Warroad River Watershed Sediment Source Assessment Project

Final Report July 29, 2013

Houston Engineering Inc.

Warroad River Watershed District

WRWD

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Acronyms and Abbreviations List

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

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:

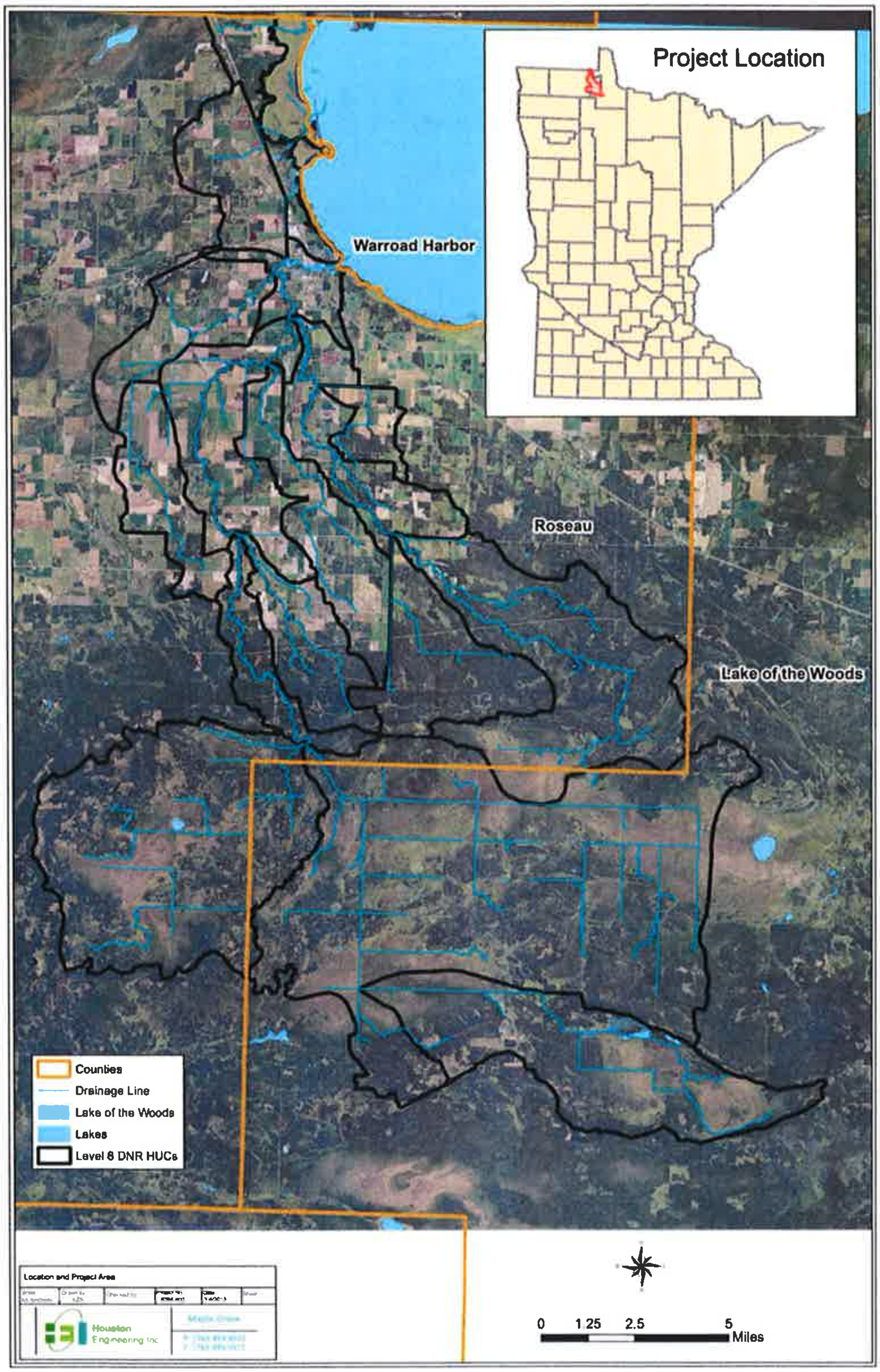
- Estimate the annual average sediment load depositing within the Warroad Harbor;
- Quantify the amount of sediment contributed to the Warroad River from overland sources in its watershed;
- Utilize Light Detection and Ranging (LiDAR) and other geographic information system (GIS) data to perform terrain 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.

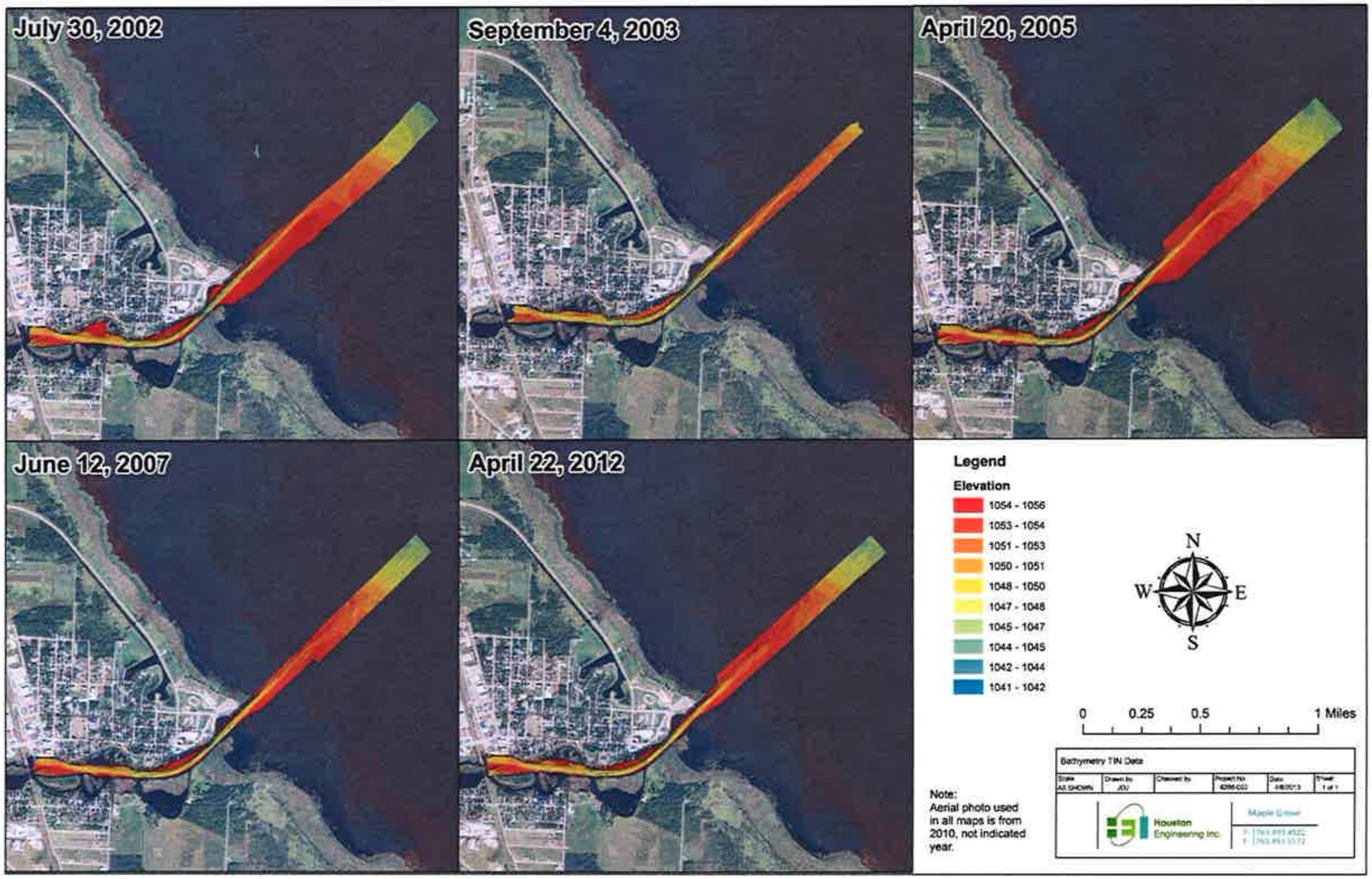
Figure 2. Harbor study area boundaries

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
- 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 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 Warroad 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^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 lbs/yd^3) (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.

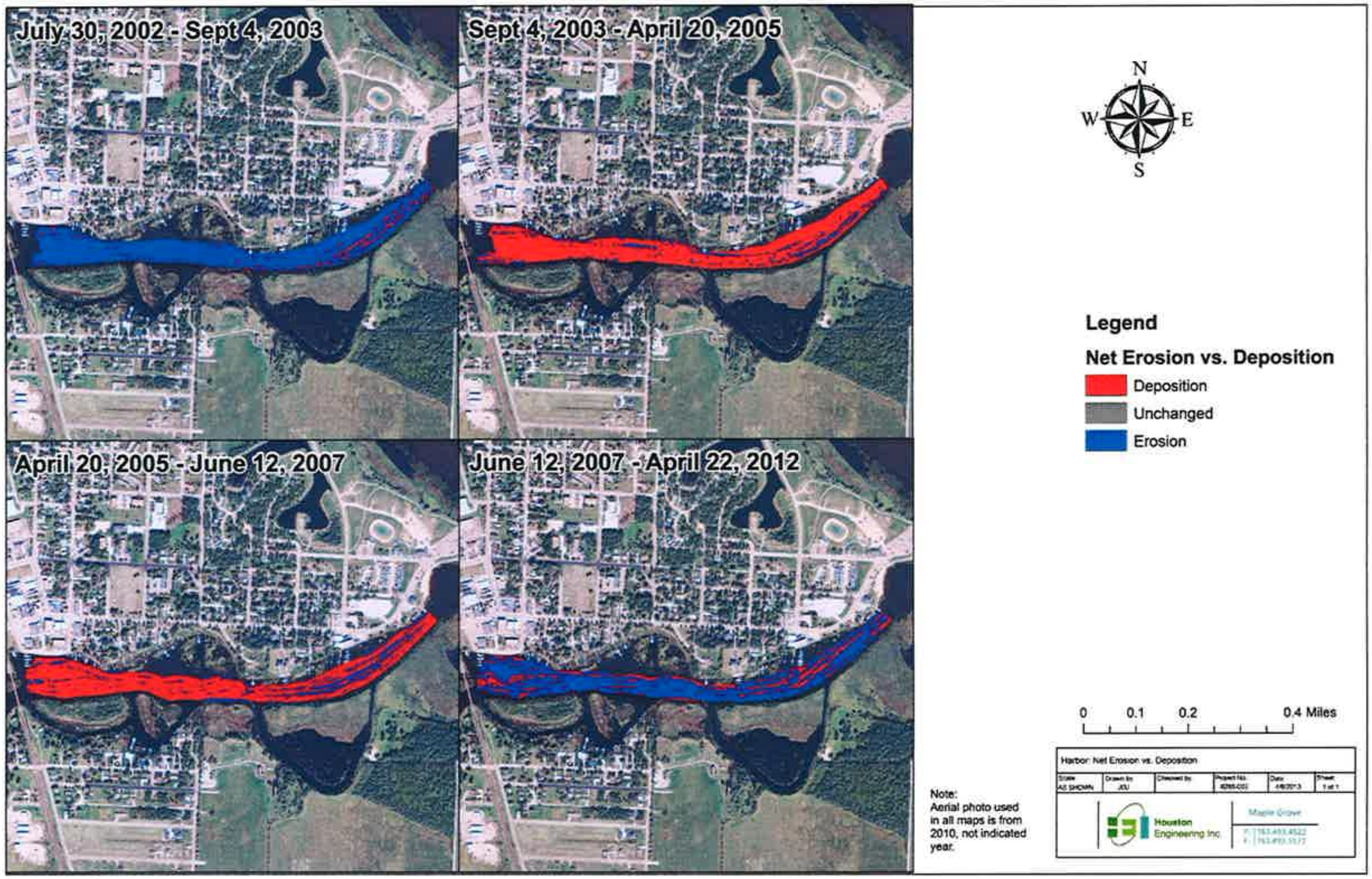
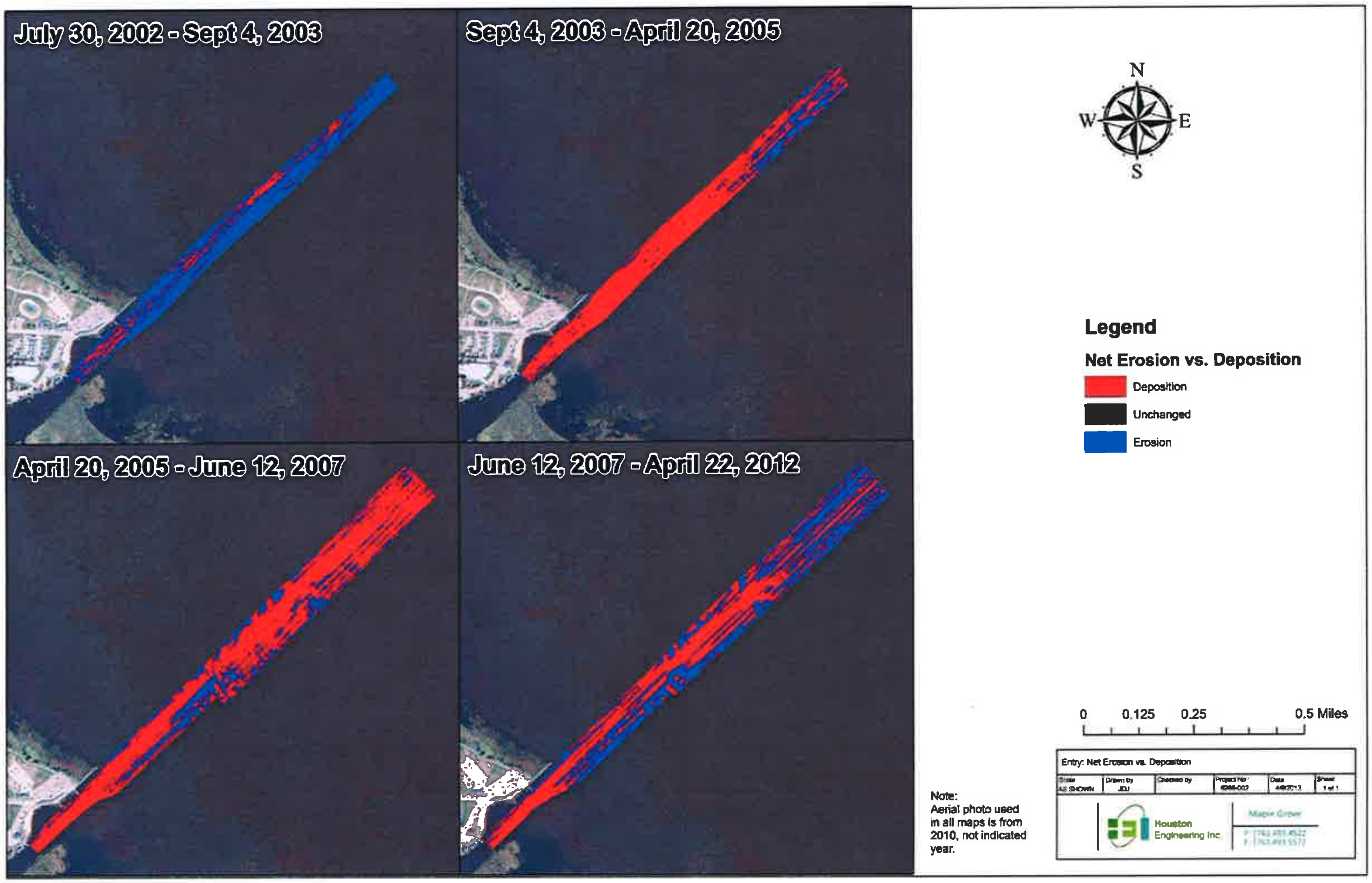


