US Army Corps of Engineers
Omaha District

# YELLOWSTONE RIVER CORRIDOR STUDY
# HYDRAULIC ANALYSIS
# MODELING AND MAPPING REPORT

**FINAL**

**October 2016**

# YELLOWSTONE RIVER CORRIDOR STUDY
# HYDRAULIC ANALYSIS
# MODELING AND MAPPING REPORT

**FINAL**

**October 2016**

**Prepared by**

**U.S. Army Corps of Engineers**
**Omaha District**

**For**

**Yellowstone River Conservation District Council**
**and**
**Technical Advisory Committee**

**YELLOWSTONE RIVER CORRIDOR STUDY**
**HYDRAULIC ANALYSIS**
**MODELING AND MAPPING REPORT**

## TABLE OF CONTENTS


**1. INTRODUCTION ..... 1**

**2. FLOODPLAIN STUDY AREA DESCRIPTION ..... 2**

**3. HYDROLOGIC ANALYSIS ..... 5**

**4. HYDRAULIC ANALYSIS ..... 6**

4.1. MODEL DESCRIPTION ..... 6

4.2. MODEL SETUP ..... 6

*4.2.1. Topographic Survey ..... 6*

*4.2.2. Model Geometry ..... 9*

*4.2.3. Developed Model Geometry ..... 10*

*4.2.3.1. Structures ..... 10*

*4.2.3.2. Low-Flow Channels ..... 13*

*4.2.3.3. Ineffective Flow Areas and Levees ..... 13*

*4.2.3.4. Roughness Value ..... 14*

*4.2.3.5. Other Variables ..... 14*

*4.2.4. Undeveloped Model Geometry ..... 14*

*4.2.5. Model Discharges ..... 16*

*4.2.6. Boundary Conditions ..... 18*

*4.2.7. Model Scenarios ..... 19*

4.3. MODEL CALIBRATION AND SENSITIVITY ..... 19

4.4. MODELING RESULTS ..... 20

4.5. MAPPING ..... 21

4.6. MAPPING RESULTS ..... 26

4.7. DIFFICULTIES AND ASSUMPTIONS ..... 27

**5. REFERENCES ..... 29**

APPENDIX A. HEC-RAS MODELING RESULTS - DEVELOPED A (METRIC)
APPENDIX B. HEC-RAS MODELING RESULTS - UNDEVELOPED B (METRIC)
APPENDIX C. WEST CONSULTANTS INC - HYDRAULIC SUMMARY REPORT
APPENDIX D. TECHNICAL REVIEW - COMMENTS & RESPONSES

**YELLOWSTONE RIVER CORRIDOR STUDY**
**HYDRAULIC ANALYSIS**
**MODELING AND MAPPING REPORT**

## LIST OF FIGURES


Figure 1. Hydraulic Study Location and Extents ..... 2
Figure 2. Hydraulic Study and County Location ..... 3
Figure 3. Bathymetric Survey Pattern ..... 7
Figure 4. Examples of Missing Terrain Data ..... 8
Figure 5. Examples of Channel Changes in Stillwater County ..... 8
Figure 6. Cross Section Layout Example, Rosebud County ..... 10
Figure 7. HEC-RAS Depiction of Interstate 94 Bridge at Glendive, MT ..... 12
Figure 8. HEC-RAS Depiction of Diversion Dam at Intake, MT ..... 12
Figure 9. HEC-RAS Low Flow Depictions in Sweet Grass County ..... 13
Figure 10. HEC-RAS Low Flow Depictions in Sweet Grass County ..... 15
Figure 11. Undeveloped Terrain Uncertainty ..... 16
Figure 12. Water Surface Profiles at the BNSF Rail Road Bridge in Glendive, MT. ..... 21
Figure 13. Backwater Inundation at Clarks Fork Confluence ..... 23
Figure 14. Ponding Areas Examples ..... 24
Figure 15. Undeveloped Conditions Shapefile and Depth Grid ..... 25
Figure 16. Depth Interval Shapefile for Custer County ..... 25
Figure 17. Historic Floodplain Isolation Example in Custer County ..... 27


## LIST OF TABLES


Table 1. Study Reaches by County, Reach Classification and River Mile ..... 4
Table 2. Summary of Available Survey Data ..... 7
Table 3. ArcGIS Software ..... 9
Table 4. Study Area Bridges Modeled in HEC-RAS ..... 11
Table 5. Manning's Roughness Values ..... 14
Table 6. Regulated Flows (cubic meter per second) ..... 16
Table 7. Unregulated Flows (cubic meter per second) ..... 17
Table 8. Boundary Conditions Used in HEC-RAS ..... 19
Table 9. Scenarios Modeled ..... 19
Table 10. Water Surface Results (elevation meters), 5% ACE, Dawson County ..... 21
Table 11. Mapping Products ..... 22

# YELLOWSTONE RIVER CORRIDOR STUDY
# HYDRAULIC ANALYSIS
# MODELING AND MAPPING REPORT

## 1. INTRODUCTION

The purpose of this analysis is to develop the water surface profiles and flood boundary delineations for selected annual exceedance floods under open water conditions in the reach of the Yellowstone River from the Park-Sweet Grass County line to the confluence with the Missouri River. This study is part of the Yellowstone River Corridor Study, from which resulting hydraulic information is utilized in defining the current and historic extent of the Yellowstone River floodplain to support the objective of the Yellowstone River Corridor Study.

Yellowstone River Corridor Study is a joint effort of the Yellowstone River Conservation Districts Council (YRCDC) and the U.S. Army Corps of Engineers, Omaha District (USACE), authorized for use under Section 431, Water Resources Development Act of 1999. The interdisciplinary study examines hydrologic, hydraulic, geomorphic, biologic and socioeconomic characteristics of and impacts on the Yellowstone River and adjacent floodplain in a 600-mile reach from Gardiner, Montana, to the confluence with the Missouri River in western North Dakota.

The purpose of the Yellowstone River Corridor Study is to perform a Cumulative Effects Assessment (CEA) for the entire river corridor and develop a comprehensive plan that provides for sustainable use of the river and its floodplain for both economic and environmental needs. The hydraulic analysis characterizes the impacts of human development, including man-made structures, encroachments, storage, diversions, and depletions on the Yellowstone River hydraulic profiles and flood boundaries by comparing current and "prehistoric" conditions. Human impacts have been evaluated by modeling two geometry files and two flow files. The geometry files include "Developed" conditions (i.e., the file represents current conditions with existing bridges, embankments, diversion dams, etc.) and "Undeveloped" conditions (i.e., human made structures will be manually removed from the geometry file.) The flow files include "Regulated" conditions (i.e., hydrologic discharges representing current conditions resulting from human-controlled reservoirs, irrigation canals, etc.) and "Unregulated" conditions (i.e., hydrologic discharges representing natural conditions). Four scenarios have been evaluated for a range of flood events using the hydraulic model by modeling combinations of the "Developed" and "Undeveloped" geometry and "Regulated" and "Unregulated" flow files. Model results were tabulated and the flood boundaries were mapped.

Comparison of the results from modeling and mapping the combinations of the geometric and hydrologic conditions provides valuable information for a range of flows that will assist the cumulative effects assessment and restoration planning process. Results critical to the cumulative effects assessment include the extent of inundated floodplain under differing scenarios, hydraulic characteristics (e.g., river stages, velocities, flow depths) and the differences between each scenario. Of particular interest to cumulative effects assessment and restoration planning is the frequency of side channel inundation and how that frequency may have changed over time due to channel modifications and water development.

## 2. STUDY AREA DESCRIPTION

From Yellowstone Lake, Wyoming, the Yellowstone River flows northeast through Wyoming, Montana and North Dakota where it drains into the Missouri River at River Mile 1581.5. The Yellowstone River is the largest tributary of the Missouri River, consisting of 55% of the combined flow (Shields et al., 1997). The Yellowstone River watershed consists of a 70,000-square-mile basin across the three states with major tributaries in the basin including Clarks Fork Yellowstone, Bighorn River, Tongue River and Powder River (USGS, 2013). With the exception of flow changes, the effects of tributaries were not included in the study.

The river corridor provides for various sized communities; supports agricultural (range and crop), industrial, commercial and recreational uses; and is home to abundant wildlife. Vegetative cover includes woodland, grassland, and irrigated and dry cropland (Zelt, et al., 1999) and were classified as herbaceous, shrub, open timber and closed timber for incorporation into the hydraulics analysis (DTM Consulting, 2008).

The study area for the Yellowstone River hydraulic analysis extends from the Park-Sweet Grass County line at River Mile 478.2 to the confluence of the Missouri River floodplain at River Mile 2.8, and shown in Figures 1 and 2. Within this 475-mile reach, the Yellowstone River and its corridor are described by its alluvial system characterized by its meandering flow path, anabranching side channels, vegetated islands and dynamic gravel bars (DTM Consulting, 2009). The Yellowstone River study reach was divided into sub-reaches as part of the CEA geomorphic study and are listed in Table 1. Full descriptions of Reach Narratives are listed in Appendix A of the Channel Migration Zone Mapping Report (DTM Consulting, 2009).

