Three-Dimensional Numerical Modeling of a Small Pond Outlet Structure

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ABSTRACT

Flow through a small pond outlet structure was modeled using the 3D volume-of-fluid method. Turbulent effects were included using the K omega SST model, and rough wall functions were used to model the regions near the solid-fluid interface. The purpose of the model was to develop a stage-discharge curve for the structure. The outlet structure includes a trash rack with horizontal bars, the hydraulic effects of which traditional 1D or 2D models cannot account for. The geometry of the structure was determined using a combination of build plans, LiDAR data, and field measurements. The results of the model were compared to the stage-discharge curve calculated using weir equations. Modeling of the flow was performed using the OpenFOAM InterFoam solver. The study demonstrates a practical method to determine stage-discharge curves for hydraulic structures, including geometry generation and meshing.

INTRODUCTION

It is common practice to use the weir and orifice equations (WOE) when developing a stage-discharge curve for dam spillways and other hydraulic structures. However, using the WOE imposes many simplifying assumptions on the flow field, and losses through the structure are accounted for using empirical coefficients, making the selection of proper loss coefficients difficult when dealing with unique or unusual hydraulic structures. In this study, a 3D numerical model was used to determine the applicability of WOE to a spillway inlet structure.

Background

Willow Lake is a small pond located in Mission Hills, Kansas, on a tributary of Brush Creek. Its location is shown in Figure 1. The outlet of Willow Lake consists of a free drop structure, which includes a trash rack. The drop structure drains into a pipe-arc culvert, which then flows into an open channel. The plan, profile, and section views are shown in Figure 2, Figure 3, and Figure 4, respectively.

Field measurements

Multiple field flow measurements were originally planned for this study; however, due to limited rain events occurring during the study time, only one field flow measurement was taken. The field flow measurement calculations are shown in Table 1. The measurement was taken at a cross section about 300 feet downstream of the outlet structure using a Marsh-McBirney magnetic flowmeter. The pool elevation at the time of the measurement was estimated to be 907.98 feet.

