HoustonEngineering Inc.

Maple Grove, MN | HEI No. 6286_004
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WARROAD RIVER IN-CHANNEL SEDIMENTATION ANALYSIS

A Targeted Plan to Reduce Sediment Delivery to the Warroad Harbor

Warroad River Watershed District (WRWD)

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1 EXECUTIVE SUMMARY

The Warroad River Watershed District used funds from a 2016 Clean Water Fund Accelerated Grant Program to contract Houston Engineering, Inc. (HEI) to target solutions to manage sediment delivered to Lake of the Woods (LOW). This study focused on determining the amount of sediment delivered to the LOW that was from in-channel sources versus overland sources. The overarching goal and purpose of this project was to identify a feasible set of implementable projects that help solve sediment issues in LOW.

Final products from this project include the proportion of sediment loading from the Warroad River that originates from river bank erosion as opposed to overland sources. These results were then used to develop a targeted implementation plan resulting in measurable sediment reductions to LOW. Project deliverables include:

- identification of the magnitude and location of in-channel and overland sediment sources to LOW;
- a targeted implementation plan provided as part of this report, a technical memorandum on in channel sediment sources assessment (Appendix A); and
- all Prioritize Target and Measure Application (PTMApp) Desktop inputs and outputs.

2 INTRODUCTION

2.1 PROJECT BACKGROUND

The Warroad River, located in Northern Minnesota, is the second largest US tributary to LOW, an important international resource and the largest lake in the state. Over the past three decades, the Warroad River has experienced severe sedimentation problems near its confluence with LOW. While water depths 50 years ago could support recreation activities, such as waterskiing in the Warroad Harbor (Johnston, 2012), current depths have reduced so that many areas outside of the main channel are in the range of 1-4 feet deep. The constricted main channel generally ranges in depth from 5-8 feet deep. As a result of this sedimentation, the US Army Corps of Engineers (USACE) has completed multiple dredging projects in the Warroad Harbor and its entrance to the LOW, removing sediment from priority locations in the area. The issue of erosion and sedimentation in the LOW basin is not unique to the Warroad River. Other systems in the area, including Zippel and Bostic Bays, are experiencing similar erosion and sedimentation concerns.

Discussion with various local entities have suggested that much of the sedimentation in the Warroad River occurs following periods of high flow, during which erosion rates are high (Battles, 2012). Water quality data collected by the Minnesota Pollution Control Agency (MPCA) show that while (under non-extreme hydrologic conditions) the Warroad River would be impaired for total phosphorus if proposed nutrient criteria were in place, the River is compliant with the State's turbidity standard. Despite these conflicting data, a large quantity of sediment is known to be depositing in the system. There is a need to understand the sources of this sediment and quantify the amounts that may be coming from the landscape versus other sources (e.g., in-lake wave action or in-stream erosion) to inform future management strategies for protecting this important regional resource.

This in-channel and overland sediment sources assessment and the targeted implementation plan expanded on previous work completed by HEI (HEI, 2013). This work identified the total amount of sediment deposited to the Warroad River in addition to the proportion of sediment delivered from overland sources. A separate methodology was needed to determine the proportion of sediment from overland sources. Results from this project serve to complete the final piece of the Warroad River sediment source assessment and identify the proportion of sediment delivered to the Warroad Harbor from in-channel sources. In addition, the proportion of overland sediment determined as part of this work was supported by the results of previous overland sediment assessment.

2.2 STUDY AREA

The Warroad River Watershed (WRW) encompasses approximately 265-square miles in the northern Minnesota counties of Roseau and Lake of the Woods, along the Canadian boundary. The WRW is defined by the US Geological Survey HUC (Hydrologic Unit Code) #09090009. **Figure 1** shows the WRW study area. Three stream Assessment Unit ID's (AUID) are contained within the study area, including the Warroad River (09020009-502), the Warroad River West Branch (09020009-503), and the Warroad River East Branch (09020009-504). None of these AUIDs are currently listed as impaired, although the West Branch of the Warroad River is currently on the draft list as being impaired for mercury. The professional judgement team has also recommended the West Branch be impaired for aquatic recreation due to bacteria. Six HUC 10 watershed are present within the study area, the northern most which are dominated by cultivated crops and hay/pasture land use and the southernmost dominated by woody and herbaceous wetlands with scattered evergreen forest.

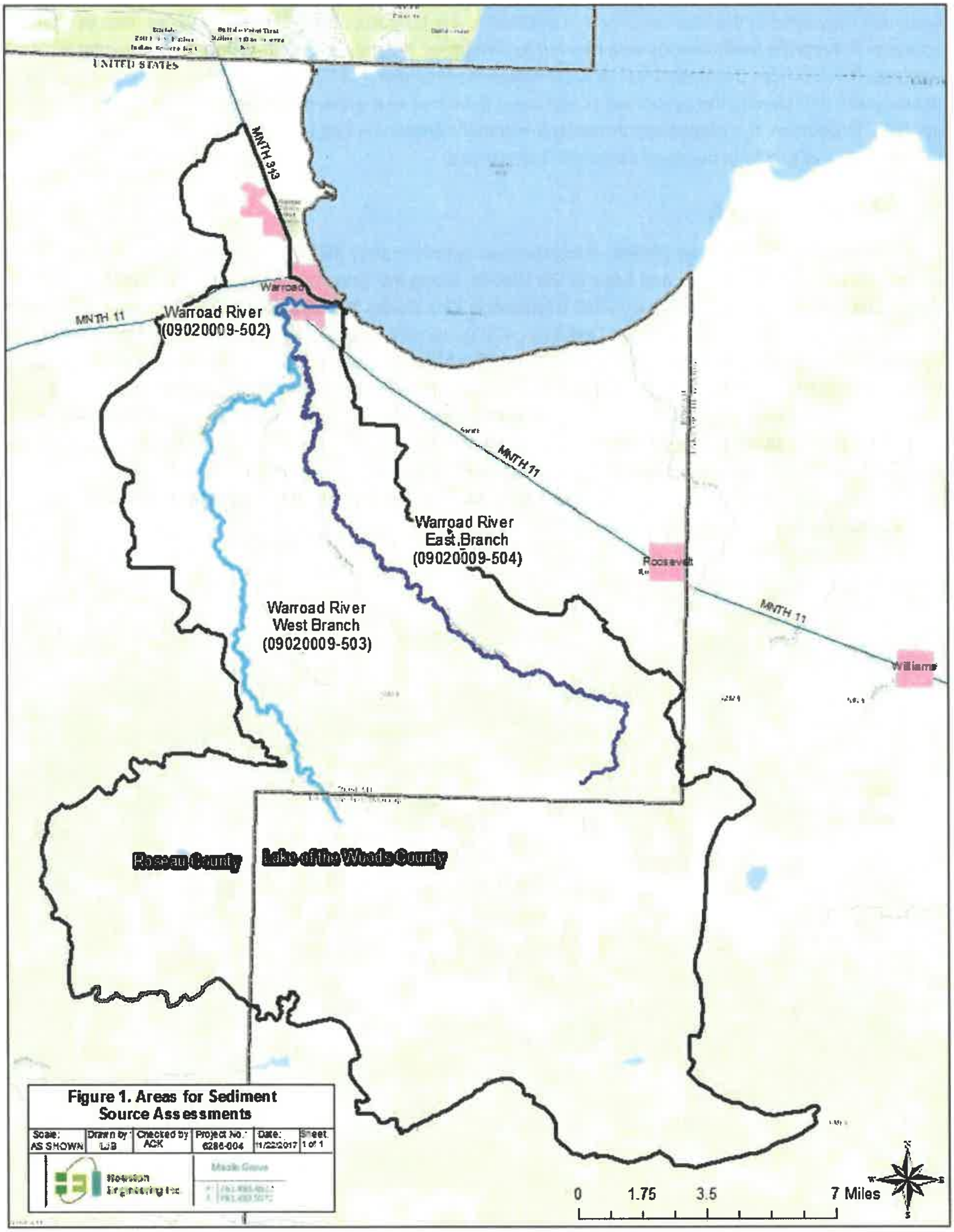

Figure 1. Areas for Sediment Source Assessments

3 METHODS

3.1 SEDIMENT MASS BALANCE

A complete sediment mass balance was determined for the WRW as outlined in the following equation:

$$Sediment\ Deposition\ \left(\frac{tons}{year}\right) = Overlandland\ Yield + In\text{-}Channel\ Processes$$

Results from previous work completed by HEI were leveraged to develop this equation. The work identified sediment deposition volumes to the Warroad Harbor in addition to the proportion from overland sources using the Revised Universal Soil Loss Equation (RUSLE) and Sediment Delivery Ratio (SDR).

3.1.1 SEDIMENT DEPOSITION IN WARROAD HARBOR

Work was previously completed to estimate the average annual amount of sediment depositing in the Warroad Harbor, using bathymetric surveys (HEI, 2013). The St. Paul District of the USACE conducts hydrographic surveys on select channeled rivers and lake harbors in Minnesota. These surveys provide bathymetric maps that document changes in channel conditions to use in dredging and engineering studies.

Five sets of bathymetry data for the Warroad Harbor were obtained from the USACE. The data collection dates for the bathymetric surveys are:

- July 30, 2002
- September 4, 2003
- April 20, 2005
- June 11-12, 2007
- April 22, 2012

The sonar bathymetry datasets have an average point density of approximately one point per 25-square feet. The raw bathymetry data were conditioned by the USACE. HEI converted the bathymetry data to elevation data (MSL 1912 Adjustment) and divided it into two study areas, referred to as the "harbor" and the "entry." The harbor study area was defined as the waterway between the railroad bridge to the west and the constricting channel leading to LOW, while the entry study area was defined as any additional data outside of the constricting channel. These areas are displayed in **Figure 2**. The dividing line between the areas is based on the perceived widening of the outfall to LOW.