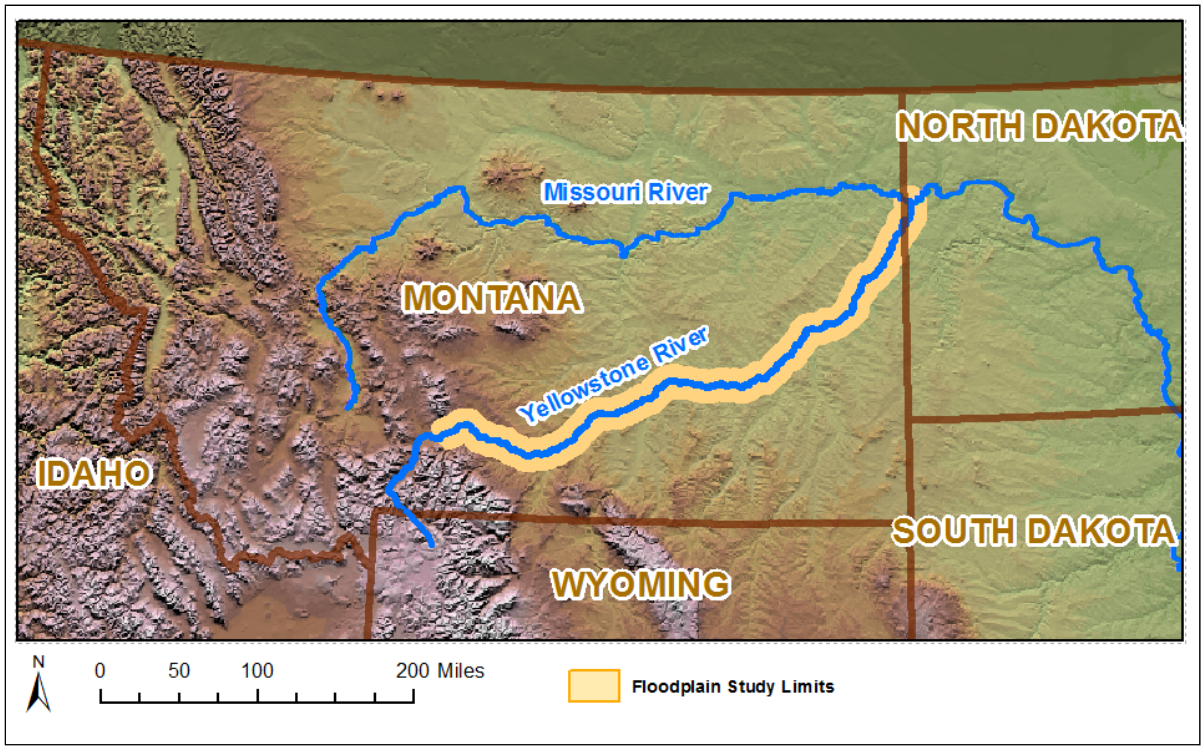


**Figure 1. Hydraulic Study Location and Extents**

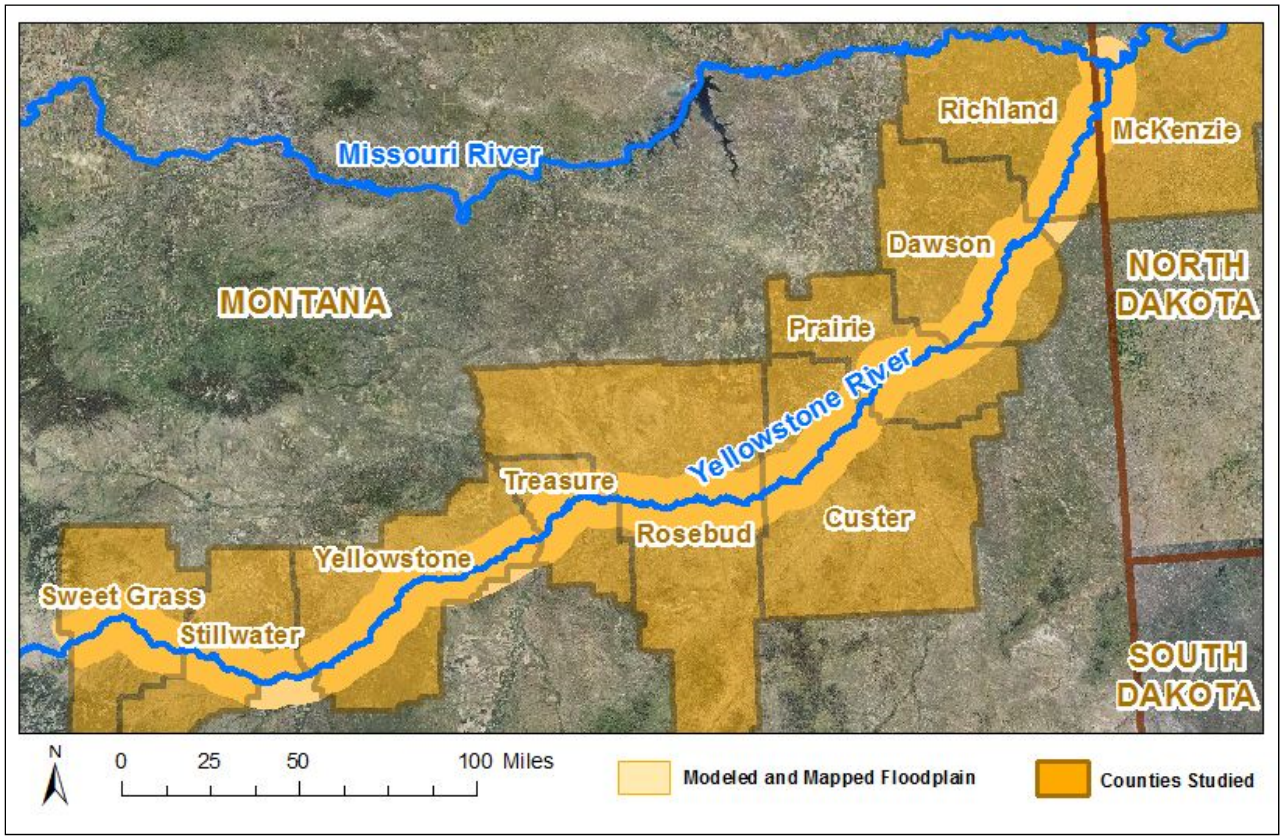


**Figure 2. Hydraulic Study and County Location**

The reach upstream of the Bighorn River consists of a steeper channel slope of approximately 0.0017; the reach below the Bighorn River is approximately 0.00055; and, nearing the Missouri River confluence the slope flattens to approximately 0.0002. The elevation range of the channel along the entire study reach is 4195-feet to 1855-feet (1278.1-meters to 565.5-meters).

The Yellowstone River is one of the longest free-flowing rivers in the lower 48 states (USGS, 2013). The river crossings in the study reach are limited to bridges and low-head weirs, and channel modifications consist of bank stabilization, flow deflectors and side channel cutoffs. Floodplain development includes urbanization; transportation routes; Federal, community and agricultural levees; and irrigated and dryland farming. The width of the 100-yr floodplain ranges from 0.12-miles to 2-miles within the study reach. Narrow floodplain widths are due to both natural and man-made flow constrictions.

**Table 1. Study Reaches by County, Reach Classification and River Mile**

| County | Reach | Modeled River Mile |
|---|---|---|
| Sweet Grass | A1 | 478.19 – 475.24 |
| | A2 | 475.12 – 468.42 |
| | A3 | 468.25 – 463.06 |
| | A4 | 462.79 – 459.62 |
| | A5 | 459.53 – 456.43 |
| | A6 | 456.29 – 453.35 |
| | A7 | 453.23 – 443.53 |
| | A8 | 443.45 – 438.43 |
| | A9 | 438.36 – 435.62 |
| Stillwater | A9 | 435.42 – 434.53 |
| | A10 | 434.49 – 430.34 |
| | A11 | 430.23 – 423.27 |
| | A12 | 423.17 – 417.20 |
| | A13 | 417.09 – 413.65 |
| | A14 | 413.44 – 405.81 |
| | A15 | 405.77 – 399.95 |
| | A16 | 399.85 – 392.44 |
| | A17 | 392.20 – 391.46 |
| Yellowstone | A17 | 391.31 – 385.79 |
| | A18 | 385.69 – 383.54 |
| | B1 | 383.39 – 368.18 |
| | B2 | 368.09 – 362.13 |
| | B3 | 362.05 – 357.69 |
| | B4 | 357.62 – 354.00 |
| | B5 | 353.90 – 346.49 |
| | B6 | 346.35 – 340.40 |
| | B7 | 340.26 – 331.74 |
| | B8 | 331.66 – 322.58 |
| | B9 | 322.51 – 317.97 |
| | B10 | 317.87 – 310.76 |
| | B11 | 310.67 – 302.70 |
| | B12 | 302.56 – 298.19 |
| Treasure | C1 | 297.98 – 292.24 |
| | C2 | 292.02 – 286.64 |
| | C3 | 286.51 – 282.02 |
| | C4 | 281.66 – 278.30 |
| | C5 | 278.09 – 275.02 |
| | C6 | 274.82 – 269.40 |
| | C7 | 269.20 – 260.60 |
| | C8 | 259.84 – 259.66 |

| County | Reach | Modeled River Mile |
|---|---|---|
| Rosebud | C8 | 259.48 – 253.82 |
| | C9 | 253.64 – 243.04 |
| | C10 | 242.86 – 236.32 |
| | C11 | 236.13 – 224.89 |
| | C12 | 224.75 – 214.90 |
| | C13 | 214.74 – 208.18 |
| | C14 | 207.99 – 204.80 |
| Custer | C14 | 204.49 – 196.07 |
| | C15 | 195.88 – 192.17 |
| | C16 | 191.95 – 185.07 |
| | C17 | 184.86 – 180.57 |
| | C18 | 180.38 – 177.41 |
| | C19 | 177.22 – 166.13 |
| | C20 | 165.98 – 158.68 |
| Prairie | C21 | 158.49 – 149.23 |
| | D1 | 149.04 – 137.00 |
| | D2 | 136.92 – 126.43 |
| | D3 | 126.40 – 120.65 |
| Dawson | D3 | 120.37 – 118.07 |
| | D4 | 117.90 – 107.13 |
| | D5 | 106.98 – 94.52 |
| | D6 | 94.42 – 88.96 |
| | D7 | 88.77 – 81.31 |
| | D8 | 81.10 – 71.31 |
| | D9 | 71.10 – 67.86 |
| | D10 | 67.57 – 64.96 |
| Richland | D10 | 64.55 – 56.39 |
| | D11 | 56.20 – 50.06 |
| | D12 | 49.86 – 36.41 |
| McKenzie | D13 | 36.25 – 27.82 |
| | D14 | 27.63 – 13.52 |
| | D15 | 13.32 – 7.49 |
| | D16 | 7.31 – 2.82 |

## 3. HYDROLOGIC ANALYSIS

A driving component of the cumulative effects assessment is to compare the current (i.e., human impacted) and historic (i.e., natural) flows. The Yellowstone River is subject to natural flow variations due to seasonal snow and rain runoff and drought conditions. Human development has necessitated flow alterations through management of tributary reservoir operation, irrigation diversions and urban depletions. Regulated flow was determined with the assumption that the entire study period was subjected to human impacted water resourcing occurring in 2002. Unregulated flow was determined assuming no water resourcing occurred throughout the study period.

The hydrologic analysis was conducted as two studies. The hydrology for the reach upstream of the Big Horn River (i.e., the Upper Reach) was conducted by the U.S. Army Corps of Engineers (USACE 2011). The study downstream of the Big Horn River (i.e., the Lower Reach) was conducted by the U.S. Geological Survey (USGS 2013). The same methodology was utilized to develop the Regulated and Unregulated discharges in both studies. Daily stream flow data were collected from gauging stations throughout the Yellowstone River Basin for the 1928-2002 study period. Missing periods were synthesized from monthly mean flows. Once an entire dataset was developed, historical depletions recorded by the Bureau of Reclamation were applied to the daily stream flow dataset to obtain the Unregulated flow data. Regulated flow data was estimated by applying the 2002 equivalent depletions to the Unregulated dataset.

From the Regulated and Unregulated daily flow datasets, the hydrologic analysis determined several flow statistics including maximum, minimum and mean annual and monthly discharges, annual and seasonal flow durations, and annual and seasonal high and low-flow *n-day* frequencies. At the request of the YRCDC Technical Advisory Committee, the discharges selected for the hydraulic analysis include the 67-, 50-, 20-, 10-, 5-, 2-, 1-, 0.5- and 0.2-% annual chance exceedance (ACE) events and the 5% by duration events. These discharges were identified as beneficial for the cumulative effects assessment, and hydraulic results are intended to support concurrent studies including aquatic, riparian, avian, socioeconomics and water quality. The 5% flow duration evaluates inundated areas typically occurring during spring runoff (18 days per year on average). The Upper Reach and the Lower Reach hydrologic studies reported stream flow statistics for the 5-% ACE and the 4-% ACE, respectively. Therefore, the 5-% ACE was interpolated for the Lower Reach from the reported dataset and applied to the hydraulic analysis. Additional low-flows requested include the 7Q10 and 30Q2; however these low-flow frequencies have not been calculated to date for the Upper Reach where underwater survey data is available.

Draft discharges were provided and used for the Lower Reach to commence modeling efforts. Final discharges were provided subsequent to the modeling effort and varied by less than 0.5%; therefore, flow inputs were not revised within the model. It is also necessary to note that the linear-interpolation of flow statistics between the Lower Yellowstone River gauges could vary as much as 6% compared to other acceptable interpolation methods. Interpolation methods are described in the hydrology reports.

The discharges and flow change locations used in the hydraulic analysis are described in Section 4.2.5 and listed in Tables 6 and 7.

# 4. HYDRAULIC ANALYSIS

Water surface profiles were modeled and physical parameters were computed for the selected flood events and scenarios, and delineations of the resulting inundated floodplain were mapped. The following sections detail the modeling and mapping procedures used in the analysis. Supplemental detail is included in Appendix C as the report summary prepared by West Consultants, Inc.

## 4.1. MODEL DESCRIPTION

Water surface profile models of the Yellowstone River were developed using the U.S. Army Corps of Engineers Hydrologic Engineering Center-River Analysis System (HEC-RAS) backwater computer program. The HEC-RAS program was developed for calculating water surface profiles for one-dimensional flows in natural or man-made open-channels. The model is capable of emulating steady and unsteady flow, moveable boundary sediment and water quality simulations for subcritical and supercritical flow computations. The main computational procedure, generally known as the standard step method, is based on the solution of the one-dimensional energy equation with energy loss from friction evaluated with Manning's equation and from flow constrictions and expansions. The model requires terrain and flow inputs to characterize the floodplain and hydrology, respectively.

This hydraulic analysis uses HEC-RAS Version 4.1.0 (Jan 2010) with steady-state and subcritical flow computations to calculate water surface profiles and associated hydraulic parameters.

## 4.2. MODEL SETUP

HEC-RAS models were created by county reaches and the geometric and hydrologic data tied into adjacent county models to ensure modeling continuity throughout the entire study reach. Tributaries of the Yellowstone River were not modeled as part of the study.

### 4.2.1. Topographic Survey

Topographic data of the Yellowstone River floodplain was collected in 2004 by Merrick and Company utilizing an ALS40 sensor and in 2007 by Eisenbraun & Associates utilizing an ALS50 sensor as Light Detection and Ranging (LiDAR) data and supplied as Triangulated Irregular Network (TIN) supported Digital Terrain Model (DTM). The data were provided in Montana State Plane Coordinates, NAD83, suitable for generation of 1-meter contours. Accuracy was evaluated with ground truthing and surveyed spot elevations, meeting National Map Accuracy Standards.

Bathymetric data was collected in 2004 by Chris Ransome and Associates for Stillwater County (RM 435.5 to 391.4), a 70-mile reach in Yellowstone County from the western county boundary to approximately Pompey’s Pillar (RM 391.4 to 322.6), and an approximately 15-mile reach in Dawson County in the Glendive area (RM 107.3 to 89.7). Floodplain and bathymetric data were merged and provided in TIN format and 2.5-meter Digital Elevation Models (DEMs). Table 2 lists the terrain and underwater data available for the hydraulic analysis.

All elevations are referenced to the North American Vertical Datum of 1988 (NAVD88) unit meters. Aerial imagery was collected by Aerial Surveys International, LLC in 2004 and by Eisenbraun & Associates in 2007

**Table 2. Summary of Available Survey Data**

| County | Terrain Survey Date | Bathymetric Survey Date |
|---|---|---|
| Sweet Grass, MT | 2007 | none |
| Stillwater, MT | 2004 | 2004 – full |
| Yellowstone, MT | 2004 | 2004 – partial |
| Treasure, MT | 2007 | none |
| Rosebud, MT | 2007 | none |
| Custer, MT | 2007 | none |
| Prairie, MT | 2007 | none |
| Dawson, MT | 2004 | 2004 – partial |
| Richland, MT | 2007 | none |
| McKenzie, ND | 2007 | none |

Topographic errors were noted during the evaluation and application of the survey data. The bathymetric data was collected during a peak runoff period; however runoff volumes were smaller than average, limiting surveys of shallow side channels. The underwater surveys were collected in a zig-zag pattern as shown below in Figure 3. This pattern provides a general description of the channel; however, the swath widths vary greatly and are not conducive to describing a floodplain cross section that is perpendicular to flow direction.

