

Bridge Modeling

Alex Sanchez, Ph.D,
Mark Jensen, M.S., Cameron Ackerman, P.E., D.WRE

USACE, Institute for Water Resources, Hydrologic Engineering Center





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

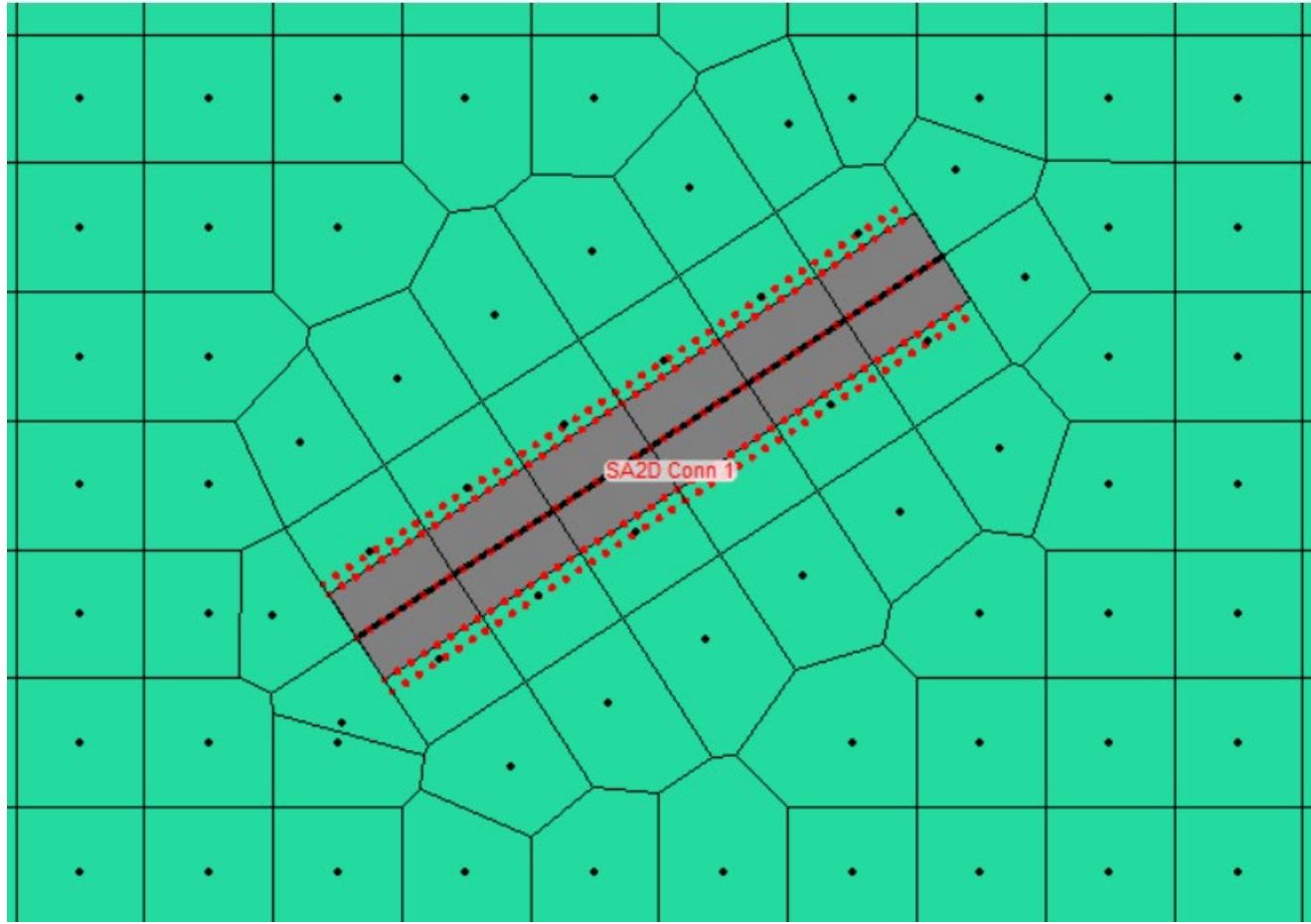


- Use HEC-RAS **1D Bridge Geometry and Cross Section** Layout (automated layout) inside of 2D Flow Area
- Develop a family of Headwater/Tailwater Flow curves from RAS 1D bridge hydraulic calculations during geometry pre-processing
- Uses a special momentum equation that gets applied only at the 2D bridge 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 through 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

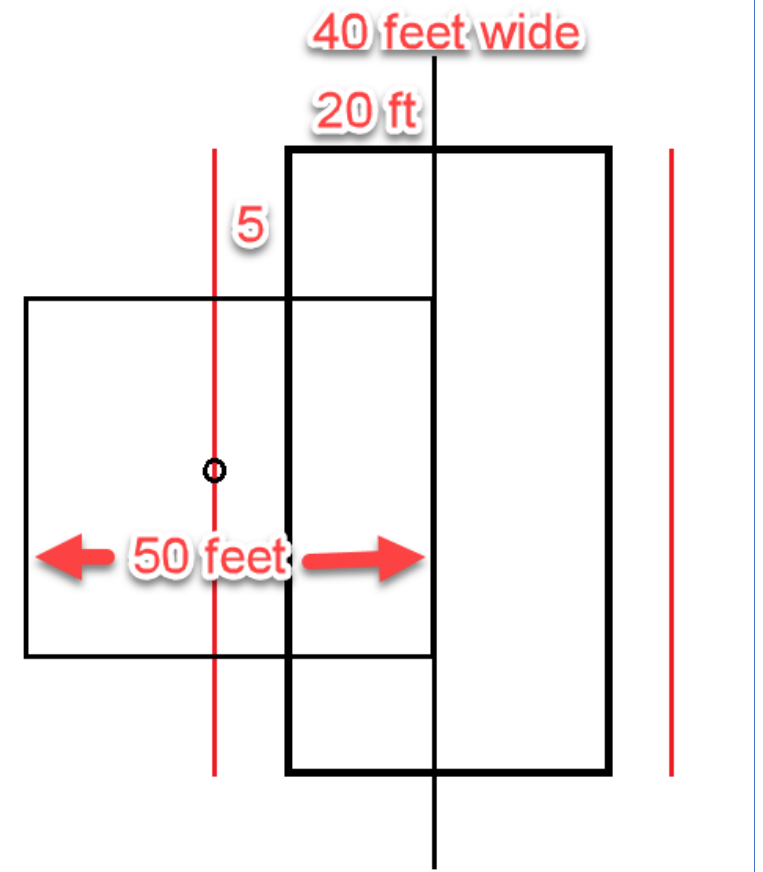
- 1D Bridge loses computed between “XS” downstream of deck through the bridge to “XS” upstream of bridge deck.
- Enforced as Breakline
- Set cells sizes (or cell US/DS length) so that the cell centers match the domain covered by 1D Bridge loses
- Model **Bridge opening** (not overbanks)





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





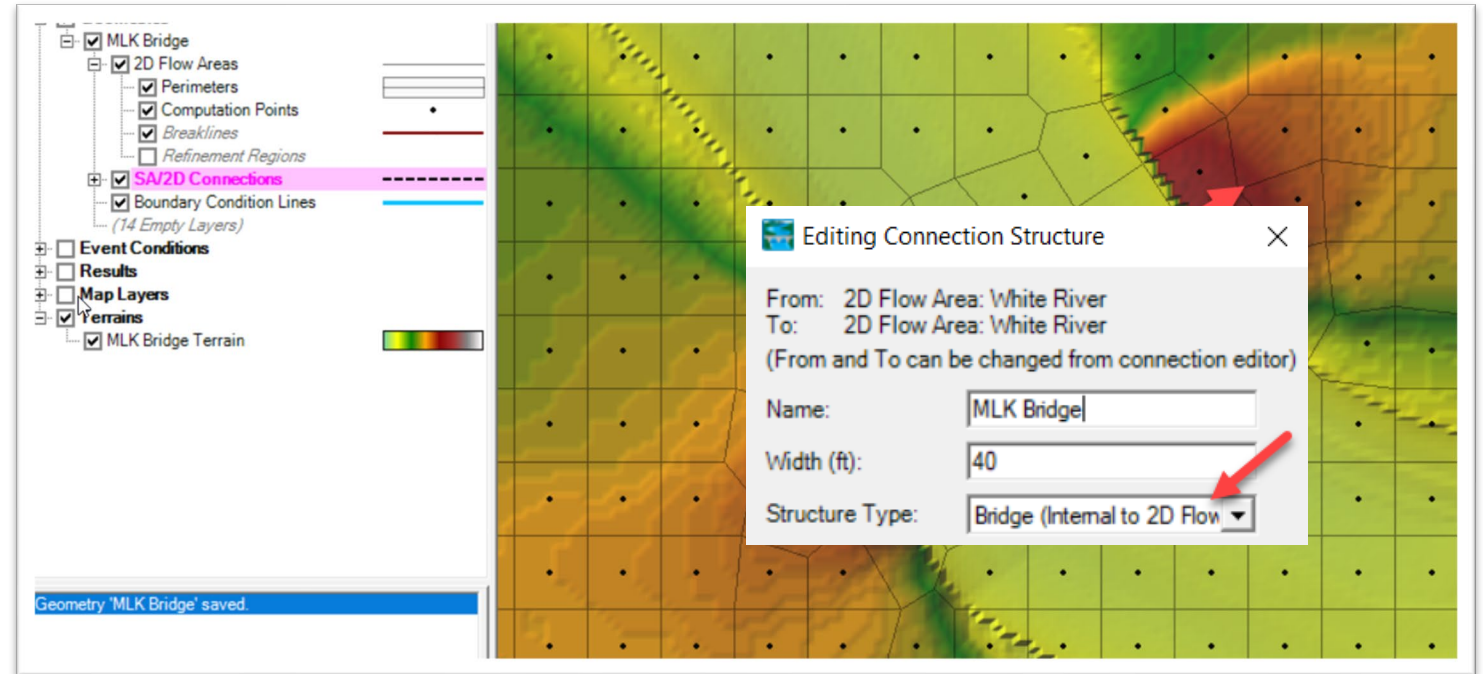
Steps for Adding a 2D Bridge

- 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



The screenshot displays the HEC-RAS software interface. On the left, the 'Model' tree shows the 'SA/2D Area Connection' layer selected. The 'Editing Connection Structure' dialog box is open, showing the following fields:

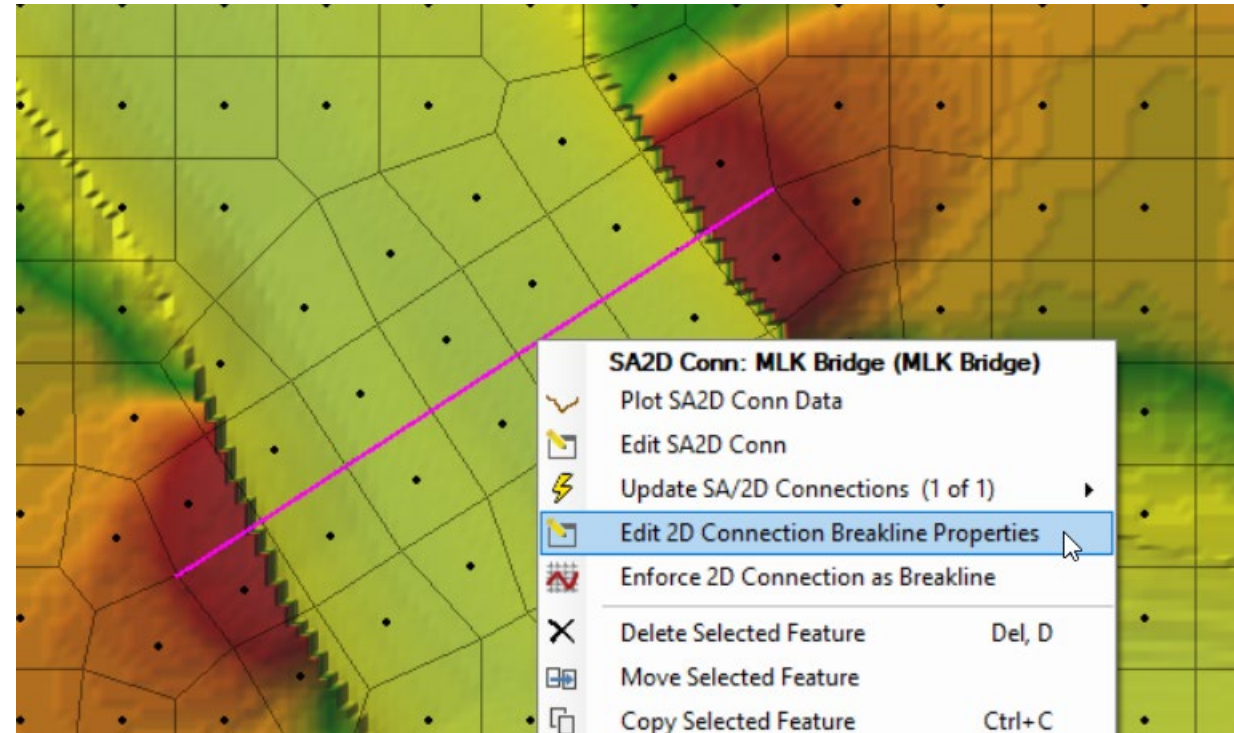
- From: 2D Flow Area: White River
- To: 2D Flow Area: White River
- (From and To can be changed from connection editor)
- Name: MLK Bridge
- Width (ft): 40
- Structure Type: Bridge (Internal to 2D Flow)

A red arrow points to the 'Structure Type' dropdown menu. The background shows a topographic map with a grid overlay and a bridge centerline drawn across it.



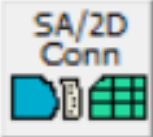
Bridge Centerline and Mesh Adjustments

- 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

Connection Data Editor - MLK Bridge

File View Options Help

Connection: MLK Bridge [Apply Data]

Description: [Breach (plan data) ...]

From: 2D Flow Area: White River [Set SA/2D ...]

To: 2D Flow Area: White River [Set SA/2D ...]

Weir Length: n/a

Centerline Length: 348.96

Centerline GIS Coords...

Cut profile from terrain ...

Clip Weir Profile to 2D Cells...

