

# Warroad River Watershed Sediment Source Assessment Project



**Final Report**

**July 29, 2013**



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## **Acronyms and Abbreviations List**

|               |                                                                        |
|---------------|------------------------------------------------------------------------|
| <b>AASHTO</b> | <b>American Association of State Highway and Transportation Office</b> |
| <b>BMP</b>    | <b>Best Management Practice</b>                                        |
| <b>BWSR</b>   | <b>Board of Water and Soil Resources</b>                               |
| <b>CDL</b>    | <b>Cropland Data Layer</b>                                             |
| <b>DEM</b>    | <b>Digital Elevation Model</b>                                         |
| <b>GIS</b>    | <b>Geographic Information System</b>                                   |
| <b>HEI</b>    | <b>Houston Engineering, Inc.</b>                                       |
| <b>LIDAR</b>  | <b>Light Detection and Ranging</b>                                     |
| <b>LOW</b>    | <b>Lake of the Woods</b>                                               |
| <b>MPCA</b>   | <b>Minnesota Pollution Control Agency</b>                              |
| <b>NASS</b>   | <b>National Agricultural Statistics Service</b>                        |
| <b>NLCD</b>   | <b>National Land Cover Dataset</b>                                     |
| <b>NRCS</b>   | <b>National Resources Conservation Service</b>                         |
| <b>RUSLE</b>  | <b>Revised Universal Soil Loss Equation</b>                            |
| <b>SDR</b>    | <b>Sediment Delivery Ratio</b>                                         |
| <b>SPI</b>    | <b>Stream Power Index</b>                                              |
| <b>SSURGO</b> | <b>Soil Survey Geographic</b>                                          |
| <b>TIN</b>    | <b>Triangulated Irregular Network</b>                                  |
| <b>USACE</b>  | <b>U.S. Army Corp of Engineers</b>                                     |
| <b>USCS</b>   | <b>Unified Soil Classification System</b>                              |
| <b>WI</b>     | <b>Wetness Index</b>                                                   |
| <b>WRW</b>    | <b>Warroad River Watershed</b>                                         |
| <b>WRWD</b>   | <b>Warroad River Watershed District</b>                                |

# 1 INTRODUCTION

The Warroad River, located in Northern Minnesota, is the second largest U.S. tributary to Lake of the Woods (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 were sufficient to 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 to 4 feet in depth. The narrow constricted main channel generally ranges in depth from 5 to 8 feet deep. As a result of this sedimentation, the U.S. Army Corps of Engineers (USACE) has undertaken a number of 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 in compliance 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.

The goals of the Warroad River Sediment Source Assessment project were to:

- Estimate the annual average sediment load depositing within the Warroad Harbor;
- Quantify the amount of sediment contributed to the Warroad River from overland sources in its watershed;
- Utilize Light Detection and Ranging (LiDAR) and other geographic information system (GIS) data to perform terrain analysis within the Warroad River Watershed (WRW);
- Identify critical management areas within the watershed to prioritize the placement of best management practices (BMPs) for reducing sediment loading from overland sources; and
- Compare the average annual sediment loading into the Warroad Harbor to the estimated loading from overland sources.

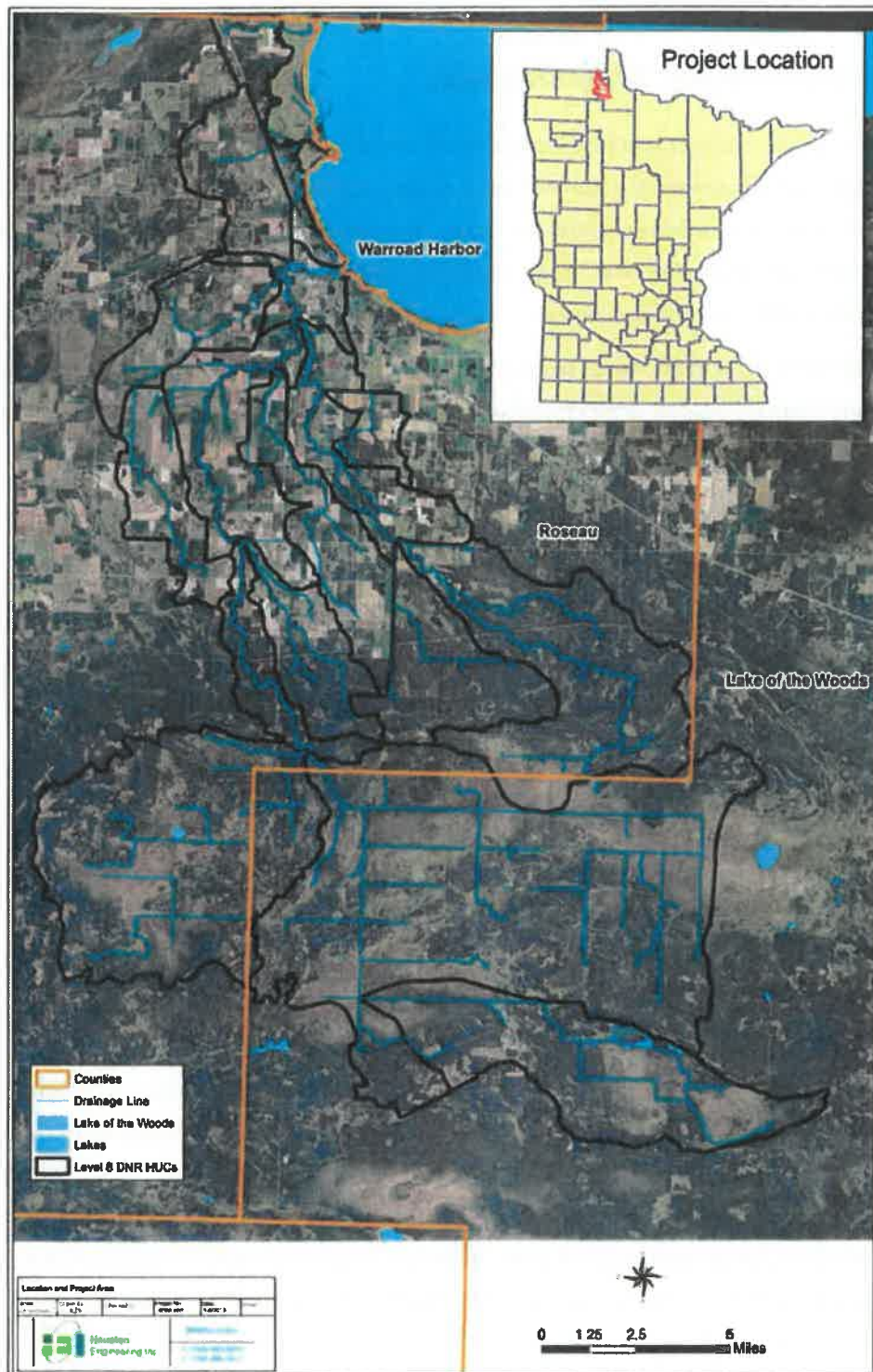
The study is funded by contributions from: the Board of Soil and Water Resources (BWSR), the Warroad River Watershed District (WRWD), Roseau County and the City of Warroad.

## **1.1 Study Area**

The WRW comprises an area of approximately 254 square miles in the northern Minnesota counties of Roseau and Lake of the Woods. The WRW is contained within the US Geological Survey HUC (Hydrologic Unit Code) # 09090009 along with approximately 6 additional square miles of area that drain directly to LOW. Figure 1 shows the WRW boundary.



Figure 1. Warroad River Watershed.



## **2 WARROAD HARBOR SEDIMENTATION**

One goal of this project was to estimate the average annual amount of sediment depositing in the Warroad Harbor, using bathymetric surveys. The Warroad Harbor receives sediment inputs from the Warroad River as well as from in-lake wave action near the mouth of the harbor. Processes within the harbor that lead to erosion and/or deposition may include wave action, boating, and vegetation. Sediment outputs from the harbor include sediment transport into LOW and maintenance dredging.

Sedimentation within the Warroad Harbor can be used as one estimate of the amount of sediment entering the system. For this study, historic bathymetry records in the harbor were examined in an attempt to estimate long-term sediment dynamics within the area.

