RESEARCH REPORT DOCUMENTATION PAGE

1. Report No.	2. Report Date	3. Contract No.	4. Project No.
UND 21-02	December, 2023	91211182	

5. Title and Subtitle

Use of HYCAT in Field Observations and Evaluations of Streambed Scours at North Dakota Bridges

6. Report Type

- Work Plan ☐
- Construction ☐
- Evaluation ☐
- Final ☒

7. Project No.

8. Project No.

9. Project No.

10. Project No.

11. Author(s)/Principal Investigator(s)

Dr. Yeo How Lim

12. Performing Organization Name and Address

- NDDOT M+R ☐
- NDDOT OTHER* ☐
- NDSU ☐
- UND ☒
- UGPTI ☐
- OTHER* ☐

*See supplementary notes

North Dakota DOT
Materials and Research Division
300 Airport Road
Bismarck ND 58504-6005

13. Sponsoring Agency Name and Address

North Dakota DOT
Materials and Research Division
300 Airport Road
Bismarck ND 58504-6005

14. Supplementary Notes

15. Abstract

Objective

The research team proposes collecting detailed bathymetry and velocity data for two bridge sites located along the Red River of the North using pre-programmed high-tech river surveying equipment, including an autonomous vehicle, to evaluate the hydraulic conditions of each site. The objectives of the study are to identify any scour-related issues that could pose a risk to the bridge structure, assess the feasibility of constructing a bridge at the identified crossing sites, and demonstrate the effectiveness of using an autonomous vehicle for data collection.

Scope

The study involved several field trips, during which the high-tech equipment was deployed to collect data and perform hydraulic modeling and analysis. The results of the field measurement using HYCAT indicated no serious scour holes were found at the two bridge sites. However, there is evidence of the streambank failures occurred at the left bank of Highway 200 Bridge site near Halstad, MN. A scour is potentially developing at the vicinity of the central pier at Highway 17 Bridge near Grafton, ND.

Summary

The project has created a good opportunity for the development of a unique method for inspecting the integrity status of bridge structure at sites where the hydraulic impacts of extreme river flow on bridge structure may lead to contraction scour, pier scour, and local scour. In this project, HYCAT installed with an ADCP-M9 has proven to be a very versatile tool in performing the general collection of bathymetric data, water depth, velocity, and discharge information.

16. Key Words	17. Distribution Statement	18. No. of Pages
Flooding, Bathymetry, HYCAT, Bridge Scour, Side Scan Sonar, Hydraulic Modeling, Streambed	No restrictions. This document is available to the public from: North Dakota Department of Transportation Materials and Research Division: 300 Airport Road Bismarck ND 58504-6005 Office: (701) 328-6900 Fax: (701) 328-0310	91 19. File type/Size Pdf/ 7.12 mb

UNIVERSITY OF NORTH DAKOTA
Grand Forks

Use of HYCAT in Field Observations and Evaluations of Streambed Scours at North Dakota Bridges

Final Report

December 21st, 2023

By:

Dr. Yeo Howe Lim, Principal Investigator
Department of Civil Engineering

NDDOT Research Report

Contents

List of Figures

List of Tables

Executive Summary

This report presents the findings of a hydraulic study conducted to investigate the potential of scour at two bridge crossings on the Red River of the North. The study utilized high-tech river surveying equipment, including an autonomous vehicle, to evaluate the hydraulic conditions of each site. The objectives of the study were to identify any scour-related issues that could pose a risk to the bridge structure, assess the feasibility of constructing a bridge at the identified crossing sites, and demonstrate the effectiveness of using an autonomous vehicle for survey equipment deployment on water. The study involved several field trips, during which the high-tech equipment was deployed to collect data and perform hydraulic modeling and analysis.

The results of the field measurement using HYCAT indicated no serious scour holes found at the two bridge sites. However, there is evidence of the streambank failures occurred at the left bank of Highway 200 Bridge site near Halstad, MN. A scour is potentially developing at the vicinity of the central pier at Highway 17 Bridge near Grafton, ND.

Hydraulic modeling requires an up-to-date flood frequency analysis to be performed. This study followed the Bulletin 17C procedures and has revealed some serious increase in the flood quantile estimates for the two sites. The site’s 100-year flood estimate increased significantly from 56,000 cfs to 81,246 cfs. The hydraulic modeling using HEC-RAS shows the Highway 200 bridge deck is submerged under a 100-year flood condition and seriously overtopped under a 200-year flood. On the other hand, the Highway 17 Bridge is expected to be not inundated under a 100-year and a 200-year flood. Additionally, the study coincided with a major flood event in 2022 that occurred during the observation periods, allowing for further validation of the study's findings.

Scour modeling using the routine in HEC-RAS provides a comprehensive assessment of each crossing site, highlighting the hydraulic characteristics and any potential scour under contraction, pier scour, and abutment scour considering relevant physical features. Model outputs presents recommendations for the design and construction of a bridge at each site based on the hydraulic conditions identified. Overall, the hydraulic study conducted not only provides valuable insights into the feasibility of constructing a bridge at the investigated crossing sites but also demonstrates the effectiveness of using an autonomous vehicle for survey equipment deployment on water. The findings of this study will assist in the design and construction of safe and reliable bridge structures, reducing the risks to human life and infrastructure in the event of severe flooding.

1. Introduction

Bridge scour is a leading cause of bridge failure in the United States (Richardson and Davis, 2001). Scour refers to the erosion caused by water of the sediments or in-situ soil materials surrounding a bridge foundation. The loss of sediments and soil particles is attributed to the impact of turbulent water movement that creates shear effects around the interface of water and the bridge foundation, such as bridge piers and bridge abutments. Any significant loss of materials around piers and abutments may undermine the structural integrity of a bridge structure via foundation failure mode. The outcome can be catastrophic, involving total or partial loss of the bridge superstructure. To mitigate these failures, Federal Highway Administration has outlined the design of bridges according to scour expectations and to monitor existing bridges for scour formation in its publication "Evaluating Scour at Bridges, 5th Ed. HEC No.18 (Arneson *et al.*, 2012). This manual includes several techniques for estimating scour depth using empirical scour equations for live bed scour, clear water scour, and local scour at piers and abutments; however, floating debris, such as tree trunks and large ice blocks, will effectively narrow bridge openings during the spring snow melting period. This dynamic condition, which adds complexity to the problem, may result in increased flow velocity and scour formation.

The factors causing scour can depend on flood flow quantiles, frequency of flooding, and in North Dakota, the formation of ice jams. The occurrence of bridge scour at each site is unique and will change over time. This makes it imperative for state DOTs to continually monitor bridges for any potential formation of scour that is considered detrimental. It is prudent to evaluate existing bridges for vulnerability even without any known significant scour (Mueller and Wagner, 2005).

2. Problem Statement

The Bridge Division of the NDDOT has expressed concerns about the potential existence of scour holes in the proximity of two highway bridge crossing sites along the Red River of the North: (A) Bridge 0017-140.372 crossing the Red River East of Grafton, ND (48°24'47.56"N 97° 8'15.99"W) and (B) Bridge 0200-415.724 near Halstad, MN (47°21'9.40"N 96°50'39.84"W). The exact locations of the bridges are shown in **Figures** 1 and 2. The two study sites are hereafter referred to as (a) **Highway 17 Bridge near Grafton** and (b) **Highway 200 Bridge near Halstad**.

Figure 1. Location of Study Site at Highway 17 Bridge near Grafton, ND.

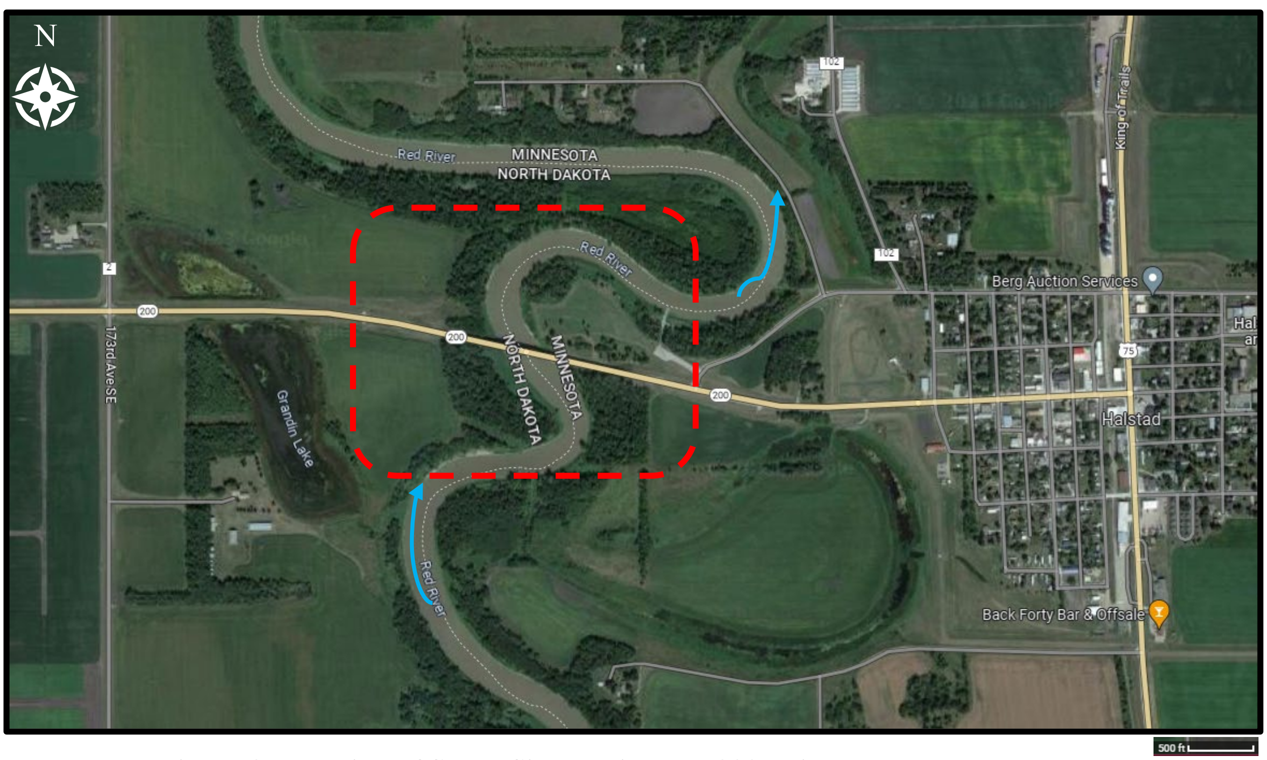


Figure 2. Location of Study Site at Highway 200 Bridge near Halstad, MN.

The complex and dynamic nature of scour formation is exhibited along the Red River, especially during snowmelt-triggered flooding events. Regular bridge site inspections for potential scour formation are essential.

In addition, there are also additional complexities such as the occurrence of tree trunks brought down by flood flow that got stuck at the upstream side of bridge piers. The reduction of effective flow area may increase the contraction scour potential. **Figure 3** shows the view of the central pier of Highway 200 Bridge near Halstad. Notice the high number of logs jammed at the bridge pier. This problem needs to be investigated on a case-by-case basis.

Figure 3. A log-jam formed at the upstream side of the double column central bridge pier of Highway 200 Bridge near Halstad.

3. Project Objectives

The main objectives of this project are:

(1) collect detailed bathymetry and velocity data for two bridge sites located along the Red River of the North using pre-programmed routes,

(2) assess the bathymetric and velocity data to make inferences on scour potential for any scouring feature found in the bathymetric mapping, and

(3) build and calibrate an HEC-RAS model of the river's reach for the bridge crossing sites and make predictions for scour potential under different flooding conditions: 100-year, 200-year, and bridge-overtopping.

4. Methods and Innovations

The central theme of this project is to make use of a state-of-the-art watercraft called HYCAT in measuring underwater bed features and current conditions in river channels around bridges and to identify any potential scour-related issues. The system allows the collection of bathymetry data remotely since the HYCAT is equipped with battery-powered thrusters, an onboard computer, M9- Acoustic Doppler Current Profiler (ADCP), GPS, and a radio communication system. UND was able to acquire an HYCAT system in 2019 under a Major Research Instrument (MRI) grant (PI: Howe Lim, Co-PI: Greg Vandeberg, Taufique Mahmood, and Jeff VanLooy). Point clouds generated from water depth data collected during streambed surveys are used for 3-D bathymetric mapping. High-resolution mapping would reveal the existence of scour hole formations. **Appendix A** shows a brief description of the use of HYCAT in bathymetry data collection in this project.

Conventional sounding techniques, including single or multiple sonar beam systems to collect depth information, are only suitable for general bathymetric mapping purposes. These techniques do not yield real-time result visualizations, and no velocity measurements are made. Since velocity data is necessary to understand the dynamics of long-term sediment transport and design countermeasures (Lagasse *et al.*, 2009), a more robust data collection method is required.

Scour observations may be limited to the time period of the project. It is not comprehensive unless scour potential under extreme flood conditions can be assessed. Since the issue of scour at bridge site has been well studied and models are available, a large part of the project would be to carry out bridge hydraulic modeling making use of the bathymetry data collected by HYCAT.

5. Progress of Project: Tasks and Activities

This section reviews the proposed project deliveries and execution of the project tasks.

5.1 Proposed Deliverables

In the project proposal, the following deliverables were listed:

Task 1: A preliminary description and characterization of the bridge sites after the initial site visits. This report will highlight the bridge hydraulic structure aspects and identify potential sites for basecamps and HYCAT launch sites.

Task 2: UND will coordinate with the NDDOT for field collection days and the task will be considered complete when all the data for Phase 1 is collected.

Task 3: A preliminary report on the Task 2 field trip findings will be delivered to the NDDOT. This report will include a preliminary analysis of the data used for plotting the 3-D bathymetry model within the study boundary. This information may be used by the NDDOT for planning purposes or to propose remedial design options, if necessary.

Task 4: The team will build and calibrate hydraulic models, including bridge scour components, in HEC-RAS. The digital model will be delivered to the NDDOT as part of the final report.

Task 5: UND will coordinate with NDDOT on the status of any remedial work and the field collection days. The task will be considered complete when all the data for Phase 2 is collected.

Task 6: A final report will be delivered to the NDDOT in an electronic format summarizing the project's findings. The report will include the literature review on equipment and data collection techniques, site descriptions, HYCAT data collection, bathymetry and velocity plots, HEC-RAS scour predictions, and comparative results in case countermeasures are introduced by the NDDOT during the project period. The bathymetry collected within the project boundary by HYCAT will allow creation of a mesh which is essential in HEC-RAS 2D bridge modeling.

5.2 Project Timeline

The project commenced on September 16, 2021, after a budget of $ $79,996.00 was allocated by NDDOT. The project was intended to terminate on March 1, 2023. However, due to the PI’s unexpected workload increase in late 2022 through spring 2023 academic semester, a no-cost extension of the project was granted with an agreed final project termination date as July 31, 2023.

5.3 Project Personnels

UND Team: Under the supervision of the PI, Dr. Yeo Howe Lim, several graduate students were involved as team members at various stages of the project. Ms. Vida Atashi and Mr. Mike

Rosati are the Ph.D. students who were involved throughout the duration of the project. Vida has worked as an HYCAT specialist maintaining the collection of bathymetry data, post-processing of bathymetry data, and providing cross-sectional data for HEC-RAS modeling. Mike Rosati helped in field logistics, GPS surveying of bridge structures and important benchmarks, and correlating water edge datum for each field trip. Mr. Innocent Anosike and Mr. Daniel Iancu are the other master's students who participated in a few field trips.

NDDOT Team: Mr. Andrew (Andy) Ayash of NDDOT was involved in overseeing the project right from the beginning of the project. When Andy transitioned to another role in NDDOT in 2022, Ms. Amy Beise, the Materials & Research Division Engineer of NDDOT, followed up on the project execution and played an important role in ensuring the completion of the project. Mr. Matt Kurle of NDDOT expressed great interest in the project. Both Andy and Amy traveled on separate occasions to meet UND project team members at the Highway 17 Bridge site near Grafton. All officers from NDDOT have provided very valuable suggestions during the field trips and as well as at the project progress presentations.

5.4 Project Tasks and Activities Implemented

The followings summarize the activities that were carried out by the project team:

5.4.1 Field Trips

Field trips that were carried out since the start of the research project in September 2021 are summarized in **Table 1** below. On every field trip, safety was a major consideration. Since the project team was operating close to the Red River, life jackets were worn whenever possible. For logistic and safety purposes, at least three people in a team was allowed to travel.

Figure 4 illustrates the designed or intended navigation path for the HYCAT while Figure 5 shows the path executed by HYCAT autonomously. Supplemental paths were added via remote joystick control. The watercraft under windy conditions and facing strong current may not be able to navigate exactly right on the planned pathway as defined by GPS waypoints. However, it is perfectly normal and fine because the purpose of defining the pathway is to provide a guide so that the bathymetric data can be collected with a good spread for the study area.

Table 1. Field Trips Made by Project Team.

Date	Site	Purposes	Deployment of HYCAT
10/15/2021	Grafton site	Inspection of the bridge site and created a temporary walkway for launching HYCAT	No
10/22/2021	Grafton site	Launched HYCAT to collect bathymetric data, flow depth, and flow velocities	Yes
10/29/2021	Grafton site	Launched HYCAT to collect bathymetric data, flow depth, and flow velocities; surveyed bridge structure	Yes
11/05/2021	Halstad site	Site inspection; launched HYCAT to collect bathymetric data, flow depth, and flow velocities; surveyed bridge structure	Yes
04/08/2022	Grafton site	Discharge and bathymetric data were collected using HYCAT	Yes
04/27/2022	Grafton site	Flood discharge measurement using HydroBoard*; performed by dragging across the river by walking across the bridge. The flood flow condition exceeded the safe operating range of HYCAT.	No
05/06/2022	Grafton site	Flood discharge measurement using HydroBoard	No
06/12/2022	Grafton site	Flood discharge measurement using HydroBoard	No
06/17/2022	Halstad site	Flood discharge measurement using HydroBoard	No
08/03/2022	Halstad site	launched HYCAT to collect bathymetric data, flow depth, and flow velocities	Yes

* A note on the operating limit of HyCAT and HydroBoard: HYCAT depends on the battery powered thrusters to propel and a differential thrust system to steer. There is a limit on the maximum water velocity that it can operate safely. The practical safe limit adopted by the research team is around 10 ft/s. When the limit is exceeded, we use a HydroBoard for discharge measurement. Hydroboard is an unsinkable floating board made of closed cell foam on which Sontek M9 ADCP can also be mounted to provide a moving boat solution for discharge measurement by dragging it across a river section bridge and a 16 ft/s water velocity limit is recommended.

For each deployment of HYCAT, an Emergency Return Point (ERP) must be established using a software control. It will allow the HYCAT to navigate autonomously back to the ERP should there be any anticipated issue, such as the level of battery power being low for subsequent operation.

