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Beyond Floodplain Analysis: A Modeler's Experience Using HEC-RAS 2D for Spillway Assessments and Designs

Yan Wang
Gannett Fleming, Inc, ywang@gfnet.com

Amanda Hess
Gannett Fleming, Inc, ahess@gfnet.com

Gregory Richards
Gannett Fleming, Inc, grichards@gfnet.com

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BEYOND FLOODPLAIN ANALYSIS: A MODELER'S EXPERIENCE USING HEC-RAS 2D FOR SPILLWAY ASSESSMENTS AND DESIGNS

Yan WANG
Gannett Fleming, Inc., USA, ywang@gfnet.com
Amanda HESS
Gannett Fleming, Inc., USA, ahess@gfnet.com
Gregory RICHARDS
Gannett Fleming, Inc., USA, grichards@gfnet.com

Abstract: HEC-RAS 5.0 (2D) has been increasingly used by the dam safety community for performing dam breach and other hydraulic analyses since its debut in 2015. While this two-dimensional hydraulic modeling software has wide applications in dam breach analysis and urban flood simulation, its ability to analyze complex multidirectional flow problems can also be used as a design tool for spillways, overtopping protection, and other hydraulic structures. In this manuscript, the authors discussed their experience using HEC-RAS and other two-dimensional hydraulic models to design and assess various hydraulic structures. This includes: 1) sizing spillway outlet channels and assessing the hydraulic adequacy of training dikes, especially where non-linear or super-elevated flow conditions are anticipated; 2) using depth, velocity, and shear stress outputs to design erosion/overtopping protection for vegetated spillways, lined channels, and earthen embankments; 3) designing temporary diversions to facilitate construction within rivers, reservoirs, or other waterways; and 4) identifying and assessing potential failure modes (e.g. erosion and headcutting of vegetated spillways). Insights are shared to help the audience understand when a two-dimensional modeling approach is effective and appropriate.

Keywords: HEC-RAS, Two-dimensional, Hydraulic Models, Hydraulic Structures.

INTRODUCTION

Dam breach and flood inundation analyses have traditionally been performed using one-dimensional (1D) hydraulic models. When developing 1D models, modelers are required to identify the center line of the studied streams/flow area, and to create cross-sections that represent the bathymetry of the streams. One-dimensional models usually require minimal run-time and perform well in situations where the stream is well defined and the flow is mostly one dimensional. However, researchers are aware of 1D models' limitations in simulating flood events where complex terrain, un-defined flow paths, complex ineffective areas, and sharp turns are involved (NORDLÖF 2017, HORRITT and BATES 2002, TAYEFI et al. 2007, ANDERSSON and BATES

1993, TAYE et al. 2007, COOK and MERWADE 2009, VOJINOVIC and TUTULIC 2008). Application of a 1D model in these situations may result in under-estimation of friction losses, inundation extents, and may lead to inaccurate flood dynamics (TAYEFI et al. 2007). Another issue for 1D models is that the simplified kinematic wave method employed by 1D models is unable to account for the downstream backwater effect, especially at river confluences with mild stream slopes (HE at al. 2006, 2008, 2015). Two-dimensional (2D) hydraulic models are considered more suitable for these hydraulic situations.

The main drawbacks of 2D models are long simulation time and high input intensity. Thanks to rapid development of super computers and techniques such as Geographical Information System (GIS) and Light Detection And Ranging (LiDAR), 2D hydraulic models have become more popular.

HEC-RAS (Hydraulic Engineering Center River Analysis System) is a hydraulic modeling tool developed by the US Army Corps of Engineers (USACE). The software has been used as the industry-standard in the United States for 1D river systems modeling, flood plain/floodway analyses, dam breach analyses, bridge and culvert analyses, and sediment transport modeling (BRUNNER, 2016). The capability of modeling 2D flow conditions has been incorporated into the HEC-RAS model since Version 5.0. Unlike other readily available 2D hydraulic modeling programs, HEC-RAS 5.0 employed a method that represents the topographical data on a sub-grid level, capturing important terrain features while keeping the computational grid large and computation time short (USACE 2015, CASULLI 2008). The sub-grid information was introduced into the model by developing a stage-volume relationship within each calculation cell and a stage-discharge relationship on each face of the calculation cell. Multiple research has concluded that the sub-grid representation can produce a better flood inundation extent than could be attained by using a non-sub-grid approach and calibrating using the roughness parameter (YU and LANE 2006, YU and LANE 2011, MCMILLAN and BRASINGTON 2007, and CASULLI 2008).

