Bridge Modeling

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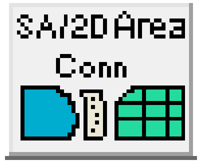
Introduction

- Two Approaches for Bridge Modeling
  - Simplified 1D/2D Bridge Modeling
    - Enforces precomputed 1D bridge curves from a nested 1D bridge model
    - Can handle any flow regime
    - Cannot simulate detailed flow
    - Terrain Modifications not necessary
  - Full 2D Modeling
    - Detailed mesh and terrain modifications used to simulate detailed flow through bridge
    - Currently, cannot handle pressured flow or overtopping

Simplified 1D/2D Bridge Hydraulics



- Utilizing existing HEC-RAS 1D Bridge Hydraulics methods inside of a 2D Flow Area

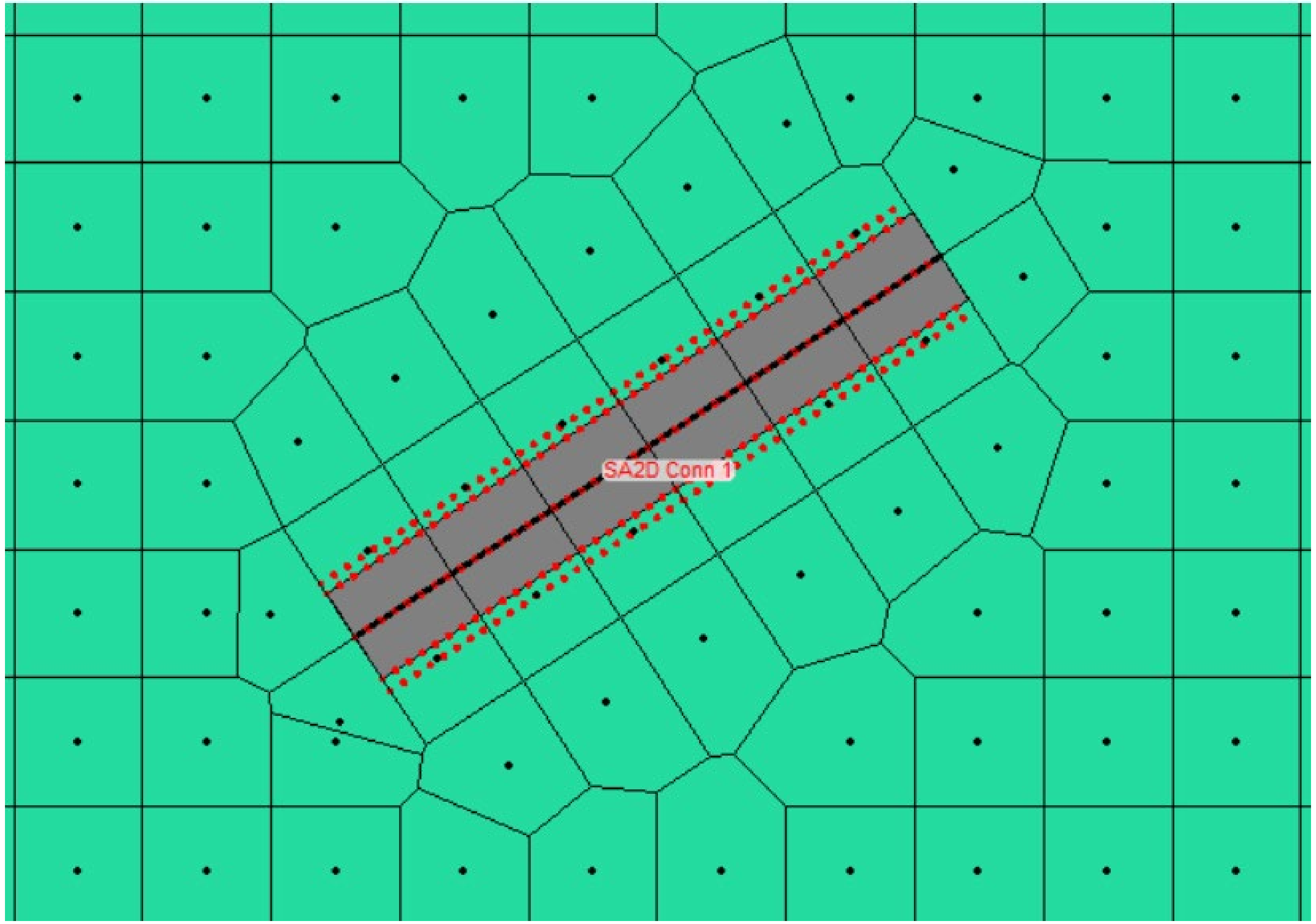
- Model complete range of Bridge Hydraulic flow regimes
  - Low flow
  - Pressure flow
  - Pressure flow and weir flow (road over topping)
  - Low flow and weir flow

Approach

- Use HEC-RAS 1D Bridge Geometry and Cross Section Layout (automated layout) inside of 2D Flow Area
- Develop a family of Headwater/Tailwater Flow curves from RAS 1D bridge hydraulic calculations during geometry pre-processing
- Uses a special momentum equation that gets applied only at the 2D bridge centerline faces:
  - Friction loss, pressure differential, and convective acceleration forces are equated from the water surface difference in the bridge curves.
  - The forces are distributed across faces though the bridge.
  - Local acceleration is calculated on the fly, as it is not a force in curves
- Bridge faces are then solved in 2D just like all other faces
- Extremely efficient – almost no increase in computations

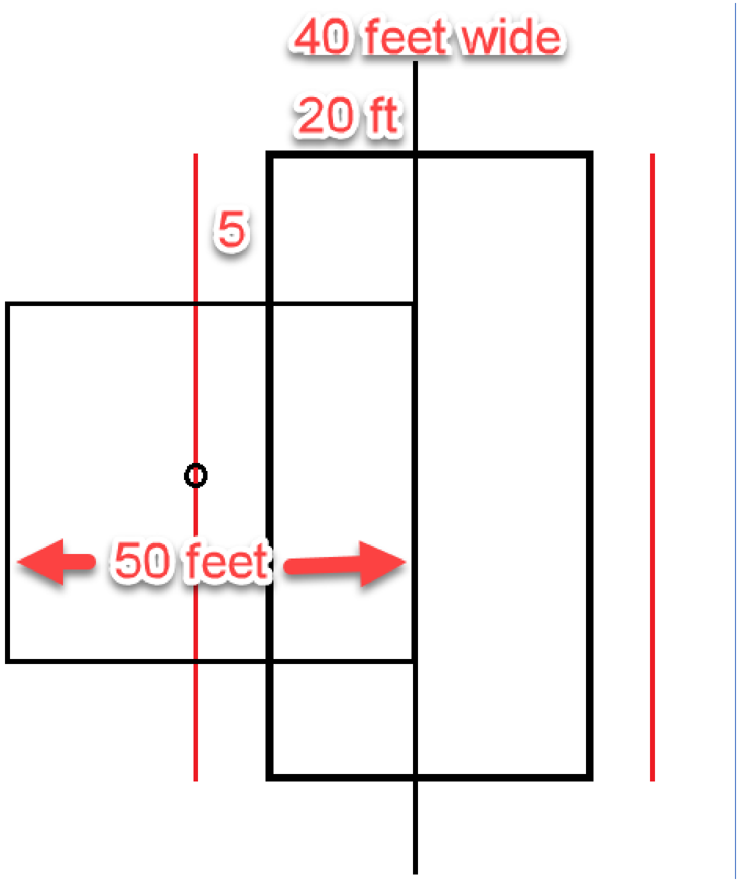
Structure Layout

- 1D Bridge loses computed between “XS” downstream of deck through the bridge to “XS” upstream of bridge deck.
- Enforced as Breakline
- Set cells sizes (or cell US/DS length) so that the cell centers match the domain covered by 1D Bridge loses
- Model Bridge opening (not overbanks)



Example Layout

- Structure is Enforced as a Breakline
- Cell Size Considerations
  - Bridge Deck width = 40 ft and US Distance = 5 feet
    - Half deck width = 40/2 = 20 ft
    - Distance from centerline to first cell center = 20 + 5 ft
    - Row of cells needs to be 50 ft

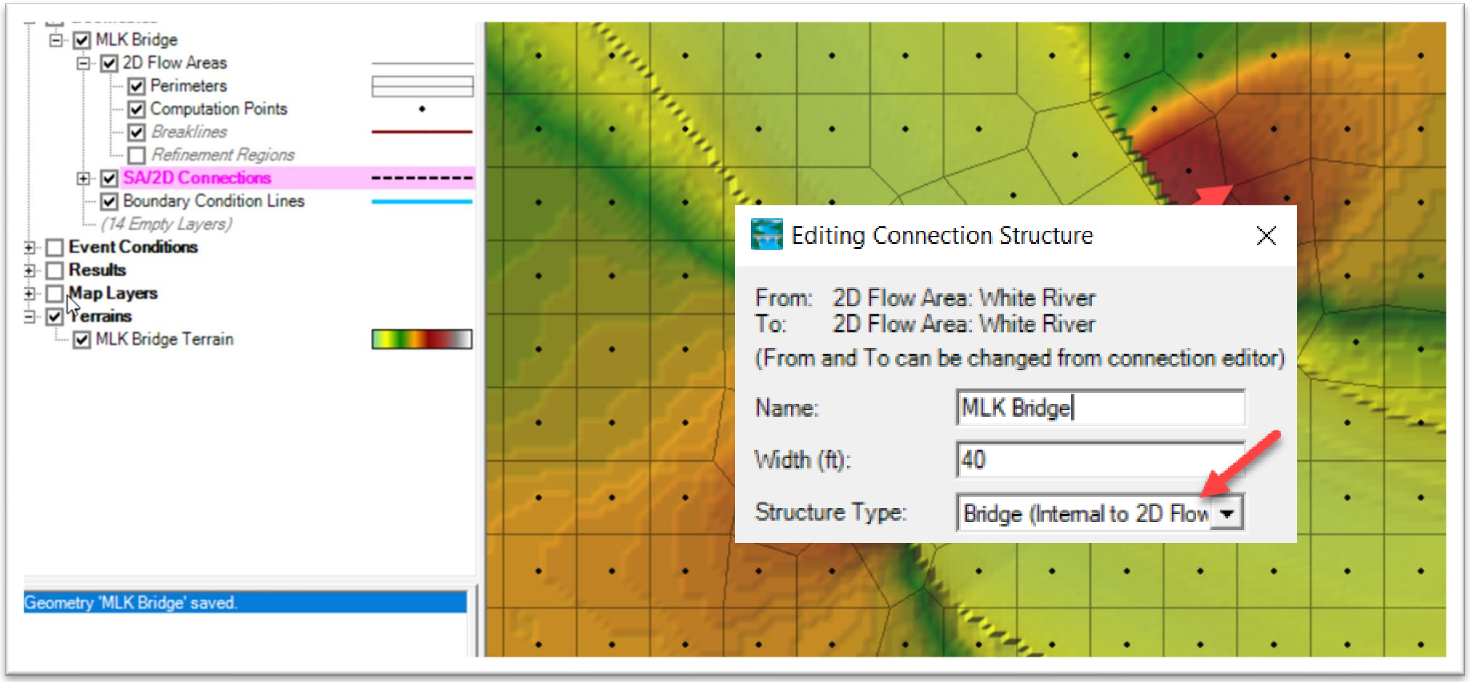


Steps for Adding a 2D Bridge

1) Draw a centerline for the bridge opening/embankment using the SA/2D Area Connection tool
   - Bridge centerline is drawn left to right looking downstream.
2) Develop an appropriate mesh (cell size and orientation) for the bridge
   - Use the structure mesh controls (cell size and enforcement). Some hand editing may be required depending on the bridge and what else is near the bridge (i.e. levee, another bridge, railroad tracks, road, etc…)
3) Enter the bridge data
   - Deck/roadway; distance from upstream bridge deck to outside cross section piers; abutments; bridge modeling approach; Manning's n values for the 1D bridge cross sections; and hydraulic tables controls (HTAB) into the SA/2D Area Connection editor.
4) Pre-process the geometry in order to create the bridge curves.
   - Review the bridge family of rating curves for hydraulic accuracy.
5) Run the model and review the results.
   - Make any necessary changes to the data in order to improve the results.

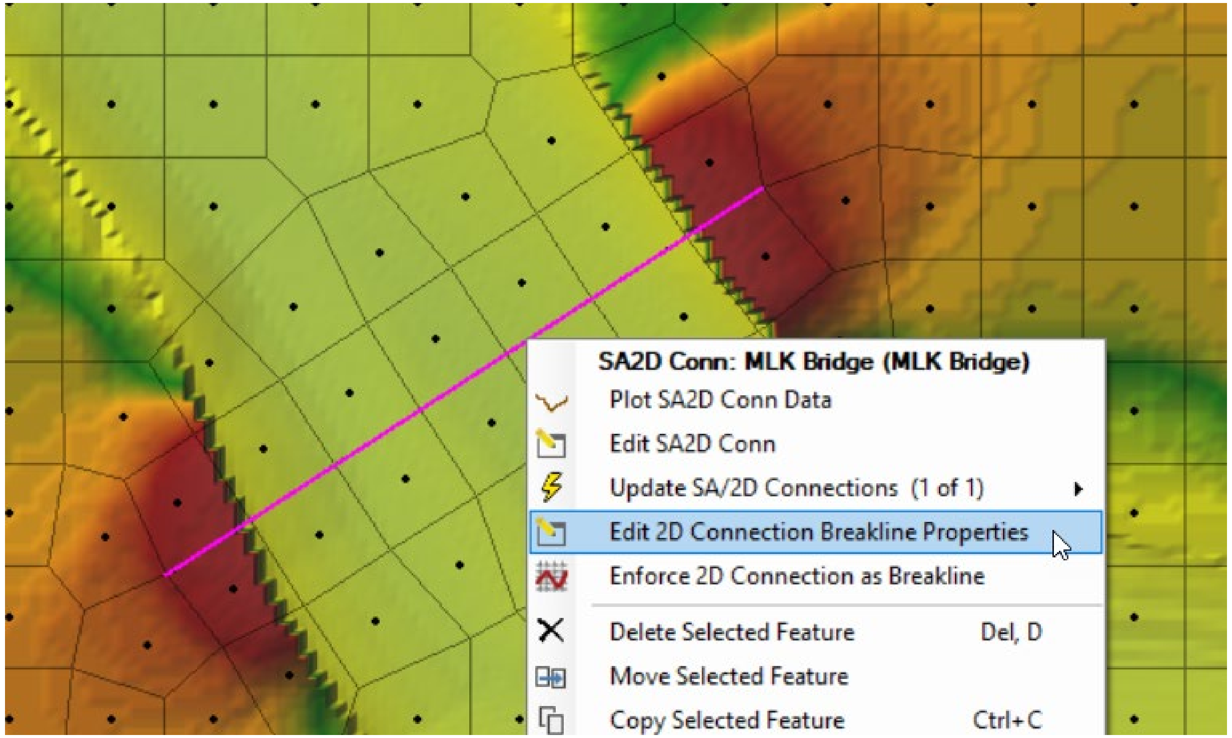
Bridge Centerline and Mesh Adjustments

- Select the **SA/2D Area Connection** layer tool and **Draw the centerline** of the bridge from left to right looking downstream
- Choose **Bridge** Type



Bridge Centerline and Mesh Adjustments

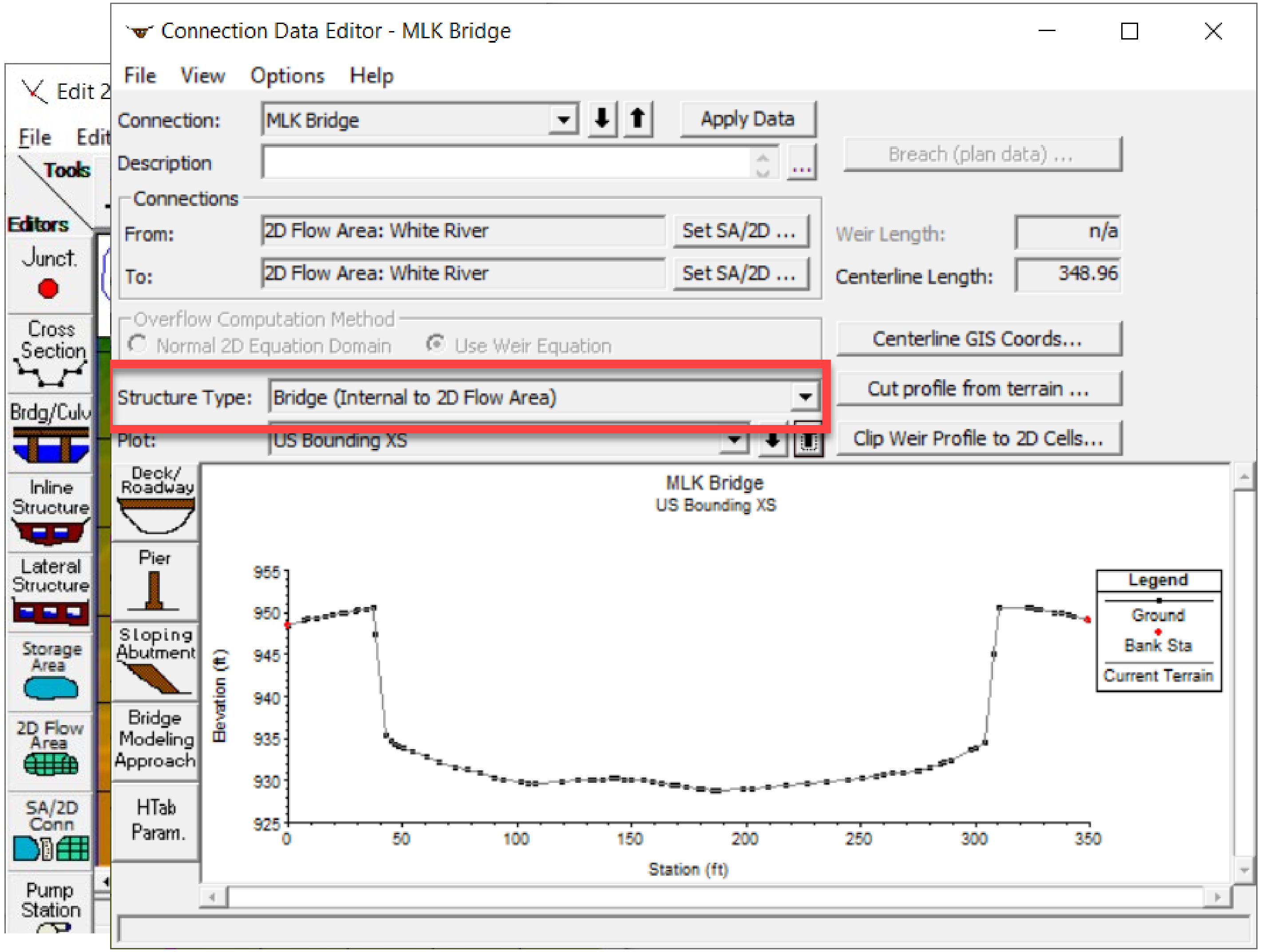
- Edit 2D Connection Breakline Properties
  - Cell Spacing
  - Near Repeats
- Cell Spacing = deck width + u/s distance
- Enforce 2D Connection as Breakline



