# Dynamic and Steady State Modeling Approaches to Riverine Hydraulic Studies Using 1-D, Looped 1-D and 2-Dimensional Topological Discretizations

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ABSTRACT: Many different types of numerical hydraulic models are currently used by consultants, government agencies, research institutions and others to study how riverine systems function. Often hydraulic models are selected for projects based solely on institutional inertia and not on their ability to simulate the key physical processes that are unique to each riverine system. Hydraulic models are only numerical representations of riverine systems and therefore must deviate from the physical processes that they attempt to simulate. These deviations are either small or large, systematic and non-systematic, and lead to errors in the results. Errors in the results are caused by model assumptions, limitations, and errors in input data. Modeling approach, data requirements, discretization, calibration, verification, and results can vary by using different types of models for the same project. Understanding (or at least recognizing) the assumptions, limitations and resulting modeling errors is sometimes overlooked by professionals and is often not understood by clients, agencies, and the public. This paper is focused on comparing three numerical modeling approaches on the Cosumnes River, California, not only from a flood wave routing point of view but also by the topological discretization method. The study includes a steady-state 1-D model (WSPRO), an unsteady looped 1-D model (MIKE 11), and an unsteady 2-D model (MIKE 21).

## 1 INTRODUCTION

Hydraulic engineers and scientists have analyzed riverine environments with countless tools over the centuries. Analyses have ranged from simple speculations about the hydrologic cycle by ancient scholars to sophisticated deterministic 3-dimensional numerical models with dynamic coupling of physical processes. The underlying trend in riverine hydraulic analysis reflects the goal of improving the accuracy of predictions.

In our quest to achieve the goal of accurate predictions of hydraulic function, we have created a wide range of conceptual, empirical, and theoretical models to understand the hydraulic, geomorphic, and biologic functions of riverine systems. This research has been aimed at not only revealing the dynamics of underlying processes but on improving the accuracy of existing methods.

These methods are improving on many fronts due to efforts in the academic, private, and public sectors. Significant advances have been made recently through a shift from steady-state approaches to fully dynamic descriptions, and through more accurate descriptions of flow paths and topography. Instead of simply delineating the flow domain into single 1-D branches, more accurate descriptions can be achieved by describing the

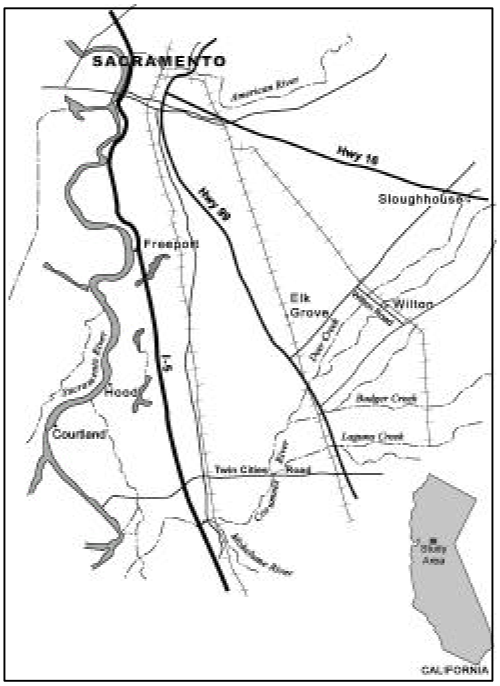


Figure 1: Site Map

flow domain with interconnected looped networks or even through 2-D or 3-D meshes.

While riverine modeling tools are providing more sophisticated descriptions, the tools are getting easier to use. User friendly graphical interfaces, graphical results presentations, and increasing computational speed allow users to simulate complex flow dynamics, easily identify problem spots, and then present results efficiently.

In this paper we compare three different modeling approaches to riverine hydraulics, using the Cosumnes River in California, USA as an example. All of the model implementations are not rigorously calibrated or validated. The simulation results presented are meant to highlight the advantages and disadvantages of different modeling approaches. The software packages used for this paper were chosen out of convenience; we are not attempting a head to head comparison of the individual software packages, many similar models exist.