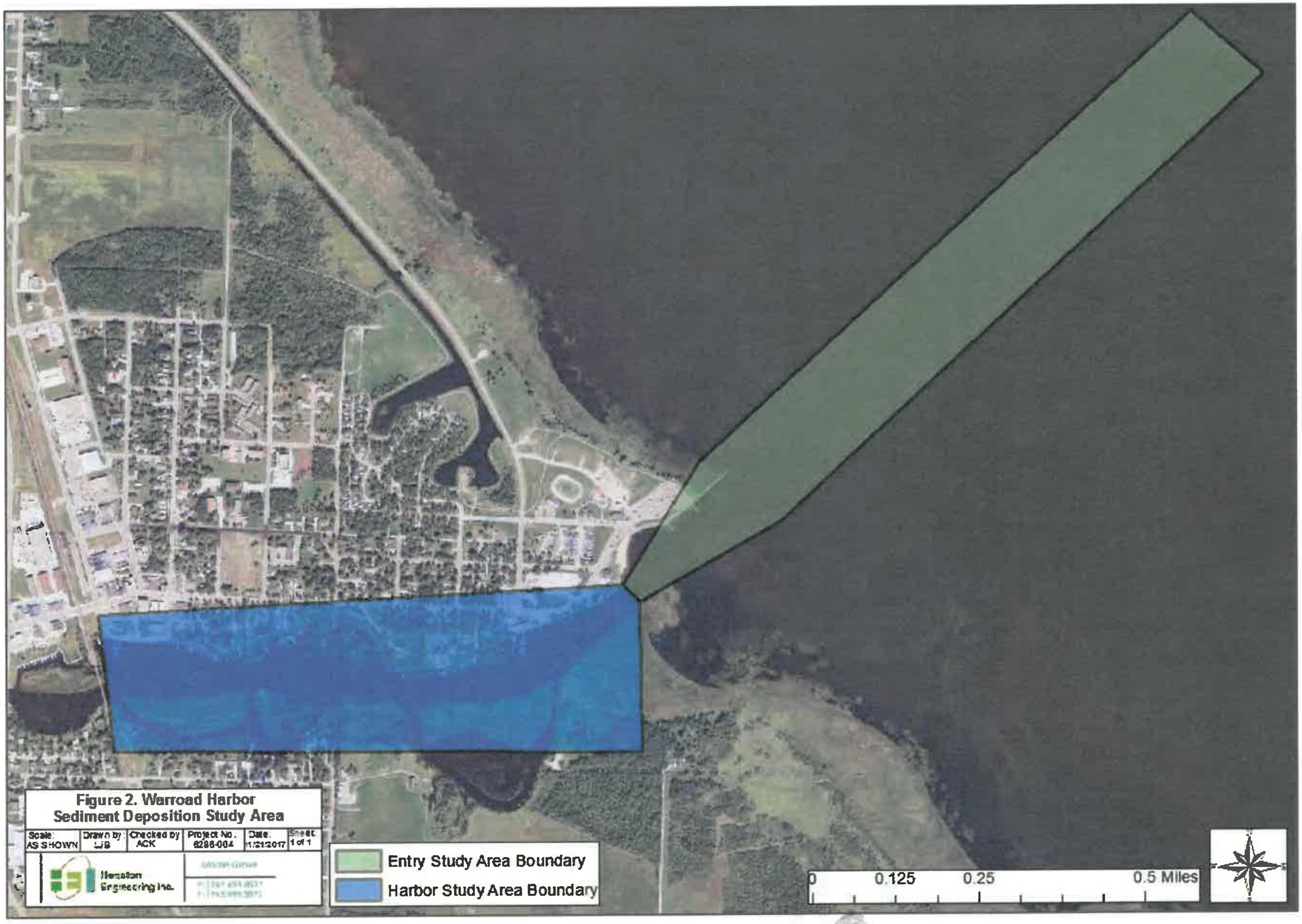

Figure 2. Warroad Harbor Sediment Deposition Study Area

GIS methods were used to transform each USACE-provided dataset into a triangulated irregular network (TIN), representing the bottom surface (i.e., bathymetry) of the harbor and the entry. The resultant surfaces for each provided dataset are shown in **Figure 3**. These TINs were then used to create raster elevation datasets for each of the bathymetric surveys. The raster elevations were interpolated using a natural neighbor method and created at a raster cell size of 25-square feet, consistent with the average point density described above. Finally, the elevation rasters were compared to determine erosion and deposition volumes between the data collection periods. The extents of the comparisons are based on the extents of the limiting survey used in the comparison (i.e., erosion and deposition volumes are only calculated for areas in which the two compared elevation rasters overlap). The available datasets allowed for erosion and deposition to be examined for five time periods:

- July 30, 2002 to September 4, 2003
- September 4, 2003 to April 20, 2005
- April 20, 2005 to June 12, 2007
- June 12, 2007 to April 22, 2012
- July30, 2002 to April 22, 2012 (average over the entire period)

Average deposition rates (in inches per year) for each of the five time periods were determined through raster comparison using the total erosion/deposition volumes divided by total areas and scaled annually . The average annual deposition rate for the entire period (2002-2012) was also converted into an average annual loading rate using an estimated soil density for similar soils in the area.

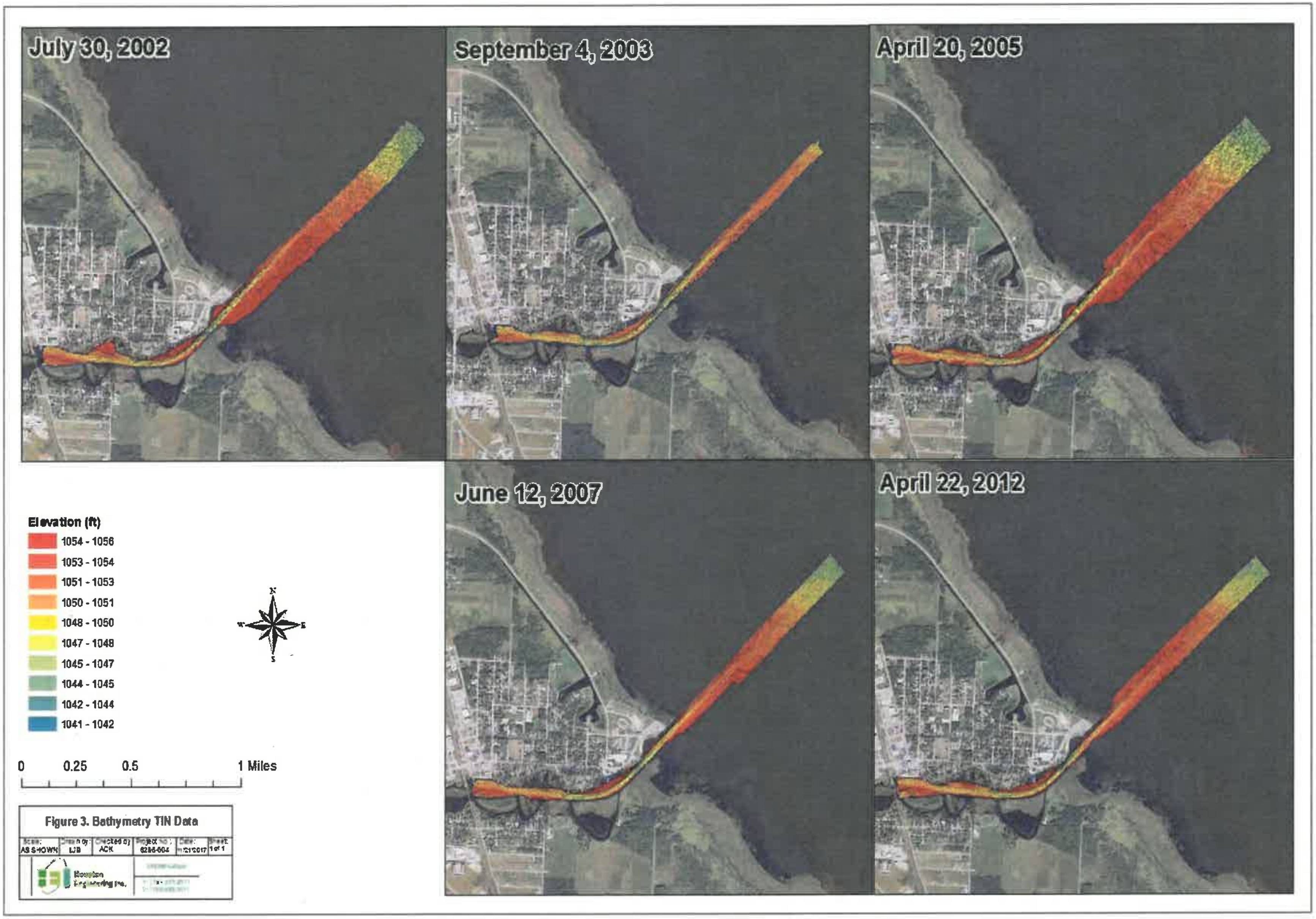

Figure 3. Bathymetry TIN Data

3.1.2 OVERLAND EROSION

3.1.2.1 PRIORITIZE, TARGET AND MEASURE APPLICATION

Development of the Targeted Conservation and Best Management Practices Implementation Plan relied on the Prioritize, Target, and Measure Application (PTMApp) (Desktop) (http://ptmapp.rrbdin.org/). Among other capabilities, PTMApp can be used in rural settings to identify field-scale source locations and amounts of sediment, nitrogen, and phosphorus, which leave the landscape and enter a downstream lake or river. These outputs rely on data from the Soil Survey Geographic Database (SSURGO), the RUSLE, and curve number values in addition to a suite of elevation products including a hydrologically enforced digital elevation model and travel time grids. From this application the amount of sediment, in tons/year, delivered to the Warroad Harbor from overland sources was identified.

Outputs from PTMApp were then scaled using the Hydrological Simulation Program – Frotran (HSPF) model. The HSPF model uses continuous rainfall and other meteorological records to compute streamflow hydrographs that simulate a variety of factors that may contribute to overland erosion including, among others, interception of soil moisture, surface runoff, interflow, baseflow, evapotranspiration, and ground-water recharge.

3.1.2.2 REVISED UNIVERAL SOIL LOSS EQUATION

Within previous work completed by HEI, RUSLE was applied across the WRW to determine average annual potential sediment yield as a result of rill/interrill erosion. Results, which were computed using a hydrologically enforced digital elevation model, are a 3X3 meter raster dataset of predicted average annual sediment yields from the landscape (HEI, 2013).

Because not all sediment that is yielded from the landscape will be transported into flowlines (some will redeposit on the landscape as it moves via overland flow), an SDR was used to reduce the potential sediment yield computed with RUSLE. The RUSLE results were adjusted based upon the SDR to estimate an effective sediment yield from each raster cell, the amount that actually makes it to nearest flowline.

3.1.2.3 SEDIMENT DELIVERY RATIO

An SDR was computed and applied to each raster cell of the study area based on its downstream flow length to the nearest flowline (defined as where the flow transitions from concentrated overland flow to in-channel flow). The SDR, when multiplied by the average annual sediment yield (predicted using RUSLE), estimates the fraction of the load reaching the nearest downstream flowline. The SDR can have a significant impact on estimates of the amount of sediment reaching these concentrated flow paths. There are numerous ways to estimate SDR. For this project, the Minnesota Phosphorus Index (MN P-Index) was used, which computes SDRs as a function of the flow length between the source of sediment yield and the location where it enters a downstream concentrated flow path (i.e., flowline) (Ouyang and Bartholic, 1997). Higher SDR values correspond to areas adjacent to channels and while lower SDR values are found at locations that are distant from the flowline. The relationship is expressed by the following equation:

$$SDR = (Downstream\ Flow\ Length)^{-0.2069}$$

3.1.3 BANK EROSION

The magnitude of sediment delivered to the Warroad Harbor from bank erosion was estimated through a historical photo analysis with the Channel Migration Toolbox (State of Washington, 2014). This resulted in identification of low-, moderate-, and high-erosive banks, in addition to an estimated annual volume of sediment (tons) delivered to the Lake of the Woods from the Warroad River (09020009-502), the Warroad River East Branch (09030009-504), and the Warroad River West Branch (09030009-503). Historical photo analysis results where then spot checked and confirmed for accuracy in the field utilizing the Bank Assessment for non-point source Consequences of Sediment (BANCS) method, which relies on information from the Bank Erosion Hazard Index (BEHI) and Near Bank Stress (NBS) measurements (Rosgen, 2008).

A technical memorandum describing this work in detail has been provided in **Appendix A**.