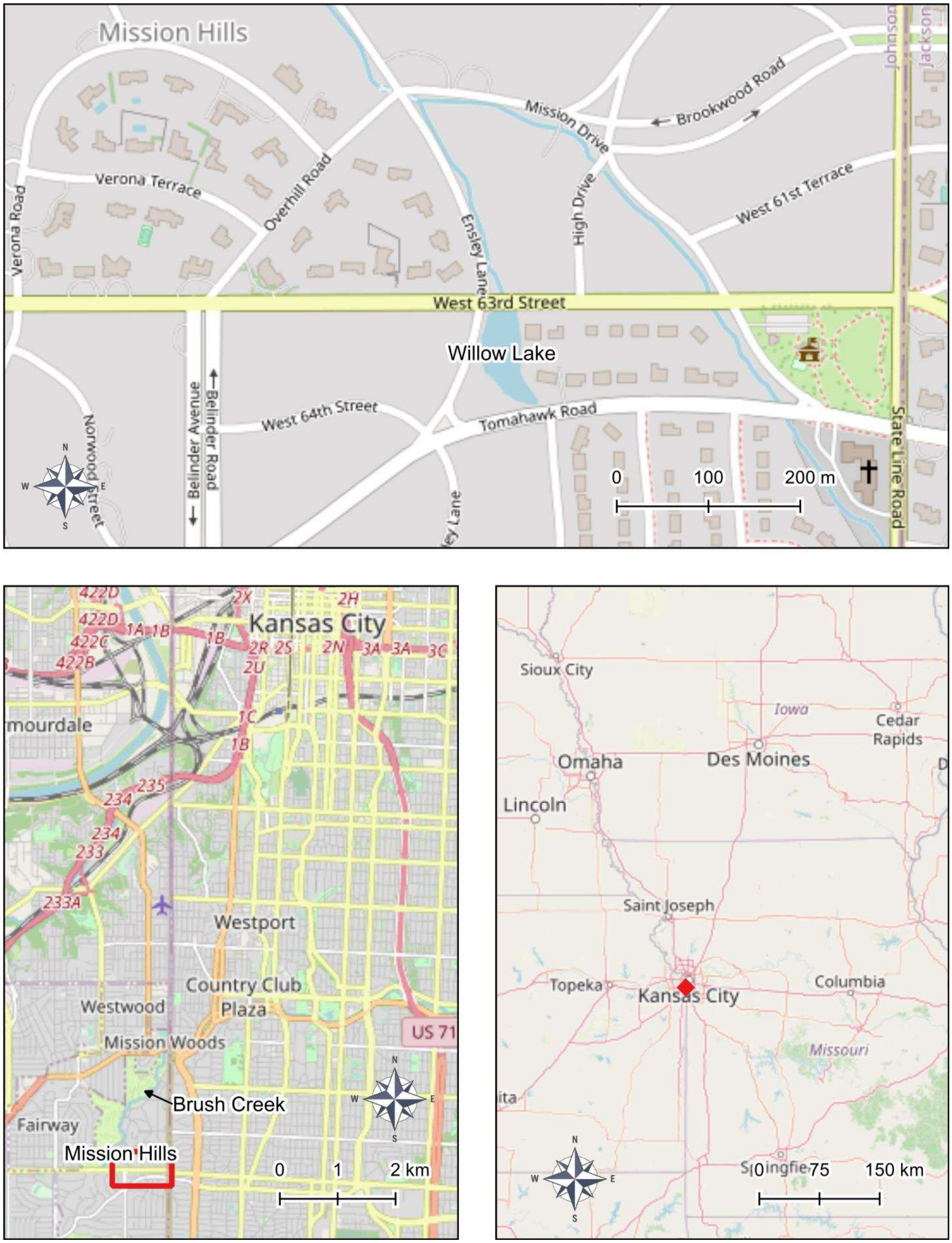

Figure 1. Willow Lake location map.

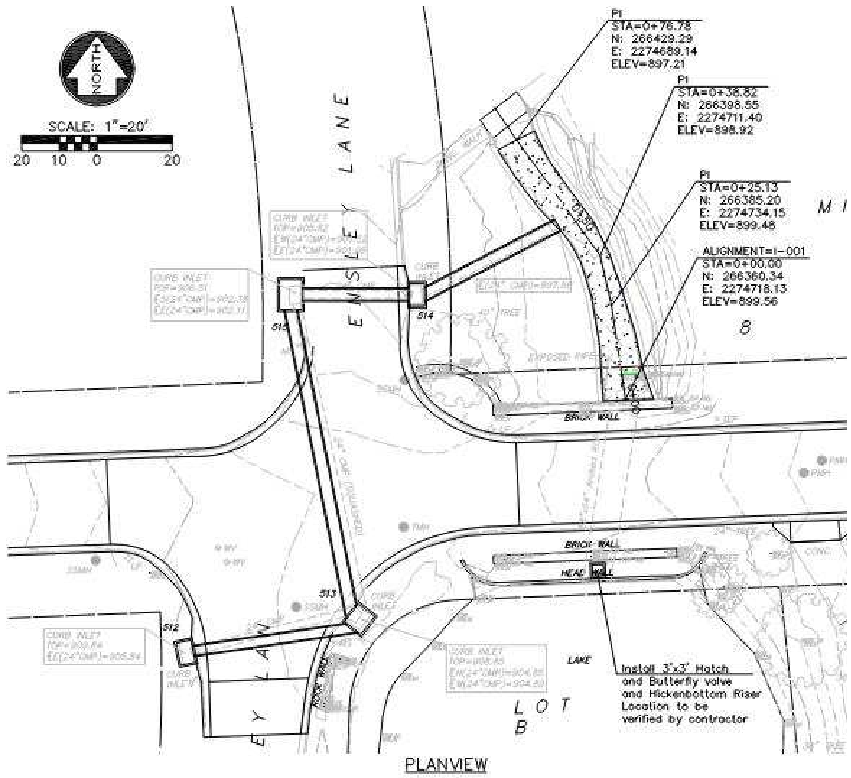

Figure 2. Willow Lake structure, planview.

