Technical Memorandum

To: SRJB
From: Chris Frias
Subject: River Bed Study
Date: September 29, 2026
Project: 34511010.21

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1 Overview

This technical memorandum presents the development and results of a riverbed sediment transport and erosion analysis for the Mouse River within the Minot, ND area. The study supports the Mouse River Enhanced Flood Protection Project (MREFPP) by evaluating potential long-term morphological changes resulting from sediment transport during high-flow events. A two-dimensional (2D) hydrodynamic and sediment transport model was constructed using HEC-RAS 6.6, incorporating terrain data from LiDAR, bathymetric surveys, and field-collected sediment samples.

The modeling effort aimed to estimate potential erosion and deposition patterns during flood events, calibrate hydraulic parameters using historic events, and evaluate the potential for general scour of various channel segments under the flood of record event. This memorandum outlines the procedures, assumptions, calibration efforts, and outcomes of the modeling process.

Overall, the scour depths obtained from the two-dimensional (2D) sediment transport model were smaller than the ones obtained from previous efforts that used a one-dimensional (1D) model. The scour depth values are used in the design of launchable riprap to estimate the extents of the toe protection (i.e., up to the estimated scour depth). Thus, obtaining smaller depths with the current analysis helps to reduce the extent of the toe protection and therefore reduces the amount of riprap to be used at each location.

2 Hydrodynamic Model Construction

2.1 Terrain

The Digital Terrain Model (DTM) used in this study was developed through merging LiDAR topographic data, field survey data, and bathymetric surveys. The LiDAR data was sourced from an aerial survey conducted by EagleView in April 2020 and from additional surveys conducted by Houston Engineering, Inc. (HEI) in May 2024. A summary of the topographic data used to construct the bathymetry incorporated in the HEC-RAS model can be found in Table C2-2 of reference [1].

2.2 Mesh and Boundary Conditions

A 2D model was developed in HEC-RAS version 6.6 based on a previously created 1D HEC-RAS model, “MREFP_S4_v6.05.” The 2D model extends from approximately 1.25 miles upstream of the North Highway 83 Bypass bridge (downstream of the confluence of the Des Lacs and Mouse Rivers) to approximately 0.85 miles downstream of the U.S. Highway 2 bridge (Figure 1). While the 2D model did include the Maple Diversion and the 27th St Diversion, it did not include the Ramstad Loop or the Green Valley Loop, as in the 1D model. The 2D mesh cell size was set to 100 feet by 100 feet, with a smaller cell size of 40 feet by 40 feet in the main channel. For features that require higher resolution, such as a rock riffle or bridge piers represented by breaklines, the cell size was set to 10 feet by 10 feet. The

upstream boundary condition of the 2D model was set to a constant flow hydrograph. An initialization event was simulated to create sediment and hydrodynamics initial conditions, along with the flood of record event. For the initialization event, a flow of approximately 2,600 ft^3/s (this flow rate is close to a 10-year event) was selected because it is an event in which most of the water is inside the main channel. For the flood of record event, a constant 27,400 ft^3/s flow was used. The downstream boundary condition was set to normal depth.

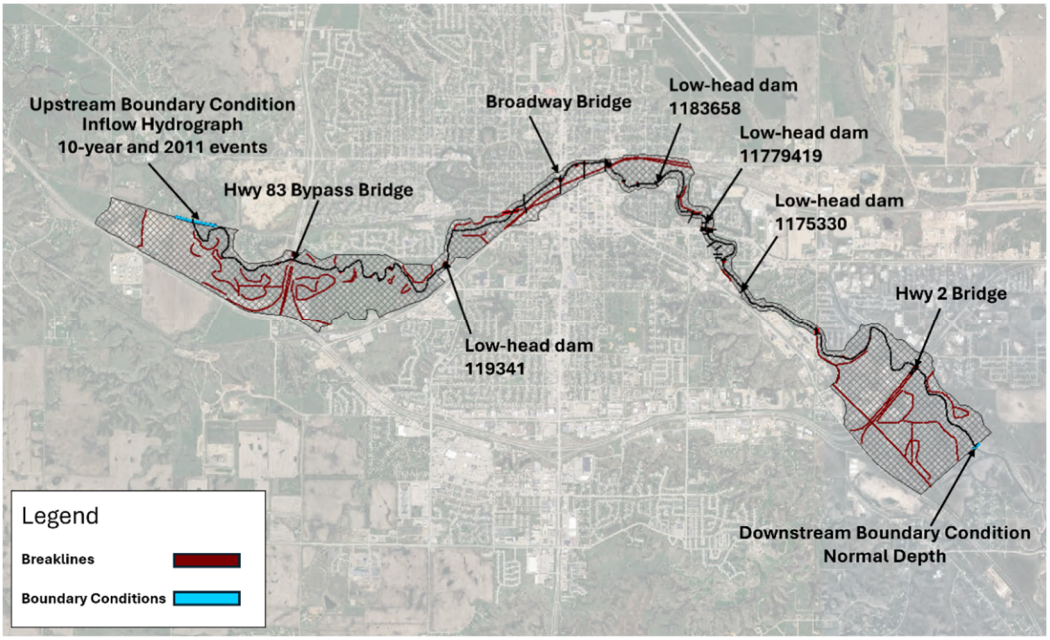


Figure 1 2D Model Extent

2.3 Bridges and Inline Structures

Features from the 1D model were incorporated into the 2D model, including 19 bridges and four weirs. Bridges present in the 1D model were translated to a 2D connection. The Highway 83 Bypass bridge, as well as the piers on the overbank regions for the 3rd St NE, Anne St, and Broadway Ave bridges, were represented with breaklines, as shown in Figure 2. Additionally, four low-head dam structures originally included in the 1D model (at cross sections 1199341, 1183658, 1179419, and 1175330) were represented through modifications in the terrain.

