PREPARED BY

Mead & Hunt

Model Input Status Report

H&H Modeling: Upstream Hydraulic Model

Pensacola Hydroelectric Project Project No. 1494

March 30, 2021

CONTENTS

Table of Contents

CONTENTS

List of Figures

CONTENTS

List of Tables

Executive Summary

Mead & Hunt is assisting Grand River Dam Authority (GRDA) with its intent to relicense the Pensacola Hydroelectric Project (Project), which is regulated by the Federal Energy Regulatory Commission (FERC). Flood control operations at the Project are regulated by the United States Army Corps of Engineers (USACE). The FERC's study plan determination requires GRDA to provide a model input status report. The FERC requested GRDA also present results of a flood frequency analysis and inflow event analysis as part of the report and propose a definition of "material difference" in the report. Mead & Hunt has performed these tasks on behalf of GRDA. This report documents the findings to be presented at the conference call.

Mead & Hunt used a Hydrologic Engineering Center River Analysis System (HEC-RAS) model, previously developed by Tetra Tech, as the base for model development. Mead & Hunt conducted a detailed review of Tetra Tech's model and identified ways in which the model should be improved (Mead & Hunt, 2016). As part of this study, Mead & Hunt transformed the Tetra Tech model by updating the version of HEC-RAS from a beta version to a full release version, modifying the geometry to contain larger flood events and to improve model stability and accuracy, updating bridge geometry, adding the Spring River and the Elk River, replacing the reservoir bathymetry to reflect newly surveyed conditions, and by using computational parameters recommended by the HEC-RAS development team. This resulted in an improved comprehensive hydraulic model of Grand Lake and the river system upstream of Pensacola Dam.

Mead & Hunt calibrated the model using measured data. Measured data included United States Geological Survey (USGS) gage elevations, high water marks, and recorded data from loggers installed by the project team. For calibration, stream gage data from the USGS were used for upstream inflow boundary conditions and Grand Lake stage data were used as the downstream boundary condition. Six historic events were used to calibrate the model. Manning's n-values were adjusted until simulated water surface elevations reasonably matched measured data. Flow roughness factors were used to fine-tune the model.

A flood frequency analysis was performed for the study area using data from USACE. Data from 1940 (dam construction date) to 2017 (latest available data at time of data delivery from USACE) were used and a graphical frequency analysis of peak inflows was performed. The analysis estimated the 100-year event flow to Grand Lake is approximately 300,000 cubic feet per second (cfs).

The largest events of recent record did not meet or exceed the 100-year event threshold at Pensacola Dam. The September 1993 event represents a 44-year flood, the July 2007 event represents a 4-year flood, the December 2015 event represents a 15-year flood, and the May 2019 event represents a 9-year flood. Mead & Hunt iteratively scaled these events until the total peak inflow to Grand Lake was approximately 300,000 cfs, or a 100-year event. The scaling factors were 1.17 for the September 1993 event, 2.15 for the July 2007 event, 1.50 for the December 2015 event, and 1.70 for the May 2019 event.

Based on Mead & Hunt's review of how government agencies approach differences in WSEL and understanding that material difference represents expected precision when comparing model results, Mead & Hunt recommends material difference in WSEL be quantified as 0.5 feet for out of bank events for the sole purpose of determining areas to be included in the model.

List of Abbreviations and Terms

1D	One-Dimensional
2D	Two-Dimensional
2DFA	Two-Dimensional Flow Area
CFS	Cubic Feet Per Second
CHM	Comprehensive Hydraulic Model
DEM	Digital Elevation Model
GRDA	Grand River Dam Authority
HEC	Hydrologic Engineering Center
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
LiDAR	Light Detection and Ranging
NAVD88	North American Vertical Datum of 1988
NGVD29	National Geodetic Vertical Datum of 1929
NED	National Elevation Dataset
NWIS	National Water Information System
PD	Pensacola Datum
POR	Period of Record
Project	Pensacola Hydroelectric Project
PSP	Proposed Study Plan
RAS	River Analysis System
RM	River Mile
RSP	Revised Study Plan
SPD	Study Plan Determination
SSP	Statistical Software Package
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
WSEL	Water Surface Elevation

1. Introduction and Background

1.1 Project Description

The Pensacola Hydroelectric Project is owned and operated by GRDA and regulated by the FERC. The Pensacola Dam is in Mayes County, Oklahoma on the Grand-Neosho River. Pensacola Dam impounds Grand Lake. Construction of Pensacola Dam was completed in 1940. **Figure 1** displays the study area. Downstream of Pensacola Dam, GRDA also owns and operates the Robert S. Kerr Dam as the Markham Ferry Hydroelectric Project. Kerr Dam is also in Mayes County and impounds Lake Hudson, also known as Markham Ferry Reservoir. Flood control operations at both Pensacola Dam and Kerr Dam are regulated by USACE.

1.2 Vertical Datums

Data sources for this study use a variety of vertical datums. Unless otherwise noted, data are presented in the Pensacola Datum (PD). To convert from PD to the National Geodetic Vertical Datum of 1929 (NGVD29), add 1.07 feet. To convert from NGVD29 to the North American Vertical Datum of 1988 (NAVD88), add 0.33 feet. **Figure 2** displays datum transformations and conversions (Hunter, Trevisan, Villa, & Smith, 2020). The HEC-RAS model discussed in this report was developed in NGVD29.

1.3 Study Plan Proposals and Determination

GRDA is currently relicensing the Project. The timeline of study plan proposals and determination is as follows:

1. On April 27, 2018, GRDA filed its Proposed Study Plan (PSP) to address hydrologic and hydraulic modeling in support of its intent to relicense the Project.
2. On September 24, 2018, GRDA filed its Revised Study Plan (RSP).
3. On November 8, 2018, the FERC issued its Study Plan Determination (SPD) for the Project.
4. On January 23, 2020, the FERC issued an Order on the Request for Clarification and Rehearing, which clarified the timeline for certain milestones applicable to the relicensing study plan.

The PSP and RSP recommended the development of a Comprehensive Hydraulic Model (CHM). This report discusses the Upstream Hydraulic Model. The FERC's SPD and Order on Request for Clarification and Rehearing included the following direction:

1. Provide a model input status report by March 30, 2021.
2. Hold a conference call on model inputs and calibration within 30 days of the input status report.
3. Present the flood frequency analysis during the conference call.
4. Perform an inflow analysis to determine if the historical inflow events selected in the RSP exceed a 100-year recurrence interval. Present the results of the analysis during the conference call.
5. Propose a definition of "material difference."

This report provides the model input status and documents the development of the Upstream Hydraulic Model and findings to be presented in the conference call.

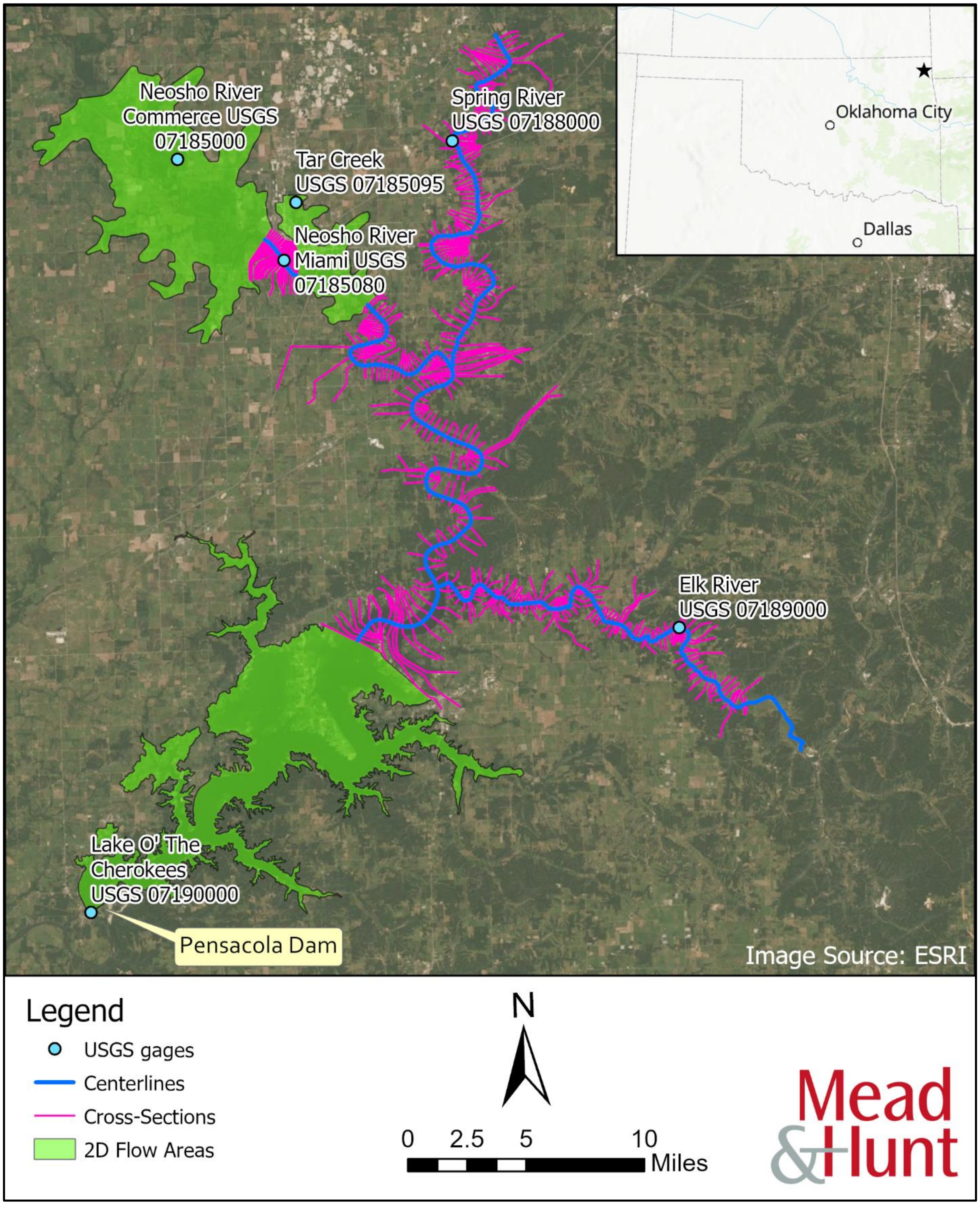
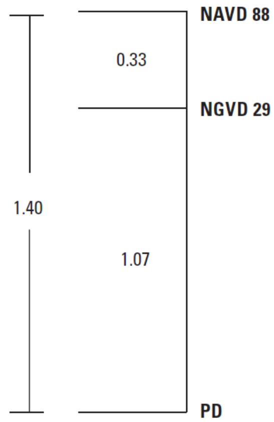


FIGURE 1. UPSTREAM HYDRAULIC MODEL STUDY AREA.



	Elevations, in feet		
	NAVD 88	NGVD 29	PD
Conservation pool	743.40	743.07	742.00
Top of the dam	758.40	758.07	757.00

FIGURE 2. DATUM TRANSFORMATIONS AND CONVERSIONS. SOURCE: (HUNTER, TREVISAN, VILLA, & SMITH, 2020).

2. Model Development

Tetra Tech previously developed a HEC-RAS model of the study area (Tetra Tech, 2015, 2016). Mead & Hunt used Tetra Tech's model as the base for Upstream Hydraulic Model development. After a detailed review, the Tetra Tech model was transformed in the following ways, resulting in an improved comprehensive hydraulic model of Grand Lake and the river system upstream of Pensacola Dam.

1. Model was converted from a beta version of HEC-RAS to version 5.0.7.
2. Two-dimensional (2D) flow area (2DFA) was added for Grand Lake, replacing cross-sections.
3. 2DFAs in the vicinity of Miami, Oklahoma were expanded to fully contain inundation from larger flow events.
4. Mesh cell centers within 2DFAs were reviewed and adjusted in accordance with best practices.
5. Cross-sections were extended to fully contain the inundation from larger flow events.
6. 1D/2D flow boundaries were reviewed and adjusted in accordance with best practices.
7. Bridge geometries were updated to reflect current conditions.
8. Bank stations and ineffective flow areas were reviewed and adjusted in accordance with best practices.
9. Elk River was added to the model.
10. Spring River was added to the model.
11. Recently published USGS Grand Lake bathymetry data were incorporated into model geometry.
12. Computational parameters were reviewed and adjusted in accordance with best practices.

Upstream Hydraulic Model improvements are discussed in detail below.

2.1 HEC-RAS Version

Tetra Tech performed hydraulic modeling with the August 2016 5.0 beta version of HEC-RAS (Tetra Tech, 2015; Tetra Tech 2016). At the time of Mead & Hunt's RSP and the FERC's SPD, the current version of HEC-RAS was 5.0.7. Therefore, Mead & Hunt used HEC-RAS 5.0.7 for analysis.