Bridge Data

- 

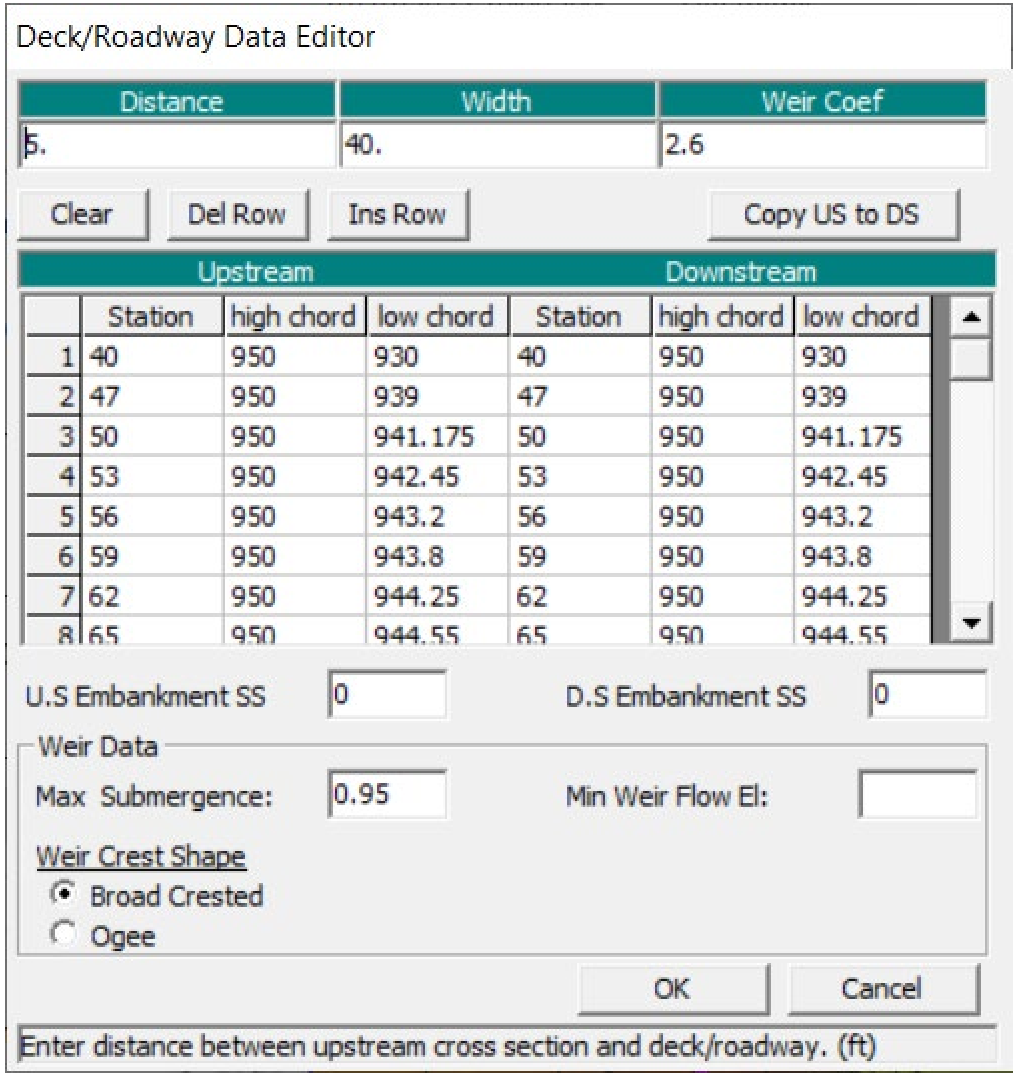
- Open in Geometric Data Editor
- Structure Type: Bridge



Deck and Roadway

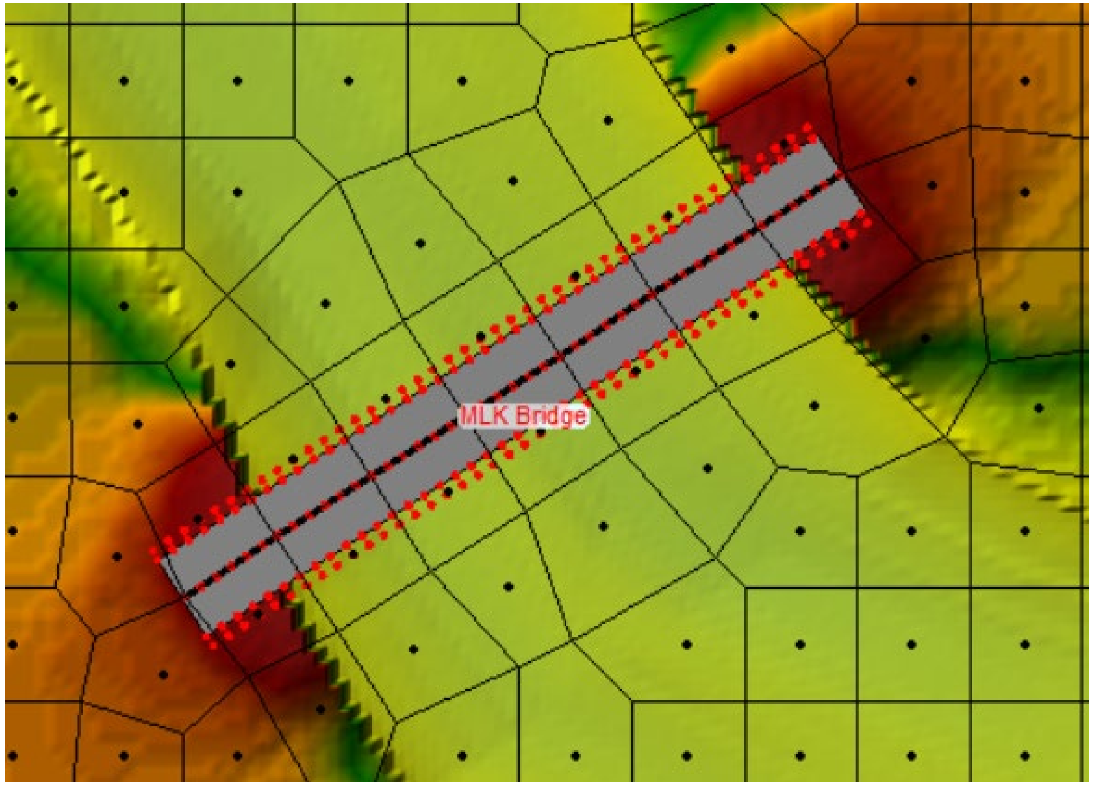
- 

- **Distance** (this is the distance from the upstream side of the bridge deck to the cross section upstream outside of the bridge, as wells as downstream outside)
- **Width** of the bridge deck in the direction of flow
- **Weir Coefficient** for flow going over the roadway
- **Station** (distance from left to right along the bridge deck/roadway), **High Chord**, and **Low Chord** elevations for the upstream and downstream side of the bridge deck



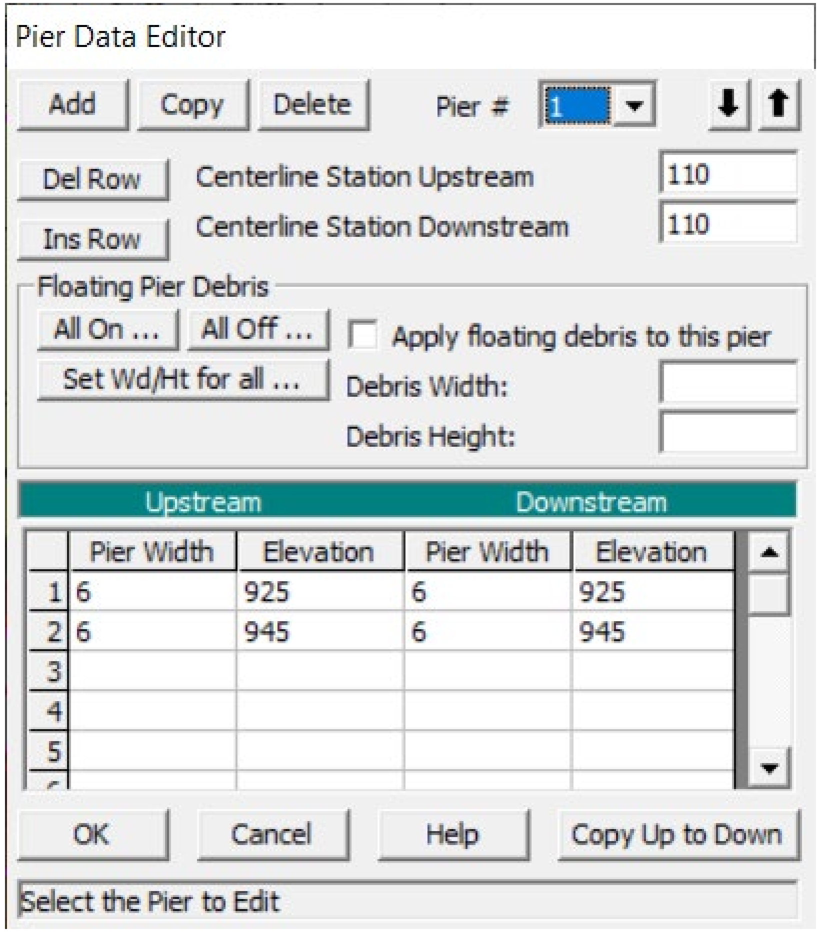
Automated Cross-Sections

- HEC-RAS will automatically create the four needed cross sections for pre-processing the bridge hydraulics into a family of curves.
  1. **Upstream just outside the bridge deck**, normally at the toe of the upstream embankment. This cross section is automatically generated upstream of the bridge deck based on the user entered **Distance** field.
  2. **Upstream just inside the bridge deck/roadway**.
  3. **Downstream just inside the bridge deck/roadway**.
  4. **Downstream outside of the bridge deck/roadway**, normally at the toe of the downstream embankment. This cross section is automatically generated downstream of the bridge deck a distance equal to what the user entered for the upstream **Distance** field.



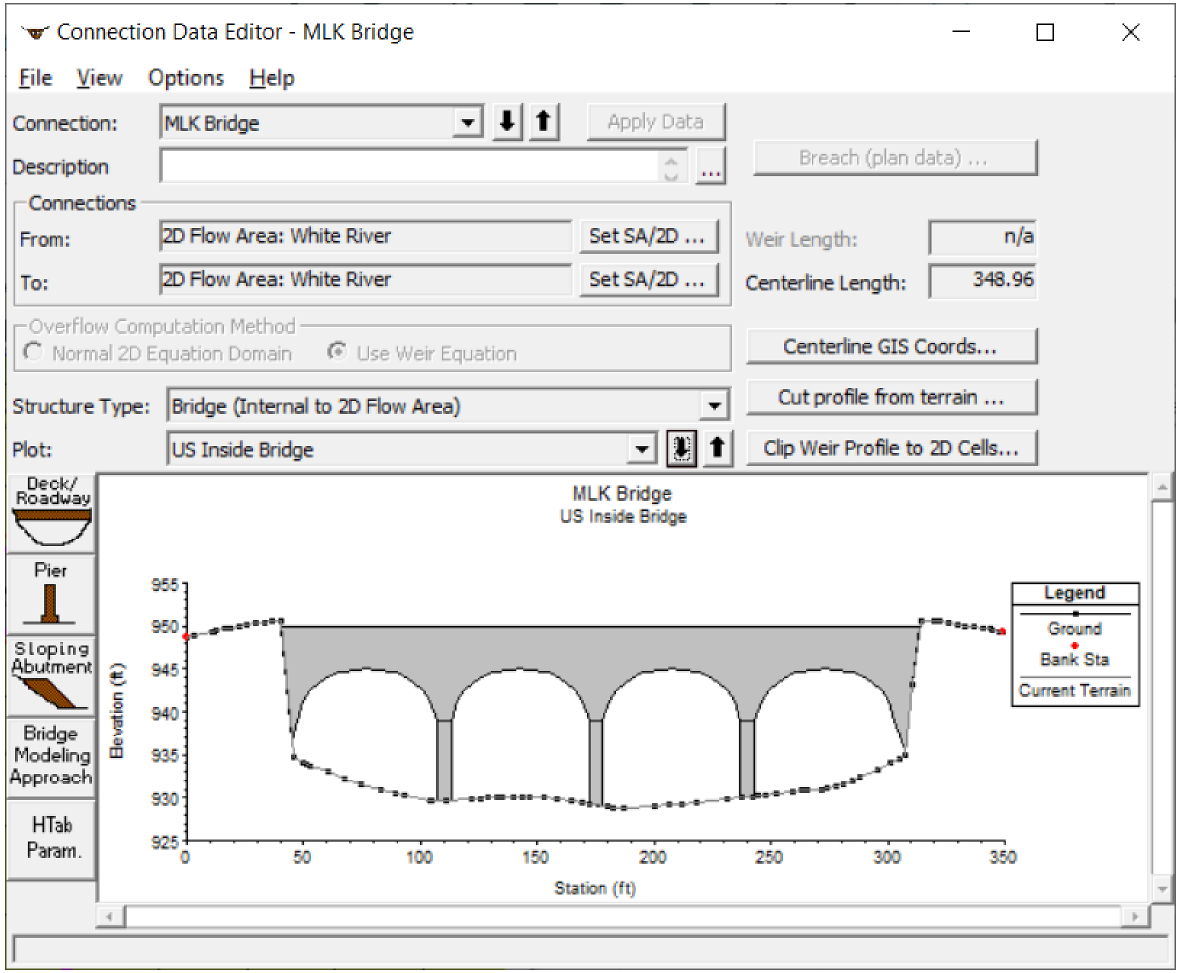
Piers and Abutments

- A Centerline Station for both the u/s and d/s for bridge pier.
- The pier is formed by entering pairs of elevations vs widths, starting below the ground and going up past the low chord of the bridge deck.
- This must be done for both the u/s and d/s side of bridge
- Copy Up to Down, if appropriate



Bridge Geometry

- For the **two cross-sections inside the bridge**, they follow the edges of the deck/roadway.
- The **outside cross-section locations** are automated by simply creating cross sections that are parallel to the inside cross sections, and the distance upstream and downstream from the bridge deck is based on what the user entered for the **Distance field in the Deck/Roadway editor**.
- **Note:** If the user changes the Deck/roadway data (Bridge width or distance field), then the location of the 1D cross sections will change.
- The user can view each of the four cross sections, as well as the centerline from the **plot by selecting the location to view**.
- **If the bridge data is changes**, the user will see that the terrain under the current 1D cross section line is different than what they currently have entered. The user can recut any of the 1D cross sections by simply pressing the **Cut profile from terrain button** while viewing a specific cross section.



Manning's n Data for the XS's

- **Options | External and Internal Bridge Cross-Sections…**

Bridge Cross Sections

Upstream Outside

Main Channel Bank Stations	
Left Bank Sta	Right Bank Sta
0	348.96

Cross Section X-Y Coordinates

	Station	Elevation	Mann n
1	0	948.51	0.035
2	7.3	949.17	
3	8.8	949.27	
4	12.42	949.33	
5	16.03	949.55	
6	19.65	949.64	
7	23.27	949.91	
8	25.15	949.97	
9	29.57	950.2	
10	30.5	950.27	
11	34.12	950.37	
12	37.05	950.56	
13	38.15	947.49	
14	42.3	935.27	
15	44.91	934.73	

Upstream Inside

Main Channel Bank Stations	
Left Bank Sta	Right Bank Sta
0	348.96

Cross Section X-Y Coordinates

	Station	Elevation	Mann n
1	0	948.61	0.035
2	3.37	948.91	
3	10.53	949.31	
4	11.34	949.33	
5	12.59	949.42	
6	16.48	949.62	
7	18.57	949.69	
8	22.19	949.96	
9	25.81	950.04	
10	29.42	950.25	
11	33.04	950.32	
12	36.66	950.56	
13	40.28	950.62	
14	45.53	934.82	
15	49.48	934.14	

Downstream Inside

Main Channel Bank Stations	
Left Bank Sta	Right Bank Sta
0	348.96

Cross Section X-Y Coordinates

	Station	Elevation	Mann n
1	0	947.96	0.035
2	0.63	948	
3	6.58	948.66	
4	12.52	948.97	
5	18.47	949.31	
6	24.42	949.62	
7	30.37	949.97	
8	31.64	950	
9	33.61	950.14	
10	36.32	950.28	
11	38.88	950.35	
12	42.49	950.62	
13	48.22	950.62	
14	50.63	943.49	
15	53.47	934.89	

Downstream Outside

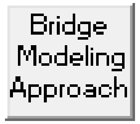
Main Channel Bank Stations	
Left Bank Sta	Right Bank Sta
0	348.96