### **2.1 Methodology**

The St. Paul District of the USACE conducts hydrographic surveys on select channeled rivers and lake harbors in Minnesota. The purpose of these surveys is to provide bathymetric maps that document changes in channel conditions, for use in dredging and engineering studies. Such surveys have routinely been conducted on the Mississippi River channel; minor waterways, such as the Warroad Harbor, are surveyed on a less frequent basis.

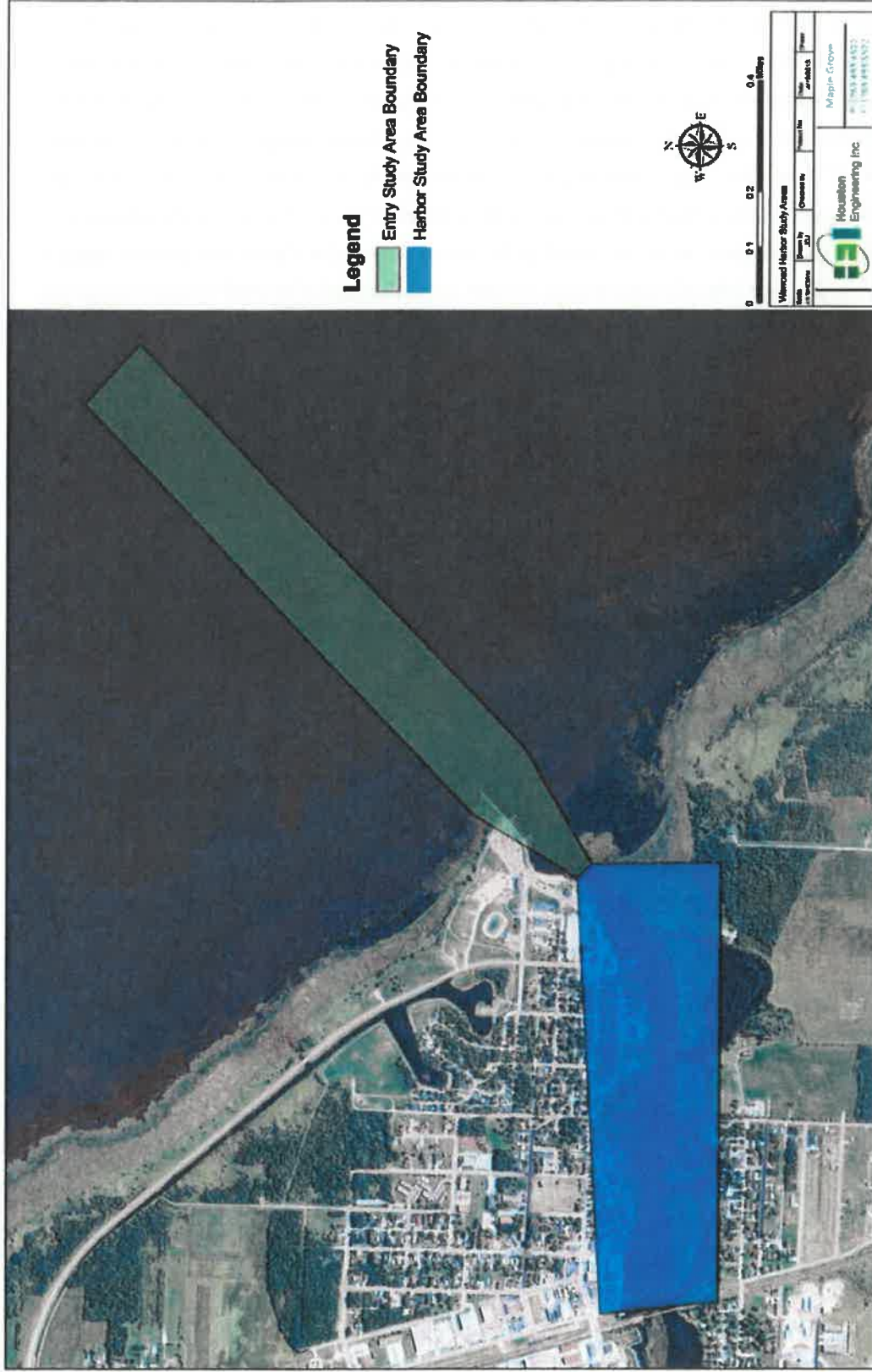
Five sets of bathymetry data for the Warroad Harbor were obtained from the USACE. The data collection dates for the bathymetric surveys are:

- July 30, 2002;
- September 4, 2003;
- April 20, 2005;
- June 11-12, 2007; and
- 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. Houston Engineering, Inc. (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 loosely 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. Harbor study area boundaries

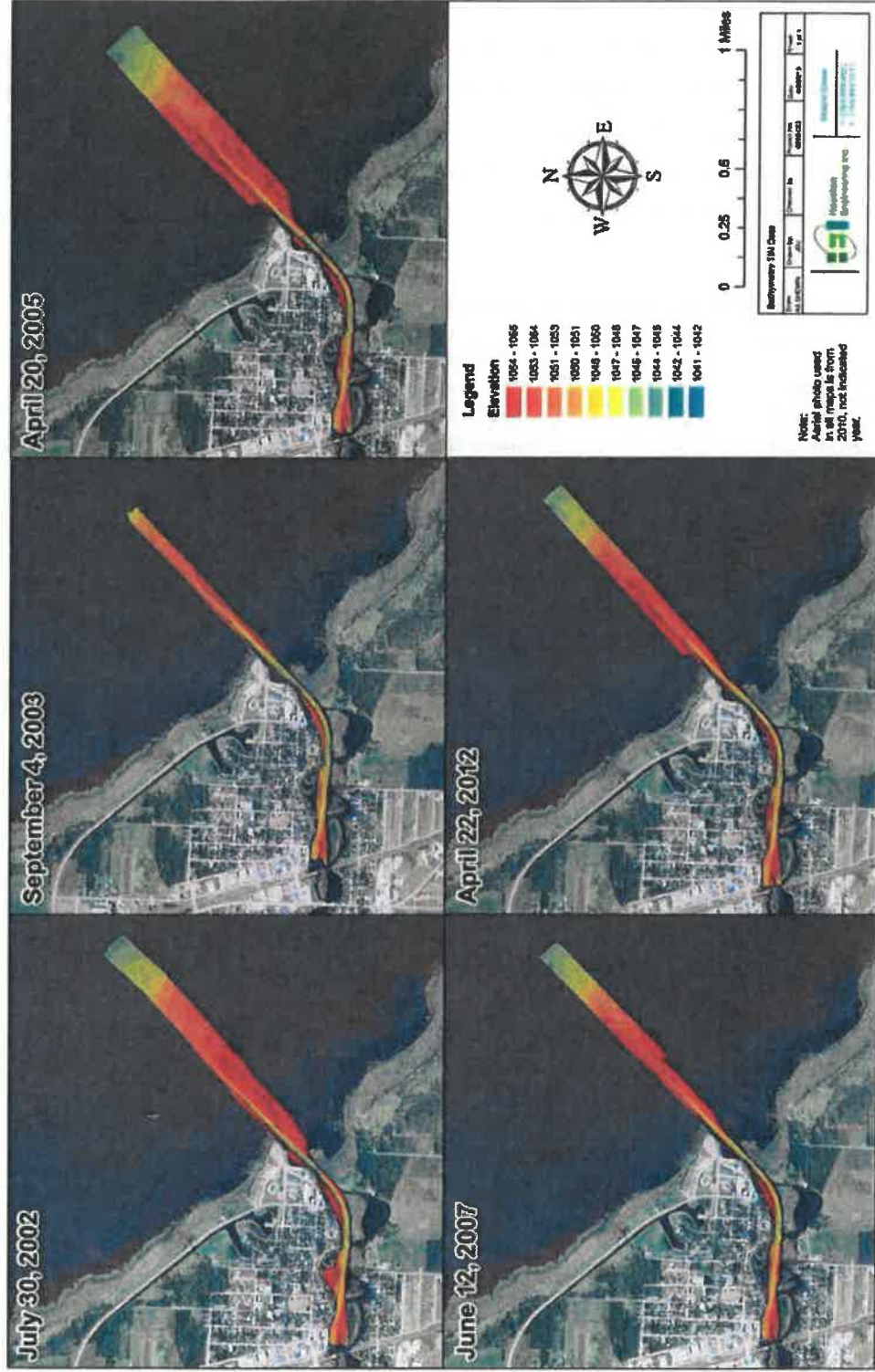


GIS methods were used to transform each USACE-provided dataset into a triangulated irregular network (TIN), representing the bottom surface (i.e., bathymetry) of the harbor and the entry. The resultant surfaces for each provided dataset are shown in Figure 3. These TINs were then used to create raster 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; and
- July 30, 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 using the total erosion/deposition volumes and total areas of each raster comparison. 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 mapping for the Wierwood Harbor.



