DEVELOPMENT OF AN INUNDATION MAP LIBRARY FOR THE CITY OF MASON CITY USING A COUPLED ONE-DIMENSIONAL/TWO-DIMENSIONAL HYDRAULIC MODEL

by

Daniel W. Gilles

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10 First Street NW
Mason City, Iowa 50401

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IIHR – Hydroscience and Engineering
College of Engineering
The University of Iowa
Iowa City, Iowa 52242-1585

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1. INTRODUCTION

The Iowa Flood Center (IFC) is developing community-based flood inundation map libraries to improve flood preparedness among Iowa communities. IFC was approached by the City of Mason City to develop an inundation map library to be hosted on IFC's Iowa Flood Information System (IFIS). The purpose of this report is to describe development of the coupled one-dimensional (1D) / two-dimensional (2D) hydraulic model of the Winnebago River and Willow Creek and the methodology used to develop the flood inundation map library.

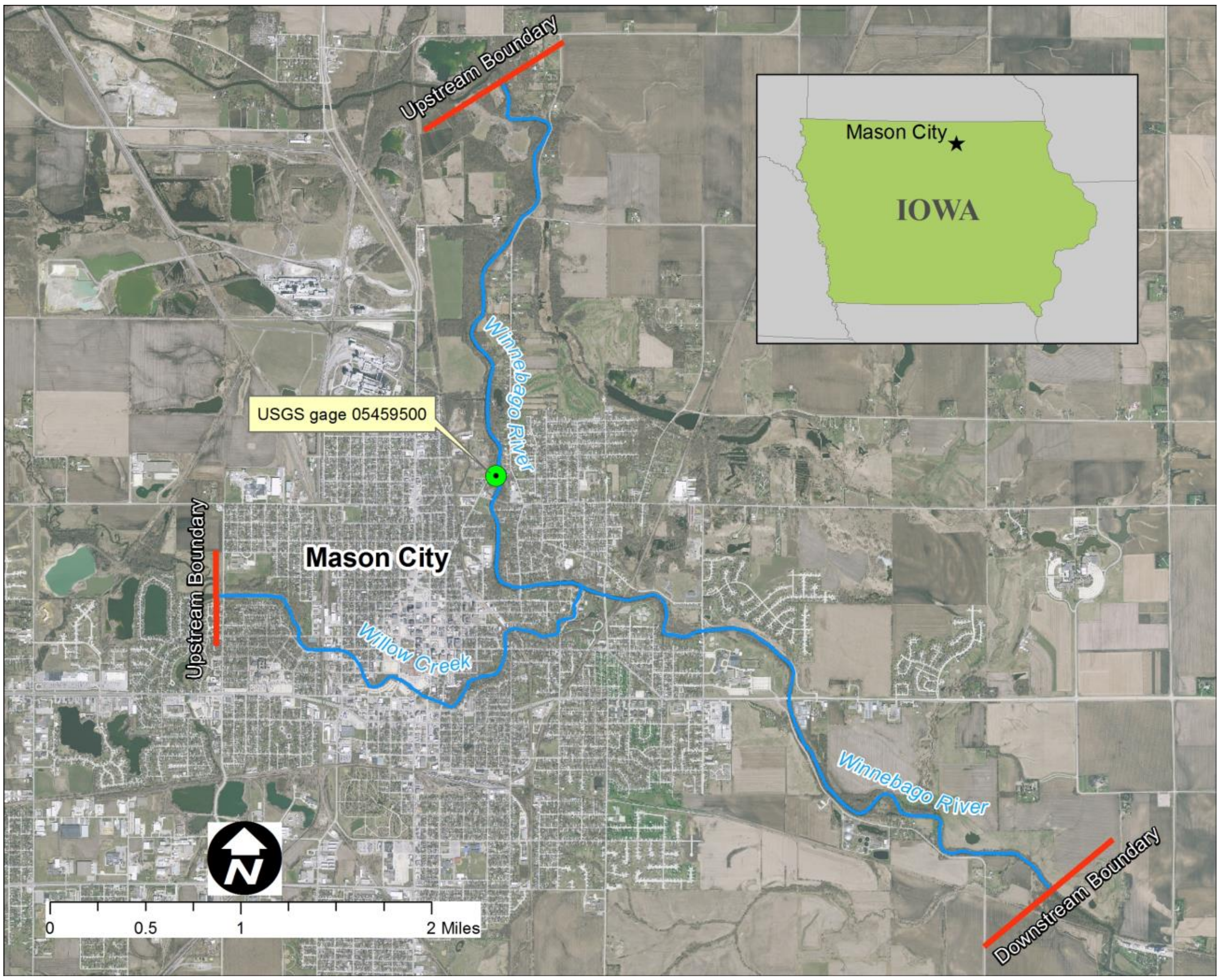

Figure 1. Mason City is situated along the banks of the Winnebago River and Willow Creek. The boundaries of the hydraulic model are shown.

Mason City is located along the banks of the Winnebago River and Willow Creek, as shown in Figure 1. A United States Geological Society (USGS) stream gage station (05459500) is located along the

Winnebago River, with a drainage area of 526 sq mi (1362 sq km). A USGS stream gage station (05460100) is located along Willow Creek 5.2 mi (8.4 km) upstream of study area shown in Figure 1. The drainage area at the Willow Creek USGS stream gage is 78.6 sq mi (203.6 sq km).

During the Flood of 2008, Mason City sustained significant damages to several residential areas, requiring approximately 160 buyouts of damaged properties. Flood waters reached the city's water treatment plant shutting down drinking water supply for five days. The estimated peak flood discharge of 13,100 cfs is estimated to be between the 1- and 0.2- percent-annual-chance flood discharge for the Winnebago River at Mason City USGS gage 05459500 (Linhart and Eash 2010).

2. ANALYSIS

2.1. Hydrologic Analysis

