1D vs 2D Unsteady Flow Modeling

Gary Brunner, P.E., D. WRE,
M.ASCE

US Army Corps
of Engineers

US Army Corps
of Engineers
Hydrologic Engineering Center

Modeler Application Guidance for Steady vs Unsteady, and 1D vs 2D vs 3D Hydraulic Modeling

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Download from HEC Website:

https://www.hec.usace.army.mil/publications/TrainingDocuments/TD-41.pdf

Authors:

1. Gary W. Brunner, HEC - primary
2. Gaurav Savant, ERDC
3. Ronnie Heath, ERDC - retired

Overview

- Definitions
- Knowledge of the River System and Purpose of the Hydraulic Modeling
- Data requirements for 1D and 2D models
- Output/results provided by 1D and 2D models
- 1D vs 2D Modeling
  - Computational Differences
  - Model Calibration
  - Time and Cost Issues
  - Summary of 1D and 2D Modeling Advantages and Disadvantages
  - Application Examples

Definitions

- **In general, almost all fluid movement is three dimensional.** However, the equations of water motion are often derived in both one and two-dimensional forms, for a wide range of practical applications.

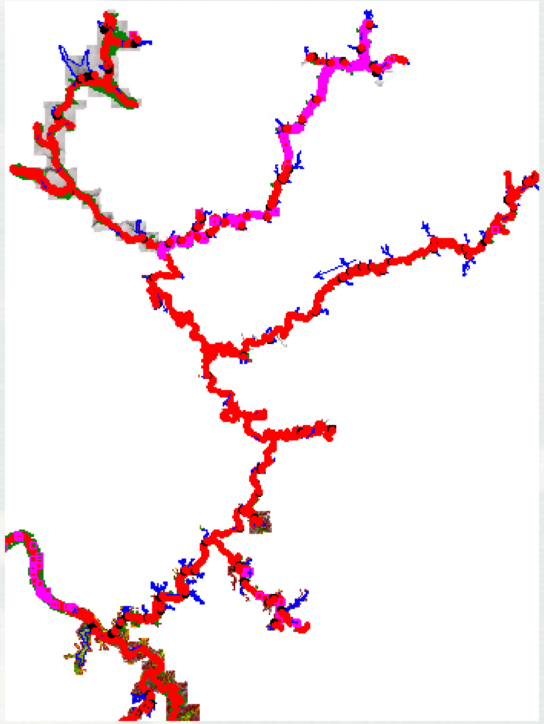
- **1D Modeling:** the equations are derived under the assumption
  - forces acting on a body of water are predominant in one direction, x, along the river channel centerline.

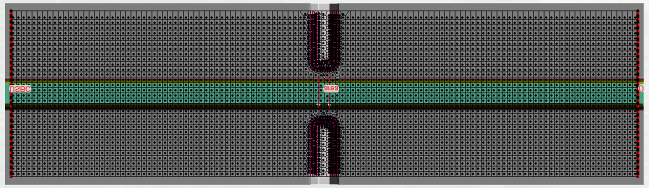
- **2D Modeling:** the equations are derived under the assumption
  - forces acting on a body of water are predominant in the x (along the river channel centerline) and the y (laterally across the channel or floodplain) direction

Knowledge of the River System

- What is the size/ length of the systems to be modelled?
  - 1 mile, 10, 50, 100, 500, or 1000 miles?
  - Detailed 2D models may not work well for very large systems due to excessive run times.
  - For very larger systems may need to use 1D or combined 1D/2D modeling

Allegheny River System





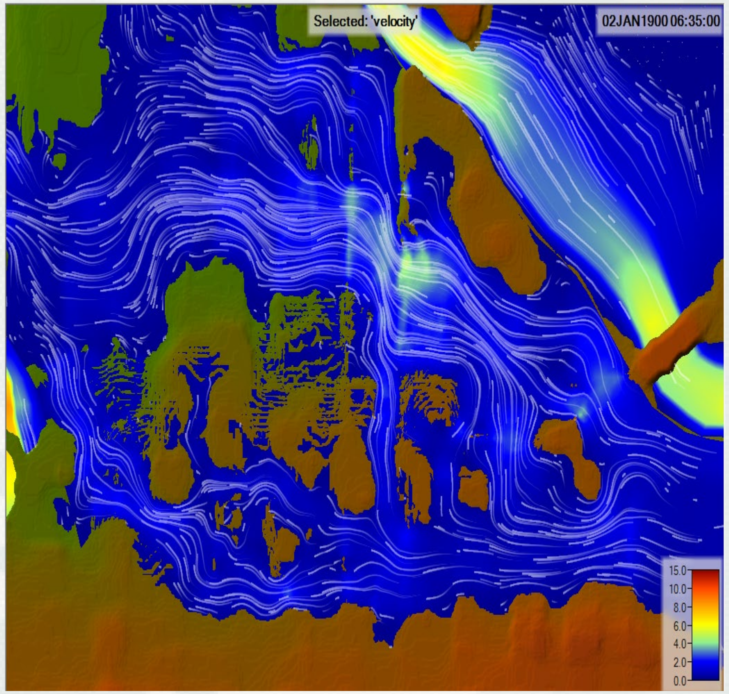
Bridge Flume

Knowledge of the River System

- What is the complexity of the system to be modelled?
  - Is the system hydraulically steep, or have steep areas?
    - Steep systems can be more difficult to model that flat river systems
    - In a hydraulically steep system there are higher velocities, and more rapid changes in depth, area, and velocity.
  - How many/what type of hydraulic structures are in the system?
    - Bridges and Culverts
    - Dams, weirs, gated structures (special operating rules)

Knowledge of the River System

- Is the flow path of the water generally known for the full range of events?
  - 1D modeling requires knowledge of the flow path before laying out the model cross sections.
  - If the flow path of the water is not fully known for all events, then 2D modeling will be more accurate and easier to use.
  - If the flow path changes during an event, 2D models can handle this and 1D cannot.



Knowledge of the River System

- Are there unique aspects of the system that will significantly affect the computed results?
  - Tidally influenced ?
  - Does wind speed affect the water surface elevations?
  - Floating ice or ice jams?
  - Debris issues during flood - does the debris tends to pile up at hydraulic structures
  - Levee systems that may be overtopped or breached?
  - Unique hydraulic structures that require specialized modeling or gate operations

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Purpose of the Model

- Hydraulic models are developed for all kinds of purposes:
  - A model to produce rough answers quickly
    - Generally 1D or 2D models that are not very detailed
    - Simple 2D model is faster to develop than a 1D model
  - Detailed Planning study
    - 1D, 2D, or combined 1D/2D
  - Design study - model will be directly used to design a structure
    - not uncommon to use a 1D or a 2D model as a preliminary screening tool
    - 3D models and physical models are generally used to design hydraulic structures
  - Real Time Modeling and Mapping, etc.
    - Generally need something that runs fast

Sources and Accuracy of the Data

- What is the level of detail and accuracy of the:
  - Terrain data
  - Cross section data
  - levee information
  - Hydraulic structure data?

- Hydrology and boundary conditions
  - Peak flows only
  - Full hydrographs at gaged locations
  - Full blown hydrologic model

Duration of Events to be Modelled

- The duration of an event depends on
  - Size of the watershed/river system
  - Study purpose

- Event durations:
  - Peak flows or snapshot in time – 1D, 2D, or 3D
  - Single events: 1 day to months – 1D, 2D
  - Period of record analysis: many years – 1D

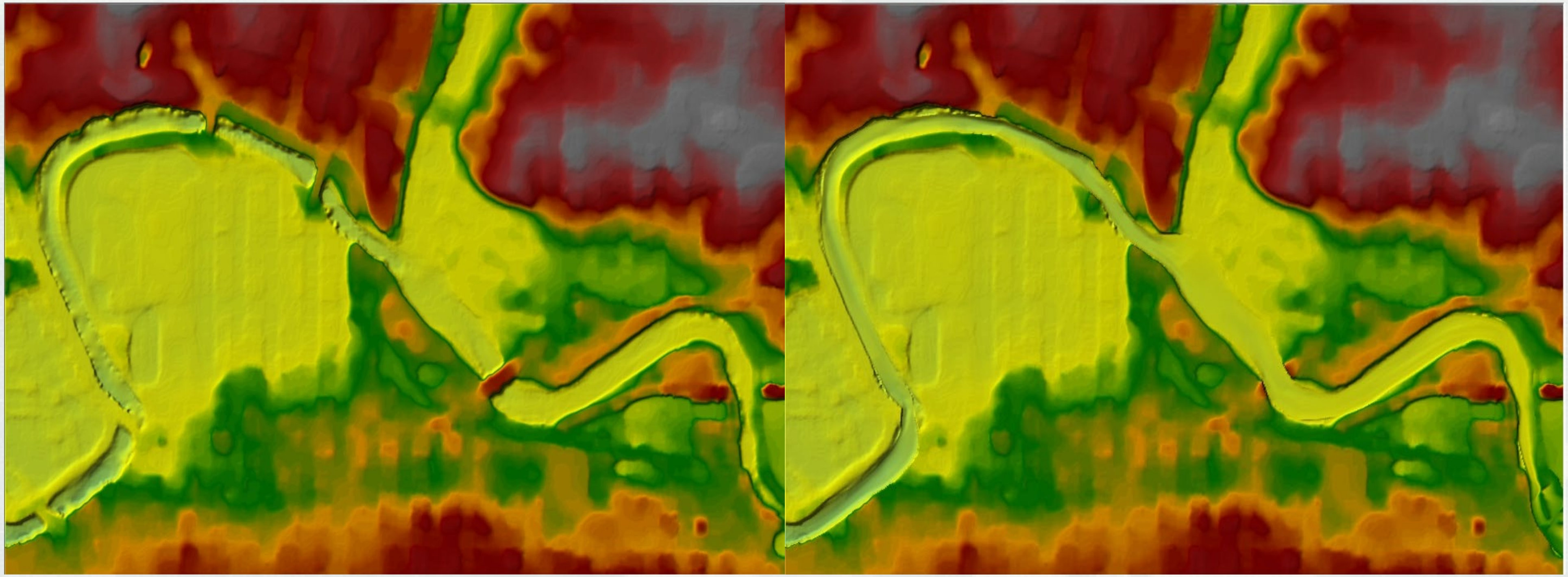
Data Requirements

- Data requirements can vary significantly for 1D and 2D modeling approaches, as well as steady versus unsteady flow modeling
- The amount and quality of available data may dictate the type of modeling that can be accomplished
- The main areas in which data requirements may be different are:
  - Terrain data
  - Roughness - channel and floodplain vegetation/landuse
  - Hydraulic Structure information
  - Calibration/validation data

Terrain Data

- **1D models**
  - Only need cross sections at the necessary locations for computing an accurate water surface
- **2D modeling**
  - Must have a terrain model (DEM or DTM) of the entire system.
- **Quality of Terrain will also affect model choice**
  - Lack of underwater channel data – 1D easier
  - 2D requires channel data in the terrain model

