HISTORIC AND MODERN SEDIMENT YIELD FROM A FORESTED WATERSHED AND ITS IMPACT ON NAVIGATION

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Abstract Sedimentation in federal channels and harbors, and the associated costly dredging, are significant concerns for the U.S. Army Corps of Engineers (USACE), which is tasked with maintaining federal navigation channels. Dredge material removed from a given harbor may originate from many sources including littoral drift, overland runoff, mass wasting, and river bank erosion. This study specifically investigates the sediment yields from upland and riverine sources and the long term sedimentation rates in a deep-draft commercial harbor in the Great Lakes region. The approach used to quantify modern and historic sediment yields over varying time scales is presented.

The highly forested, and predominantly undeveloped, Ontonagon River Watershed in Michigan's Upper Peninsula is the focus of the presented approach. The Ontonagon River watershed yields significant amounts of sediment due to mass wasting of the highly incised valleys. A Geographic Information Systems (GIS) model was developed to estimate long-term sediment yields by reconstructing the likely watershed topography at the start of the Holocene. In addition, modern sediment yields were determined using existing USGS data. These results show a significant reduction in sediment yields over geologic time scales. Moreover, the various approaches and results of our analyses are used to prioritize mitigation options for reducing sediment delivery to the federal navigation channel.

INTRODUCTION

The US Army Corps of Engineers (USACE) is responsible for maintaining the federal navigation channels and harbors in the United States. Often, much of the sediment that deposits in the channels and harbors originates from upland areas, and can consist of overland runoff, river bank material, sediment from valley walls, and numerous other sources. In the Great Lakes Basin, USACE is authorized to study these upland sediment sources under the Water Resources Development Act, Section 516(e), which directs USACE to develop models that local stakeholders can use to mitigate sediment mobilization processes in a watershed.

The 516(e) watershed studies often identify anthropogenic causes for high sediment yields, which result from watershed activities, such as unsustainable forestry practices and the conversion of land to urban or agricultural uses. However, this study investigated the sediment dynamics in the Ontonagon River Watershed, which is a large, undeveloped, forested watershed in Michigan's Upper Peninsula. Despite the low population density, sustainable forestry practices, and lack of large tracks of agriculture, the Ontonagon has been identified as the second largest contributor of sediment to Lake Superior (Robertson, 1997).

Figure 1 Location of study area and associated land use.

DESCRIPTION OF THE STUDY AREA

The Ontonagon River Watershed contains 1384 square miles and is predominantly located in the western portion of Michigan's Upper Peninsula. The watershed includes portions of the following Michigan counties: Ontonagon; Houghton; Gogebic; and Iron; as well as a portion of Vilas County, Wisconsin.

Land Use The watershed's land use (fig. 1) is predominantly forest (74%) and wetland (15%). The Ottawa National Forest covers approximately 57% of the watershed, or about 790 square miles. Where logging is present in the watershed, sustainable forestry practices are overwhelmingly implemented. Agricultural and urban land uses are very sparse, covering 5% and 0.1% respectively (Gunderman & Baker, 2008). Consequently, population densities within the watershed are very low, averaging approximately 10 people per square mile, or about 13,800 total residents.

Geology The topography and geology of the watershed has been described in detail in previous publications (Genderman & Baker, 2008; Hack, 1965). In general, the headwaters and "lakes" area of the watershed consists of end moraines of coarse-textured till. The South Branch, Middle Branch – lower, East Branch, and Main Stem of the Ontonagon River predominantly consist of lacustrine clay and silt, where significant valley incision is evident. In the lacustrine regions, upland terraces are very flat and valley walls (often fully exposed) reach heights of over 250 feet. Valley and river incision is exacerbated by the glacial rebound that is significant in this area, estimated at approximately 14cm per century (Clark, 2007).

