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COMPARISON OF MODELLING APPROACHES FOR DEVELOPMENT OF DISCHARGE RATING CURVES FOR SPILLWAY/BRIDGE COMBINATIONS

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ABSTRACT

When estimating spillway discharge rating curves, engineers can use a variety of methods such as empirical equations, one- (1D) or two-dimensional (2D) hydraulic computer models, or a combination thereof; however, conservative assumptions are often applied to such methods. The use of three-dimensional (3D) computational fluid dynamics (CFD) models is an alternative modelling approach that can often better estimate spillway discharge rating curves, especially for complex flow situations. In this study, the results of 3D CFD models are compared to estimates of spillway discharge rating curves developed with a combination of empirical equations and other hydraulic computer models for spillway/bridge combinations. It is shown that results typically agree for lower order methods that share approximations whereas higher order models can produce significantly different results. It is recommended that careful consideration be given to governing equations and effectiveness of representing site geometries when selecting which method(s) to use to develop a discharge rating curve, especially when complex site conditions may be better captured with a higher order model.

Keywords: Spillway, modelling, rating curve, CFD

INTRODUCTION

Knowledge of a dam's spillway capacity – the maximum discharge a spillway can pass with the reservoir at its maximum level – is of great importance to the practicing hydraulic engineer. The associated stage and discharge relationship leading to the spillway capacity and beyond comprises the spillway discharge rating curve and is necessary when estimating reservoir levels for various hydrologic events. A variety of methods are available to develop a discharge rating curve such as empirical equations (e.g., unsubmerged/submerged weir equation), one- (1D) or two-dimensional (2D) hydraulic computer models based on conservation of energy and momentum equations (e.g., Federal Highway Administration's HY-8 Culvert Analysis Program, United States Army Corps of Engineers Hydrologic Engineering Center River Analysis System [HEC-RAS]), or a combination thereof. These methods may not always accurately reflect site-specific geometry or complex hydraulic conditions, such as a spillway in close proximity to a bridge with confining openings. To account for uncertainty with these methods, conservative assumptions are often applied such as selecting a reduced discharge coefficient or an increased tailwater elevation. The use of detailed, three-dimensional (3D) computational fluid dynamics (CFD) models (e.g., Flow 3D) is becoming

more common and can provide an alternate approach to better estimate discharge rating curves for spillways while reducing uncertainty for complex situations, such as converging channels, spillways combined with bridges or culverts, or submergence.

While much research has been conducted on comparing various modelling techniques, little information was found regarding modelling of the type of spillways common in Delaware that are often subject to tailwater submergence and are in close proximity to bridges. Therefore, several modelling techniques, including empirical equations and hydraulic computer models, were used to develop and compare spillway discharge rating curves for multiple spillways in Delaware. Based on these comparisons, recommendations are made as to when it may be appropriate to employ a more complex modelling approach.

BACKGROUND

The COLORADO WATER CONSERVATION BOARD (2006) (CWCB) provided an overview of 2D hydraulic computer modelling in which it stated that the defining assumption for 1D models – that only streamwise forces, velocities, and variations are significant while those in the transverse direction are negligible – does not apply to 2D models. Rather, 2D modelling includes computation of transverse components, therefore providing advantages compared to 1D models. The CWCB tabulated differences between the two modelling approaches, which are shown here as Table 1. Furthermore, the CWCB listed factors to consider when selecting a 1D or 2D hydraulic computer model including the nature of the watercourse, required accuracy, experience of the modeller with the technique, and availability of site specific or physical hydraulic model data.

Table 1 – Differences between One-Dimensional and Two-Dimensional Modelling (COLORADO WATER CONSERVATION BOARD 2006)

Property or Factor	One-Dimensional Modelling	Two-Dimensional Modelling
Flow direction	Prescribed (streamwise)	Computed
Transverse velocity and momentum	Neglected	Computed
Vertical velocity and momentum	Neglected	Neglected
Velocity averaged over	Cross sectional area	Depth at a point
Transverse velocity distribution	Assumed proportional to conveyance	Computed
Transverse variations in water surface	Neglected	Computed
Vertical variance	Neglected	Neglected
Unsteady flow routing	Can be included	Can be included

TOOMBES and CHANSON (2011) discussed limitations of hydraulic computer models, specifically how conservation of momentum and energy are approximated in several software packages. Common numerical approximations in 1D models that the authors discussed were: assumed small channel grades, use of empirical methods to estimate friction losses (e.g., Manning's coefficient), assumed gradually varied flow (steady state), and inability to accommodate two boundary conditions at the

same boundary (unsteady) (e.g., supercritical flow). For 2D models, numerical approximations included: horizontal length scale assumed to be significantly greater than the vertical scale (vertical velocities are negligible) and estimations of forces acting on each fluid component (e.g., shear stress, bed friction). 3D models were stated to remove many limitations related to 1D and 2D models at the expense of increasing complexity and required computations; however, 3D models allow compressible fluids, multi-phase flow, and other effects to be investigated.

