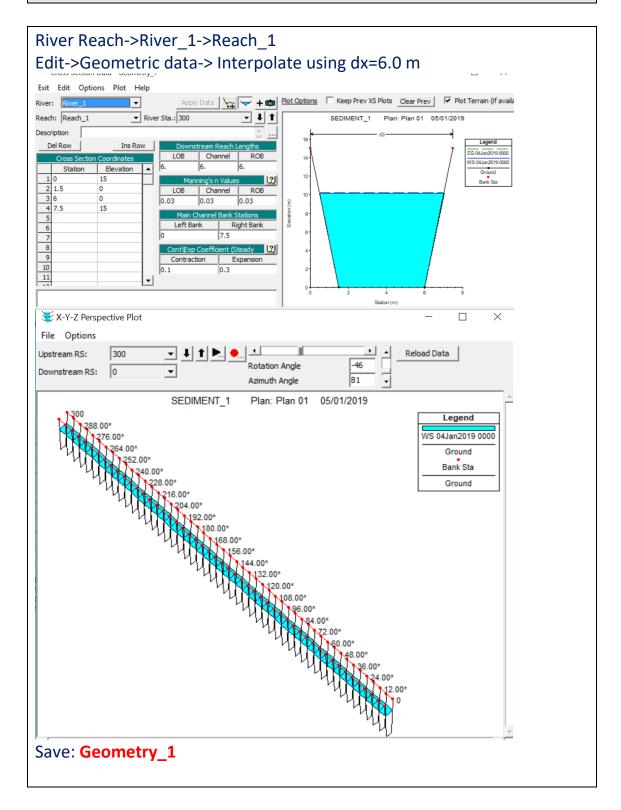
RIVER DATA

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 °C
SEDIMENT DATA	
Material – Gradation cur	ve; Coarse sand
Fine sand (0.5 mm	i): 0 % and Coarse sand (1.0 mm): 100 %
Sediment Transport Fun	ction: Yang
Equation for calculating	fall velocity: Rubey
Bed sorting method: The	omas
Mobile bed channels=1;	Max (erosion) depth=3.0 m
Rating Curve for Upstrea	Im 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

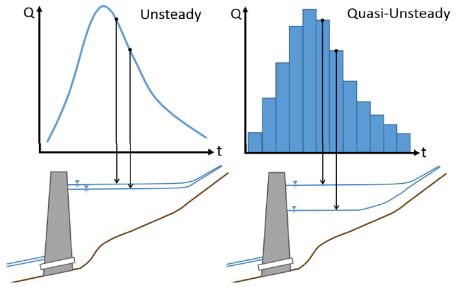
New project: **SEDIMENT_1**

Step 1: Construction of the geometry – Geometric Data



Step 2: Quasi-Unsteady Flow

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



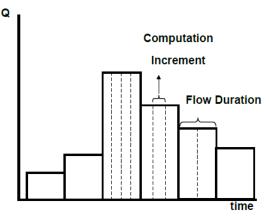
Unsteady flow

- ✓ It conserves water volume, making reservoir models much more viable, especially mid-model reservoirs and even reservoir cascades.
- \checkmark 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</u> <u>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)

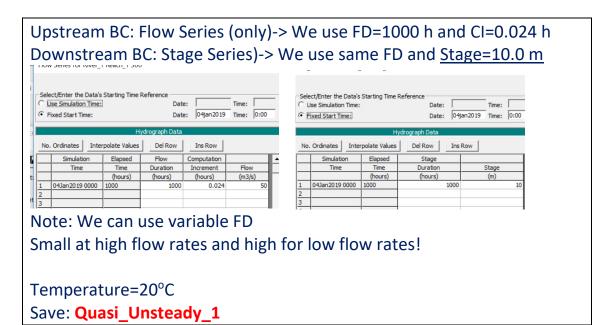
- ✓ Coarsest time step
- ✓ Flow, stage, temperature and sediment are constant.

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.



