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St. Paul District

Appendix C1: Hydraulics and Hydrology

Fargo Moorhead Metropolitan Area
Flood Risk Management Project

Reach 5 Lower Rush River Inlet/Drop Structure

Engineering and Design Phase

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References

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Attachments

Attachment 01 – Geomorphology Study of the Fargo, ND & Moorhead, MN Flood Risk Management Project. WEST Consultants. Oct 2012.

Attachment 02 – AWD-00001 Amendment 1: Meander Belt Width Analysis. Barr Engineering. July 2012.

Attachment 03 – Sediment Transport Analysis for Diversions in the Red River Basin near Fargo-Moorhead (DRAFT). USACE. July 2012.

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Appendix C1: Hydraulics and Hydrology

C.1 PROJECT DESCRIPTION

The project description can be found in *Appendix C: Hydraulics and Hydrology*

C.2 REACH 5 DIVERSION CHANNEL HYDRAULIC DESIGN

The Diversion Channel Hydraulic Design can be found in *Appendix C: Hydraulics and Hydrology*

C.3 LOCAL DRAINAGE

In addition to the discussion on Local Drainage found in *Appendix C: Hydraulics and Hydrology,* one additional swale drainage culvert was added to the Lower Rush Inlet design. This is the 24"culvert entering the inlet near station LR21+00. The new alignment of the Lower Rush River passes through a swale that currently drains into the Lower Rush approximately 675 feet north-northeast of the new Lower Rush centerline. This existing culvert is a 24" CMP. While the drainage area will be smaller for the new pipe, it was deemed reasonable to utilize a pipe matching the diameter of the existing pipe. A check of this design confirmed that the 24" pipe will be adequate. Design data related to this pipe is presented in Table C- 1. The discharge value was computed using the same regression equation used in the local drainage plan.

Table C- 1 - Local Drainage Culvert Design Parameters		
Contributing Area	*0.034*	sq mi
Basin Slope	*7.0*	ft/mile
Discharge (Q10)	*13*	cfs
Length	*154*	ft
Invert US/DS	*891.50/888.00*	ft

C.4 LOWER RUSH RIVER INLET STRUCTURE

The Lower Rush Inlet Structure serves three main purposes:

1) Convey flows from the Lower Rush River to the diversion Channel.
2) Convey local drainage into the diversion channel.
3) Provide required energy dissipation and erosion protection.

Various constraints need to be met to develop a design that can meet both purposes:

1) Span a 20 foot vertical drop from the Lower Rush River invert to the diversion low-flow channel invert.

2) Apply reasonable measures to maintain the 1% chance exceedance elevation in the Lower Rush River channel upstream of the structure.
3) Provide adequate vegetation and rock protection to avoid having large areas of exposed bare soil.
4) Consider fish passage, but it is not a primary design constraint.

A rock ramp concept was developed for the design of the Lower Rush River inlet structure. This concept allows for a design that incorporates flow conveyance while minimizing cost by avoiding a concrete hydraulic structure.

Following a Value Engineering Study for the entire project (more specifically, Proposal No. 17 to completely divert the Lower Rush into the Rush and to construct only one drop structure with a separate fish passage at the Rush), and a successful experience with the Value Based Design Charrette for the Outlet, an alternative assessment was performed by Barr Engineering to re-examine the feasibility proposal. See Appendix M (Attachment M-9) for the Barr Engineering technical memorandum. This analysis determined that the best alternative was to construct rock ramp at the Lower Rush River. The rock ramp structure is able to accommodate the full range of flows experienced on the Lower Rush River. The requirement of fish passage was removed from the design by St. Paul District Environmental Branch.

C.4.1 Design Flow Rates and Stages

System wide modeling was performed by HMG to determine stages and flow rates for each of the inlets to the diversion. Flow rates at select frequencies from the Lower Rush River were taken from the models at the inlet location and were provided to the design team. These values can be seen in Table C-2. This design added additional flows to represent a full range of possible inflows. The 1% chance exceedance elevation of 894.85 feet in the Lower Rush River was also provided for the design by HMG. For this design, the tail water was assumed to be equal to normal depth in the diversion channel with only the flow from the Lower Rush River. This case was selected since construction of the full diversion will take years to complete. After completion, there will be additional inflows upstream of the Lower Rush Inlet, so there will be higher tail water conditions representing a less critical design condition.