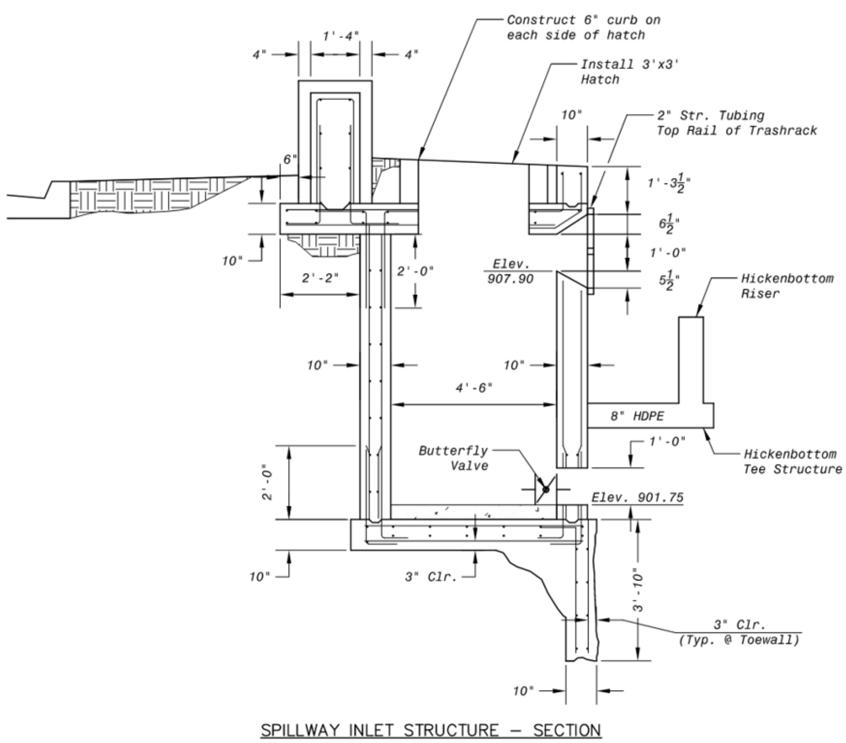

Figure 3. Willow Lake structure, section view.

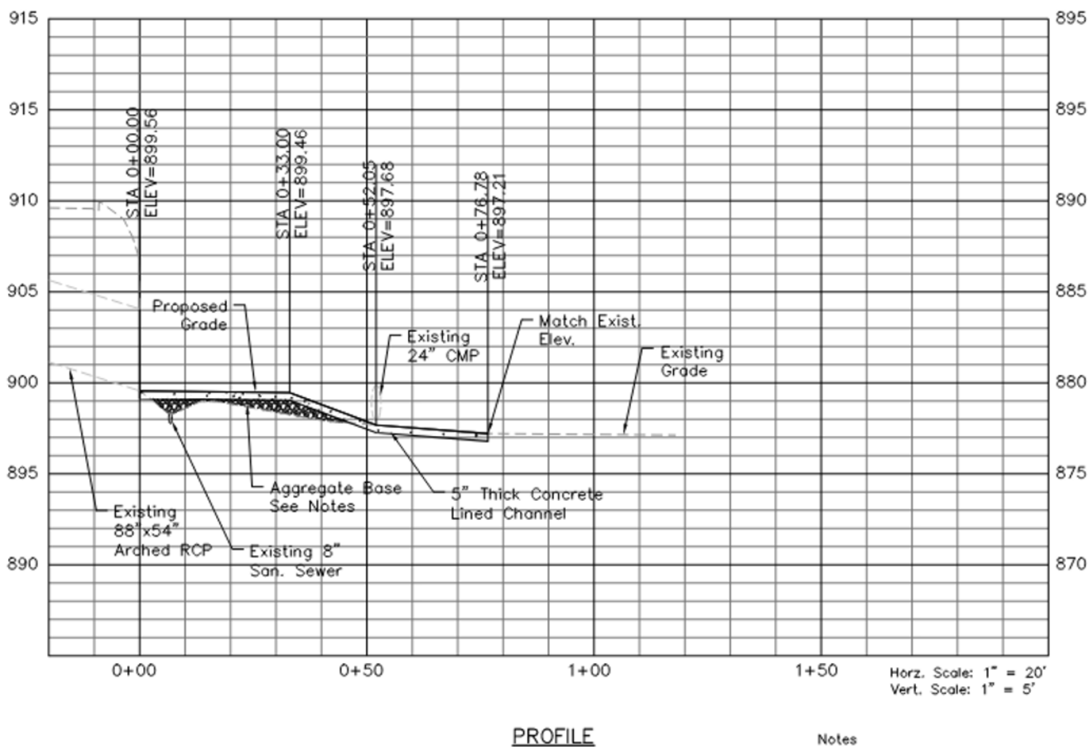

Figure 4. Willow Lake structure, profile.