HISTORIC SEDIMENT BUDGET

Process The Ontonagon Watershed, like other watersheds in the region, is geologically young. The final glacial retreat in Michigan's Upper Peninsula occurred approximately 11,000 years before present (Peterson, 1986). Following this period the watershed is presumed to have been relatively flat, and there is evidence that the deep valleys and steep walls that exist today are due to natural sediment transport processes that have carved out the valleys and deepened the Ontonagon River and its tributaries. Frequent examples of mass wasting of the valley walls exist throughout the downstream reaches of the Ontonagon River and a flat terrace with steep valleys adjacent to a narrow beltwidth and meandering channel are typical downstream reach conditions (fig 2).

In order to calculate the rate of sediment transport and valley incision in the Ontonagon River Watershed a comparison of probable historic topography and present day topography was performed using a GIS model developed by USACE for this project. The process associated with the GIS model is outlined below.

Calculation of valley slopes The typical valley slopes adjacent to incised alluvial streams were determined by importing a 10-meter Digital Elevation Model (DEM) and calculating the slope between elevations of adjacent raster cells. The ArcGIS Spatial Analyst extension was used to calculate the slope of the valley by determining the

maximum rate of change of adjacent cells and dividing by the resolution length of the DEM (Burrough & McDonell, 1998). The slope raster layer was resampled and classified as either steep or mild. The metric defining a steep slope was determined by overlaying the output of several cutoff values on a 3-dimensional terrain model (fig. 2). A slope value of 35 degrees was found to identify unstable valley slopes and exclude flatter alluvial channels and upper terraces.

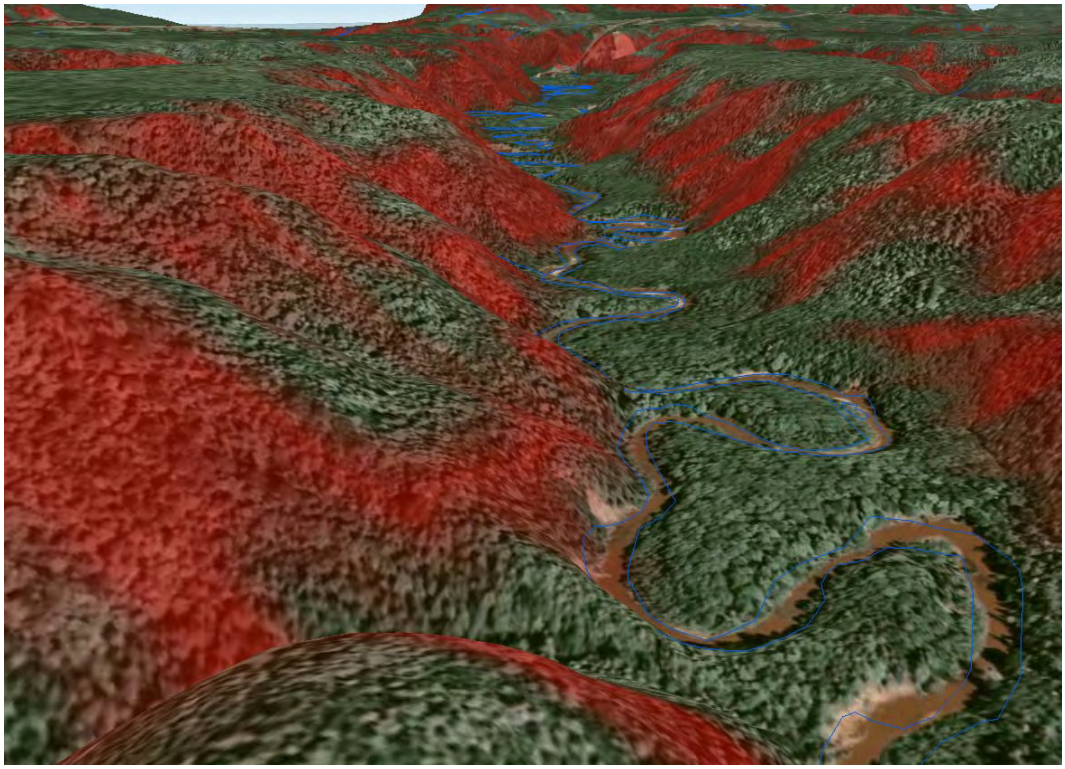

Figure 2 Middle Branch of the Ontonogan River. Steep valley walls are typical of most downstream reaches of the Ontonagon River Watershed. Valley slopes greater than 35 degrees are shown in red.