## 2.2 Results

Areas of net erosion and deposition, in the Warroad Harbor, are shown for each analyzed time period in **Figure 4**; **Figure 5** shows the results for the entry. Erosional values indicate that the bathymetric surface was higher at the beginning of the analyzed time period than it was at the end; depositional values indicate the opposite. 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                                    | 45.00           | -8.77        | Erosion               |
|            | 09/04/03 – 04/20/05 | 33.39                                     | 46.76           | 5.27         | Deposition            |
|            | 04/20/05 – 06/12/07 | 23.60                                     | 68.47           | 1.93         | Deposition            |
|            | 06/12/07 – 04/22/12 | 5.73                                      | 44.80           | 0.32         | Deposition            |
|            | 07/30/02 – 04/22/12 | 17.16                                     | 42.55           | 0.50         | 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                                     | 75.10           | -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.

The amount of sediment entering/exiting the Warroad Harbor can be estimated as a function of the amount of sediment that deposits and/or erodes. This (sediment) flux in and out of the study areas is caused by a number of factors, including sediment transport via the Warroad River or by means of wave action from LOW. Sediment

removal from a system can also be anthropogenic in nature, such as removal by dredging. From March 12 – April 2, 2007, the USACE dredged a portion of the Warroad Harbor entry so as to facilitate boat entry into and out of the area. The dredging included the removal of 8,900 cubic yards of sediment (USACE, 2007a and 2007b).

Using the long-term average annual deposition rate (2002 through 2012) of 0.50 in/yr, 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. Ideally, the most accurate way to determine the density of deposited material is to collect and analyze a soil core from the harbor itself; no data of this type is available for Warroad Harbor. Instead, 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 LOW, indicates an average density of approximately 31.2 lb/ft<sup>3</sup> (0.5 g/cm<sup>3</sup>) 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<sup>3</sup> (1300 lbs/yd<sup>3</sup>) (NRCS, 2013). For this study, both of the referenced densities are used to report a range of depositional loading based on the bathymetric data. The results of the mass loading, as determined using the bathymetry data, are highly dependent on the density of the sediments in Warroad Harbor.

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 have been 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.



Figure 4. Net Erosion and Deposition in Warroad Harbor.

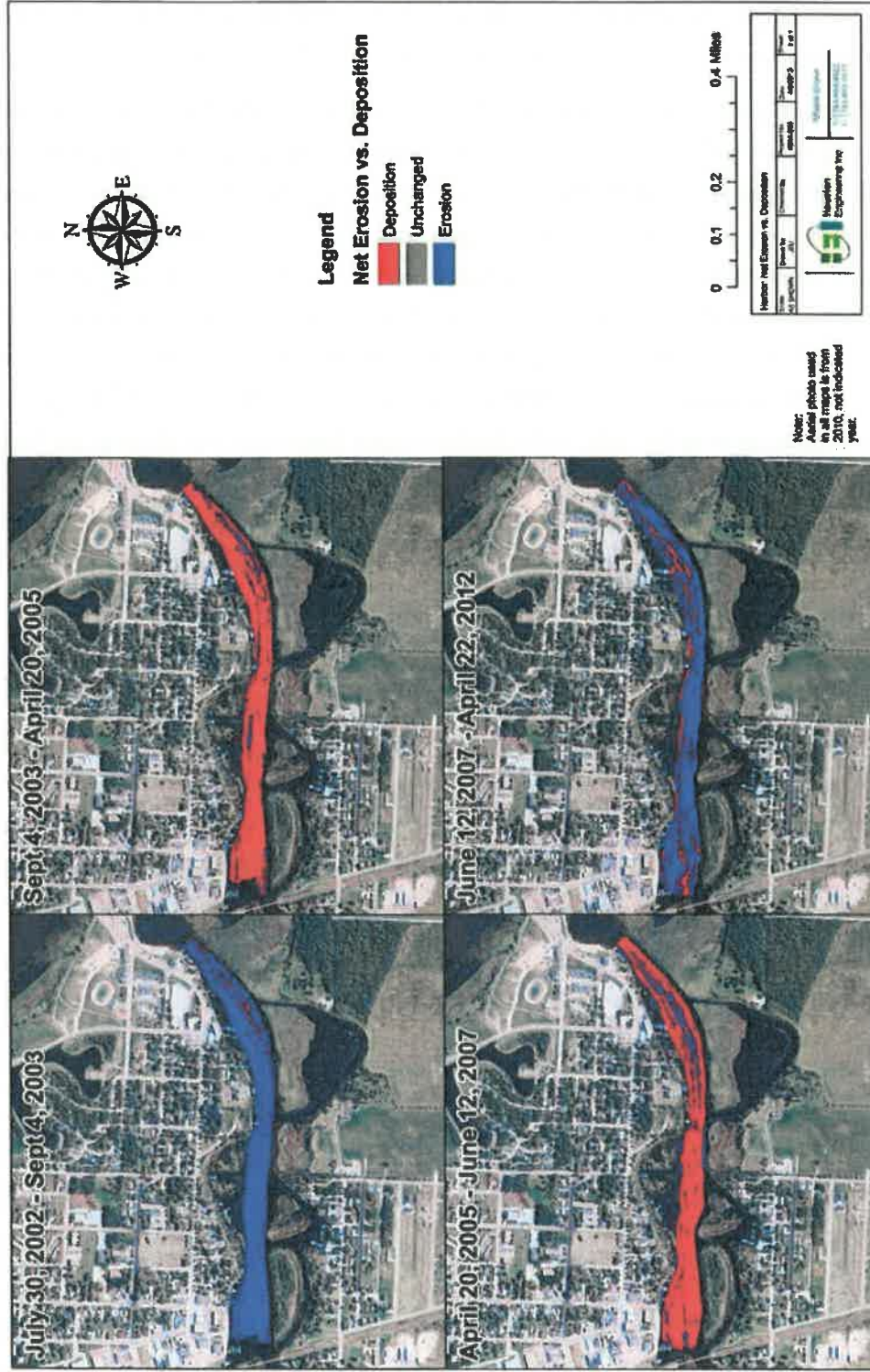
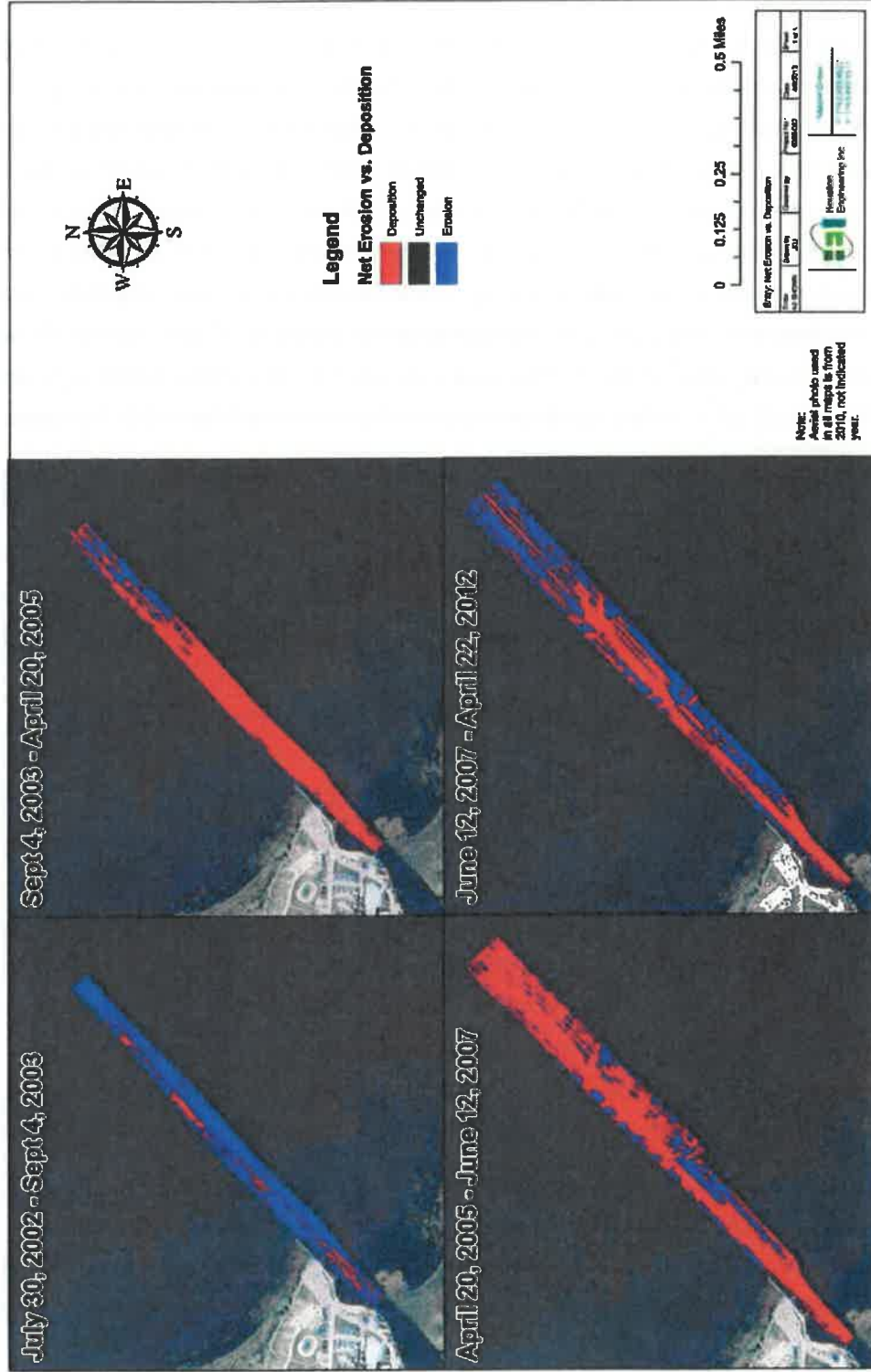