USGS stream gage station 05459500 located along the Winnebago River has a drainage area of 526 sq mi. The period of record is 78 years, spanning from 1933 to present. USGS stream gage station 05460100 located along Willow Creek has a drainage area of 78.6 sq mi and is located 5.2 mi upstream of study area. The period of record is 44 years, spanning from 1966 to 2010. To determine appropriate coincident discharges on Willow Creek and Winnebago River, an analysis of historical coincident flows was executed.

The total number of coincident annual peak discharge events totaled approximately 21. The ratio of discharge at the Willow Creek gage (05460100) to discharge at the Winnebago gage (05459500) is plotted with respect to the discharge at the Winnebago USGS gage (05459500) in Figure 2. A clear relationship can be seen between coincident discharges at the gage locations. The ratio is higher at lower Winnebago River discharges, and decreases up to 9,000 cfs. At discharges greater than 9,000 cfs on the Winnebago River, the ratio begins to increase based on two data points. The ratio at the time of the Flood of 2008 was approximately 0.18.

To estimate discharges at the upstream boundary for Willow Creek, it is necessary to determine drainage area at the upstream boundary. ESRI ArcGIS's ArcHydro extension was used to estimate drainage area along stream centerlines for the Willow Creek basin. The drainage area at the upstream Willow Creek boundary was calculated as 98.7 sq mi. Discharges at the Willow Creek USGS gage were weighted by area using Equation 1 developed by Eash (2001).

$$Q_{t(aw)} = Q_{t(wg)} \left(\frac{A_u}{A_g} \right)^x \tag{1}$$

Where $Q_{t(aw)}$ is the area-weighted discharge estimate for an ungaged site on a gaged stream for recurrence interval t, $Q_{t(wg)}$ is the weighted discharge estimate for a gaged site for recurrence interval t, A_u is the drainage area of the ungaged site, A_g is the drainage area of the gaged site, and x is the mean exponent for 2001 hydrologic region 1, 0.665.

Using Equation 1, an area weighting factor of 1.163 was calculated to shift historic peak annual discharges at the Willow Creek gage according to estimated drainage area at the upstream Willow Creek study boundary. Plotting the ratio of these area weighted discharge values to those on the Winnebago River with respect to discharge at the Winnebago River gage can be seen in Figure 3. The ratio between discharges on Willow Creek and the Winnebago River ranges from approximately 0.15 to 0.4.