4 RESULTS

4.1 SEDIMENT MASS BALANCE

Results of this work included a complete sediment mass balance equation for the WRW. Each term in the equation was calculated independently from one another and is explained in the following subsections. The terms are as follows:

Sediment Deposition	=	**Overland Yield**	+	**In-Channel Processes**
1,302 to 2,008 tons/year		PTMApp: *931 tons/year* RUSLE/SDR: *887 tons/year*		*1,434 tons/year*

When looking specifically at the sum of overland yield and in-channel processes, the deposition value increases slightly from the upper bound of the independently calculated value to approximately 2,321 to 2,365 tons/year deposited to the Warroad Harbor. This value is within a reasonable range of the values identified in previous work. Given the level of uncertainly that is present within these methodologies explored in past studies (HEI, 2016), this equation serves to identify the relative magnitude of sediment delivered from overland yield versus in-channel processes. From these values we can approximate that ~40% of sediment is being delivered from overland yield the remaining ~60% from in-channel processes. Detailed methodology for determination of sediment deposition, overland yield, and in-channel processes are provided in the following sections.

4.1.1 SEDIMENT DEPOSITION IN WARROAD HARBOR

Volumes of net erosion and deposition, in the Warroad Harbor, are shown for each analyzed time period. When comparing the bathymetric surface rasters, if the latter year (e.g. 2012) is higher than the former year (e.g. 2002), deposition has occurred; if the opposite conditions exist erosion has occurred. The erosion and deposition datasets were used to estimate the overall volume of sediment eroded or deposited in each study area during each time period. From this data, estimated erosion and deposition rates were determined; results are given in **Table 1**.

Table 1. Sediment erosion and deposition rates in the Warroad Harbor and entry.

Study Area	Period	Overall Change in Sediment Volume (ac-ft)	Total Area (ac)	Rate (in/yr)	Erosion or Deposition
Harbor	07/30/02 – 09/04/03	-36.12	45	-8.77	Erosion
	09/04/03 – 04/20/05	33.39	46.76	5.27	Deposition
	04/20/05 – 06/12/07	23.6	68.47	1.93	Deposition
	06/12/07 – 04/22/12	5.73	44.8	0.32	Deposition
	07/30/02 – 04/22/12	17.16	42.55	0.5	Deposition
Entry	07/30/02 – 09/04/03	-35.89	49.92	-7.86	Erosion
	09/04/03 – 04/20/05	33.69	52.08	4.77	Deposition
	04/20/05 – 06/12/07	14.66	79.87	1.03*	Deposition
	06/12/07 – 04/22/12	-1.16	75.1	-0.04	Erosion
	07/30/02 – 04/22/12	9.89	50.19	0.24*	Deposition

*Deposition rate includes dredging removal of 8,900 cubic yards of sediment. The actual deposition rate, without dredging is 1.41 in/yr for 2005-2007 and 0.33 in/yr from 2002-2012.

Using the long-term average annual deposition rate (2002-2012) of 0.50 in/year, the average annual net loading of sediment into the Warroad Harbor was estimated assuming that all sediment that enters the harbor settles out. However, converting sedimentation values to loading required some knowledge of sediment densities in the area. Two references were used to determine a range of possible sediment densities. Data obtained from the St. Croix Watershed Research Station, from sediment coring in Zippel Bay and in the LOW, indicates an average density of approximately 31.2 lb./ft^3 (0.5 g/cm^3) for saturated, deposited sediments in the area (Schottler, 2013). An additional report by the National Resource Conservation Service (NRCS) on the Bostic and Zippel Creek watersheds estimates Zippel Bay sediments to have a density of 48.1 lb./ft^3 (1300 lb./yd^3) (NRCS, 2013). For this study, both referenced densities are used to report a range of depositional loading based on the bathymetric data.

The total area of the harbor was delineated based on the 2010 aerial photograph and is defined as any wet area inside of the harbor between the railroad bridge to the west and the harbor/entry boundary to the east (see **Figure 2**); side channels within the harbor were excluded from the area calculation, as the majority of the sediment deposition and erosion is most likely to occur within the main channel of the harbor. Using this technique, the depositional area of the harbor is estimated to be approximately 46 acres. Using the long-term average annual deposition rate of 0.50 in/yr, the harbor area, and densities described above, it is estimated that an approximate range of 1,302 to 2,008 tons of sediment is deposited in the Warroad Harbor on an average annual basis.

4.1.2 OVERLAND EROSION

4.1.2.1 PRIORITIZE, TARGET AND MEASURE APPLICATION

Results from the Prioritize, Target and Measure Application found an annual sediment delivery of 931 tons delivered to the Warroad Harbor from overland sources. Figure 4 below shows the relative magnitude of sediment delivery on a field catchment scale.

4.1.2.2 REVISED UNIVERSAL SOIL LOSS EQUATION AND SEDIMENT DELIEVERY RATIO

By combining the RUSLE-estimated sediment yields in the WRW with the MN-P Index SDR method and channel routing equation, the average annual amount of sediment entering the Warroad Harbor due to overland rill/interill erosion was computed. **Table 2** shows the result.

Table 2. Estimated average annual sediment loading into the Warroad Harbor from overland rill/interill erosion.

Average Annual Sediment Load (tons)	Watershed Area (square miles)	Average (tons/acre/year)
887	240	0.006

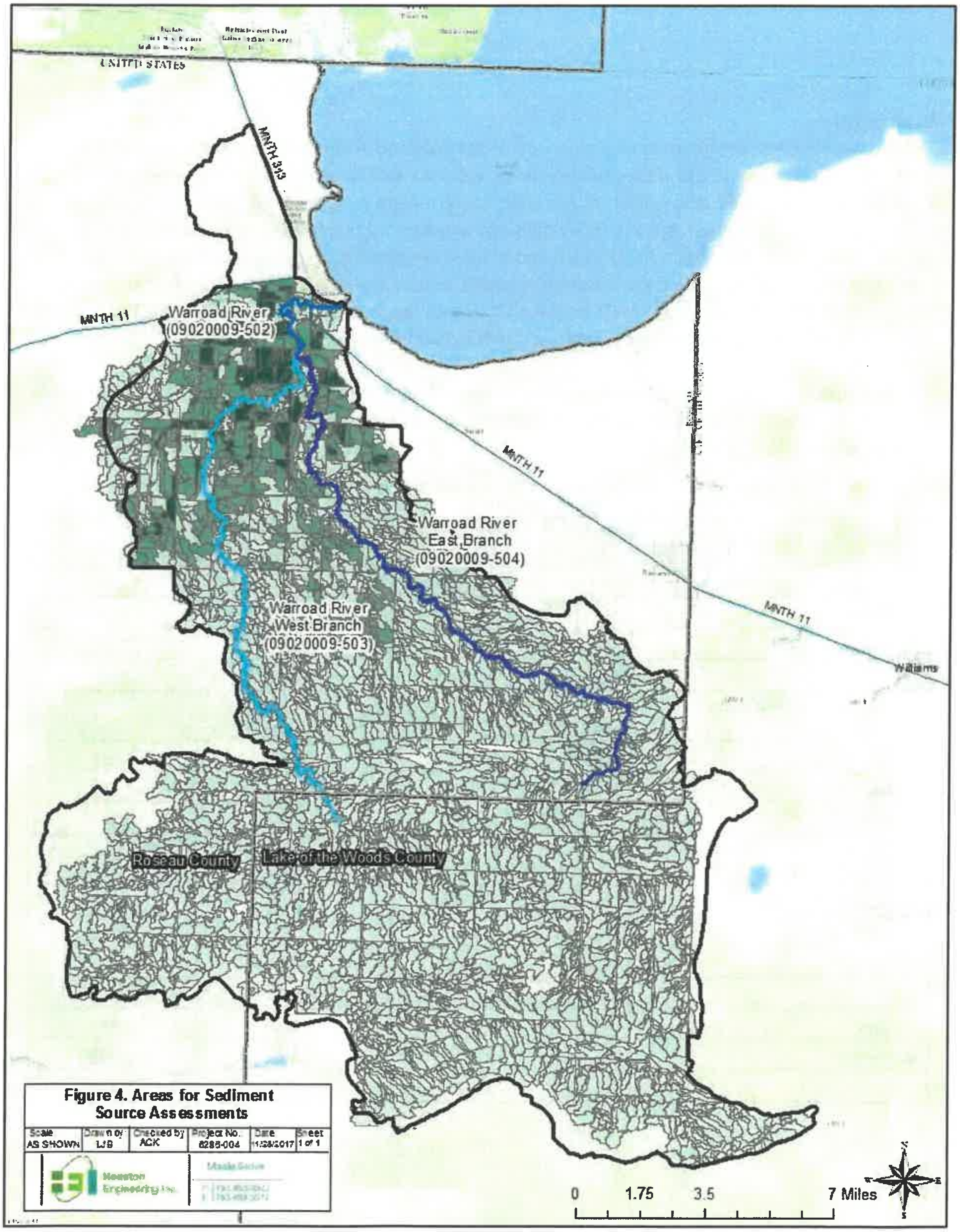

Figure 4. Areas for Sediment Source Assessments

Bank Erosion

Table 3 outlines the net stream bank erosion within the Warroad Watershed for each assessed AUID of the River. This analysis spans a 69-year period and includes erosional and depositional calculations for total and annual volumes along with tons per year. Cubic meters per year were converted to tons per year utilizing values obtained from the SSURGO data and average 1.2 gram/cm^3 across the watershed. Across the 69-year period each AUID was found to have net erosion, implying that the stream has degraded since 1940. Based on this historical analysis, annual net erosion from in-channel sediment sources delivered from the Warroad River to the LOW was found to be 1,434 tons/year. **Figure 5** displays zones and relative magnitude of erosion along the Warroad River.

These results were field verified using the BANCS model that relies on the BEHI and NBS Assessments. A detailed methodology for the bank erosion assessment has been provided in a technical memorandum in **Appendix A**.

Table 3. Net Streambank Erosion and Deposition within the Warroad River.

