HYDRAULIC MODELING AND MAPPING OF THE YELLOWSTONE RIVER TO SUPPORT CUMULATIVE EFFECTS ASSESSMENT

Laurel J. Hamilton, E.I., Hydraulic Engineer, U.S. Army Corps of Engineers, Omaha, NE, laurel.j.hamilton@usace.army.mil; Kevin K. Adams, P.E., Hydraulic Engineer, U.S. Army Corps of Engineers, Omaha, NE, kevin.k.adams@usace.army.mil; Megan A. Splattstoesser, Geographer, U.S. Army Corps of Engineers, Omaha, NE, megan.a.splattstoesser@usace.army.mil; Roger L. Kay, P.E., Hydraulic Engineer, U.S. Army Corps of Engineers, Omaha, NE, roger.l.kay@usace.army.mil

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Abstract: Hydraulic modeling was performed in support of the Yellowstone River Corridor Cumulative Effects Assessment (CEA). The CEA is a joint effort of the Yellowstone River Conservation Districts Council and the U.S. Army Corps of Engineers, Omaha District (Omaha District). The interdisciplinary study examines hydrologic, hydraulic, geomorphic, biologic and socioeconomic characteristics of and impacts on the Yellowstone River and adjacent floodplain in a 565-mile reach from Gardiner, Montana, to the confluence with the Missouri River in western North Dakota. The purpose of the study is to perform an assessment of the cumulative impacts 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 is intended to detect changes associated with two potential drivers of cumulative effects: altered (regulated) hydrology due to water resources development within the Yellowstone River basin and physical alteration (development) of the Yellowstone River floodplain. One facet of the cumulative impacts assessment is to characterize 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 "pre-historic" conditions.

The hydraulic analysis utilized the modeling software HEC-RAS and geospatial software ArcGIS and the Geo-RAS extension for model geometry development and floodplain mapping. Flow information was obtained from an intensive hydrology study of the basin performed jointly by Montana U.S. Geological Survey (USGS) and Omaha District. The hydraulic model was developed to evaluate human impacts by generating 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 are 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 represent natural conditions). Four scenarios were modeled using these input files.

Comparison of the results from modeling and mapping the combinations of the geometric and hydrologic conditions provided valuable information for a range of flow frequencies that will

assist the CEA 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 and floodplain inundation and how that frequency may have changed over time due to channel modifications and water resourcing.

INTRODUCTION

The Yellowstone River is one of the longest free-flowing rivers in the lower 48 states (USGS, 2013). The river corridor provides for various sized communities; supports agricultural (range and crop), industrial, commercial and recreational uses; and is home to abundant wildlife. 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.

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 (Figure 1). Within the study 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).