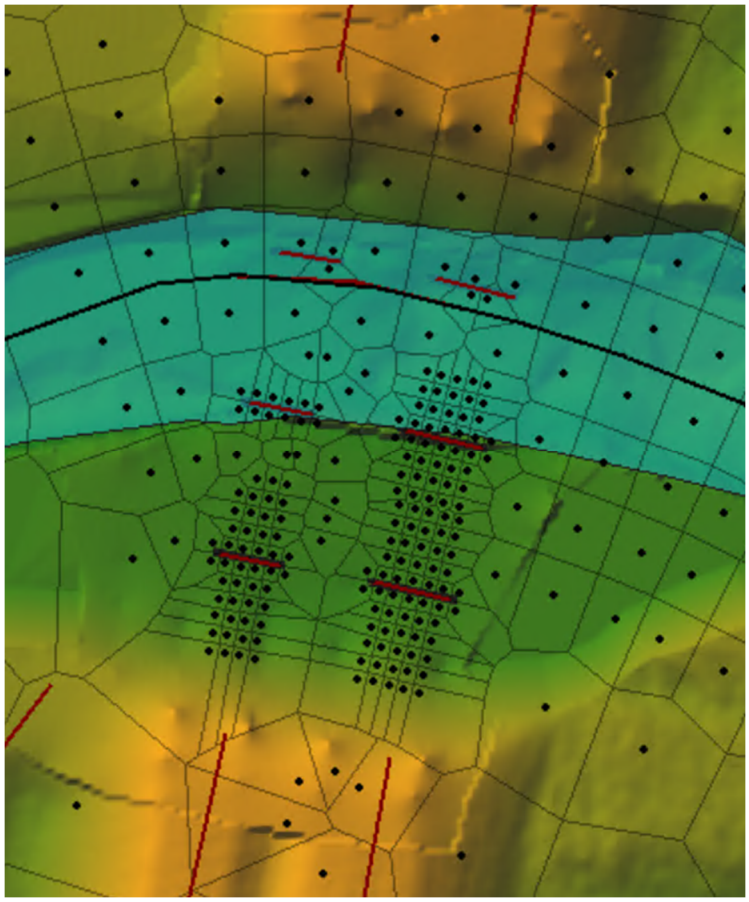


Figure 2 Highway 83 Bypass Piers Represented by Breaklines

2.4 Calibration Process and Results

The calibration process was conducted in two parts. First, a constant flow hydrograph representative of the 10-year flood event (peak flow of 2,600 ft^3/s) was simulated through both the 1D and 2D models. The Manning's n for the 2D model main channel was then adjusted until the water surface elevation (WSE) along the channel matched the 1D model. A range of values between 0.03 and 0.04 was tested. Next, the peak flow for the 2011 event (27,400 ft^3/s) was then simulated through both models to determine the Manning's n for the channel overbanks, with values of 0.035 and 0.04 tested.

Three statistical metrics were used to assess the goodness-of-fit between the WSE of the 1D and 2D models: the Nash-Sutcliffe Efficiency coefficient (NSE), the Root Mean Square Error (RMSE), and the Pearson correlation coefficient. The NSE represents the ratio of the variance of the predicted model (in this case, the 2D model WSE) divided by the variance of the observed model (1D model WSE). In this case, a larger value indicates a superior model fit. RMSE is also commonly used to quantify model goodness of fit and represents the square root of the variance of the residuals of the models, where a smaller value indicates better model fit. Lastly, the Pearson correlation coefficient represents the linear relationship between models, where a value of 1 indicates a perfect fit. Table 1 and Table 2 show the results of the model goodness of fit for the 10-year and 2011 events, respectively. Values shown in bold font represent the ones with the best fit for that metric. Thus, for the 10-year event, the best fit values for

the main channel Manning's n, NSE, RMSE, and Pearson Correlation were 0.03, 0.9945, 0.5709, and 0.9975, respectively. For the 2011 event, the best fit values for the main channel Manning's n, Overbank Manning's n, NSE, RMSE, and Pearson Correlation were 0.03, 0.035, 0.9949, 0.4683, and 0.99822, respectively.

Based on these three metrics, the 2D model with a main channel Manning's n set to 0.03 resulted in the most favorable scores for the 10-year event simulation (Table 1). For the 2011 event simulation (Table 2), a Manning's n set to 0.03 for the main channel and 0.035 for the overbank region produced the best model fit for both the NSE and RMSE metrics, and produced only a slightly lower Pearson correlation coefficient compared to 0.03 for the main channel and 0.04 for the overbank region.

Table 1 Goodness of Fit Metrics for 2D Model Main Channel Calibration for a 10-year Event

Main Channel Manning's n	Nash-Sutcliffe Coefficient	Root Mean Square Error	Pearson Correlation Coefficient
0.03	**0.9945**	**0.5709**	**0.9975**
0.035	0.9928	0.546	0.9966

Table 2 Goodness of Fit Metrics for 2D Model Main Channel Calibration for a 2011 Event

Main Channel Manning's n	Overbank Manning's n	Nash-Sutcliffe Coefficient	Root Mean Square Error	Pearson Correlation Coefficient
0.03	**0.035**	**0.9949**	**0.4683**	0.99821
0.03	0.04	0.9948	0.4927	**0.99822**
0.035	0.035	0.9948	0.4923	0.99821
0.035	0.04	0.9948	0.4746	0.99821

3 Sediment Transport Model Construction

3.1 Sediment Data

Sediment data was needed for the riverbed evolution models to impose a sediment flux at the upstream end and assign the river material properties. This data included 1) sediment rating curves for total load, 2) grain-size distribution of sediment in suspension, and 3) grain-size distributions of the riverbed. The available sediment bed layer was set to 40 feet to avoid running out of sediment at the bed during the simulation (i.e., bedrock was set to 40 feet below the existing ground).

3.2 Total Load Sediment Rating Curve

The sediment rating curve total load was estimated using the rating curve calculator tool in HEC-RAS and information from the USGS gaging station 05122000 in Bantry, North Dakota, which was the closest USGS station with daily sediment data. The available sediment data was collected from December 1985 to November 2000. The HEC-RAS rating curve calculator used a piecewise linear two-slope regression

method with a Duan (reference [2]) bias correction factor. Figure 3 shows an example of the output from this tool, and Table 3 shows the parameters obtained for the rating curve equation below.

$Q_s = EaQ^b$

Where,

Q_s : Sediment Flux (ft^3/s)
E, a, b : piecewise linear coefficients
Q : Flowrate (ft^3/s)

