Lake of the Woods Sediment & Nutrient Budget Investigation

Focusing on Watershed and Southern Shoreline Loads

Final Report

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1.0 Introduction

The second largest lake in Minnesota, Lake of the Woods (LOW) lies on the United States-Canadian border and serves as an important local, regional, and international recreational and economic resource. The lake is highly managed, with dams at both the outlet (at Kenora, Canada) and upstream at Rainy Lake (which discharges into LOW's major tributary, the Rainy River). Both of these dams are used for hydropower production. In recent years there has been concern that the cyanobacteria algal blooms that LOW typically experiences throughout the spring and summer have increased in frequency and magnitude. In 2008, the lake was listed on the U.S. federal Clean Water Act 303(d) List as impaired for eutrophication and biological indicators. In addition to the concerns over algal blossoms, LOW faces significant erosion problems, particularly along its southern shoreline and at Pine and Curry Islands. Preliminary evidence and studies report that habitat loss is occurring at an alarming rate; a 2004 study showed that some shoreline areas along Four Mile Bay have receded by 600 meters since the 1940s and about 1500 meters of Pine Island has disappeared (Herb et al. 2004). Efforts to characterize the function of the LOW and the factors that contribute to its water quality and erosion concerns have increased in the recent years. Results will be used to inform Total Maximum Daily Load (TMDL) studies, which began for the watershed in 2012 and will begin for the lake in 2014.

In its 2010 – 2015 plan, the International Multi-Agency Working Group identified the quantification of LOW's southern shoreline erosion and its contribution to nutrient loading to the Lake as a priority data gap. The U.S. Environmental Protection Agency (USEPA) responded with dedicated funding (through its Water Quality Program) to investigate this question in 2011. The effort described in this report was supported under this funding through USEPA contract # X7-00E00918: Lake of the Woods Sediment and Nutrient Budget Investigation. The intent of this work was to contribute to the understanding of how sediment and nutrients move through and within the LOW system. The study built upon recent efforts to characterize the function of LOW and the factors that contribute to its water quality and erosion concerns. A main focus of this project was to refine the characterization of how shoreline erosion along the U.S. side of the lake contributes to the lake's problems, addressing both erosion rates and the nutrient loads that result from this erosion. An additional focus was to refine the estimate of sediment and nutrient loads from the U.S.-based tributaries. Work performed under this project focused on the over 40-miles (i.e., 40+ miles) of shoreline between Warroad and Wheelers Point (**Figure 1**).

Figure 1. Lake of the Woods Location Map.

2.0 Previous Work

Several studies have recently been conducted to characterize some of the challenges in LOW. These studies include a qualitative assessment of the lake's southern shoreline erosion and two total phosphorus (TP) budgets for the lake. These studies played an important role in this project, serving as a starting point for much of our effort. This section summarizes the two studies.

2.1 SAFL Shoreline Erosion Study

The University of Minnesota Saint Anthony Falls Laboratory (SAFL) completed a study on the erosion of the Lake of the Woods County portion of the southern shoreline in 2004 (Herb et al. 2004). The objectives of their study were to determine causes and estimate the magnitude of shoreline erosion rates, using data from 1940 through 2003 (Herb et al. 2004). A particular focus was to examine the historic wind and water level data to assess trends and determine if shoreline erosion patterns could be related to those variables. This work started to address the perception (among some local residents) that management of the Kenora Dam is a primary driver in shoreline erosion (Phillips and Rasid 1996).

Results of the SAFL study showed significant erosion in certain undeveloped areas of the LOW shoreline and relatively slow recession in the more developed locations. Researchers reviewed lake level data back to 1913 and found no systematic increase in annual averages. In addition, they found that recent high water events did not stand out when compared to the long-term record. Similarly, examination of 50-years of wind records showed no dramatic long-term trends. Other findings of interest to the current study were that the Flag Island monitoring station best represents wind velocity and direction on the southern side of Big Traverse Bay, that wind predominantly originates out of the west-northwest, that local wave height is well-correlated to local wind velocity, and that the largest waves are produced by winds coming out of the northwest.

2.2 LOW Water and TP Budgets

Two mean annual TP budgets have been created for LOW in recent years (Hadash 2010; Hargan et al. 2011). Each budget was created using different approaches and considering different phosphorus sources and sinks. The Hargan et al. budget was based largely on empirical data and addressed the entire LOW watershed (i.e., both the U.S. and Canadian sides), while the Hadash budget focused only on the U.S. side and modeled the system using models developed by the U.S. Army Corps of Engineers (USACE), BATHTUB and FLUX. Findings of these two studies are summarized in **Figure 2** and **Figure 3**.

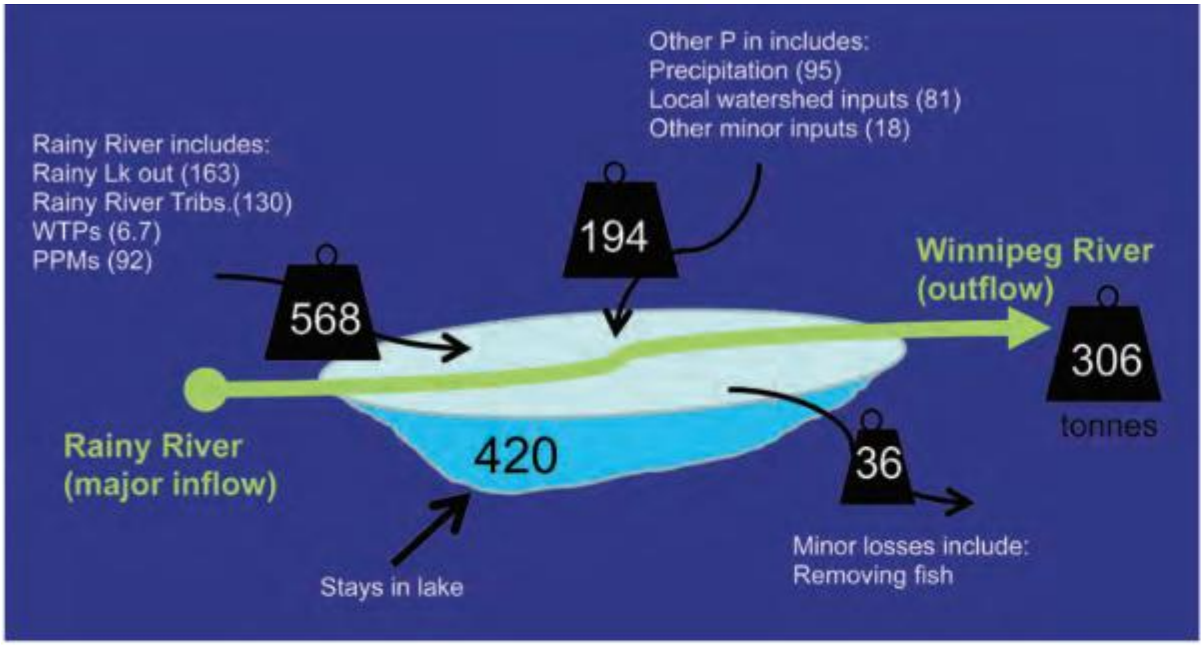


Figure 2: Hargan et al. Phosphorus Budget (in metric tonnes/year) for LOW (LOW Water Sustainability Foundation, 2011); WTP = wastewater treatment plants; PPM = pulp and paper mills

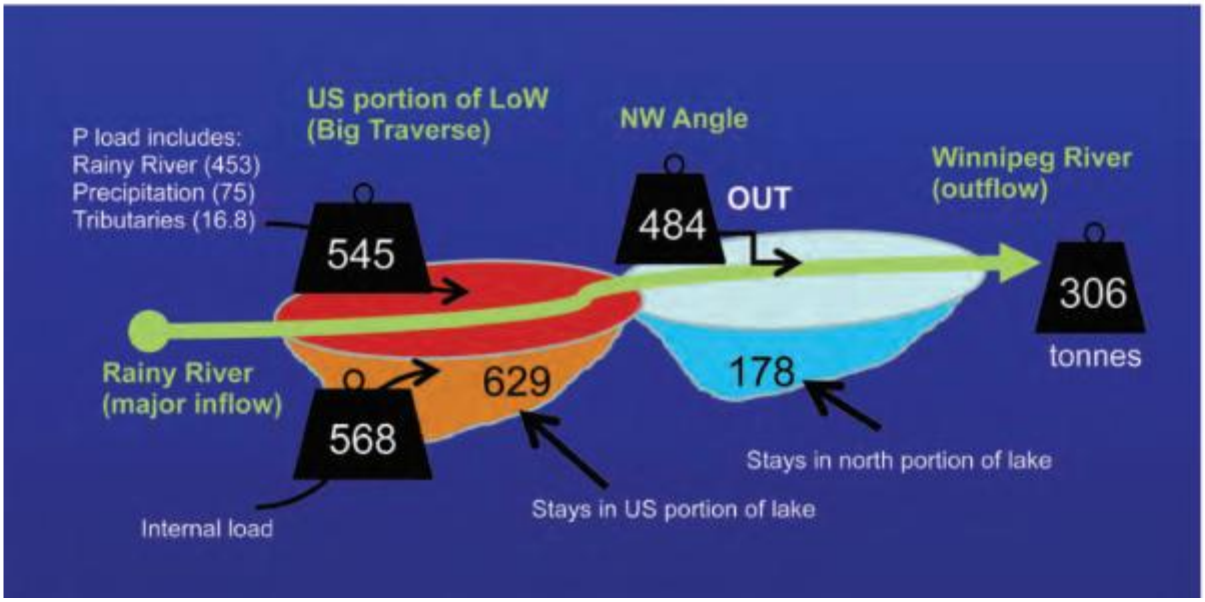


Figure 3: Hadash Phosphorus Budget (in metric tonnes/year) for U.S. Portion of LOW (LOW Water Sustainability Foundation, 2011)

While the two studies took different approaches to addressing the issue, their main findings were similar: the main source of TP to LOW is the Rainy River and a considerable amount of the TP entering the LOW is retained. Hargan et al. did not address internal loading of TP, but the Hadash study suggested that it's also a considerable component of the overall balance. The Hargan et al. work provided a more detailed assessment of the various TP loading sources to the lake and provided a more comprehensive result. Findings included an estimate of the amount of TP entering LOW from local watershed inputs and from wastewater treatment plants that discharge to the Rainy River. Neither of these studies considered TP loading to LOW from shoreline erosion.

3.0 LOW Watershed Sediment and Nutrient Loading

One component of the current study was to create a detailed estimate of sediment and nutrient loading from the U.S. tributaries (excluding the Rainy River) to LOW, using data collected since 2000. The U.S. side of the LOW watershed consists of fourteen subwatersheds that drain directly into the Lake, as shown in **Figure 4** and listed in **Table 1**. These subwatersheds were modified from MN Department of Natural Resources (DNR) data to create single drainage areas for each outlet into the lake (HEI 2012).

Figure 4: Subwatersheds of the U.S. Tributaries to LOW (Excluding the Rainy River); Labeled by MN DNR Minor ID

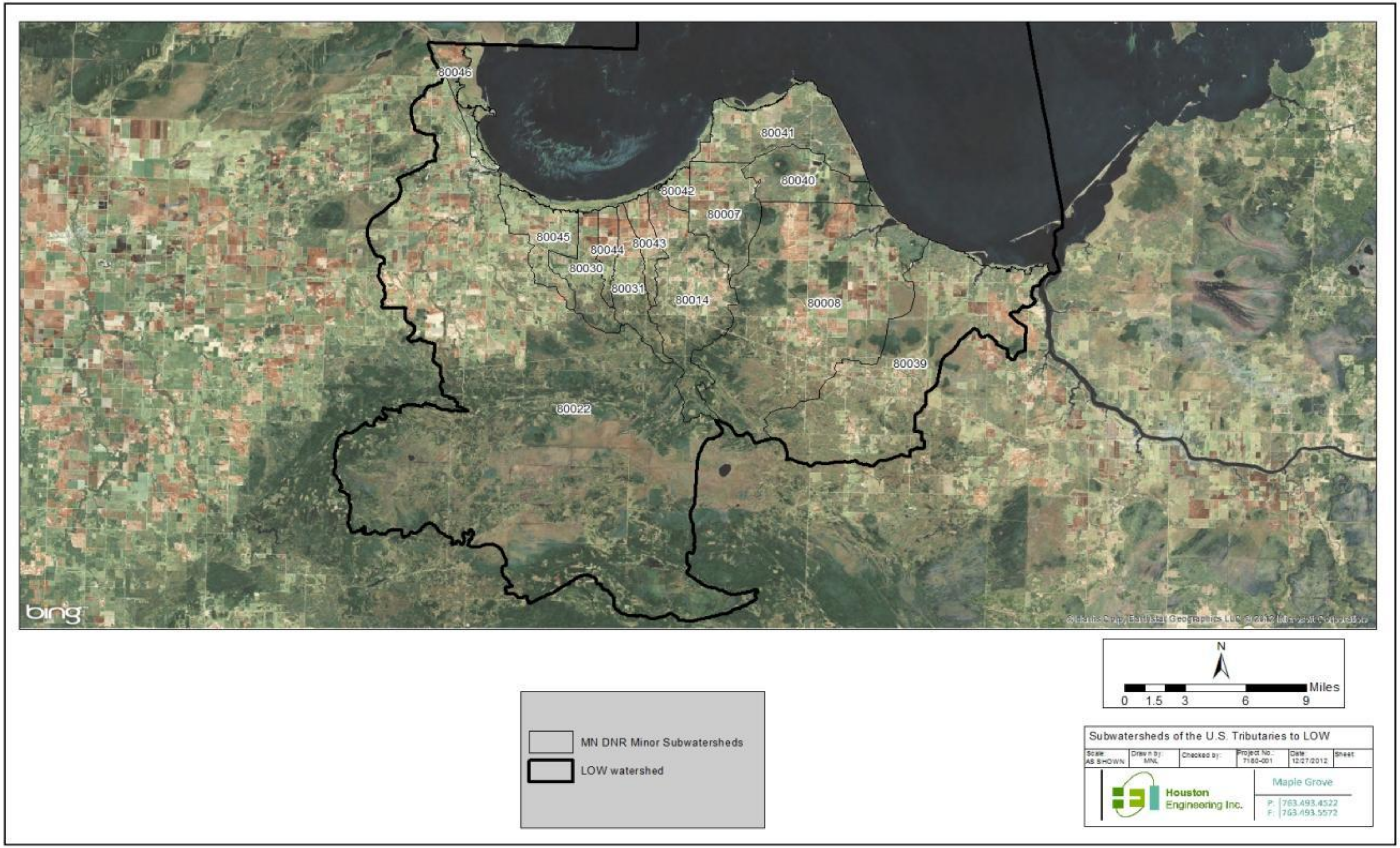


Table 1: Subwatersheds of the U.S. Tributaries to LOW (Excluding the Rainy River)

MN DNR Minor ID	HUC 10 Name	HUC 12 Name	Area (sq. mi.)
80046	Muskeg Bay	West Shore-Muskeg Bay	5.3
80041	Muskeg Bay	Long Point-Muskeg Bay	22.1
80040	Muskeg Bay	Long Point-Muskeg Bay	12.8
80022	Warroad River	**Combined Minor Watersheds	265.2
80007	Muskeg Bay	Judicial Ditch No 22	15.6
80042	Muskeg Bay	Judicial Ditch No 22	2.3
80045	Muskeg Bay	Muskeg Bay-South Shore Tributaries	11.6
80014	Muskeg Bay	Willow Creek	27.6
80043	Muskeg Bay	Muskeg Bay-South Shore Tributaries	4.7
80031	Muskeg Bay	Muskeg Bay-South Shore Tributaries	9.6
80008	Zippel Creek	**Combined Minor Watersheds	85.5
80044	Muskeg Bay	Muskeg Bay-South Shore Tributaries	3.9
80030	Muskeg Bay	Muskeg Bay-South Shore Tributaries	9.5
80039	Bostic Creek	**Combined Minor Watersheds	63.5

3.1 Hydrology

To estimate sediment and nutrient loading from the area shown in **Figure 4**, the hydrology of the system must first be known. Unfortunately, continuous (daily) flow data collected within the area is sparse, with only two gauges collecting continuous data since 2000. Therefore, estimates of the surface water hydrology of these 14 subwatersheds had to be created. A July 30, 2012 memorandum details the methods used to perform this task using the simple drainage area transfer method and the long-term (daily) streamflow gauging record from nearby Sprague Creek (HEI 2012). The memorandum that details this work is included as **Appendix A**. **Table 2** summarizes the results of the analysis in terms of estimated annual discharge volumes from each subwatershed.

Table 2: Estimated Annual Discharge Volumes (acre-feet) for LOW Watershed Subwatersheds (HEI 2012)

	Sprague Creek	West Shore-Muskeg Bay	Long Point-Muskeg Bay	Long Point-Muskeg Bay	Warroad River	Judicial Ditch No 22	Judicial Ditch No 22	Muskeg Bay-South Shore Trib.	Willow Creek	Muskeg Bay-South Shore Trib.	Muskeg Bay-South Shore Trib.	Zippel Creek	Muskeg Bay-South Shore Trib.	Muskeg Bay-South Shore Trib.	Bostic Creek
DNR Minor		80046	80041	80040	80022*	80007	80042	80045	80014	80043	80031	80008*	80044	80030	80039*
Drainage Area (mi^2)	176	5.2	22.1	12.8	265.2	15.6	2.3	11.6	27.6	4.7	9.6	85.5	3.9	9.5	63.5
2000	68,821	2,044	8,660	5,014	103,713	6,100	886	4,528	10,810	1,832	3,747	33,421	1,508	3,731	24,832
2001	65,867	1,957	8,289	4,799	99,261	5,838	848	4,333	10,346	1,753	3,586	31,986	1,443	3,571	23,766
2002	107,910	3,206	13,579	7,862	162,620	9,565	1,389	7,099	16,950	2,872	5,875	52,403	2,364	5,850	38,935
2003	33,498	995	4,215	2,441	50,481	2,969	431	2,204	5,262	892	1,824	16,267	734	1,816	12,086
2004	116,361	3,457	14,643	8,478	175,355	10,314	1,498	7,655	18,278	3,097	6,335	56,507	2,550	6,308	41,985
2005	92,546	2,749	11,646	6,743	139,466	8,203	1,191	6,088	14,537	2,463	5,039	44,942	2,028	5,017	33,392
2006	49,229	1,462	6,195	3,587	74,187	4,364	634	3,239	7,733	1,310	2,680	23,906	1,079	2,669	17,762
2007	69,682	2,070	8,769	5,077	105,010	6,177	897	4,584	10,946	1,855	3,794	33,839	1,527	3,778	25,142
2008	64,206	1,907	8,080	4,678	96,758	5,691	826	4,224	10,085	1,709	3,496	31,179	1,407	3,481	23,166
2009	92,009	2,733	11,578	6,704	138,658	8,156	1,184	6,053	14,453	2,449	5,009	44,681	2,016	4,988	33,198
2010	100,572	2,988	12,656	7,328	151,562	8,915	1,294	6,616	15,798	2,677	5,476	48,839	2,204	5,452	36,288
2011	63,113	1,875	7,942	4,598	95,112	5,594	812	4,152	9,914	1,680	3,436	30,649	1,383	3,422	22,772

*this subwatershed combines multiple DNR Minor subwatersheds

3.2 Sediment and Nutrient Loading

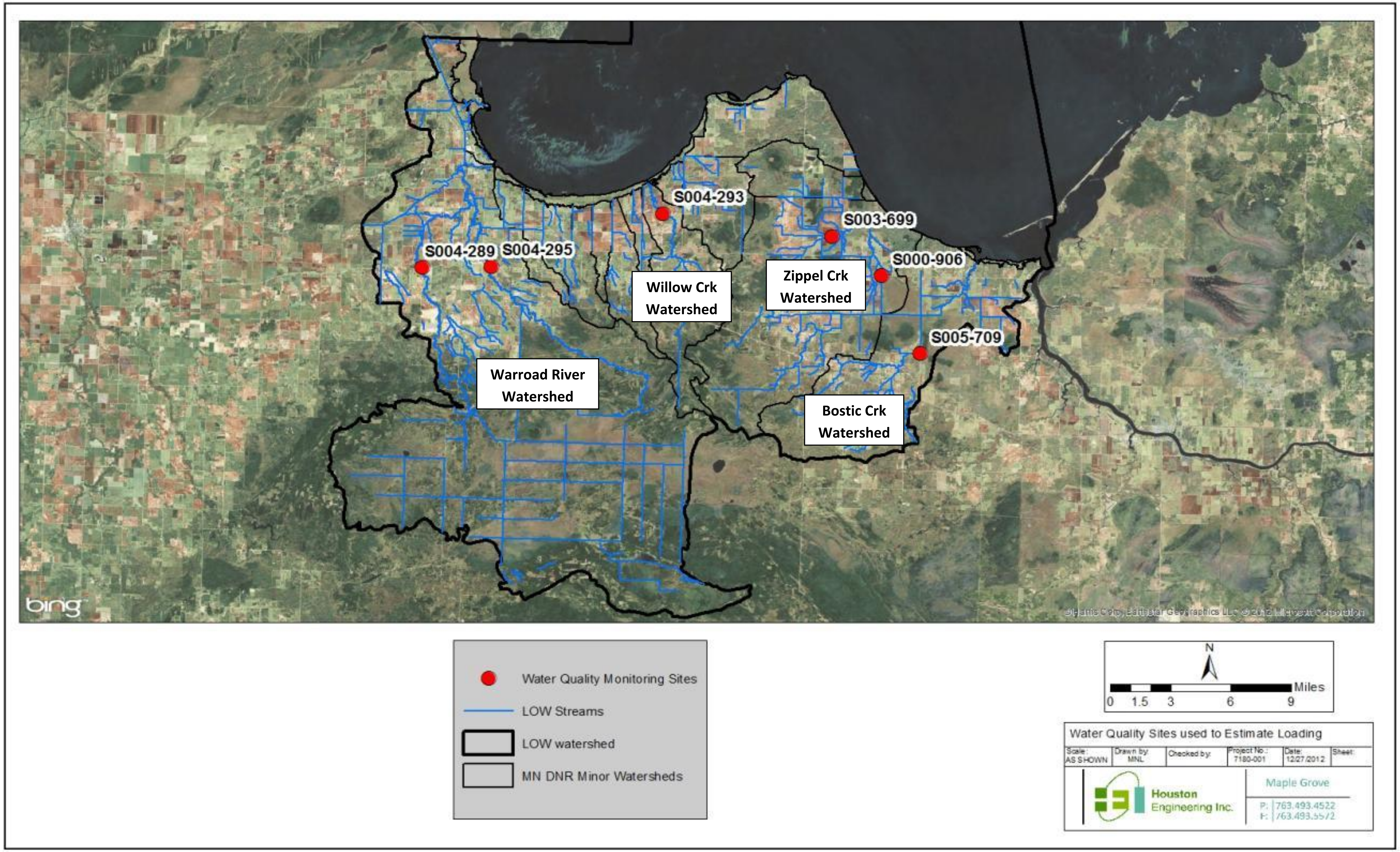
The USACE’s FLUX 3.09 program was used to estimate sediment and nutrient loading to LOW from the LOW watershed. FLUX estimates loading using a continuous flow record and instantaneous water quality data, through the use of regression techniques. In this case, sediment and TP loadings were computed in kilograms (kg) per year; results were then converted to tons per year.