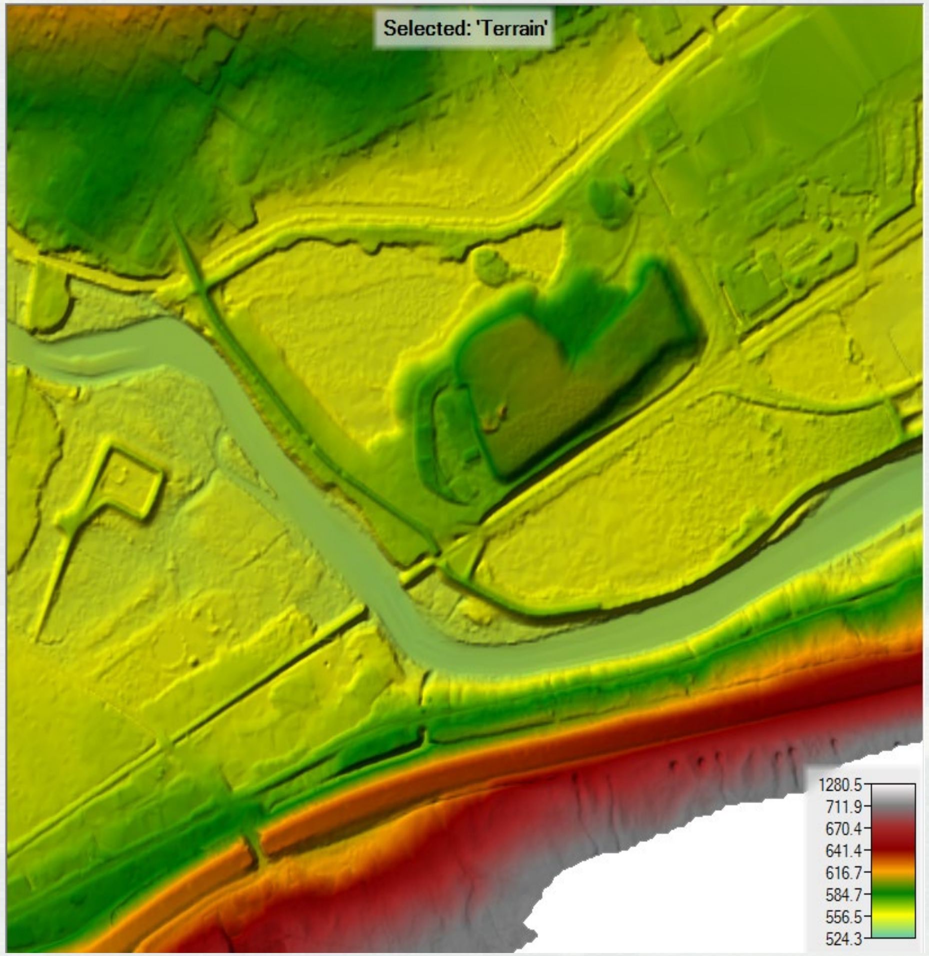
Example Terrain with and without Channel Data and Bridges Removed

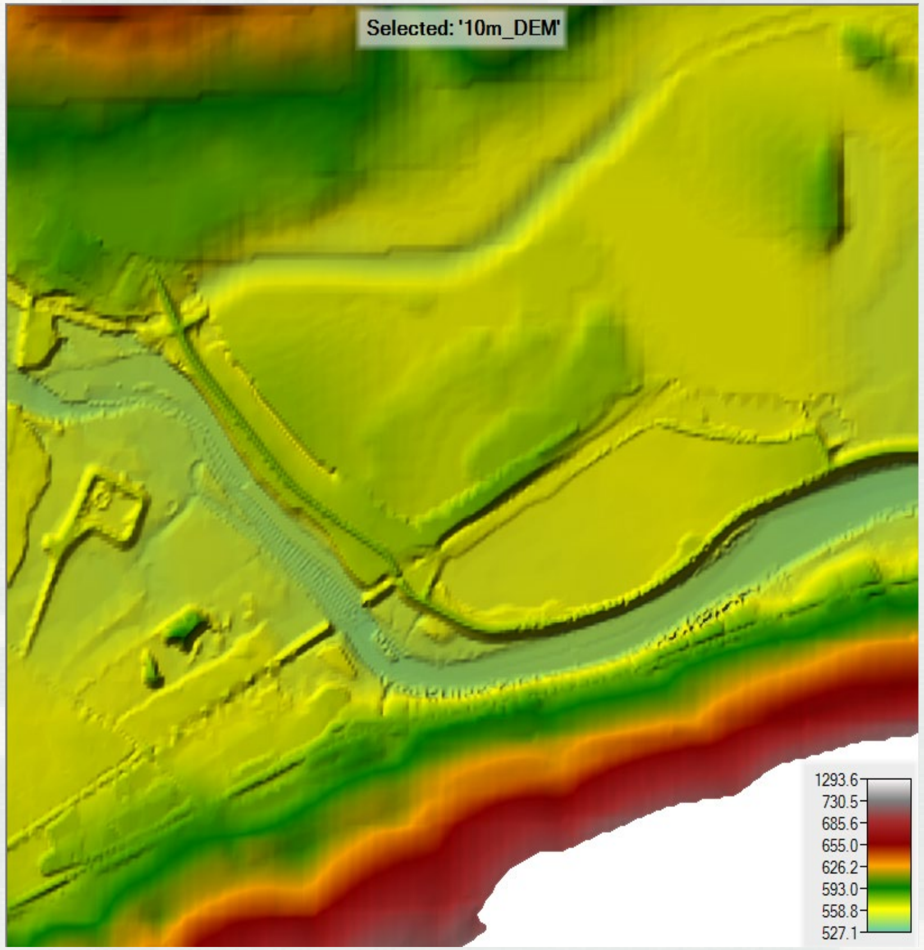


Terrain model without under water channel data

Terrain model with channel data burned into terrain model

Example Lidar and Channel data (left) vs 10m DEM (right)



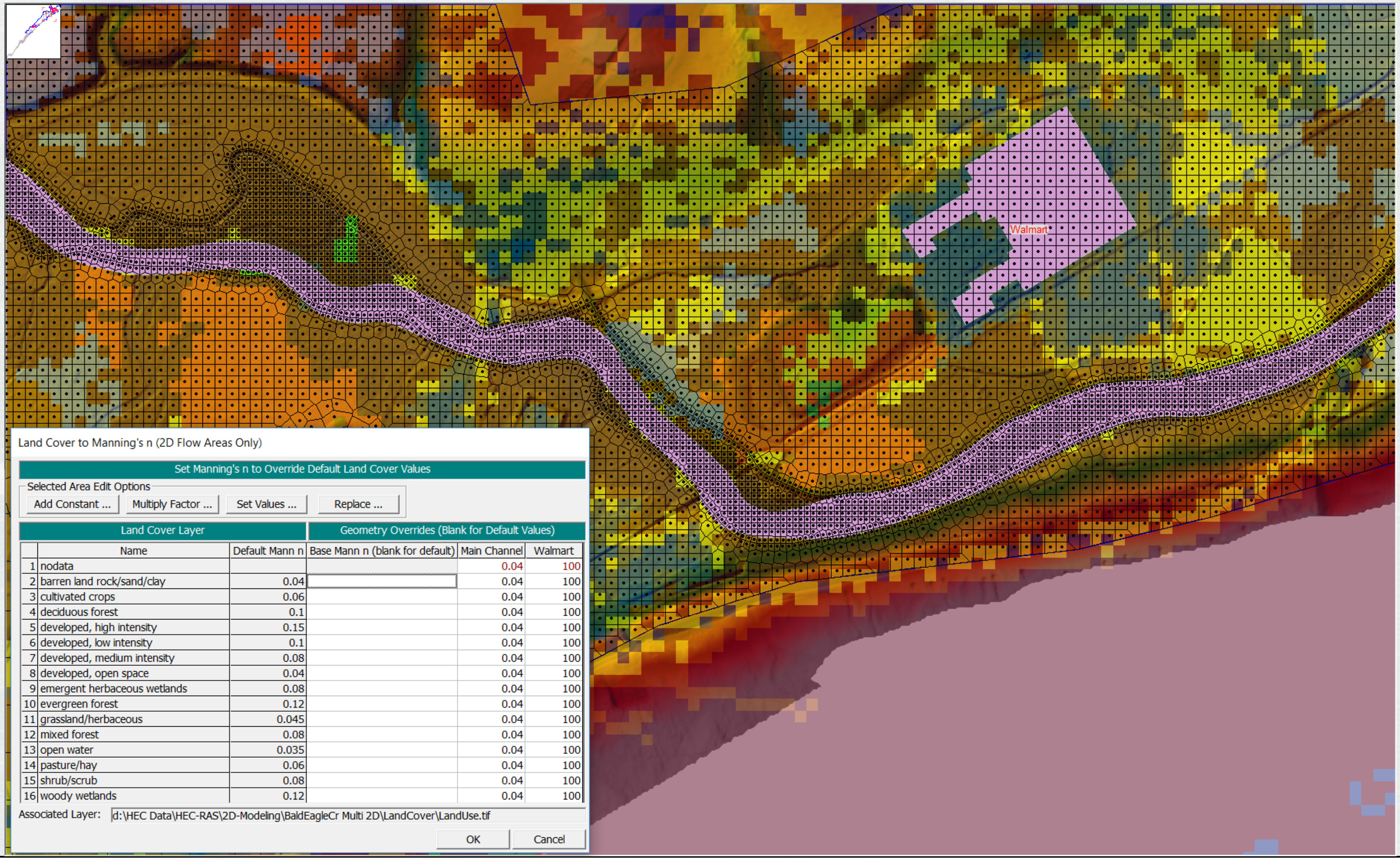


Channel and Floodplain Roughness Vegetation/Landuse

- 1D modeling approach
  - Roughness can be defined cross section by cross section
  - or with spatial vegetation/landuse

- 2D modeling approaches
  - Require spatial vegetation/landuse approach
  - Main channel roughness must be defined with separate user defined polygons