Overflow Computation Method: Normal 2D Equation Domain Use Weir Equation

Structure Type: **Bridge (Internal to 2D Flow Area)**

Plot: US Bounding XS

MLK Bridge
US Bounding XS

Elevation (ft)

Station (ft)

Legend

- Ground
- Bank Sta
- Current Terrain



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 well 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

Deck/Roadway Data Editor

Distance	Width	Weir Coef
5.	40.	2.6

Upstream				Downstream		
	Station	high chord	low chord	Station	high chord	low chord
1	40	950	930	40	950	930
2	47	950	939	47	950	939
3	50	950	941.175	50	950	941.175
4	53	950	942.45	53	950	942.45
5	56	950	943.2	56	950	943.2
6	59	950	943.8	59	950	943.8
7	62	950	944.25	62	950	944.25
8	65	950	944.55	65	950	944.55

U.S Embankment SS
 D.S Embankment SS

Weir Data
 Max Submergence:
 Min Weir Flow El:

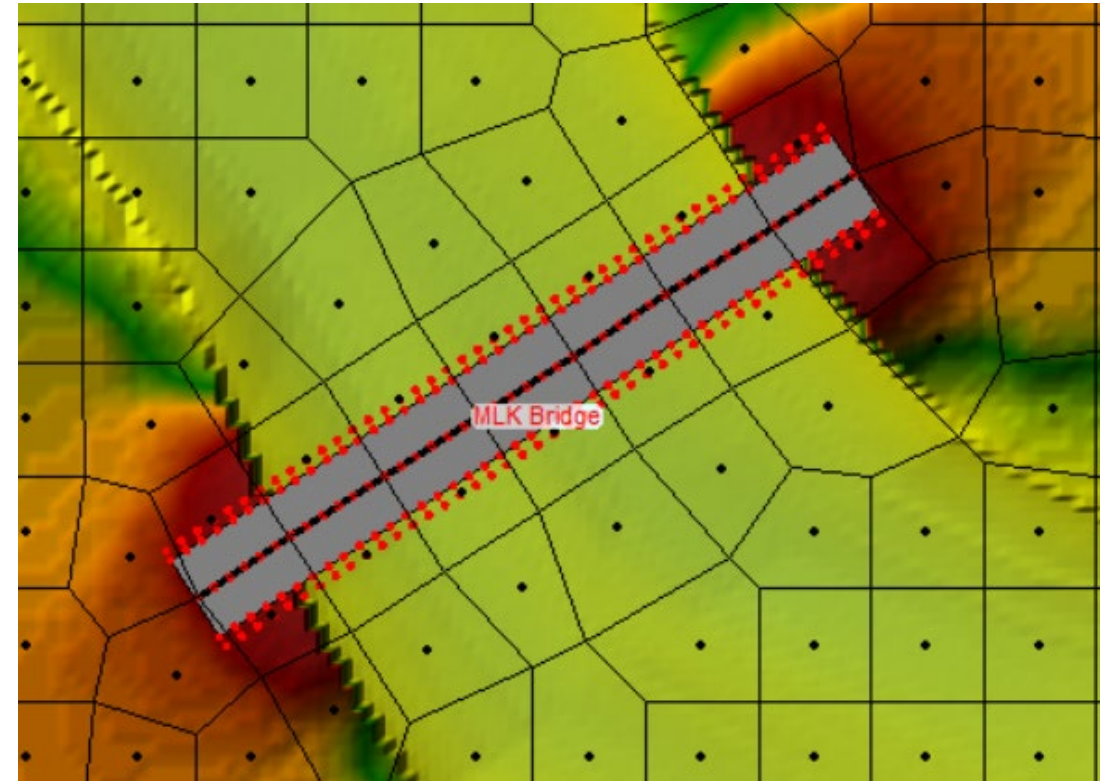
Weir Crest Shape
 Broad Crested
 Ogee

Enter distance between upstream cross section and deck/roadway. (ft)



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

Pier Data Editor

Add Copy Delete Pier # 1 ↓ ↑

Del Row Centerline Station Upstream 110

Ins Row Centerline Station Downstream 110

Floating Pier Debris

All On ... All Off ... Apply floating debris to this pier

Set Wd/Ht for all ... Debris Width:

Debris Height:

	Upstream		Downstream		
	Pier Width	Elevation	Pier Width	Elevation	
1	6	925	6	925	▲
2	6	945	6	945	
3					
4					
5					
6					▼

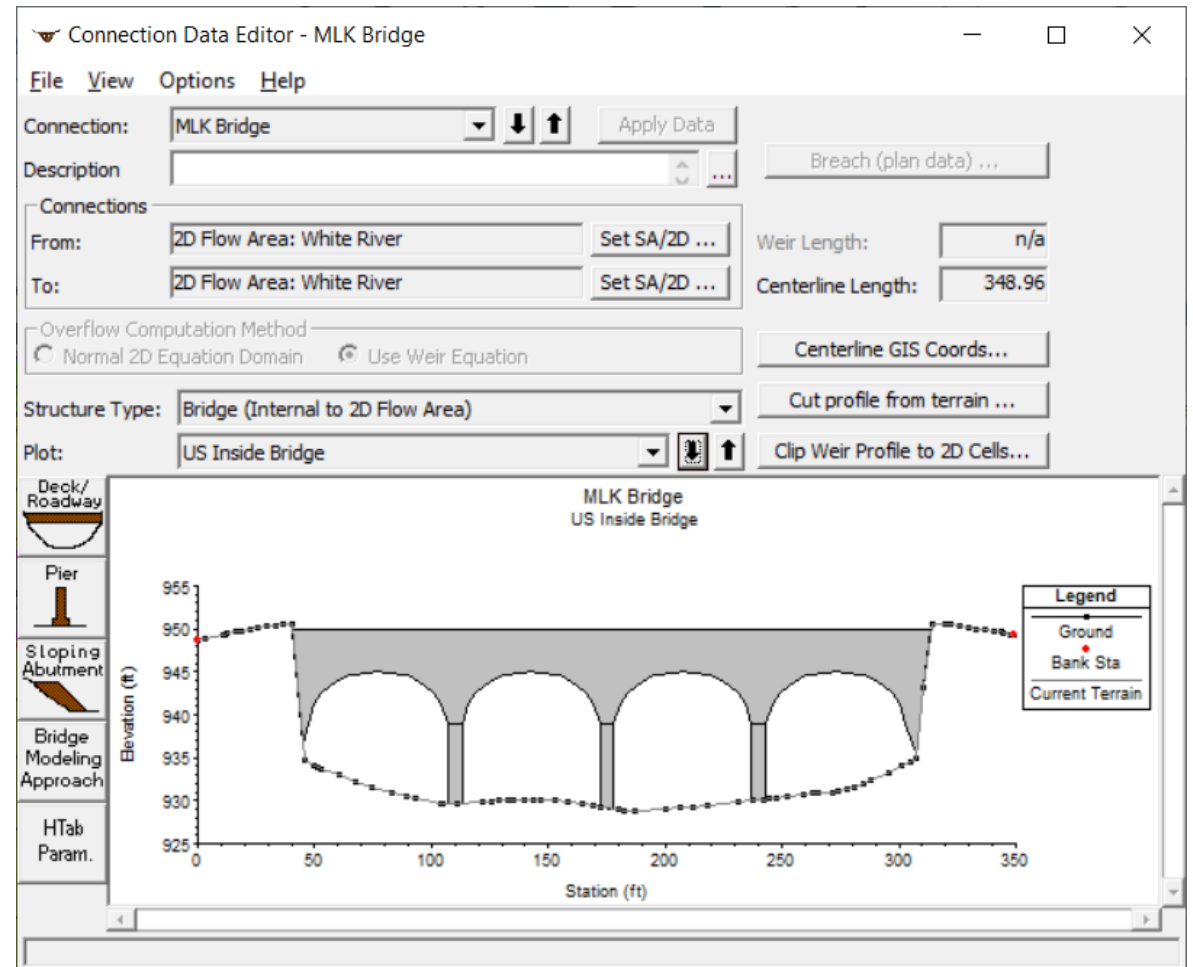
OK Cancel Help Copy Up to Down

Select the Pier to Edit



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				Upstream Inside				Downstream Inside				Downstream Outside			
Main Channel Bank Stations				Main Channel Bank Stations				Main Channel Bank Stations				Main Channel Bank Stations			
Left Bank Sta		Right Bank Sta		Left Bank Sta		Right Bank Sta		Left Bank Sta		Right Bank Sta		Left Bank Sta		Right Bank Sta	
0		348.96		0		348.96		0		348.96		0		348.96	
Cross Section X-Y Coordinates				Cross Section X-Y Coordinates				Cross Section X-Y Coordinates				Cross Section X-Y Coordinates			
Station	Elevation	Mann n		Station	Elevation	Mann n		Station	Elevation	Mann n		Station	Elevation	Mann n	
1	0	948.51	0.035	1	0	948.61	0.035	1	0	947.96	0.035	1	0	947.78	0.035
2	7.3	949.17		2	3.37	948.91		2	0.63	948		2	3.85	948	
3	8.8	949.27		3	10.53	949.31		3	6.58	948.66		3	9.8	948.66	
4	12.42	949.33		4	11.34	949.33		4	12.52	948.97		4	15.75	948.97	
5	16.03	949.55		5	12.59	949.42		5	18.47	949.31		5	21.7	949.31	
6	19.65	949.64		6	16.48	949.62		6	24.42	949.62		6	27.65	949.62	
7	23.27	949.91		7	18.57	949.69		7	30.37	949.97		7	33.6	949.97	
8	25.15	949.97		8	22.19	949.96		8	31.64	950		8	39.55	950.28	
9	29.57	950.2		9	25.81	950.04		9	33.61	950.14		9	45.5	950.62	
10	30.5	950.27		10	29.42	950.25		10	36.32	950.28		10	50.75	935.55	
11	34.12	950.37		11	33.04	950.32		11	38.88	950.35		11	56.7	934.53	
12	37.05	950.56		12	36.66	950.56		12	42.49	950.62		12	59.64	934.17	
13	38.15	947.49		13	40.28	950.62		13	48.22	950.62		13	62.65	933.86	
14	42.3	935.27		14	45.53	934.82		14	50.63	943.49		14	68.6	933.29	
15	44.91	934.73		15	49.48	934.14		15	53.47	934.89		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

Connection Bridge Modeling Approach Editor

Low Flow Methods

Use Compute

Energy (Standard Step)

Momentum Coef Drag Cd 2. ?

Yarnell (Class A only) Pier Shape K ?

Highest Energy Answer

High Flow Methods

Energy Only (Standard Step)

Pressure and/or Weir

Submerged Inlet Cd (Blank for table)

Submerged Inlet + Outlet Cd 0.8

Max Low Chord (Blank for default)

OK Cancel Help

Use pressure and/or weir method for high flow



Hydraulic Table Parameters

HTab
Param.

- 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.

Connection Hydraulic Property Table Parameters

Number of points on free flow curve:	<input type="text" value="50"/>
Number of submerged curves:	<input type="text" value="50"/>
Number of points on each submerged curves:	<input type="text" value="20"/>
<input type="button" value="Apply number of points to all Connections"/>	
Head water maximum elevation:	<input type="text" value="955"/>
Tail water maximum elevation (Optional):	<input type="text"/>
Maximum Flow (Recommended):	<input type="text"/>
<input type="button" value="OK"/> <input type="button" value="Cancel"/>	



Hydraulic Table Parameters

HTab
Param.

- **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

Connection Hydraulic Property Table Parameters

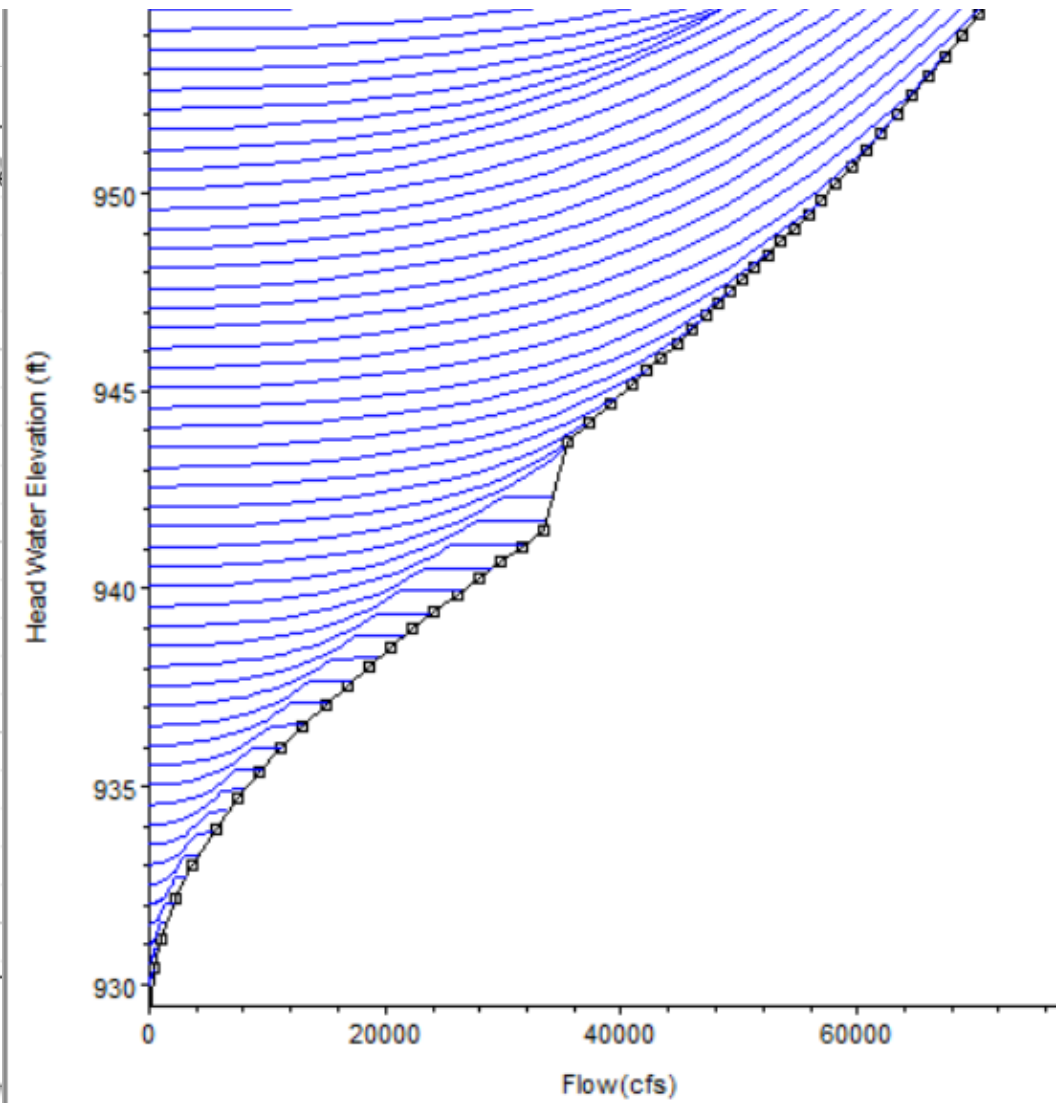
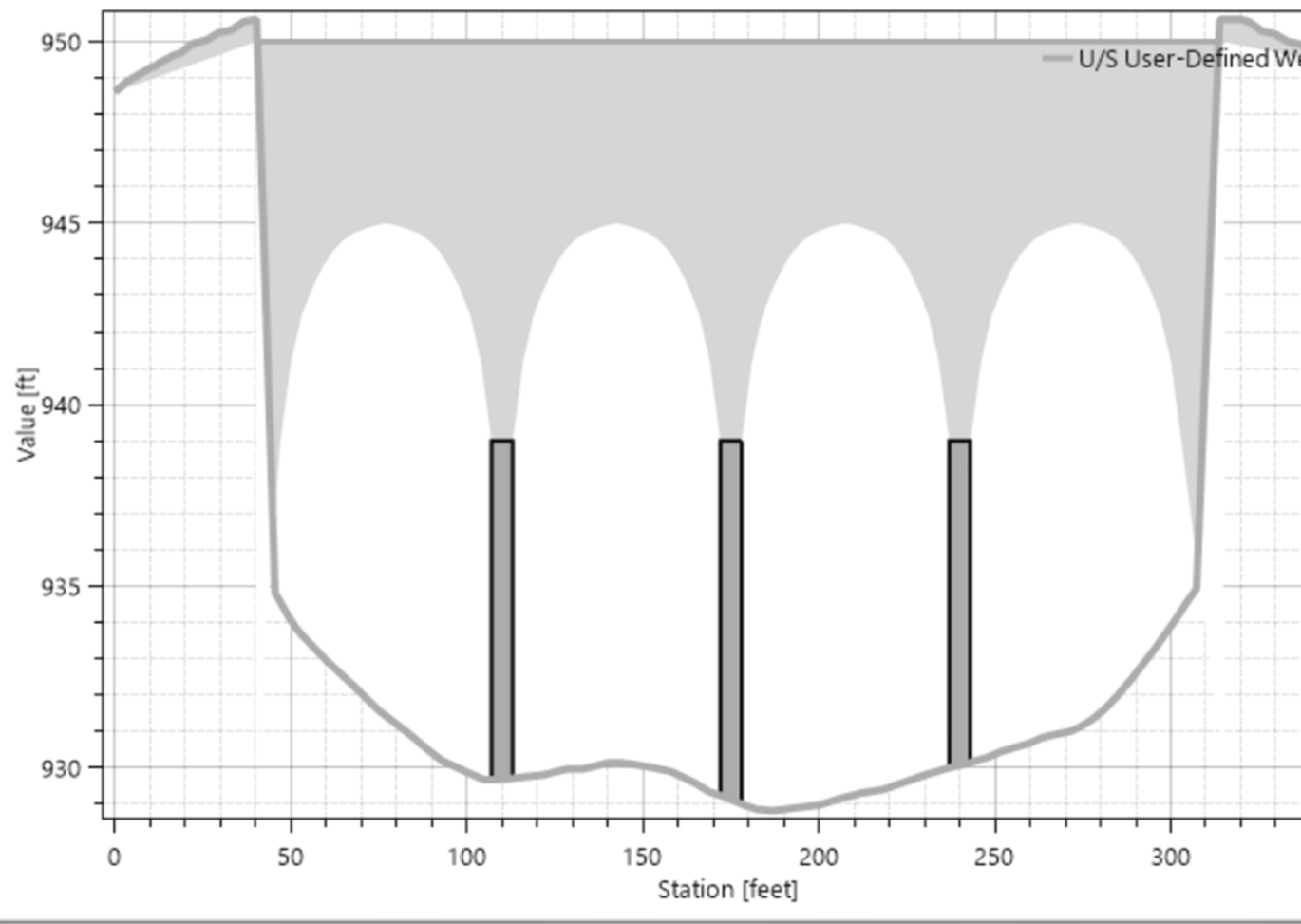
Number of points on free flow curve:	<input type="text" value="100"/>
Number of submerged curves:	<input type="text" value="60"/>
Number of points on each submerged curves:	<input type="text" value="60"/>
<input type="button" value="Apply number of points to all Connections"/>	
Head water maximum elevation:	<input type="text" value="595"/>
Tail water maximum elevation (Optional):	<input type="text"/>
Maximum Flow (Recommended):	<input type="text"/>