Figure 5. Net Erosion and Deposition in Warroad Harbor Entry.



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/interrill 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.

Data	Source
Elevation	State of Minnesota's LiDAR elevation data
Rainfall Frequency/Duration	US Weather Bureau's Rainfall Frequency Atlas of the United Sates (Technical Paper No. 40)
Land Use/Land Cover	2006 National Land Cover Dataset (NLCD) (land cover) 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) 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.

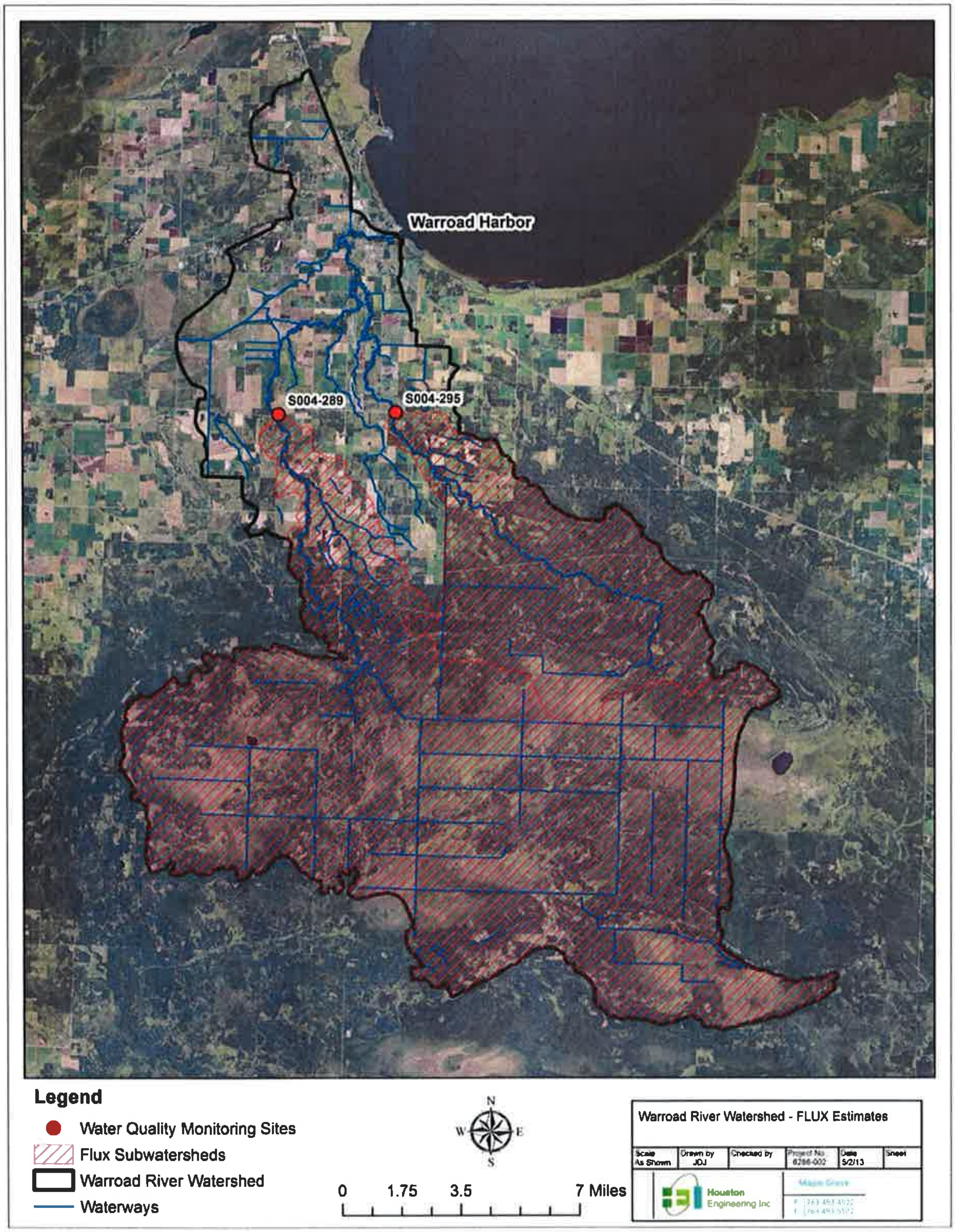
Since not all sediment that is yielded from the landscape will be transported into flowlines (some will redeposit on the landscape as it moves via overland flow), a SDR is used to reduce the potential sediment yield computed with RUSLE and estimate an effective sediment yield from each raster cell, the 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/interill 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 <u>Sediment Delivery Ratio</u>

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:

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

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:

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

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:

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

The SDR equation can then be described as:

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

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 <u>Channel Routing</u>

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:

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

Where *t* is the travel time to the downstream location; β is a channel routing coefficient; and 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 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, β, was assumed to be 0.2 based on work by Williams, 1977.

3.1.4.3 <u>Validation and Sensitivity Analysis</u>

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

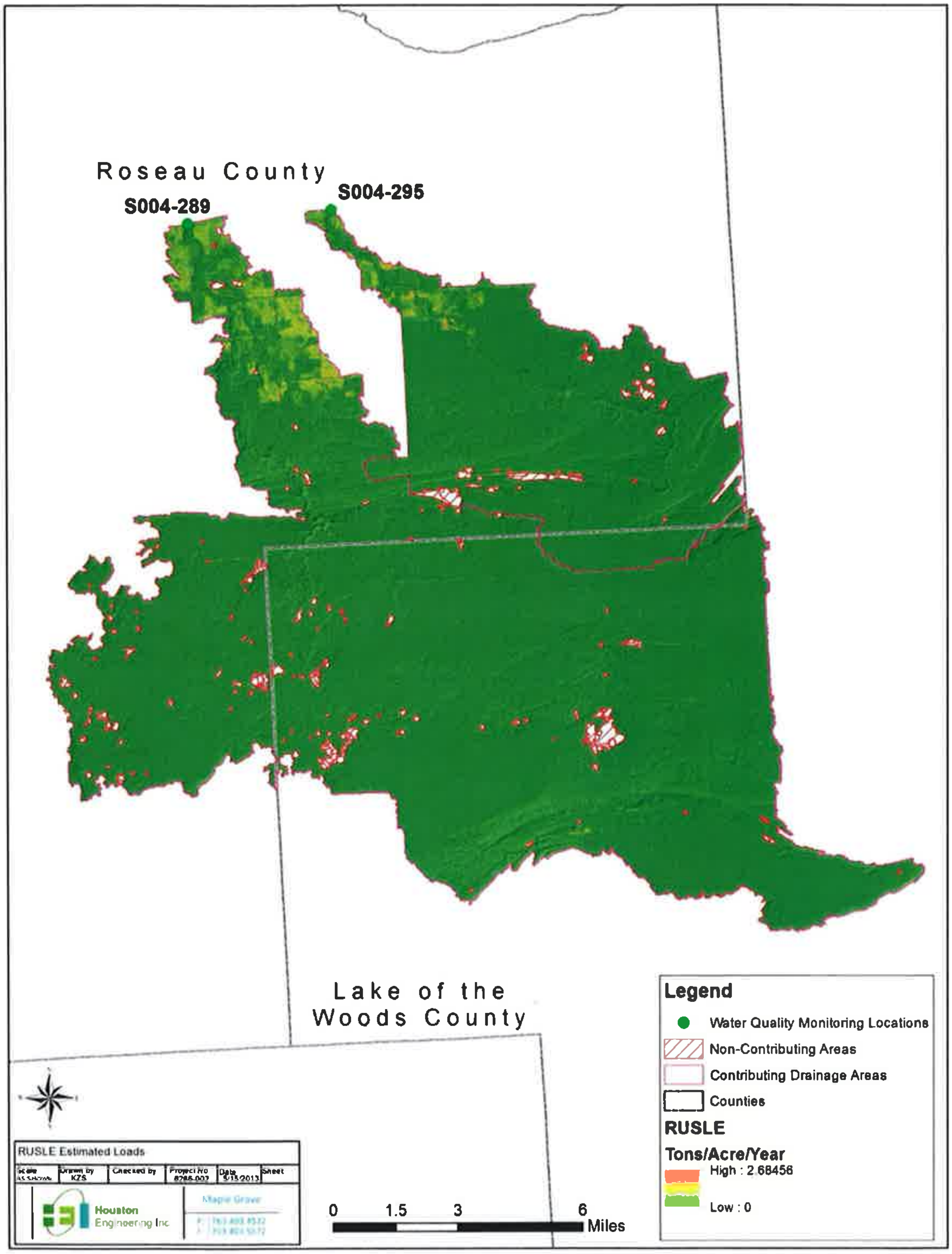
The terrain analysis results are generally summarized in the Terrain Analysis Report included in **Appendix A**. This report contains individual figures showing the RUSLE and SPI values in rasters of the WRW.

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.

Subwatershed	Total (tons/year)	Area (square miles)	Average (tons/acre/year)
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^2/year (1.9 tons/km^2/year) upstream of S004-289 and 2.8 tons/mile^2/year (1.1 tons/km^2/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^2/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
25th Percentile	0.160	0	0
75th 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 (tons/yr)	Velocity SDR (tons/yr)	Wetness Index SDR (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 (tons/year)	Velocity SDR (tons/year)	Wetness Index SDR (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 wells 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.