3.2.1 Water Quality Data Selection and Preparation

The water quality data used for this analysis was obtained from the Minnesota Pollution Control Agency’s (MPCA) Environmental Quality Information System (EQuIS) database (Garvin 2012). Data was available for 27 stream locations in the study area; seven are on the Warroad River (the east and west branch combined), one is on the Willow River, ten are in the Zippel Creek watershed (Zippel Creek, Williams Creek, and other associated tributaries), and nine are in the Bostic Creek watershed. For purposes of this analysis, data collected within the ten-year period (2002-2011) was considered. None of the 27 sites in the watershed had data for all 10-years. Thirteen sites had at least 5-years of data, five had at least 2-years of data but less than 5-years of data, and nine sites had one year of data.

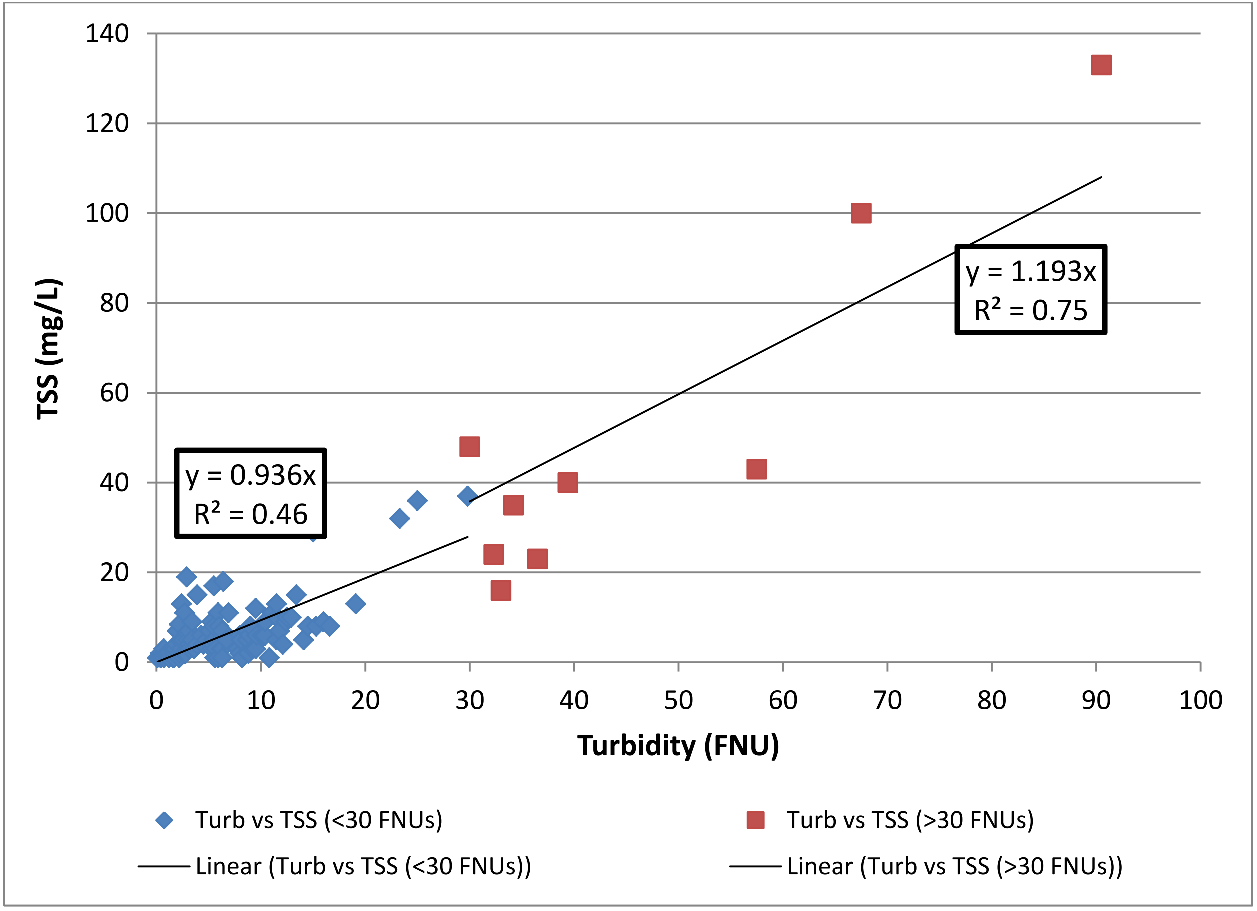
Ideally the sites chosen for this work would be located at the outlet of each subwatershed to LOW and have numerous TP and turbidity measurements. Unfortunately, no sites fit that description and further refinement was necessary. The water quality sites used in this analysis were selected based on the number of TP and turbidity observations available, in addition to the drainage area of the site, and the overlap of drainage area with the other sites. After review of the available data, six water quality sites were selected to use in the FLUX analysis for computing subwatershed loadings. The selected sites consist of two sites in the Warroad River watershed, two sites in the Zippel Creek watershed, one site on Willow Creek, and one site on Bostic Creek. The chosen sites are shown in **Figure 5**.

Figure 5: Water Quality Sites used to Estimate LOW Watershed Loading



The majority of data available for characterizing sediment loading in the study area were sampled in the form of turbidity. In a few cases total suspended sediment (TSS) data were also available. For use in the FLUX simulations, the available turbidity data were converted to estimates of TSS, which were then assumed to represent the concentration of sediment within the river water. A regression equation was developed to create a relationship between those turbidity and TSS measurements that were taken coincidently (i.e., at the same time and at the same location) in the LOW watershed. The regression was split into two categories, turbidity values less than 30 FNUs and those greater than or equal to 30 FNUs. Results were then used to convert turbidity measurements at the selected water quality sites (**Figure 5**) to TSS. **Figure 6** shows the turbidity – TSS relationship developed for the LOW watershed and used in this analysis.

Figure 6: Turbidity – TSS Relationship for Estimating Sediment Concentrations



3.2.2 Methods

The hydrology data discussed in **Section 3.1** and water quality data discussed in **Section 3.2.1** were used as inputs to the FLUX program. Unit runoff values from the Sprague Creek watershed were used to estimate continuous (daily) streamflow records at each of the water quality monitoring sites. Both seasonal and flow stratifications were reviewed and attempted in the FLUX simulations. No clear correlation was present; therefore, no stratifications were used in the final analysis. FLUX provides six different methods for computing pollutant loading. After attempting each of the options, Method 6 provided the lowest coefficient of variability for the six sites analyzed and was selected for use in the final estimations.

The FLUX simulations resulted in estimated average annual sediment and TP loadings at the six water quality sites shown in **Figure 5**. To estimate pollutant loads at the point where each of the four corresponding subwatersheds (i.e., Warroad, Willow, Zippel, and Bostic) discharge into LOW, unit loading values were computed for the areas upstream of each sampling location. The total pollutant loadings from the Willow and Bostic Creek subwatersheds were then estimated by multiplying the drainage area of that entire subwatershed by the unit loading values for Sites S004-293 and S005-709, respectively. Loads from the Zippel Creek and Warroad River subwatersheds were estimated by multiplying those subwatershed drainage areas by the average unit loadings for the two sites located within each of those subwatersheds. Loads from the remaining (un-monitored) subwatersheds were estimated by computing an overall average unit loading value (considering all six monitoring sites) and multiplying that by the drainage area of each of the remaining 12 subwatersheds.

3.2.3 Results

Estimates of annual TSS and TP loadings from the study area subwatersheds are shown in **Table 3** and **Table 4**. **Figure 7** and **Figure 8** show the estimated TSS and TP unit loads for each subwatershed. Unit loadings of both constituents are fairly uniform across the watershed. An exception to that uniformity is seen in the estimated TSS loading at Site S000-906 and the estimated TP loading at Site S004-293. At both these locations, estimated loads are about twice that of the other stations.

Table 3: FLUX-Estimated TSS Loading from Study Area Subwatersheds

Sample Site	Site Description	Area (miles^2)	TSS (tons/yr)	TSS (tons/yr/mi^2)
S004-295	East Branch Warroad River	43	119	2.8[1]
S004-289	West Branch Warroad River	160	696	4.4[1]
S004-293	Willow Creek	24	94	3.9[1]
S003-699	Zippel Creek	25	84	3.3[1]
S000-906	Zippel Creek	28	189	6.8[1]
S005-709	Bostic Creek	33	124	3.7[1]
	Un-gaged Warroad	62	221	3.6[2]
	Un-gaged Willow	3	13	3.9[2]
	Un-gaged Zippel	33	165	5.1[2]
	Un-gaged Bostic	30	112	3.7[2]
	Un-gaged All	97	403	4.1[3]
	Total	**539**	**2,218**	

[1] computed from observed water quality data and estimated hydrology; [2] estimated as an average of computed unit loading values in the subwatershed; [3] estimated as an average of all other computed unit loadings in the watershed.

Table 4: FLUX-Estimated TP Loading from Study Area Subwatersheds

Sample Site	Site Description	Area (mile^2)	TP (tons/yr)	TP (tons/yr/mi^2)
S004-295	East Branch Warroad River	43	0.8	0.019[1]
S004-289	West Branch Warroad River	160	3.5	0.022[1]
S004-293	Willow Creek	24	2.0	0.080[1]
S003-699	Zippel Creek	25	0.7	0.029[1]
S000-906	Zippel Creek	28	1.0	0.034[1]
S006-838[4]	Bostic Creek	33	0.8	0.023[1]
	Un-gaged Warroad	62	1.3	0.020[2]
	Un-gaged Willow	3	0.3	0.080[2]
	Un-gaged Zippel	33	1.0	0.032[2]
	Un-gaged Bostic	30	0.7	0.023[2]
	Un-gaged All	97	3.4	0.035[3]
	Total	**539**	**15.4**	

[1] computed from observed water quality data and estimated hydrology; [2] estimated as an average of computed unit loading values in the subwatershed; [3] estimated as an average of all other computed unit loadings in the watershed. [4]Site S006-838 is co-located with site S005-709.

Figure 7: FLUX-Estimated Unit Loads of TSS for Water Quality Site Drainage Areas

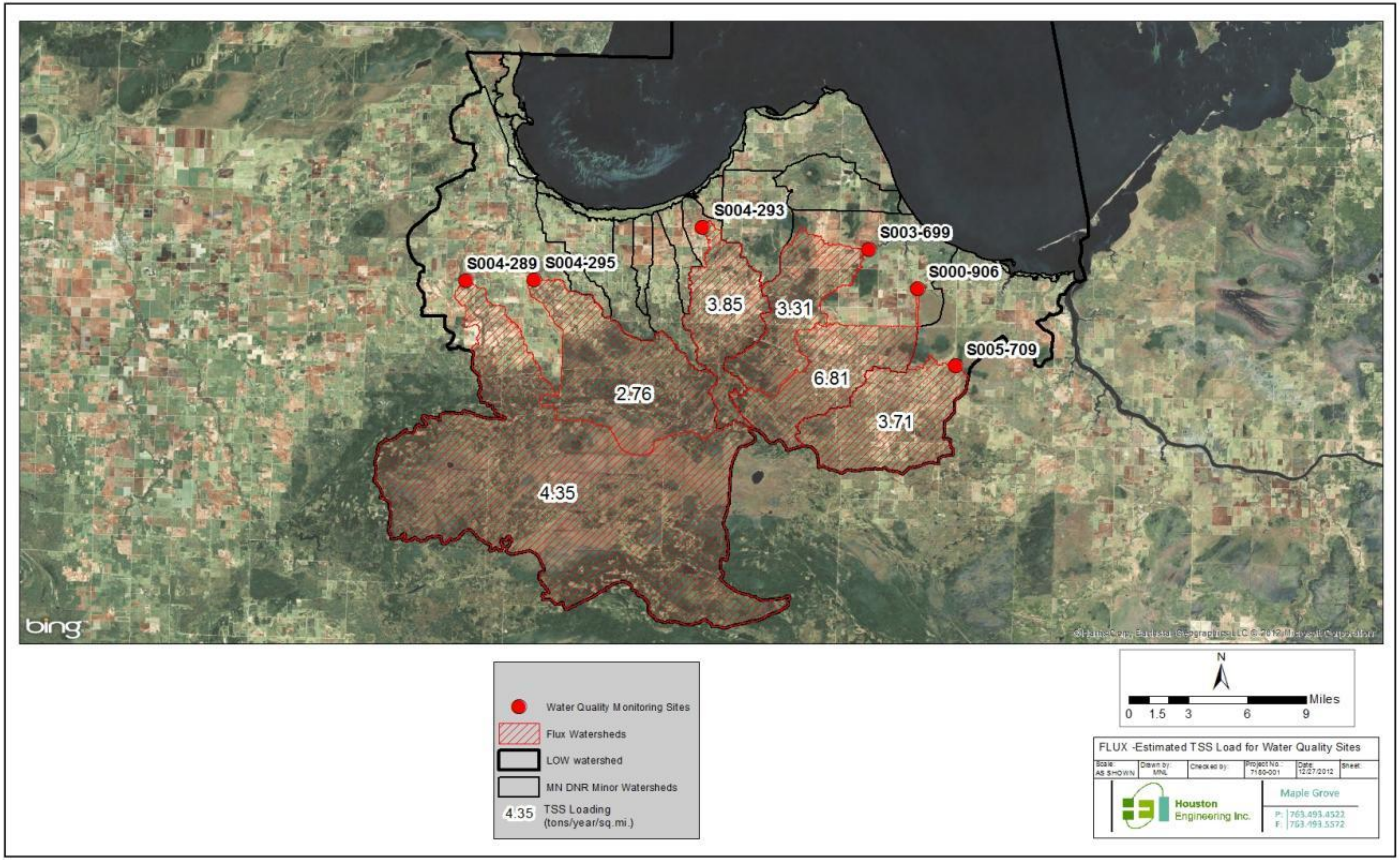
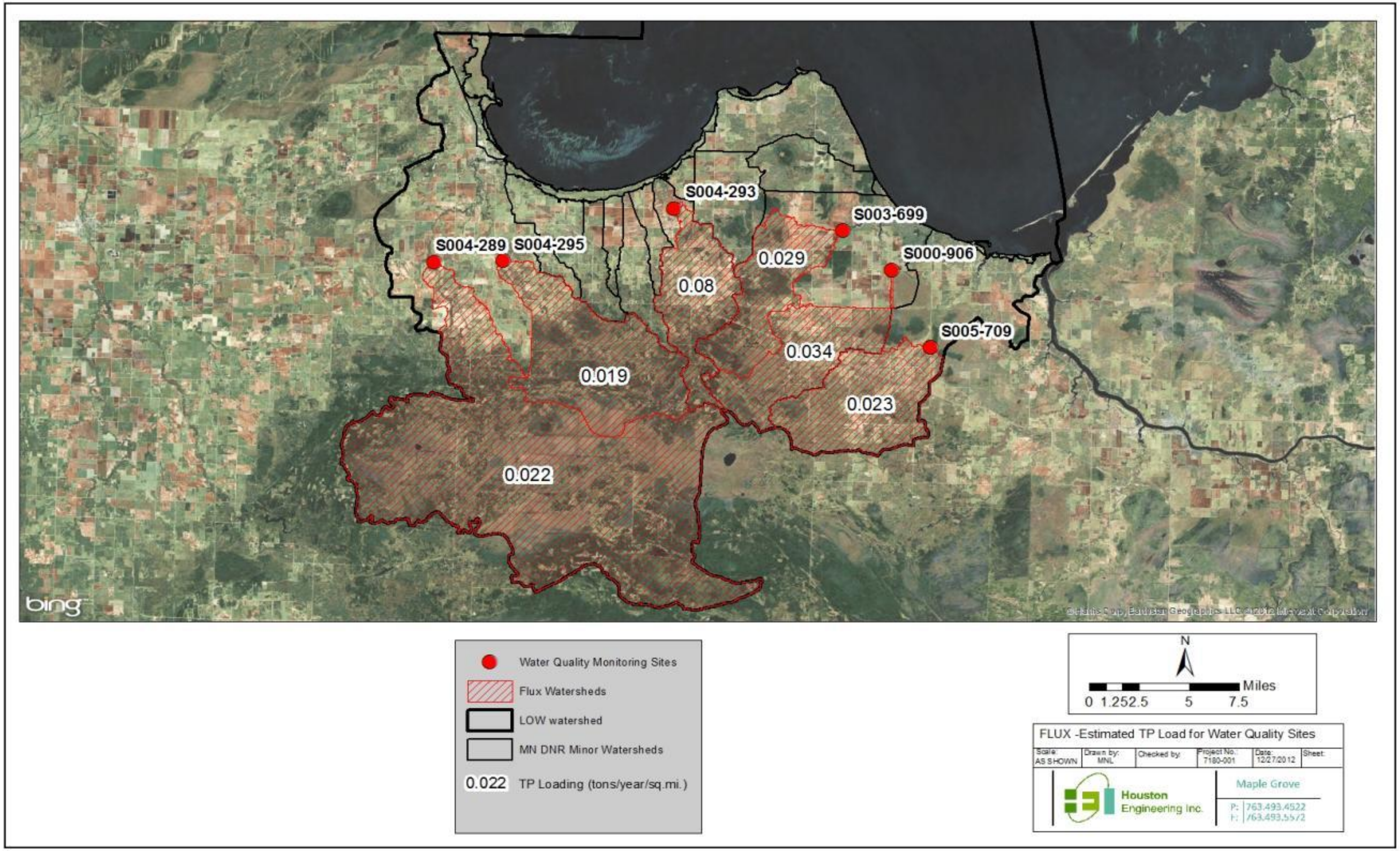


Figure 8: FLUX-Estimated Unit Loads of TP for Water Quality Site Drainage Areas



The total estimated amount of sediment entering LOW through the LOW watershed tributaries is 2,218 tons per year. The total estimated phosphorus entering the Lake from these tributaries is approximately 15 tons year. This result is consistent with what was estimated by Hargan et al. and Hadash; their results are summarized in **Figure 2** and **Figure 3**. If the "local watershed inputs" term of Hargan's LOW TP budget is equally apportioned across the entire LOW drainage area (i.e., both the Canadian and U.S. sides), an estimated 11 tons (10 metric tonnes) per year of TP is contributed to LOW from our study area. Similarly, Hadash estimated this average annual TP load at 16.8 tons/year.

4.0 Southern Shoreline Erosion and Nutrient Loading

The main focus of this project was the estimation of sediment and nutrient loading to LOW from erosion of the lake's southern shoreline. Products from this portion of the work include estimates of average annual shoreline erosion rates and average annual nutrient loading from shoreline erosion. Overall volumes of sediment eroded and nutrient loaded into the lake (from shoreline erosion) over the study period are also provided.

4.1 Methods

4.1.1 Data Sources

Much of work performed in this part of the study relied on Geographic Information Systems (GIS) data. Numerous GIS shapefiles were downloaded from the MN DNR's Data Deli or provided by credible sources (e.g., LOW Soil and Water Conservation District and MPCA). These sources, along with data collected as a part of this project, provided the information needed to estimate the annual shoreline erosion and nutrient loading rates and quantify the overall volume of sediment lost and nutrients loaded to LOW from that erosion. The data also assisted in creating a framework for sub-dividing the shoreline, based on shoreline characteristics, for the sediment and nutrient sampling portion of the project. These sub-divisions will also help local planning and resource agencies in targeting sections of shoreline for future erosion management and identifying appropriate management techniques.

4.1.1.1 Aerial Photographs

Aerial photographs of the southern shoreline of LOW were obtained for the years 1940, 1961, 1975, 1991, 1996, 2003, and 2009 (MGIO 2011, MN DNR 2011, UML 2011). The quality of these photos varies over time as the technology for recording the images has progressed. However, each image allows a good estimate of the relative shoreline location at the time that the photograph was taken. The photographs from 1975, 1985, and 1996 were provided by the LOW County Soil and Water Conservation District (SWCD) and were only available for LOW County, missing the approximately ten and a half miles of the study area shoreline that falls in Roseau County. These photographs were georeferenced by SWCD staff during previous projects. Aerial photographs taken in 1940 and 1961 were georeferenced by HEI for this project, while photographs from 2003 and 2009 were provided through the State of Minnesota Land Management Information Center (LMIC) aerial photography server, which delivers the data georeferenced.

4.1.1.2 Light Detection and Ranging

Light Detection and Ranging (LiDAR) is a method of collecting extremely accurate elevation data over wide expanses through aerial flight. LiDAR data is available for the study area and was downloaded from the Minnesota Geospatial Information Office (MGIO). The most recent data available was collected in 2009. When downloaded from MGIO, the LiDAR data comes in a package with several classifications for different land types. Work under this project utilized the bare earth and vegetation classifications to determine shoreline characteristics (e.g., location of the shoreline, vegetation height, and bank height).

4.1.1.3 Shoreline Delineations

Shoreline delineations were created to estimate the lateral recession or deposition of the shoreline within the project area. Shorelines were delineated for 1940, 1975, 1985, 1991, 1996, 2003, and 2009 to provide an assessment of erosion or deposition over longer periods of time. Viewing these trends over longer periods reduces some of the uncertainty related with year-to-year variability and also allows for uncertainty in shoreline delineations (created by tracing along the aerial photography images and by interpreting the LiDAR data) to play a smaller role in the overall estimates. The shoreline delineations were completed by various entities and delineated for varying lengths of shoreline. For example, the delineations completed by the MN DNR using the 1975, 1985, and 1996 images were only completed for Lake of the Woods County. The entity responsible for each shoreline delineation, the method used for determining the shoreline location, and the extent of the shoreline delineated are described in **Table 5**.