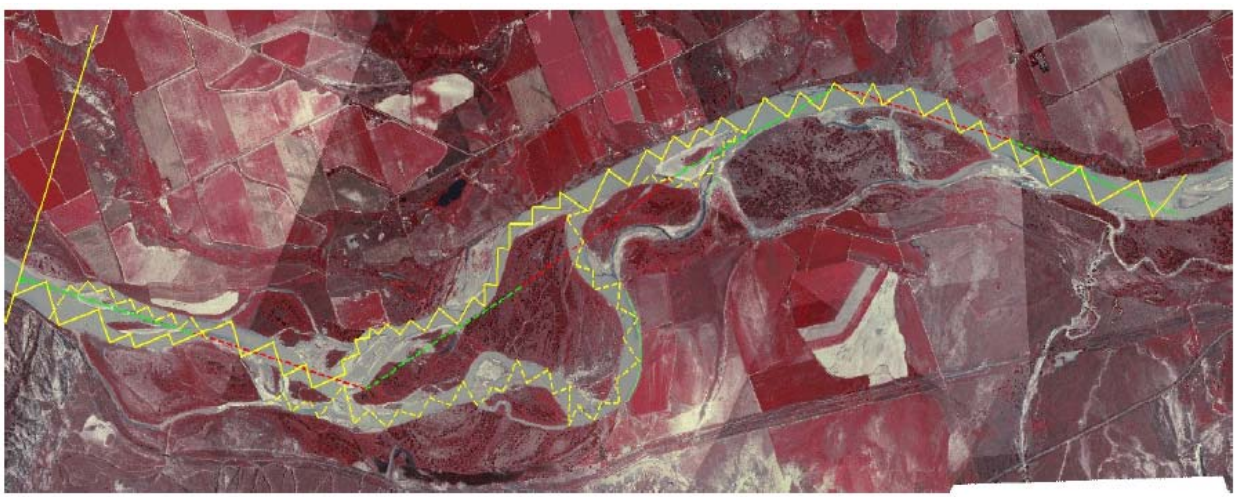

**Figure 3. Bathymetric Survey Pattern (CRA, 2004)** shown as the yellow zig-zag line.

Additional errors noted with the LiDAR and bathymetry data sets include missing data within the channel and floodplain (particularly at tile seams) and suspicious elevations. Examples of missing data are shown in Figure 4. An additional evaluation of the bathymetric data was conducted by the Montana Department of Natural Resources and Conservation (2005) and cautioned the use of the terrain data sets for in-depth hydraulic studies due to errors and anomalies in data collection, processing and manual manipulations. However, the 2004 and 2007 data sets are the most detailed and most recent available surveys for the study reach and were used for the hydraulic analysis.

Although use of the TIN data is the preferred data source due to the higher level of accuracy, several TIN files provided could not be loaded into the more recent versions of the GIS software and the corresponding 2.5-meter DEMs were used instead. ArcView 3.2 was used for the model setup of Stillwater, Yellowstone and Dawson Counties and was able to read and process the TIN datasets. Subsequent ArcMap versions of 9.3 and 10.0, were used for the remaining counties and utilized the DEM datasets.

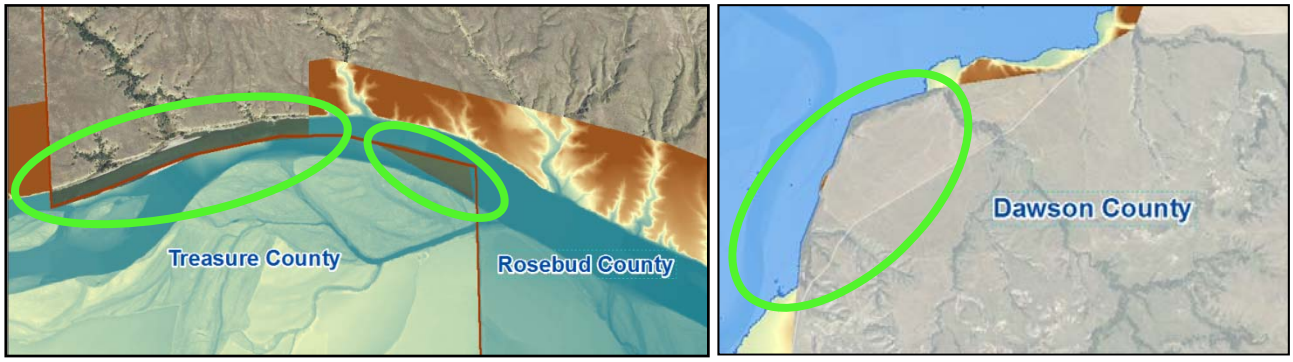


**Figure 4. Examples of Missing Terrain Data.** Sections of missing elevation data are circled in green at the Treasure-Prairie County Line. In Dawson County, the inundation boundary, shown in blue, extends to the edge of the DEM where the full extent of the floodplain was not surveyed and is also circled in green.

Rivers and floodplains are dynamic systems continuously experiencing varying degrees of island formation and depletion, channel migration and large scale erosion and deposition. The Yellowstone River experienced high flows in 2011 that reached the 1% ACE in some locations, and changes in the channel and adjacent floodplain were apparent. From the start of the study with the terrain surveyed in 2004 to the completion of the hydraulic analysis in 2013, the channel and floodplain has experienced various changes. The images shown in Figure 5 depict a section of the Yellowstone River in Stillwater County within the study period. Both images reflect a stream flow of approximately 2,000 cfs. By comparison of the channel and overbank pathways and extents and the vegetative cover, moderate channel changes can be observed. Therefore, the terrain data used in the hydraulic study may not correctly represent current channel geometry in all locations.

**Figure 5. Examples of Channel Changes in Stillwater County. (USDA, 2013)**

### 4.2.2. Model Geometry

The hydraulic model geometry was created utilizing the ESRI ArcGIS software and HEC-GeoRAS, a GIS extension specifically designed to process geospatial data for use with HEC-RAS. Due to the duration of the study, several versions were used and are listed in Table 3. The HEC-GeoRAS extension allows the creation of an HEC-RAS import file containing geometric attribute data from an existing digital terrain and complementary data sets. Water surface profile results exported from HEC-RAS may also be processed and are described in Section 4.5. The corresponding ArcGIS software extensions 3D Analyst and Spatial Analyst were also utilized for geometry development.

**Table 3. ArcGIS Software**

| ArcGIS | Extension |
|---|---|
| ArcView 3.2 | HEC-GeoRAS 3.1.1 |
| ArcView 9.3 | HEC-GeoRAS 4.2.93 |
| ArcMap 9.3.1 | HEC-GeoRAS 4.3 |
| ArcMap 10.0 | HEC-GeoRAS 10 |

In HEC-GeoRAS, the user creates an import file containing river, reach and station identifiers by generating GeoRAS layers consisting of a stream centerline, cross-sectional cut lines, bank stations, overbank flowpaths, and cross-sectional roughness coefficients. Additional geometric data defining levee alignments, ineffective flow areas, bridges and storage areas may also be written to the HEC-RAS GIS import file. These GeoRAS layers are combined with the terrain elevation files, and the software calculates the downstream reach lengths for overbanks and channel, extracts cross-sectional station and elevations points, and generates the HEC-RAS input file.

Nine individual HEC-RAS projects were created covering the ten counties included within the study. Each county is represented by an individual model with the exception of Richland County, MT and McKenzie County, ND which were combined into one model since the river length from the county line to the confluence was only 15 river miles.

A stream centerline was drawn for each county of the Yellowstone River along the main channel thalweg. The 2001 primary flowpath (*fl_1999_2001_route_primary.shp*) created for the geomorphology Phase I portion of the study and was used as a guide; however, deviations from the 2004 and 2007 main channel surveys and aerials were apparent. Modeling the river as a split flow around large islands was considered for a portion of Stillwater, Yellowstone and Dawson Counties. Modeling the river split as separate reaches allows the program to calculate separate hydraulic parameters on either side of the island. For example, differences in water surface elevation and velocity may vary across the island. However, due to potential instabilities occurring during the split flow computations and the large range of stream discharges being modeled, the introduced error outweighed the benefits of split flow modeling.

Cross sectional cutlines were spaced approximately 500 to 1000 feet apart, with closer spacing near structures and areas of specific interest to adequately represent the hydraulic impacts of the structure. Spacing exceeded 1000 feet in areas of sharp channel bends to prevent the cutlines from overlapping in the overbanks and in areas of inadequate survey data. Cutlines were drawn perpendicular to both channel and overbank flow. Due to the sinuosity of the Yellowstone River and range of discharges modeled, cross sections were often dog-legged to adequately represent the channel and overbanks as a one-dimensional system. Cross sections were extended to high ground to ensure capture of elevation data for the 0.2% ACE. An example of cross section layout for Rosebud County is depicted in Figure 6 and shows dog-legs and narrow spacing around the bridge.

The additional GeoRAS layers were also drawn, and the roughness shapefile was incorporated. The overbank flow paths were drawn based on the anticipated flow path of the 1% ACE. Once the GeoRAS layers were compiled, the HEC-RAS import file was generated and brought into the program. In the HEC-RAS program, the structures such as bridges, levees and diversion dams were characterized, channel bank locations were edited and river mileage was included.

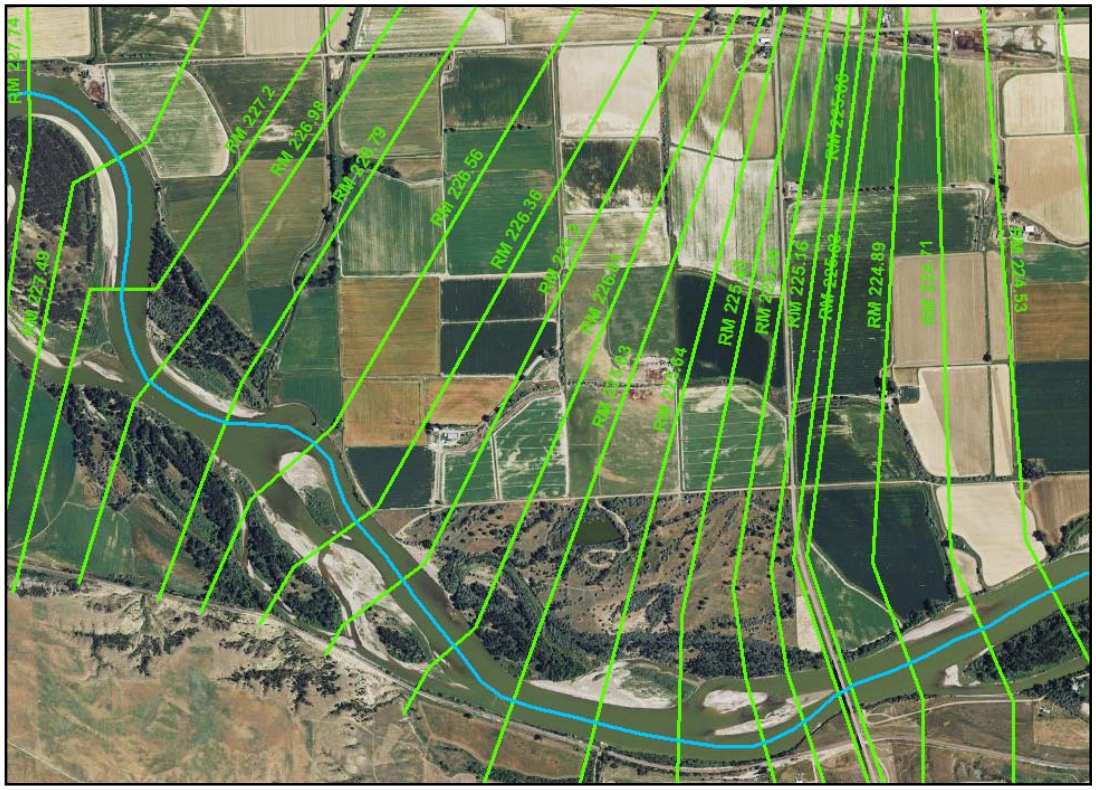


**Figure 6. Cross Section Layout Example, Portion of Rosebud County**

### 4.2.3. Developed Model Geometry

The developed model geometry represents current conditions and includes terrain alterations due to human development. Structures incorporated into the model include transportation embankments, Federal and agricultural levees, canals and ditches, wastewater treatment lagoons, and designed depressions and pilings (e.g., quarries and electrical tower pilings). Most terrain descriptions and alterations were captured in the LiDAR surveys and GeoRAS file; however, some structures and descriptions required manual input.

#### 4.2.3.1. Structures

Yellowstone River structures requiring additional descriptions in HEC-RAS include bridges and low head dams. Bridge surveys were performed by the Montana U.S. Geologic Survey between 2005 and 2009 and included bridge dimensions, chord elevations, and pier and channel descriptions. A total of 39 bridges were modeled and are listed in Table 4. One low head dam was modeled at Intake, MT in

Dawson County. Surveys of Intake Diversion Dam were obtained from the Intake Fish Passage Study (USACE, 2009). Examples of structure depictions as coded in the HEC-RAS model are shown in Figure 7 for the Interstate 94 Bridge in Glendive, MT and in Figure 8 for the Intake Diversion Dam.

Culverts were not modeled. The bridge survey did not report culverts through the bridge embankments, and floodplain culverts were not identified as part of this study. Similarly, bridge debris was not included as part of this analysis.

An in-depth Physical Feature Inventory was generated as part of the CEA study. This database includes locations and descriptions of various structures including bridges, embankments, low-head dams, canals, irrigation returns, and bank stabilization. The inventory and geo-database was useful in determining structures location, type and applicability to the hydraulic modeling.