Since the debut of HEC-RAS 5.0, 2D hydraulic models have been widely applied to river system analyses for flood extents determination in various flood plain configurations under various flow conditions. The applications (NEAL et al. 2012, NORDLÖF 2017) mainly focus on dam breach analyses, urban flooding analyses, levee breach analyses, and other flood related topics. Application of HEC-RAS 2D in other fields is rare. HEC-RAS is able to analyze complex multidirectional flow problems and provide geo-spatial information on hydraulic parameters including depth, velocity, and shear stress everywhere within the inundation areas. It can also be used as a design tool for spillways and other hydraulic structures, as well as assisting in erosion control and overtopping protection. In this manuscript, applications of HEC-RAS for design and assessment of various hydraulic structures is discussed. Insights are shared for effective and appropriate application of 2D modeling in hydraulic structure design and assessment.

METHODOLOGY

Model Inputs

The input data required for running a 2D hydraulic model using HEC-RAS includes a terrain grid encapsulating the entire study area, Manning's surface roughness coefficients, boundary conditions, and hydrologic loading conditions such as precipitation/inflow hydrographs/stage hydrographs.

HEC-RAS uses terrain data in the form of a Geo-Tiff or a Grid raster file. Terrain data with various resolutions can be obtained from the USGS National Map Viewer. High resolution LiDAR data are not available in many areas but can be obtained from different State Agencies. High resolution terrain data can also be obtained from survey data. Since HEC-RAS applies the sub-grid terrain method, using high resolution terrain data does not compromise the simulation run time. It is recommended that terrain data with the highest resolution be used in a 2D HEC-RAS model.

Manning's roughness coefficients are assigned based on land cover data. Large scale land cover information can be obtained from the National Land Cover Database (NLCD). State/local government may have land cover data with higher resolutions. User-defined land cover divisions are allowed if more accurate data is available. HEC-RAS uses land cover data in the form of a Geo-Tiff or a Shape file. Manning's roughness coefficients are advised to be assigned according to CHOW's Open Channel (CHOW, 1987).

External boundary conditions applied in 2D HEC-RAS can be set as flow hydrograph, stage hydrograph, rating curve, and normal depth among others. Internal boundary condition lines can also be applied within the 2D calculation mesh and can be connected to one or more cells through the cell face points. Precipitation in the form of direct runoff can also be applied as a boundary condition in 2D HEC-RAS (USACE 2015).

Model Setup

Setting up a 2D HEC-RAS model requires a geometry file, an unsteady flow file, and a plan file. The geometry file needs to be associated with the terrain data and the Manning's Roughness layer. One or multiple 2D calculation areas can be defined in the geometry file as long as the 2D areas are entirely within the extents of the terrain data. Calculation cell sizes need to be defined for each of the defined 2D areas. Selection of cell size affects the accuracy of model results and the model run time. Smaller cell size can be defined within any 2D area where refined results are desired. Break lines can be created within the 2D areas. Calculation cells near the break lines can be enforced so that the cells are aligned with the break lines. Different calculation cell sizes along cells enforced near the break lines can be defined in order to provide a more refined analysis for the area. Boundary conditions are introduced into the model as unsteady flow data. A plan file is a master control file telling the program which geometry file and plan file to use. In a plan file, important 2D parameters include calculation interval, 2D modeling methods, and output controls (USACE 2015).