Table 5: LOW Southern Shoreline Delineation Information

Year	Creating Entity[1]	Data Used for Delineation	Delineated Shoreline Extent
1940	HEI	Historic aerial photographs	Warroad to Wheelers Point
1960	HEI	Historic aerial photographs	Lake of the Woods County
1975	MN DNR	Historic aerial photographs	Lake of the Woods County
1985	MN DNR	Historic aerial photographs	Lake of the Woods County
1991	MN DNR / SAFL	Historic aerial photographs	Warroad to Wheelers Point
1996	MN DNR	Historic aerial photographs	Lake of the Woods County
2003	HEI	Historic aerial photographs	Warroad to Wheelers Point
2009	HEI	2009 LiDAR data and historic aerial photographs	Warroad to Wheelers Point

[1] HEI = Houston Engineering Inc., MN DNR = Minnesota Department of Natural Resources, SAFL = Saint Anthony Falls Laboratory

The MN DNR shoreline delineations were provided by MPCA personnel (Baratono, 2011). MPCA provided two shoreline shapefiles for each year; one termed ‘shoreline’ and one termed ‘waterline’. Several MN DNR and MPCA personnel were contacted to determine the methods used to create each shapefile and no definite answer was provided as to how each was determined (i.e., what constituted a ‘shoreline’ vs. a ‘waterline’ during the delineation process). After review of the data, the decision was made to use the ‘waterline’ delineation for erosion comparison since this delineation most closely matched the delineation approach used by HEI in developing delineations for this project (i.e., tracing along the water/land interface in the image).

All shorelines delineated by HEI, with the exception of 2009, were delineated using aerial photography at a scale of 1:2,000 or less. The shoreline was interpreted as the location where the land meets the water, because this is the most recognizable feature when using aerial photography. In areas where the shoreline was difficult to determine (usually due to low resolution of the imagery), professional best judgment was used. The 2009 shoreline was delineated using LiDAR (bare earth classification) and aerial photography. The primary data source was the LiDAR, using differences in elevation to denote where land meets water. When it was difficult to determine a shoreline through LiDAR, aerial photography was used to fill in data gaps.

Since the shoreline was defined as the location where the land meets the water, water levels at the time of the photograph could affect the resultant delineation. As such, the water levels at the time each series of photographs were captured were taken into account. Water levels were defined using data from the gauge at Warroad (station 05PD001). The 1940 and 2003 shoreline delineation layers were corrected for water elevations. The beginning water elevation for each adjusted layer was defined as the average water elevation during the time period that the series of photos was taken (e.g., if the photos were taken over a 5-day period, the average water elevation during those 5-days was used). Metadata associated with each aerial photograph provided the timeframe that the aerial photos were collected. The 1940 photographs provided specific dates, while the 2003 data provided a timeframe (June through August). The resultant values were then compared with the average elevation for the 2009 data and a difference-from-2009 value was computed. An average shoreline slope was developed from the field survey profiles (see **Section 4.3**) and combined with each delineation’s difference-from-2009 value to compute the distance that delineation should be laterally adjusted. **Table 6** summarizes the adjustments that were made. The resultant (lateral) adjustments were performed through the offset command in ArcGIS.

Table 6: Shoreline Adjustment Methodology and Distances

Year	Mean Water Level (m)	Water Level Difference (m)	Shoreline Slope (%)	Lateral Adjustment to Shoreline (m)
1940	322.52	0.51	3.2	15.7
2003	322.50	0.53	3.2	16.3
2009	323.03	-	-	-

4.1.2 Shoreline Characteristics

In order to ease the characterization of erosion along the 40+ miles of shoreline that this study includes, it was desirable to segment the shoreline into categories. These categories are based on features that may have an impact on the propensity for erosion. Development of these categories is described in this section.

4.1.2.1 Top of Bank

Many of the shoreline characteristics investigated were best assessed on the consolidated portion of the shoreline bank, not immediately along the water's edge. An estimate of the 'top of bank' (TOB) along the shoreline was developed to assist in this step. The TOB was defined as the highest point along the shoreline and delineated by HEI personnel using the three meter grid, bare earth classified LiDAR data. This delineation was segmented into 500 foot sections along the entire study area. Each 500 foot section was then given a specific identification number (i.e., station), based on its relative distance (in miles) from Warroad, to distinguish between each section as well as to provide spatial identification. These 500 foot sections were used throughout the classification process to provide a more detailed analysis of where sediment erosion is occurring and a method for targeting future shoreline management.

4.1.2.2 Rip-Rapped Areas

Numerous areas along the LOW shoreline have been rip-rapped to protect from erosion. Locations with existing rip-rap were estimated by LOW SWCD staff, based on the review of maps, the location of structures, and their intimate knowledge of the area. Rip-rapped locations were provided in a shapefile format. Approximately 16% of the 40+ miles of project shoreline was designated as rip-rapped.

In general, rip-rap along the LOW shoreline is located in areas were homes and/or resorts have been developed. These areas are typically not located in mucky soils and often have bank heights of over five feet. The main locations of rip-rap within the study area include Rocky and Long Points, the Sandy Beach area, and a few locations near Morris Point.

4.1.2.3 Degree of Erosion

The degree of erosion was defined by HEI as the difference between the 1940 and 2009 delineated shorelines. Use of these data provided an approach to classify the shoreline by the amount of erosion experienced over the past seventy-years. Each 500 foot section of shoreline was classified into one of four degrees of erosion categories, based on the maximum amount of erosion within that section. The categories were as follows: high erosion (>500 feet), moderate erosion (100 – 500 feet), low erosion (<100 feet), and deposition. Results provided a good general view of where the most significant erosion has occurred along the LOW southern shoreline.

4.1.2.4 Soils

The United States Natural Resources Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO) GIS shapefile was used to classify the soils near the shoreline (NRCS 2005). The soils layer was joined to the 2009 shoreline shapefile to provide a detailed assessment of the soil types that are directly eroding into the lake. Soils were classified into general soil type categories based on the soil name. Soil type categories included muck, sand, loamy fine sand, very fine sandy loam, fine sandy loam, clay, clay loam, silt loam and loam. The percent of the 40+ miles of study area shoreline that each soil type category encompasses is listed in **Table 7**.

Table 7: Soil Type Category and Percent of Shoreline

Soil Type Category	Percent of Shoreline
Muck	60%
Sand	19%
Loamy Fine Sand	8%
Very Fine Sandy Loam	5%
Fine Sandy Loam	4%
Clay	1%
Clay Loam	1%
Silt Loam	1%
Loam	1%

4.1.2.5 Vegetation Height

Vegetation height was estimated using the vegetation classification of the LiDAR data. The LiDAR vegetation classification reports the average maximum vegetation elevation observed within a three meter grid. The difference between that maximum elevation and the elevation of the ground surface then provides an estimate of maximum vegetation height. These heights were analyzed to observe if a relationship existed between the vegetation height and the amount of erosion (1940-2009) observed along the shoreline. This analysis tested the theory that taller vegetation has a more extensive root system and thus provides more resistance to erosion (than areas with shorter vegetation). Vegetation heights were categorized into one of three general categories, which were assigned to each 500 foot section of shoreline based on the dominant height in that area. The vegetation height categories were as follows: 1-5 feet, 5-10 feet, and 10+ feet.

4.1.2.6 Fetch

Maximum fetch was calculated for each 500 foot section to observe if a relationship existed between that parameter and the degree of shoreline erosion. Longer fetches typically result in more energy being stored in waves, which results in a more erosive force being exerted on the shoreline. A series of lines were drawn (in GIS) in the northwest direction, along the southern shoreline, to estimate the length of maximum fetch. The northwest direction was chosen because winds in the area predominantly originate from that area and also create the largest waves when coming from that direction (Herb et al., 2004). The fetch lines were clipped to the LOW boundary and the length for each line was calculated. The fetch was then classified into one of five categories based on the length of maximum fetch within each 500 foot shoreline section. The categories were as follows: 0-5 miles, 5-10 miles, 10-15 miles, 15-20 miles, and 20+ miles.

4.1.2.7 Bank Height

The height of the bank was estimated to observe if a pattern existed between this parameter and the amount of erosion occurring along each section of shoreline. The bank height was calculated in GIS as the difference between the 2009 shoreline delineation and the TOB. Each 500 foot section was classified into one of three categories based on the most predominant bank height within each 500 foot section. The bank height classifications were as follows: 1-5 feet, 5-10 feet, or 10+ feet.

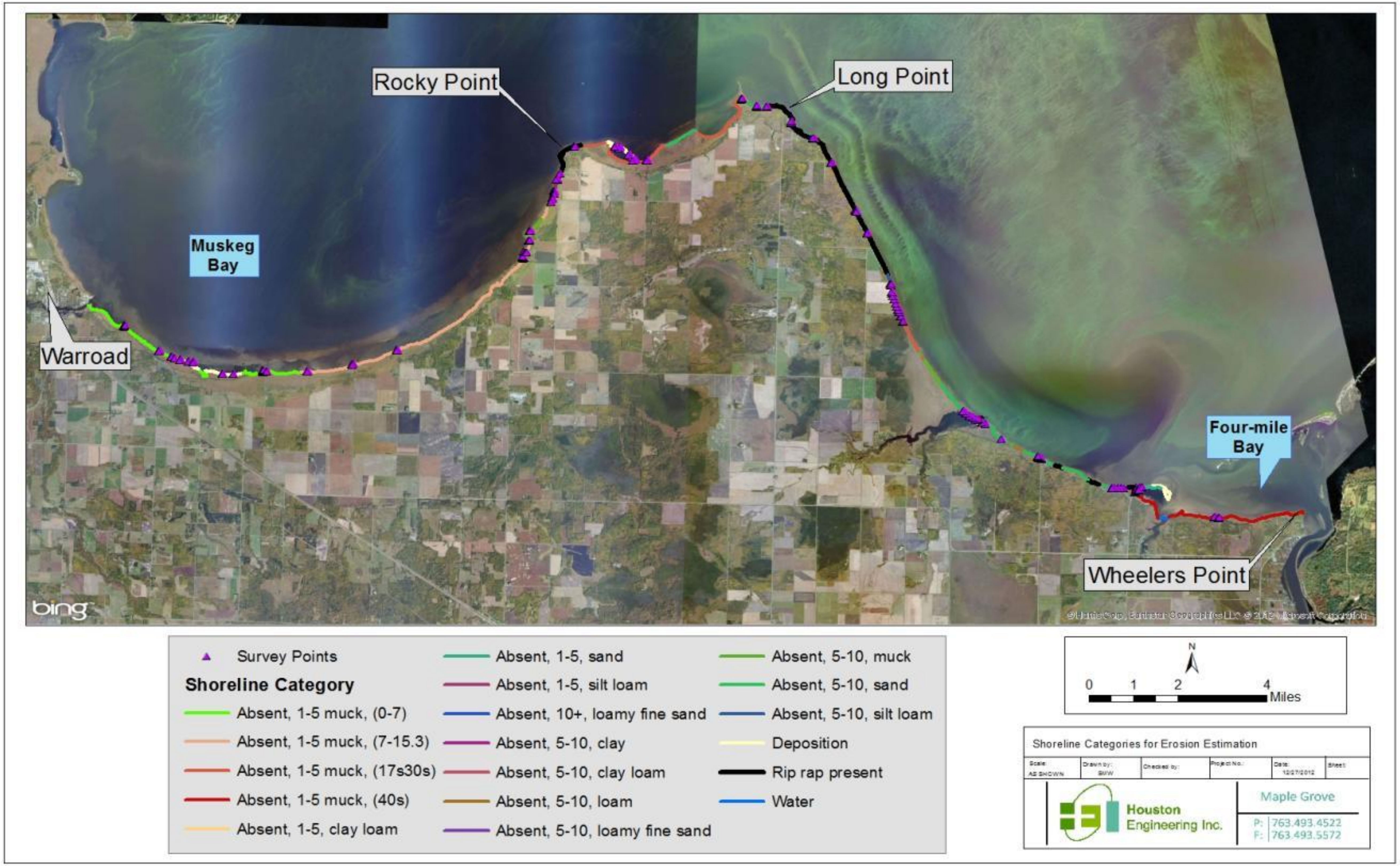
4.1.3 Shoreline Categories for Erosion Estimation

In order to better classify the shoreline and to create groups for performing the erosion and nutrient loading estimates, each 500 foot section of shoreline was grouped into a shoreline category. These categories were based on the presence/absence of rip-rap, bank height, and general soil type (e.g., muck, clay, sand, etc.). These categories were chosen as the basis for grouping shoreline sections because analysis showed a relationship between these parameters and the degree of shoreline erosion from 1940-2009 (i.e., high, medium, and low). The other parameters investigated (e.g., height of vegetation) did not show a consistent relationship with the degree of shoreline erosion. **Table 8** summarizes these categories and the percent of the study area shoreline that falls in each. Only those areas without rip-rap are included in the table (since rip-rapped areas were not included in the estimate of shoreline erosion volumes/rates/loads). **Figure 9** shows the distribution of the categories. The category names in the figure summarize the presence/absence of rip-rap, bank height, and soil type (e.g., category "Absent, 1-5, clay loam" represents shoreline without rip-rap, with a bank height between one and five feet, and in clay loam soils). The "Absent, 1-5, muck" category was sub-divided for analysis, as explained in **Section 4.1.5**.

Table 8: Shoreline Categories and Percent of Non-Rip-Rapped Shoreline

Bank Height	Soil Type	Shoreline Category	Percent of Study Area Shoreline
1-5	muck	1-5, muck	71%
5-10	sand	5-10, sand	15%
5-10	muck	5-10, muck	5%
1-5	sand	1-5, sand	5%
5-10	silt loam	5-10, silt loam	1%
5-10	clay	5-10, clay	<1%
1-5	clay loam	1-5, clay loam	<1%
5-10	loam	5-10, loam	<1%
5-10	clay loam	5-10, clay loam	<1%
1-5	silt loam	1-5, silt loam	<1%

Figure 9: LOW Shoreline Categories for Erosion Estimation



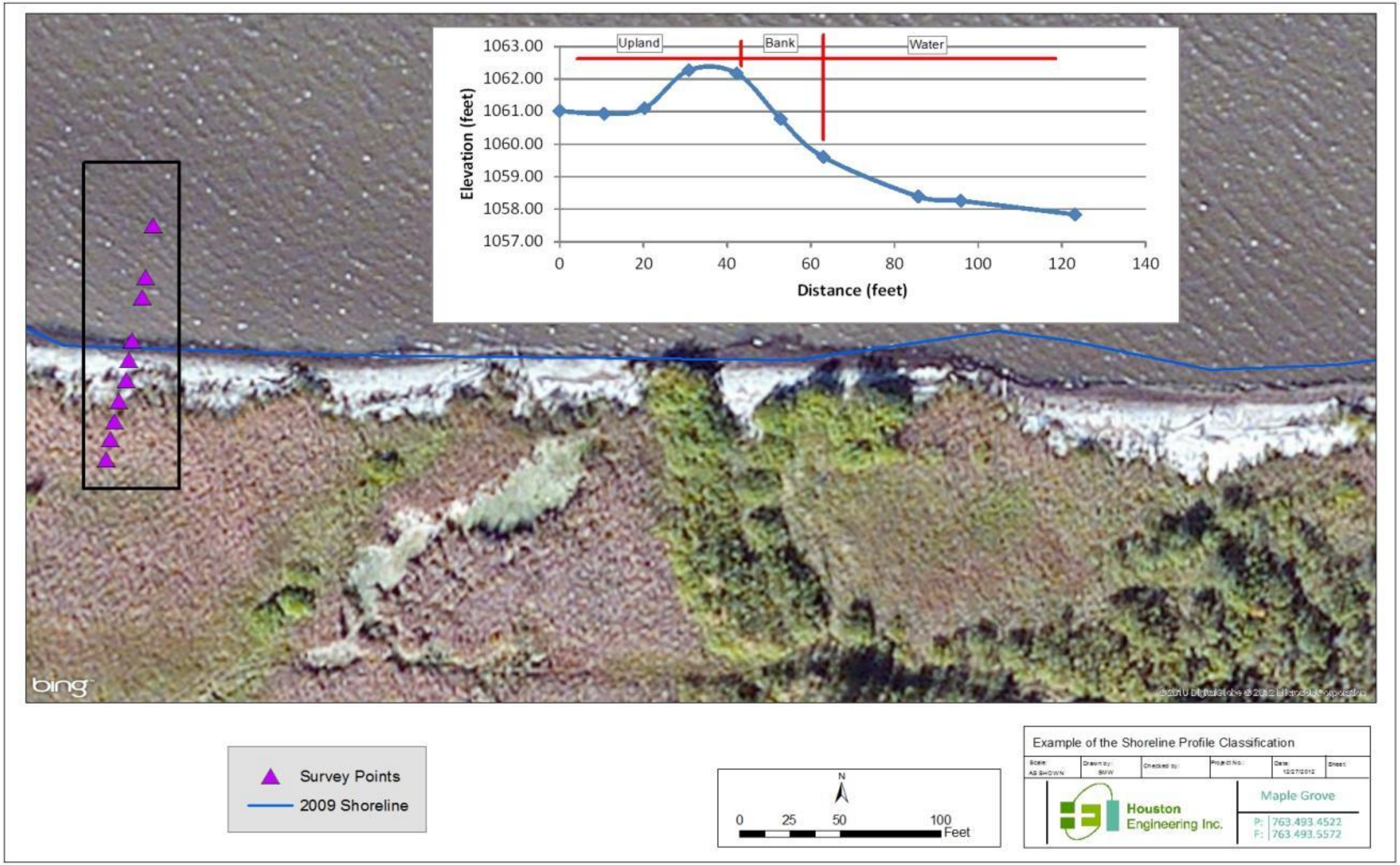
4.1.4 Field Survey

Field survey data provided measured cross-sections of the study area shoreline for use in estimating erosional (or depositional) volumes. The entire 40+ miles of the study area shoreline (from Warroad to Wheelers Point) were surveyed. Ninety-eight cross-sections were collected from a minimum of approximately 50-feet landward of the land-water interface to lake depths of approximately 2-feet deep. **Figure 9** shows the location of the surveyed cross-sections. All data were collected using a Trimble survey grade Global Positioning System (GPS) as outlined in the project's Quality Assurance Protection Plan (QAPP) (LOW SWCD & HEI 2012). Two field survey trips were performed; November 29-December 1, 2011 and May 23-24, 2012.

4.1.5 Shoreline Profiles

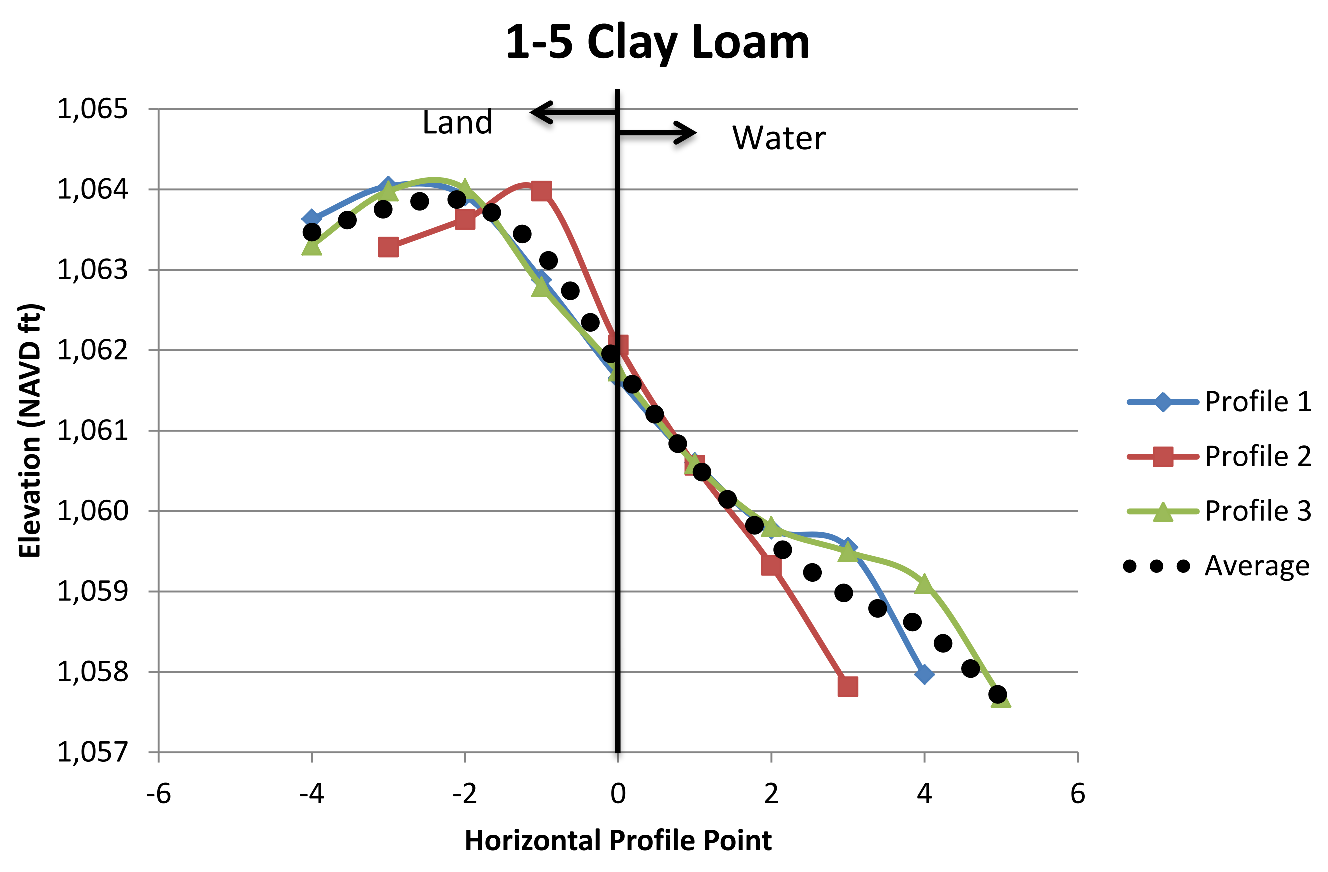
Shoreline profiles were created for each of the 98 survey cross-sections in Microsoft Excel. Using aerial photography and comparing each survey points' location relative to the TOB and 2009 shoreline delineation, each point was classified as being in the water, on the rising bank, or on the upland area. **Figure 10** shows an example of this, where points between the TOB and water are noted as being the bank and those landward of the TOB are noted as being on upland.