## 2 SITE DESCRIPTION

The Cosumnes River flows from the Sierra Nevada Mountains to its confluence with the Mokelumne River in the Sacramento Valley, California. The Cosumnes River flows through steep, narrow canyons in the foothills to a wide lowland valley. On the valley floor, a discontinuous levee system is in place on both banks of the river. Deer Creek is a tributary to the Cosumnes River and generally flows parallel with the main river. The drainage for Cosumnes River is 1470km$^2$ and 323 km$^2$ for Deer Creek. The flood-frequency analysis (USGS, 1998) for Cosumnes River is based on a United States Geological Survey (USGS) 90 year (1907-1997) record for the Michigan Bar station. The Deer Creek flood-frequency analysis is based on a 17 year (1961-1977) record for the Sloughhouse station. The 100-year peak discharge for Cosumnes River is 2350 m$^3$/s and 320 m$^3$/s for Deer Creek. The modeled reach is roughly 2 km wide by 25 km long and flows in a southwest direction between Hwy 16 and Hwy 99 (see Figure 1) southeast of Sacramento.

## 3 MODELING APPROACHES

### *3.1 1-D Steady-State Model*

#### *3.1.1 Description of Model*

WSPRO is a 1-D model for analysis of gradually varied, steady flow in open channels with fixed beds and flows through bridges using the step-backwater solution technique (Sherman, 1990). The WSPRO is similar to the commonly used HEC-2 and HEC-RAS models. Results from the WSPRO model show the longitudinal variability of flow in riverine systems with the steady state and 1-D flow assumptions.

#### *3.1.2 Cosumnes Implementation*

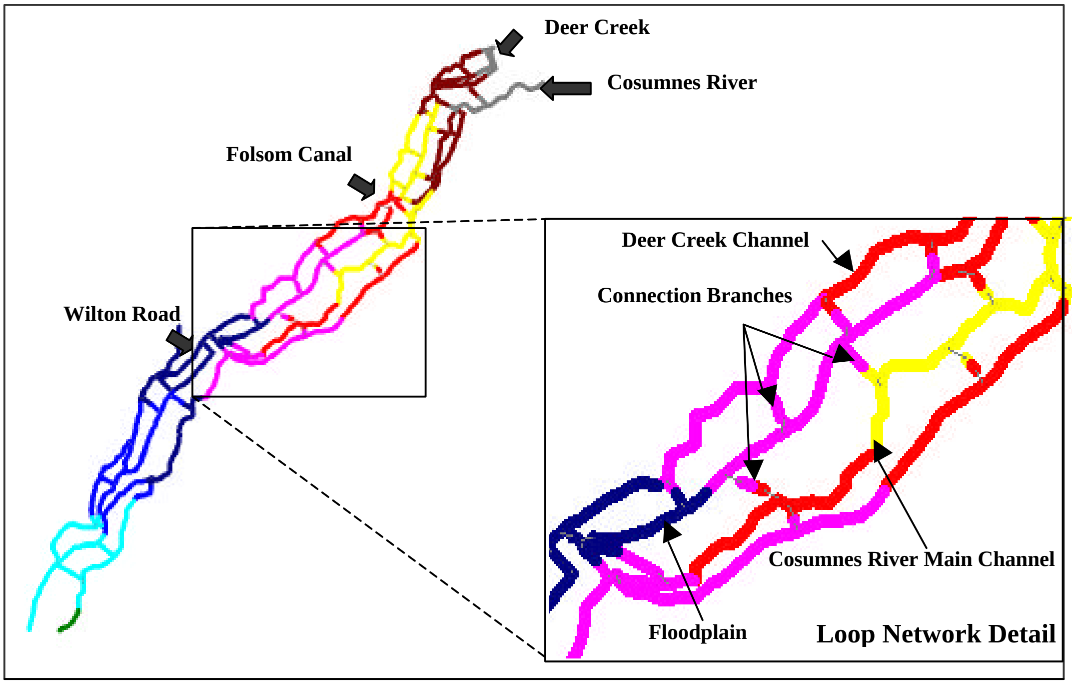


Figure 2: MIKE 11 Looped Network Model of the Cosumnes River

For a 1998 USGS study, the WSPRO model was used. Multiple runs of individual branches or specific detailed areas were computed by the USGS to accommodate hydraulic details, such as multiple bridge openings, bypass channels and levee failures. The resistance number was distributed, and dependent on the channel geometry and elevation. The model was used to compute conditions during several major flood events. For the purpose of this study the results from $Q_{100}$ were used.