Table C- 2 Design Flow Rates

Event	Peak Discharge (cfs)
50%	258
10%	904
1%	1899
0.2%	2930

C.4.2 Layout

Alignment of the Lower Rush River Inlet structure was based on several factors. The location of the inlet abuts a design reach for the County Road 22 Bridge. This forced the inlet to be located upstream of the bridge. The junction of the inlet and main diversion channel was placed as close as possible to the downstream end of Reach 5 to minimize the amount of realigned channel upstream. The inlet structure was placed to minimize the angle between the inlet centerline and the main diversion channel centerline. A curve was placed in the inlet channel to minimize turbulence and erosion potential at the junction. Upstream of the rock ramp, the remainder of the alignment consists of two curves and a straight segment to tie the structure into the existing channel. A plan view of the inlet design can be seen in Figure C. 1.

The realigned channel section has a 40 foot bottom width to match the existing Lower Rush River channel. Between the realigned channel and the rock ramp, the channel transitions from the 40 foot bottom width to a 120 foot bottom width over a distance of approximately 450 feet. This 120 foot width continues down the ramp to the junction with the diversion low flow channel.

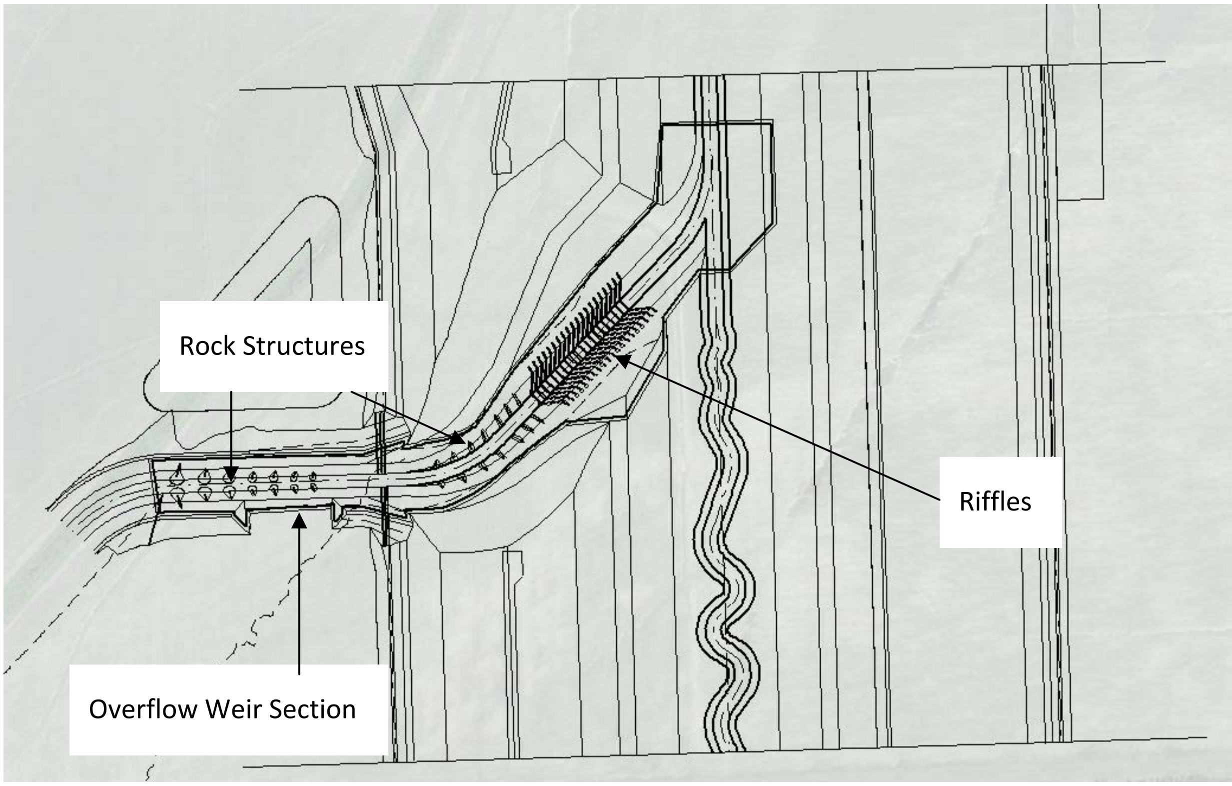

Figure C. 1 Plan View of the Lower Rush River Inlet Structure

C.4.3 Rock Ramp Structure

Design guidance presented in Aadland (2010) was used for this design. Additionally, discussion with Luther Aadland (MNDNR), St. Paul District H&H, and St. Paul District environmental contributed to the selection of various details of the design. The ramp has a five percent slope with one foot step heights. Step height was selected based on previous fish passage design in the Red River Basin. One foot is no longer recommended as the maximum drop for fish passage. Smaller drops, as small as 0.6 foot, are now recommended since there were observations that some fish could not pass through structures with one foot drops. Fish passage is not required at this structure but some early designs utilized this step height and saw some success at passing fish. Slopes greater than 5% were considered, but constructability of the ramp becomes an issue. As the slope increases above 5%, the spacing between riffles decreases such that standard construction equipment will no longer fit between the riffles. This slope and step height combination has proven to be stable in several rock ramp structures in the Red River Basin.

Using a drop of one foot per riffle over the 20 foot vertical drop requires 20 riffles to be constructed down the ramp. One additional riffle upstream of the ramp and one additional riffle downstream were added to the design to better accommodate the one foot drops for low to moderate flows, resulting in 22 riffles total. Large natural stone boulders were selected to comprise each of the riffles. These boulder riffles will be constructed perpendicularly across the center third of the channel, tying into the bank slopes at 30 degree angles to direct flow toward the center of the channel. A summary table of the rock ramp design can be seen in Table C- 3.

Table C- 3 Lower Rush Inlet Dimensions

Height of Inlet Drop	20	ft
Length of Inlet	2400	ft
Number of Boulder Weirs	22	-
Median Boulder Diameter	5	ft
Drop across each Boulder Weir	1	ft
Distance between each Boulder Weir	30	ft

C.4.4 Boulder Placement

Boulders with a median diameter of 5 feet, and minimum of 4 feet, will be placed adjacent to one another perpendicularly across the channel so that they create a series of pools and riffles throughout the inlet structure. The construction and placement of these boulder weirs will allow for some field fitting and minor adjustments to achieve the best accommodation for flow variety and fish passage. Larger sized boulders, those greater in weight than the median stone size, shall be placed toward the center of the channel to best withstand impacts from ice and debris. Boulders along the fringes of the boulder weirs shall be those that are at or below the median stone size as these areas should have less impact from ice and debris than the center of the channel. It was determined that each boulder shall be embedded with a minimum of 2 feet of riprap to provide additional resistance to movement. This minimum 2 feet of riprap was determined by analyzing the overturning of spherical boulders due to ice sheets, as shown in Figure C. 2.