Cross Section X-Y Coordinates

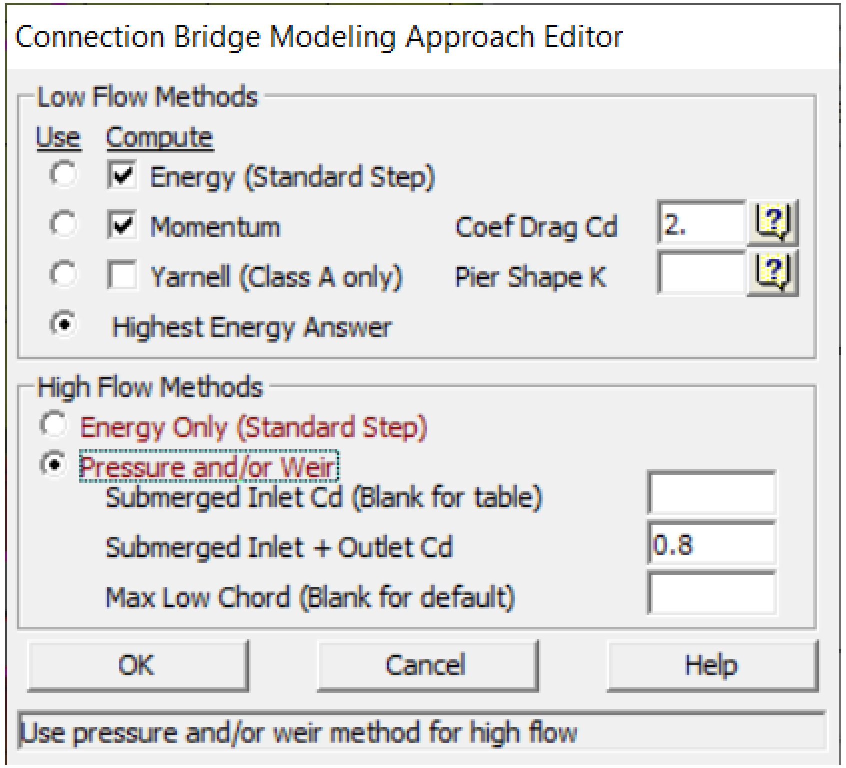
	Station	Elevation	Mann n
1	0	947.78	0.035
2	3.85	948	
3	9.8	948.66	
4	15.75	948.97	
5	21.7	949.31	
6	27.65	949.62	
7	33.6	949.97	
8	39.55	950.28	
9	45.5	950.62	
10	50.75	935.55	
11	56.7	934.53	
12	59.64	934.17	
13	62.65	933.86	
14	68.6	933.29	
15	72.32	932.95	

OK Cancel Help

1D Bridge Modeling Approach

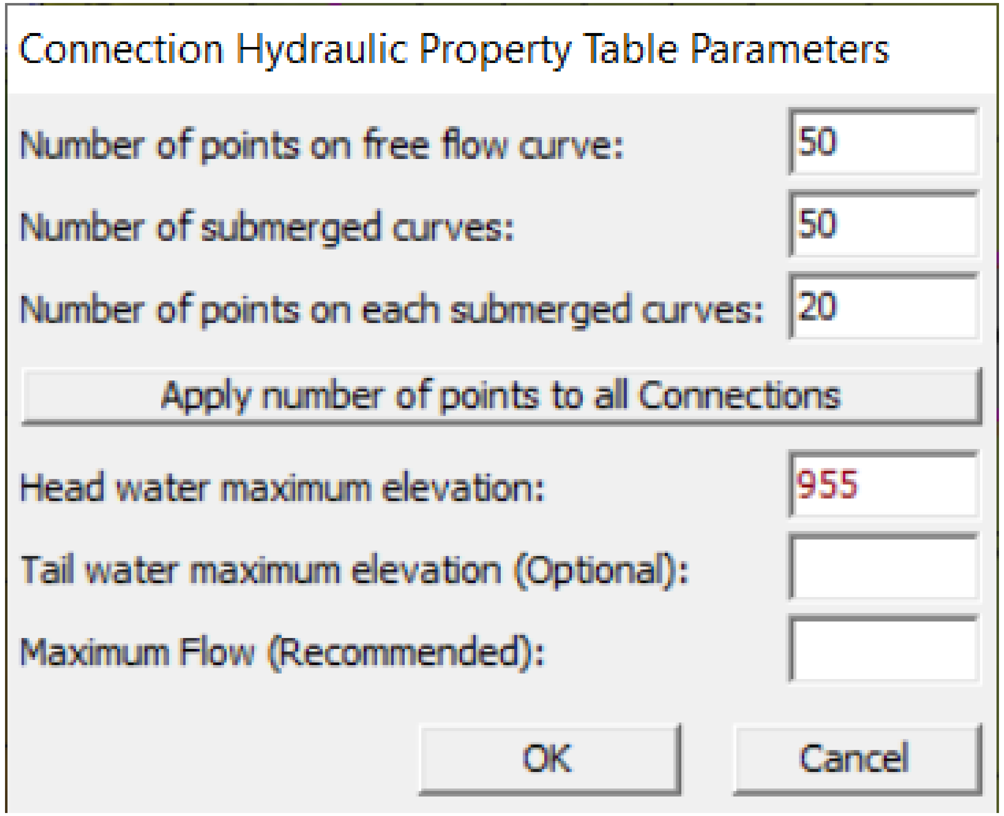


- Low flow methods:
  - Energy
  - Momentum
  - Yarnell
- High flow methods:
  - Energy
  - Pressure/Weir flow



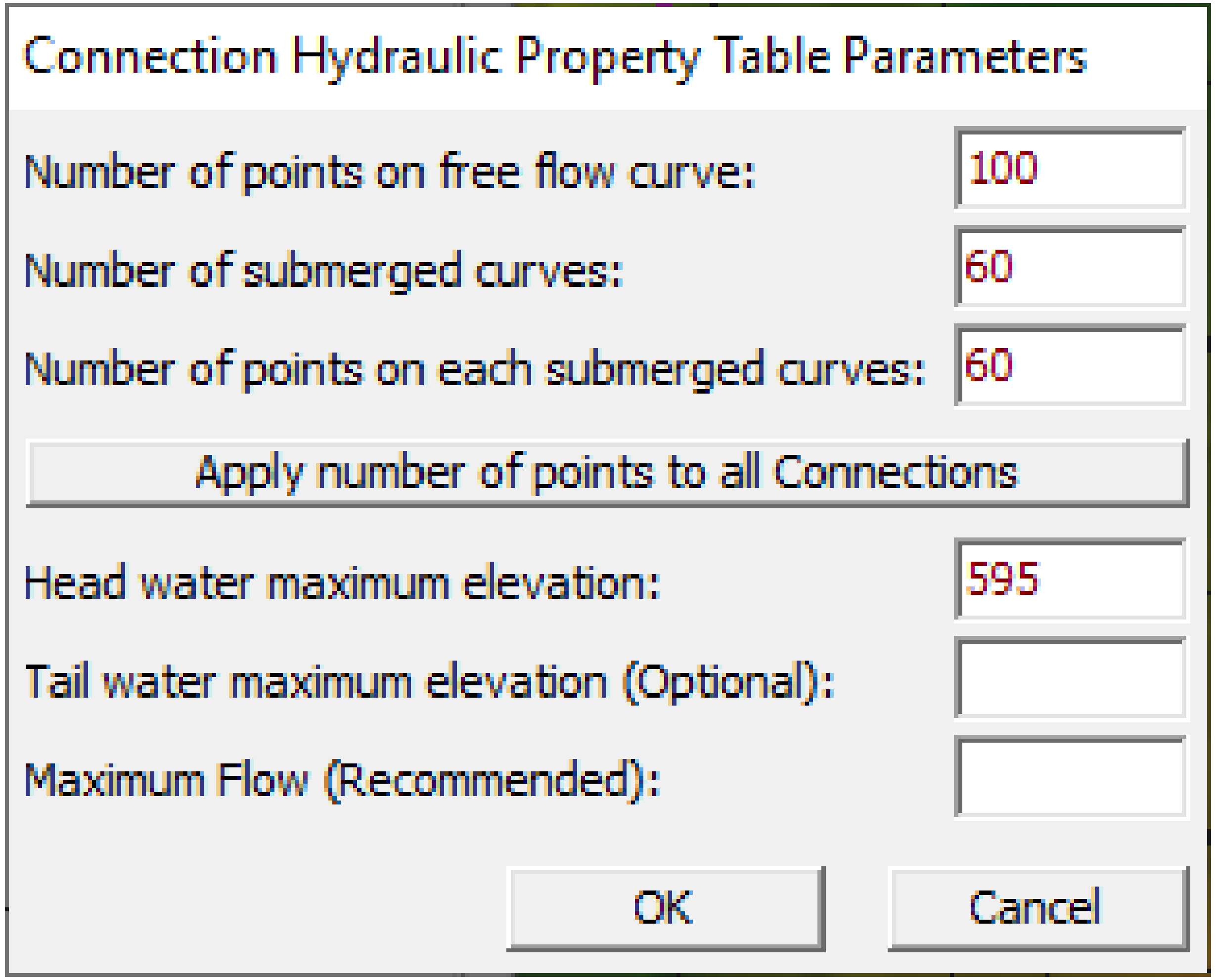
Hydraulic Table Parameters

- Number of points on free flow curve (100 max)
- Number of submerged curves (60 max)
- Number of points on each submerged curve (60 max)
- Headwater maximum elevation
- Tailwater maximum elevation is optional, as is the Maximum Flow.

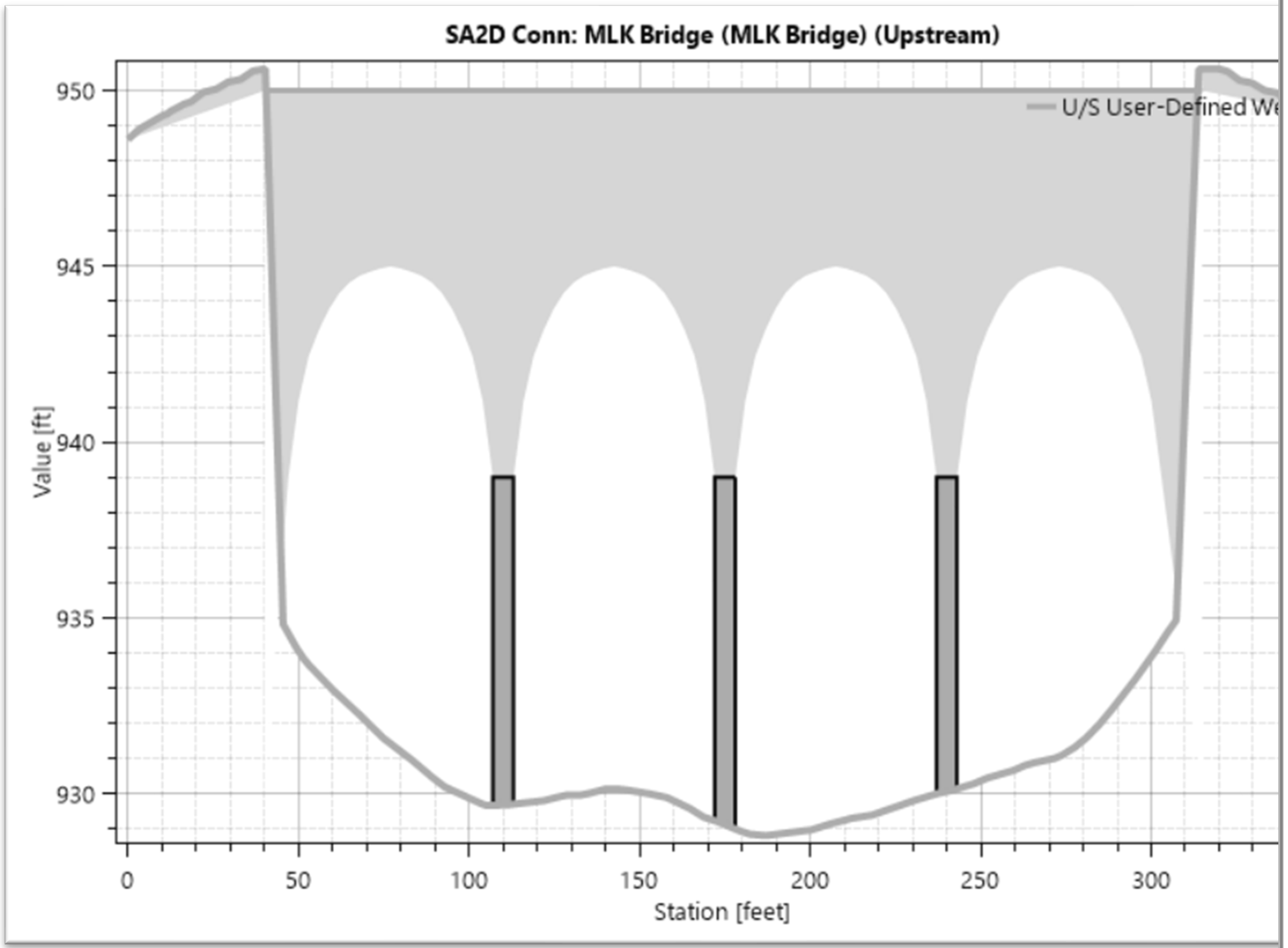


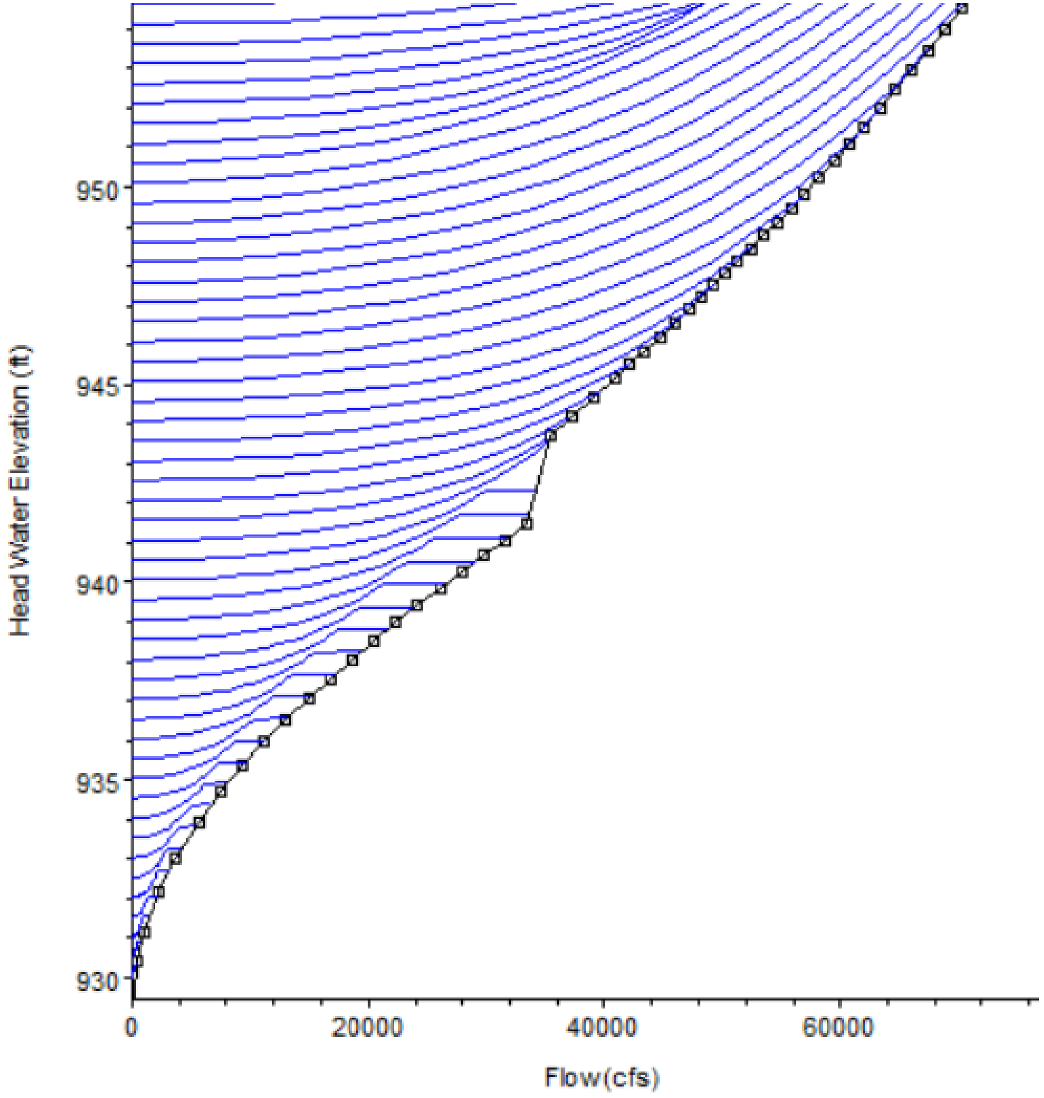
Hydraulic Table Parameters

- **Number of points on free flow curve** (maximum is 100)
- **Number of submerged curves** (maximum is 60)
- **Number of points on each submerged curve** (maximum is 60)
- **Head water maximum elevation**.
- Tail water maximum **elevation** is optional, as is the Maximum Flow