HTab – Family of Bridge Curves



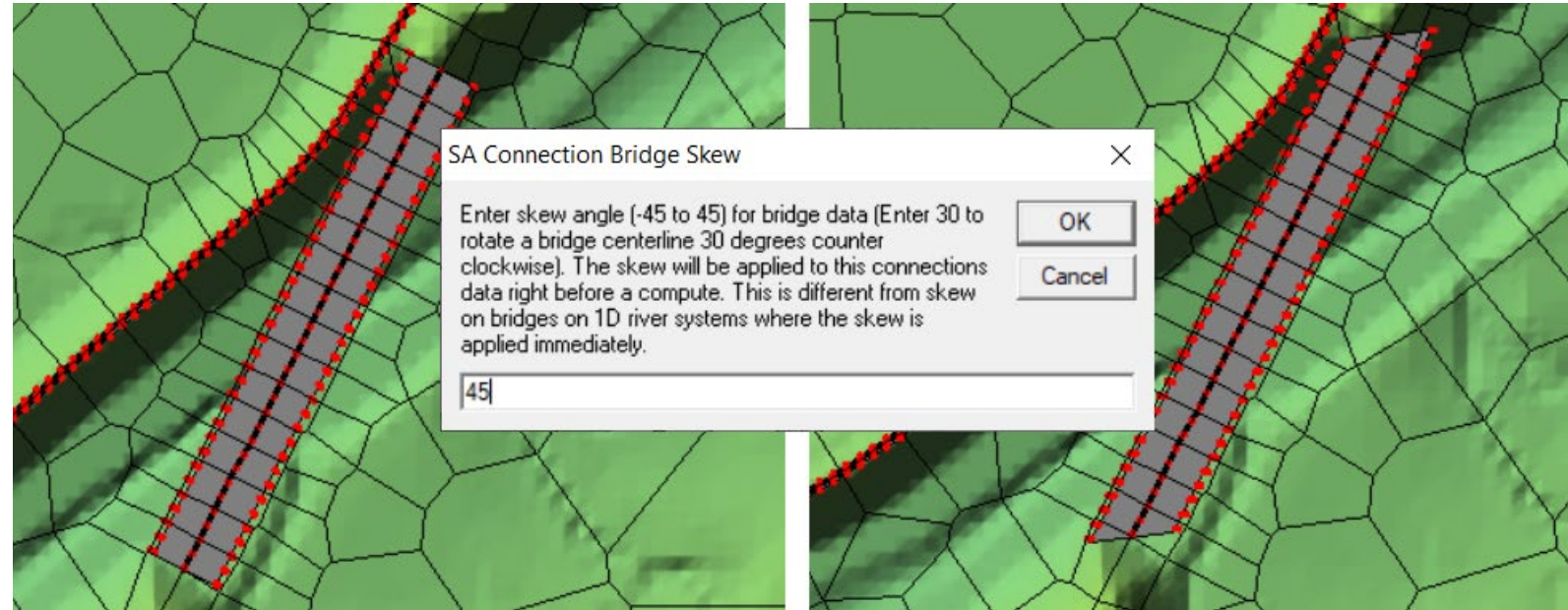
SA2D Conn: MLK Bridge (MLK Bridge) (Upstream)



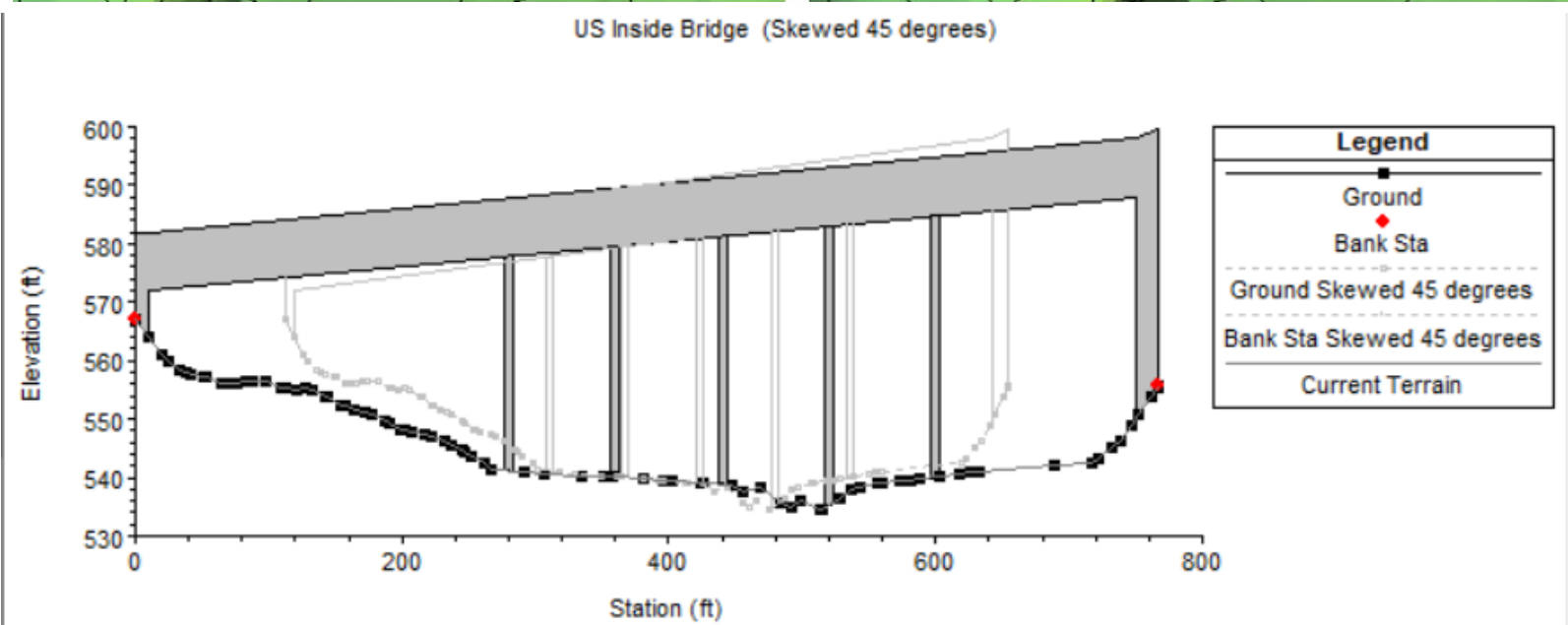


Bridge Skew

- 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

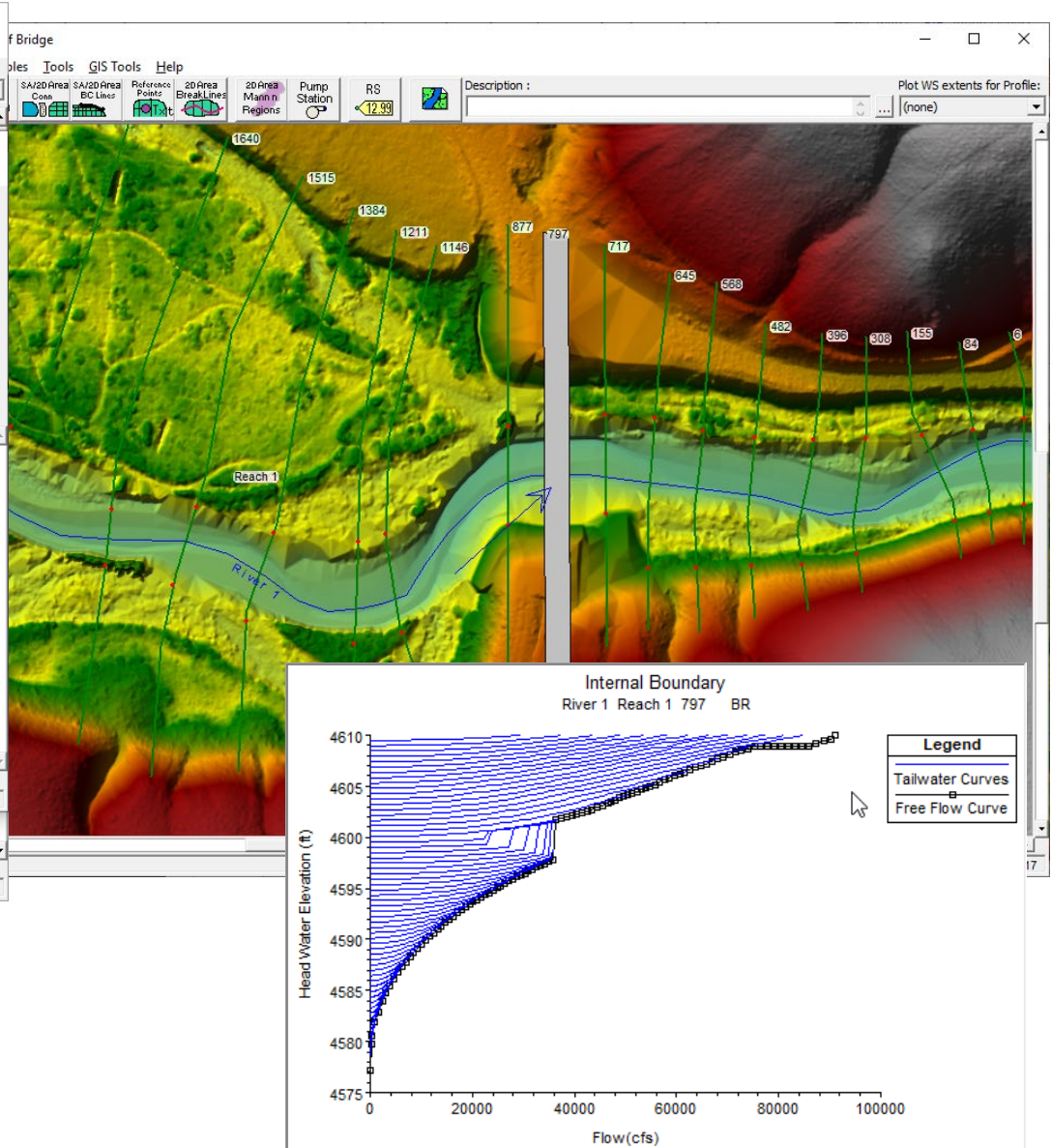
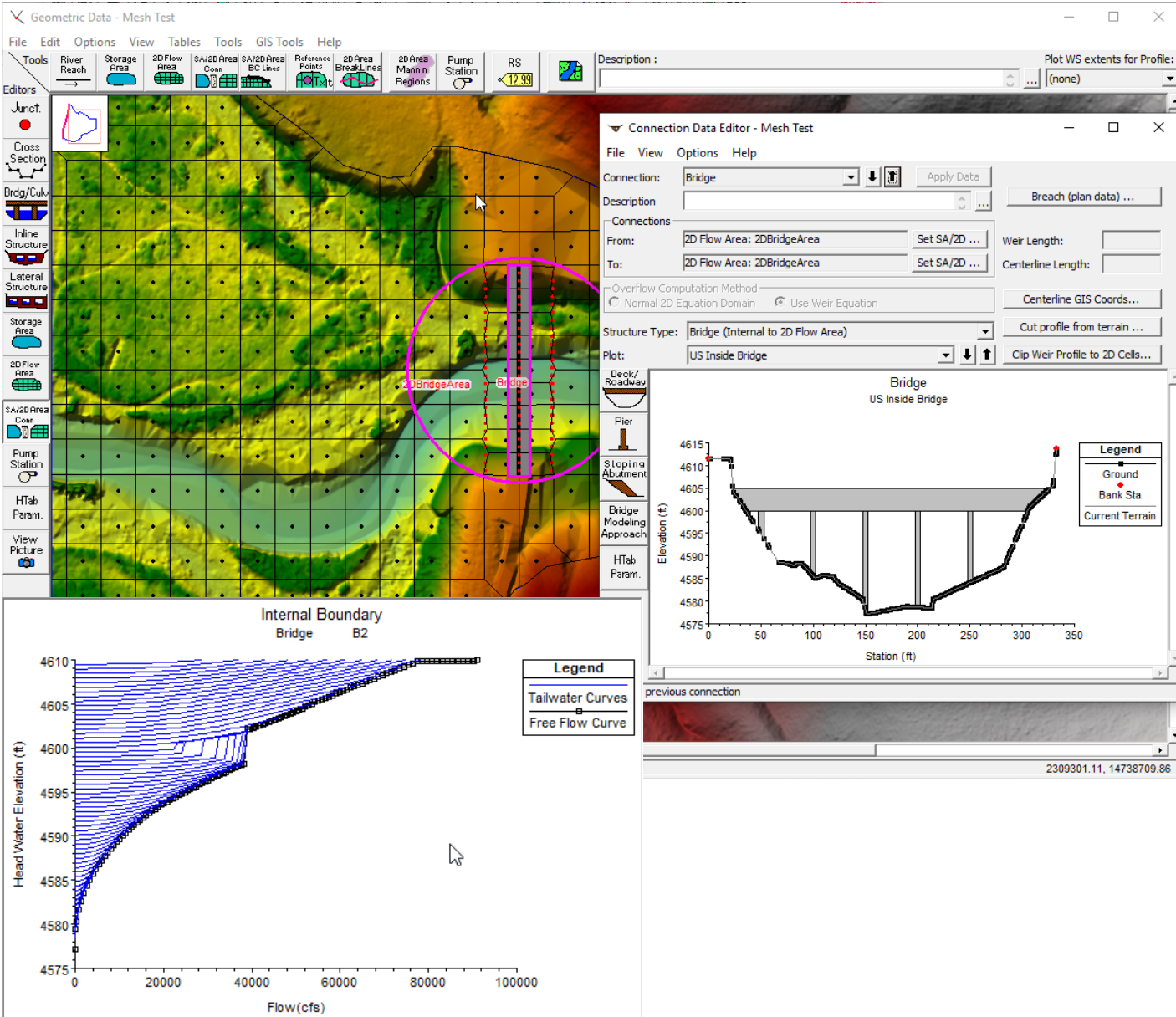