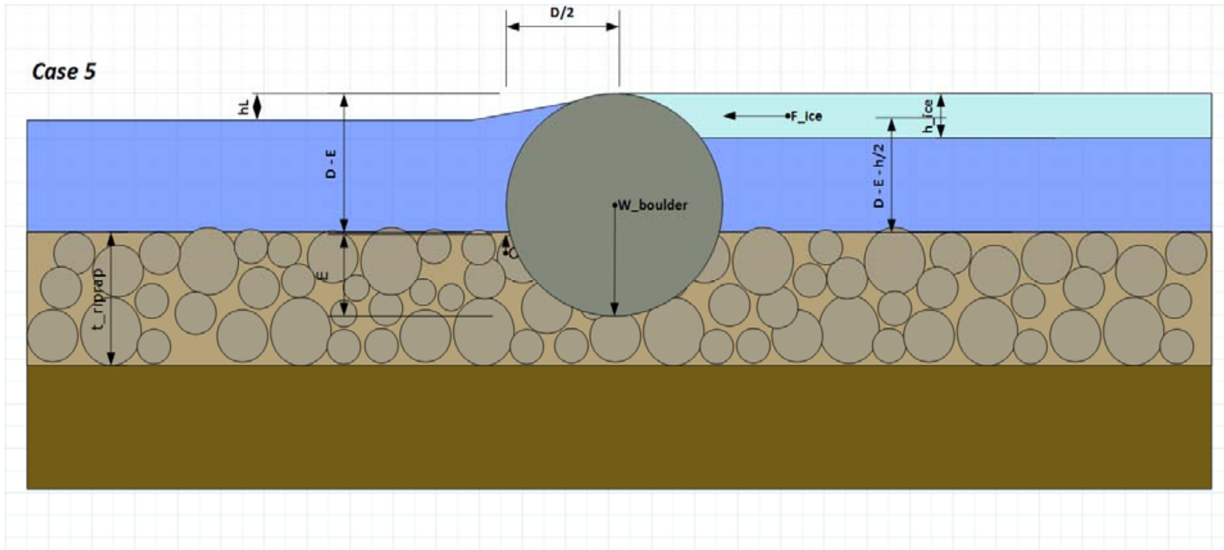

Figure C. 2 Schematic of Ice Impacts to Embedded Boulders

A constant riprap layer thickness will be used on the ramp portion of the Lower Rush Inlet Structure. Boulders will be embedded in this layer to form the boulder weirs, with the boulders in the center of the channel embedded 4 feet. The tops of the boulders along the weir shall rise at a constant slope so that they tie in to the bank slope approximately 1.0 foot higher than the top of the boulder at the center of the channel. Figure C. 3 and Figure C. 4 shows the plan and profile views for a typical boulder weir.

