

Sherwood Gage Erosion Control Investigation

Renville County, North Dakota

SWC Project
North Dakota State Water Commission
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Prepared for:
United States Geological Survey

March 2016

Prepared by:



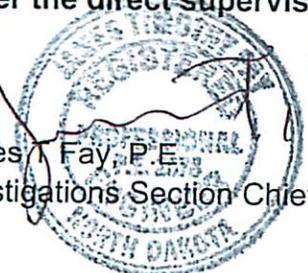
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1. Introduction

Sherwood gage is a United States Geological Survey (USGS) stream gage located near the City of Sherwood on the Mouse River. Over the last several years, sustained high flows have increased the rate at which the stream banks have been eroding. The increase in erosion has jeopardized the gage.

The USGS requested the North Dakota State Water Commission (SWC) to conduct an investigation to determine possible solutions or measures that could be taken to reduce or prevent erosion near the gage. This report presents the results of the study and identifies alternatives for the USGS to consider.

2. Site Location

Sherwood Gage is located in northern Renville County just south of the 49th parallel, which is the border of the United States of America (U.S.) and Canada. The gage is located in Sections 33 of Township 164 North, Range 87 West.

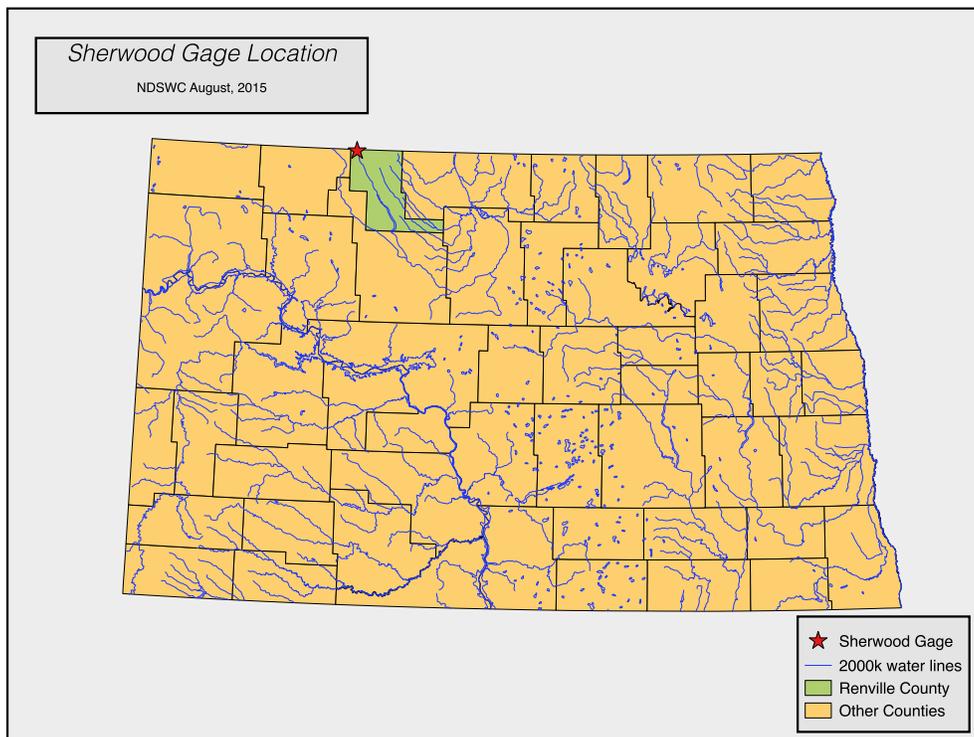


Figure 1. Site Location



Figure 2. Site location (2)

3. Background

The Sherwood gage has collected stream flow data from 1930 to present day. This long record and its status as a control point for operations of the flood protection system give a strong incentive to maintaining the existing site. It is located on an outside bend of a meander on the Mouse River. The banks upstream of the gage slumped into the river and downstream of the gage appeared to have recently slumped and are cut back several feet further than the gage structure. These observations indicate a high potential for failure along the stream bank. A levee exists approximately 50 feet south of the top of bank.

4. Geomorphology

The Mouse River was formed from glacial waters approximately 12,000 years ago. Glacial flows from Lake Regina carved the Mouse River Valley and eventually ended up in glacial Lake Souris. The formation of this river left the upper reaches of the Mouse River to have a steeper grade with slight meandering and the opposite for the lower reaches of the river. This change in the river occurs downstream of the City of Velva.

Soil particles along the Mouse River are typically composed of clay to sand particles that erode and deposit in a predictable process: the river's adjustments to maintain its energy grade cause the river to remove sediments to keep the stream length. Figure 3 is a depiction of how a typical meander erodes and deposits sediment material. The process causes the outside bends, or pools, of meanders to erode away, while the inside bends, or point bars, typically gain new material. On each end of the bend in a meander shallow areas form, known as riffles. The deepest path, known as the thalweg, is the area with the largest erosion potential due to the increased velocity. The geomorphic features can be identified using the same process depicted in Figure 3 and by viewing the topography and aerial imagery of an area.