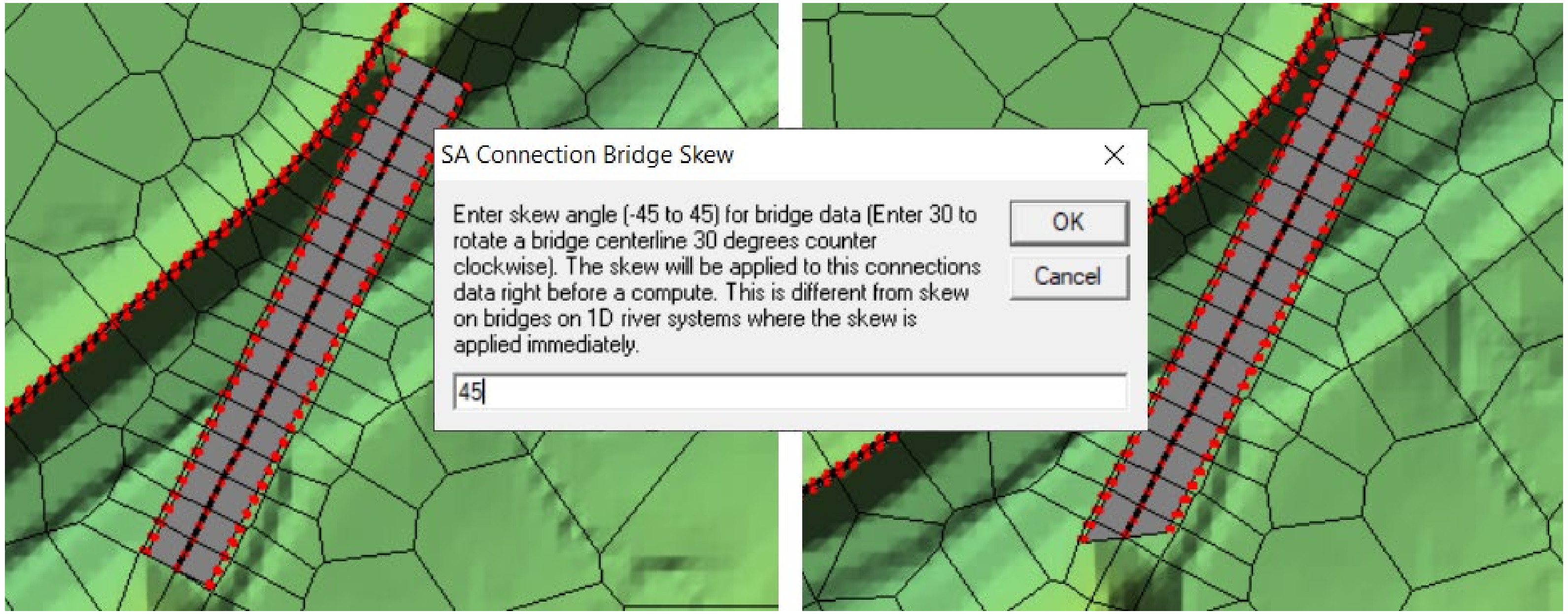
HTab – Family of Bridge Curves

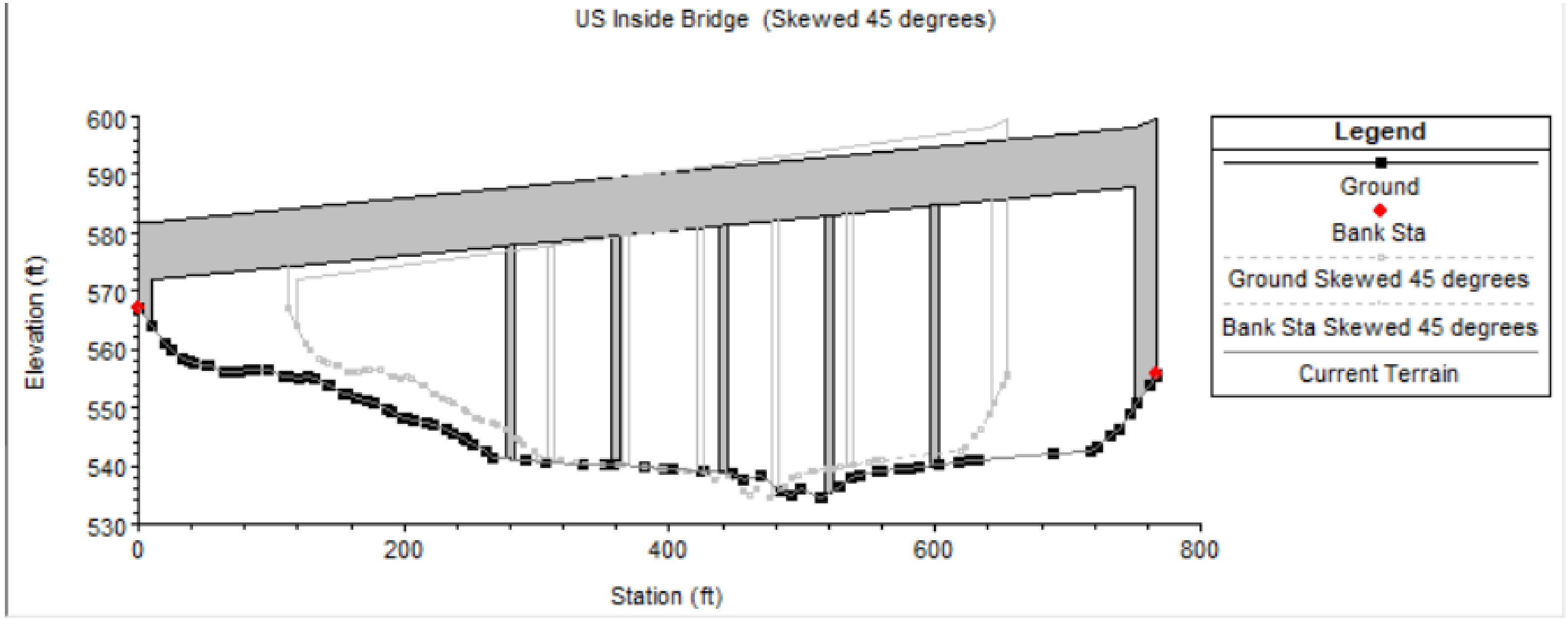




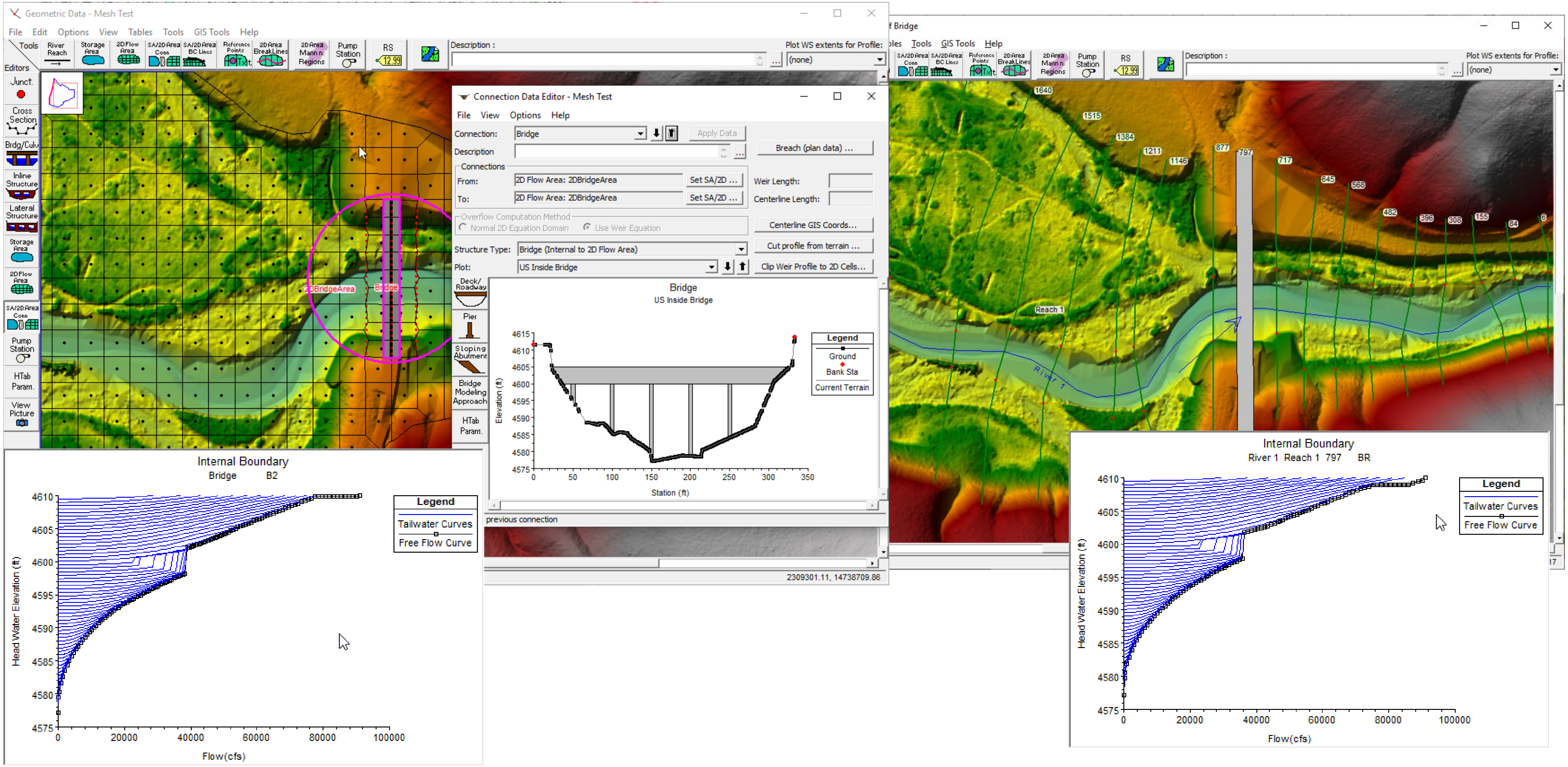
Bridge Skew

- New in 6.5
- Skew angle used to reduce the effective length of the bridge opening by projecting the internal and external bridge cross-sections
- Multiplies the stationing by the cosine of the skew angle





1D vs 2D Model Comparison



1D and 2D Comparison Animation

Flow Tracers

Computation Procedure

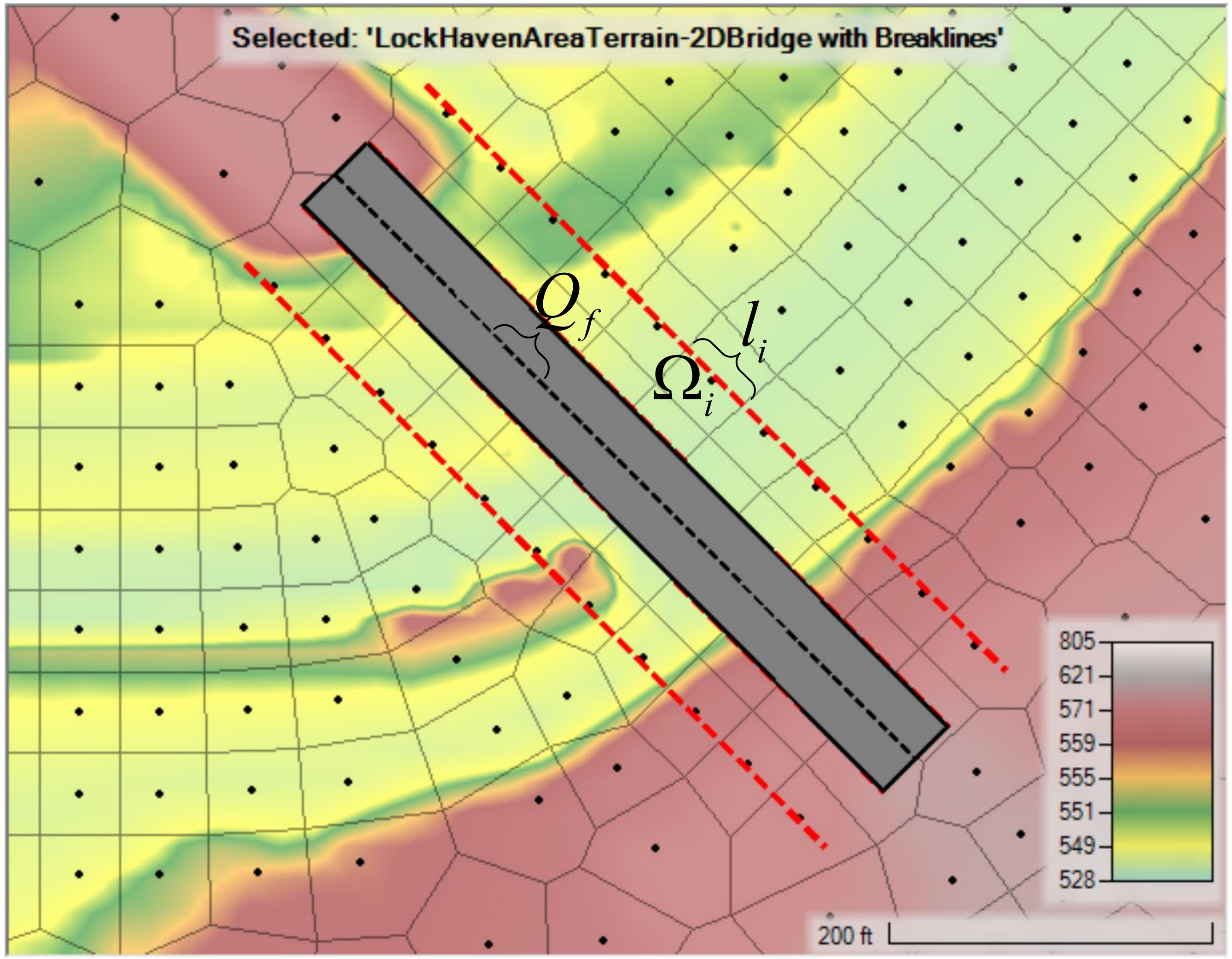
1. Estimate total bridge flow and tailwater elevation as

$$Q_B = \sum_f Q_{B,f}$$

$$\overline{z}_{s,T} = \frac{\sum_{i \in T} \Omega_i l_i z_{s,i}}{\sum_{i \in T} \Omega_i l_i}$$

Ω_i : XS cell volume

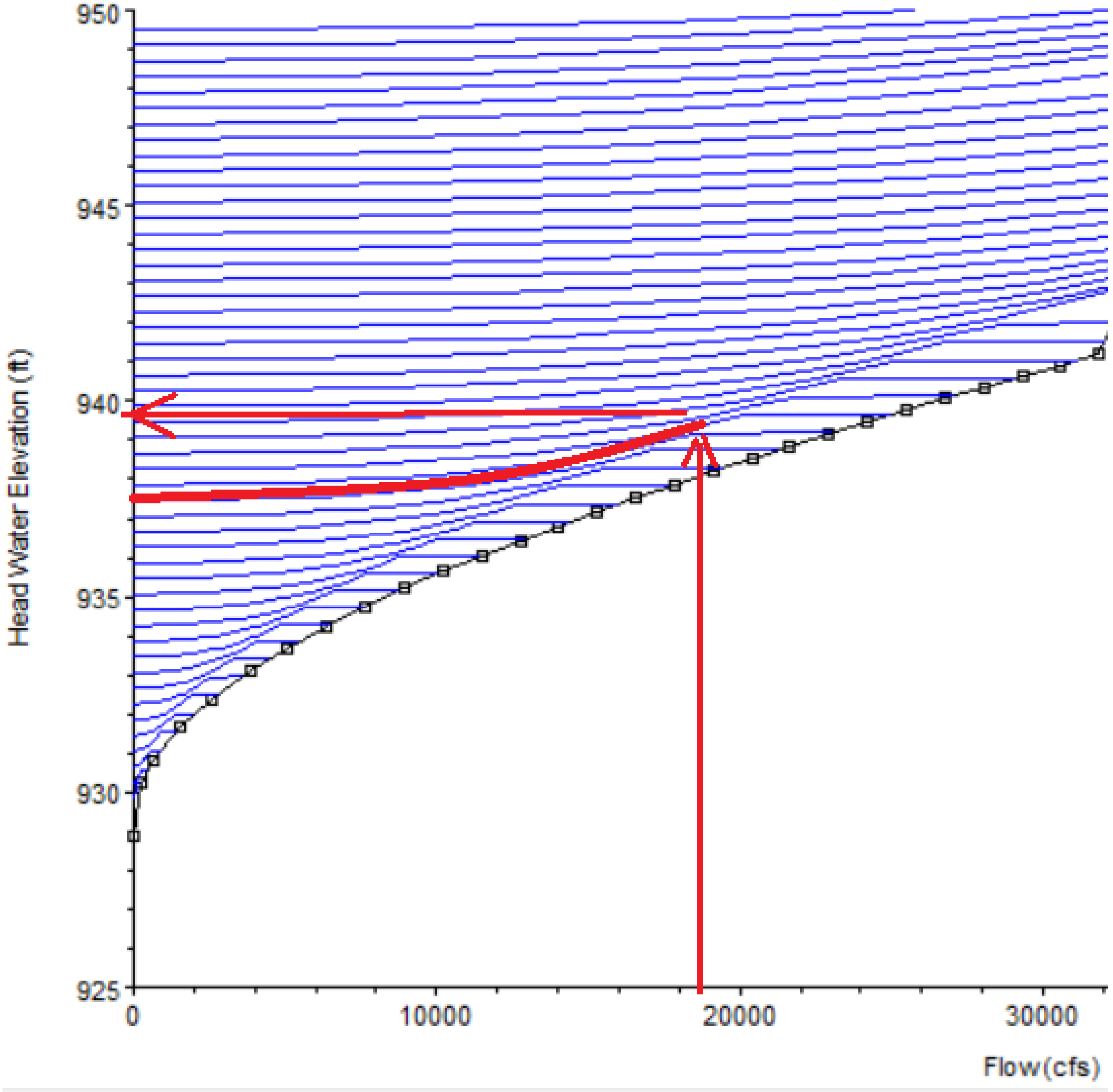
l_i : XS length in cell



Computation Procedure

2. Compute target headwater elevation from bridge curves

$$z_{s,H} = f(Q_B, \overline{z}_{s,T})$$



Computation Procedure

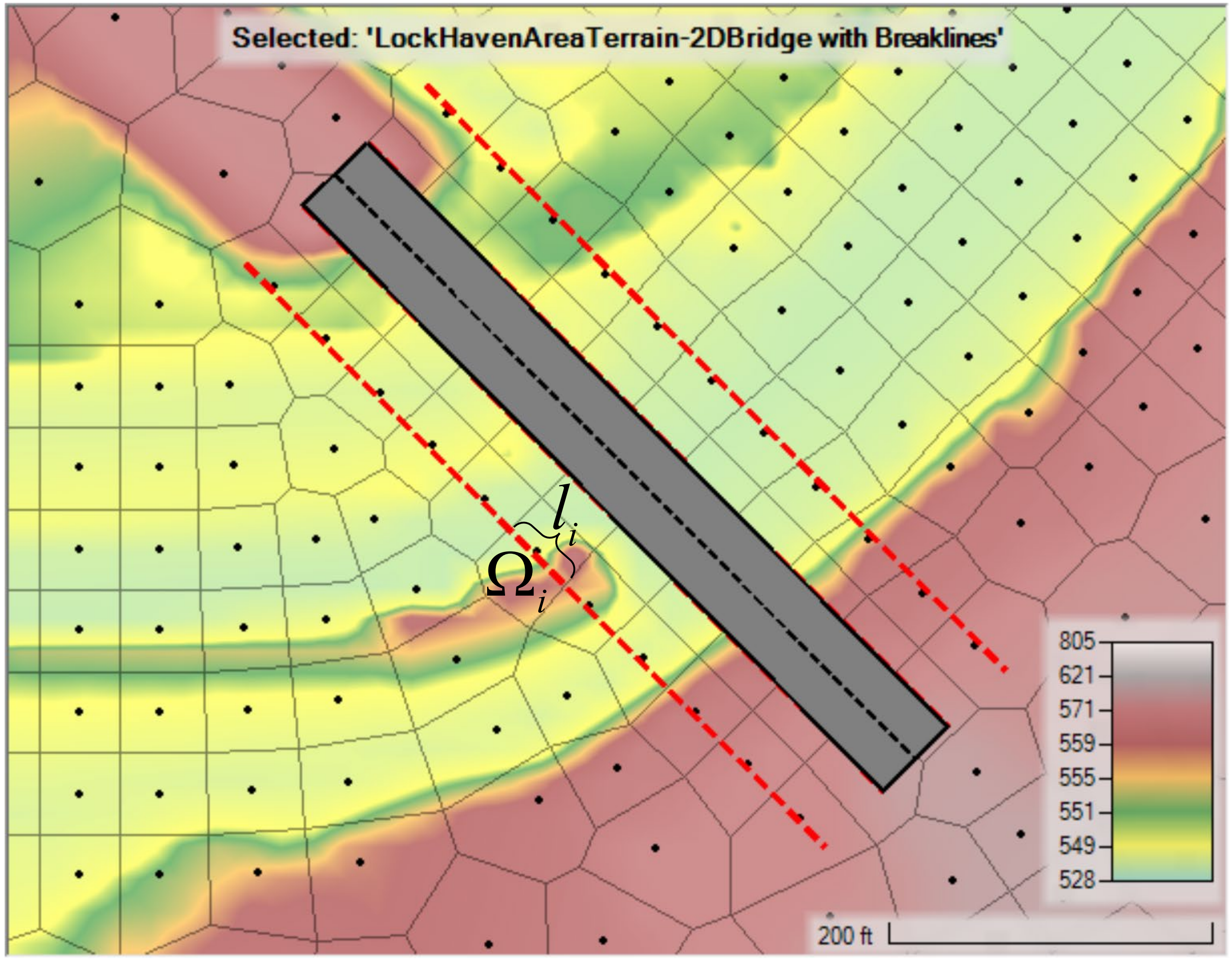
- Bridge energy losses simulated by increasing bottom shear stresses by a bridge drag factor under bridge faces

$$\boldsymbol{\tau}_b = \lambda_B \rho C_D |V| V \qquad \lambda_B(t) \geq 1$$

3. Proportional-Integral-Derivative Controller used to adjust bridge drag factor to impose headwater elevation

$$\frac{d\lambda_B(t)}{dt} = K_i e(t) + K_p \frac{de(t)}{dt} + K_d \frac{d^2 e(t)}{dt^2}$$

$$e(t) = z_{s,H} - \overline{z}_{s,H} \qquad \overline{z}_{s,H} = \frac{\sum_{i \in H} \Omega_i l_i z_{s,i}}{\sum_{i \in H} \Omega_i l_i}$$