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:

- η = channel elevation
- λ_p = active layer porosity

t = time

x = distance

Qs = 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 multiphase 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-out}) associated with each cross section, comparing it to the sediment supply (Q_{s-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.
- Bed gradation = Coarse_Sand 1 🖏 Bed Gradation \times Reach: View Number of Bed Gradation Template: Coarse_Sand_1 II 🗋 🏠 🖿 🖻 Enter Multiple Gradations in a Table. River River_1 Class diam (mm) % Finer 100 2 River_1 Legend 1 Clay 0.004 3 River_1 2 VFM 0.008 Gradation Curve 4 River_1 3 FM 0.016 5 River_1 4 MM 0.032 80 6 River_1 5 CM 0.0625 7 River_1 6 VFS 0.125 8 River_1 7 FS 0.25 9 River_1 8 MS 0.5 60 10 River_1 9 CS 100 % Finer 11 River_1 10 VCS 11 VFG 12 River_1 4 13 River_1 14 River_1 12 FG 8 40 13 MG 16 15 River_1 14 CG 32 16 River_1 15 VCG 64 17 River_1 18 River_1 16 SC 128 20 17 LC 256 19 River_1 18 SB 512 20 River_1 19 MB 20 LB 1024 21 River_1 2048 22 River_1 23 River_1 24 River_1 % Finer C Grain Class % Convert: %finer<-->% Grain Size (mm) 25 River_1 🗍 Set Sample Specific Cohesive Parameters 26 River_1 OK Close
- ✓ Default: 20 grain classes.

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 Se	ediment Transp	ort Function	
by Yang	, from ASCE Jouri	nal of Hydraulics, Oct 197	'3, Dec 1984
Input Parameters			
Temperature, F	T = 55	Average Velocity, ft/s	V = 5.46
Kinematic viscosity, ft²/s	$\nu = 0.00001315$	Discharge, ft³/s	Q = 5000
Hydraulic Radius, ft	R = 10.68	Unit Weight water, Ib/ft ³	$\gamma_w = 62.385$
Slope,	S = 0.0001		
Meidan Particle Diamter, ft	d _{si} = 0.00232		
Specific Gravity of Sedimer	nt	s = 2.65	
Constants			
Acceleration of gravity, ft/s	²g = 32.2		
Solution			
Shear Velocity, ft/s,			
$u_* = \sqrt{g \cdot R \cdot S}$			u _* = 0.185
Particle Fall Velocity, ft/s,			
Use Rubey's equation,	Vanoni p. 169		
$F_{1} = \sqrt{\frac{2}{3} + \frac{36 \cdot v^{2}}{g \cdot d_{s}^{3} \cdot (s-1)}}$ $F_{1} = 0.725$	$\frac{1}{1} - \sqrt{\frac{36 \cdot v^2}{g \cdot d_{si}^3 \cdot (s-1)}}$	- <u>)</u>	
F1 - 0.720			
$\omega = F_1 \cdot \sqrt{(s-1) \cdot g \cdot d_{si}}$			<i>ω</i> = 0.255
Shear Revnold's Number			

Shear Reynold's Number,

Critical Velocity, ft/s,

E-20

Appendix E Sediment Transport Functions-Sample Calculations

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

Log of Concentration,

$$\log C_{t} = \begin{bmatrix} 5.435 - 0.286 \cdot \log\left(\frac{\omega \cdot d_{u}}{\nu}\right) - 0.457 \cdot \log\left(\frac{u_{\star}}{\omega}\right) \\ + \left(1.799 - 0.409 \cdot \log\left(\frac{\omega \cdot d_{u}}{\nu}\right) - 0.314 \cdot \log\left(\frac{u_{\star}}{\omega}\right)\right) \cdot \log\left(\frac{V \cdot S}{\omega} - \frac{V_{\sigma} \cdot S}{\omega}\right) \end{bmatrix} & \text{if } d_{u} < 0.00656 \quad \text{Sand} \\ \begin{bmatrix} 6.681 - 0.633 \cdot \log\left(\frac{\omega \cdot d_{u}}{\nu}\right) - 4.816 \cdot \log\left(\frac{u_{\star}}{\omega}\right) \\ + \left(2.784 - 0.305 \cdot \log\left(\frac{\omega \cdot d_{u}}{\nu}\right) - 0.282 \cdot \log\left(\frac{u_{\star}}{\omega}\right) \right) \cdot \log\left(\frac{V \cdot S}{\omega} - \frac{V_{\sigma} \cdot S}{\omega}\right) \end{bmatrix} & \text{if } d_{u} \geq 0.00656 \quad \text{Gravel} \\ \end{bmatrix}$$

 $\log C_t = 1.853$

Concentration, ppm

$$C_t = 10^{\log C_t}$$
 $C_t = 71.284$

Sediment Discharge, Ib/s

$$G = \frac{\gamma_{w} \cdot Q \cdot C_{i}}{1000000} \qquad \qquad G = 22.235$$

Sediment Discharge, tons/day

$$G_s = \frac{86400}{2000} \cdot G$$
 $G_s = 961$

3.6 Fall Velocity

✓ Very important!