Figure 10: Example of the Shoreline Profile Classification



Since survey data could not be collected for every 500 foot section of shoreline, a representative shoreline profile was created for each shoreline category (e.g., absent, 1-5, clay loam). The representative profile was developed by combining all surveyed cross-sections within that shoreline category and taking an average of the elevations along the profile (i.e., taking an average of the values on the y-axis of the plot, for each x-value). The 98 profiles varied in length, but were aligned (for computing averages) by setting the first survey point located in the water (determined above) as the zero stationing and laying the profiles on top of one another accordingly. An example is shown in **Figure 11**.

Figure 11: Example of Developing Representative Profiles for Shoreline Categories



Non-rip-rapped areas classified as 'muck' with a bank height of 1-5 feet comprise approximately 70% of the erodible (i.e., non-rip-rapped) shoreline and are spatially spread out from Muskeg Bay to portions between Long and Rocky Points and Four-Mile Bay. Due to the variability that exists between these locations (and, to a lesser extent, also to the difference in the fetch of each segment), the shoreline category of '1-5, muck' was broken down into four sub-categories for representative profile development. These sub-categories were based on the location of the segments and also on the similarity of the surveyed cross-sections. The sub-categories were named based on their relative distance from Warroad (noted as relative miles in parentheses) and include: '1-5 muck (1-7)', '1-5 muck

(7-15.3)’, ‘1-5 muck (17-30s)’, and ‘1-5 muck (40s)’. This is the only shoreline category for which sub-categories were developed.

A few shoreline categories had no surveyed cross-sections collected within them. Typically, these areas comprised only a few 500 foot sections. In these areas, surrogate (representative) profiles were used. Surrogates were chosen by similarity of bank height, soil type (when possible), and spatial location. It should also be noted that one 500 foot section comprises the shoreline category of ‘10+, loamy fine sand’. No survey data were collected in areas where the bank height was determined to be greater than ten feet; thus, no representative profile was applied to this 500 foot section and erosional volumes were not estimated. **Table 9** summarizes the representative profiles that were used to for calculating volumes of erosion for each shoreline category.

Table 9: Shoreline Category and the Profile Used for Calculating Erosion Volumes

Shoreline Category	General Profile used for Volume Calculation
1-5 muck (0-7)	1-5 muck (0-7)
1-5 muck (7-15.3)	1-5 muck (7-15.3)
1-5 muck (17s-30s)	1-5 muck (17s-30s)
1-5 muck (40s)	1-5 muck (40s)
5-10 muck	5-10 muck
5-10 clay	5-10 clay
5-10 silt loam	5-10 silt loam
5-10 sand	5-10 sand
10+ loamy fine sand	Not calculated
1-5 clay loam	1-5 clay loam
1-5 sand	1-5 sand
1-5 silt loam	5-10 silt loam (station 33.3)[1]
5-10 clay loam	5-10 clay loam
5-10 loam	5-10 silt loam[1]

[1] Soil grouping with similar bank height and soil type.

4.1.6 Estimating Annual Shoreline Erosion and Deposition Rates

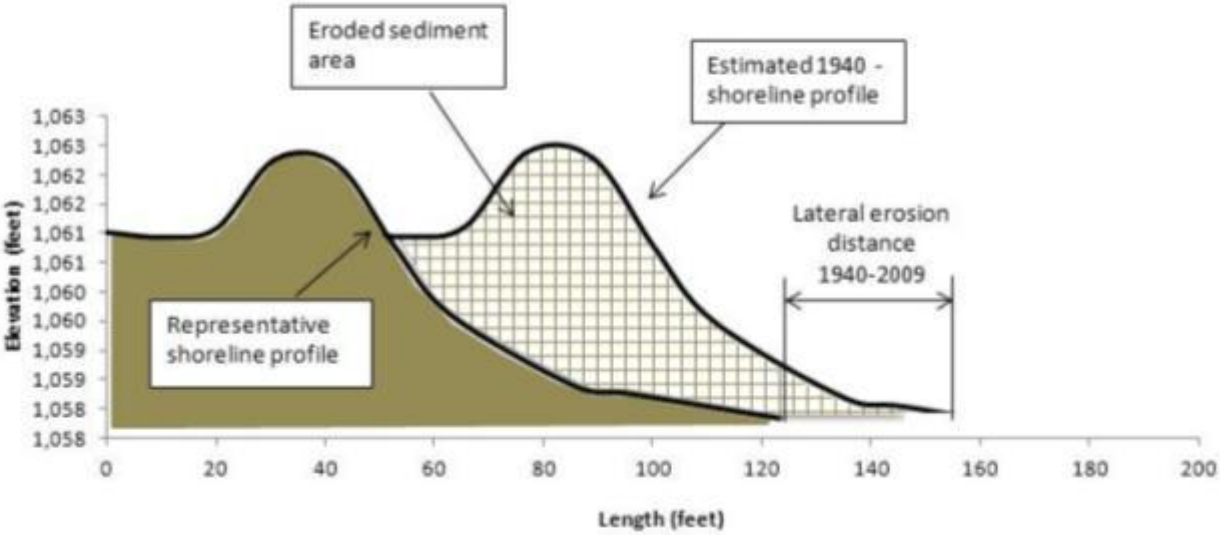
4.1.6.1 Lateral Erosional and Depositional Distance

Calculating the volume of erosion or deposition requires the shape or profile of the shore and the lateral distance that the shoreline has eroded and/or deposited. The process of computing lateral erosion/deposition was completed in GIS. A line was drawn in the center of each 500 foot section and clipped to the shorelines of interest (i.e., 1940 and 2009 or 2003 and 2009). The distance between each shoreline was then calculated for every 500 foot section in GIS. The lines were classified as either areas of erosion or deposition.

4.1.6.2 Volume of Eroded and Deposited Sediment

Since the actual shape of the bank from previous years is unknown, it was assumed that the profiles collected during the 2011-2012 field survey can be used to represent the average profile of the bank over time. Areas of sediment eroded or deposited were computed as a function of the lateral erosion/deposition distance of each shoreline segment. **Figure 12** shows an example of how the calculation was done to compute the area eroded between 1940 and 2009 for an example profile. The resultant estimate of sediment area eroded was then multiplied by 500 feet (the length of each shoreline section) to compute a volume of eroded sediment for that segment. A similar approach was taken in areas of deposition.

Figure 12: Method for Calculating Areas of Eroded Sediment



Shoreline sections that have rip-rap present were excluded from this portion of the project, since these areas would not currently be experiencing significant erosion and excluding them provides a better estimate of what current day loading rates may be. However, most of the rip-rap that's currently installed within the project area is less than 10-years old. It is likely that these rip-rapped areas contributed sediment loading to the lake prior to the rip-rap being installed. This is considered a source of uncertainty in our shoreline sediment loading estimates and is further discussed in **Section 5**.

4.1.6.3 Depositional Arms

Three locations along the southern shoreline showed significant deposition during the study period. When comparing the aerial photographs from 1940 through 2009, 'arms' of sediment can be seen depositing at these locations near Rocky Point, Bostic Bay, and Morris Point. Due to the uniqueness of the shape of these arms and the type of data available to analyze them, a different approach was needed for estimating their depositional volumes. **Appendix B** contains details of the calculations at these locations. The general approach taken was to use available survey data at each location to estimate the average elevation of the arms above 2009 lake levels and then multiply that height by the length and average width of each 'arm' to compute a volume.

4.1.7 Near Shore Sediment Sampling

Near shore sediment sampling was conducted to gather more information on the soil properties along the shoreline and also to gain insight to the concentration of nutrients within the soil. These results were then used to estimate nutrient loading to the lake from southern shoreline erosion. All sediment sampling was performed according to the procedures set forth in the project's QAPP (LOW SWCD & HEI 2012).

4.1.7.1 Sediment Sampling Locations

Sediment sampling sites were identified through random stratified sampling. As discussed in the project QAPP (LOW SWCD & HEI 2012), the sediment sampling was to result in 30 samples being collected at 18 locations. These locations were distributed along the shoreline as a function of shoreline category. The shoreline categories that comprise the vast majority of the shoreline were prioritized for sample collection; those categories that comprised more than 1% of the overall study shoreline length had a sample collected in them. **Table 10** shows the percent of the study area shoreline that each sampled category represents; it also shows the number of sampling locations that were identified in each category.

Sample locations within each shoreline category were identified by assigning a random number to each 500 foot section. A random number generator was then queried to identify in which shoreline section the sample would be sited. Two alternative sites were also (randomly) selected for each shoreline category to be sampled. If the soil sampling crew was not able to access one of the primary sites, the crew was advised to use one of the alternates. The table of the suggested soil sampling locations (including primary and alternate locations) is contained in **Appendix C**. The Quality Assurance and Quality Control (QA/QC) samples to be collected are included in the table.

Soil samples were collected by RMB Environmental Laboratories on May 30th and 31st, 2012. **Table 11** lists the sites were actually sampled by the field crew. **Figure 13** shows their locations. The shoreline categories that were sampled for nutrients constitute 85% of the overall study shoreline length (considering both rip-rapped and non-rip-rapped areas) and over 90% of the un-rip-rapped shoreline.

Table 10: Number of Nutrient Soil Samples by Shoreline Category

Shoreline Category	Number 500 foot sections	Percent of total shoreline	Number of soil sampling sites
1-5 muck, (7-15.3)	82	17%	4
1-5 muck, (17s30s)	78	16%	3
5-10, sand	67	14%	3
1-5 muck, (0-7)	68	14%	3
1-5 muck, (40s)	47	10%	2
5-10, loamy fine sand	30	6%	1
1-5, sand	27	5%	1
5-10, muck	16	3%	1

Table 11: Nutrient Soil Sampling Locations

RMB Site ID	Sampling Point Classification	Shoreline Category	Stationing	Location		Soil Sampling Horizon Depths (in)	Sample type		# of study samples	QA/QC samples		Observed Bank Height (in)
				Latitude	Longitude		Composite	Horizon		QA/QC samples	QA/QC Sample Depth (in)	
1	Primary	1-5 muck (0-7)	1.3	48.89	-95.27	0-17	1		1			17
3	Primary	1-5 muck (0-7)	6	48.89	-95.21	0-16	1		1	1	0-16	16
5	Alternate	1-5 muck (0-7)	2.4	48.89	-95.26	0-21, 21-27, 27-60		1	3			23
6	Primary	1-5 muck (7-15.3)	9	48.89	-95.16	0-27	1		1			27
7	Primary	1-5 muck (7-15.3)	13	48.92	-95.10	0-41	1		1			41
8	Primary	1-5 muck (7-15.3)	15.3	48.94	-95.08	0-21, 21-27, 27-60		1	3			29
9	Primary	1-5 muck (7-15.3)	7.1	48.88	-95.19	0-29	1		1			29
12	Primary	1-5 muck (17s30s)	17.7	48.96	-95.06	0-54	1		1			54
13	Primary	1-5 muck (17s30s)	23	48.96	-95.03	0-21, 21-27, 27-60		1	3	1	21-27	41
14	Primary	1-5 muck (17s30s)	34.9	48.90	-94.89	0-42	1		1			42
19	Alternate	5-10 loamy fine sand	29.9	48.96	-94.93	0-96	1		1			96
20	Primary	5-10 muck	35.6	48.89	-94.88	0-69	1		1			69
23	Primary	5-10 sand	38.3	48.87	-94.85	0-57	1		1			57
24	Primary	5-10 sand	39.6	48.86	-94.83	0-75	1		1			75
25	Primary	5-10 sand	41.3	48.85	-94.80	0-8, 8-84		1	2	1	8-84	76
30	Alternate	1-5 sand	42.4	48.85	-94.77	0-8, 8-60		1	2			108
32	Primary	1-5 muck (40s)	48.8	48.85	-94.71	1-36	1		1			36
33	Alternate	1-5 muck (40s)	46.8	48.84	-94.74	1-44	1		1	1	1-44	44
						Subtotal	13	5	26	4		
						Total	18		30			

Figure 13: Soil Nutrient Sampling Locations

4.1.7.2 Sampling Depth

Soil sampling was completed using two collection methods, termed the 'composite' and 'horizon' methods for the purpose of this project. In the 'composite' sampling method, one (composite) sample was collected and analyzed for the entire soil column at each sampling site (**Figure 14**). For banks under five feet in height, the depth of the sample collected was set equal to the bank height (the sampling crew surveyed in bank heights before the sample was collected). When bank heights were greater than five feet, the maximum depth of the sample was set to the depth limitations of the field crew's equipment. The composite method provides an approach to quantify the average nutrient concentration that can be expected at a location and to quantify bulk nutrient loadings due to shoreline erosion.

The second method is the 'horizons' soil profile sample (**Figure 15**). In this case, the total depth of the boring was set using the NRCS horizon characteristics (as reported in the LOW County Soils Guide (NRCS 2011)) for the soil type being sampled and the maximum depth of the bank height as identified in its shoreline category. For example, the Soils Guide reports three horizon depths (0-21, 21-27, 27-60) for muck. In the category of '1-5, muck', these were the horizon depths collected and analyzed. When shoreline categories had a depth greater than five feet (the depth that the Soils Guide reports to), the maximum depth of the sample was set to the depth limitations of the field crew's equipment.

Figure 14: Schematic of the Composite Soil Collection Method

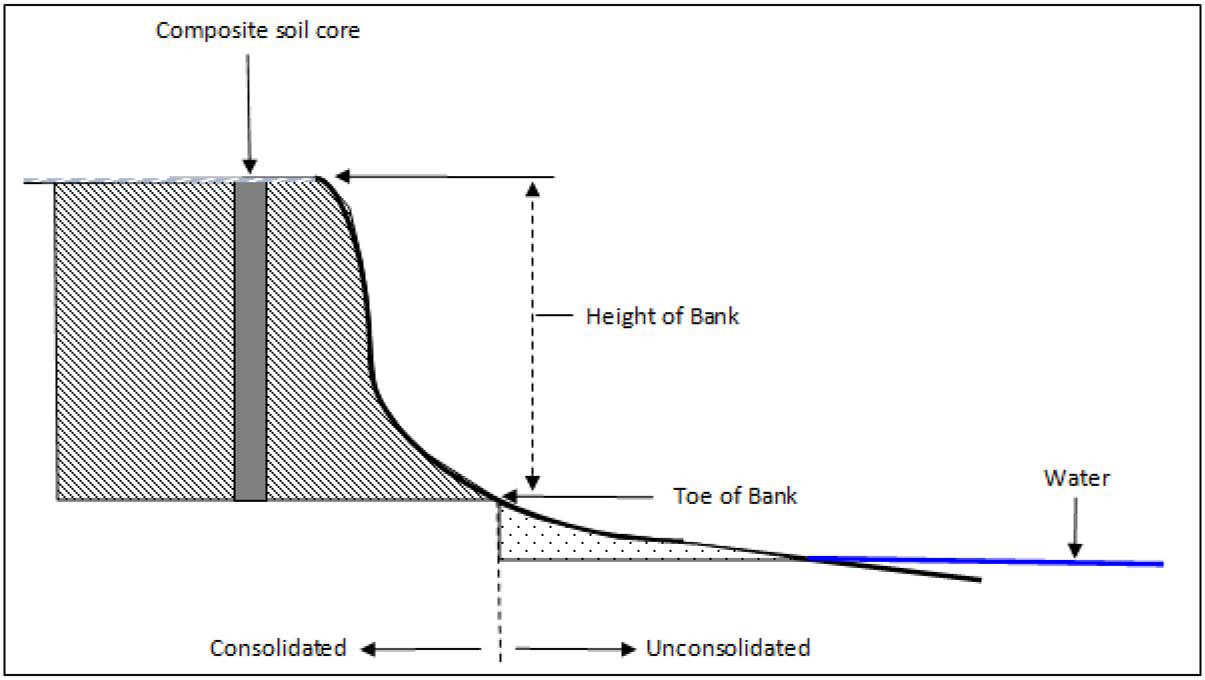
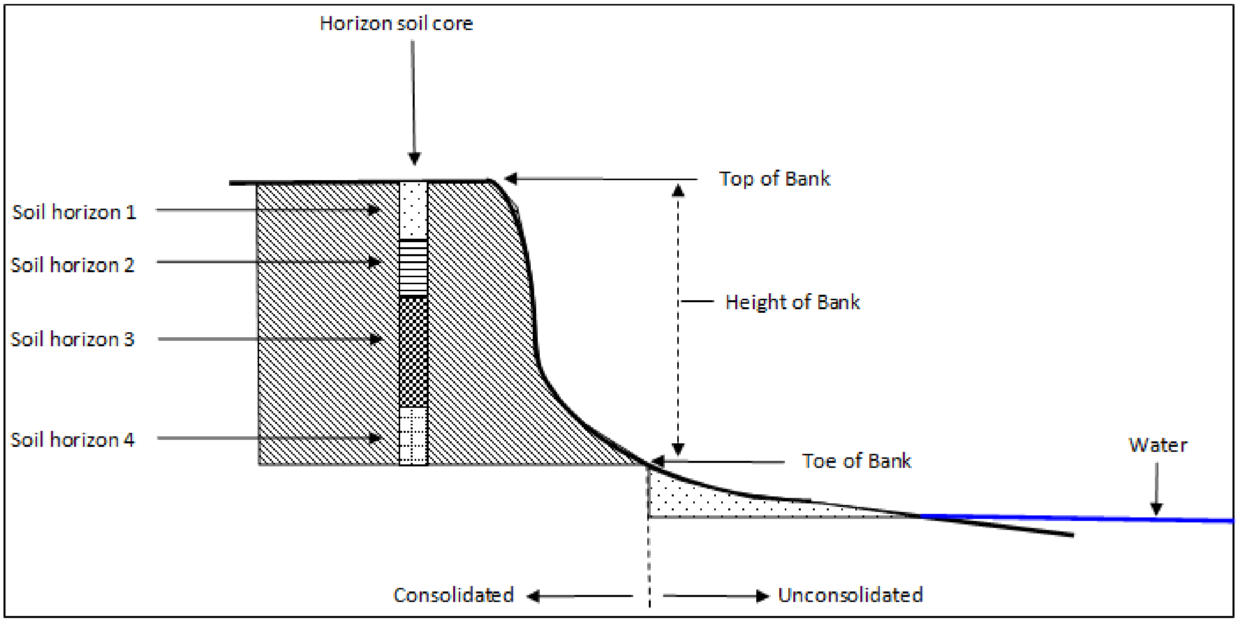


Figure 15: Schematic of the Horizon Soil Collection Method



A total of thirty samples were collected from 18 sites. Thirteen of those samples were composites and five were horizons. Field replicate samples (quality assurance/quality control samples) were taken at four locations and included two composite samples and two horizon samples. **Table 11** lists the sampling locations.

4.1.7.3 Laboratory Analysis

All thirty samples were collected, analyzed, and classified by grain size distribution and texture, as described in the project QAPP (LOW SWCD & HEI 2012). Laboratory analyses were performed (by Braun Intertec and MVTL Laboratories) to quantify the soil concentrations of the parameters described in **Table 12**. Results of the shoreline erosion rate estimates were combined with results of the sediment sampling to estimate the average annual nutrient loading into LOW from shoreline erosion and also the weight (in tons) of sediment eroded.

Table 12: Nutrient Soil Sampling Analysis Parameters

Parameter	Analysis Method
Total Phosphorus	SM 4500 P
Nitrate-Nitrite	SM 4500 NO3 F
Ammonia	SM 4500 NH3
Total Kjedhal Nitrogen	SM 4500 N
Total Organic Carbon	ASTM D5373
Sieve and Grain Size	ASTM D 1140, D6913
Soil package A	NCR-13
Bray I – Phos.	NCR-13
Clay	NCR-13
Nitrate-Nitrogen	NCR-13
Olson Phos	NCR-13
Organic Matter	NCR-13
pH	NCR-13
Potassium	NCR-13
Salinity	NCR-13
Sand	NCR-13
Silt	NCR-13
Texture	NCR-13

4.1.7.4 Soil Unit Weights

The laboratory analysis performed on the samples did not include calculations of unit weight, either dry or wet. However, all of the soil samples were classified using the Unified Soil Classification System (USCS). The USCS is a system which describes the texture and grain size of a soil. While the system does not explicitly specify unit weights for each soil category, it can provide a typical range of unit weights for the category.

A range of typical dry unit weights is provided in the Military Soils Engineering Field Handbook (Army 1992). The averages of these ranges were used to compute unit weights for each sample and shoreline category. In cases when multiple USCS soil classifications were given per shoreline category, unit weights were averaged. For those shoreline categories where no soil samples were taken, an overall average unit weight was computed (i.e., the average of all unit weights at the sampled locations) and assigned. The unit weights used for computing tons of shoreline sediment eroded are shown in **Table 13**.