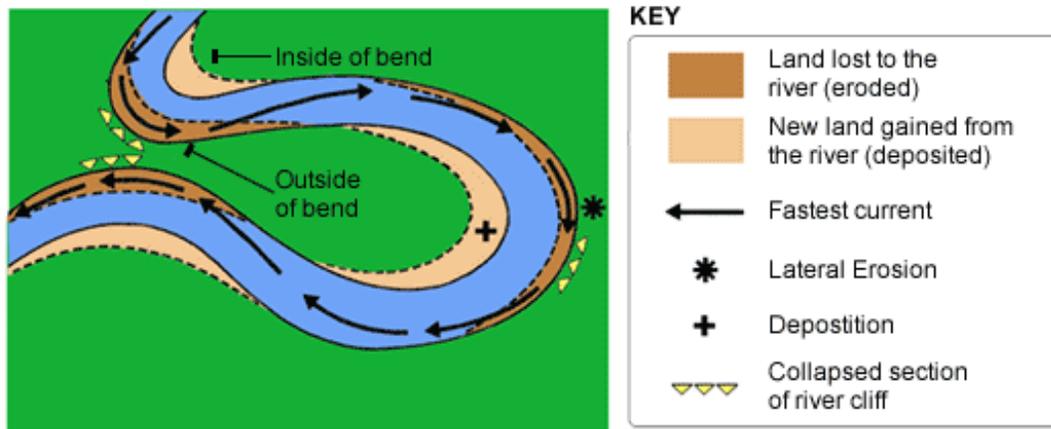


Figure 3. Meandering river sediment distribution.

Pools, riffles, and point bars also help identify what type of meander is forming. Reaches are often classified by their degree of meander or by their meander classification. The Modified Brice Classification System (MBCS) can be used to determine a reach's meander classification. The reach of the Mouse River near Sherwood gage is wider at its bends with point bars on each bend. Using MBCS the reach can be classified under the G2 category by examining aerial photography. The G2 category of MBCS describes the reach as a two phase, bimodal bank-full sinuosity that is wider at the bends. A G2 category reach is normally formed by bank-full flow or extremely large flood events. The meanders in a G2 category reach typically have excessive movement of the banks and can have extremely variable channel migration. The extreme variability of the reach can be verified by the oxbow lakes along the Mouse River from the Canadian border to Lake Darling.

5. Factors Contributing to Bank Retreat

In order to identify stream bank erosion mitigation solutions, the cause of the erosion had to be determined. The meander classification identified that bank-full and extremely large flows are what form this particular type of reach. The processes that are responsible are high channel velocities increasing excess shear stress on the stream bank, subaerial processes, and mass failure of the stream bank.

Two of these four processes must be evaluated using a hydraulic model of the area in question. Two-dimensional hydraulic models can determine the applied shear stress the water surface exerts on the stream bank and calculate the channel velocities in the problem area.

5.1 Channel Velocity

Channel velocities play an important role in forming a river channel. As channel velocities increase so does the river's momentum. Increased channel momentum increases the hydraulic shear stress a river places on its banks, increasing erosion. The NRCS "Stream Restoration Planning and Design Fluvial System Stabilization and Restoration Field Guide" describes bank-full flows to be major channel forming events.

"Bank-full flow is often considered to be synonymous with channel-forming discharge in stable channels, and is used in some channel classification systems, as well as for an initial determination of main channel dimensions, plan and profile. In many situations, the channel velocity approaches maximum velocity at bank-full stage. In some cases, on wide, flat floodplains, it has been observed that the channel velocity can drop as the stream overtops its bank, and spills onto the floodplain." (NRCS, 2011)

Channel velocities can be used to determine if erosion is taking place if the permissible velocity of soil type is exceeded. Table 1 is a list of mean permissible velocities of a channel based on channel materials from the NRCS's National Engineering Handbook (NRCS, 2007).

Channel material	Mean channel velocity	
	(ft/s)	(m/s)
Fine sand	2.0	0.61
Coarse sand	4.0	1.22
Fine gravel	6.0	1.83
Earth		
Sandy silt	2.0	0.61
Silt clay	3.5	1.07
Clay	6.0	1.83
Grass-lined earth (slopes <5%)		
Bermudagrass		
Sandy silt	6.0	1.83
Silt clay	8.0	2.44
Kentucky bluegrass		
Sandy silt	5.0	1.52
Silt clay	7.0	2.13
Poor rock (usually sedimentary)	10.0	3.05
Soft sandstone	8.0	2.44
Soft shale	3.5	1.07
Good rock (usually igneous or hard metamorphic)	20.0	6.08

Table 1. Permissible channel velocities in riparian areas (NRCS, 2007).