Figure 5. Net Erosion and Deposition in Warroad Harbor Entry.





## 2.3 Additional Data

In December of 2005, the USACE released an economic analysis of the maintenance of the small harbors on LOW (URS, 2005). The report identifies the economic and social impacts associated with maintenance dredging of four harbors (including Warroad Harbor) and examines the cost-benefit of these activities. The report includes historic dredging records for 1975, 1983, and 1996. The report indicates that 65,000 cubic yards (cy) of sediment were removed from Warroad Harbor in 1975; 43,500 cy were removed in 1983; and 65,560 cy were removed in 1996. The dredging records were used to make estimates of sedimentation rates and critical threshold dredging volumes for the Warroad Harbor. These estimates make the assumption that the sedimentation rate in the Harbor is equal to the amount of material removed divided by the time since the previous dredging. Using this method, the report estimates the average harbor sedimentation rate to be 5,438 cy per year from 1975-1983 and 5,043 cy per year from 1983-1996. Dredging volumes assume maintenance of a minimum harbor depth required for boat access.

These estimates, when converted to tons per year via the same density methods applied above, result in loading estimates ranging from 2,124 to 3,531 tons per year; this range is the same order of magnitude but larger than the estimate made via bathymetric methods. However, the estimates made in the USACE economic analysis assume that dredged material volumes are representative of the newly deposited sediment and that all other conditions outside of the dredged area remain unchanged; based on bathymetric comparisons in Figure 4, this is likely not the case.

## 3 OVERLAND SEDIMENT SOURCES

The Warroad River is a primary source of sediment loading into the Warroad Harbor. Sediment transported by the river originates from various sources, including overland rill/interill erosion in subwatersheds draining to the river, gully erosion draining to the river and in-stream processes occurring within the river itself (e.g., bank sloughing). Varying proportions of this sediment are transported through the catchments, down the river, and eventually into the harbor and deposited. This section summarizes the methods used to quantify the overland rill/interill erosion sources of sediment within the WRW, estimating overland sediment loading and transport, and checking the loading accuracy at various downstream points. Finally, this section presents an estimate of the resulting sediment loading at the Warroad Harbor as a result of overland rill/interill erosion. Gully erosion is not estimated as part of this analysis.

Results of this section are then compared to the average annual harbor sediment loading rate, estimated in Section 2, to gain a sense of the role that overland rill/interill erosion plays in sedimentation issues in the harbor. Much of the methodology applied in estimating overland rill/interill erosion in the WRW, using GIS terrain analysis,

is derived from the *WRW GIS Terrain Analysis Report* (i.e., Terrain Analysis Report) submitted to the WRWD (HEI, 2013a). The report is included in **Appendix A**.

### 3.1 Methodology

The methodology used to determine overland sediment contribution is a continuation of the sediment yield work described in the Terrain Analysis Report, included in **Appendix A**. The Terrain Analysis Report describes, in depth, the methods briefly summarized in **Section 3.1.1** through **Section 3.1.3**. Additional methods used to determine sediment routing and transport to the Warroad Harbor are described in detail in this report.

The general methodology used to determine the sediment loading due to rill/interill erosion to the Warroad Harbor is as follows:

- Use the Revised Universal Soil Loss Equation (RUSLE) to determine the maximum potential sediment yield from each overland catchment in the watershed;
- Determine, validate, and apply an appropriate Sediment Delivery Ratio (SDR) to the RUSLE yield results to determine the sediment load that reaches flowlines or channels within the catchments; and
- Determine and apply an appropriate channel routing function to determine the fraction of sediment load that is ultimately transported downstream to the Warroad Harbor.

The following sections describe this methodology in detail.

#### 3.1.1 Terrain Analysis

Several data sources were used to perform the initial terrain analysis. The data sources are included in **Table 2**.

**Table 2. Terrain analysis data sources.**

| <b>Data</b>                          | <b>Source</b>                                                                                                                                                   |
|--------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Elevation                            | State of Minnesota's LIDAR elevation data                                                                                                                       |
| Rainfall<br>Frequency/Duration       | US Weather Bureau's Rainfall Frequency Atlas of the United States (Technical Paper No. 40)                                                                      |
| Land Use/Land Cover                  | 2006 National Land Cover Dataset (NLCD) (land cover)<br>The National Agricultural Statistics Service (NASS) 2011 Cropland Data Layer (CDL) (land use practices) |
| Soils                                | NRCS Soil Survey Geographic (SSURGO) Database                                                                                                                   |
| Rainfall-Runoff (R-factor)<br>Values | NRCS MN Field Guide                                                                                                                                             |

A digital elevation model (DEM) was created from the LIDAR data; this DEM then underwent hydrologic conditioning, an iterative process involving hydrologic interpretation and DEM modification. The result of this step is a highly-accurate DEM, used to study how water (and any pollutants that move via overland surface water flow) moves through the study area's landscape.

Non-contributing areas in the DEM were determined based on a 10-year recurrence, 24-hour runoff event for the study area (3.4 inches of precipitation). This task also involves an iterative process, performed by computing surface water runoff volumes across the watershed and identifying non-contributing areas as those with depressions large enough to hold their contributed runoff without excesses continuing downstream. The output of this process is a hydrologically-reconditioned DEM that accounts for non-contributing areas, referred to as the hydroDEM. This hydroDEM was delivered to the WRWD and checked for accuracy against local knowledge of flowpaths and hydrography in the area. A figure of the WRW hydroDEM, showing non-contributing areas, can be found in the Terrain Analysis Report in **Appendix A**.