Delineation of Valley Boundary The outside of the valley boundaries were delineated manually in ArcGIS by digitizing the edge of the terrace along the top of the steep-sloped areas. This results in identifying the unstable valleys that are actively evolving due to mass wasting and rill erosion. The total area of this valley boundary was calculated to be 68.5 square miles.

Development of a Three-Dimensional Cap of the Valley Following the valley delineation, elevations extracted from the Ontonagon DEM were assigned to the resultant polygon boundaries, creating a 3-dimensional surface. This surface was converted to a Triangular Irregular Network (TIN), and was used to calculate the volume difference between present day and historic topographies.

Calculation of Sediment Volume and Mass The total volume between the top of the valley cap layer and the existing DEM was calculated using ArcGIS cut/fill tools and

resulted in a volume of 1.52×10^{10} m^3. This value was converted to a mass in order to calculate historic sediment loadings. Assuming average in-situ soil density values of approximately 100 lbs per cubic foot, the associated mass of the valley that has been eroded in since the last glaciation is about 2.6×10^{10} tons.

Historic Average Annual Sediment Loading Following the glacial retreat, fluvial processes carved out the incised valleys and continue to create mass wasting events and bank erosion to this day in many areas. Therefore, an average annual sediment load from the watershed may be estimated by dividing the eroded volume by the number of years that fluvial processes have been occurring. This amounts to an average annualized sediment yield of 2.4×10^6 tons/year.