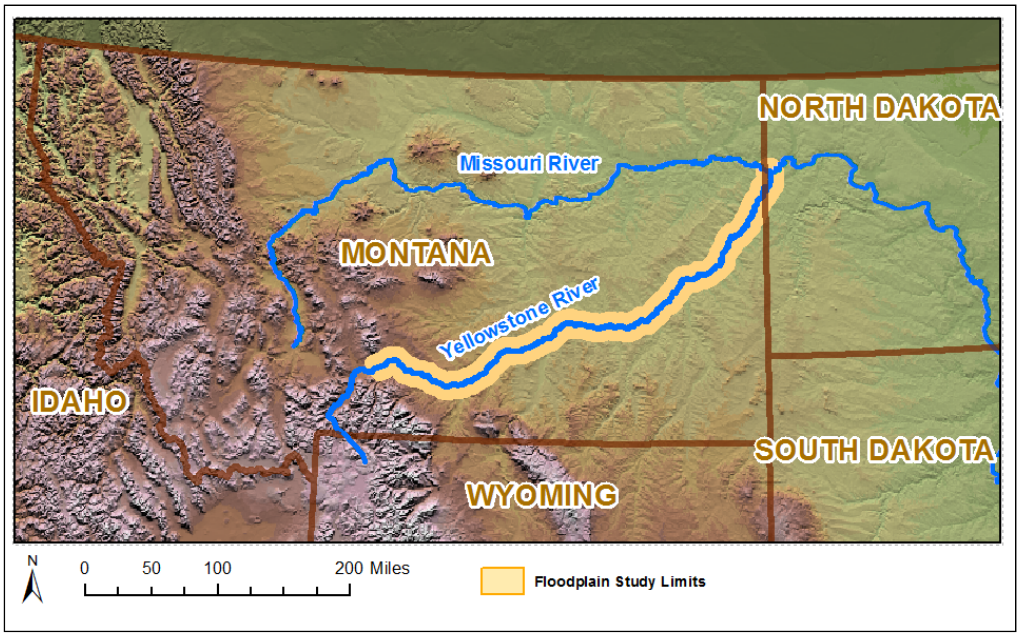

Figure 1 Hydraulic Study Location and Extents

MODELING APPROACH

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 Version 4.1 (USACE, 2010) utilizing steady-state and subcritical flow computations to calculate water surface profiles and associated hydraulic parameters. 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.

Hydrologic Data: The hydrologic analysis was conducted as two studies. The hydrology for the reach upstream of the Big Horn River was conducted by the Omaha District (USACE, 2011). The study downstream of the Big Horn River was conducted by the USGS (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 of observed flows was developed for the period of record, historical depletions (including reservoir holdouts) recorded by the Bureau of Reclamation were added to the observed flow dataset, and Bulletin 17B methodology was used to generate the Unregulated peak-flow frequency data. Then, the depletions recorded in 2002 were subtracted from the Unregulated dataset to generate the Regulated peak-flow data. 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 event. 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.

Topographic Data: Topographic data was collected in 2004 and in 2007 as Light Detection and Ranging (LiDaR) data and supplied as Triangulated Irregular Network (TIN) data file. 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 for select study reaches. Floodplain and bathymetric data were merged and provided in TIN format and 2.5-meter Digital Elevation Models (DEMs). All elevations are referenced to the North American Vertical Datum of 1988 (NAVD88) unit meters. Aerial imagery was collected in 2004 and 2007.

Hydraulic Model: Nine individual HEC-RAS projects were created covering the ten counties included within the study. 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. 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. The corresponding ArcGIS software extensions 3D Analyst and Spatial Analyst were also utilized for geometry development.

In HEC-GeoRAS, an import file was created 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. These GeoRAS layers were combined with the terrain elevation files, and the software calculated the downstream reach lengths for overbanks and channel, extracted cross-sectional station and elevations points, and generated the HEC-RAS input file.

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 and often dog-legged to adequately represent the overbanks and sinuous channel as a one-dimensional system. Cross sections were extended to high ground to ensure capture of elevation data for the 0.2% ACE.

Additional GeoRAS layers were incorporated. 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. 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 HEC-RAS, the structures such as bridges, levees and diversion dams were characterized, channel bank locations were edited and river mileage was included. The roughness values imported from GeoRAS were verified for the channel and overbanks and adjusted where appropriate. 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 placed at locations defining the main channel and typically assigned elevations between the 67% ACE and 0.2% ACE profiles.

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 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.

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). Yellowstone River structures requiring manually-entered descriptions in HEC-RAS include bridges and low head dams. Bridge surveys were performed by the Montana USGS between 2005 and 2009 and included bridge dimensions, chord elevations, and pier and channel descriptions. A total of 39 bridges were modeled, and 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).

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.

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.

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 estimate 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 2 shows a cross section in Billings, MT at River Mile 366.2. The cross section, high-lighted in red on the top image, is depicted in the bottom image. 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.

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 such as embankments and levees 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.

Most 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 undeveloped terrain.