5.2 Excessive Shear Stress

A soil's plasticity is the ability of its particles to adhere to one another. It is measured by its plasticity index, which is defined as the difference between a soil's liquid limit and its plastic limit. The plasticity index is important in classifying fine-grained soils. The plasticity index of a soil can be related to the shear stress a soil could endure without eroding from a stream bank (Clark, 2007).

Excess shear stress is a contributor to erosion of stream banks that have non-plastic soils. The excess shear stress equation approximates the amount of soil particles detached from the stream bank due to hydraulic forces, also known as fluvial entrainment. The excessive shear stress equation can be used to approximate the amount of erosion taking place in cohesive soils (Equation 1, Clark, 2007).

$$\varepsilon = k_d * (\tau_a - \tau_c)^a \quad (\text{Eq. 1})$$

ε = erosion rate (m/s)
 a = exponent typically assumed to be 1
 k_d = erodibility coefficient ($\text{m}^3/\text{N}\cdot\text{s}$)
 τ_a = applied shear stress on the soil boundary (Pa)
 τ_c = critical shear stress (Pa)

Equation 2 is the empirical equation developed from a flume study to compute the critical shear stress of a soil using the soil's plasticity index (Equation 2, Clark, 2007). The critical shear stress of a soil was derived to be inversely related to a soils erodibility coefficient (Equation 3, Clark, 2007).

$$\tau_c = 0.16 * (I_w)^{0.84} \quad (\text{Eq. 2})$$

τ_c = critical shear stress (Pa)
 I_w = plasticity index

$$k_d = 0.2 * (\tau_c)^{-0.5} \quad (\text{Eq. 3})$$

k_d = erodibility coefficient ($\text{cm}^3/\text{N}\cdot\text{s}$)
 τ_c = critical shear stress (Pa)

5.3 Subaerial Processes

Subaerial processes are climate-controlled conditions that reduce soil strength. Frost heave is the main component of subaerial processes. Subaerial processes control erosion in the upper reaches of a stream basin due to generally lower discharges in the upper reaches.

5.4 Mass Failure of Stream Banks

Mass wasting occurs when the weight of the bank is greater than the shear strength of the soil (Clark, 2007). Mass wasting occurs from increases in bank height and bank angle due to fluvial entrainment. This process typically takes place after large flood events and is a separate component from fluvial entrainment. Fluvial entrainment and mass failure work together to complete the geomorphological process and define a stream's banks. Mass failure tends to occur near pools on meandering rivers due to the sharp change in elevation.

5.5 Observed Factors Contributing to Bank Retreat

Subaerial processes appear to be the only factor not contributing to bank retreat in this reach. Subaerial processes typically contribute to bank retreat in the most upstream reaches of a riverine system; this is due to the frost heave cycle having more of an affect than flow. It is generally understood that less drainage area produces less flow; this relationship of lower flows and less drainage area point to major erosion in the upper reaches of a river to be caused by subaerial processes.

It was observed that pools had formed on each sharp meander of the stream while wading into the stream on a site visit on July 27, 2015. The banks throughout the meander were steep and in some areas sediment was observed from portions of the bank slumping off into the stream. These observations support that mass failure is occurring along this reach of the Mouse River.

The steep stream banks along the reach also appear to overtop at higher flows than other reaches of the Mouse River. Bank full events in this reach would contain high flows and increased velocities, which would contribute to velocities and shear stress being major factors in the reach's geomorphologic process.

6. Hydraulic Analysis

The hydraulics of the region was examined to determine the variability of shear stress and velocity near the Sherwood Gage. The hydraulics were examined for bank-full flows since that is the most likely event contributing to erosion near the gage.

6.1 Flood Frequency Analysis

The United States Army Corps of Engineers (USACE) calculated natural and regulated flows for each gage on the Mouse River for their Regional Reconstructed Hydrology study. A regulated hydrograph for the Sherwood Gage represents Rafferty, Alameda, and Darling dams being present over the entire gage's record. The regulated hydrographs used to determine a regulated period of record are in Appendix B. A flood flow frequency analysis of the regulated hydrograph was produced. Figure 4 is a Bulletin 17B plot for the flood flow frequency analysis, and Table 2 are the flow values for certain frequency events.