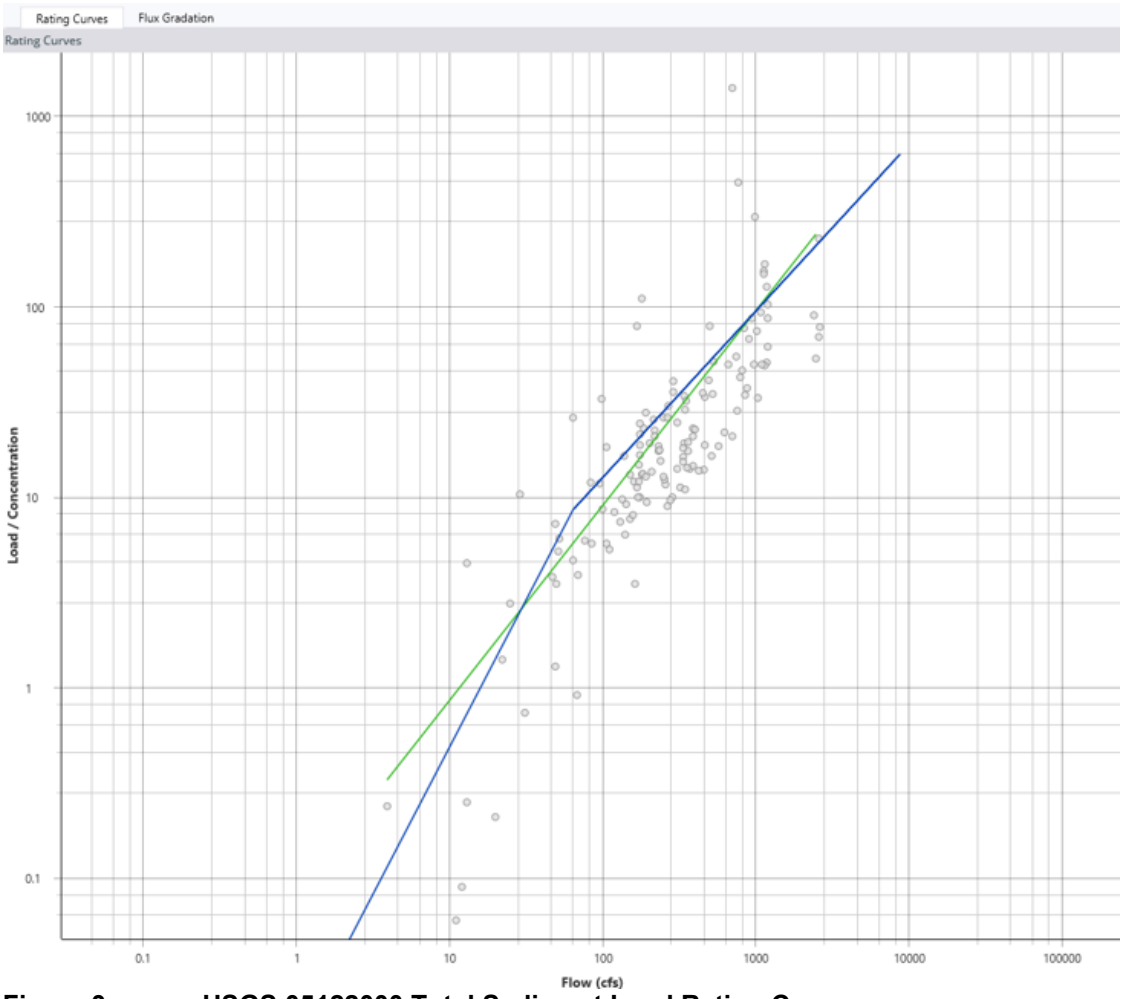


Figure 3 USGS 05122000 Total Sediment Load Rating Curve

Table 3 Sediment Curve Parameters

Parameter	Value
E	1.4974
a	0.052215
b	1.013
$E_{piecewise}$	1.523
Knot	64

The suspended sediment rating curve (Table 4) was determined using the rating curve calculator tool in HEC-RAS v 6.3.1 and the USGS gage sediment data.

Table 4 Suspended Sediment Rating Curve Used in HEC-RAS Model

Flow (ft3/s)	Total Load (tons/day)
1,000	87
5,000	444
10,000	896
15,000	1,352
20,000	1,809
25,000	2,268
30,000	2,728

3.3 Suspended Grain Size Distribution

The HEC-RAS sediment transport module needs the grain-size distribution for the sediment in suspension. The gradation from USGS gaging station 05124000 at Westhope, North Dakota, was used to develop the grain-size distribution shown in Table 5. It is downstream of the Bantry gage. Westhope gage data was used to determine the grain-size distribution because it was the only Souris River gage where suspended sediment was collected in the field and tested in the lab. The suspended sediment was measured by sieve diameter and reported as a percentage smaller than 0.0625mm. The percentage of particle-size class changed once the flows passed 5,000 ft^3/s.

Table 5 Suspended Sediment Grain-Size Distribution Used in HEC-RAS Model

Flow (ft3/s)	Particle size class (mm)	Percentage in each class (%)
1,000–5,000	0.032 to 0.0625	95.0
	0.0625 to 0.125	5.0
5,000–30,000	0.032 to 0.0625	68.0
	0.0625 to 0.125	32.0

3.4 Riverbed Grain Size Distribution

Barr sampled the bed material from the Mouse River channel at various locations in February 2025. The sampling campaign is documented in a separate memorandum (reference [3]). Only samples inside the area of Minot were considered in the analysis herein. Therefore, only samples SR-10 to SR-13 were processed for use in the grain size distribution used for the sediment transport modeling. Figure 4 to Figure 7 show the location where the samples SR-10 to SR-13 were taken. The grain size distribution of both samples was simplified based on the layer depths, and an attempt was made to avoid more than two layers per sample. Table 6 summarizes the riverbed gradation used in HEC-RAS.