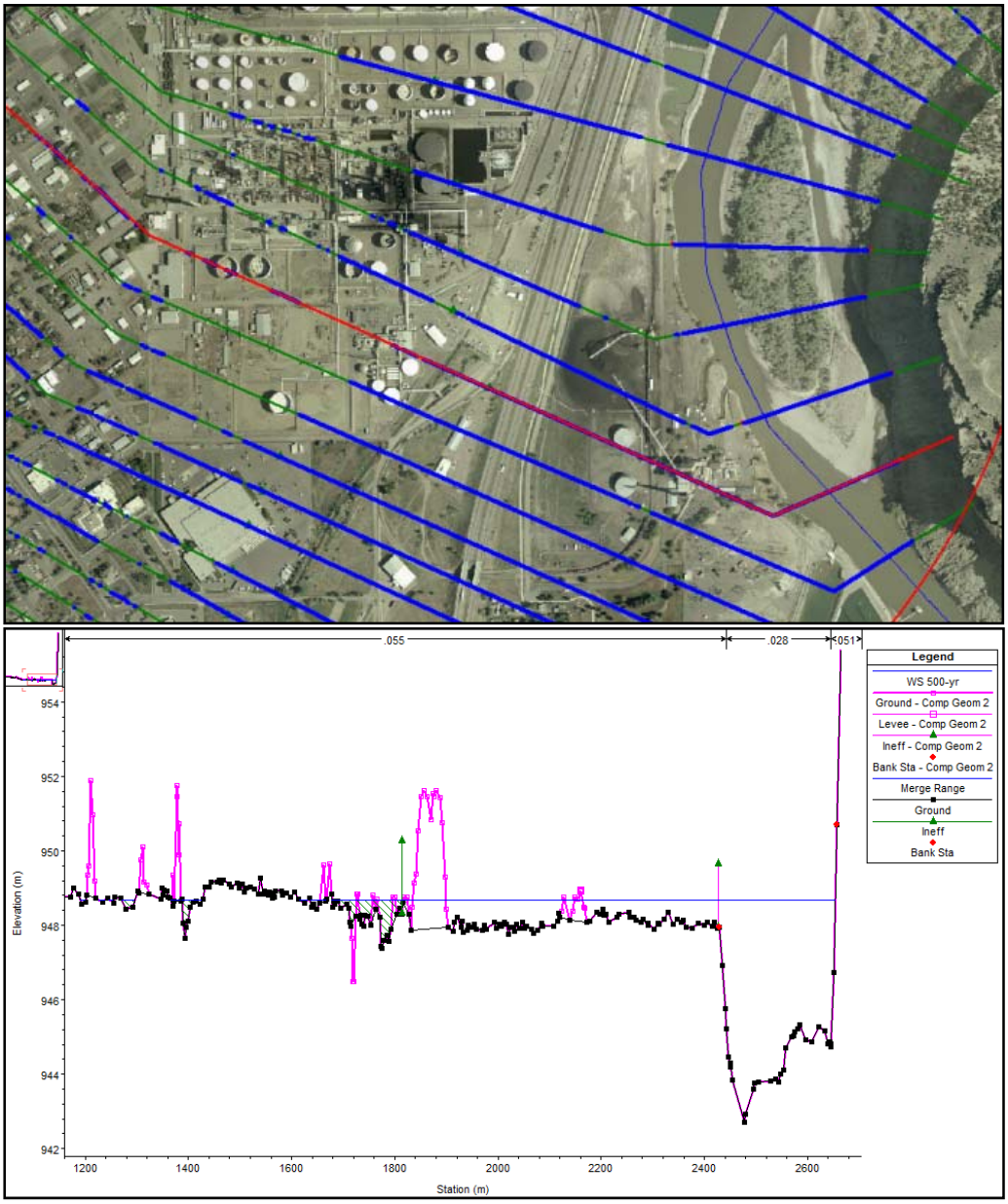

Figure 2 Removed Man-Made Structures in Undeveloped Geometry File, Billings, MT

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 3 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.