AUID	Length (m)	Total Cubic Meters	Cubic Meters/Year	Tons/Year
Warroad River (09030009-502)	7,197			
Erosion		19,440	282	338
Deposition		7,767	113	135
Net:		11,674	169	203
Warroad River, West Branch (09030009-503)	44,906			
Erosion		168,633	2,444	2,933
Deposition		127,235	1,844	2,213
Net:		41,398	600	720
Warroad River, East Branch (09030009-504)	53,430			
Erosion		195,570	2,834	3,401
Deposition		166,201	2,409	2,890
Net:		29,369	426	511
All:	105,533			
Erosion		383,643	5,560	6,672
Deposition		301,203	4,365	5,238
Net:		82,440	1,195	1,434

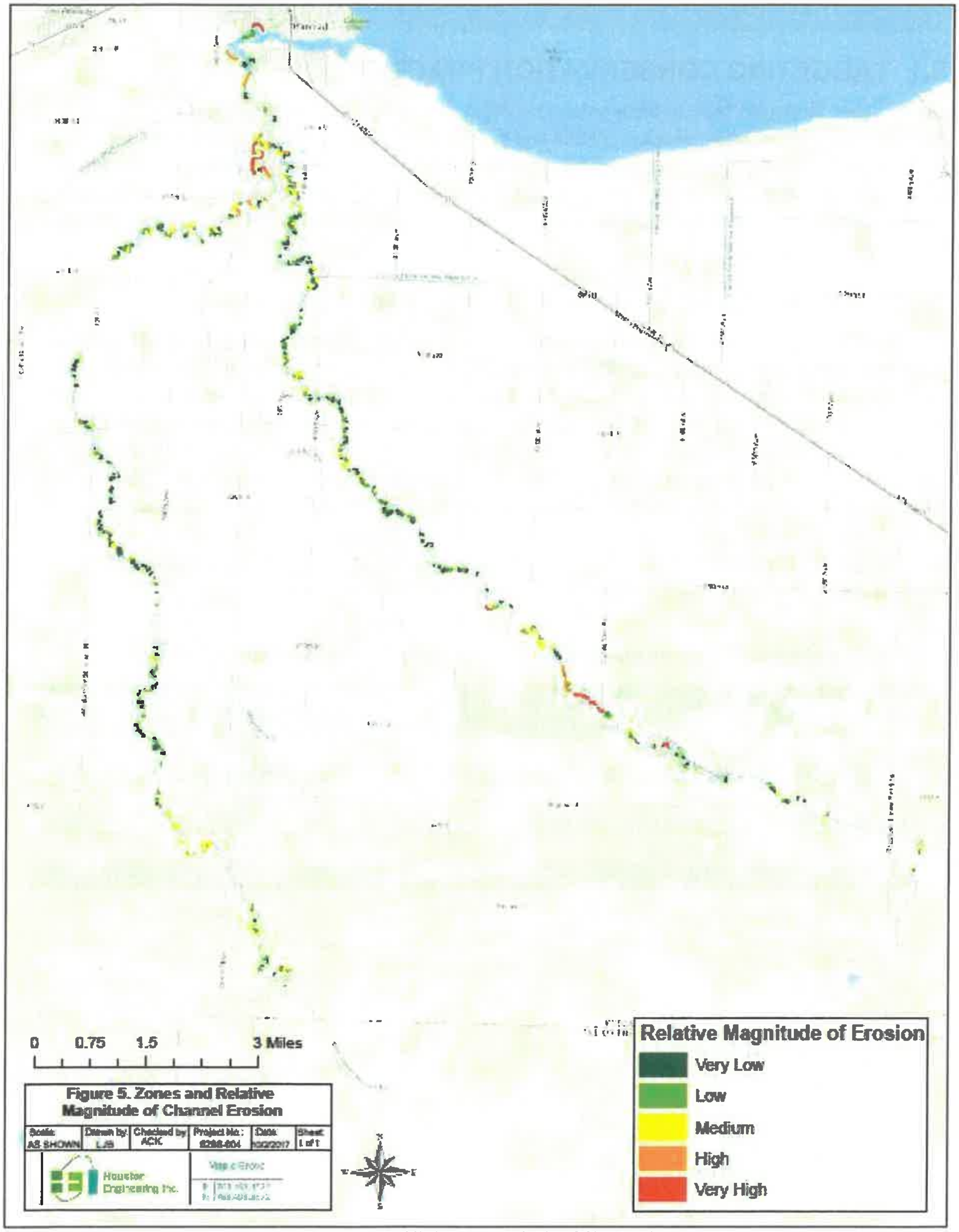

Figure 5. Zones and Relative Magnitude of Channel Erosion

5 TARGETING PRACTICE TO REDUCE SEDIMENT

5.1 TARGETING CONSERVATION PRACTICES

Conservation strategies need to be targeted to address both overland (~ 40% contribution) and in-channel (~60% contribution) sources contributing to the sedimentation in the Warroad Harbor. Through the various modeling and field techniques described earlier, locations have been identified to address overland sediment sources through structural and management practice and in-channel sources through bank stabilization and restoration efforts in order to reduce the amount of sediment reaching LOW near the Warroad Harbor.

5.1.1 POTENTIAL UPLAND CONSERVATION PRACTICES

The WRW has a developed baseline of feasible structural and management practices which consider sediment reduction goals alongside other nutrient reduction goals for the region. It is understood that this baseline identifies more practices than can realistically be accomplished in a 10-year plan and is largely influenced by available funding and local acceptance of the practices. In the forthcoming addendum based on the 1W1P for the Warroad River Planning Region, this large amount of practices will be narrowed down by assuming varying percentages of baseline funding which will go toward the various treatment groups based of goals and cost-effectiveness of the practices to reach those goals.

Currently, 3,327 potential feasible structural practices (**Table 4**; **Figure 6**) and 801 potential feasible management practices (**Table 5**; **Figure 6**) have been identified in the WRW.

Table 4: Breakdown of feasible structural practices in the in the Warroad River Planning Region.

Structural Practice Treatment Groups	Total Number of Practices in Planning Region
Biofiltration	124
Filtration	1,008
Infiltration	93
Protection	1,190
Storage	812
Total	3327

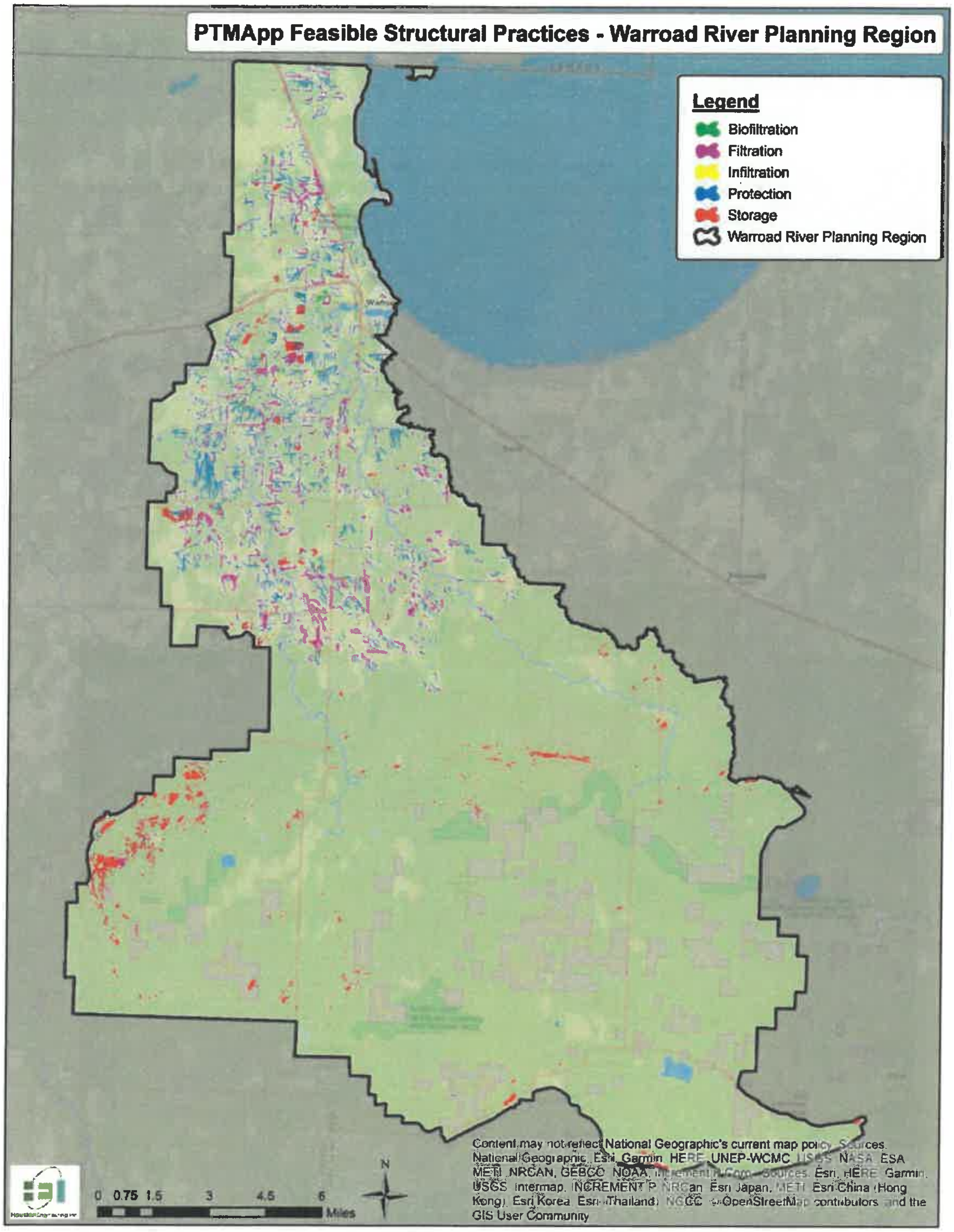

Figure 6: Potential feasible structural practice location in the WRW

Table 5: Feasible management practices in the in the Warroad River Planning Region.

PTMApp Management Practice Treatment Groups	Total Number of Practices in Planning Region
Source Reduction	801