**Table 4. Study Area Bridges Modeled in HEC-RAS**

| County | RM | Bridge Name | Piers | Deck/Pier Skew | Survey Date |
|---|---|---|---|---|---|
| Sweet Grass | 469.45 | Exit 362 | 2 | 0 | 10/16/2009 |
| Sweet Grass | 460.61 | Big Timber | 2 | 0 | 10/6/2009 |
| Sweet Grass | 448.21 | Greycliff | 2 | 0 | 10/5/2009 |
| Stillwater | 434.48 | Reed Point | 3 | 0 | 9/26/2005 |
| Stillwater | 428.18 | Springtime Rail Road | 3 | 12/12 | 9/26/2005 |
| Stillwater | 428.16 | Springtime Old Hwy | 4 | 12/12 | 9/27/2005 |
| Stillwater | 427.74 | Interstate 90 | 3 | 0 | 9/27/2005 |
| Stillwater | 415.53 | Columbus | 3 | 40/40 | 9/27/2005 |
| Yellowstone | 385.82 | Laurel | 4 | 0 | 9/28/2005 |
| Yellowstone | 377.95 | Duck Creek | 4 | 45/0 | 9/28/2005 |
| Yellowstone | 371.03 | South Billings | 4 | 0 | 9/29/2005 |
| Yellowstone | 364.87 | Interstate 90 | 11 | 36/0 | 9/29/2005 |
| Yellowstone | 364.63 | East Billings Rail Road | 4 | 0 | 6/27/2006 |
| Yellowstone | 364.58 | East Billings Hwy | 4 | 12/0 | 6/27/2006 |
| Yellowstone | 352.63 | Huntley | 5 | 36/0 | 6/29/2006 |
| Yellowstone | 332.2 | New Pompey | 5 | 12/0 | 6/28/2006 |
| Yellowstone | 332.16 | Old Pompey | 4 | 0 | 6/28/2006 |
| Yellowstone | 300.55 | Custer | 3 | 16/0 | 6/28/2006 |
| Treasure | 286.71 | Old Myers Piers | 2 | 0 | 8/22/2007 |
| Treasure | 286.44 | Myers | 5 | 0 | 8/22/2007 |
| Rosebud | 239.84 | Highway 12 | 7 | 0 | 8/9/07 & 8/22/07 |
| Rosebud | 239.55 | Old Forsyth | 2 | 0 | 8/9/07 & 8/22/07 |
| Rosebud | 225.04 | Highway 446 | 7 | 0 | 8/8/2007 |
| Custer | 189.63 | Paragon | 3 | 0 | 7/26/2007 |
| Custer | 186.61 | Fort Keough | 6 | 0 | 7/26/2007 |
| Custer | 184.09 | Highway 22 | 6 | 0 | 7/26/2007 |
| Custer | 172.11 | Kingsley | 3 | 0 | 7/25/2007 |

| County | RM | Bridge Name | Piers | Deck/Pier Skew | Survey Date |
|---|---|---|---|---|---|
| Prairie | 144.54 | Milwauki | 3 | 0 | 7/25/2007 |
| Prairie | 137.03 | Highway 235 | 5 | 0 | 7/24/2007 |
| Prairie | 136.7 | Old Piers | 4 | 0 | 7/24/2007 |
| Prairie | 126.4 | Interstate 94 | 5 | 0 | 7/24/2007 |
| Prairie | 126.37 | Frontage | 3 | 0 | 7/24/2007 |
| Dawson | 94.55 | BNSF Rail Road | 6 | 35/35 | 7/12/2007, 8/7/2007 |
| Dawson | 93.52 | Bell | 6 | 0 | 7/12/2007, 8/7/2007 |
| Dawson | 93.42 | Towne | 7 | 0 | 7/12/2007, 8/7/2007 |
| Dawson | 92.14 | Interstate 94 | 8 | 0 | 7/11&12/2007, 8/7/2007 |
| Richland | 31.1 | Highway 23 | 4 | 45/0 | 7/11/2007, 8/7/2007 |
| McKenzie | 9.23 | Old Railroad/Walkway | 10 | 0 | 7/10/2007, 8/7/2007 |
| McKenzie | 9.02 | Highway 68 | 9 | 0 | 7/10/2007, 8/7/2007 |

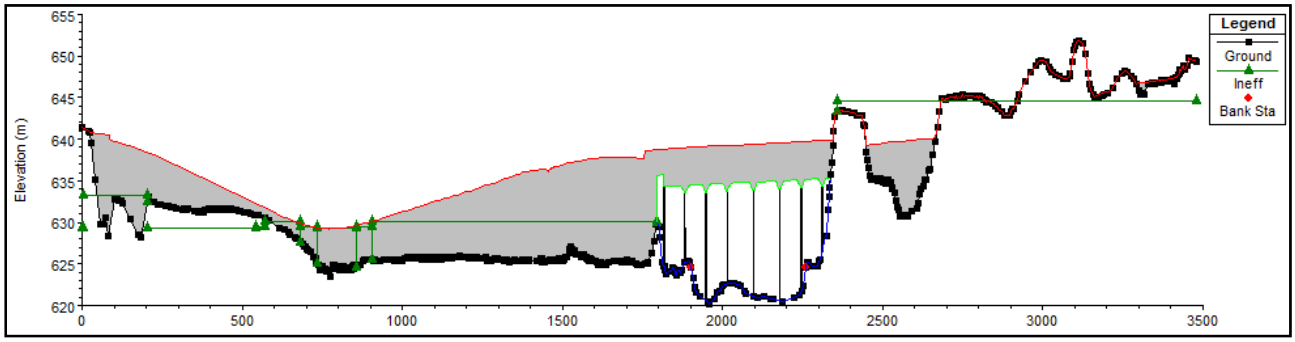


**Figure 7. HEC-RAS Depiction of Interstate 94 Bridge at Glendive, MT**

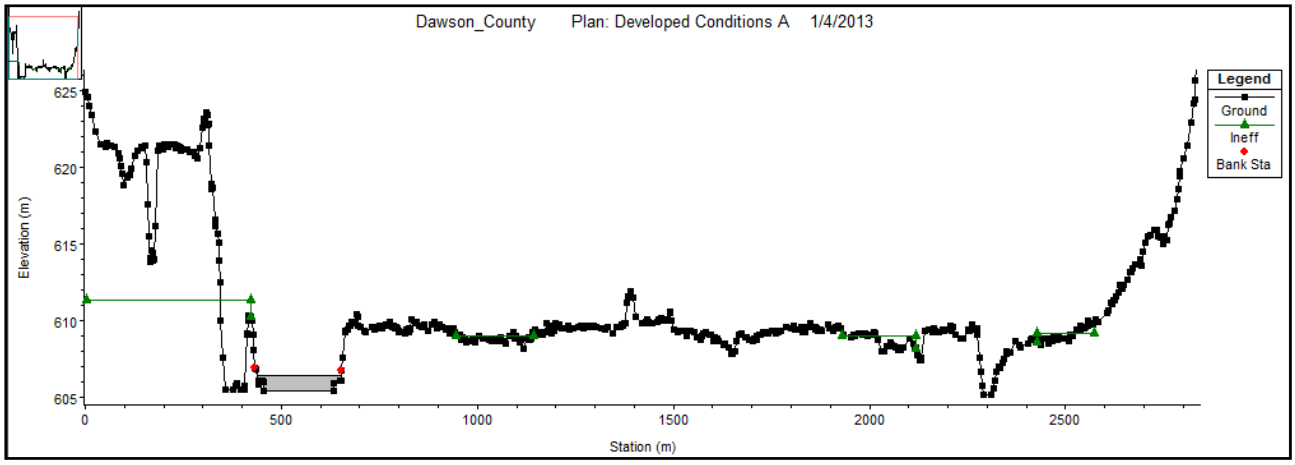


**Figure 8. HEC-RAS Depiction of Diversion Dam at Intake, MT**

#### 4.2.3.2. Low-Flow Channels

In areas where bathymetric data was not collected, a low-flow trapezoidal channel was incorporated into the model geometry. The channel flows at the time the LiDAR surveys and aerial photographs were collected and were used to approximate the channel width and depth and applied to the entire county reach. The modeled low-flow water surface was compared and calibrated to the LiDAR water surface and the wetted channel shown in the aerials. Adjustments to the low-flow channel dimensions were made to individual cross sections. The calibration of the low-flow channel was generally within one foot of the LiDAR surveyed water surface. The mapped low-flow water surface boundaries are shown in Figure 9 for an area in upstream Sweet Grass County. The HEC-RAS plan view with the low-flow water extents and boundary is shown in the image on the left. The HEC-RAS cross section in red is shown on the right. The incorporated trapezoidal channel is circled in green highlighting the difference between the original channel (shown in pink) and imported from the LiDAR survey and the final channel geometry (shown in black).

The method of an incorporated low-flow channel is an acceptable calibration tool for high flow studies. However, caution should be used in low-flow studies due to the generalization of the underwater geometry.

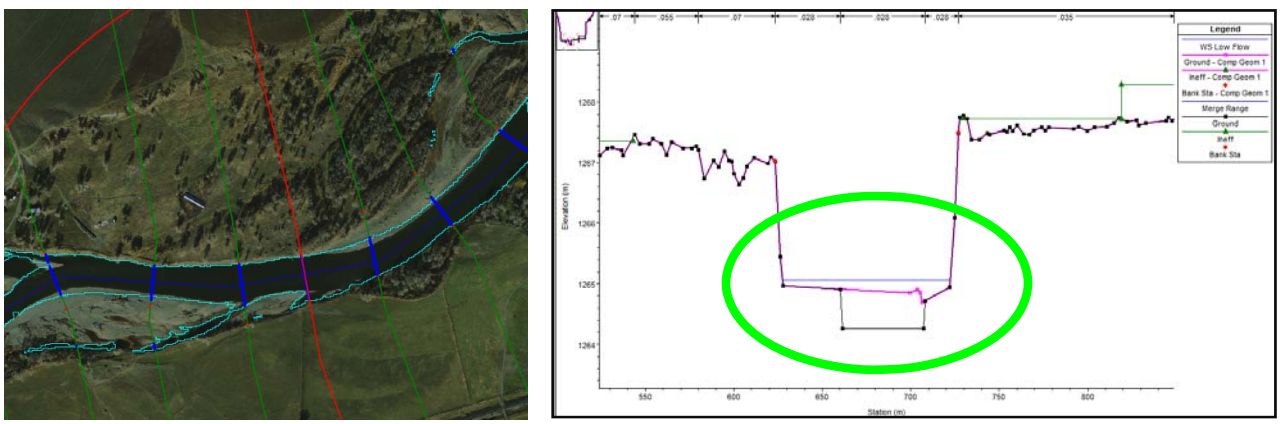


**Figure 9. HEC-RAS Low-flow Depictions in Sweet Grass County.** HEC-RAS plan view and water extents are shown in the image on the left. The HEC-RAS cross section highlighted in red with low-flow channel is shown on the right.

#### 4.2.3.3. Ineffective Flow Areas and Levees

Ineffective flow areas and levees were coded into the HEC-RAS model by inspecting cross sections, contours, aerial photographs and structure descriptions to determine applicability, location and elevation.

The locations of Federal levees were verified, and natural and agricultural levees were identified based on the terrain elevation and flow characteristics between adjacent cross sections. Ineffective flow restraints were also added manually to the geometry to follow conveyance expansion and contraction guidelines.

The ineffective flow area and levee options were set with the attempt to represent all stream flows; however the 1% ACE was used as the basis for calibration.

#### 4.2.3.4. Roughness Value

A vegetative cover shapefile was provided by the Montana Natural Resource Conservation Service (NRCS) for the entire study area as a 2006 vegetative cover map. Corresponding Manning's Roughness Values were assigned based on available reference data and engineering judgment and are listed in Table 5. The roughness values were imported from GeoRAS, verified for the channel and overbanks and adjusted where appropriate.

**Table 5. Manning's Roughness Values**

| Class Code | Description | Manning's Roughness Value |
|---|---|---|
| **w** | Water | 0.028 |
| **c** | Crop cover | 0.035 |
| **h1, h2, h3** | Herbaceous/Graminoid complex | 0.040 |
| **p1** | Open canopy, short woody | 0.050 |
| **r1** | Open canopy, tall woody | 0.055 |
| **s** | Closed canopy, short woody | 0.060 |
| **t** | Closed canopy, tall woody | 0.070 |
| **a** | Artificial cover | 0.100 |
| **XX** | N/A (outside vegetative study limits) | 0.051 |

#### 4.2.3.5. Other Variables

Expansion and contraction coefficients were 0.3 and 0.1, respectively, for typical channel cross sections. The coefficients of 0.5 and 0.3, respectively, were used to characterize all bridges and the diversion dam.

Bank stations were assigned elevations between the 67% ACE and 0.2% ACE, with a target elevation equivalent to the 50% ACE.

Cross section node descriptions were included into each HEC-RAS model referencing the corresponding river mile, based on the 2001 primary flow path shapefile.

Multiple geometries were developed for some counties in an attempt to better represent the hydraulic properties associated with the range of stream flows modeled. It is common to use the same set of cross sections with a single centerline to hydraulically model a river or channel even though the cross section orientation and description may differ if each discharge was modeled independently. Separate geometries is generally cost prohibitive. The HEC-RAS models with multiple geometries are Treasure, Rosebud, Custer, Prairie and Richland/McKenzie Counties, and the primary difference between the high and low-flow geometries are the location and elevation of ineffective flow area designations.

### 4.2.4. Undeveloped Model Geometry

The Developed model geometry was used as a base for the Undeveloped model geometry. The Undeveloped geometry was generated by manually adjusting each cross section's station elevation points from the Developed geometry file that represent man-made features such as railroad embankments, levees, elevated roads, etc. Elevations of natural land adjacent to the structures were

used to determine natural elevations at the structure. Bridges and inline structures and the immediate downstream bounding cross section were also removed within the HEC-RAS model. Manning's Roughness Values for urban areas, decreased expansion and contraction coefficients which define bridges, ineffective flow areas representing flow restriction due to man-made structures, and other associated geometric components attributed to human impacts were also adjusted or eliminated to reflect natural conditions.

