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Modeling 1D Floodplain Deposition in HEC-RAS with a Rouse-Diffusion Algorithm: An Alternative to Veneer in the Floodplain

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PURPOSE: One-dimensional sediment transport models struggle with floodplain processes. But floodplain deposition affects regional sediment budgets and RSM strategies. This Tech Note describes a new 1D morphodynamic algorithm that improves floodplain deposition estimates and presents the interface and sample results from its implementation as in HEC-RAS version 6.2.

INTRODUCTION: One-dimensional (1D) morphodynamic models are particularly useful for evaluating Regional Sediment Management (RSM) strategies and alternatives. The scale and runtime of 1D models allows analysts to build large regional models and encourages project teams to imagine and evaluate regional alternatives. However, 1D morphodynamic models often simulate floodplain deposition poorly. If floodplain deposition is a substantial component of a regional sediment budget, 1D sediment models can generate unrealistic results that require awkward and labor-intensive workarounds. For example, Gibson and Shelley (2020) demonstrated that the Missouri river deposited approximately the same volume in the floodplain as it scoured from the channel during the 2011 flood, making floodplain deposition a critical component of the sediment budget. But the classic 1D modeling methods were unstable with the wide Missouri floodplains, requiring *ad hoc* modeling methods that were difficult to generalize. The RSM effort described in this tech note added new floodplain deposition algorithms to HEC-RAS, the Corp’s 1D hydraulic and morphodynamic model, which is commonly used for riverine RSM and RSM-type studies (Shelley, 2021, Creech et al., 2018, Gibson et al, 2017, Gibson and Boyd, 2016).

LIABILITIES OF CLASSIC FLOODPLAIN DEPOSITION IN 1D MODELS:

Most 1D morphodynamic models follow the HEC6 convention (USACE, 1993) of simulating floodplain deposition with the “veneer method”. One-Dimensional sediment models compute bulk erosion or deposition volumes for each cross section. These models then change the shape of the cross section in response to erosion or deposition, by raising or lowering the cross-section nodes. The veneer method makes the simplest assumption that all wet nodes within the movable bed limits are raised or lowered an equal distance to account for the erosion or deposition volume. The veneer method usually works relatively well in the river channel but extending this method to the floodplain introduces complications.

HEC-RAS computes floodplain deposition in the same manner as HEC6 and 6T, which did not erode or deposit in the floodplains by default. Users can choose to apply the veneer method to floodplain deposition, but these models never erode outside the movable bed limits.