2.2 Grand Lake 2DFA

Tetra Tech used cross-sections to represent Grand Lake. Mead & Hunt replaced the cross-sections downstream of River Mile (RM) 100 with a 2DFA. The 2DFA better accounts for the volume in Grand Lake. **Figure 3** displays a comparison of Tetra Tech's model geometry to Mead & Hunt's geometry.

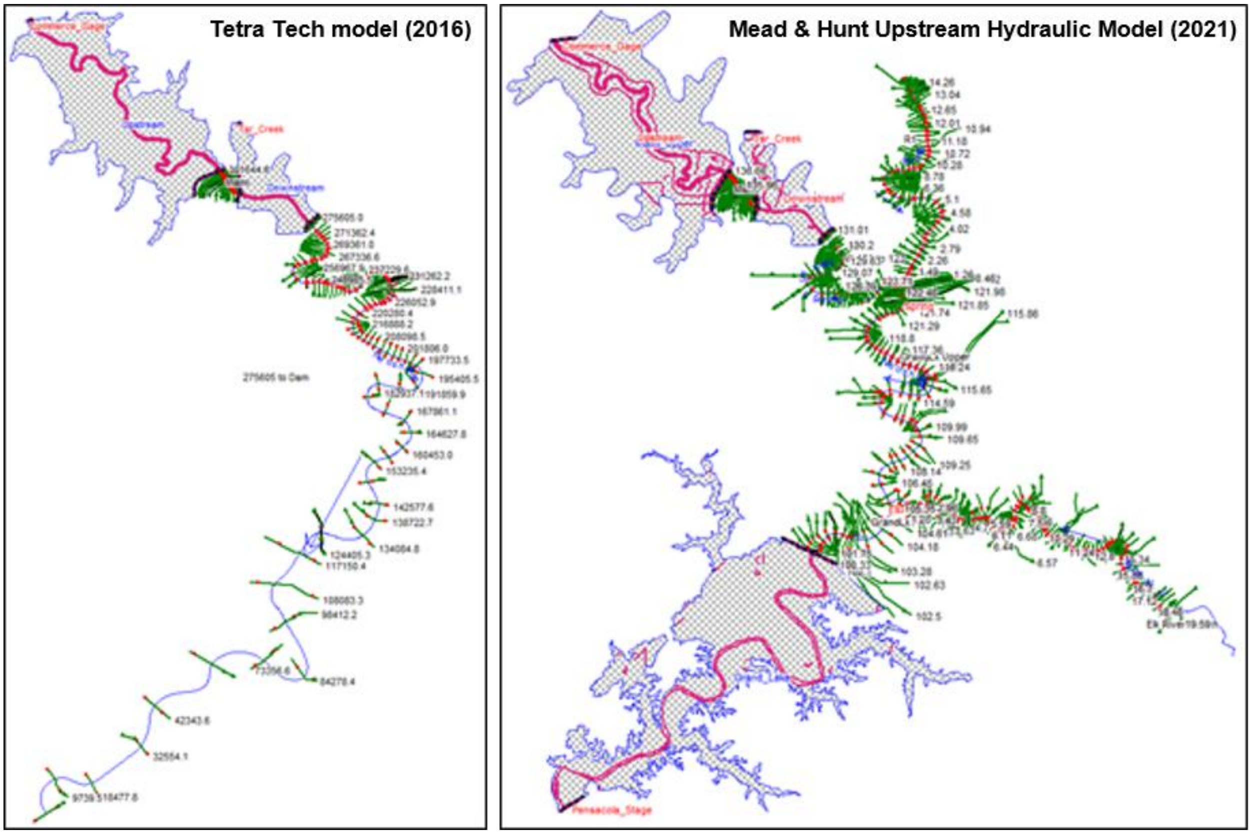


FIGURE 3. COMPARISON OF MODEL GEOMETRIES.

2.3 Upstream 2DFAs

Tetra Tech included two 2DFAs in their HEC-RAS model: one just downstream of the City of Miami and one upstream of the City of Miami. Preliminary simulations showed that large flow events (e.g., the 100-year event) were not contained within the 2DFAs. Mead & Hunt expanded the 2DFAs so large flow events could be contained within the model boundaries. The expanded 2DFAs are displayed in **Figure 3**. In Mead & Hunt's model, the most upstream 2DFA is named "Miami_Upper" and the next 2DFA downstream is named "Miami_Lower".

The upstream boundary of the model along the Neosho River was not modified. Tetra Tech determined that it takes 4 hours for a flood wave to travel from the upstream end of the model (RM 152.2) to the Commerce gage (Tetra Tech, 2015). Mead & Hunt's preliminary simulations confirmed the 4-hour travel time. Therefore, Mead & Hunt applied a negative 4.0 hour offset to the USGS flow hydrographs, which were used as inflows at the upstream end of the Neosho River 2DFA. Flow data is further discussed in Section 3.1.

2.4 2DFA Cell Refinement

Tetra Tech included some refinement of 2DFA cells. However, cell faces were not aligned to the top of the river channel. Mead & Hunt refined cell alignments to follow the banks of the Neosho River. **Figure 4** displays an example comparison of Tetra Tech's 2DFA cell alignment to Mead & Hunt's cell alignment.

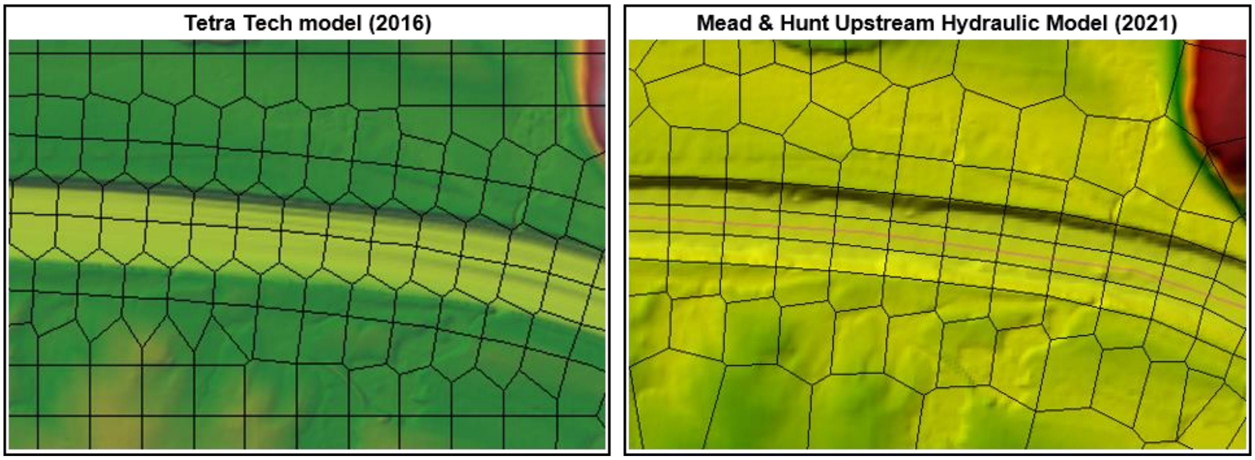


FIGURE 4. COMPARISON OF 2DFA CELLS.

2.5 Cross-Section Adjustments

Like the 2DFAs, preliminary simulations showed large flow events (e.g., 100-year event) were not contained within the cross-sections. Mead & Hunt extended the cross-sections laterally so large flow events were contained within the cross-sections. An example of extended cross-sections is displayed in **Figure 5**.

2.6 1D/2D Boundaries

Mead & Hunt reviewed the 1D/2D boundaries in the Tetra Tech model and moved the boundaries to determine if model stability could be improved. Moving the most upstream 1D/2D boundary further upstream resulted in a more stable, accurate model. The revised location of the 1D/2D model boundary is displayed in **Figure 5**.

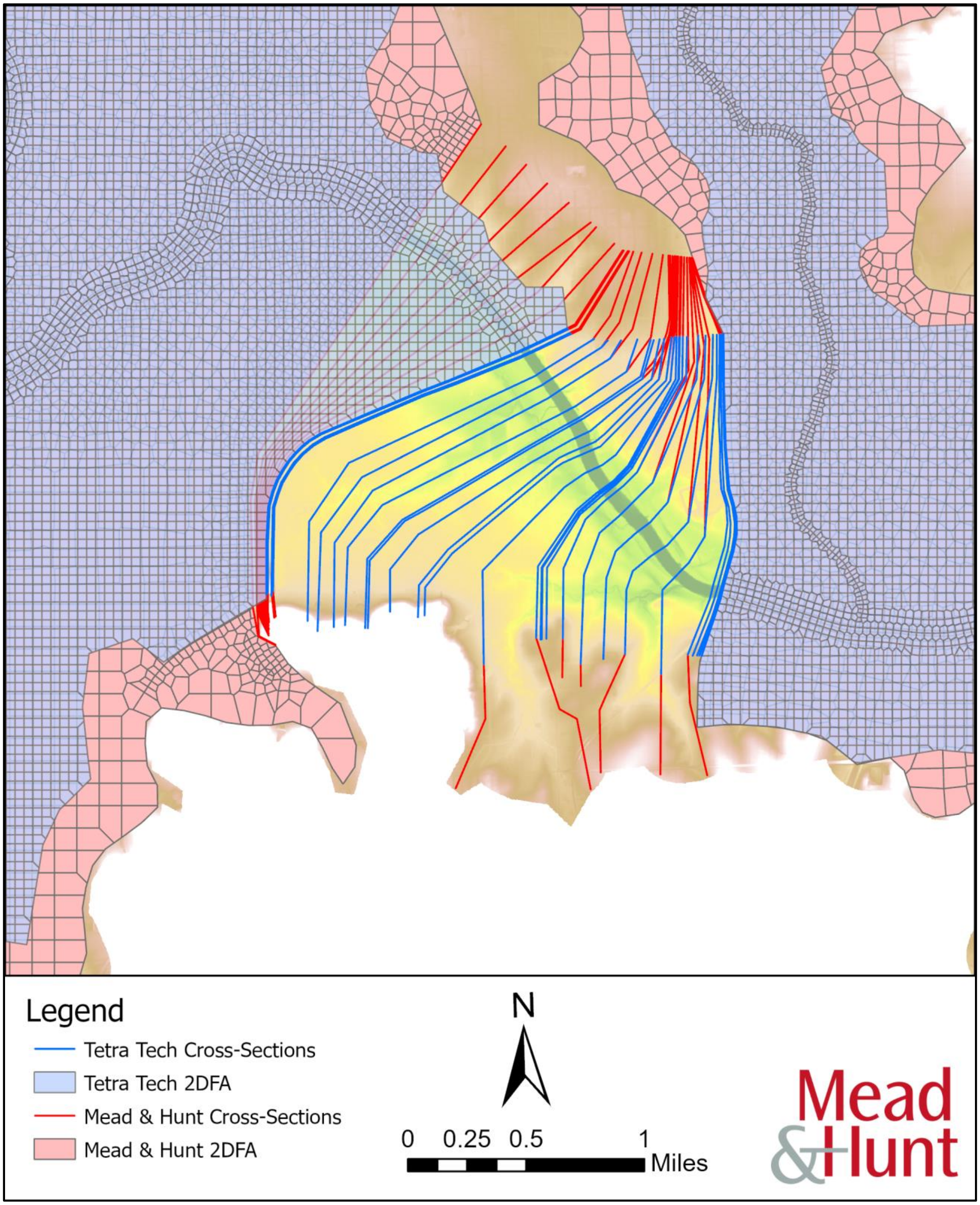


FIGURE 5. COMPARISON OF CROSS-SECTIONS AND MOST UPSTREAM 1D/2D BOUNDARY.

2.7 Bridge Geometries

Tetra Tech (2016) stated bridge geometry in their HEC-RAS model was primarily obtained from a Simons & Associates HEC-2 model (Simons & Associates, Inc., 1996). Mead & Hunt updated roadway bridge geometry using as-built drawings obtained from the Oklahoma Department of Transportation, Missouri Department of Transportation, and local/county road commissions. Railroad bridge geometries were updated using measurements provided by GRDA. An example of the updated bridge geometry at the Old Highway 69 Bridge in Miami, OK (RM 135.941) is displayed in **Figure 6**.