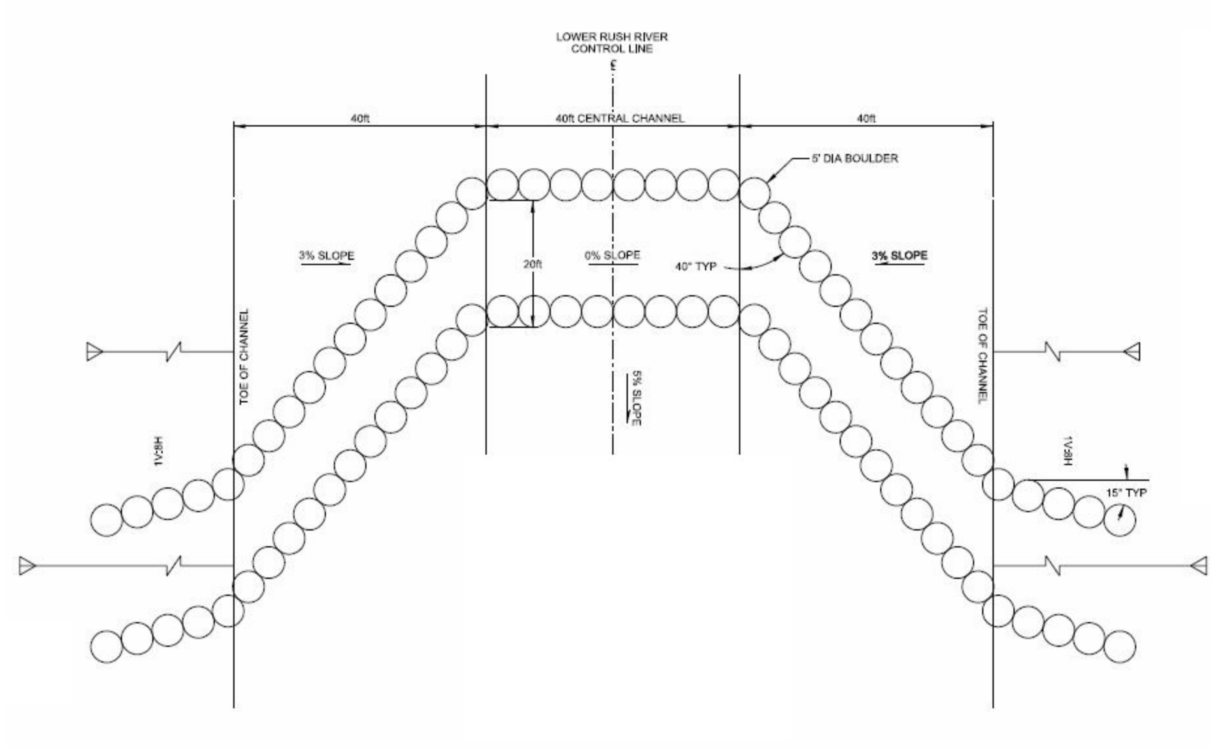

Figure C. 3 Plan View of Typical Boulder Weir

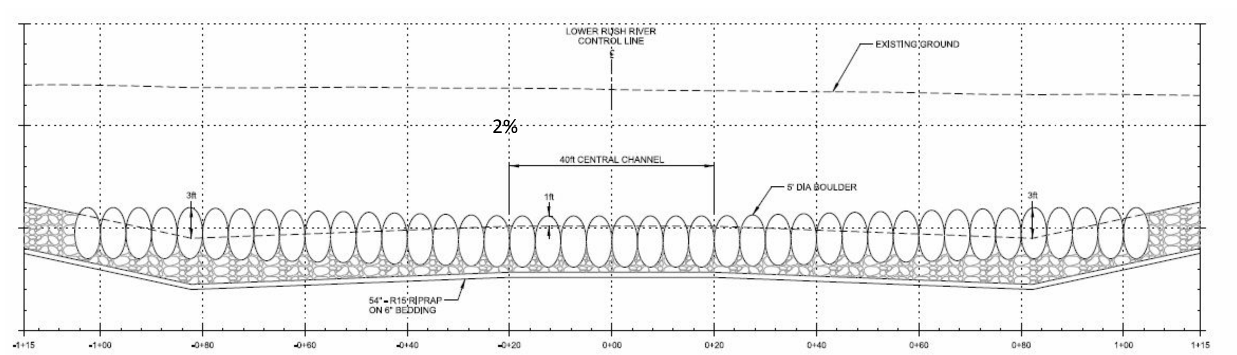

Figure C. 4 Profile for Typical Boulder Weir

C.4.5 Overflow Weir

As part of the local drainage plan, an overflow weir was designed to minimize impacts on the Lower Rush River during the 0.2% chance exceedance event. This structure will have a 260 foot bottom width with an invert elevation of 893.35 feet and will be placed along the right descending bank of the Lower Rush Inlet structure. The Reach 5 design team determined the best placement of the overflow structure is along a section where the existing ground surface elevation is near the design invert elevation of the weir. Limits of the weir invert were placed between Stations 1600+00 and 1860+00 of the Lower Rush Inlet structure. Placement of the overflow weir can be seen in Figure C. 5.

C.4.6 Upstream Rock Structures

Upstream of the ramp there are 14 rock structures that will be used to lower velocities in the transition from the Lower Rush River to the diversion channel and maintain the existing 1% chance exceedance water surface profile upstream of the inlet structure. The rock structures will be placed in two sections of the inlet. Breaking the structures into two groups was required to maintain a 1% flood profile below the invert of the overflow weir. Without these rock structures, water surface profiles upstream of the ramp would change from an M1 profile to an M2 profile. This would result in high shear and velocities with large amounts of scour.