### *3.2 1-D Dynamic Looped Network Model*

### 3.2.1 *Description of Model*

MIKE 11 (DHI, 1986) is a commercial 1-D model for the detailed design, management and prediction of behavior of both simple and complex rivers and floodplain systems. The model uses an implicit finite difference scheme for computation of unsteady flow based on the Saint Venant Equations. The model can be applied to describe looped networks.

One of the major advantages of using a looped network system is the possibility to describe separate flow patterns and flow exchange in the floodplain. The simulated area can be divided into individual branches connected into a system that is better suited to analyze flood wave propagation. The topological discretizations fully depend on the user and his/her experience with the model and on the knowledge of the modeling area. The modeling area is typically divided into major channels and floodplains depending on topography, cross-section shape and estimated flow patterns. Interaction between individual branches is accomplished through connection channels with structures to describe flow over banks or levees.

### *3.2.2 Cosumnes Implementation*

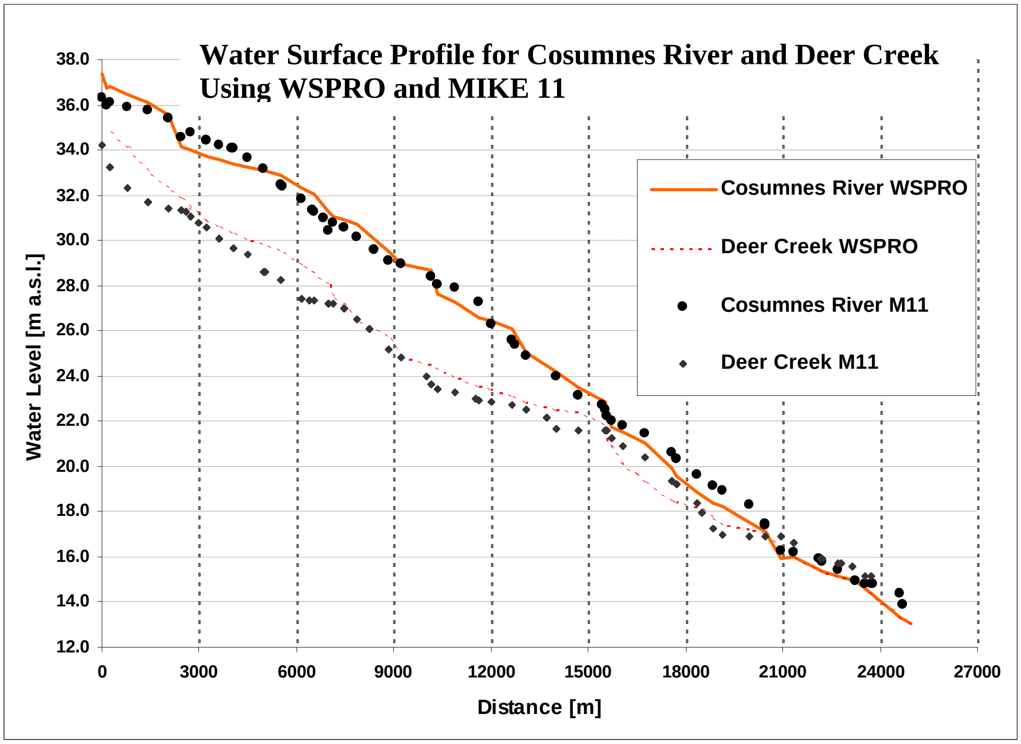


Figure 3: Water Surface Profiles for Cosumnes River and Deer Creek (WSPRO & MIKE11)

Approximately 55 cross sections, derived from the WSPRO model channel geometry, were used to describe the area. Up to four major branches were used to describe flow patterns and discharge distribution between river & tributary channels and the floodplain. Because each connection branch describes flow over the bank or levee, overflow connections are modeled as broadcrested weirs. The MIKE 11 topological discretization for the Cosumnes River is shown in Figure 2.