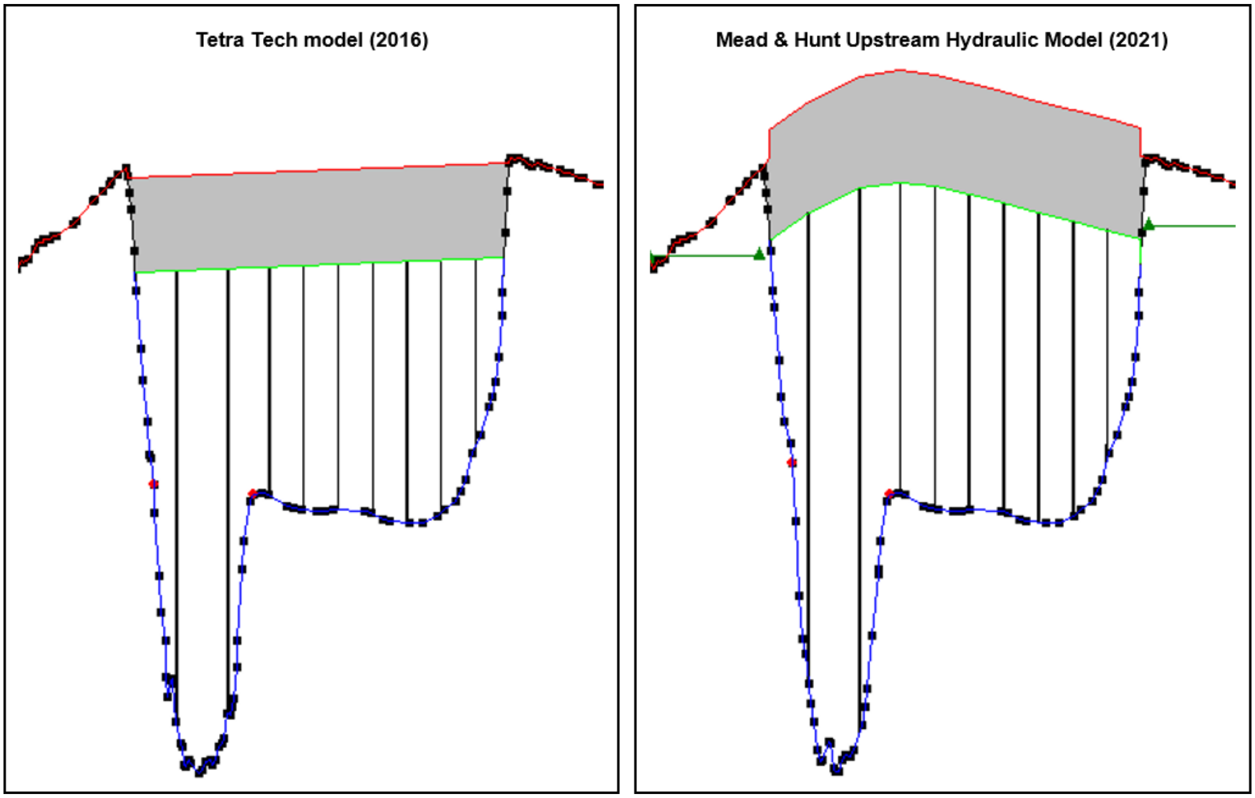


FIGURE 6. EXAMPLE COMPARISON OF BRIDGE GEOMETRY.

2.8 Bank Stations and Ineffective Flow Areas

Mead & Hunt reviewed and adjusted the bank stations and ineffective flow areas in the Upstream Hydraulic Model according to best practices and the HEC-RAS Reference Manual (U.S. Army Corps of Engineers, 2016a). Most adjustments to ineffective flow areas were upstream and downstream of bridges and were due to the updated bridge geometry. An example comparison of ineffective flow areas is displayed in **Figure 7**.

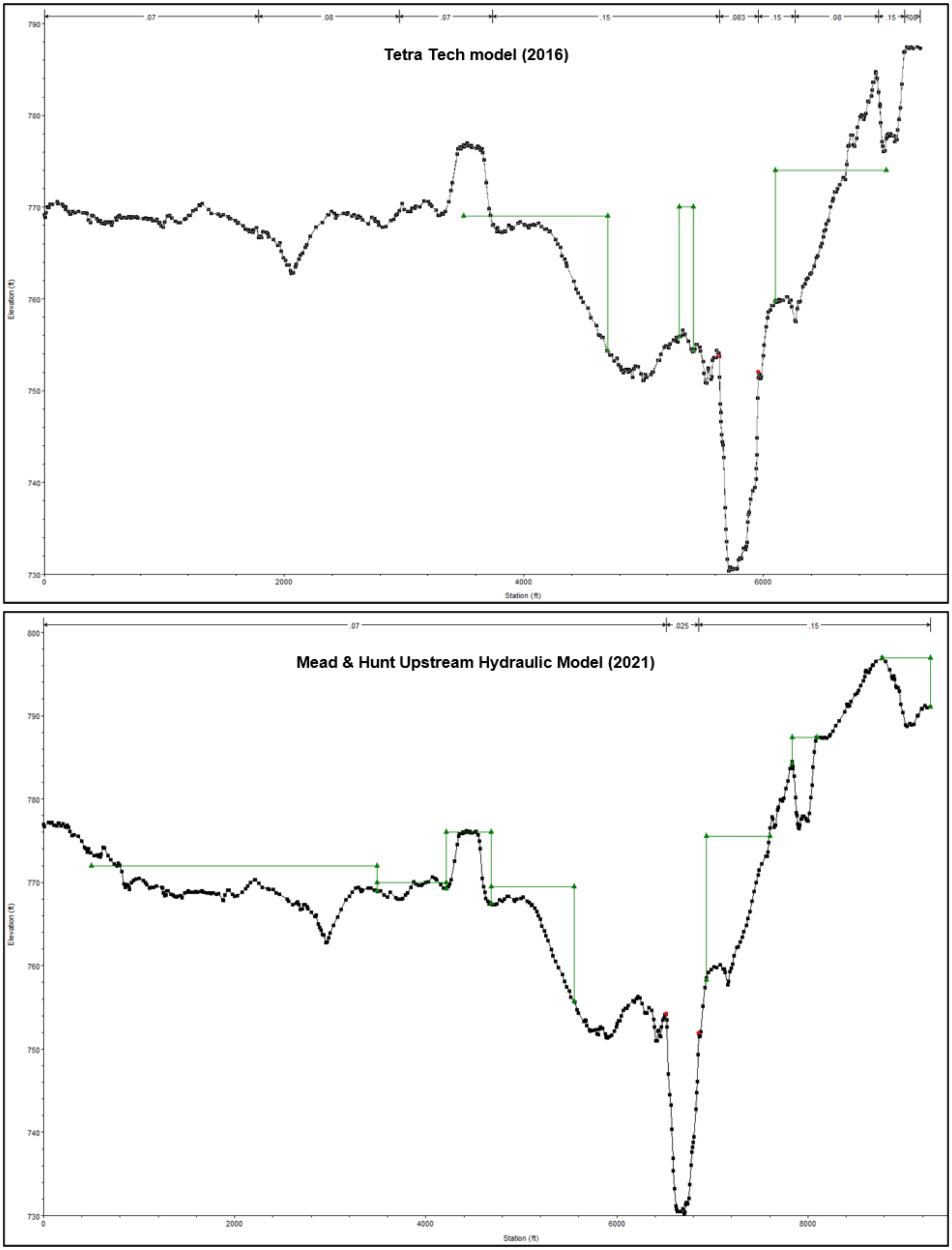


FIGURE 7. EXAMPLE COMPARISON OF MODIFIED INEFFECTIVE FLOW AREAS.

2.9 Spring River

Mead & Hunt added the Spring River to the Upstream Hydraulic Model. The portion of the Spring River modeled by Mead & Hunt extended from the confluence with the Neosho River at the downstream end to RM 21.0 at the upstream end. The river centerline was digitized, and cross-sections were drawn perpendicular to the flow. Cross-sections were extended laterally far enough to contain large flow events (e.g., 100-year event). Bank stations were digitized and then adjusted in HEC-RAS. Ineffective flow areas were defined using guidance from the HEC-RAS Reference Manual (U.S. Army Corps of Engineers, 2016a). **Figure 8** displays the riverbed profile of the Spring River. There are four bridges within the modeled reach:

1. E 57 Road (RM 14.16),
2. Interstate 44 Will Rogers Turnpike (RM 13.50),
3. OK 100 / E 10 Road (RM 8.01), and
4. US Highway 60 (RM 0.57).

There is one stream gage within the reach: Spring River near Quapaw, OK (USGS Gage No. 07188000). The gage is at E 57 Road (RM 14.16). Preliminary simulations indicated it takes 2.5 hours for a flood wave to travel from RM 21.0 (upstream end of the Spring River reach) to the USGS gage. Therefore, a negative 2.5-hour offset was applied to the USGS flow hydrographs, which were used as inflows at the upstream end of the Spring River.

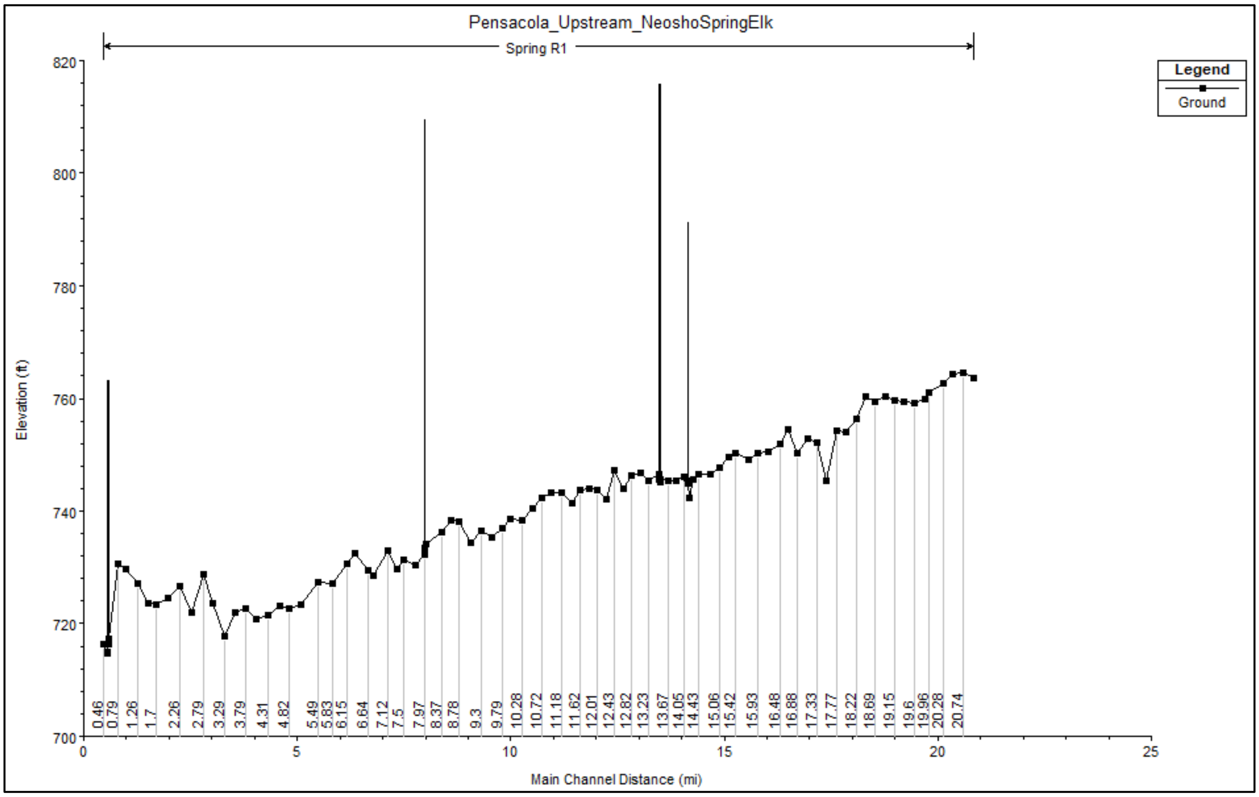


FIGURE 8. RIVERBED PROFILE OF THE SPRING RIVER.

2.10 Elk River

Mead & Hunt added the Elk River to the Upstream Hydraulic Model. The portion of the Elk River modeled by Mead & Hunt extended from the confluence with Grand Lake at the downstream end to RM 19.59 at the upstream end. The river centerline, cross-sections, bank stations, and ineffective flow areas were defined with the same methodology used for the Spring River. **Figure 9** displays the riverbed profile of the Elk River. There are two bridges within the modeled reach:

1. Highway 10 (RM 4.67) and
2. Highway 43 (RM 14.22).

There is one stream gage within the reach: Elk River near Tiff City, MO (USGS Gage No. 07189000). The gage is at Highway 43 (RM 14.22). Preliminary simulations indicated that it takes 2 hours for a flood wave to travel from RM 19.59 (upstream end of the Elk River reach) to the USGS gage. Therefore, a negative 2.0-hour offset was applied to the USGS flow hydrographs, which were used as inflows at the upstream end of the Elk River.