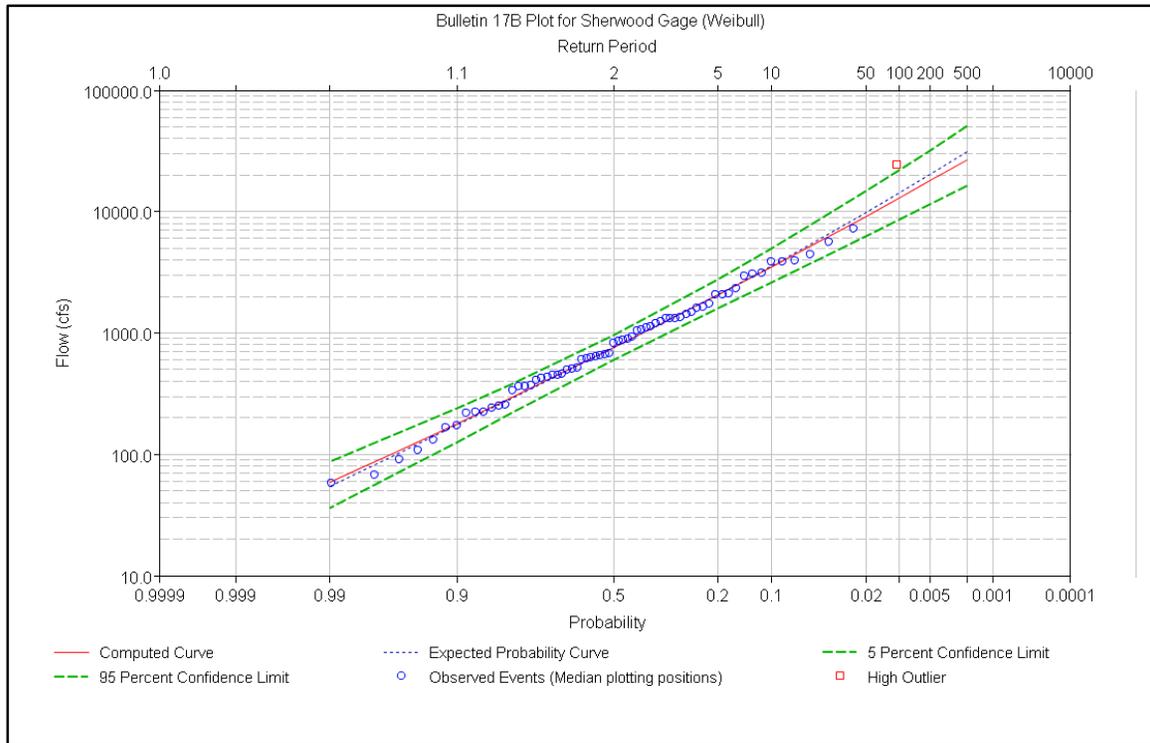


Figure 4. Sherwood gage bulletin 17B plot.

Table 2. Sherwood gage discharge frequency events.

Percent Chance of Exceedance	Frequency event	Flow (cfs)
1%	100 YR	12,995
2%	50 YR	9,175
5%	20 YR	5,485
10%	10 YR	3,499
20%	5 YR	2,050
50%	2 YR	759

6.2 Hydraulic Modeling

Two-dimensional hydraulic modeling can calculate applied shear stress across a channel due to its ability to have independent water surfaces on each node of a grid. The International River Interface Cooperative's (iRIC) solver System for Transport and River Modeling (SToRM) was chosen to model the hydraulic effects of the Mouse River. SToRM's solver documentation is located in Appendix C.

SToRM is a two-dimensional solver that uses an unstructured grid to compute the momentum equation over a Digital Elevation Model (DEM). SToRM was used for the hydraulic analysis due to its ability to determine bed shear stress, map channel and over bank velocities, and its ability to identify the thalweg of the river system. The SToRM model is located in Appendix C.

Survey data (Appendix D) along with 1-meter LiDAR data from the Mouse River collect was used to create the DEM. The survey data collected were within the banks in order to properly capture the geometry of the channel. The survey data collected is coarser than expected due to conditions in the field. The survey was originally intended to be 3 to 4 survey shots across the channel every 30 feet. The conditions only allowed for 2 survey shots in the channel every 30 feet. This was overcome by placing break lines around the edge of the LIDAR data. The break lines allowed the interpolated channel to resemble the actual channel. The unstructured grid created for the model uses a 30 square meter grid for the out of bank regions and 10 square meter grid between the banks.

The model was then calibrated to several existing events. Table 3 describes the list of events to which the SToRM model was calibrated.

Table 3. Events calibrated to the Sherwood Gage in the SToRM model.

Event	Flow (cfs)	Gage Stage (ft)	Modeled Stage (ft)	Difference [Model-Gage] (in)
May 9 2001	2,179	1620.39	1620.28	-1.32
April 18 2009	1,320	1617.43	1617.4	-0.36
April 10 2013	2,320	1625.24	1625.29	0.6
April 8 2015	1,720	1618.16	1618.48	3.84

Each event, except for the 2013 event, uses the same slope when determining an outflow elevation. The 2013 event uses a more relaxed slope due to an ice jam that formed downstream of the gage.

7. Erosion Analysis

The outer bank on the meander of the Mouse River at the site is severely eroded. Approximately 900-feet of the outer bank is in need of erosion protection (Figure 5) as determined by visual inspection and model results. Using the SToRM model created as part of this study, the channel velocities and excess shear stress during approximate bank full events were evaluated to determine appropriate erosion control measures.