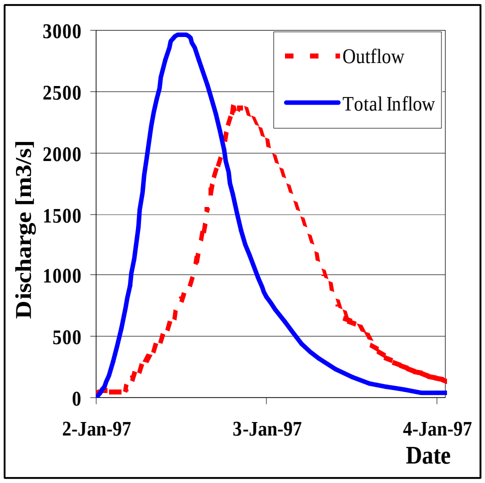
The network was checked with the existing topography from maps and a Digital Elevation Model (DEM). Hydrographs for the 100-year floods were generated using the SCS dimensionless unit hydrograph method to develop dynamic boundary conditions for the Cosumnes River, Deer Creek, Folsom Canal and Wilton Road.

### *3.3 2-D Dynamic Model*

#### *3.3.1 Description of Model*

MIKE 21 (DHI, 1998) is a two-dimensional implicit finite difference scheme used for computation of unsteady flows in rivers and estuaries. MIKE 21 is a versatile model that simulates the water level variations and flows in response to a variety of forcing functions in rivers, lakes, estuaries and coastal areas. The system solves the depth-averaged fully time-dependent non-linear equations of continuity and conservation of momentum.

The water levels and flows are resolved on a rectangular grid covering the area of interest when provided with the bathymetry, bed resistance coefficients, wind field, hydrographic boundary conditions, etc. Results from the MIKE 21 model include water depth, x-fluxes, and y-fluxes for all grid points and at all timesteps. From these basic outputs it is possible to compute other basic hydraulic variables (velocities in both the x- and y-directions, speed, water surface elevation, etc.).



*3.3.2 Cosumnes Implementation*

The MIKE 21 bathymetric grid was constructed using a combination of available data, including the same cross-sections as were used in the 1-D models, a 30-meter USGS DEM, and other topographic data. The model was run with 2 different upstream boundary conditions in combination with 1 downstream water level. The first boundary condition scenario starts the model dry and runs constant 100-year peak discharges at the two upstream boundaries until steady state conditions occur. The second boundary condition scenario routes the full 100-year design hydrograph through the 2-D grid. The model was run without calibration or validation, solely for the purpose of showing some of the capabilities of 2-dimensional modeling of dynamic riverine environments.

The bathymetric grid was discretized with a horizontal resolution of 30 meters. The 30 meter grid resolution was chosen for two main reasons: available DEM data for the site was available at 30 meter resolution, and because of the large area of interest (20 km North-South by 22.5 km East-West or 665 dx points and 751 dy points). The obvious drawback in using a 30 meter resolution is the challenge of characterizing the channel. Since the purpose of the 2-D model was to show the 2-dimensional flow patterns on a dynamic floodplain under extreme flooding, we felt the 30 meter DEM was sufficient. For more detailed studies of the Cosumnes River (calibrated, validated, and used for planning), a finer grid is recommended.. To maintain small Courant numbers (Cr), we chose a timestep of 10 seconds, giving Cr less than one for velocities less than 3 m/s.

Resistance values for the MIKE 21 model were set to a Manning's "n" of 0.04. The resistance value was chosen based on prior knowledge of the system and is entirely uncalibrated. Obviously for more accurate results, a proper sensitivity analysis, calibration, and validation are necessary for all parameters.