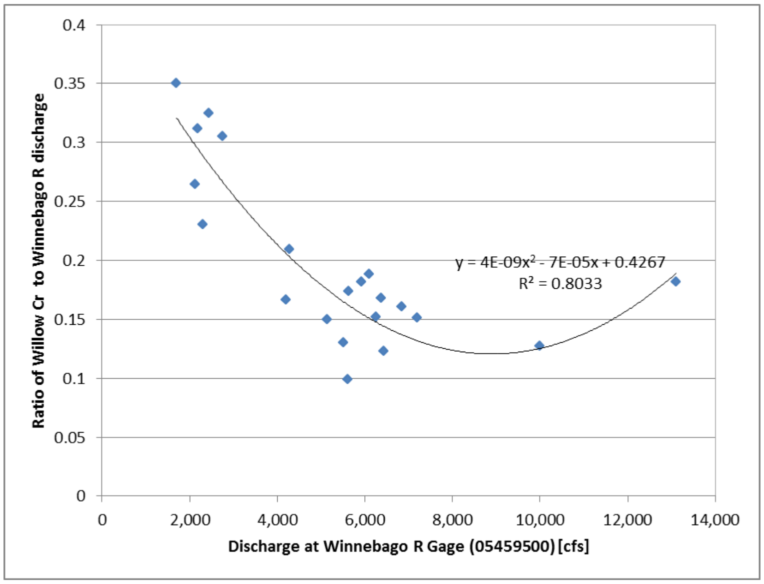

Figure 2. The ratio of discharge at the Willow Creek USGS gage (05460100) to discharge at the Winnebago River USGS gage (05459500) is plotted with respect to the historic discharge at the Winnebago River USGS gage (05459500)

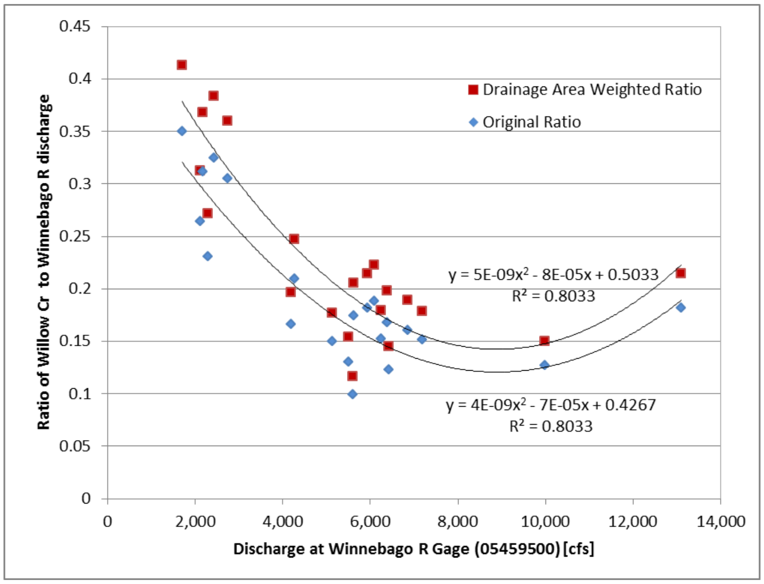

Figure 3. The ratio of area-weighted discharge at the upstream Willow Creek study boundary to discharge at the Winnebago River USGS gage (05459500) is plotted with respect to the historic discharge at the Winnebago River USGS gage (05459500)

2.2. Hydraulic Analysis

The presence of hydraulic structures (e.g., levees, weirs, and bridges) within the study reach required use of the energy equation to correctly predict head loss, while urban floodplain complexity required the depth-averaged Saint-Venant equations to accurately predict multi-directional flow patterns. DHI Water and Environment's (DHI) MIKE FLOOD 2011, a 1D/2D coupled hydrodynamic modeling software package was used to model the study area. MIKE FLOOD models the river channel using MIKE 11, a 1D model, and the floodplain using MIKE 21, a 2D model. Data required for model development includes a high-resolution DEM of the terrain and river bed, distributed roughness, and structure geometry.