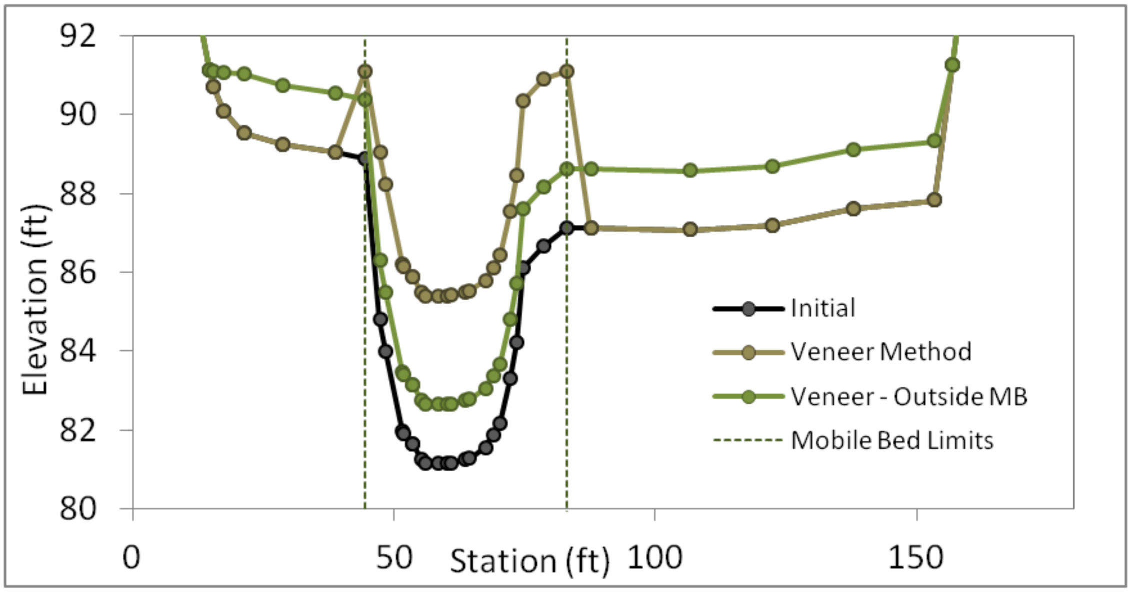


Figure 1: Veneer method results (from the HEC-RAS manual). The brown line (default) limits deposition to the channel, under predicting floodplain deposition, over predicting channel deposition, generating an unlikely cross section shape, and often making the model unstable. The green line extends the veneer method to the floodplain, which usually over predicts floodplain deposition, reducing the sediment available for the channel, which can also make the model inaccurate and unstable.

Gibson and Nelson (2017) demonstrated how the 1D veneer method can sometimes replicate unusual floodplain dynamics. But, excluding bed change in the floodplain usually under predicts floodplain deposition and allowing veneer deposition in the floodplain usually overpredicts floodplain deposition. In most cases, these issues affect the model accuracy. In some cases, ignoring floodplain deposition or over depositing with the veneer method alters the sediment budget enough that it will make the model unstable. Over or under predicting floodplain deposition can cause the numerical channel to fill or scour.

Modelers need a middle-way option, between the often-unhelpful end members of ignoring floodplain deposition altogether or over-predicting it with the veneer method. This work developed a set of algorithms that use physical processes to approximate floodplain deposition more realistically.

METHOD:

Real rivers deposit less sediment in the floodplain than the veneer method for three reasons:

1. Sediment transported in the channel is concentrated at the bottom of the channel and is not all available for floodplain deposition.
2. Sediment rarely transports or deposits across the whole wet floodplain. Floodplain deposits are often concentrated near the channel, sometimes forming natural levee features.
3. The sediment that does make it onto the floodplain is much finer than the bulk transportable gradation. These grain classes take much longer to settle and do not necessarily deposit in the time the floodplain is inundated.

This RSM project added a Rouse-Diffusion method to HEC-RAS which account for all three limitations. This Rouse-Diffusion method computes floodplain deposition with five steps:

Step 1: Compute "Floodplain Available" Concentration and Grain Classes

The first step in the Rouse-Diffusion floodplain deposition method addresses the first – and usually most egregious – liability of the veneer method. This method uses the Rouse (1937) distribution to compute the concentration of each grain class in the portion of the water column above the bank station, which is the fraction of the sediment in that grain class available for floodplain deposition. For example, if the river does not lift any cobbles above the channel banks, no cobble mass should deposit in the floodplain. The Rouse approach to computing the Floodplain Available Concertation (C_{fp}) is illustrated in Figure 2.