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Model Outputs and Analysis

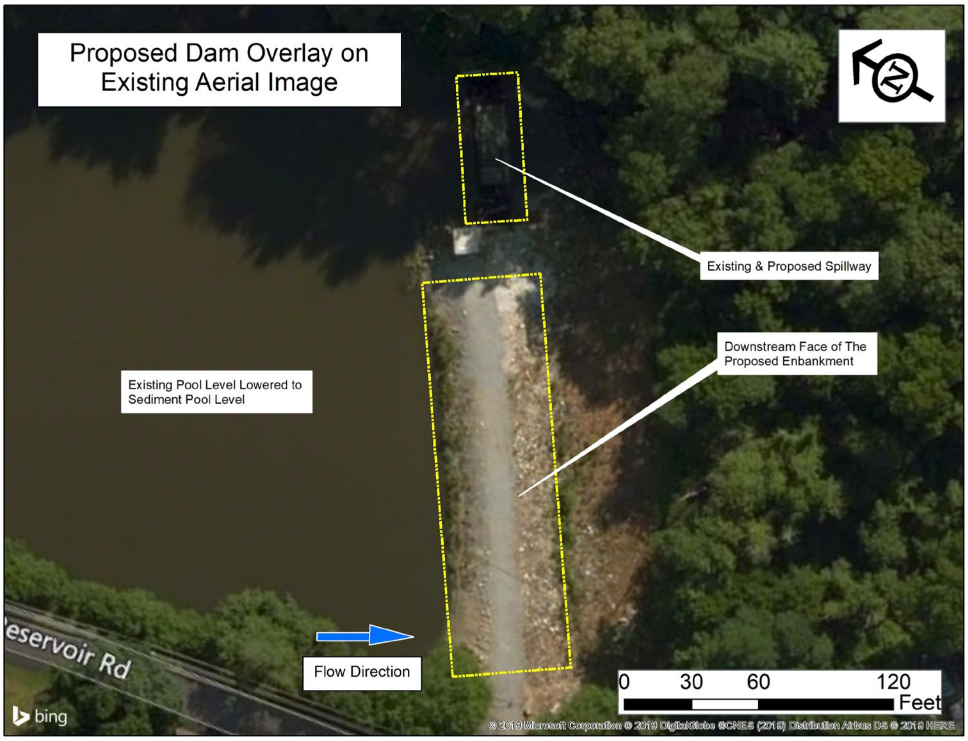
HEC-RAS provides multiple types of results which can be used in the design and assessment of hydraulic structures. Depth, velocity, shear stress, stream power, depth-velocity product, and other information for the entire flood inundation area can be obtained at their maximum values or at a specific time step. Time series data for depth and velocity at any point within the inundation area can be retrieved. Profile lines can be created within the 2D areas. Depth, water surface elevation, and velocity along the profile lines at any specific time step can be obtained. Flow hydrograph across the profile lines can also be obtained from the model output.

CASE STUDIES

Case 1

Dam A, located in Pennsylvania, USA, is currently classified as a high hazard structure and the Spillway Design Flood (SDF) is established as the 1/2 Probable Maximum Flood (PMF). The dam owner would like to reduce the hazard classification of Dam A by reducing the height of the structure and the storage volume retained by the structure by partially breaching the top of dam to the current sediment pool level. Aerial imagery of the existing dam is presented in Fig. 1. A two-dimensional HEC-RAS hydraulic model of the proposed dam was developed to evaluate embankment protection design. The simulated velocity field at the downstream face of the proposed dam embankment was used for riprap sizing.

Fig. 1 – Aerial Imagery of the Existing Dam A



The proposed dam embankment was drafted in AutoCAD and brought in HEC-RAS as the

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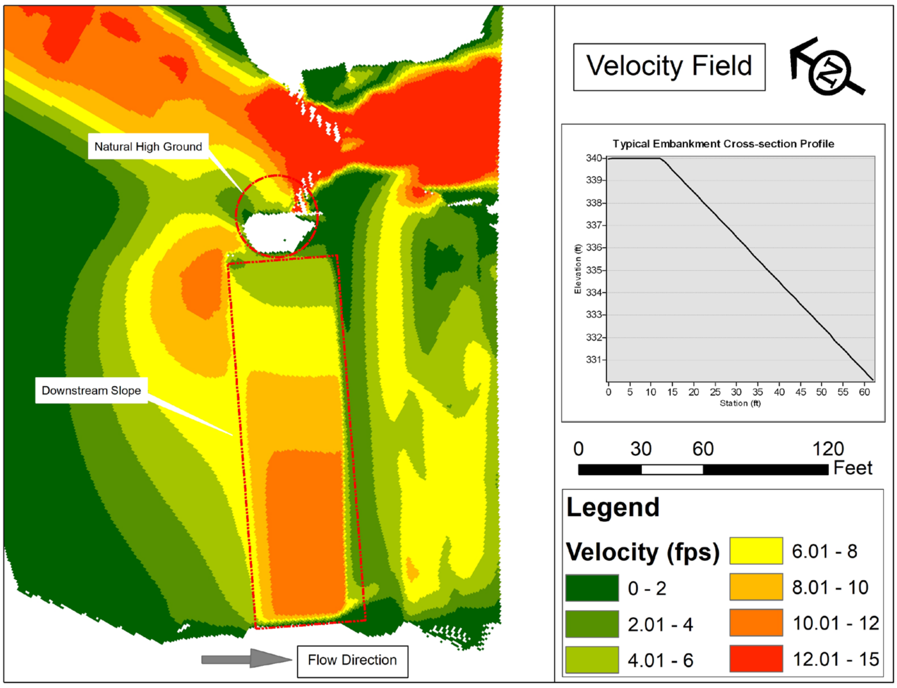
proposed 2D surface. The roughness coefficients are defined as 0.03 for stream bed, 0.013 for the spillway, 0.06 for downstream slope of the dam embankment, and 0.045 for other parts of the 2D area. Other information regarding model setup is listed in Table 1.