Figure 10, shown below, depicts a cross section in Billings, MT at River Mile 366.2. The cross section, highlighted in red, is depicted in the image on the right. The station elevation points shown in pink, represent the man-made structures captured in the LiDAR surveys. These points were manually removed and the final undeveloped geometry is shown in black. Similarly, the ineffective flow areas were widened due to the removal of the man-made structures allowing more of the overbanks to convey flow.

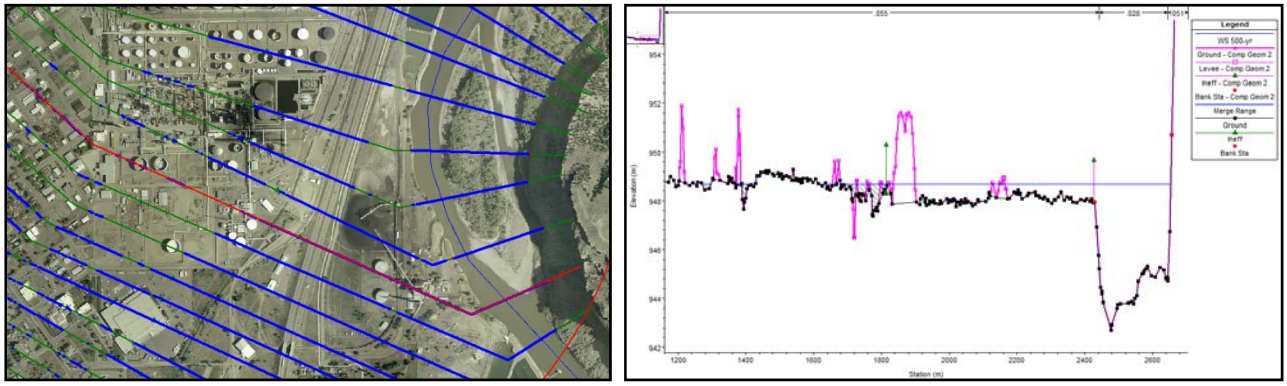


**Figure 10. HEC-RAS Low-flow Depictions in Sweet Grass County** HEC-RAS plan view and water extents (heavy blue line) are shown in the image on the left. The HEC-RAS cross section highlighted in red is shown in the image on the right with removed structures in pink.

The channel geometry, including the approximated low-flow channel, was not adjusted as part of the Undeveloped geometry characterization. Although locations of bank stabilization (e.g., riprap protection, flow deflectors, etc.) have been identified through the CEA, it is difficult to predict the spatial and vertical degradation and aggradation potential and the extent of channel migration under completely natural terrain and flow conditions.

Flowpaths were not adjusted as part of the Undeveloped geometry adjustments. The 1% ACE flowpath was used to describe channel and overbank flow distances between cross sections for the Developed geometry. Structures may cause significant flow restrictions and affect the flow path and distance. Removing a flow-restricting structure would widen the conveyance area resulting in a shorter flowpath.

The majority of the structures are apparent on the recent aerial photographs and terrain surveys and were listed in the physical feature inventory. In some areas with significant or questionable development, the 1950 historic aerial photographs (DTM Consulting, 2006) were used as a guide to estimate the extent and contours of the natural system. However, significant engineering judgment was used to create the Undeveloped geometry files due to the limited historic information and the use of current terrain data to estimate historic terrain.

In several instances, human modification was apparent, but the level and extent was uncertain as comparison of adjacent terrain and current and historic aerials did not always offer an indication of historic conditions. For example, much of the floodplain consists of irrigated cropland that has been terraced and sloped in an effort to maximize irrigation efforts. However, it is difficult to discern if soil was added, removed, or both, in order to obtain the gentle slope. A potential example of this is shown in Figure 11 and highlighted in green for River Mile 68.1 in Dawson County. In areas of uncertainty, the Undeveloped terrain was not adjusted, and the Developed geometry obtained from the LiDAR surveys was used.

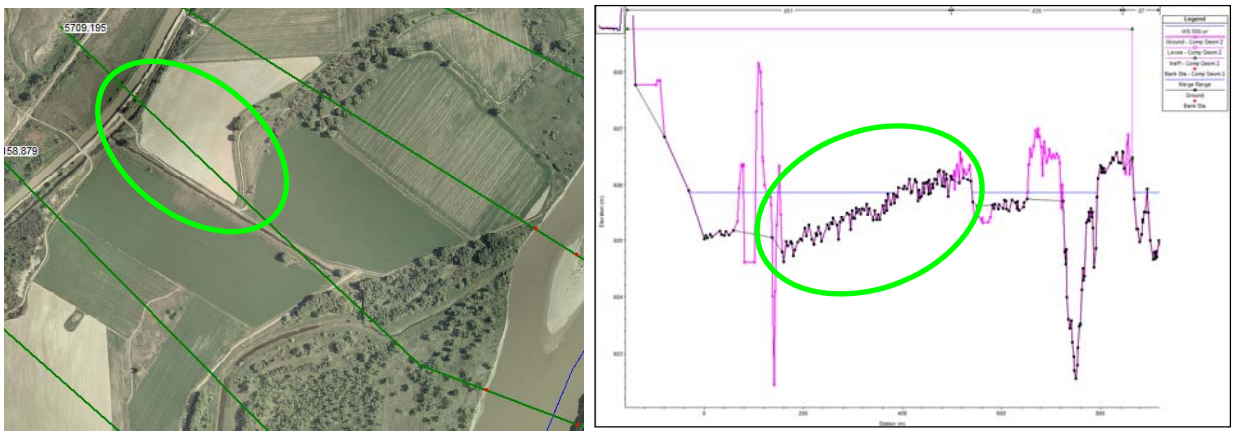


**Figure 11. Undeveloped Terrain Uncertainty.** HEC-RAS plan view and cross section for RM 68.1 identifying and area of uncertain terrain modifications due to agriculture practices.

### 4.2.5. Model Discharges

This analysis utilized constant peak discharges with steady flow simulations. Computed flows for the 67-, 50-, 20-, 10-, 5-, 2-, 1-, 0.5- and 0.2-% annual chance exceedance (ACE) events and the 5% by duration event were selected for the hydraulic modeling. This range of stream flows represents a wide range of conditions that will benefit related studies associated with the CEA.

The discharges and flow changes locations used in the hydraulic analysis were obtained from the hydrologic study, as described in Section 3, and are listed in Tables 6 and 7 for the Regulated and Unregulated flows, respectively.

**Table 6. Regulated Flows (cubic meter per second)**

| Reach (River Mile) | 5% by Duration | Percent Annual Chance Exceedance (Return Intervals) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 67% (1.5 yr) | 50% (2-yr) | 20% (5-yr) | 10% (10-yr) | 5% (20 yr) | 2% (50-yr) | 1% (100-yr) | 0.5% (200-yr) | 0.2% (500-yr) |
| A1 (478.19) | 437 | 571 | 648 | 816 | 915 | 1008 | 1119 | 1203 | 1280 | 1382 |
| A4 (459.72) | 480 | 627 | 711 | 892 | 1000 | 1102 | 1220 | 1311 | 1393 | 1504 |
| A7 (450.34) | 505 | 656 | 745 | 934 | 1051 | 1152 | 1283 | 1376 | 1467 | 1580 |
| A9 (435.62) | 505 | 657 | 745 | 935 | 1051 | 1153 | 1283 | 1376 | 1467 | 1580 |
| A10 (432.2) | 519 | 675 | 765 | 963 | 1079 | 1187 | 1320 | 1416 | 1507 | 1625 |
| A12 (417.4) | 584 | 764 | 867 | 1090 | 1223 | 1345 | 1498 | 1606 | 1711 | 1843 |

| Reach (River Mile) | 5% by Duration | Percent Annual Chance Exceedance (Return Intervals) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 67% (1.5 yr) | 50% (2-yr) | 20% (5-yr) | 10% (10-yr) | 5% (20 yr) | 2% (50-yr) | 1% (100-yr) | 0.5% (200-yr) | 0.2% (500-yr) |
| A17 (391.3) | 584 | 764 | 866 | 1090 | 1223 | 1345 | 1498 | 1606 | 1710 | 1843 |
| B1 (383.4) | 712 | 957 | 1090 | 1379 | 1557 | 1716 | 1911 | 2053 | 2192 | 2370 |
| B1 (374.5) | 728 | 992 | 1130 | 1427 | 1608 | 1773 | 1974 | 2121 | 2265 | 2447 |
| B3 (360) | 732 | 1002 | 1141 | 1441 | 1623 | 1790 | 1994 | 2141 | 2282 | 2466 |
| B5 (353.8) | 761 | 1055 | 1201 | 1521 | 1713 | 1892 | 2107 | 2265 | 2418 | 2614 |
| B5 (349) | 787 | 1118 | 1271 | 1606 | 1809 | 1994 | 2223 | 2387 | 2543 | 2752 |
| B8 (329.2) | 831 | 1231 | 1399 | 1761 | 1985 | 2186 | 2432 | 2611 | 2778 | 2999 |
| B9 (319.1) | 831 | 1231 | 1399 | 1761 | 1985 | 2186 | 2432 | 2611 | 2778 | 2999 |
| C11 (298.1) | 966 | 1167 | 1337 | 1744 | 2008 | 2234 | 2568 | 2803 | 3030 | 3341 |
| C12 (259.6) | 966 | 1167 | 1339 | 1747 | 2008 | 2234 | 2566 | 2801 | 3030 | 3341 |
| C12 (225.5) | 966 | 1167 | 1339 | 1747 | 2008 | 2234 | 2566 | 2798 | 3030 | 3341 |
| C14 (204.6) | 966 | 1170 | 1339 | 1747 | 2008 | 2231 | 2563 | 2792 | 3030 | 3341 |
| C15 (196) | 968 | 1170 | 1339 | 1747 | 2008 | 2229 | 2560 | 2792 | 3030 | 3313 |
| C16 (192.4) | 968 | 1170 | 1339 | 1747 | 2008 | 2229 | 2560 | 2789 | 3030 | 3313 |
| C16 (185.9) | 988 | 1181 | 1364 | 1774 | 2018 | 2195 | 2492 | 2673 | 2860 | 3058 |
| C18 (181) | 988 | 1181 | 1365 | 1776 | 2019 | 2195 | 2492 | 2673 | 2860 | 3058 |
| C19 (177.7) | 991 | 1187 | 1373 | 1793 | 2042 | 2226 | 2532 | 2721 | 2888 | 3115 |
| C20 (166.2) | 994 | 1189 | 1376 | 1795 | 2047 | 2231 | 2540 | 2730 | 2917 | 3143 |
| C21 (158.7) | 994 | 1189 | 1376 | 1798 | 2053 | 2237 | 2549 | 2741 | 2917 | 3143 |
| C21 (150.6) | 1039 | 1277 | 1498 | 2030 | 2367 | 2648 | 3075 | 3367 | 3653 | 4021 |
| D1 (148.9) | 1039 | 1277 | 1501 | 2030 | 2367 | 2651 | 3078 | 3370 | 3653 | 4021 |
| D2 (137) | 1042 | 1280 | 1504 | 2039 | 2379 | 2665 | 3095 | 3392 | 3681 | 4049 |
| D3 (129.2) | 1048 | 1291 | 1521 | 2067 | 2418 | 2716 | 3163 | 3472 | 3766 | 4163 |
| D3 (118.1) | 1051 | 1297 | 1526 | 2082 | 2438 | 2741 | 3195 | 3509 | 3823 | 4220 |
| D5 (107) | 1051 | 1300 | 1529 | 2087 | 2447 | 2753 | 3209 | 3523 | 3823 | 4248 |
| D6 (94.3) | 1054 | 1303 | 1535 | 2097 | 2459 | 2767 | 3229 | 3549 | 3852 | 4276 |
| D6 (89) | 1054 | 1303 | 1535 | 2101 | 2470 | 2787 | 3254 | 3585 | 3908 | 4333 |
| D7 (81.31) | 1051 | 1303 | 1535 | 2104 | 2475 | 2801 | 3277 | 3614 | 3937 | 4390 |
| D9 (71.1) | 1051 | 1303 | 1535 | 2107 | 2481 | 2812 | 3291 | 3634 | 3965 | 4418 |
| D10 (67.6) | 1048 | 1303 | 1535 | 2116 | 2495 | 2838 | 3328 | 3682 | 4050 | 4503 |
| D10 (64.5) | 1048 | 1303 | 1535 | 2115 | 2495 | 2837 | 3327 | 3681 | 4049 | 4502 |
| D11 (56.5) | 1048 | 1303 | 1535 | 2118 | 2503 | 2852 | 3350 | 3712 | 4078 | 4559 |
| D12 (50) | 1048 | 1303 | 1538 | 2121 | 2509 | 2866 | 3370 | 3741 | 4106 | 4616 |
| D12 (36.4) | 1045 | 1303 | 1537 | 2127 | 2523 | 2891 | 3404 | 3786 | 4163 | 4701 |