Table 1. Field Flow Calculations.

Station ft	Width ft	Depth ft	Velocity SFS	Area CF	Flow CFS
0.2	LEW	-	-	-	-
0.5	0.4	0.2	0.02	0.08	0.0016
1	0.5	0.5	0.06	0.25	0.015
1.5	1.15	0.9	1.9	1.035	1.9665
3.3	1.2	1.3	1.6	1.56	2.496
3.9	0.75	1	1.8	0.75	1.35
4.8	1	1.2	1.2	1.2	1.44
5.9	1.1	0.8	1.2	0.88	1.056
7	1.05	0.6	0.3	0.63	0.189
8	1.5	0.6	0.2	0.9	0.18
10	REW	-	-	-	-
Σ	8.65				8.694

WEIR EQUATIONS

Two rating curves using common empirical equations were calculated for the structure: One, using Equation (1) the United States Bureau of Reclamation (USBR) Ogee Weir Equation and a second, using Equation (2) the Francis Equation (USBR 2001). In both cases, the effect of the trash rack was accounted for using Equation (3), which was originally developed by the USBR to account for pier and abutment effects.

$$Q = CLH^{\frac{2}{3}} \tag{1}$$

Where:
Q = flow rate,
C = variable discharge coefficient,
L = effective length, and
H = head on crest.

$$Q \ = \ 3.33H^{\frac{3}{2}}(L - 0.2H) \tag{2}$$

Where:
Q = flow rate,
L = effective length of crest, and
H = head on crest.

$$L = L' - 2\left(NK_p \ + K_a\right)H \tag{3}$$

Where:
L = effective length of crest,
L' = net length of crest,
N = number of piers
K_p = pier contraction coefficient,
K_a = abutment contraction coefficient, and
H= head on crest.

NUMERICAL MODEL

Flow through the Willow Lake spillway was numerically modeled using ESI-OpenCFD OpenFOAM v2206. OpenFOAM is a free and open source CFD software that can solve a wide range of complex flow problems. The ESI-OpenCFD version of OpenFOAM is professionally released every six months. The code undergoes verification and validation testing before release. OpenFOAM is well established and widely used.

Geometry and mesh

Geometry was constructed using a lidar DEM, field measurements, and as built plans. From the as built plans and field measurements, CAD models of the spillway drop structure, trash-rack, and outlet culvert were constructed. For the rest of the domain, the DEM was used to create surface geometry. Blender was used to convert both the CAD data and surface DEM data into stereolithography (STL) surfaces.

The domain was discretized into an unstructured mesh, using OpenFOAM's SnappyHexMesh. The snappyHexMesh utility generates 3D meshes containing hexahedra (hex) and split-hexahedra (split-hex) automatically from triangulated surface geometries in STL format. The mesh approximately conforms to the surface by iteratively refining a starting mesh and morphing the resulting split-hex mesh to the surface (OpenFOAM 2022). Figure 5 illustrates a typical mesh.

One difficulty with using OpenFOAM to model flow through the complex geometries commonly encountered in civil engineering applications is the lack of a graphical user interface for pre-processing. This usability deficiency was overcome using the free and open-source SnappyHexMesh GUI add-on for Blender. SnappyHexMesh GUI add-on generates OpenFOAM dictionary files for the surface mesh objects in Blender. Dictionary creation is based on string replacements using template files located in the add-on's skel directory (Keskitalo 2022).

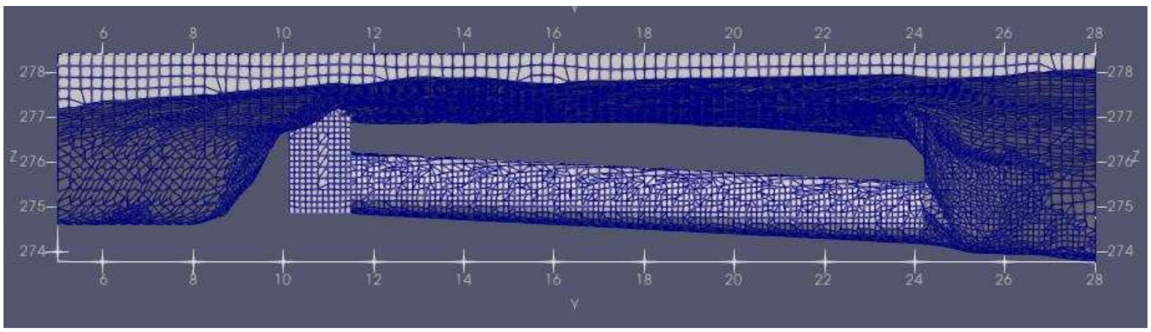

Figure 5. Mesh cells.

