US Army Corps of Engineers®
St. Paul District

Appendix C – Hydrology and Hydraulics

Riverbank Stabilization Project Feasibility Report and Integrated Environmental Assessment

Section 203 Tribal Partnership Program

2022

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1.0 Project Description

The study area is located along the right descending bank of the Minnesota River just south of Morton, MN. As much as 180 feet of lateral bank migration has occurred between 1992 and 2019 resulting in significant loss to Tribal Lands, prompting the Lower Sioux Indian Community to reach out to USACE MVP in 2019 for assistance in identifying drivers of the erosion and developing erosion countermeasure solutions.

1.1 Minnesota River at the Study Area

The Minnesota River at the study area appears to be in flux; both from a hydrologic and morphological perspective. The Minnesota River Basin Interagency Study (USACE, 2020) evaluated hydrologic, sediment, and nutrient runoff response to historic, existing, and probable future conditions. The Interagency Study noted that there were clear increasing trends in flow at all of the main stem gages along the Minnesota River. A USGS gage 1.5 miles upstream of the study area (USGS 05316580 Minnesota River at Morton, MN) has captured stage and flow data since 01 October 2000 but does not have a period of record long enough to identify statistically significant trends in flows at the study site and was not used within the Interagency Study.

A geomorphic assessment of the river in the vicinity of the study area noted the presence of downstream channel cutoffs that had reduced the channel length by roughly 6,000 feet over a 23-year period from 1992 to 2015. This combination of downstream channel cutoffs and an increasing trend in annual peak flows indicate that a “no action” condition in the study area would likely result in further lateral migration of the channel and further land loss for the Lower Sioux Indian Community.

One constraint that influenced project alternative development was the fact that the study area falls within a Regulatory Floodway as defined by the Flood Insurance Study for Renville County, Minnesota and Incorporated Areas (Effective: September 25, 2009) (FEMA, 2009). Legal requirements of a Regulatory Floodway state that any projects that fall within the floodway boundary are held to a “no-rise condition.” The no-rise condition as defined by the state of Minnesota states that project features within a Regulatory Floodway must cause no more than a 0.005-foot increase in water surface elevations during the 100-year flood event.

1.2 Watershed Information

The Minnesota River Valley was formed by the glacial River Warren, which flowed from the south end of Lake Agassiz approximately 9,000 to 12,000 years ago. The Minnesota River is an “underfit” river because the watercourse is small compared to the large valley cut by the glacial River Warren (Waters, 1977). Sandy terraces and potholes are present far above the existing river, which is evidence the river was once much larger than it is presently (Waters, 1977). Retreating glaciers formed the modern water course. After the glacier retreated past the continental divide at Brown’s Valley, water no longer flowed from the glacial lake though the Minnesota River Valley. The valley is large compared to the water course and has sections which are five miles wide and locations where the river lies 250 feet below the bluffs (Waters, 1977).

The Minnesota River flows a total distance of 355 miles, of which 270 miles extend from the outlet of Lac qui Parle Reservoir to the Minnesota River’s confluence with the Mississippi River (Waters, 1977). The headwaters of the Minnesota River Basin consist of a series of natural, large lakes including Big Stone Lake, Marsh Lake, and Lac qui Parle Lake. Although these lakes are naturally formed, dams have been built to control fluctuations in lake level to prevent flooding and to provide recreational opportunities.

The Minnesota River Basin is comprised of flat plains leading to steep bluffs near the mainstem Minnesota River. The bluffs are steep enough that tributaries have formed rapids, waterfalls, and deep gorges along the mainstem of the river. Rivers in the watershed are underlain by alluvial materials like sand and silt which are easily erodible. The Minnesota River is a “muddy” stream and carries large quantities of clay and silt to the Mississippi River. Sediment transport from the Minnesota River Basin is an important issue affecting the Upper Mississippi River Watershed and the Mississippi River at Lake Pepin (Waters, 1977).

1.2.1 Climate

Climate in Minnesota is highly variable with four distinct seasons. Temperatures can reach in excess of 100 degrees Fahrenheit during the summer months and well below freezing during the winter months (MN DNR, 2013). The Minnesota River Basin encompasses a large portion of the state and the climate varies across the basin. Normal annual precipitation in the basin ranges from 25 to 30 inches. Average annual snowfall is typically between 40 and 45 inches. Average annual temperatures are 44 degrees Fahrenheit in the spring, 70 degrees Fahrenheit in the summer, 46 degrees Fahrenheit in the fall, and 16 degrees Fahrenheit in the winter (MN DNR, 2013). Flooding is primarily caused by snowmelt runoff in early spring or heavy precipitation during the summer months. It is typical for intense precipitation to combine with snowmelt in the early spring to exacerbate flooding (Musser et al., 2009; USACE, 2017).

1.2.2 Land Use and Land Cover Change

The Minnesota River Basin was once comprised of prairies, prairie wetlands, and deciduous forest as recently as the late 1800s (Johnson et al., 2012). During the 19th and 20th centuries, European settlement began in the watershed. Much of the native landscape was progressively converted to agricultural land since soil in the Minnesota River watershed is highly productive (Musser et al., 2009). Approximately 90% of the prairie wetlands native to the Minnesota River Watershed have been lost (Musser et al., 2009). Today, more than 90% of the land is managed for agriculture and less than 5% of the native ecosystem remains (Johnson et al., 2012).

Much of the Minnesota River watershed is in the prairie pothole region. Prairie potholes formed isolated wetland and lake basins which were not connected to rivers by surface flow. These prairie potholes stored runoff from rain and snowmelt until the water evaporated or infiltrated the landscape rather than contributing to runoff. Settlers developed expansive surface and subsurface drainage networks to manage runoff on the land to support agriculture. The addition of artificial drainage networks increased substantially in the 1940s (MPCA, 2015). Around 1940, there was a large transition from small grain agriculture to row crops like corn and soy beans (MPCA, 2015). Native prairie ecosystems have extensive root systems which promote infiltration and plant use of water. The post European settlement era and removal of native prairies and wetlands, the conversion from small grain agricultural to row crop agriculture, and the addition of surface and subsurface artificial drainage forced precipitation to follow surface runoff paths, ditches, and drain tile which rapidly removed water from the landscape. The alterations to the landscape have influenced Hydrology of the Minnesota River watershed (MPCA, 2015).

1.2.3 Soil Erosion and Sediment Transport

Changes to the landscape and hydrology of the watershed have contributed to changes in soil erosion and sediment transport. Sediment in the Minnesota River and its tributaries can be from point sources and nonpoint sources. Point sources of sediment include wastewater treatment facilities, water treatment facilities, municipal stormwater, industrial storm water, and construction stormwater (MPCA, 2015). Additional point sources include non-regulated urban stormwater and non-urban runoff as well as near-channel sources like gullies, ravines, stream banks, floodplains, and bluffs (MPCA, 2015).

The largest source of sediment to rivers in the Minnesota River watershed are nonpoint sources (MPCA, 2015). Upland erosion from agricultural fields was a major source of sediment delivery to rivers starting in the 20^{th} century and continues to be an ongoing issue (MPCA, 2015). In recent decades, higher discharge on the main stem of the Minnesota River and its major tributaries were observed. The increase in discharge have been linked to increased rates of erosion from non-field and near-channel sources as well (MPCA, 2015). Near-channel sediment sources are caused by erosions of streambanks and bluffs in the watershed. This type of erosion is driven by increased river discharge at the toe, which triggers slope failure (MPCA, 2009).

1.3 Reach Description

The study area was broken up into four separate reaches due to the unique hydraulic characteristics present within each reach. Reach 1 is the most downstream reach, defined by unvegetated vertical banks, and encompasses the area of maximum lateral bank retreat. Reach 2 appears to be a transition reach with more vertical banks near Reach 1 that taper into a sloped vegetated bank near Reach 3. A bedrock outcropping is the defining feature of Reach 3 where vertical unvegetated banks appear to be partially stabilized by tree roots. Reach 4 is the upstream-most reach of the project area and encompasses a meander pool with lower bank heights at the location of an apparent overflow area. A lack of quantifiable erosion within Reach 4 led the PDT to determine that no bank protection measures were needed for this reach.

Figure 1: Project area with reaches labeled. Smaller numbers represent the locations of subsurface borings.

Figure 2: Unvegetated vertical banks along Reach 1

Figure 3: Reach 2 with more vertical banks at the downstream extent and shallower sloped banks at the upstream extent

Figure 4: Exposed bedrock outcrop and unvegetated vertical bank define Reach 3

Figure 5: Reach 4 consists of a meander pool with vegetated banks. Portions of the bank are unvegetated but observed erosion has not been significant enough to justify erosion countermeasures.

2.0 Alternative Plans

Four alternative plans were identified as potential project designs over the course of the feasibility study. Each plan was developed to address the observed erosion while adhering to stage impact restrictions imposed upon projects located within FEMA Regulatory Floodways.

2.1 Alternative 1

Alternative 1 consists of bendway weirs spaced approximately 100 feet apart and longitudinal stone toe protection placed at the toe of the bank within Reaches 1 and 2. The unvegetated vertical banks within Reach 3 will be cut back to a stable slope and protected with riprap revetment. No erosion countermeasures are proposed for Reach 4. Figure 6 provides an aerial view of Alternative 1.

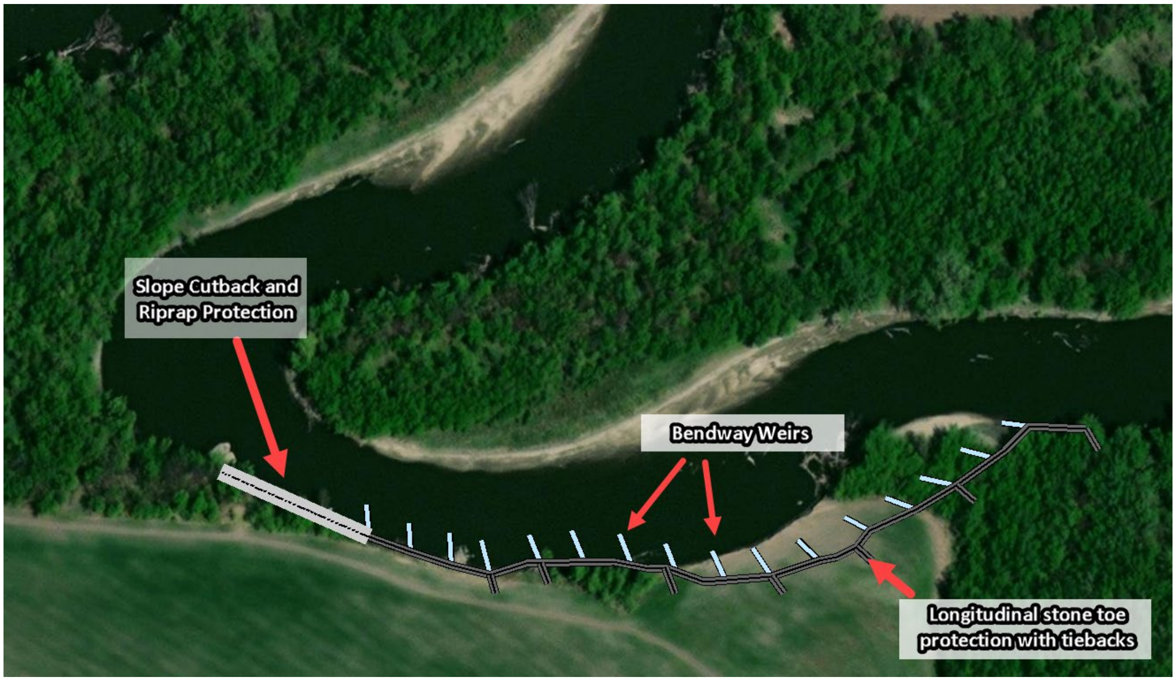


Figure 6: Alternative 1 with 2015 aerial imagery. Stone toe protection and tieback locations based upon 2020 survey data as recent aerial imagery of the study area could not be found.

2.1.1 Longitudinal Stone Toe Protection

The longitudinal stone toe protection (LSTP) provides the toe stability that appears to be present in Reach 2 but is lacking in Reach 1 while allowing natural vegetation establishment to occur post-construction. By providing toe stability Alternative 1 would allow the banks of Reach 1 and 2 to assume a naturally stable angle that can be vegetated by seeds present within the water as well as by willows present at the study area and by vegetation that is culturally significant to the Lower Sioux Indian Community. To prevent flanking of the LSTP tiebacks would be used to connect the LSTP to the bank. By offsetting the LSTP and carefully spacing the tiebacks stilling basins could be created between the stone and that bank that would naturally fill with sediment, creating a vegetated planting bench. The crest of the LSTP was set at approximately the same elevation as the vegetation line on the opposite bank. This was estimated at 817 feet (NAVD88).

The construction of LSTP would result in minimal disturbance to the area as most of the revetment would be placed at the toe of the bank. The design would also not result in any wetland impacts. The Upper Mississippi River Restoration Design Handbook notes that the success of longitudinal stone toe protection "depends on the ability of the stone to launch into the scour hole." As such the stone toe protection would be sized so that it can successfully launch into any scour holes and still provide stability to the toe of the bank.

Figure 7: Bayou Pierre River, MS; Illustrating EWN-LPSTP Approximately 2-years After Construction-Sediment Infilling Behind LPSTP and Keys

2.1.2 Bendway Weirs

The Upper Mississippi River Restoration Environmental Design Handbook describes a bendway weir as a low-level rock structure positioned along the outside bank of the river bend and angled upstream toward the flow. A bendway weir alters the pattern of spiraling currents through the bend and pushes the main energy of flow towards the center of the channel, away from the toe of the bank (USACE, 2012). By pushing the secondary currents away from the toe of the bank we can reduce the amount of energy being exerted upon the toe and subsequently reduce the risk of erosion and further lateral bank retreat. There have also been significant environmental benefits associated with bendway weirs. Bendway weir fields have been shown to provide habitat for a number of fish species.

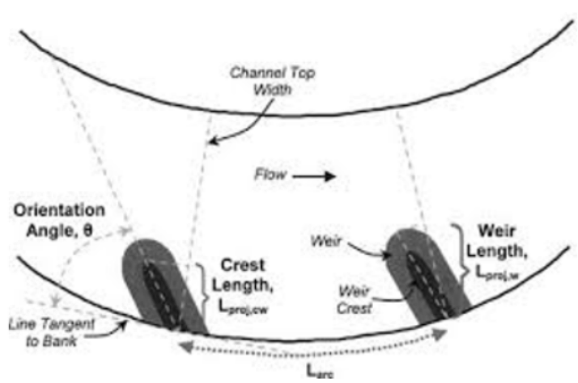


Figure 8: Conceptual design of bendway weirs

2.1.3 Riprap Protection

Due to the presence of a bedrock outcropping at Reach 3 a simple riprap revetment on a 3H:1V slope was proposed. Currently this slope will be cut into the existing back, but during Design phase there may be an opportunity to place fill on the outcrop to minimize impacts to the unvegetated vertical banks and large trees while minimizing impacts to the areas of the outcropping used by members of the Lower Sioux Indian Community.

2.2 Alternative 2

Alternative 2 consists of riprap built out into the river from the bank of Reaches 1, 2, and 3 at a 1.5H:1V slope. No grading, bedding, or geotextile is proposed for this alternative. No action is proposed for Reach 4. Riprap has been shown to effectively protect against flow velocities and would be used to protect Reaches 1, 2, and 3. The riprap would extend from the toe of the bank to the top of the bank in Reach 1, Reach 2, and Reach 3 at a 1.5H:1V slope. The rock would be placed at the toe of the bank and built up without any grading of the existing vertical banks to minimize cost. This would reduce the amount of vegetation that could be incorporated into the design. Additional description of the riprap protection is described in Section 5.4 Riprap Design.