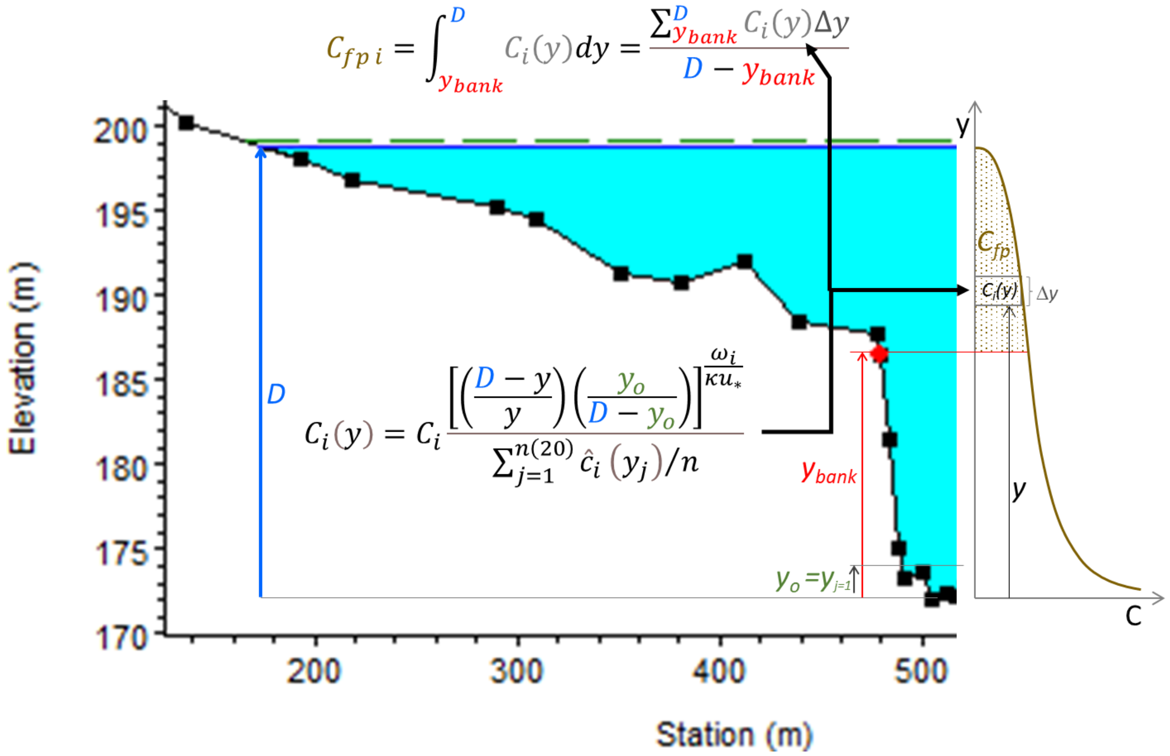


Figure 2 – HEC-RAS uses the Rouse equation to distribute the mass flux vertically, and then integrates the available mass for each grain class above the bank station, finding the concentration of each grain class available to move into the floodplain and deposit here.

Most models that compute vertical concentration with the Rouse distribution use an externally computed or measured reference concentration (C_o), the maximum concentration near the bottom of the water column. This algorithm inverts that approach. HEC-RAS already calculates the total mass transported by the model; it only uses the Rouse equation to distribute it vertically. Therefore, HEC-RAS computes a "unit rouse profile," computing the vertical distribution for an arbitrary reference concentration of 1 (C_o=1) for twenty, evenly-spaced (Δy), vertical layers between the thalweg and water surface:

$$\hat{c}_i(y) = 1 \cdot \left[\left(\frac{D-y}{y}\right)\left(\frac{y_o}{D-y_o}\right)\right]^{\beta\frac{\omega_i}{\kappa u_*}}$$

where $\hat{c}_i(y)$ is the unit Rouse concentration at y, y is the vertical distance between the thalweg and the water column layer, D is the total depth, y_o is set to a single Δy, w_i is the fall velocity of grain class i, κ is the von Karmen coefficient (~0.4), and u^* is the shear velocity. However, the Rouse distribution is a theoretical curve that can overpredict or underpredict the vertical distribution. Therefore, the equation includes a calibration parameter (β), exposed as a user coefficient. Increasing beta ($\beta > 1$) will *decrease* floodplain deposition while decreasing beta ($\beta < 1$) will *increase* floodplain deposition.

The method then fits this unit distribution to the mass flux by multiplying it by the ratio of the total concentration to the average of all the unit distributions, such that:

$$C_i(y) = C_i \frac{\hat{c}_i(y)}{\sum_{j=1}^{n(20)} \hat{c}_i(y_j)/n}$$

where each j is one of the 20 vertical layers and C_i is the sediment flux of each grain class (HEC-RAS variable MassIn) entering the control volume. To translate concentration to deposition without requiring strict Courant limitations, the method must use mass flux instead of concentration. The algorithm then computes the concentration of each grain class available for floodplain diffusion and deposition by integrating the concentrations in the layers above the channel bank ($y_{bank} < y < D$). HEC-RAS does this analysis for the left and right floodplains individually because different bank elevations will translate to different floodplain available concentrations.

Step 2: Compute Lateral Concentration Profile with the Diffusion Equation

Sediment can transport into the floodplain by advection or diffusion. These are both multi-dimensional processes that require external constituent theory to apply to a 1D model. While diffusion may not be the dominant process in many systems (see Limitations Section below) a lateral diffusion model can be integrated into a 1D framework. Therefore, the second step of the Rouse-Diffusion method addresses the second limitation of the veneer method: sediment is less likely to transport or deposit farther from the channel.

This method uses an analytical diffusion equation to translate the floodplain available sediment at the channel bank across the floodplain. This equation computes sediment concentration at each floodplain node. The channel bank will have the highest floodplain available sediment. Concentration decreases farther from the channel.