Example 2D Model Landuse and Channel Roughness Polygons



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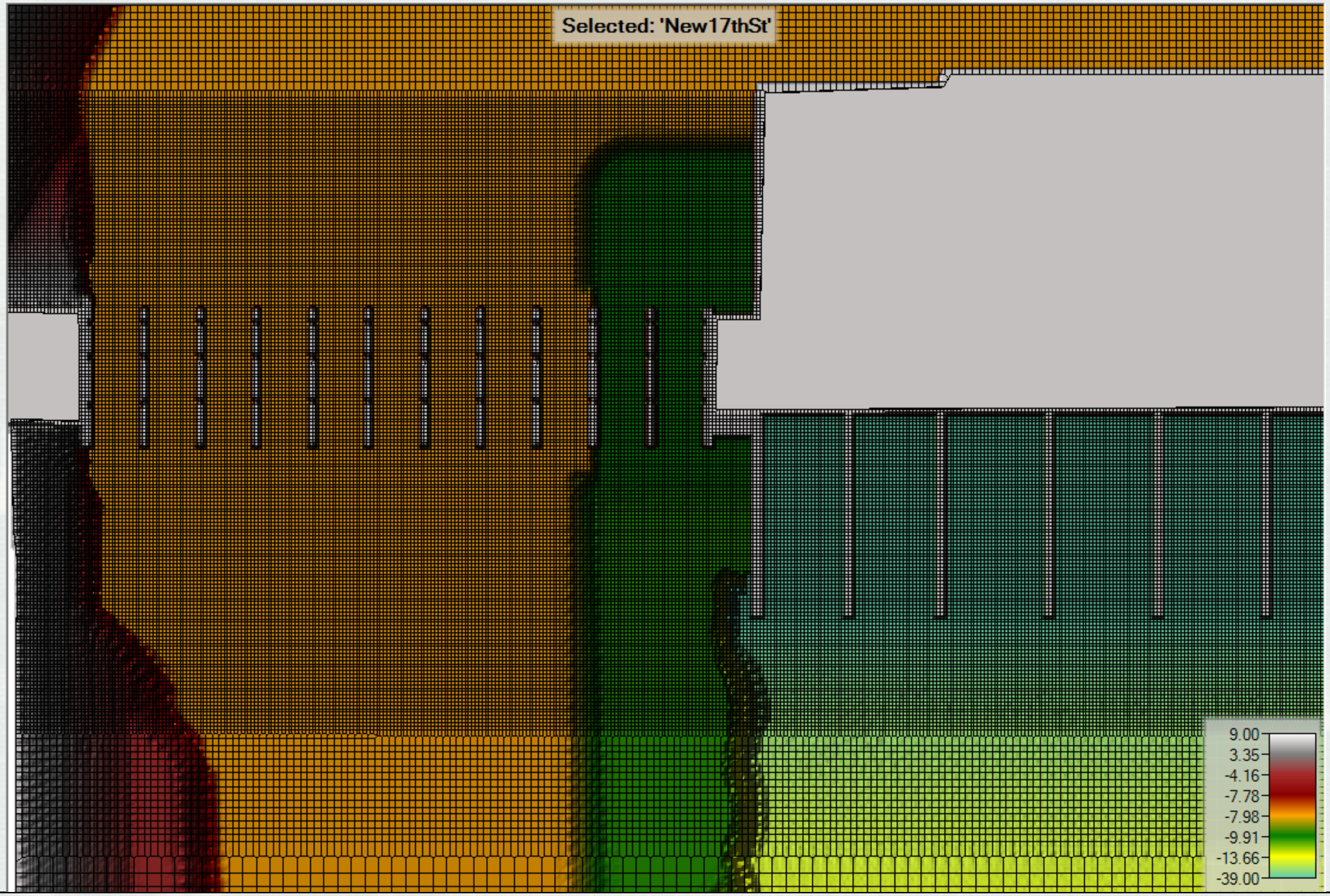
Hydraulic Structures

- The data requirements will vary between 1D and 2D modeling approaches

  - 1D models:
    - Physics based equations (energy, momentum): cross sections, roughness
    - Semi empirical equations: user defined coefficients
    - rating curves: computed outside of the model.

  - 2D modeling approaches
    - Same as 1D approaches above (1D Hydraulics)
    - True 2D modeling through and over the structure – Much more detail need to describe the terrain data. Eddy viscosity coefficients.

Example Detailed 2D Model of New Orleans 17th Street Canal Gates



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Calibration/Verification Data

- Calibration and validation of the model is required regardless of the model type.

  - **1D Unsteady Flow modeling**
    - Observed flow and stage hydrographs at gages
    - High water marks
    - Historical Inundation maps

  - **2D Unsteady Flow models**
    - Observed flow and stage hydrographs at gages
    - High water marks
    - Historical Inundation maps
    - Observed velocity

Model Output/Results

- Requirements for hydraulic model outputs, as well as level of detail, will influence the type of model used for a study.

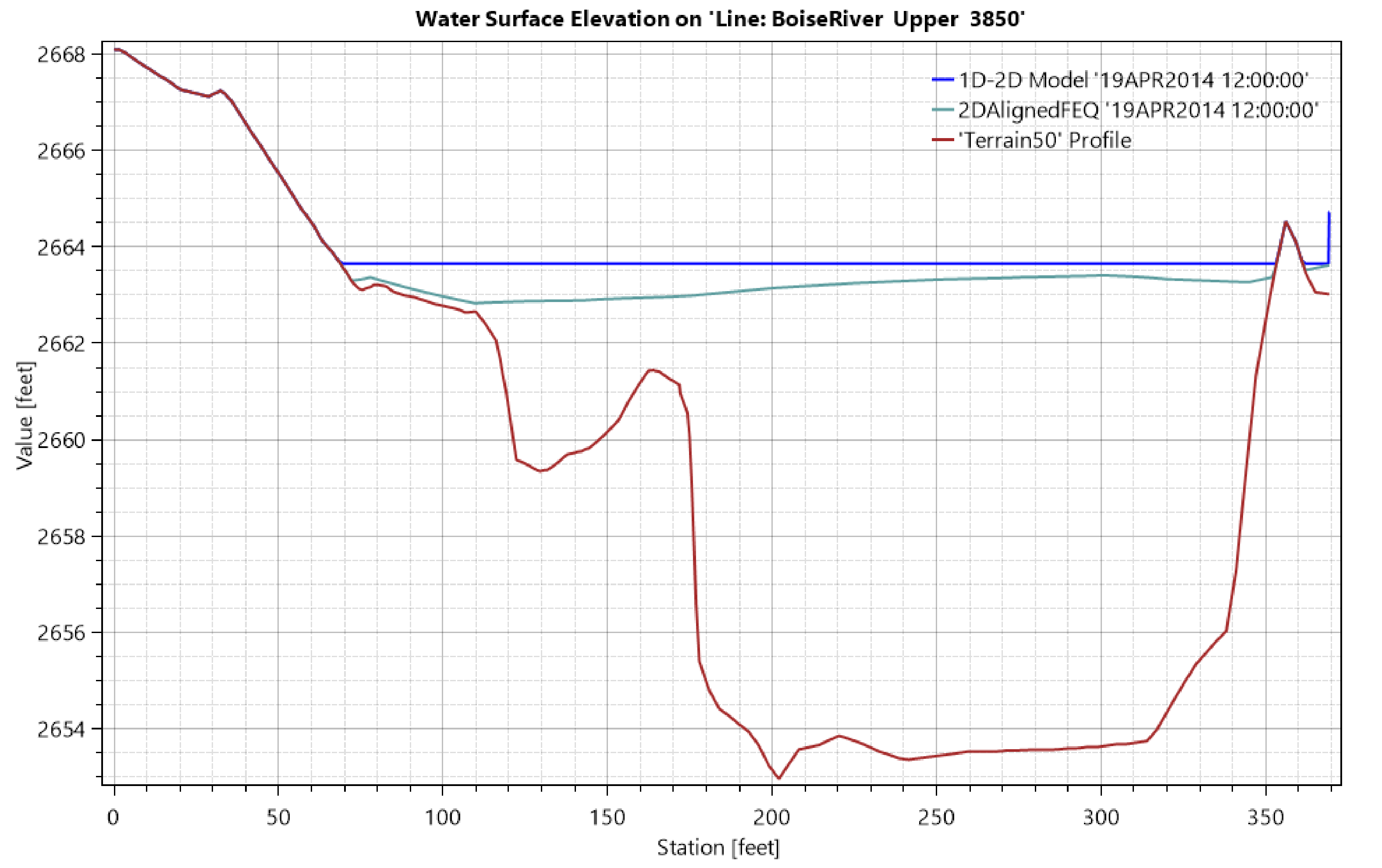
- So the questions that modelers should ask at the beginning of a study are:
  - what are the required hydraulic results needed for this study?
  - what level of detail is needed?
  - what level of accuracy is expected/desired?

Hydraulic Model Outputs for 1D, 2D, and 3D Level of Detail

Hydraulic Output/Results	1D Unsteady Flow Modeling	2D Unsteady Flow Modeling	3D Unsteady Flow Modeling
Max Water Surface Elevation (WSE)	Single average WSE per cross section and storage area.	Horizontally varying WSE. One WSE for each cell	Horizontally varying WSE. One WSE for each cell/node
Stage Hydrographs	Average WSE vs. time for cross sections and storage areas	Horizontally varying WSE vs. time for each computational cell/node	Horizontally varying WSE vs. time for each computational cell/node
Peak Flow Rates	Peak flow at each cross section and hydraulic structures	Peak flows at user defined output/profile lines and hydraulic structures	Peak flows at user defined output/profile lines and hydraulic structures
Flow Hydrographs	Flow vs time at each cross sections, boundary conditions and hydraulic structures	Flow vs. time at user defined output/profile lines, boundary conditions, and hydraulic structures	Flow vs. time at user defined output/profile lines, boundary conditions, and hydraulic structures
Velocities	Average velocities for main channel, left overbank and right overbank. Further discretization is based on conveyance based subdivisions.	Horizontally varying but vertically averaged velocities. One average velocity for each cell/element face	Horizontally and vertically varying velocities. One velocity per computational mesh face

Hydraulic Output/Results	1D Unsteady Flow Modeling	2D Unsteady Flow Modeling	3D Unsteady Flow Modeling
Flow directions and patterns	Flow direction must be defined by the modeler when laying out river reaches and storage areas.	Horizontal flow direction is computed based on the details of the terrain and computational mesh. Horizontal circulation patterns can be ascertained.	Three dimensional directions and flow patterns are computed directly.
Flood Arrival Times	Flood arrival times are based on the computations of 1D average velocities and interpolation of water surfaces between cross sections. Level pool routing cannot be used for estimation of flood arrival times in storage areas.	Flood arrival times are based on two dimensional velocities and flow patterns, as well as water surface elevations within each cell/node.	Flood arrival times are based on three dimensional velocities and flow patterns, as well as water surface elevations within each vertical cells. 3D modeling is currently not used that often for arrival times
Hazard Mapping Depth x Velocity	Depth is computed from spatially interpolated water surface elevations minus the terrain elevation at that location. Velocity is interpolated from interpolating 1D averaged velocities described above.	Depth is computed from cell water surface minus terrain elevations at each location. Velocity is interpolated from 2D spatially computed velocities at each cell/node Face.	Depth is computed from cell/node water surface minus terrain elevations at each location. Velocity is vertically averaged at each location.
Inundation Boundaries	Water surface boundary is computed at each cross section, then an interpolation surface is made and intersected with the terrain to find the water boundary (zero depth elevation)	The zero depth boundary is computed for every cell/node that is partially wet. These boundaries are merged to make continuous polygons.	The zero depth boundary is computed for every cell/node that is partially wet. These boundaries are merged to make continuous polygons.
Shear stress computed as: (γ R Sf).	For 1D cross sections, the cross section is broken into user defined slices, then average values are computed for each slice. Values are interpolated between cross sections using the cross section interpolation surface.	For 2D cells/nodes it is the average shear stress across each face, then interpolated between faces.	Hydraulic Properties are vertically averaged, then the average shear stress is computed across each face, then interpolated between faces.
Stream Power computed as average velocity times average shear stress	For 1D cross sections, the cross section is broken into user defined slices, then average values are computed for each slice. Values are interpolated between cross sections using the cross section interpolation surface.	For 2D cells/nodes it is the average velocity times average shear stress across each face, then interpolated between faces.	Hydraulic Properties are vertically averaged, then the average stream power is computed across each face, then interpolated between faces.