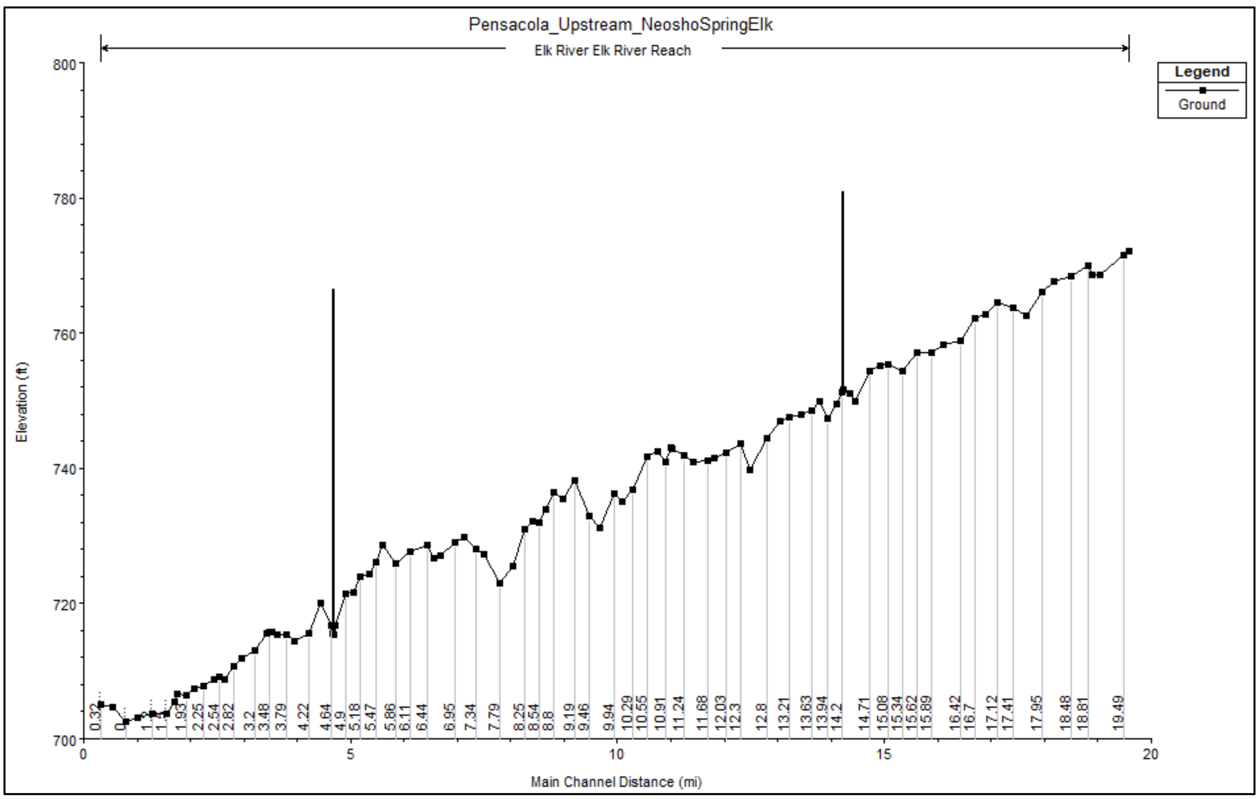


FIGURE 9. RIVERBED PROFILE OF THE ELK RIVER.

2.11 Updated Bathymetry

In response to the FERC's SPD, GRDA enlisted USGS to perform a bathymetric survey of Grand Lake (Hunter, Trevisan, Villa, & Smith, 2020). Mead & Hunt integrated the Grand Lake bathymetry with a combined Digital Elevation Model (DEM) of the study area. The DEM was created with the following data, in descending order of priority:

1. USGS 2020 bathymetry, representing Grand Lake (Hunter, Trevisan, Villa, & Smith, 2020).
2. USGS 2017 bathymetry, representing the Neosho River, Spring River, and Elk River (Smith, Hunter, & Ashworth, 2017).
3. Federal Emergency Management Agency (FEMA) 2016 bathymetry from cross-section data, representing Tar Creek (Federal Emergency Management Agency, 2019).
4. Dewberry 2011 Light Detection and Ranging (LiDAR) overbank area (Dewberry, 2011).
5. USGS National Elevation Dataset (NED) 1/3 arc-second elevation layer, representing the overbank area in areas where no LiDAR data were available (U.S. Geological Survey, 2017).

Figure 10 displays bathymetric and topographic data sources. USGS's 2020 report compared the capacity of Grand Lake, based on 2020 bathymetry, to previous capacity curves. **Figure 11** displays the capacity curves presented in USGS's report (Hunter, Trevisan, Villa, & Smith, 2020).

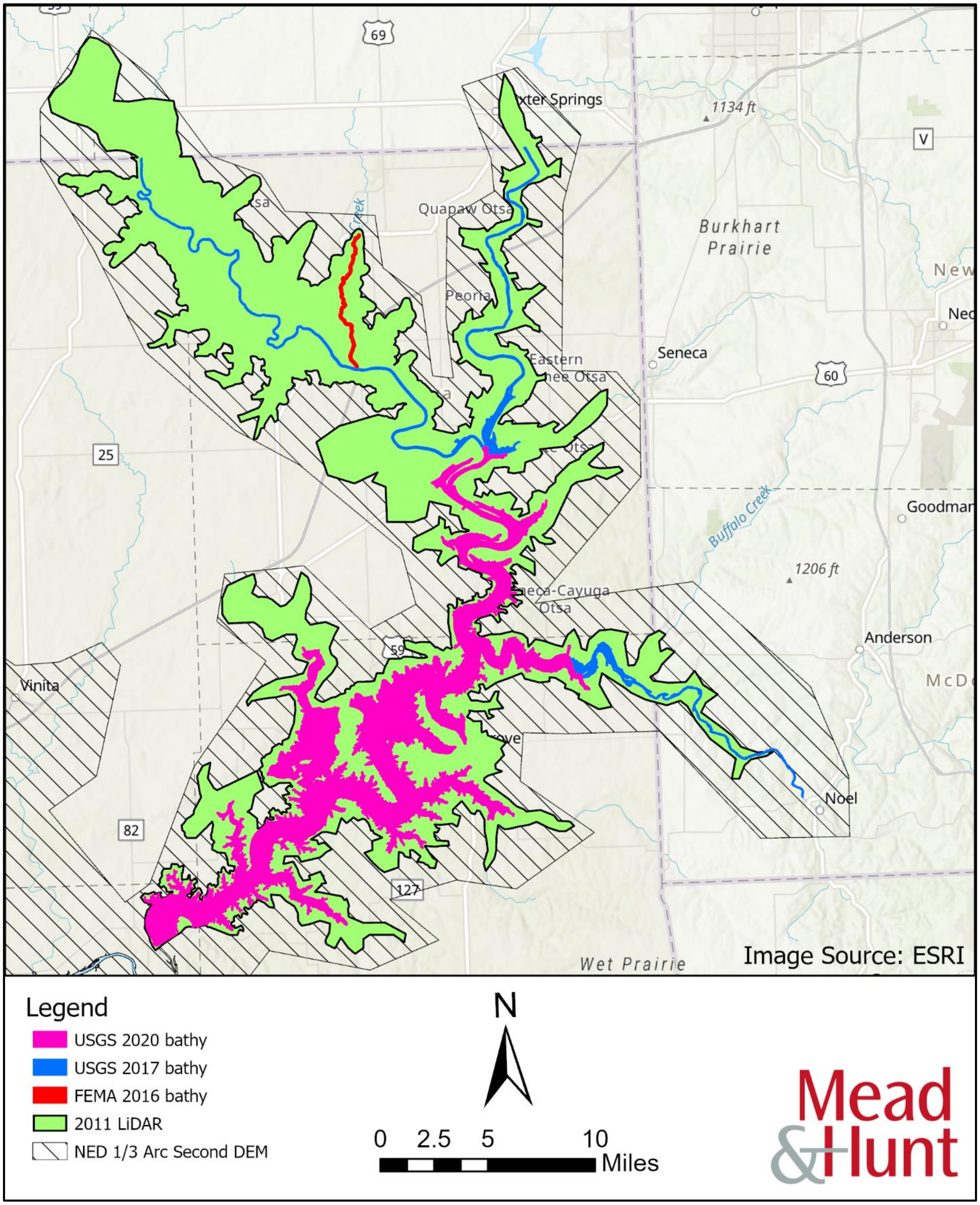


FIGURE 10. BATHYMETRIC AND TOPOGRAPHIC DATA SOURCES.

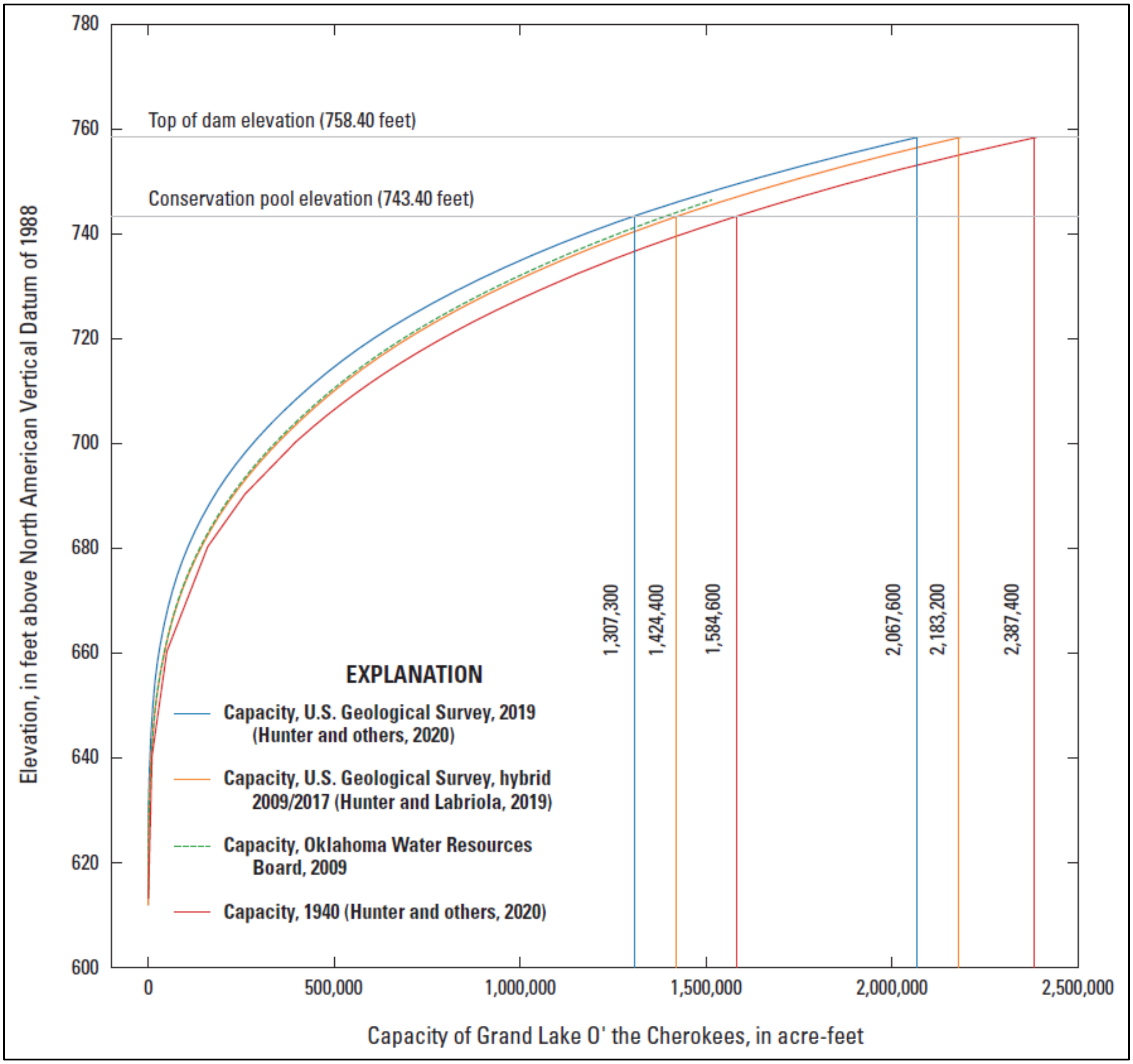


FIGURE 11. GRAND LAKE CAPACITY CURVES.
SOURCE: (HUNTER, TREVISAN, VILLA, & SMITH, 2020).