US Inside Bridge (Skewed 45 degrees)





1D vs 2D Model Comparison





1D and 2D Comparison Animation





Flow Tracers





Computation Procedure

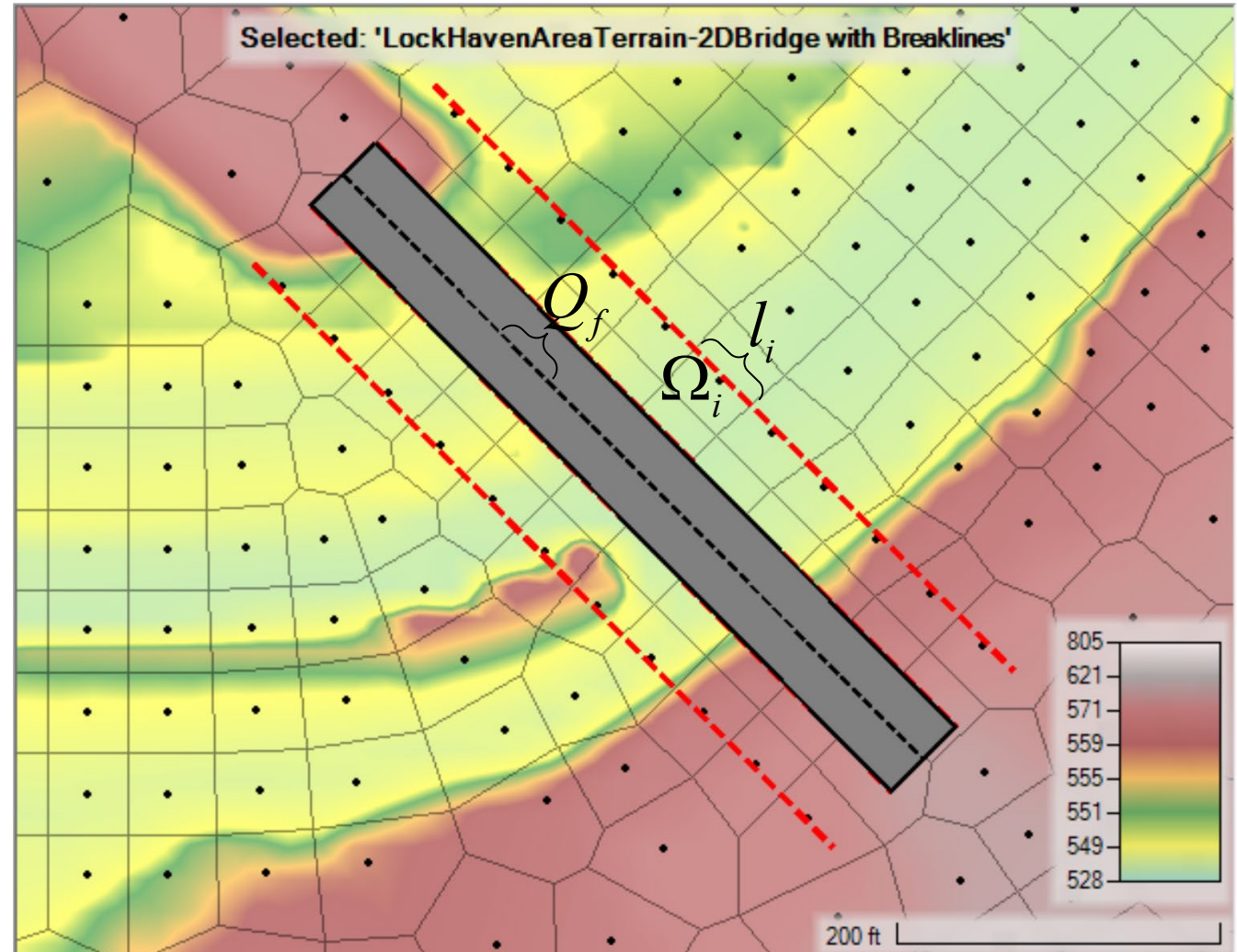
1. Estimate total bridge flow and tailwater elevation as

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

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

Ω_i : XS cell volume

l_i : XS length in cell

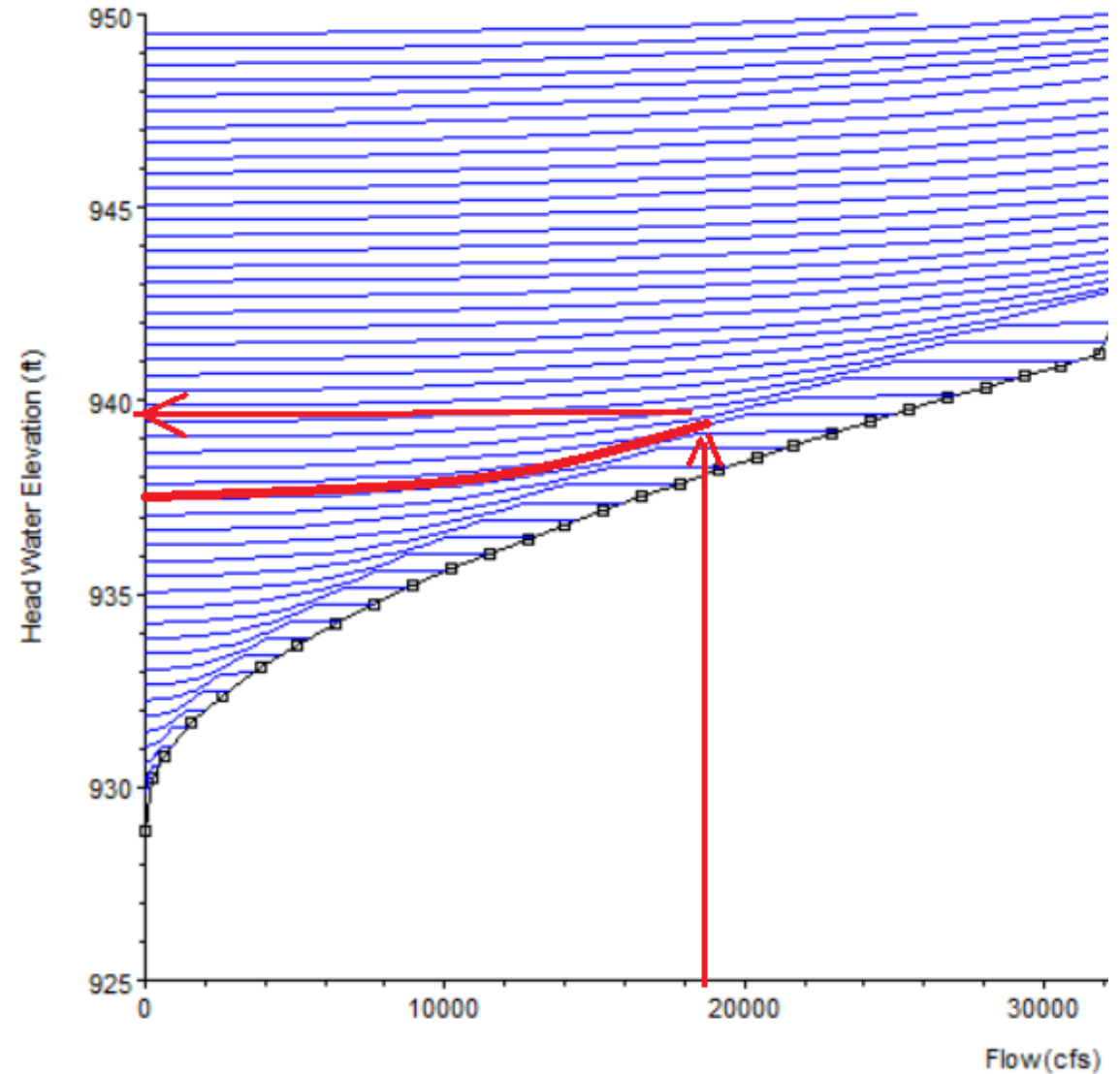




Computation Procedure

2. Compute target headwater elevation from bridge curves

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





Computation Procedure

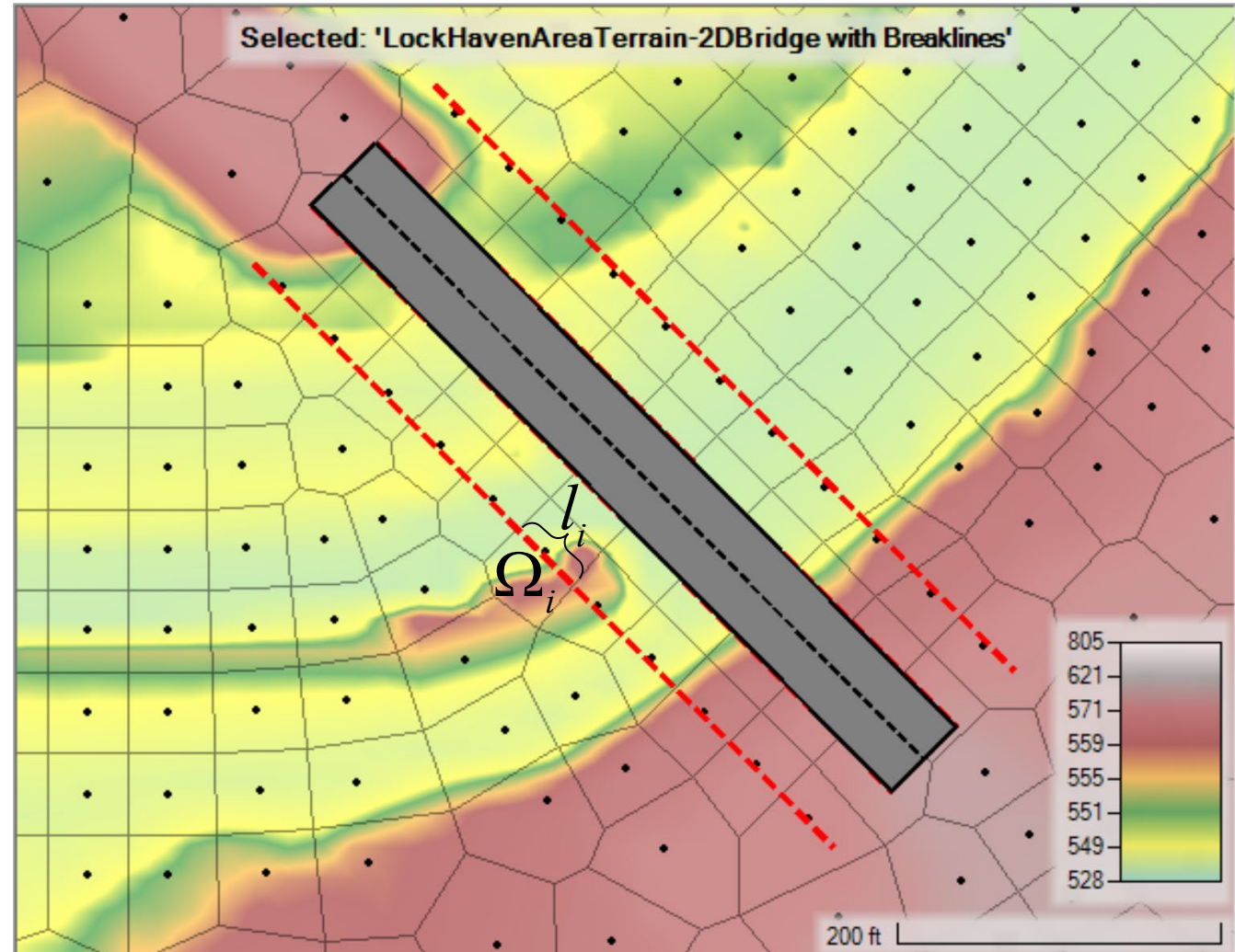
- Bridge energy losses simulated by increasing bottom shear stresses by a bridge drag factor under bridge faces

$$\tau_b = \lambda_B \rho C_D |V| V \quad \lambda_B(t) \geq 1$$

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

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

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





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 loss 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