The model results show that for the design flood, the velocity ranges from 4.0 feet per second (fps) to 11.7 fps at the downstream slope of the dam embankment. The natural high ground and the geometry of the reservoir result in a non-uniform velocity distribution along the length of the embankment. The velocity field of the entire two-dimensional hydraulic model is presented in Fig. 2. The simulated velocity field on the downstream slope of the embankment allowed a detailed analysis of the distribution and the percentage of area within each velocity range. A cost-effective design for riprap selection and layout was selected based on the 2D results.

Fig. 2 – Velocity Field of Embankment Downstream Slope



<u>Case 2</u>

Dam B is an earthen embankment dam with one riser structure and an auxiliary spillway located in Pennsylvania, USA. The auxiliary spillway consists of a horseshoe-shaped embankment/weir at the left dam abutment. The spillway channel has encountered significant erosion during large spillway flow events in 1975 and in 2011. Aerial imagery of the spillway exit channel is presented in Fig. 3.

Fig. 3 – Aerial Imagery of the Existing Dam B

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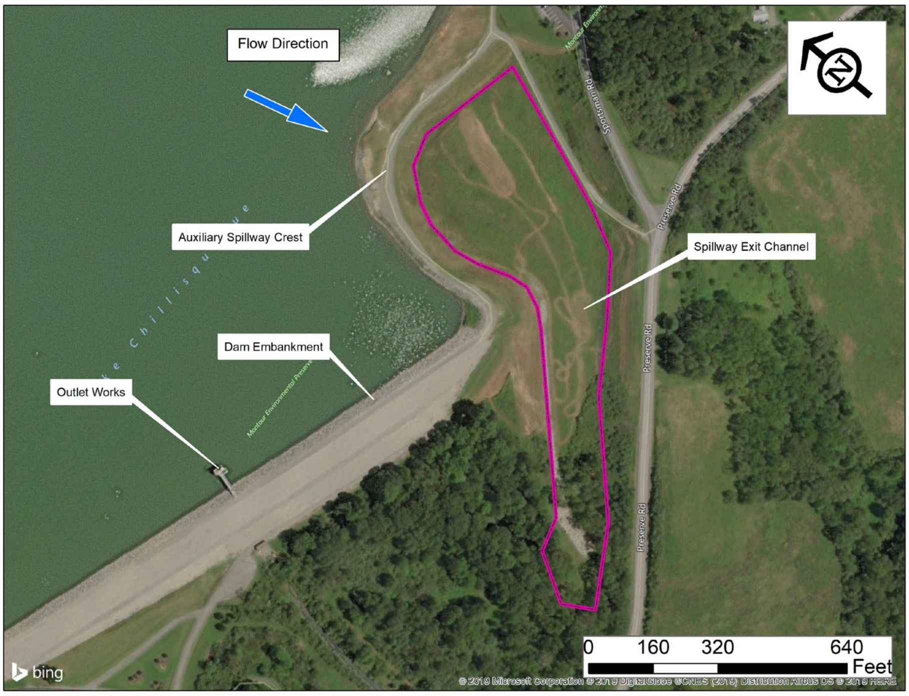
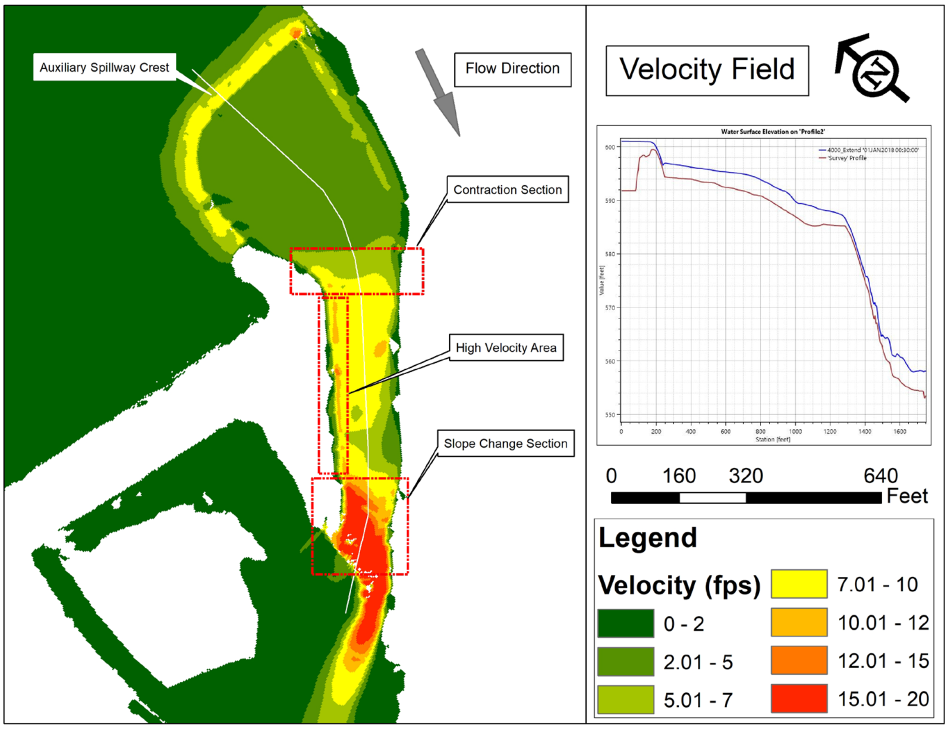