Yotsukura and Cobb developed this approach for solutes in (1972) and Pizzuto (1987) applied it to sediment. HEC-RAS computes the concentration available to deposit at each node with the equation:

$$C(x_i) = \frac{C_{fp}}{1 + e^{2D_T L}}\left(e^{D_T x_i} + e^{D_T(2L - x_i)}\right)$$

where $C(x)$ is the concentration at each overbank station-elevation point (a lateral distance x from the channel bank), C_{fp} is the floodplain available concentration for the appropriate overbank from Step 1, L is the total horizontal distance between the bank station and the edge of the wetted perimeter, and D_T is a user specified lateral diffusion coefficient. The equation, variables, and conceptual model are illustrated in Figure 3.

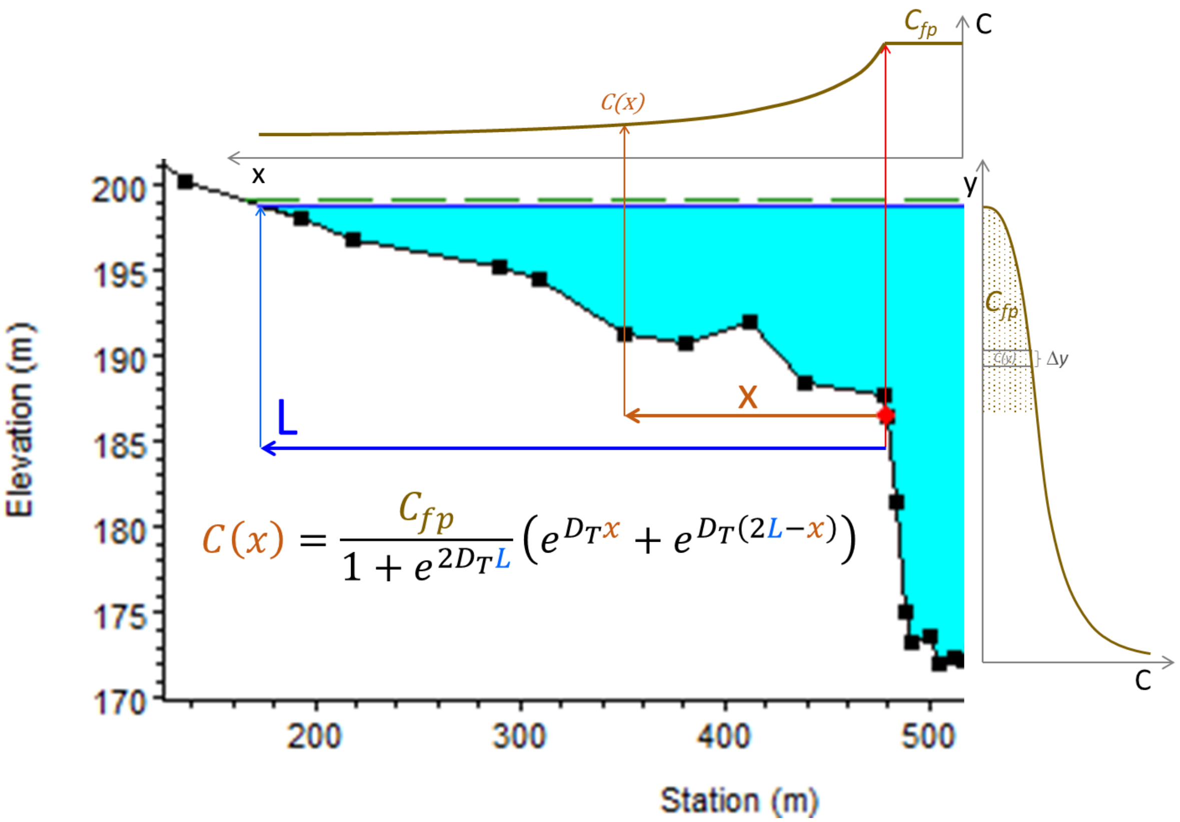


Figure 3 – Use the diffusion equation from Pizzuto (1987) to compute the concentration at each cross-section station-elevation point.

Step 3: Compute the Water Flux Associated with Each Floodplain Node

The HEC-RAS mobile bed model is a mass-balance model. Therefore, the model must eventually convert concentration into sediment mass to determine how much sediment deposits at each floodplain location. Estimating deposition is a simple matter of comparing fall velocity to depth and residence time. However, the HEC-RAS sediment model is not Courant controlled, requiring an additional step to compute residence time.

Selecting a time step that places the “Sediment Courant Condition” close to 1 (*i.e.* the sediment travels through a control volume in one time step) is best practice for 1D sediment modeling. However, because different grain classes have different transport velocities at different flows, most models do not have universal, sediment, Courant number. During each sediment time step, the water volume that passes through a control volume can be much greater or much smaller than the control volume itself. To estimate the mass of sediment that has an opportunity to deposit at each cross-section node in a time step, the model must compute the water flux that passed over it.