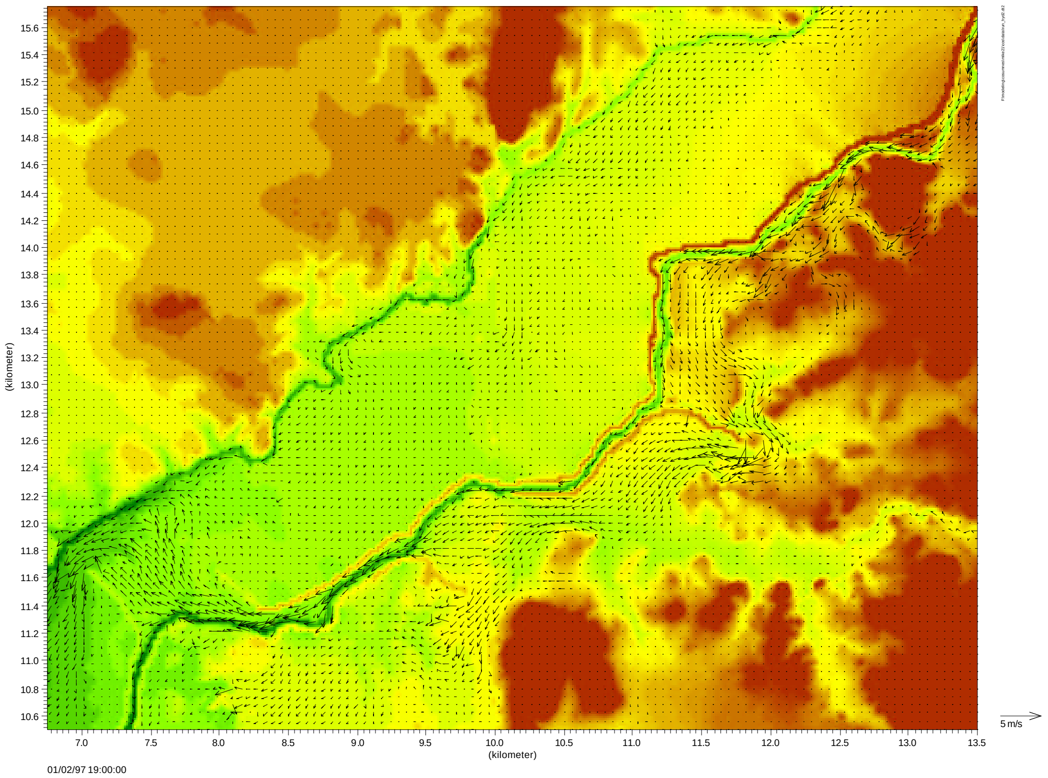
Results from the uncalibrated MIKE 21 model are not sufficient for planning, but are sufficiently accurate to show the potential spatial and temporal variability of flow in riverine systems when computed using a 2-D unsteady model.

## 4. RESULTS COMPARISON

### *4.1 Steady – Unsteady*

WSPRO model results were calibrated by the USGS for the 1997 flood event. The MIKE 11 model was calibrated for the 1997 flood event. Unfortunately there are only three calibration points available with two at the boundaries. The results from WSPRO (calculated water surface profile) and from MIKE 11 (maximum water level during the simulation) are compared on Figure 3. There are significant differences for the Deer Creek results and for Cosumnes River results from river distance 16km to 25km. There are also local differences in the upper part of the Cosumnes River. It is not surprising to have various results from two unlike models with very different topological discretizations.

An explanation is that the looped 1-D unsteady MIKE 11 topological discretization has an influence on the exchange between floodplain and individual channels whereas the 1-D WSPRO does not. The differences in the lower part of the river show higher water



levels for both Deer Creek and for the Cosumnes River even though the discharge attenuation decreases peak flow. Figure 4 illustrates flood wave attenuation in the river system. The total inflow shown combines all of the tributaries into one hydrograph.