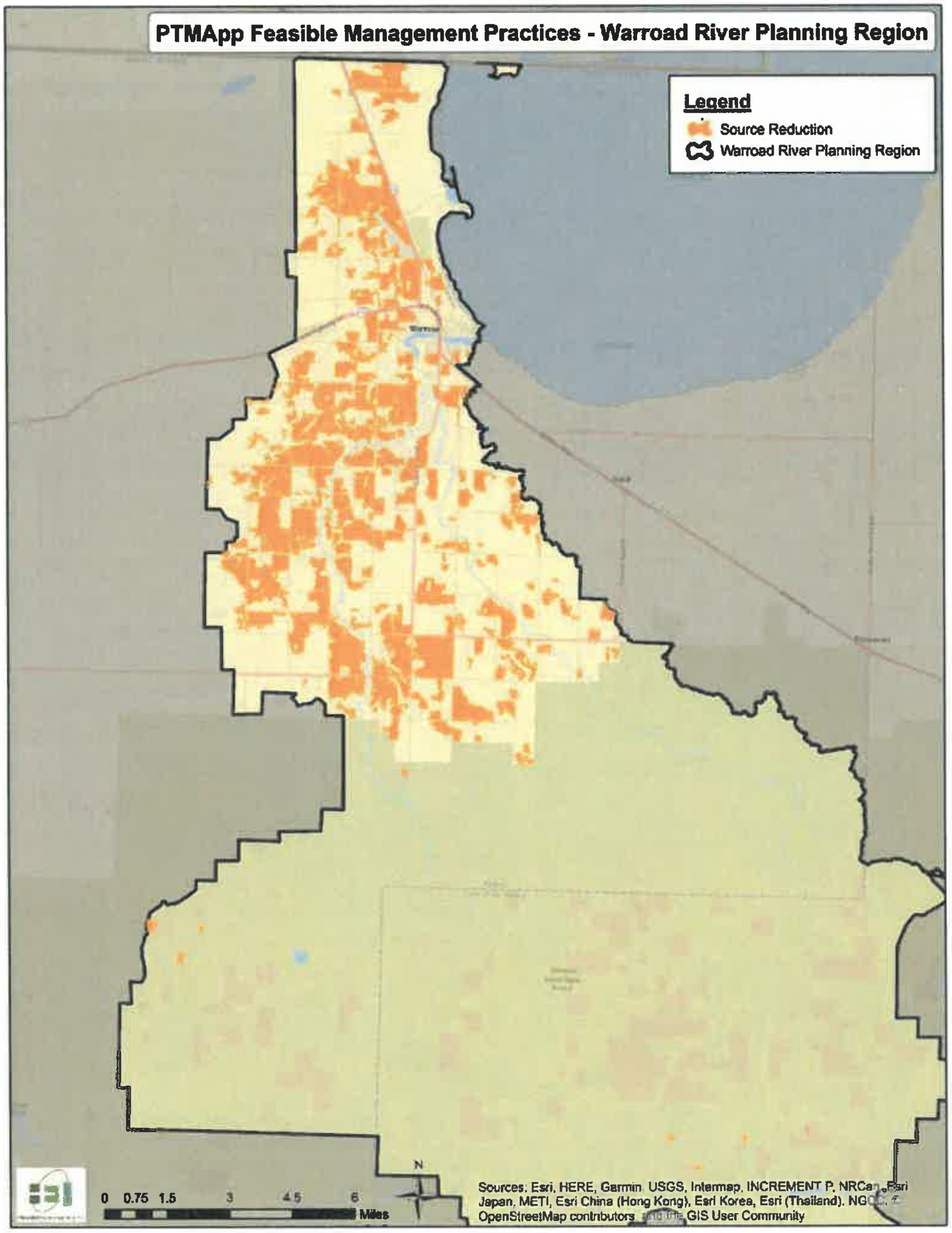

Figure 7. Potential feasible management practice location in the WRW

5.1.2 BANK STABILIZATION AND RESOTRATION

With in-channel sources constituting ~60% of the deposition occurring in the Warroad Harbor, a focal point for mitigating sedimentation issue needs to target bank stabilization of restoration efforts. Seventeen potential in-channel project locations were identified within the Warroad River planning region (**Table 6**; **Figure 8**). **Table 6** also displays the auxiliary benefit from Total Phosphorus (TP) reductions associated with the projects vital to meeting overall stream restoration goals. These locations were identified based on historical photo analysis to quantify long-term rates of river bank retreat in addition to estimated annual volume of sediment (tons) delivered to the LOW from the Warroad River (09020009-502), the Warroad River East Branch (09030009-504), and the Warroad River West Branch (09030009-503). Historical photo analysis results where spot checked and confirmed for accuracy in the field using the BANCS method, which relies on information from the BEHI and NBS measurements.

Table 6: Potential in-channel projects within the Warroad River planning region.

Stream Protection & Restoration Location	Waterbody	Approximate Length (ft)[1]	Cost Benefit		
			Estimated Sediment Removal (tons)[1]	Estimated TP Removal (lbs)[2]	Estimated Cost ($)[3]
W-1	West Branch Warroad River	919	15	9	$275,616
W-2	West Branch Warroad River	438	15	9	$131,472
W-3	West Branch Warroad River	470	29	175	$140,976
W-4	West Branch Warroad River	581	21	130	$174,240
W-5	West Branch Warroad River	312	16	11	$93,456
W-6	West Branch Warroad River	908	35	225	$272,448
W-7	West Branch Warroad River	459	59	385	$137,808
W-8	West Branch Warroad River	2,144	105	38	$643,104
W-9	West Branch Warroad River	327	15	6	$98,208
W-10	West Branch Warroad River	1,077	103	44	$323,136
W-11	Warroad River	1,484	51	21	$445,104
W-12	Warroad River	1,045	35	128	$313,632
W-13	East Branch Warroad River	285	16	67	$85,536
W-14	East Branch Warroad River	507	23	10	$152,064
W-15	East Branch Warroad River	512	32	7	$153,648
W-16	East Branch Warroad River	723	19	4	$217,008
W-17	East Branch Warroad River	502	38	9	$150,480
	Totals	**12,693**	**627**	**1,278**	**$3,807,936**

[1] Based on historic bank erosion survey completed in 2017. Sediment removal is measured at Warroad Harbor.

[2] Based on PTMApp catchment sediment to phosphorus ratios for each location. TP removal is measured at Warroad Harbor.

[3] Assumed $300 per foot for all projects.

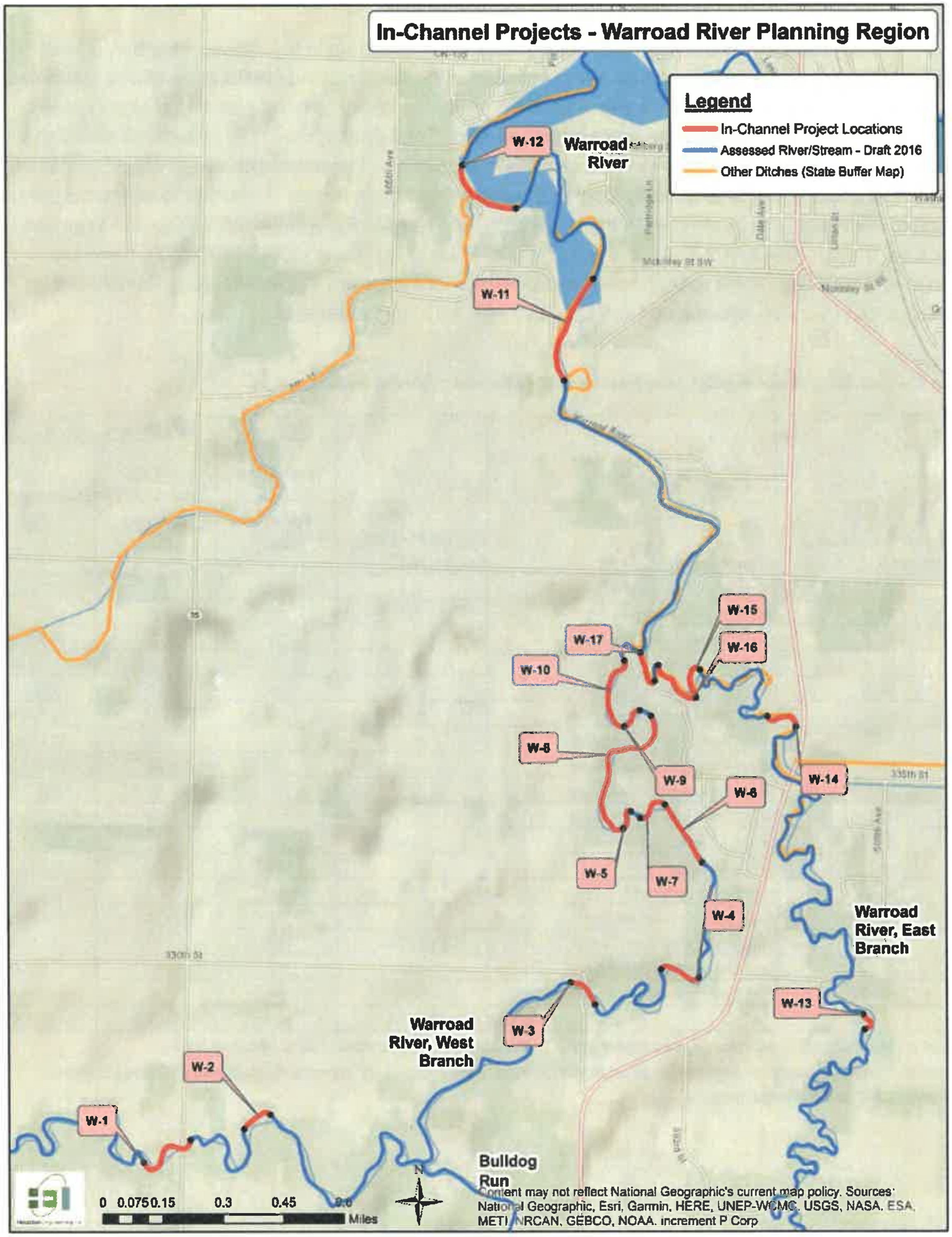

Figure 8. Potential in-channel project locations

TARGETED IMPLMENTATION PLAN

The specific targeted implementation plan for the Warroad River Planning Region will be presented in a forthcoming addendum from the Lake of the Woods 1W1P report. This is to ensure that one cohesive plan exists to meet all the water quality goals for the region.

6 CONCLUSIONS

A ten year span of recent bathemetric data reveal that approximately 1,302-2,008 tons of sediment is deposited in the Warroad Harbor on an average annual basis or 0.5 inches/year. Of the deposited sediment, the majority comes from in-channel sources (~60%). Overland sediment sources contribute the remaining ~40% of sediment to the Warroad Harbor. To help mitigate sediment originating from in-channel sources, 17 potential locations have been identified along the Warroad River (including East and West branches) based on historcal aerial photograhic analysis with field work spot checks. These locations were selected based on high past erosional rates and assigned a project cost along with the benefits expected from each potential project location. To address overland sediment sources, a forthcoming addendum will contain a targeted implementation plan identifying best management practices for the Warroad River Planning Region to meet sediment and water quality goals.

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APPENDIX A
Technical Memorandum

To: Warroad River Watershed District

Cc: Scott Johnson

From: Laura Bender
Houston Engineering, Inc.