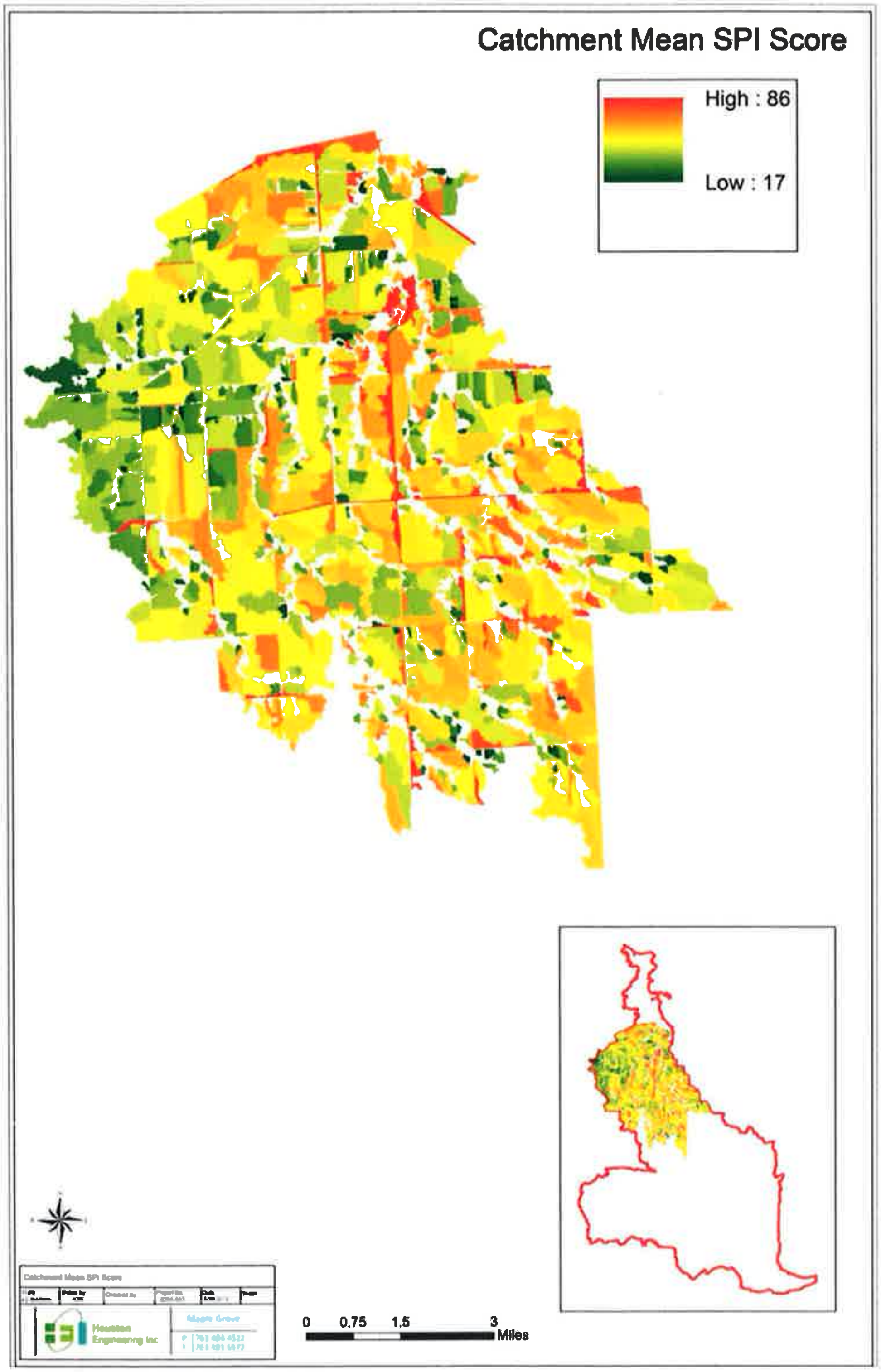


Figure 9. Catchment mean RUSLE scores for agricultural areas in the WRW.

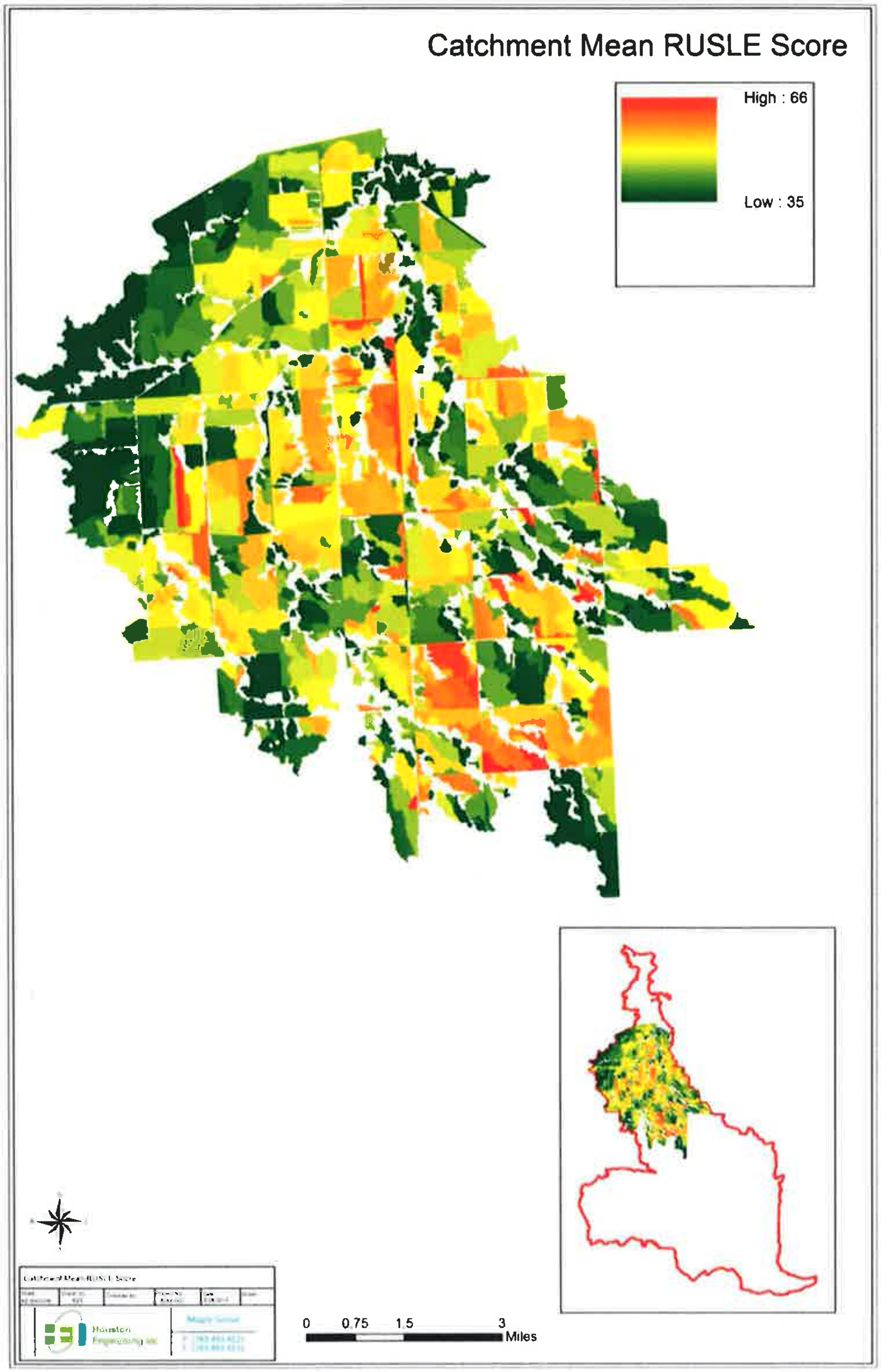
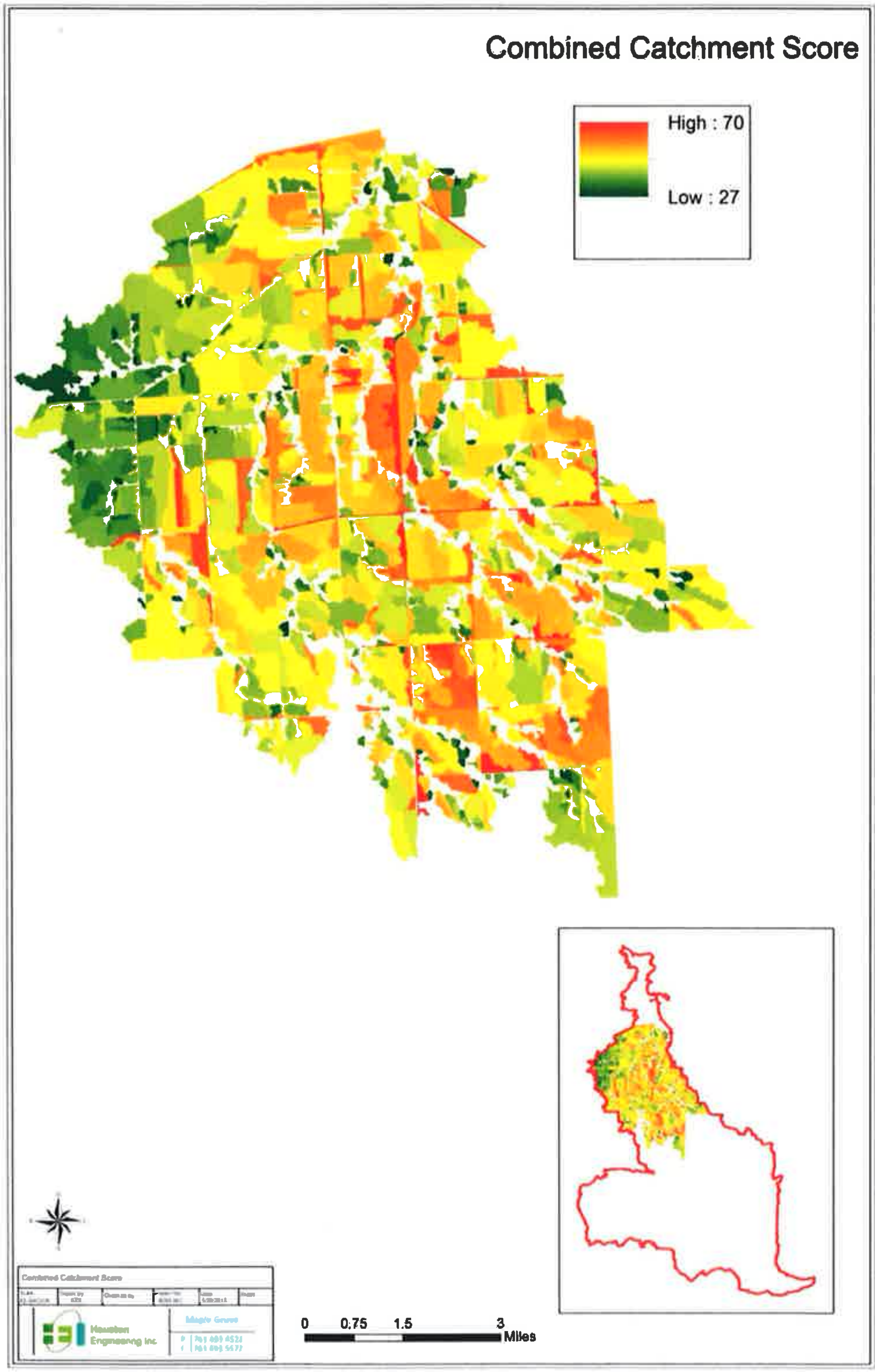


Figure 10. Combined catchment scores for agricultural areas in the WRW.



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

Warroad River Watershed

GIS Terrain Analysis Report

January 11, 2013

Submitted to:

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Appendix A – Additional Figures

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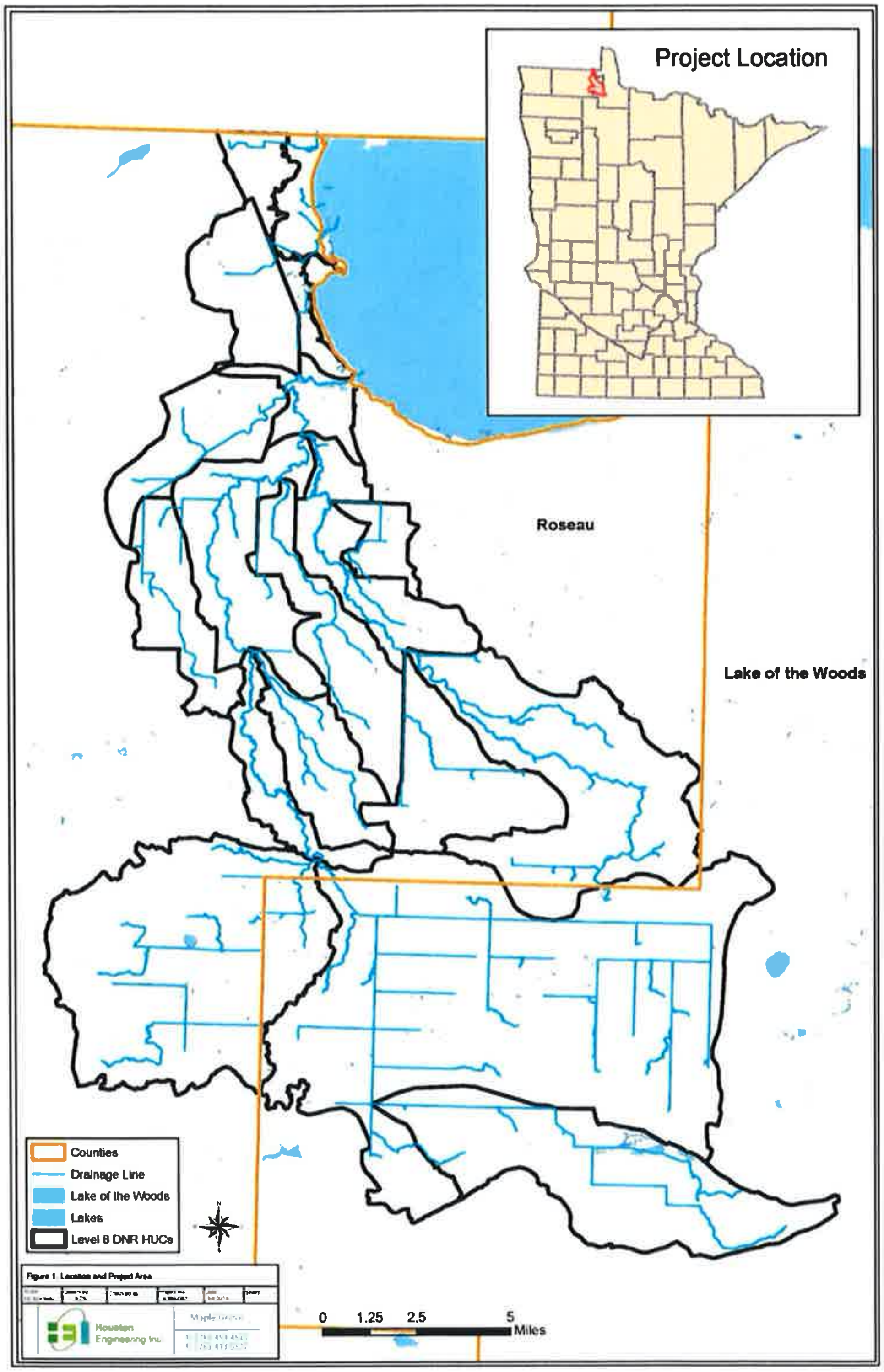
1. INTRODUCTION

The Warroad River Watershed is currently being studied to quantify primary sources of sediment deposited in the lower Warroad River and identify critical management areas to prioritize the implementation of best management practices (BMPs). This report describes a process called Terrain Analysis that utilizes Geographic Information Systems (GIS) and high resolution LiDAR elevation data combined with soil and land use information to identify critical areas across the watershed where erosion and sediment loss may be caused by surface water runoff. This analysis includes creating a raster of Stream Power Index (SPI) values, which provide a (relative) indication of the erosive power of overland, concentrated, surface water runoff at locations across the landscape. Also included is a raster of potential soil yields from overland flow areas, computed using the Revised Universal Soil Loss Equation (RUSLE). Priority management areas in the watershed are identified by analyzing and combining the SPI and RUSLE results to locate those areas where the most (potentially) erosive flows and highest predicted sediment yields combine. 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.