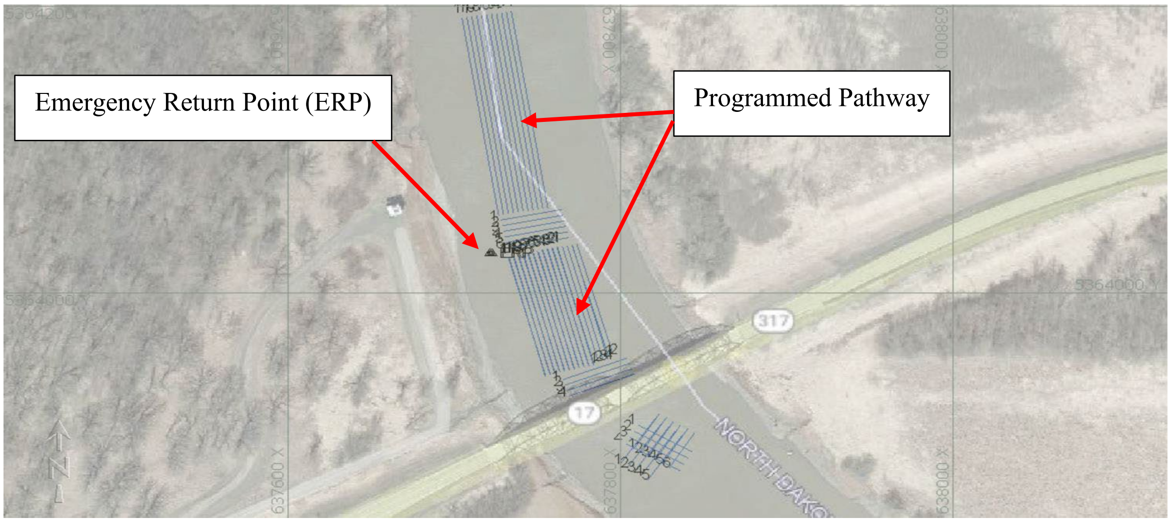


Figure 4. Planned navigation pathway at the site of Highway 17 Bridge near Grafton.

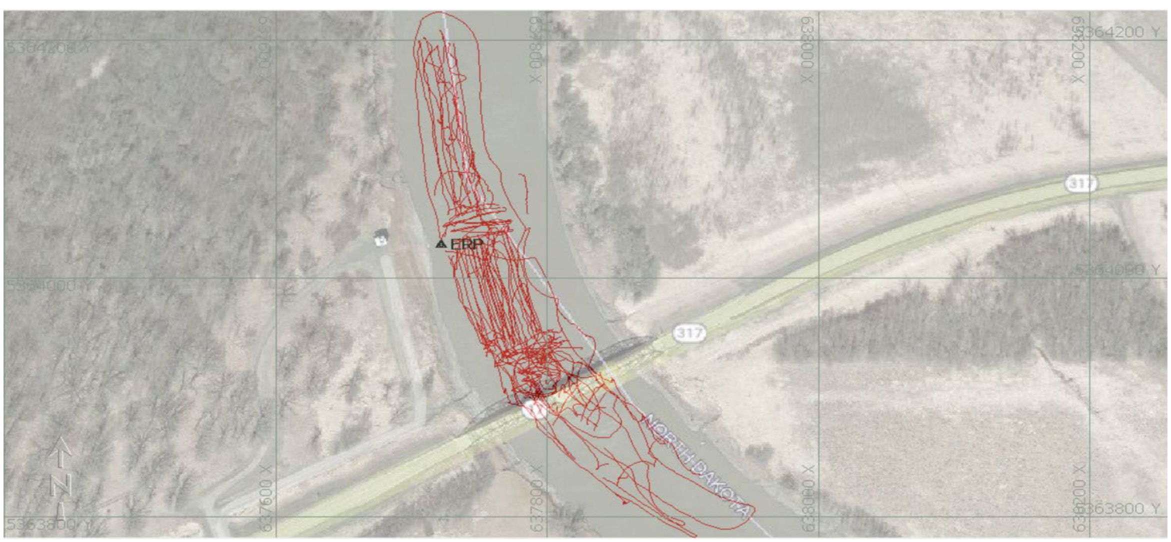


Figure 5. HYCAT's autonomous route at the site of Highway 17 Bridge near Grafton.

Figure 6 is a depiction of a pathway plan for HYCAT navigating the river channel around the Highway 200 Bridge near Halstad. This site has a large pile of floating debris formed in front streamwise of the middle bridge pier, which introduced difficulties in making use of the autonomous mode of operation. As a precaution, remote manual navigation control was used in navigating around the pier and debris pile.

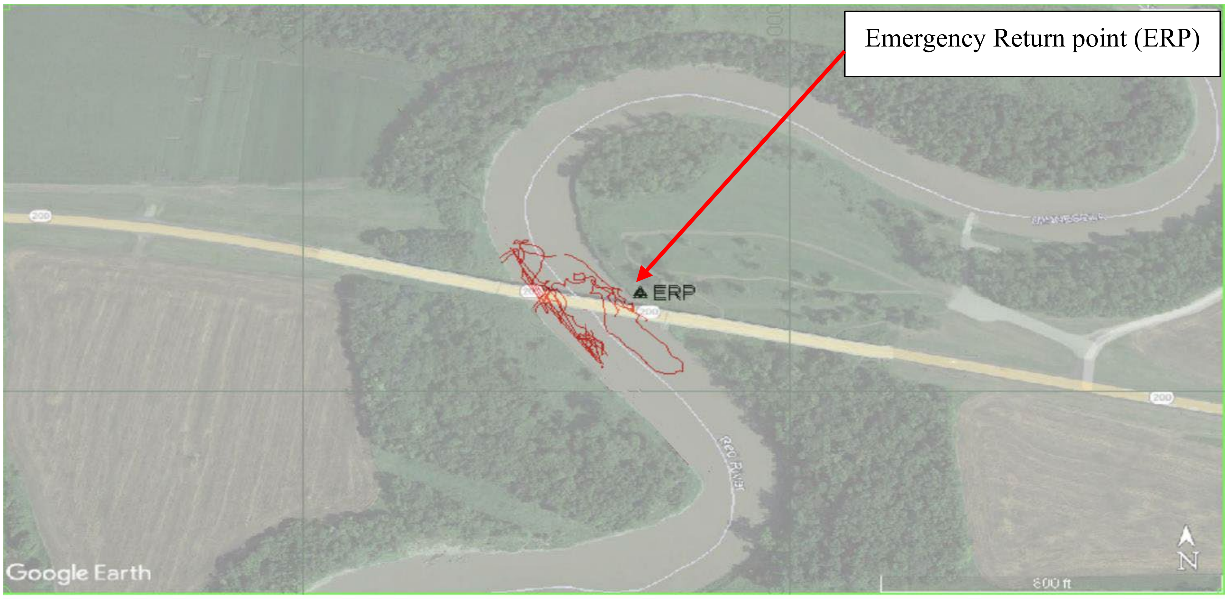


Figure 6. A HYCAT's navigation route at the site of Highway 200 Bridge near Halstad.

Figure 6 shows the path for one field collection. We had two visits to this site. In general, all the collected x, y, z cloud points are merged together and the software is used to fit a surface model to the cloud points. It is akin to making several topographic surveying trips and combing the data points collected to get a topographic map plotted.

5.4.2 Project Presentations

Three project presentations were made and attended by NDDOT officers via Team Meetings on these dates: (a) 12/03/2021, (b) 06/26/2022, and (c) 09/19/2022. The PI also presented the project to the 2023 NDDOT Annual Research Advisory Committee Meeting held online via Team Meeting on 10/24/2022.

5.4.3 Project Files Processing

A set of bathymetric data collected at the site of Highway 17 Bridge near Grafton was sent to Mr. Andrew Ayash of NDDOT on 08/05/2022. The files contain points defining the streambed surface. Each point is represented by x, y, and z values, where x is the Easting in meter, y is the Northing in meter, and z is the elevation in feet. A final new set of digital files is now processed and presented as part of the digital components of this final project report.

5.4.4 Hydraulic and Scour Modeling

After the bathymetric data are processed, cross-sectional data of the sites are created which in turn allows the creation of bridge hydraulic models and scour analysis. A great amount of time was spent on this aspect of work which is described in detail later in Section 7 and 8.

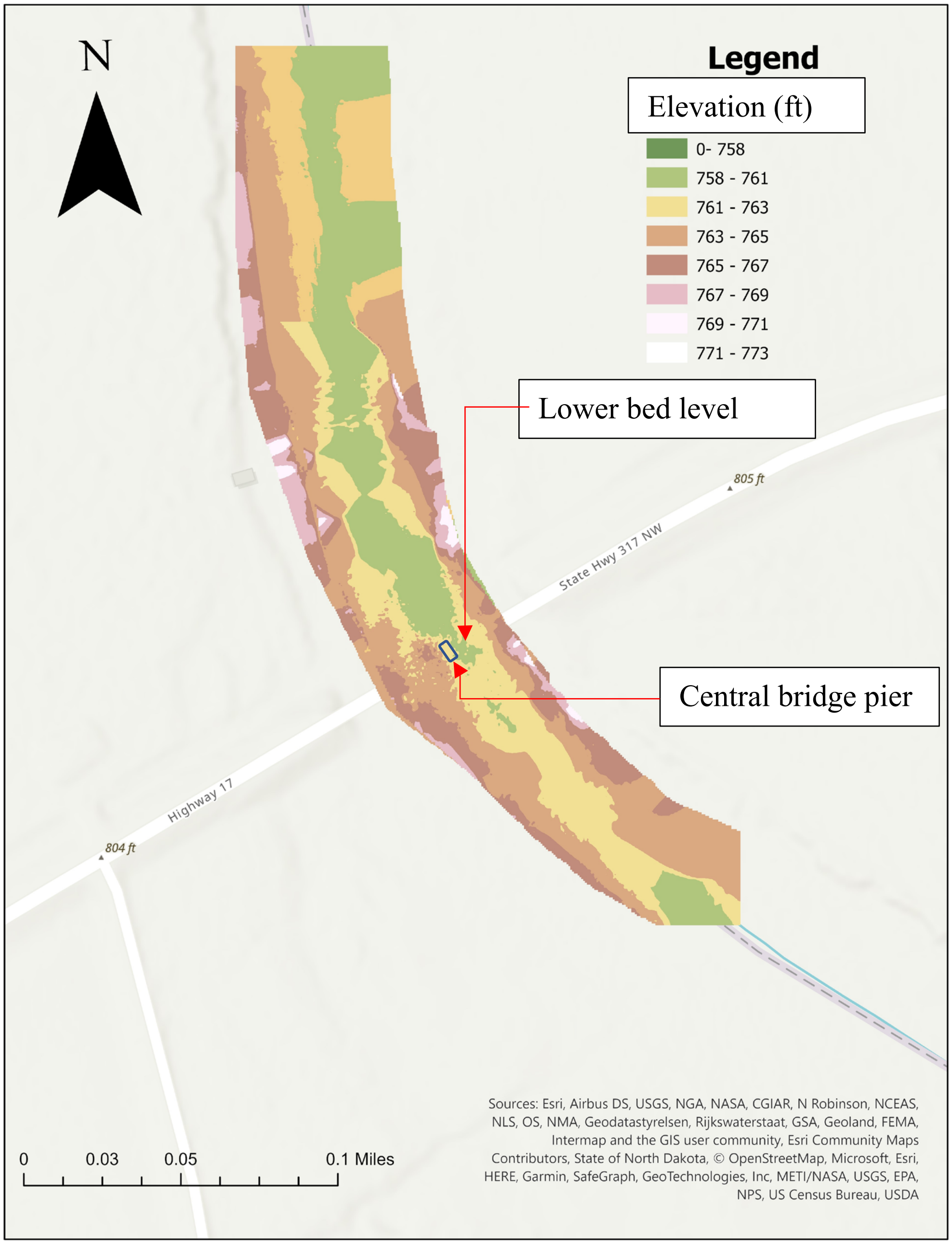


Figure 7. Bathymetry of the study site at Highway 17 Bridge near Grafton.

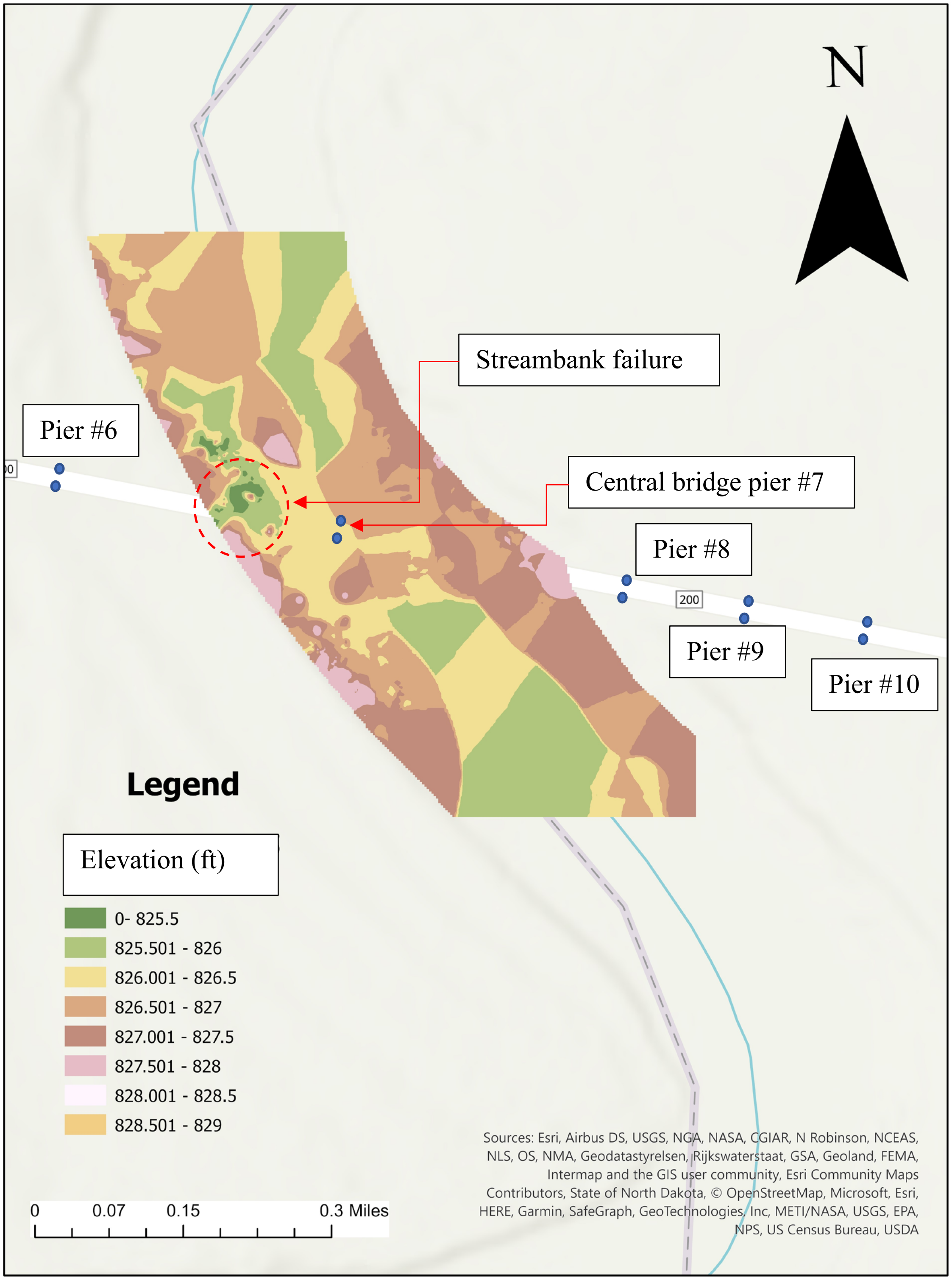


Figure 8. Bathymetry of the study site at Highway 200 Bridge near Halstad.

6. Field Investigation Results

6.1 Bathymetric Data for the Bridge Sites

Getting accurate bathymetric data of the Red River of the North around the two bridge sites involving the use of HYCAT is one of the greatest tasks as far as this project is concerned. This section discusses the results of the bathymetric data collection.

6.2 Bathymetry Interpretation

6.2.1 Bathymetry of Highway 17 Bridge near Grafton.

In the zoom in bathymetry plot of **Figure 9**, it can be seen that on the east side of the pier, there are patches of area (colored green) having lower elevation, between 758 to 761 ft. The bottom of the current pier foundation cap was set at 757.9 ft. So, if the potential scour area gets larger, the pile cap may be exposed. By reading the engineering drawing of the bridge dated 2/22/2013, it is noted that the rip-rap layer around the center pier was replaced.

6.2.3 Descriptions of the Data Files

Several sets of bathymetric data files were collected by HYCAT in each field trip. These are essentially x-y-z data points representing the submerged streambed surface. The elevation data are tied to NAD83 and the Universal Transverse Mercator (UTM) Grid are used. These data are processed using ArcGIS Pro and stored as Excel- CSV files. Each Excel file is related to each site:

Highway 200 Bridge near Halstad: File name: Halstad-complied.csv

Highway 17 Bridge near Grafton: File name: Grafton-complied.csv

Each Excel file includes 3 columns: X data is the location or Easting in meter, Y data is the location or Northing in meter, and Z data is corrected elevations based on GPS measurements to NAD83, in feet.

6.2.4 Supplementary Topographic Data

Supplementary topographic data on a much larger scale are collected. These include LiDAR data and general topographic maps for the study areas. **Figures 11** and **12** show examples of US Topo maps at 1:24,000 scale being used to cross check the river cross section data obtained by LiDAR.

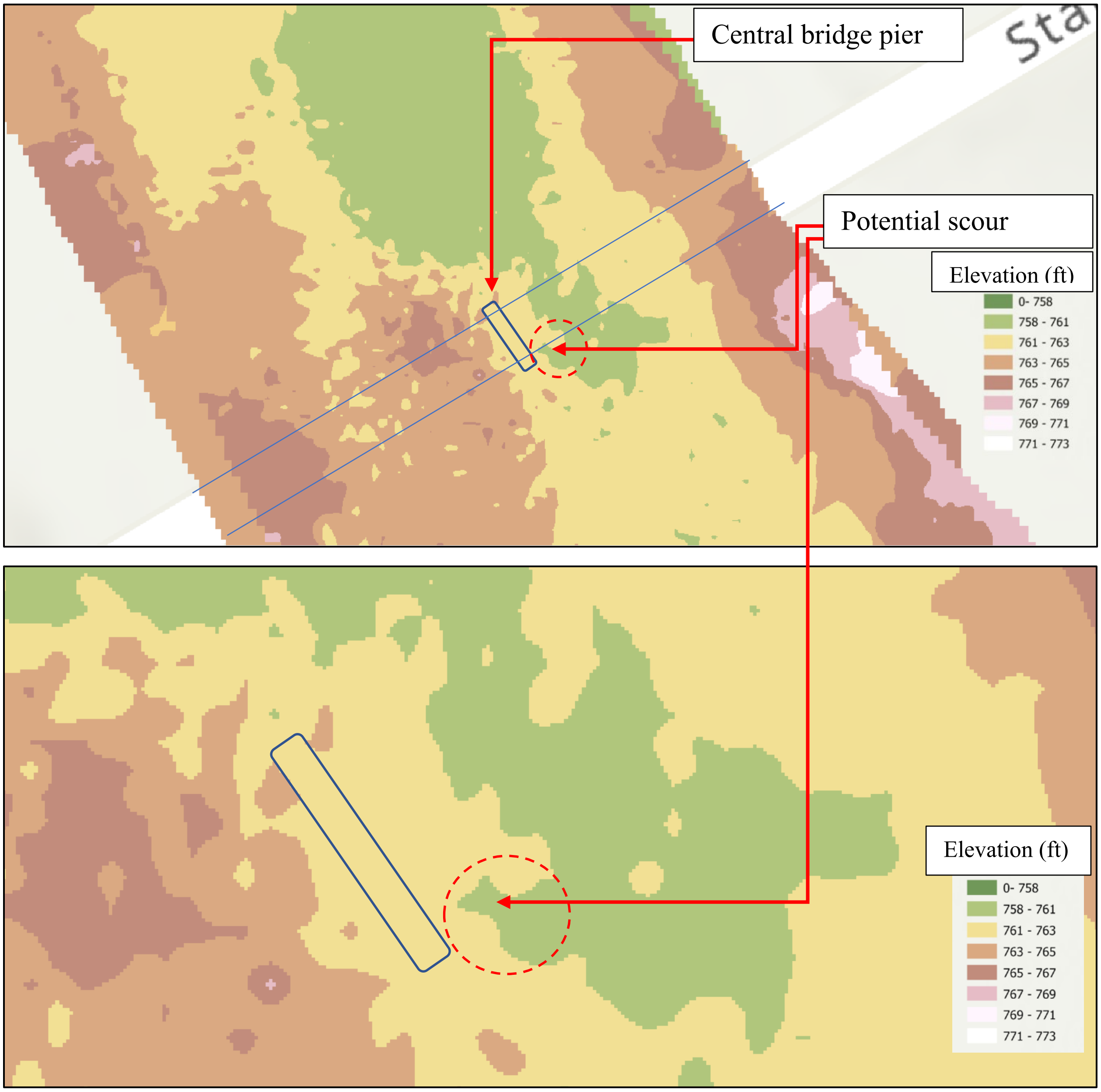


Figure 9. Detail bathymetry around central bridge pier of Highway 17 Bridge near Grafton.