Figure 9: Alternative 2 (2015 aerial imagery)

2.3 Alternative 3

Alternative 3 consists of riprap built out into the river from the bank in Reaches 1, 2, and 3. Additional information regarding riprap protection can be found in Section 5.4. This alternative would include three bendway weirs in Reach 1 and four bendway weirs in Reach 2.

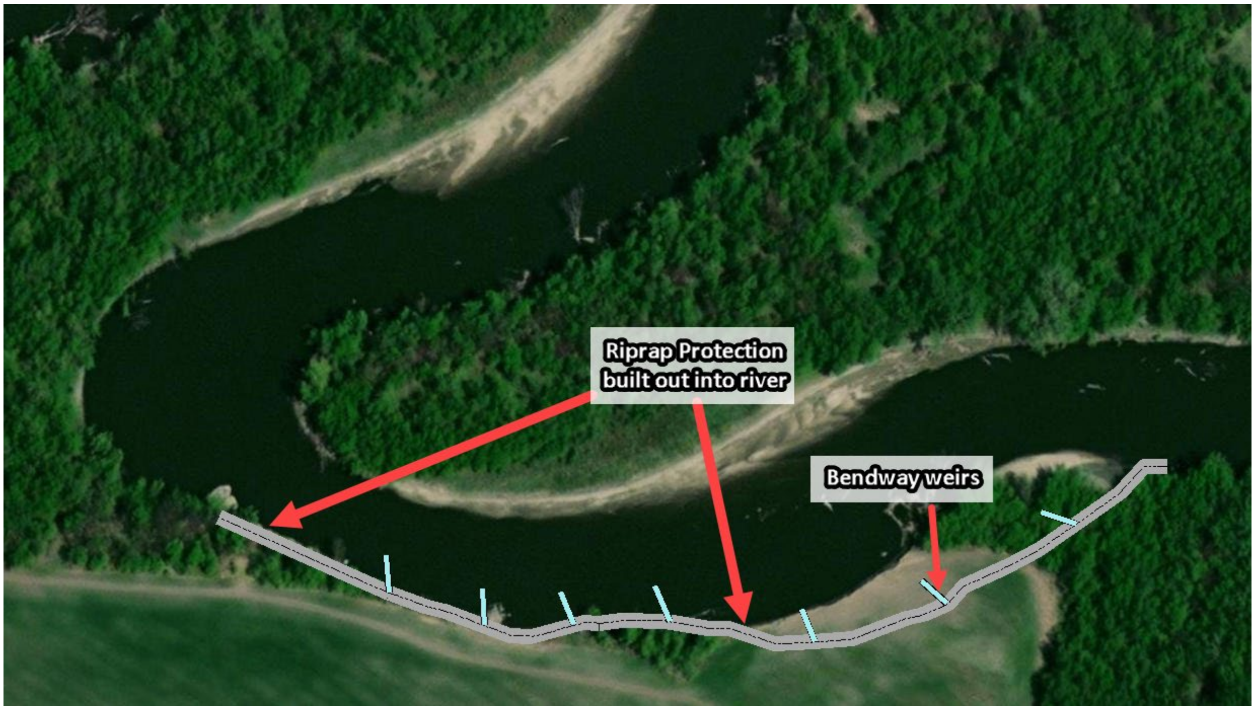


Figure 10: Alternative 3 (2015 aerial imagery)

2.3.1 Bendway Weirs

The Upper Mississippi River Restoration Environmental Design Handbook describes a bendway weir as a low-level rock structure positioned along the outside bank of the river bend and angled upstream toward the flow. A bendway weir alters the pattern of spiraling currents through the bend and pushes the main energy of flow towards the center of the channel, away from the toe of the bank (USACE, 2012). By pushing the secondary currents away from the toe of the bank we can reduce the amount of energy being exerted upon the toe and subsequently reduce the risk of erosion and further lateral bank retreat. There have also been significant environmental benefits associated with bendway weirs. Bendway weir fields have been shown to provide habitat for a number of fish species.

2.4 Alternative 4

Alternative 4 provides erosion protection by cutting the vertical banks in Reaches 1, 2, and 3 back to a stable 3H:1V slope and placing 30 inches of riprap revetment overtop of 6 inches of bedding material. Launchable stone toe at the toe of the slope will protect against any scour that may occur during a 24,000 cfs flow event. The vertical riprap extents will be from the toe of the bank to the top of the bank in Reaches 1 and 2 and from the bedrock outcropping to the top of the bank in Reach 3. Additional description of the riprap protection is described in Section 5.4 Riprap Design. This design will result in wetland impacts that can be offset by purchasing wetland credits.

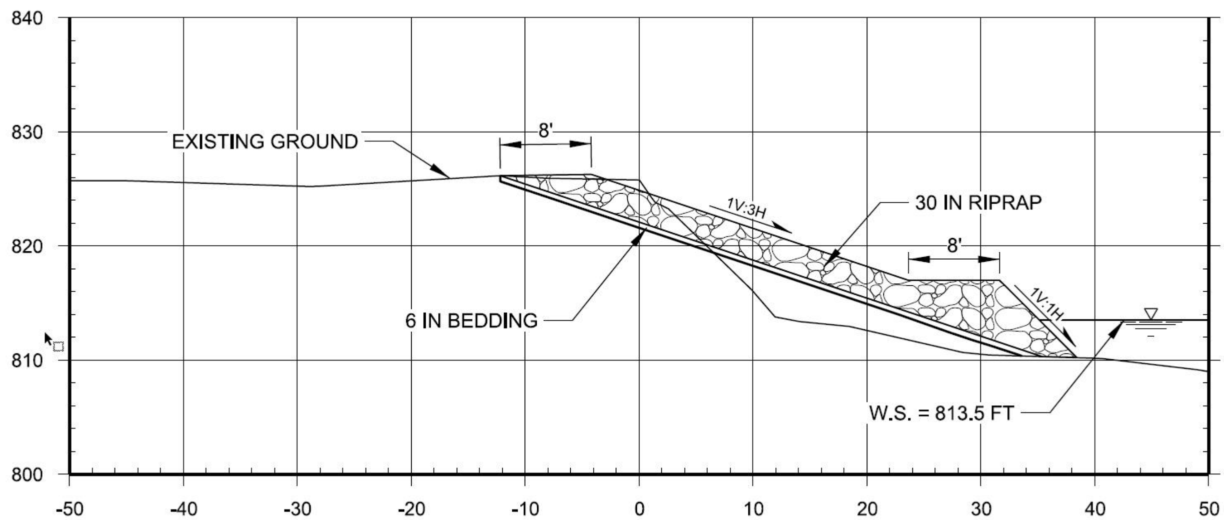


Figure 11: Alternative 4 bank cutback/mass balance and riprap protection for Reaches 1 and 2

2.4.1 Bank Cutback

The vertical banks in Reaches 1, 2, and 3 will be cut back to a 3H:1V slope. Boring logs and geotechnical slope stability analyses indicated that this would provide the slope stability necessary for long-term success of the Alternative. There may be opportunities to minimize impacts to the forested ecosystem near the top of the bank in Reach 3 by moving the revetment onto the bedrock outcropping. This will be explored in design phase.

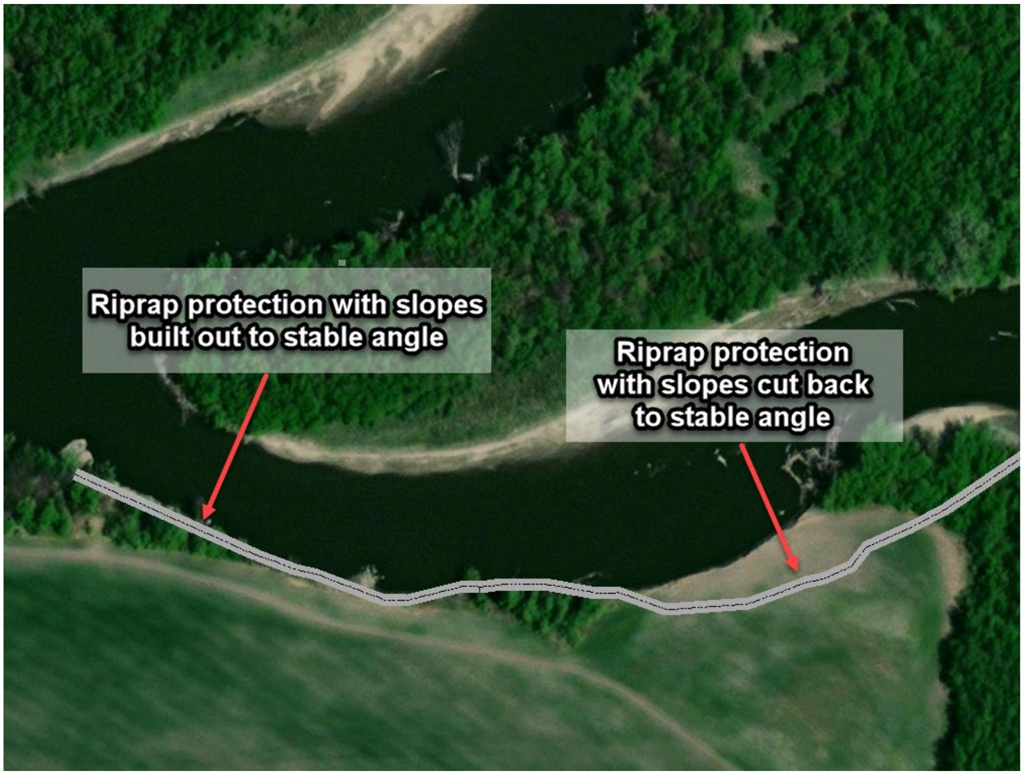
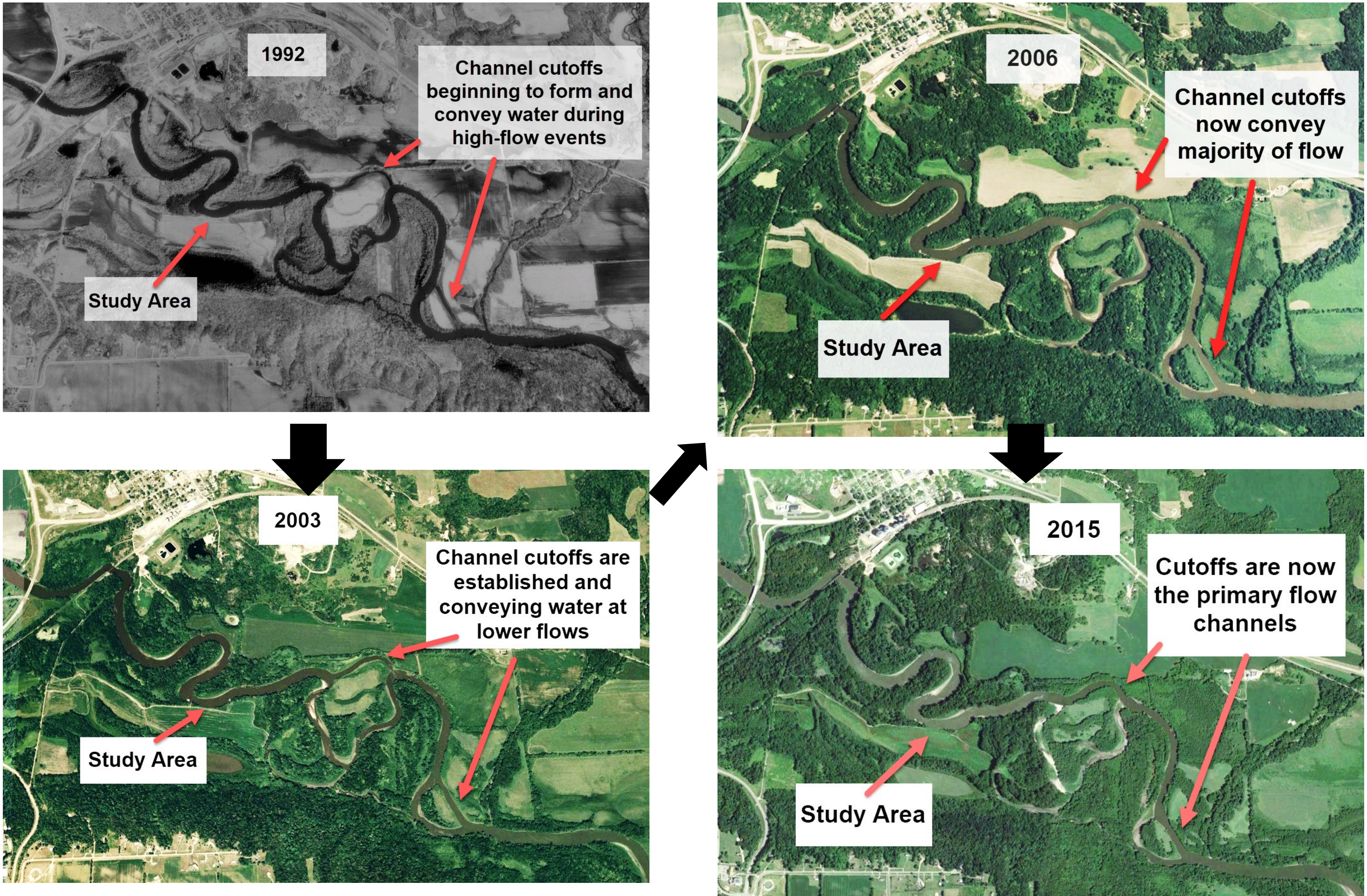


Figure 12: Alternative 4 with 2015 aerial imagery. Riprap revetment locations based upon 2020 survey data as recent aerial imagery of the study area could not be found.

3.0 Geomorphology

A geomorphic assessment of the study area was conducted with the assistance of the USACE Engineer Research and Development Center (ERDC) through a Watershed Operations Technical Support (WOTS) request. This request allowed the St. Paul team to leverage subject matter expert knowledge to assess the study area and identify potential geomorphological processes contributing to erosion within the study area.

At the project location the Minnesota River has a meandering pattern with numerous tight bends and historic channel cutoffs. Two channel cutoffs immediately downstream of the study area reduced stream length by approximately 6,000 feet between 1992 and 2015 and steepened local channel slopes. The figures below illustrate the formation and evolution of the channel cutoffs.



By reducing the channel length and increasing channel slope both local velocities and sediment transport capacities are expected to increase. These increases often lead to channel degradation progressing upstream. The cause of these channel cutoffs is currently unknown but may be part of a natural down valley channel migration or result of land use changes upstream of the study area.

This concept is perhaps best illustrated by E.W. Lane's stream balance equation (Lane, 1955). Figure 11 below describes stream balance as an equation with four variables: sediment discharge, median grainsize, water discharge (flow), and channel slope. When one or more change occurs on one side of the equation the variables on the other side will adjust to accommodate those changes. The increase in stream slope and increase in flow (described in the Hydrologic Analysis section) have likely led to an increased ability of the Minnesota River to transport more sediment with larger size. This would result in channel migration and can be readily within Reach 1 of the study area. Frequent out of channel flows in the past twenty years likely contributed to the rapid bank retreat observed within the study area. No grain-size distribution data was available at the study site but may be collected during Design phase to further refine scour depth calculations.