2.12 Computational Parameters

Tetra Tech's simulations all used the Diffusion Wave equation set. The HEC-RAS 2D Modeling User's Manual states the Diffusion Wave equations can be used while developing the model, but the Full Momentum equations should always be tested:

> *Once the model is in good working order, then make a second HEC-RAS Plan and switch the computational method to the Full Momentum equation option… Run the second plan and compare the two answers throughout the system. If there are significant differences between the two runs, the user should assume the Full Momentum (Saint Venant equations) answer is more accurate, and proceed with that equation set for model calibration and other event simulations (U.S. Army Corps of Engineers, 2016b).*

Mead & Hunt ran preliminary simulations of the Upstream Hydraulic Model with both Diffusion Wave and Full Momentum equation sets. Results from one simulation are displayed in **Figure 12**. The displayed reach (RM 131.0 to RM 134.5) is approximately the same as the extent of the Miami Upper 2DFA. Based on the test results, Mead & Hunt used Full Momentum for the two most upstream 2DFAs: Miami Upper and Miami Lower (see again **Figure 12**).

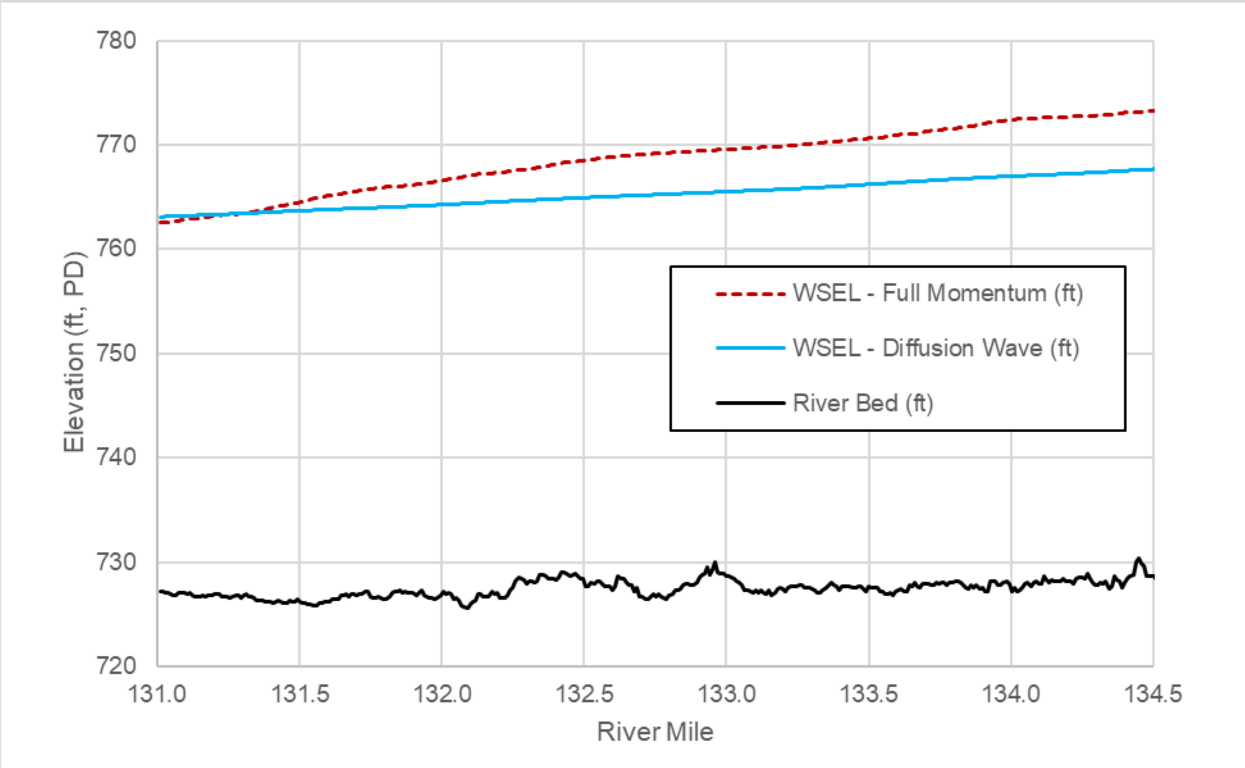


FIGURE 12. SIMULATION RESULTS FROM PRELIMINARY COMPARISON OF DIFFUSION WAVE TO FULL MOMENTUM EQUATION SETS.

Test results showed very little difference in water surface elevation (WSEL) in the Grand Lake 2DFA. Therefore, Mead & Hunt used the Diffusion Wave equation set for the Grand Lake 2DFA.

3. Model Calibration

The Upstream Hydraulic Model was calibrated using several historical inflow events that represented a range of flows. Stream gage data were used for model boundary conditions and to compare measured WSEL to simulated values. High water marks and loggers installed by the project team were also used to compare measured and simulated WSEL.

3.1 Stream Gage Data

Data from the following stream gages were used for calibration:

1. Neosho River near Commerce, OK (USGS Gage No. 07185000)
2. Neosho River at Miami, OK (USGS Gage No. 07185080)
3. Tar Creek at 22nd Street Bridge at Miami, OK (USGS Gage No. 07185095)
4. Spring River near Quapaw, OK (USGS Gage No. 07188000)
5. Elk River near Tiff City, MO (USGS Gage No. 07189000)
6. Lake O' the Cherokees at Langley, OK (USGS Gage No. 07190000)

Details regarding the individual stream gages are discussed below.

3.1.1 Neosho River near Commerce, OK

The Neosho River near Commerce, OK (USGS Gage No. 07185000) stream gage is at the Stepps Ford Bridge, approximately 6.7 miles downstream of the upper boundary of the model. Discharge data are available in hourly increments from April 1990 onward and stage data are available in hourly increments from October 2007 onward. The gage datum is 748.97 feet above NGVD29 (U.S. Geological Survey, 2021a). Stage data at the gage were used in calibration.

Flow data were used as an upstream boundary condition for the Neosho River. Tetra Tech determined that it takes 4 hours for a flood wave to travel from the upstream end of the model (RM 152.2) to the Commerce gage (Tetra Tech, 2015). Mead & Hunt's preliminary simulations confirmed the 4-hour travel time. Therefore, Mead & Hunt applied a negative 4.0 hour offset to the USGS flow hydrographs, which were used as inflows at the upstream end of the Neosho River 2DFA.

3.1.2 Neosho River at Miami, OK

The Neosho River at Miami, OK (USGS Gage No. 07185080) stream gage is at the Highway 125 Bridge (RM 135.46) in the City of Miami. Stage data are available in hourly increments from October 2007 onward. Daily minimum, maximum, and mean stage data are available from October 1994 onward (U.S. Geological Survey, 2021b). Stage data at the gage were used in calibration. Regarding the gage datum, Tetra Tech concluded that:

> *Although the NWIS website indicates that the datum for the Miami gage is referenced to NGVD29, field surveys to support this and previous Tetra Tech studies indicate that the datum is actually reported in the GRDA Pensacola Datum (PD). The reported values were, therefore, converted to NGVD29 for use in this analysis by adding 1.07 feet so that they are consistent with the Commerce data and the mapping and other data used for the modeling.*

Mead & Hunt analyzed the gage data and came to the same conclusion. Note that sometime after Mead & Hunt accessed the National Water Information System (NWIS) website in support of this analysis, USGS modified the published gage datum. The Miami gage datum is now listed as 751.00 feet above NAVD88, which is equal to 750.67 feet above NGVD29.

3.1.3 Tar Creek at 22nd Street Bridge at Miami, OK

The Tar Creek at 22nd Street Bridge at Miami, OK (USGS Gage No. 07185095) stream gage has stage data available in hourly increments from October 2007 onward and has discharge data available in hourly increments from October 1989 onward. The gage datum is 762.23 feet above NGVD29 (U.S. Geological Survey, 2021c).

Flow data were used as an upstream boundary condition for Tar Creek. No time offset was necessary because the gage is located at the upstream end of the model.

3.1.4 Spring River near Quapaw, OK

The Spring River near Quapaw, OK (USGS Gage No. 07188000) stream gage is at E 57 Road (RM 14.16). Stage data are available in hourly increments from October 2007 onward and discharge data are available in hourly increments from October 1989 onward. The gage datum is 746.25 feet above NGVD29 (U.S. Geological Survey, 2021d).

Stage data at the gage were used in calibration. Flow data were used as an upstream boundary condition for the Spring River. As discussed in Section 2.9, a negative 2.5-hour offset was applied to flow hydrographs to account for flood wave travel time.

3.1.5 Elk River near Tiff City, MO

The Elk River near Tiff City, MO (USGS Gage No. 07189000) stream gage is at Highway 43 (RM 14.22). Stage data are available in hourly increments from October 2007 onward and discharge data are available in hourly increments from May 1990 onward. The gage datum is 750.61 feet above NGVD29 (U.S. Geological Survey, 2021e).

Stage data at the gage were used in calibration. Flow data were used as an upstream boundary condition for the Elk River. As discussed in Section 2.10, a negative 2.0-hour offset was applied to flow hydrographs to account for flood wave travel time.

3.1.6 Lake O’ the Cherokees at Langley, OK

The Lake O’ the Cherokees at Langley, OK (USGS Gage No. 07190000) gage measures Grand Lake stage levels. Hourly stage data are available from October 2010 onward (U.S. Geological Survey, 2021f). Stage data prior to October 2010 were provided by GRDA. Stage data were used as the downstream boundary condition for the model.

3.2 Historical Events

The following historical inflow events were used for calibration of the Upstream Hydraulic Model.

1. July 2007
2. October 2009
3. December 2015
4. January 2017
5. April 2017
6. May 2019

Details regarding the individual inflow events are discussed below. For all historical events used in calibration of the Upstream Hydraulic Model, USGS gage data were used for the upstream inflow boundaries and WSELs at Pensacola Dam were used for the downstream stage boundary. **Table 1** lists a summary of the historical event boundary conditions.

TABLE 1. SUMMARY OF HISTORICAL EVENT BOUNDARY CONDITIONS

Historical Event	Peak Inflow (cfs)				Pensacola Peak Stage (feet, PD)
	Neosho River	Tar Creek	Spring River	Elk River	
July 2007	141,000	2,490	105,000	4,830	754.53
October 2009	46,100	4,630	66,200	39,300	749.59
December 2015	45,400	4,790	151,000	107,000	754.93
January 2017	10,200	678	15,900	1,140	742.82
April 2017	58,200	3,550	114,000	107,000	754.59
May 2019	91,400	6,410	109,000	66,500	755.08

3.2.1 July 2007

For the July 2007 event, hourly flow data were available for the Neosho River at Commerce gage, Tar Creek at Miami gage, Spring River at Quapaw gage, and Elk River near Tiff City gage. Daily minimum, mean, and maximum WSELs were available for the Neosho River at Miami gage. Grand Lake stage data were provided by GRDA. High water marks, compiled by Tetra Tech (2016), were available for this inflow event. Of the selected calibration events, the July 2007 event had the highest recorded flow on the Neosho River at the Commerce gage.

3.2.2 October 2009

For the October 2009 event, hourly flow and stage data were available for the Neosho River at Commerce gage, Tar Creek at Miami gage, Spring River at Quapaw gage, and Elk River near Tiff City gage. Hourly stage data were available for the Neosho River at Miami gage and Lake O' the Cherokees at Langley gage. High water marks, compiled by Tetra Tech (2016), were available for this inflow event.

3.2.3 December 2015

For the December 2015 event, hourly flow and stage data were available for the Neosho River at Commerce gage, Tar Creek at Miami gage, Spring River at Quapaw gage, and Elk River near Tiff City gage. Hourly stage data were available for the Neosho River at Miami gage and Lake O' the Cherokees at Langley gage. High water marks, compiled by Tetra Tech (2016), were available for this inflow event. Of the selected calibration events, the December 2015 event had the highest recorded flow on the Spring River at Quapaw gage. The peak flow at the Elk River near Tiff City gage was 107,000 cfs, which is equal to the peak flow that occurred at this gage during the April 2017 event. This flow is the highest recorded flow on the Elk River for the selected calibration events.

3.2.4 January 2017

For the January 2017 event, hourly flow and stage data were available for the Neosho River at Commerce gage, Tar Creek at Miami gage, Spring River at Quapaw gage, and Elk River near Tiff City gage. Hourly stage data were available for the Neosho River at Miami gage and Lake O' the Cherokees at Langley gage. Hourly WSEL logger data throughout the study area were collected by the project team for this event. Of the selected calibration events, the January 2017 event had the lowest recorded flow on all gages.

3.2.5 April 2017

For the April 2017 event, hourly flow and stage data were available for the Neosho River at Commerce gage, Tar Creek at Miami gage, Spring River at Quapaw gage, and Elk River near Tiff City gage. Hourly stage data were available for the Neosho River at Miami gage and Lake O' the Cherokees at Langley gage. Hourly WSEL logger data throughout the study area were collected by the project team for this event. The peak flow at the Elk River near Tiff City gage was 107,000 cfs, which is equal to the peak flow that occurred at this gage during the December 2015 event. This flow is the highest recorded flow on the Elk River for the selected calibration events.