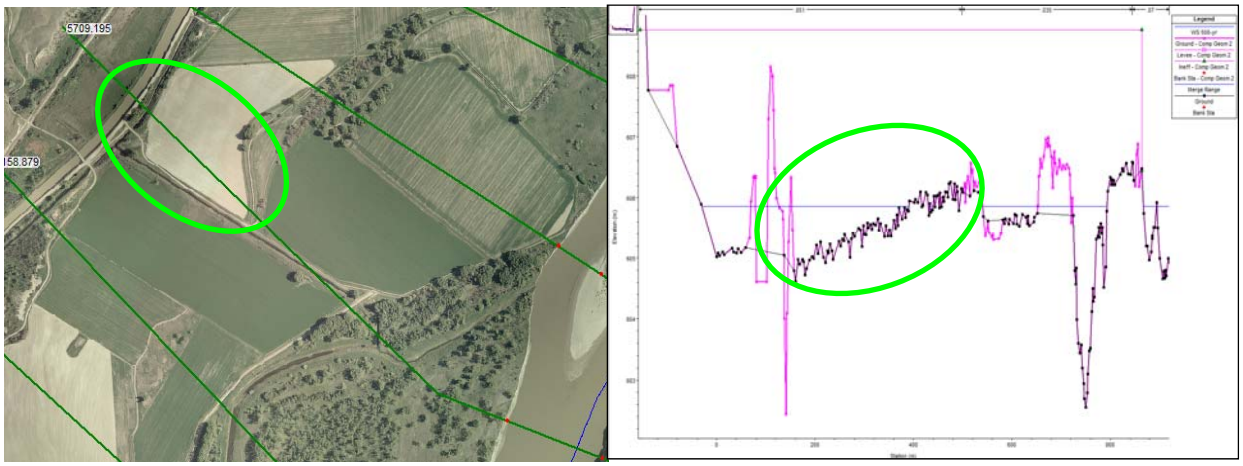

Figure 3 Undeveloped Terrain Uncertainty

Model Plans: 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.

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 1.

Table 1 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

By comparing results from the four modeled scenarios, it is possible to characterize the impacts of human influence on the system. Table 2 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 4 depicts the resulting water surface profiles for the four scenarios at the railroad bridge in Glendive, MT.

Table 2 Water Surface Results (elevation meters), 5% ACE (20-yr), Dawson County

Location	River Mile	Develop A	Develop B	Undevelop A	Undevelop B
Five miles upstream of Glendive	99.68	632.77	633.13	632.77	633.13
Upstream of the BNSF RR Bridge in Glendive	94.57	628.46	628.90	628.07	628.38
Upstream of the I-90 Bridge in Glendive	92.18	625.62	626.03	625.35	625.70
Five miles downstream of Glendive	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

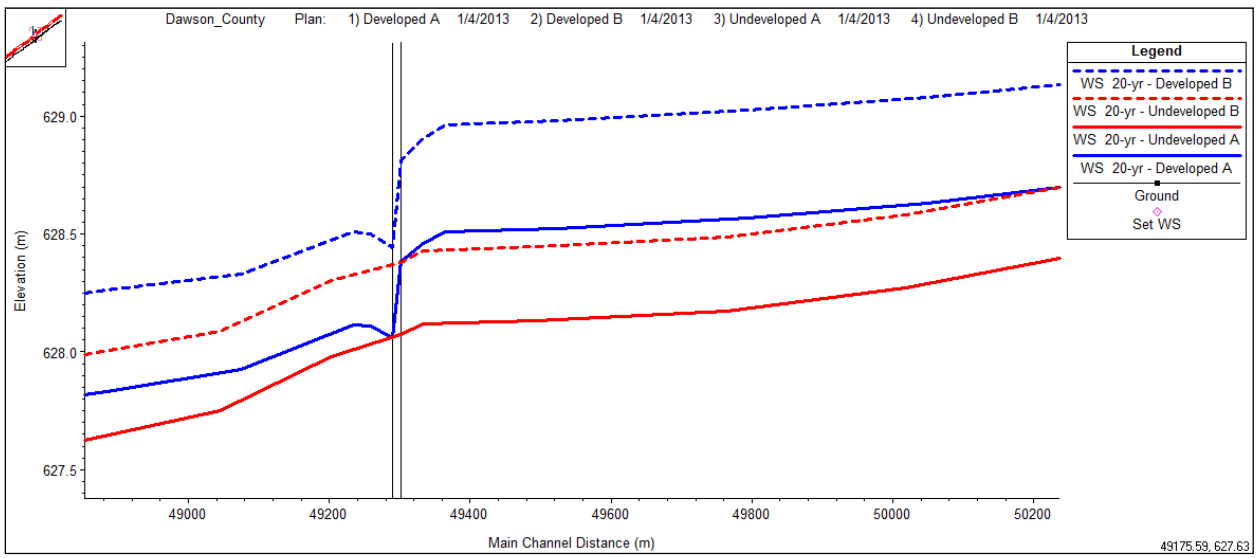

Figure 4 Water Surface Profiles at the BNSF Railroad Bridge in Glendive, MT

MAPPING APPROACH

Inundation maps were generated for select water surface profiles and scenarios to the extent of the survey data and as shapefile polygons, depth grids and 0.2-meter depth interval polygons. 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 within 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 flood profiles were considered and remapped.