A 2D hydraulic model was developed to analyze the existing spillway and the exit channel and to assist in repair alternative selection. The model evaluated the velocity patterns in the spillway for a range of discharges up to the approximate spillway capacity discharge of 25,000 cfs. Detailed survey data was used to represent the 2D surface. The roughness coefficients are defined as 0.045 for the vegetated portion of the spillway exit channel, 0.055 for the rock-lined portion, 0.015 for paved areas, and 0.12 for forested areas. Break lines were added into the 2D extents to allow more refined cell sizes in desired areas. Other information regarding model setup is included in Table 1.

The model results indicate that the highest velocity was observed on the right edge of the spillway exit channel. The modeling results agree with the field observation of severe erosion near the same location after a large storm event. The simulated flow velocities within a large portion of the spillway exit channel exceed 17 fps, which indicates that the existing spillway channel is susceptible to severe erosion and that spillway improvement is needed to reduce/stop erosion. The velocity field of the entire 2D hydraulic model is presented in Fig. 4. The 2D modeling results show that significant velocity increases were caused by a flow contraction approximately 400 feet downstream of the spillway crest and an abrupt increase in channel slope approximately 2,000 feet downstream of the spillway crest. Due to steep channel slope, velocity within the exit channel is not likely to be affected by downstream backwater. The profile of the exit channel center line is also presented in Fig. 4. These findings suggest possibly moving the existing spillway to the flow contraction section and re-sloping the exit channel. Several spillway improvement alternatives were designed based on the results from the 2D analysis. Other factors such as cost were included in the final selection of repair design.

Fig. 4 – Velocity Field of Spillway Exit Channel



Case 3

A water company was planning to build a new water intake facility including intake, outfall, transition chamber, raw water and finished water pipeline, and other supporting facilities. In order to construct the facility, a cofferdam and a full-width causeway were proposed. The construction schedule indicated that the cofferdam would be used in phase 1 (summer), both the cofferdam and the causeway would be used in phase 2 (fall), and the cofferdam would be removed while the causeway remained in phase 3 (winter). Aerial imagery of the proposed project site is presented in Fig. 5. In order to determine erosion protection measures, a 2D hydraulic model of the project site was created to analyze the reasonably anticipated impact of the temporary causeway and cofferdam on river flow conditions.