3.2.6 May 2019

For the May 2019 event, hourly flow and stage data were available for the Neosho River at Commerce gage, Tar Creek at Miami gage, Spring River at Quapaw gage, and Elk River near Tiff City gage. Hourly stage data were available for the Neosho River at Miami gage and Lake O' the Cherokees at Langley gage. Hourly WSEL logger data throughout the study area were collected by the project team for this event. Of the selected calibration events, the May 2019 event had the highest recorded flow at the Tar Creek at Miami gage.

3.3 Methodology

The goal of model calibration was to create a single geometry file that could be used for a variety of synthetic/hypothetical simulations. Simulated WSEL values were compared to stream gage elevations within the study area, high water marks, and WSEL logger data collected by the project team.

Tetra Tech previously digitized land cover along the Neosho River from the confluence with the Spring River to the upstream end of the model (Tetra Tech, 2015). Mead & Hunt expanded the coverage, digitizing land cover in the following areas:

1. Neosho River, downstream of the confluence with the Spring River
2. Grand Lake
3. Elk River
4. Spring River

Tetra Tech assigned Manning's n-values to land cover categories (Tetra Tech, 2015). Tetra Tech's work relied on commonly used guidance (Arcement & Schneider, 1989) and area-specific investigation (Mussetter, 1998). Mead & Hunt continued to use the same Manning's n-values in overbank areas.

Mead & Hunt digitized two new categories of land cover: field crops and dense urban areas. Manning's n-values were assigned to these categories based on other n-values and engineering judgement. Horizontal variation in n-values was applied to the cross-sections and spatially varied n-values were applied to the 2DFAs. **Table 2** lists the overbank Manning's n-values.

TABLE 2. OVERBANK MANNING'S N-VALUES.

Land Cover	n-value
Field crops	0.040
Pasture	0.080
Urban	0.070
Urban, dense	0.090
Water	0.040
Woody vegetation	0.100
Woody vegetation, dense	0.150

Manning's n-values in the main channel were iteratively adjusted until simulated WSELs reasonably agreed with measured data. **Table 3** lists the in-channel Manning's n-values that resulted from model calibration.

TABLE 3. CHANNEL MANNING'S N-VALUES.

Reach	n-value
Grand Lake (reservoir, up to RM 121.29)	0.020
Neosho River (RM 121.51 up to128.81)	0.035
Neosho River (RM 129.07 up to RM 135.44)	0.037
Neosho River (RM 135.47 up to RM 152.2)	0.025
Elk River (full reach)	0.042
Spring River (full reach)	0.038

After the base n-values were determined, flow roughness factors were iteratively applied to further decrease the differences between simulated and measured WSELs. **Table 4** lists the flow roughness factors that resulted from model calibration.

TABLE 4. FLOW ROUGHNESS FACTORS.

Neosho River		Spring River		Elk River	
Flow (cfs)	Roughness Factor	Flow (cfs)	Roughness Factor	Flow (cfs)	Roughness Factor
0	0.60	0	0.79	0	1.15
20,000	0.60	20,000	0.79	40,000	1.15
40,000	0.70	40,000	0.94	60,000	0.80
45,000	0.70	60,000	0.94	80,000	0.80
50,000	1.00	80,000	0.94	100,000	1.00
55,000	1.25	100,000	1.00	120,000	1.00
60,000	1.25	120,000	1.00	140,000	1.00
80,000	1.25	140,000	1.10	160,000	1.00
90,000	1.30	160,000	1.10	350,000	1.00
110,000	1.30	180,000	1.00		
140,000	1.30	350,000	1.00		
150,000	1.30				
160,000	1.00				
350,000	1.00				

3.4 Results

The results from the model calibration are discussed in the following paragraphs. **Figure 13** displays the over/underprediction of peak simulated WSEL at USGS gages. The average difference between simulated WSELs and measured USGS gage WSELs is -0.1 feet; the model is slightly underpredicting the WSEL at USGS gages.

Upstream Hydraulic Model results were also compared to the high water marks compiled by Tetra Tech (2016). **Figure 14** compares model results to the July 2007 high water marks, **Figure 15** compares results to the October 2009 marks, and **Figure 16** compares results to the December 2015 marks. The average underprediction of simulated WSEL is 0.5 feet for the July 2007 event, the average overprediction is 0.4 feet for the October 2009 event, and the average underprediction is 0.1 feet for the December 2015 event.

The project team installed WSEL loggers throughout the study area. Loggers were in place during three calibration events: January 2017, April 2017, and May 2019. **Figure 17** displays the logger locations. Not all logger locations have data for a given event; some loggers were missing when the project team visited to perform maintenance and download data. Loggers 3, 4, 11, and 12 were missing for the May 2019 event. Logger 9 was missing for all three events. Data from loggers 7, 8, 13, 14, and 15 were not included in calibration because the logger WSEL was influenced by incoming, un-gaged streams not modeled in the Upstream Hydraulic Model. The loggers were placed in support of the Sedimentation Study, early in the pre-study period before model parameters were fully defined. **Figure 18** displays the over/underprediction of peak simulated WSEL at the loggers used for model calibration for the three events. The average difference between simulated WSELs and measured WSELs is -0.6 feet; the model is underpredicting the WSEL at the loggers.

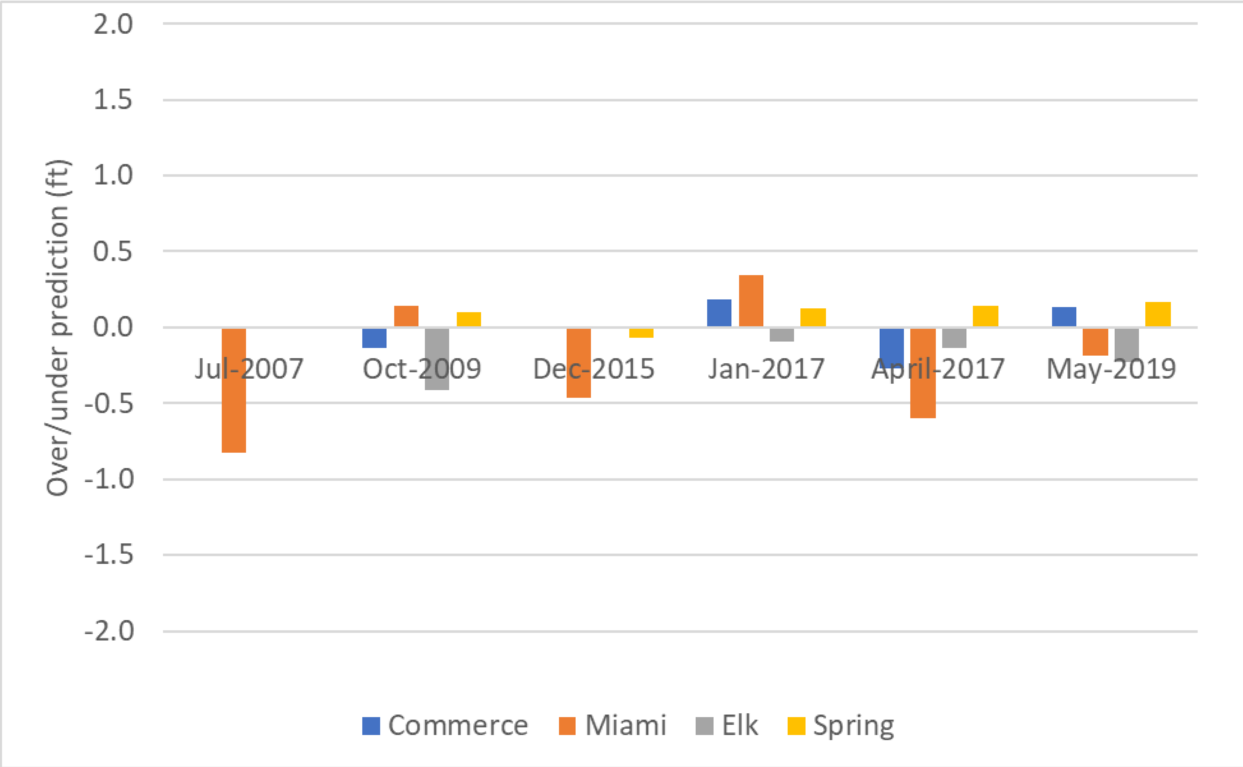


FIGURE 13. OVER/UNDERPREDICTION OF SIMULATED WSEL AT USGS GAGES.

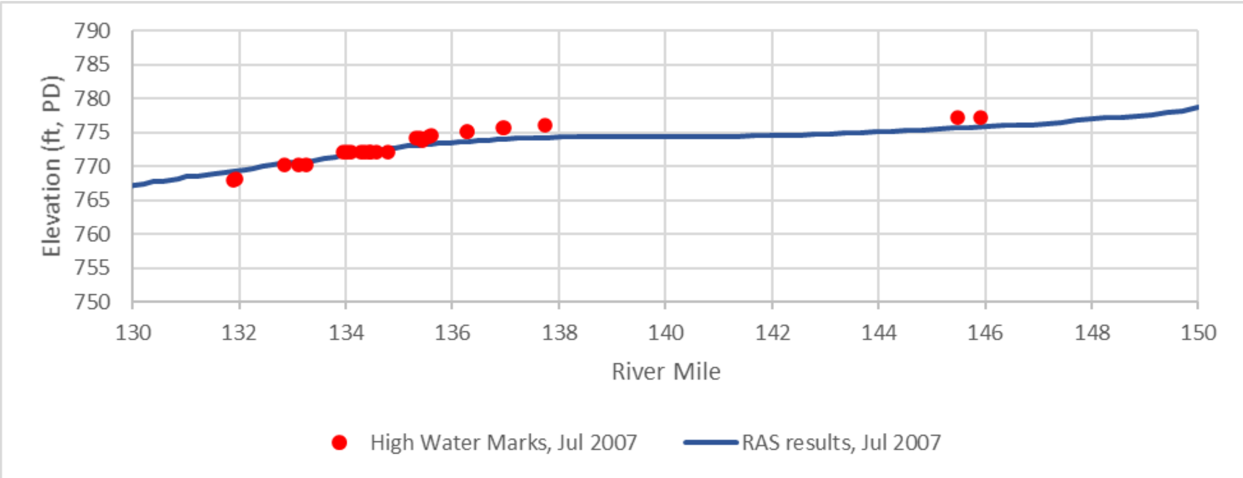


FIGURE 14. COMPARISON OF UPSTREAM HYDRAULIC MODEL RESULTS TO JULY 2007 HIGH WATER MARKS.

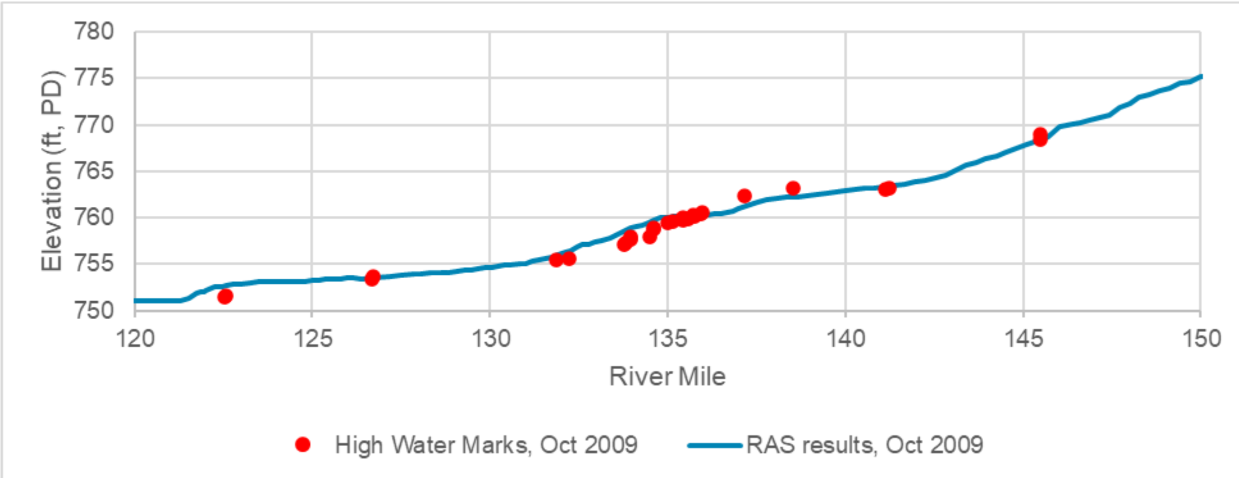


FIGURE 15. COMPARISON OF UPSTREAM HYDRAULIC MODEL RESULTS TO OCTOBER 2009 HIGH WATER MARKS.