Through: Drew Kessler, Pd.D.,

Subject: Warroad River Bank Erosion Technical Memorandum

Date: January 2017

Project: Warroad River In-channel Sedimentation Analysis

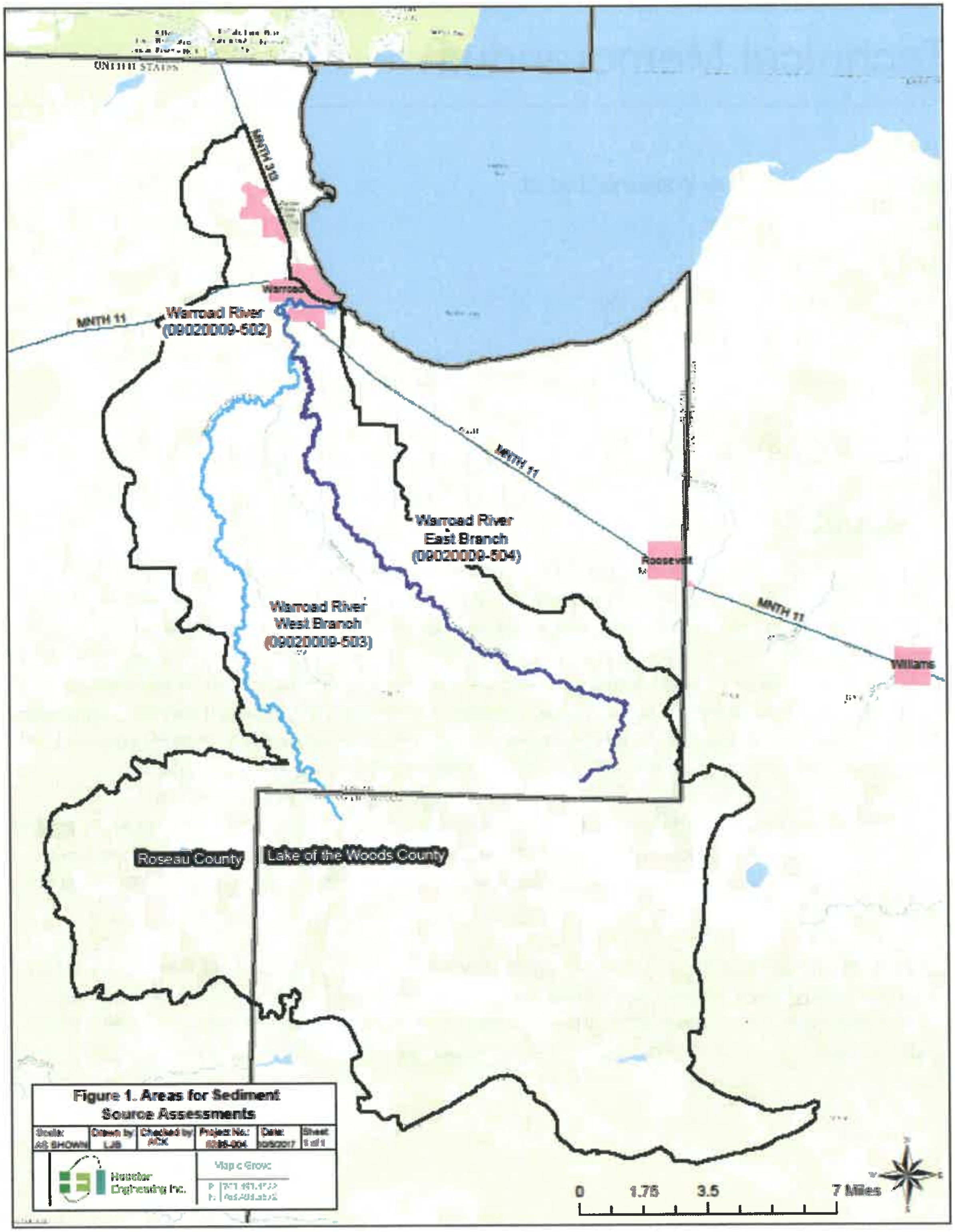
INTRODUCTION

This technical memorandum outlines the methodology and results of a bank erosion assessment completed along the Warroad River by Houston Engineering, Inc. (HEI) under agreement with the Warroad River Watershed District (WRWD). This assessment was done to determine the proportion of sediment from the Warroad River reaching Lake of the Woods (39-0002-01) that originates from in-channel sources as opposed to overland sources. The purpose of this work is to conduct a sediment source assessment of the Warroad River Watershed (WRW) and develop a targeted implementation plan for managing sediment delivering to the outlet of the Warroad River. The goal of the targeted implementation plan is to reduce the amount of sediment at the outlet of the WRW to mitigate sediment issues in Lake of the Woods near the Warroad Harbor.

This technical memorandum only address methods and results of the near channel sediment assessment and is intended to satisfy the technical memorandum deliverable for TASK 2 of the project. A full sediment mass balance for the WRW and a targeted implementation plan for managing sediment will be presented as part of a full report for this study.

It is worth noting that littoral drift, or the movement of sediment driven by breaking waves from the Lake of the Woods within the Warroad Harbor, was not addressed in this study. The focus of this study was sediment transported to the Harbor by the Warroad River. It is likely that sediment issues related to littoral drift will also need to be addressed to fully address sediment management within the Warroad Harbor.

Figure 1. Areas for Sediment Source Assessments



METHODS

The assessment included a historical photo analysis to quantify long-term rates of river bank retreat in addition to an estimated annual volume of sediment (tons) delivered to the Lake of the Woods from the Warroad River (09020009-502), the Warroad River East Branch (09030009-504), and the Warroad River West Branch (09030009-503). Historical photo analysis results where then spot checked and confirmed for accuracy in the field using the Bank Assessment for Non-Point Source Consequences of Sediment (BANCS) method, which relies on information from the Bank Erosion Hazard Index (BEHI) and Near Bank Stress (NBS) measurements.

Historic Bank Retreat

A historic bank retreat assessment was completed to estimate net bank erosion within the Warroad River Watershed (0903000903) using aerial photography analysis and an ArcMap Channel Migration Toolbox (State of Washington, 2014). Historic aerial photography within the study area from 1940 was obtained in digital format from the University of Minnesota's Historical Aerial Photograph Online database. These aerial photographs were georeferenced in ArcMap 10.3.1 using a minimum of seven user selected ground control points while maintaining a root mean square error (RMS) of less than five, with an emphasis on identifying points near the river.

Aerial photography within the study area from 2009 was obtained from the Minnesota Geospatial Information Office in digital format. Associated Light Detection and Ranging Data (LiDAR) flown in 2009 was also obtained from the Minnesota Geospatial Commons Office to aid in channel centerline digitization. River centerlines were digitized from both 1940 and 2009 aerial photography across three Assessment Units Identifiers (AUID) as defined by the Minnesota Pollution Control Agency within the Warroad River Watershed to assess net sediment movement across a 69-year study period. AUIDs included the Warroad River (09030009-502), Warroad River, West Branch (09030009-503) and Warroad River, East Branch (09030009-504).

River migration rates between 1940 and 2009 were determined by running centerlines through a Channel Migration Toolbox. Model outputs included a shapefile containing discrete polygons for each instance of channel migration along each AUID. Each polygon characterized the total area of movement between each centerline. These polygons were used to identify areas and magnitude of both erosion and deposition along the Warroad River, which in turn were used to target BEHI field surveys used for the BANCS assessments.

In order to obtain an estimate of net erosion and deposition across the study period, heights were obtained for both left and right banks at each instance of channel migration. Bank heights were identified by digitizing left and right bank areas at each instance of migration from a 2009 hill shade layer obtained from the Minnesota Geospatial Information Office and then run through a Zonal Statistics function in ArcGIS 10.3.1. Each bank was identified as either an area of deposition or erosion. The area of movement was then multiplied by the height of the bank to estimate volume loss and deposition for eroding and aggrading bank, respectively. Due to a lack of data from 1940, bank heights were assumed to be consistent between 1940 to 2009. The volumes were then multiplied by a soil bulk density taken from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO) to estimate a mass of soil loss and deposition. The sum of soil loss and deposition was used to estimate the net contribution of sediment from bank retreat to the Warroad River Channel over the 69 year-study period. In addition to a net erosion value, net erosion was also scaled by the percent of fine materials including silt and clay (**Table 2** and **Table 3**). This provides a reasonable range of estimated sediment delivery to the harbor as some sandy materials likely settle within the floodplain of the Warroad River.

Bank Assessment for Non-point source Consequences of Sediment (BANCS)

Bank erosion was estimated using the BANCS method, which relies on information from the BEHI and NBS measurements. The BANCS analysis was conducted for 10 field locations across a range of low, moderate, and high erosion sites as identified within the historical aerial photo analysis (Rosgen, 2008). In addition, rapid BEHIs were conducted at 35 streambank locations (**Figure 6**) in order to field validate results obtained during the historical aerial photography assessment.

Bank Erosion Hazard Index

The BEHI evaluates potential for bank erosion utilizing multiple combined variables including study bank height, bankfull height, root depth, root density, bank angle and surface protection which are converted to a numerical BEHI rating of very low to extreme as shown in **Figure 2** (HEI, 2014). A rapid BEHI analyzes a subset of the BEHI metrics including root depth as percent of bank height, root density (%), surface protection (%), and bank angle (degrees) (**Table 1**).

Figure 2. Streambank erodibility criteria and bank variables to BEHI rating

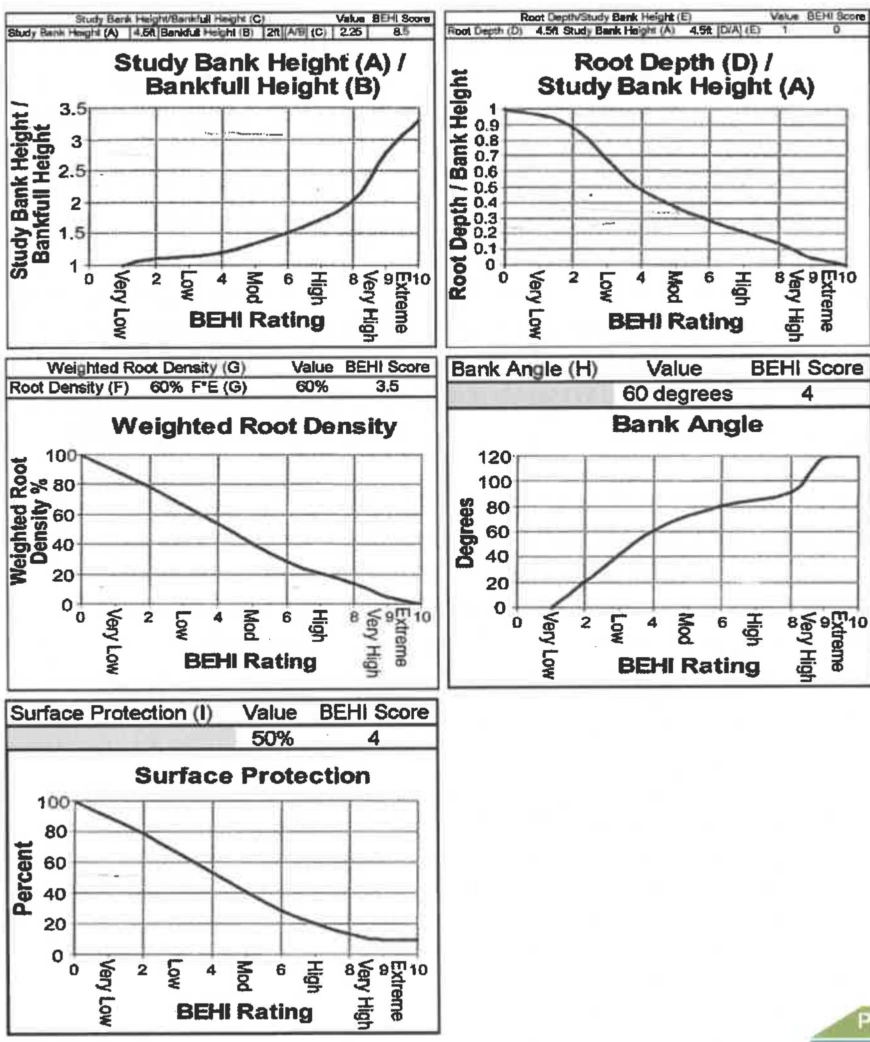


Table 1. Rapid Bank Erosion Hazard Index Metrics

Root Depth (%)	Scores	Root Density (%)	Scores	Surface Protection (%)	Scores	Bank Angle (degrees)	Scores	Total Score Categories	Ranking
90-100	1.45	80-100	1.45	80-100	1.45	0-20	1.45	<= 5.8	Very Low
50-89	2.95	55-79	2.95	55-79	2.95	21-60	2.95	5.8-11.8	Low
30-49	4.95	30-54	4.95	30-54	4.95	61-80	4.95	11.9-19.8	Moderate
15-29	6.95	15-29	6.95	15-29	6.95	81-90	6.95	19.9-27.8	High
5-14	8.5	5-14	8.5	10-14	8.5	91-119	8.5	27.9-34.0	Very high
<5	10	<5	10	<10	10	>119	10	34.1-40	Extreme

Near Bank Stress Measurements

In predicting annual streambank erosion rates, an estimate of Near-Bank Stress (NBS) is required for the BANCS assessment methods. NBS can be estimated using seven different methodologies within four levels as shown in **Figure 3.** NBS is an approximation of the four purposes of this work, a Level 4 Technique 7 NBS analysis was conducted utilizing velocity gradient measurements at each field site obtained from the Hydrologic Engineering Centers River Analysis (HEC-RAS) model. **Figure 3** shows how an NBS value is transcribed into a rating for the BANCS assessment.