6.2.2 Bathymetry of Highway 200 Bridge near Halstad.

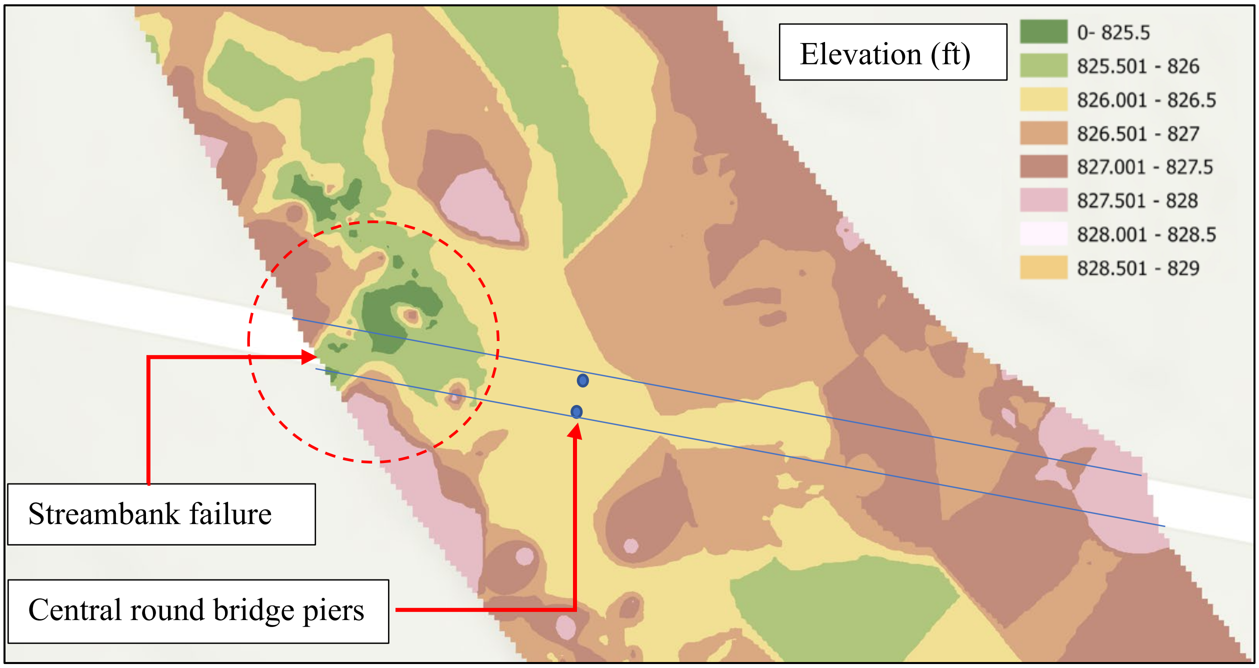


Figure 10. Detail bathymetry around central bridge pier of Highway 200 Bridge near Halstad.

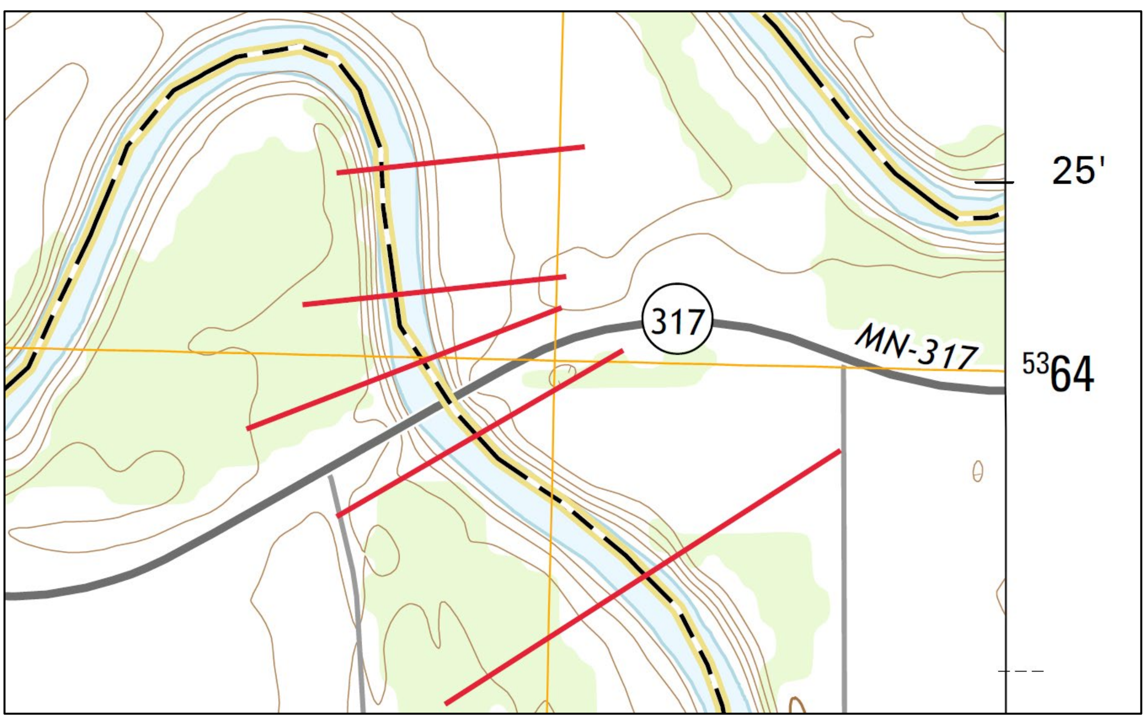


Figure 11. Use of US Topo map in checking cross-sectional data obtained by LiDAR at Highway 17.

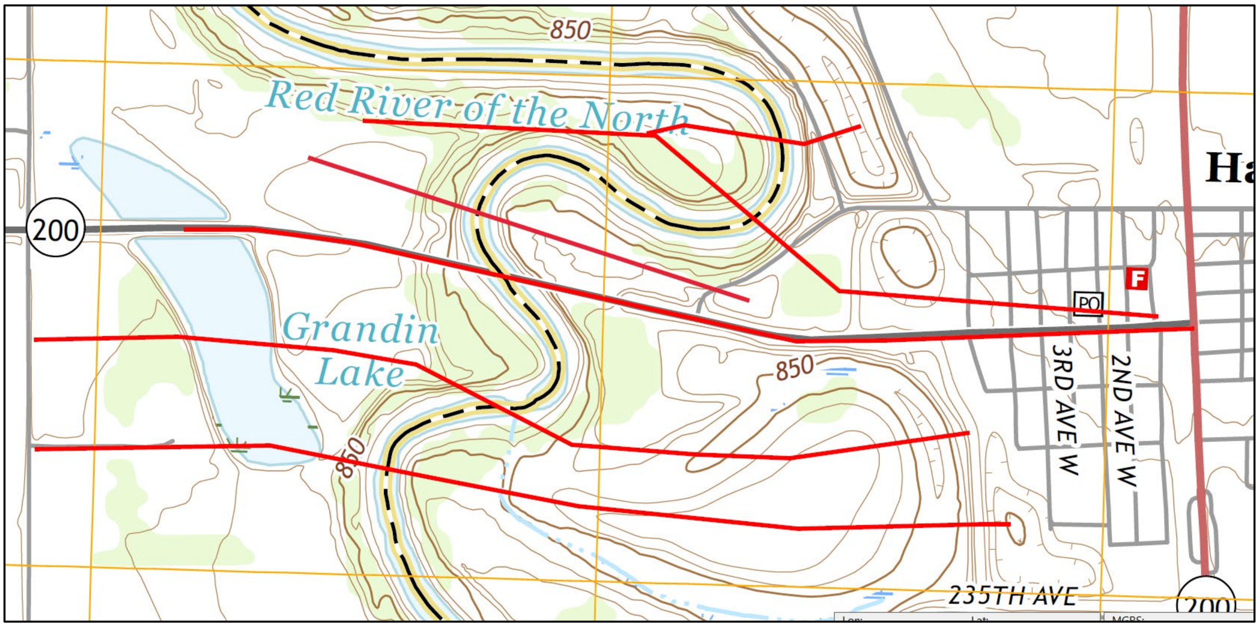


Figure 12. Use of US Topo map in checking cross-sectional data obtained by LiDAR at Highway 200.

6.3. Water Velocity and Discharge Data Collection

It has been known that extreme flood flow presents the greatest threat to the integrity of any bridge structure and associated appurtenances. A good understanding of the flow condition at each bridge site would be essential in a bridge inspection.

For the research project, it was coincidental that we encountered one of the most extreme floods in history passing through the area. The Red River of the North reached flood stage at Grand Forks (USGS Stream Gage 05082500) on April 22th, 2022 and peak discharge of 64,800 cfs occurred on April 26th, 2022. The project team took many discharge measurements at the site of the Highway 17 Bridge crossing Red River near Grafton.

Table 2 shows the summary of the flood flow measurements making full use of a rubber dinghy called HydroBoard. The M9 was transferred from the HYCAT and mounted on the HydroBoard which has a separate GPS unit.

The consecutive measurements of discharge spread over many days are plotted in **Figure 13** to form a flood hydrograph. The measurement of flow velocities using M9 is shown in **Figure 14**. The maximum velocity recorded in the period of measurements was found to be 7.06 ft/s with a flow of 47,144 cfs through the river section on 4/27/2022. The limit of water velocity for safe operation of HYCAT is recommended as at 4 knots, which is 6.72 ft/s. It means the project team decided not to use HYCAT for that day's measurement was the right call.

Table 2. Flood Flow Measurements at Highway 17 Bridge near Grafton in 2022.

Date	Discharge (cfs)	Duration	Time	No. of Sample	Mean Speed (ft/s)	Maximum Velocity (ft/s)
6/12/2022	19,385.4	8:47	11:52	527		3.47
6/12/2022	19,324.3	7:29	12:00	449		
5/27/2022	27,439.9	9:05	11:29	545	0.052	4.04
5/27/2022	27,895.1	7:42	11:36	462	0.48	
5/7/2022	36,843.3	7:51	15:01	471	1.392	4.92
5/7/2022	35,647.2	19:16	14:53	1156	0.126	
4/27/2022	47,144.3	8:04	14:20	484	0.347	7.06
4/27/2022	44,816.8	11:13	11:48	673	0.652	
4/8/2022	13,362.1	2:21	14:50	141	0.68	2.69
4/8/2022	13,220.7	2:45	14:18	165	0.857	
4/8/2022	13,161.1	2:16	14:14	136	0.817	
4/8/2022	13567.3	1:54	14:12	114	0.86	
4/8/2022	12868.3	2:52	14:53	172	0.713	

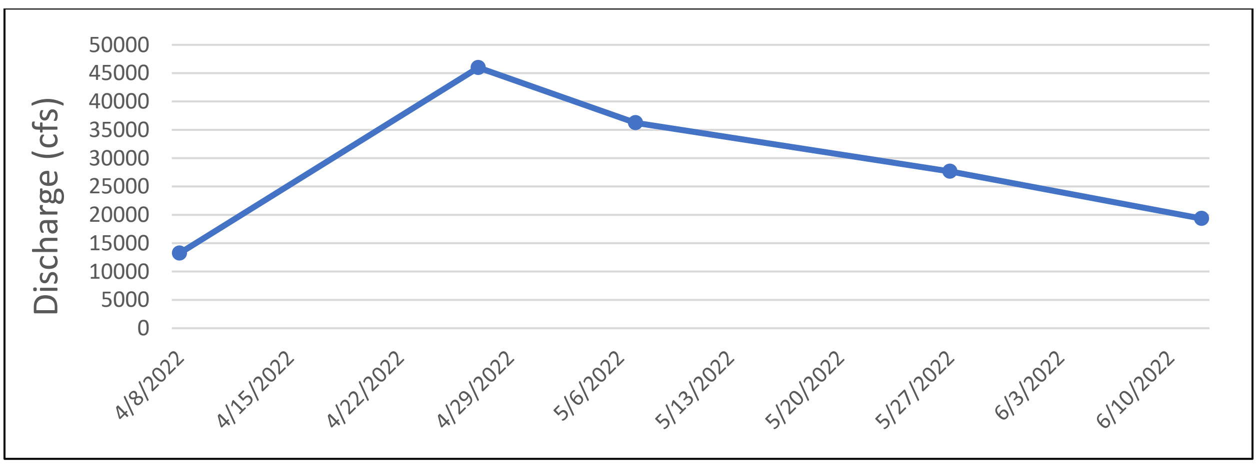


Figure 13. Measured Flood Hydrograph at Highway 17 Bridge Site Near Grafton.

It is of interest to compare the measurements of flood peak discharges at three locations during the 2022 spring flood. Table 3 illustrates the comparison of the discharges measured.

Table 3. Comparison of Flood Peak Discharges in Spring Flood of 2022

River Section	Date of peak	Peak Discharge (cfs)	Note
Halstad -USGS Station	04/27/2022	25,700	
Grand Forks-USGS Station	04/27/2022	64,300	Combined flow from Red River and Red Lake River
Grafton-bridge measured by UND's team	04/27/2022	47,144	Attenuation effect of channel routing

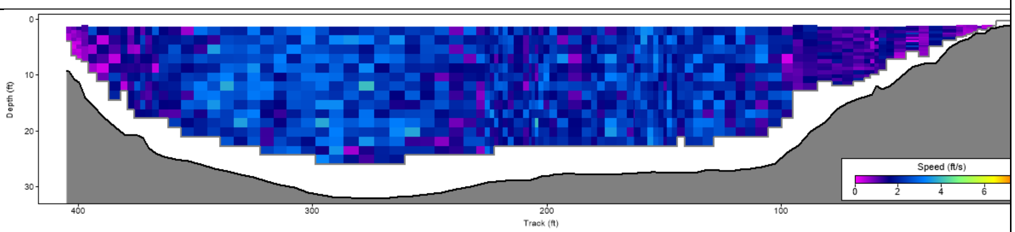
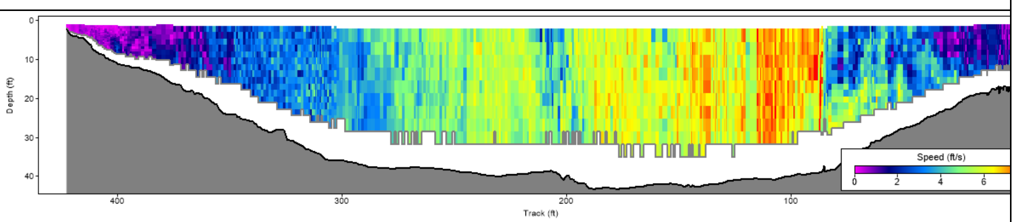
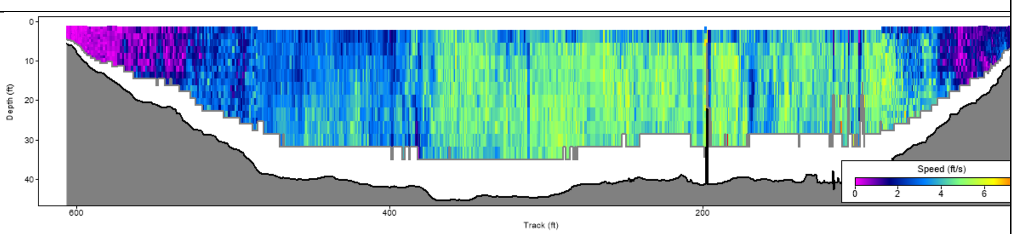
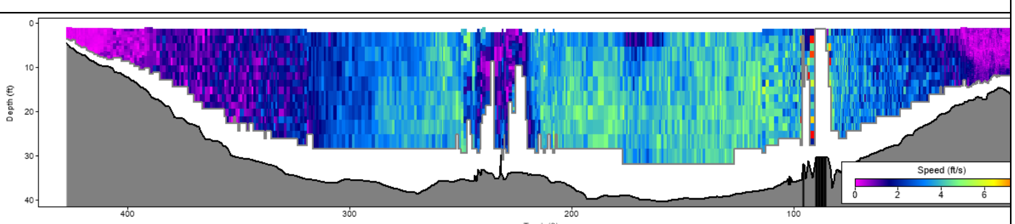
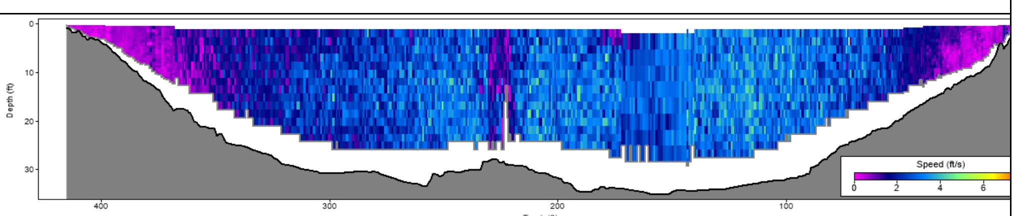
Q (cfs)	**V max (ft/s)**	**Cross Section with Velocity Cells**
13,250	2.69	
Date: 4/8/2022		
44,820	7.06	
Date: 4/27/2022		
36,250	4.92	
Date: 5/7/2022		
27,700	4.04	
Date: 5/27/2022		
19,500	3.47	
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Figure 14. Discharge Measurement at Highway 17 Bridge Site Near Grafton

7. Bridge Hydraulic Modeling and Analysis

Bridge hydraulic modeling and analysis is an essential exercise to be conducted for a bridge site inspection and assessment, focusing on understanding the hydraulic conditions of the bridge site under extreme flood conditions. The flood quantiles of extreme events such as the 100-year and 200-year floods are to be determined first through flood frequency analysis. Then, the flood quantiles are loaded in computational hydraulic models prepared specifically for each site. This section describes these aspects of work being performed in this project.