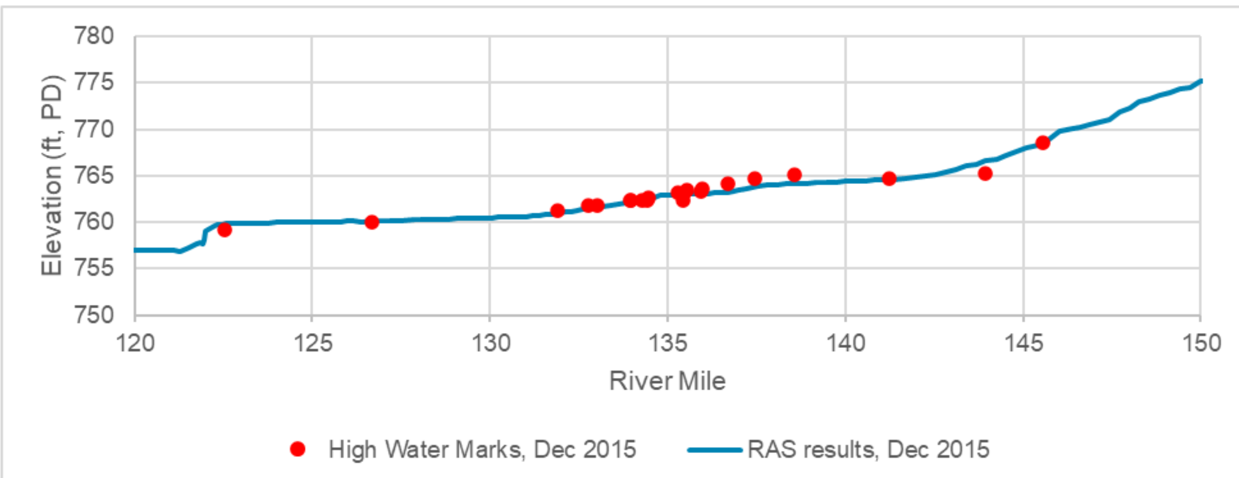


FIGURE 16. COMPARISON OF UPSTREAM HYDRAULIC MODEL RESULTS TO DECEMBER 2015 HIGH WATER MARKS.

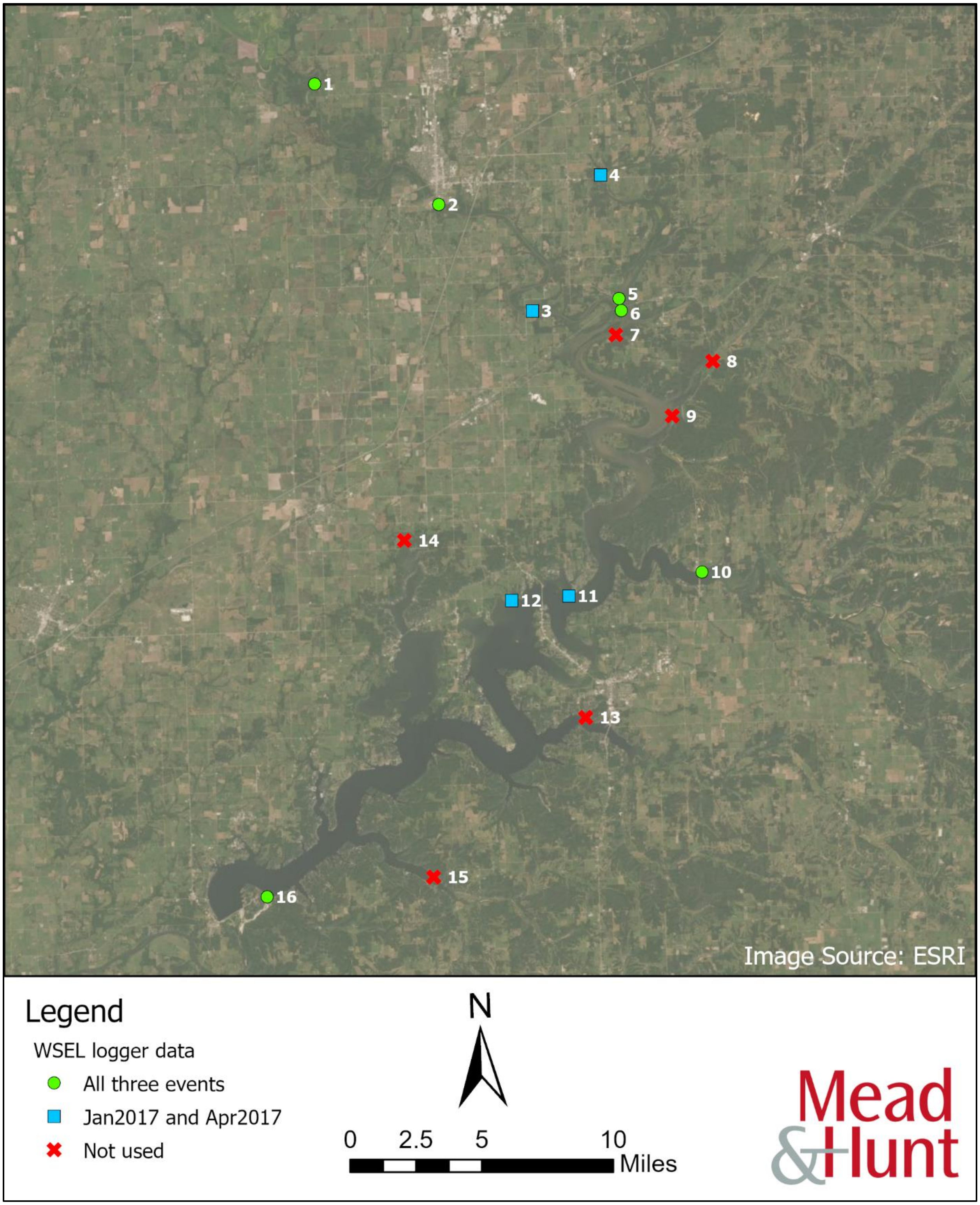


FIGURE 17. LOCATIONS OF WSEL LOGGERS INSTALLED BY PROJECT TEAM.

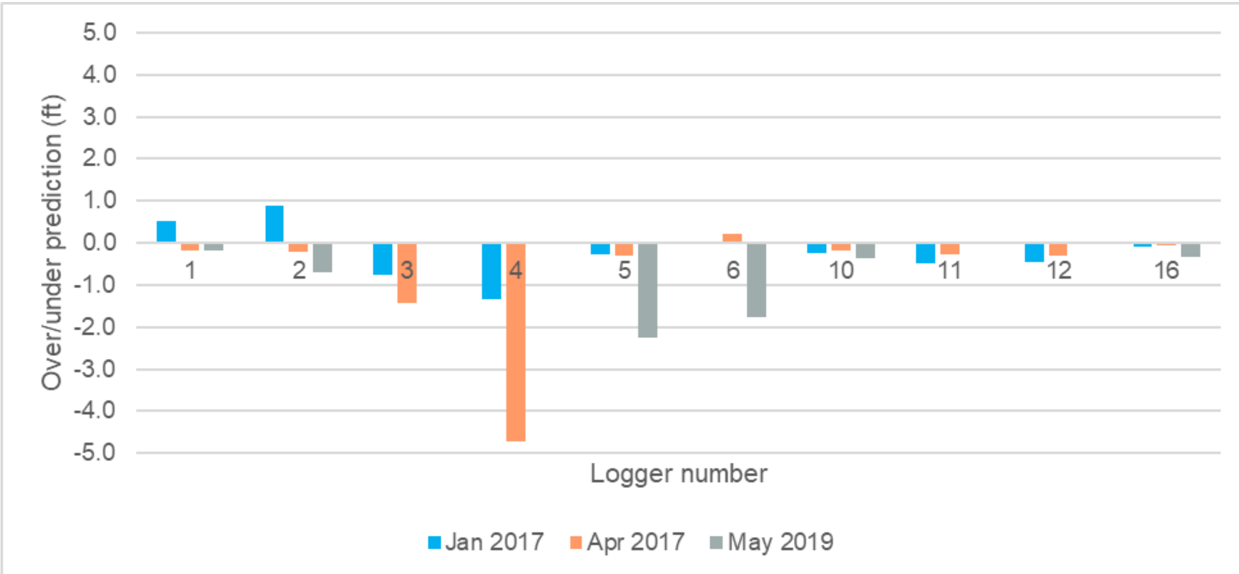


FIGURE 18. OVER/UNDERPREDICTION OF SIMULATED WSEL AT LOGGERS INSTALLED BY PROJECT TEAM.

4. Flood Frequency Analysis

Mead & Hunt performed a flood frequency analysis for the study area. USACE has developed a Period of Record (POR) RiverWare model that includes Pensacola Dam. Mead & Hunt extracted the total inflow to Grand Lake from 1940 (dam construction date) to 2017 (latest available data at time of data delivery from USACE) from the RiverWare model.

Annual peak inflows to Grand Lake were extracted using HEC's Statistical Software Package (SSP) version 2.2. The full inflow time series was imported into HEC-SSP and the annual peaks were automatically filtered. Water years were set to start at October 1st to align with USGS water years (U.S. Geological Survey, 2016). One manual adjustment was necessary for an event that occurred in September and October 1986. HEC-SSP automatically selected September 30, 1986 for the peak of water year 1986 and October 2, 1986 for the peak of water year 1987, as displayed in **Figure 19**. The September 30th peak is not hydrologically independent of the October 2nd peak. Mead & Hunt manually selected the next highest peak for water year 1986: November 19, 1985. Manually correct flood peaks were re-imported and a Graphical Frequency Analysis of Peak Inflows was performed in HEC-SSP. Weibull plotting positions were used and a best-fit was digitized through the peak flows. Annual recurrence interval flows were rounded to the nearest thousand cubic feet per second (cfs).

Tabular results of flood frequency analysis are presented in **Table 5** and graphical results are presented in **Figure 20**. **Figure 20** also displays the exceedance curve from the Real Estate Adequacy Study (U.S. Army Corps of Engineers, 1998), which was developed using similar methodology as Mead & Hunt's analysis. At lower recurrence intervals (2-year through 10-year), the new analysis resulted in higher flows. At higher recurrence intervals (20-year through 500-year), the new analysis resulted in lower flows. Differences between the Mead & Hunt analysis and the Real Estate Adequacy Study Analysis are primarily due to the additional two decades of data used in the new analysis.

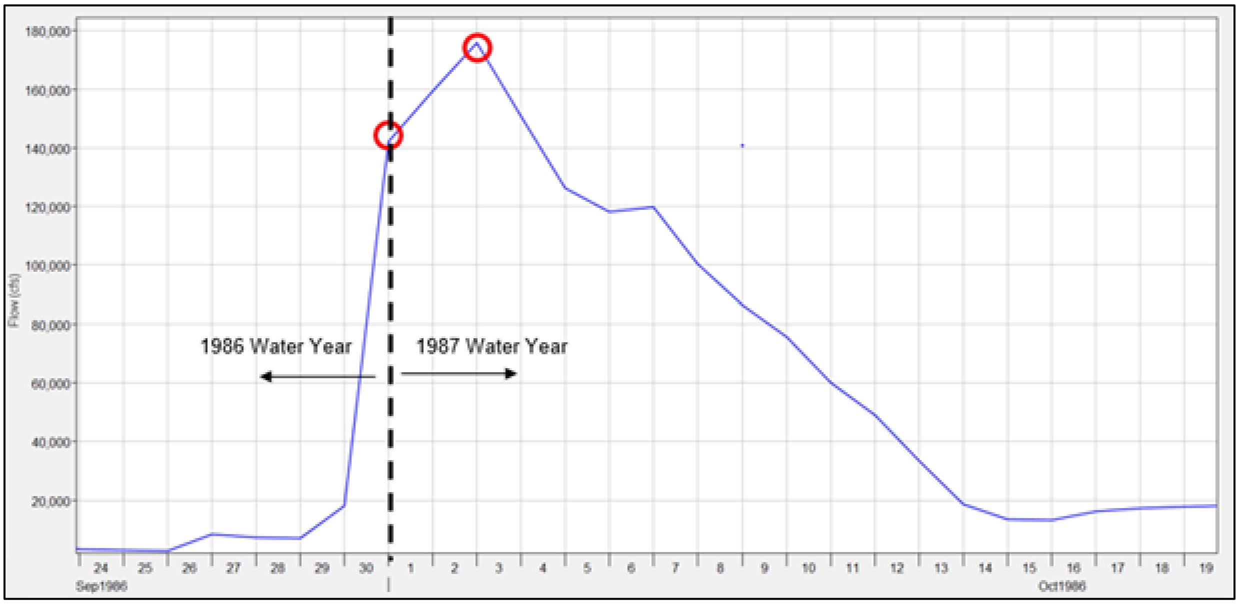


FIGURE 19. 1986 AND 1987 WATER YEARS IN HEC-SSP.