Figure 3. Near-Bank Stress Worksheet for the BANCS Method

Estimating Near-Bank Stress (NBS)

Stream: | Location: | Date: | Crew:

Methods for Estimating Near-Bank Stress

(1) Transverse bar or split channel/central bar creating NBS/high velocity gradient: Level I - Reconnaissance.
(2) Channel pattern (Rc/W): Level II - General Prediction.
(3) Ratio of pool slope to average water surface slope (S_p/S): Level II - General Prediction.
(4) Ratio of pool slope to riffle slope (S_p/S_{rif}): Level II - General Prediction.
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb}/d_{bkf}): Level III - Detailed Prediction.
(6) Ratio of near-bank shear stress to bankfull shear stress (t_{nb}/t_{bkf}): Level III - Detailed Prediction.
(7) Velocity profiles/Isovels/Velocity gradient: Level IV - Validation.

Level I	(1)	Transverse and/or central bars - short and/or discontinuous. NBS = High/Very High							
		Extensive deposition (continuous, cross channel). NBS = Extreme							
		Chute cutoffs, down-valley meander migration, converging flow (Figure X). NBS = Extreme							
Level II	(2)	Radius of Curvature Rc (feet)	Bankfull Width W_{bkf} (feet)	Ratio Rc/W	Near-Bank Stress				
	(3)	Pool Slope S_p	Average Slope S	Ratio S_p/S	Near-Bank Stress		Dominant Near-Bank Stress		
	(4)	Pool Slope S_p	Riffle Slope S_{rif}	Ratio S_p/S_{rif}	Near-Bank Stress				
Level III	(5)	Near-Bank Max Depth d_{nb} (feet)	Mean Depth d (feet)	Ratio d_{nb}/d	Near-Bank Stress				
	(6)	Near-Bank Max Depth d_{nb} (feet)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d (feet)	Average Slope S	Shear Stress τ (lb/ft^2)	Ratio τ_{nb}/τ	Near-Bank Stress
Level IV	(7)	Velocity Gradient (ft/s/ft)		Near-Bank Stress					

Converting Values to a Near-Bank Stress Rating

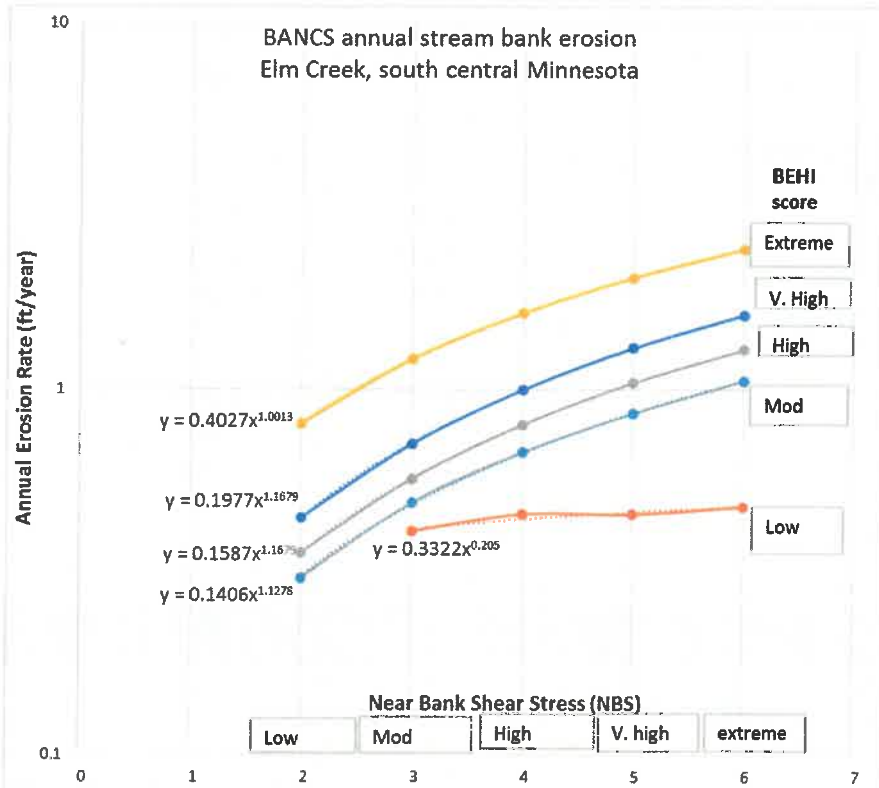
Near-Bank Stress Rating	Method Number (1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N/A	>3.0	< 0.20	< 0.4	<1.0	<0.8	<1.0
Low		2.21 - 3.0	0.20 - 0.40	0.41 - 0.60	1.0 - 1.5	0.8 - 1.05	1.0 - 1.2
Moderate		2.01 - 2.2	0.41 - 0.60	0.61 - 0.80	1.51 - 1.8	1.06 - 1.14	1.21 - 1.6
High	See (1) Above	1.81 - 2.0	0.61 - 0.80	0.81 - 1.0	1.81 - 2.5	1.15 - 1.19	1.61 - 2.0
Very High		1.5 - 1.8	0.81 - 1.0	1.01 - 1.2	2.51 - 3.0	1.20 - 1.60	2.01 - 2.3
Extreme		< 1.5	> 1.0	> 1.2	> 3.0	> 1.6	> 2.3

Overall Near-Bank Stress Rating

Regional Curves

Regional curves have been developed for transcribing BEHI and NBS index values into rates of river bank retreat (Lenhart et al., 2015). Curves developed by Lenhart et al., 2015 for Elm Creek in south central Minnesota were used to transcribe the BANCS method results of this project to rates (ft/year) of river bank retreat (**Figure 4**).

Figure 4. BANCS curves for translating NBS and BEHI scores into rates of river bank retreat. Analysis was performed by Lenhart et al. (2015) on Elm Creek in south central Minnesota



RESULTS

Historic Channel Assessment

Historic erosion and deposition rates across the entire 69-year study period, annual cubic meters of erosion and deposition, annual tons of erosion and deposition as well as the net transport for each of these values, are displayed in **Table 2** and **Table 3**. Cubic meters per year were converted to ton per year utilizing values obtained from the SSURGO data and average 1.2 cm/gram across the watershed. Across the 69-year period, each AUID was found to have net erosion, implying that the stream has degraded since 1940. Based on this historical analysis, annual net erosion from in-channel sediment sources delivered from the Warroad River to the Lake of the Woods was found to be 1,434 tons/year. **Figure 5** displays zones and relative magnitude of erosion along the Warroad River.

Table 2. Net Streambank Erosion and Deposition within the Warroad River

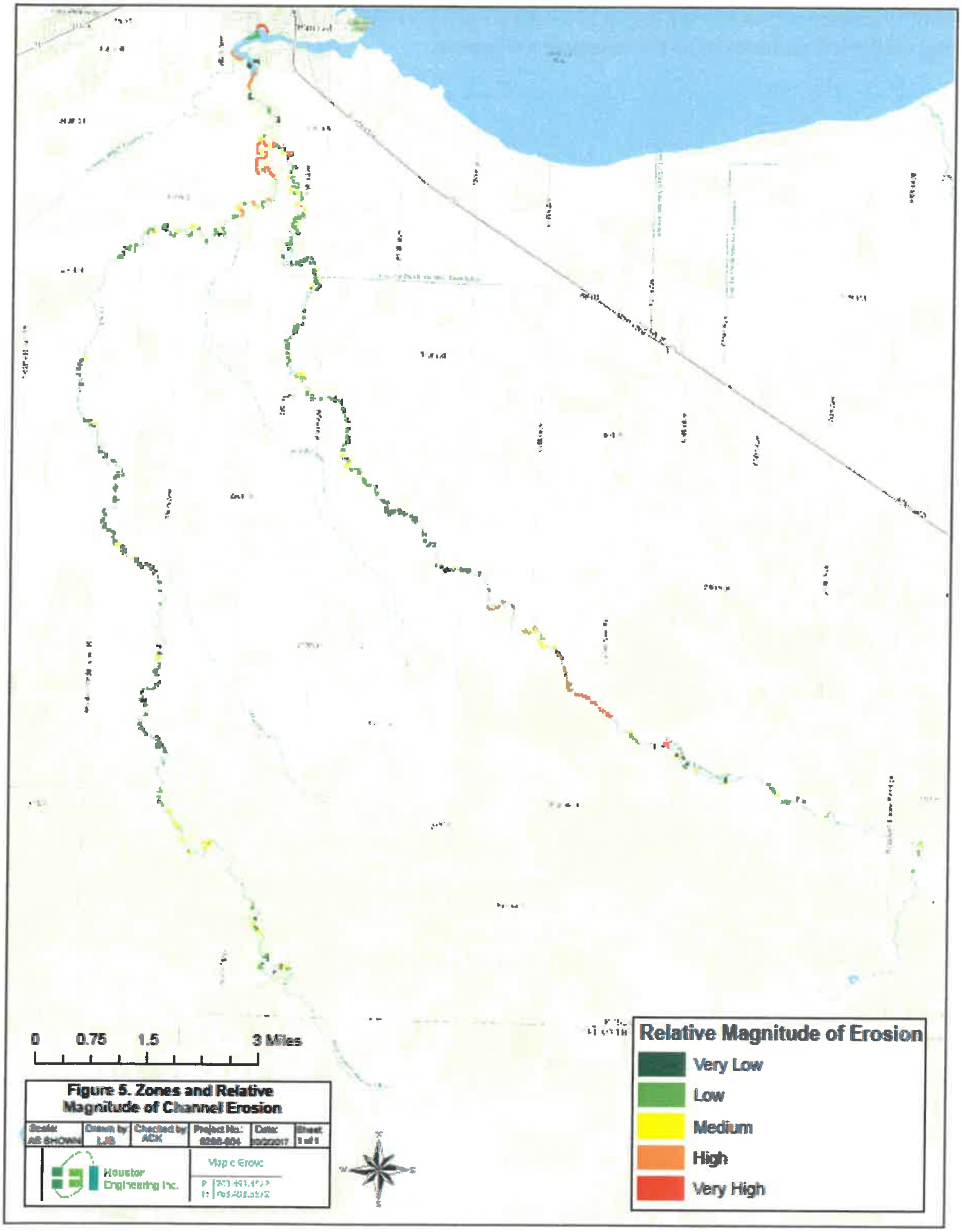
AUID	Length (m)	Total Cubic Meters	Cubic Meters/Year	Tons/Year
Warroad River (09030009-502)	7,197			
Erosion		19,440	282	338
Deposition		7,767	113	135
Net:		11,674	169	203
Warroad River, West Branch (09030009-503)	44,906			
Erosion		168,633	2,444	2,933
Deposition		127,235	1,844	2,213
Net:		41,398	600	720
Warroad River, East Branch (09030009-504)	53,430			
Erosion		195,570	2,834	3,401
Deposition		166,201	2,409	2,890
Net:		29,369	426	511
All:	105,533			
Erosion		383,643	5,560	6,672
Deposition		301,203	4,365	5,238
Net:		82,440	1,195	**1,434**

Table 3. Net Streambank Erosion to the Warroad Harbor Scaled for Silt and Clay

Minimum Percent Silt and Clay	Median Percent Silt and Clay	Mean Percent Silt and Clay	Maximum Percent Silt and Clay
4.6%	40.8%	41.4%	84.7%
Net Transport (Tons/Year)	**Net Transport (Tons/Year)**	**Net Transport (Tons/Year)**	**Net Transport (Tons/Year)**
66	585	594	1,215

In addition, average rates of lateral migration were calculated at each field sampling site using area and channel length for comparison to lateral migration rates calculated from the BANCS methodology (**Table 4, Appendix A**).