Additional analyses of channel stability and continuing geomorphic changes due to the channel cutoffs are recommended during design phase to improve the team's understanding of the study area and the potential for the future channel migration without any erosion countermeasures in place.

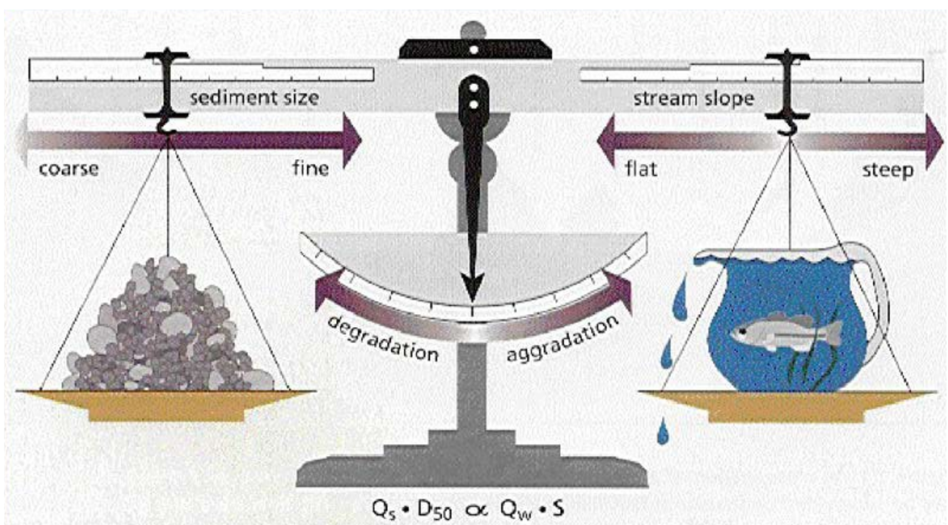


Figure 13:Stream Balance Equation (Lane, 1955), where sediment discharge (Qs) and median grainsize (D50) of bottom sediment balances with water discharge (Qw) and channel slope (S)

4.0 Hydrologic Analysis

The USGS gaging station closest to the study area is located at Morton, MN approximately 500 feet upstream of the Highway 71 bridge and 1.5 miles upstream of the project site (USGS 05316580) (Figure 12).

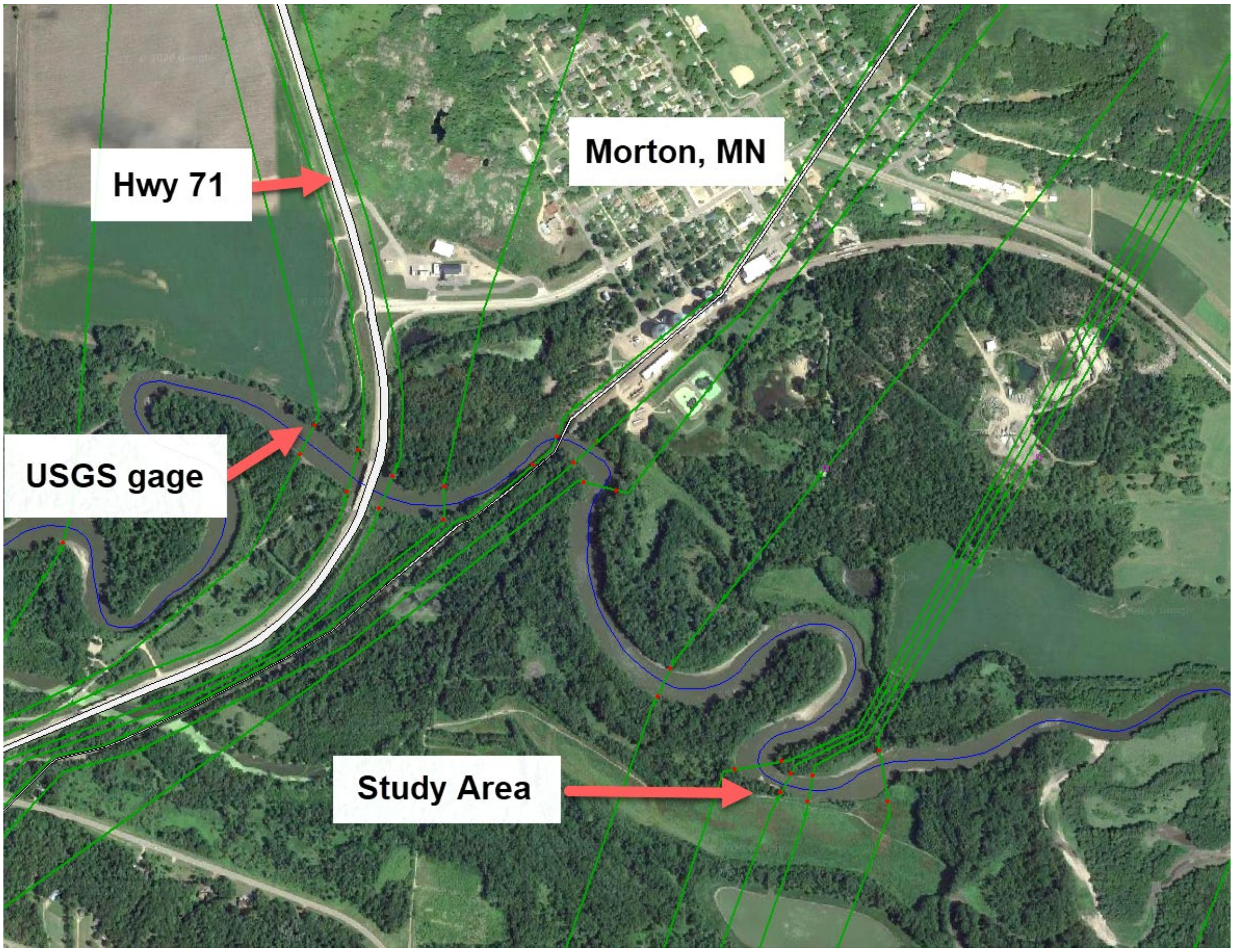


Figure 14: USGS gage 05316580 location in relation the study area

At this gage the Minnesota River watershed is 8,970 mi^2. There are a number of dams upstream of the study area with the Lac qui Parle dam being the closest at 85 miles upstream of the study area. It is not currently known how much influence this dam has upon flows within the Minnesota River at the study area. Unfortunately, this gage has less than 30 years of recorded data and cannot be used to perform a Bulletin 17C analysis, nonstationarity analysis, or trend analysis. Previously completed studies of the Minnesota River provide additional hydrologic information and are described in more detail in the sections below.

4.1 Hydrologic Trends

The Minnesota River Integrated Watershed Study (USACE, 2017) provided updated elevation and discharge frequencies for the headwater reservoirs, the mainstem of the Minnesota River, and its large tributaries. The Study provided updated elevation and discharge frequencies at locations both upstream and downstream of the study site but not at the study area itself. At Montevideo, MN, 70 miles upstream of the study site, flows are heavily influenced by the Big Stone Lake, Highway 75, Marsh Lake, and Lac qui Parle dams. At Mankato, MN, 80 miles downstream of the study site, the effects of dam regulation are no longer detectable.

The results of the updated discharge frequencies were determined using a graphical frequency analysis for Montevideo and an analytical flow frequency analysis at Mankato (Table 1).

Table 1: Annual Peak Discharge Probabilities at Montevideo and Mankato, MN

Exceedance Probability	Peak Flow (cfs)	
	Montevideo drainage area = 6,100 mi^2	Mankato drainage area = 14,900 mi^2
1%	47,000	97,700
2%	36,100	81,800
5%	24,100	61,900
10%	12,800	47,900
20%	10,000	34,700
50%	4,400	18,100

The Minnesota River Basin Interagency Study (MRBIS) (USACE, 2020) compared these updated flows to previous flows and found an increasing trend at all gages along the mainstem of the Minnesota River. The Interagency Study attributed these increases to land use changes and climate factors. Interestingly these increases did not apply to several tributaries to the Minnesota upstream of the project area. The South Branch of the Yellow Medicine River, the Yellow Medicine River, and the Redwood River all saw deceases in the 1%, 2%, and 10% annual exceedance probability (AEP) flow events.

A trend analysis of 116 years of annual peak streamflow data (1903 – 2019) was performed at Mankato, MN as a part of the Climate Change Assessment for this project. This analysis found that there was a statistically significant increasing trend in annual peak flow events along the Minnesota River at Mankato. More information can be found in Section 1.2 Trend Analysis of the Climate Change Appendix (Appendix I).

A statistical analysis of flow changes at the study area was not performed within the Interagency Study. USGS gage 05316580 Minnesota River at Morton, MN is located 1.5 miles upstream of the study area and has recorded daily data since 01 October 2000 and collected 19 annual peak flow measurements. This period of record is not long enough to perform a trend analysis with statistical significance, but it can provide an understanding of flow patterns within the period of record.

4.2 Flow Frequency Data

A Flood Insurance Study (FIS) of the Minnesota River provided by FEMA listed a 60,000 cfs flood event as the 100-year flood event (or 1% Annual Chance Exceedance event) (FEMA, 2009). This flow event was determined as part of a 2001 effort by the St. Paul District to develop frequency distributions for peak flood flows at numerous locations along the Minnesota River. A flow frequency analysis was not performed at Morton, MN but the FIS identifies a 1% ACE flood event of 61,000 cfs on the Minnesota River below the confluence of the Redwood River. The study area is approximately 10 miles downstream of the Redwood River confluence. A Bridge Hydraulics Report from the Minnesota Department of Transportation for the US – 71 bridge identifies a flow of 26,470 cfs as the 50-year flood event and a flow of 53,830 cfs as the 100-year flood event (MN DOT, 2021). No information related to the development of these recurrence intervals were provided in the Bridge Hydraulics Report. The US-71 bridge is approximately 1.5 miles upstream of the study area. Table 2 lists the 1% and 2% ACE event at the study area (Morton, MN) in comparison to the flow events determined by the Minnesota River Integrated Watershed Study (USACE, 2017). Further analysis could prove beneficial to many of the calculations associated with rock volumes and sizing and result in changes to the overall project cost.

Table 2: Annual Chance Exceedance floods at, upstream, and downstream of the study area

Exceedance Probability	Peak Flow (cfs)			
	Montevideo (70 miles upstream)	Morton FIS (study area)	MN DOT US-71 Bridge Hydraulics Report	Mankato (80 miles downstream)
1%	47,000	61,000	58,830	97,700
2%	36,100	-	26,470	81,800

4.3 Bankfull Flow Determination

Members of the Lower Sioux Indian Community had mentioned that flow within the Minnesota River had overtopped the banks at the study area frequently and for long durations in recent years. Many natural riverine erosion processes occur when flows are close to or above the riverbank. Determining this flow would allow the PDT to better understand the frequency and hydraulic conditions of this flow event at the study site. An HEC-RAS hydraulic model was used to determine the flow at which the channel within the study area is overtopped and flow spills out into the adjacent floodplain. Model results indicated that at approximately 9,500 cfs flow would spill out of the channel between Reach 1 and 2 and into Lower Sioux Indian Community land (Figure 12 and Figure 13). More information about the HEC-RAS hydraulic model can be found in Section 5.0 Hydraulic Analysis.

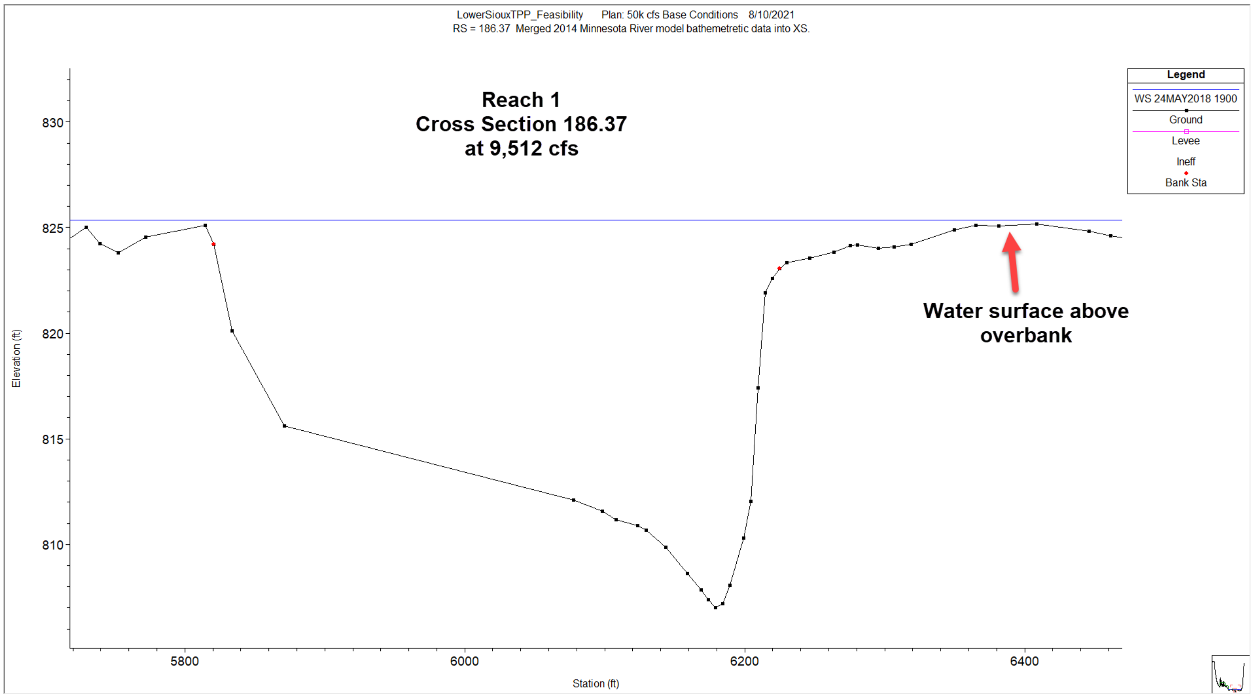


Figure 15: Water surface elevation at Reach 1 cross section (RM 186.37) at 9,512 cfs