Family of Rating Curves - 2D Flow Areas

- Curves are used differently from 1D solution
- Compute US XS and DS XS are used to compute expected 1D Flow
- Friction lose terms are adjusted so that compute 2D flows match expected 1D Flow (one adjustment factor for all the bridge faces)

Bridge – Output

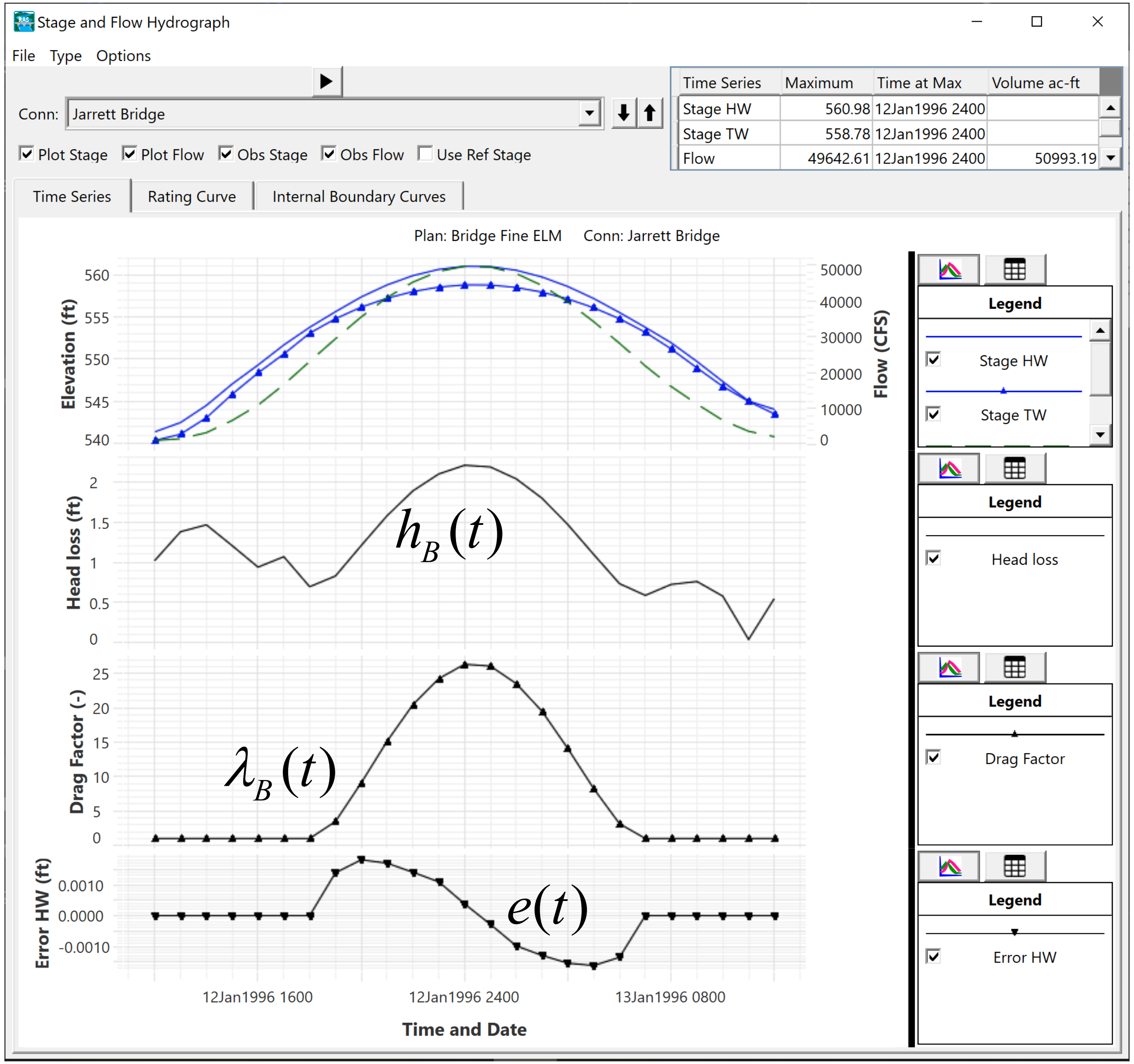
- Head loss through bridge

$$h_B = \overline{z}_{s,H} - \overline{z}_{s,T}$$

- Drag factor
  - Limited to 1
  - Constant under bridge
- Error

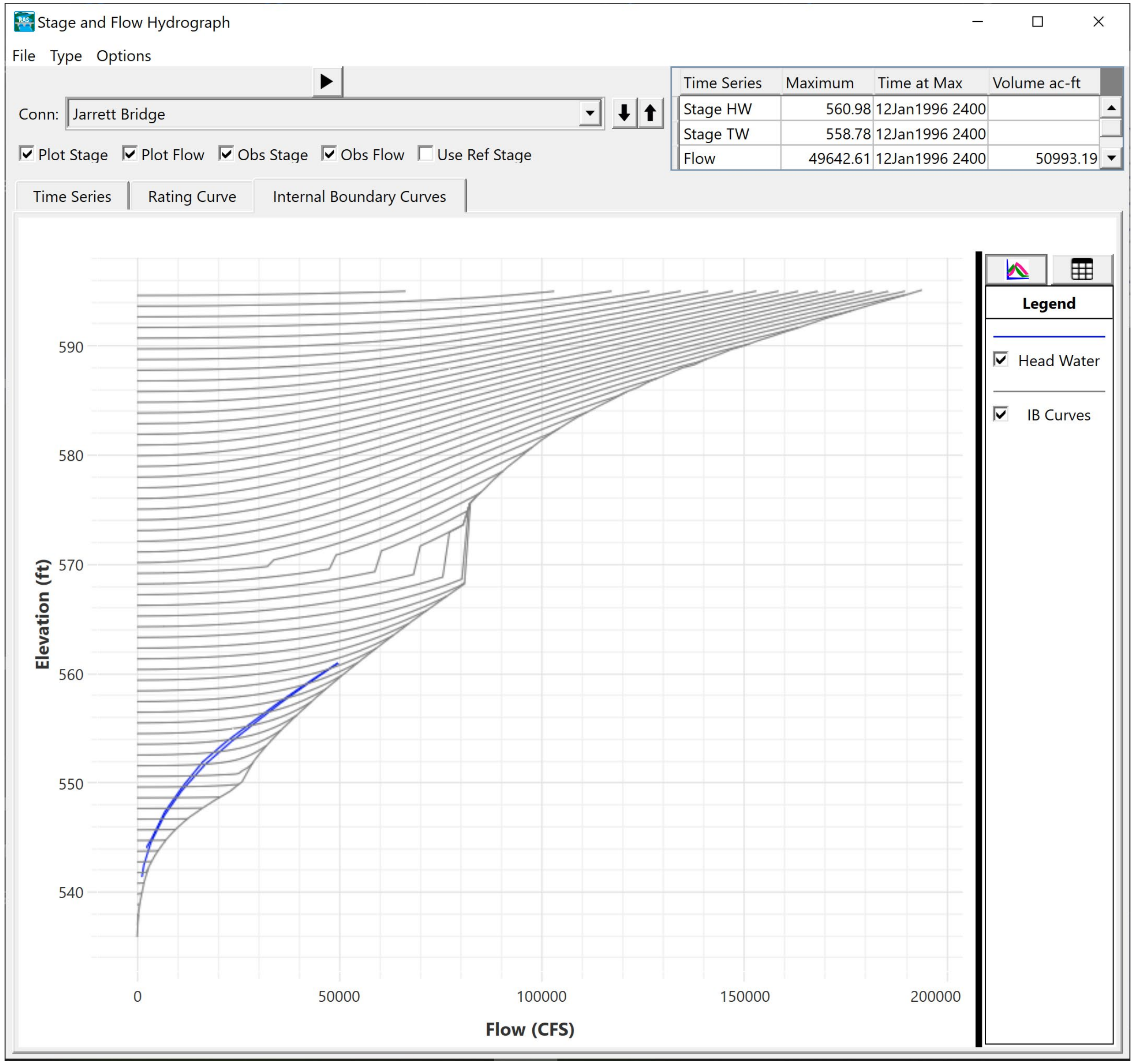
$$e(t) = z_{s,H} - \overline{z}_{s,H}$$

  - Usually small but can be increase if controller has trouble especially during flow transitions

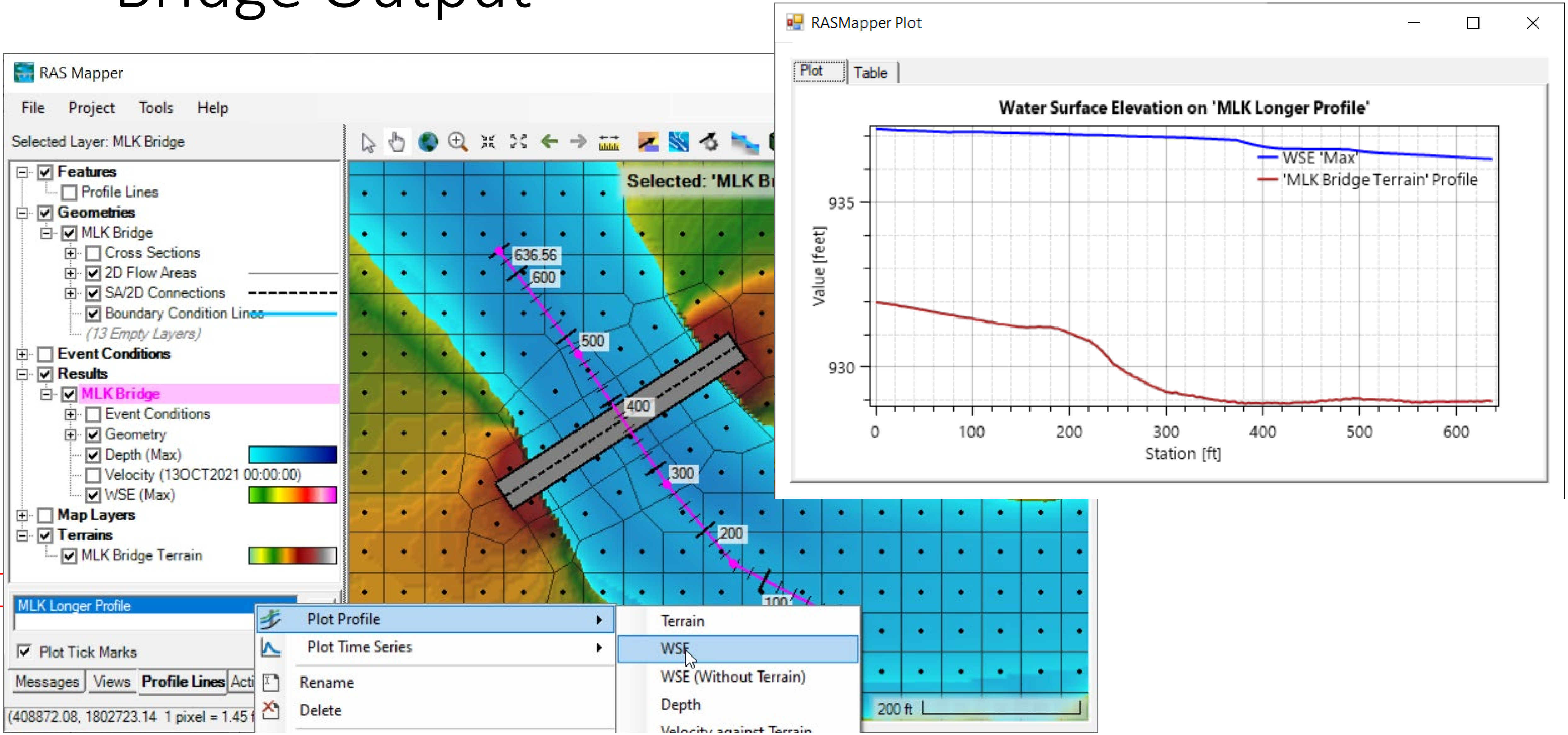


Bridge – Output

- Blue line represents actual flows and stages during simulation
- If PID Controller has trouble, the blue line can go outside of the rating curve data



Bridge Output

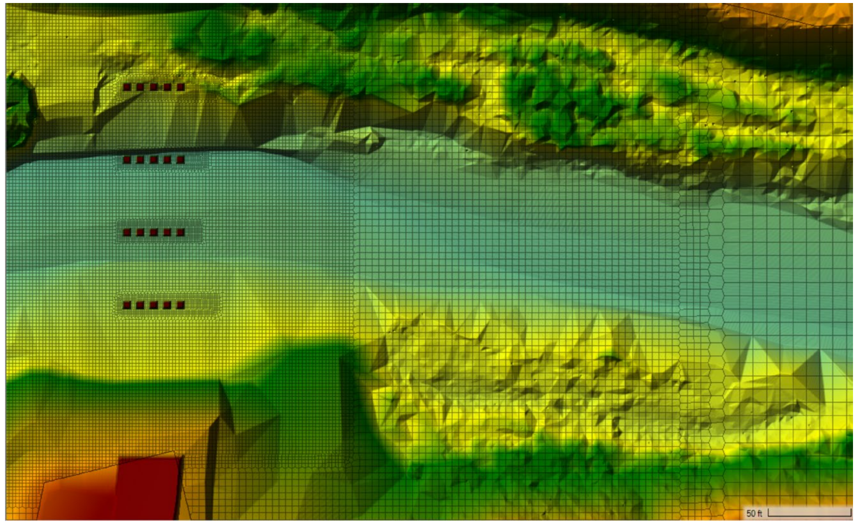


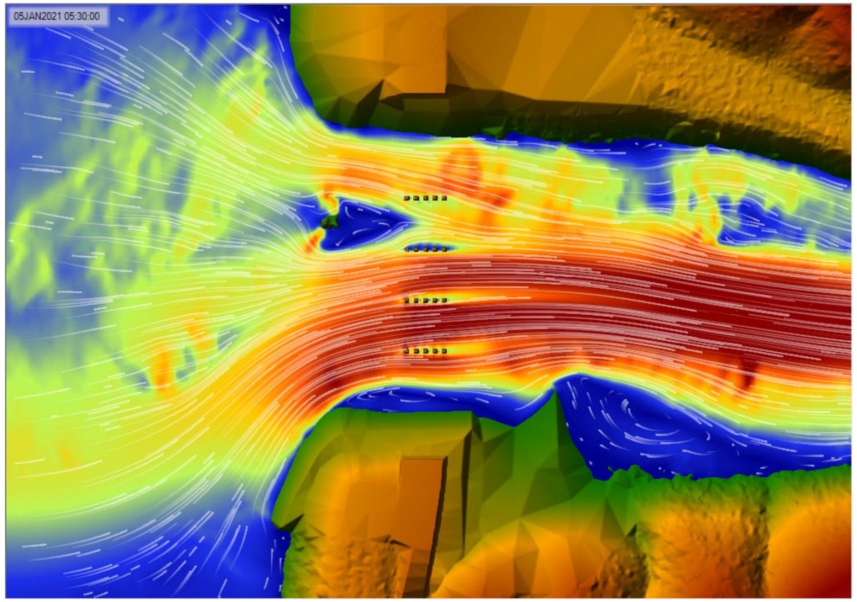
Considerations

- Spacing/cell sizes through a bridge modeled as 1D are generally larger than users would like
- Necessary to use these cell sizes so that we do not duplicate contraction and expansion losses (however small they may be) in 2D domain and in 1D curves
- Cannot tune PID controller parameters for specific applications