2. STUDY AREA

The Warroad River Watershed comprises an area of approximately 254 square miles in the northwestern Minnesota counties of Roseau and Lake of the Woods. The Warroad River Watershed 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 Lake of the Woods. **Figure** 1 shows the Warroad River watershed boundary.

Figure 1: Project Location and Study Area



3. DATA SOURCES

A number of different data sources were used in the performance of the GIS terrain analysis work. Following are the main data sources used and a general description of their origin and content.

Elevation data: This study utilizes the State of Minnesota's LiDAR elevation data (http://www.mngeo.state.mn.us/committee/elevation/mn_elev_mapping.html) collected to a maximum root mean square error (RMSE) of plus or minus six inches. For purposes of this work, the bare earth LiDAR points were generalized into a digital elevation model (DEM) at 3 meter by 3 meter resolution.

Rainfall Frequency/Duration data: The hydrologic conditioning process included analysis to identify areas that do contribute runoff downstream. Runoff estimates from the 10-year recurrence, 24-hour runoff duration event, as defined by the US Weather Bureau's *Rainfall Frequency Atlas of the United Sates* (Technical Paper No. 40) were used to determine the non-contributing areas.

Land Use/Land Cover: The 2006 National Land Cover Dataset (NLCD) was used to develop a runoff Curve Number for assessing non-contributing areas when creating the hydrologically-conditioned DEM. The National Agricultural Statistics Service (NASS) 2011 Cropland Data Layer (CDL) was used for assigning C and P values for various land use practices in the RUSLE equation.

Soils: Hydrologic Soil Group designations from the Natural Resources Conservation Service's (NRCS) SSURGO database were also used in the developing the Curve Number for hydrologic conditioning of the DEM. Soil Erodibility Factors (K_w) from these data were used as input to the RUSLE equation.

Rainfall-Runoff (R-factor) Values: Information on R-factors used in the RUSLE equation is available from the NRCS MN Field Guide. The R-factor accounts for the impact of meteorological characteristics on erosion rates.

4. METHODS

4.1. Hydrologic Conditioning

Hydrologic conditioning is the process of modifying the elevation values in a raw "bare earth" DEM raster through GIS processing to make the DEM more suitable for most hydrologic analyses. The modification process typically involves breeching digital dams (lowering the outlet) and elevating user-defined sinks to ensure that water flow paths are accurately represented in the conditioned DEM. Hydrologic conditioning is sometimes referred to as hydrologic correction.

"Burning in" Process

Conditioning the DEM is an iterative process that requires user interpretation of runoff characteristics within the watershed. The "bare earth" DEM fails to account for sub-surface drainage structures, such as culverts and flood control structures, and creates false digital dams in the DEM. Conditioning involves the interpretation of these structures and accounting for them by "burning in" their location to the "bare earth" DEM. The term "burning in" refers to artificially lowering the DEM along the alignment of the subsurface drainage structure to allow flow accumulation through the digital dam. The resultant DEM after the "burning in" process is referred to as the AgreeDEM. The AgreeDEM is then processed through a series of GIS watershed processing techniques to determine drainage lines and catchment polygons for the analyzed watershed. These drainage lines and catchment polygons are interpreted by the user to verify the results and also used in subsequent watershed analysis. This process is repeated until the results of the GIS watershed processing on the AgreeDEM match the user's interpretation of the DEM.

Non-Contributing Analysis

Depressional areas (e.g., sinks, wetlands, potholes) are a naturally-occurring feature in most landscapes. During runoff events the runoff volume to the depressional areas is not contributed downstream until the runoff volume exceeds the depressional area volume. If the runoff volume does not exceed the depressional area volume, the area is categorized as "non-contributing". This determination is dependent on the size of the runoff event analyzed. For the purposes of this study, non-contributing areas were defined as areas that contain the 10-year recurrence, 24-hour runoff event, as defined by the US Weather Bureau's *Rainfall Frequency Atlas of the United Sates* (i.e., Technical Paper No. 40). For the study area, this event was defined as 3.4 inches of precipitation. The non-contributing determination is done using a series of GIS processes in which the available storage of a depressional area is compared to the runoff volume generated from the contributing watershed of the depressional area. This is an iterative process in which the excess runoff of contributing areas is accumulated with downstream non-contributing areas until no excess runoff is produced. The output of this process is a hydrologically-reconditioned DEM that accounts for non-contributing areas, referred to as the HydroDEM. All depressional areas determined to be contributing are adjusted by elevating their elevation values to create a continuous flow path that traverses the depressional area. Flow paths are allowed to terminate within non-contributing depressional areas.

4.2. Stream Power Index (SPI)

The Stream Power Index accounts for physical characteristics of a landscape to estimate the potential of overland, concentrated surface water flow to cause erosion. SPI values are computed by multiplying the slope of a point on the landscape by its contributing drainage area.

$$SPI = ln[(flow\ accumulation)\ x\ (slope)]$$

The higher the SPI value, the greater the energy that surface water moving across the landscape at that point will potentially have to cause erosion. SPI is a simple analysis, not accounting for land cover, land use, soil type or other factors that impact surface water erosion. For this reason, it is best to compare SPI values across areas with similar land management practices, land covers, and soils.

SPI values were computed across the study area using the raster data discussed above. Landscape slope was determined from the raw "bare earth" DEM. Contributing areas were determined using the 3 meter by 3 meter flow accumulation raster created from the HydroDEM. SPI values across the study area were computed by multiplying the two rasters together.

A main focus of the SPI analysis is to locate areas with high potential for erosion due to gully formation. Since the likelihood of gully erosion is generally low where rill and interrill flow occurs, areas of the watershed where the upstream flow length is less than 300 feet were eliminated from the SPI analysis. In-channel flow areas were also removed from the SPI raster, since this method focuses on overland, not channelized, flow.

4.3. Revised Universal Soil Loss Equation (RUSLE)

RUSLE accounts for land cover, soil type, topography, and management practices to determine an average annual sediment yield estimate as a result of rill and interrill flow. RUSLE requires several input parameters to be developed and multiplied in the equation to form the estimated annual sediment yield. The discussion below summarizes the development of input variables to RUSLE. Figures are included in **Appendix A** that show the input variables and their variation across the project area.

$$A = R\ x\ K\ x\ LS\ x\ C\ x\ P$$

Where, R = Rainfall and Runoff Factor
K = Soil Erodibility Factor
LS = Length-Slope Factor
C = Cover and Management Factor
P = Support Practice Factor

Equation Input Descriptions

Rainfall and Runoff Factor (R-factor) – The R-factor accounts for the impact of meteorological characteristics of the watershed on erosion rates. Information on R-factors across the State of MN is available from the NRCS MN Field Guide, on a county-by-county basis. Values for Roseau and Lake of the Woods Counties were used in this study.

Soil Erodibility Factor (K-factor) – Soil erodibility factors used in this analysis were taken directly from the NRCS's SSURGO Database. The K factor accounts for the effects of soil characteristics on erosion rates.

Length-Slope Factor (LS-factor) – The LS-factor accounts for physical characteristics of the landscape on erosion rates. The US Department of Agriculture's (USDA) *Predicting Soil Erosion by Water: A Guide to Conservation Planning with RUSLE*, Agricultural Handbook No. 703 summarizes the methodology used to derive the LS-factors for this work. Length data was derived from the HydroDEM and slope data was derived from the raw "bare earth" DEM.

Cover and Management Factor (C-factor) – The C-factor accounts for land cover effects on erosion rates. C-values in the NRCS's MN Field Office Technical Guide and were used as the basis for developing the values used in this analysis. The USDA's 2011 National Agricultural Statistics Service's (NASS) cropland data layer (CDL) were used to define land cover and crop type in the study area. **Table 1** summarizes 2011 NASS land cover classification in the study area and the corresponding C-factors used.

The C-factors used in this project were generalized due to the scale of the project watershed. Since future crop rotations are unknown and outputs of this project are planned to be used for future implementation, C-factors were generalized under the assumption that row crops will typically be rotated with other row crops. These types of crops were given a common value. Other crops and land covers were given the appropriate C-factor. Because of this generalization, it is recommended that the RUSLE analysis be used mainly in comparison to other areas in the project watershed for purposes of prioritizing land use management.

Table 1 – Cover and Management Factors for NASS Cropland Data Layer Categories

C- Factor	NASS CDL Classification
0.200	Corn, Soybeans, Sunflower, Barley, Spring Wheat, Durum Wheat, Winter Wheat, Rye, Oats, Canola, Flaxseed, Sorghum, Peas, Herbs, Dry Beans, Potatoes, Other Crops, Fallow/Idle Cropland,
0.100	Alfalfa, Other Hay/Non Alfalfa, Sod/Grass Seed, Herbs
0.005	Clover/Wildflowers
0.003	Developed/Open Space, Developed/Low Intensity, Developed/Medium Intensity, Developed/High Intensity, Barren
0.002	Woodland, Deciduous Forest, Evergreen Forest, Shrubland, Mixed Forest
0.001	Grassland Herbaceous, Woody Wetlands, Herbaceous Wetlands
0.000	Open Water

Support Practice Factor (P-factor) – The P-factor accounts for the impact of support practices on erosion rates. Examples of support practices include contour farming, cross-slope farming, and buffer strips. For the purposes of this analysis, variations in P-factors across the study area were not accounted for since there is not sufficient information to derive P-factors at the scale required for this analysis. Support practice P-factors are typically less than one and result in lower estimates of sediment yield than if the support practices were not accounted for. As such, the results of the RUSLE analysis in this work is conservative in its estimate of soil erosion, not accounting for support practices that may be in-place. If future users of this data have more information on support practices and desire to include those in their analysis, P-factors can be derived data and the analysis can be re-run to account for these practices in the estimation of soil erosion.

Potential Sediment Yield

Once all of the required input variables were derived for RUSLE, the values were multiplied to determine the potential sediment yield for each (3 meter by 3 meter) raster cell in the study area. Only areas of the watershed that are estimated to exhibit rill and interrill flow types were considered for the analysis. The HydroDEM was used to estimate areas of rill and interrill flow based on an upstream flow length of less than 500 feet.

Sediment Delivery Ratio

To determine the amount of sediment yielded at each raster cell that actually reaches the downstream overland catchment (defined in **Section 4.4**) pour point, a Sediment Delivery Ratio (SDR) was applied. SDRs were developed following methods defined in the Minnesota Phosphorus Index (MN P-Index) which uses methodology based on previous sediment delivery analysis (Ouyang and Bartholic, 1997). The SDR is computed as a function of the flow length between the source of sediment loading and the downstream point of interest (in this case, the overland catchment pour point). Higher SDR values correspond to areas adjacent to in-channel areas and lower SDR values are found as distance from in-channel areas increases.

$$SDR = (downstream\ flow\ length)^{-0.2069}$$

The downstream flow length was derived from the HydroDEM. The SDR values are multiplied by the potential sediment yield results to estimate effective sediment yields.

Effective Sediment Load at Overland Catchment Pour Point

The effective sediment yield values were accumulated downstream to the overland catchment pour points to compute an estimated total sediment load (accounting for the SDR) from each overland catchment area.

4.4. Overland Catchment Definition

For the purposes of summarizing the results of the SPI and RUSLE analyses, overland catchment areas needed to be defined. As used in this work, the term overland catchment refers to the area that drains to the location where flow transitions from concentrated overland flow to in-channel flow. Based on a review of aerial photography in the Red River Basin, a drainage area threshold of 124 acres was used to define the transition from concentrated overland flow to in-channel flow. In addition, a minimum drainage area of 5 acres was assigned. The outlet from the overland catchment area is identified as the "overland catchment pour point".