It is useful to estimate residence time with a “Courant” factor, the ratio of the volume in the cross-section centered control volume Vol_{CV-XS} and the water flux that enters the control volume in the time step ($Vol_{Flux-XS}$):

$$C = \frac{Vol_{Flux-XS}}{Vol_{CV-XS}}$$

The Rouse-Diffusion deposition method then subdivides both the flux volume ($Vol_{Flux\text{-}XS}$) and the static control volume ($Vol_{CV\text{-}XS}$) of the floodplain into sub-volumes associated with each node ($Vol_{flux(x)}$ and $Vol_{CV(x)}$ respectively). The method computes the static, sub-control volume ($Vol_{CV(x)}$) with the approach and equation illustrated in Figure 4.

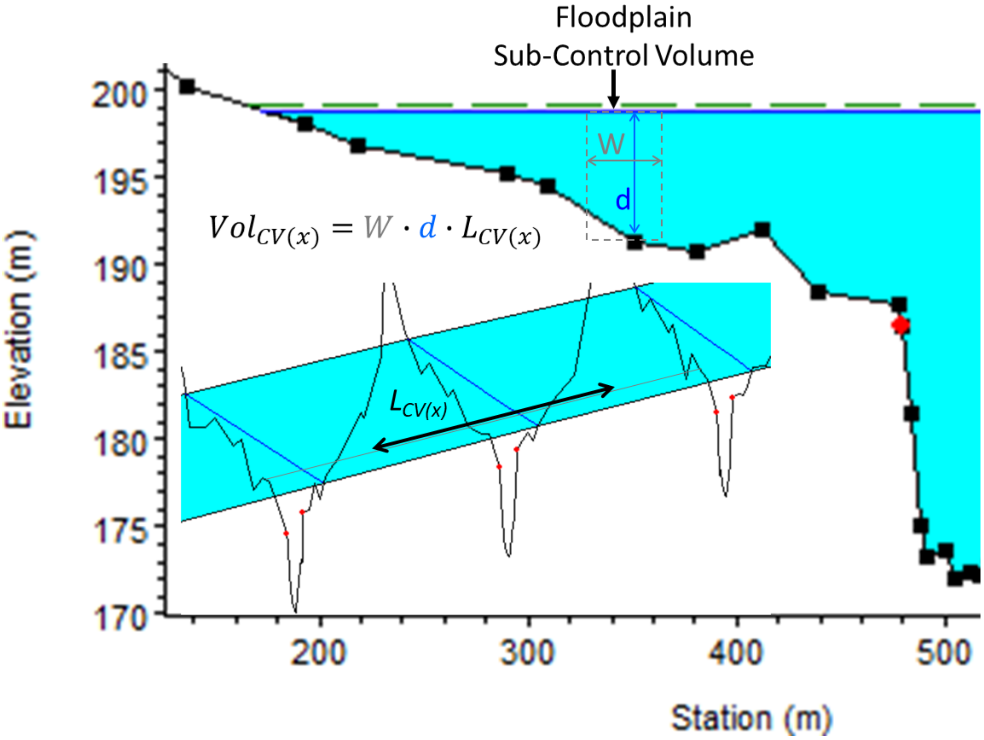


Figure 4 – The static volume associated with each node. The model compares this to the area-weighted flux volume to compute a residence time.

HEC-RAS computes how much water passes through the floodplain-node, sub-control-volume in a time step ($Vol_{flux(x)}$) by weighting the total, cross-section flux by the ratio of the static volume in the floodplain sub-section to the total volume associated with the cross section:

$$Vol_{flux(x)} = Vol_{Flux-XS}\frac{Vol_{CV(x)}}{Vol_{CV-XS}}$$

Step 4: Compute Deposition at each Node

With the water flux passing over each floodplain node (Step 3) and the concentration at each floodplain node (Step 2) the model can compute the mass that passes through each floodplain-node, sub-control volume (Figure 4) with the simple relationship: Mass=Concentration*Volume, for each grain class (*i*), such that:

$$Mass(x) = C_i(x) \cdot Vol_{flux(x)}$$

HEC-RAS then computes deposition ($\Delta Mass$) at each floodplain node by comparing the residence time to the depth (d in Figure 4) fall velocity (ω_i). The residence time is flux based, so it becomes the ratio of the time step (Δt) to the Courant Factor (C – computed above), such that:

$$\Delta Mass(x) = Mass(x)\frac{\omega_i \cdot \Delta t/Courant}{d}$$

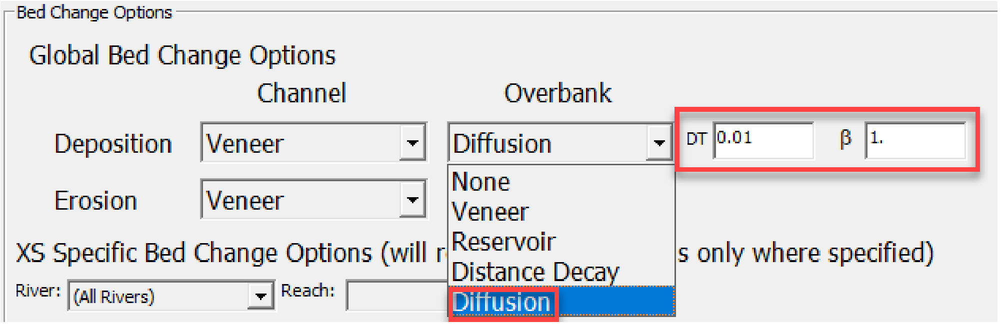
Finally, the algorithm increases the elevation of the node (Δz), computing the vertical displacement based on the area of the sub-control volume ($W{*}L_{CV(x)}$ in Figure 4) and the unit weight of the material (that accounts for the porosity of the deposits).

This algorithm computes the floodplain diffusion and deposition before the channel deposition or erosion. The sediment volume diffused into the floodplain is not available to satisfy channel capacity or deposit in the channel. HEC-RAS removes this floodplain transporting/depositing sediment from the channel mass balance, and then applies the Exner equation to the channel alone, with the remaining sediment. Therefore, in some cases the channel can erode and the floodplain can deposit in the same time step.

Isolating the channel mass balance without the floodplain sediment, generates a middle approach between ignoring floodplain dynamics and over-depositing in the floodplain with the veneer equation.

INTERFACE:

HEC-RAS users can select these methods in the Options→Bed Change Options (1D)… menu of the Sediment Transport Data Editor. The Global Overbank Deposition methods include a "Diffusion" option in HEC-RAS version 6.2 (Figure 5). Selecting the Diffusion method will activate two user parameters, *DT*, which is the lateral diffusion coefficient and β, which is the calibration parameter in the Rouse equation.



Bed Change Options
Global Bed Change Options
Channel Overbank
Deposition Veneer Diffusion DT 0.01 β 1.
Erosion Veneer
XS Specific Bed Change Options (will r
s only where specified)
River: (All Rivers) Reach:

Figure 5 – The Lateral Diffusion option in the HEC-RAS interface and the lateral diffusion coefficient (*DT*) and the beta coefficient in the Rouse number (β).

RESULTS: HEC-RAS includes several intermediate results that can help users visualize and understand their lateral diffusion simulation. First, the model can generate time series (Figure 6) of C_{fp} the floodplain available concentration (for each bank).

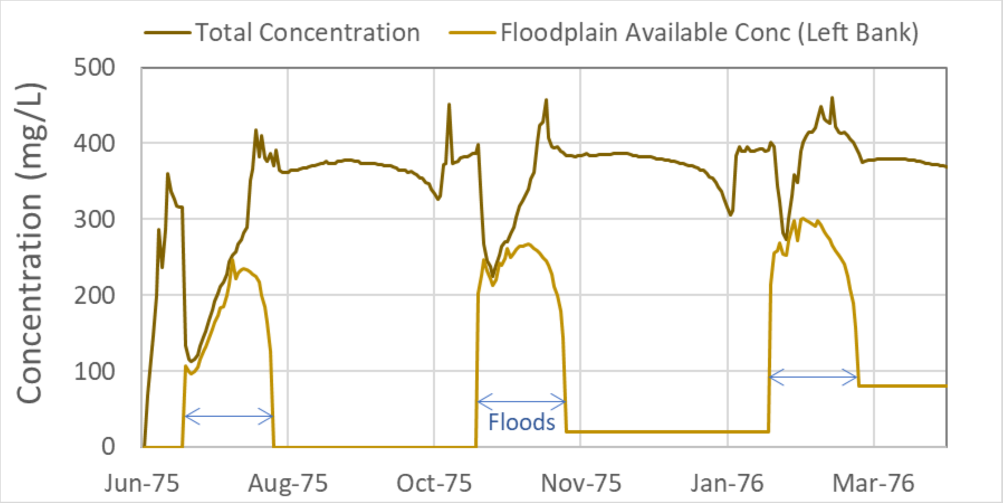


Figure 6 – Time series of total concentration and the concentration available to diffuse into the right floodplain (C_{fp}). The floodplain available sediment at this low floodplain approaches the total concentration during floods.