2.2.1. Bathymetric Survey

River bathymetry data was collected using a hydrographic sensor to measure depths. The horizontal and vertical positions of the hydrographic sensor were measured using a Trimble R8 real time kinetic (RTK) global navigation satellite system (GNSS). The Trimble R8 is rated with horizontal and vertical accuracy of ± 0.033 feet (0.01 meters) and ± 0.066 feet (0.02 meters), respectively, with real-time corrections from a ground-based reference station. Real-time corrections were provided via cellular modem by the Iowa Real Time Network (IaRTN), a statewide system of reference stations operated by the Iowa Department of Transportation (IDOT). In IIHR's experience, vertical accuracy of the IaRTN corrections is approximately ± 0.13 feet (0.04 meters).

IIHR performed hydrographic measurements along the Winnebago River channel by deploying a hydrographic sensor from a 12-foot Lowe flat-bottom Jon boat upstream the mouth of Willow Creek. Downstream of the mouth of Willow Creek, an 8-foot Aire inflatable kayak was used to deploy a hydrographic sensor.

Measurements performed from the 12-foot Lowe flat-bottom Jon boat used an Odom Hydrographic HT100, survey grade, 200 kHz, single-beam echosounder with a three-degree transducer. The HT100 measurement accuracy is rated at 0.033 feet (0.01 meters) (displayed resolution) ± 0.1-percent of distance (measurement accuracy). During bathymetric data collection, the Trimble R8 RTK GNSS receiver antenna was centered over the single-beam echosounder transducer. Depth measurements were synchronized in real time with vertical and horizontal position reported by the GNSS using HYPACK software. HYPACK software is used to navigate, track spatial coverage of collected data, and provide and initial assessment of data quality in real time.

Measurements performed from the 8-foot Aire inflatable kayak used a SonTek RiverSureyor M9 acoustic Doppler profiler (ADP). The portability of the SonTek RiverSurveyor M9 system allowed measurements in reaches inaccessible by boat. The sensor has nine beams, consisting of two sets of four velocity-profiling beams (each having its own frequency) and one vertical echosounder. Corrections for pitch and roll are incorporated in real-time. During bathymetric data collection, the Trimble R8 RTK GNSS receiver antenna was centered over the transducer. The face of the transducer was submerged below the water surface, a depth sufficient to prevent air entrained at the bow from interfering with measurements. The reported accuracy of the depth measured by the vertical echosounder is 1% of the measured depth with a resolution of 0.0033 feet (0.001 m). Depth measurements were synchronized in real time with vertical and horizontal position reported by the GNSS using SonTek's RiverSurveyor Live software. The software was also used to integrate system components and store measured data.

2.2.2. Model Development

Bathymetric data was integrated into the LiDAR-derived terrain data to develop a 1-m resolution DEM of the study area. Using this high-resolution DEM, a 1D hydrodynamic model of the river channel was developed using DHI's MIKE 11 GIS ArcGIS extension to create geometric files. Cross-sections were digitized at an approximate spacing of 300 feet. Bridge and weir geometries were taken from the most recent FEMA FIS Hec-RAS model.

A 2D structured computational mesh was created by aggregating the 1-m resolution DEM to a less computationally intensive 10-m resolution grid. The dilution of levee and embankment elevations during aggregation of the DEM requires manual insertion of unaltered structure elevations using GIS techniques.

Some terrain features, such as bike paths, are not clearly defined in bare-earth LiDAR due to vegetation. Top of embankment elevations were estimated from raw LiDAR LAS points in the absence of as-built plan sets.

The 1D and 2D models were coupled using MIKE FLOOD such that the river channel is represented by fully dynamic, section-averaged solutions to the Saint-Venant equations at discrete cross sections and the floodplain is represented by depth-averaged Saint-Venant equations at structured grid cells. MIKE FLOOD 1D/2D coupling allows two models to dynamically exchange information about water levels and discharge. Lateral links are 1D explicit elements intended to model over-topping of a river bank or levee. A simple weir equation calculates flow through the lateral link. Lateral weir structure elevations are based on a bed level determined by cross-section endpoints and a width determined from the resolution of points defined along the structure (DHI 2011). The distribution of flow through the linked model nodes is determined by the range of influence each structure has upon each linked node (DHI 2011).