Detailed Bridge Modeling

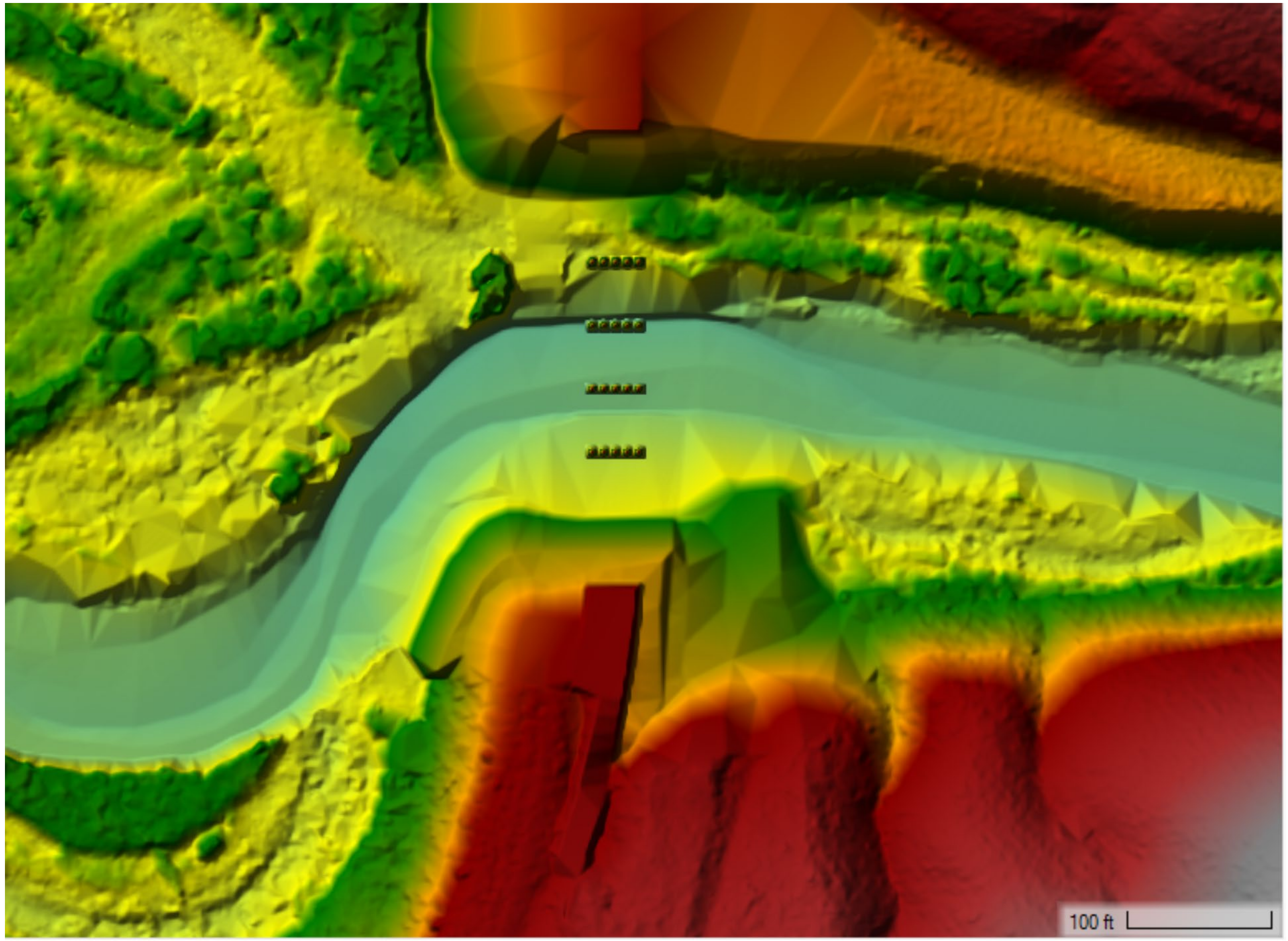
- Simulating all energy loses with a high-resolution 2D model
- Requirements high-resolution terrain and mesh
- Pros
  - Physics-based
  - High-resolution results
- Cons
  - Depth-averaged assumption
  - No pressurized flow or overtopping in Versions 6.3 and earlier
  - Computationally Expensive





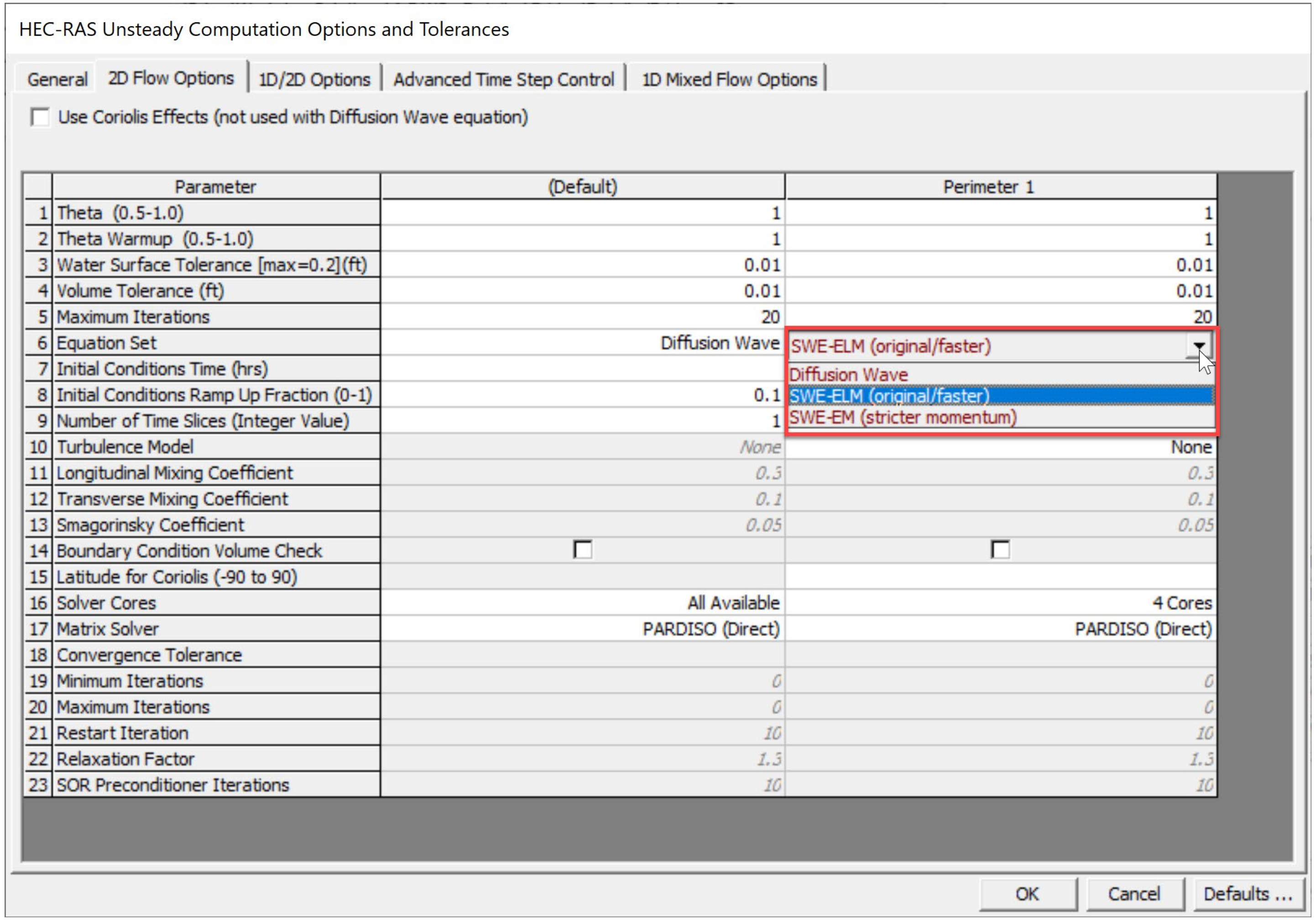
Terrain for Detailed Bridge Modeling

- Requirements
  - High-resolution
  - High-quality
- Terrain Modifications
  - Piers
  - Embankments
  - Bathymetry Modifications



Equation Set

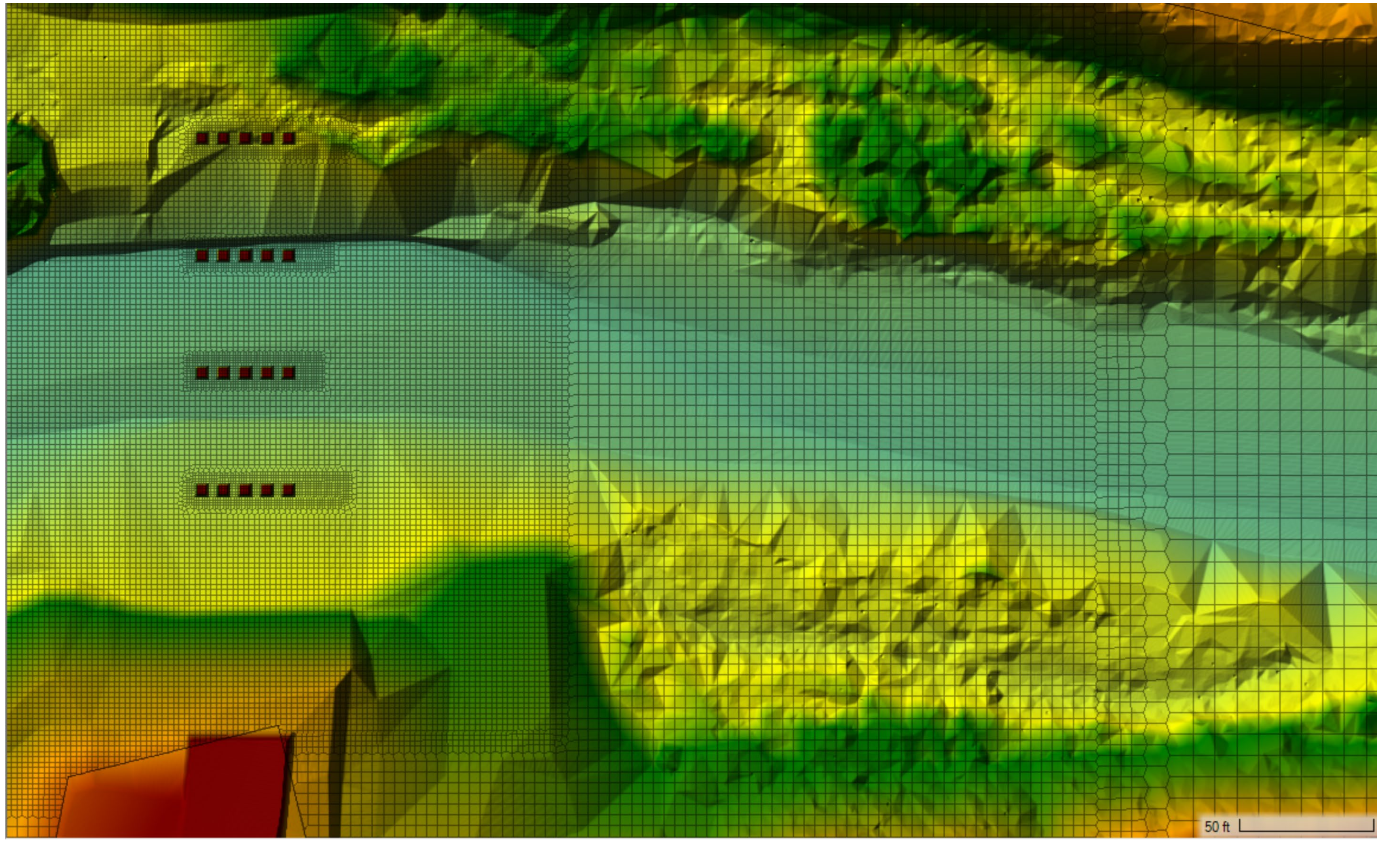
- Diffusion Wave Equation
  - For preliminary runs and/or initialization
  - Cannot simulate contraction and expansions
  - Cannot simulate mixed flow
- Shallow Water Equations
  - Production runs
  - Necessary to include Turbulence
  - SWE-EM has better momentum conservation



	Parameter	(Default)	Perimeter 1
1	Theta (0.5-1.0)	1	1
2	Theta Warmup (0.5-1.0)	1	1
3	Water Surface Tolerance [max=0.2](ft)	0.01	0.01
4	Volume Tolerance (ft)	0.01	0.01
5	Maximum Iterations	20	20
6	Equation Set	Diffusion Wave	SWE-ELM (original/faster)
7	Initial Conditions Time (hrs)		
8	Initial Conditions Ramp Up Fraction (0-1)	0.1	
9	Number of Time Slices (Integer Value)	1	
10	Turbulence Model	None	None
11	Longitudinal Mixing Coefficient	0.3	0.3
12	Transverse Mixing Coefficient	0.1	0.1
13	Smagorinsky Coefficient	0.05	0.05
14	Boundary Condition Volume Check	☐	☐
15	Latitude for Coriolis (-90 to 90)		
16	Solver Cores	All Available	4 Cores
17	Matrix Solver	PARDISO (Direct)	PARDISO (Direct)
18	Convergence Tolerance		
19	Minimum Iterations	6	6
20	Maximum Iterations	6	6
21	Restart Iteration	10	10
22	Relaxation Factor	1.3	1.3
23	SOR Preconditioner Iterations	10	10

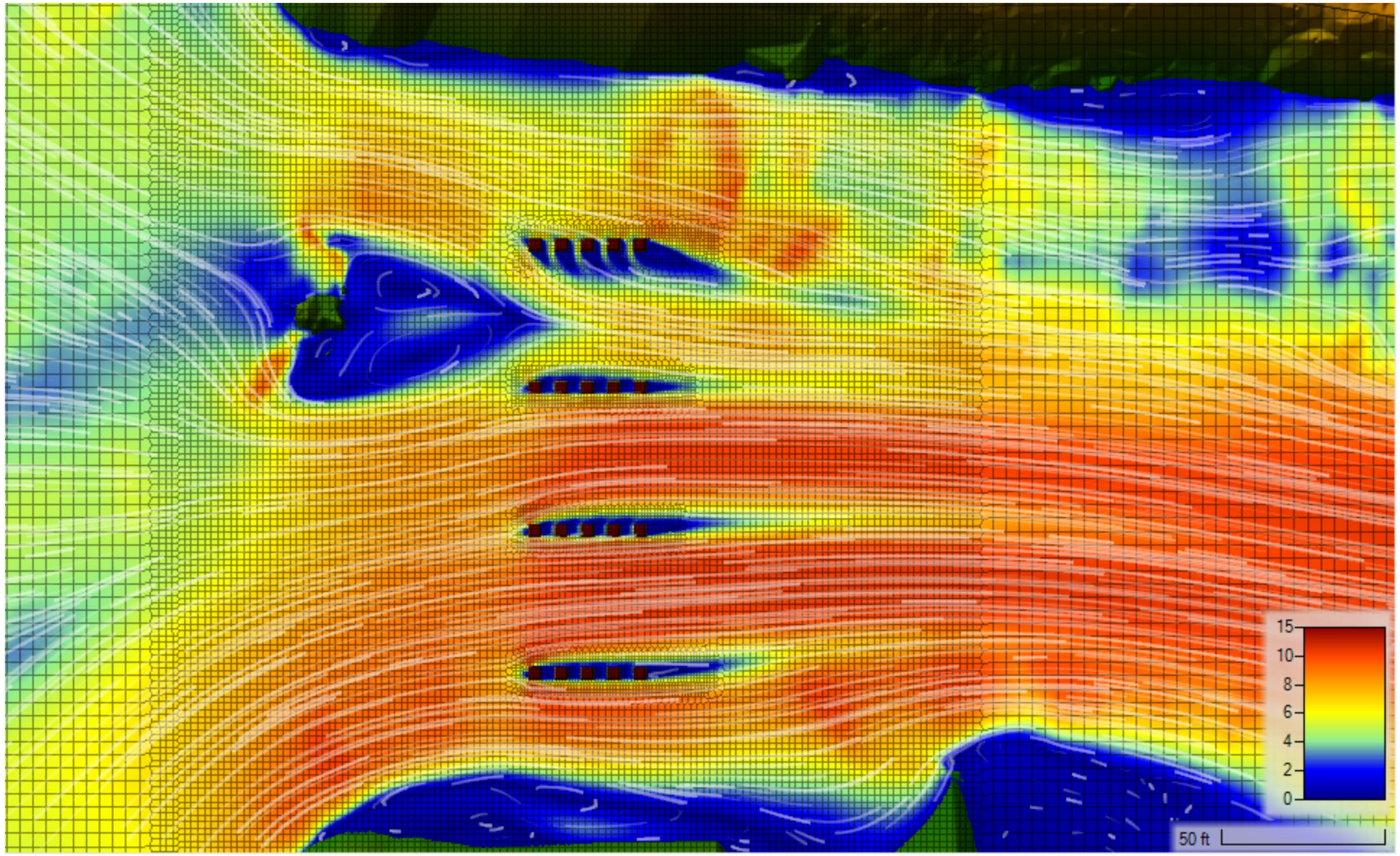
Computational Mesh

- Preliminary runs with simple coarse mesh
- Breaklines and refinement regions for high-resolution meshes
  - Minimum cell size will drive time step
- Perform grid convergence