TABLE 5. FLOOD FREQUENCY ANALYSIS TABULAR RESULTS.

Annual Recurrence Interval	Flow (cfs)
2	90,000
5	152,000
10	192,000
20	225,000
50	266,000
100	299,000
200	330,000
500	375,000

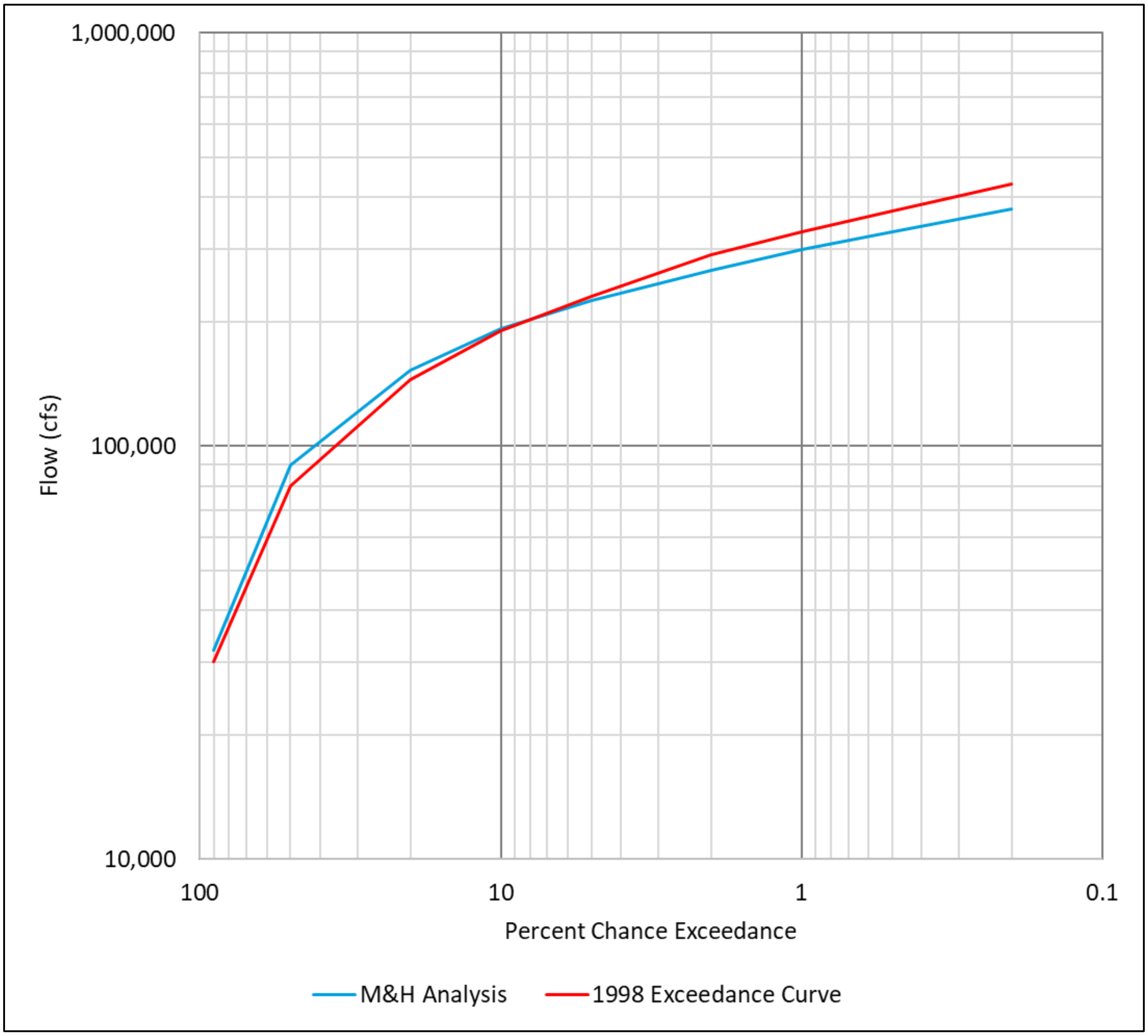


FIGURE 20. FLOOD FREQUENCY ANALYSIS GRAPHICAL RESULTS.

5. Inflow Event Analysis

The flood frequency analysis estimated that the 100-year event flow at Pensacola Dam is approximately 300,000 cfs. The July 2007 event is the largest event of recent record on the Neosho River, with a peak flow of 141,000 cfs at the Commerce gage. Simulation results estimated a total peak inflow of approximately 130,000 to Grand Lake, which includes inflow from Tar Creek, the Elk River, and the Spring River. It also includes attenuation of the flood peaks as they travel to Pensacola Dam. When flood frequency at Pensacola Dam is considered, the July 2007 event is a 4-year return period event.

Three other recent events resulted in a large inflow to Grand Lake: September 1993, December 2015, and May 2019. Simulation results estimated a total peak inflow to Grand Lake of 250,000 cfs for the September 1993 event; 210,000 cfs for the December 2015 event; and 190,000 cfs for the May 2019 event. The peak inflow for the September 1993, July 2007, December 2015, and May 2019 events are listed in **Table 6**, along with the estimated return period.

The FERC's SPD stated that "If the flood frequency analysis shows that the selected historical inflow events do not exceed a 100-year recurrence interval, inflow events up to and including the 100-year recurrence interval would be evaluated." Therefore, Mead & Hunt iteratively scaled the events listed in **Table 6** until the total peak inflow to Grand Lake was approximately 300,000 cfs. The scaling factors are listed in **Table 6**. The scaled events were simulated in the Upstream Hydraulic Model.

TABLE 6. PEAK INFLOWS TO GRAND LAKE FOR FOUR RECENT EVENTS.

Event	Peak Inflow[1] to Grand Lake (cfs)	Estimated Return Period	Scaling Factor to Estimate 100-year Return Period
September 1993	250,000	44 years	1.17
July 2007	130,000	4 years	2.15
December 2015	210,000	15 years	1.50
May 2019	190,000	9 years	1.70

1 Peak inflow rounded to the nearest 10,000 cfs

6. Definition of "Material Difference"

The RSP states that:

> *The H&H study area will encompass the channel and overbank areas of the Grand/Neosho River watershed that have a material difference in water surface elevation due to Project operation during the measured inflow events of the H&H Study. A material difference in water surface elevation due to Project operations will be based on professional judgment.*

In the SPD, the FERC recommended GRDA propose a definition of "material difference." On GRDA's behalf, Mead & Hunt reviewed how various government entities quantify difference in WSEL, and the findings are as follows:

1. FEMA requires base flood elevations, which is commonly the 100-year event WSEL, to "match within one-half foot" at the transition between a revised study and the study it is replacing (Office of the Federal Register, 2021).
2. USACE published an engineering manual for the Hydrologic Engineering Requirements for Reservoirs (U.S. Army Corps of Engineers, 2018). The manual dictates the point of intersection between pre-project and post-project WSEL profiles is established where the profiles are within one foot of each other.
3. USGS defines field measurements of discharge as "excellent" if the flow measurement is within 2% of the actual value and as "good" if the measurement is within 5% of the actual value. Mead & Hunt ran all the calibration simulations with the gage inflows increased and decreased by 2%. WSELs between the two sets of simulations were compared at the USGS gages within the study area. There was a difference in WSEL of approximately one-half foot between the simulation results.

Based on Mead & Hunt's review of how government agencies approach differences in WSEL and understanding that material difference represents expected precision when comparing model results, Mead & Hunt recommends material difference in WSEL be quantified as 0.5 feet for out of bank events for the sole purpose of determining areas to be included in the model.

7. Summary

GRDA is currently relicensing the Pensacola Hydroelectric Project and has enlisted Mead & Hunt to support the intent to relicense. Mead & Hunt developed a PSP and RSP that recommended the development of a hydraulic model upstream of Pensacola Dam. The FERC's SPD requires GRDA to provide a model input status report that includes model inputs and calibration, presents the flood frequency analysis, performs an inflow analysis to determine if the historical inflow events selected in the RSP exceed a 100-year recurrence interval, and proposes a definition of material difference in WSEL. This report documents the development of the Upstream Hydraulic Model and findings that will be presented at the FERC-recommended conference call.

8. References

Arcement, G., & Schneider, V. (1989). *Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Floodplains. U.S. Geological Survey Water Supply Paper 2339.*

Dewberry. (2011). *USGS Grand Lake, OK LiDAR Project, Prepared for the U.S. Geological Survey.*

Federal Emergency Management Agency. (2019). *Flood Insurance Study - Ottawa County, Oklahoma and Incorporated Areas (40115CV000B).* Washington.

Hunter, S. L., Trevisan, A. R., Villa, J., & Smith, K. A. (2020). *Bathymetric Map, Surface Area, and Capacity of Grand Lake O' the Cherokees, Northeastern Oklahoma, 2019.* Denver: USGS.

Mead & Hunt. (2016). *Review of Tetra Tech's Hydraulic Modeling for the Pensacola Project.*

Mussetter, R. (1998). *Evaluation of the Roughness Characteristics of the Neosho River in the Vicinity of Miami, Oklahoma.*

Office of the Federal Register. (2021, February 11). 44 C.F.R. § 65.6(a)(2). *Title 44: Emergency Management and Assistance*. Retrieved from https://www.ecfr.gov/.

Simons & Associates, Inc. (1996). *Backwater Analysis of Pensacola Reservoir on the Neosho River, Miami, Oklahoma.*

Smith, S., Hunter, S., & Ashworth, C. (2017). *Bathymetric surveyes of the Neosho River, Spring River, and Elk River, northeastern Oklahoma and southwestern Missouri, 2016-2017.* Denver: USGS.

Tetra Tech. (2015). *Hydraulic Analysis of the Effects of Pensacola Dam on the Neosho River in the Vicinity of Miami, Oklahoma.* Fort Collins.

Tetra Tech. (2016). *Hydraulic Analysis of the Effects of Proposed Rule Curve Change at Pensacola Dam on Neosho River Flooding in the Vicinity of Miami, Oklahoma.* Fort Collins.

U.S. Army Corps of Engineers. (1998). *Grand Lake, Oklahoma Real Estate Adequacy Study.*

U.S. Army Corps of Engineers. (2016a). *HEC-RAS River Analysis System Hydraulic Reference Manual.* Davis: Hydrologic Engineering Center.

U.S. Army Corps of Engineers. (2016b). *HEC-RAS River Analysis System 2D Modeling User's Manual.* Davis: Hydrologic Engineering Center.

U.S. Army Corps of Engineers. (2018). *Engineering Manual No. 1110-2-1420: Hydrologic Engineering Requirements for Reservoirs.* Washington.

U.S. Geological Survey. (2016, February 10). *Explainations for the National Water Conditions*. Retrieved from Water Resources of the United States: https://water.usgs.gov/nwc/explain_data.html.

U.S. Geological Survey. (2017, March 21). *National Geospatial Program.* Retrieved from The National Map Viewer: https://www.usgs.gov/core-science-systems/national-geospatial-program/national-map.

U.S. Geological Survey. (2021a, February 5). *USGS 07185000 Neosho River near Commerce, OK*. Retrieved from National Water Information System: https://waterdata.usgs.gov/nwis/uv?site_no=07185000.

U.S. Geological Survey. (2021b, February 5). *USGS 07185080 Neosho River at Miami, OK*. Retrieved from National Water Information System: https://waterdata.usgs.gov/ok/nwis/uv?site_no=07185080.

U.S. Geological Survey. (2021c, February 5). *USGS 07185095 Tar Creek at 22nd Street Bridge at Miami, OK*. Retrieved from National Water Information System: https://waterdata.usgs.gov/nwis/uv?site_no=07185095.

U.S. Geological Survey. (2021d, February 5). *USGS 07188000 Spring River near Quapaw, OK*. Retrieved from National Water Information System: https://waterdata.usgs.gov/nwis/uv?site_no=07188000.

U.S. Geological Survey. (2021e, February 5). *USGS 07189000 Elk River near Tiff City, Mo*. Retrieved from National Water Information System: https://waterdata.usgs.gov/mo/nwis/uv?site_no=07189000.

U.S. Geological Survey. (2021f, February 5). *USGS 07190000 Lake O' the Cherokees at Langley, OK*. Retrieved from National Water Information System: https://waterdata.usgs.gov/ok/nwis/uv?site_no=07190000.