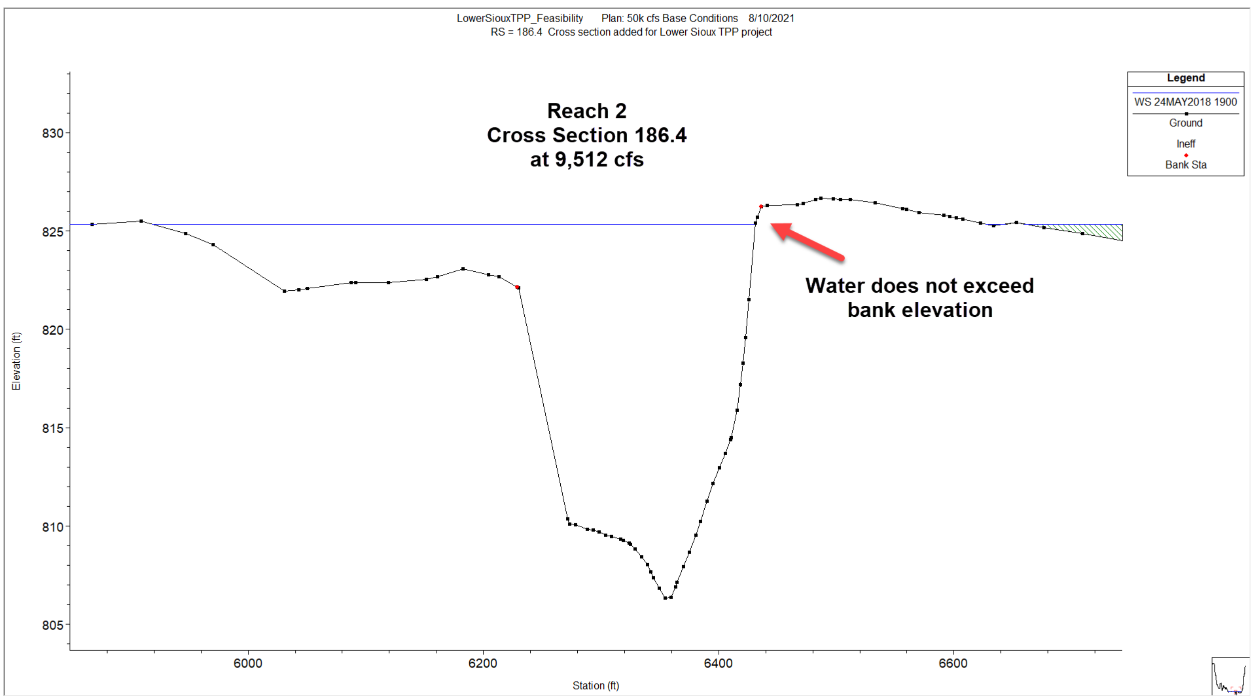
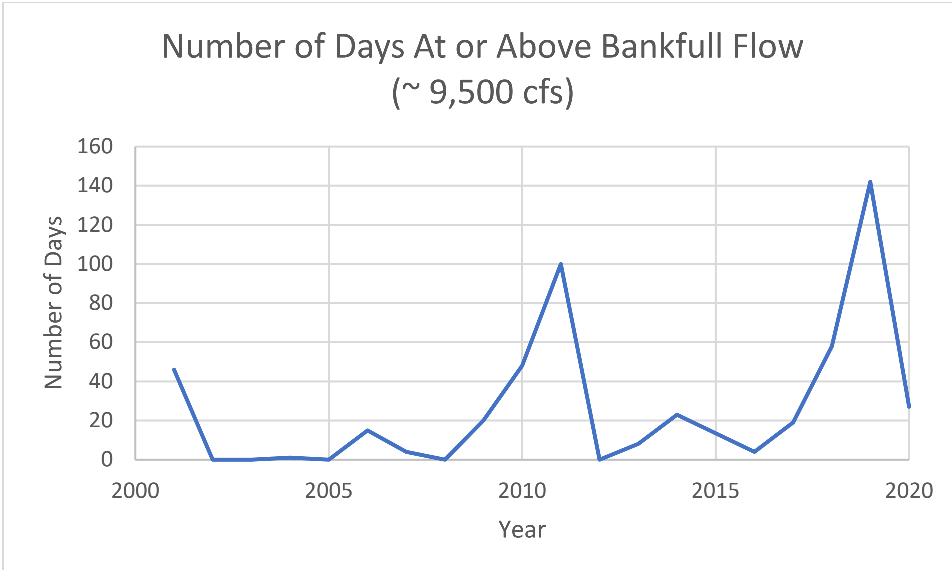


Figure 16: Water surface elevation at Reach 2 cross section (RM 186.4) at 9,512 cfs

The graph below illustrates the approximate number of days that daily mean flows at the gage exceeded the bankfull capacity at the Lower Sioux study site between 01 Oct 2000 and 28 Nov 2020. 2019 and 2011 easily stand out in the graph as years where flows may have been at or above 9,500 cfs (or approximately bankfull flow at the study site) for 142 and 100 days, respectively. Flooding that occurs this frequently and for such long durations could easily have contributed to rapid lateral bank retreat. With only a relatively short period of record at the nearby USGS gage station trends cannot be identified with confidence, but other reports indicate that the Minnesota River in general is seeing an increasing trend in flow events. Without some sort of erosion countermeasure features at the study site it is expected that the lateral bank retreat will continue, and the Lower Sioux Indian Community will continue to lose land.



4.4 Duration Analysis

While a trend analysis or traditional flow frequency analysis cannot be performed with the limited period of record at the USGS gage station upstream of the study area a duration analysis can provide some insight into the amount of time the Minnesota River was at a certain flow. This duration analysis was performed using daily mean flow data from 01 Oct 2000 to 28 Nov 2020. A duration analysis of the daily mean flow data indicated that the bankfull flow of 9,500 cfs falls somewhere between the 10% and 5% Time Exceeded flow (Table 3).

Table 3: Duration analysis results at USGS gage at Morton, MN

PERCENT OF TIME EXCEEDED	ANNUAL FLOW (CFS)
99	120
95	222
90	315
80	523
50	1,590
25	3,990
15	5,760
10	7,630
5.0	11,100
2.0	17,172
1.0	24,200
0.1	38,410

Scour depths were calculated using a flow of 24,000 cfs which was exceeded 1% of the time within the period of record. The rationale for using this flow was based upon the desire to provide a sufficient level of protection to the Lower Sioux Indian Community's land without driving the total project cost above what would be acceptable to the Tribe. Protecting against scour up to the 1% ACE (60,000 cfs) flow event was determined to likely drive the overall project cost above what would be deemed acceptable. Lacking additional hydrologic data the 24,000 cfs event was selected as the flow at which scour depths would be calculated.

5.0 Hydraulic Analysis

A hydraulic analysis was performed in support of this project. This analysis focused upon four major topics:

1. Hydraulic Modeling
2. Stage Impacts
3. Scour Analysis
4. Riprap Design

5.1 Hydraulic Modeling

Hydraulic modeling was performed using a one-dimensional (1D) Hydrologic Engineering Center River Analysis System (HEC-RAS) version 5.0.7 model. Two models were used during feasibility, one to calculate stage impacts of proposed design alternatives and one to calculate both scour depths and appropriate launchable rock volumes and determine appropriate riprap revetment sizing within the project area.

5.1.1 HEC-RAS Models

The effective FEMA Regulatory Floodway HEC-RAS model for Redwood and Renville County was used to calculate stage impacts. It will be referred to as the effective FEMA model for the remainder of this document. The effective FEMA model was used to determine the Regulatory Floodway elevation along the Minnesota River for Redwood and Renville County. It is an un-georeferenced model that contains four bridges and fifty-two cross sections. It is unknown what version of HEC-RAS was used to develop the model. It was determined that cross section 202.37 fell within the project area, corresponding to cross section 186.37, and was modified to calculate stage impacts.

The HEC-RAS model used to calculate scour depths and riprap sizing for this project was originally developed in 2016 for the Minnesota River basin Corps Watershed Modeling System (CWMS) model. It will be referred to as the Lower Sioux Indian Community (LSIC) TPP model for the remainder of this document (Figure 17). The large-scale basin-wide modeling capabilities were not conducive to the level of detail needed for this project and the model was edited so that it included only the Minnesota River from river mile (RM) 256.58, just downstream of Montevideo to RM 115.55, at USGS gage 05317500 (Minnesota River at Judson, MN). River miles are measured as the distance from the mouth of the river, in this instance where the Minnesota River joins the Mississippi River in St. Paul, MN. Additional survey data was collected in November 2020 and incorporated into the LSIC TPP model geometry. The smaller geometry and additional cross sections allowed for faster model run times and more refined model outputs.

Output from the LSIC TPP model was compared to the observed rating curve at USGS gage 05316580 (approximately 1.5 miles upstream of the study area). The results are displayed below (Figure 17 through Figure 20) and show that the LSIC TPP model rating curve falls within the spread of observed stage/flow data.

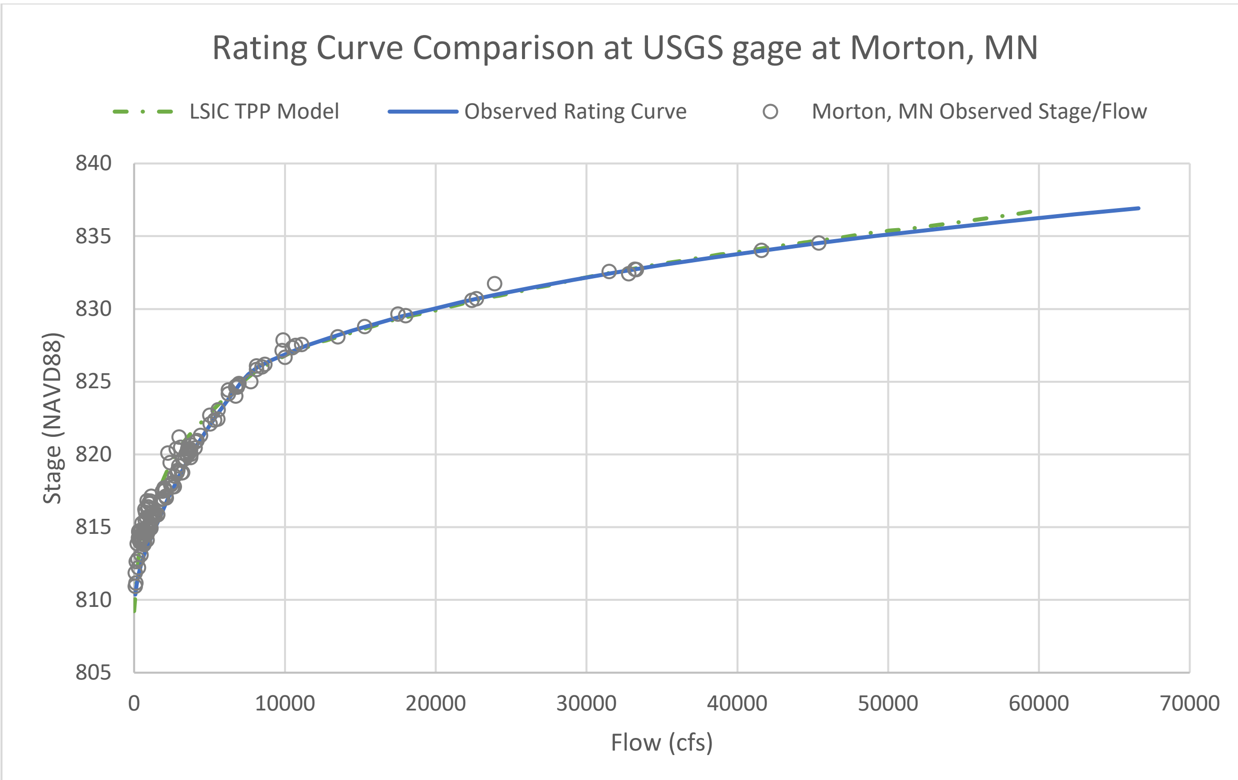


Figure 17: Rating curve comparison between USGS gage, CWMS Minnesota River model, and LSIC TPP model