7.1 Bridge Hydraulic Modeling Method

The structural components of the bridges are represented in bridge hydraulic modeling through a popular hydraulic modeling software HEC-RAS version 6.3.1 (Hydrologic Engineering Center, 2022). The software allows users to model the hydraulic conditions of river systems including the presence of hydraulic structures such as bridges, culverts, and spillways. For the modeling of the performance of bridge structures under scour potential investigations, extreme flood quantiles are needed. This can be found via flood frequency analysis of known streamflow records. In addition, the geometry of the river channels, bridge structural components, abutments, and highway embankments must be defined.

7.2 Bridge Structural Drawings and GPS Surveying

Two sets of historical engineering drawings were provided by NDDOT. The major features of the bridges that are relevant in creating the hydraulic model for the bridge crossing sites were extracted, such as the bridge pier location, width of pier members, etc. **Figures 15** and **16** shows portions of the drawings that provide critical information for creating the bridge hydraulic models. The major positions are noted and cross-checked by using GPS surveys during the field trips. The features include the bridge abutment and piers. Another important task that was done is to relate the known survey benchmarks found on the bridge with the river water surface at the time of bathymetry survey. This is a backup effort since the GPS onboard HYCAT also provides the coordinate and elevation values.

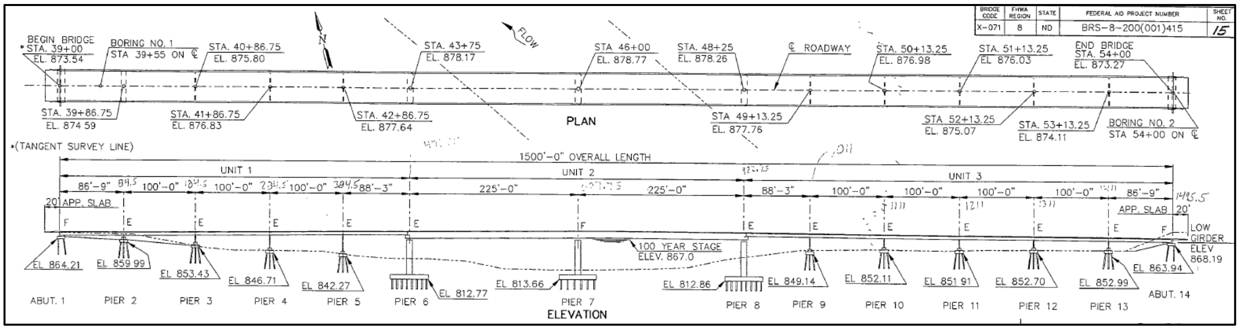

Figure 15. Engineering drawing showing elevation view of the Highway 200 Bridge near Halstad.

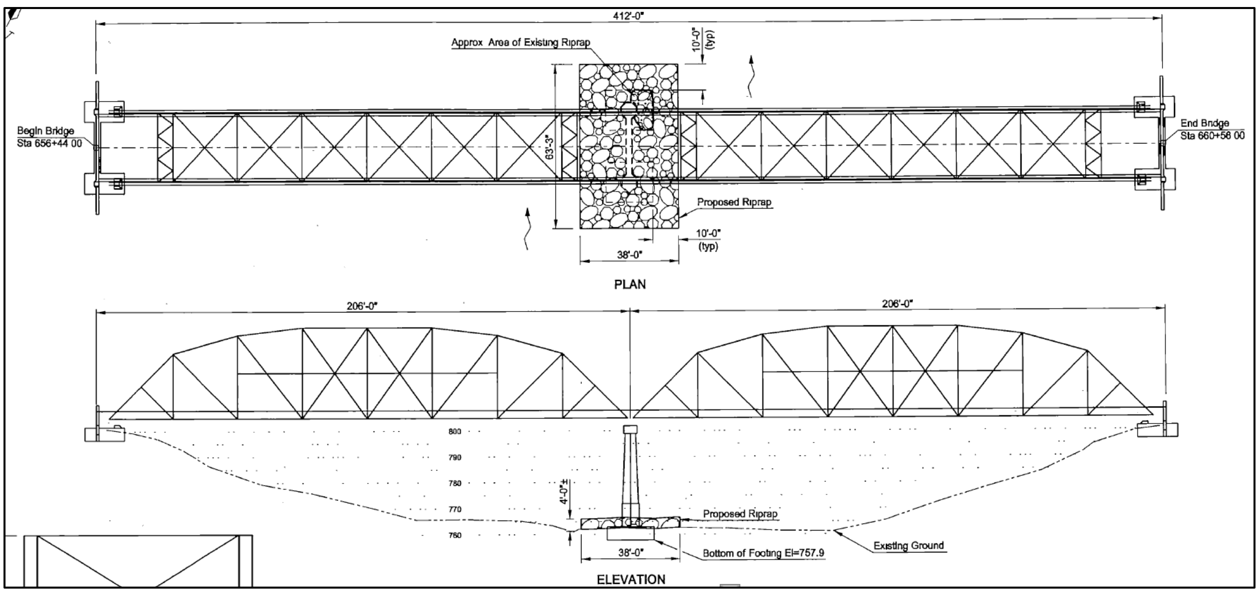

Figure 16. Engineering drawing showing elevation view of the Highway 17 Bridge near Grafton.

7.3 Flood Frequency Analysis

Flood frequency at two locations along the Red River of the North are determined, using the latest Bulletin 17C procedure (U.S. Geological Survey, 2019). The two sites with sufficient flood records are used. One is at the project site of Highway 200 Bridge near Halstad where USGS has maintained a stream gauging station (station number: 05064500). The other site is at Grand Forks (station number 05082500). HEC-SSP software published by USACE is used in the analysis which yields the results as depicted in **Tables 4, 5, and 6**. The frequency curves are shown in **Figures 17, 18, and 19** respectively.

Table 4. Flood Frequency Analysis – Halstad (05064500) – 1942 -2021.

Exceedance Probability	0.01	0.005
Return Period	100-Year	200-Year
Quantile Estimate (cfs)	81,247	98,778
Confidence Limit-_Lower (cfs)	57,526	64,208
Confidence Limit _Upper (cfs)	115,915	145,931

Table 5. Flood Frequency Analysis – Grand Forks (05082500) – 1882-2021.

Exceedance Probability	0.01	0.005
Return Period	100-Year	200-Year
Quantile Estimate (cfs)	106,924	125,213
Confidence Limit-_Lower (cfs)	83,619	93,264
Confidence Limit _Upper (cfs)	144,991	178,858

Table 6. Flood Frequency Analysis – Drayton (5092000) – 1941-2021.

Exceedance Probability	0.01	0.005
Return Period	100-Year	200-Year
Quantile Estimate (cfs)	113,297	127,501
Confidence Limit-_Lower (cfs)	87,206	93,038
Confidence Limit _Upper (cfs)	155,945	185,133

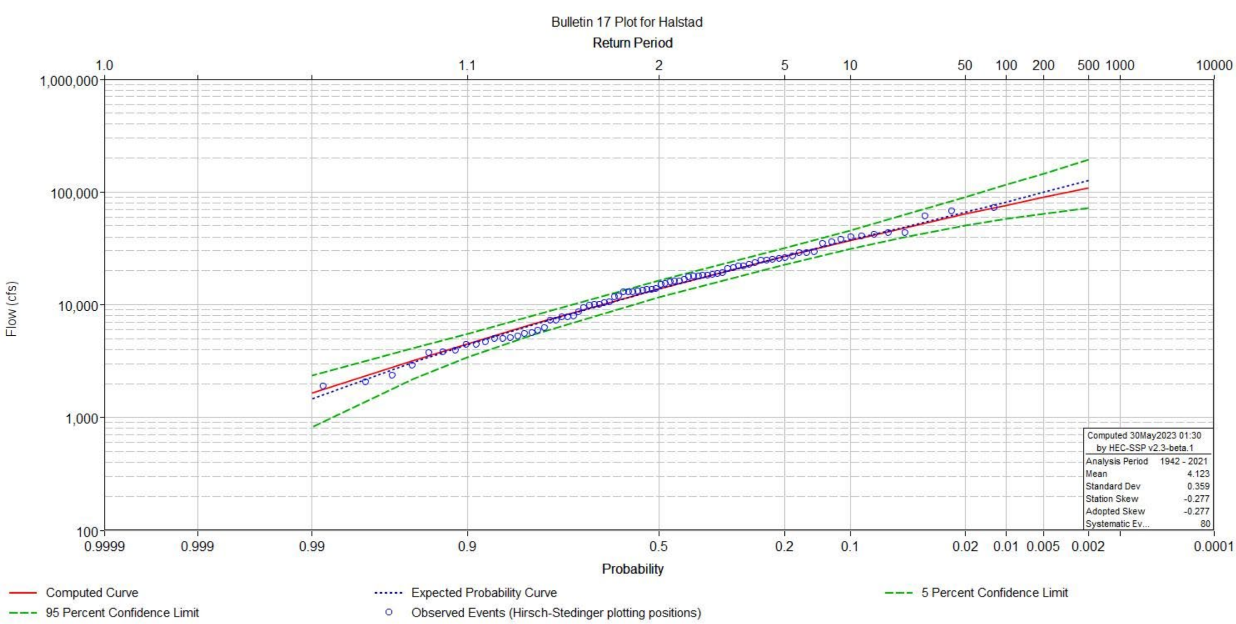

Figure 17. Flood Frequency Curve for Halstad, MN.

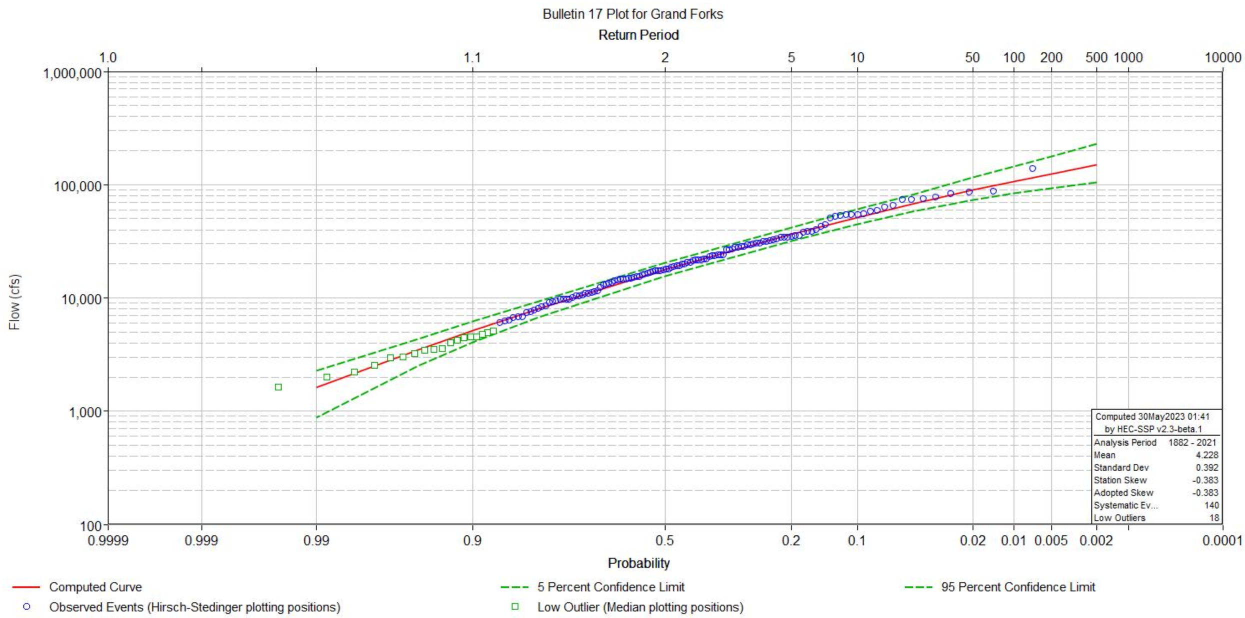

Figure 18. Flood Frequency Curve for Grand Forks, ND.

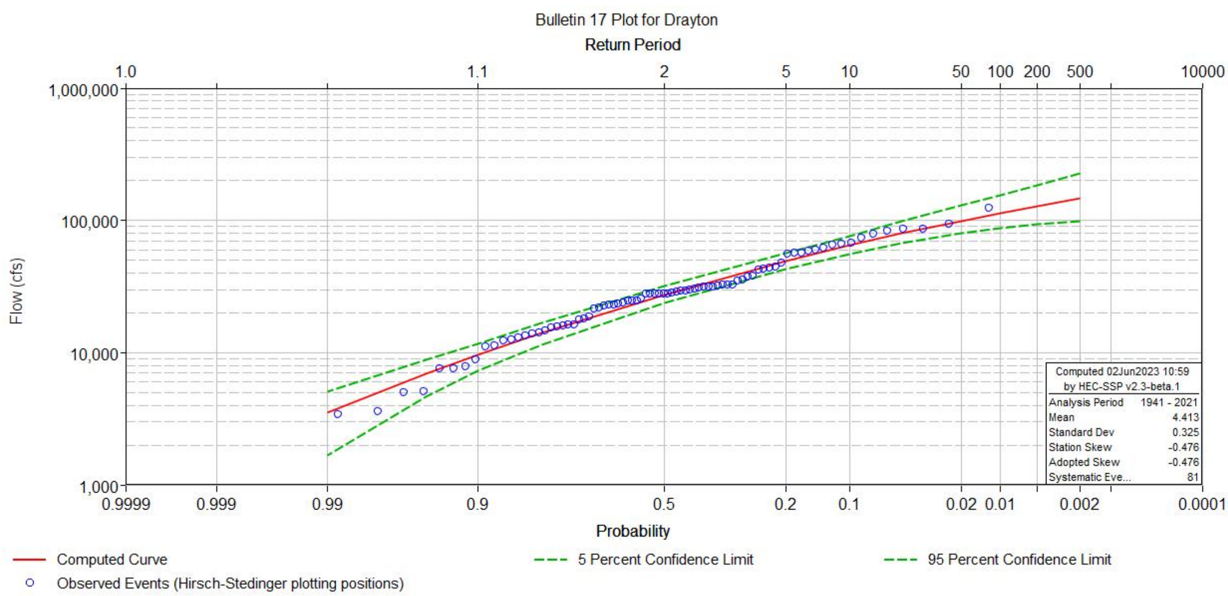

Figure 19. Flood Frequency Curve for Drayton, ND.

The Highway 200 Bridge site is located along the Red River in between Grand Forks and Drayton. The distance measured streamwise from the site to Drayton as compared with the distance between the site and Grand Forks located in the upstream side is in the order of 1:3. The flood quantile estimated for the Highway 17 Bridge site near Grafton is shown in **Table 6**.

Table 7. Flood Frequency Analysis – Highway 17 Bridge Site near Grafton.

Exceedance Probability	0.01	0.005
Return Period	100-Year	200-Year
Quantile Estimate (cfs)	111,704	126,929
Confidence Limit-_Lower (cfs)	86,309	93,095
Confidence Limit _Upper (cfs)	153,207	183,564

For the hydraulic model of bridge Hec-RAS model, these flood flow quantiles are used for simulating flow conditions and determining the scour potential. As a summary the flood quantiles to be used in hydraulic modeling are summarized in **Table 8**.

Table 8. Selected Flood Quantiles for Hydraulic Modeling.

	Quantile Estimate (cfs)	
Project Study Sites	**100-Year Flood**	**200-Year Flood**
Highway 17 Bridge near Grafton	111,704	126,929
Highway 200 Bridge near Halstad	81,247	98,778

Judging by the written information found in the 1997 engineering drawing of the bridge at Highway 200 near Halstad, which is exhibited below in **Figure 20**, the designed flood quantile for a 50-year flood was 45,000 cfs while the 100-year flood was cited as 56,000 cfs.

In comparison with the new flood frequency analysis using Bulletin 17C procedure based on the extended flood record series (from 1997 until 2021), **the 100-year flood discharge for this bridge site has increased from 56,000 cfs to 81,247 cfs** as shown in **Table 8.** This near 45% increase in flood discharge estimate means there is a very significant increase in flood risk. In fact, the bridge was designed for 50-year flood (45,000 cfs) and the bridge deck was kept just above the 100-year flood level of 867.21 ft (discharge of 56,000 cfs) as defined in 1997. The corresponding return period for 56,000 cfs is only 35 years instead of 100 years when using the latest flood frequency curve as presented in **Figure 17**.

The flood quantile estimated for every site change with time as more flood records are collected. Hence, it is important to be aware of the possible increase in flood risk as shown in the case of the Highway 200 Bridge. **An effort to do periodic assessments on all bridges in the flood risk aspect is highly recommended.**

HYDRAULIC DESIGN DATA (AT UPSTREAM HEC-2 SECTION 12100):

Drainage Area	21,800 Sq. Mi. (3,800 Sq. Mi. Closed Basin)
Design Frequency	50 year
Design Discharge	45,000 cfs
Design Stage	866.19
Stream Gradient	.00002 Ft./Ft.
Waterway (provided below design stage)	26,028 Ft.^{2}
Waterway (provided below clearance elevation)	29,000 Ft.^{2}
Average Velocity of Flow in Natural Channel	1.7 fps
Depth of Flow	40.8 Ft.
Velocity of Flow under Bridge	2.4 fps
Free Board Provided	1.5 ft.
100-Year Frequency Discharge	56,000 cfs
100-Year Frequency Stage	867.21
Overtopping Discharge	<73,000 cfs
Minimum Water Elevation	825.2

Figure 20. Hydraulic Design Data Derived in 1997 for the Highway 200 Bridge near Halstad.

Cross sections of the Red River on the upstream and downstream sides of the bridges were derived from the surface terrain model which was created based on an integration of bathymetry collected by HYCAT, LiDAR terrain data, and features found on US Topo maps.

7.4. Hydraulic Model Calibration and Output

Flood level at the bridge sites is an important aspect of bridge performance assessment. The hydraulic model can provide the information needed. The bridge at Highway 200 has a USGS stream gauge and the flood levels were recorded. The historical flood level at this location was used to calibrate the model for this site. The main values used to tune the model to match the historical flood levels are the values of Manning's n in the main channel and flood plain areas. The Manning's n values are assumed to be similar at the Highway 17 Bridge site.

HEC-RAS model simulation using different return period floods are established and the results are available in various forms of plots and data tables.

7.4.1 Highway 17 Bridge near Grafton under 100-year flood condition (111,704 cfs)

The model is established using the information collected from the sites. Manning's n of 0.04 is selected for the overbank areas based on the calibration value obtained at the Highway 200 site, which are also covered with crops. The main channel is smooth without rifles and pools, and a Manning's n value of 0.03 is selected, similar to the calibration done for the Highway 200 site. The bed slope varies between 0.0001 and 0.0002 using the bathymetric data collected from the site as well as from regional estimates. **Figure 21** shows the bridge model being depicted and configured in HEC-RAS.