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

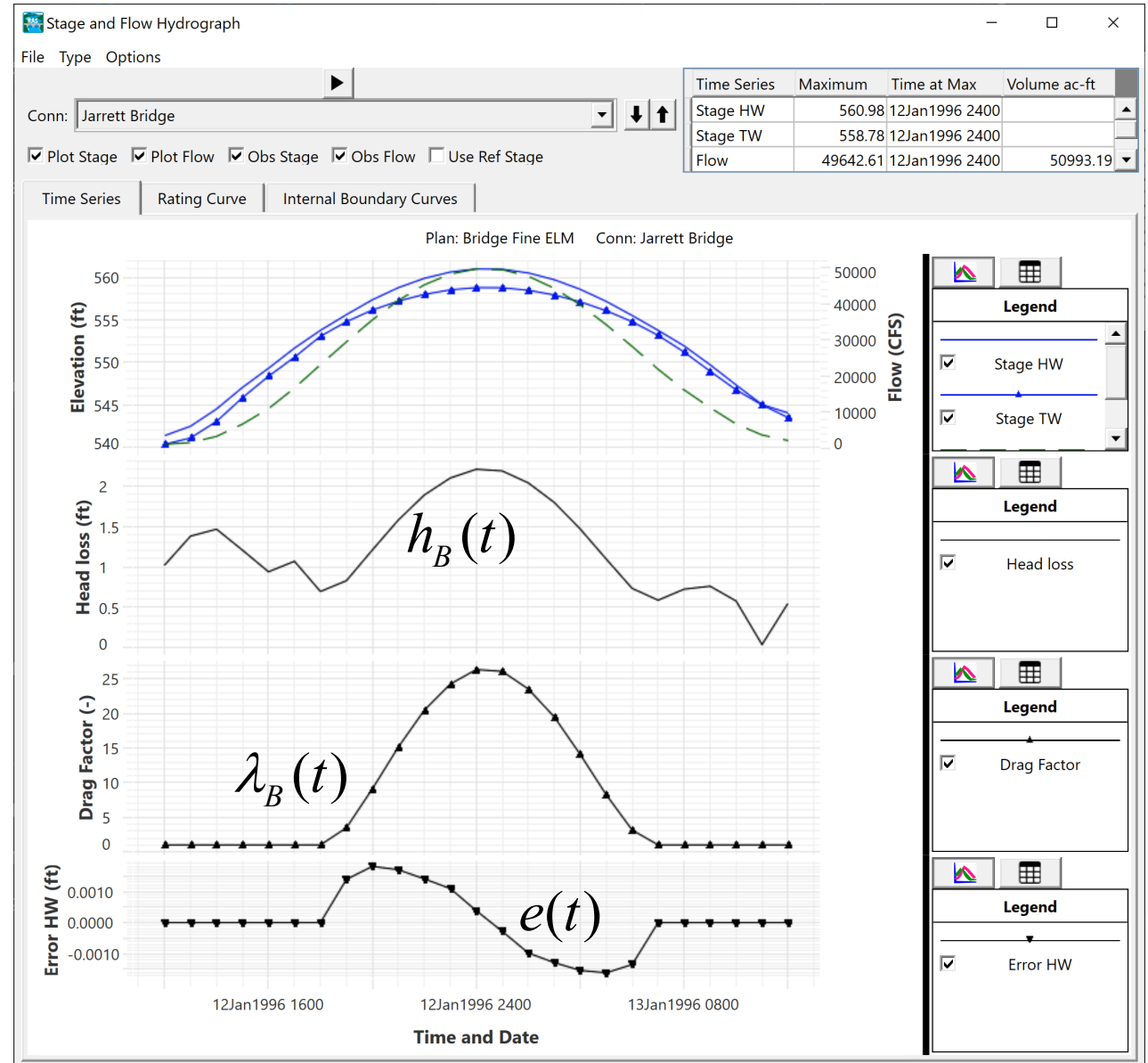
- Drag factor

- Limited to 1
- Constant under bridge

- Error

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

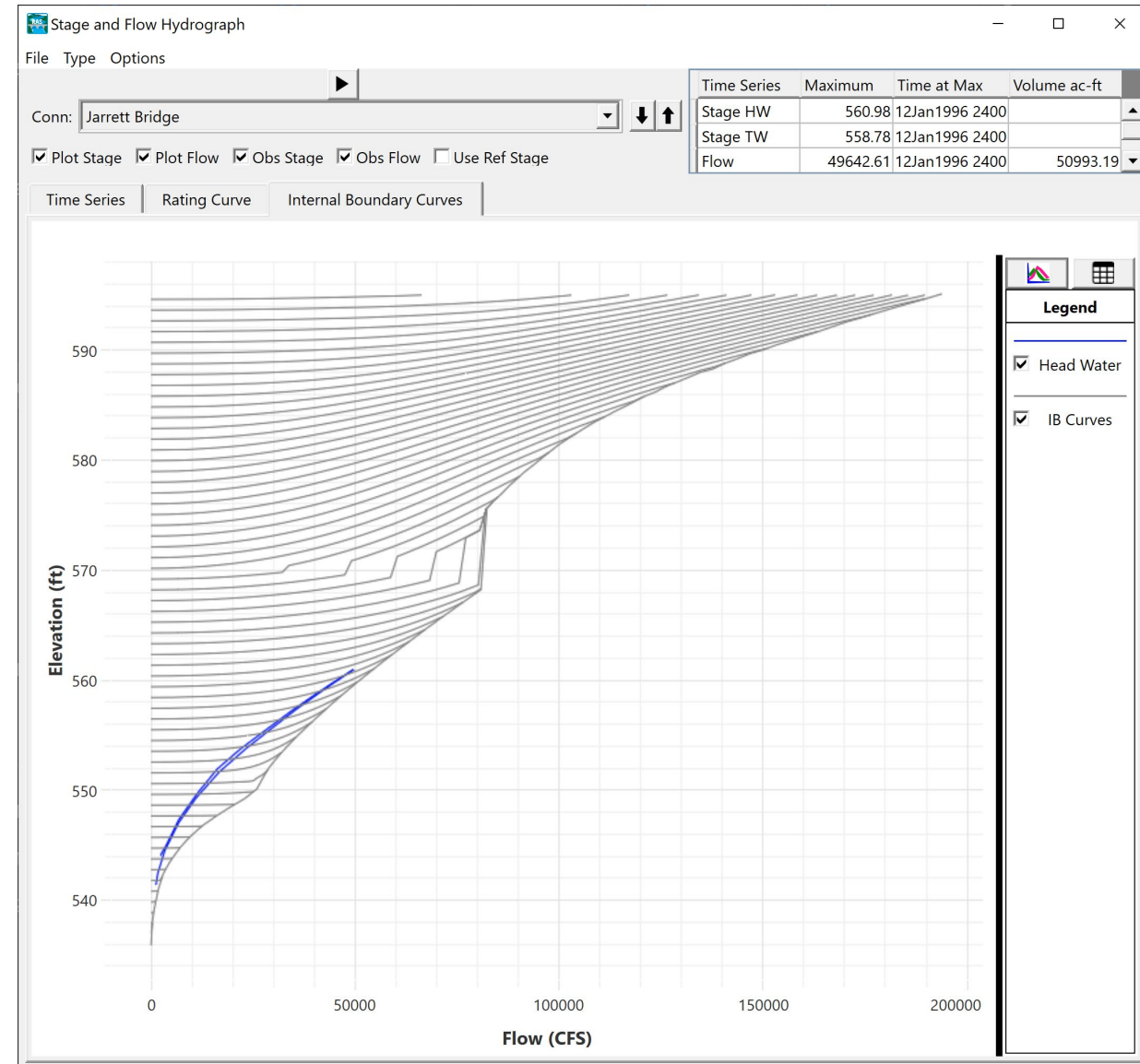
- Usually small but can be increase if controller has trouble especially during flow transitions





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

RAS Mapper

File Project Tools Help

Selected Layer: MLK Bridge

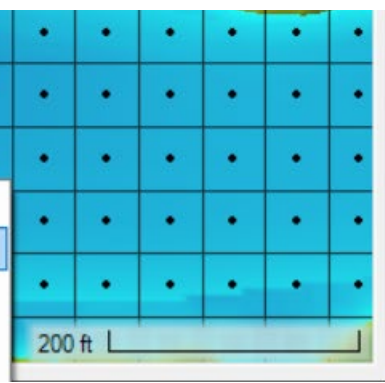
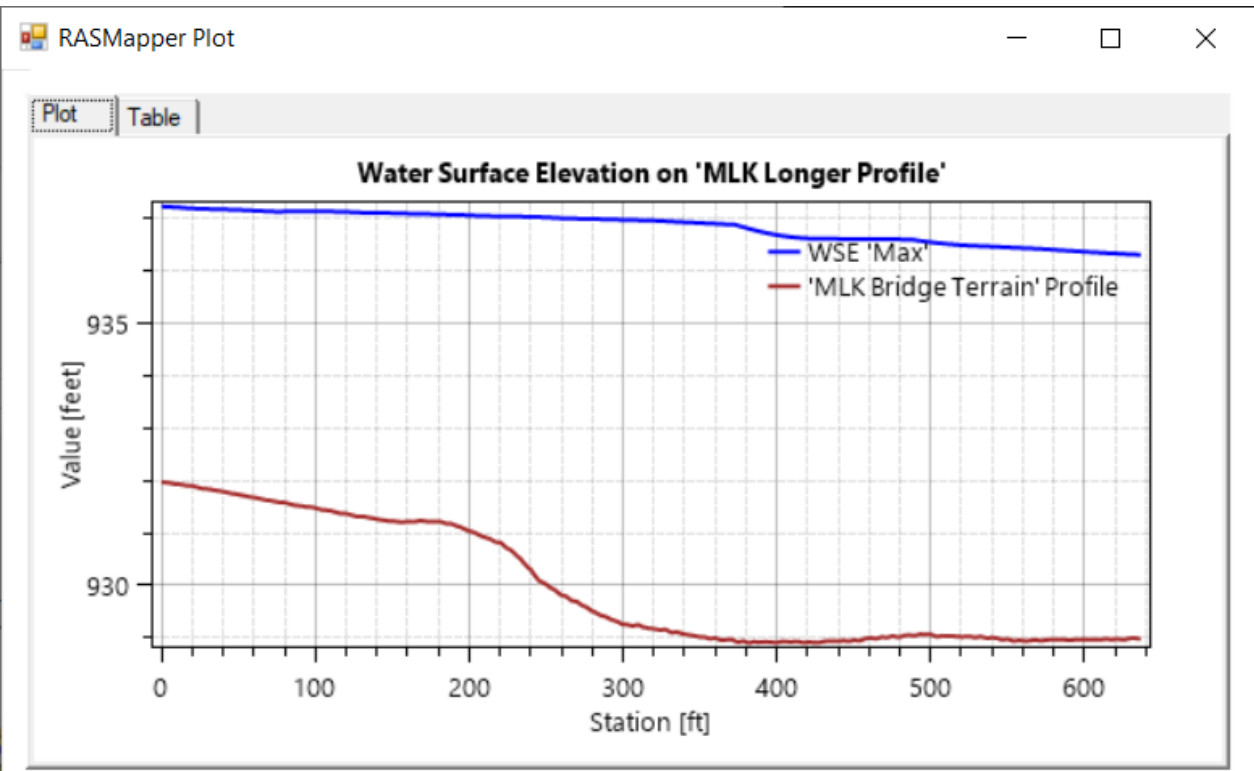
- Features
 - Profile Lines
- Geometries
 - MLK Bridge
 - Cross Sections
 - 2D Flow Areas
 - SA/2D Connections
 - Boundary Condition Lines
- Event Conditions
- Results
 - MLK Bridge
 - Event Conditions
 - Geometry
 - Depth (Max)
 - Velocity (13OCT2021 00:00:00)
 - WSE (Max)
- Map Layers
- Terrains
 - MLK Bridge Terrain

MLK Longer Profile

- Plot Profile
 - Terrain
 - WSE
 - WSE (Without Terrain)
 - Depth
 - Velocity against Terrain
- Plot Time Series
- Rename
- Delete

Messages Views Profile Lines Acti

(408872.08, 1802723.14 1 pixel = 1.45 f





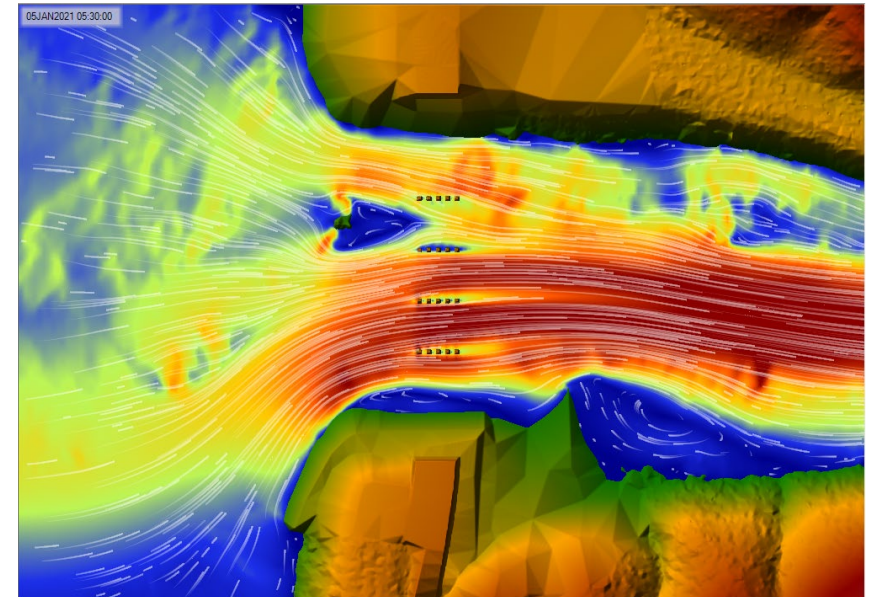
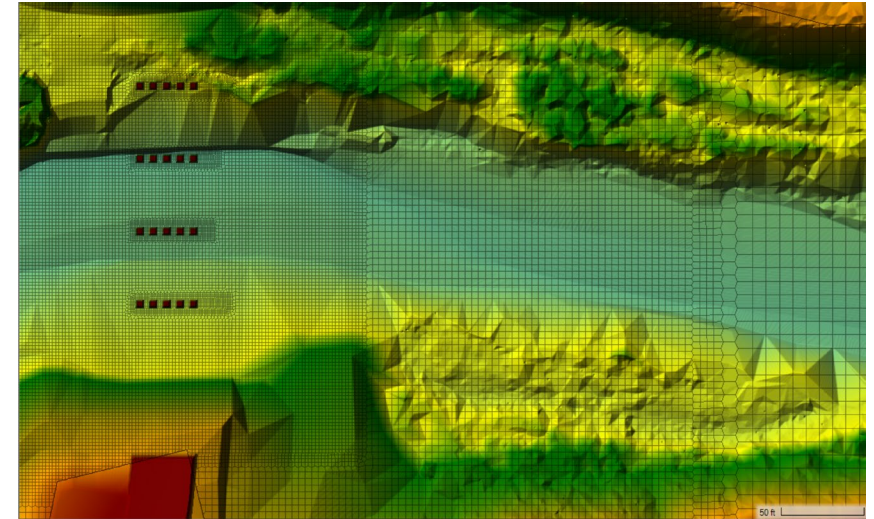
Considerations