Table 13: Estimated Average Soil Unit Weights per Shoreline Category

Shoreline Category	Estimated Average Soil Unit Weight (lb/ft^3)
1-5, muck (0-7)	116
1-5, muck (17s30s)	112
1-5, muck (40s)	116
1-5, muck (7-15.3)	93
1-5, sand	109
5-10, muck	110
5-10, sand	106
Assigned Values:	
5-10 silt loam	109
1-5 clay loam	109
5-10 clay loam	109
1-5 silt loam	109
5-10 loam	109

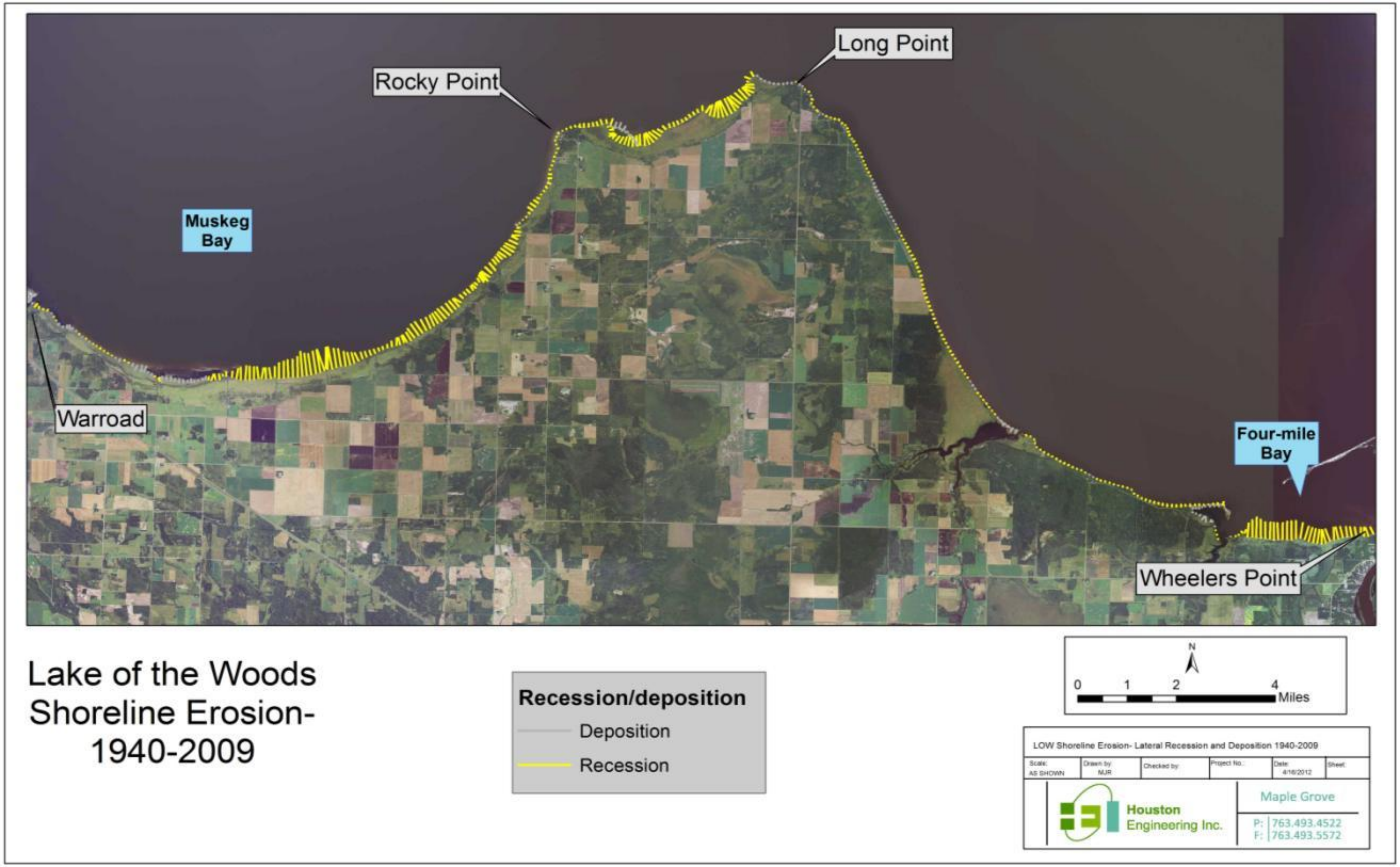
4.2 Results

4.2.1 Erosion and Deposition Rates and Volumes

Since 1940, portions of the LOW lakeshore have eroded by more than 2,600 feet while other portions have deposited sediment; the average erosion distance during this period was 430 feet (per 500 foot shoreline segment). **Figure 16** and **Figure 17** display the lateral recession and deposition of the lakeshore from 1940 and 2003, respectively, in relation to 2009. The areas with the highest amount of erosion are seen in mucky soils.

Table 14 summarizes the estimated shoreline erosion and deposition volumes, by shoreline category, from 1940-2009. **Table 15** shows the same information for the time period 2003-2009. The estimated average annual erosion rates during these time periods are fairly consistent. Between 1940 and 2009, 94% of the eroding sediment came from areas with mucky soils and a bank height of 1-5 feet. Similarly, between 2003 and 2009, 97% of the eroded sediment came from this category. The estimated average annual deposition rate during these two time periods varies significantly, with the estimated rates from 2003-2009 being nearly ten times those from 1940-2009. This increased deposition rate from 2003-2009 results in a significantly greater estimated average annual net erosion rate between 1940-2009 when compared to those from 2003-2009.

Figure 16: LOW Shoreline Lateral Recession and Deposition of Sediment from 1940-2009



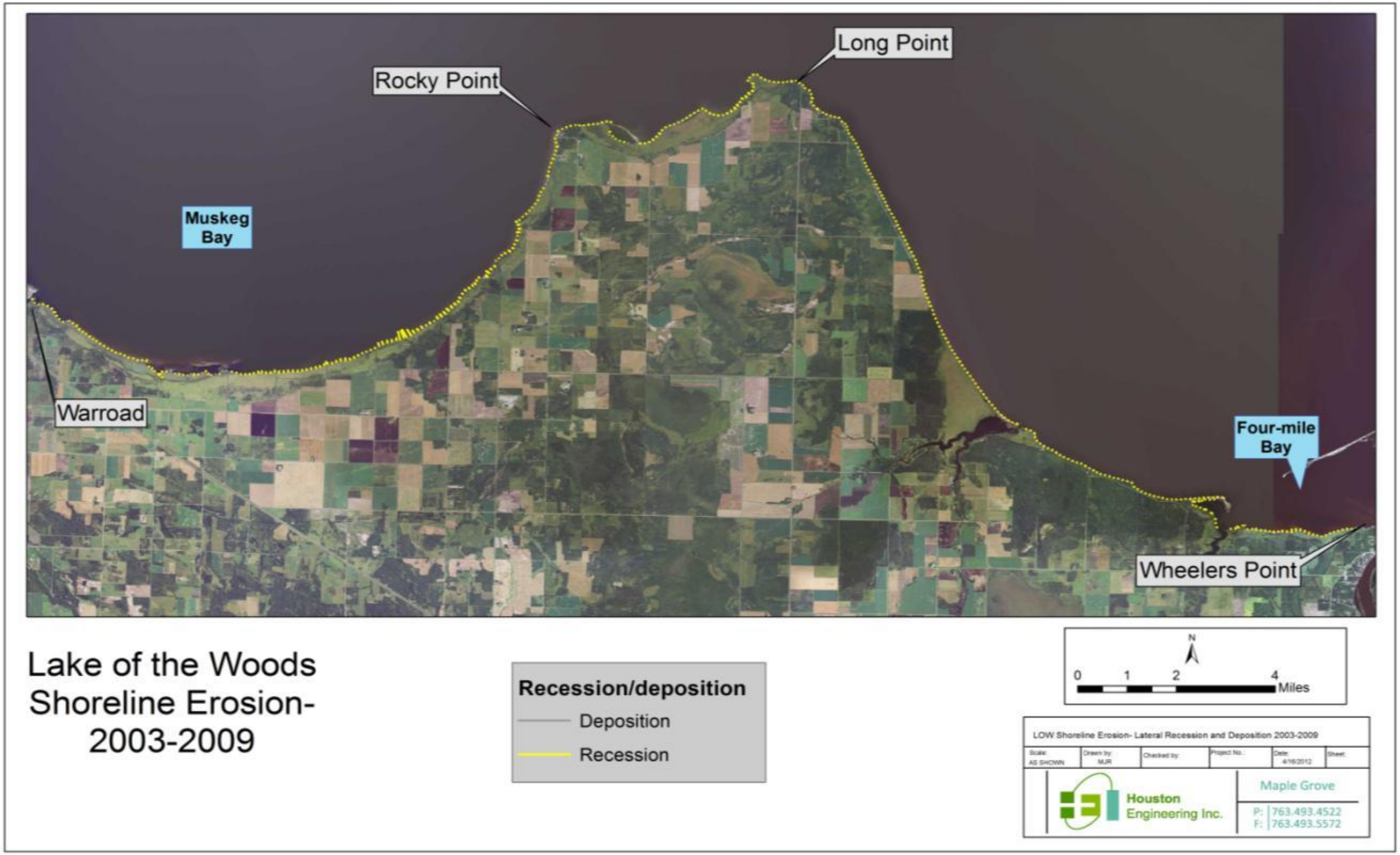


Figure 17: LOW Shoreline Lateral Recession and Deposition of Sediment from 2003-2009

Table 14: Estimated Shoreline Erosion and Deposition Volumes from 1940-2009

Shoreline Categories	Total Volume Eroded (yd^3)	Total Volume Deposited (yd^3)	Net Erosion Volume (yd^3)
1-5 muck (0-7)	718,228	366,041	352,187
1-5 muck (7-15.3)	4,095,119	0	4,095,119
1-5 muck (17s-30s)	3,568,736	0	3,568,736
1-5 muck (40s)	2,747,720	95,054	2,652,666
5-10 muck	89,019	35,530	53,489
5-10 clay	0	31,601	-31,601
5-10 silt loam	68,950	0	68,950
5-10 sand	310,400	83,571	226,829
1-5 clay loam	51,708	0	51,708
1-5 sand	151,086	32,508	118,578
1-5 silt loam	7,542	0	7,542
5-10 clay loam	11,360	0	11,360
5-10 loam	22,696	0	22,696
1-5 clay	0	83,985	-83,985
‘Deposition Arms’	0	194,460	-194,460
Total Erosion Volume	11,842,564	-922,751	10,919,814
Erosion Vol. per Year	171,631	-13,373	158,258

Table 15: Estimated Shoreline Erosion and Deposition Volumes from 2003-2009

Shoreline Categories	Total Volume Eroded (yd^3)	Total Volume Deposited (yd^3)	Net Erosion Volume (yd^3)
1-5 muck (0-7)	58,869	88,598	-29,729
1-5 muck (7-15.3)	494,858	36,535	458,322
1-5 muck (17s-30s)	93,675	181,810	-88,136
1-5 muck (40s)	63,335	88,762	-25,427
5-10 muck	323	43,317	-42,995
5-10 clay	0	6,560	-6,560
5-10 silt loam	1,940	3,741	-1,801
5-10 sand	17,579	121,253	-103,673
1-5 clay loam	2,021	553	1,469
1-5 sand	2,817	58,836	-56,019
1-5 silt loam	1,402	0	1,402
5-10 clay loam	75	0	75
5-10 loam	0	2,737	-2,737
1-5 clay	0	15,107	-15,107
‘Deposition Arms’	0	0	0
Total Erosion Volume	736,893	-647,809	89,084
Erosion Vol. per Year	122,816	-107,968	14,847

To view the difference in estimated erosion rates for each shoreline category, the “total volume eroded” results presented in **Table 14** and **Table 15** were normalized by the length of each shoreline category. The result of this analysis provides insight on the relative erodibility of each shoreline category. **Table 16** and **Table 17** summarize the results of this analysis for both the years 1940-2009 and 2003-2009. As expected, the 1-5 muck category is the most highly eroded. The mucky shoreline in western Muskeg Bay showed less erosion than in other areas.

Table 16: Estimated Shoreline Erosion per Linear Foot, Overall and Annually (1940-2009)

Shoreline Categories	Total Volume Eroded 1940-2009 (yd^3/ft)	Avg Annual Volume Eroded 1940-2009 ($yd^3/ft/yr$)
1-5 muck (0-7)	46	0.7
1-5 muck (7-15.3)	106	1.5
1-5 muck (17s-30s)	119	1.7
1-5 muck (40s)	149	2.2
5-10 muck	16	0.2
5-10 clay	0	0
5-10 silt loam	34	0.5
5-10 sand	18	0.3
1-5 clay loam	34	0.5
1-5 sand	27	0.4
1-5 silt loam	15	0.2
5-10 clay loam	23	0.3
5-10 loam	23	0.3
1-5 clay	0	0

Table 17: Estimated Shoreline Erosion per Linear Foot, Overall and Annually (2003-2009)

Shoreline Categories	Total Volume Eroded 2003-2009 (yd^3/ft)	Avg Annual Volume Eroded 2003-2009 ($yd^3/ft/yr$)
1-5 muck (0-7)	3.6	0.6
1-5 muck (7-15.3)	15.5	2.6
1-5 muck (17s-30s)	9.4	1.6
1-5 muck (40s)	8.4	1.4
5-10 muck	0.7	0.1
5-10 clay	0	0
5-10 silt loam	3.9	0.7
5-10 sand	3.9	0.7
1-5 clay loam	2.0	0.3
1-5 sand	1.9	0.3
1-5 silt loam	2.8	0.5
5-10 clay loam	0.2	0.02
5-10 loam	0	0
1-5 clay	0	0

4.2.2 Soil Sampling Results

4.2.2.1 Nutrient Concentration QA/QC Results

Table 18 shows the soil nutrient concentration QA/QC results for the four sites where they were collected. The results show TP concentrations compare favorably between the duplicate samples, while Total Nitrogen (TN) values are more inconsistent. The TN results, in general, have a far greater range in values amongst the samples than the TP.

Table 18: QA/QC Results from Soil Samples

RMB Site ID	Shoreline Category	Depth Profile	TP (mg/kg dry)	% diff.	TN (mg/kg dry)	% diff.
3	1-5, muck (0-7)	0-16"	250	-8%	221	9%
3	1-5, muck (0-7)	0-16"	230		241	
13	1-5, muck (17s30s)	21-27"	170	12%	401	-72%
13	1-5, muck (17s30s)	21-27"	190		111	
25	5-10, sand	8-84"	280	-7%	291	24%
25	5-10, sand	8-84"	260		361	
33	1-5, muck (40s)	1-44"	230	13%	621	142%
33	1-5, muck (40s)	1-44"	260		1,501	

4.2.2.2 Nutrient Concentrations in Horizon Samples

Sample sites where multiple depths of sample were collected and analyzed (i.e., the horizon samples) are shown in **Table 19**. Similar to the QA/QC results, we see fairly consistent TP concentrations amongst the depths at each site, while TN levels show more variability. Site #8 shows a spike in both TP and TN levels in the 21-27" profile.

Table 19: Nutrient Content by Depth in Horizon Samples

RMB Site ID	Shoreline Category	Depth Profile	TP (mg/kg dry)	TN (mg/kg dry)
5	1-5, muck (0-7)	0-21"	300	461
5	1-5, muck (0-7)	21-27"	280	381
5	1-5, muck (0-7)	27-60"	320	571
8	1-5, muck (7-15.3)	0-21"	280	471
8	1-5, muck (7-15.3)	21-27"	910	20,003
8	1-5, muck (7-15.3)	27-60"	670	1,401
13	1-5, muck (17s30s)	0-21"	160	391
13	1-5, muck (17s30s)	21-27"	170	401
13	1-5, muck (17s30s)	27-60"	400	6,602
25	5-10, sand	0-8"	330	86
25	5-10, sand	8-84"	280	291
30	1-5, sand	0-8"	240	241
30	1-5, sand	8-60"	210	66

4.2.2.3 Nutrient Concentrations by Sampling Site and Shoreline Category

The nutrient sampling results at each site are summarized in **Table 20**. In the case of horizon samples, the average nutrient concentration (weighted by profile depth) is presented. Values from **Table 20** were then averaged to compute a single, representative soil TP and TN concentration for each shoreline category. Those results are shown in **Table 21**.

Table 20: Soil Nutrient Concentration Results for each Sample Site

RMB Site ID	Shoreline Category	Bank Height	TP (mg/kg dry)	TN (mg/kg dry)
1	1-5, muck (0-7)	17"	310	1301
3	1-5, muck (0-7)	16"	250	221
5	1-5, muck (0-7)	23"	300	461
6	1-5, muck (7-15.3)	27"	870	24,019
7	1-5, muck (7-15.3)	41"	180	56
8	1-5, muck (7-15.3)	29"	454	5,859
9	1-5, muck (7-15.3)	29"	690	15,008
12	1-5, muck (17s30s)	54"	190	251
13	1-5, muck (17s30s)	41"	243	2,513
14	5-10, sand	42"	230	76
19	1-5, sand	96"	490	231
20	5-10, muck	69"	270	111
23	5-10, sand	57"	210	411
24	5-10, sand	75"	350	311
25	5-10, sand	76"	285	269
30	1-5, sand	108"	214	89
32	1-5, muck (40s)	36"	270	1,301
33	1-5, muck (40s)	44"	230	621

Shoreline categories that did not have soil samples taken were assigned values from nearby sample sites. Categories without samples were found to be congregated in two primary areas; one near sites 14 and 20 and the other near sites 23 and 24. The first area contained four un-sampled categories: 5-10 silt loam, 1-5 clay loam, 5-10 clay loam, and 1-5 silt loam. Nutrient concentrations at sites 14 and 20 were averaged and assigned to those segments. The second area (near sites 23 and 24) contained the shoreline category 5-10 loam. Again, nutrient concentrations at sites 23 and 24 were averaged and applied to the 5-10 loam category.

Table 21: Representative Soil Nutrient Concentrations for each Shoreline Category

Category	Average TP (mg/kg dry)	Average TN (mg/kg dry)
1-5, muck (0-7)	287	661
1-5, muck (17s30s)	217	1,382
1-5, muck (40s)	250	961
1-5, muck (7-15.3)	548	11,235
1-5, sand	352	160
5-10, muck	270	111
5-10, sand	269	267
Assigned Values:		
5-10 silt loam	250	94
1-5 clay loam	250	94
5-10 clay loam	250	94
1-5 silt loam	250	94
5-10 loam	280	361

4.2.2.4 Sediment and Nutrient Loading from Shoreline Erosion

The estimated unit weights and nutrient concentrations for each shoreline category were combined with the estimated (total) erosion volumes (i.e., the “total volume eroded” values in **Table 14** and **Table 15**) to compute sediment and nutrient loading into LOW from shoreline erosion. **Table 22** summarizes the results of this analysis for the time period from 1940-2009. **Table 23** summarizes the results from 2003-2009.

Table 22: Sediment and Nutrient Loading from Shoreline Erosion (1940-2009)

Shoreline Category	Sediment Load (tons)	TP Load (tons)	TN Load (tons)
1-5 muck (0-7)	1,127,169	323	745
1-5 muck (7-15.3)	5,137,609	2,818	57,722
1-5 muck (17s-30s)	5,389,907	1,168	7,449
1-5 muck (40s)	4,289,019	1,072	4,121
5-10 muck	132,193	36	15
5-10 clay	0	0	0
5-10 silt loam	101,300	25	9
5-10 sand	445,712	120	119
1-5 sand	221,813	78	35
1-5 clay loam	75,968	19	7
5-10 clay loam	16,690	4	2
1-5 silt loam	11,081	3	1
5-10 loam	33,344	9	12
1-5 clay	0	0	0
Total Load	16,981,805	5,675	70,238
Average Annual Load	246,113	82	1,018

Table 23: Sediment and Nutrient Loading from Shoreline Erosion (2003-2009)

Shoreline Category	Sediment Load (tons)	TP Load (tons)	TN Load (tons)
1-5 muck (0-7)	92,387	26	61
1-5 muck (7-15.3)	620,833	340	6,975
1-5 muck (17s-30s)	141,478	31	196
1-5 muck (40s)	98,862	25	95
5-10 muck	479	0	0
5-10 clay	0	0	0
5-10 silt loam	2,851	1	0
5-10 sand	25,243	7	7
1-5 sand	4,136	1	1
1-5 clay loam	2,969	1	0
5-10 clay loam	110	0	0
1-5 silt loam	2,060	1	0
5-10 loam	0	0	0
1-5 clay	0	0	0
Total Load	991,408	433	7,335
Average Annual Load	165,235	72	1,223

5.0 Uncertainty

An analysis of this scale has considerable uncertainty associated with the results. While it is not possible to quantify all of the potential sources of uncertainty in our work, some of the major potential sources can be addressed. In the following sections we discuss and quantify select sources of uncertainty, estimating the amount of error that each may introduce into the analysis. The uncertainties discussed herein are presented independently of one another even though, in reality, some may be compounding. A statistical analysis of the complexity needed to address that compounding is beyond the scope of this study.

5.1 LOW Watershed Hydrology

While necessary, due to a lack of continuous flow data, using the simple drainage area transfer method to estimate the hydrology of the LOW watershed based on continuous (daily) flow data from Sprague Creek introduced considerable uncertainty into the estimated sediment and TP loads from the area. As detailed in **Appendix A**, it is estimated that the error associated with this method was up to 66% in one case; the average error of the estimates was 38%. **Table24** summarizes this error analysis, which compares the observed and estimated discharge volumes at six locations within the LOW watershed at various time periods.

Table 24: Errors Associated with Estimating LOW Watershed Hydrology

Gauge	Time Period	Observed Volume (acre-ft)	Estimated Volume (acre-ft)	% difference
H80013001	5/1/2000 - 9/30/2000	4,384	3,400	-22%
H80010001	6/1/2000 - 9/30/2000	2,835	4,718	66%
05139500	5/1/1980- 9/30/1980	603	473	-22%
H80013001	6/3/2008 - 9/30/2008	2,430	2,819	16%
05140500	6/1/1950 - 9/30/1950	10,164	14,385	42%
05140500	6/1/1966 - 9/30/1977	190,573	259,696	36%
Total		**206,605**	**285,491**	**38%**

5.2 Sediment and TP Loading from the LOW Watershed

In addition to the uncertainty associated with the flow estimates used to compute sediment and TP loads from the LOW watershed, variability in the water quality data and the relationship between water quality and flow also introduces error into these estimates. For this analysis of error, we assume that the daily flow values input to the FLUX program were error-free. The FLUX program was then used to estimate the uncertainty associated with estimating sediment and TP loads for the years 2000-2011 using the available water quality data and the estimated relationships between daily flow and sediment/TP concentrations.

Uncertainty in the FLUX calculations was estimated by using a confidence interval. To compute a 95% confidence interval (assuming the variability of the data is normally distributed) the standard deviation of the analysis is multiplied by 1.96. This value, when added and subtracted from the estimated average annual pollutant load, represents the 95% confidence interval. **Table 25** shows the results of this work for the estimated average annual sediment (simulated as TSS) loading from each of the study area subwatersheds. The uncertainty in this case ranges from 21 to 55%, averaging at 30%. **Table 26** shows the results for the estimated average annual TP loads, with uncertainties ranging from 26 to 242% and averaging at 56%.