*Conversion of 1 cms to 35.31 cfs.*

**Table 7. Unregulated Flows (cubic meter per second)**

| Reach (River Mile) | 5% by Duration | Percent Annual Chance Exceedance (Return Intervals) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 67% (1.5 yr) | 50% (2-yr) | 20% (5-yr) | 10% (10-yr) | 5% (20 yr) | 2% (50-yr) | 1% (100-yr) | 0.5% (200-yr) | 0.2% (500-yr) |
| A1 (478.19) | 462 | 583 | 660 | 827 | 926 | 1017 | 1127 | 1209 | 1286 | 1385 |
| A4 (459.72) | 516 | 642 | 725 | 906 | 1014 | 1113 | 1232 | 1320 | 1402 | 1510 |
| A7 (450.34) | 548 | 679 | 768 | 957 | 1071 | 1173 | 1300 | 1391 | 1478 | 1589 |

| Reach (River Mile) | 5% by Duration | Percent Annual Chance Exceedance (Return Intervals) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 67% (1.5 yr) | 50% (2-yr) | 20% (5-yr) | 10% (10-yr) | 5% (20 yr) | 2% (50-yr) | 1% (100-yr) | 0.5% (200-yr) | 0.2% (500-yr) |
| A9 (435.62) | 548 | 679 | 768 | 957 | 1071 | 1173 | 1300 | 1391 | 1478 | 1589 |
| A10 (432.2) | 565 | 700 | 790 | 986 | 1102 | 1207 | 1337 | 1430 | 1518 | 1634 |
| A12 (417.4) | 647 | 809 | 912 | 1133 | 1263 | 1382 | 1529 | 1631 | 1733 | 1861 |
| A17 (391.3) | 647 | 809 | 912 | 1133 | 1263 | 1382 | 1529 | 1631 | 1733 | 1860 |
| B1 (383.4) | 809 | 1078 | 1209 | 1489 | 1659 | 1809 | 1994 | 2124 | 2251 | 2413 |
| B1 (374.5) | 829 | 1117 | 1254 | 1543 | 1716 | 1872 | 2059 | 2195 | 2325 | 2489 |
| B3 (360) | 835 | 1128 | 1266 | 1557 | 1730 | 1889 | 2078 | 2214 | 2345 | 2512 |
| B5 (353.8) | 871 | 1202 | 1348 | 1657 | 1841 | 2008 | 2206 | 2350 | 2489 | 2665 |
| B5 (349) | 903 | 1273 | 1427 | 1750 | 1943 | 2115 | 2328 | 2478 | 2619 | 2806 |
| B8 (329.2) | 959 | 1405 | 1572 | 1923 | 2132 | 2322 | 2549 | 2710 | 2860 | 3058 |
| B9 (319.1) | 959 | 1405 | 1572 | 1923 | 2132 | 2322 | 2549 | 2710 | 2860 | 3058 |
| C11 (298.1) | 1286 | 1566 | 1750 | 2200 | 2492 | 2752 | 3129 | 3401 | 3681 | 4049 |
| C12 (259.6) | 1286 | 1566 | 1753 | 2203 | 2495 | 2755 | 3129 | 3398 | 3681 | 4049 |
| C12 (225.5) | 1286 | 1566 | 1753 | 2203 | 2495 | 2752 | 3126 | 3395 | 3681 | 4021 |
| C14 (204.6) | 1288 | 1569 | 1753 | 2203 | 2495 | 2752 | 3126 | 3392 | 3653 | 4021 |
| C15 (196) | 1288 | 1569 | 1756 | 2203 | 2495 | 2752 | 3123 | 3392 | 3653 | 4021 |
| C16 (192.4) | 1288 | 1569 | 1756 | 2206 | 2495 | 2752 | 3123 | 3392 | 3653 | 4021 |
| C16 (185.9) | 1322 | 1606 | 1795 | 2235 | 2509 | 2735 | 3081 | 3316 | 3540 | 3851 |
| C18 (181) | 1322 | 1606 | 1795 | 2234 | 2509 | 2735 | 3081 | 3316 | 3540 | 3851 |
| C19 (177.7) | 1328 | 1614 | 1804 | 2251 | 2532 | 2764 | 3118 | 3361 | 3596 | 3908 |
| C20 (166.2) | 1328 | 1614 | 1807 | 2254 | 2534 | 2769 | 3126 | 3370 | 3596 | 3936 |
| C21 (158.7) | 1328 | 1617 | 1809 | 2257 | 2540 | 2775 | 3132 | 3378 | 3625 | 3936 |
| C21 (150.6) | 1393 | 1710 | 1928 | 2469 | 2826 | 3155 | 3616 | 3959 | 4304 | 4786 |
| D1 (148.9) | 1393 | 1710 | 1931 | 2472 | 2829 | 3157 | 3619 | 3964 | 4304 | 4786 |
| D2 (137) | 1396 | 1713 | 1934 | 2478 | 2837 | 3169 | 3636 | 3981 | 4333 | 4814 |
| D3 (129.2) | 1405 | 1725 | 1951 | 2506 | 2874 | 3217 | 3698 | 4058 | 4417 | 4927 |
| D3 (118.1) | 1410 | 1730 | 1957 | 2518 | 2892 | 3240 | 3727 | 4092 | 4475 | 4956 |
| D5 (107) | 1410 | 1733 | 1960 | 2523 | 2900 | 3251 | 3738 | 4106 | 4475 | 4984 |
| D6 (94.3) | 1413 | 1739 | 1965 | 2532 | 2910 | 3265 | 3758 | 4129 | 4503 | 5013 |
| D6 (89) | 1413 | 1739 | 1968 | 2538 | 2914 | 3263 | 3752 | 4118 | 4475 | 4984 |
| D7 (81.31) | 1410 | 1739 | 1968 | 2540 | 2917 | 3263 | 3750 | 4109 | 4475 | 4956 |
| D9 (71.1) | 1410 | 1739 | 1971 | 2543 | 2917 | 3260 | 3747 | 4104 | 4475 | 4956 |
| D10 (67.6) | 1410 | 1739 | 1974 | 2549 | 2923 | 3257 | 3738 | 4087 | 4446 | 4899 |
| D10 (64.5) | 1410 | 1739 | 1974 | 2549 | 2922 | 3256 | 3738 | 4086 | 4446 | 4899 |
| D11 (56.5) | 1410 | 1739 | 1977 | 2551 | 2925 | 3254 | 3735 | 4078 | 4417 | 4871 |
| D12 (50) | 1407 | 1739 | 1977 | 2557 | 2928 | 3254 | 3729 | 4069 | 4417 | 4871 |
| D12 (36.4) | 1407 | 1739 | 1981 | 2562 | 2933 | 3251 | 3724 | 4055 | 4389 | 4814 |

*Conversion of 1 cms to 35.31 cfs.*

### 4.2.6. Boundary Conditions

A starting water surface for each profile was either computed by HEC-RAS using the normal depth calculation based on the energy slope for subcritical flow or was defined by water surface results from

adjacent models. Results were incorporated between adjacent models to ensure continuity throughout the study reach. Boundary conditions used in each model are listed in Table 8.

Park County was not part of this hydraulic study. Limited water surface profiles may be available, but may not readily tie into results from the Sweet Grass County results due to difference in terrain surveys, modeling approach and boundary conditions.

**Table 8. Boundary Conditions Used in HEC-RAS**

| County Reach | Upstream Boundary Condition | Downstream Boundary Condition |
|---|---|---|
| Sweet Grass | None | Stillwater water surfaces |
| Stillwater | Sweet Grass water surfaces | Yellowstone water surfaces |
| Yellowstone | None | Treasure water surfaces |
| Treasure | None | Rosebud water surfaces |
| Rosebud | None | Custer water surfaces |
| Custer | None | Prairie water surfaces |
| Prairie | None | Normal Depth |
| Dawson | Prairie water surfaces | Richland and McKenzie water surfaces |
| Richland and McKenzie | None | Normal Depth |

### 4.2.7. Model Scenarios

Four modeling scenarios were executed as individual HEC-RAS plans for each model. By modeling a combination of the Developed and Undeveloped geometries with the Regulated and Unregulated flows, the individual components of human impacts on the terrain and flow regulations, can be evaluated. The scenarios modeled are listed in Table 9.

**Table 9. Scenarios Modeled**

| Scenario | Geometry File | Flow File | Characterization Intent |
|---|---|---|---|
| Developed Floodplain Conditions A | Developed | Regulated | Current conditions |
| Developed Floodplain Conditions B | Developed | Unregulated | Storage reservoirs and irrigation diversions impacts |
| Undeveloped Floodplain Conditions A | Undeveloped | Regulated | Man-made structures impacts |
| Undeveloped Floodplain Conditions B | Undeveloped | Unregulated | Natural conditions |

## 4.3. MODEL CALIBRATION AND SENSITIVITY

Calibration was performed for current conditions, using the Developed geometry and known high and low discharges. Limited calibration data was available for the study reach. USGS gauge stations are sparse, but available rating curves and peak flow-stages were used, if available. High water aerials were taken during the 1997 flood and used to calibrate the Stillwater and Yellowstone Counties. High water marks were collected in limited locations after the May 2011 high water event (Tetra Tech, 2011);

however the marks were surveyed several months after the high water event. A Flood Insurance Study was produced for Yellowstone County and the profiles and maps were used for calibration. Low-flow calibration efforts were made to justify the dimensions of the incorporated underwater channel.

Model stability efforts were reasonably made for all modeled discharges but with a focus on the 1% ACE event. Efforts included ensuring the water surface profiles did not cross each other, profile dips were insignificant, the system did not become super critical and the expansion and contraction of the conveyance path was reasonable.

Sensitivity analyses were performed on the 1-% ACE flood event at select locations. Effects of "n" value adjustments were analyzed for both channel and overbank. Based on the *Engineer's Manual 1110-2-1619*, Figure 5-4, and the observed channel roughness, "n" values for the channel and overbanks were varied by ±0.007. Normal depth was also varied by ±20%, and expansion and contraction coefficients at bridges were varied by ±0.05. Results from the sensitivity analyses were compared to verify that changes to the system yielded minimal impact.

Sensitivity analyses were run in Sweet Grass, Stillwater and Dawson County models and, in general, showed that applying ±0.007 to the overbanks and channels resulted in an approximate water surface elevation difference of 1.5 feet for the 1% ACE event. Similarly, a normal depth adjustment of ±20% yielded a water surface difference of less than 0.5ft at the very downstream reach.

## 4.4. MODELING RESULTS

HEC-RAS outputs for the CEA scenarios include water surface profiles, velocities, and other physical characteristics computed by HEC-RAS. Results were tabulated at each cross section for all profiles modeled in each CEA scenario and provided electronically as a spreadsheet. Some results may be less accurate/more approximate in areas where bathymetry data are not available. Similarly, the models are a one dimensional system used to calculate hydraulic parameters for a large range of stream flows. Therefore, results show a general representation of the entire cross section and may not accurately characterize localized conditions, such as side channel low-flow velocities. Results are listed in Appendix A and B for the Developed A and Undeveloped B metric units, respectively.

The following parameters were calculated and reported for the main channel and total cross section

- Average velocity (ft/s and m/s)
- Average shear stress (lbs/sq ft and N/sq m)
- Total wetted topwidth (ft and m)
- Average depth (as hydraulic depth (ft and m) for areas with bathymetric data)
- Maximum depth (ft and m) for areas with bathymetric data and generalized maximum depth for areas with an estimated channel

By comparing results from the four modeled scenarios, it is possible to characterize the impacts of human influence on the system. Table 10 lists the water surface elevation computed for the 5% ACE at selected locations upstream and downstream of structures. By comparing the resulting elevations of the four scenarios, the impacts of the structures and flow regulations on the river stages are apparent. Similarly, Figure 12 depicts the resulting water surface profiles for the four scenarios at the railroad bridge.

**Table 10. Water Surface Results (elevation meters), 5% ACE, Dawson County**

| Location | River Mile | Developed A | Developed B | Undeveloped A | Undeveloped B |
|---|---|---|---|---|---|
| Five miles upstream of Glendive, MT | 99.68 | 632.77 | 633.13 | 632.77 | 633.13 |
| Upstream of the BNSF RR Bridge in Glendive, MT | 94.57 | 628.46 | 628.90 | 628.07 | 628.38 |
| Upstream of the I-90 Bridge in Glendive, MT | 92.18 | 625.62 | 626.03 | 625.35 | 625.70 |
| Five miles downstream of Glendive, MT | 87.17 | 620.65 | 620.99 | 620.65 | 620.99 |
| Upstream of the Intake Diversion | 73.07 | 609.25 | 609.52 | 608.94 | 609.23 |
| Downstream of the Intake Diversion | 72.83 | 608.60 | 608.92 | 608.60 | 608.92 |

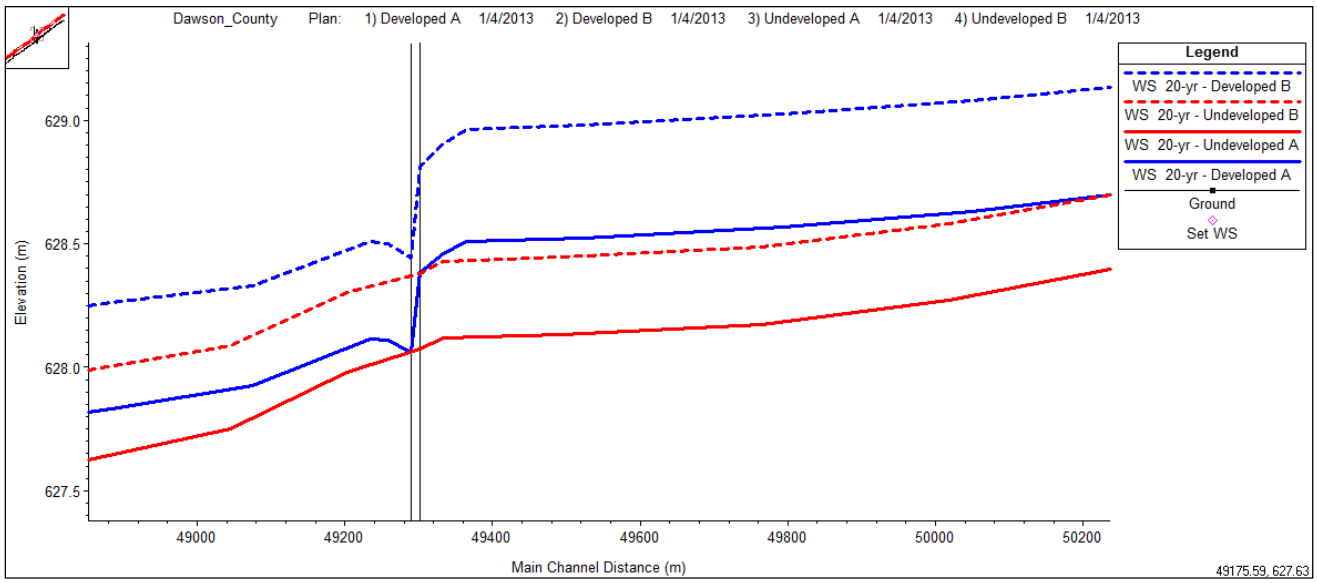


**Figure 12. Water Surface Profiles at the BNSF Railroad Bridge in Glendive, MT.**

## 4.5. MAPPING

Inundated areas maps were generated for select water surface profiles and scenarios to the extent of the survey data and provided to the TAC in electronic format as shapefile polygons, depth grids and 0.2-meter depth interval polygons. The mapping products generated for the hydraulic analysis are listed in Table 11. All mapping products have a projection of NAD 1983 Montana State Plane and NAVD 88 datum, unit meters. Due to ArcMap constraints, all inundation mapping was performed utilizing the 2.5-meter DEMs generated from the LiDAR surveys.