2.2.3. Boundary Conditions

All hydrodynamic boundary conditions were specified in the 1D model. Flow rate was specified at the upstream 1D boundary and water surface elevation was calculated at the downstream 1D boundary according to a rating curve developed with a normal depth assumption. The upstream and downstream model extents are placed sufficiently far away from the area of interest such that artificial boundary effects are minimized.

2.2.4. Roughness Values

Spatial variation in flow resistance due to land cover is characterized in MIKE Flood using Manning's roughness coefficients. The USGS 2001 National Land Cover Database (NLCD 2001) was used to select roughness values throughout the study area. NLCD 2001 data are satellite-derived 30-m resolution classifications of land cover. Roughness coefficients associated with each land cover description were selected based upon published values in Chow (1959) and Mattock and Forbes (2008). Roughness values assigned to corresponding land cover classifications are shown in Figure 4.

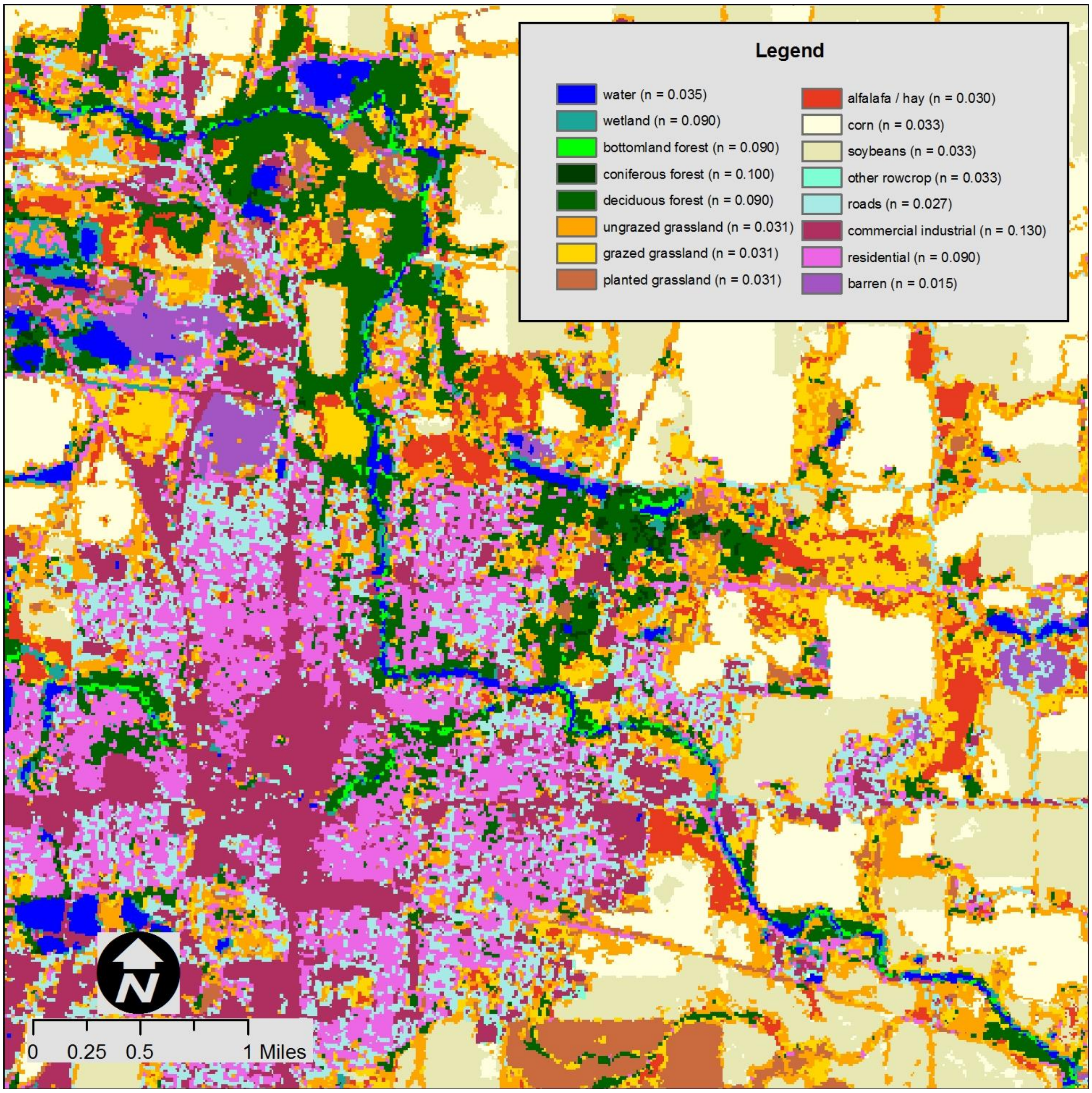

Figure 4. Manning's roughness values assigned to corresponding the USGS 2001 National Land Cover Database classifications.

2.2.5 Model Calibration

The model was calibrated to the USGS discharge – stage relationship at Winnebago River gage (05459500). The calibration process consisted of adjusting Manning's roughness in the 1D model at lower flows, and then adjusting Manning's roughness in the 2D grid at higher, out of channel flows. A plot comparing the established USGS rating curve to the simulated rating curve at the gaging station is shown in Figure 4.

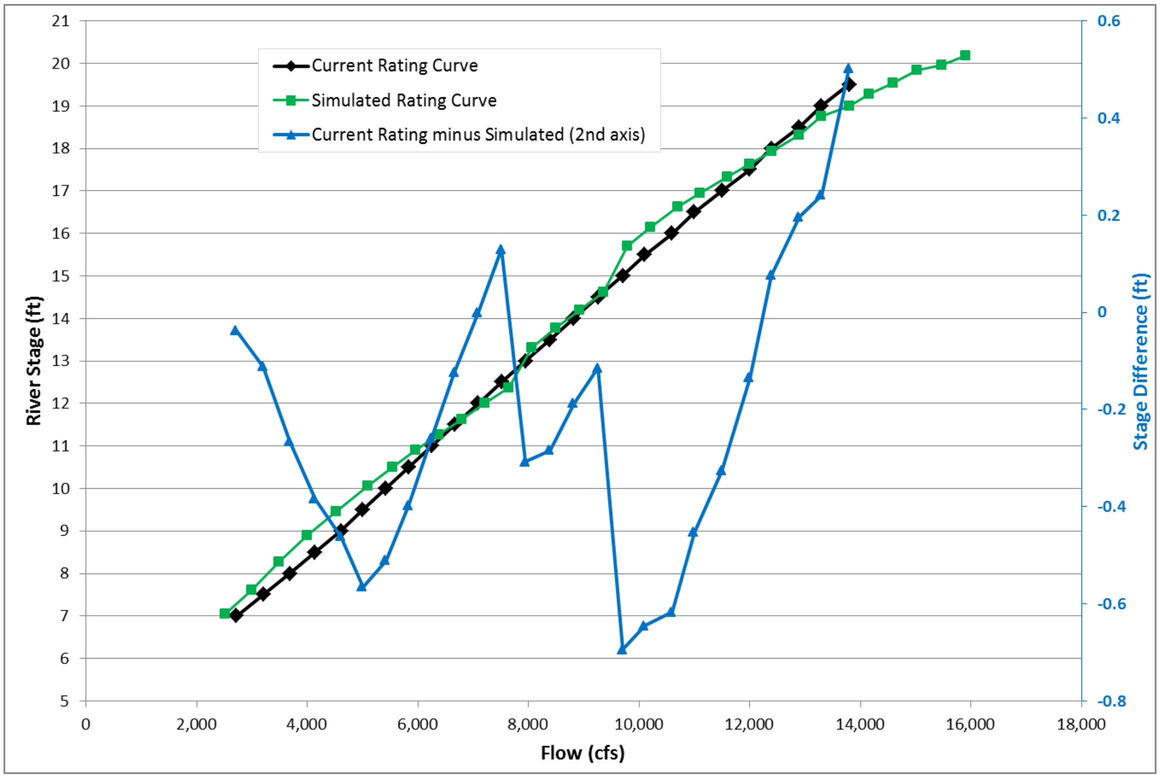

Figure 5. Plot comparing the established USGS rating curve compared to simulated rating curve at the river gaging station (05459500).