4.5. SPI and RUSLE Raster Scoring

As mentioned above, the results of the SPI and RUSLE analyses are most valuable when compared relative to one another across a similar landscape/soil/land management scenario. To do this for the project watershed, SPI raster values were given a percentile ranking using a log-normal distribution. The percentile ranking represents a cell's relative rank for potential erosion issues. The result of this was to provide context to each SPI, showing the severity of the values relative to others in the study area.

A similar process was repeated for the accumulated effective sediment yield raster from the RUSLE analysis. However, in this case, areas where upstream flow length is less than 300 feet were eliminated. This step was necessary due to the size of the effective sediment load raster (i.e., the number of values that it contained) and introduces minimal error since effective sediment loading for overland sheet flow areas (areas where flow length <300 feet) is small. The result of this step was to highlight those areas in the watershed where elevated sediment loadings from overland sources are occurring.

The rankings grids for the SPI values and accumulated effective sediment loading values were then averaged to create a grid of combined SPI/loading scores. Finally, a mean combined score value was computed for each overland catchment scale. This combined overland catchment score accounts for both the SPI's index of erosion potential and RUSLE's estimate of overland erosion. 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 loading from overland flow.

$$Combined\ Overland\ Catchment\ Score = Average\ \frac{SPI\ Rank + RUSLE\ Rank}{2}$$

5. RESULTS

5.1. Hydrologically-Conditioned DEM

The result of the hydrologic conditioning process is a DEM (HydroDEM) from which accurate water flow paths can be developed. GIS processes are run on the HydroDEM to create rasters representing flow direction and upstream contributing cell count to each cell along with a stream network raster. These rasters are then used in the SPI and RUSLE analysis. **Figure 2** displays the HydroDEM, major drainage paths derived from the HydroDEM and results from the non-contributing analysis.

5.2. SPI Values

Figure 3 shows the raster of mean SPI rankings for the overland catchments in the study area. The areas of the watershed with greater slopes have higher corresponding mean SPI values.

5.3. Accumulated Effective Sediment Loading

Figure 4 shows the accumulated effective sediment load for each overland catchment in the watershed. Higher values are seen closer to flowpaths become more concentrated and channelized.

5.4. Catchment Prioritization

Figure 5 shows the combined overland catchment scores, computed as an average of the SPI and accumulated effective loading rankings, across the study area. The variation in scores indicates the relative difference in potential sediment loading from the combined effects of the SPI's prediction of erosive flows and RUSLE's prediction of sediment yields. Higher catchment rankings appear in the central and northern portions of the Warroad River Watershed. This is due to a combination of soil type, crop types and the terrain slope in this location, in addition to the fact that other areas of the watershed are predominantly made up of wetlands.

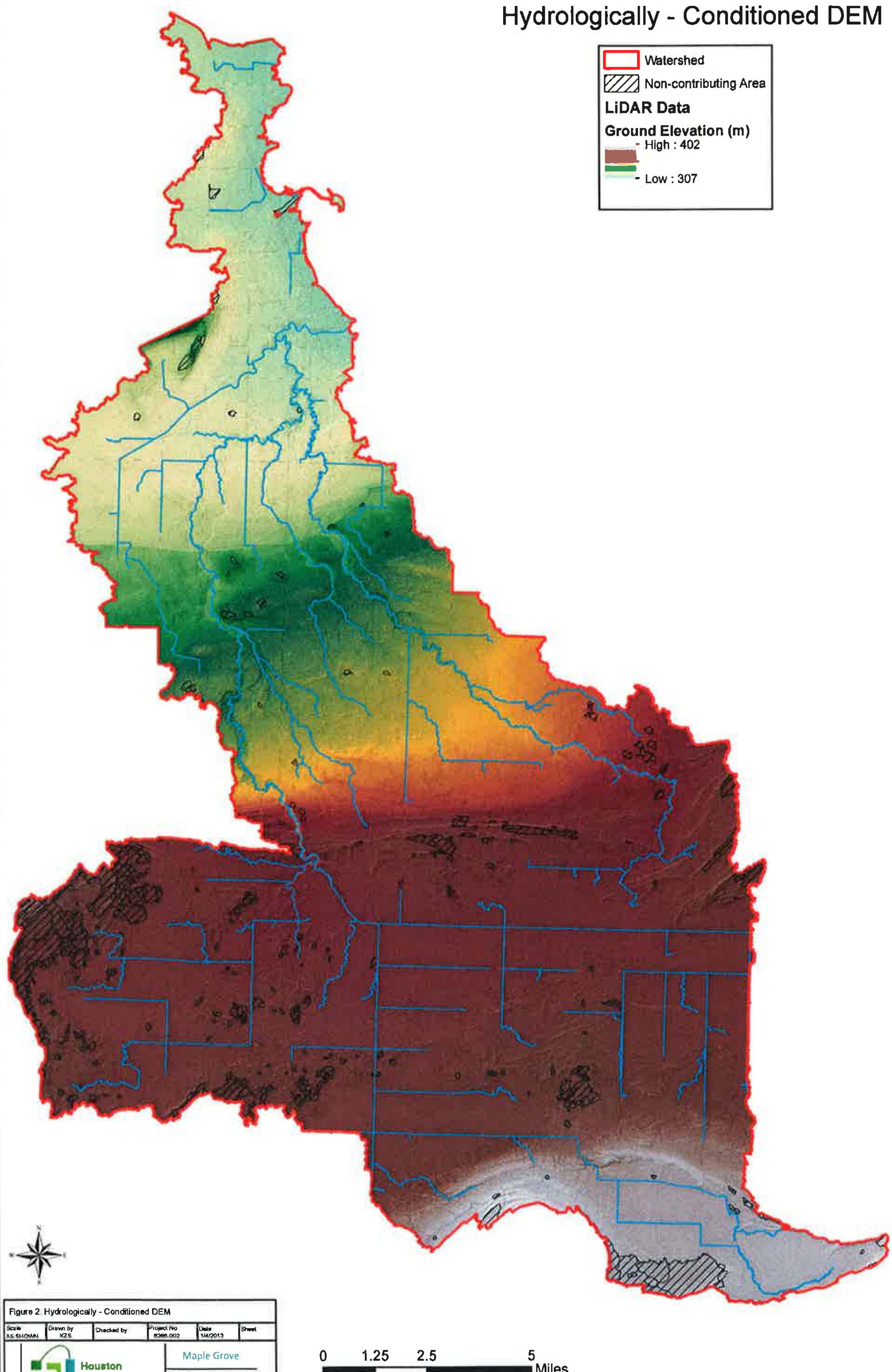


Figure 2. Hydrologically - Conditioned DEM

Scale	Drawn by	Checked by	Project No	Date	Sheet
AS SHOWN	KZS		6286.002	1/4/2013	

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P: 763.493.4522
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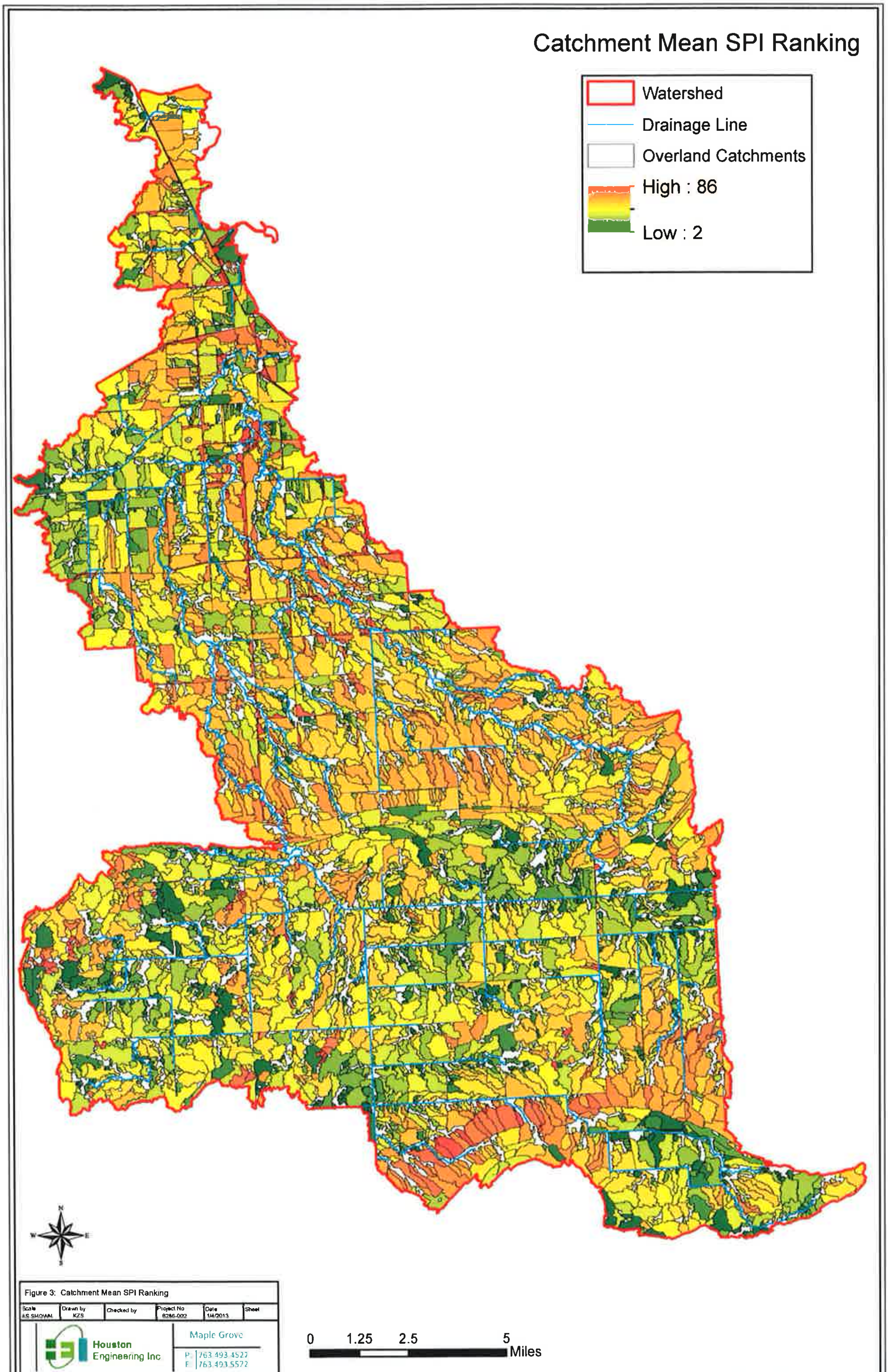
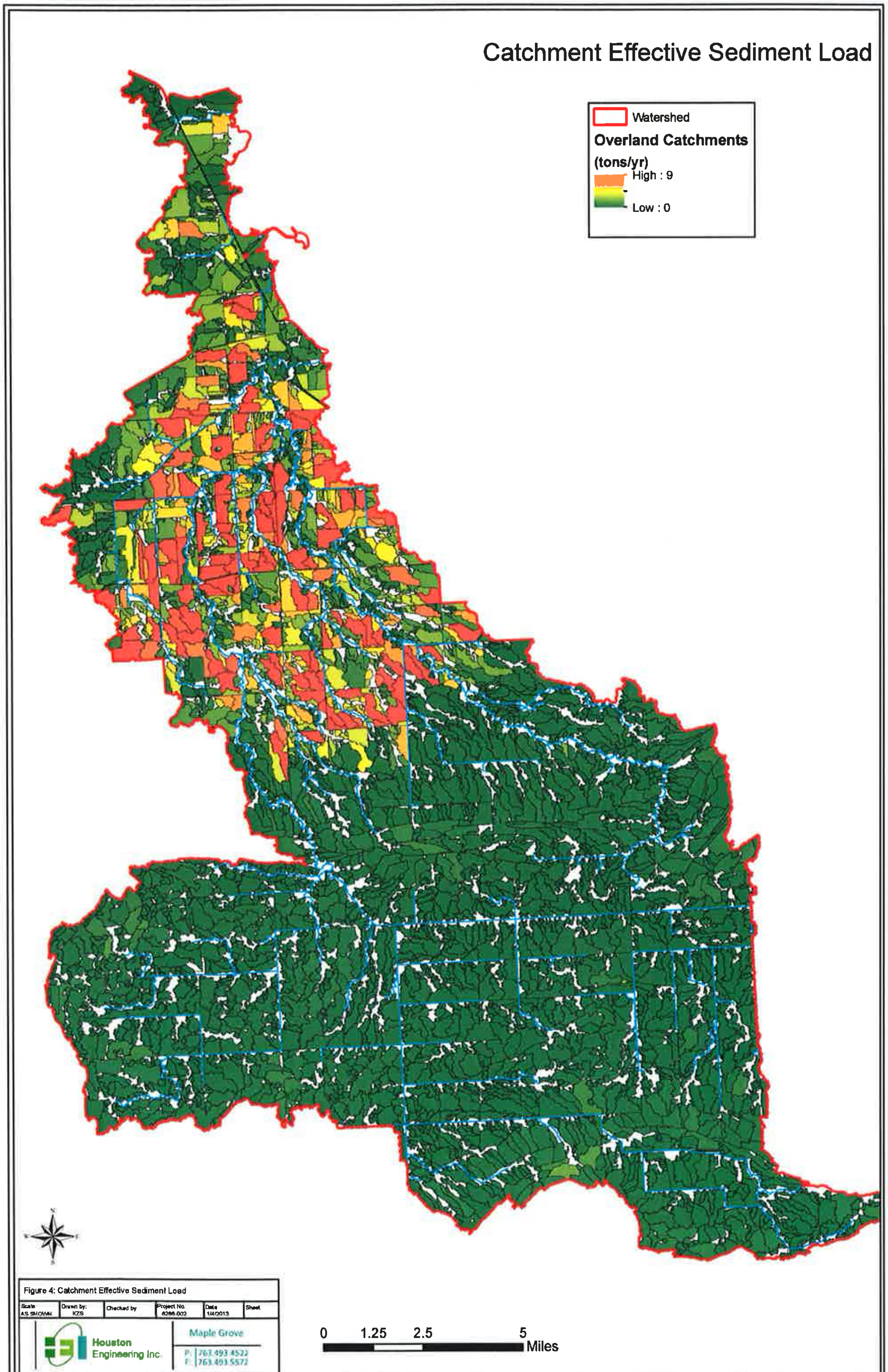