The rock structures immediately upstream of the ramp from station 950+00 to 1300+00 are intended to maintain a velocity of 9 feet per second or less through the transition from the 40 foot natural channel of the Lower Rush River to the expanded 120 foot wide rock ramp. These structures also begin the process of increasing the 1% profile toward the existing profile at the upstream end of the inlet channel.

The second (upstream) set of rock structures were used to increase the 1% water surface profile of the Lower Rush River between Stations 1650+00 and 2100+00. The current 1% water surface profile in this area is 894.85 feet. With the structures in place the water surface profile will be 894.78 feet, less than one tenth of a foot difference.

The rock structures will be angled 15 degrees upstream from perpendicular to the direction of flow and will be keyed in to the bank. A summary table of the rock structures can be seen in Table C- 4 shows the rock structures as a green dashed line.

Table C- 4 - Rock Structure Dimensions

	Inlet Structure Centerline Station (ft)	*Height (ft)*	*Structure Opening (ft)*
Step 1	963	0.7	40
Step 2	1003	1.0	40
Step 3	1046	1.4	40
Step 4	1110	1.7	40
Step 5	1166	2.1	40
Step 6	1231	2.8	40
Step 7	1290	2.8	40
Step 9	1659	2.1	10
Step 10	1716	2.8	10
Step 11	1776	3.5	10
Step 12	1840	3.5	10
Step 13	1910	5.6	10
Step 14	1983	6.3	10
Step 15	2065	7.0	10