### *4.2 1-D, Looped 1-D, and 2-D*

Since 1-D models use single branches for computing riverine hydraulics, the complexities of floodplain topography and flow patterns are lost in most heterogeneous riverine systems. Typical 1-D models are not able to describe the interconnection of main channels, parallel channels, tributaries, and floodplains (see Figure 2). While 1-D looped network models, and 2-D models are able to describe the aforementioned interconnections. However, Figure 5 clearly shows that flow paths are not as simple as those shown in typical 1-D or looped 1-D models (Figure 2). Natural and manmade topographic features make real floodplain flow paths extremely complex. Users need to be aware of all potential topographic intricacies when selecting and discretizing hydraulic models.

Figure 6 shows flow depths computed for a single timestep using the 2-dimensional model. A close examination of the results used to generate the 2-D results reveal that water surface elevations (WSE), and velocities are variable across the floodplain, both laterally and longitudinally. Longitudinal variability is computed for 1-D models, while lateral variability is not (without independently simulating multiple branches). Since unsteady 1-D models are able to dynamically connect branches by using looped networks, flow variables are computed laterally, with lateral resolution defined, and restricted to, the number of lateral branches (see Figure 7). With regards to topological

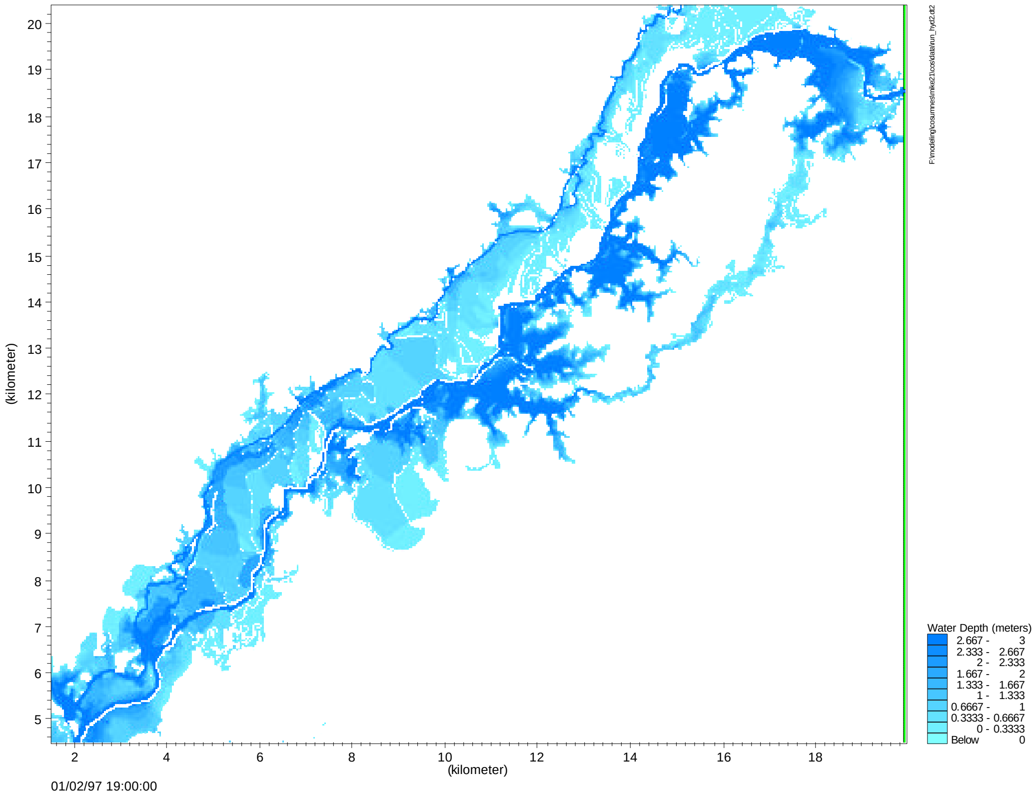


Figure 6: MIKE 21 Water Depth Map For Entire Study Reach

discretizations, the accuracy of spatially variable flow variables for 2-D models is limited by grid resolution, and the fact that flows are depth averaged and not 3-D.