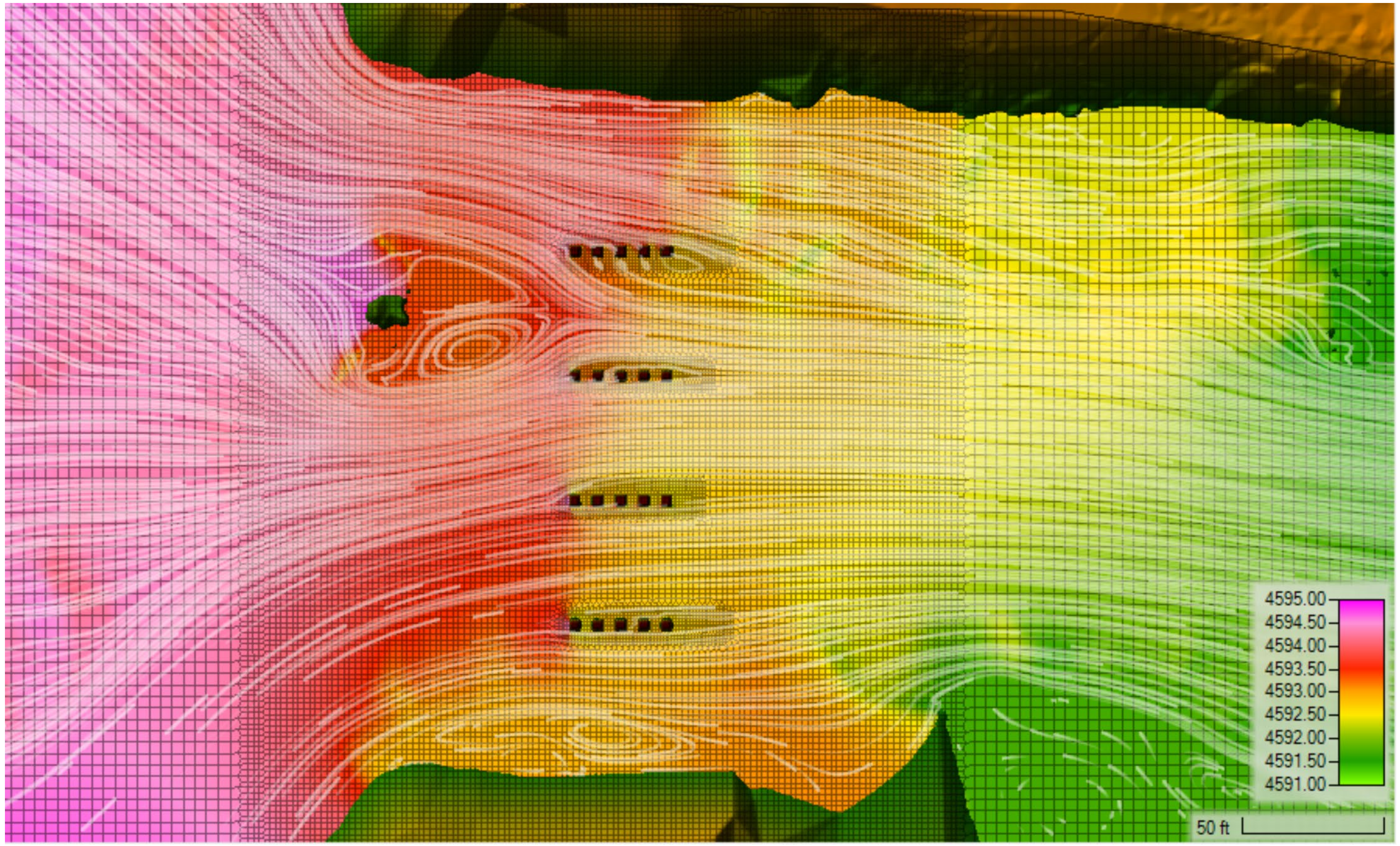
Momentum Diffusion

- Diffusion Term
  - Use Conservative Formulation!
- Eddy Viscosity Model
  - Use Parabolic-Smagorisnky
  - Calibrate if possible
  - In lieu of calibration, perform sensitivity analysis



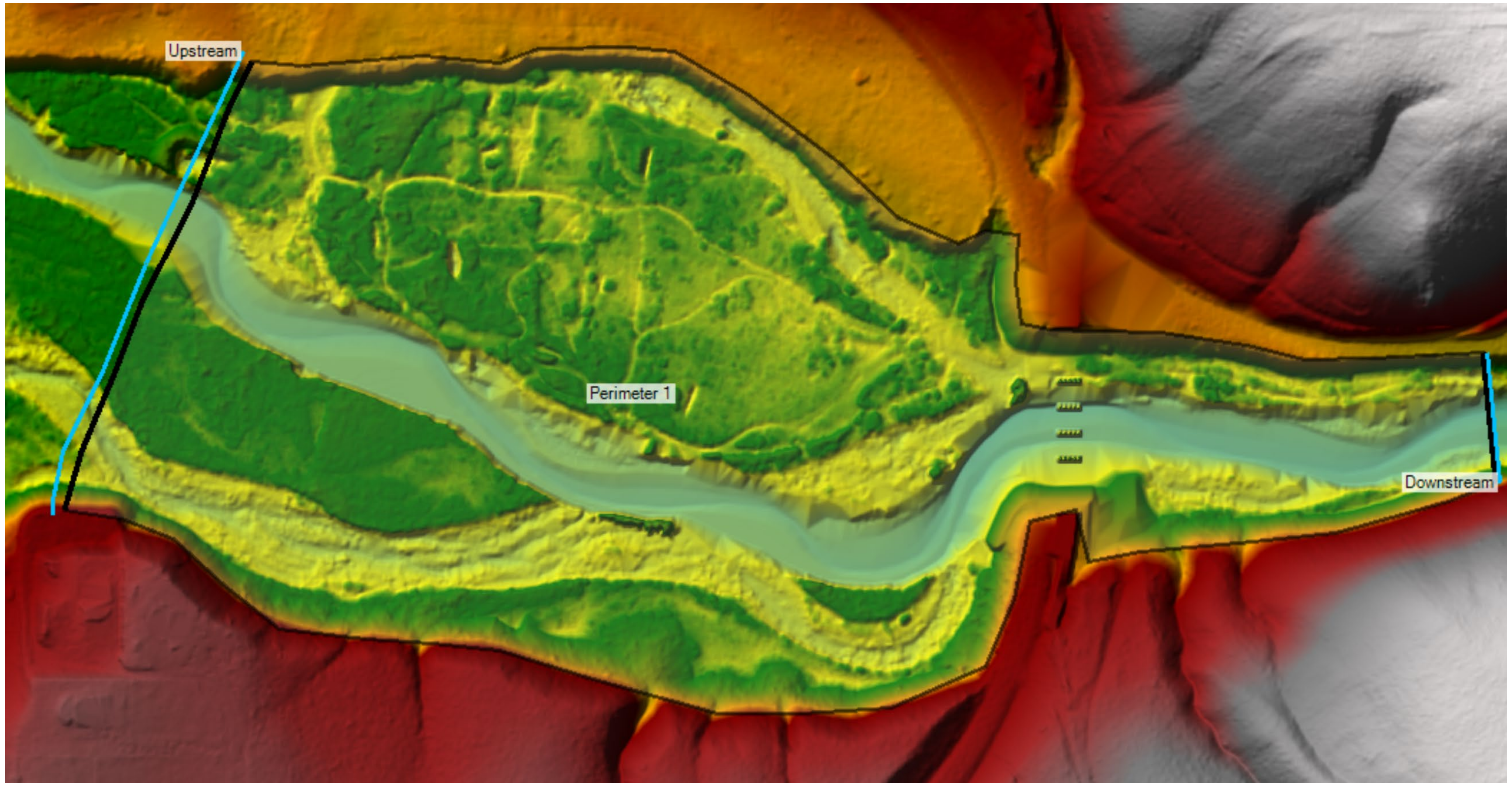
Bottom Roughness

- Use spatially variable Manning's n
- Different flows may require different bottom roughness



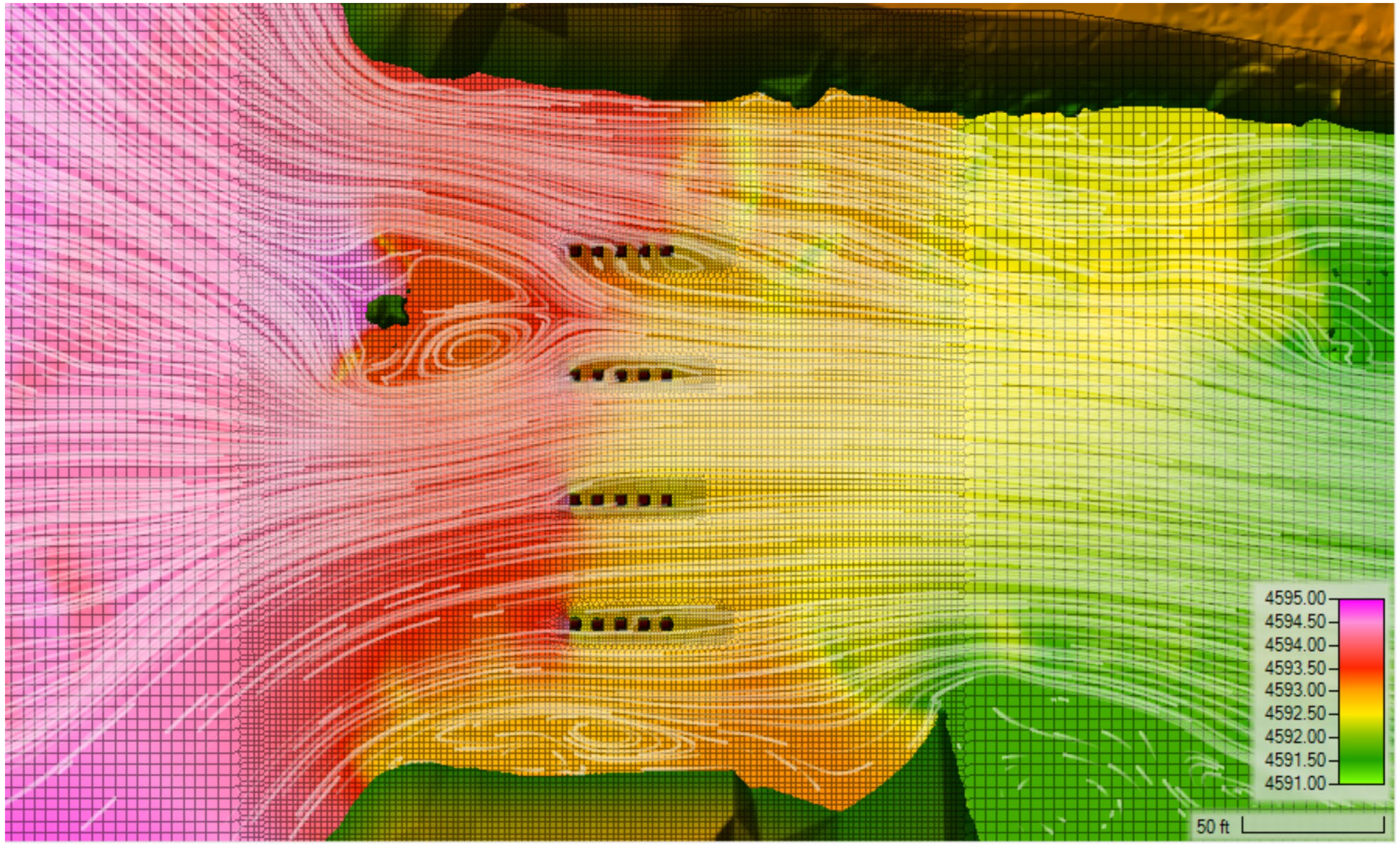
Boundary Conditions

- Tempting to place them very close to the bridge but don't
- Perform sensitivity on boundary placement and boundary values (such as friction slope)
- Place boundaries in areas with 1D flow (i.e. no recirculation, or sharp contracts and expansions)



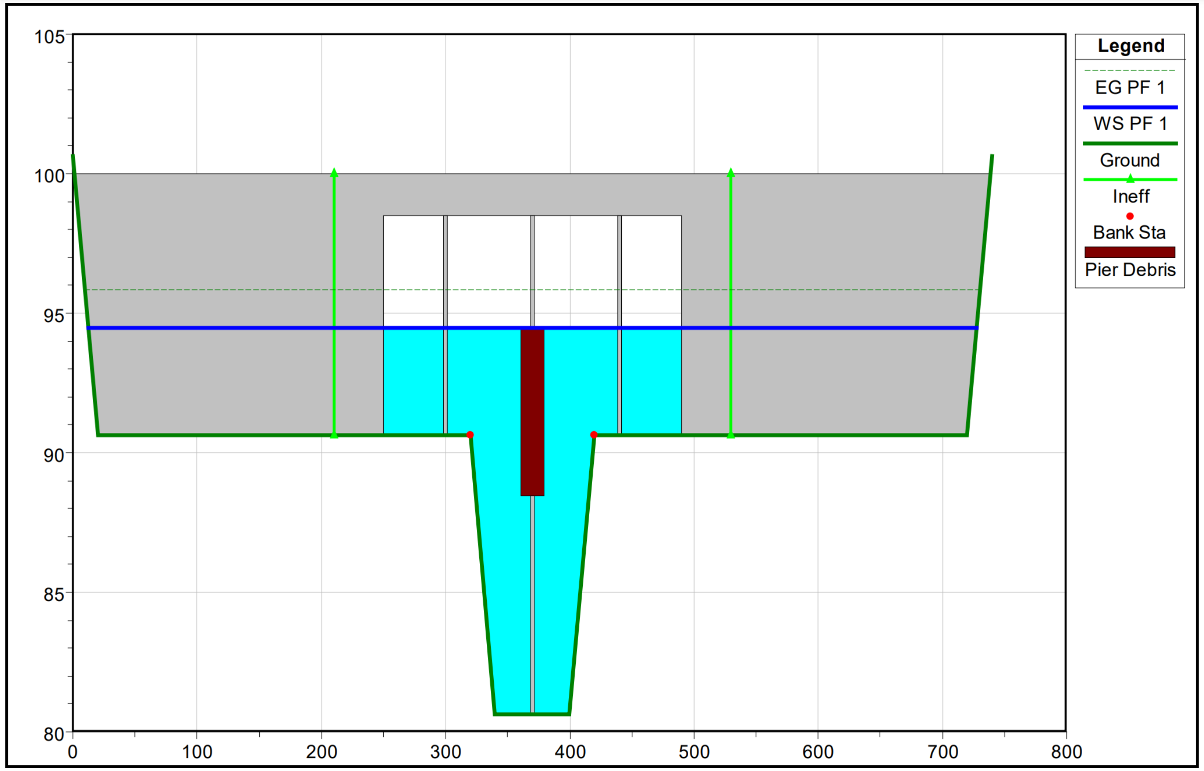
Advanced Computational Parameters and Options

- Time Step
  - Variable time step algorithm
  - Hand calculations of Courant
  - Model stability
- Implicit Weighting Factor
  - 1.0 for preliminary runs
  - 0.5-0.6 for production unsteady flow runs
  - Not important for steady flow

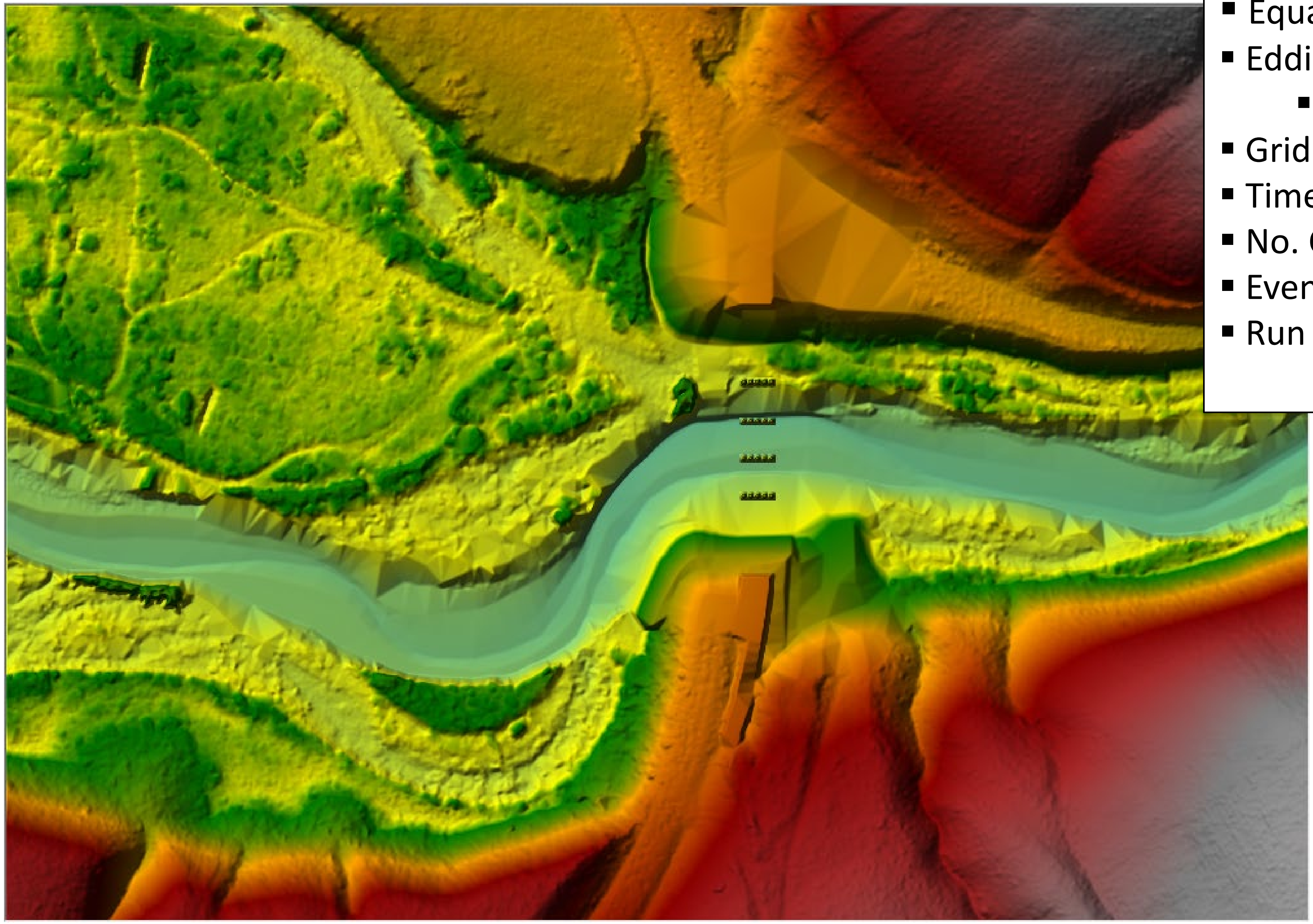


Limitations

- Flow must be below bridge deck
  - No pressured flow
  - No flow overtopping
- 2D Flow Assumption
  - Breaks down when cell resolution is much finer than depth
- Hydrostatic Pressure Assumption
- Cannot simulate
  - Bridge openings such as culverts
  - Debris (can be done in 1D)
  - Ice (can be done in 1D)
  - Waves