Backwater modeling efforts included one of two approaches, depending on the number 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 elevation was merged with the main channel. This was done for both the inundation shapefiles and the inundation depth grids.

An example of the backwater mapping result is shown in Figure 5. 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 (shown 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.

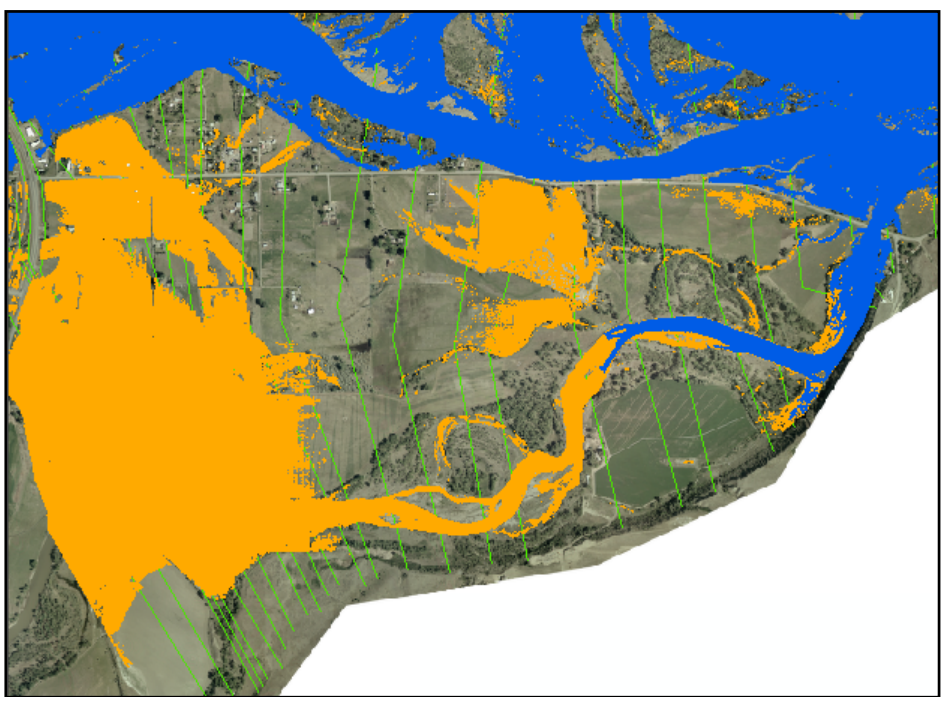

Figure 5 Backwater Inundation Remapped at Clarks Fork Confluence

During mapping editing, excess ponding areas and disconnected floodplains were removed if they were 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 mapped as inundated. If a connection was uncertain, then the inundated area was considered disconnected and removed.

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 manually connected to reflect the Undeveloped inundation extent. 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 point, etc.) causes an unnatural boundary. Although the inundation shapefiles were edited, the depth grids reflect the depths with respect to structures since they were generated from the DEMs.

Figure 6 shows the mapping results for the Undeveloped conditions at 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 south overbank and significantly restricts floodplain conveyance, apparent in the image on the left. 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.