Table 25: Uncertainty in FLUX-Estimated TSS Loading

Sample Site	Site Description	Avg Annual Load (tons)	95 % Conf. Interval +/- (tons)	% Difference
S004-295	E Branch Warroad River	119	26	22%
S004-289	W Branch Warroad River	696	148	21%
S004-293	Willow Creek	94	48	52%
S003-699	Zippel Creek	84	46	55%
S000-906	Zippel Creek	189	73	39%
S005-709	Bostic Creek	124	31	25%
	Ungaged Warroad	221	47	21%
	Ungaged Willow	13	7	52%
	Ungaged Zippel	165	73	44%
	Ungaged Bostic	112	28	25%
	Ungaged All	403	144	36%
	Total	**2,218**	**671**	**30%**

Table 26: Uncertainty in FLUX-Estimated TP Loading

Sample Site	Site Description	Avg Annual Load (tons)	95 % Conf. Interval +/- (tons)	% Difference
S004-295	E Branch Warroad River	0.8	0.4	47%
S004-289	W Branch Warroad River	3.5	0.9	26%
S004-293	Willow Creek	2.0	0.6	30%
S003-699	Zippel Creek	0.7	1.8	242%
S000-906	Zippel Creek	1.0	0.3	35%
S005-709	Bostic Creek	0.8	0.4	46%
	Ungaged Warroad	1.3	0.5	36%
	Ungaged Willow	0.3	0.1	30%
	Ungaged Zippel	1.0	1.3	130%
	Ungaged Bostic	0.7	0.3	46%
	Ungaged All	3.4	2.1	63%
	Total	**15.4**	**8.7**	**56%**

5.3 Shoreline Erosion and Deposition Volumes

5.3.1 Shoreline Delineations

Delineating a shoreline from aerial photography can be difficult and performing this task in a system as complex as LOW has a large amount of uncertainty associated with it. The resolution of older photographs makes it difficult to determine exactly where the land ends and water begins. In addition, defining areas as true shoreline (i.e., edge of consolidated material) or areas with aquatic vegetation can be difficult; this was a particular challenge in Muskeg Bay where the presence of aquatic vegetation often made the shoreline appear further into the lake than it actually was. Georeferencing of photographs also introduces error, since no recognizable georeferencing points are in the lake itself (the photos georeferenced by HEI were done using anchor points on the landscape). Finally, the interpretation and determination of exactly where to delineate the shoreline will differ from one practitioner to the next; this introduces error when comparing delineations performed by multiple individuals.

The shoreline delineations that were performed by HEI staff were created with these potential sources of error in mind. Attempts were made to trace along areas of consolidated material, as much as possible, and to not call weed beds shoreline if it was possible to determine that they were, in fact, vegetation.

To estimate the amount of uncertainty associated with shoreline delineations, the delineation of the 1940 shoreline was revisited. This shoreline delineation was chosen since it is expected to have the highest degree of uncertainty due to the resolution of the aerial photograph used to create it. An estimate of the potential variability in the shoreline at each 500 segment was performed by revisiting the final shoreline delineation and judging the uncertainty in the placement of that line (i.e., determining how much the line could have shifted landward or lakeward at each 500 foot interval). This analysis resulted in variations from 1 to 236 feet, with an average variation of 28 feet. Eighty percent of the segments analyzed had delineation fluctuations of less than 50 feet.

To quantify the impact of this uncertainty on the computation of shoreline erosion volumes, the potential variations at each 500 segment were both added and then subtracted from the estimated 1940-2009 lateral recession distance. Erosion volumes for each segment were then re-computed using the methods discussed in **Section 4.1.6.2**. For example, the original estimate of shoreline erosion between 1940 and 2009 at station 0.2 was 416 feet. When revisited, it was estimated that the 1940 shoreline delineation had an uncertainty of approximately 35 feet. To quantify the impact of this uncertainty on the overall estimation of shoreline erosion volume, the calculations described in **Section 4.1.6.2** were re-run with a 1940-2009 erosion distance of both 451 and 381 feet. The results of performing these calculations along the entire 40+ mile study shoreline are shown in **Table 27**. The estimated uncertainty in shoreline erosion volumes from variability in the 1940 shoreline delineation is between 4 and 5%.

Table 27: Uncertainty in Estimates of Erosion Volume (1940-2009) due to Shoreline Delineation

Shoreline Category	Originally Estimated	Subtracting Variability		Adding Variability	
	Total Volume Eroded (yd^3)	Total Volume Eroded (yd^3)	% Difference	Total Volume Eroded (yd^3)	% Difference
1-5 muck (0-7)	718,228	668,236	-7%	824,193	15%
1-5 muck (7-15.3)	4,095,119	3,927,197	-4%	4,263,041	4%
1-5 muck (17s-30s)	3,568,736	3,477,989	-3%	3,659,483	3%
1-5 muck (40s)	2,747,720	2,722,079	-1%	2,776,186	1%
5-10 muck	89,019	64,016	-28%	137,113	54%
5-10 clay	0	0	0%	0	0%
5-10 silt loam	68,950	53,606	-22%	84,294	22%
5-10 sand	310,400	263,905	-15%	377,430	22%
1-5 sand	151,086	144,966	-4%	157,232	4%
1-5 clay loam	51,708	50,102	-3%	53,313	3%
5-10 clay loam	11,360	11,047	-3%	11,673	3%
1-5 silt loam	7,542	7,203	-4%	7,881	4%
5-10 loam	22,696	21,542	-5%	23,850	5%
1-5 clay	0	0	0	0	0%
Total	**11,842,564**	**11,411,888**	**-4%**	**12,375,690**	**5%**
Average Annual Erosion Rate (yd^3/yr)	**171,631**	**165,390**	**-4%**	**179,358**	**5%**

Additional sources of uncertainty in shoreline delineations include the impact of water levels. Since the shoreline was defined as the location where the water and land meet, water levels at the time the aerial photograph was taken could affect the amount of shoreline that appears to increase or decrease in a given time period. To address this, the delineated shorelines were adjusted to account for water levels at the time each series of photographs were taken (based on the date stamp on the photos). More details on this adjustment are given in **Section 4.1.1.3**.

5.3.2 Shoreline Profiles

While developing and using representative shoreline profiles to compute erosion/deposition volumes for each shoreline category is another source of error, it was not quantified in this uncertainty analysis. Attempts were made to gather sufficient data to reduce the level of uncertainty associated with using representative averages. The highest level of uncertainty in the shoreline profile estimation came when estimating profiles of the ‘depositional arms’. This was particularly true for the arm at the mouth of Bostic Creek, which had very limited data available for creating a profile.

5.3.3 Rip-Rapped Shoreline

Approximately 16% of the study area shoreline is covered in rip-rap, which has typically been installed within the last 10-years. The decision was made to exclude rip-rapped areas from all shoreline erosion calculations to gain a better understanding of current loadings based on historic trends. However, given that the rip-rap was not in place during the entire time period of our study (i.e., since 1940), this exclusion introduces a source of error in our erosion estimates. To quantify this error and also to provide estimated historic erosion rates, calculations were re-run to include erosion from the rip-rapped areas. For the purpose of these calculations, it was assumed that all rip-rap within the study area is 10-years old.

The majority of rip-rapped areas along the LOW shoreline are located in shoreline categories of 5-10 loamy fine sand or 5-10 very fine sandy loam and bordered by shoreline categories 5-10 silt loam and 5-10 sand. The average annual erosion of the 5-10 silt loam category between 1940 and 2009 is 0.5 yd^3/ft/yr, while that of the 5-10 sand category is 0.26 yd^3/ft/yr. To estimate the uncertainty associated with excluding rip-rapped areas from the shoreline erosion calculations, the estimated average annual rates of erosion (in yd^3/ft/yr) of the 5-10 silt loam and 5-10 sand categories were averaged and applied to the rip-rapped segments. Given an average rip-rap age of 10-years, the erosion would have occurred over a 59-year period (i.e., 1940-1999). **Table 28** shows the results of this work.

Table 28: Estimated Uncertainty from Excluding Rip-Rapped Areas from Shoreline Erosion Calculations

Rip-Rapped Shoreline (ft)	Representative Avg Rate of Erosion (yd^3/ft/yr)	Time Period of Erosion (yrs)	Estimated Erosion Volume (yd^3)	% of Total Estimated Erosion
38,500	0.38	59	868,004	7%

5.3.4 Sediment Nutrient Concentrations

Variability in the nutrient concentration in the shoreline sediments is an additional source of uncertainty in this project. As discussed in **Section 4.2.2.1**, the QA/QC work performed as part of the sediment sampling showed little variation in TP concentrations at all but one site. The TN concentrations, however, did show considerable variation.

To estimate the uncertainty associated with variability in sediment nutrient concentrations, the calculations discussed in **Section 4.2.2.4** were re-run using the minimum and maximum observed TP and TN concentrations in each shoreline category. For those shoreline categories where data from other category were used (e.g., 5-10 silt loam), the minimum and maximum TP and TN concentrations in those surrogate categories were used for the analysis. For this calculation, minimum and maximum values were considered regardless of their location within the sampling profile (i.e., which horizon they were collected from) and regardless of their classification as QA/QC or not. **Table 29** summarizes the results of this analysis for TP loads, while **Table 30** summarizes the results for TN. Again, there is considerable uncertainty associated with the TN loads; less uncertainty is seen in the TP loads.

Table 29: Uncertainty in Estimated TP Loading from Shoreline Erosion due to Variability in Nutrient Concentrations (1940-2009)

Shoreline Category	Estimated TP Load (tons)	Max TP Conc (mg/kg)	Max TP Load (tons)	% Difference	Min TP Conc (mg/kg)	Min TP Load (tons)	% Difference
1-5 muck (0-7)	323	320	361	12%	230	259	-20%
1-5 muck (7-15.3)	2,818	910	4,675	66%	180	925	-67%
1-5 muck (17s-30s)	1,168	400	2,156	85%	170	916	-22%
1-5 muck (40s)	1,072	270	1,158	8%	230	986	-8%
5-10 muck[2]	36	270	36	0%	270	36	0%
5-10 silt loam[1]	25	270	27	8%	230	23	-8%
5-10 sand	120	350	156	30%	210	94	-22%
1-5 sand	78	490	109	39%	210	47	-40%
1-5 clay loam[1]	19	270	21	8%	230	17	-8%
5-10 clay loam[1]	4	270	5	8%	230	4	-8%
1-5 silt loam[1]	3	270	3	8%	230	3	-8%
5-10 loam[1]	9	350	12	25%	210	7	-25%
Total Load (tons)	5,675	---	8,717	54%	---	3,317	-42%
Average Annual Load (tons/yr)	82	---	126	54%	---	48	-42%

[1] Sediment samples were not collected in these categories; as such concentrations from nearby categories were assigned to these locations; [2] only one sediment sample was taken in this category.

Table 30: Uncertainty in Estimated TN Loading from Shoreline Erosion due to Variability in Nutrient Concentrations (1940-2009)

Shoreline Category	Estimated TN Load (tons)	Max TN Conc (mg/kg)	Max TN Load (tons)	% Difference	Min TN Conc (mg/kg)	Min TN Load (tons)	% Difference
1-5 muck (0-7)	745	1,301	1,466	97%	221	249	-67%
1-5 muck (7-15.3)	57,722	20,002	102,762	78%	56	288	-100%
1-5 muck (17s-30s)	7,449	6,602	35,584	378%	111	598	-92%
1-5 muck (40s)	4,121	1,501	6,438	56%	621	2,663	-35%
5-10 muck[2]	15	111	15	0%	111	15	0%
5-10 silt loam[1]	9	111	11	19%	76	8	-19%
5-10 sand	119	411	183	54%	77	34	-71%
1-5 sand	35	241	53	51%	67	15	-58%
1-5 clay loam[1]	7	111	8	19%	76	6	-19%
5-10 clay loam[1]	2	111	2	19%	76	1	-19%
1-5 silt loam[1]	1	111	1	19%	76	1	-19%
5-10 loam[1]	12	411	14	14%	311	10	-14%
Total Load (tons)	70,238	---	146,539	109%	---	3,888	-94%
Average Annual Load (tons/yr)	1,018	---	2,124	109%	---	56	-94%

[1] Sediment samples were not collected in these categories; as such concentrations from nearby categories were assigned to these locations; [2] only one sediment sample was taken in this category.

6.0 Conclusions

The purpose of the Lake of the Woods Sediment and Nutrient Budget Investigation project was to contribute to the understanding of how sediment and nutrients move through and within the LOW system. The study built upon recent efforts to characterize the function of LOW and the factors that contribute to its water quality and erosion concerns. The main focus of this project was to refine the characterization of how shoreline erosion along the U.S. side of the lake contributes to the lake's problems, addressing both erosion rates and the nutrient loads that result from this erosion. An additional focus was to refine the estimate of sediment and nutrient loads from the tributaries. Work performed under this project focused on the over 40-miles (i.e., 40+ miles) of shoreline between Warroad and Wheelers Point.

Results of our analysis show an estimated average annual sediment loading of 2,218 tons/yr from the LOW watershed. The coincident average annual TP loading from the area is 15 tons/yr. This agrees with estimates recently developed in overall nutrient budget for the Lake, which estimated loadings from this area at approximately 11-16 tons/year (Hargan et al. 2011; Hadash 2010).

Similar to what was qualitatively observed in the 2004 study by SAFL (Herb et al. 2004), the shoreline areas with the largest amount of lateral erosion were seen in mucky soils. Areas of particular interest include the eastern half of Muskeg Bay; the highest estimated lateral erosion rates (in yd^3/ft/yr) were seen between shoreline stations 7 and 15.3. Areas between Rocky and Long Points and between Bostic Bay and Wheelers Point also showed high erosion rates. It is noteworthy that emergent vegetation in these mucky soil areas can make it difficult to used aerial photography to define where the shoreline begins/ends. Attempts were made to trace along areas of consolidated material, as much as possible, and to not call weed beds shoreline if it was possible to determine that they were, in fact, vegetation. However, it is likely that some of the measured lateral erosion distance in these mucky areas is actually due to vegetation growth/die-off and not solely to erosive processes. Uncertainty analysis estimated that the most uncertain shoreline that was delineated (1940) had an accuracy of, on average, about 28 lateral feet. It was estimated that this uncertainty introduces about 4-5% error into the erosion volume and rate results.

Average annual rates of total shoreline erosion during the two time periods analyzed were consistent, with values of 171,631 yd^3/yr from 1940-2009 and 122,816 yd^3/yr from 2003-2009. However, deposition rates during these two time periods were considerably different, with an estimated rate of 13,373 yd^3/yr from 1940-2009 and 107,968 yd^3/yr from 2003-2009. This difference in deposition rates made the net erosion estimates between the two time periods significantly different, as well. The results show an estimated average annual net erosion rate of 158,258 yd^3/yr from 1940-2009 and 14,847 yd^3/yr from 2003-2009. Again, the mucky soil areas of the shoreline were shown to have the highest rates of sediment erosion, with estimates up to 10 times the rate of other categories (e.g., 2.2 yd^3/ft/yr for 1-5 muck (40s) vs. 0.2 yd^3/ft/yr for 1-5 silt loam).

The average annual sediment loading to LOW from shoreline erosion was estimated at 246,113 tons/yr. The coincident average annual TP loading to the Lake was estimated at 82 tons/yr, while that for TN was estimated at 1,018 tons/yr. Uncertainty analysis estimates the annual rate of TP loading may be as high as 126 tons/yr or as low as 48 tons/yr. TN loading has more uncertainty, with results varying from 2,124 to 56 tons/yr.

Overall, the results of the uncertainty analysis showed that performing a study of this scale results in considerable uncertainty. However, the results of this work are of sufficient quality to inform future studies, understand the magnitude of sediment and nutrient loading from the LOW watershed and southern shoreline, and to inform future management decisions. Comparing the results of this work with the outcomes of the Hargan, et al. and Hadash studies, TP loading to LOW from southern shoreline erosion may be a significant source of nutrients to the lake. Results are on the order of loading from precipitation and local watershed inputs (estimated by Hargan, et al. at 105 and 89 tons/year, respectively). They are also an order of magnitude higher than TP loading from the LOW watershed (estimated at around 15 tons/year). This information should be taken into consideration in future water quality work in LOW and also when making future land management decisions.

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Appendix A: Estimating LOW Watershed Hydrology

MEMO

(External Correspondence)

HoustonEngineering Inc.

From: Mike Lawrence, P.E.

To: Corryn Trask,
Lake of the Woods SWCD

Through: Stephanie Johnson, Ph.D., P.E.

Date: July 30, 2012

Subject: Calculating Direct Drainage Flows into LOW from MN Subwatersheds

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As part of a larger study to compute and compare the loading of sediment and nutrients (in particular, total phosphorus (TP)) into Lake of the Woods (LOW) from various sources, Houston Engineering, Inc. (HEI) was tasked with creating water, sediment, and nutrient budgets for the Lake. The overall goal of the effort is to gain a "big picture" understanding of how the system receives and processes water, sediment, and TP. An order of magnitude ranking of the various sources and sinks will then be developed. This memorandum specifically addresses one component of this task: the water budget for tributaries in Minnesota draining directly into LOW. The time period of primary interest for the water budget is from 2000-2011.

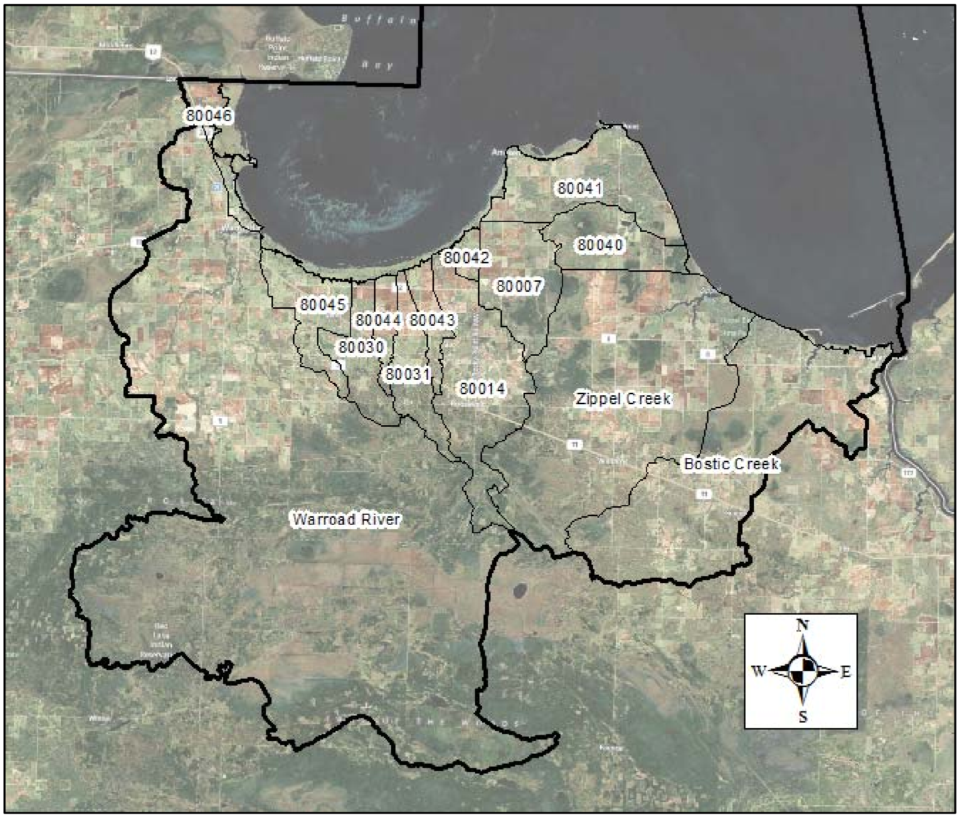
Task Area

The area to be addressed in this component of the work is shown in **Figure 1** and consists of 14 subwatersheds that drain directly into LOW, more specifically into Big Traverse Bay. The subwatersheds shown in **Figure 1** were created by the Minnesota Department of Natural Resources (MN DNR). In three cases, the Warroad River, Bostic Creek, and Zippel Creek, the MN DNR drainage areas were lumped to create single subwatersheds representing the outlet of each of these systems into LOW. The 14 subwatersheds are listed and shown in **Table 1** and **Figure 1**, respectively.

Table 1: Subwatersheds of the Task Area

MN DNR Minor ID	Subwatershed Name	Area (sq. mi.)
80046	West Shore-Muskeg Bay	5.2
80041	Long Point-Muskeg Bay	22.1
80040	Long Point-Muskeg Bay	12.8
multiple	Warroad River	265.2
80007	Judicial Ditch No 22	15.6
80042	Judicial Ditch No 22	2.3
80045	Muskeg Bay-South Shore Tributaries	11.6
80014	Willow Creek	27.6
80043	Muskeg Bay-South Shore Tributaries	4.7
80031	Muskeg Bay-South Shore Tributaries	9.6
multiple	Zippel Creek	85.5
80044	Muskeg Bay-South Shore Tributaries	3.9
80030	Muskeg Bay-South Shore Tributaries	9.5
multiple	Bostic Creek	63.5

Figure 1: Subwatersheds of the Task Area with DNR Minor ID/Subwatershed Name



Existing Streamflow Data

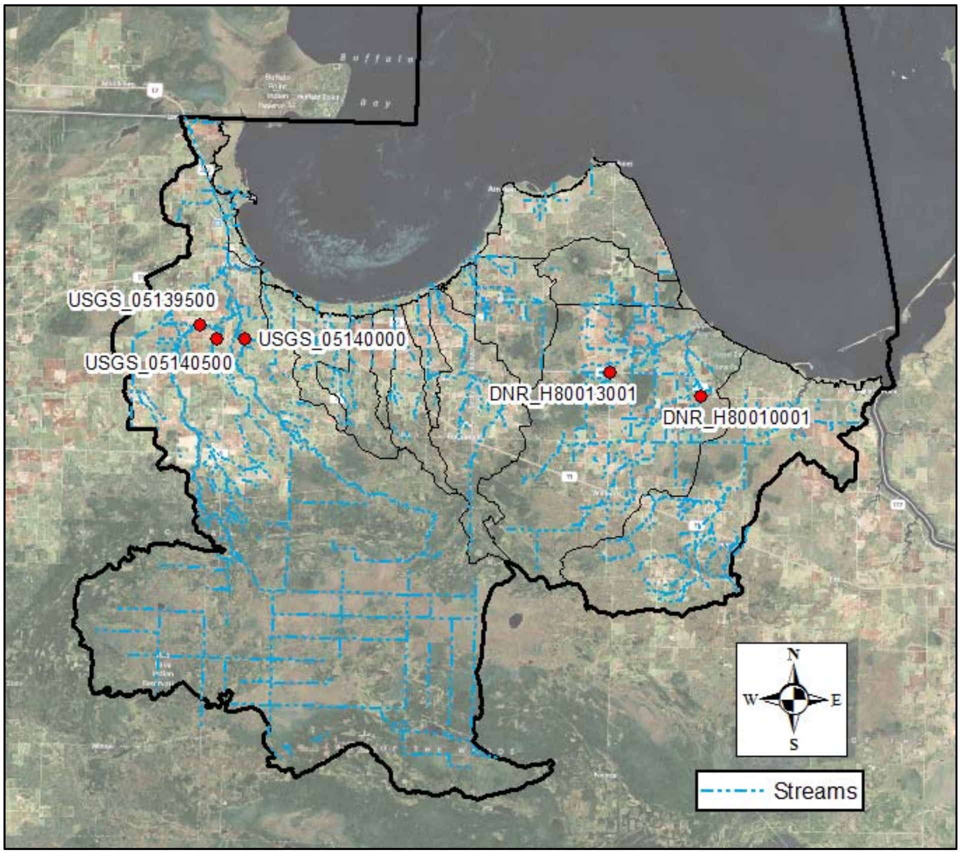
Continuous flow data collected in the Task Area since the year 2000 is sparse, with only two continuous streamflow gauges operating during that time. The sites are both maintained by the MN DNR. One is located on the west branch of Zippel Creek (H80013001), where flow data was collected from 2000-2001, and 2004-2008. The other is located on the south branch of Zippel Creek (H80010001); flow data was collected here from 2000-2001.