Catchment Mean SPI Ranking
Watershed
Drainage Line
Overland Catchments
High : 86
Low : 2
N
W
E
S
0
1.25
2.5
5
Miles
Figure 3: Catchment Mean SPI Ranking
Scale AS SHOWN
Drawn by KZS
Checked by
Project No
Date 1/4/2013
Sheet
Houston Engineering Inc
Maple Grove
P: 763.493.4522
F: 763.493.5572



Catchment Effective Sediment Load
Watershed
Overland Catchments (tons/yr)
High : 9
Low : 0
0
1.25
2.5
5
Miles
Figure 4: Catchment Effective Sediment Load
Scale
AS SHOWN
Drawn by:
KZS
Checked by
Project No.
Date
1/4/2013
Sheet
Houston Engineering Inc
Maple Grove
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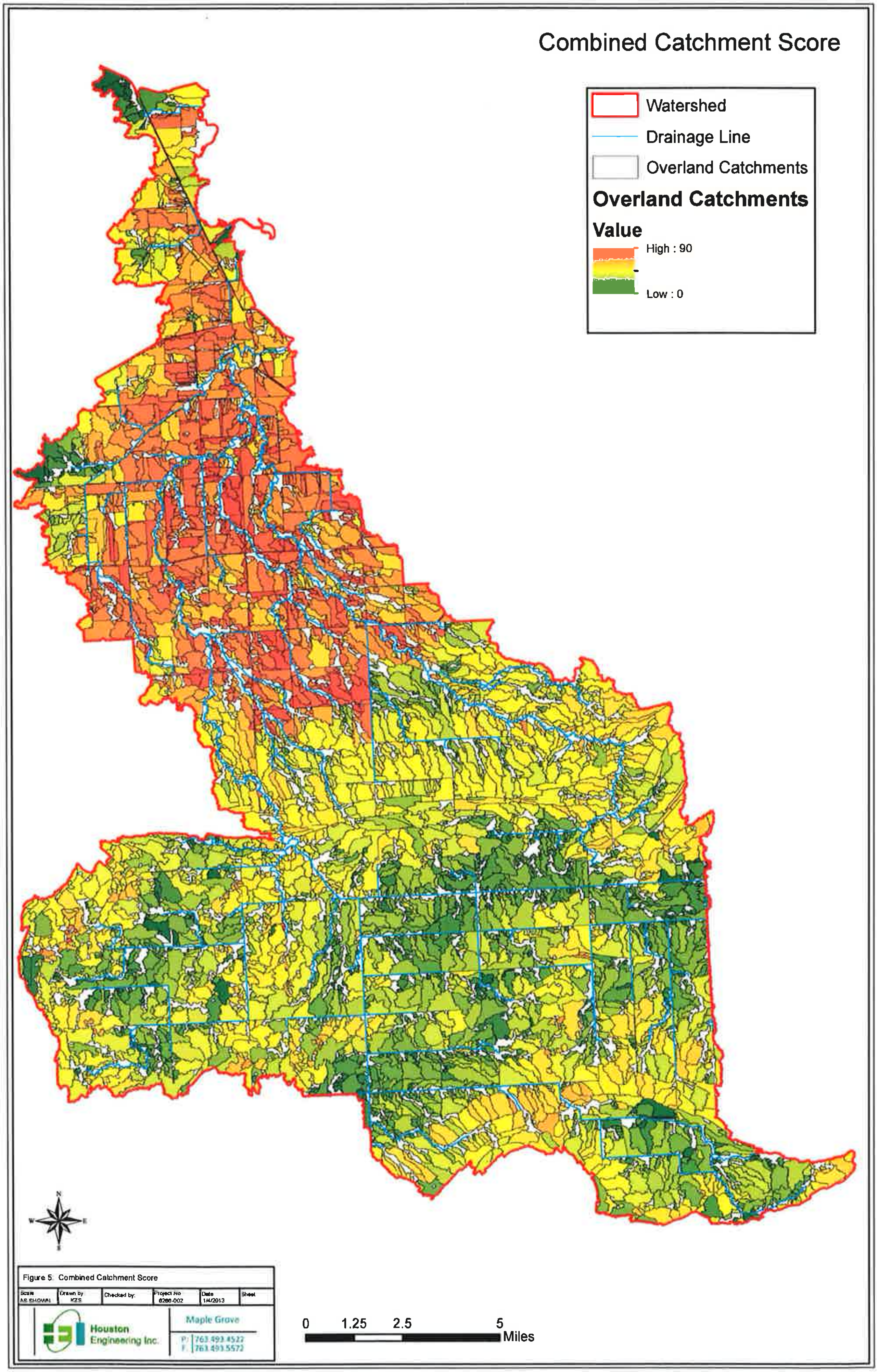
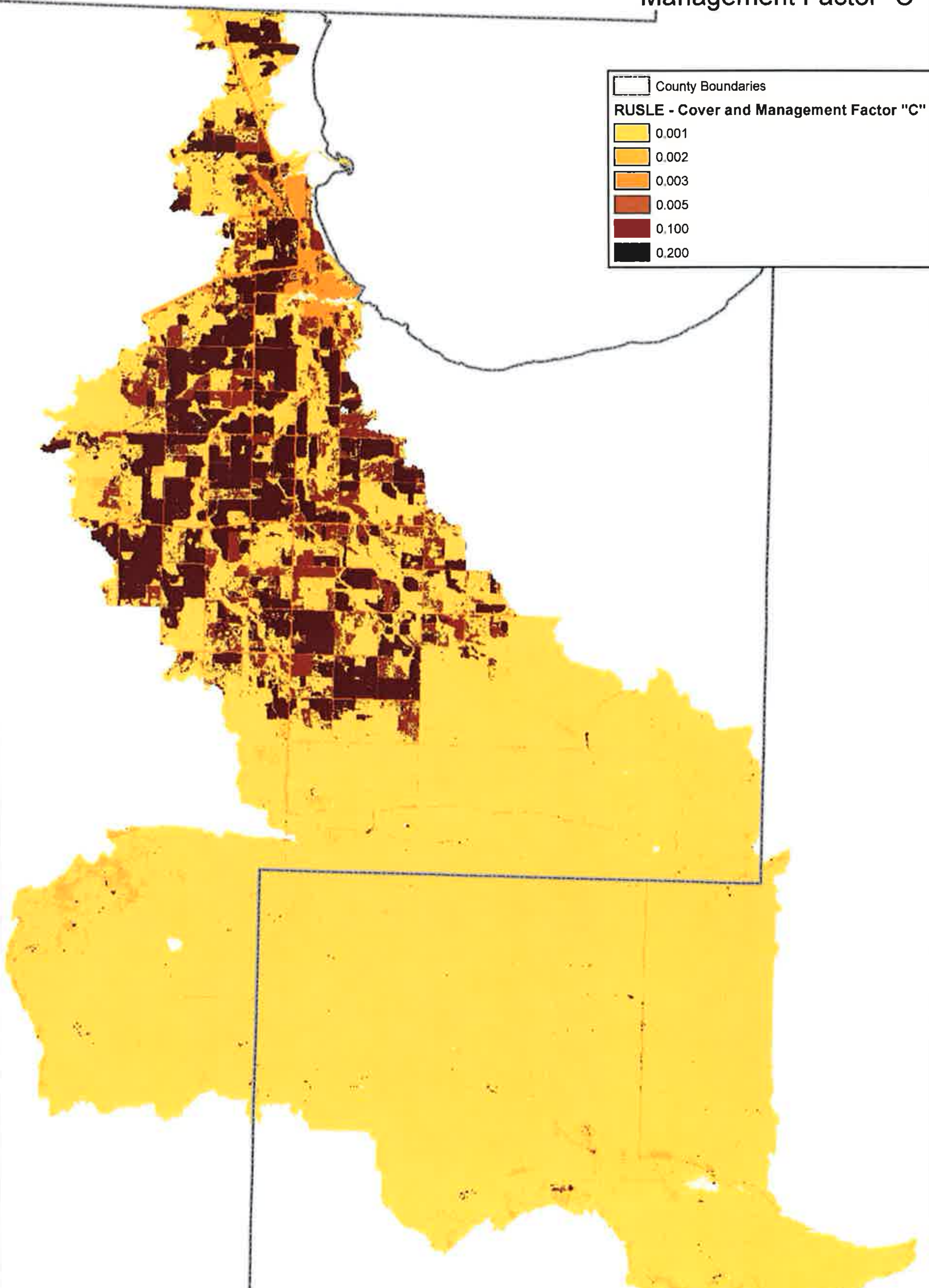


Figure 5. Combined Catchment Score

APPENDIX A

Cover and Management Factor "C"



Cover and Management Factor - "C"					
Scale AS SHOWN	Drawn by KZS	Checked by	Project No 6266 002	Date 1/4/2013	Sheet

Houston Engineering Inc.