Example 1D vs 2D Water Surface Elevation Plot



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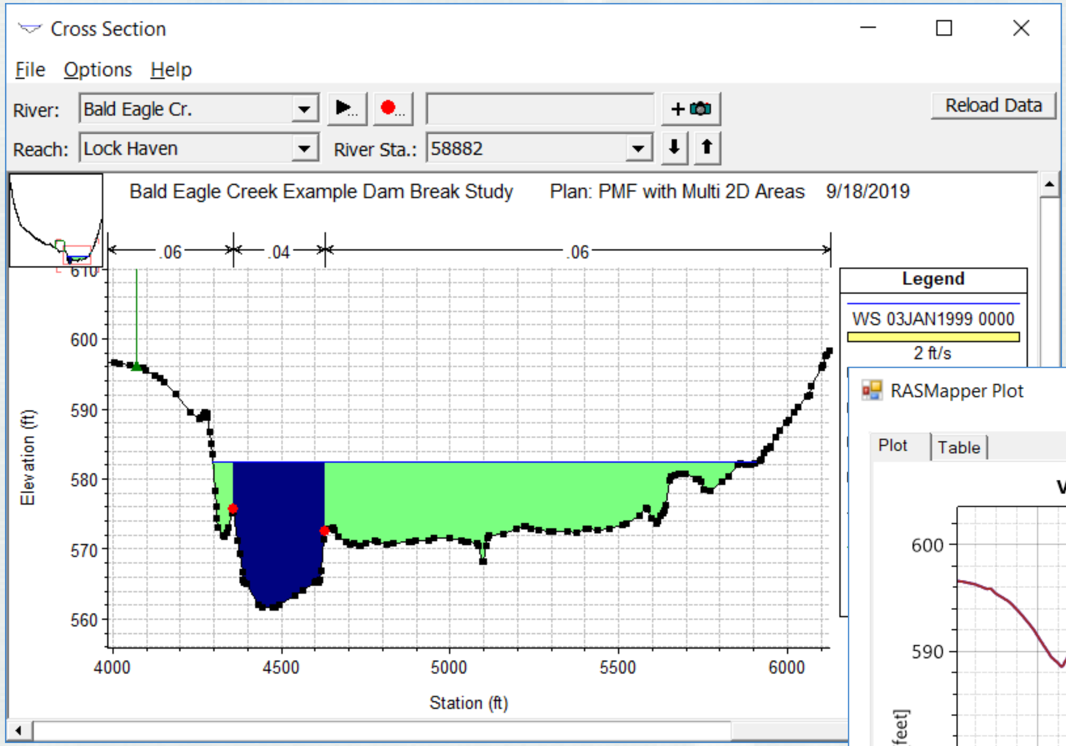
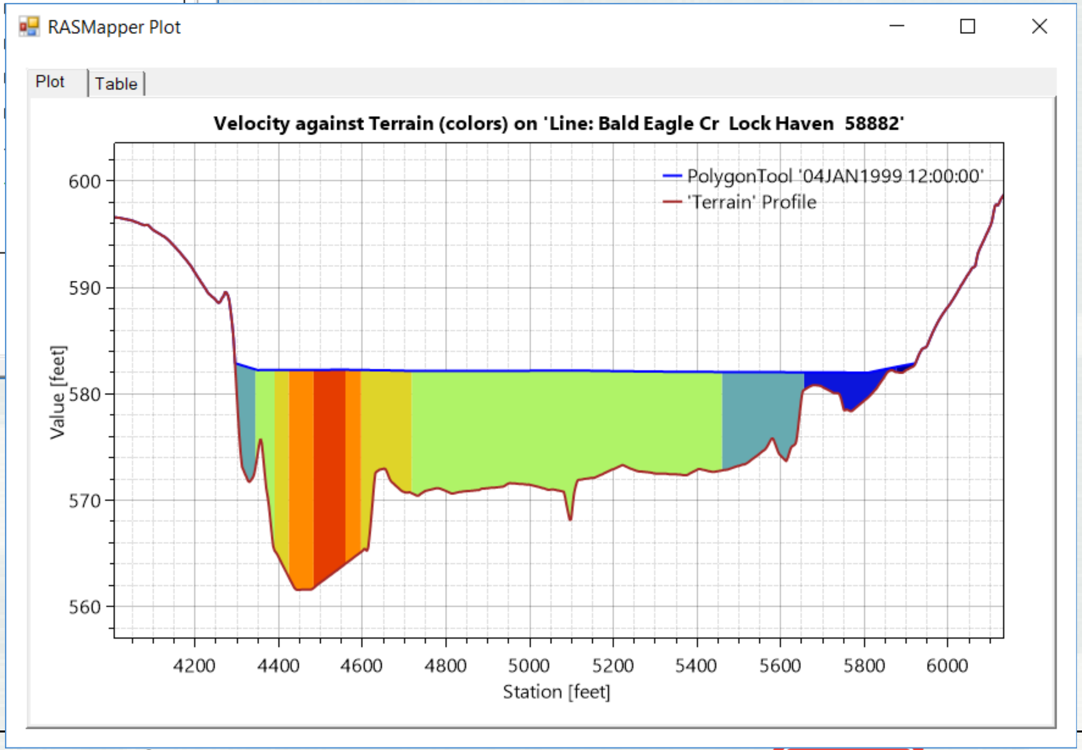
Example 1D and 2D XS Velocities





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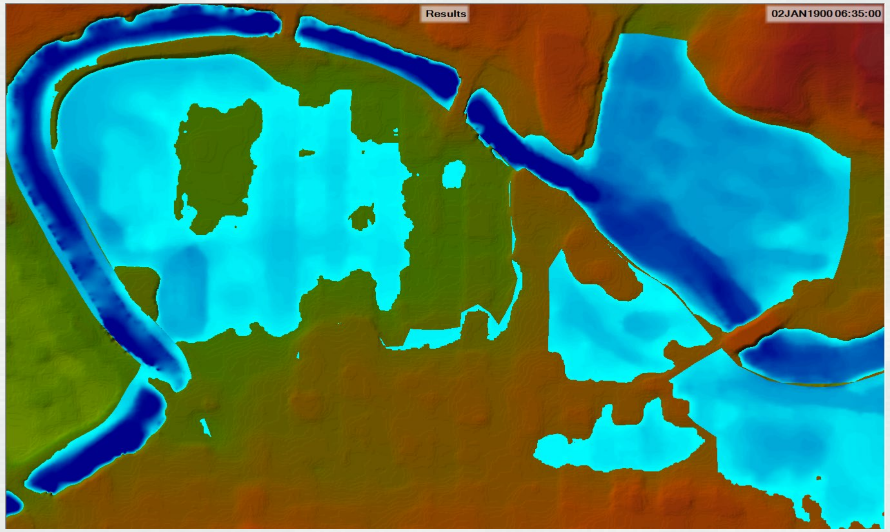
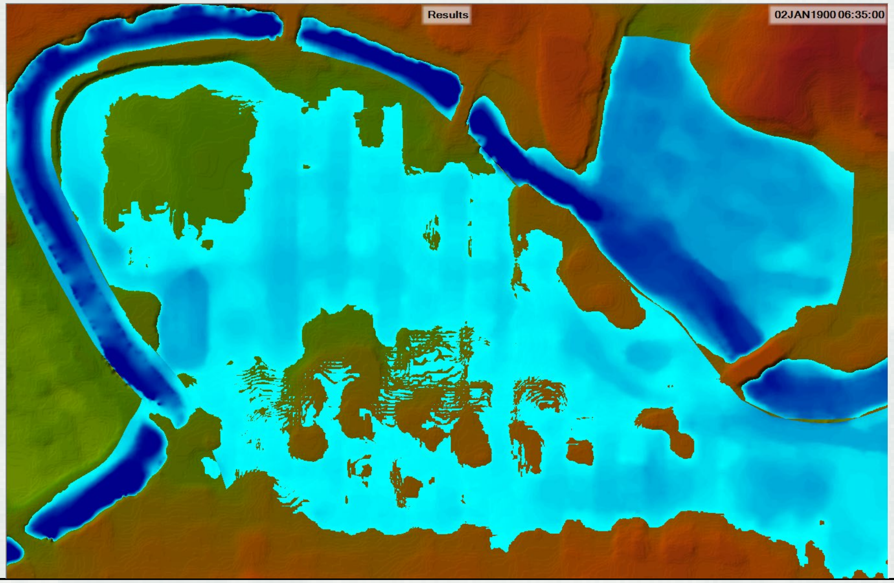
Example 1D vs 2D Inundation Map