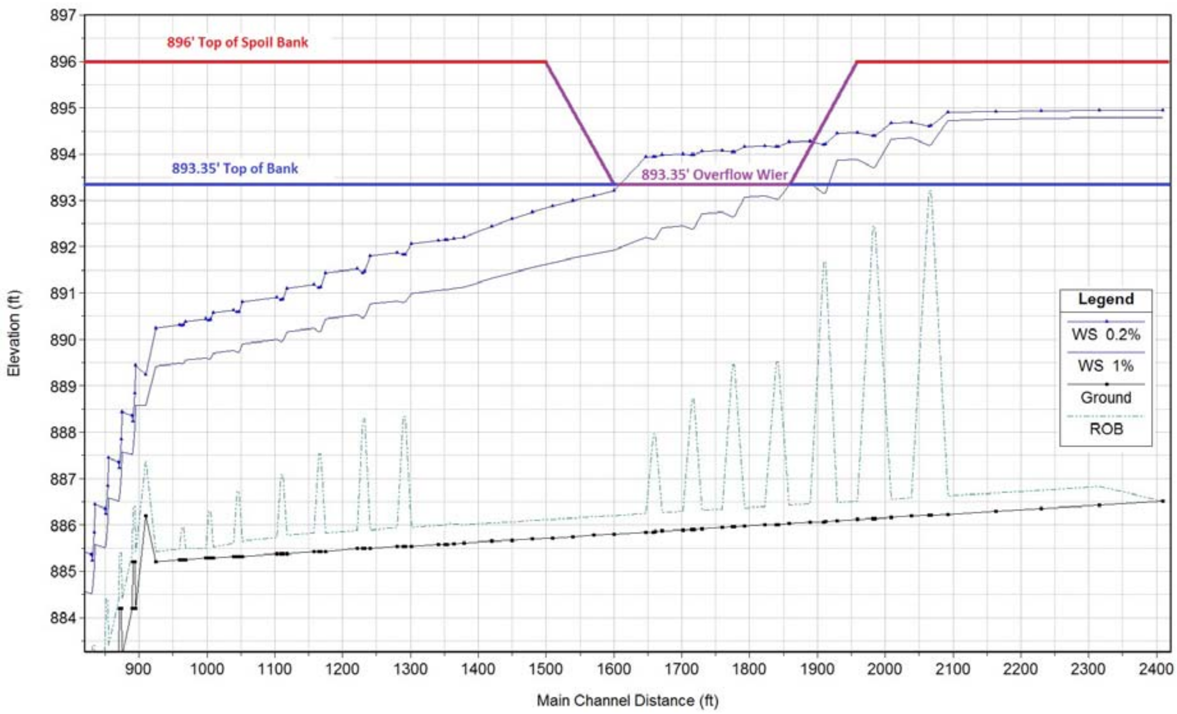

Figure C. 5 Profile View of Rock Structures and Overflow Weir

Alternatives to rock structures were considered, including sheet pile cells and raising the stream bed, but none were found to be as low cost, durable, or fish passage friendly. Sheet pile cells would not be able to produce a diverse velocity field near the structure to aid in fish passage, and they would also be cost prohibitive. The slope of the existing Rush River is 0.017% (0.9 feet/mile), so even changes to the stream bed elevation would result in the inability of the stream to drain during low flows.

C.4.7 Riprap Sizing

Due to the complexity of the geometry of the inlet structure, judgment needs to be used in addition to the Engineering Manual methodology for sizing riprap. Peak velocities and shear stresses were estimated throughout the Lower Rush inlet structure using a one-dimensional HEC-RAS model. Figure C. 6 shows the velocities along the length of the Lower Rush River inlet structure for six steady flow values. Figure C. 7 shows the water surface profiles along the length of the inlet structure for the 0.2% design event.