2.3. Map Development

2.3.1 Simulation Scenarios

Three different flow combination scenarios were selected to provide a robust inundation map library. These featured an additional 15%, 25% and 40% flow contribution from Willow Creek for a given Winnebago River flow. Table 1 shows each stream flow at the upstream model boundaries. Flows on the Winnebago River are consistent across scenarios upstream of the confluence with Willow Creek. Flows from the confluence to the downstream boundary are the sum of the input stream flows. Some 0.4 flow ratio simulations were not stable at Winnebago River stages higher than 20 feet. These 0.4 ratio flow combinations are less likely to occur at higher Winnebago River stages, as shown in the earlier coincident flow analysis.

Table 1. Inflow discharge scenarios used in MIKE Flood simulations.

River Stage [ft]	Elevation (NAVD88) [ft]	Winnebago River Inflow [cfs]	Willow Creek Inflow [cfs] 0.15 ratio	0.25 ratio	0.4 ratio
7.0	1076.51	2,520	378	630	1,008
7.5	1077.01	3,000	450	750	1,200
8.0	1077.51	3,490	524	873	1,396
8.5	1078.01	4,000	600	1,000	1,600
9.0	1078.51	4,530	680	1,133	1,812
9.5	1079.01	5,100	765	1,275	2,040
10.0	1079.51	5,540	831	1,385	2,216
10.5	1080.01	5,960	894	1,490	2,384
11.0	1080.51	6,370	956	1,593	2,548
11.5	1081.01	6,790	1,019	1,698	2,716
12.0	1081.51	7,210	1,082	1,803	2,884
12.5	1082.01	7,640	1,146	1,910	3,056
13.0	1082.51	8,060	1,209	2,015	3,224
13.5	1083.01	8,490	1,274	2,123	3,396
14.0	1083.51	8,920	1,338	2,230	3,568
14.5	1084.01	9,360	1,404	2,340	3,744
15.0	1084.51	9,790	1,469	2,448	3,916
15.5	1085.01	10,200	1,530	2,550	4,080
16.0	1085.51	10,700	1,605	2,675	4,280
16.5	1086.01	11,100	1,665	2,775	4,440
17.0	1086.51	11,600	1,740	2,900	4,640
17.5	1087.01	12,000	1,800	3,000	4,800
18.0	1087.51	12,400	1,860	3,100	4,960
18.5	1088.01	12,900	1,935	3,225	5,160
19.0	1088.51	13,300	1,995	3,325	5,320
19.5	1089.01	13,800	2,070	3,450	5,520
20.0	1089.51	14,160	2,124	3,540	5,664
20.5	1090.01	14,590	2,189	3,648	N/A
21.0	1090.51	15,030	2,255	3,758	N/A
21.5	1091.01	15,470	2,321	3,868	N/A
22.0	1091.51	15,900	2,385	3,975	N/A

2.3.2 Post-Processing Script

Simulation results were processed to improve the spatial resolution of the inundation results. A Geographic Information System (GIS) script was written in Python coding language to run ESRI's ArcGIS 9.3 GIS tools. This "remapping" script takes advantage of high-resolution LiDAR topographic data to produce results at a higher resolution than results generated by the 10-m resolution structured computational mesh. The script laterally extends the edge of the coarse-resolution simulated water surface. This extended water surface can then be intersected with a high-resolution DEM to improve fidelity of the inundation products. The script also removed disconnected and not-wetted regions interior to the floodplain boundaries based on a user defined area. Some manual editing of inundation polygons and depth rasters generated by the remapping script was necessary. Any not-wetted regions with a straight-line dimension less than 250 feet was filled with an inundation depth of 0.1 feet.

3. REFERENCES

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