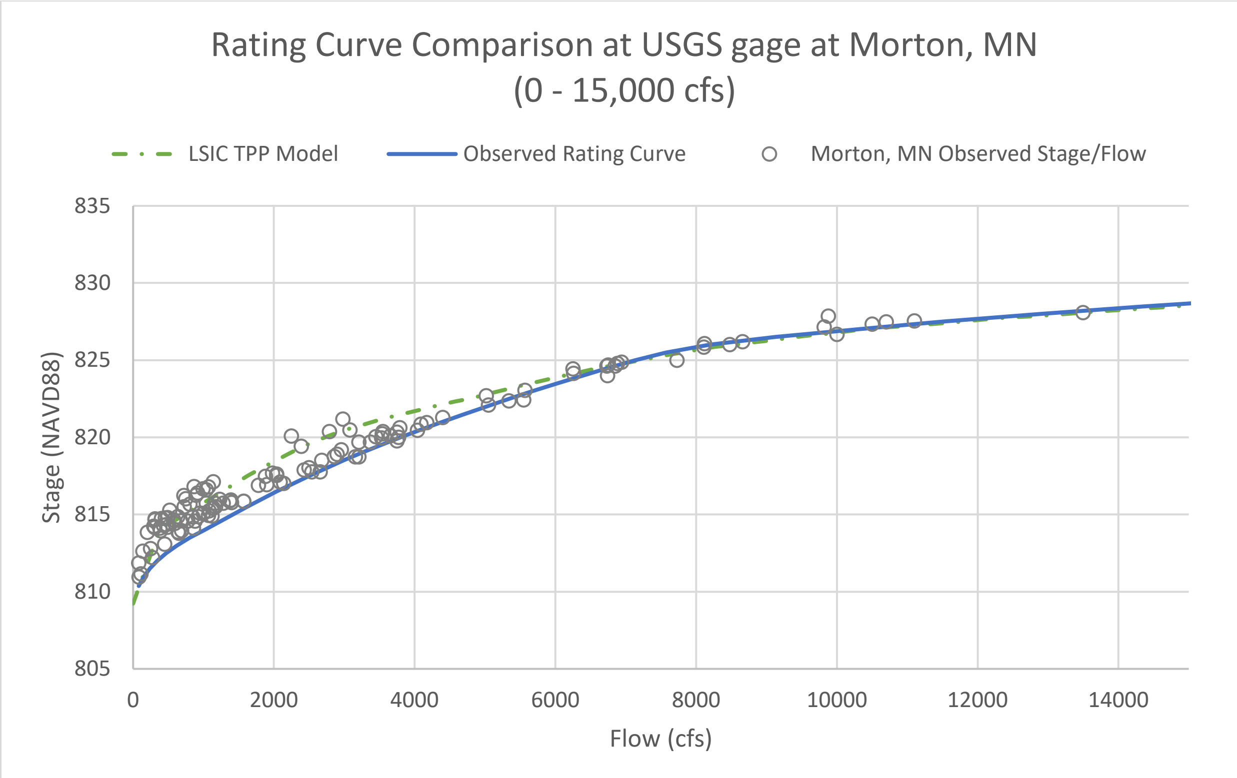


Figure 18: Rating curve comparison from 0 to 15,000 cfs

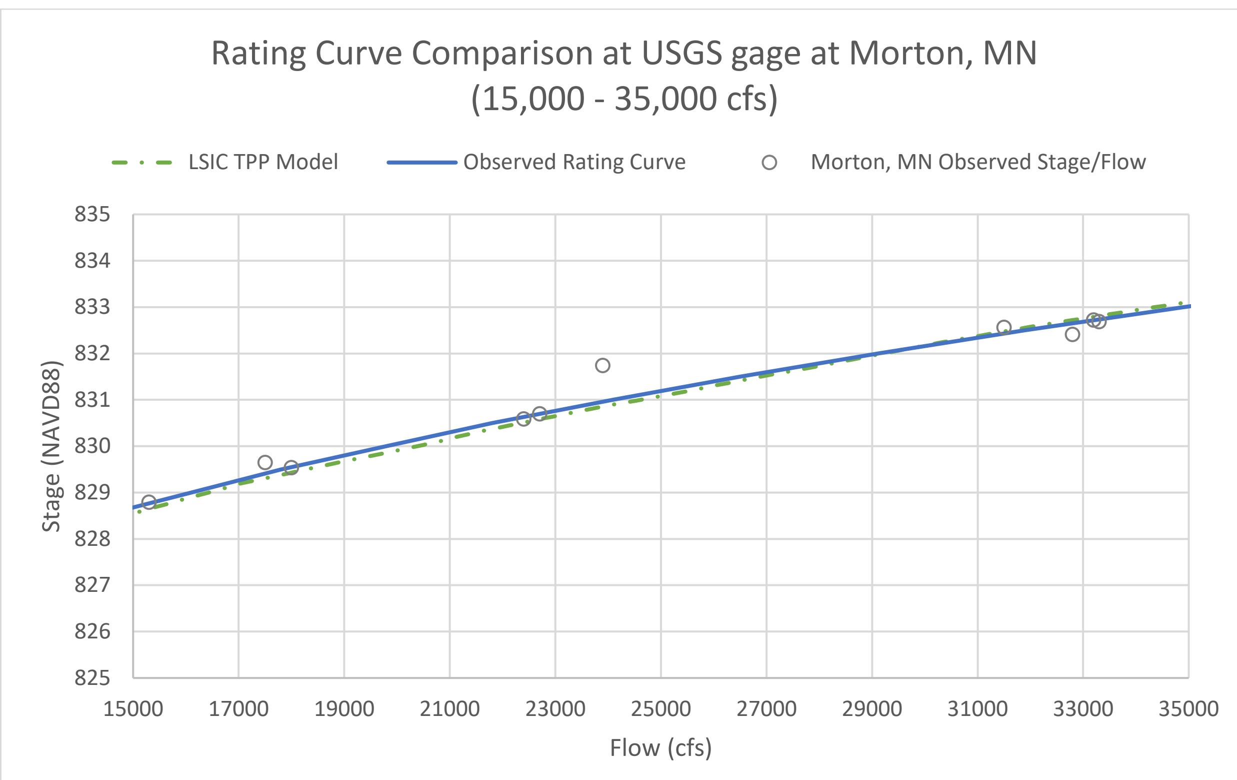


Figure 19: Rating curve comparison from 15,000 to 35,000 cfs

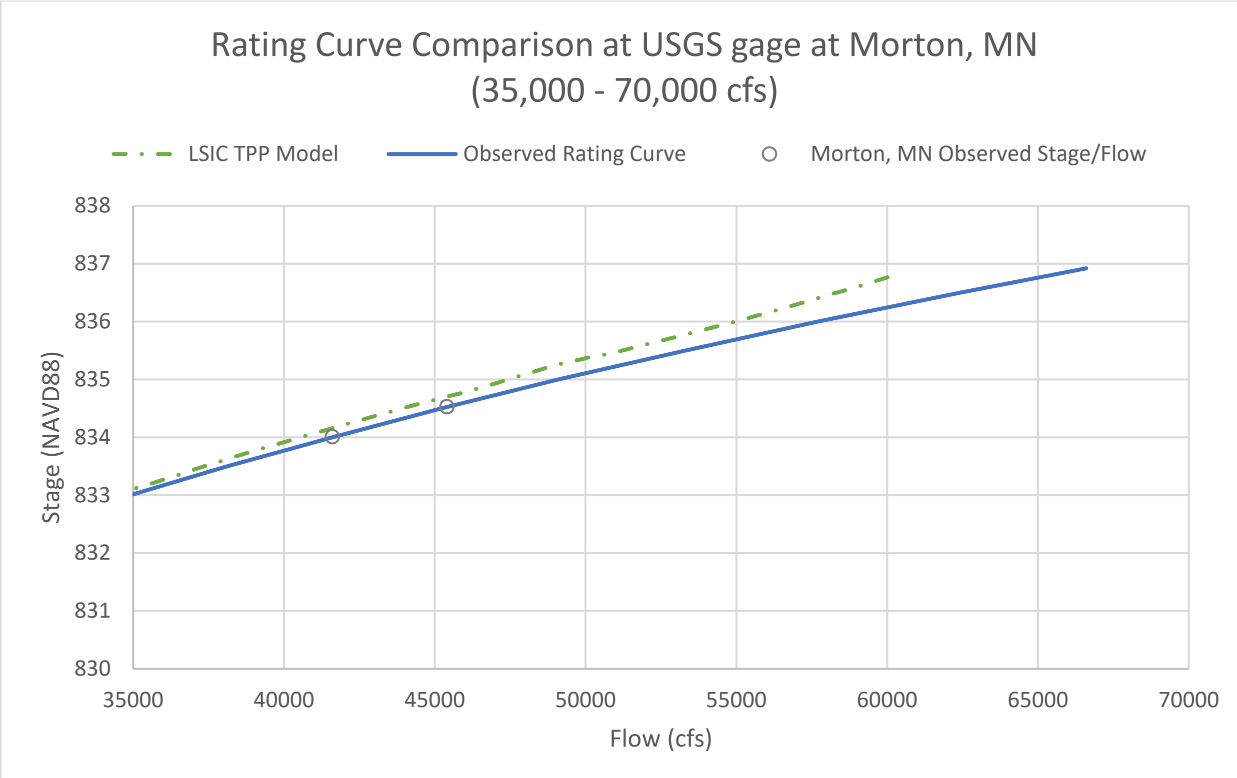


Figure 20: Rating curve comparison from 35,000 to 70,000 cfs

5.1.2 Boundary Conditions

The effective FEMA model was run using a steady flow file with three profiles. Profile 3 is representative of the 100-year flow event and was used to calculate stage impacts. This flow was equal to 61,000 cubic feet per second (cfs) at the project area, cross section 202.37.

The LSIC TPP model was run using an unsteady flow file as the CWMS – Minnesota River model had been developed to run using unsteady flows. The upstream boundary condition for the model used a flow hydrograph that increased steadily from 1,000 cfs to 60,000 cfs. The flow was then held at 60,000 cfs for 24 days to ensure that the study area experienced a 60,000 cfs flow event. The downstream boundary condition was set at cross section 115.55 using the observed rating curve at USGS gage 05317500 (Minnesota River at Judson, MN).

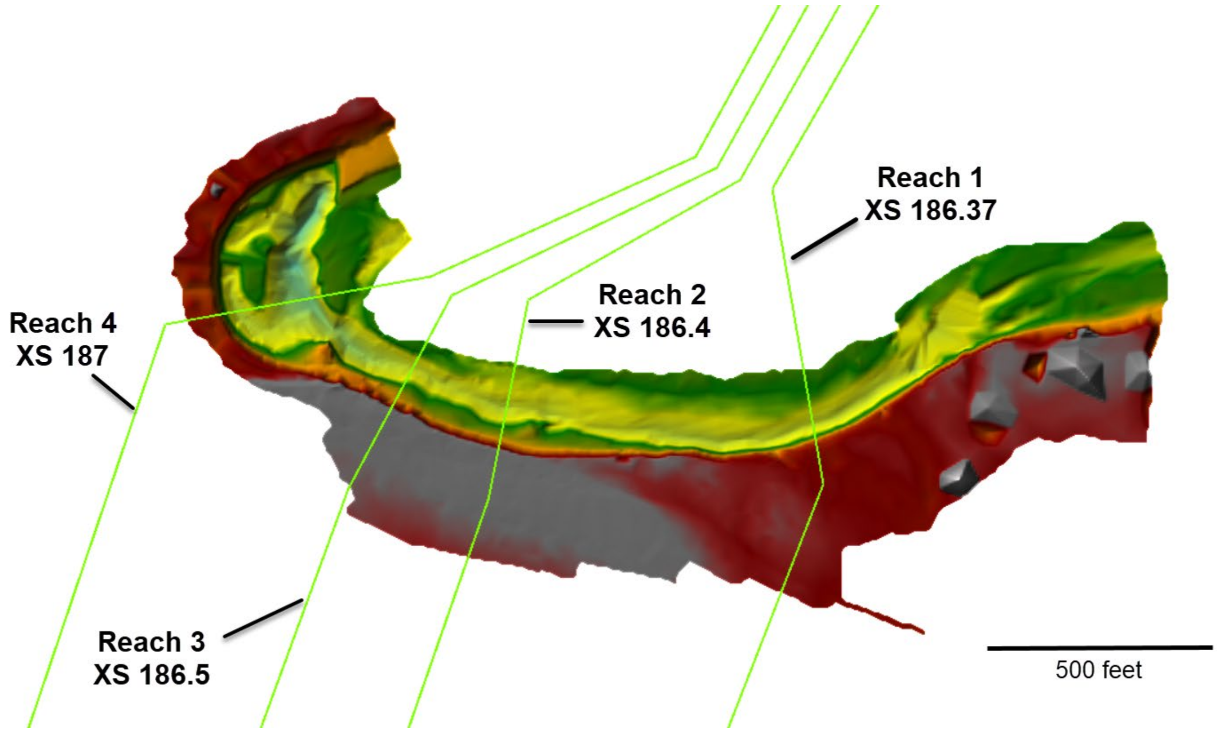


Figure 21: LSIC TPP model study area with surveyed 2020 terrain, original cross section (XS) in Reach 1 (XS 186.37), and added cross sections in Reach 2 (XS 186.4), Reach 3 (186.5), and Reach 4 (XS 187)

5.1.3 Cross Section Data

It is unknown by whom the cross section station/elevation data within the effective FEMA model was collected but it was updated and effective as of 2013 (FEMA, 2013).

The study area is captured by four cross sections at river mile (RM) 186.37, 186.47, 186.5, and 186.55. The cross section at RM 186.37 was original to the CWMS model and was modified where the 2020 survey data was available. The next three cross sections were added specifically for this feasibility study and were modified such that the overbank was reflective of the terrain within the CWMS – Minnesota River Basin model and the channel was reflective of the 2020 survey data.

Alternative plan design concepts were incorporated into the cross sections based upon input from the Geotechnical and Civil Design engineers as shown in Figure 18 and Figure 19.

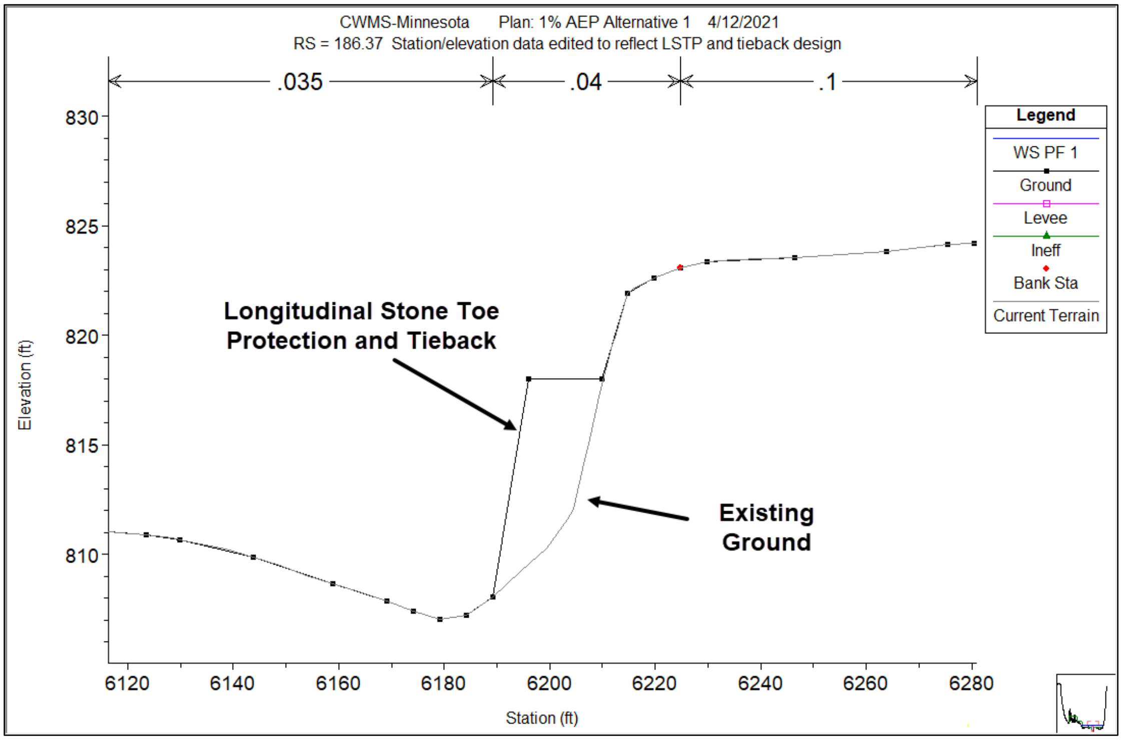


Figure 22: Station-elevation data at cross section 186.37 edited to reflect Alternative 1 features in Reach 1 and Reach 2

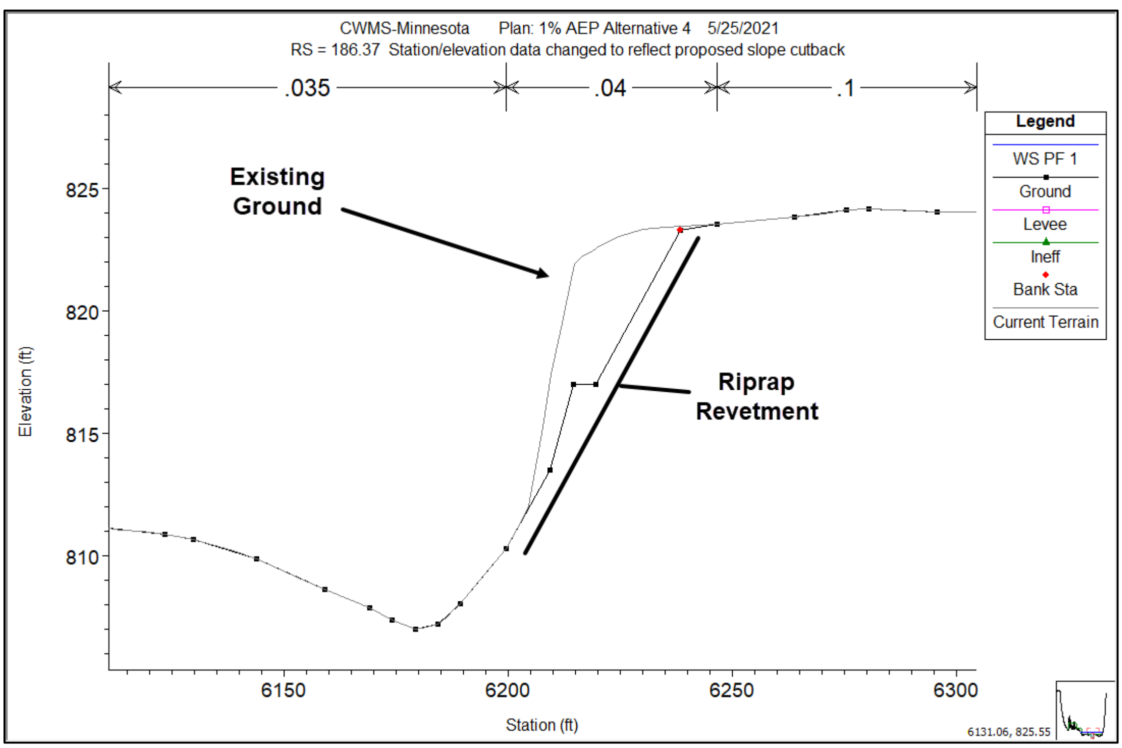


Figure 23: Station-elevation data at cross section 186.37 edited to reflect Alternative 4 features in Reach 1 and Reach 2