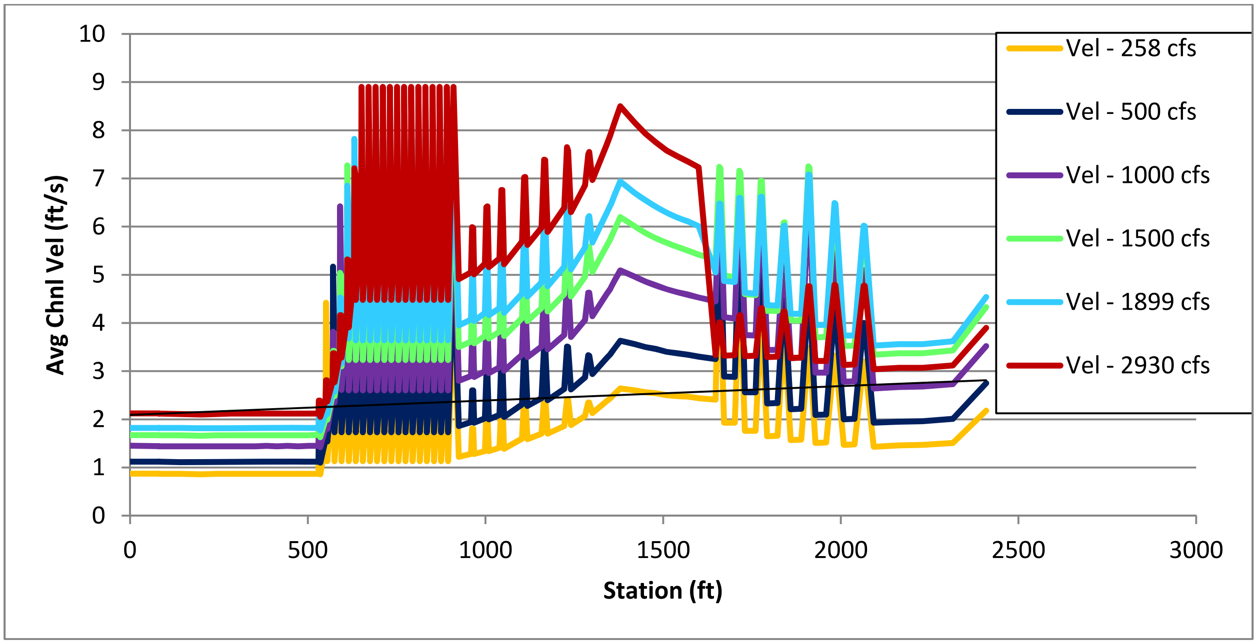

Figure C. 6 Velocity Profiles for Lower Rush River Inlet Structure

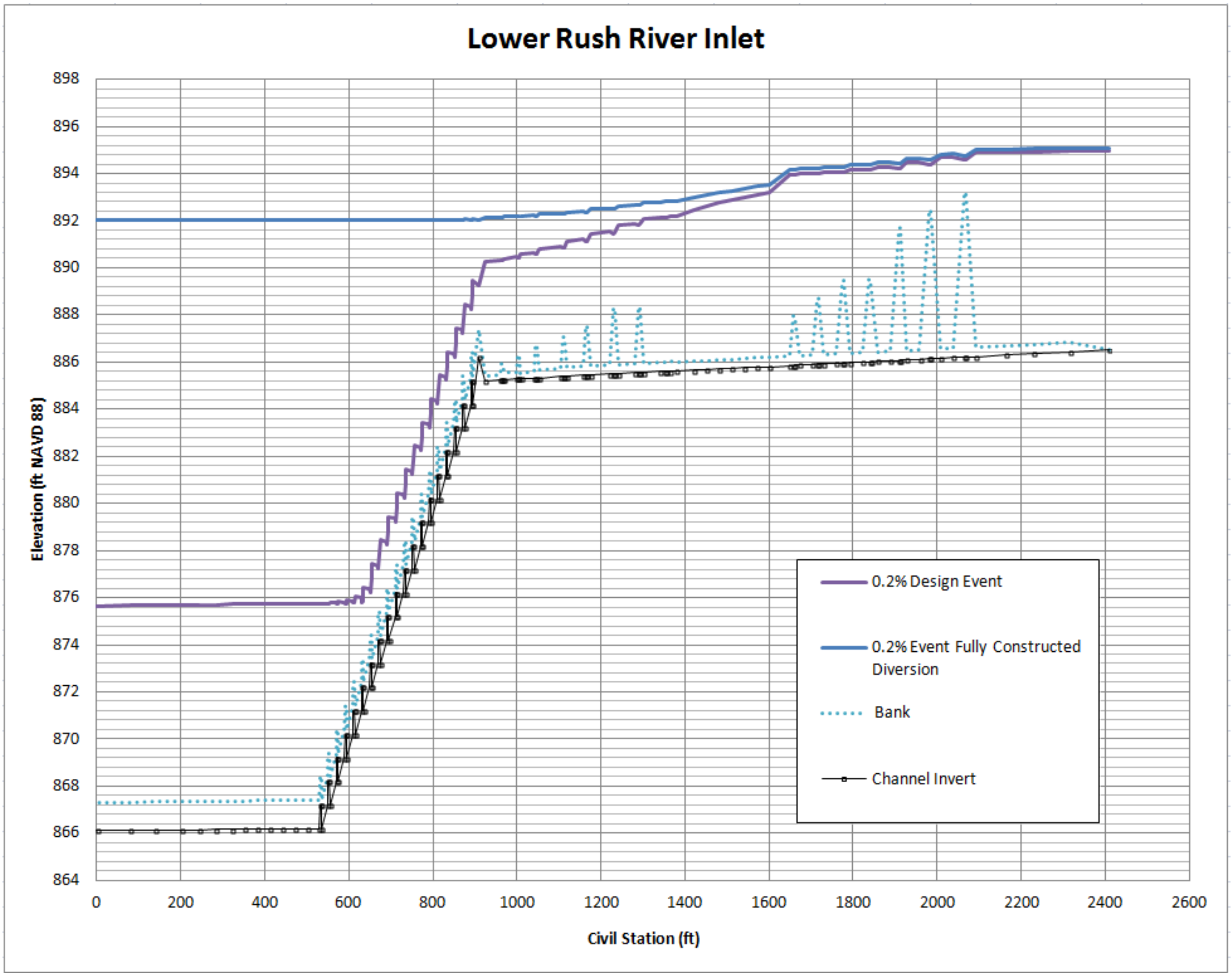

Figure C. 7 Design Water Surface Profiles for Lower Rush River Inlet Structure

The ramp of the inlet structure experiences the highest velocities at a discharge of approximately 2900 cfs. The inlet was designed for a condition with no upstream flow in the diversion to model the worst case. Even with these conditions the velocity does not exceed 9 feet per second. For the fully constructed diversion condition the structure is affected by the downstream tail water condition during large flow events and peak velocities are reduced greatly.

Riprap sizing was based on the peak velocity and shear in three distinct segments of the structure; upstream of the ramp, on the ramp, and downstream of the ramp. The highest of these velocities, around 9 feet per second, was computed on the ramp. Based on the velocities, the riprap and layer thickness vary on the ramp, upstream, and downstream areas of the inlet structure. The riprap sizing for the inlet structure was based on the shear based equations for riprap sizing EM-1110-2-1601 (1970), equation 33 and EM-1110-2-1601 (1994), Equation 3-5. Using the Shear equations a sizing gradation of R30 at a 21" layer thickness was used for areas upstream and downstream of the ramp. The banks on the upstream of the ramp use a gradation of R30 at a 14” layer thickness. The riprap sizing for the ramp is a gradation of R270 at a 54” layer thickness. A layer of R30 with a thickness of 21” was also used to armor the slope at the overflow weir.

Thicknesses for the R270 and the 21” R30 gradations are based on high turbulence conditions for rounded rock being placed in the dry. A 25% rock diameter increase was added to allow for the use of rounded stone. Thickness on the ramp also included a factor for impact and ice loading per Section 3-13 of EM 1110-2-1601. Stone size was not increased since the boulder weirs will be present on the ramp. All riprap will be placed on bedding stone. A 12 inch layer of B3 will be used under the R270, and a 6 inch layer of B1 bedding will be used under all other riprap.