### **3.1.2 Stream Power Index**

Stream Power Index (SPI) values were computed across the study area (as a function of contributing drainage area and slope) using raster data described in **Table 2**. The result of this simple analysis is to locate areas with high potential for erosion due to gully formation. Results of the analysis are presented both on a flowpath basis, as well as averaged by overland catchment (indicating areas with higher and lower likelihood of experiencing gullies within the watershed). A figure showing mean SPI ratings for each overland catchment in the WRW can be found in the Terrain Analysis Report in **Appendix A**.

### **3.1.3 Revised Universal Soil Loss Equation**

The RUSLE was applied across the WRW to determine average annual potential sediment yield as a result of rill/interrill erosion. Results (computed using the hydroDEM) are a 3X3 meter raster dataset of predicted average annual sediment yields from the landscape.

Since 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), a SDR is used to reduce the potential sediment yield computed with RUSLE and estimate an effective sediment yield from each raster cell, the amount that actually makes it to nearest flowline. Three different SDR methods were investigated for use in this project (as discussed in **Section 3.1.4**); ultimately, the MN Phosphorus Index approach was chosen for computing the SDR. The Terrain Analysis Report in **Appendix A** includes a figure showing the estimated effective sediment yields (tons/yr) for each overland catchment in the WRW.

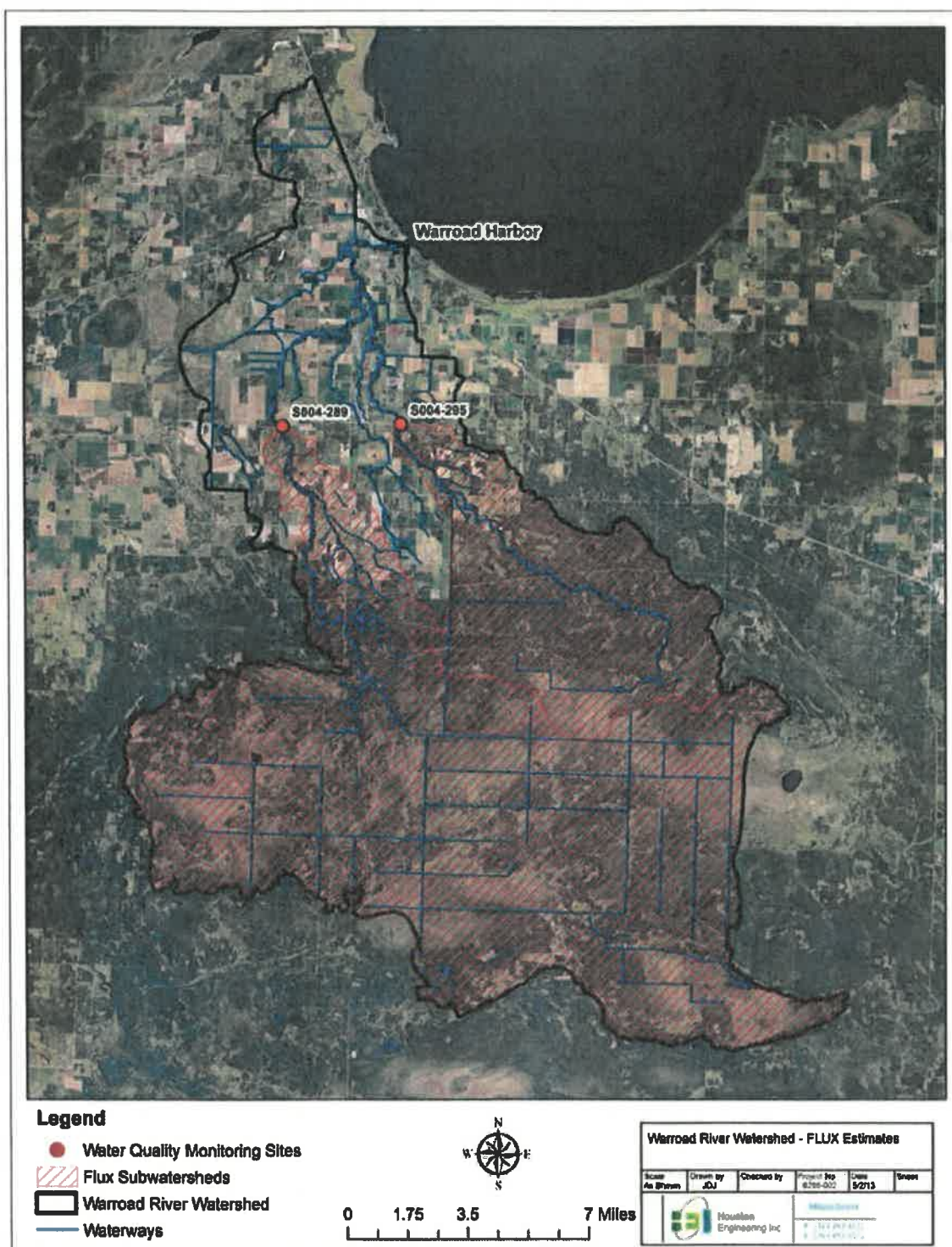
### **3.1.4 Sediment Transport and Routing**

As mentioned, not all sediment that is yielded from the WRW is transported into the nearest flowlines. Similarly, not all sediment that enters a flowline is transported downstream and deposited in the Warroad Harbor. In order to use the results of the RUSLE analysis to estimate the amount of sediment from overland rill/interrill erosion that enters the Warroad Harbor, various sediment transport and routing methods were used. This section describes the

methods that were investigated for use in this work and indicates those that were ultimately chosen, along with their results.

To assess the accuracy of the various sediment transport and routing methods, their predicted results (reported as sediment loading in the streams/rivers) were compared to those estimated using empirical water quality and flow data at two water quality sites in the WRW. The sites used for this comparison are S004-289 and S004-295, and are shown in Figure 6. Empirical data from these monitoring locations were used in a USACE FLUX model to estimate annual sediment loading at these two locations. The detailed methodology used for performing these calculations was completed and is described in a recent study in the LOW Watershed (HEI, 2013b).

Figure 6. Water quality sites used in FLUX loading estimates.



#### **3.1.4.1 Sediment Delivery Ratio**

A 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 and there are numerous ways to estimate SDR. For this project, three different methods of computing SDR were evaluated. The methods are described below.

##### **Minnesota Phosphorus Index SDR**

The Minnesota Phosphorus Index (MN P-Index) 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:

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

##### **Velocity SDR**

An alternative SDR relationship is described by Dickenson et al, 1986. This relationship expresses the SDR as a function of the overland flow velocity and downstream flow length to a concentrated flow path. The SDR is computed using the following equation:

$$SDR = a \frac{\text{Velocity}}{\text{Downstream Flow Length}}^b$$

Variables  $a$  and  $b$  are coefficients used to calibrate the relationship. In this work, the variables were set to 0.1 and 0.5, respectively, based on data found in a previous study that uses the velocity SDR approach (Dickinson et al, 1986). To implement this method in the WRW, a travel time raster was computed using a GIS tool developed by the MnDNR. The tool uses Manning's Equation, estimating  $n$  values based on land use and slopes computed from the DEM to determine the velocity for each individual grid cell in the project area. The grid velocities along with the downstream flow length are then used to compute the SDR as shown in the above equation.

##### **Wetness Index SDR**

Another variation of the SDR uses a relative term called Wetness Index (WI) to replace the depth term in the Manning's Equation portion of the Velocity SDR relationship. This variation is described by May et al, 2005. The WI provides an identification of areas more likely to generate surface flow and thus the greater rill and interrill erosion associated with higher runoff. The WI is computed by taking the natural log of the ratio of drainage area to slope:



$$WI = \ln \frac{\text{Drainage Area}}{\text{Slope}}$$

The SDR equation can then be described as:

$$SDR = a \frac{WI \times \text{Slope}^{0.5} \times n^{-1}}{\text{Downstream Flow Length}}^b$$

Variable  $n$  is the roughness of the drainage path, as employed in the Manning's Equation. As with the velocity SDR, the variables  $a$  and  $b$  were set to 0.1 and 0.5, respectively.