## 5. DISCUSSION

The hydrologic response of rivers is not constant in time and space, but characterized by rising and falling water levels, with minor and major peaks in the hydrographs over time and across space. With the availability of sophisticated tools and easy access to high performance desktop computers today, there is no reason to limit ourselves to steady-state and/or lumped approximations in highly dynamic and spatially heterogeneous riverine environments. We believe the number one reason users still compute riverine hydraulics with steady state and/or inappropriately discretized tools is institutional inertia, and not model applicability. We hope users will expand their knowledge of available modeling tools, and utilize the best options for their projects.

The forefront of riverine hydraulics involves complex modeling issues such as: coupled dimension models (1-D & 2-D, etc.), 3-D models, helical flow, finite element & finite difference, nested grids, boundary fitting adaptive meshes, error reporting, scaling & subgrid processes, non-hydrostatic flow, density currents, sediment transport, turbulence, dynamic biologic coupling, integrated hydrologic cycle modeling, real-time data feedback, user friendly graphical interfaces, etc. While not every project must use these capabilities in the analysis of every problem, it is crucial for users to be aware that all models have assumptions and limitations. Users should make sure that the model they choose (and the calibration of that model), will not significantly misrepresent the

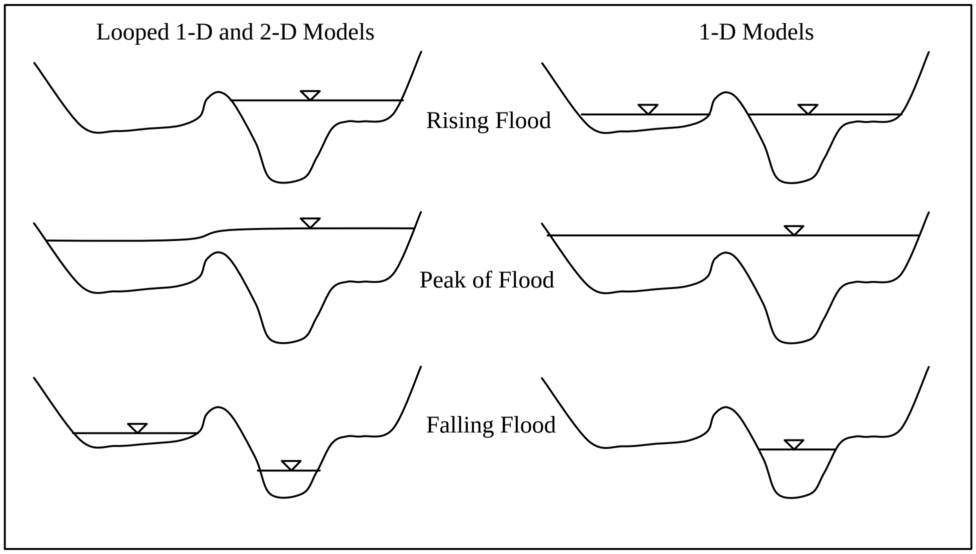


Figure 7: Cartoon of Topological Discretization Effects for Various Times at a Single Hypothetical Cross-Section

functioning of the system given the purpose of their analysis.

## 6. CONCLUSIONS

Since hydraulic models are simplified, discrete representations of continuous and complex real physical flows, all predictions of flow variables deviate from the actual flow conditions. Highly complex 3-D topography is simplified in the modeling process, and represented as 1-D, looped 1-D, 2-D, and 3-D topological discretizations with resolutions courser than reality. In current hydraulic models, the physics of flow is assumed to follow continuous equations which contain simplifying assumptions. Our ability to reproduce and predict flows at a desired resolution for a project, is dependent on: the selection and proper use of the appropriate modeling tools, the quality of data that describes the project, calibration and validation of the tools, and our ability to correctly interpret the results. With increasingly detailed descriptions of physical processes encapsulated in modern, user-friendly hydroinformatics tools, engineers and scientists need to understand the assumptions, limitations, and resulting errors involved in modeling riverine environments.

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