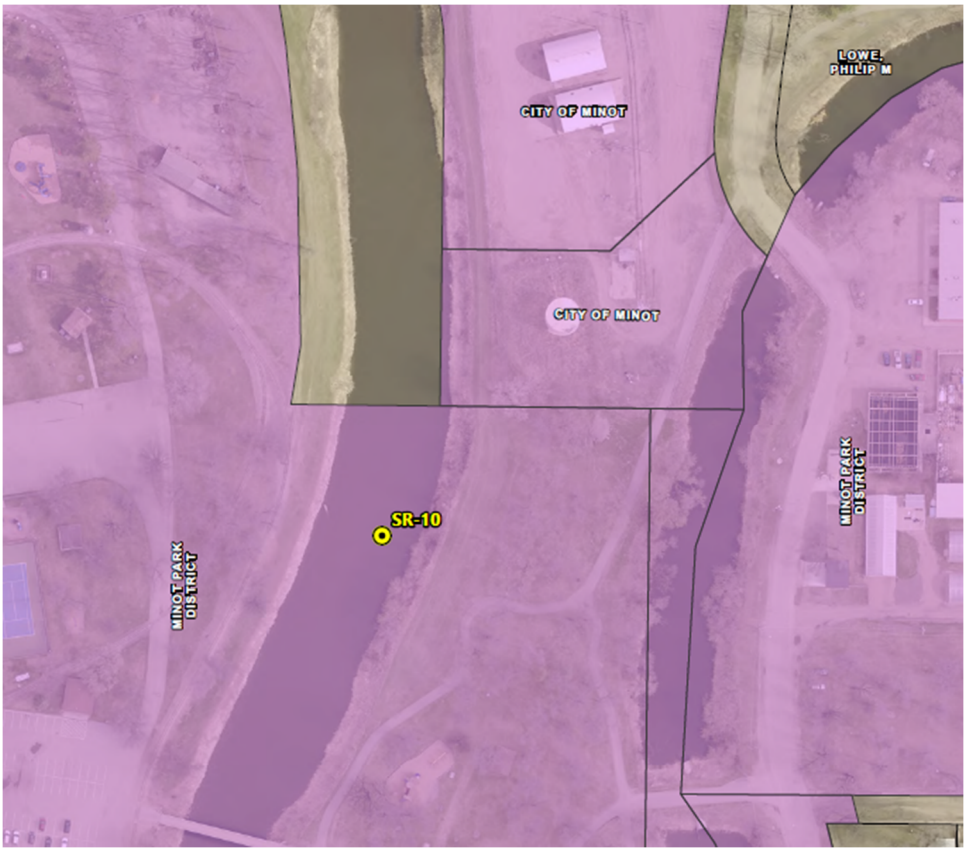


Figure 4 Sample SR-10 Location Map

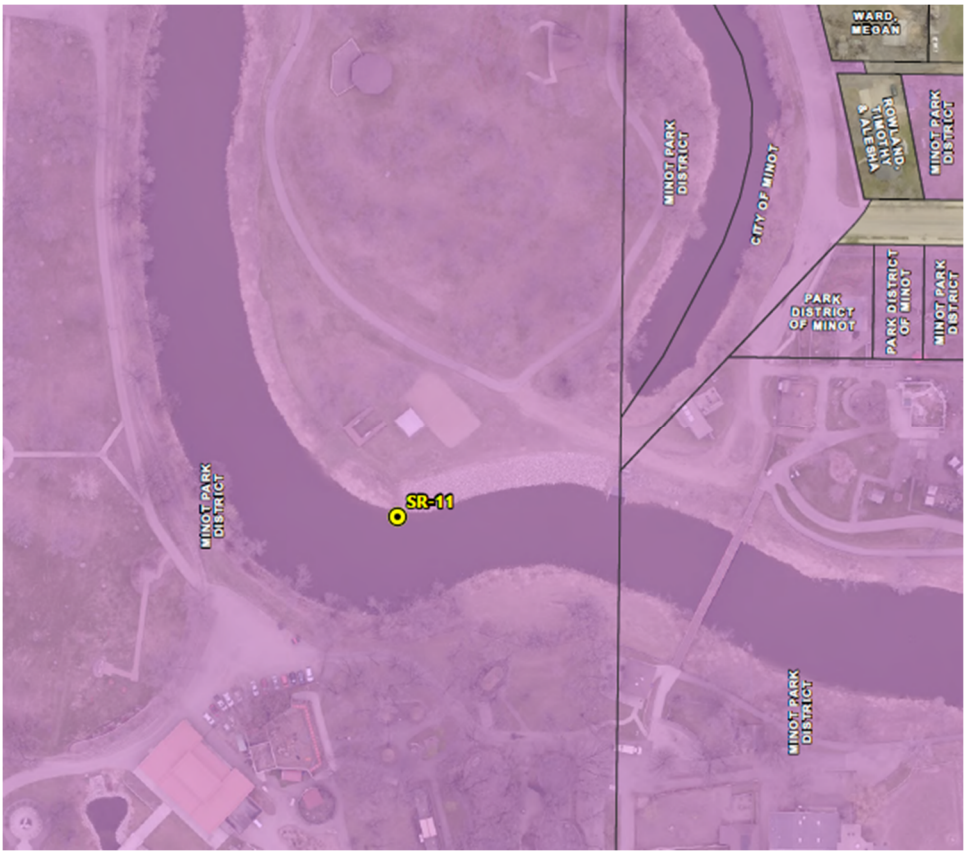


Figure 5 Sample SR-11 Location Map

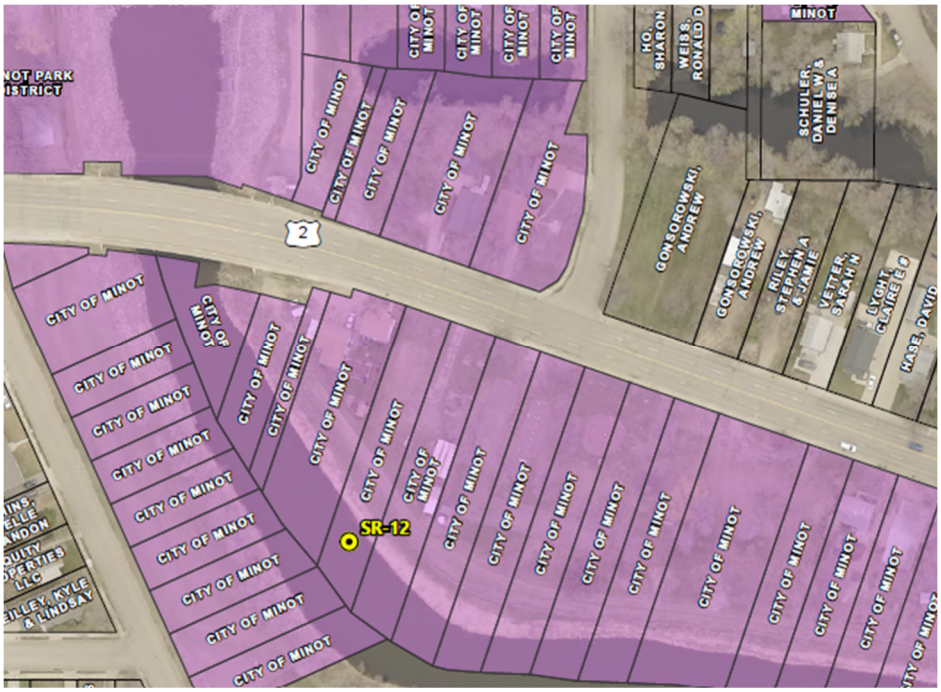


Figure 6 Sample SR-12 Location Map

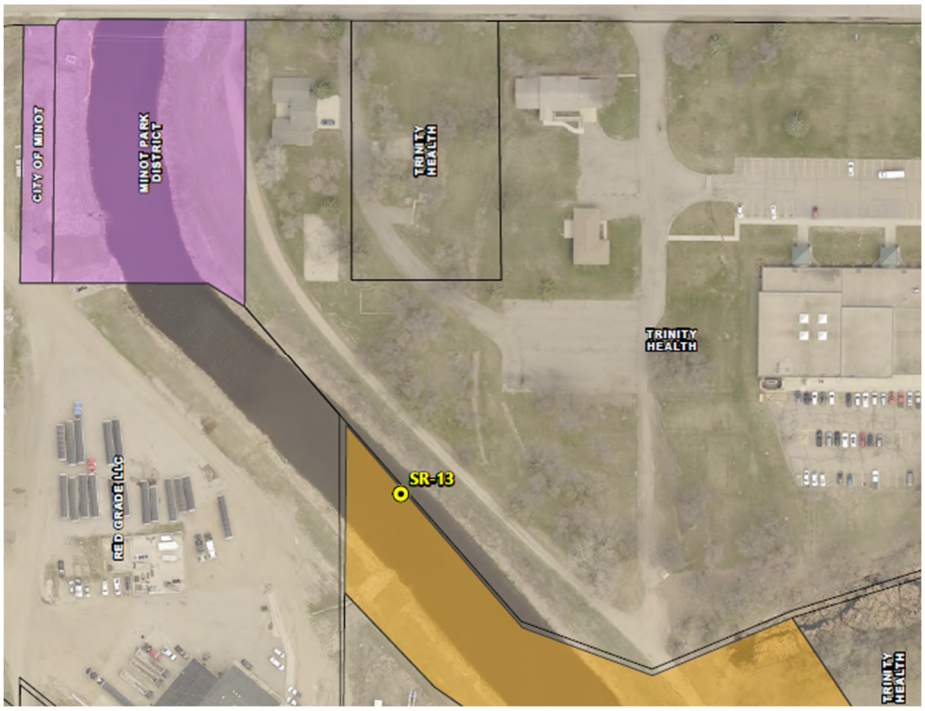


Figure 7 Sample SR-13 Location Map

Table 6 Riverbed Gradation Used in HEC-RAS Model

Class	Diameter (mm)	% Finer					
		SR-10 0' to 5'	SR-10 > 5'	SR-11 0' to 16. 5'	SR-11 > 16. 5'	SR-12 and SR-13 0' to 4'	SR-12 and SR-13 > 4'
CM	0.0625	1.0	93.6	17.0	97.8	10.4	97.7
VFS	0.125	1.7	95.7	25.9	98.7	19.6	98.7
FS	0.25	4.0	97.5	45.9	99.2	44.7	99.4
MS	0.5	11.0	98.9	76.3	99.5	82.2	100.0
CS	1	34.2	99.5	91.8	99.7	91.2	100.0
VCS	2	70.7	100.0	96.4	100.0	96.8	100.0
VFG	4	84.4	100.0	97.1	100.0	98.5	100.0
FG	8	96.7	100.0	97.7	100.0	99.7	100.0
MG	16	100.0	100.0	97.8	100.0	100.0	100.0
CG	32	100.0	100.0	100.0	100.0	100.0	100.0

3.5 Sediment Bed Material Regions

Figure 8 and Table 7 show the sediment bed material regions used in the model. At the Maple and 27th St Diversion channels, grass will be placed, and therefore, the riverbed needed to be modeled differently than the rest of the river main channel. Since no information is available, it was assumed that a 3-foot layer with similar erodibility characteristics to grass was present. The 3-foot layer was modeled as a cohesive soil with the same sediment parameters as for the rest of the cohesive part in the main channel. The deeper layers in the diversion channels were modeled with the same properties as those of the SR10 layer for a depth greater than 5 feet.