1D Model with Storage Areas used for interior floodplain area

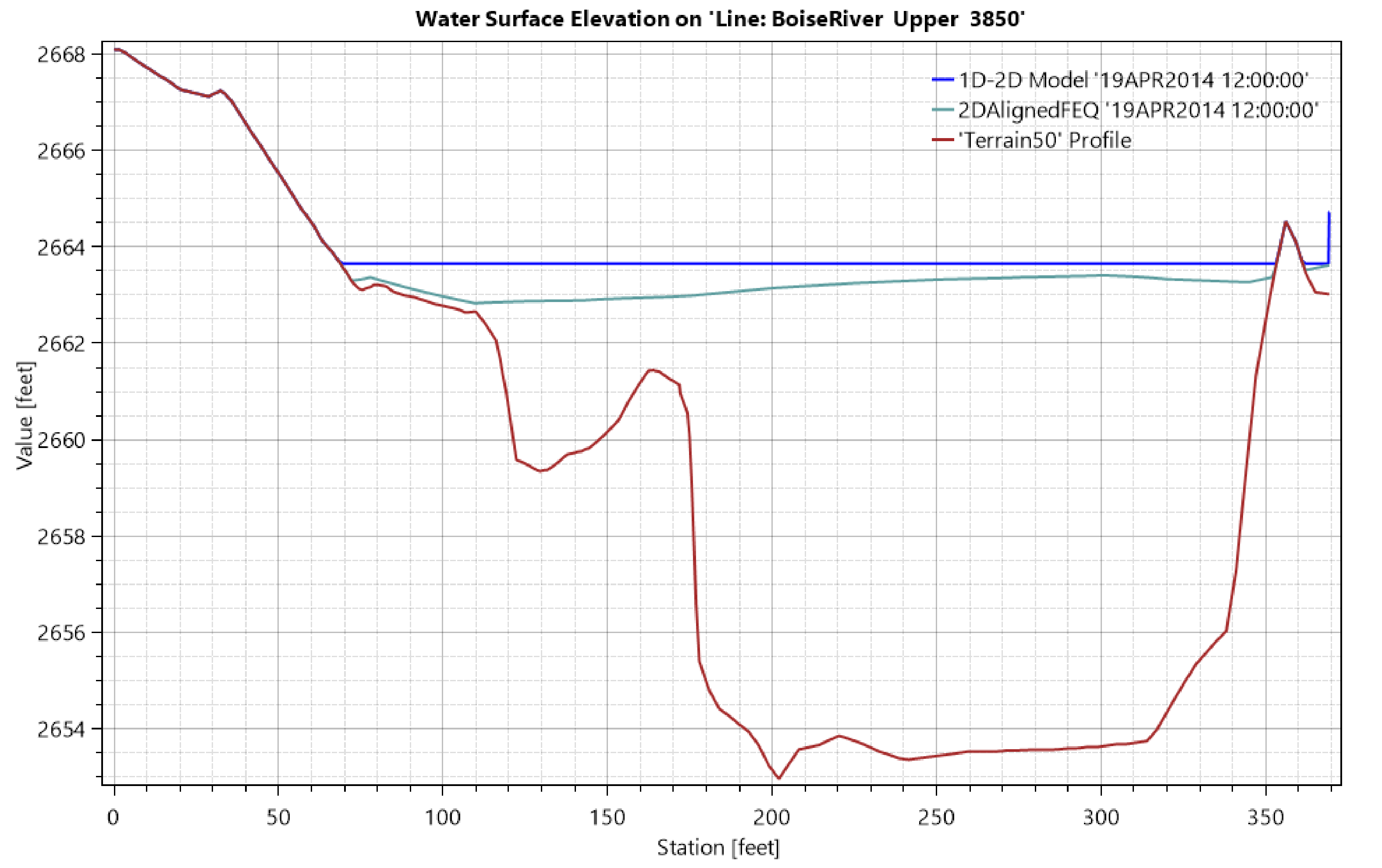


2D Model of Interior Floodplain area

1D vs 2D
Computational Differences

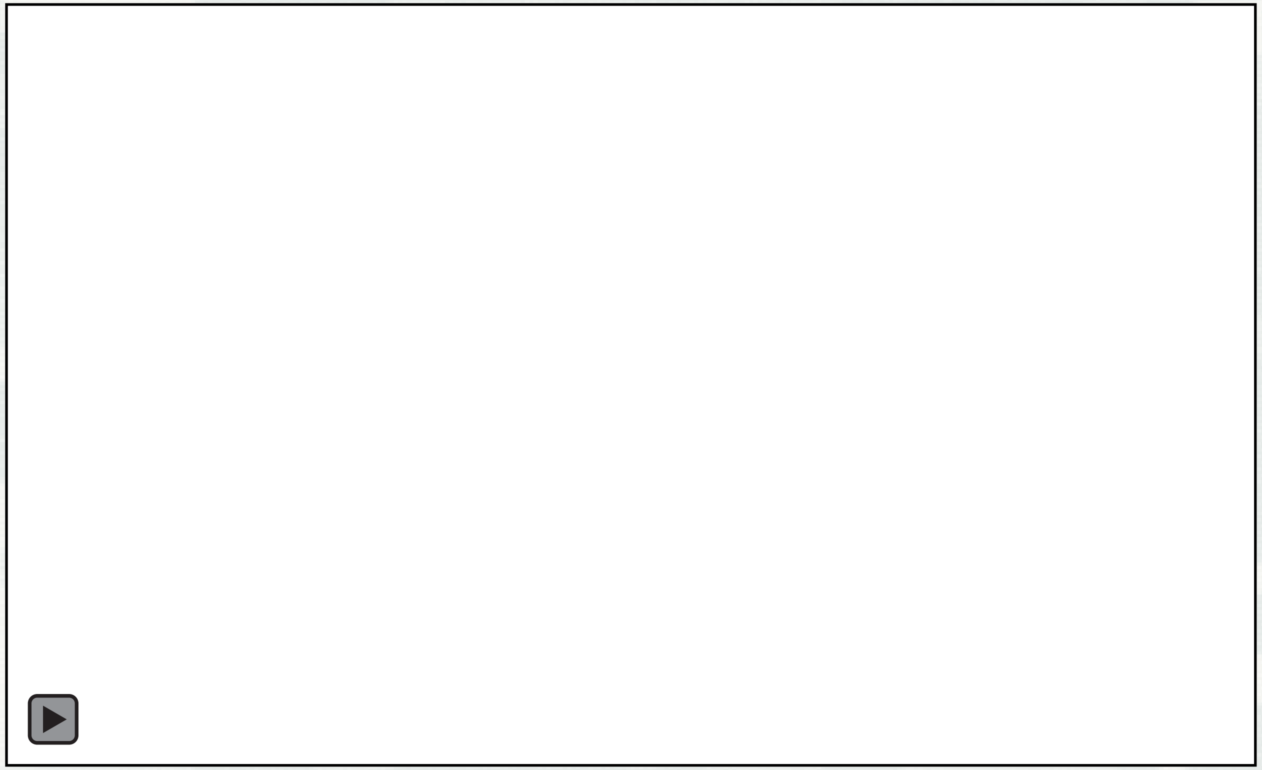
- Computed Water Surfaces Elevations
- Computed Velocities
- Cross section spacing vs cell size
- Friction Loss computations
- Contractions and Expansions
- Storage/Ineffective Flow Areas
- Hydraulic Structures

Example 1D vs 2D Water Surface Elevation Plot

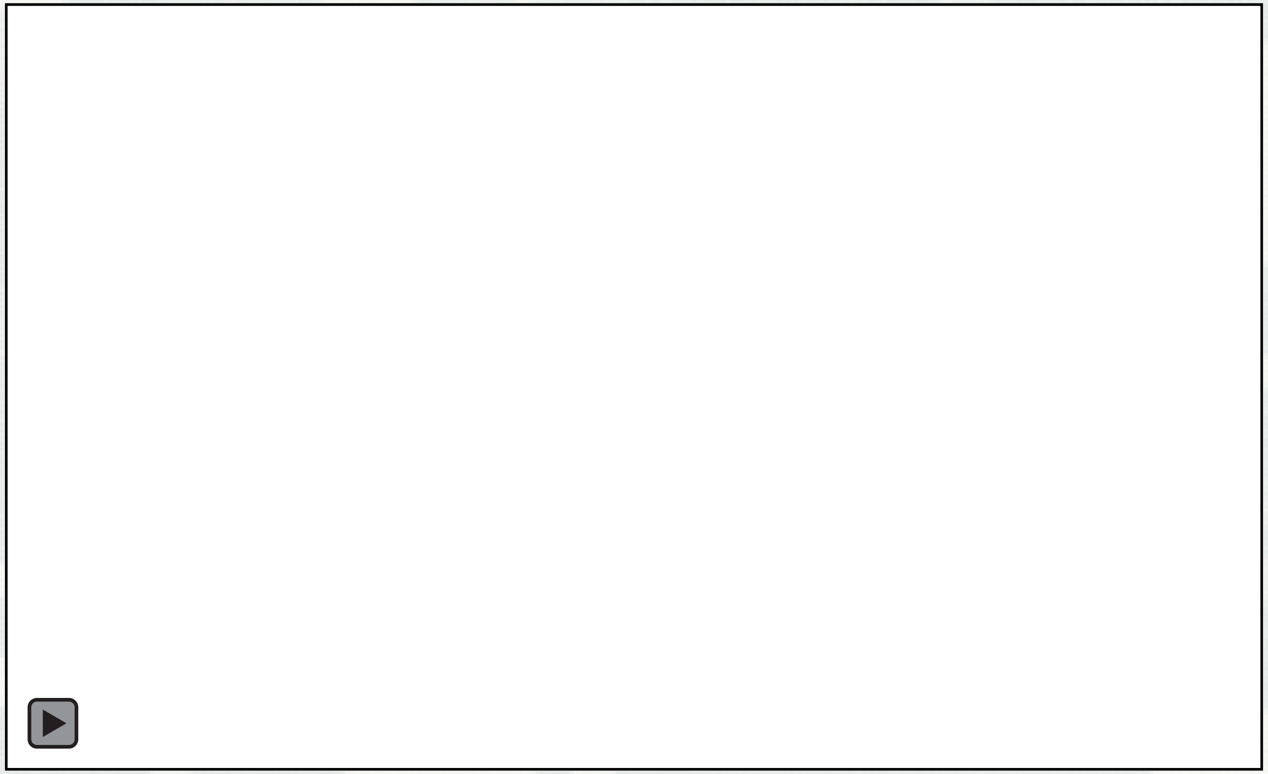


1D vs 2D Velocities

1D Velocities



2D Velocities



Computational Spacing

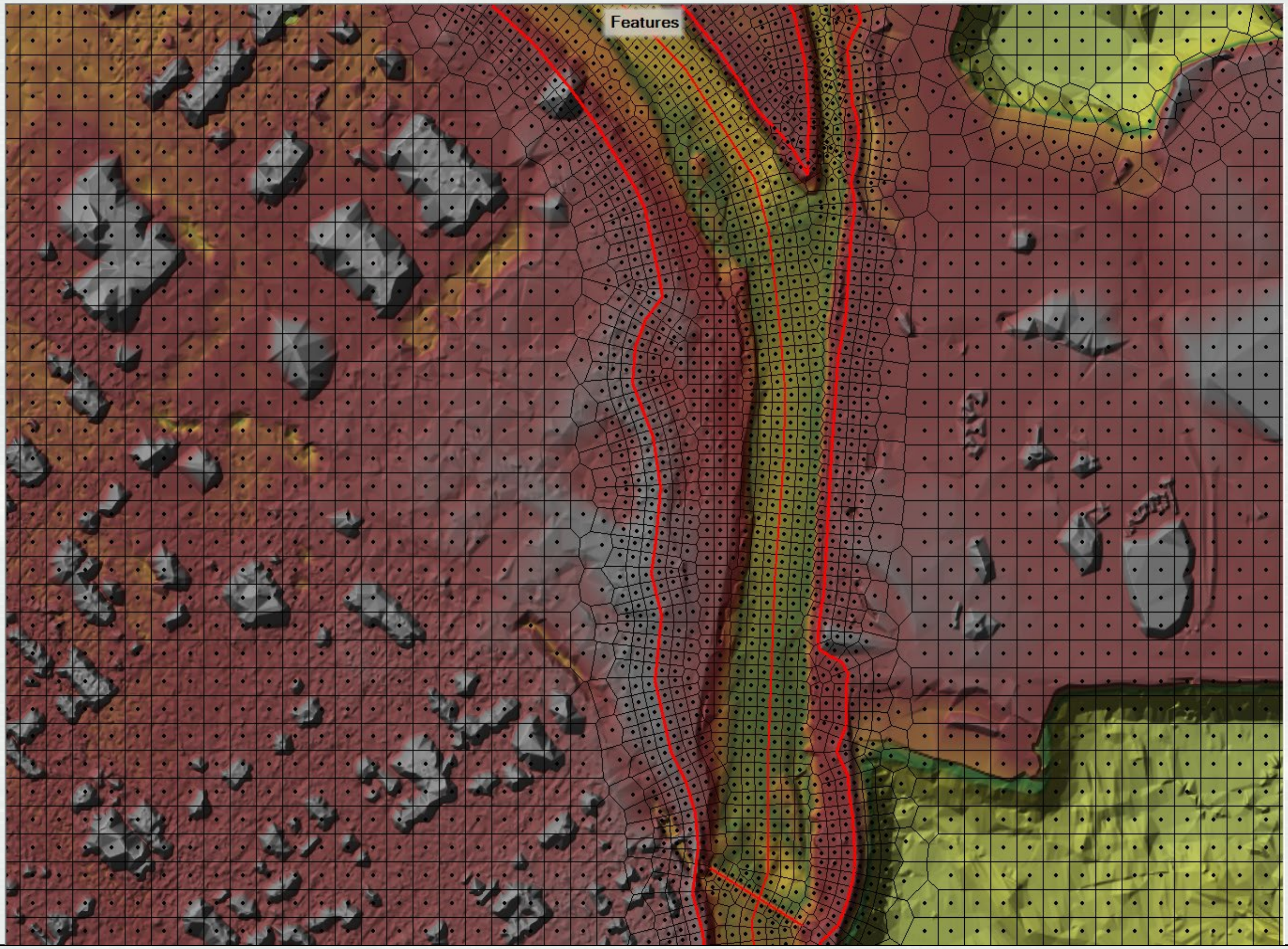
- 1D cross section spacing and 2D Cell faces (Cell size) have similar requirements:

  1. Should be placed at representative locations to describe significant changes in geometry.
  2. Additional XS/cells are needed at significant changes in water surface, ground slope, velocity, and roughness.
  3. XS/cells must also be added around levees, bridges, culverts, and other structures.
  4. Bed slope also plays an important role; steeper streams/slopes require tighter spacing

Additional 2D Mesh Requirements

- Refinement and alignment of cells required to accurately describe the main channel
  - Align faces to the high ground of main channel bank lines
  - Refinement regions to control channel cell size
  - Breaklines to align cells with the channel
- Roads, levees, and other high ground barriers to flow require breaklines
- Structures require breaklines to capture high ground and align to flow

Example 2D mesh with a detailed mesh of the main channel, with grids aligned to the flow



Friction Loss Computations

- 1D modeling:
  - friction slope is computed at each cross section, then averaged.

$$\overline{S}_f = \frac{S_{f1} + S_{f2}}{2}$$

- 2D Modeling:
  - Friction slope is calculated at each Face and directly used to calculate a friction coefficient. No spatial averaging is done.

Contractions and Expansions

- Contractions and expansions are inherently a three-dimensional flow phenomenon.
- **1D models**
  - empirical coefficients times a change in velocity head (1D steady and unsteady flow)
  - changes in pressure forces (1D unsteady flow momentum eq).
- **2D models**
  - Capture the effects of contractions and expansions directly in the development of the 2D momentum solutions.
  - However, the full three-dimensional effects of contractions and expansion may not be captured without turning on turbulence modeling, and calibrating turbulence coefficients.

Storage/Ineffective Flow Areas

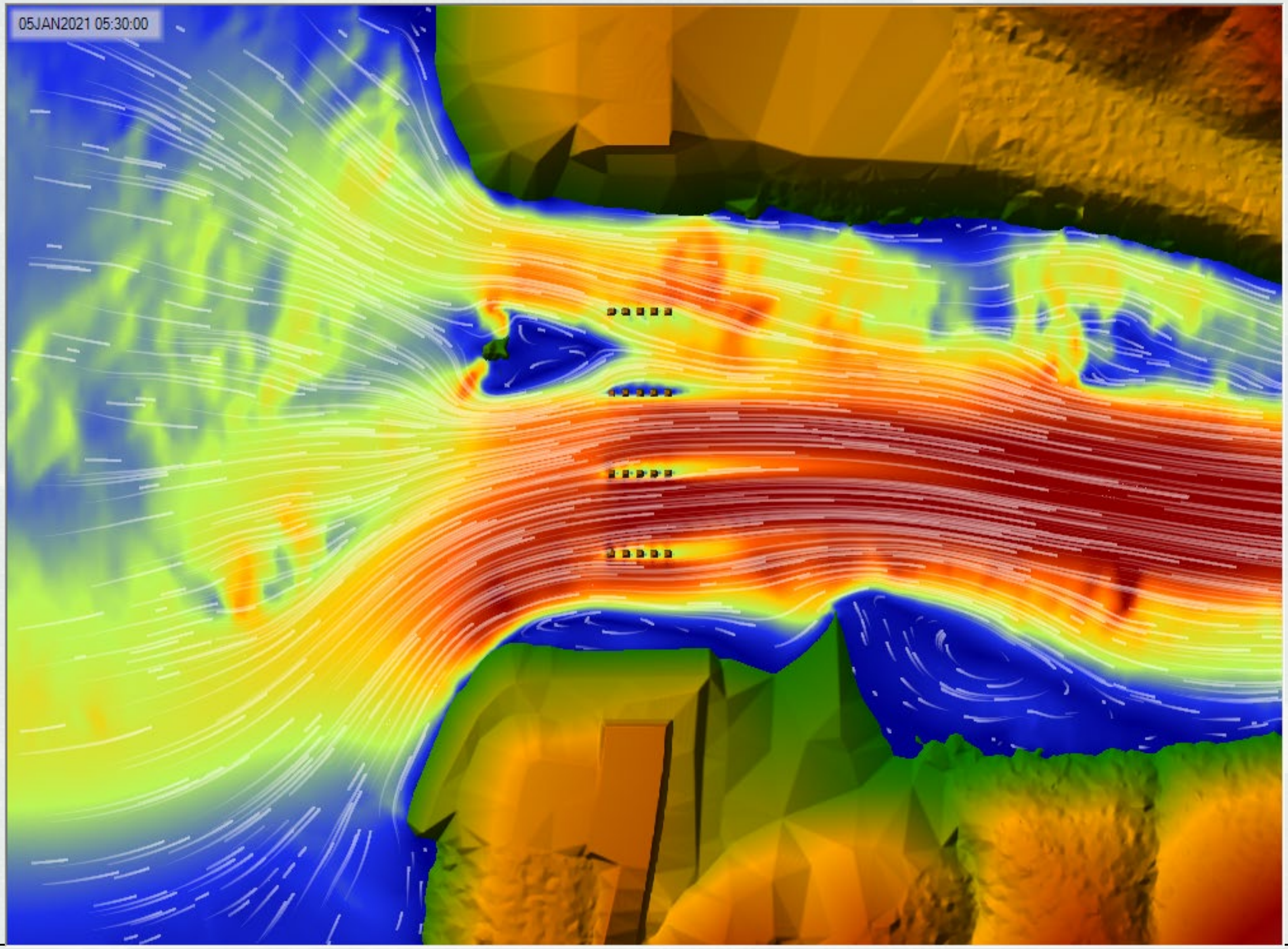
- **1D Modeling**
  - Ineffective flow areas are required in order to get the correct amount of active (effective) flow area.
  - **1D storage areas** can also be used to model off channel storage.
- **2D Modeling**
  - Ineffective flow areas are not required, as ineffective flow areas (Eddy's) are automatically computed from the basic equations.

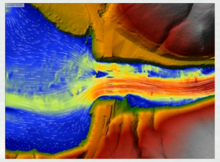
Hydraulic Structures

- **1D models**:
  - Physics based equations (energy, momentum)
  - Semi empirical equations (Yarnell, Pressure flow, weir flow)
  - rating curves

- **2D modeling approaches**
  - Same as 1D approaches above (1D Hydraulics)
  - True 2D modeling through and over the structure

Example velocity output for a detailed 2D model of a bridge

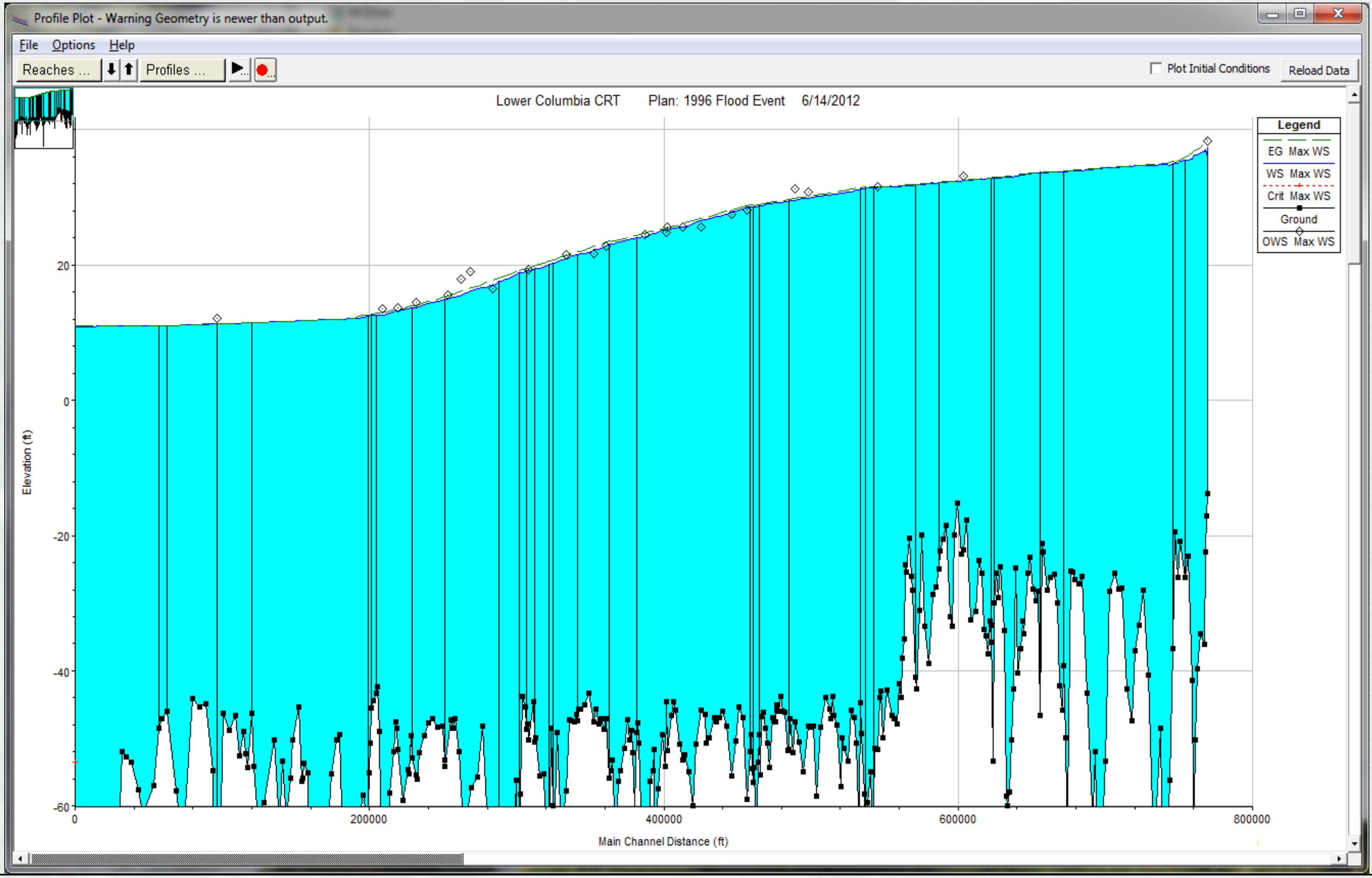




1D Model Calibration

- Calibrating of 1D modeling reaches is accomplished by changing/adjusting the following:
  - Roughness parameters
  - Contraction and expansion coefficients
  - Ineffective flow area extents and height trigger elevations
  - Hydraulic structure coefficients
  - Bend loss coefficients (rare to use these)
  - Boundary condition information, such as energy slopes, or even potentially rating curve values.
  - Debris blockage information at structures
  - Levee breach dimensions and timing values.