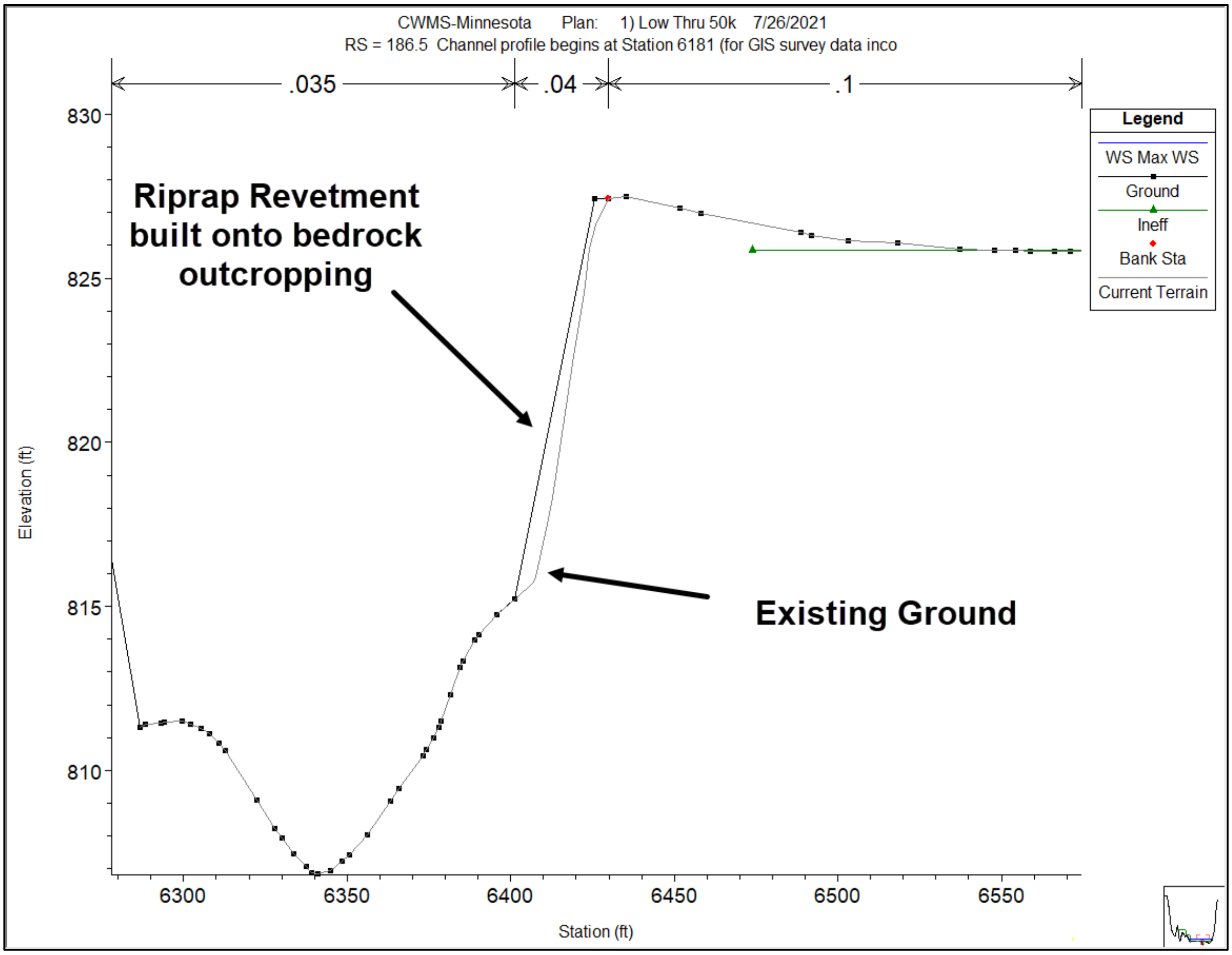


Figure 24: Station-elevation data at cross section 186.5 edited to reflect Alternative 1 and 4 features in Reach 3 (features are the same in both alternatives)

5.1.4 Roughness Values

Manning's n roughness values were changed within the effective FEMA model at cross section 202.37 to reflect project features within the proposed alternatives. The Manning's n value of riprap revetment was set to 0.040. This value was extended up the riverbank within Alternative 2, 3, and 4. For Alternative 1 only the Manning's n value where riprap revetment is included in the Longitudinal Stone Toe Protection at the toe of the bank was changed to 0.040. The Manning's n value for the portion of the existing bank that will not include revetment was unchanged. The Manning's n values for the overbanks and portion of the channel not affected by project features were unchanged.

Channel Manning's n values were also changed within the LSIC TPP model when compared to the CWMS – Minnesota River Basin model. Channel Manning's n values had been set to 0.030 from RM 235.16 to RM 183.63 and to 0.035 from RM 183.63 (just downstream of the study area) to 107.21 within the CWMS – Minnesota River Basin model. As previously mentioned, this model was developed to assess basin-wide hydraulic conditions and was not necessarily meant to assess hydraulic conditions at small sections within the Minnesota River. Similarities between the channel sinuosity and bed characteristics at the study area and at RM 183.65 led the hydraulic modeler to change the manning's n value of the channel at the study area from 0.030 to 0.035. This value can be seen in the figures above. The impact of these changes in Manning's n values is demonstrated in Figure 25 below. From approximately RM 184 to RM 186.5 the LSIC TPP model produces higher WSE data, but as the flow gets closer to the bridge, the CWMS model WSE data becomes higher. Both models produce reasonable results when compared to the USGS gage at the bridge and the changes in channel Manning's n values are not expected to significantly impact HEC-RAS modeling results.

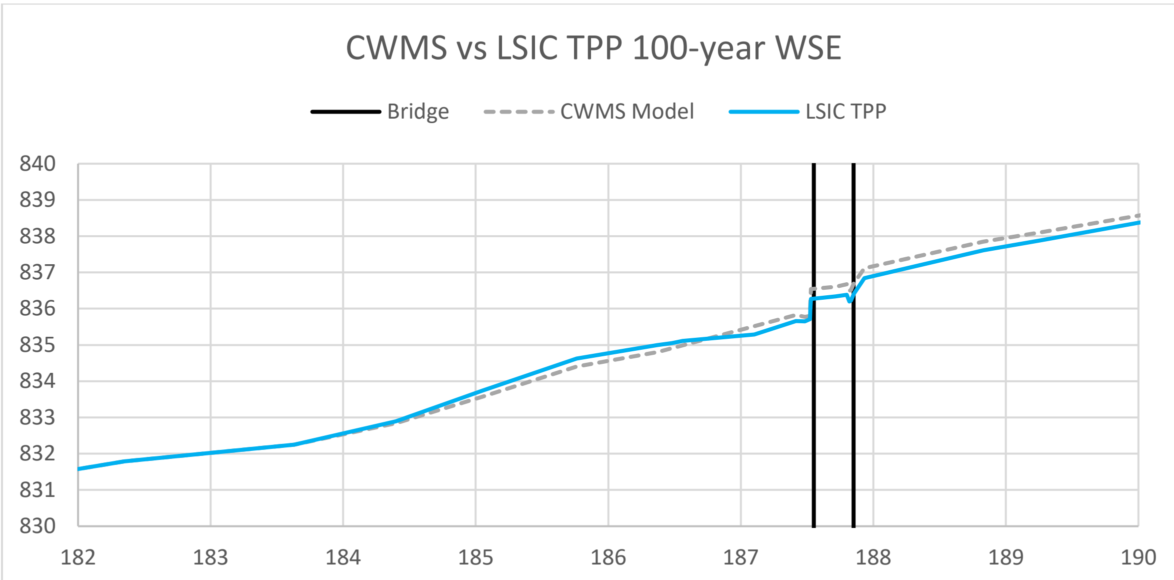


Figure 25: CWMS and LSIC TPP HEC-RAS water surface elevation (WSE) data for the 100-year flood event (project area highlighted in red)

The Manning's n value of riprap revetment was set to 0.040. This value was extended up the riverbank within Alternative 1 to reflect the presence of tiebacks throughout the longitudinal stone toe protection feature.

The Manning's n value of the overbanks was originally set to 0.10 in the CWMS Minnesota River Basin model and was not changed for the feasibility study model.

5.2 Stage Impact Analysis

A stage impact analysis was performed to assess the increase that proposed design alternatives would have on water surface elevations during a 1% Annual Exceedance Probability (AEP) flood event. As the project area is located within a FEMA Regulatory Floodway these impacts could not exceed 0.005 feet. This event is defined as the 61,000 cfs flow event for the Minnesota River below the confluence of the Redwood River by the Renville County, Minnesota Flood Insurance Study (effective: September 25, 2009) (FEMA, 2013). A stage impact analysis was performed using the effective FEMA model to ensure that proposed project features did not increase water surface elevations by more than 0.005 feet. Formal No-Rise Certification will be pursued during the design phase and will follow the guidelines outlined by FEMA (FEMA, 2021).

5.2.1 Stage Impact Methodology

The stage impact analysis was performed per the requirements listed in the No-Rise Certification section of the Minnesota Department of Natural Resources (Mn DNR) LOMC Guide (Mn DNR, 2021). This document states that “a No-Rise Certificate must be completed for any work completed in a Zone A area or the floodway portion of a Zone AE area.” The No-Rise Certification process requires showing projects have no impact (0.00-feet increase or decrease in water surface elevation) and that the No-Rise Certification “must be based on the effective FEMA profile.”

The effective FEMA model was run using the current information related to the 100-year flood event, a Steady Flow file with a profile set to 61,000 cfs and a geometry intended for use with the 100-year flood event. This produced an elevation of 833.85 feet (NAVD88) at cross section 202.37. The cross section station/elevation data was updated with bathymetry data collected in 2019. This illustrated the lateral retreat that was the main driver for this feasibility study and represents the geometry used for the LSIC TPP Base Conditions model run (Figure 25).

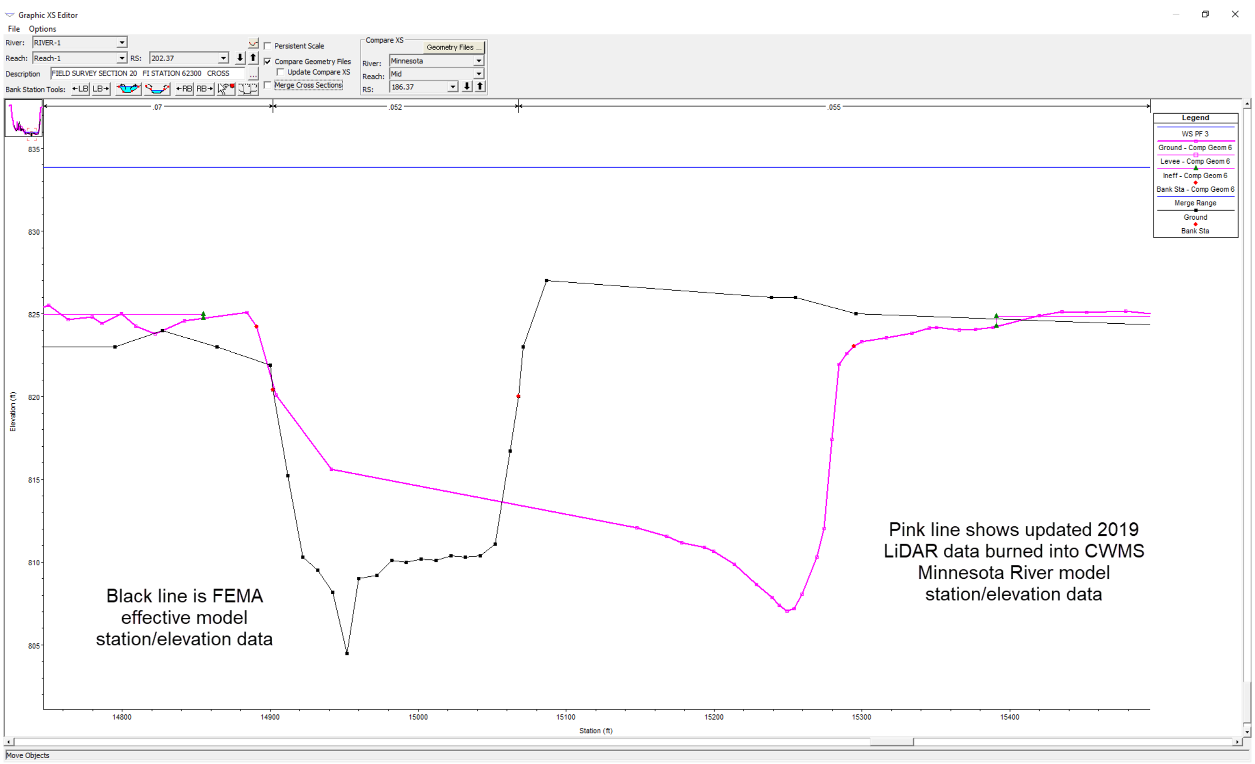


Figure 26: Changes between effective FEMA model station/elevation data (black) and 2019 bathymetry data (pink).

The updated cross section was then modified to reflect the four proposed alternatives (Figure 26 - Figure 29). The FEMA 100-year flood steady flow file was then run through the modified geometries to calculate water surface elevations (WSEs) that would be compared against the WSE from the effective FEMA model (Table 5).

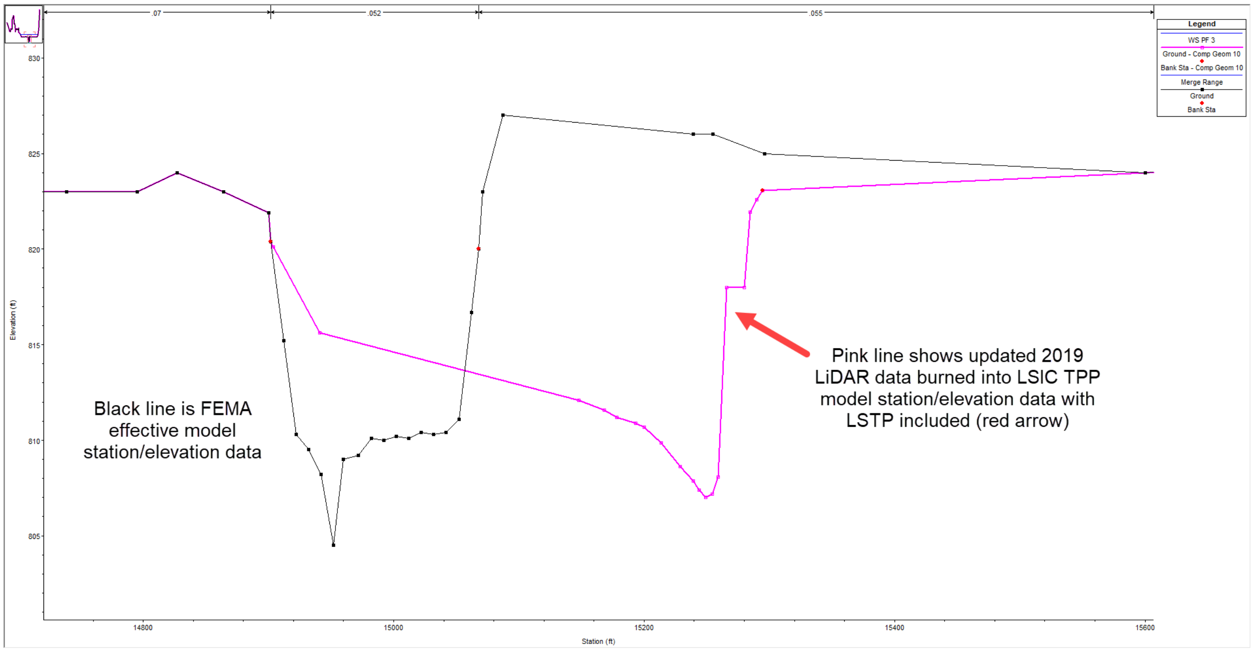


Figure 27: Changes between effective FEMA model station/elevation data (black) and Alternative 1 (pink)