Similar to the method used to model the grass on the diversion channels, the boulders placed on the rock pool-riffles upstream of Highway 83 and upstream of the 16th St Bridge were incorporated using a 3-foot top layer to incorporate the boulders. The boulder layer was modeled assuming a D50=3 feet, and the deeper layers were modeled with the same properties as for the SR10 layer for a depth greater than 5 feet.

Some regions in the model were treated as non-erodible due to the very small probability of developing scour areas during a flooding event. Such regions included the low head dams, the bridge piers, and the areas on the floodplain outside of the main channel. Although some erosion can be developed on the floodplain, it will not significantly impact the overall erosion/deposition depths in the river main channel.

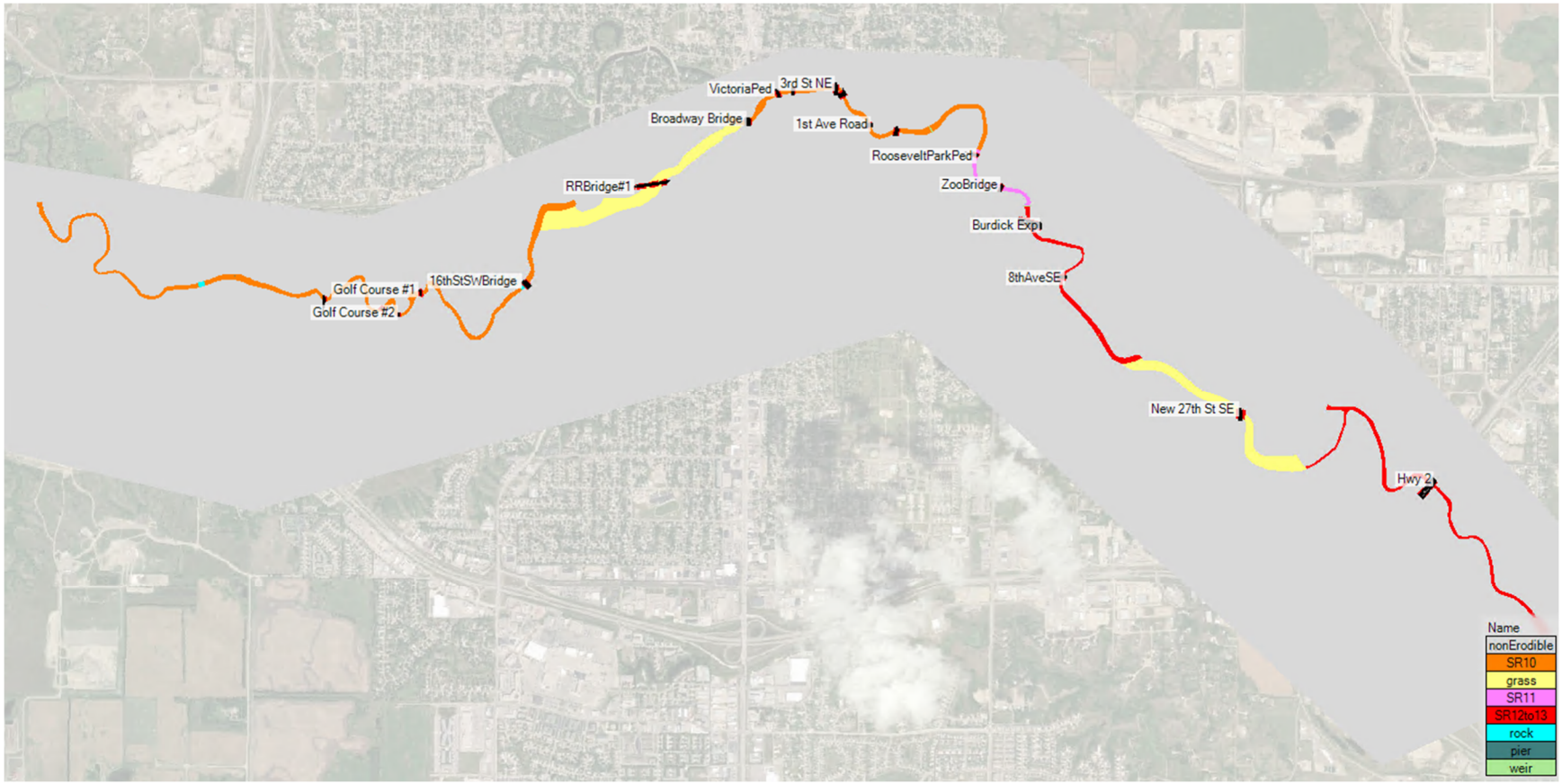


Figure 8 Sediment Layers Map

Table 7 Sediment Layers Summary

RAS Sediment Layer Name	Description	Location	Grain Size Distribution
SR10	Main channel material upstream of Roosevelt Park Pedestrian Bridge	From model upstream end to upstream of Roosevelt Park Bridge	Based on the SR-10 sample
SR11	Main channel material between Roosevelt Park Bridge and Burdick Expressway	Between Roosevelt Park Bridge and Burdick Expressway	Based on the SR-11 sample
SR12to13	Main channel material downstream of Burdick Expressway to the end of the model except for the 27th Street Diversion channel	Between Burdick Expressway and the inlet of the 27th Street Diversion Channel and downstream of the 27th Street Diversion channel to the end of the model	Based on the SR-12 and Sr-13 samples
Rock	Represents the area of boulders for the rock riffle	At rock riffle weir upstream of Hwy 83 and upstream of the 16th St Bridge	A 3ft layer of rock was assumed and deeper than that, the grain size material at sample SR-10 deeper than 5 ft was used
Grass	Represents the area of main channel that is vegetated	At the Maple and 27th St diversion channels	A 3ft layer of grass was assumed, and deeper than that, the grain size material at sample SR-10 deeper than 5 ft was used
Pier	Represents the area of concrete bridge piers	At bridge piers	Non-Erodible
Non-Erodible	Represents areas outside of the main channel	Outside of the main channel	Non-Erodible
Weir	Represents concrete weirs in the main channel	At low head dams	Non-Erodible

3.6 Erodibility Parameters for Cohesive Soil

The cohesive soil grain size classes (i.e., silts and clays with a size smaller than 0.0625 mm) of the grain size distribution are modeled differently from the coarser portions. For those finer grain size classes, the erosion was computed using an excess shear stress model that needed as input data the critical shear stress and the erosion rate. Since no direct soil tests to estimate critical shear stress or erosion rates were carried out, those parameters were estimated indirectly using a method developed by Briaud (reference [4]) which uses as input data Plastic Index, Unconfined Compressive Strength, Water Content, and Fraction of Fines. The following process was conducted to compute the critical shear stress and the erosion rate values for sample SR-11.