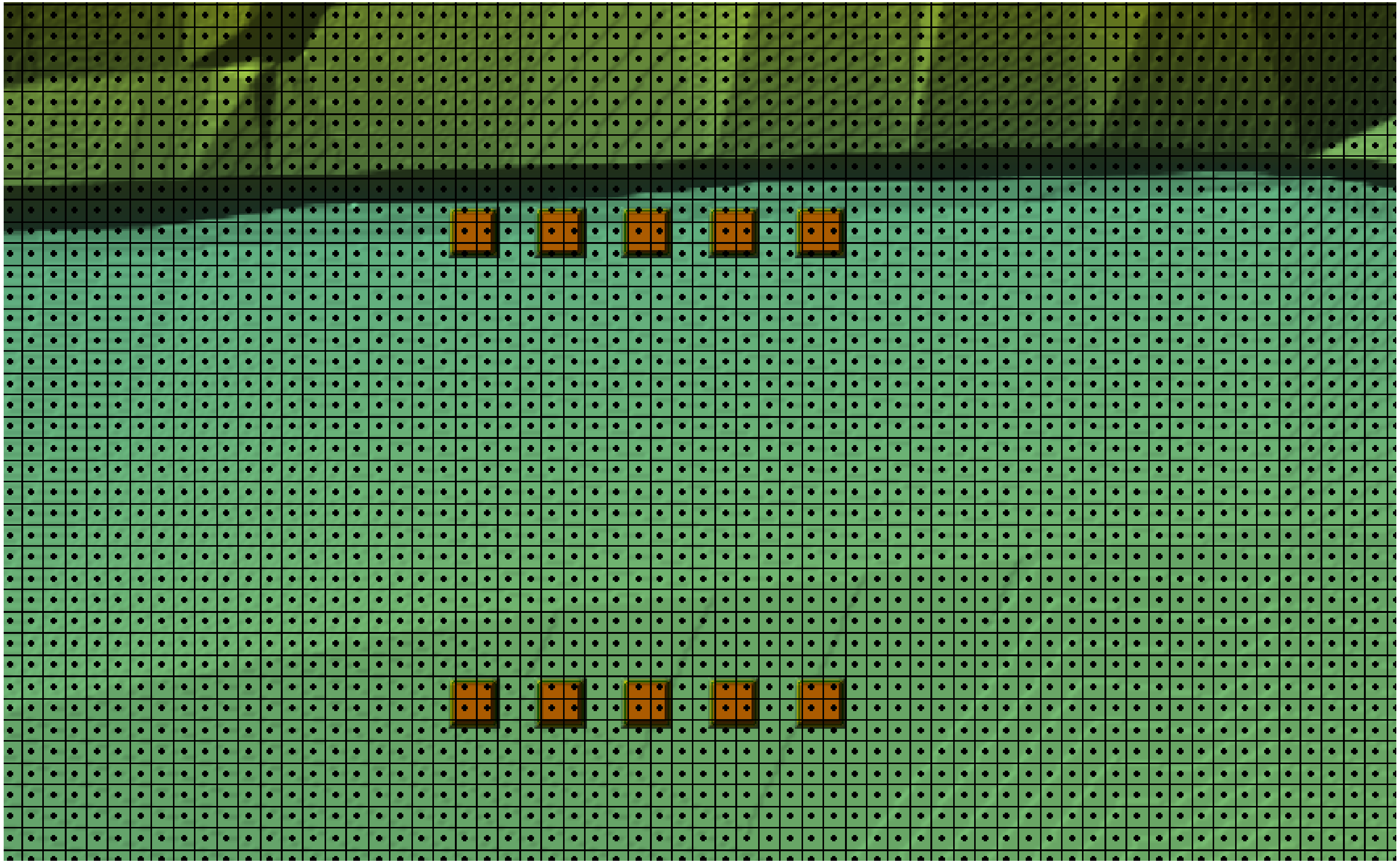


Detailed Bridge Modeling



- Equation set = SWE-ELM
- Eddie Viscosity Coefficient
  - Conservative D_L and D_T = 0.5
- Grid Size = 2x2 ft up to 8x8 ft
- Time step = 0.2 seconds
- No. Cells = 45,000
- Event Duration = 20 min. Steady Flow
- Run Time = 3min 39s

Detailed Bridge Modeling



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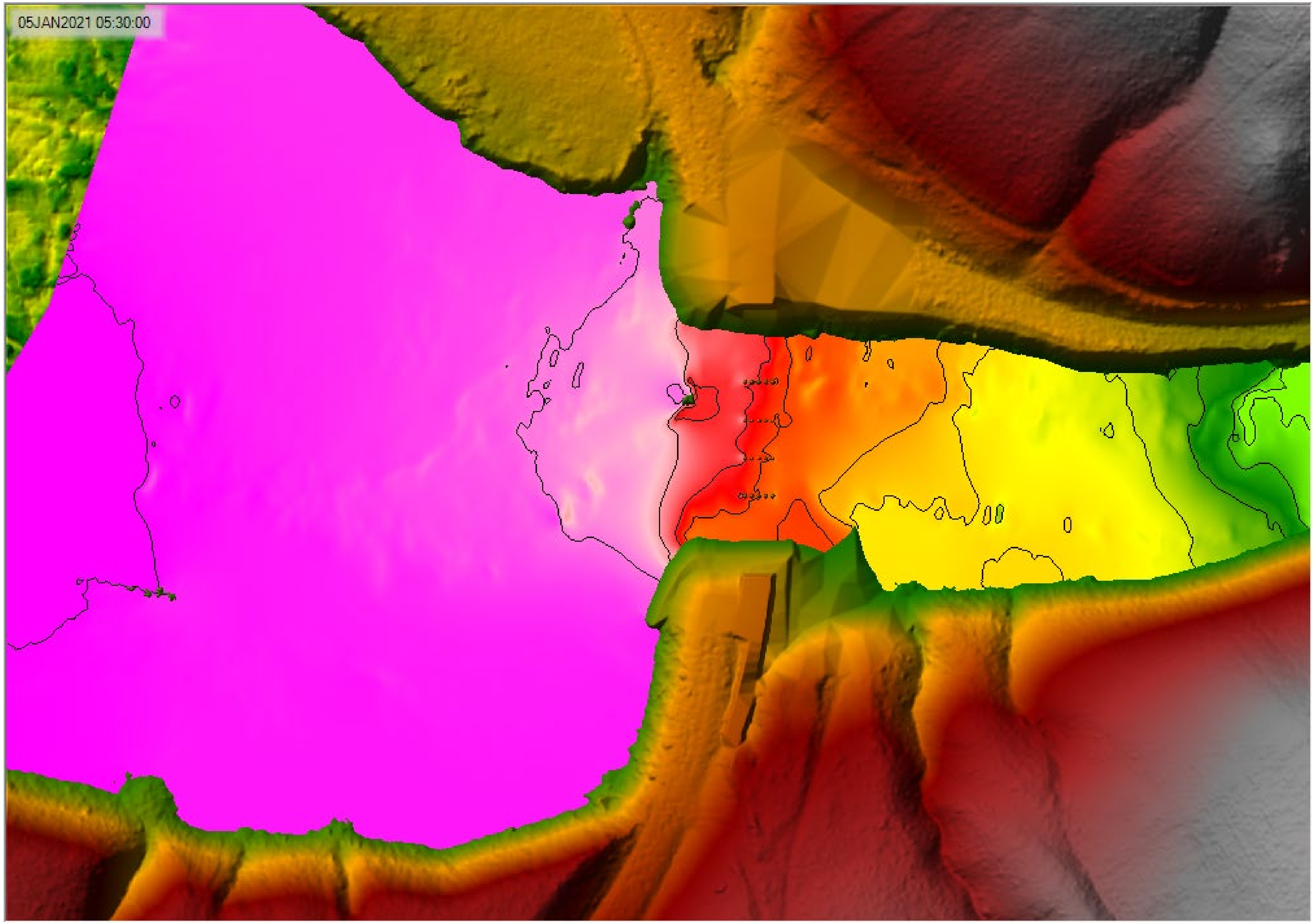
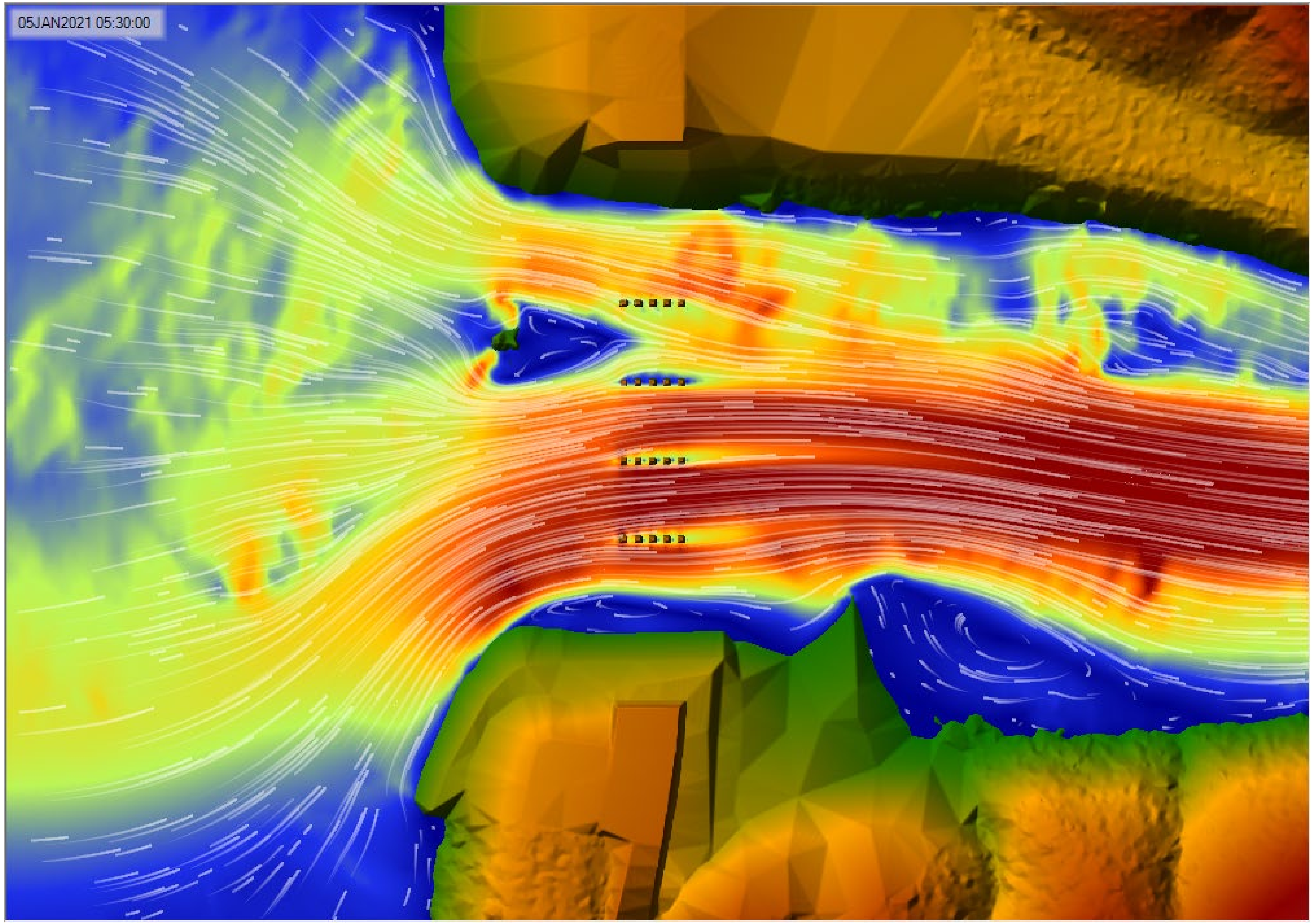
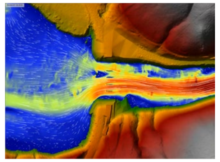
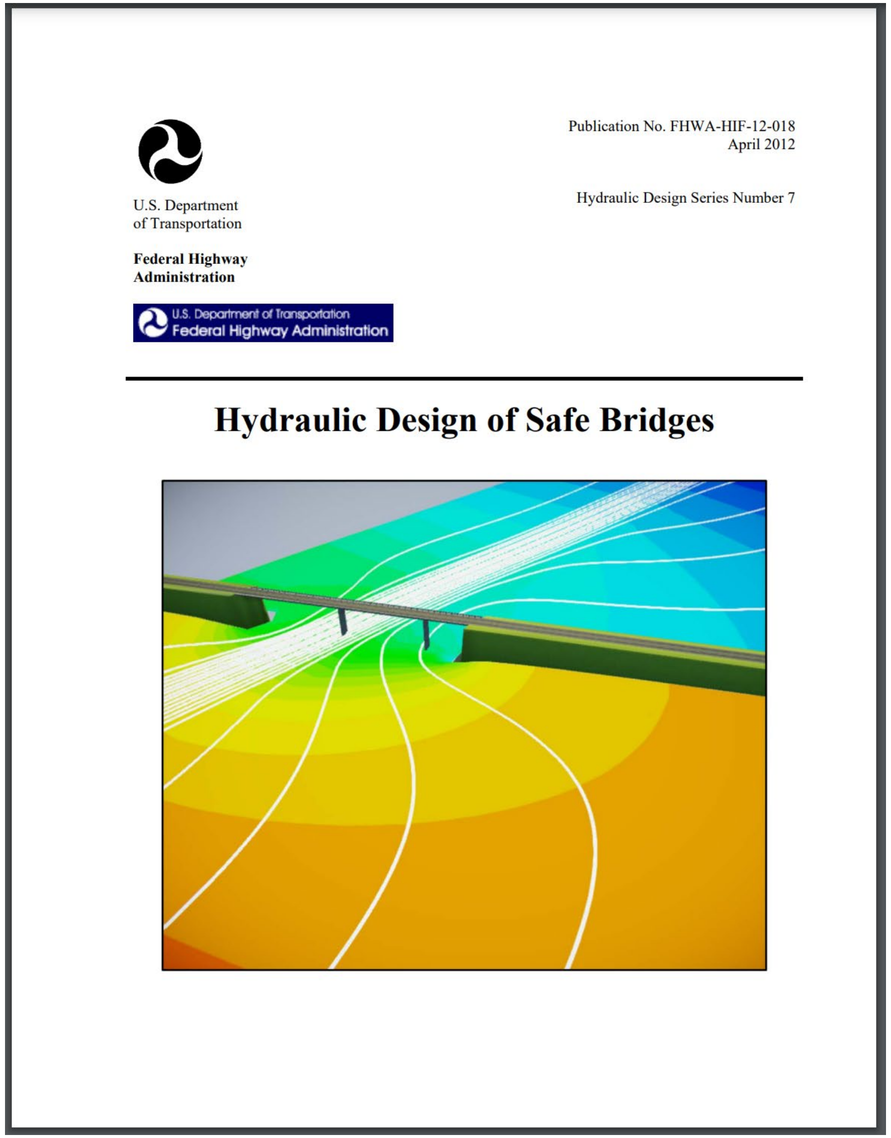


Detailed Bridge Animation





Resources



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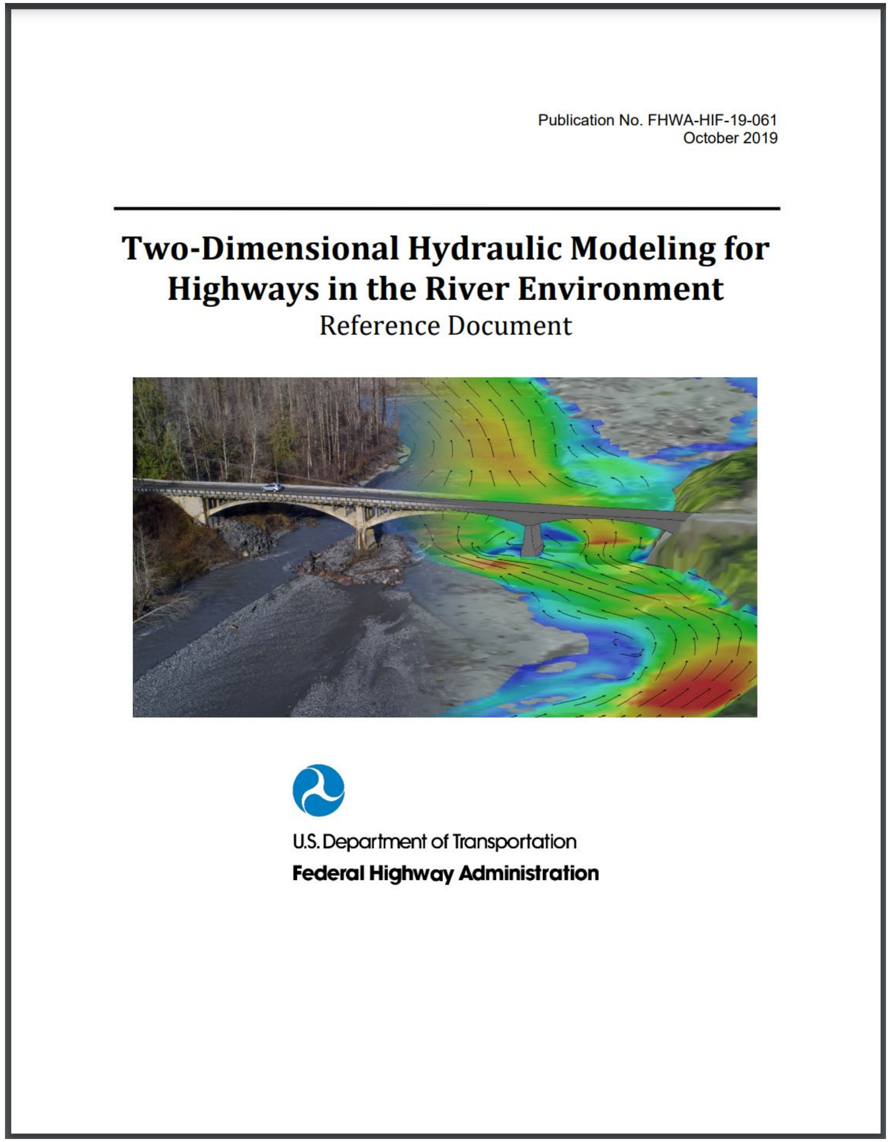
Hydraulic Design Series Number 7

U.S. Department
of Transportation

**Federal Highway
Administration**

U.S. Department of Transportation
Federal Highway Administration

Hydraulic Design of Safe Bridges



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October 2019

Two-Dimensional Hydraulic Modeling for Highways in the River Environment
Reference Document

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Questions?

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