Second, HEC-RAS plots the Rouse profiles for each grain class at each cross section and each time step (Figure 7). This allows users to evaluate the shape of these profiles and the impact of their parameterization.

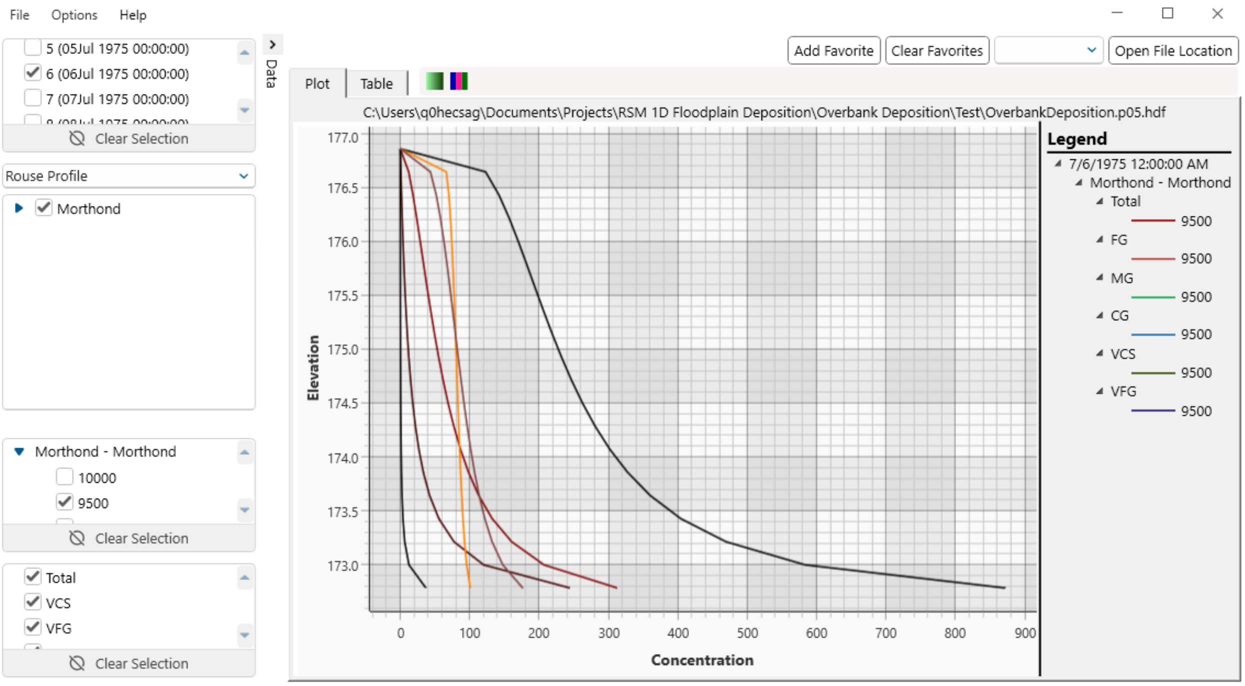


Figure 7 – Vertical Rouse distributions computed for the specified cross section at the specified time step for several grain classes (and total) during a flood.

Finally, HEC-RAS plots and animates repeated cross sections that illustrate simulated deposition and allows users to evaluate the non-veneer assumptions and compare floodplain deposition patterns to observed trends. The example in Figure 8 illustrated natural levee formation and a classical lateral deposition pattern from a 1D HEC-RAS simulation.