TOOMBES and CHANSON (2011) continued their study by verifying software output with two physical hydraulic models: a weir experiment and an open channel flow (hydraulic jump) experiment. For the weir experiment, it was shown that steady HEC-RAS (1D) achieved a good match to the physical hydraulic model data for a low-flow scenario but differed significantly for a high-flow scenario. Flow 3D achieved an excellent match to the physical hydraulic model data for both scenarios of the weir experiment. For the open channel flow experiment, steady HEC-RAS (1D) achieved good agreement with the measured jump location but showed the jump as an instantaneous transition between cross sections, that is the development length was not determined. Similar to the weir experiment, Flow 3D achieved excellent agreement with the physical hydraulic model data of the open channel flow experiment. The authors advised that modellers should study the software documentation to understand its limitations and required approximations, and perform a "reality check" to verify that hydraulic computer model results are reasonable.

RAO et al. (2017) paralleled the work of TOOMBES and CHANSON (2011) by testing several computer programs – including HY-8, HEC-RAS 1D (steady and unsteady), and Flow 3D – to predict the magnitude and location of the hydraulic jump for a similar geometry and flow condition. Differences between the experiments of RAO et al. and TOOMBES and CHANSON were the channel length (15.24 m instead of 12 m), upstream depth (0.04 m instead of 0.062 m), and channel slope (0.012 instead of 0.028). Comparisons of software output with experimental data were as follows:

- HY-8 predicted greater headwater and a more upstream jump location
- Steady and unsteady HEC-RAS predicted a water surface that compared well to the physical hydraulic model data, but the jump occurred more upstream
- Flow 3D also predicted a water surface that compared well, but the jump occurred more downstream and varied per time step

The authors cautioned that while some computer models produce convincing animations and color gradients in great detail, they should be chosen with care and results should be critically interpreted.

SCHNABEL (2015) assessed several alternative modelling approaches for a spillway in Delaware that was subject to tailwater submergence and in close proximity to downstream bridges. Among the

alternative modelling approaches studied, a 3D CFD model was developed to compare the estimated spillway discharge rating curve to the results of an unsteady HEC-RAS 1D model. Results indicated that the discharge rating curve developed with HEC-RAS was acceptable but more conservative (lower capacity) than the 3D CFD model. Possible contributing factors were identified as selection of model elements to represent the spillway and adjacent areas in HEC-RAS, challenges achieving model stability, model interpolation techniques, and computed tailwater submergence. SCHNABEL recommended employing 3D CFD for dams where spillway capacity was of concern as costly rehabilitation efforts might be avoided by acquiring a refined discharge rating curve.

METHOD

The focus of this study was to test several methods to develop and compare spillway discharge rating curves for spillway/bridge combinations common in Delaware. The author endeavoured to use best modelling practices such as sufficient grid refinement, selection of appropriate empirical coefficients, changes of default model numerics, achievement of model stability, etc. No measured hydraulic data was available to verify the results of modelling techniques; therefore, comparisons were limited among employed methods. The following methods were selected for use:

1. Weir Equation and HY-8 Combination: the culvert modelling software HY-8 v7.5 (FHWA 2016) was used to compute the headwater elevations and flow profiles at bridges downstream of investigated spillways. The weir equation shown in Eqn. 1 was used to estimate weir flow with weir coefficients, C, and methods to account for submergence effects taken from BRATER and KING (1976). Weir tailwater elevations were assumed to equal the bridge headwater elevations.

$$Q = Q_1 \times \frac{Q}{Q_1} \text{ where } Q_1 = CLH_1^{1.5} = CH_1^n \text{ and } \frac{Q}{Q_1} = f\left(\left(\frac{H_2}{H_1}\right)^n\right) \tag{1}$$

2. HEC-RAS 1D: steady HEC-RAS 1D v5.0.7 (USACE 2016) was used to solve conservation of energy for sites of interest while accounting for energy losses from friction and contraction/expansion effects. Terrains developed with computer aided design (CAD) and geographic information systems (GIS) were represented with a series of cross sections. Weirs were modelled using inline structure elements and bridges were modelled using bridge elements.