Fig. 5 – Aerial Imagery of Project Site for Case 3

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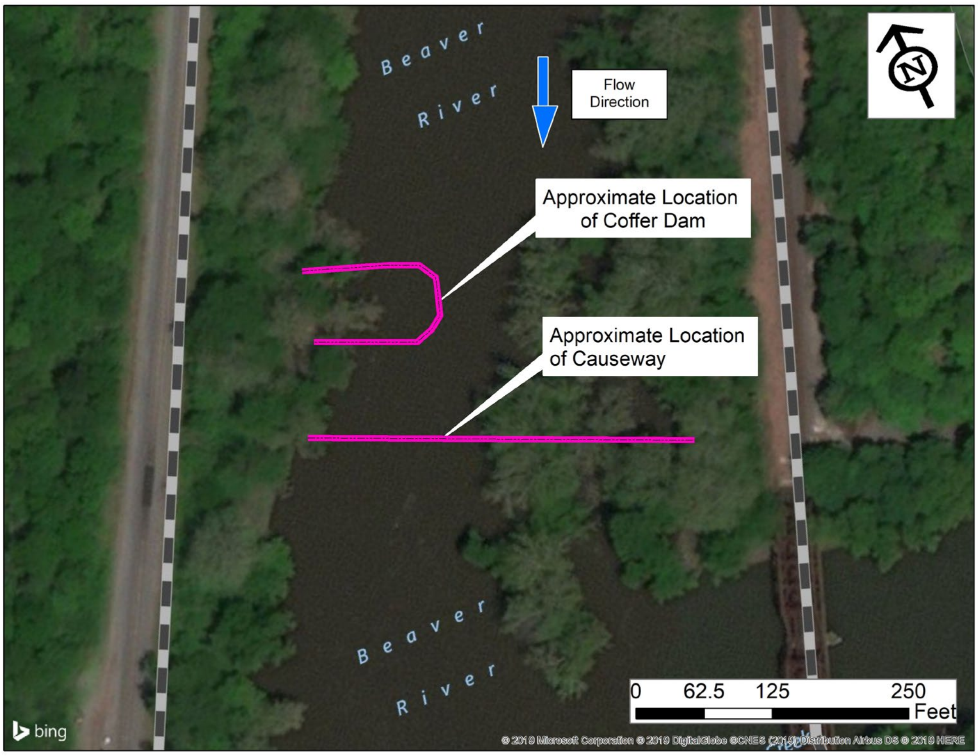

Both the cofferdam and the causeway were modeled as internal connections. Four different scenarios were analyzed: existing condition, coffer dam only, causeway only, and cofferdam and causeway. Average seasonal flow conditions were estimated and were applied to different scenarios according to the construction timeline. The roughness coefficients are defined as 0.03 for stream bed and 0.1 for forested areas. Other information regarding model setup is listed in Table 1.

Simulation results indicated that the most severe riverbed and bank scour potential was observed when both the causeway and cofferdam are installed in the river. The highest water surface velocities within the main river channel, adjacent to the cofferdam structure, are approximately 13 fps. The velocity fields simulated under the four scenarios are presented in Fig. 6. Scour protection was selected based on the highest modeled velocity and was installed in the form of cable concrete mats over the high flow velocity areas identified in the model.