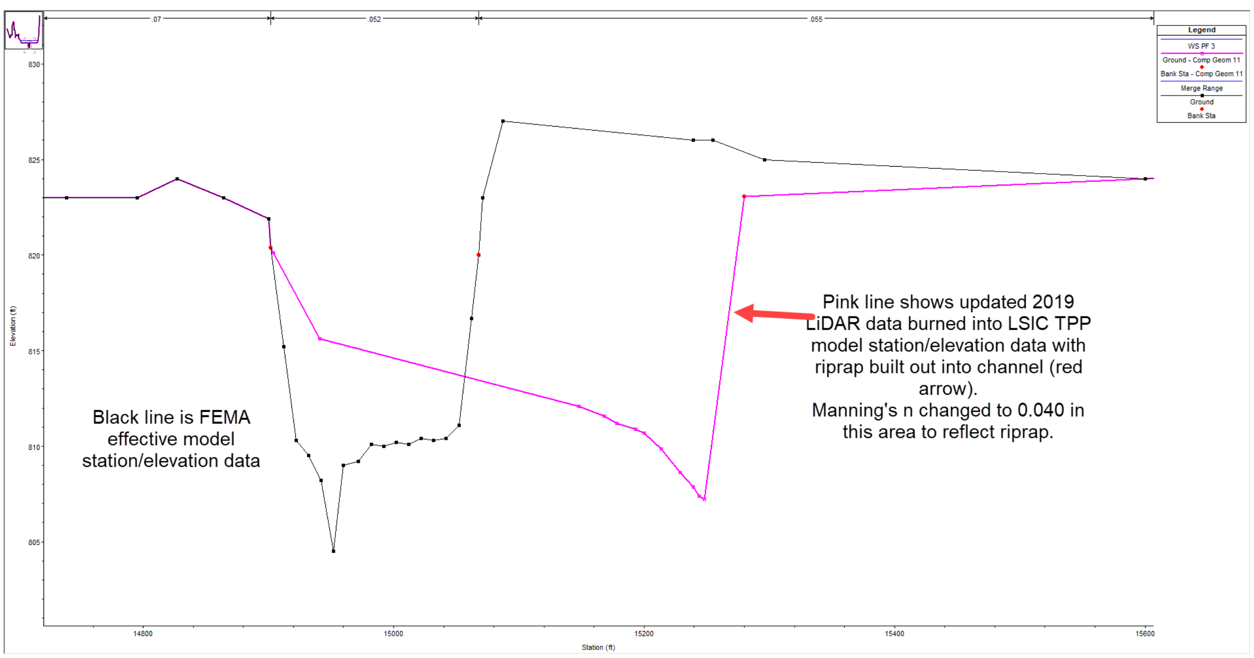


Figure 28: Changes between effective FEMA model station/elevation data (black) and Alternative 2 (pink)

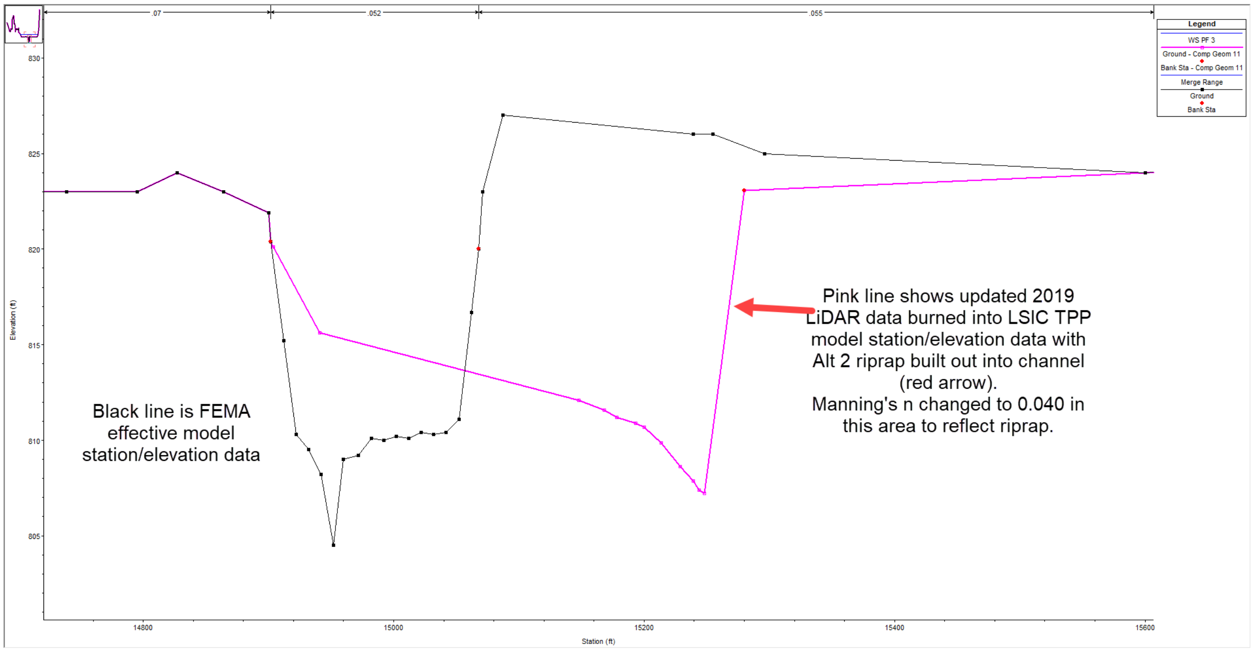


Figure 29: Changes between effective FEMA model station/elevation data (black) and Alternative 3 (pink)

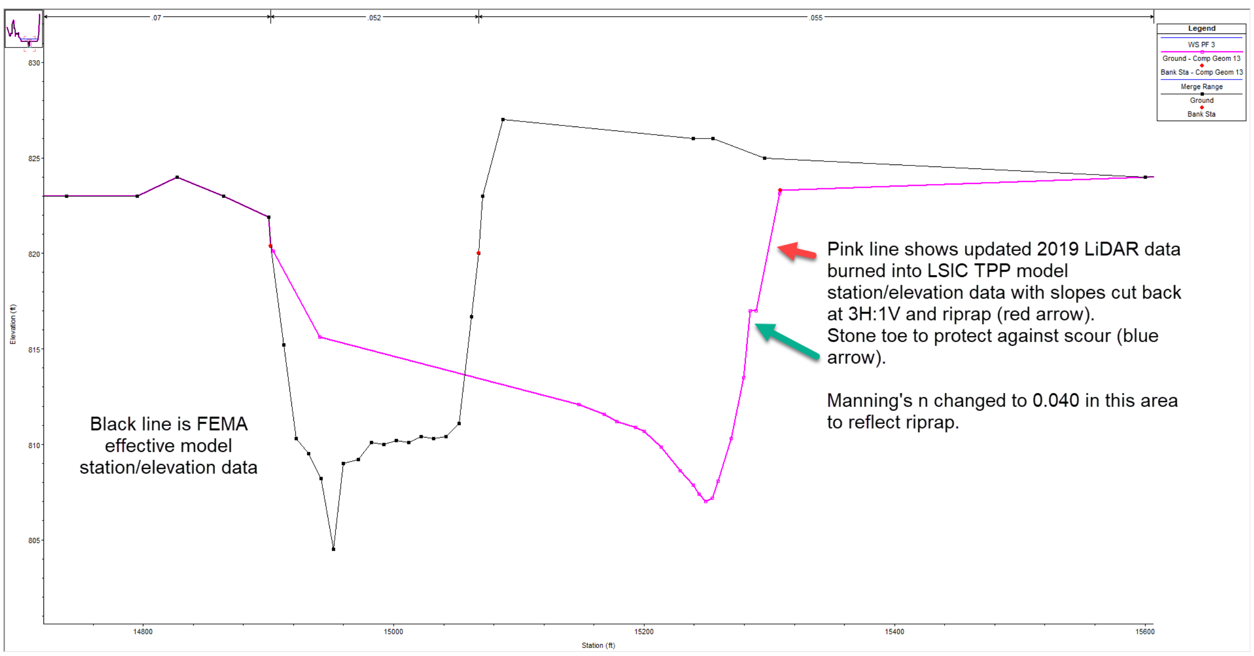


Figure 30: Changes between effective FEMA model station/elevation data (black) and Alternative 4 (pink)

5.2.2 Stage Impact Analysis Results

The stage impact analysis results for the alternatives developed prior to identification of the TSP are listed in the table below.

Table 4: Water surface elevations and stage impacts of LSIC TPP Alternatives at 61,000 cfs

Model Scenario		Water Surface Elevation (NAVD88)	Stage Impact (ft)
Effective FEMA		833.877	-
LSIC TPP	Base Conditions	833.851	-0.026
	Alternative 1	833.852	-0.025
	Alternative 2	833.850	-0.027
	Alternative 3	833.853	-0.024
	Alternative 4	833.850	-0.027

Because of the lateral bank migration modeled in the LSIC TPP Base Conditions, reflected in the collected bathymetric data, none of the alternatives violated the No-Rise criteria of increasing stages more than 0.005 feet.

5.3 Riprap Design

Riprap sizing was calculated using the guidance provided in Engineering Manual (EM) 1110-2-1601 (USACE, 1994). The HEC-RAS model provided the hydraulic properties necessary to calculate riprap size within the study area.

Before selecting a flow event to design the riprap protection an investigation of the hydraulic response of each reach was performed to guarantee that the design flow used accurately captured the critical velocity in each reach. Figure 31 through Figure 34 show flow versus velocity plots within each reach with the associated cross section (XS) identified in parentheses.