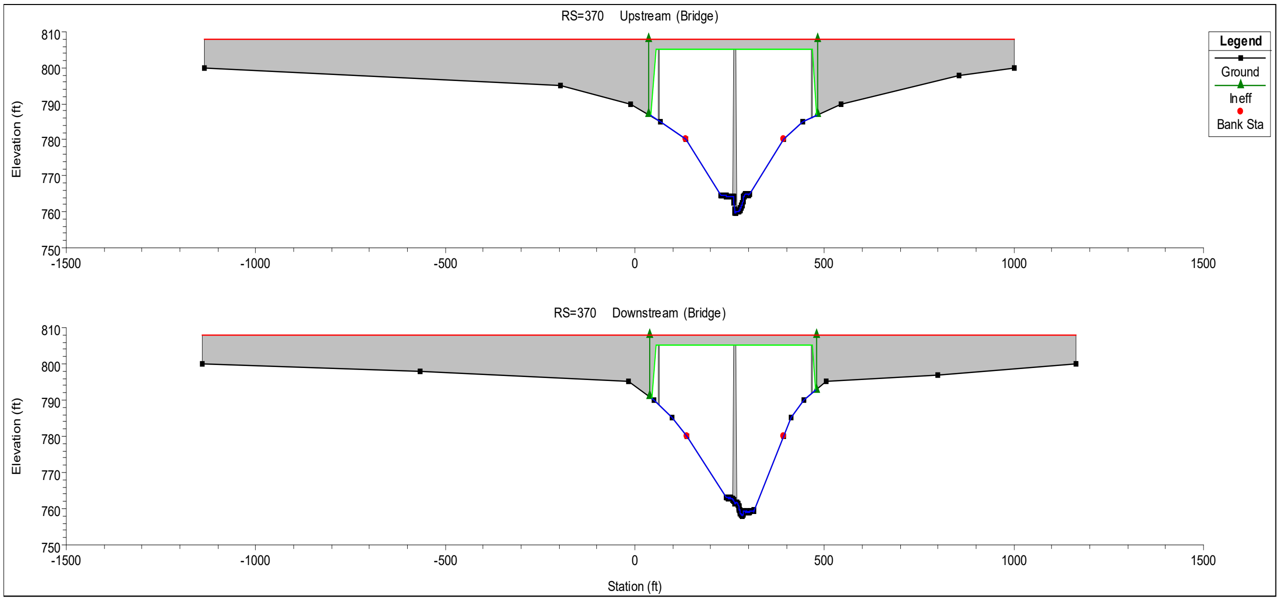

Figure 21. HEC-RAS Bridge model for Highway 17 Bridge near Grafton.

It can be seen from **Figure 22** that the water surface (WS PF1-blue line) is at the bridge deck level under the 100-year flood flow condition. Another perspective is the streamwise flood profile plot shown in **Figure 22**. The bridge deck is half submerged.

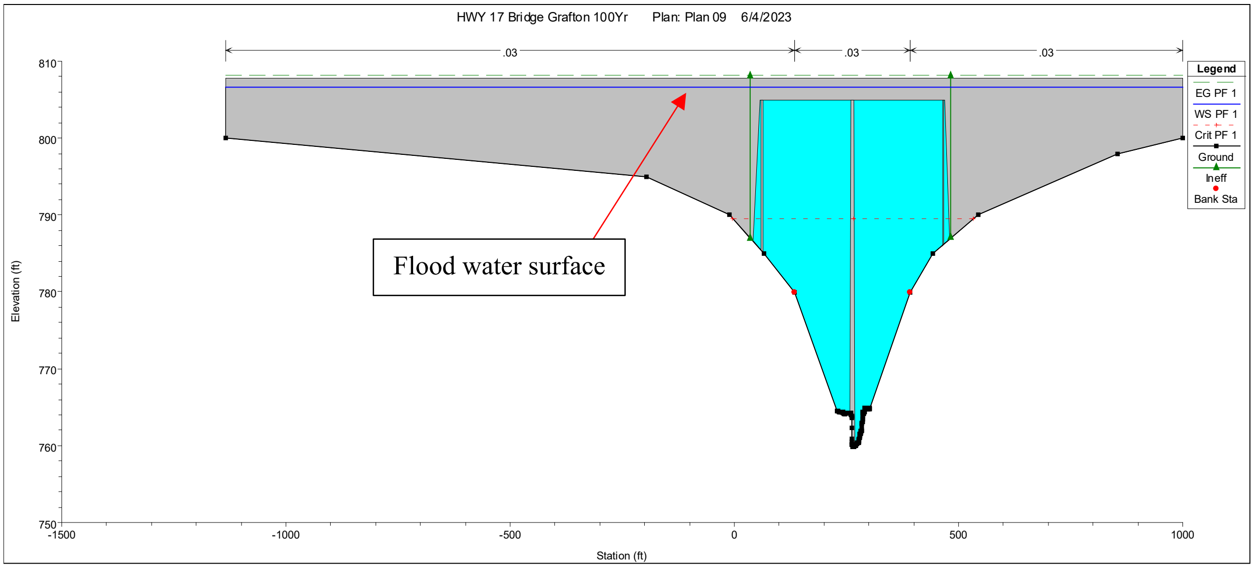

Figure 22. Cross-sectional view of Highway 17 Bridge near Grafton under 100-year flood.

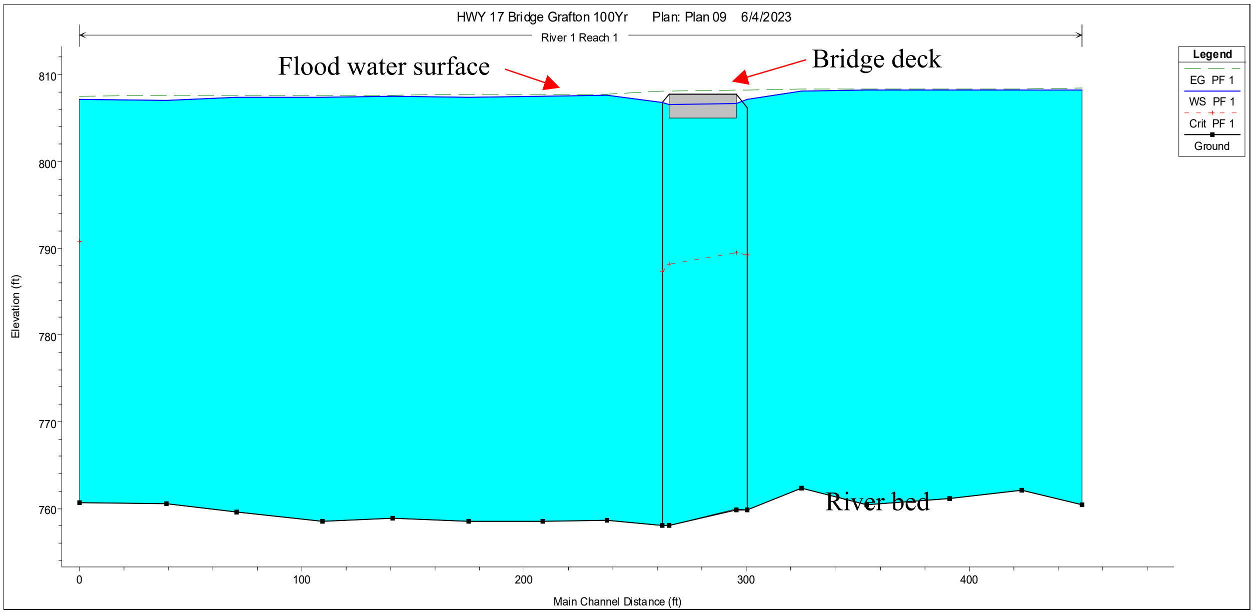

Figure 23. Streamwise flood profile plot of Highway 17 Bridge near Grafton under 100-year flood.

Each line in **Table 9** shows the hydraulic parameters of flow at each cross-section. In this case, the water surface elevation at the immediate upstream side of the bridge is 807.10 ft and 806.82 at the downstream side of the bridge.

Table 10 shows the summary of bridge data output from the modeling. It is of interest to note that the velocity inside the bridge opening is around 9.6 ft/s and 9.68 ft/s. The Froude number, a ratio of velocity to wave speed, is at 0.25. This means the flow is still under subcritical flow condition.

Table 9. Flood Profile of Highway 17 Bridge near Grafton under 100-year flood.

Reach	River Sta	Profile	Q Total	Min Ch El	W.S. Elev	Crit W.S.	E.G. Elev	E.G. Slope	Vel Chnl	Flow Area	Top Width	Froude # Chl
			(cfs)	(ft)	(ft)	(ft)	(ft)	(ft/ft)	(ft/s)	(sq ft)	(ft)	
Reach 1	540	PF 1	17704.00	760.46	808.18		808.42	0.000090	5.20	55937.41	4000.00	0.15
Reach 1	513	PF 1	17704.00	762.06	808.28		808.37	0.000038	3.38	58452.80	4000.00	0.10
Reach 1	481	PF 1	17704.00	761.13	808.24		808.36	0.000051	3.91	50244.68	3500.00	0.11
Reach 1	444	PF 1	17704.00	760.43	808.25		808.36	0.000045	3.67	54693.88	3911.00	0.11
Reach 1	414	PF 1	17704.00	762.34	808.17		808.35	0.000074	4.72	42820.84	3134.40	0.14
Reach 1	390	PF 1	17704.00	759.85	807.10	789.27	808.25	0.000281	9.12	14047.03	2134.40	0.26
Reach 1	370		Bridge									
Reach 1	352	PF 1	17704.00	758.07	806.82	787.37	808.07	0.000290	9.56	13635.07	2303.60	0.27
Reach 1	327	PF 1	17704.00	758.63	807.58		807.74	0.000121	3.98	40083.62	3141.30	0.11
Reach 1	298	PF 1	17704.00	758.47	807.50		807.73	0.000090	4.97	39611.57	3141.30	0.15
Reach 1	265	PF 1	17704.00	758.53	807.40		807.71	0.000112	5.44	30828.25	1897.65	0.16
Reach 1	231	PF 1	17704.00	758.85	807.48		807.68	0.000075	4.71	40023.48	2605.79	0.14
Reach 1	199	PF 1	17704.00	758.51	807.34		807.66	0.000110	5.71	30630.86	1824.25	0.16
Reach 1	161	PF 1	17704.00	759.56	807.38		807.64	0.000096	5.27	36958.72	2850.00	0.15
Reach 1	129	PF 1	17704.00	760.49	807.02		807.60	0.000190	7.83	23264.18	1391.00	0.22
Reach 1	90	PF 1	17704.00	760.62	807.14	790.80	807.54	0.000150	6.83	30832.68	2593.50	0.19

Table 10. Summary of bridge output data for Highway 17 Bridge near Grafton under 100-year flood.

E.G. US. (ft)	808.25	Element	Inside BR US	Inside BR DS
W.S. US. (ft)	807.10	E.G. Elev (ft)	808.21	808.17
Q Total (cfs)	117704.00	W.S. Elev (ft)	806.69	806.60
Q Bridge (cfs)	117704.00	Crit W.S. (ft)	789.51	788.19
Q Weir (cfs)		Max Chl Dpth (ft)	46.72	48.53
Weir Sta Lft (ft)		Vel Total (ft/s)	9.60	9.68
Weir Sta Rgt (ft)		Flow Area (sq ft)	12263.87	12157.34
Weir Submerg		Froude # Chl	0.25	0.25
Weir Max Depth (ft)		Specif Force (cu ft)	252262.70	258596.50
Min El Weir Flow (ft)	807.82	Hydr Depth (ft)		
Min El Prs (ft)	805.00	W.P. Total (ft)	1035.79	1001.88
Delta EG (ft)	0.18	Conv. Total (cfs)	3367787.0	3427476.0
Delta WS (ft)	0.29	Top Width (ft)		
BR Open Area (sq ft)	12157.34	Frctn Loss (ft)	0.04	0.00
BR Open Vel (ft/s)	9.68	C & E Loss (ft)	0.01	0.09
BR Sluice Coef		Shear Total (lb/sq ft)	0.90	0.89
BR Sel Method	Energy only	Power Total (lb/ft s)	8.67	8.65

7.4.2 Highway 17 Bridge near Grafton under 200-year flood condition (126,929 cfs)

The following diagrams and tables are similar to the previous section except that the flood flow has been increase to 126, 929 cfs corresponding to a 200-year flood flow condition. **Figure 24** shows that the flood level (blue line) is still slightly below the top of the bridge deck. Another perspective view of the flood profile is shown in **Figure 25**.

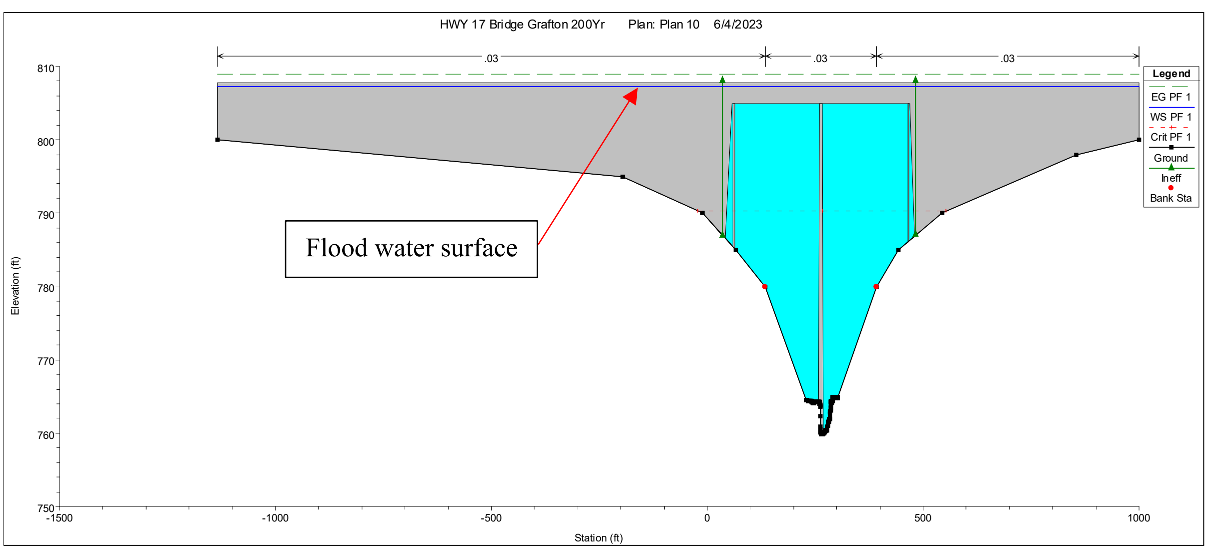

Figure 24. Cross-sectional view of Highway 17 Bridge near Grafton under 200-year flood.

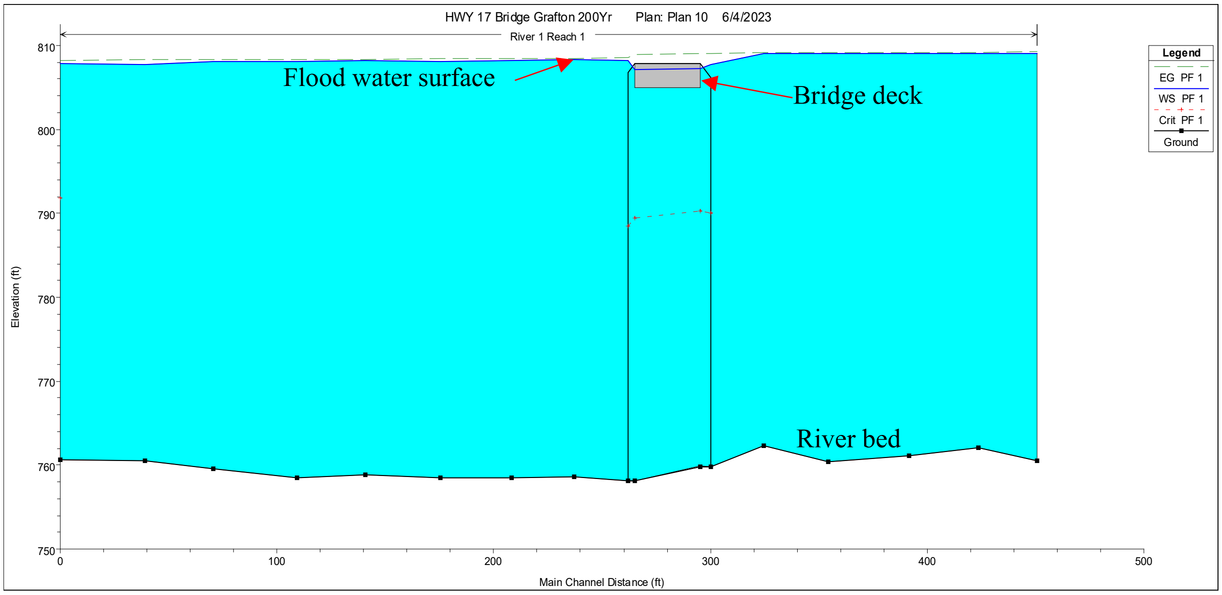

Figure 25. Streamwise flood profile plot of Highway 17 Bridge near Grafton under 100-year flood.

Table 11. Streamwise flood profile plot of Highway 17 Bridge near Grafton under 200-year flood.

Reach	River Sta	Profile	Q Total (cfs)	Min Ch El (ft)	W.S. Elev (ft)	Crit W.S. (ft)	E.G. Elev (ft)	E.G. Slope (ft/ft)	Vel Chnl (ft/s)	Flow Area (sq ft)	Top Width (ft)	Froude # Chl
Reach 1	540	PF 1	26929.00	760.46	808.99		809.23	0.000091	5.30	59198.88	4000.00	0.15
Reach 1	513	PF 1	26929.00	762.06	809.10		809.19	0.000037	3.41	61719.16	4000.00	0.10
Reach 1	481	PF 1	26929.00	761.13	809.06		809.18	0.000050	3.95	53102.52	3500.00	0.11
Reach 1	444	PF 1	26929.00	760.43	809.07		809.17	0.000044	3.69	57889.47	3911.00	0.11
Reach 1	414	PF 1	26929.00	762.34	808.99		809.17	0.000072	4.75	45383.82	3134.40	0.13
Reach 1	390	PF 1	26929.00	759.85	807.78	789.98	809.05	0.000305	9.62	14349.18	2134.40	0.27
Reach 1	370		Bridge									
Reach 1	352	PF 1	26929.00	758.07	808.17	788.43	808.51	0.000113	6.09	34210.54	2303.60	0.17
Reach 1	327	PF 1	26929.00	758.63	808.29		808.45	0.000119	4.00	42311.91	3141.30	0.11
Reach 1	298	PF 1	26929.00	758.47	808.22		808.44	0.000090	5.03	41845.03	3141.30	0.15
Reach 1	265	PF 1	26929.00	758.53	808.10		808.43	0.000115	5.60	32147.36	1897.65	0.17
Reach 1	231	PF 1	26929.00	758.85	808.19		808.38	0.000076	4.82	41850.75	2605.79	0.14
Reach 1	199	PF 1	26929.00	758.51	808.03		808.37	0.000114	5.88	31889.82	1824.25	0.17
Reach 1	161	PF 1	26929.00	759.56	808.08		808.34	0.000097	5.35	38951.66	2850.00	0.15
Reach 1	129	PF 1	26929.00	760.49	807.69		808.30	0.000198	8.08	24194.34	1391.00	0.22
Reach 1	90	PF 1	26929.00	760.62	807.83	791.88	808.23	0.000150	6.91	32622.98	2593.50	0.19

Table 12. Summary of bridge output data for Highway 17 Bridge near Grafton under 200-year flood.