Fig. 6 – Velocity Field of River Diversion Flows

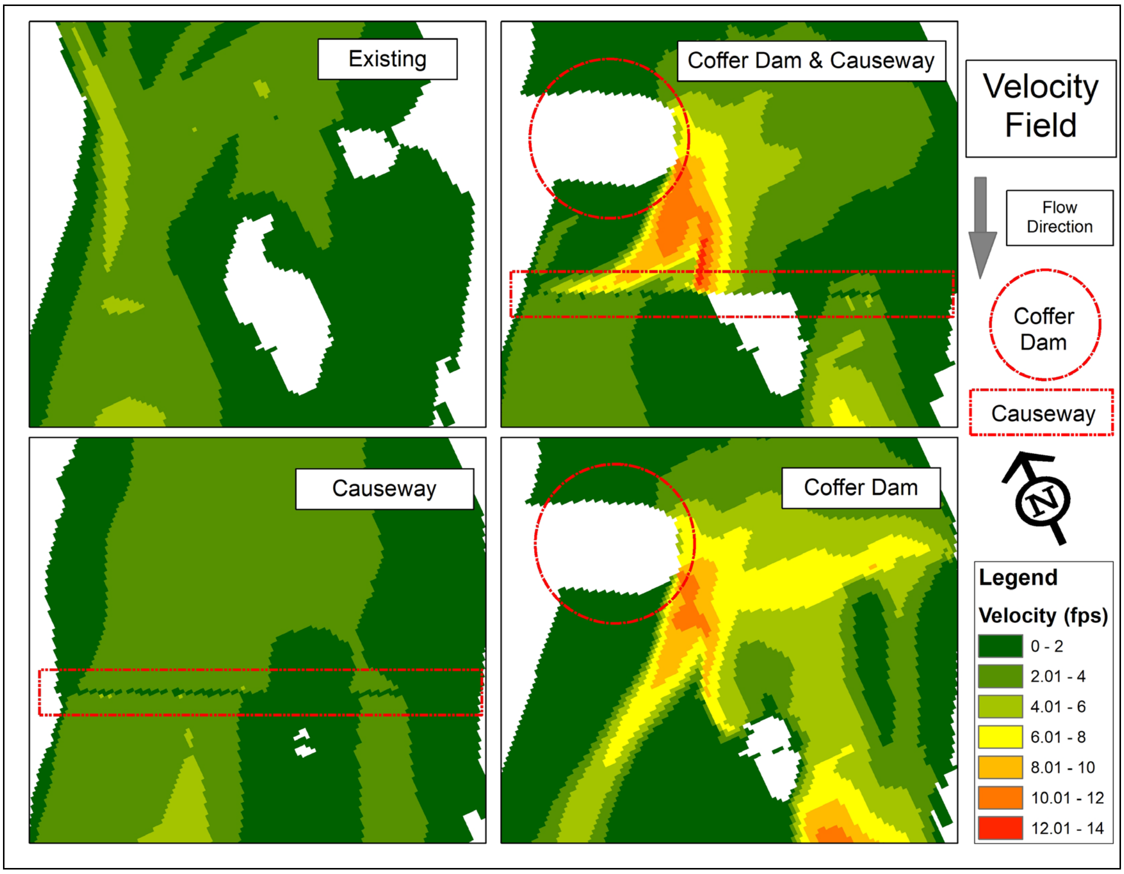

Table 1 – Two-Dimensional Hydraulic Model Setup

Case (1)	Terrain Resolution (feet) (2)	2D Grid Resolution (feet) (3)	Computation Interval (s) (4)	Hydrologic Loading (5)
Case 1	1.5	1.5	0.1	100-year
Case 2	1.0	2.0 & 4.0	0.5-varied	A range of flows
Case 3	6.0	3.0	0.2	A range of flows

DISCUSSION

As described in this manuscript, the authors used 2D hydraulic models to evaluate various hydraulic structures. With the help of the simulated velocity and depth grids from a 2D model: 1) slope protection measures were determined; 2) existing spillway deficiencies in terms of capacity and erodibility were identified; and 3) hydraulic performance, overtopping flood event, and erosion control measures of temporary in-stream structures were evaluated and analyzed.

Most of these analyses can be done using a 1D model. However, there are several advantages of using a 2D model in these applications.

- 2D models use a digital terrain model that captures all available details in ground elevation. 1D models use cross-sections to represent the channel geometry. The longer the distance between two cross-sections, the more terrain information loss is expected. In cases where the spillway channel surface is not uniform and smooth, losing terrain details may significantly affect model results.

- 2D models can more accurately simulate eddies, vortices, super elevation, and other complex flow conditions. It is known that 1D models are not good at simulating channels with bends and sudden changes in cross-section geometries. Using a 2D model can provide more accurate results in channels with irregular shapes.
- 2D models are more efficient in simulating in-stream structures that have irregular shape and orientation. With care, in-stream structures can be simulated as in-line structures in 1D models, but with 2D models, in-stream structures can be included within the 2D calculation area regardless of the shape and orientation.
- 2D models generate result fields, meaning the results are available at every cell within the flooded area. With output presented in such detail, it is easier to identify possible hotspots in small local areas and ensure that the design meets the requirement of the worst-case scenario.

Ideally, flow over a structure with a three-dimensional (3D) configuration is best simulated using a 3D computational fluid dynamics (CFD) model. However, CFD models are usually more expensive and the model run time is significant compared to 2D models. CFD is definitely needed for analyzing flow conditions where vertical movement of water is severe, such as flow over a labyrinth weir or a stepped spillway. However, in cases where the vertical movement of water flow is significantly less prominent than the horizontal movement, a 2D model can be used as an alternative. A comparison of flow simulation was not performed between a 2D and 3D model in this study. More analyses and comparison with physical models are needed to quantify performances of a 2D model in simulating flow conditions for 3D hydraulic structures.

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