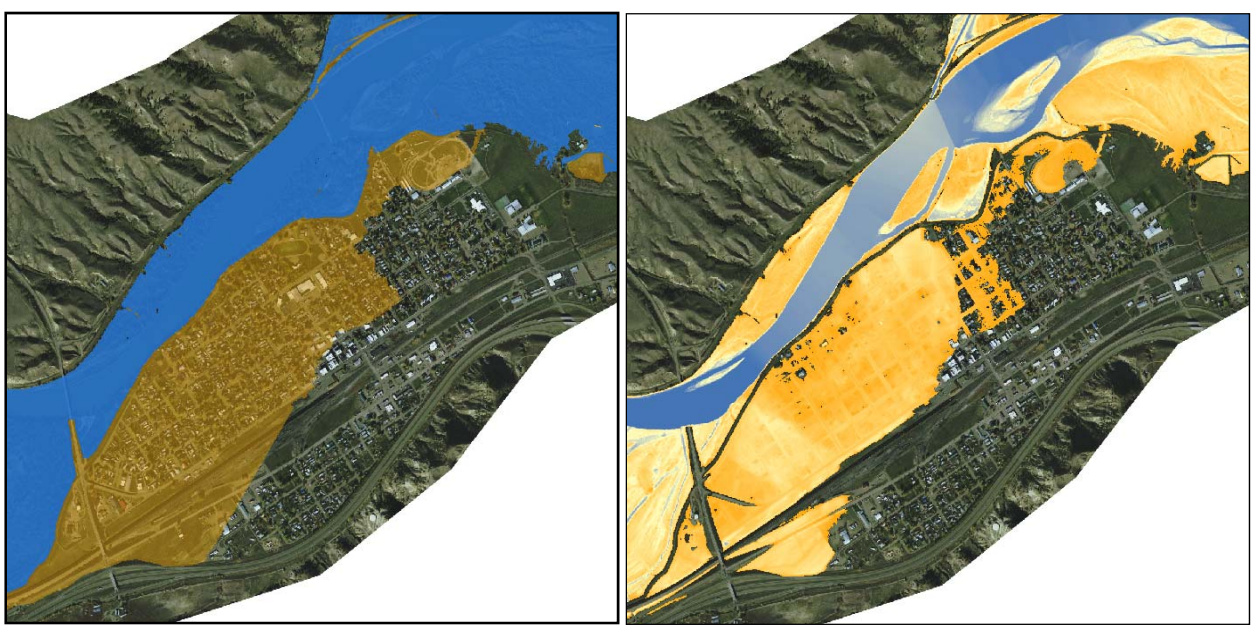

Figure 6 Undeveloped Conditions Shapefile and Depth Grid

DIFFICULTIES AND ASSUMPTIONS

Topographic data was provided as TINs and DEMs. When performing the 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.

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.

CUMULATIVE EFFECTS ASSESSMENT

Comparison of the results from modeling and mapping the combinations of the geometric and hydrologic conditions will provide valuable information for a range of flow frequencies 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, resulting 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 and floodplain inundation and how that frequency may have changed due to channel modifications and water resourcing.

Inundation shapefiles have been generated for select locations, scenarios and profiles. 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 floodplains due to 1) flow regulation, 2) physical structures, and 3) both flow regulation and physical structures were evaluated as part of the CEA to characterize the impacts humans have had on the floodplain for the 50%-, 20%- and 1%-ACE. An example of Historic Floodplain Isolation is depicted in Figure 7 at the Rosebud-Custer County Line for the 1% ACE. The orange polygon represents the area of natural floodplain that is no longer inundated due to human development and flow regulation, and the blue polygon represents the current floodplain inundation.

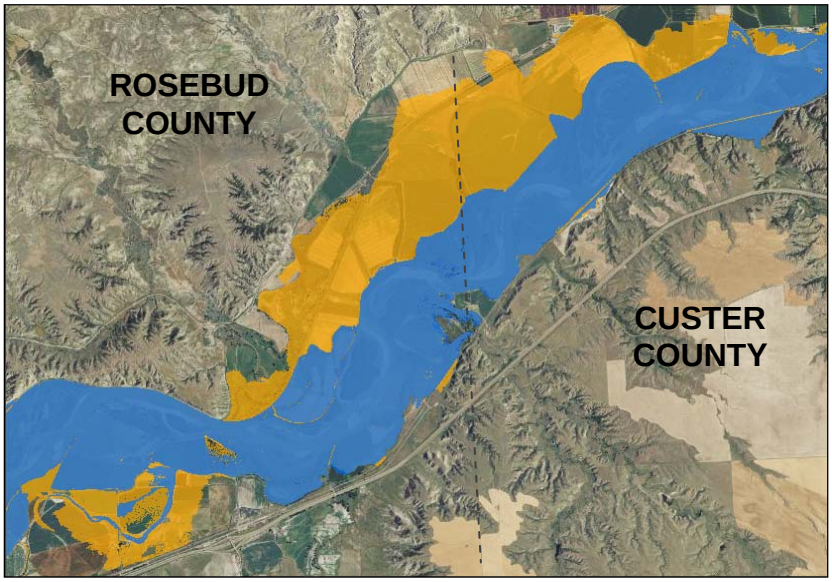

Figure 7 Historic 1% ACE Floodplain Isolation Example at the Rosebud-Custer County Line

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