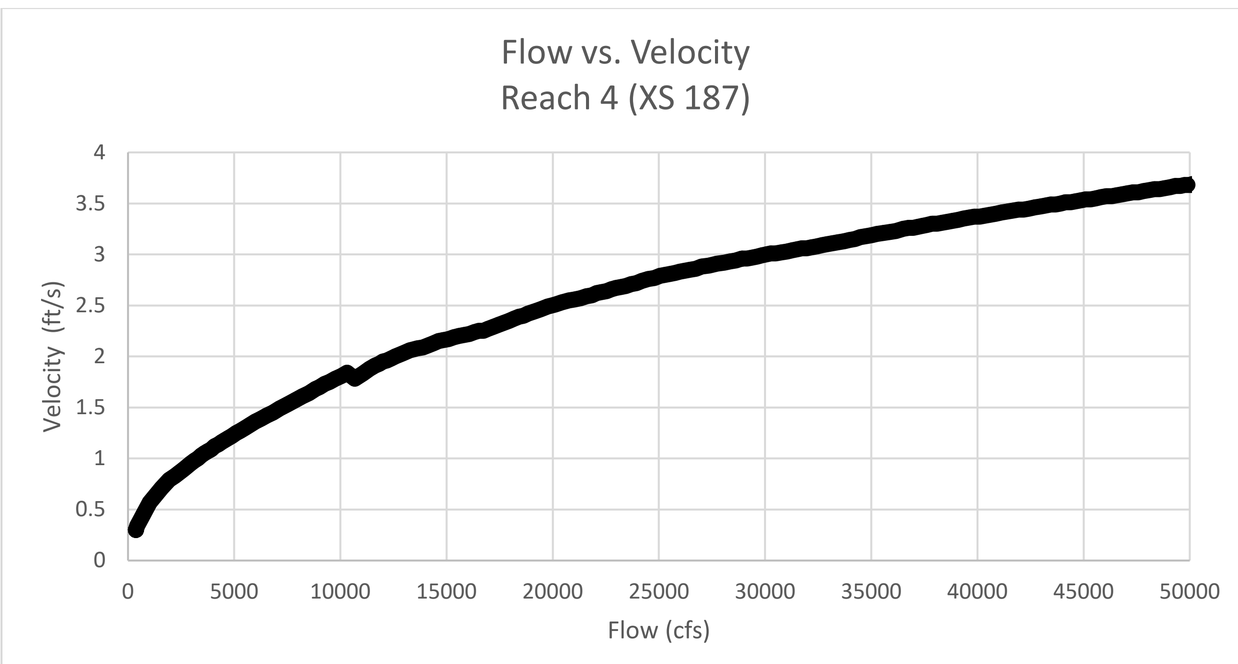


Figure 31: Flow vs. Velocity plot for Reach 4

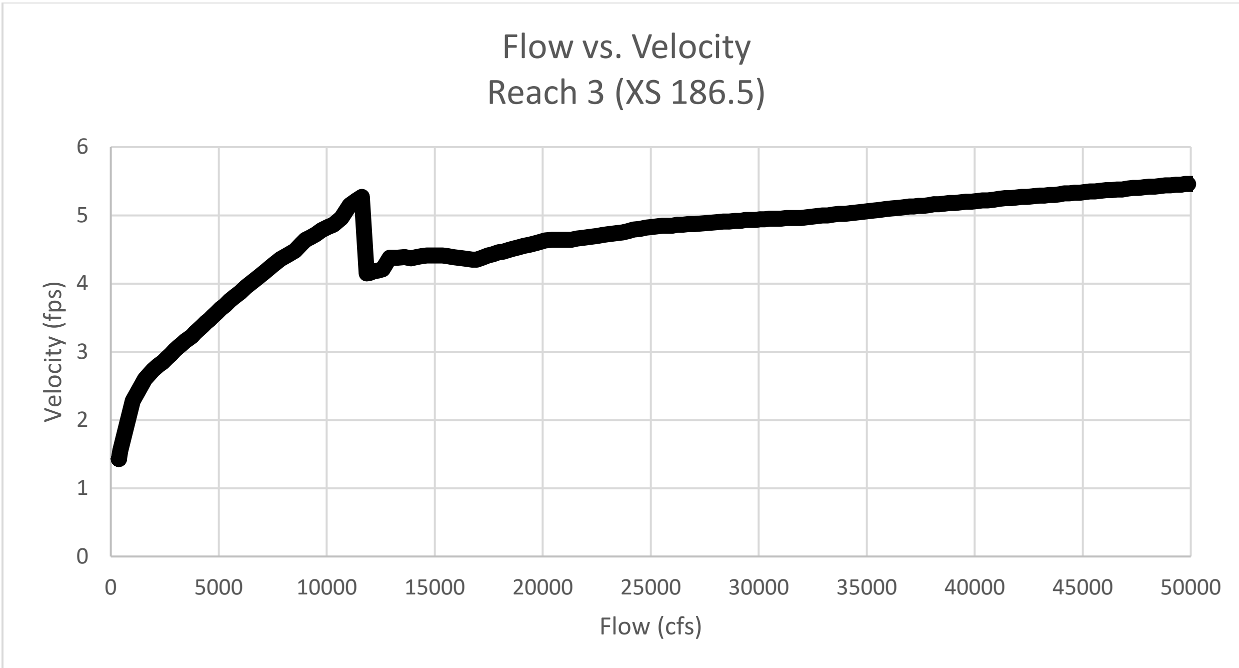


Figure 32: Flow vs. Velocity plot for Reach 3

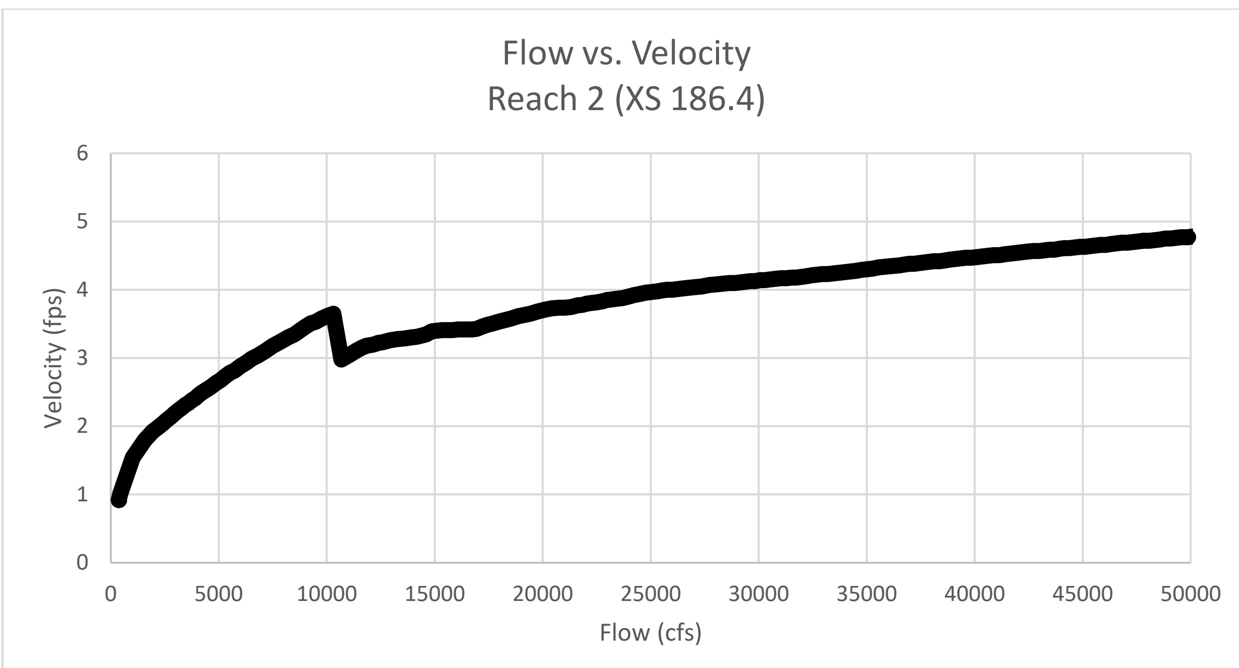


Figure 33: Flow vs. Velocity plot for Reach 2

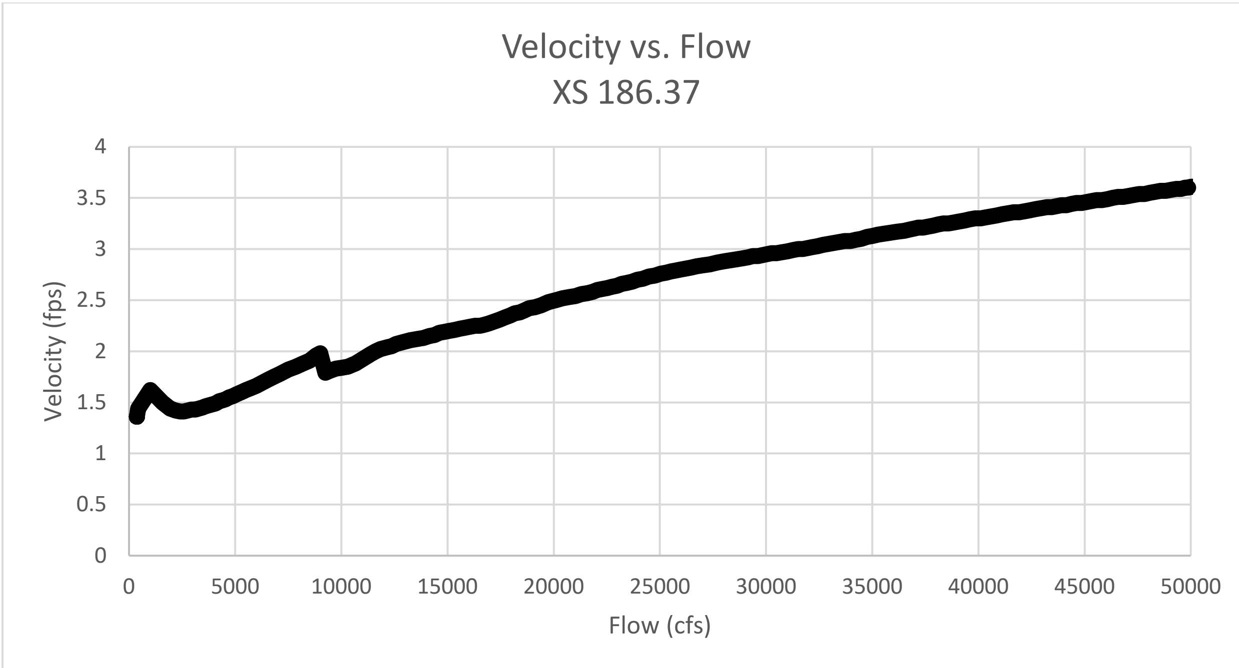


Figure 34: Flow vs. Velocity plot for Reach 1

Reach 3 (Figure 25) has the most obvious change in velocity as flow increases. This is due to the high bank along the right bank constraining flow within the channel until the flow can spill over into the left overbank area (Figure 28). The channel is also considerably narrower within this reach at 162 feet compared to 208 and 404 feet for reaches 2 and 1, respectively.

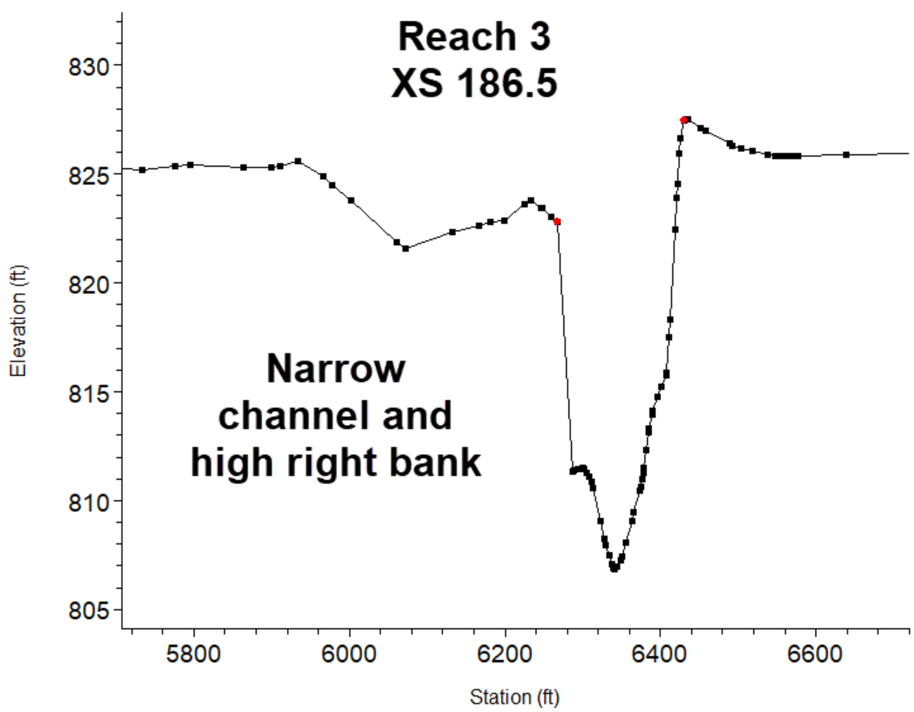


Figure 35: Reach 3 cross section with right bank elevation identified

While the launchable rock required to protect against scour was based upon the 24,000 cfs event the riprap gradation calculations used the velocity from Reach 3. This was due to the previously mentioned peak in velocity that occurred before flow spilled into the overbanks. Additionally, due to the sinuosity of the channel at the study area calculated velocities were above the peak velocity of 5.27 ft/s in Reach 3. Table 6 displays the velocities when accounting for channel sinuosity. The Reach 3 velocity of 6.61 ft/s was used to calculate the riprap D_{30}.

Table 5: Velocities calculated in each reach when accounting for channel sinuosity (Reach 3 velocity used to size riprap)

Study Area Reach	Calculated Velocity for Riprap Sizing (V_{ss}) (ft/s)
1	4.51
2	5.91
3	6.61
4	5.17

An applied factor of safety of 1.5 due to the presence of large trees within the main channel and the associated risk of debris impact upon the study area (Figure 29).

Figure 36: Large trees within the main channel near Reach 1

The equation below is provided in EM 1110-2-1601 to calculate an appropriate D_{30} rock sized for a given flow event. Table 7 provides a description of each variable as well as the value used in the rock sizing equation.

$$D_{30} = S_f C_s C_v C_T d \left[\left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{\frac{1}{2}} \left(\frac{V_{ss}}{\sqrt{K_l g d}} \right) \right]^{2.5}$$

Table 6: Input parameters, descriptions, and values used in the riprap sizing equation

Input Parameter	Parameter Description	Value Used in Assessment

D_{30}	Riprap size of which 30% is finer by weight	Calculated value
S_f	Safety Factor	1.5
C_s	Stability Coefficient	0.30 for angular rock
C_v	Vertical velocity distribution coefficient	Varies by reach (1.19 – 1.34)
C_T	Thickness coefficient	1.0, design uses 1*D_{100} or 1.5*D_{50} per EM 1601 guidance
d	Local flow depth	Varies by reach
γ_w	Unit weight of water	62.4 lb/ft^3
γ_s	Unit weight of stone	155 lb/ft^3
V	Local depth averaged velocity, V_{ss}	Used V_{ss} in calculations due to study location within bend (Table 5)
K_l	Side slope correction factor	Calculated based on a design sideslope of 2H:1V and 40° riprap angle of repose. Calculations were not significantly different at 3H:1V slope.
g	Gravitational constant	32.2 ft/s^2

5.3.1 Riprap Sizing Results

Following EM 1601 riprap sizing guidelines a riprap with a D_{30} of 4.4 inches was identified as appropriate for protecting against velocities during the 24,000 cfs flow event. A gradation of R20 was found to match the required D_{30} and will be used at all revetment locations within the project area.

Design D_{30}	R20 D_{30} Range	R20 D_{100} Range
4.4 inches	5.7 – 7.7 inches	9.6 – 12 inches

5.3.2 Rock Thickness

The required thickness based upon EM 1601 guidance was initially calculated at 20 inches using the 1.5*D_{50} calculation with the R20 riprap gradation. However, observed trees within the main channel, anticipated large floating debris during a flood event, and the likelihood of ice flow during the winter led the team to increase the revetment thickness to 30 inches.

Design R20 Rock Thickness	Recommended R20 Rock Thickness
30 inches	12 – 18 inches

5.3.3 Rock Volume Requirements

Launchable rock will be included in reaches 1 and 2 to protect the riprap revetment against scour. The volume calculation was based upon the calculated Reach 1 scour depth of 17 feet.

To determine the volume of rock required it was assumed that a post-launch slope of 2H:1V would occur and that the post-launch thickness was assumed to be the 1.5*D_{50} of 13 inches per EM 1601 guidelines. Method D from EM 1601 was used to determine the necessary volume of launchable rock with volumes increased to account for underwater placement. To protect against the calculated scour depths a stone toe with a rock volume of 68 ft^3/ft was included within the Reach 1 and 2 designs. The bedrock outcrop present in Reach 3 led the team to consider scour to be non-threatening to revetment in that reach and launchable stone toe was not included in the revetment design. More information regarding scour depth calculations can be found in Section 5.4 Scour Analysis

Launchable Rock Volume
68 ft^3/ft

5.4 Scour Analysis

Scour within a riverine system generally refers to the process of channel bed erosion which results in a local drop in bed elevation. Properly accounting for scour within a project area is critical in the overall success of the project design features. The success of the riprap revetment identified in both Alternative plans relies upon rock placed at the toe of the slope that will launch into any areas of scour and ensure the long-term stability of the revetment. Scour depths were assessed at the 24,000 cfs flow event which is exceeded 1% of the time for the period of record of the USGS gage upstream of the project area. As noted in the Hydrologic Analysis section of this appendix a MN DOT bridge hydraulics report notes that this flow event is roughly equivalent to the 2% Annual Exceedance Probability (AEP) flow event.

5.4.1 Scour Methodology

Scour calculations were performed within the project area using the methodology outlined in Technical Report no. 21-7 “Approaches for assessing riverine scour.” This methodology allows designers to calculate scour using a variety of equations and a variety of scour components (USACE, 2021a). For this analysis the scour depths within reaches 1, 2, and 3 were calculated by averaging the Zeller bend, Maynord bend, Thorne bend, and EM 1601 Plate B41 scour depths (equations below). The scour depths within Reach 4 were calculated by averaging the Lacey, Blench, and Zeller general scour depths. As no erosion counter measures are proposed for Reach 4 these scour equations were not written out.

Zeller Bend

$$\Delta y = \frac{0.0685 * D_{max} * V_{avg}^{0.8}}{D_h^{0.4} * E^{0.3}} * \left(2.1 * \left(\frac{W}{4 * Rc}\right)^{0.2} - 1\right)$$

Where:

Δy = scour depth (ft)

D_{max} = Channel maximum depth at design flow (ft)

V_{avg} = Channel average velocity at design flow (ft/s)

D_h = Channel hydraulic mean depth (ft)

E = Energy slope (ft/ft)

W = Channel top width at design flow (ft)

Rc = Bend radius (ft)

Maynord Bend

$$\Delta y = D_h * \left(1.8 - 0.051 * \frac{R_c}{W_u} + 0.0084 * \left(\frac{W}{D_h}\right)\right) - D_h$$

Where:

Δy = scour depth (ft)

D_h = Channel hydraulic mean depth (ft)

R_c = Bend Radius (ft)

W_u = bankfull width (ft)

W = Channel top width at design flow (ft)

Thorne Bend

$$\Delta y = \left(2.07 - 0.19LOG\left(\frac{R_c}{W} - 2\right)\right) * D_h - D_h$$

Where:

Δy = scour depth (ft)

R_c = Bend Radius (ft)

W = Channel top width at design flow (ft)

D_h = Channel hydraulic mean depth (ft)

EM 1601 Plate B41

$$\Delta y = \left(-1.51 * LOG\left(\frac{R_c}{W}\right) + 3.37\right) * D_h - D_{max}$$

Where:

Δy = scour depth (ft)

R_c = Bend Radius (ft)

W = Channel top width at design flow (ft)

D_h = Channel hydraulic mean depth (ft)

D_{max} = Channel maximum depth at design flow (ft)

A channel bed gradation is necessary for any scour analysis. Bed gradations were not collected for the feasibility study (RM 186) but collected bed gradation data of the Minnesota River at Mankato (RM 104) were available and used for the feasibility-level scour analysis. The channel bed at Mankato consisted of a well-graded sand which appeared to match the bed at the study area (Figure 30).

Figure 37: Sediment taken from a sand bar just downstream of the study area consisting of well-graded sand.

5.4.2 Scour Results

The scour calculations for each reach are listed below. The design scour depth is the average value of the four scour calculations. The radius of curvature in reach 4 was less than the channel top width and did not produce a scour calculation using the Thorne Bend equation.

Table 7: Calculated scour depths during a 24,000 cfs flow event (rounded to two significant digits)

Reach	Zeller Bend (ft)	Maynord Bend (ft)	Thorne Bend (ft)	EM 1601 Plate B41 (ft)	Design Scour Depth (ft)
1	6	14	18	31	17
2	5	15	17	20	14
3	9	14	23	20	17
4	13	14	-	33	14

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