Figure 5. Zones and Relative Magnitude of Channel Erosion



__Bank Assessment for Non-point source Consequences of Sediment (BANCS)__

Full BEHI assessments were completed at 10 locations and rapid BEHIs were completed at 35 locations by using the BANCS methodology for this assessment (**Figure 6**).

Figure 6. Full and Rapid BEHI Survey Locations

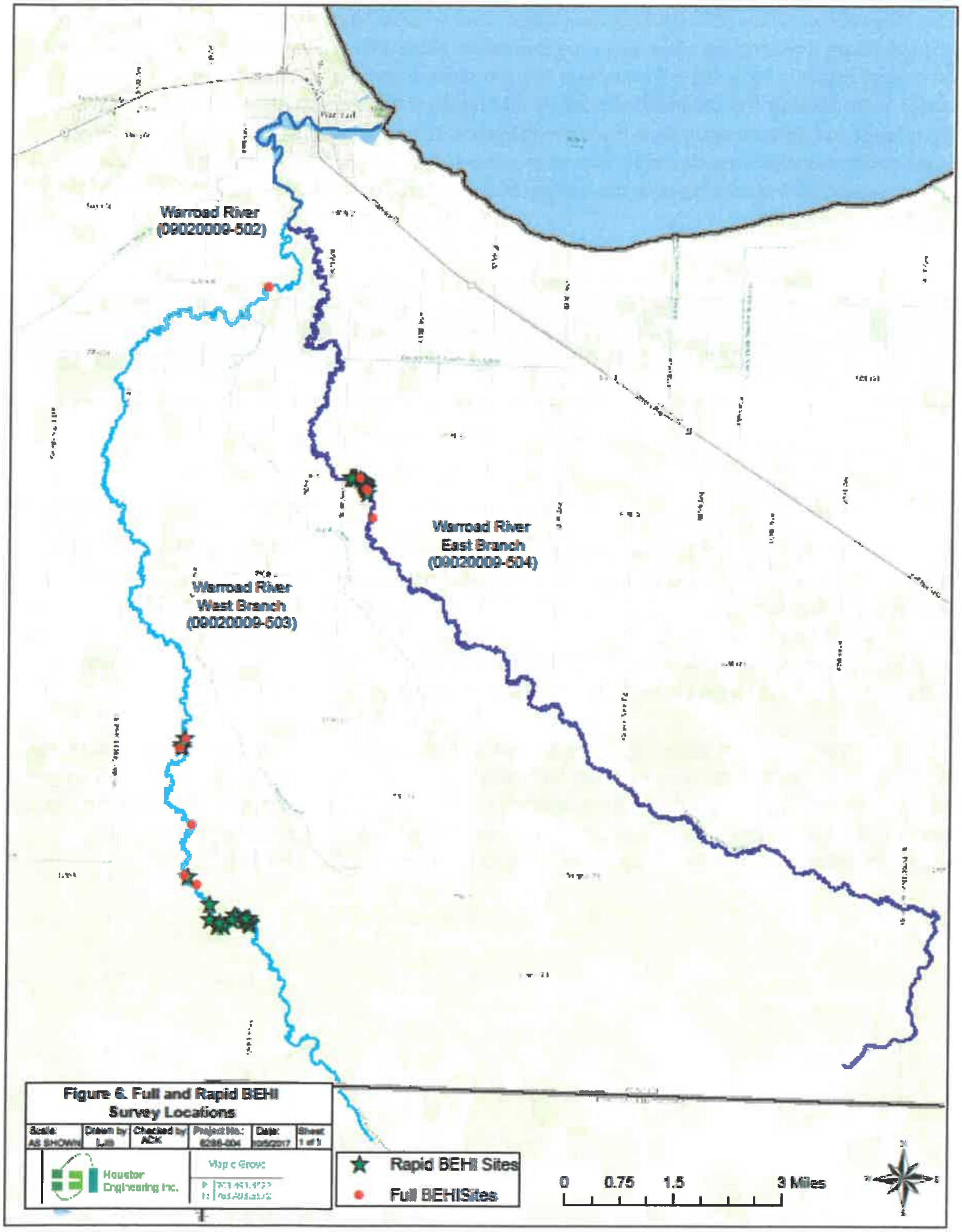


Table 4 displays the channel migration rate in feet per year as calculated utilizing both historical aerial photography methodology and the BANCS methodology, which relies on field collected BEHI data, near bank stress measurements from HEC-RAS obtained stream flow velocities, and the region curves to translate BEHI and NBS values. The complete set of data used to generate **Table 3** have been provided within **Appendix A**. The channel migration rates determined by field data are similar to the migration rates determined by the desktop historical data. This serves to validates the final results of the historical desktop analysis and the final value of sediment delivered annually to the Warroad Harbor. To further validate the results, a z-test for two means statistical analysis was run on the dataset provided in Appendix A, determined to be non-parametric, and found no significant difference between the average Historical Desktop Retreat Rate and the Average BANCS retreat rate.

Table 4. Summary of Historical Desktop and BANCS Lateral Migration Rates

Average BANCS Retreat Rate (ft/yr)	Average Historical Desktop Retreat Rate (ft/yr)	Difference Between Averages	Average Difference Among Sample Points
0.35	0.31	0.04	0.08

CONCLUSIONS

The results of this assessment indicated that near channel erosion within the WRW is contributing 1,434 tons/year of sediment to Lake of the Woods, with a range of 66 tons/year to 1,215 tons/year when scaled for fine materials. Field investigations indicated that the 69-year average retreat rates derived from the historic air photos were statistically similar to modern day bank retreat estimates derived using the BANCS method. This increases confidence that the net erosion estimated with the historic air photos is providing a reasonable estimate of near channel sediment contribution to the Warroad Harbor from the WRW.

The next step in this assessment is integrating the near channel sediment erosion estimates presented in this technical memorandum into a sediment mass balance approach with estimates of overland sediment delivery to and estimates of sediment settling within the Warroad Harbor. The completed sediment source assessment can then be used in conjunction with the Prioritize, Target, and Measure Application (PTMApp) to develop a targeted implementation plan to address the delivery of sediment to the Warroad Harbor.

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Lenhart, Chris; Neiber, John (2015). MDA priority setting in water restoration, final report. Minnesota Department of Agriculture. September, 2015.

Rosgen, Dave. 2008. River Stability Field Guide. Wildland Hydrology: Fort Collins, Colorado.

State of Washington, Department of Ecology. 2014. The Channel Migration Toolbox, ArcGIS Tools for Measuring Stream Channel Migration. Publication no. 14-06-032. October, 2014.

APPENDIX A: HISTORICAL DESKTOP AND BANCS DETERMINED LATERAL MIGRATION RATES AT FIELD SURVEY LOCATIONS

Site ID	Type	Branch	BEHI	NBS	BANCS Retreat Rate (ft/yr)	Historical Desktop Retreat Rate (ft/yr)	Difference
1	Full	West	31, High	2.18	0.39	0.33	0.06
2	Full	West	18, Low	2.78	0.41	0.42	0.01
3	Full	West	19.5, Low	1.35	0.35	0.33	0.02
4	Full	West	28, Moderate	1.89	0.29	0.29	0.00
5	Full	West	33, High	3.16	0.61	0.43	0.18
6	Full	West	19, Low	2.34	0.40	0.32	0.08
7	Full	East	29, Moderate	1.51	0.22	0.15	0.07
8	Full	East	31, High	1.48	0.25	0.30	0.05
9	Full	East	29, Moderate	1.39	0.20	0.21	0.01
10	Full	East	22, Moderate	4.46	0.76	0.40	0.36
11	Rapid	West	7.3, Low	9.79	0.53	0.89	0.36
12	Rapid	West	10.3, Low	2.10	0.39	0.28	0.11
13	Rapid	West	15.85, Moderate	2.10	0.32	0.23	0.09
14	Rapid	West	8.8, Low	2.10	0.39	0.22	0.17
15	Rapid	West	12.8, Moderate	2.10	0.32	0.21	0.11
16	Rapid	West	12.8, Moderate	1.83	0.28	0.28	0.00
17	Rapid	West	12.3, Moderate	1.83	0.28	0.21	0.07
18	Rapid	West	15.85, Moderate	3.10	0.50	0.57	0.07
19	Rapid	West	19.35, Moderate	2.11	0.33	0.30	0.03
20	Rapid	West	23.35, High	2.09	0.38	0.40	0.02
21	Rapid	West	19.35, Moderate	2.15	0.33	0.41	0.08
22	Rapid	West	7.3, Low	3.31	0.42	0.44	0.02
23	Rapid	West	14.35, Moderate	2.62	0.42	0.44	0.02
24	Rapid	West	23.4, High	2.62	0.49	0.42	0.07

Site ID	Type	Branch	BEHI	NBS	BANCS Retreat Rate (ft/yr)	Historical Desktop Retreat Rate (ft/yr)	Difference
25	Rapid	West	21.35, High	3.55	0.70	0.26	0.44
26	Rapid	West	12.8, Moderate	1.60	0.24	0.22	0.02
27	Rapid	West	25.35, High	1.79	0.31	0.32	0.01
28	Rapid	West	23.4, High	1.89	0.33	0.34	0.01
29	Rapid	West	15.85, Moderate	3.16	0.51	0.34	0.17
30	Rapid	West	22.9, High	2.88	0.55	0.44	0.11
31	Rapid	East	17.35, Moderate	2.34	0.37	0.23	0.14
32	Rapid	East	17.85, Moderate	1.51	0.22	0.16	0.06
33	Rapid	East	21.35, High	1.48	0.25	0.23	0.02
34	Rapid	East	8.8, Low	1.28	0.35	0.28	0.07
35	Rapid	East	14.3, Moderate	1.28	0.19	0.18	0.01
36	Rapid	East	8.8, Low	1.28	0.35	0.26	0.09
37	Rapid	East	12.3, Moderate	1.28	0.19	0.21	0.02
38	Rapid	East	13.8, Moderate	1.20	0.17	0.23	0.06
39	Rapid	East	21.4, High	1.20	0.20	0.11	0.09
40	Rapid	East	19.85, High	1.59	0.27	0.27	0.00
41	Rapid	East	8.8, Low	1.85	0.38	0.43	0.05
42	Rapid	East	14.35, Moderate	1.85	0.28	0.27	0.01
43	Rapid	East	12.8, Moderate	1.85	0.28	0.19	0.09
44	Rapid	East	12.8, Moderate	1.80	0.27	0.12	0.15
45	Rapid	East	14.3, Moderate	1.80	0.27	0.17	0.10
			Mean:		***0.35***	***0.31***	***0.08***

APPENDIX B: Z-TEST FOR TWO MEANS STATISTICAL ANALYSIS RESULTS SUMMARY

Sample Means:	Population Standard Deviations:	Population Sample Sizes:
$\bar{X}$ 1 = 0.35	σ1 = 0.13	n1 = 45
$\bar{X}$ 2 = 0.31	σ2 = 0.13	n2 = 45

Null and Alternative Hypotheses:
Ho: $\mu1 = \mu2$
Ha: $\mu1 \neq \mu2$

Significance Level: α = .05 — Critical Value: z_c = 1.96

Test Statistic: |z| =1.758 — P-Value: p = 0.079

$|z| = 1.758 \leq z_c = 1.96$

Null hypothesis is not rejected

$p = 0.0787 \geq .05$

Null hypothesis is not rejected