- 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

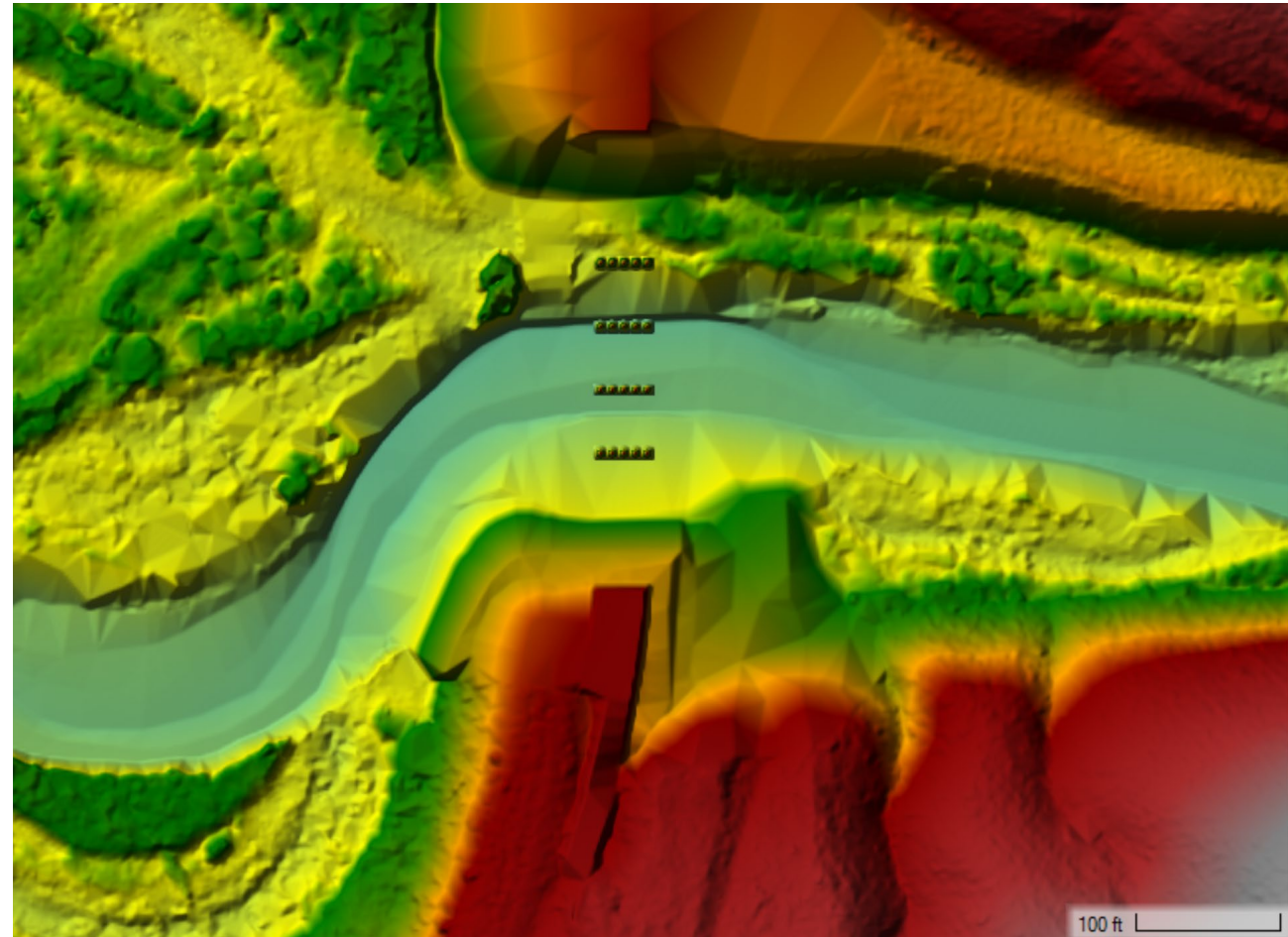
- Simulating all energy losses with a high-resolution 2D model
- Requirements high-resolution terrain and mesh
- Pros
 - Physics-based
 - High-resolution results
- Cons
 - Depth-averaged assumption
 - No pressurized flow or overtopping in Versions 6.3 and earlier
 - Computationally Expensive





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

HEC-RAS Unsteady Computation Options and Tolerances

General | 2D Flow Options | 1D/2D Options | Advanced Time Step Control | 1D Mixed Flow Options

Use Coriolis Effects (not used with Diffusion Wave equation)

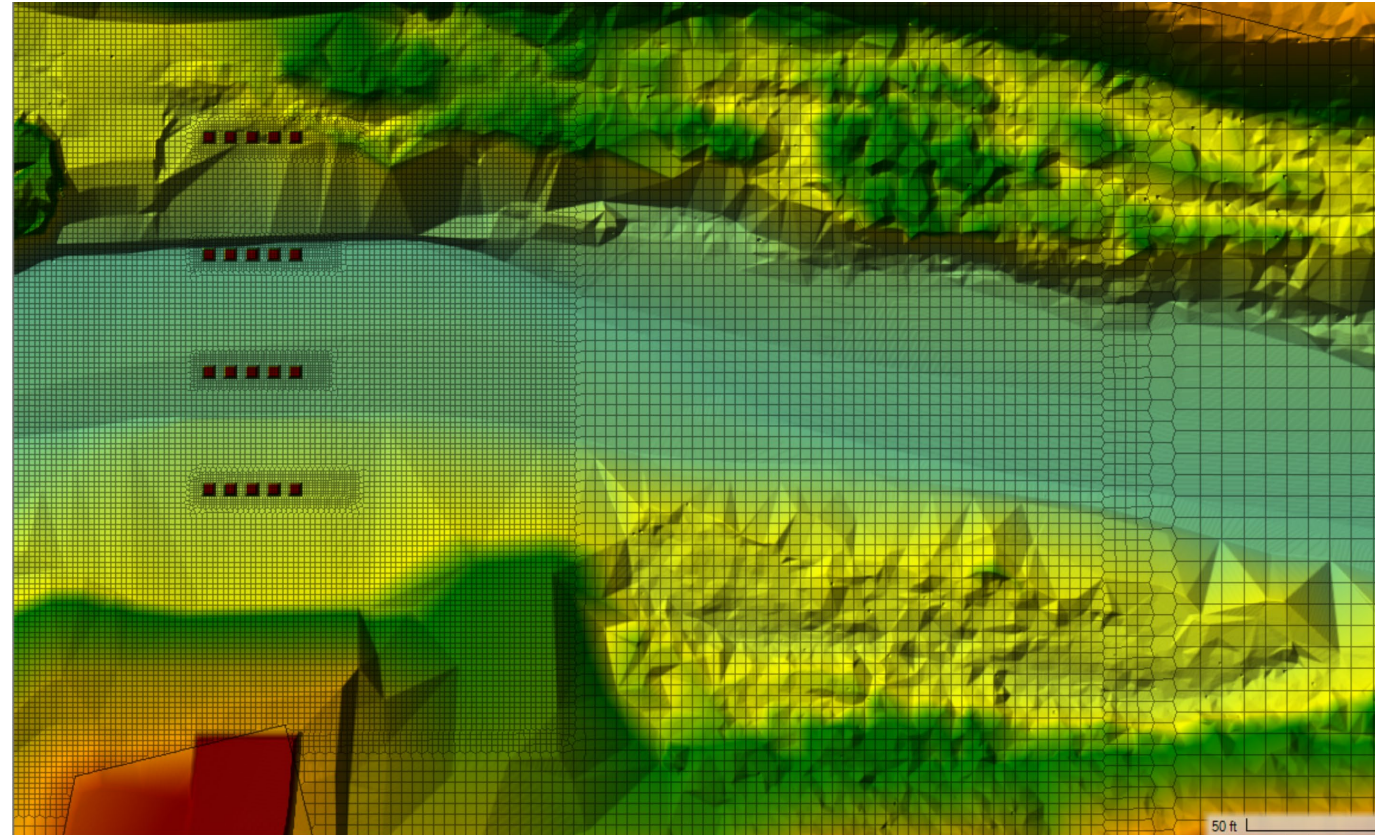
Parameter	(Default)	Perimeter 1
1 Theta (0.5-1.0)	1	1
2 Theta Warmup (0.5-1.0)	1	1
3 Water Surface Tolerance [max=0.2](ft)	0.01	0.01
4 Volume Tolerance (ft)	0.01	0.01
5 Maximum Iterations	20	20
6 Equation Set	Diffusion Wave	SWE-ELM (original/faster)
7 Initial Conditions Time (hrs)	1	1
8 Initial Conditions Ramp Up Fraction (0-1)	0.1	0.1
9 Number of Time Slices (Integer Value)	1	1
10 Turbulence Model	None	None
11 Longitudinal Mixing Coefficient	0.5	0.5
12 Transverse Mixing Coefficient	0.1	0.1
13 Smagorinsky Coefficient	0.05	0.05
14 Boundary Condition Volume Check	<input type="checkbox"/>	<input type="checkbox"/>
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	0	0
20 Maximum Iterations	0	0
21 Restart Iteration	10	10
22 Relaxation Factor	1.3	1.3
23 SOR Preconditioner Iterations	10	10

OK Cancel Defaults ...



Computational Mesh

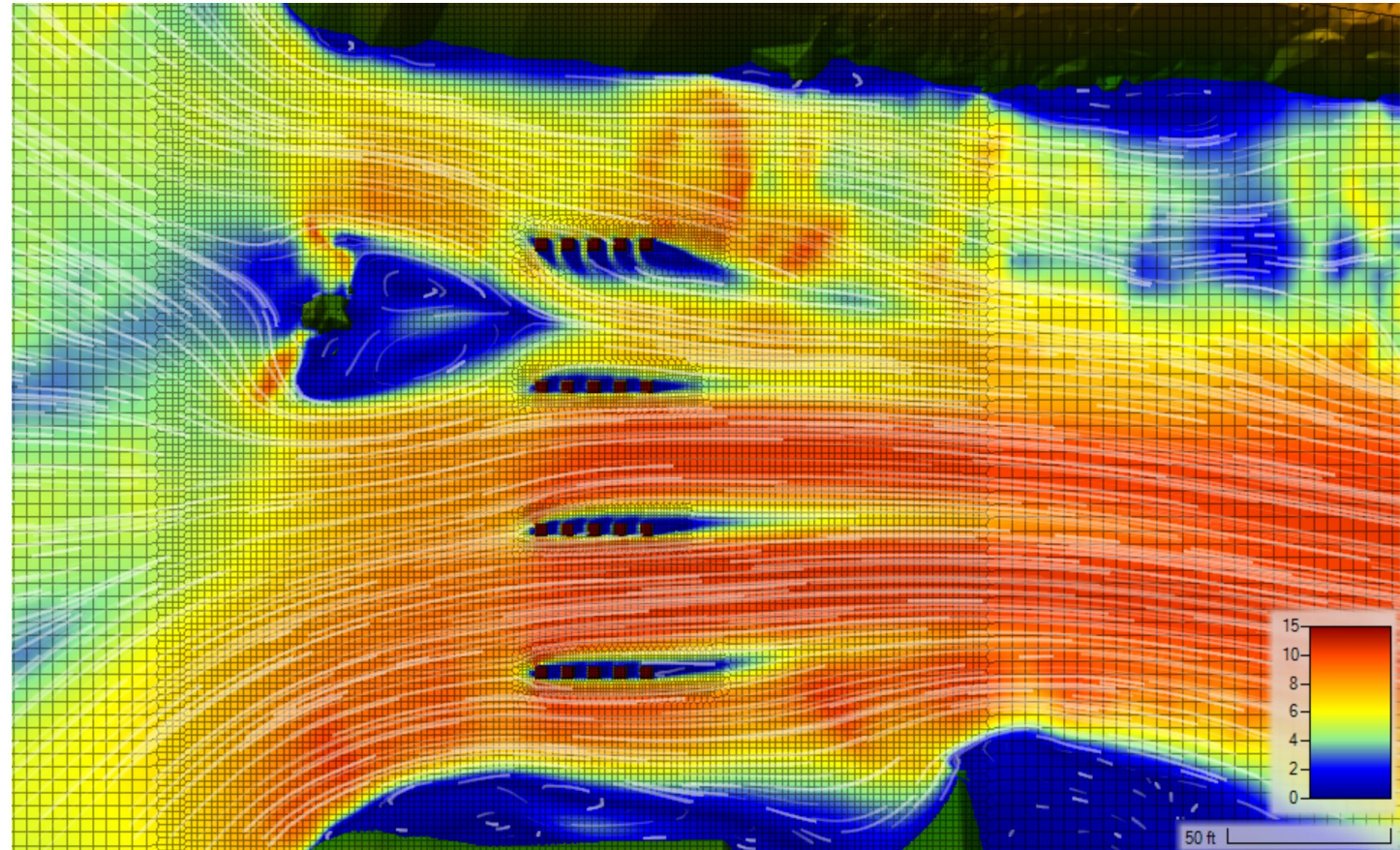
- Preliminary runs with simple coarse mesh
- Breaklines and refinement regions for high-resolution meshes
 - Minimum cell size will drive time step
- Perform grid convergence





Momentum Diffusion

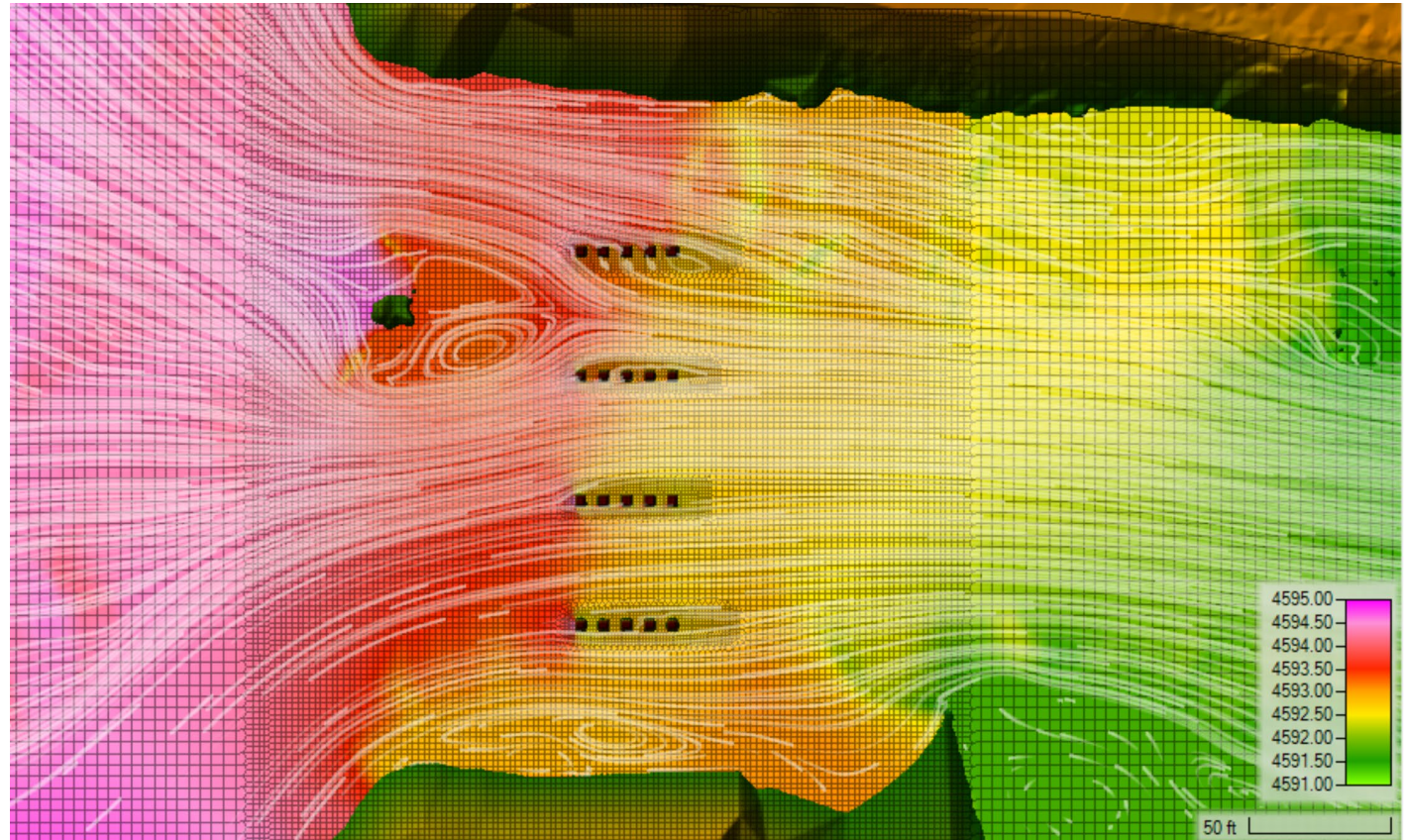
- Diffusion Term
 - Use Conservative Formulation!
- Eddy Viscosity Model
 - Use Parabolic-Smagorinsky
 - Calibrate if possible
 - In lieu of calibration, perform sensitivity analysis