E.G. US. (ft)	809.05	Element	Inside BR US	Inside BR DS
W.S. US. (ft)	807.78	E.G. Elev (ft)	809.00	808.95
Q Total (cfs)	126929.00	W.S. Elev (ft)	807.24	807.13
Q Bridge (cfs)	126929.00	Crit W.S. (ft)	790.27	789.40
Q Weir (cfs)		Max Chl Dpth (ft)	47.27	49.06
Weir Sta Lft (ft)		Vel Total (ft/s)	10.35	10.44
Weir Sta Rgt (ft)		Flow Area (sq ft)	12263.87	12157.34
Weir Submerg		Froude # Chl	0.27	0.27
Weir Max Depth (ft)		Specif Force (cu ft)	264793.10	270972.90
Min El Weir Flow (ft)	807.82	Hydr Depth (ft)		
Min El Prs (ft)	805.00	W.P. Total (ft)	1035.79	1001.88
Delta EG (ft)	0.55	Conv. Total (cfs)	3367786.0	3427477.0
Delta WS (ft)	-0.39	Top Width (ft)		
BR Open Area (sq ft)	12157.34	Frctn Loss (ft)	0.04	0.00
BR Open Vel (ft/s)	10.44	C & E Loss (ft)	0.01	0.44
BR Sluice Coef		Shear Total (lb/sq ft)	1.05	1.04
BR Sel Method	Energy only	Power Total (lb/ft s)	10.87	10.85

7.4.3 Highway 17 Bridge near Grafton under extreme flood >200-year flood condition (140,000 cfs)

Since the 200-year flood at Highway 17 Bridge does not overtop the bridge deck, an extra exercise is conducted to see what is the flood discharge that will create an overtop flow condition. A discharge of 140,000 cfs is shown to create this condition as shown in the following **Figures 26** and **26**. A supercritical flow is formed on top of the deck, ie., with very high velocity.

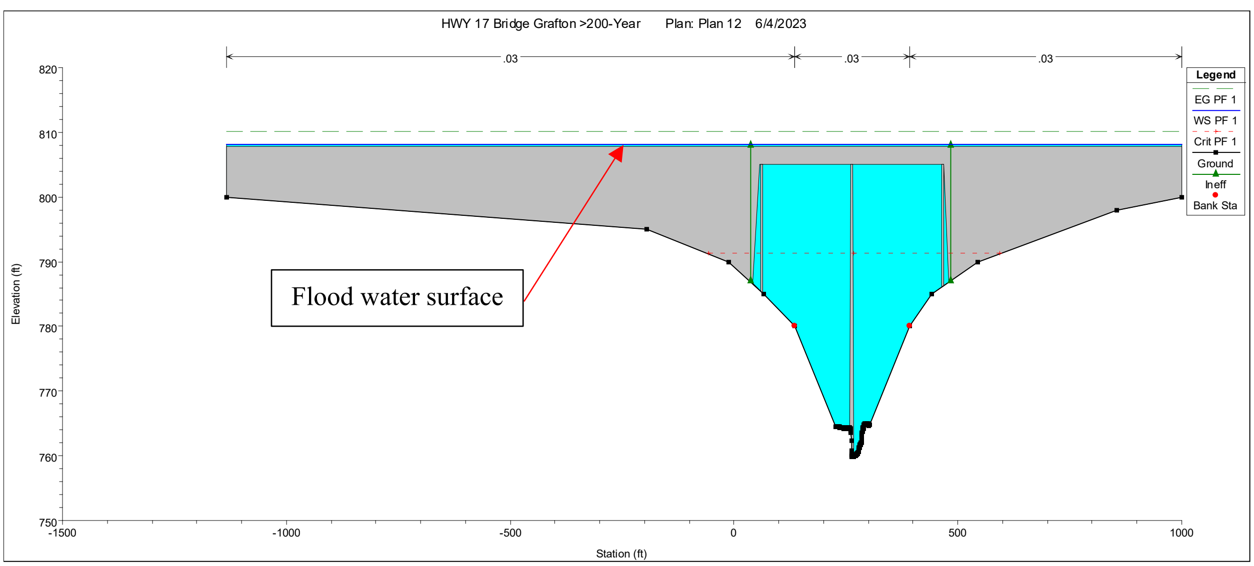

Figure 26. Cross-sectional view of Highway 17 Bridge near Grafton under extreme flood (140,000 cfs).

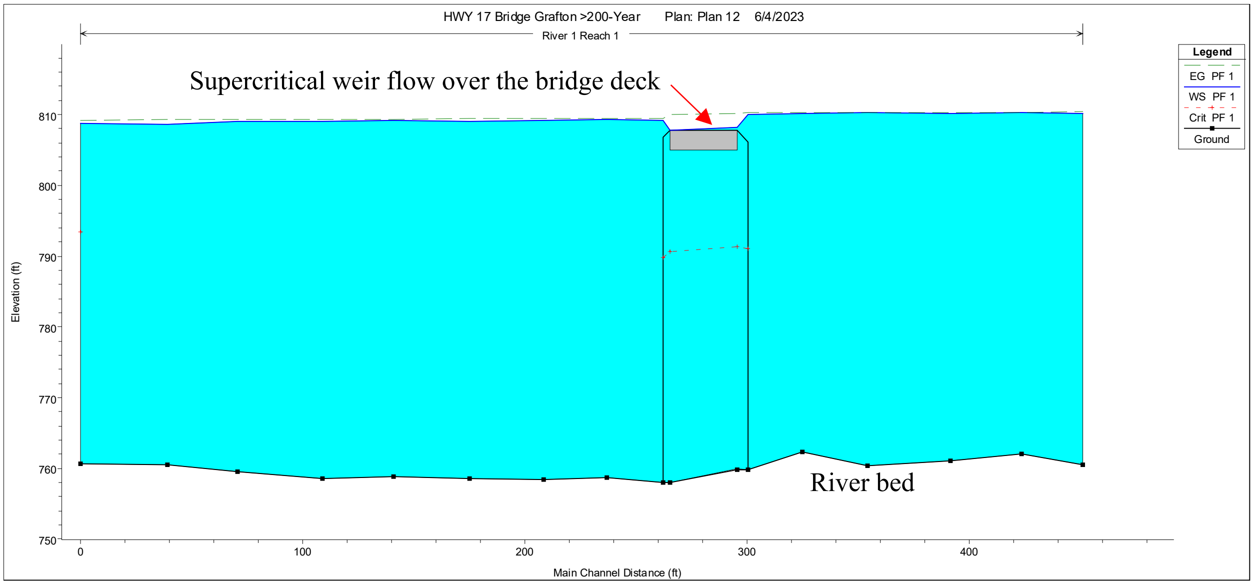

Figure 27. Streamwise flood profile plot of Highway 17 Bridge near Grafton under extreme flood (140,000 cfs).

7.4.4 Highway 200 Bridge near Halstad under 100-year flood condition (81, 247cfs)

Flood flow at the Highway 200 Bridge near Halstad is placed under a 100-year flood flow condition. This is not good as compared with the Highway 17 Bridge near Grafton. The bridge here gets overtopped in this 1% chance scenario. **Figure 28** shows the flood level as above the deck, and **Figure 29** shows another perspective. The flood level is at 870.95ft as shown in **Tables 13** and **14**.

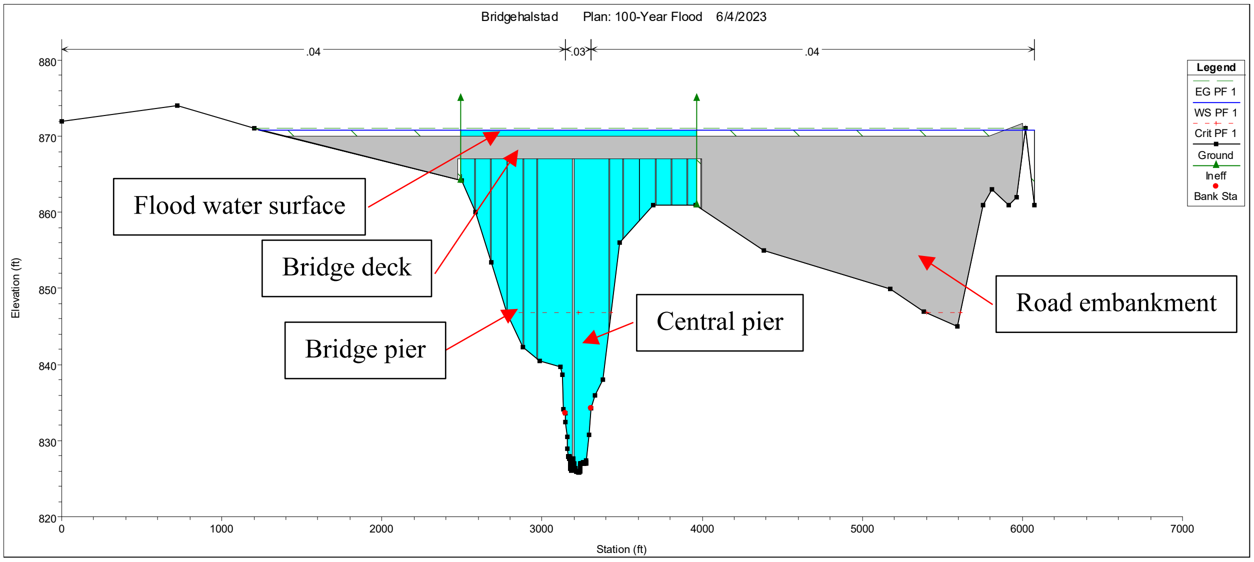

Figure 28. Highway 200 Bridge near Halstad under 100-year flood condition (81, 247cfs).

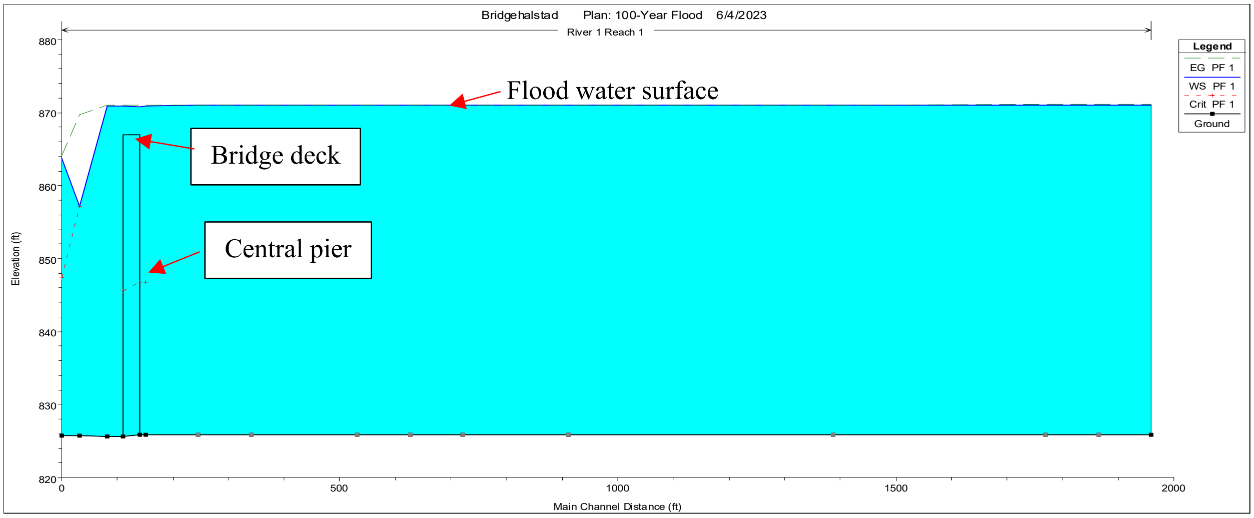

Figure 29. Streamwise flood profile plot of Highway 200 Bridge near Halstad under 100-year flood.

Table 13. Flood profile of Highway 200 Bridge near Halstad under 100-year flood.

Reach	River Sta	Profile	Q Total (cfs)	Min Ch El (ft)	W.S. Elev (ft)	Crit W.S. (ft)	E.G. Elev (ft)	E.G. Slope (ft/ft)	Vel Chnl (ft/s)	Flow Area (sq ft)	Top Width (ft)	Froude # Chl
Reach 1	1742	PF 1	81247.00	825.84	871.07		871.10	0.000014	2.01	82296.09	5304.31	0.06
Reach 1	1658.95*	PF 1	81247.00	825.84	871.07		871.10	0.000014	2.03	82028.48	5277.15	0.06
Reach 1	1575.90*	PF 1	81247.00	825.84	871.07		871.10	0.000014	2.05	81749.64	5251.92	0.06
Reach 1	1243.68*	PF 1	81247.00	825.84	871.06		871.09	0.000030	2.31	80269.54	5149.01	0.07
Reach 1	828.42*	PF 1	81247.00	825.84	871.05		871.08	0.000016	2.30	77801.26	5038.05	0.06
Reach 1	662.32*	PF 1	81247.00	825.84	871.04		871.07	0.000016	2.36	76611.78	4994.54	0.07
Reach 1	579.26*	PF 1	81247.00	825.84	871.04		871.07	0.000017	2.40	75973.96	4974.43	0.07
Reach 1	496.21*	PF 1	81247.00	825.84	871.04		871.07	0.000017	2.44	75302.61	4953.27	0.07
Reach 1	330.11*	PF 1	81247.00	825.84	871.03		871.07	0.000018	2.53	73884.07	4913.72	0.07
Reach 1	247.05*	PF 1	81247.00	825.84	871.03		871.07	0.000018	2.57	73128.33	4895.28	0.07
Reach 1	164	PF 1	81247.00	825.84	870.90	846.77	871.05	0.000054	4.39	32294.75	4849.29	0.12
Reach 1	124		Bridge									
Reach 1	96	PF 1	81247.00	825.65	870.95		870.98	0.000016	2.24	74235.43	4165.62	0.06
Reach 1	69	PF 1	81247.00	825.78	857.21	857.21	869.73	0.004623	28.85	3106.37	156.56	0.94
Reach 1	1	PF 1	81247.00	825.78	863.78	847.33	864.11	0.000150	5.62	26232.25	2883.36	0.18

Table 14. Summary of bridge output data for Highway 200 Bridge near Halstad under 100-year flood.

		Element	Inside BR US	Inside BR DS
E.G. US. (ft)	871.05	E.G. Elev (ft)	871.05	871.01
W.S. US. (ft)	870.90	W.S. Elev (ft)	870.84	870.88
Q Total (cfs)	81247.00	Crit W.S. (ft)	846.82	845.56
Q Bridge (cfs)	80543.04	Max Chl Dpth (ft)	45.00	45.23
Q Weir (cfs)		Vel Total (ft/s)	3.06	2.49
Weir Sta Lft (ft)		Flow Area (sq ft)	26573.01	32678.92
Weir Sta Rgt (ft)		Froude # Chl	0.09	0.08
Weir Submerg		Specif Force (cu ft)	426826.70	472812.60
Weir Max Depth (ft)		Hydr Depth (ft)	18.02	8.05
Min El Weir Flow (ft)	870.01	W.P. Total (ft)	4675.97	7462.69
Min El Prs (ft)	867.00	Conv. Total (cfs)	4104842.0	4658332.0
Delta EG (ft)	0.07	Top Width (ft)	4736.22	4057.94
Delta WS (ft)	-0.06	Frctn Loss (ft)	0.01	0.00
BR Open Area (sq ft)	25327.30	C & E Loss (ft)	0.02	0.03
BR Open Vel (ft/s)	3.18	Shear Total (lb/sq ft)	0.14	0.08
BR Sluice Coef		Power Total (lb/ft s)	0.42	0.21
BR Sel Method	Energy only			

This bridge at Highway 200 was designed to take care of a 50-year flood, as discussed earlier in section 7.3. The other factor was the increase in flood quantile estimates using the latest data and flood frequency analysis. It can be seen in **Table 14** that the flow velocity and Froude numbers are not high as the bridge opening is large enough. The limiting factor is top of the bridge deck is set at around 870 ft while the sofit is set at 867 ft, which was considered then as the 100-year flood level (referring to **Figure 15**).

7.4.5 Highway 200 Bridge near Halstad under 200-year flood condition (98,778 cfs)

The bridge is now placed under a 200-year flood condition. An overtopping condition is expected since the 100-year flood has already overtopped the top of the deck. **Figures 30** and **31** show the massive overtopping flow over the deck and highway embankment by around 5.57 ft, as read from **Tables 15** and **16**.

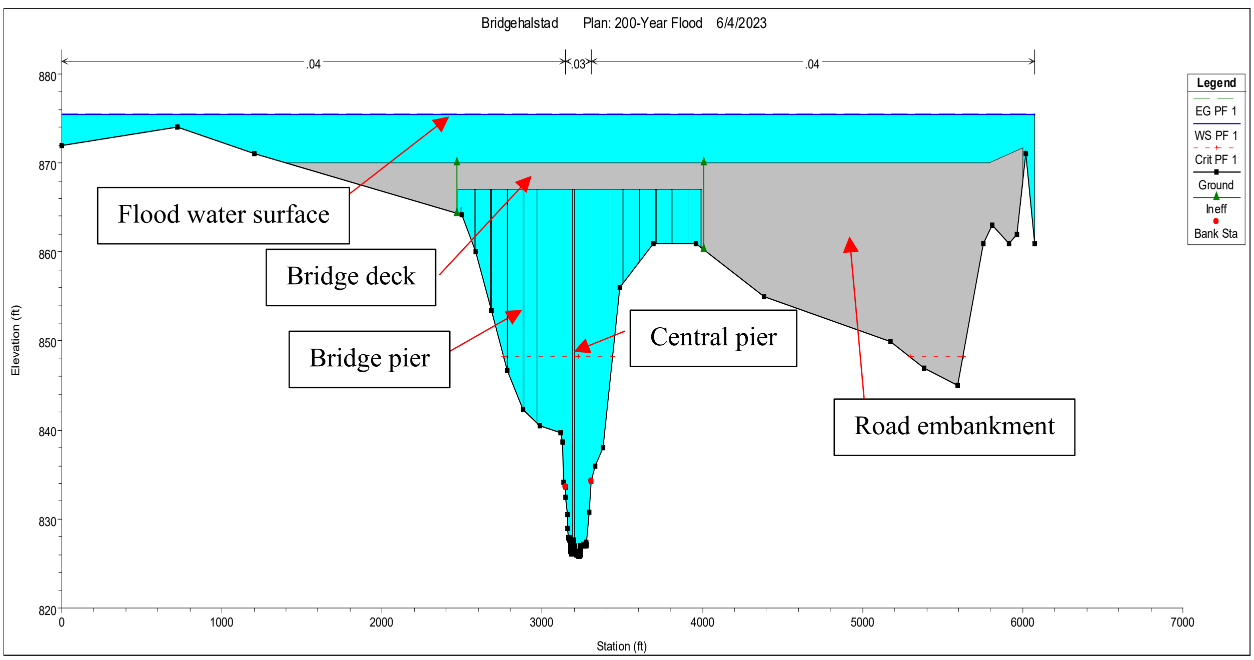

Figure 30. Highway 200 Bridge near Halstad under 200-year flood condition (98,778 cfs).