3. HEC-RAS 2D: unsteady HEC-RAS 2D v5.0.7 (USACE 2016) was used to solve the depth-averaged St. Venant equations using a grid system to represent the underlying terrain, as developed with CAD and GIS. Spillways and bridges were modelled using SA/2D Area Connections with bridge openings represented as culverts per limitations of the software.

4. Flow 3D: Flow 3D v12.0 (FLOW SCIENCE 2019), a commercially available CFD software, was used to solve the 3D, transient Navier-Stokes equations with the volume of fluid (VOF) method. The VOF method allowed the interface between the fluid and air to be sharp without using a very fine mesh, lending itself to reduced calculations compared to other CFD codes.

Additionally, the program provided 3D flow fields not available in lower order models. The spillway geometries and surrounding terrains were represented with solids in stereolithographic (STL) format developed with CAD and SketchUp.

All tested methods used topographic information and structure data provided by the Delaware Department of Transportation (DelDOT) and Department of Natural Resources and Environmental Control (DNREC). Two sites were investigated for this study, designated as Site 1 and Site 2 as shown in Fig. 1. Site 1 consisted of a semi-circular sheet pile drop structure that discharged outflows through two downstream bridges, the first consisting of a single rectangular opening and the second consisting of three arched openings. Site 2 consisted of a primary linear weir and auxiliary linear weirs to either side that allowed flow to plunge into a rectangular channel and pass through a single rectangular bridge opening.

Fig. 1 – Modelled Spillways: (a) Site 1 and (b) Site 2 (Photos courtesy of Schnabel Engineering)

For all tested methods, the upstream boundary condition (BC) of Site 1 was specified as a volume flow rate while the upstream BC of Site 2 was specified as a fluid elevation to represent the associated reservoir level. The downstream BCs for both sites were modelled with rating curves developed in previous studies that accounted for tailwater. Manning's coefficients were taken from CHOW (1959) to account for friction losses in the channel and surrounding floodplain. Viscous flow in the Flow 3D models was included with the renormalized group (RNG) turbulence model. Selection of this turbulence model was based on guidance from FLOW SCIENCE (2019) that the RNG model was the most robust turbulence closure scheme available. Model numerics were adjusted from their defaults based on the author's experience; one such change was the use of the full momentum (St. Venant) equations for the HEC-RAS 2D model.

Cross sections used in the HEC-RAS 1D models were located approximately 50 ft and 20 ft apart for Sites 1 and 2, respectively. HEC-RAS 2D models included total cell counts of approximately 39,900 and 11,400 for Sites 1 and 2, respectively, with refinement and grid face alignment at structures. For

the Flow 3D models, nested meshes were used with refined mesh blocks located at areas of special interest (e.g., weir crest, downstream apron); total cell counts were 24.4 million and 4.3 million for Sites 1 and 2, respectively.

RESULTS AND DISCUSSION

Site 1

The spillway discharge rating curves for Site 1 were developed to an elevation approximately 9 ft above normal pool using the investigated methods. Only three flow rates were modelled with Flow 3D for comparison as simulations required great lengths of time. Populating the computed discharge rating curve with additional data points was not feasible. The required effort to develop a discharge rating curve with each tested method varied from least effort required to most effort required as follows: weir equation and HY-8 combination, HEC-RAS 1D, HEC-RAS 2D, and lastly Flow 3D. Select graphical output for the employed methods are presented in Fig. 2 and the developed spillway discharge rating curves are presented in Fig. 3. An inset table is included in Fig. 3 that summarizes relative error among Flow 3D results and the other tested methods. Relative errors were calculated with Eqn. 2.