Equations and numerics

Because the trash rack includes a horizonal bar that completely blocks the flow through a horizontal section of the structure, it cannot be assumed that the horizontal velocity field is constant throughout the depth of the flow at or above the elevation of the vertical bar. As a result, the equations cannot be vertically integrated without risking inaccuracies in the solution. Therefore, the three-dimensional Reynolds-averaged Navier-Stokes equations for incompressible flow were solved. For incompressible flow, the Navier-Stokes equations are Equation (4), conservation of mass, and Equation (5), conservation of momentum (Torres Et al. 2021).

$$\nabla \times u = 0 \tag{4}$$

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \times \nabla \boldsymbol{u}\right) = -\nabla p + \mu\nabla^2 \boldsymbol{u} - \rho\nabla \times (\overline{\boldsymbol{u}'\boldsymbol{u}'}) + G \tag{5}$$

For this study OpenFOAM's Interfoam solver was used to solve Equation (4) and Equation (5). Interfoam solves the Navier-Stokes equations for two incompressible, isothermal immiscible fluids using VOF phase-fraction based interface capturing.

Boundary and initial conditions

The model was set such that initially the water surface elevation upstream of the structure was 276.8 meters and downstream of the structure 275 meters. As shown in Figure 6, the terrain patch was rendered with opacity, to improve visibility of downstream conditions. To solve for the water surface elevation within the domain for a specified flowrate, the combination of the variable height flowrate boundary condition for the phase fraction and variable height flowrate inlet velocity was used at the inlet boundary. The boundary conditions prescribed at boundary patches are shown in Table 2 and Table 3.

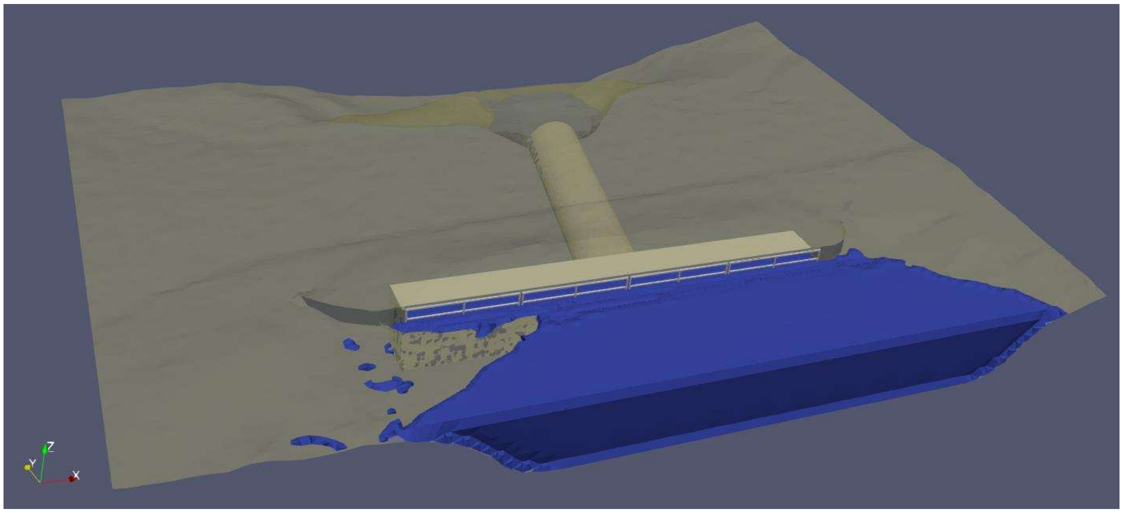

Figure 6. Initial conditions.