Example of a Calibrated 1D model for the Lower Columbia River



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2D Model Calibration

- Calibrating a 2D model is very similar to 1D approaches, but with some of the following differences:
  - Modifying Roughness is more difficult and time consuming
  - No contraction/expansion coefficients
  - No ineffective flow areas
  - Refinement of 2D models may require changes in order to match observed velocity measurements
  - Calibration to velocity information will generally require changes in roughness, possible eddy viscosity coefficients, and maybe even terrain adjustments, if appropriate and justified.
  - Models runs take longer, so may have less time to change parameters and see cause and affect (sensitivity analysis).

Time and Cost Issues

- The time to develop a model with the 1D or 2D approach can vary, depending on the type and purpose of the model:
  - "Quick and Dirty" model during a flood emergency
    - much faster to lay out a 2D Model – draw flow area polygon, set a basic cell/element size, attach some boundary conditions, and go.
  - Detailed model is being developed,
    - both approaches will ultimately take about the same amount of time to develop the initial model.
    - 1D models require XS layout, ineffective flows, etc…
    - 2D models require changes in mesh resolution; breaklines; refinement regions.
- Computational Time and Hardware Requirements:
  - 1D is much faster and can run on almost any machine: single thread
  - 2D much slower, generally high-level computational machine:
    - Suggested machine: 12 to 32 fast cpu cores; 64 GB RAM; SSD hard disk

1D Modeling Advantages

- In general 1D models require less terrain data, in that the channel portion of the model can be from separate detailed cross-sectional surveys, or it can be approximated with a trapezoid.
- 1D models are often (not always) easier to calibrate, due to the simplicity of changing parameters such as roughness coefficients, and other variables.
- Modeling of hydraulic structures is often easier, requiring less data and computational requirements.
- 1D models require significantly less computational time and computer resources.

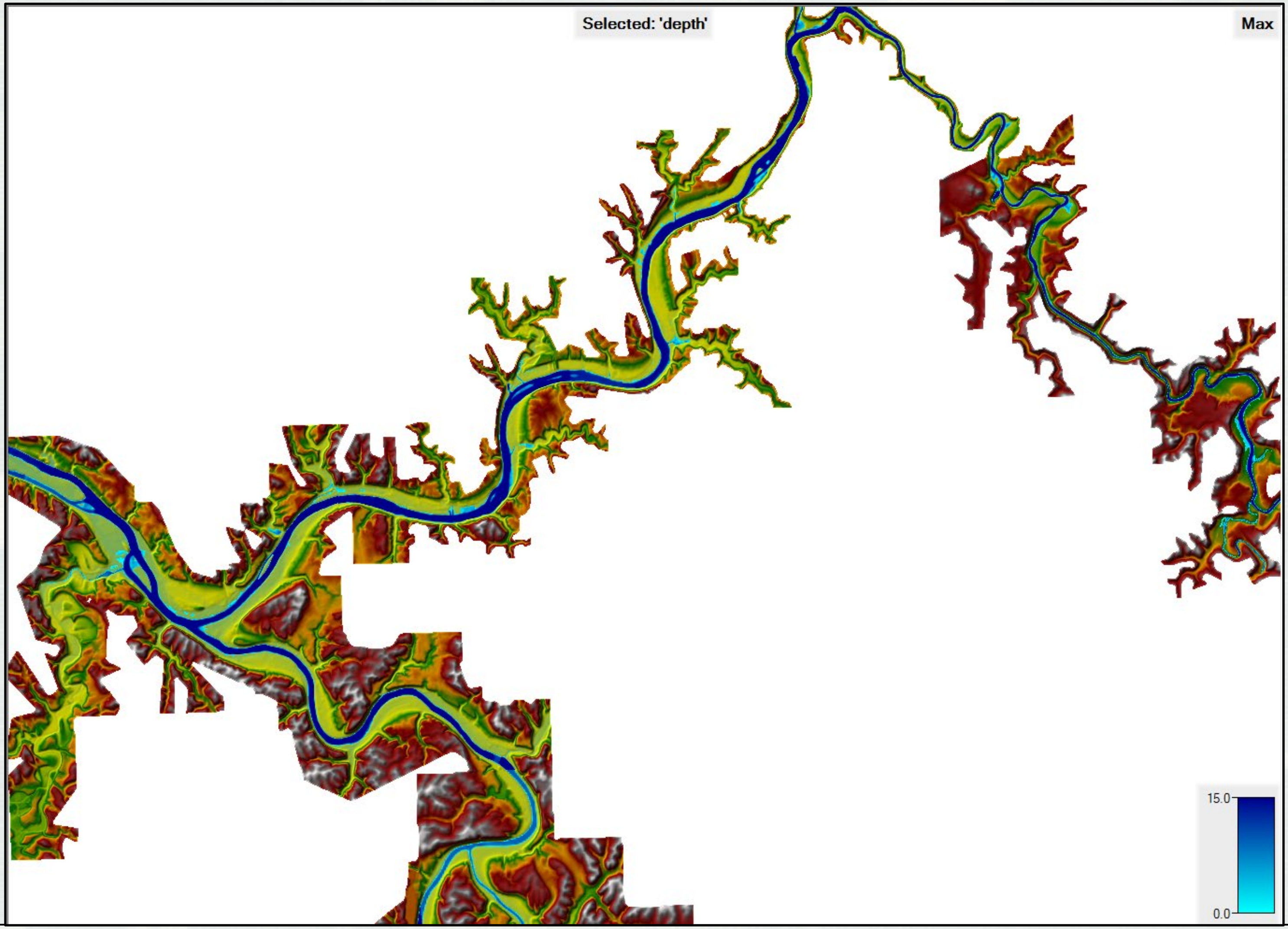
1D Modeling Disadvantages

- The flow path of the water, for all events, must be known before developing the model. This is not always possible to know, especially in flat areas.
- 1D cross sections must be laid out perpendicular to the flow in order to get an accurate representation of the true flow area. It is not always possible to do this for the full range of events, and therefore may require more than one geometric representation of the system
- You only get a single averaged water surface elevation per cross section
- Velocity output is limited to average values for the main channel and overbanks.
- Friction losses are averaged between cross sections
- Energy and/or force losses due to contractions and expansion require the modeler to define empirical coefficients (Cc and Ce) and ineffective flow areas.
- Flow distribution is based on the individual cross section conveyance, and does not take into account momentum and continuity of surrounding cross sections
- Mapping of the inundated area is based on the assumption that the water surface changes linearly between any two cross sections, and that the water surface is flat inside of storage areas.

Areas Where 1D Modeling Can Produce similar results to 2D Modeling (with less effort)

- Steep streams that are highly gravity driven and have small overbank areas
- Rivers and floodplains in which the dominant flow directions and forces follow the general river flow path.
- Medium to large river systems, where we are modeling a large portion of the system (100 or more miles), and it is necessary to run longer time period simulations (i.e. 2 week to 6 month events, or period of record simulations).
- River systems that contain a lot of bridges/culverts, weirs, dams, gated structures, levees, pump stations, etc.…
- Areas in which the basic data does not support the potential gain of using a 2D model.

Example of a highly one-dimensional flowing river system (Allegheny - Monongahela Rivers, confluence at Pittsburgh, PA)



2D Modeling Advantages

- The flow path of the water, for all events, does not have to be known to develop the model. However, the extent of the flooding does need to be correctly defined.
- The direction of the flow can change during the event. Water can move in any direction, based on energy and momentum of the flow.
- Velocity, momentum, and the direction of the flow are more accurately accounted for. This is especially true for flow going over roads, levees, barriers, structures, around bends, and at flow junctions/splits. Additionally, 2D models can be used to analyze eddy zones within the flow field. Around bends, 2D models produce accurate water surface elevations, but velocity distributions might be erroneous due to the existence of helical flow.
- Energy and force losses due to contractions and expansions, etc. are directly accounted for, and do not require empirical coefficients, increased roughness, or user defined ineffective flow areas.
- The mapping of the inundated area, as well as velocities, and flood hazards (depth x velocity) is more accurate.
- Detailed modeling of hydraulic structures, in a full 2D modeling approach, can provide more insight into the flow distribution approaching, going through, and coming out of a structure.

2D Modeling Disadvantages

- More detailed terrain models are required in order to run a 2D model. The terrain must include the details of the channels at all locations within the model.
- Defining and modifying roughness values requires more spatial definition and can be more difficult and time consuming during the calibration process.
- Turbulence Modeling coefficients must be calibrated
- Requires significantly more computational time and/or computational resources. May require the purchase of a very high-level computer (many cores, fast CPU's, lots of RAM, and fast hard disk), or utilizing HPC and cloud computing solutions.
- May require using larger grid sizes than desirable for the problem, in order to reduce the run times to a manageable amount of time.
- May not really produce better results, if the data used to perform the modeling (terrain, channel data, and roughness) do not support the level required for accurate 2D modeling.