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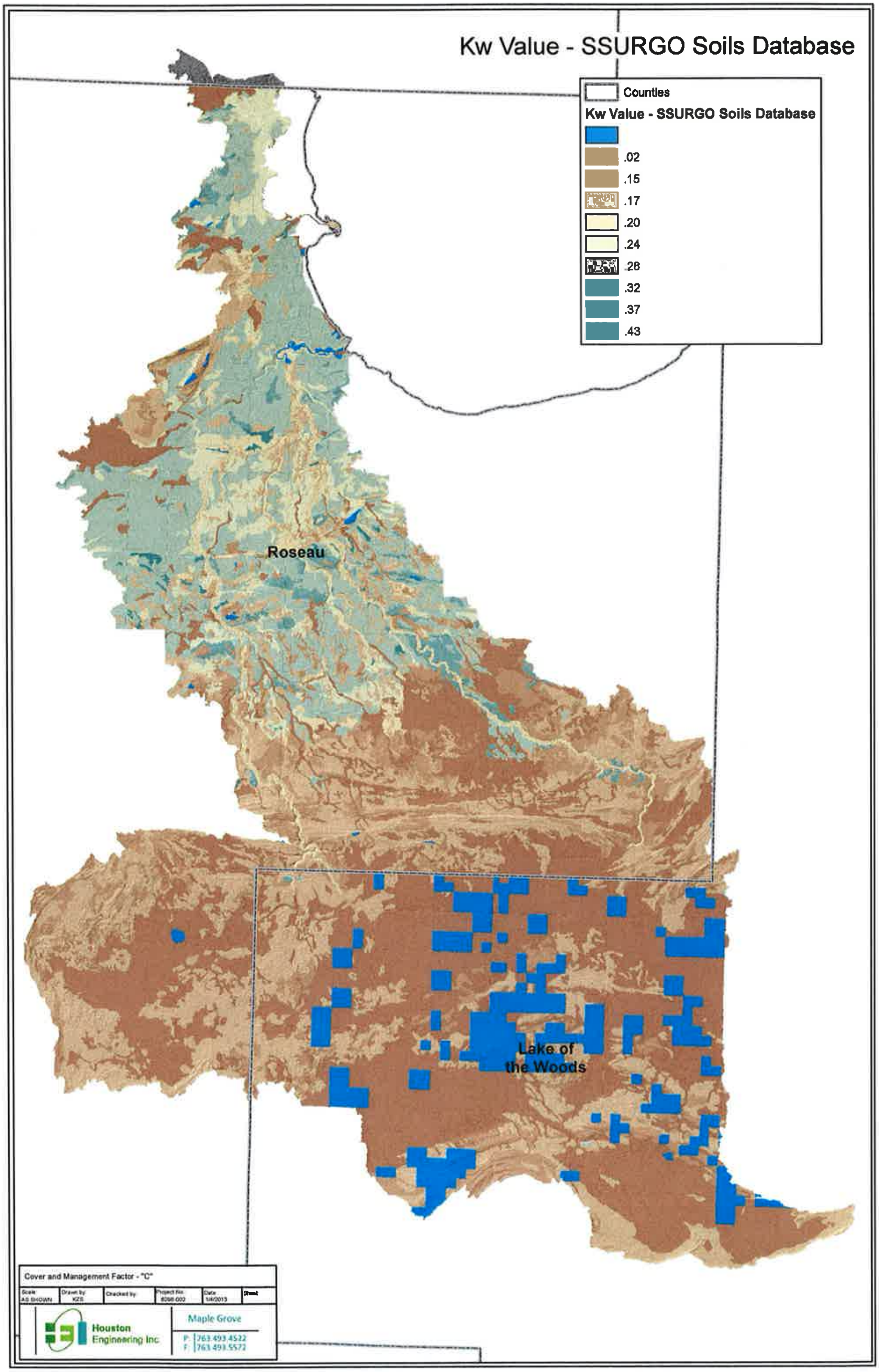
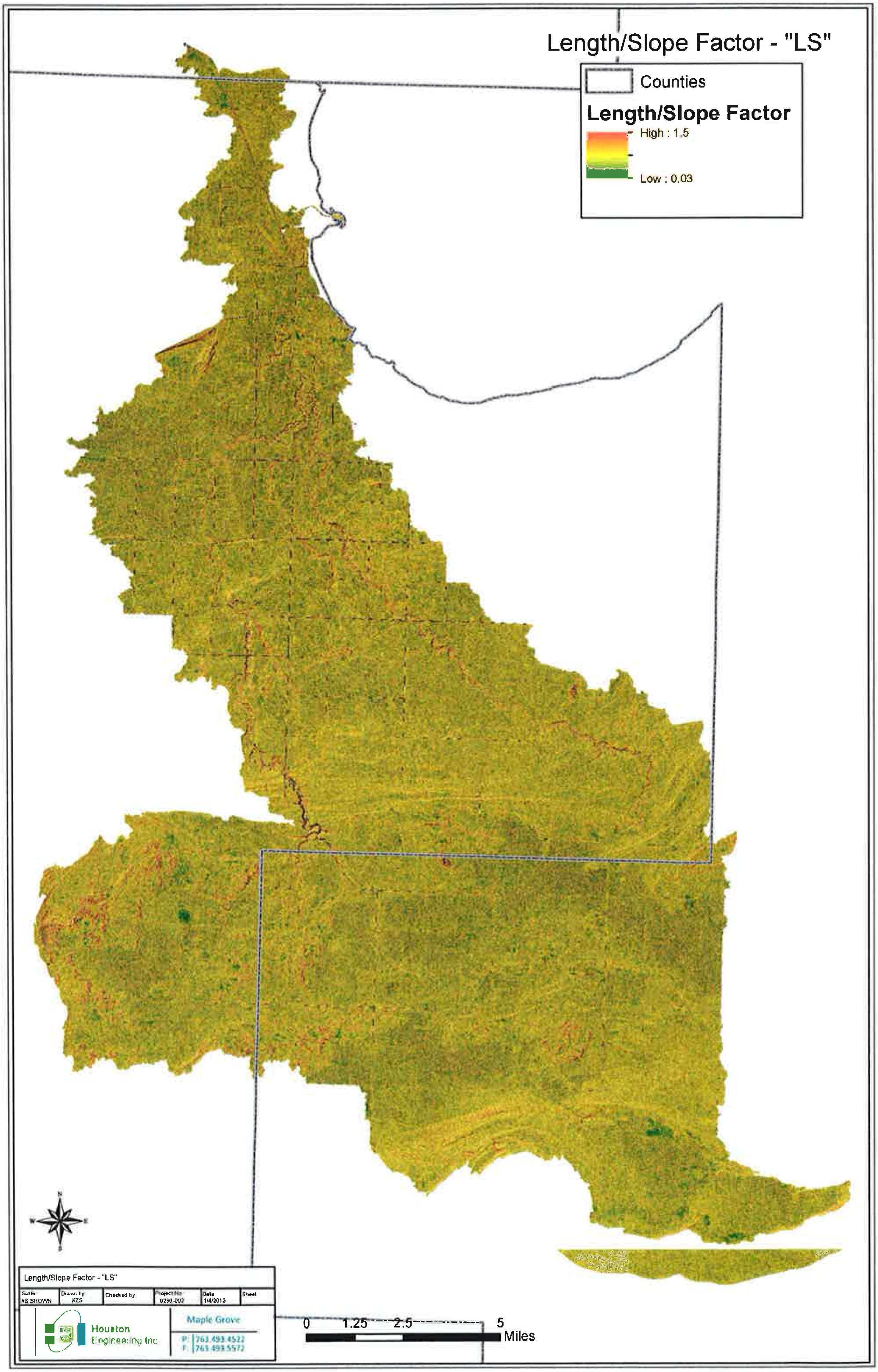
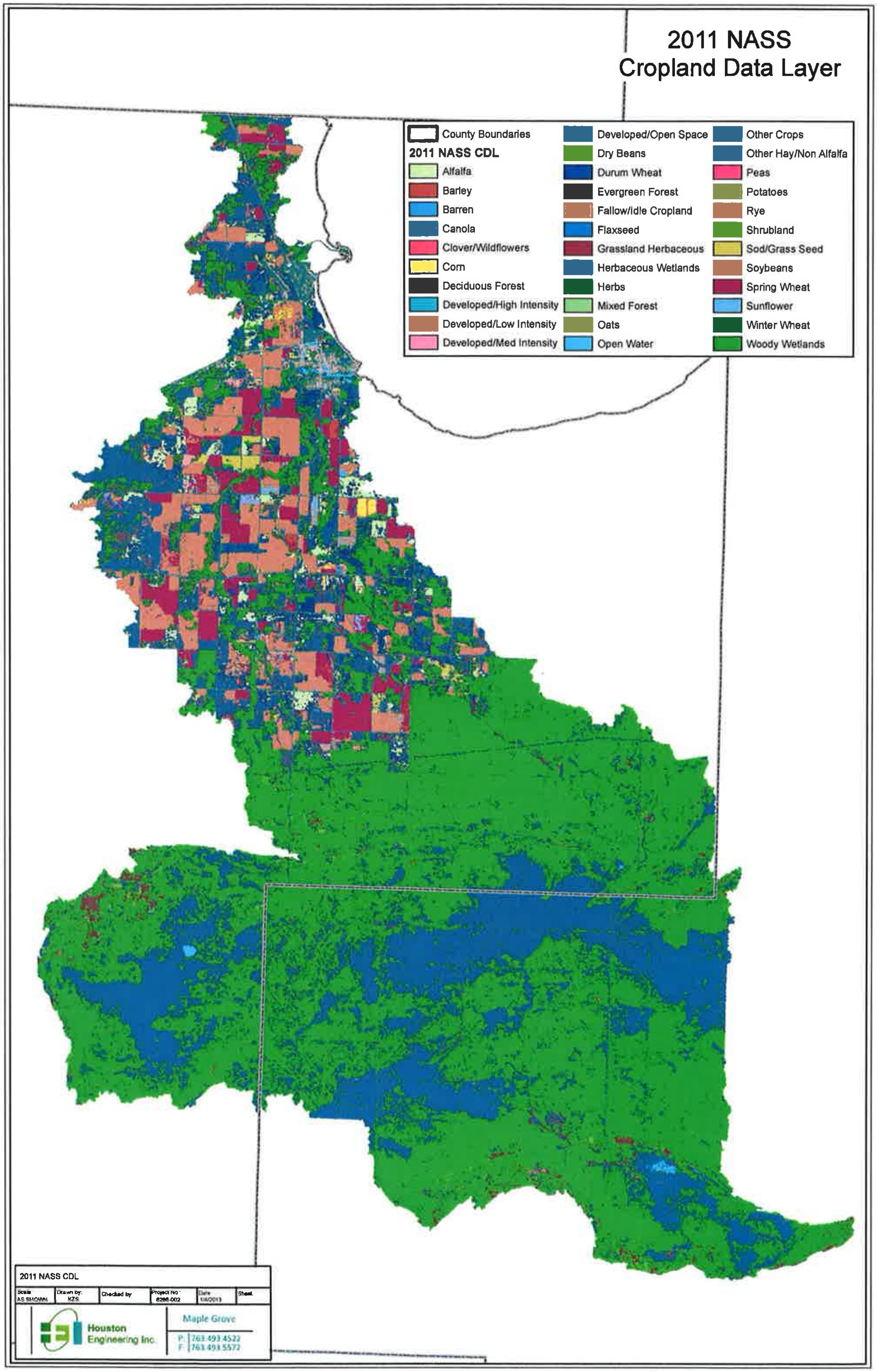
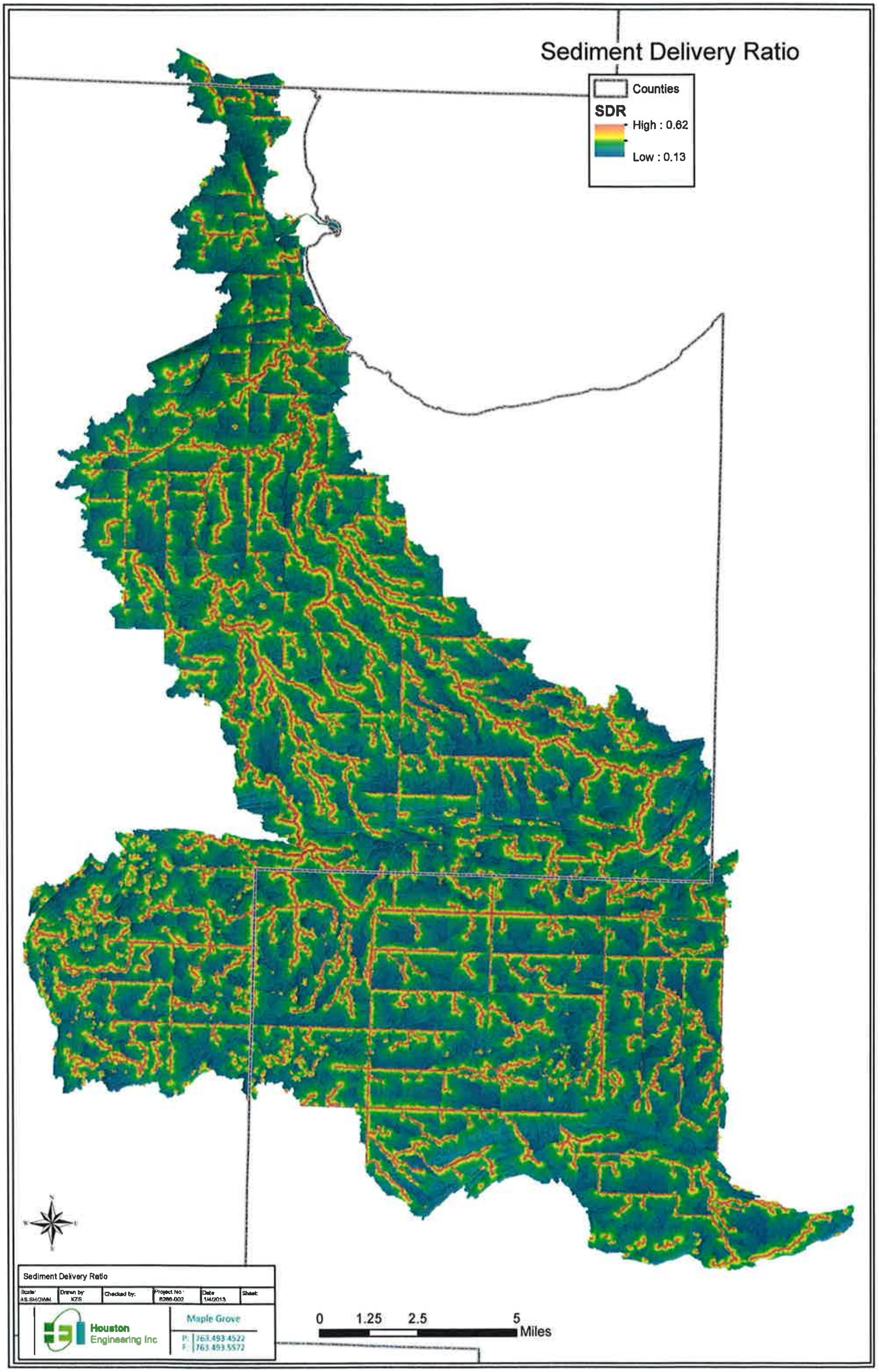
F: 763.493.5572