Table 2. Flow Boundaries.

patch	alpha.water	p_rgh	U
inlet	variable height flowrate	fixedFluxPressure	variable height flowrate inlet velocity
terrain	zeroGradient	fixedFluxPressure	noSlip
trash_rack	zeroGradient	fixedFluxPressure	noSlip
pipe	zeroGradient	fixedFluxPressure	noSlip
structure	zeroGradient	fixedFluxPressure	noSlip
outlet	zeroGradient	fixedFluxPressure	presureInletOutletVelocity
top	inletOutlet	totalPressure	presureInletOutletVelocity
sides	symmetry	symmetry	symmetry

Table 3. Turbulence Boundaries.

patch	k	nut	omega
inlet	fixedValue	calculated	fixedValue
terrain	kqRWallFunction	nutkRoughWallFunction	omegaWallFunction
trash_rack	kqRWallFunction	nutkRoughWallFunction	omegaWallFunction
pipe	kqRWallFunction	nutkRoughWallFunction	omegaWallFunction
structure	kqRWallFunction	nutkRoughWallFunction	omegaWallFunction
outlet	inletOutlet	calculated	inletOutlet
top	inletOutlet	calculated	inletOutlet
sides	symmetry	symmetry	symmetry

Post processing and model results

Post-processing and visualization was performed using Kitware's Paraview, which is the default post-processing platform for OpenFOAM. Paraview is a graphical user interface that allows the user to choose various tools to visualize model results and to extract numerical result information. Paraview was used to calculate the average upstream water surface elevation. The downstream flowrate was determined using an OpenFOAM function object. Paraview was also used to determine the calculated velocity of the flowfield.

RESULTS

The calculated rating curves using Equation (1) and Equation (2), the computed rating curve from the openFOAM models, and the measured rating curve are shown in Table 4. Figure 7 is a plot of the rating curves.

Table 4. Willow Lake Rating Curve.

Stage ft	OpenFOAM Flow CFS	Ogee Flow CFS	Francis Flow CFS	Field Measurement CFS
907.90	0	0	0	0
907.98	-	-	-	8.69
908.15	19.07	8.26	9.88	-
908.40	53.68	38.25	43.26	-
908.65	92.52	83.59	87.43	-
908.90	151.15	134.07	133.94	-
909.15	212.00	211.11	210.59	-
909.70	351.38	434.03	431.38	-

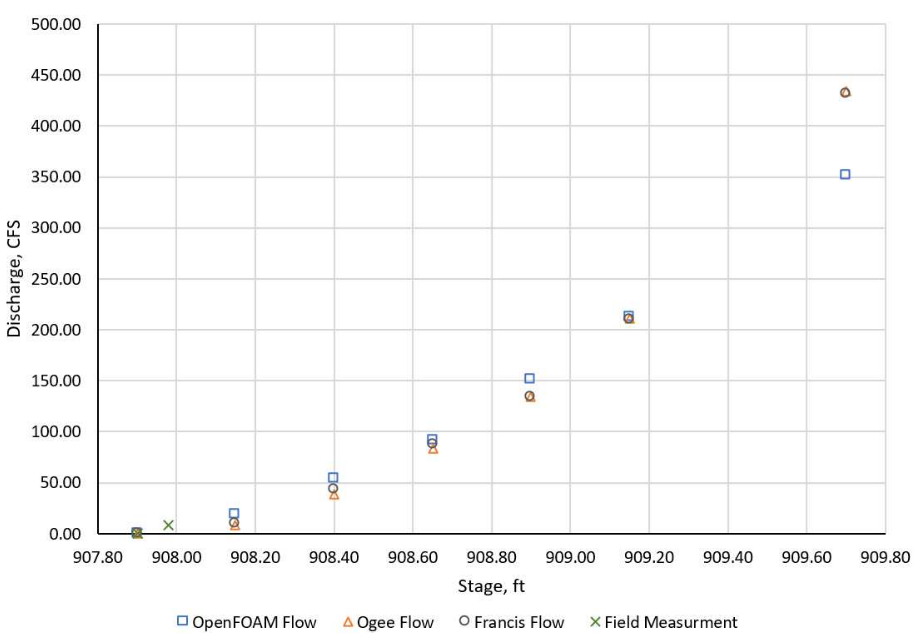

Figure 7. Stage-discharge plot.

CONCLUSION

This paper describes a practical method of developing rating curves for hydraulic structures with complex geometry using 3D CFD. During weir flow, the model used shows good agreement with the Francis flow equation. The result provides reasonable justification to assume the model provides accurate results for larger weir flow events. Similar methodology could be used for developing rating curves for 2D flood modeling as well as other applications when an applicable empirical model cannot be found for a hydraulic structure of interest.

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