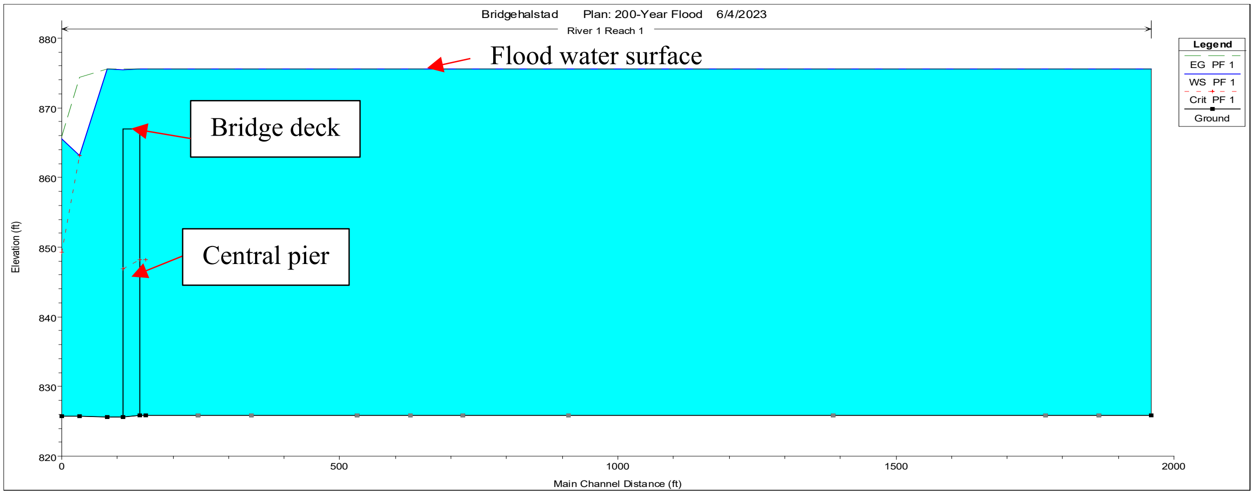

Figure 31. Streamwise flood profile plot of Highway 200 Bridge near Halstad under 200-year flood (98,778 cfs).

Table 15. Streamwise flood profile plot of Highway 200 Bridge near Halstad under 200-year flood.

Reach	River Sta	Profile	Q Total	Min Ch El	W.S. Elev	Crit W.S.	E.G. Elev	E.G. Slope	Vel Chnl	Flow Area	Top Width	Froude # Chl
			(cfs)	(ft)	(ft)	(ft)	(ft)	(ft/ft)	(ft/s)	(sq ft)	(ft)	
Reach 1	1742	PF 1	98778.00	825.84	875.60		875.62	0.000010	1.87	.09609.20	6494.40	0.05
Reach 1	1658.95*	PF 1	98778.00	825.84	875.60		875.62	0.000010	1.89	.09253.60	6472.17	0.05
Reach 1	1575.90*	PF 1	98778.00	825.84	875.60		875.62	0.000010	1.90	.08884.70	6449.94	0.05
Reach 1	1243.68*	PF 1	98778.00	825.84	875.59		875.61	0.000022	2.13	.07038.10	6361.01	0.06
Reach 1	828.42*	PF 1	98778.00	825.84	875.58		875.60	0.000011	2.09	.04099.90	6249.85	0.06
Reach 1	662.32*	PF 1	98778.00	825.84	875.58		875.60	0.000012	2.15	.02701.00	6205.39	0.06
Reach 1	579.26*	PF 1	98778.00	825.84	875.58		875.60	0.000012	2.18	.01960.20	6183.16	0.06
Reach 1	496.21*	PF 1	98778.00	825.84	875.57		875.60	0.000012	2.21	.01177.90	6160.93	0.06
Reach 1	330.11*	PF 1	98778.00	825.84	875.57		875.60	0.000013	2.28	99542.57	6116.46	0.06
Reach 1	247.05*	PF 1	98778.00	825.84	875.57		875.60	0.000013	2.31	98679.34	6094.23	0.06
Reach 1	164	PF 1	98778.00	825.84	875.57	848.25	875.59	0.000013	2.35	97772.70	6072.00	0.06
Reach 1	124		Bridge									
Reach 1	96	PF 1	98778.00	825.65	875.55		875.57	0.000012	2.08	95070.69	4596.00	0.06
Reach 1	69	PF 1	98778.00	825.78	863.15	863.15	874.44	0.003393	27.95	4321.00	259.69	0.83
Reach 1	1	PF 1	98778.00	825.78	865.57	849.32	865.90	0.000150	5.85	31486.84	3003.42	0.19

Table 16. Summary of bridge output data for Highway 200 Bridge near Halstad under 200-year flood.

		Element	Inside BR US	Inside BR DS
E.G. US. (ft)	875.59	E.G. Elev (ft)	875.59	875.58
W.S. US. (ft)	875.57	W.S. Elev (ft)	875.52	875.52
Q Total (cfs)	98778.00	Crit W.S. (ft)	848.23	846.94
Q Bridge (cfs)	59116.15	Max Chl Dpth (ft)	49.68	49.87
Q Weir (cfs)		Vel Total (ft/s)	1.77	1.84
Weir Sta Lft (ft)		Flow Area (sq ft)	55658.55	53634.25
Weir Sta Rgt (ft)		Froude # Chl	0.05	0.05
Weir Submerg		Specif Force (cu ft)	624218.80	671286.50
Weir Max Depth (ft)		Hydr Depth (ft)	9.17	11.67
Min El Weir Flow (ft)	870.01	W.P. Total (ft)	9404.44	8008.71
Min El Prs (ft)	867.00	Conv. Total (cfs)	7936006.0	8005756.0
Delta EG (ft)	0.02	Top Width (ft)	6072.00	4596.00
Delta WS (ft)	0.02	Frctn Loss (ft)	0.00	0.00
BR Open Area (sq ft)	25547.62	C & E Loss (ft)	0.00	0.01
BR Open Vel (ft/s)	2.31	Shear Total (lb/sq ft)	0.06	0.06
BR Sluice Coef		Power Total (lb/ft s)	0.10	0.12
BR Sel Method	Energy only			

8. Scour Modeling and Analysis

Potential streambed scour of the Red River at the bridges can be assessed based on hydraulic modeling. The scour model are based on the Colorado State University's Equations or CSU equation.. Grain size distribution of soil collected at the river bed are essential data needed for the computation. In HEC-RAS, the scour computation is done in routine called Perform hydraulic design computations.

8.1 Soil Data Collected and Grain Size Distribution

Table 17. Grain size distribution of soil sample taken at the Highway 17 Bridge near Grafton.

Sieve Size	Sieve Size (mm)	Material Retained Gram	%	Cumulative %	% Finer		
3/8 inch	9.5	0	0	0	100		
No. 4	4.75	326.15	36.74	36.74	63.26		
No. 8	2.36	289.63	32.62	69.36	30.64		
No. 16	1.18	148.77	16.76	86.12	13.88		
No. 30	0.6	58.63	6.60	92.72	7.28		
No. 50	0.3	23.48	2.64	95.37	4.63		
No. 100	0.15	11.54	1.30	96.67	3.33		
Pan	0	29.59	3.33	100	0		
Total		887.79	100			**D50**	**D95**
						3.78 mm	8.85 mm

Table 18. Grain size distribution of soil sample taken at the Highway 200 Bridge near Halstad.

Sieve Size	Sieve Size (mm)	Material Retained Gram	%	Cumulative %	% Finer		
3/8 inch	4.75	19.91	4.83	4.83	95.17		
No. 4	2.36	86.41	20.95	25.78	74.22		
No. 16	1.18	103.38	25.07	50.84	49.16		
No. 30	0.60	68.07	16.50	67.35	32.65		
No. 50	0.30	50.41	12.22	79.57	20.43		
No. 100	0.15	34.79	8.44	88.01	11.99		
Pan	0.00	49.46	11.99	100.00	0.00		
Total		412.23	100			**D50**	**D95**
						1.22 mm	4.73 mm

8.2 Hydraulic Design -Scour Analysis - Highway17 Bridge site near Grafton

Scour analysis was performed on Highway 17 Bridge under 100-year and 200-year flood flow conditions. Contraction scour, pier scour, and abutment scour are the three types of scours evaluated individually and the overall combination of the scour effects are determined.

8.3.1 Scour Analysis - Highway17 Bridge site near Grafton under 100-year flood

The output of the scour analysis is summarized in a plot shown in **Figure 32**. The total scour line is the extent considering all the contributions from scour components.

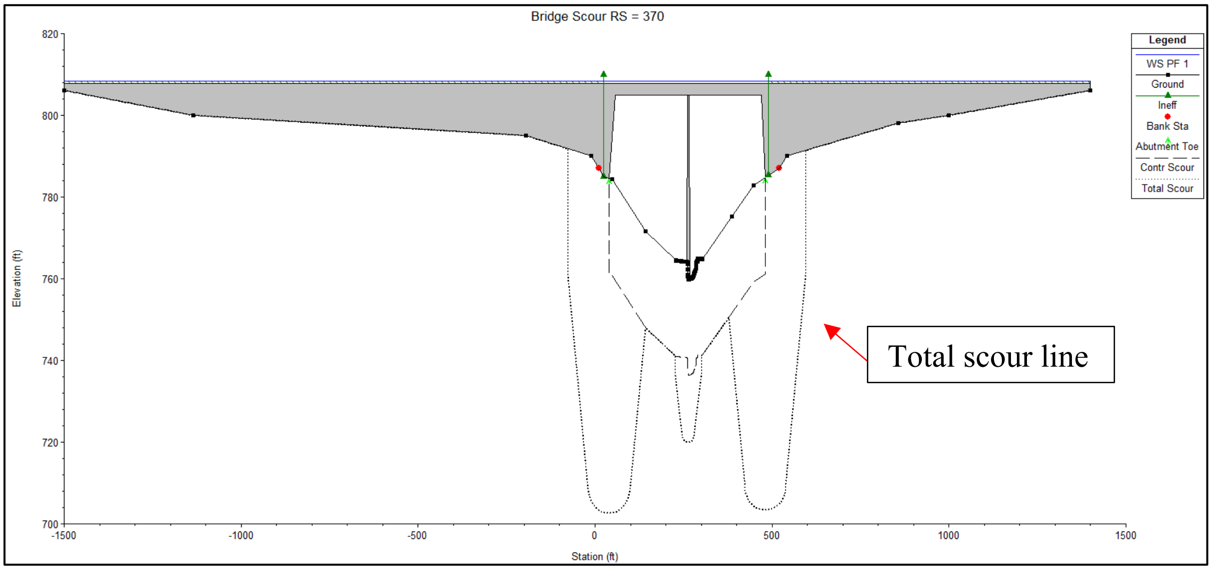

Figure 32. Predicted scour depth at Highway17 Bridge site near Grafton under 100-year flood.

Table 19. Scour Report for Highway 17Bridge site near Grafton under 100-year flood.

Contraction Scour				
		Left	Channel	Right
Input Data				
	Average Depth (ft):	14.10	39.04	11.76
	Approach Velocity (ft/s):	1.93	5.04	1.71
	Br Average Depth (ft):		29.90	
	BR Opening Flow (cfs):		117704.00	
	BR Top WD (ft):		465.00	
	Grain Size D50 (mm):	0.20	0.20	0.20
	Approach Flow (cfs):	34565.00	50750.50	32388.51
	Approach Top WD (ft):	1268.99	257.83	1607.57
	K1 Coefficient:	0.690	0.690	0.640
Results				
	Scour Depth Ys (ft):		23.54	
	Critical Velocity (ft/s):	4.03	1.79	1.47
	Equation:		Live	

Pier Scour

All piers have the same scour depth

Input Data

Pier Shape:	Round nose
Pier Width (ft):	8.00
Grain Size D50 (mm):	0.20000
Depth Upstream (ft):	45.19
Velocity Upstream (ft/s):	8.07
K1 Nose Shape:	1.00
Pier Angle:	
Pier Length (ft):	30.00
K2 Angle Coef:	1.00
K3 Bed Cond Coef:	1.10
Grain Size D90 (mm):	1.22000
K4 Armouring Coef:	1.00

Set K1 value to 1.0 because angle > 5 degrees

Results

Scour Depth Ys (ft):	16.55
Froude #:	0.21
Equation:	CSU equation

Abutment Scour

Input Data

	Left	Right
Station at Toe (ft):	39.38	480.59
Toe Sta at appr (ft):	163.97	353.02
Abutment Length (ft):	1298.37	1646.98
Depth at Toe (ft):	24.24	24.10
K1 Shape Coef:	0.55 - Spill-through abutment	
Degree of Skew (degrees):	90.00	90.00
K2 Skew Coef:	1.00	1.00
Projected Length L' (ft):	1298.37	1646.98
Avg Depth Obstructed Ya (ft):	14.55	12.27
Flow Obstructed Qe (cfs):	39079.46	38221.84
Area Obstructed Ae (sq ft):	18889.52	20207.30

Results

	Left	Right
Scour Depth Ys (ft):	58.40	57.79

8.3.2 Scour Analysis - Highway17 Bridge site near Grafton under 200-year flood

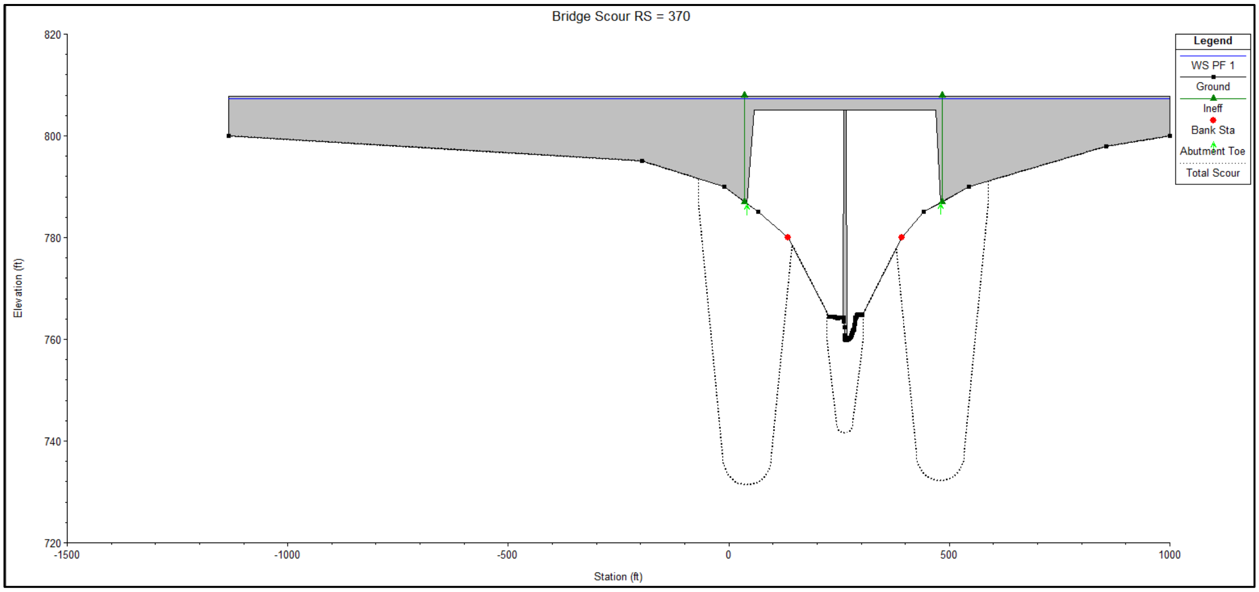

Figure 33, Predicted scour depth at Highway17 Bridge site near Grafton under 200-year flood.

Table 20. Scour Report for Highway 17 Bridge site near Grafton under 200-year flood.

Pier Scour		
	All piers have the same scour depth	
Input Data		
	Pier Shape:	Round nose
	Pier Width (ft):	8.00
	Grain Size D50 (mm):	0.20000
	Depth Upstream (ft):	45.17
	Velocity Upstream (ft/s):	10.36
	K1 Nose Shape:	1.00
	Pier Angle:	
	Pier Length (ft):	30.00
	K2 Angle Coef:	1.00
	K3 Bed Cond Coef:	1.10
	Grain Size D90 (mm):	4.73000
	K4 Armouring Coef:	1.00
	Set K1 value to 1.0 because angle > 5 degrees	
Results		
	Scour Depth Ys (ft):	18.42
	Froude #:	0.27
	Equation:	CSU equation

Abutment Scour

		Left	Right
Input Data			
	Station at Toe (ft):	41.17	479.38
	Toe Sta at appr (ft):	41.17	479.38
	Abutment Length (ft):	1175.57	1520.62
	Depth at Toe (ft):	21.12	20.94
	K1 Shape Coef:	0.55 - Spill-through abutment	
	Degree of Skew (degrees):	90.00	90.00
	K2 Skew Coef:	1.00	1.00
	Projected Length L' (ft):	1175.57	1520.62
	Avg Depth Obstructed Ya (ft):	13.02	10.80
	Flow Obstructed Qe (cfs):	35299.27	33464.54
	Area Obstructed Ae (sq ft):	15302.68	16426.68
Results			
	Scour Depth Ys (ft):	55.30	54.65
	Froude #:	0.28	0.27
	Equation:	HIRE	HIRE

8.3.2 Scour Report for Highway200 Bridge site near Halstad under 100-year flood

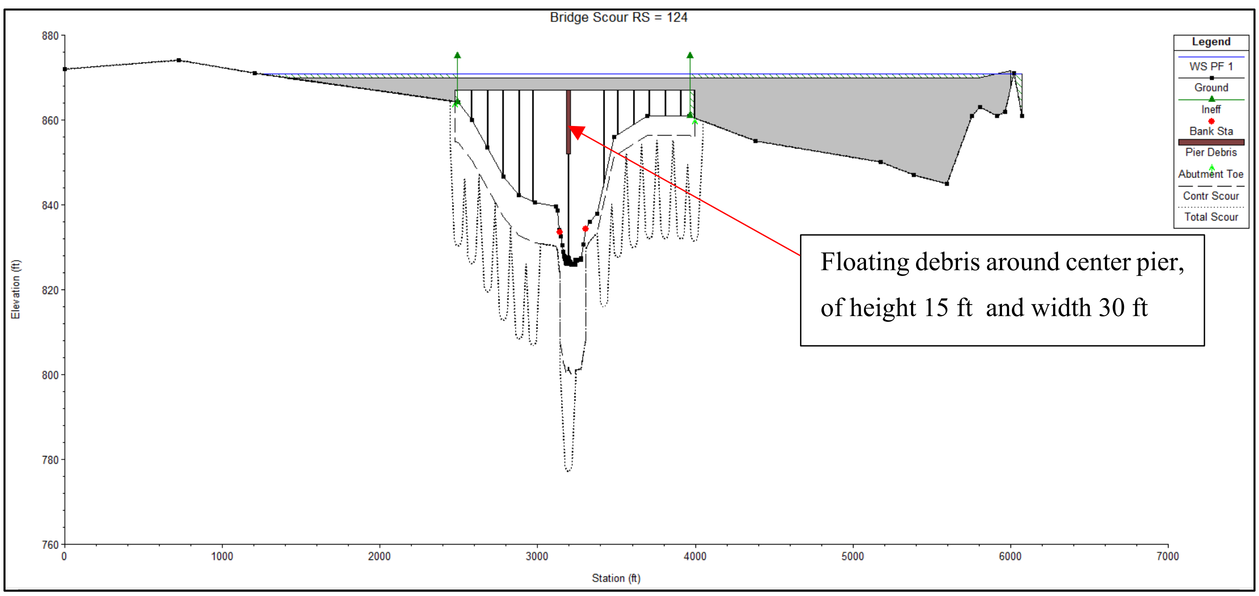

Figure 34. Predicted scour depth at Highway 200 Bridge site near Halstad under 100-year flood.