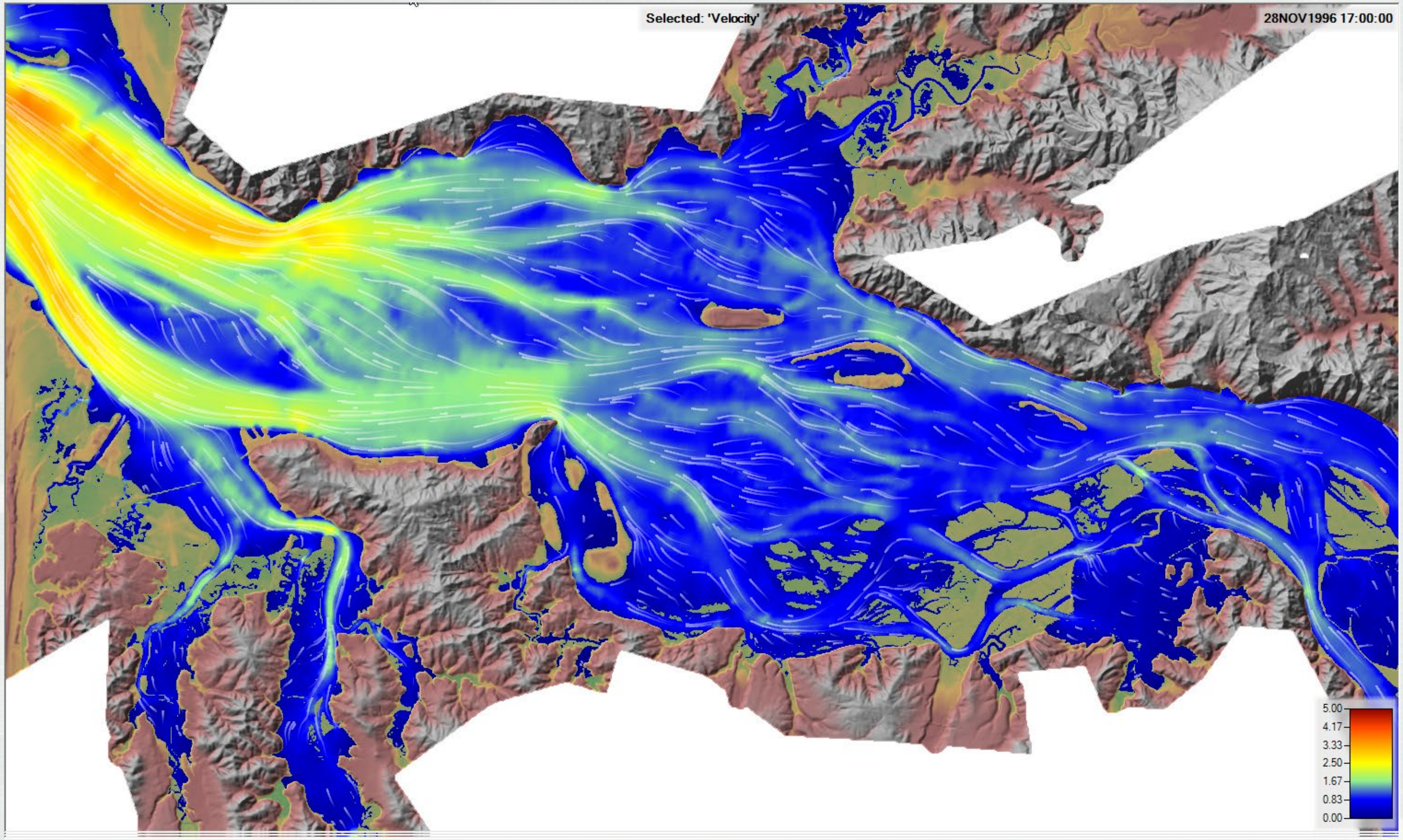
Areas Where 2D Modeling Can Give Better Results than 1D Modeling

- When modeling an area behind a levee system in which the flow will go in multiple directions.
- Areas and/or events in which the flow path of the water is not completely known, or could change during the event.
- Very wide and flat flood plains, where water will go in multiple directions when it enters the floodplain
- Bays and estuaries in which the flow will continuously go in multiple directions.
- Highly braided streams
- Alluvial fans
- Flow around abrupt bends in which a significant amount of super elevation will occur
- At Hydraulic Structures where it is very important to obtain detailed water surface elevations and velocities in two dimensions

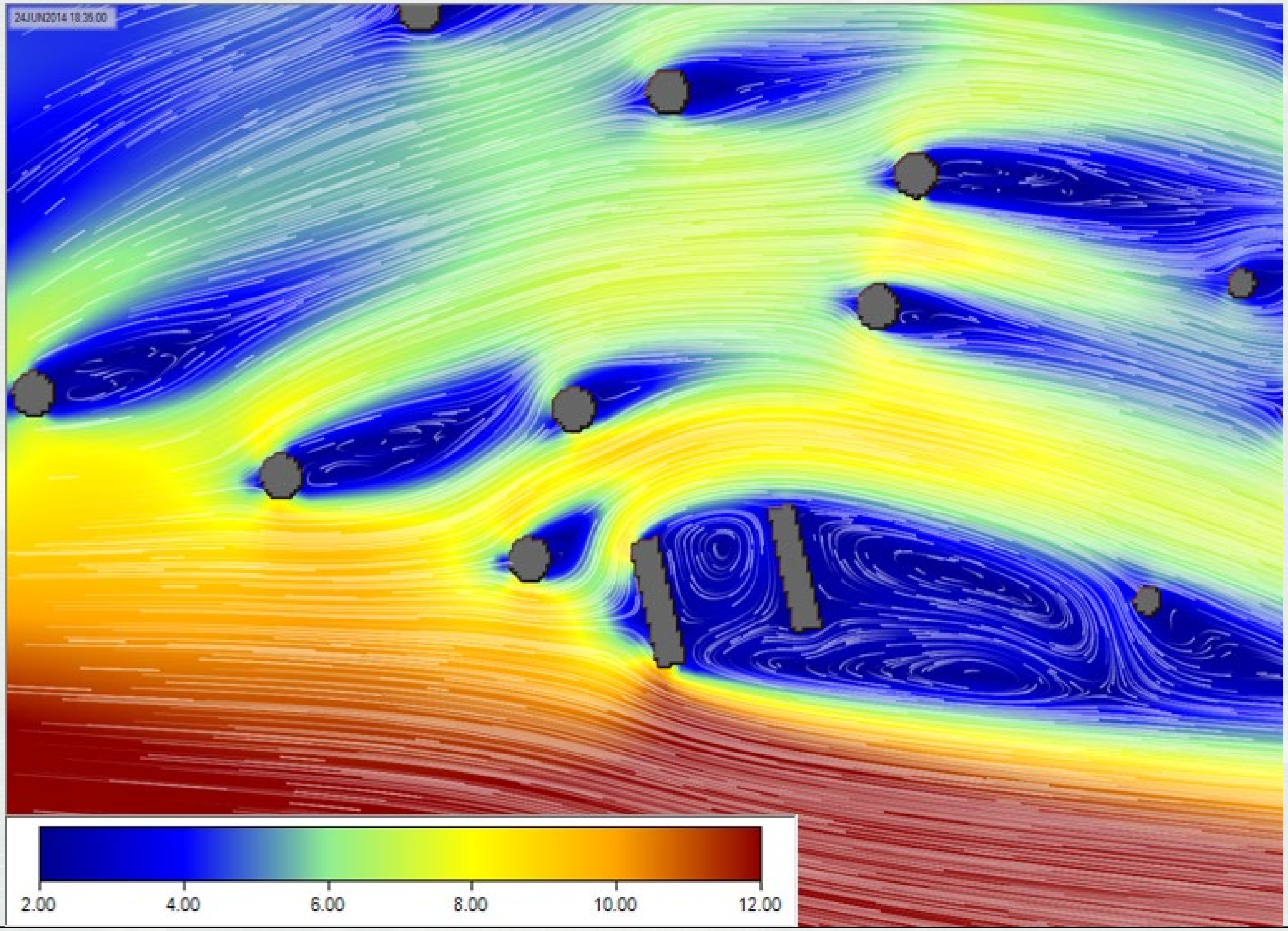
Example of a leveed system breach with water going in many directions

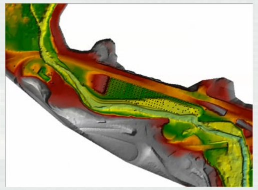
Example Dambreak that goes out into an extremely flat area and spreads out

Lower Columbia River Bay with water depths shown in shades of blue

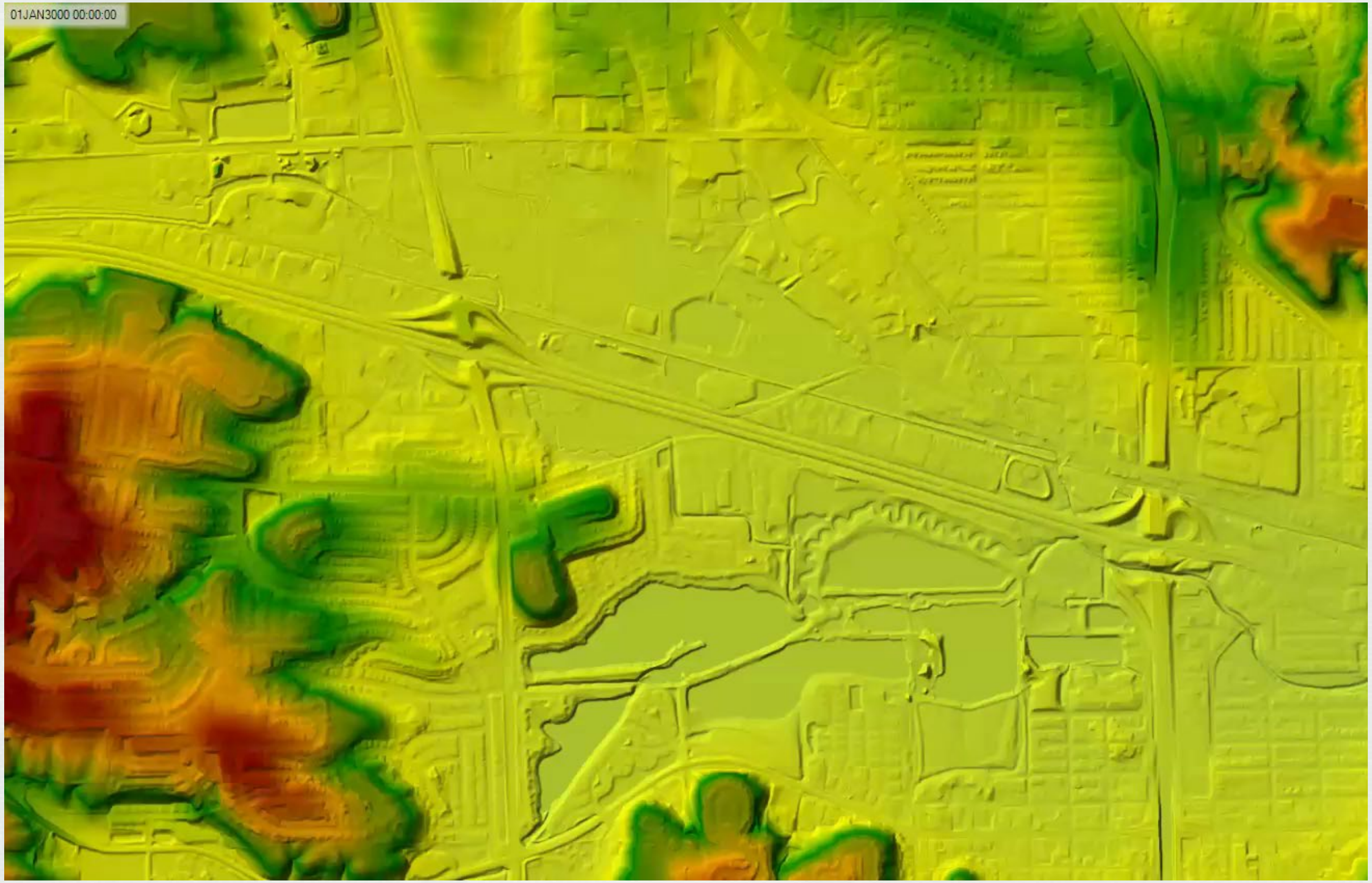


Detailed 2D model of flow going around piers from a railroad station platform





Overbank Flow in an Urban Area



Questions?