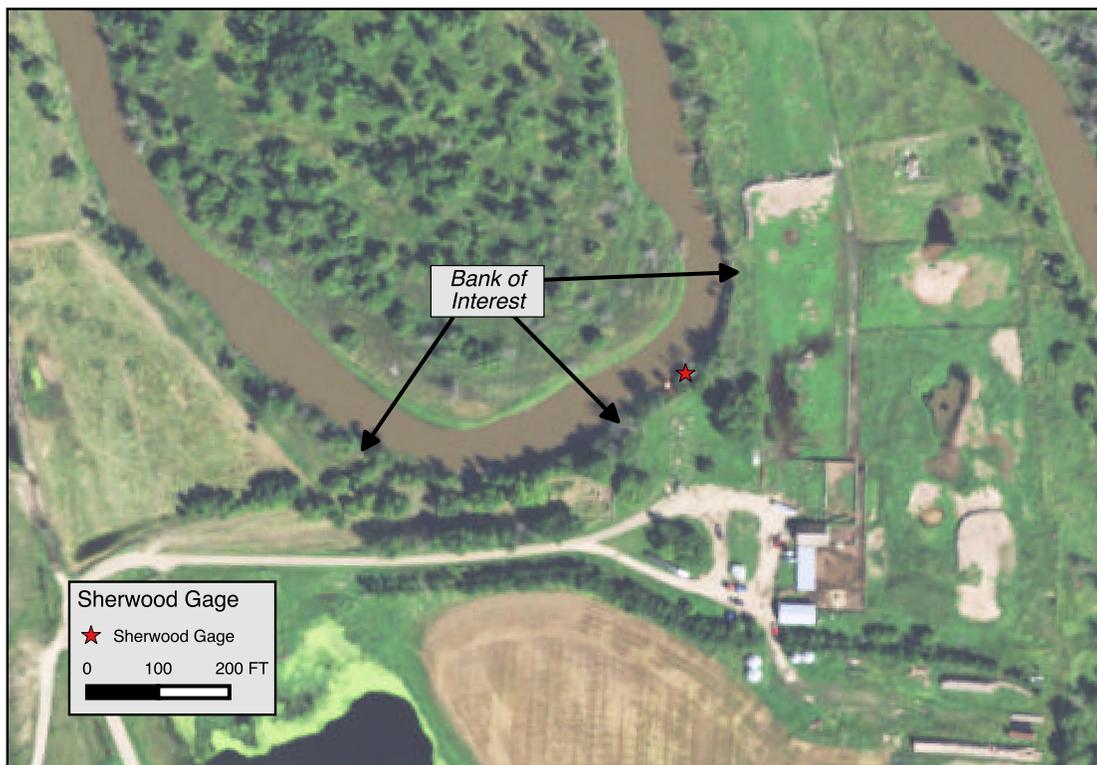


Figure 5. Bank of Interest.

The bank of interest (Figure 5) is classified as a LaDelle silty clay loam by the National Resources Conservation Service (NRCS). The NRCS' Web Soil Survey was used to determine physical properties of LaDelle silty clay loam (Appendix E). LaDelle silty clay loam has 100 percent passing the number 40 sieve and close to 95 percent of the material passing the number 200 sieve. LaDelle silty clay loam has an average plasticity index of 21.

7.1 Channel Velocity and Bed Shear Stress Analysis

The STORM model also approximated channel velocities at bank-full conditions. Velocities of nearly 4 feet per second were produced at the gage using a quasi-steady inflow of 3,450 cfs, which are approximately bank full conditions in this reach. The model also produced bed shear stress values of approximately 0.1 pounds per square foot on the bank near the gage.

Based on the bank's soil composition and the results of the hydraulic model, an estimated erosion rate for bank full events can be calculated. The erosion rate calculated based on the STORM model's bank full event (3,450 cfs) that produced a bed shear stress of approximately 0.1 pounds per square foot is 0.12 feet/day (Eq. 1). The erosion rate calculation does not account for vegetative armoring and is typically thought to be a higher value than what occurs during a flood event.

8. Erosion Mitigation/Protection

Erosion protection structures are divided into two categories: soil bioengineering and hard engineering. Soil bioengineering techniques use vegetation to protect the stream banks from high velocities and shear stresses. Hard engineering practices consist of revetments, sheet piling, and hard armoring.

The site requires protection of the toe, re-grading or stabilization of the bank to prevent mass failure, and protection of the top of bank to prevent erosion during large flood events.

8.1 Soil Bioengineering Techniques (Soft Armoring)

“Streambank soil bioengineering is defined as the use of living and nonliving plant materials in combination with natural and synthetic support materials for slope stabilization, erosion reduction, and vegetative establishment.” (NRCS, 2007). Soil bioengineering provides a more aesthetic approach to stream bank protection and provides many benefits to wildlife. Improving riparian areas by selecting certain plant materials can boost the habitat of the area by providing food and cover for birds, mammals, and aquatic life. Soil bioengineering typically encompasses hard structure components to strengthen the stream bank during bank full flows. Bioengineering techniques do however slow the movement of water through the channel, reducing the energy of the stream and increasing the stage.