Table 21. Scour Report for Highway 200 Bridge site near Halstad under 100-year flood.

Contraction Scour

		Left	Channel	Right
Input Data				
	Average Depth (ft):	10.17	42.73	16.43
	Approach Velocity (ft/s):	0.75	2.57	1.03
	Br Average Depth (ft):	19.03	35.95	12.04
	BR Opening Flow (cfs):	34549.83	28179.88	18517.28
	BR Top WD (ft):	653.00	164.68	657.32
	Grain Size D50 (mm):	0.2	0.2	0.2
	Approach Flow (cfs):	14403.58	19040.45	47802.97
	Approach Top WD (ft):	1892.90	173.28	2830.06
	K1 Coefficient:	0.590	0.640	0.590
Results				
	Scour Depth Ys (ft):	9.48	25.82	4.56
	Critical Velocity (ft/s):	1.43	1.82	1.55
	Equation:	Clear	Live	Clear

Pier Scour

	All piers have the same scour depth	
Input Data		
	Pier Shape:	Round nose
	Pier Width (ft):	5.00
	Grain Size D50 (mm):	1.22000
	Depth Upstream (ft):	44.90
	Velocity Upstream (ft/s):	4.55
	K1 Nose Shape:	1.00
	Pier Angle:	35.00
	Pier Length (ft):	30.00
	K2 Angle Coef:	2.57
	K3 Bed Cond Coef:	1.10
	Grain Size D90 (mm):	4.73000
	K4 Armouring Coef:	1.00
	Set K1 value to 1.0 because angle > 5 degrees	
Results		
	Scour Depth Ys (ft):	24.45
	Froude #:	0.12
	Equation:	CSU equation

Abutment Scour

		Left	Right
Input Data			
	Station at Toe (ft):	2476.00	3999.00
	Toe Sta at appr (ft):	2423.89	3955.49
	Abutment Length (ft):	1225.90	2138.74
	Depth at Toe (ft):	6.59	10.46
	K1 Shape Coef:	0.55 - Spill-through abutment	
	Degree of Skew (degrees):	125.00	55.00
	K2 Skew Coef:	1.04	0.94
	Projected Length L' (ft):	1004.20	1751.95
	Avg Depth Obstructed Ya (ft):	3.72	16.50
	Flow Obstructed Qe (cfs):	1426.57	36520.81
	Area Obstructed Ae (sq ft):	4563.84	35280.79
Results			
	Scour Depth Ys (ft):	0.00	0.00

	Froude #:	0.00	0.00
	Equation:	HIRE	HIRE
Combined Scour Depths			
	Pier Scour + Contraction Scour (ft):		
		Left Bank:	33.93
		Channel:	50.28
		Right Bank:	29.01
	Left abutment scour + contraction scour (ft):	9.48	
	Right abutment scour + contraction scour (ft):	4.56	

8.3.4 Scour Report for Highway200 Bridge site near Halstad under 200-year flood

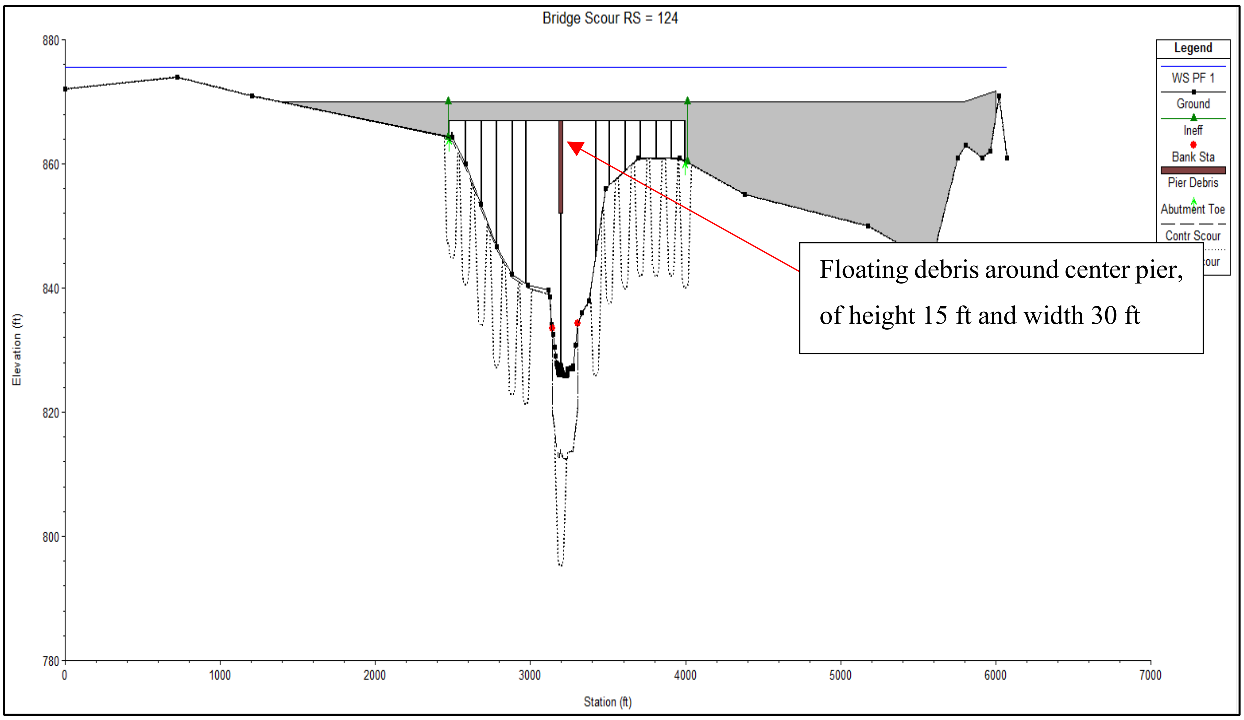

Figure 35. Predicted scour depth at Highway 200 Bridge site near Halstad under 200-year flood.

Table 22. Scour Report for Highway 200 Bridge site near Halstad under 200-year flood.

Contraction Scour

		Left	Channel	Right
Input Data				
	Average Depth (ft):	10.08	47.27	20.96
	Approach Velocity (ft/s):	0.63	2.31	1.02
	Br Average Depth (ft):	8.21	40.61	8.27
	BR Opening Flow (cfs):	42131.64	21314.09	35332.26
	BR Top WD (ft):	3143.00	164.68	2764.32
	Grain Size D50 (mm):	0.2	0.2	0.2
	Approach Flow (cfs):	19503.92	18957.40	60316.68
	Approach Top WD (ft):	3090.89	173.28	2830.06
	K1 Coefficient:	0.590	0.640	0.590
Results				
	Scour Depth Ys (ft):	0.57	13.38	0.16
	Critical Velocity (ft/s):	1.43	1.85	1.62
	Equation:	Clear	Live	Clear

Pier Scour

All piers have the same scour depth

Input Data		
	Pier Shape:	Round nose
	Pier Width (ft):	5.00
	Grain Size D50 (mm):	1.22000
	Depth Upstream (ft):	49.56
	Velocity Upstream (ft/s):	2.43
	K1 Nose Shape:	1.00
	Pier Angle:	35.00
	Pier Length (ft):	30.00
	K2 Angle Coef:	2.57
	K3 Bed Cond Coef:	1.10
	Grain Size D90 (mm):	4.73000
	K4 Armouring Coef:	1.00
	Set K1 value to 1.0 because angle > 5 degrees	
Results		
	Scour Depth Ys (ft):	18.93
	Froude #:	0.06
	Equation:	CSU equation

Abutment Scour

		Left	Right
Input Data			
	Station at Toe (ft):	2476.00	3999.00
	Toe Sta at appr (ft):	2423.89	3955.49
	Abutment Length (ft):	2423.89	2138.74
	Depth at Toe (ft):	11.26	15.12
	K1 Shape Coef:	0.55 - Spill-through abutment	
	Degree of Skew (degrees):	125.00	55.00
	K2 Skew Coef:	1.04	0.94
	Projected Length L' (ft):	1985.54	1751.95
	Avg Depth Obstructed Ya (ft):	5.55	21.03
	Flow Obstructed Qe (cfs):	4601.84	45922.39
	Area Obstructed Ae (sq ft):	13451.98	44973.13
Results			
	Scour Depth Ys (ft):	16.79	20.34

9. Summary and Discussions

(a). Field measurement of bathymetry

A streambank failure is shown on the left bank at the site of Highway 200 Bridge near Halstad. A potential scour may potentially be developing near the central pier of the Highway 17 Bridge near Grafton. HYCAT has proven its capability to measure bathymetry, velocity and flow,

(b). Flood levels under 100-year and 200 -year floods

The flooding conditions at the two bridge sites as modeled by HEC-RAS are shown in **Table 23**.

Table 23. Summary of major flood modeling results.

Flood Quantile	Highway 17 Bridge near Grafton		Highway 200 Bridge near Halstad	
	Flood Elevation vs Deck Elevation (ft)	**Discharge (cfs)**	**Flood Elevation vs Deck Elevation (ft)**	**Discharge (cfs)**
100-year	806.82 / 807.81	111,704	870.95 / 870.00	81,247
200-year	808.17 / 807.81	126,929	875.55 / 870.00	98,778

Flooding of the Highway 200 Bridge near Halstad is likely to be more prevailing given the deck datum being set low as the bridge was designed for 50-year flood.

(c). Flood frequency updating

Updating the flood frequency analysis for existing bridges and compare the impacts on the previous flood design is getting critical as more data on flood are available. The flood quantile for the Halstad site jumped by almost 45% for the 100-year flood discharge estimate. An effort to do periodic assessments on all bridges in the flood risk aspect is highly recommended.

(d). Good Practice to keep old records especially old bathymetry

If any bathymetry data is available at the time the bridge was constructed, we can compare elevation data to see if there is any scour around the bridge. However, the only information we could obtain was the engineering drawings with a few cross-sectional plots.

(e) **HYCAT operational issues**

(i) To have good access to the river

It is essential to identify a gradual footpath that allows personnel to launch the HYCAT, which weighs 115.5 lbs, on the river. HYCAT can be carried by at least two persons. On a slope that is rough with loose rocks and generally steep, it is best to provide a temporary walkway for safety reasons and also to avoid scratching the sensitive M9 sensor surfaces. This was the situation the project team encountered at the Highway 17 Bridge site near Grafton. A temporary walkway was constructed using abandoned pallets found nearby. **Figure 36** shows the setup. The full specifications of HYCAT is: Length: 5.9 ft (1.8 m). Beam: 2.83 ft (.86 m). Draft (when the antenna is down): .5 ft (.15 m). Weight: 53 kg (115.5 lbs).

Figure 36. Temporary walkway built for launching HYCAT on a rocky steep slope.

(ii) Need to have a standby emergency powered boat nearby

The higher endurance range of HYCAT is stated in the product specification as 2.7 hrs @ 4 knots or about 6.75 ft/s. It can go against a higher current speed but positioning the watercraft at a desired location can be risky and may pose a danger that it is being swept away by the strong current, and out of the line of sight and lost communication contacts. To operate HYCAT in extreme flood conditions, it is prudent that a power boat with an operator is prearranged to be on standby. During this project, this arrangement was not necessary in flood flow measurements because the bridges allow the team members to walk across the bridge pulling a HydroBoard with an M9 mounted on it. A strong long rope was used to tie the HyroBoard and dragged slowly by an operator going across the river. Another personnel carried a notebook computer, which has a radio communication system built in, to collect the M9 data instantaneously. The cross section map with velocity cells are processed to provide the total discharge through the cross-section.

(iii) New HYCAT update

The PI Howe Lim was successful in getting an EPSCoR grant to enhance the current HYCAT in 2023. The enhancements are: 1. adding a water quality Sonde unit, 2. adding a side-scan sonar (Hull mounted side-scan sonar), and 3. upgrade the basic Garmin GS system to RTK GPS. The enhancement will certainly increase the capability of HYCAT, especially on the installation of the side-scan sonar which will allow much higher resolution output of bathymetry data from field measurement trips. With this new system upgrade, the opportunity to obtain the bed profile in much higher resolution using the side-scan sonar is created. Hopefully, more beneficial studies can be carried out by UND's team of students and faculty.

8. Conclusions

The project has created a good opportunity for the development of a unique method for inspecting the integrity status of bridge structure at sites where the hydraulic impacts of extreme river flow on bridge structure may lead to contraction scour, pier scour, and local scour. In this project, HYCAT installed with an ADCP-M9 has proven to be a very versatile tool in performing the general collection of bathymetric data, water depth, velocity, and discharge information.

For the Highway 17 Bridge site near Grafton, there is a potential area near the central pier that may be developing scour. The bathymetry for the site of Highway 200 near Halstad indicated that no prominent local scour features are detected at the vicinity of the central pier except weakened slopes along the left abutment area.

Flooding will be more prevailing at the Highway 200 Bridge near Halstad as the bridge deck is overtopped under the simulated flood condition of a 100-year flood. The deck of Highway 17 Bridge near Grafton is just partially submerged under the 100-year and 200-year floods.

Flood frequency analysis should be regularly performed and updated for all bridge sites as the flood discharge estimated may be drastically increased given the new flood data are gradually added to the flood records.

Historical bathymetry would be kept so that any comparison of bathymetry data is available at the time the bridge was constructed, we can compare elevation data to see if there is any scour formation around the bridge has occurred. Historical engineering drawings are valuable assets when performing bridge inspections and evaluations.

More studies of this nature can be performed at a much higher resolution given that the PI has obtained an EPSCoR grant in 2023 to upgrade the HYCAT system into a complete system equipped with side-scan sonar and other sensors.

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8. Appendices

Appendix A

A Brief Description on Operation of HYCAT in Bridge Monitoring

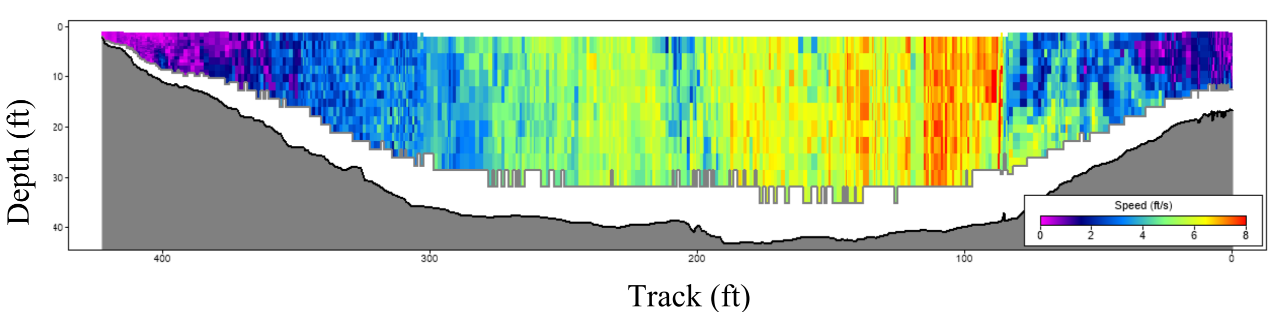
This project involved using a HYCAT, is an autonomous surface vehicle (ASV), which is equipped with a SonTek M-9 ADCP system. The HYCAT-M9 system was purchased under an NSF MRI grant (NSF Grant #1828710) awarded to a team led by the PI (Dr. Lim).

The current capability of UND's HYCAT are dependent on the equipped Acoustic Doppler Current Profilers which can collect velocity and depth data. It has GPS on board providing GPS positioning navigation. Communicate with HYCAT can be done via radio with a control unit to be placed on the riverbank. A user can use a joystick to manually control or it moves according to a pre-programmed path autonomously. The bathymetry of the streambed can be obtained. In addition, it can perform flow velocity-discharge measurements

Figures shown below the deployment of UND's HYCAT for discharge measurement. HYCAT can navigate on any open water with a GPS positioning system and is controlled by a remote-control system via radio communication.

(a) (b)

UND's HYCAT with SonTek M9 ADCP was deployed by a team of UND students on the Red River to measure discharge and bathymetric data. (a) the HYCAT navigated near Highway 17 Bridge near Grafton, (b) students checked the status of the HYCAT via a remote-control system.



Velocity field output from ADCP plotted for one of the flood peak discharge measurements taken on April 27, 2022, at Red River near Grafton, ND. The river's top width was 126 m (415 ft), a maximum depth of 13.1 m (43 ft), a maximum velocity of 2.44 m/s (8 ft/s), and a measured discharge of 1334.8 m^3/s (47,144 cfs).

Appendix B

Regional Flood Frequency Analysis

Regional Flood Estimation - An alternative Approach

Flood peak discharge for 100- and 200-year flows

There are alternative ways to estimate flood quantiles apart from the standard use of Bulletin 17 (B or C). One alternative way is through regional flood studies which derive regional frequency equations based on known basin parameters such area and slope.

There is a study complete by USGS for North Dakota: USGS Scientific Investigations Report 2015-5096 “Regional Regression Equations to Estimate Peak-Flow Frequency at Sites in North Dakota using Data through 2009.” The regional flood frequency equations for three identified regions are also made available at the USGS StreamStats website.

The followings are the results of computation specific for the two study sites:

Highway 200 Bridge Site Near Halstad

Peak_Region_A_2015_5096 Region

Drainage Area = 21800 (mi^2)

Stream Slope 10 and 85 Longest Flow Path = 2 (ft/mi)

[SEe, Standard Error of Estimate; SEp, Standard Error of Prediction; SE, Standard Error (other -- see report)]

Peak_Region_A_2015_5096 Region	Value
Description	**(ft^3/s)**
Maximum instantaneous flow that occurs with a 50% annual exceedance probability (PK50AEP)	3920
Maximum instantaneous flow that occurs with a 20% annual exceedance probability (PK20AEP)	11800
Maximum instantaneous flow that occurs with a 10% annual exceedance probability (PK10AEP)	20300
Maximum instantaneous flow that occurs with a 4% annual exceedance probability (PK4AEP)	34900
Maximum instantaneous flow that occurs with a 2% annual exceedance probability (PK2AEP)	49000
Maximum instantaneous flow that occurs with a 1% annual exceedance probability (PK1AEP)	66300
Maximum instantaneous flow that occurs with a 0.2% annual exceedance probability (PK0_2AEP)	116000

Highway 17 Bridge Site Near Grafton

Peak_Region_A_2015_5096 Region

Drainage Area = 34800 (mi^2)

Stream Slope 10 and 85 Longest Flow Path = 2 (ft/mi)

[SEe, Standard Error of Estimate; SEp, Standard Error of Prediction; SE, Standard Error (other -- see report)]

Peak_Region_A_2015_5096 Region	Value
Description	**(ft^3/s)**
Maximum instantaneous flow that occurs with a 50% annual exceedance probability (PK50AEP)	5150
Maximum instantaneous flow that occurs with a 20% annual exceedance probability (PK20AEP)	15700
Maximum instantaneous flow that occurs with a 10% annual exceedance probability (PK10AEP)	27200
Maximum instantaneous flow that occurs with a 4% annual exceedance probability (PK4AEP)	47300
Maximum instantaneous flow that occurs with a 2% annual exceedance probability (PK2AEP)	66900
Maximum instantaneous flow that occurs with a 1% annual exceedance probability (PK1AEP)	91200
Maximum instantaneous flow that occurs with a 0.2% annual exceedance probability (PK0_2AEP)	162000