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

$$\int F_D = \frac{1}{2} \pi \rho c_D \left(\frac{D}{2}\right)^2 v_s^2$$
$$\int F_g = \frac{4}{3} \pi \rho Rg \left(\frac{D}{2}\right)^3$$

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

3.7 Bed Sorting Method

- \checkmark 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.
- \checkmark 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= $\frac{D_{50,5ul}}{D_{50,subsurface}}$ $\frac{D_{50,surface}}{1}$ >1 when armoring present.





Wilcock (2005)

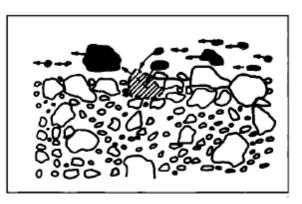
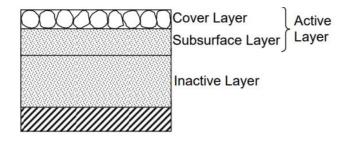


Fig. 10. Schematization of vertical winnowing of fine particles.

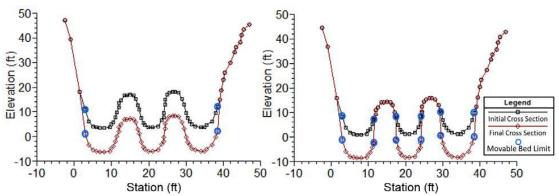
Curran & Tan (2010)

- ✓ 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.

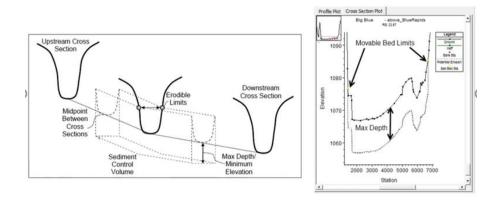


✓ Bed coarsening is simulated by removing fines initially from a thin cover layer. During each time step, the composition of this cover layer is evaluated and if, according to a rough empirical relationship, the bed is partially or fully armored, the amount of material available to satisfy excess capacity 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; V Sediment Data - Sediment × Options View Help ions and Transport Paran Model (BSTEM) (Beta) ns USDA-ARS Bank Sta Transport Function: Yang (All Rivers) -Define/Edit Bed Gradation • Profile Plot Cross Section Plot Thomas (Ex5 Sorting Method: Ŧ Reach: • River_1 - Reach 1 1 Fall Velocity Method: Ruby ٠ 0.0 Number of m bile bed channels: • Ground RS Invert Max Depth Min Elev Left Sta Right Sta Bed Gradation 300 0 3 0 7.5 Coarse_Sand_1 Reach Rive iver_1 each_1 300 294.00* 288.00* 282.00* 276.00* 270.00* 264.00* -0.5 ver_1 each_1 each_1 -1.0 264.00* 258.00* 252.00* 246.00* 240.00* 234.00* 228.00* liver_ ver_1 Elevation ver_ -2.0 -2.5 -30 each_1 each_1 each_1 each_1 ach_1 ach_1 7.5 Coarse_Sand_1 7.5 Coarse_Sand_1 150 • Station 77.67, -1.43 Use Banks for Extents Interpolate Grad Rating Curve for Upstream Cross Section and Transport Parameters Boundary Conditions USDA-ARS Bank Stability and Toe Erosion Model (BSTEM) (Beta) n(s) Delete Current Row Define Sec ent Split at Junction... ndary Local Rating Curve nt Load Series Equilibrium Load Sedin Rating Curve for River_1 Reach_1 300 — Minin r of flow-load points 2 sets Plot. Table 50 2000 nent Load Series Flow (m3/s) Total Load (tor 1 24 Legend 200 Load Duration 100 50 20 oad. 100

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Step 4: Perform Sediment Transport Analysis for 7 days

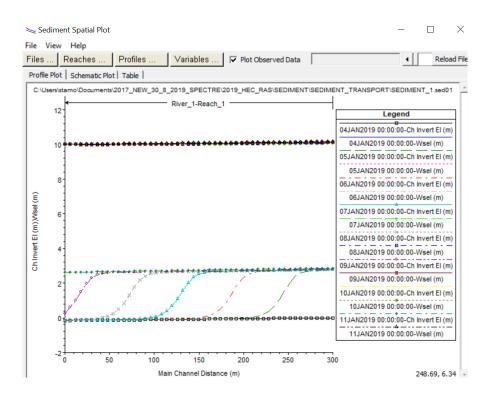
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REFERENCES

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