Bottom Roughness

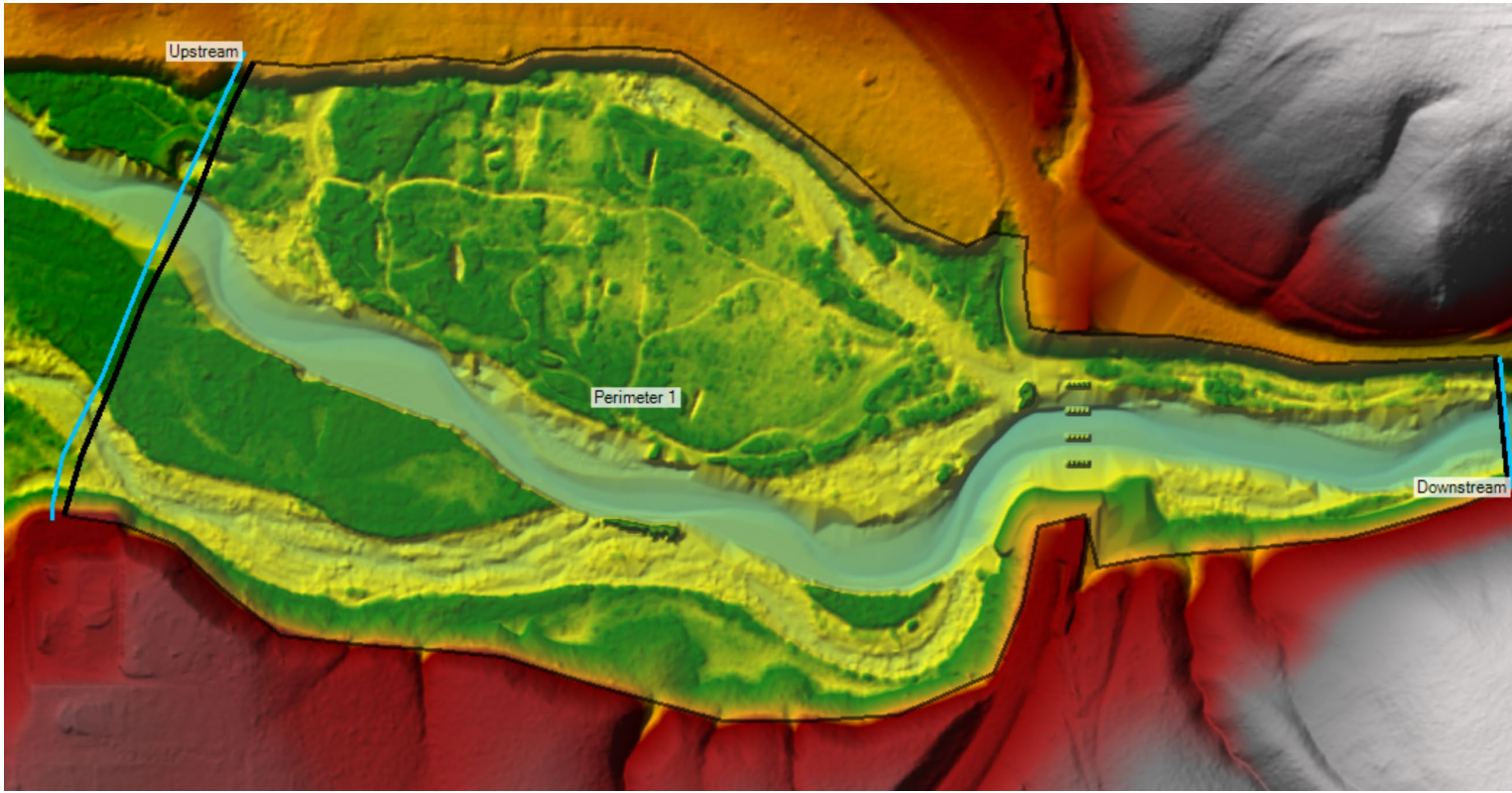
- Use spatially variable Manning's n
- Different flows may require different bottom roughness





Boundary Conditions

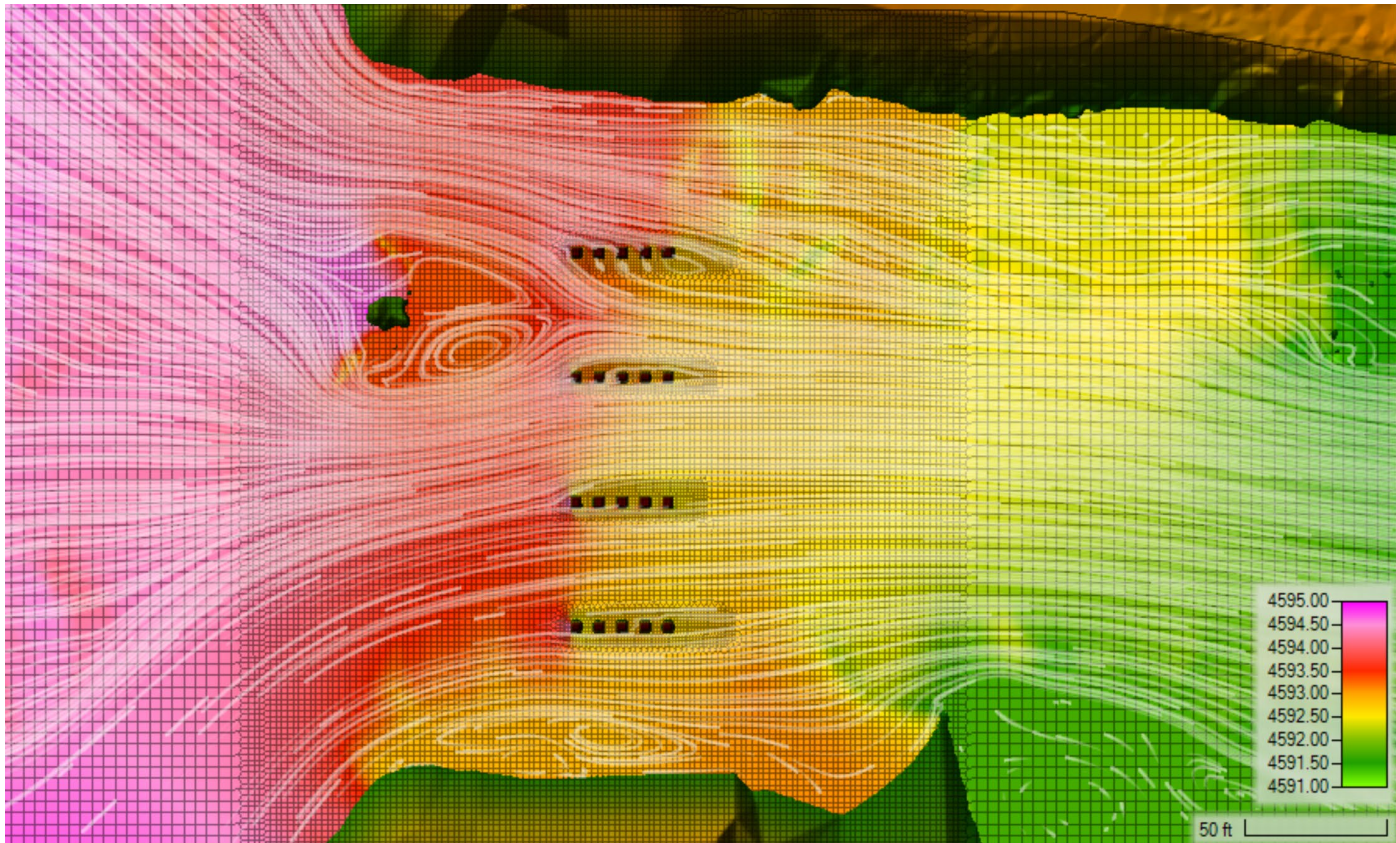
- Tempting to place them very close to the bridge but don't
- Perform sensitivity on boundary placement and boundary values (such as friction slope)
- Place boundaries in areas with 1D flow (i.e. no recirculation, or sharp contracts and expansions)





Advanced Computational Parameters and Options

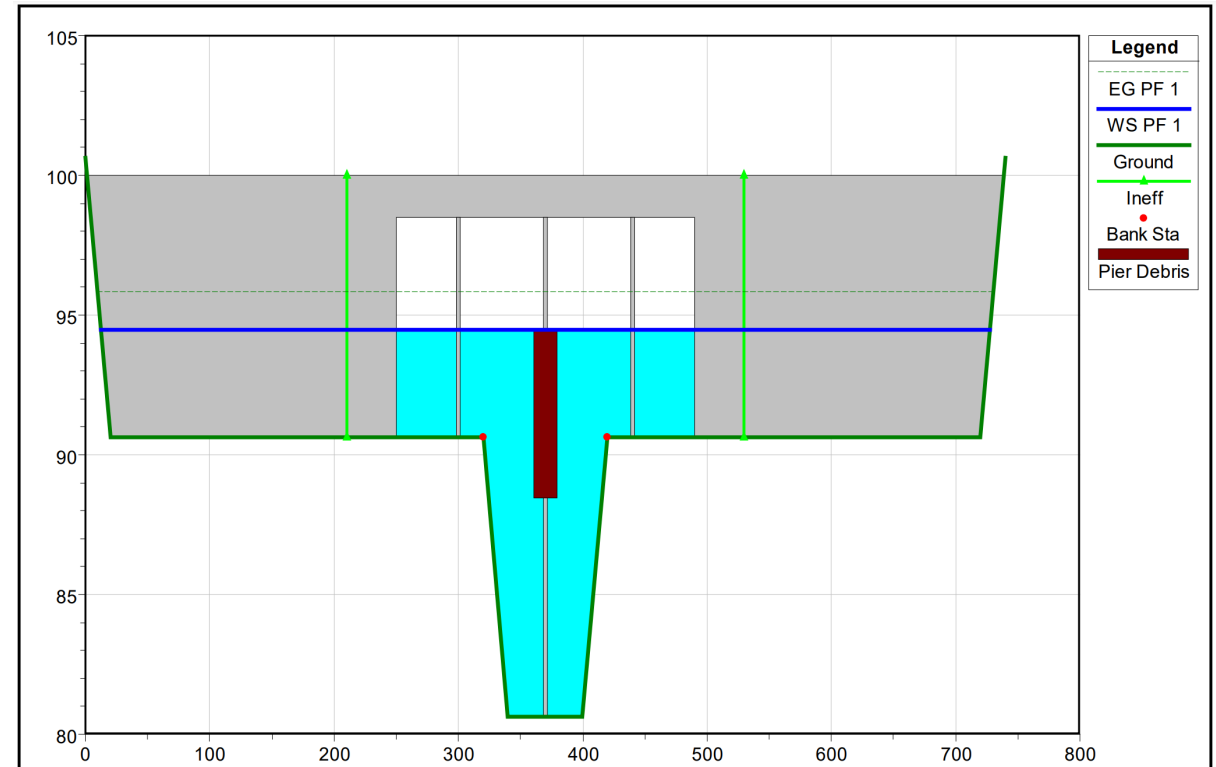
- Time Step
 - Variable time step algorithm
 - Hand calculations of Courant
 - Model stability
- Implicit Weighting Factor
 - 1.0 for preliminary runs
 - 0.5-0.6 for production unsteady flow runs
 - Not important for steady flow





Limitations

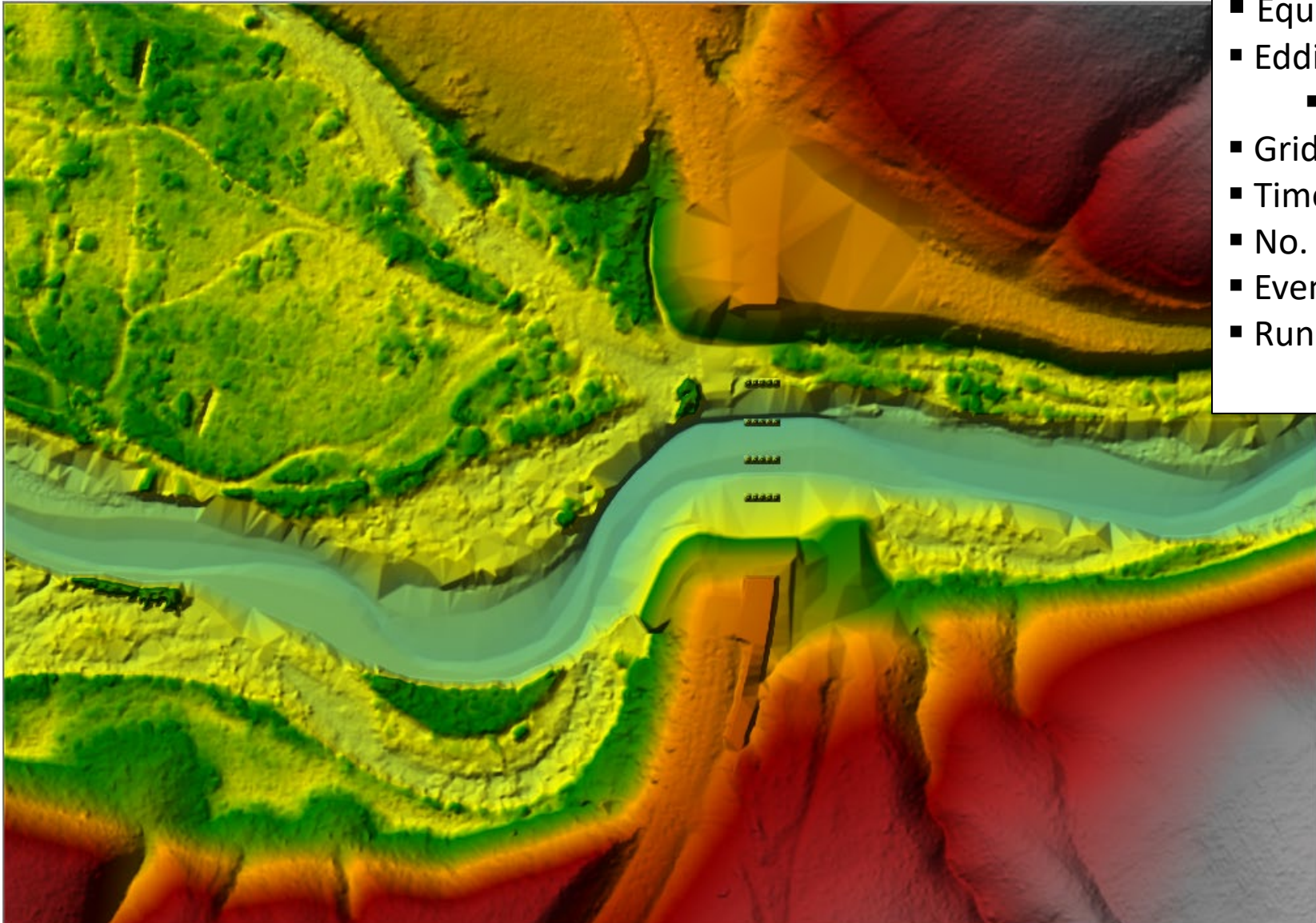
- Flow must be below bridge deck
 - No pressured flow
 - No flow overtopping
- 2D Flow Assumption
 - Breaks down when cell resolution is much finer than depth
- Hydrostatic Pressure Assumption
- Cannot simulate
 - Bridge openings such as culverts
 - Debris (can be done in 1D)
 - Ice (can be done in 1D)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