1) Compute the critical shear stress using the following empirical equation.

$$\tau_c = \alpha_d \left(\frac{w}{F}\right)^{-2.0} PI^{1.3} {q_u}^{0.4}$$

Where:

α_d: unit conversion constant for design, 0.007 in US customary units

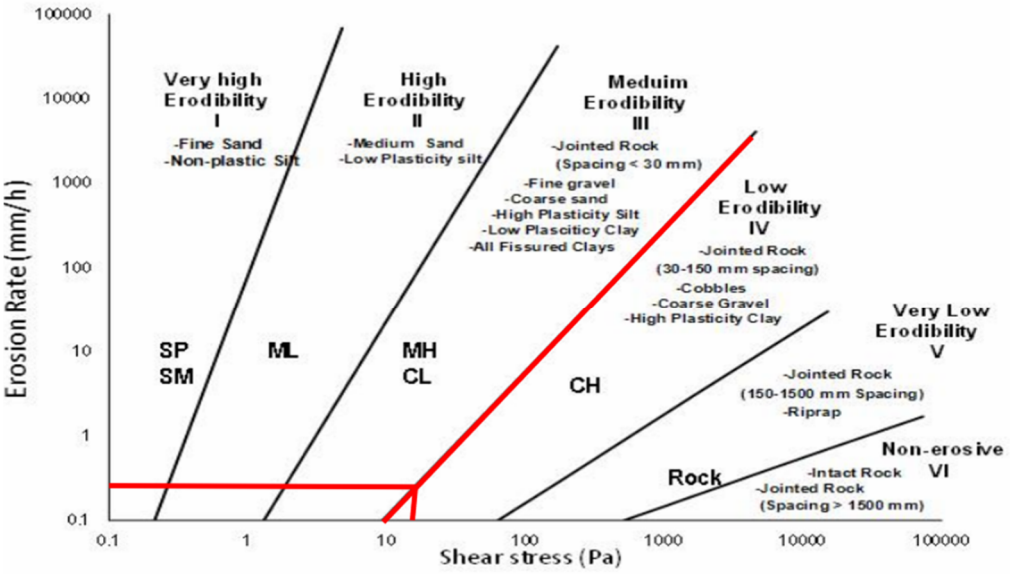
w: water content percentage

F: fraction of fines percentage

PI: plastic index

q_u: unconfined compressive strength

2) Next, the computed critical shear stress is used to estimate the erosion rate in mm/hour based on the Unified Soil Classification (USC) category found in sample SR-11. In this case, the USC classification for SR-11 is CL/CH. Therefore, using the chart shown in Figure 9, it was determined that the erosion rate is about 0.3 mm hour.



1 inch = 25.4 mm.
1 lbf/ft^2 = 47.8 Pa.

Figure 9 Erosion Rate vs. Shear Stress (Briaud reference [4])

3) Finally, since HEC-RAS needs the erosion rate in lb/ft^2/hr units, the average wet unit weight of the soil (83.8 lb/ft^3) was used to convert the erosion rate from mm/hour units to lb/ft^2/hr, which resulted in a value of 0.082 lb/ft^2/hr.

Table 8 shows a summary of the values used in the HEC-RAS model.

Table 8 Summary of Cohesive Parameters Used in HEC-RAS Model

Description	SR-11
Sample Depth	16.5’ to 21’
Plastic Index	0.3
Unconfined Compressive Strength (tsf)	1.25
Water Content (%)	35.1
Fraction of Fines (%)	97.8
Critical shear Stress (psf)	0.27
M (mm/hr)	0.3
Wet unit weight (lb/ft3)	83.8
M (lb/ft2/hr) from Briaud Chart	0.082

3.7 Sediment Transport Settings

3.7.1 Transport Function

The sediment transport setting that highly affects the results of a HEC-RAS 2D sediment transport analysis is the transport function. Because of that, a sensitivity analysis was conducted to test the impact on the riverbed change to three sediment transport functions, based on the work of Wu et al., Toffaleti, and Yang, respectively. The results of the sensitivity analysis showed that the transport function with the deepest estimated scour depths was Yang, whereas the one with the shallower estimated erosion depths was Toffaleti. The difference in erosion depth among the transport functions did not exceed 2.0 feet, and generally, the locations of erosion and deposition were consistent across all transport functions. Ultimately, Barr used results from the Wu et al. method because it resulted in average bed changes among the three transport functions tested herein.

3.7.2 Active Layer

The active layer represents the sediment transported once the critical shear stress is exceeded. The active layer thickness was set to the d90 multiplied by 500. A minimum thickness of 0.5 feet was set to provide stability for the program. No hiding function was selected.

4 Results

Figure 10 shows the riverbed change profile along the centerline after a 2011 event. Overall, the trend inside the limits of the City of Minot will be erosion, with the highest values located between the 8th Ave SE bridge and the New 27th St SE bridge. Note that the scour depths from this modeling are classified as general scour. In other words, local scour depths resulting from obstructions or contractions in the channel (e.g., bridges or weirs) must be evaluated separately. Also note that this profile shows results only along the centerline, and therefore, zones of erosion and deposition could form to the sides of the main channel. The following sections provide more detailed information on the bed change trend per segment.

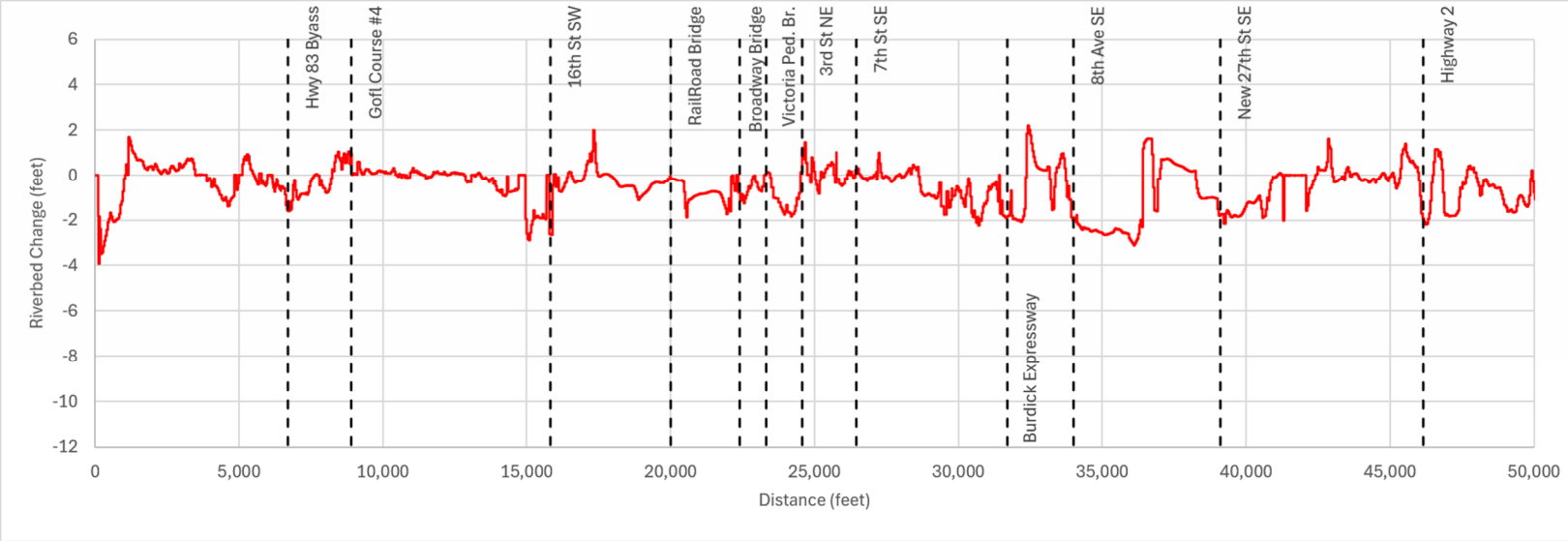


Figure 10 Bed Change Profile for the 2011 Event Along the City of Minot (not all bridges are shown for clarity purposes)

4.1 Tierrecita Vallejo

Figure 11 shows the bed change results for the Tierrecita Vallejo segment. The trend along the Tierrecita Vallejo segment is erosion, with the maximum erosion depth of about 1.8 feet at the Hwy 83 Bypass.