A low turbulence thickness was used on the side slopes of the upper portion of the structure. Sizing calculations indicated that a very small riprap would be suitable over much of the upper section of the structure. The smallest gradation was selected. After stepping up one gradation to account for rounded stone, etc, it was decided that the design was conservative enough to utilize the low turbulence thickness on the side slopes in this area. The high turbulence thickness was maintained along the bottom of the channel where velocities would be focused by the rock dike structures and on the slope where the overflow section enters the channel.

A plan view of the riprap sizes can be seen in Figure C. 8. Note that all riprap gradations identified in this report refer to St. Paul District gradation identifiers designated as R followed by W_{50}min.

Riprap extents were set two feet above the 0.2% profile with normal depth tail water on the realigned channel and the rock ramp. Riprap will extend 50 feet upstream of the most upstream rock structure in the channel. In the diversion channel, riprap will be placed from the toe of the left slope, through the low flow channel, to five feet up the right slope. Upstream riprap extents will be where the Lower Rush Inlet right top of bank meets the low flow channel left top of bank. It will extend 100 feet downstream of the junction of the Lower Rush Inlet and the diversion channel. To reduce the amount of riprap needed, the riprap upstream of the junction and right of the low flow channel will stop at an angle matching the inlet structure angle. To prevent erosion of the upstream separation berm, riprap was added 40 feet on the main channel side and 80 feet on the Rush River side of the berm. This riprap extended to the top of the channel bench, which results in rip rap protection to the 1% level in the diversion channel.

Figure C. 8 Plan View of Riprap Gradations and Thicknesses of the Lower Rush River Inlet Structure

C.5 FURTHER DESIGN GUIDELINES

Further guidance for the design of this reach and other reaches can be found in *Appendix M: Memos for Record and Guidance Memos.*