#### **3.1.4.2 Channel Routing**

Once sediment enters a flow path, a certain portion of it will be transported downstream while a portion will settle out and deposit within the stream system. For this study, the ratio of channel sediment load (i.e., that in the flow path) that is transported downstream was estimated using an exponential decay function. The function is described in Williams, 1977. Physical inputs to the channel routing function include travel time to the downstream location and the estimated median sediment particle diameter. The function can be described as:

$$\text{Ratio of Sediment Delivered to Down Stream Point} = e^{2-\beta t \overline{d_{50}}}$$

Where  $t$  is the travel time to the downstream location;  $\beta$  is a channel routing coefficient; and  $\overline{d_{50}}$  is the mean sediment particle diameter. The travel time raster is derived from the velocity raster (developed under the Velocity SDR) and is used as the estimate for the time component of the equation. The raster grid velocities in each grid cell are accumulated downstream to compute travel times along the channelized flow paths.

Sediment samples taken in the South Branch of the Buffalo River Watershed in the southern Red River Valley near Moorhead, MN were used to select a  $\overline{d_{50}}$  of 0.1 mm. A report prepared by Lauer et al, 2006 presented particle size distributions from the sediment samples. The channel routing coefficient,  $\beta$ , was assumed to be 0.2 based on work by Williams, 1977.

#### **3.1.4.3 Validation and Sensitivity Analysis**

Sensitivity analysis was performed on both the calibration coefficients in the Velocity and WI SDRs as well as on the channel routing coefficient. A range of values were entered to test both the sensitivity of the coefficients themselves as well as the effect on estimated loading at the monitoring locations shown in Figure 6. Results from the sensitivity testing can be found in Section 0.

#### **3.1.5 Harbor Loading**

As a final step in this analysis, the RUSLE-estimated average annual (effective) sediment yield values across the WRW were combined with the respective SDRs and channel routing ratios and summed over the entire watershed

to determine the estimated average annual sediment load into the Warroad Harbor due to overland rill/interill erosion.

## **3.2 Results**

The following section presents the results of the methods used to determine sediment loading into the Warroad Harbor via overland (rill/interill erosion) sediment yields from the WRW.

### **3.2.1 Terrain Analysis and RUSLE**

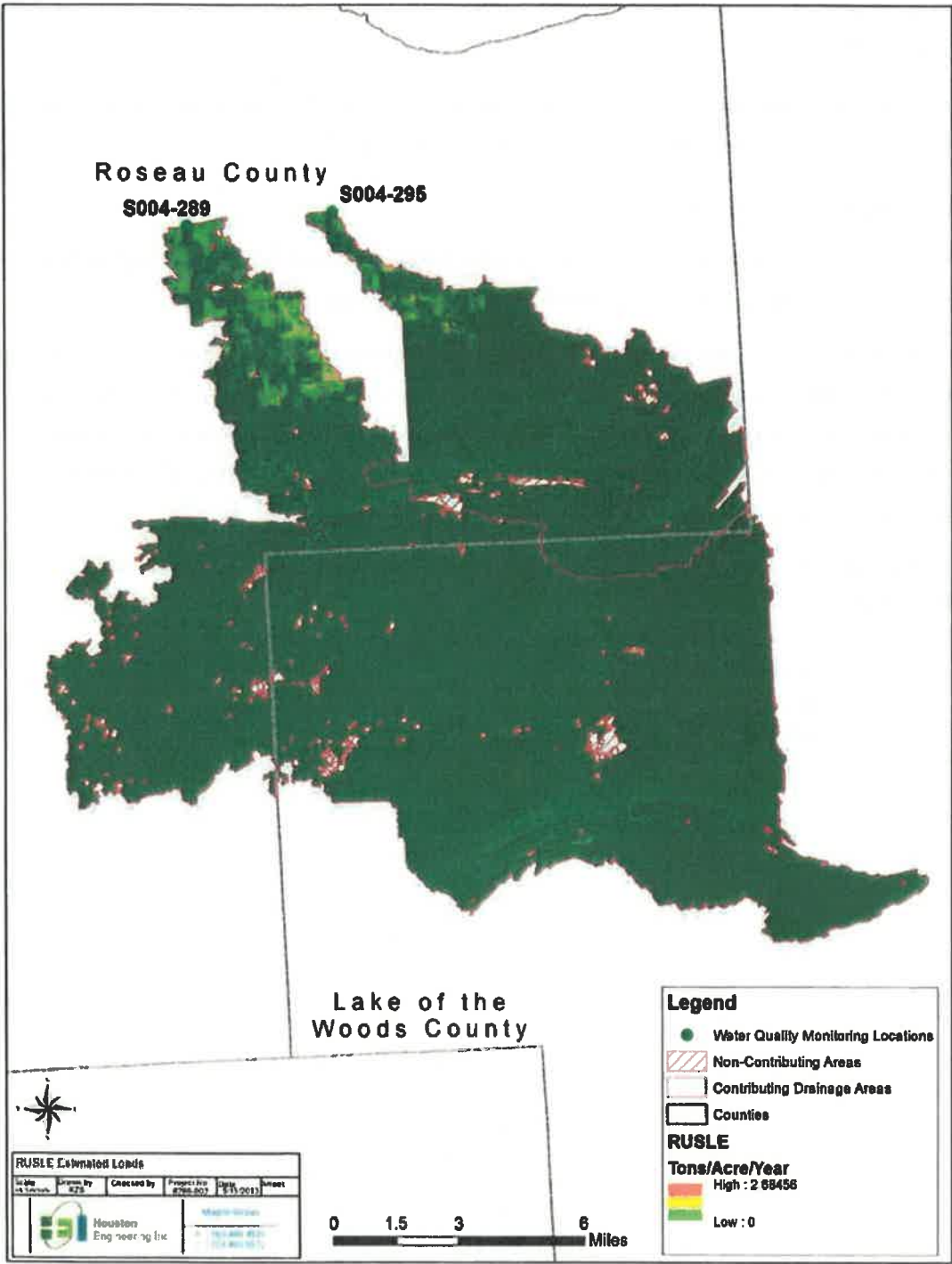
The terrain analysis results are generally summarized in the Terrain Analysis Report included in **Appendix A**. This report contains individual figures showing the RUSLE and SPI values in rasters of the WRW.

The results of the RUSLE analysis within the subwatersheds draining to the water quality monitoring sites in **Figure 6** are shown in **Table 3** and in **Figure 7**. These results show, in general, similar overland erosion characteristics (estimated as effective sediment yield) within the two subwatersheds. The drainage area of the S004-289 subwatershed is much larger than that to S004-295, resulting in a larger annual total yield of sediment being created within this area.

**Table 3. Estimated average annual soil loss using RUSLE (i.e., effective sediment yield) in subwatersheds upstream of S004-289 and S004-295.**

| <b>Subwatershed</b> | <b>Total<br/>(tons/year)</b> | <b>Area<br/>(square miles)</b> | <b>Average<br/>(tons/acre/year)</b> |
|---------------------|------------------------------|--------------------------------|-------------------------------------|
| S004-289            | 1,228                        | 143                            | 0.013                               |
| S004-295            | 381                          | 42                             | 0.014                               |

Figure 7. RUSLE analysis results for catchments draining to monitoring locations.



### 3.2.1.1 FLUX Estimate Comparison

The FLUX-estimated average annual sediment loads at the two monitoring locations shown in **Figure 6** are summarized in **Table 4**. These results were compared to the sediment loading results determined via RUSLE and the various SDR/channel routing methods. The comparison was made to determine: 1) an appropriate SDR method to use; and 2) appropriate coefficients for SDR and channel routing methods.

**Table 4. FLUX-estimated average annual sediment loads (tons/year) at Warroad River monitoring sites.**

| Monitoring Location | Sediment Loading (tons/year) |
|---------------------|------------------------------|
| S004-289            | 696                          |
| S004-295            | 119                          |

Converting the FLUX estimates to unit loadings of sediment from the watersheds upstream of these monitoring sites, results in values of 4.4 tons/mile<sup>2</sup>/year (1.9 tons/km<sup>2</sup>/year) upstream of S004-289 and 2.8 tons/mile<sup>2</sup>/year (1.1 tons/km<sup>2</sup>/year) upstream of S004-295. These values compare relatively well to sediment yield values computed by Klimetz and Simon in a 2009 study of sediment yields across the State of Minnesota. Klimetz and Simon report a mean suspended-sediment yield of 2.1 tons/km<sup>2</sup>/year for the Northern Lakes and Forest Ecoregion; the ecoregion that most closely represents conditions in the WRW given that the Northern Minnesota Wetlands Ecoregion was not represented due to lack of data.