Figure 11 Bed Change for the 2011 Event Along Tierrecita Vallejo

4.2 Napa Valley

Figure 12 shows the bed change results for the Napa Valley segment. The trend along the Napa Valley segment is erosion, with the erosion depths no higher than 1.3 feet downstream of Hwy 83 Bypass.

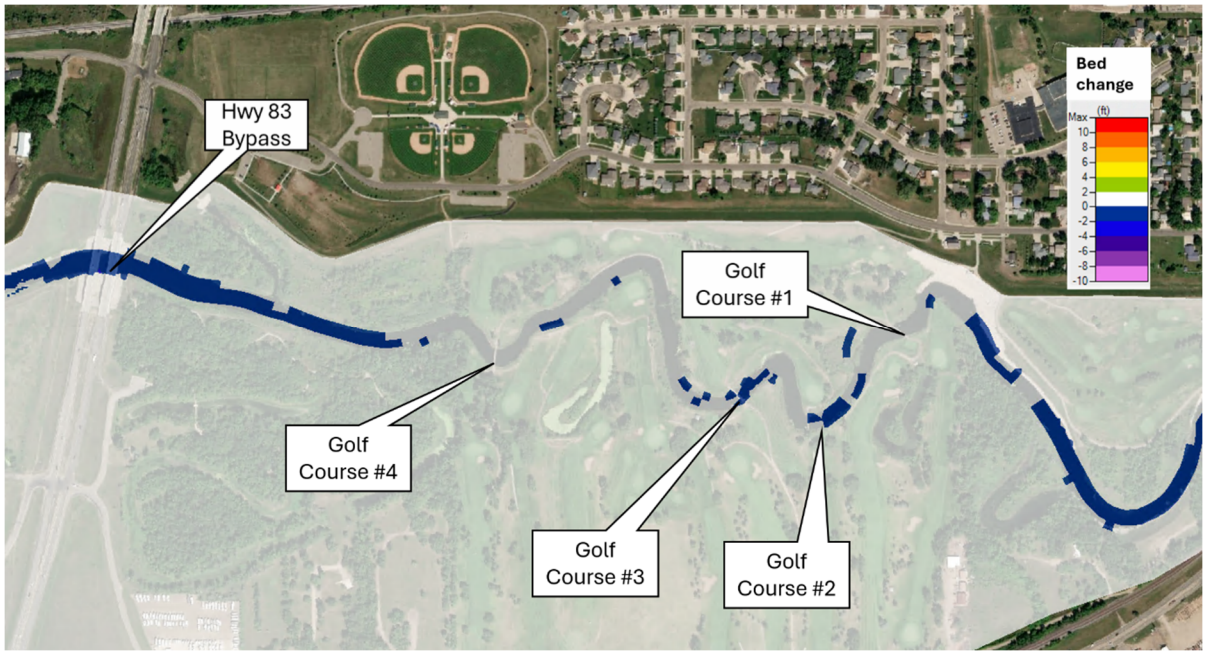


Figure 12 Bed Change for the 2011 Event Along Napa Valley

4.3 Forest Road

Figure 13 shows the bed change results for the Forest Road segment. The trend along the Forest Road segment is erosion, with the maximum erosion depth of about 2.6 feet at the 16th St SW Bridge.



Figure 13 Bed Change for the 2011 Event Along Forest Road

4.4 Maple Diversion Channel

Figure 14 shows the bed change results for the Maple Diversion segment. At the entrance of the Maple Diversion channel, the model estimates a deposition area of up to 2.2 feet. Inside the Maple Diversion, the trend is erosion with a maximum erosion depth of 2.2 feet downstream of the Railroad Bridge. At the outlet of the Maple Diversion channel, there is also an erosion area of up to 2.2 feet.



Figure 14 Bed Change for the 2011 Event Along Maple Diversion

4.5 4th Avenue NE and Roosevelt Park

Figure 15 shows the bed change results for the 4th Ave NE and Roosevelt Park segment. In general, the trend along that segment is erosion, resulting in erosion depths between 1.0 and 2.0 feet for most of the segment. The exceptions are at the Roosevelt Park Pedestrian Bridge and at the Zoo Pedestrian Bridge. At the Roosevelt Park Pedestrian Bridge, the erosion depth can reach up to 3.6 feet.



Figure 15 Bed Change for the 2011 Event Along 4th Avenue NE and Roosevelt Park

4.6 Valker Road

Figure 16 shows the bed change results for the Valker Road segment. In general, the trend along that segment is erosion, resulting in the highest values downstream of the 8th Ave SE Bridge, which reach erosion depths of up to 3.1 feet. The model suggests that all of the eroded material downstream of the 8th Ave SE Bridge is later deposited immediately upstream of the 27th St Diversion channel and pushed toward the gates located at the 27th St Green Valley channel loop. The model estimates a deposition area of up to 8.6 feet upstream of those gates, which may have been overestimated. However, this deposition trend can be a problem for the operation of the gates since dredging may be needed to keep them functioning after a large storm event.