$$Relative\ Error = \frac{Flow\ 3D - Method}{Method} \times 100\% \tag{2}$$

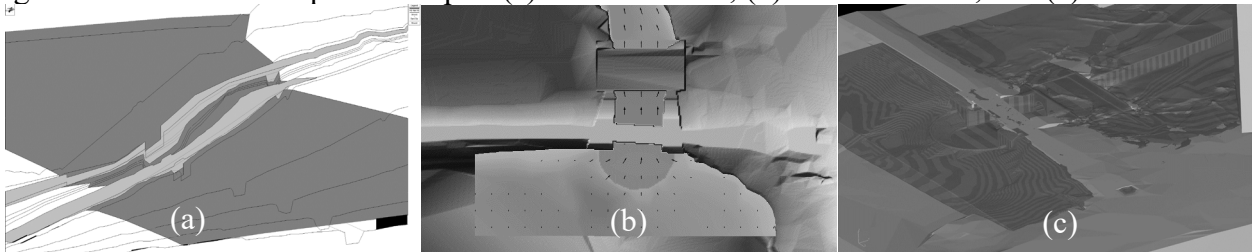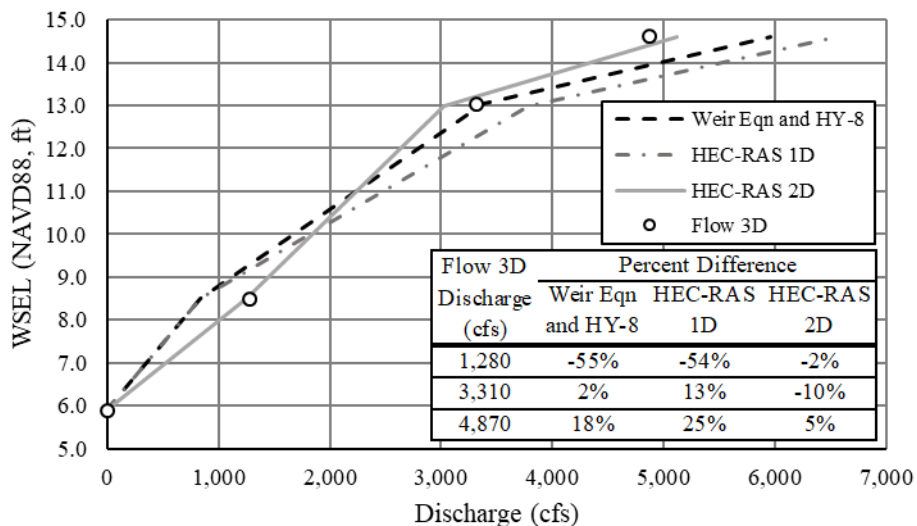Fig. 2 – Site 1 Select Graphical Output: (a) HEC-RAS 1D, (b) HEC-RAS 2D, and (c) Flow 3D

Fig. 3 – Site 1 Spillway Discharge Rating Curve

Flow 3D Discharge (cfs)	Percent Difference		
	Weir Eqn and HY-8	HEC-RAS 1D	HEC-RAS 2D
1,280	-55%	-54%	-2%
3,310	2%	13%	-10%
4,870	18%	25%	5%

As shown in Fig. 3, the weir equation and HY-8 combination tended to produce lower discharges up to approximately EL 13.0 as compared to Flow 3D; however, for reservoir levels greater than this, the weir equation and HY-8 combination estimated greater discharges than Flow 3D. Similar results occurred for the HEC-RAS 1D model with greater differences than those of the weir equation and HY-8 combination. HEC-RAS 2D showed relatively good agreement with Flow 3D for its three tested flow rates.

Site 2

The spillway discharge rating curves for Site 2 were developed to an elevation approximately 9 ft above normal pool. Four upstream reservoir levels were tested with Flow 3D as simulation times were less than those for Site 1, largely due to the fewer number of cells. The required effort to develop a discharge rating curve for Site 2 varied in the same manner as Site 1. Select graphical output for Site 2 are presented in Fig. 4 and the developed spillway discharge rating curves are presented in Fig. 5. An inset table summarizing relative errors among Flow 3D and the other tested methods, calculated with Eqn. 2, is included in Fig. 5.