There are a wide variety of different soil bioengineering techniques that can be incorporated at a given site. With the incorporation of hard engineering and soil bioengineering techniques it becomes difficult to explain each option on an individual and descriptive basis. The NRCS has put together guides for selecting and viewing each of the most common soil bioengineering practices. The “Technical Supplement 14I Streambank Soil Bioengineering” guide for each soil bioengineering practices is attached in Appendix F.

8.2 Hard Armoring

Hard armoring increases the bank resistance to erosive forces, but does not significantly reduce the energy of the water. Hard armoring redirects energy from the bank and creates a more permanent change to the surrounding area. The two most common types of hard armoring for decreasing erosive forces are sheet piling and riprap revetments.

8.3 No Change Alternative

Depending on the severity of events the stream gage could become inoperable in a few years.

8.4 Soil Bioengineering (Soft Armoring) Alternatives

Channel velocities, water-applied shear stress, and slope of the stream bank determine which soil bioengineering techniques can be applied to a project area. Each technique can have a wide variation of costs. The soil bioengineering analysis for the sites on the Mouse River near the Sherwood Gage was governed by the maximum applied shear stress and the maximum velocity created by a bank full event. The velocities and applied shear stresses were then compared to the permissible velocity, permissible shear stress, and the maximum slope of each technique, as described in the NRCS's "Technical Supplement 141" (Appendix F).

Table 4 is the suggested and non-suggested soil bioengineering techniques based on the analysis described. If both initial and established requirements meet bank full shear stress and velocity, the method of stream bank restoration can be completed without extreme reshaping of the stream bank. Soil bioengineering techniques not meeting initial requirements are not successful. Most soil bioengineering techniques require plant development to be effective in mitigating erosion along a stream bank. If plants do not have a long enough period to establish before becoming inundated, the project will fail.

Soil bioengineering techniques also have a greater success rate if they are placed on less severe slopes. 1H:1V slopes have a greater chance of failure. It is suggested to use as shallow a slope as project budgets allow. Slopes of at least 3H:1V are suggested.

Soft armoring or soil bioengineering techniques are extremely variable in cost depending on availability of natural resources. Onsite vegetation and stone can affect costs dramatically; in some cases costs can be cut substantially depending on local knowledge of these natural resources. Because of the variability, costs for this alternative were not included.

Table 4. Soft armoring stream bank restoration alternatives (Descriptions in Appendix F, Technical Reference 14I).

Site: Sherwood Gage	Permissible shear stress	Permissible velocity	Slope Requirements	Meets Requirements
Practice	(lb/ft ²)	(ft/s)	ft/ft	Yes/No
Live poles (Depends on the length of the poles and nature of the soil)	Initial: 0.5 to 2 Established: 2 to 5	Initial: 1 to 2.5 Established: 3 to 10	5H:1V to 1H:1V See TS14I for Design Details	Initial: No Established: No
Live poles in woven coir TRM (Depends on installation and anchoring coir)	Initial: 2 to 2.5 Established: 3 to 5	Initial: 3 to 5 Established: 3 to 10	5H:1V to 1H:1V See TS14I for Design Details	Initial: No Established: No
Live poles in riprap (joint planting) (Depends on riprap stability)	Initial: 3+ Established: 6 to 8	Initial: 5 to 10+ Established: 12+	5H:1V to 1H:1V See TS14I for Design Details	Initial: Yes Established: Yes
Live brush sills with rock (Depends on riprap stability)	Initial: 3+ Established: 6+	Initial: 5 to 10+ Established: 12+	6H:1V to 2H:1V See TS14I for Design Details	Initial: Yes Established: Yes
Brush mattress (Depends on soil conditions and anchoring)	Initial: 0.4 to 4.2 Established: 2.8 to 8	Initial: 3 to 4 Established: 10+	4H:1V to 2H:1V See TS14I for Design Details	Initial: No Established: Yes
Live fascine (Very dependent on anchoring)	Initial: 1.2 to 3.1 Established: 1.4 to 3	Initial: 5 to 8 Established: 8 to 10+	5H:1V to 1H:1V See TS14I for Design Details	Initial: Yes Established: Yes
Brush layer/branch packing (Depends on soil conditions)	Initial: 0.2 to 1 Established: 2.9 to 6	Initial: 2 to 4 Established: 10+	6H:1V to 2H:1V See TS14I for Design Details	Initial: No Established: Yes
Live cribwall (Depends on nature of fill, compaction, and anchoring)	Initial: 2 to 4 Established: 5 to 6	Initial: 3 to 6 Established: 10 to 12	1H:4V to 1H:6V See TS14I for Design Details	Initial: No Established: Yes
Vegetated reinforced soil slopes VRSS (depends on soil conditions and anchoring)	Initial: 3 to 5 Established: 7+	Initial: 4 to 9 Established: 10+	1H:1V or Greater See TS14I for Design Details	Initial: Yes Established: Yes
Grass turf (Depends on vegetation type and condition)	Established: 3.2	Established: 3 to 8	Up to 2H:1V See TS14I for Design Details	Initial: No
Live brush wattle fence (Depends on soil condition and depth of stakes)	Initial: 0.2 to 2 Established: 1 to 5	Initial: 1 to 2.5 Established: 3 to 10	6H:1V to 4H:1V See TS14I for Design Details	Initial: No Established: No
Vertical bundles (Depends on bank conditions, anchoring, and vegetation)	Initial: 1.2 to 3 Established: 1.4 to 3	Initial: 5 to 8 Established: 6 to 10+	Up to 1H:1V See TS14I for Design Details	Initial: Yes Established: Yes