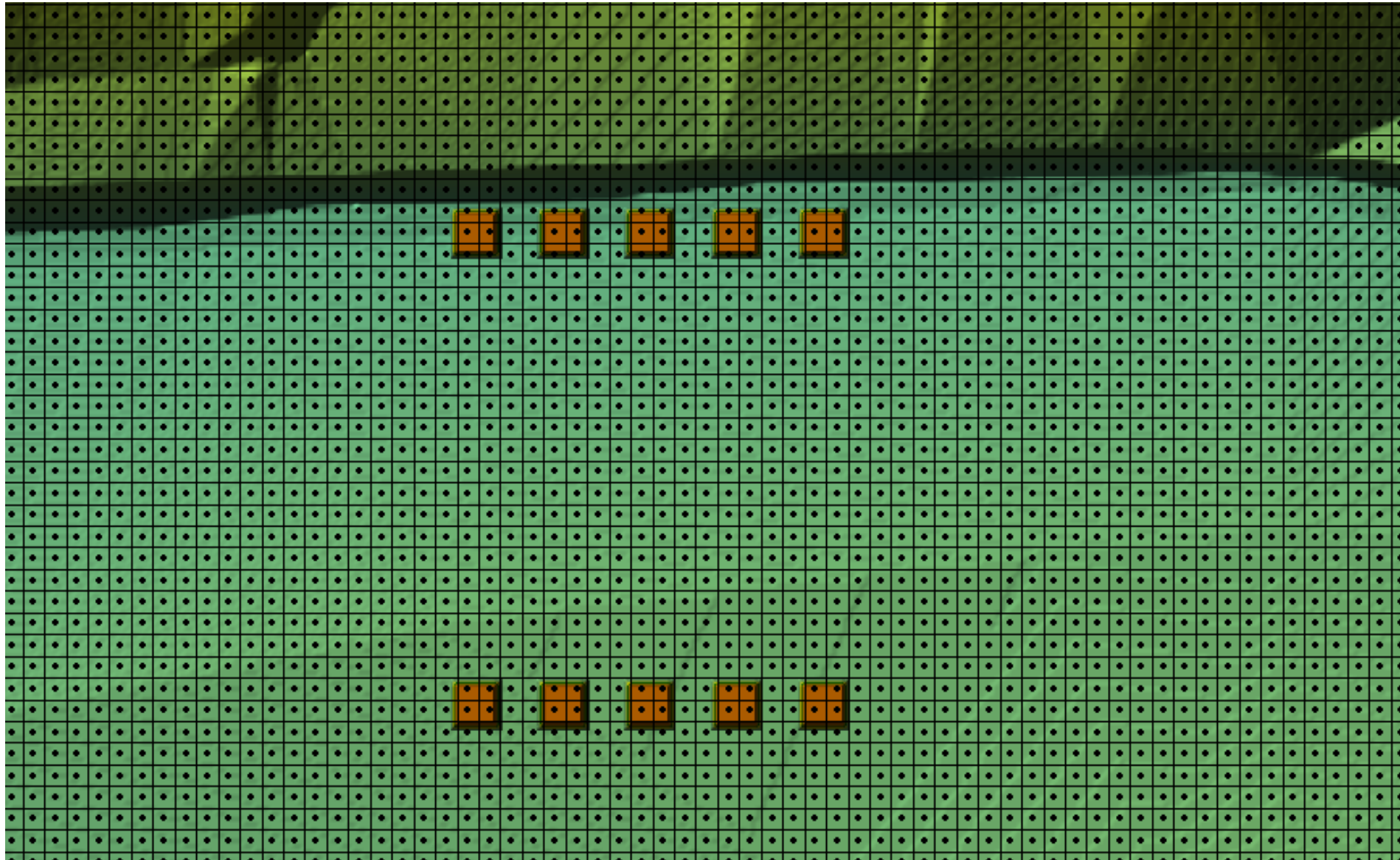
Detailed Bridge Modeling

- Equation set = SWE-ELM
- Eddy 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



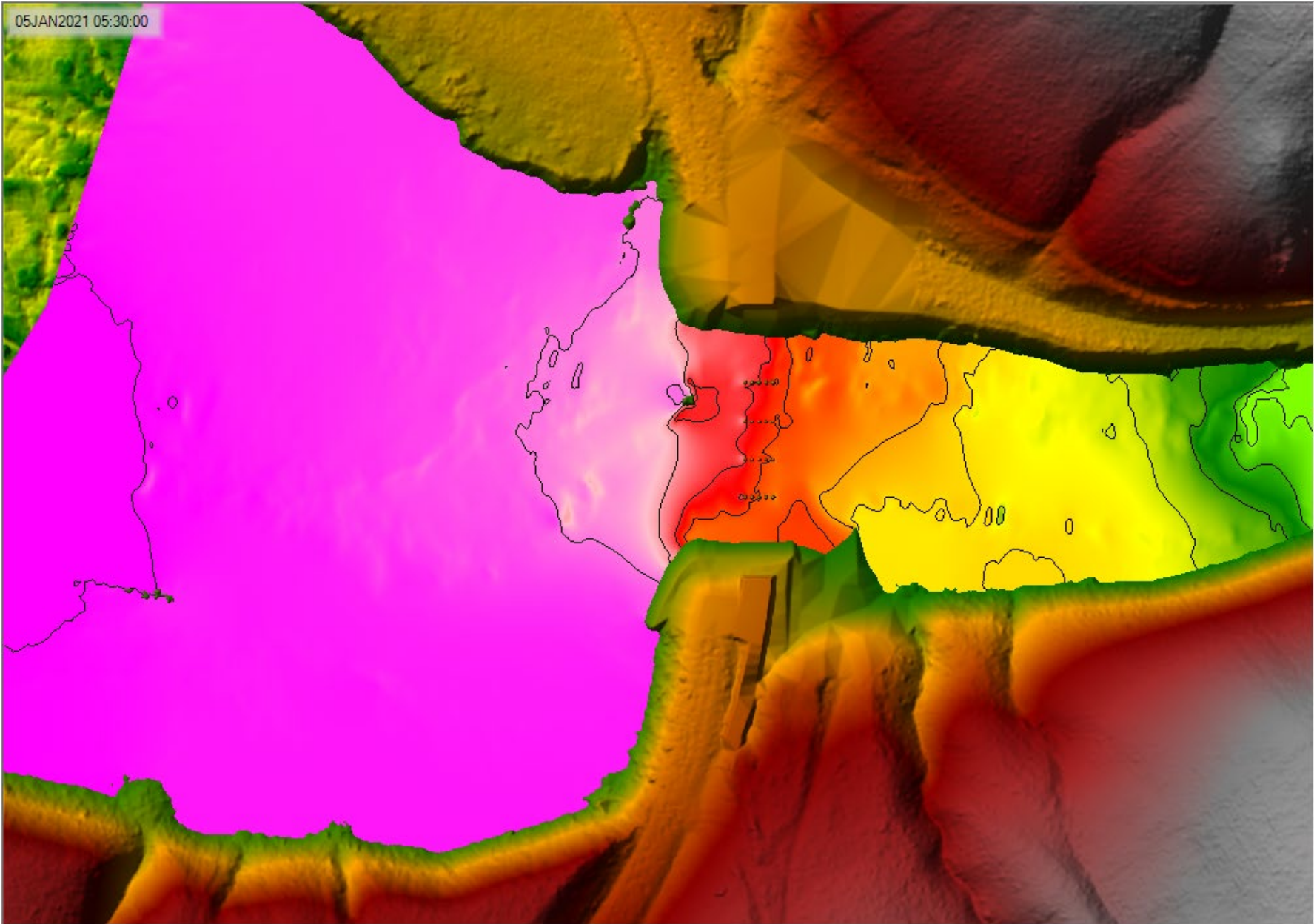


Detailed Bridge Modeling



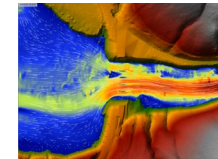
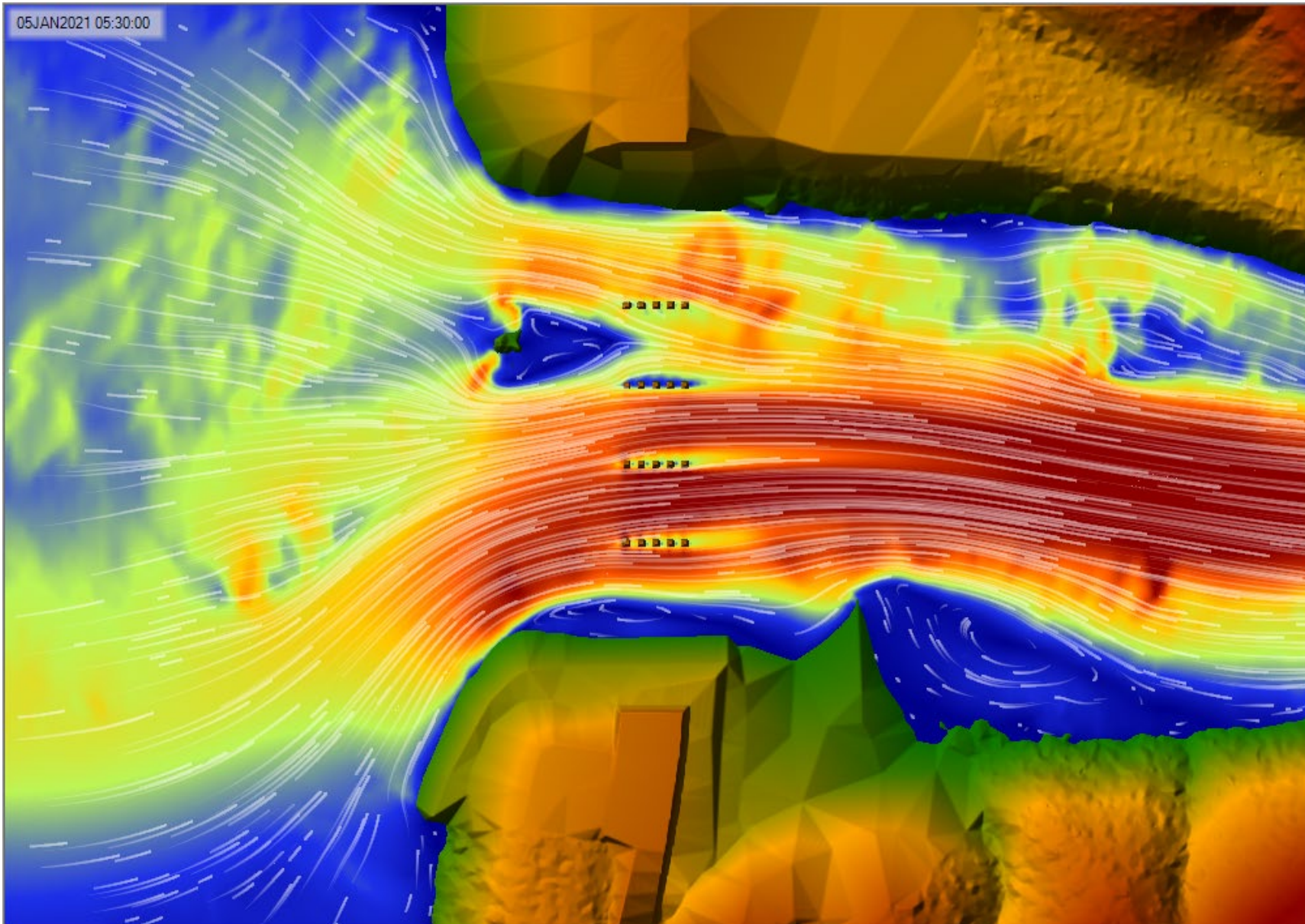


Detailed Bridge Modeling





Detailed Bridge Animation





Resources



U.S. Department
of Transportation

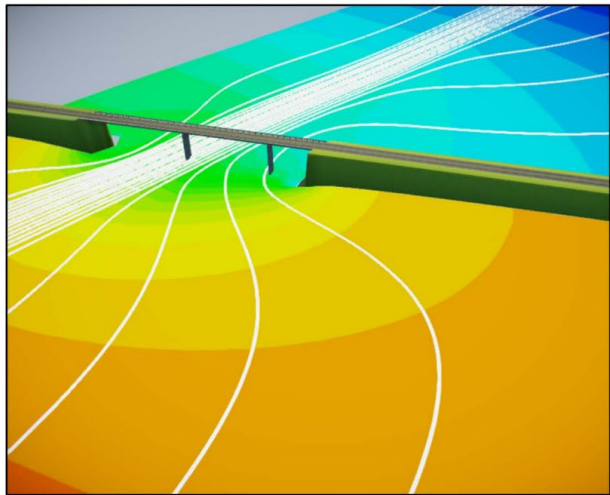
Federal Highway
Administration



Publication No. FHWA-HIF-12-018
April 2012

Hydraulic Design Series Number 7

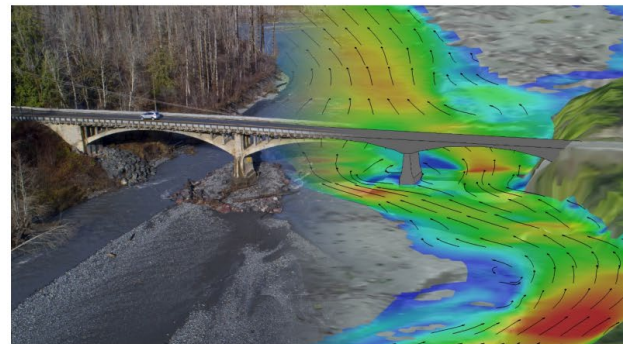
Hydraulic Design of Safe Bridges



Publication No. FHWA-HIF-19-061
October 2019

Two-Dimensional Hydraulic Modeling for Highways in the River Environment

Reference Document



U.S. Department of Transportation
Federal Highway Administration

Questions?