### 3.2.1.2 Sediment Delivery Ratio

The three SDR methods described in **Section 3.1.4.1** were used to calculate SDR values in the S004-289 and S004-295 subwatersheds. The resultant distributions of SDR values across these two subwatersheds are summarized in **Table 5**. As shown, the various methods produce significantly different results.

**Table 5. SDR distributions, for various SDR methods, within the S004-289 and S004-295 subwatersheds.**

|                             | MN-P Index SDR | Velocity SDR | Wetness Index SDR |
|-----------------------------|----------------|--------------|-------------------|
| Mean                        | 0.231          | 0.002        | 0.040             |
| Median                      | 0.233          | 0.002        | 0.050             |
| Standard Deviation          | 0.108          | 0.006        | 0.88              |
| Maximum                     | 1.00           | 0.425        | 4.98              |
| Minimum                     | 0.015          | 0            | 0                 |
| 25 <sup>th</sup> Percentile | 0.160          | 0            | 0                 |
| 75 <sup>th</sup> Percentile | 0.306          | 0.007        | 0.110             |

Combining the various SDR rasters with estimated sediment yields (estimated using RUSLE) results in estimates of the amount of sediment reaching the flowpaths in the areas upstream of S004-289 and S004-295. **Table 6** summarizes these results.

**Table 6. Total effective sediment loads (amount reaching a flowline) upstream of monitoring sites S004-289 and S004-295.**

| Monitoring Site | MN-P Index SDR<br>(tons/yr) | Velocity SDR<br>(tons/yr) | Wetness Index SDR<br>(tons/yr) |
|-----------------|-----------------------------|---------------------------|--------------------------------|
| S004-289        | 309.9                       | 3.7                       | 59.4                           |
| S004-295        | 103.6                       | 1.6                       | 20.3                           |

### **3.2.1.3 Channel Routing**

Finally, the estimated average annual sediment loading at the monitoring sites was calculated by applying the channel routing equation, shown in Section 3.1.4.2. The results are presented in Table 7 for each of the SDR methods.

**Table 7. Estimated average annual sediment load at monitoring sites S004-289 and S004-295.**

| Monitoring Site | MN-P Index SDR<br>(tons/year) | Velocity SDR<br>(tons/year) | Wetness Index SDR<br>(tons/year) |
|-----------------|-------------------------------|-----------------------------|----------------------------------|
| S004-289        | 172.0                         | 2.1                         | 33.1                             |
| S004-295        | 73.4                          | 1.1                         | 14.4                             |

Based on these results, the MN-P Index SDR method was chosen to estimate the sediment loading delivered to flow paths. A comparison of the FLUX estimates in Table 4 and the sediment loading in Table 7 shows the MN-P Index loading most closely matching the FLUX estimates and estimating that approximately 25-60% of the observed loading at these locations may be coming from overland rill/interill sources. It is worthy to note that there are significant factors that could be affecting these estimates:

- The large amount uncertainty associated with the FLUX estimates (see HEI, 2013b for more details);
- The fact that RUSLE estimates only the amount of sediment contributed from overland rill/interill erosion, not sediment that originates from gully erosion or of in-channel sediment sources; and
- Uncertainty in the RUSLE calculations and routing.

Despite these uncertainties, the results of this analysis provide some insight on sediment sources in the area.

In addition to the work that was done to determine the most appropriate SDR method to use in this study, sensitivity analyses were also performed on the Velocity and Wetness Index SDR coefficients and the channel routing coefficient (in the sediment routing function). Discussion of that work is not included in the main body of this report, but is included as **Appendix B**.

### 3.2.2 Estimated Sediment Delivery to Warroad Harbor

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 8 shows the result.

Table 8. 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                    |

## 4 COMPARISON OF SEDIMENT DEPOSITED AND CONTRIBUTED

Based on the harbor bathymetry data evaluated in Section 2, the estimated range of average annual sediment load deposited in the Warroad Harbor is approximately 1,302 to 2,008 tons. The analysis performed in Section 3 estimates that approximately 887 tons of this sediment is from overland rill/interill erosion within the WRW, constituting roughly 44-68% of the sediment load. The remaining percentage is likely due to some combination of in-channel erosion, gully erosion, and sources originating from the LOW.

## 5 IDENTIFYING PRIORITY MANAGEMENT AREAS

Although results of this study show that overland rill/interill erosion is not the only contributor of the sediment being deposited in the Warroad Harbor, it is a significant source. Results of the GIS terrain analysis described in Section 3.1.1 through Section 3.1.3, and detailed in the Terrain Analysis Report in Appendix A, can be used to prioritize areas within the WRW for overland sediment management. This analysis was completed and is detailed in the Terrain Analysis Report in Appendix A. It is summarized here for reference.

Results of the GIS terrain analysis work in the WRW include SPI values, identifying areas with high likelihood of gully erosion, and RUSLE-estimated effective sediment yields, identifying areas with highly erosive physical and management characteristics. In order to use these results to prioritize areas in the WRW for erosion management, the SPI and RUSLE values were ranked from highest to lowest values (indicating areas of most vs. least concern) and then averaged for each overland catchment. The overland catchment average SPI scores were then ranked to identify those areas in the watershed that are of most concern for gully erosion. Similarly, the overland catchment average effective sediment yield scores (i.e., RUSLE scores) were ranked to identify those areas of most concern for rill/interill erosion. Figure 3 and Figure 4 in Appendix A show the results of this analysis.



In addition to presenting the results of the SPI and RUSLE analyses independently, a combined score was also computed. In this case, high scores correlate to overland catchments that have areas where a high likelihood of gully erosion exists as well as a high value of estimated sediment yield from overland flow. **Figure 5 in Appendix A** shows the SPI and RUSLE combined results for each overland catchment.

## **5.1 Priority Management Areas in Agricultural Areas**

While **Figure 5 in Appendix A** identifies combined SPI/RUSLE results for the entire WRW, the nature of the RUSLE calculation and resolution of the scoring tends to produce results that primarily identify the agricultural northern portion of the watershed as high sediment yields and the forested southern portion of the watershed as having much lower sediment yields. While this is likely the case, it does little to refine and identify target management catchments within the agricultural portion of the WRW. Finer analysis of the agricultural portion of the watershed was done by refining the scoring solely in the agricultural areas. **Figure 8 through Figure 10**, below, show the refined SPI, RUSLE, and SPI/RUSLE combined scores, respectively, for the agricultural portions of the WRW. These figures can be used to identify high yield agricultural catchments within the watershed and can aid in BMP targeting and placement.

Figure 8. Catchment mean SPI scores for agricultural areas in the WRW.