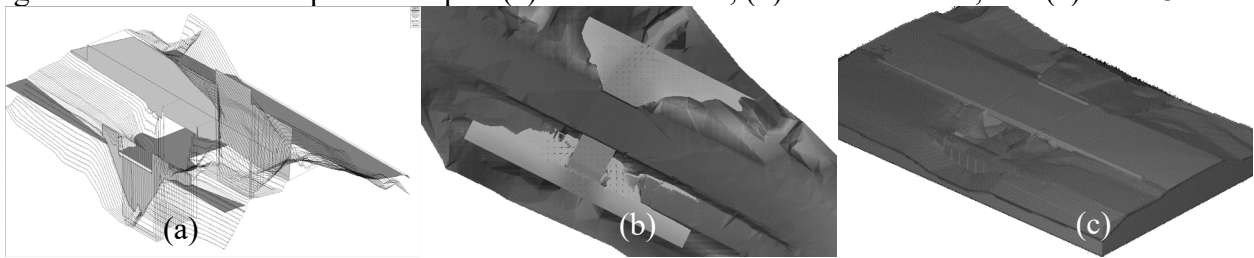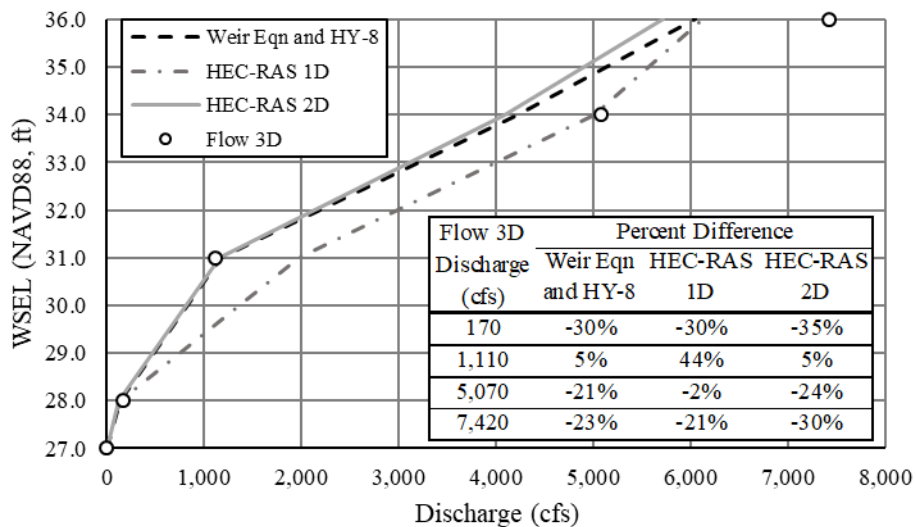Fig. 4 – Site 2 Select Graphical Output: (a) HEC-RAS 1D, (b) HEC-RAS 2D, and (c) Flow 3D

Fig. 5 – Site 2 Spillway Discharge Rating Curve

Flow 3D Discharge (cfs)	Percent Difference		
	Weir Eqn and HY-8	HEC-RAS 1D	HEC-RAS 2D
170	-30%	-30%	-35%
1,110	5%	44%	5%
5,070	-21%	-2%	-24%
7,420	-23%	-21%	-30%

For Site 2, the weir equation and HY-8 combination method tended to produce lower discharges for almost all tested reservoir levels of the Flow 3D model, save EL 31.0 where results showed good agreement. The HEC-RAS 1D results only showed good agreement at EL 34.0, otherwise discharges were not consistently lower or greater than those estimated with Flow 3D. HEC-RAS 2D produced results similar to the weir equation and HY-8 combination with slightly lower discharges estimated.

Although no verification of the results was possible due to the lack of measured physical hydraulic data, it is the author's opinion that the Flow 3D model better captured the complex hydraulics of Site 2, specifically flow over the walls perpendicular to the primary weir and the turbulent nature in the rectangular channel upstream of the bridge opening. For both Sites 1 and 2, differences among developed spillway discharge rating curves may have been due to a number of factors including: structure representation (e.g., inline structure, SA/2D Area Connection, STL image), selection of coefficients (e.g., constant weir coefficient, Manning's coefficient), boundary condition parameters (e.g., zero velocity), employed numerical method (e.g., finite difference, finite volume), bias from the modeller, etc. Without measured data it is difficult to know which method(s) produced the most accurate spillway discharge rating curve for the sites investigated. With additional information, it is likely that most if not all methods could be calibrated and brought into agreement with one another. However, it is often the engineer's knowledge and understanding of the available modelling techniques that allow for the successful estimation of a discharge rating curve and associated spillway capacity.

CONCLUSION

In this study, several modelling techniques were tested to develop spillway discharge rating curves for two spillways in Delaware, both in close proximity to downstream bridges and often subject to tailwater submergence. Each method produced a unique discharge rating curve; however, lower order methods that shared approximations tended to agree up to a site-specific threshold. The discharges calculated with 3D CFD were not always greater or lower than those calculated with empirical equations, 1D or 2D hydraulic computer models, or combinations thereof.

The successful selection of an appropriate modelling technique and interpretation of its results are dependent on an engineer's knowledge and understanding of the site-specific conditions and available methods. Careful consideration should be given to governing equations and effectiveness of representing site geometries when selecting which method(s) to use when developing a spillway discharge rating curve and associated spillway capacity, especially when complex site conditions or hydraulics may be better captured with a higher order model.

LIST OF SYMBOLS

C Weir coefficient [$L^{-1/2}T^{-1}$]

H_1 Upstream head [L]

H_2	Downstream head [L]
L	Weir length [L]
n	Exponent in the free discharge equation
Q	Submerged volumetric flow rate [L^3T^{-1}]
Q_1	Free volumetric flow rate [L^3T^{-1}]

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