8.6 Riprap Revetment

Riprap revetments are the most common riverine erosion mitigation measures. Riprap revetments are a hard armoring technique utilizing geotextile material to hold the fine particles in place while armoring the bank with large angular rock. Designed riprap revetments can protect against toe erosion, high velocities, and mass failure.

Riprap is sized based on the average sized particle of riprap to be found in the gradation of rock to be placed. The most common method to size riprap is known as the Ishbash Method of Stone Sizing (Equation 4).

Figure TS14K-2 Typical riprap section

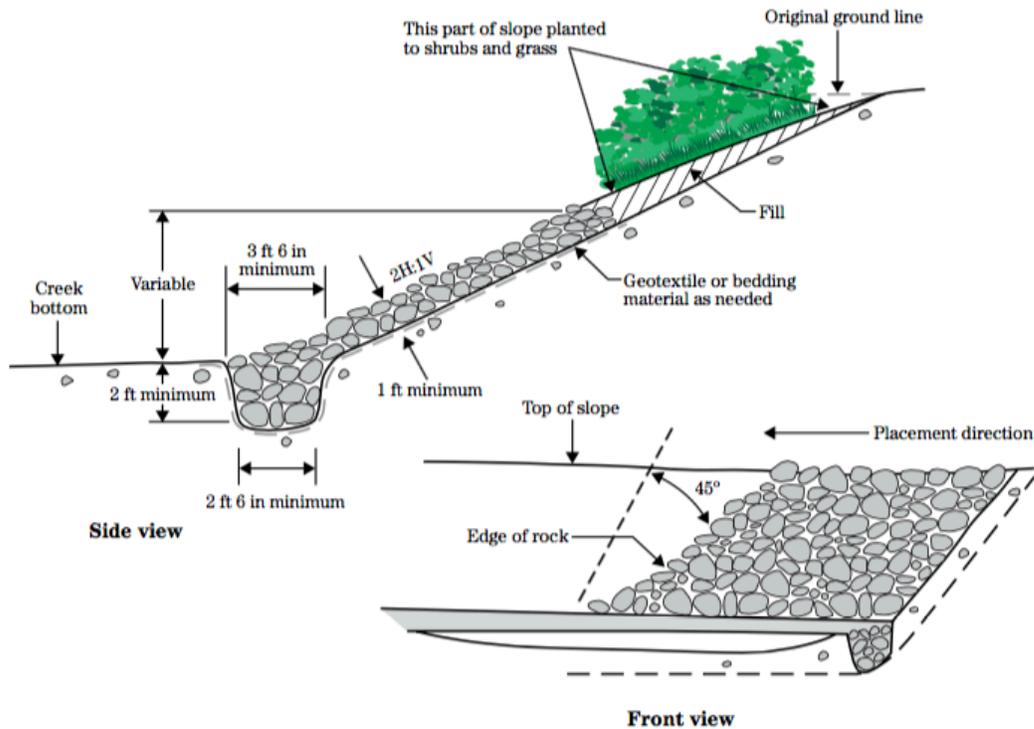


Figure 6. Typical riprap section (NRCS, 2007)

$$V_c = C * (2 * g * ((\gamma_s - \gamma_w) / \gamma_w))^{0.50} * (D_{50})^{0.50} \quad (\text{Eq. 4})$$

- V_c = critical velocity (ft/s)
- C = 0.86 for high turbulence
- C = 1.20 for low turbulence
- g = 32.2 ft/s²
- γ_s = stone density (165 lb/ft³)
- γ_w = water density (62.4 lb/ft³)
- D₅₀ = mean stone diameter (ft)

The average particle size, D₅₀, for riprap at the site was approximately 4 inches. It is standard practice, using the Ishbash Method, to choose stone with a minimum particle size larger than 6 inches if the average stone size is less than or equal to the suggested minimum particle size. Since the method yielded a 4-inch median particle size, a 6-inch median particle size should be used.

The volume of riprap was determined for the site by calculating the surface area of bank slope to be armored and multiplying the surface area by a depth three times greater than the minimum particle size, 6 inches. The height of riprap on the bank can be variable. It is generally assumed the higher the riprap is placed up the bank the more stability would be added.