Mapping was performed for each county model utilizing the HEC-GeoRAS ArcMap extension and inundations extend to the county lines to ensure continuity of the study reach. Once initially mapped, backwater areas were identified. Backwater areas connect to the inundated system at one location resulting in a single water surface elevation for the backwater area. Since HEC-GeoRAS mapping is performed using a sloping water surface TIN for the entire river reach, proper mapping of backwater

areas required additional efforts. For Undeveloped conditions, only backwater areas that occurred due to the natural terrain were remapped. Due to the additional level of effort, only backwater areas that affect large areas and several profiles were considered and remapped.

Backwater modeling efforts included one of two approaches, depending on the number of and locations of backwater areas. If several backwater locations were identified in a county reach, a new water surface TIN was generated that incorporated the sloping profile of the main channel and the single elevation of each backwater, and the entire reach was remapped with the GeoRAS extension. If only a couple backwater areas were identified, these locations were remapped individually. The original, sloping backwater was clipped out and the revised backwater was merged with the main channel. This was done for both the inundation shapefiles and the inundation depth grids.

**Table 11. Mapping Products**

| Locations | Profiles | Scenarios | Products |
|---|---|---|---|
| Full Study Reach<br>*(Sweet Grass Co. to confluence)* | 50% (2-yr)<br>20% (5-yr)<br>1% (100-yr) | Developed Floodplain Conditions A<br>Developed Floodplain Conditions B<br>Undeveloped Floodplain Conditions A<br>Undeveloped Floodplain Conditions B | Inundation Shapefiles<br>Depth Grids |
| | 50% (2-yr)<br>20% (5-yr)<br>10% (10-yr)<br>5% (20-yr)<br>2% (50-yr)<br>1% (100-yr)<br>0.2% (500-yr) | Developed Floodplain Conditions A<br>Undeveloped Floodplain Conditions B | Inundation Shapefiles<br>Depth Grids |
| Fisheries Study Reach<br>*(Yellowstone Co. to confluence)* | 5% duration<br>67% (1.5-yr)<br>50% (2-yr)<br>20% (5-yr)<br>10% (10-yr)<br>5% (20-yr)<br>2% (50-yr)<br>1% (100-yr)<br>0.5% (200-yr)<br>0.2% (500-yr) | Developed Floodplain Conditions A<br>Undeveloped Floodplain Conditions A | Inundation Shapefiles<br>Depth Grids<br>Depth Intervals Shapefiles |
| Partial Lower Reach<br>*(Treasure Co. through Prairie Co., Richland)* | 5% duration<br>67% (1.5-yr)<br>50% (2-yr)<br>20% (5-yr)<br>10% (10-yr)<br>5% (20-yr)<br>2% (50-yr)<br>1% (100-yr)<br>0.5% (200-yr)<br>0.2% (500-yr) | Developed Floodplain Conditions A<br>Developed Floodplain Conditions B<br>Undeveloped Floodplain Conditions A<br>Undeveloped Floodplain Conditions B | Inundation Shapefiles<br>Depth Grids |

An example of the backwater mapping result is shown in Figure 13. The image shows the right bank of the Yellowstone River just downstream of the Highway 310 Bridge in Laurel, MT at the Clarks Fork confluence for the Developed Floodplain Conditions A 1% ACE. Traditional GeoRAS mapping extends the calculated water surface profile from the main channel across the entire cross sections, which are depicted as green lines, and results in an inundation boundary shown in orange. Upon close examination, the inundated area only connects to the main channel at one downstream location. The elevation at the connecting point was used to reprocess the water surface and the resulting main channel and backwater inundation area is shown in blue. Tributaries to the Yellowstone River were not part of this study; therefore the final backwater inundation only represents the impacts from the Yellowstone River flood event.

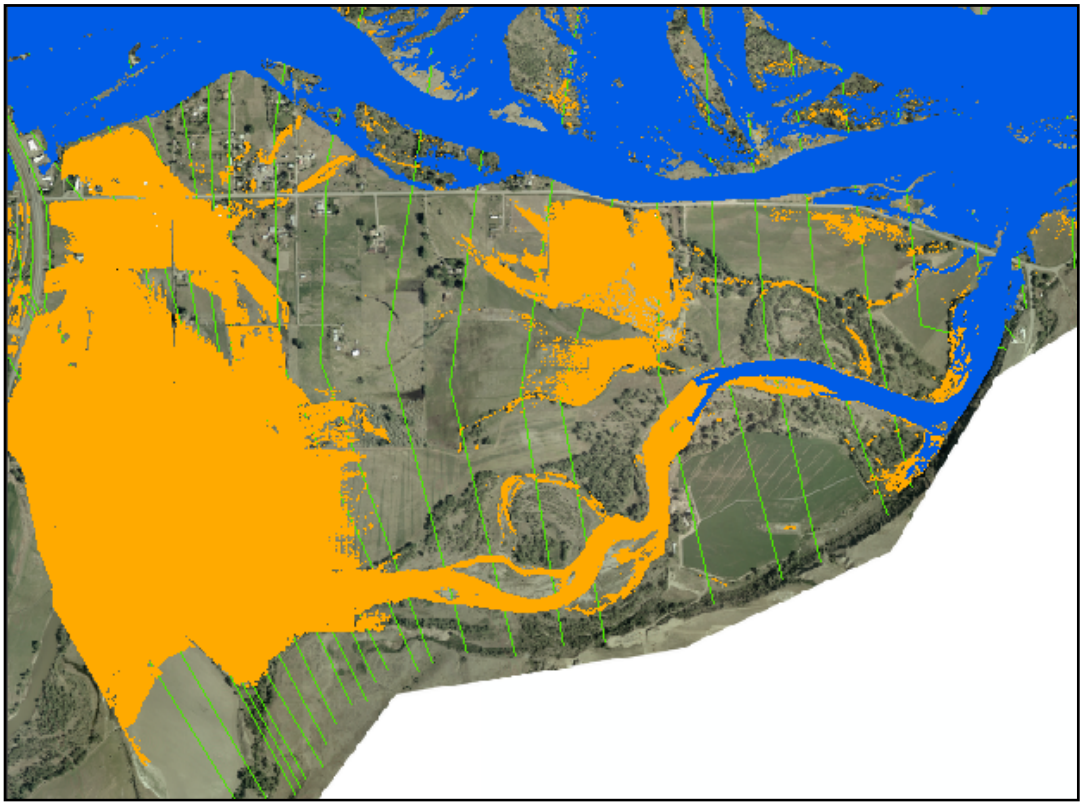

**Figure 13. Backwater Inundation at Clarks Fork Confluence**

During mapping editing, excess ponding areas and disconnected floodplains were removed if not directly connected to the main channel. Some areas appeared connected through a culvert or a bridge that was not removed in the survey data. If a culvert, bridge or other connection point is evident in the aerials or survey data then the area was considered connected and inundated. If a connection is uncertain, then the inundated area was considered disconnected and removed. Figure 14 shows two examples of ponding. The image on left shows lagoons, in orange, as inundated. However, they are not connected to the main channel and were removed from the floodplain resulting in the final inundation boundary in blue. In contrast, the image on the right depicts an area that is disconnected from the main channel due to the road embankments. However, a culvert and drainage ditch are apparent in the aerials and were included as inundated floodplain.

Undeveloped geometry mapping required additional efforts. Although the structures and station-elevation points were removed in the HEC-RAS models, the man-made features were not modified in the terrain data files. Therefore, manual adjustments were made to the inundation shapefiles in areas where man-made structures are present. For example, the presence of a road embankment may detach an inundated area of the floodplain from the main channel, and these areas were connected. Only disconnected areas or backwater locations due to the natural terrain were removed or remapped, respectively. Similarly, inundations boundaries were smoothed where any structure (e.g., bridge embankment, fishing access, etc.) causes an unnatural boundary. Although the inundation shapefiles were edited, the depth grids show depths with respect to structures since they were generated from the DEMs.

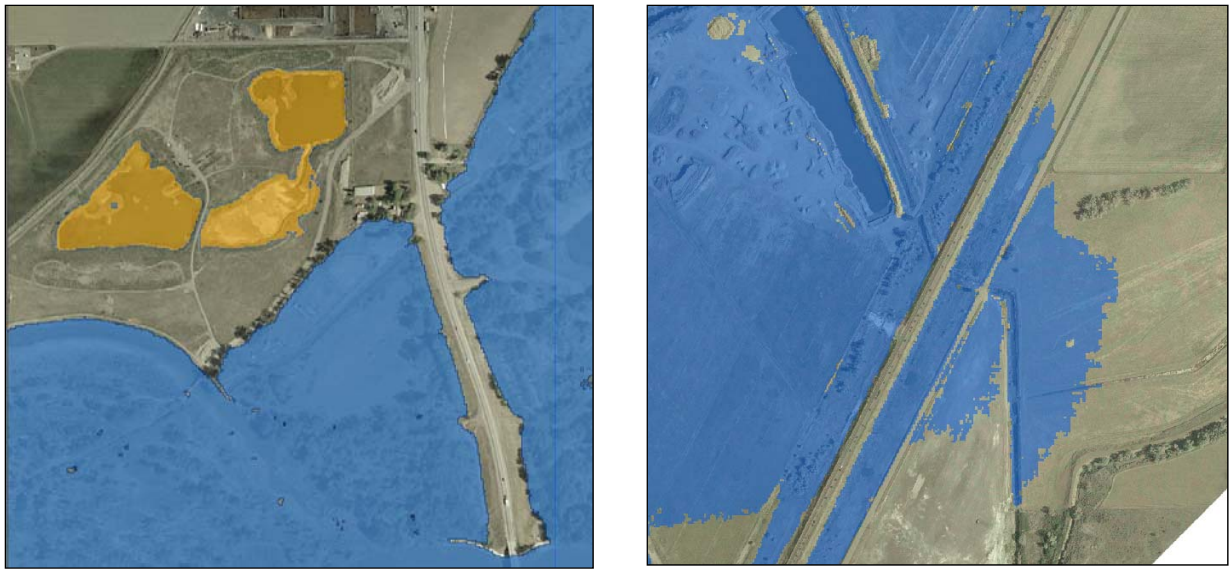

**Figure 14. Ponding Areas Examples.** The image on the left (RM 371.2) shows ponding areas that are disconnected and removed from the floodplain maps. The image on the right (RM 361.0) shows an area connected to the main channel via a culvert.

Figure 15 depicts the mapping results for the Undeveloped conditions for Forsyth, MT. The image on the left compares the edited inundation boundary of the Developed condition in blue to the Undeveloped condition in orange for the 1% ACE Regulated flow. The Federal Levee is located on the right overbank and significantly restricts floodplain conveyance. The image on the right depicts the same area as a depth grid for the Undeveloped condition. The structures captured in the LiDAR survey are apparent and were not adjusted for the final depth grid. However, these features were edited for the inundation shapefile to show the areas spanning the structures as flooded.