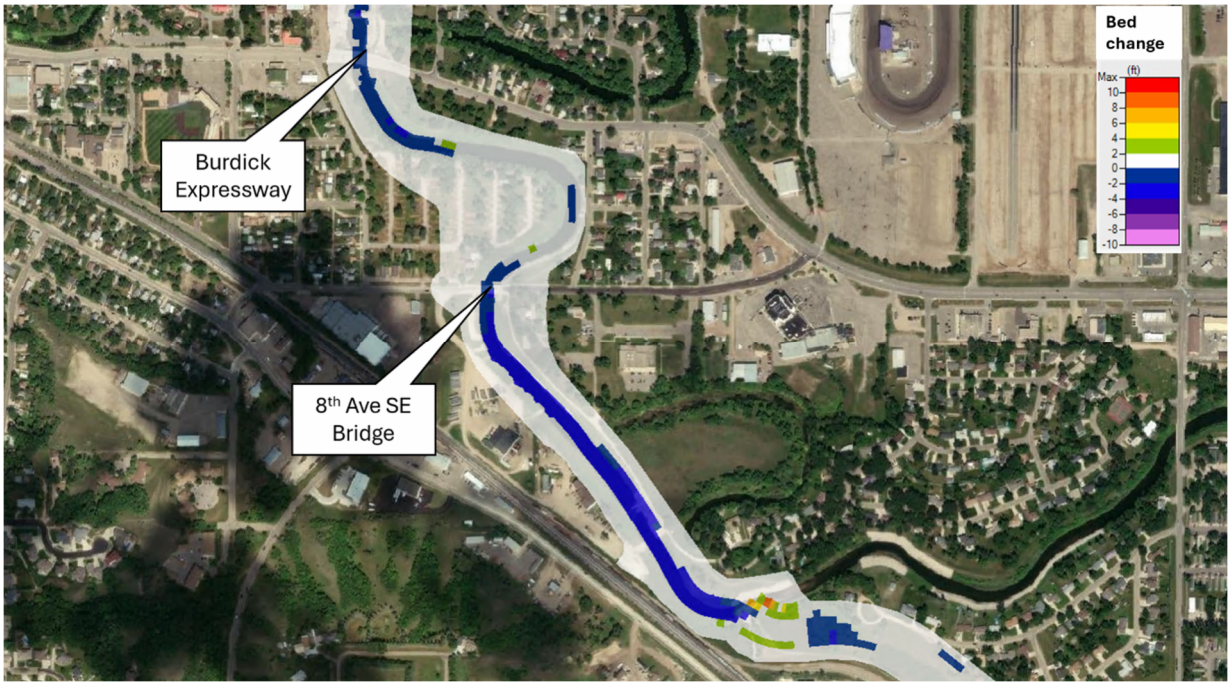


Figure 16 Bed Change for the 2011 Event Along Valker Road

4.7 27th St Diversion Channel

Figure 17 shows the bed change results for the 27th St segment. In general, the trend along that segment is erosion, resulting in the highest values downstream of the New 27th St SE Bridge, immediately upstream of the Diversion channel outlet, with a maximum erosion depth of 1.8 feet.



Figure 17 Bed Change for the 2011 Event Along the 27th St Diversion Channel

4.8 South Keller

Figure 18 shows the bed change results for the South Keller segment. In general, the trend along that segment is erosion, resulting in the highest values at the Highway 2 Bridge. The erosion depths at the Highway 2 Bridge are about 2.2 feet maximum. Downstream of the Highway 2 Bridge, the erosion depths are reduced to values smaller than 2 feet.

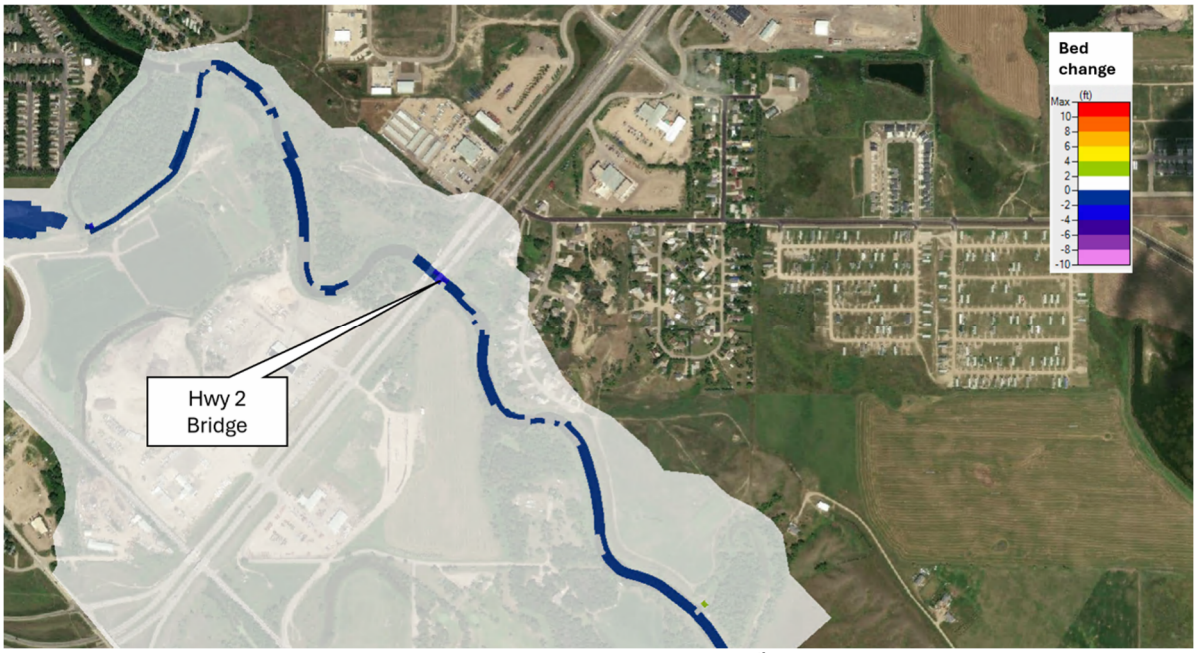


Figure 18 Bed Change for the 2011 Event Along the 27th St Diversion Channel

5 Evaluation of Riprap Requirements Based on 2D Sediment Transport Analysis

Previous riprap design efforts along the Mouse River relied primarily on empirical equations to estimate local and contraction scour depths for riprap sizing and placement. In addition to these empirical methods, a one-dimensional sediment transport model was also applied; however, that model was informed by only a single grain size distribution sample for the project reach (reference [5]). While these approaches provided a preliminary basis for design, their simplified representation of hydraulic–sediment interactions and limited soil characterization introduced significant uncertainty, which resulted in more conservative scour estimates.

As a result, substantial quantities of riprap were specified and procured under earlier design phases, leading to considerable construction costs. To refine these estimates and reduce uncertainty, a more advanced sediment transport analysis was undertaken using a two-dimensional HEC-RAS model. This model was supported by an expanded soil data collection program (reference [3]), which provided multiple grain size distributions and additional geotechnical information. These data allowed for the determination of site-specific erodibility parameters—critical shear stress and erosion rate coefficients—that were incorporated directly into the model, resulting in a more realistic simulation of sediment mobility and bed evolution.

By resolving hydraulic conditions in two dimensions and using robust, spatially distributed soil inputs, the current analysis produces scour depth estimates that more accurately reflect actual sediment behavior under design flow conditions. The results indicate that predicted scour depths are notably lower than those derived from the earlier empirical and 1D modeling approaches. For example, between Broadway Bridge and the 7th St Bridge, the estimated scour depth from the 2D model was overall less than two feet, whereas based on the 1D model, the scour depth in that segment varied between 5 feet and 15 feet.

A smaller estimated scour depth has a direct cost-saving implication: it reduces the vertical extent to which riprap must be placed along the riverbank toe. Since riprap protection is typically designed to extend from the channel bed up to the calculated scour elevation, a lower scour depth means less rock volume is required to achieve the same level of protection. This reduction in riprap quantity not only decreases material and placement costs but also minimizes construction footprint while maintaining structural stability and erosion resistance. Optimizing riprap design based on these refined model results enables more targeted protection, minimizes overdesign, and supports cost-effective implementation without compromising channel stability or infrastructure resilience.

6 Conclusions

The 2D HEC-RAS model successfully simulated sediment transport dynamics along the Mouse River through Minot, ND, capturing spatial variations in erosion and deposition for the flood of record (i.e**.,** the 2011 event).

The sediment transport analysis showed that erosion is the dominant process along most channel segments, with localized deposition occurring at diversion channel outlets and low-slope reaches. Overall areas with higher erosion showed erosion depths in the order of 2 to 4 feet. One area of concern was Valker Road and 27th St Diversion at which potential for sediment accumulation could impact infrastructure functionality.

Two-dimensional sediment transport modeling resulted in smaller scour depths compared to the previous analysis done with a one-dimensional model. That outcome can help to reduce the amount of material to be used in launchable riprap in future designs.

7 References

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[5] Barr Engineering Co., "Milestone 2 General Scour Analysis," 2023.