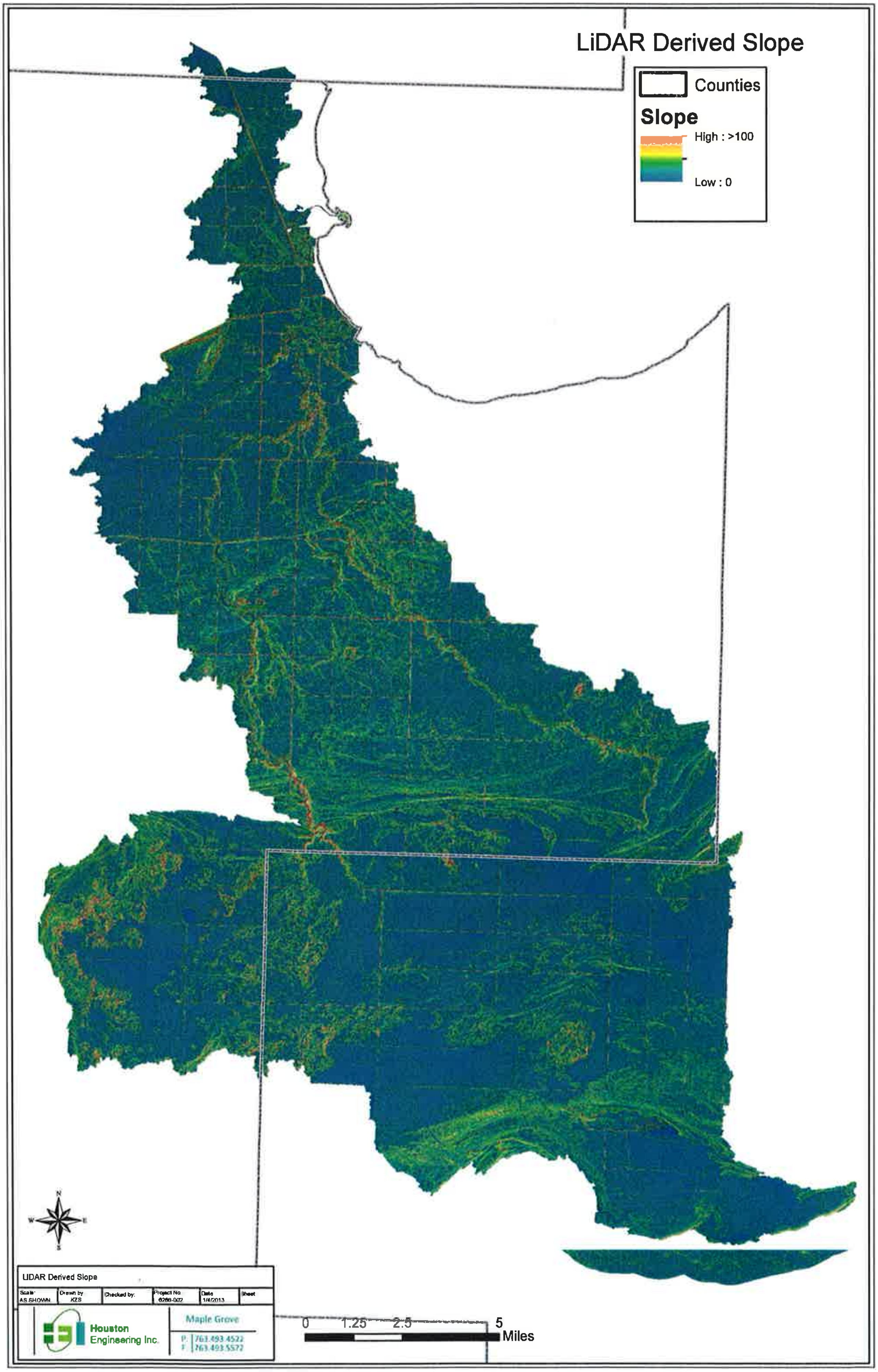

Kw Value - SSURGO Soils Database
Counties
Kw Value - SSURGO Soils Database
.02
.15
.17
.20
.24
.28
.32
.37
.43
Roseau
Lake of the Woods
Cover and Management Factor - "C"
Scale AS SHOWN
Drawn by: KZS
Checked by:
Project No.:
Date:
Sheet
Houston Engineering Inc
Maple Grove
P: 763.493.4522
F: 763.493.5572



Length/Slope Factor - "LS"
Counties
Length/Slope Factor
High : 1.5
Low : 0.03
N
W
E
S
0
1.25
2.5
5
Miles
Length/Slope Factor - "LS"
Scale
AS SHOWN
Drawn by
KZS
Checked by
Project No.
6266-002
Date
1/4/2013
Sheet
Houston
Engineering Inc
Maple Grove
P: 763.493.4522
F: 763.493.5572


2011 NASS
Cropland Data Layer
County Boundaries
2011 NASS CDL
Alfalfa
Barley
Barren
Canola
Clover/Wildflowers
Corn
Deciduous Forest
Developed/High Intensity
Developed/Low Intensity
Developed/Med Intensity
Developed/Open Space
Dry Beans
Durum Wheat
Evergreen Forest
Fallow/Idle Cropland
Flaxseed
Grassland Herbaceous
Herbaceous Wetlands
Herbs
Mixed Forest
Oats
Open Water
Other Crops
Other Hay/Non Alfalfa
Peas
Potatoes
Rye
Shrubland
Sod/Grass Seed
Soybeans
Spring Wheat
Sunflower
Winter Wheat
Woody Wetlands
2011 NASS CDL
Scale
AS SHOWN
Drawn by:
KZS
Checked by
Project No
6266-002
Date
Sheet
Houston
Engineering Inc.
Maple Grove
P: 763 493 4522
F: 763 493 5572


Sediment Delivery Ratio
Counties
SDR
High : 0.62
Low : 0.13
0 1.25 2.5 5 Miles
Sediment Delivery Ratio
Scale: AS SHOWN
Drawn by: KZS
Checked by:
Project No.:
Date:
Sheet:
Houston Engineering Inc
Maple Grove
P: 763.493.4522
F: 763.493.5572


LiDAR Derived Slope
Counties
Slope
High : >100
Low : 0
N
W
E
S
LiDAR Derived Slope
Scale: AS SHOWN
Drawn by KZS
Checked by:
Project No. 6288-002
Date 1/4/2013
Sheet
Houston Engineering Inc.
Maple Grove
P. 763.493.4522
F. 763.493.5572
0
1.25
2.5
5
Miles

APPENDIX B

GIS Data Summary

1. **Raw_DEM**
   a. *Data type:* Raster
   b. *Summary:* Raw LiDAR derived DEM. 3 meter by 3 meter resolution. Elevation units are in feet (NAVD 88).
2. **Score**
   a. *Data type:* Raster
   b. *Summary:* Combined scoring of the SPI and RUSLE percentile rankings. The score is based on equal weighting between the SPI and RUSLE percentile rank for channelized overland flow.
3. **LS_Factor**
   a. *Data type:* Raster
   b. *Summary:* Length/Slope factor used in RUSLE. It is created from the hydrologically conditioned DEM and methodology from USDA Agricultural Handbook No. 703.
4. **SDR**
   a. *Data type:* Raster
   b. *Summary:* Ratio used to multiply the total potential sediment load to obtain the effective sediment load. The ration is derived from the downstream flow length to the point of interest (overland catchment pour point).
5. **total_load**
   a. *Data type:* Raster
   b. *Summary:* The total potential sediment yield from RUSLE for each individual raster cell. The values are in tons/acre.
6. **eff_load**
   a. *Data type:* Raster
   b. *Summary:* The effective sediment load for each raster cell from RUSLE. The values have been multiplied by the Sediment Delivery Ratio to the overland catchment pour point. The values are in tons/acre.
7. **acc_eff_load**
   a. *Data type:* Raster
   b. *Summary:* The eff_load raster accumulated in the downstream direction to create a total effective sediment loading from the upstream area from RUSLE.
8. **RUSLE_ranks**
   a. *Data type:* Raster
   b. *Summary:* Ranking of the acc_eff_load raster for areas of channelized overland flow (upstream flow length > 300 feet and contributing area > 0.5 sq. km.). Cumulative percentile rank uses log-normal distribution.
9. **SPI_raster**
   a. *Data type:* Raster
   b. *Summary:* Raster cell values represent the result of the SPI equation.

10. SPI_ranks

a. *Data type:* Raster
b. *Summary:* SPI percentile ranking for areas of channelized overland flow (upstream flow length > 300 feet and contributing area > 0.5 sq. km.). Cumulative percentile rank uses log-normal distribution.

11. Flowpaths.shp

a. *Data type:* Polyline Shapefile
b. *Summary:* LiDAR derived flowpaths for areas with > 5 acres of drainage area.
c. *Attributes:*
    i. Type:
        1. Overland (greater than 5 acres of drainage area but less than 0.5 sq. km.)
        2. In-channel (greater than 0.5 sq. km. drainage area)

12. Overland_Catchments.shp

a. *Data type:* Polygon Shapefile
b. *Summary:* Contributing areas for overland flow for drainage areas between 0.5 square kilometers and 5 acres.
c. *Terrain Analysis Attributes*
    i. *GRIDCODE* – Common ID corresponding to Overland_Pourpoint.shp
    ii. *Max_eff* – Value from acc_eff_load at overland catchment pour point.
    iii. *Mean_SPI* - Mean value of the SPI_ranks raster dataset for the overland catchment area.
    iv. *Mean_RSL* – Mean value of the RUSLE_ranks raster dataset for the overland catchment area.
    v. *Score* – Mean value of the score raster dataset for the overland catchment area.

13. Overland_Pourpoint.shp

a. *Data type:* Point Shapefile
b. *Summary:* Outlet locations of overland flow into in-channel flow using the thresholds of drainage areas greater than 5 acres and less than 0.5 sq. km.
c. *Attributes:*
    i. *GRIDCODE* – Common ID corresponding to Overland_Catchment.shp.

14. Ranked_Overland_Flowpaths.shp

a. Data type: Polyline Shapefile
b. *Summary:* Overland flowpaths were classified into priority categories based on the score raster dataset.
c. *Attributes:*
    i. *SedBasin:* Areas generally acceptable for sediment control baisns
        1. *Value = 1:* Contributing area is less than 40 acres (ideal for sediment control basins.
        2. *Value = 2:* Contributing area is greater than 40 acres (not ideal for sediment control basins.
    ii. *MinScore:* Minimum score of range used for priority classification. Source data is from the score raster dataset.

- iii. *MaxScore:* Maximum score of range used for priority classification. Source data is from the score raster dataset.
- iv. *Priority:* Priority classification for implementation based on the range established in the MinScore and MaxScore fields.
    1. *Extremely Low* (score < 75)
    2. *Low* (75 < score < 85)
    3. *Moderate* (85 < score < 95)
    4. *High* (score > 95)

15. ContribWatershed_10yr24hr_rainfall.shp

- a. *Data type:* Polygon Shapefile
- b. Summary: Total contributing area for the project. Contributing area is defined as areas that would contribute to downstream area during a 10-year, 24-hour rainfall event (TP-40).
    - i. *Area_SqMi:* Total area in square miles.
    - ii. *Acres:* Total area in acres

16. NonContribAreas_10yr24hr_rainfall.shp

- a. *Data type:* Polygon Shapefile
- b. *Summary:* Non-contributing areas as defined by areas that would not contribute runoff to downstream areas during a 10-year, 24-hour rainfall event (TP-40).
    - i. *Area_SqMi:* Total area in square miles.
    - ii. *Acres:* Total area in acres

17. Project_Watershed.shp

- a. *Data type:* Polygon Shapefile
- *b. Summary:* Total project area including contributing and non-contributing areas.
- *c. Attributes:*
    - i. *Area_SqMi:* Total area in square miles.
    - ii. *Acres:* Total area in acres

18. 10yr_Depressions.shp

- a. *Data type:* Polygon Shapefile
- b. *Summary:* Footprint of non-contributing basins at the spill out elevation for the depressed area.
- *c. Attributes:*
    - i. GridID: Commin ID with GridID field from the 10yr_DepressionDA.shp
    - ii. *FillElev:* Elevation in feet of the spill out elevation.
    - iii. *FillArea:* Surface area of depression and spill out elevation.
    - iv. *DrainArea:* Drainage area to depression.

19. 10yr_DepressionDA.shp

- a. *Data type:* Polygon Shapefile
- b. *Summary:* Corresponding contributing area of 10yr_Depressions.shp
- *c. Attributes:*
    - i. *GridID:* Common ID with GridID field from the 10yr_Depressions.shp
    - ii. *DrainArea:* Drainage area in acres.

APPENDIX B – SENSITIVITY ANALYSIS

Warroad River Watershed Overland Erosion Sensitivity Analysis

Sediment Delivery Ratio

Since the RUSLE/SDR-estimated amount of sediment delivered to the downstream monitoring locations is substantially lower than the estimated FLUX loads, the sensitivity of the SDR and channel routing coefficients were tested.

The sensitivity of the *a* and *b* coefficient values on the channel sediment load was checked by varying the *a* and *b* values in the Wetness Index version of the SDR. The table below summarizes the impact of varying the coefficients, for different combination, on the distribution of Wetness Index SDR values.

	a = 0.1 & b = 0.5	**a = 0.2 & b = 0.5**	**a = 0.1 & b = 0.25**	**a = 0.2 & b = 0.25**
Mean	0.040	0.081	0.059	0.119
Median	0.050	0.101	0.061	0.121
Std Deviation	0.088	0.177	0.037	0.075
Min	0	0	0.001	0.003
Max	4.98	9.96	0.706	1.412
25^{th} Percentile	0	0	0.035	0.072
75^{th} Percentile	0.110	0.22	0.086	0.171

The combination of *a* = 0.2 and *b* = 0.25 resulted in the largest Wetness Index SDR values, while the combination of *a* = 0.1 and *b* = 0.5 resulted in the smallest. The table below shows the impact of these two different coefficient combinations on the estimated average annual sediment load at the two water quality sites.

Monitoring Site	**Wetness Index SDR: a = 0.1 & b = 0.5**	**Wetness Index SDR: a = 0.2 & b = 0.25**
S004-289	49.1	141.6
S004-295	17.5	45.4

Channel Routing

The sensitivity of the in-channel sediment routing coefficient, β, was also checked by varying the value from 0.2 to 0.01. The Phosphorus Index SDR was used to see the impact of the β variation. The table below summarizes the results in the adjustment, showing the estimated average annual sediment loading at the two water quality sites with two different β values.

Monitoring Site	**β = 0.2**	**β = 0.01**
S004-289	172.0	300.0
S004-295	73.4	101.7