The site was to be graded to a 1 vertical to 3 horizontal slope to increase stability. Table 5 is a volume estimate for the amount of riprap needed for the site.

Table 5. Riprap revetment quantities based on height of protection.

Riprap (tons)	Height above channel bottom (ft)	Flow (cfs)	Percent chance of over topping (per year)
2,576	8	705	50% (approximate)
4,831	16	2,250	20% (approximate)
6,910	24 (top of bank)	3,450	10% (approximate)

A non-woven geotextile fabric would underlay the riprap revetment, decreasing particle transport and supporting particle deposition onto the site. Table 6 is the amount of non-woven geotextile fabric underlay for the designed riprap revetment.

Table 6. Geotextile quantities based on height of protection.

Height above channel bottom (ft)	Geotextile (sq yd)
8	3830
16	6360
24 (top of bank)	8334

Based on the chance of overtopping and amount of armored bank created, a riprap revetment covering up to 16 ft of height is the minimum recommended.

Cost estimates were developed from the computed volume of riprap. Riprap volumes were estimated for a 3H:1V slope at 1.5 ft of depth with a toe trench that is 2.5 ft deep having a top width of 4 ft and bottom width of 3 ft. The price estimates for the site are based off of RSMeans "Heavy Construction Estimator 2014" and through contacting local contractors. Table 7 is a cost estimate to re-grade the stream bank and place riprap along the stream bank. The initial cost estimate is driven by the price of riprap. The cost of riprap was estimated based on delivery from the nearest commercial pit in Minot, ND. Majority of the cost associated with the current cost estimate is the delivery of the riprap nearly 73 miles to the project site. If riprap or suitable field rock is found closer to the project site the costs of riprap could decrease dramatically.

Table 7. Sherwood Gage riprap revetment cost estimate.

Task	Quantity	Unit	Material Cost	Labor Cost	Equipment Cost	Total Cost O&P
Mobalization of equipment	2	EA		\$100.00	\$320.00	\$20,000.00
Site clearing with 335 H.P. dozer, trees to 24 in	30	EA		\$5.40	\$18.15	\$840.00
Grub stumps, trees to 36in	30	EA		\$2.76	\$9.30	\$433.00
Top soil stripping and storing on site 300 H.P. dozer ideal conditions	925	C.Y.		\$0.18	\$0.61	\$869.00
Subsoil removal/rough grading 1.5 C.Y. excavator	3141	C.Y.		\$1.61	\$2.39	\$16,019.00
Cutting toe trench	380	C.Y.		\$1.61	\$2.39	\$2,519.00
Geotextile fabric placement	8334	S.Y.	\$1.88	\$0.23		\$20,251.00
Riprap placement	4800	Ton				\$400,000.00
Final topsoil grading above riprap section	3605	S.Y.	-	\$0.41	\$0.29	\$2,848
Seeding of newly graded topsoil	32.45	M.S.F.	\$26.00	\$12.30	\$8.85	\$1,850
Total cost before contingency and mobilization.						\$465,629
Design Costs						
10% Design						\$46,563
Total Costs O&P						
\$512,192						
15 percent contingency						\$76,829
Total Costs (rounded to nearest \$10,000)						\$590,000

9. Summary

The banks of the Mouse River near the Sherwood Gage are eroding due to stream velocities, excess shear stress, and mass failure. Removal of the stream bank toe, due to excess shear stress and stream velocities, is increasing the stream bank slope, which causes mass failure of the banks. If this magnitude of erosion continues, the stream bank near the gage will be removed, and the bank housing will likely be unusable.

Several methods could be used to mitigate or protect the stream bank from these types of erosion. These methods would need to incorporate re-grading of the bank to provide relief from mass failure and armoring to protect soil from erosion. Re-grading of the stream bank will also fall into the footprint of the levee. Consideration should be given to raising the entrance road into the farmstead located directly to the south of the existing levee to prevent flows from moving across the fields to the south and maintain usability of the roadway.

The stabilization of the stream bank on the Mouse River would require several permits. The State of North Dakota would require a Sovereign Lands Permit, since the project would take place on sovereign land. The federal government would require a permit under Section 10 of the Rivers and Harbors Act to build within navigable waters. The federal government would also require a permit under Section 404 of the Clean Water Act to place materials within a wetland.

Riprap revetments, the most common erosion control technique in North Dakota, would successfully protect the bank from further retreat and offer the highest probability of success, but could be extremely expensive due to the material costs. Soft armoring techniques with riprap toes could provide cost relief if building materials can be found locally. Soft armoring techniques that could prevent/mitigate erosion and mass failure on this stream bank include live poles in riprap, live brush sills with a rock toe, live fascines, vegetated reinforced soil slopes, and vertical bundles. Live fascines would be a cost effective option if willows were available near the project site. A fascine without a riprap toe with willows available near the project site would be comparable to the cost estimate in **Table 7** minus the cost of the riprap revetment. However, a riprap toe would be advised to increase probability of establishing a fascine.

10. Citations

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