Other sites within the Task Area have either stage data (with no associated discharge records) or have streamflow data collected prior to 2000. These sites were maintained by the United States Geological Survey (USGS), MN DNR, and MPCA. **Table 2** lists those locations where streamflow data is available; **Figure 2** shows these locations on a map. As shown from this information, the vast majority of the Task Area is un-gauged and has little to no streamflow data available.

Table 2: Streamflow Gauging Locations within the Task Area

Site ID	Collecting Agency	Period of Record
05139500	USGS	1946-1980
05140500	USGS	1946-1954, 1966-1977
05140000	USGS	1946-1951, 1966-1977
H80010001	MN DNR	2000-2001
H80013001	MN DNR	2000-2001, 2004-2008

Figure 2: Map of Streamflow Gauging Locations within the Task Area



Methods Evaluated to Develop Continuous Streamflow Records

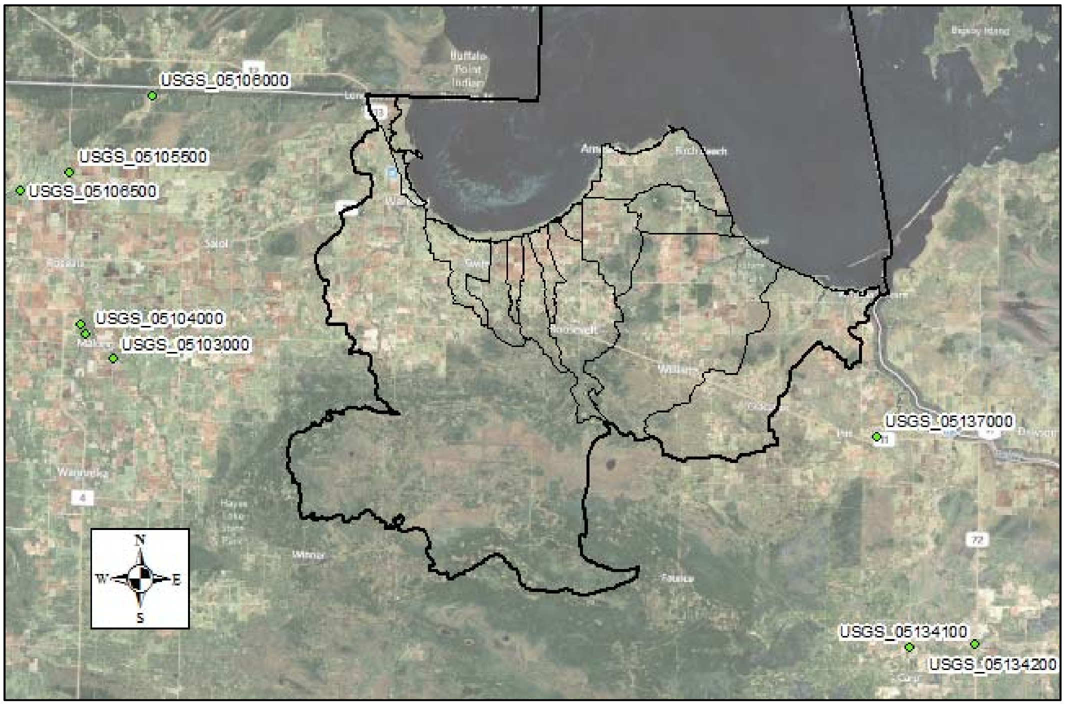
Numerous methodologies were evaluated to determine the best approach to estimate surface water runoff from the Task Area. All of these methods use observed streamflow data to estimate runoff from un-gauged areas. Ideally there would be numerous continuous streamflow monitoring sites in the project area that would be operational for the entire time period of interest. Most ideally there would be monitoring at the outlet of each subwatershed entering LOW. This is not the case; in fact, no flow monitoring occurred in the Task Area from 2002-2003 or from 2008-2011. These data gaps require that we look outside the Task Area for a continuous record of streamflow data during our time period of interest.

To locate a suitable continuous streamflow gauging station for use in estimating flows in the Task Area, gauging stations from the USGS were searched. Nine stations were found within approximately 20-miles of the Task Area. These are listed in **Table 3** and shown in **Figure 3**. Some of the sites only had periodic field measurements and some had little or no data in the time period of interest. Two of the stations covered the time period of interest: Roseau River near Malung, MN and Sprague Creek near Sprague, MB. The station on the Roseau River has a drainage area of 1,090 square miles and the Sprague Creek station has a drainage area of 176 square miles.

Table 3: Continuous Streamflow Monitoring Locations near the Task Area

Site ID	Site Name	Period of Record
05103000	Roseau River near Malung, MN	1939-1946
05104500	Roseau River below South Fork near Malung, MN	1946-2012
05106000	Sprague Creek near Sprague, Manitoba, Canada	1928-1981, 1999-2012
05134200	Rapid River near Baudette, MN	1956-1985, 2008-2012
05134100	North Branch Rapid River near Baudette, MN	Periodic Field Measurements Only
05104000	South Fork Roseau River near Malung, MN	1911-1946
05106500	Roseau River at Roseau Lake MN	Periodic Field Measurements Only
05105500	Roseau River near Roseau , MN	Periodic Field Measurements Only
05137000	Winter Road River near Baudette, MN	Periodic Field Measurements Only

Figure 3: Map of Continuous Streamflow Monitoring Locations near the Task Area



Three methods were evaluated for using the continuous streamflow data to estimate flows from un-gauged areas. All methods were evaluated using observed flows from both the Roseau River and Sprague Creek gauges. The first method is a simple drainage area transfer, which involves taking the ratio of the un-gauged drainage area to the gauged drainage area and multiplying by the flow at the gauge to estimate the flow from the un-gauged area, shown in **Equation 1**.

$$Flow_{ungaged} = Flow_{gauged} \times \left(\frac{Area_{ungauged}}{Area_{gauged}}\right) \quad \textbf{(1)}$$

The second method evaluated was the USGS method for transfer of flood flow data upstream or downstream from a gauged site. This method is outlined in the USGS regression equations for estimating flood flows in Minnesota (USGS 1988). The method is very similar to drainage area transfer, except that the drainage area ratio is raised to an exponent as shown in **Equation 2**. The exponent comes from a part of the USGS regression equation developed for the specified site. The USGS recommends that the drainage area for the un-gauged site be from 75 to 150 percent of the drainage area for the gauged site. As this method was used in the Task Area, many of the drainage area ratios fell outside of the 75-150% range. It should also be noted that the USGS regression equations have been updated in 2009, and the exponents from the 2009 report were used for the computations (USGS 2009).

$$Flow_{ungaged} = Flow_{ungauged} \times \left(\frac{Area_{ungauged}}{Area_{gauged}}\right)^{(USGS\ Regression\ Exponent)} \quad \textbf{(2)}$$

The third method evaluated is the USGS method for estimating the frequency of low flows at partial-record stations by relating discharge measurements to nearby continuous gauging stations (USGS 1977). Under this method, the discharges at the partial-record station are plotted on log paper against the concurrent daily flows at a nearby continuous flow gaging station. A line of best fit is drawn through the plotted points. This regression line is used to transfer the flow characteristics from the continuous gauging station to the partial-record station. For this project, the data was plotted in Excel and lines of best fit were computed. This was done for four sites; both a linear regression line and a power regression line provided a good relationship at the four sites. Overall, it was determined that a power function collectively provided the best fit for all the sites.

Other methods for estimating flows from un-gauged areas were investigated but not formally evaluated. These included trying to develop a relationship using the existing USGS regression equations for the area and developing a relationship from those. The current USGS regression equations utilize drainage area, slope, and percent lakes. After a review of available data, this approach was abandoned since the process would have been quite complex and most likely would not have resulted in anything much different than the results of the drainage area transfer method. It is also notable that the USGS regression equations were created with the intent to predict flood flows and not continuous flow records; the reports are titled "Techniques for Estimating the Magnitude and Frequency of Floods".

The three methods chosen for use in this task were evaluated by comparing the available observed streamflow data within the Task Area to the estimated streamflows computed via the three methods during the same time period. The results of this comparison are presented in **Table 4**. While flows were estimated each day, the data were summarized for comparison by computing overall volumes for the time period of observation. The gauges and time periods used were varied spatially and temporally to provide a better evaluation of the methods.

The results of the comparison show that the standard drainage area transfer and the USGS Low Flow Partial-Record Method outperform the USGS Drainage Area Transfer method. It also shows that using the observed data from Sprague Creek to estimate streamflows in the Task Area provides a better result than using observations from the Roseau River. This is most likely due to the similarity in size of the drainage area of Sprague Creek to the sites located in the Task Area.

Table 4: Evaluation of Various Streamflow Estimation Methods

Gauge	Time Period	Observed Volume for Period (ac-ft)	Sprague Creek				Roseau River				USGS Low Flow Partial-Record Method	
			Drainage Area Transfer		USGS Drainage Area Transfer		Drainage Area Transfer		USGS Drainage Area Transfer			
			Estimated Vol (ac-ft)	% diff.	Estimated Vol (ac-ft)	% diff.	Estimated Vol (ac-ft)	% diff.	Estimated Vol (ac-ft)	% diff.	Estimated Vol (ac-ft)	% diff.
H80013001	5/1/2000 - 9/30/2000	4,384	3,400	-22%	6,142	40%	2,037	-54%	5,912	35%	3,338	-24%
H80010001	6/1/2000 - 9/30/2000	2,835	4,718	66%	7,623	169%	2,698	-5%	7,005	147%	3,050	8%
05139500	5/1/1980- 9/30/1980	603	473	-22%	483	-20%	812	35%	1,333	121%	437	-27%
H80013001	6/3/2008 - 9/30/2008	2,430	2,819	16%	5,093	110%	1,448	-40%	4,202	73%	2,858	18%
05140500	6/1/1950 - 9/30/1950	10,164	14,385	42%	16,577	63%	16,831	66%	31,161	207%	6,353	-37%
05140500	6/1/1966 - 9/30/1977	190,573	259,696	36%	299,270	57%	247,921	30%	458,996	141%	111,344	-42%
Avg of Absolute % Diff.				34%		76%		38%		121%		26%

The evaluation shows that the drainage area transfer method and the USGS partial-record method result in similar error, with slightly better results for the USGS method, when using streamflow observations from the Sprague Creek site. There are issues with using the USGS method to create flow records for all 14 subwatersheds in the Task Area. First, there is no data to create lines of best fit for the other subwatersheds. Second, for the areas that do have a line of best fit, these are not at the outlet to the lake and would require some sort of drainage area transfer to estimate runoff from the entire subwatershed anyway. Due to the similarity in results and the additional issues with using the USGS method, the drainage area transfer method will be used, with observations from the Sprague Creek site, to estimate flows from the MN tributaries draining directly into LOW (**Figure 1**).

Estimating Streamflow Volumes from the Task Area

The Sprague Creek gauge and drainage area transfer method were used to compute volumes in acre-feet from 2000 to 2011 for the 14 subwatersheds in the Task Area. The results of this estimation are displayed in **Table 5**. The location of each subwatershed is shown in **Figure 1**.

Table 5: Estimated Streamflow Volumes (ac-ft) by Year and Subwatershed for the TaskArea

Subwatershed	Sprague Creek	West Shore-Muskeg Bay	Long Point-Muskeg Bay	Long Point-Muskeg Bay	Warroad River	Judicial Ditch No 22	Judicial Ditch No 22	Muskeg Bay-South Shore Trib.	Willow Creek	Muskeg Bay-South Shore Trib.	Muskeg Bay-South Shore Trib.	Zippel Creek	Muskeg Bay-South Shore Trib.	Muskeg Bay-South Shore Trib.	Bostic Creek
DNR Minor		80046	80041	80040	multiple	80007	80042	80045	80014	80043	80031	multiple	80044	80030	multiple
Drainage Area (sq. mi.)	176	5.2	22.1	12.8	265.2	15.6	2.3	11.6	27.6	4.7	9.6	85.5	3.9	9.5	63.5
2000	68,821	2,044	8,660	5,014	103,713	6,100	886	4,528	10,810	1,832	3,747	33,421	1,508	3,731	24,832
2001	65,867	1,957	8,289	4,799	99,261	5,838	848	4,333	10,346	1,753	3,586	31,986	1,443	3,571	23,766
2002	107,910	3,206	13,579	7,862	162,620	9,565	1,389	7,099	16,950	2,872	5,875	52,403	2,364	5,850	38,935
2003	33,498	995	4,215	2,441	50,481	2,969	431	2,204	5,262	892	1,824	16,267	734	1,816	12,086
2004	116,361	3,457	14,643	8,478	175,355	10,314	1,498	7,655	18,278	3,097	6,335	56,507	2,550	6,308	41,985
2005	92,546	2,749	11,646	6,743	139,466	8,203	1,191	6,088	14,537	2,463	5,039	44,942	2,028	5,017	33,392
2006	49,229	1,462	6,195	3,587	74,187	4,364	634	3,239	7,733	1,310	2,680	23,906	1,079	2,669	17,762
2007	69,682	2,070	8,769	5,077	105,010	6,177	897	4,584	10,946	1,855	3,794	33,839	1,527	3,778	25,142
2008	64,206	1,907	8,080	4,678	96,758	5,691	826	4,224	10,085	1,709	3,496	31,179	1,407	3,481	23,166
2009	92,009	2,733	11,578	6,704	138,658	8,156	1,184	6,053	14,453	2,449	5,009	44,681	2,016	4,988	33,198
2010	100,572	2,988	12,656	7,328	151,562	8,915	1,294	6,616	15,798	2,677	5,476	48,839	2,204	5,452	36,288
2011	63,113	1,875	7,942	4,598	95,112	5,594	812	4,152	9,914	1,680	3,436	30,649	1,383	3,422	22,772
Average	**76,985**	**2,287**	**9,688**	**5,609**	**116,015**	**6,824**	**991**	**5,065**	**12,093**	**2,049**	**4,191**	**37,385**	**1,687**	**4,174**	**27,777**

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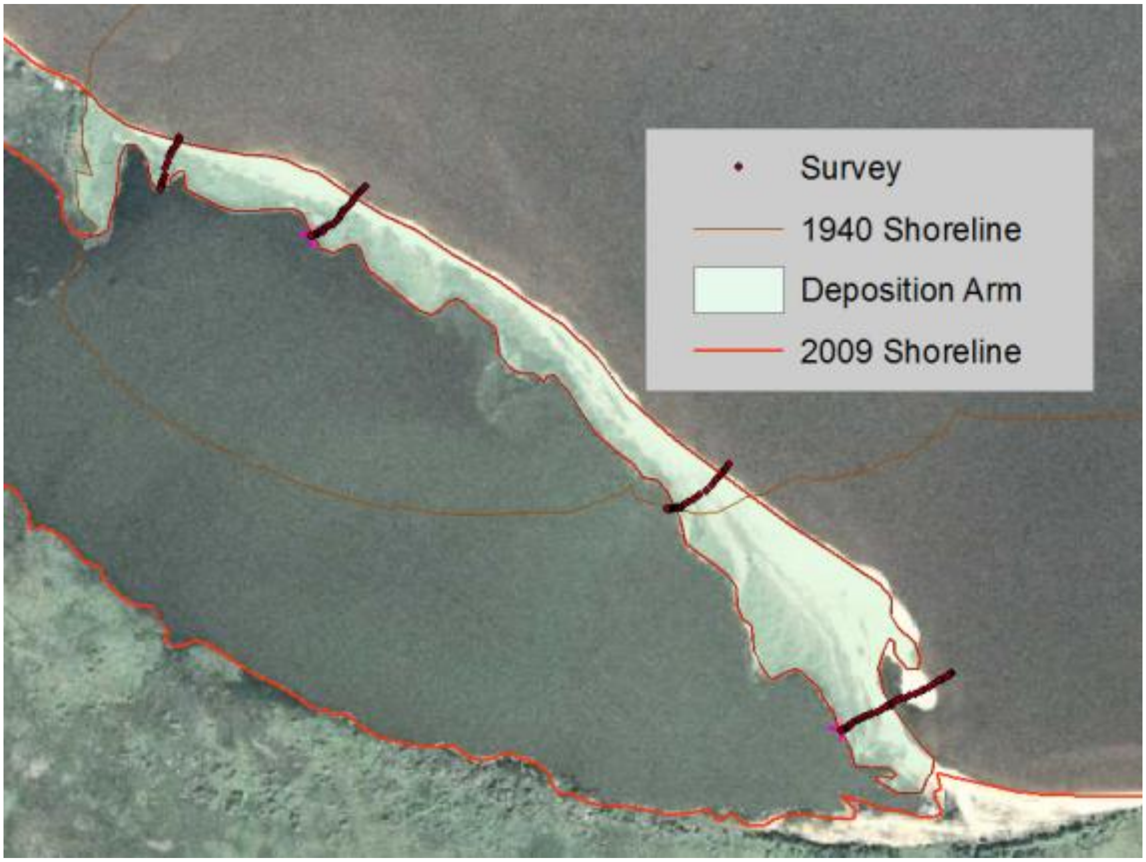
Appendix B: Computing Depositional Arm Volumes

Shoreline erosion and deposition was calculated along the southern shore of Lake of the Woods for 1940-2009 and 2003-2009. This was done by calculating the lateral distance between the 1940 and 2003 shorelines and the 2009 shoreline at set stationing and then developing volume estimates. This worked well for 2003, however, when calculating for 1940 there were three areas of deposition that presented problems with this method. These deposition areas (a.k.a. 'depositional arms') required a different methodology to calculate volume, due to their unique shape and formation. This methodology is outlined below.

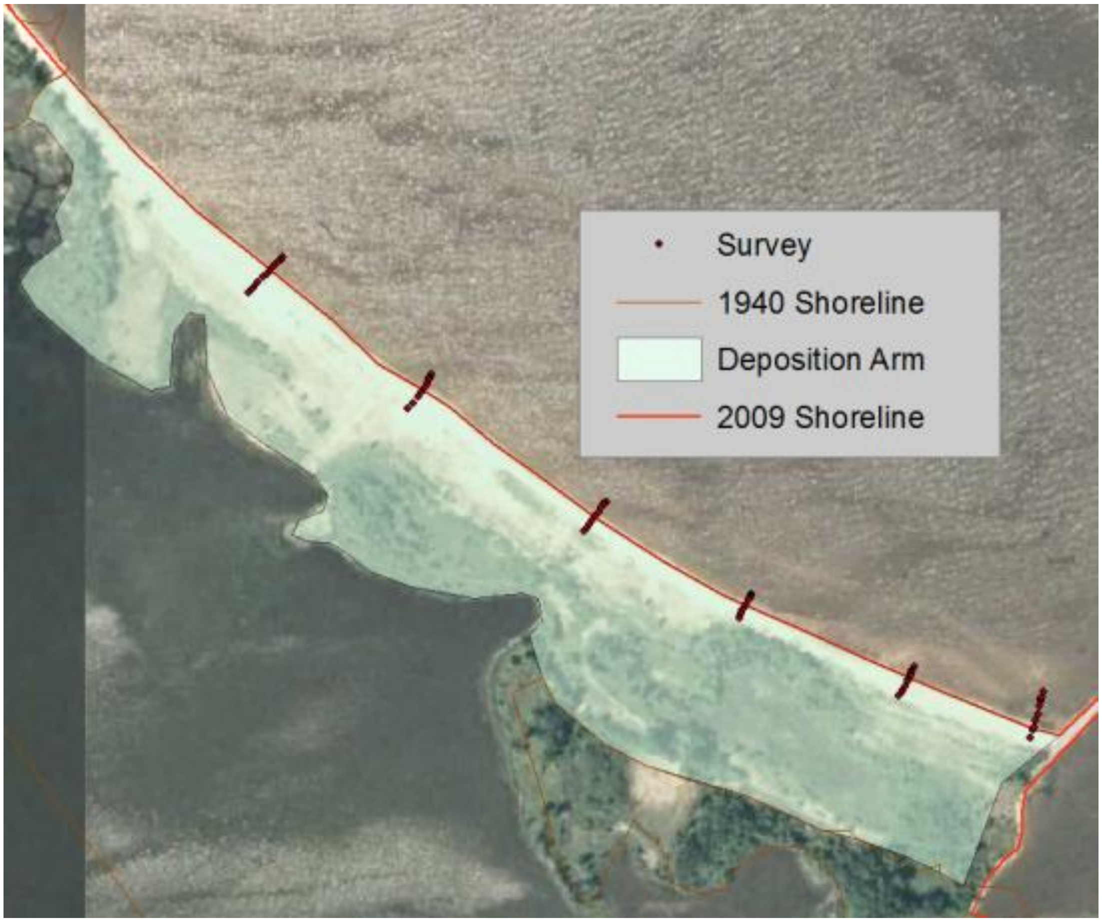
Deposition Arm 18.5 to 21.2, Rocky Point Area

Four cross sections across this deposition arm were collected by Houston Engineering, Inc. in May of 2012. To develop the volume of deposition for this area, the area of each cross section above the 2009 water surface (1059.81) was calculated. These areas were then averaged and multiplied by the length of the depositional arm. The average cross section area above the water surface was 440 square feet on the 3,408 foot long arm, resulting in a depositional volume of 56,656 cubic yards.