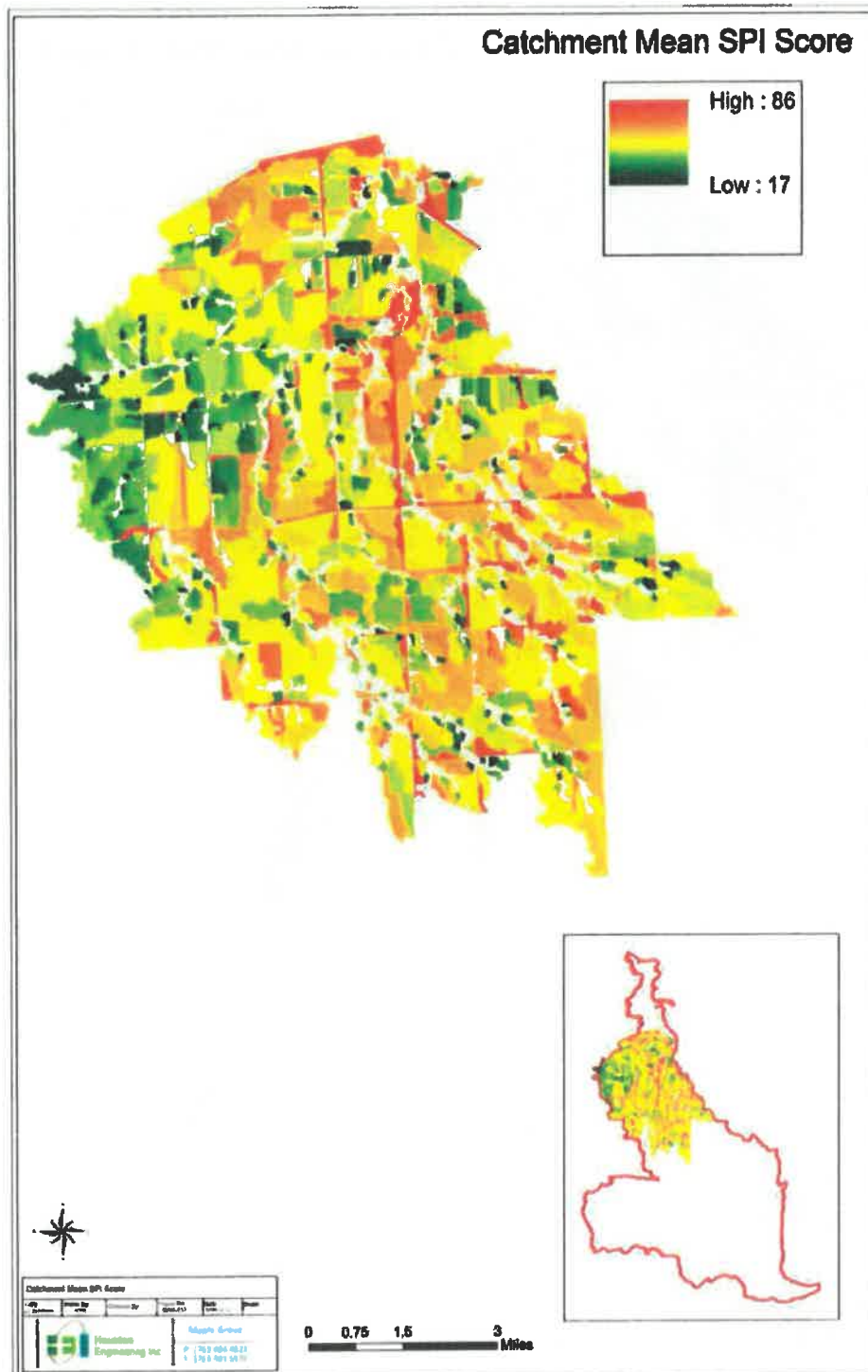
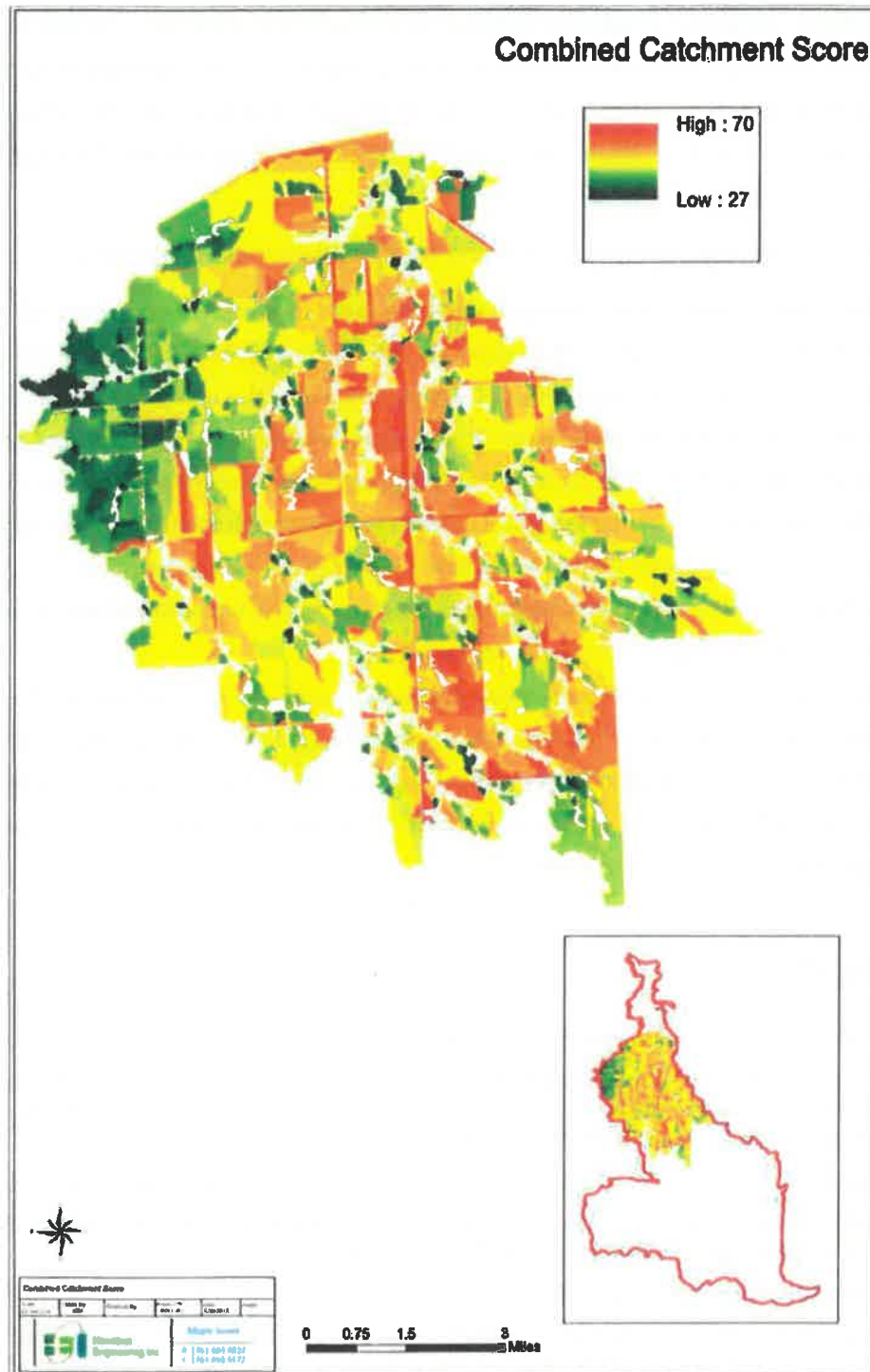


Figure 9. Catchment mean RUSLE scores for agricultural areas in the WRW.



Figure 10. Combined catchment scores for agricultural areas in the WRW.



## **6 RECOMMENDATIONS FOR FUTURE WORK**

This report presents a comparison of sediment loading to the Warroad Harbor estimated via two methods: historic bathymetric data collected in the harbor and overland rill/interill erosion within the watershed. While the results of this work provide guidance and estimates on the amount of sediment being deposited in the harbor and some potential sources, there is much uncertainty involved with various portions of the estimates and not all sediment sources to the harbor were explored.

HEI recommends two potential opportunities to improve the estimates presented in this report.

- Collect additional data on other possible sources of sediment not examined in this report. These sources include in-channel erosion, gully erosion within the watershed and contributions to/from LOW. This report only compares what has been deposited in the harbor to what is estimated from overland rill/interill erosion; any additional sediment is assumed to come from other sources. According to the work presented here, these sources could contribute a significant amount of sediment. The quantification of these sources would allow for a sediment balance to be completed on the harbor and reduce uncertainty in the estimates. WRWD officials have noted a perceived large contribution of in-channel erosion to the sedimentation in Warroad Harbor. It is recommended that additional study of sediment sources in the area begin with in-channel erosion.
- Improve the accuracy of the harbor sediment density value used to estimate sediment loading. The sediment density used in this study is given as a range of values, based on data collected in other (similar) studies in the area. The collection and analysis of sediment cores in Warroad Harbor would give a more accurate analysis of sediment densities specific to the study area and, therefore, reduce the uncertainty involved with that portion of the analysis.

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## **APPENDIX A – TERRAIN ANALYSIS REPORT**