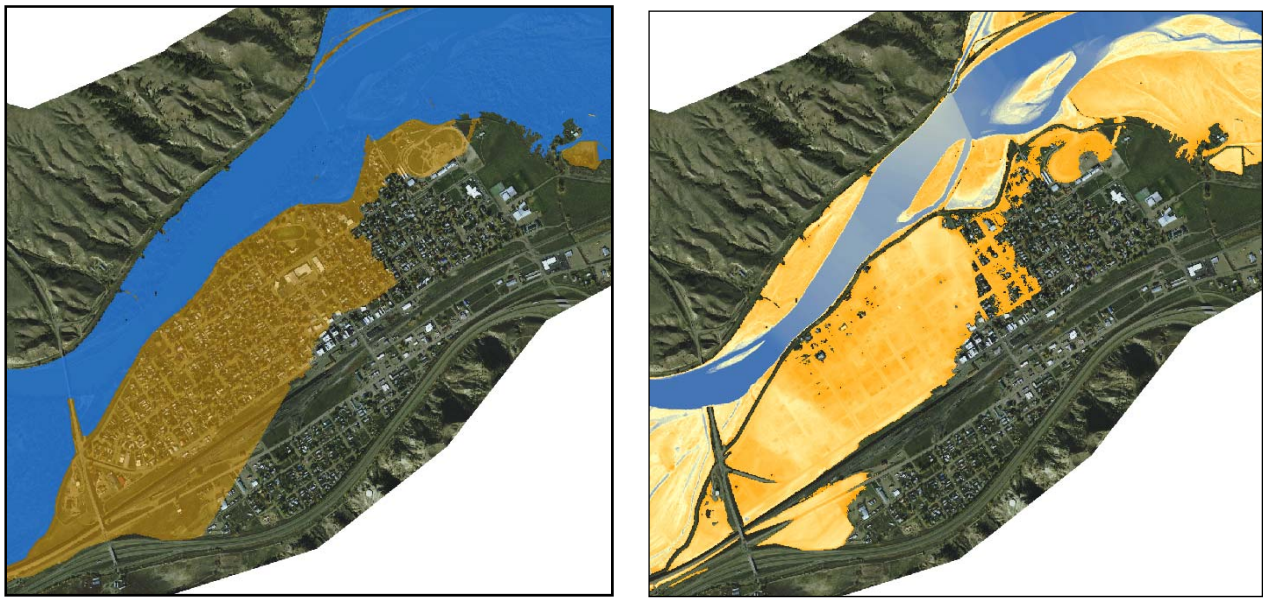

**Figure 15. Undeveloped Conditions Shapefile and Depth Grid**

Depth interval polygons were generated from the final depth grids for the Regulated flow scenarios. A 0.2-meter interval was selected to support the fisheries study component of the CEA. The final depth grids were reclassified with 0.2-meter intervals and converted to a color-graded shapefile polygon. The shapefile's attributes table was formatted to incorporate the depth ranges. In areas without bathymetry data, the actual channel depth is uncertain so the depth is reported as a value greater than at a known survey point (e.g., channel depth may be reported as > 2.2 meters). Figure 16 shows the depth interval shapefile for an area in Custer County just upstream of the Kingsley Bridge. This area does not contain bathymetric data so the channel depth is defined as greater than 2.6-meters. The final depth grids for the Developed Floodplain Conditions A and Undeveloped Floodplain Conditions A were used to generate the depth intervals.

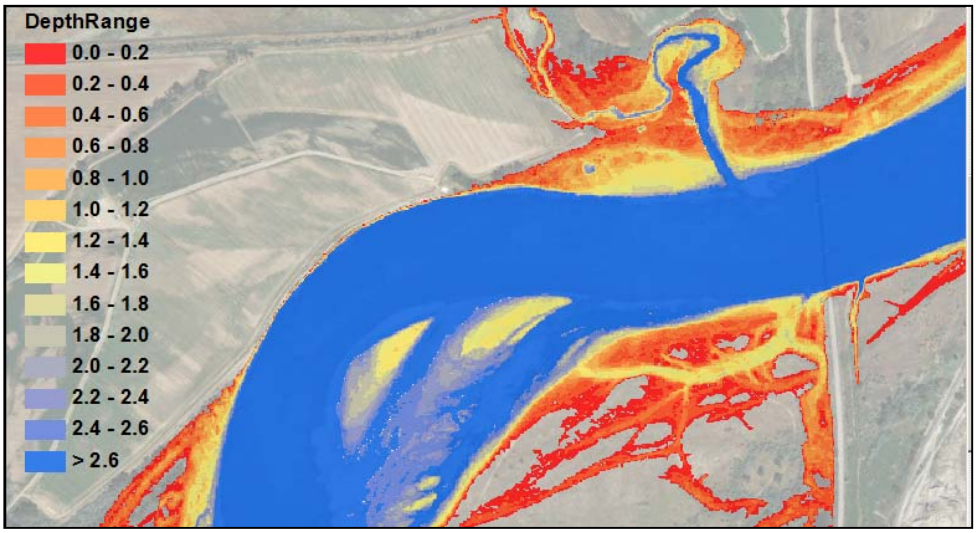


**Figure 16. Depth Interval Shapefile for Custer County (RM 172.3)**

## 4.6. MAPPING RESULTS

Inundation shapefile have been generated for various locations, scenarios and profiles, as listed in Section 4.5, Table 11. From these mapping results, comparisons can be made to characterize the impacts that man-made structures, flow regulation, or both have on the Yellowstone River Corridor. Isolated floodplain shapefiles will be generated as part of the CEA by comparing the flood boundary shapefiles of the described scenarios to characterize the impacts that regulated hydrology and physical structures have had on the floodplain and will include the following comparisons. The isolated floodplain comparisons are to be performed for the 50%-, 20%- and 1%-ACE utilizing the four modeled and mapped scenarios.

**1)** ***Isolated Floodplain Due to Flows*** shapefile will be generated by intersecting the Developed Floodplain Conditions A with the Developed Floodplain Conditions B to evaluate the impact of regulated flows on the flood boundaries.

**2)** ***Isolated Floodplain Due to Physical Structures*** shapefile will be generated by intersecting the Developed Floodplain Conditions A with the Undeveloped Floodplain Conditions A to evaluate the impact of physical structures on the flood boundaries. In order to support floodplain management efforts under current hydrologic conditions, it is important to compare how current, regulated flows have been isolated from the modern floodplain solely by physical features. This will help identify areas of potential floodplain re-connection or wetland restoration.

**3)** ***Historic Floodplain Isolations*** shapefile will be generated by intersecting the Developed Floodplain Conditions A with the Undeveloped Floodplain Conditions B to evaluate the impact of combined regulated flows and physical structures on the flood boundaries. The comparison will allow an assessment of the cumulative effects of both hydrology and physical features on floodplain access.

An example of Historic Floodplain Isolation is depicted in Figure 17 for Reaches C13 and C14 in Custer County. The orange inundation area represents the area of natural floodplain that has been restricted due to human development and flow regulation.

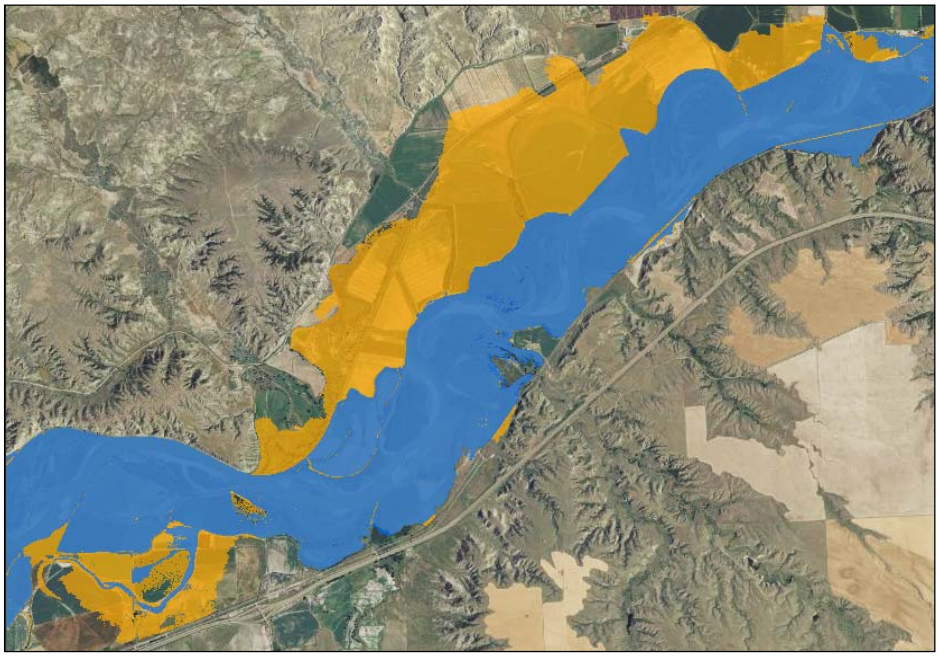

**Figure 17. Historic Floodplain Isolation Example in Custer County**

## 4.7. DIFFICULTIES AND ASSUMPTIONS

Topographic data was provided as TINs and DEMs. When performing hydraulic analyses, utilization of the TINs are preferred due to the slight increased level of accuracy over the generated DEMs. However, several of the TINs supplied contained errors and could not be read by the ArcMap software. For consistency throughout the study, the DEMs were used for the majority of the modeling and all of the mapping products. The DEMs were created using 2.5-meter pixels. This high resolution resulted in minimal added error.

Portions of the floodplain terrain were not fully captured or were incomplete. In areas of incomplete data, cross sections were spaced further than the desired 1,000 feet, were modeled by manual adjustments within HEC-RAS using USGS topology maps, or the DEMs were patched with USGS digital terrain data.

Mapping discrepancies were noted in the areas of Billings and Forsyth, Montana. In the developed geometries, inundation occurred west of Interstate 90 within the City of Billings due to connection points across the embankment which is apparent in the terrain data and aerial photographs. However, Federal Emergency Management Agency mapping indicates this area as unaffected (FEMA, 2013.) For this analysis, the final mapping products closely match that of the FEMA maps. However, the area behind the interstate was mapped as potentially inundated pending additional surveys at the connection points. Similarly, the 0.2% ACE flood showed overtopping of the Forsyth Levee at a very small width. The area behind the levee was mapped as a potentially inundated area pending additional survey data of the levee crest.

In some mapping products, the edges of the floodplain shapefiles and depth grids do not line up exactly with the source DEMs. This was observed between the shapefiles and corresponding depth grids, between individual profiles and between scenarios. The error varies between products and is less than one pixel (2.5-meter). The source of the error appears to occur during the extraction of the shapefiles and depth grids from the HEC-GeoRAS geodatabase. Although the error is small, caution should be used when comparing mapping products.

The HEC-RAS program is a one-dimensional model that was used to represent a wide floodplain and a range of stream flows. The one-dimensional computations assume a constant water surface elevation across the entire cross section. In reaches with large islands, this assumption may not be accurate and would warrant a split flow analyses. Similarly, ineffective flow area locations may be unique to each stream flow based on water surface elevations and terrain conditions. Therefore, the single or dual geometry files used in this analysis may not accurately characterize all flow conditions and results should be considered a general representation of the system.

The Undeveloped geometry created for this study is a generalized representation of the natural topography of the floodplain. The use of the developed terrain to generate the undeveloped conditions is a significant limitation to the hydraulic analysis. Although manmade structures were removed within the model and maps, some components such as inhibited channel migration and floodplain aggradation and degradation, which may have occurred extensively under natural conditions, could not be represented without significant further analysis and was beyond the scope of this study.

Technical review comments and responses are included in Appendix D. The review and comments were conducted by the USGS WY-MT. Responses were included and shown in green text. In general, suggested model adjustments would impact water stages only minimally and locally and were not incorporated. However comments should be considered by future users of the HEC-RAS models.

## 5. REFERENCES


Chris Ransome & Associates, Inc. October 2004. Hydrographic Survey Report, Yellowstone River, Dawson, Yellowstone and Stillwater Counties Montana.

DTM Consulting, Inc. 2006. U.S. Geologic Survey Circa 1950s aerials, developed and geo-referenced as part of the Yellowstone River Cumulative Effects Study.

DTM Consulting, Inc. and Applied Geomorphology, Inc. 2008. Yellowstone River Riparian Vegetation Mapping Report Draft.

DTM Consulting, Inc. and Applied Geomorphology, Inc. 2009 Yellowstone River Channel Migration Zone Mapping Report.
.
Federal Emergency Management Agency. January 1980. Flood Insurance Study, City of Glendive, Montana.

Federal Emergency Management Agency. November 2013. Flood Insurance Rate Maps: City of Billings (Panel 1290E) and Incorporated Areas at the City of Laurel (Panels 1420E and 1440) and City of Huntley (Panels 1040 and 1045).

Merrick and Company. October 2005. Aerials, LiDAR surveys, triangulated irregular network (TIN) datasets and 2.5-meter Digital Elevation Models for the Yellowstone River Corridor, Stillwater, Yellowstone, and Dawson Counties, Montana, collected 2004.

Montana Department of Natural Resources and Conservation. November 2005. Lower Yellowstone River Bathymetric Data Development to Support Geomorphic and Aquatic Habitat Analysis.

Montana Natural Resource Conservation Service. 2006. Vegetative cover shapefile.

Shields, R.R., White, M.K., Ladd, P.B., and Chambers, C.L., 1997, Water resources data, Montana, water year 1996: U.S Geological Survey Water-Data Report MT-96-1.

Tetra Tech. Inc. October 2011. High water marks for the Yellowstone River, May 2011 flood event, collected for the US Army Corps of Engineer, Omaha District.

U.S. Army Corps of Engineers. August 1996. Engineering and Design. Engineer Manual 1110-2-1619, Risk-Based Analysis for Flood Damage Reduction Studies.

U.S. Army Corps of Engineers, Omaha District. April 2009. Lower Yellowstone Project Fish Passage and Screening, Preliminary Design Report, Draft.

U.S. Army Corps of Engineers, Omaha District. September 2011. Yellowstone River Corridor Study, Upper Yellowstone River Hydrology.

U.S. Department of Agriculture, Farm Service Agency. 2013. Google Earth Imagery.

U.S. Geologic Survey. November 2013. Streamflow Statistics for Unregulated and Regulated Conditions for Selected Locations on the Yellowstone, Tongue, and Powder Rivers, Montana, 1928–2002.

Woolpert, Inc. 2010. Aerials, LiDAR surveys, triangulated irregular network (TIN) datasets and 2.5-meter Digital Elevation Models for the Yellowstone River Corridor, Custer, Prairie, Richland, Rosebud, Sweet Grass, and Treasure Counties, Montana, and McKenzie County, North Dakota, collected 2007 by Eisenbraun and Associates.

Zelt, R.B., Boughton, G.K, Miller, K.A., Mason, J.P., and Gianakos, L.M., 1999, Environmental setting of the Yellow-stone River basin, Montana, North Dakota, and Wyoming: U.S. Geological Survey Water-Resources Investigations Report 98–4269.