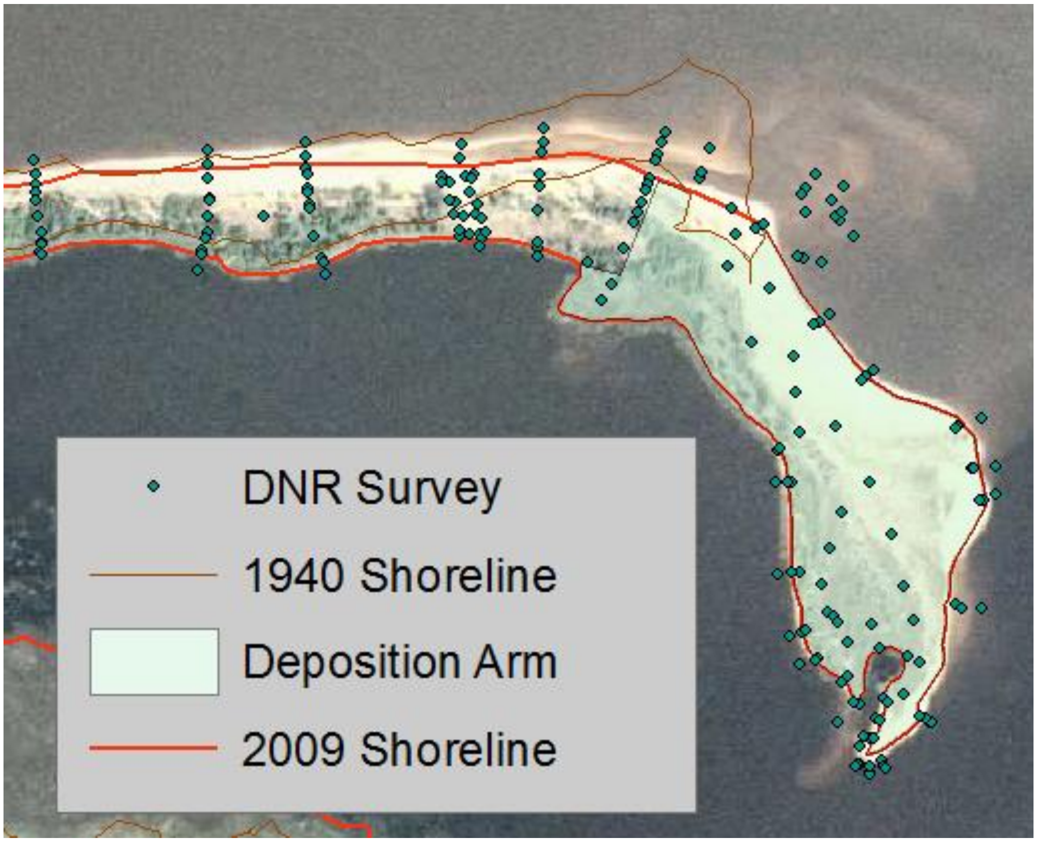
Deposition Arm 36.8 to 37.3, Mouth of Bostic Creek

For this depositional area, Houston Engineering Inc. had collected survey only for the purpose of developing a bank profile and not a complete cross section of the deposition. Due to this, all survey points collected above the 2009 water surface were averaged for elevation. The average elevation of these points was 1062.42, for an average height above the water surface of 2.61 feet. After multiplying by the length and average width of the depositional area, the depositional volume computed was 96,653 cubic yards.



Deposition Arm 42.8 to 43.5, Morris Point

The DNR collected survey of this depositional arm in 2011. While cross sections were taken further up the point, the areas of deposition were collected in a more scattered approach. Therefore, all survey points above the 2009 water surface were averaged for elevation. The average elevation of the depositional area based on the survey points was 1061.58, for a height above the water of 1.77. Multiplying by length and average width, results in a depositional volume of 42,151 cubic yards.



Appendix C: Sediment Sampling Details & Results

Table C1: Proposed nutrient soil sampling locations

Sampling Point Classification	Shoreline Category	Stationing	Location		Soil Sampling Horizon Depths (inches)	Sample type		# of study samples	QA/QC samples	
			Latitude	Longitude		Composite	Horizon		QA/QC samples	QA/QC Sample Depth (inches)
Primary	1-5 muck (0-7)	1.3	48.90	-95.28	0-60	1		1		
Primary	1-5 muck (0-7)	3.7	48.88	-95.24	0-21, 21-27, 27-60		1	3		
Primary	1-5 muck (0-7)	6	48.89	-95.21	0-60	1		1	1	0-60
Alternate	Alternate, 1-5 muck (0-7)	1.7	48.89	-95.28	0-60					
Alternate	Alternate, 1-5 muck (0-7)	2.4	48.89	-95.26	0-60					
Primary	1-5 muck (7-15.3)	9	48.89	-95.16	0-60	1		1		
Primary	1-5 muck (7-15.3)	13	48.92	-95.10	0-60	1		1		
Primary	1-5 muck (7-15.3)	15.3	48.94	-95.08	0-21, 21-27, 27-60		1	3		
Primary	1-5 muck (7-15.3)	7.1	48.88	-95.19	0-60	1		1		
Alternate	Alternate, 1-5 muck (7-15.3)	7.7	48.89	-95.18						
Alternate	Alternate, 1-5 muck (7-15.3)	9.5	48.89	-95.15						
Primary	1-5 muck (17s30s)	17.7	48.96	-95.06	0-60	1		1		
Primary	1-5 muck (17s30s)	23	48.96	-95.03	0-21, 21-27, 27-60		1	3	1	21-27
Primary	1-5 muck (17s30s)	34.9	48.90	-94.89	0-60	1		1		
Alternate	Alternate, 1-5 muck (17s30s)	22.5	48.96	-95.03						
Alternate	Alternate, 1-5 muck (17s30s)	25.6	48.97	-94.98						
Primary	5-10 loamy fine sand	29.4	48.96	-94.94	0-60	1		1		
Alternate	Alternate, 5-10 loamy fine sand	29	48.97	-94.94						
Alternate	Alternate, 5-10 loamy fine sand	29.9	48.96	-94.93						
Primary	5-10 muck	35.6	48.89	-94.88	0-60	1		1		
Alternate	Alternate, 5-10 muck	14.8	48.94	-95.08						
Alternate	Alternate, 5-10 muck	35.2	48.90	-94.89						
Primary	5-10 sand	38.3	48.87	-94.85	0-60	1		1		
Primary	5-10 sand	39.6	48.86	-94.83	0-60	1		1		
Primary	5-10 sand	41.3	48.85	-94.80	0-8, 8-60		1	2	1	8-60
Alternate	Alternate, 5-10 sand	24.3	48.97	-95.01						
Alternate	Alternate, 5-10 sand	38.5	48.87	-94.85						
Primary	1-5 sand	41.8	48.85	-94.79	0-60		1	2		
Alternate	Alternate, 1-5 sand	41.4	48.85	-94.79	0-60					
Alternate	Alternate, 1-5 sand	42.4	48.85	-94.77	0-60					
Primary	1-5 muck (40s)	45.9	48.84	-94.76	0-60	1		1	1	0-60
Primary	1-5 muck (40s)	48.8	48.85	-94.71	0-60	1		1		
Alternate	Alternate, 1-5 muck (40s)	46.8	48.84	-94.74						
Alternate	Alternate, 1-5 muck (40s)	48.3	48.84	-94.72						
					Subtotal	13	5	26	4	
					Total	18		30		

Table C2: Soil sampling field and lab results

RMB Lab Code	RMB Site ID	Project FID	Site Description	Depth Profile	Time	Bank Height	QC	QPS Waypoint	Latitude	Longitude	Comments
172761	1	15		0-17"	17:05	17"		75	48.894601	-95.274917	
172762	3	1		0-16"	14:20	16"		73	48.887048	-95.216168	Original site turned out to be .19 miles inland, collected sample at waterfront bank
172763	3	1		0-16"	14:45	16"	QC	73	48.887048	-95.216168	Original site turned out to be .19 miles inland, collected sample at waterfront bank
172764	5	33	Alternate site for FID 0	0-21"	15:40	23"		74	48.88997	-95.263522	Moved to alternate site due to access permissions not granted at primary FID 0
172765	5	33		21-27"	16:01	23"		74	48.88997	-95.263522	
172766	5	33		27-60"	16:20	23"		74	48.88997	-95.263522	
172767	6	3		0-27"	13:15	27"		71	48.889215	-95.157441	
172768	7	4		0-41"	12:30	41"		70	48.915994	-95.098577	moved west to find exposed bank, 500 yards either direction protected by 100 yard deep reeds/cattails
172769	8	5		0-21"	10:50	29"		69	48.940738	-95.075217	
172770	8	5		21-27"	10:10	29"		69	48.940738	-95.075217	
172771	8	5		27-60"	11:30	29"		69	48.940738	-95.075217	
172772	9	2		0-29"	13:50	29"		72	48.884271	-95.193132	
172773	12	11		0-54"	18:10	54"		76	48.962945	-95.058188	Moved ~50 yards East to avoid large boulder riprap
172774	13	7		0-21"	8:00	41"		68	48.958275	-95.027751	
172775	13	7		21-27"	8:30	41"		68	48.958275	-95.027751	
172776	13	7		21-27"	9:15	41"	QC	68	48.958275	-95.027751	
172777	13	7		27-60"	9:30	41"		68	48.958275	-95.027751	
172778	14	6		1-42"	19:20	42"		77	48.900236	48.958275	
172779	19	21	Alternate site for FID 17	0-96"	17:35	96"		86	48.958501	-94.934157	Moved to alternate site due to original site on top of septic and unmarked power lines
172780	20	8		0-69"	20:10	69"		78	48.891444	-94.884291	
172781	23	16		0-57"	15:20	57"		85	48.869996	-94.851828	
172782	24	14		0-75"	14:30	75"		84	48.861908	-94.828551	Moved west to state land to avoid private land access restaints
172783	25	13		0-8"	10:55	76"		83	48.853197	-94.797266	Moved west to avoid mowed grass lawn, difficult site, hard packed soils
172784	25	13		8-84"	12:10	76"		83	48.853197	-94.797266	Moved west to avoid mowed grass lawn, difficult site, hard packed soils
172785	25	13		8-84"	13:25	76"	QC	83	48.853197	-94.797266	Moved west to avoid mowed grass lawn, difficult site, hard packed soils
172786	30	18	Alternate site for FID 12	0-8"	9:50	108"		82	48.853121	-94.774092	Moved to alternate site due to access permissions not granted at primary FID 12
172787	30	18	Alternate site for FID 12	8-60"	10:15	108"		82	48.853121	-94.774092	Moved to alternate site due to access permissions not granted at primary FID 12
172788	32	10		1-36"	7:35	36"		80	48.844987	-94.708135	
172789	33	24	Alternate site for FID 9	1-44"	8:35	44"		81	48.843048	-94.745384	Moved to alternate site due to poor sampling conditions, no measurable bank, just tons of debris/logs
172790	33	24	Alternate site for FID 9	1-44"	8:45	44"	QC	81	48.843048	-94.745384	Moved to alternate site due to poor sampling conditions, no measurable bank, just tons of debris/logs

Table C2: Soil sampling field and lab results (continued)

On-site soil observations	Solids (% wt)	TP (mg/kg dry)	TP (mg/kg wet)	Nitrate + Nitrite Nitrogen (mg/kg dry)	Nitrate + Nitrite Nitrogen (mg/kg wet)	Ammonia (mg/kg dry)	Ammonia (mg/kg wet)	Total Kjeldahl Nitrogen (mg/kg dry)
0-9" rooted peat, 9-17" sandy clay	68	310	210.8	< 2.1	< 1.4	< 1.7	< 1.2	1300
0-16" sandy loam	77	250	192.5	< 1.5	< 1.2	< 1.2	< 0.9	220
0-16" sandy loam	79	230	181.7	< 1.6	< 1.3	< 1.3	< 1.0	240
0-21 sandy loam with lots of rooted veg, 21-25" decaying material, 25"-57" sandy loam very wet, 57-60" clay	75	300	225.0	< 2.1	< 1.6	< 1.7	< 1.3	460
0-21 sandy loam with lots of rooted veg, 21-25" decaying material, 25"-57" sandy loam very wet, 57-60" clay	77	280	215.6	< 1.8	< 1.4	< 1.5	< 1.2	380
0-21 sandy loam with lots of rooted veg, 21-25" decaying material, 25"-57" sandy loam very wet, 57-60" clay	78	320	249.6	< 1.9	< 1.5	< 1.5	< 1.2	570
0-27" peat	18	870	156.6	37	6.7	< 6.3	< 1.1	24000
0-41" sand	92	180	165.6	< 1.4	< 1.3	< 1.1	< 1.0	< 110
0-13" sand, 13-20" peat, 20-60" clay	83	280	232.4	< 1.5	< 1.2	< 1.2	< 1.0	470
0-13" sand, 13-20" peat, 20-60" clay	23	910	209.3	< 5.1	< 1.2	< 4.0	< 0.9	20000
0-13" sand, 13-20" peat, 20-60" clay	67	670	448.9	< 2.2	< 1.5	10	6.7	1400
0-29" peat	21	690	144.9	16	3.4	< 5.7	< 1.2	15000
0-54" sand	92	190	174.8	< 1.7	< 1.6	< 1.4	< 1.3	250
1-27" sand, 27-60" Sand (minimal peat)	95	160	152.0	< 1.4	< 1.3	< 1.1	< 1.0	390
1-27" sand, 27-60" Sand (minimal peat)	91	170	154.7	< 1.5	< 1.4	< 1.2	< 1.1	400
1-27" sand, 27-60" Sand (minimal peat)	95	190	180.5	< 1.6	< 1.5	< 1.3	< 1.2	110
1-27" sand, 27-60" Sand (minimal peat)	34	400	136.0	< 4.4	< 1.5	< 3.5	< 1.2	6600
0-30" sand, 30-42" med gravel	94	230	216.2	2.3	2.2	< 1.2	< 1.1	< 150
0-12" black top soil, 12-86 sandy clay, 86-96" clay	86	490	421.4	< 1.6	< 1.4	3.5	3.0	230
0-69" sand	95	270	256.5	< 1.7	< 1.6	< 1.3	< 1.2	110
0-32" sand, 32-43" courser sand/gravel, 43-57" clay	82	210	172.2	< 1.6	< 1.3	< 1.3	< 1.1	410
0-37" sand, 37-75" clay	91	350	318.5	< 1.7	< 1.5	< 1.3	< 1.2	310
0-37" sand, 37-75" clay	96	330	316.8	< 1.4	< 1.3	< 1.2	< 1.2	< 170
0-37" sand, 37-75" clay	90	280	252.0	< 1.4	< 1.3	< 1.1	< 1.0	290
0-37" sand, 37-75" clay	86	260	223.6	< 1.5	< 1.3	< 1.2	< 1.0	360
0-108" sand	98	240	235.2	2.8	2.7	< 1.3	< 1.3	240
0-108" sand	96	210	201.6	< 1.5	< 1.4	< 1.2	< 1.2	< 130
0-21" peat, 21-36" sand	73	270	197.1	< 1.9	< 1.4	< 1.6	< 1.2	1300
1-20" Sand, 20-26" Decaying material (log), 26-40" sandy clay, 40-44" clay	79	230	181.7	< 1.8	< 1.4	< 1.5	< 1.2	620
1-20" Sand, 20-26" Decaying material (log), 26-40" sandy clay, 40-44" clay	78	260	202.8	< 2.0	< 1.6	< 1.6	< 1.2	1500

Table C2: Soil sampling field and lab results (continued)

Total Kjeldahl Nitrogen (mg/kg wet)	Total Organic Carbon (% wt)	Total Organic Carbon (mg/kg dry)	pH (units)	Organic Matter (%)	Salinity (mmhos/cm)	Bray-I Phosphorus (ppm)	Olsen Phosphorus (ppm)	Nitrate-Nitrogen (ppm)	Potassium (ppm)
884	1.91	19,100	7.7	3.1	0.1	13	2	0.3	20
169.4	< 0.5	< 5,000	8.1	0.8	0.1	10	2	0.4	16
189.6	< 0.5	< 5,000	8.2	0.8	0.1	6	2	0.5	10
345	0.71	7,100	7.9	1.2	0.1	9	2	0.3	15
292.6	< 0.5	< 5,000	7.8	1.1	0.1	12	2	0.3	12
444.6	0.56	5,600	8.4	1.2	0.1	6	2	0.3	20
4320	9.50	95,000	6.7	57.6	0.1	3	2	5.9	15
< 101.2	< 0.5	< 5,000	7.9	0.4	0.1	6	2	2.0	15
390.1	1.73	17,300	8.0	2.4	0.1	6	2	1.6	21
4600	8.40	84,000	6.9	39.7	0.1	3	2	0.4	16
938	2.29	22,900	7.7	6.7	0.3	2	2	0.5	39
3150	10.60	106,000	7.2	66.8	0.2	3	2	2.0	14
230	3.45	34,500	8.0	0.8	0.1	6	3	2.1	10
370.5	0.90	9,000	7.7	1.1	0.1	4	2	4.1	10
364	1.57	15,700	7.9	0.9	0.1	5	2	3.7	10
104.5	< 0.5	< 5,000	7.9	0.2	0.1	2	2	1.7	8
2244	5.18	51,800	6.8	14.4	0.1	4	2	0.6	10
< 141	2.94	29,400	8.2	0.4	0.1	5	3	5.5	20
197.8	2.13	21,300	8.2	0.7	0.2	2	2	0.5	51
104.5	1.28	12,800	8.4	0.3	0.1	5	2	0.6	14
336.2	1.14	11,400	7.9	0.8	0.1	5	2	2.5	10
282.1	2.53	25,300	8.3	0.9	0.2	2	2	0.7	45
< 163.2	0.57	5,700	8.5	0.1	0.2	4	2	4.3	17
261	1.93	19,300	8.0	0.9	0.2	4	2	0.3	26
309.6	1.34	13,400	8.2	0.6	0.2	4	2	1.3	20
235.2	0.75	7,500	8.0	0.2	0.1	6	2	4.4	12
< 124.8	1.07	10,700	8.5	0.1	0.1	4	2	0.4	10
949	2.25	22,500	6.3	4.7	0.1	6	2	2.0	16
489.8	1.86	18,600	7.5	3.0	0.3	9	3	4.5	21
1170	1.90	19,000	7.5	2.4	0.3	11	3	5.2	25

Table C2: Soil sampling field and lab results (continued)

Sand (%)	Silt (%)	Clay (%)	Texture (calculated by sand/silt/clay)	Texture (calculated by organic matter)	Gravel %	Sand %	Silt %	Clay %	Classification
77.5	15.0	7.5	Sandy Loam		1.1	66.4	27.3	5.2	Silty Sand (SM)
90.0	7.5	2.5	Sand		2.1	90.6	3.5	3.8	Poorly Graded Sand with Silt (SP-SM)
92.5	2.5	5.0	Sand		3.4	89.6	4.6	2.4	Poorly Graded Sand with Silt (SP-SM)
Texture by Hydrometer NA				Coarse	4.7	67.6	24.5	3.1	Silty Sand (SM)
90.0	5.0	5.0	Sand		0.9	65.6	29.7	3.8	Silty Sand (SM)
87.5	2.5	10.0	Sand		0	57.3	30	12.7	Silty Sand (SM)
Texture by Hydrometer NA			Peat		19.5	70.4	5	5	Peat
92.5	0.0	7.5	Sand		0.5	98.3	0	1.1	Poorly Graded Sand (SP)
85.0	7.5	7.5	Sand		1.5	94.2	1.9	2.5	Poorly Graded Sand (SP)
Texture by Hydrometer NA			Peat		3.6	45.7	29.4	21.3	Peat
Texture by Hydrometer NA				Med/Fine	0	5.1	19.4	75.5	Fat Clay (CH)
Texture by Hydrometer NA			Peat		15.9	73.8	5	5.3	Peat
90.0	7.5	2.5	Sand		3.3	90	2.9	3.8	Poorly Graded Sand with Silt (SP-SM)
90.0	10.0	0.0	Sand		0.1	98.8	0.2	0.9	Poorly Graded Sand (SP)
92.5	2.5	5.0	Sand		0.9	98.7	0.2	0.3	Poorly Graded Sand (SP)
97.5	0.0	2.5	Sand		0.1	99.6	0.1	0.2	Poorly Graded Sand (SP)
90.0	7.5	2.5	Sand		15.3	81.7	1	2	Poorly Graded Sand with Gravel (SP)
92.5	7.5	0.0	Sand		4.2	88.6	3.2	3.9	Peat
62.5	20.0	17.5	Sandy Loam		0.5	43.3	36.4	19.7	Sandy Lean Clay (CL)
92.5	5.0	2.5	Sand		6.6	91	1.4	1	Poorly Graded Sand (SP)
92.5	5.0	2.5	Sand		4	90.1	3.4	2.5	Poorly Graded Sand with Silt (SP-SM)
65.0	17.5	17.5	Sandy Loam		6.4	60.4	17.3	15.9	Clayey Sand (SC)
97.5	2.5	0.0	Sand		0	99	0.2	0.7	Poorly Graded Sand (SP)
87.5	5.0	7.5	Sand		2.8	84.2	3.1	9.9	Silty Sand (SM)
90.0	2.5	7.5	Sand		3.1	85.4	2.4	9.1	Poorly Graded Sand with Silt (SP-SM)
97.5	0.0	2.5	Sand		0	97.4	0.5	2.1	Poorly Graded Sand (SP)
92.5	5.0	2.5	Sand		4.5	93.3	0.2	1.9	Poorly Graded Sand (SP)
82.5	12.5	5.0	Sandy Loam		0.8	81.1	13.2	4.9	Silty Sand (SM)
85.0	10.0	5.0	Sand		0.6	87.9	4.5	7	Poorly Graded Sand with Silt (SP-SM)
85.0	7.5	7.5	Sand		1	88.8	4.7	5.5	Poorly Graded Sand with Silt (SP-SM)