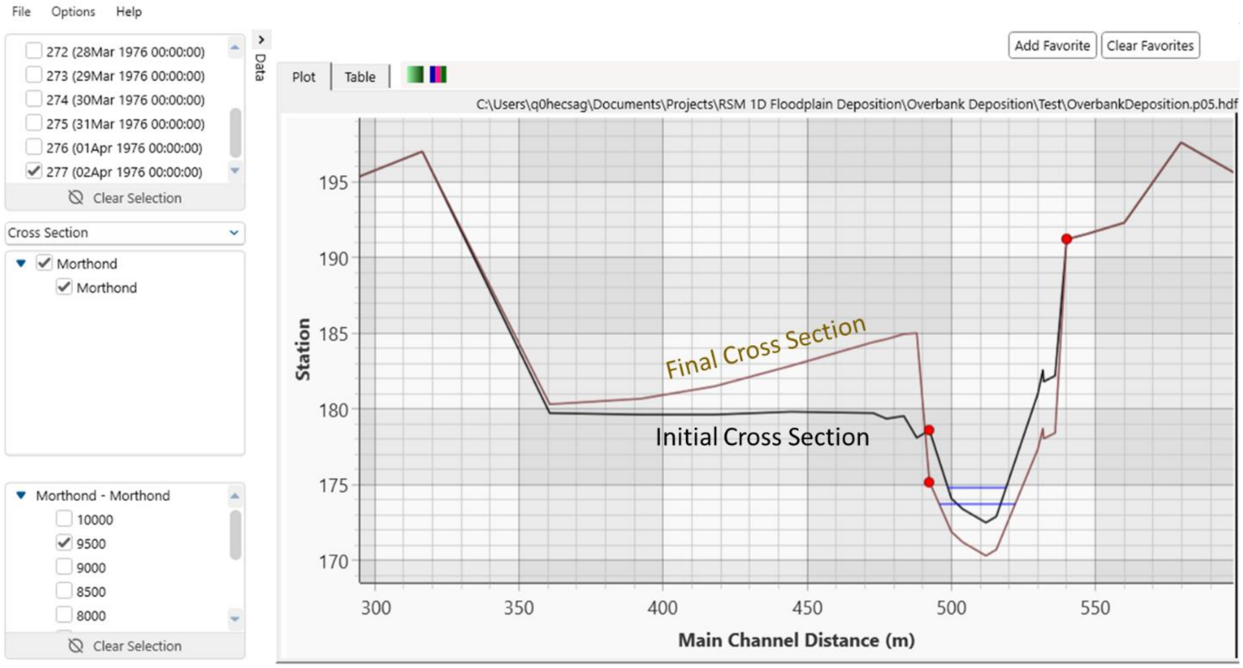


Figure 8 – One-dimensional, non-veneer, floodplain deposition from the Rouse-Diffusion method.

LIMITATIONS: This method only accounts for diffusion-driven floodplain deposition. The fluvial floodplain research community recognizes diffusion as a second-order floodplain deposition mechanism. Advection (transport in the direction of flow) is the first-order cause of most floodplain deposition (Pizzuto, personal communication). However, 1D models assume flow is perpendicular to the cross section, excluding advective exchange between the floodplain and channel by definition. Therefore, the diffusion model becomes a heuristic for a wider range of physical processes that transfer and deposit floodplain sediment. This will often require larger DT and β coefficients than particle diffusion can justify. If these coefficients become unrealistic to the point that the model cannot evaluate the simulation objectives, a 2D model may be required. However, in many cases, applying the Rouse-Diffusion method, even with exaggerated coefficients, will simulate floodplain deposition better than the current options of ignoring the process or over-predicting deposition with the veneer method.

CONCLUSION: A Rouse-Diffusion floodplain-deposition algorithm provides an intermediate option between the classic options of under predicting deposition by ignoring it or over predicting deposition with the veneer method. This will improve RSM analyses because it will allow more realistic assessment of regional sediment budgets and sediment management alternatives where floodplain deposition is significant. This RSM initiative included these capabilities in HEC-RAS 6.2.

ADDITIONAL INFORMATION: This USACE Regional Sediment Management (RSM) Technical Note (TN) was prepared Dr. Stanford Gibson stanford.gibson@usace.army.mil USACE Hydrologic Engineering Center (HEC) and Dr. John Shelley john.shelley@usace.army.mil USACE – Kansas City District (NWK). This study was conducted as an activity of the USACE National Regional Sediment Management (RSM) Program, a Navigation Research, Development, and Technology (RD&T) portfolio program administered by Headquarters (HQ) USACE. Additional information pertaining to this RSM TN can be obtained from Dr. Gibson. For information pertaining to the USACE National RSM Program, please consult the RSM website (http://rsm.usace.army.mil), or contact the USACE National RSM Program Manager, Dr. Katherine Brutsche Katherine.E.Brutsche@usace.army.mil

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