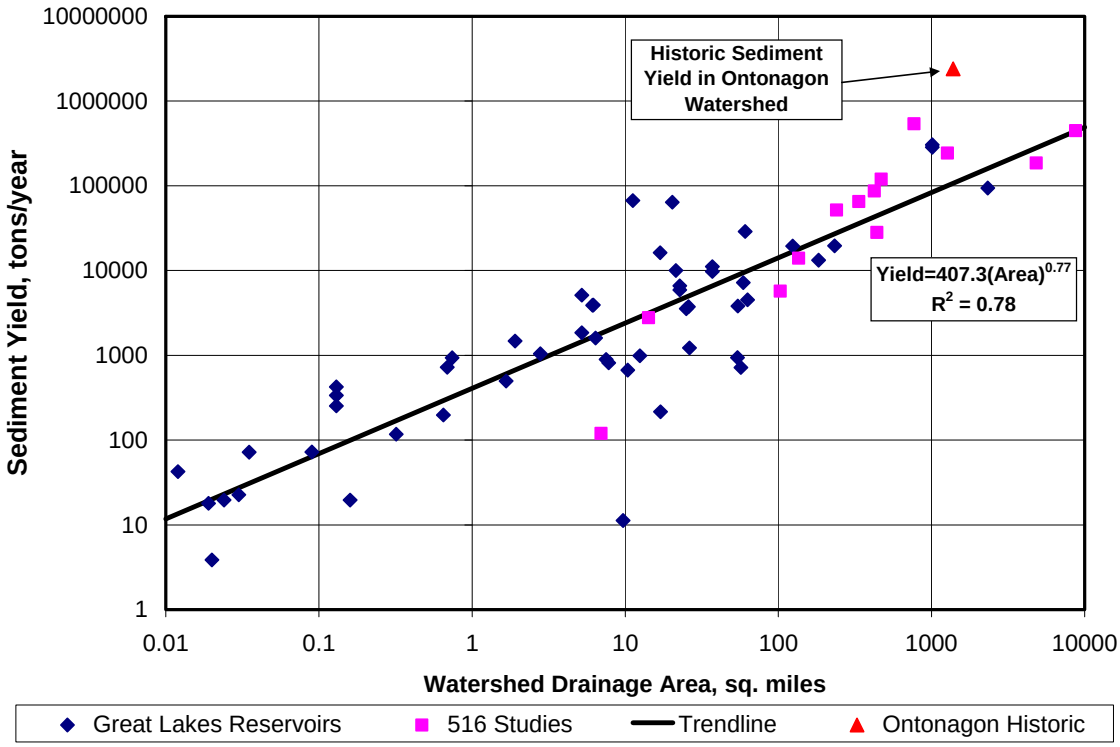

Figure 3 Annual Sediment Yield from Historic Ontonagon and other Studies.

Comparison of Historic Sediment Budget with Previous Studies The Ontonagon historic sediment loadings were compared with a total of 13 data points from previous USACE 516(e) models in Great Lakes watersheds, and a total of 48 Great Lakes Reservoirs from the Advisory Committee on Water Information (ACWI) Subcommittee on Sedimentation's Reservoir Sedimentation (RESSED) database (fig. 3). A regression equation has been developed that relates total sediment yield in tons per year to the watershed area, in square miles based on these additional studies. The resulting Great Lakes regional sediment yield equation is:

$$Y = 407.3 Area^{0.77} \quad (1)$$

where Y is the sediment yield in tons per year, and Area is the watershed drainage area in square miles.

Using this regression equation, the predicted sediment yield for the 1384 square mile Ontonagon River Watershed is 180,000 tons per year. The calculated average sediment load of approximately 2.4 million tons/year is over an order of magnitude greater than the predicted value obtained from the regression of previous studies. This analysis suggests that over geologic time scales, erosion rates have not been constant. It is presumed that sediment yield rates are likely decreasing over time, and this assumption can be confirmed if modern sediment yields are less than the historic average yields. A calculation of the modern sediment budget was completed to confirm this assumption.

MODERN SEDIMENT YIELDS

The present day un-impounded area of the Ontonagon River Watershed is approximately 500 square miles. Dams significantly impound the South Branch, West Branch, Cisco Branch, and Middle Branch (upper) subwatersheds. The Victoria Dam alone impounds an area equivalent to approximately 40% of the entire watershed. Coupled with historic forestry practices, these alterations have significantly changed the sediment loadings that reach the downstream harbor and navigation channel.

The primary sources of sediment that is mobilized and ultimately deposited in the downstream navigation channel may be attributed to valley mass wasting and river bank erosion. Due to the combined effects of relatively low amounts of rainfall, land use consisting primarily of forest and wetlands, flat upland terraces, and sustainable forestry practices, very little overland flow is available to mobilize upland sediment.

Suspended Sediment Data: A significant amount of sediment data from the years 1974 through 1995 was collected at USGS gage 04040000, near Rockland, Michigan (fig. 4). The majority of the relevant data collected at this gage consists of suspended sediment loading and streamflow data.

The gradations of the samples included in the sediment rating curve are not provided, however, the silt/clay fraction of sediment is included with most of the suspended sediment data points. These data are summarized in Table 1, which shows that much of the suspended sediment data consists of silts and clays (less than 0.0625mm diameter particles).

Table 1 Summary of Suspended Sediment Data at USGS Gage 04040000.

Sediment Variable	Value
Period of Record	10/03/1974 - 08/29/1995
Data Points	120
Average Percent Finer than 0.0625mm	95.3%
Standard Deviation of Percent Finer than 0.0625mm	8.8%

Larger flow events in the USGS database for this gage do show reduced clay fractions in the suspended sediment loads. Representative values were extracted from the period of record to approximate the fraction of sand and clay as a function of the flow (table 2).

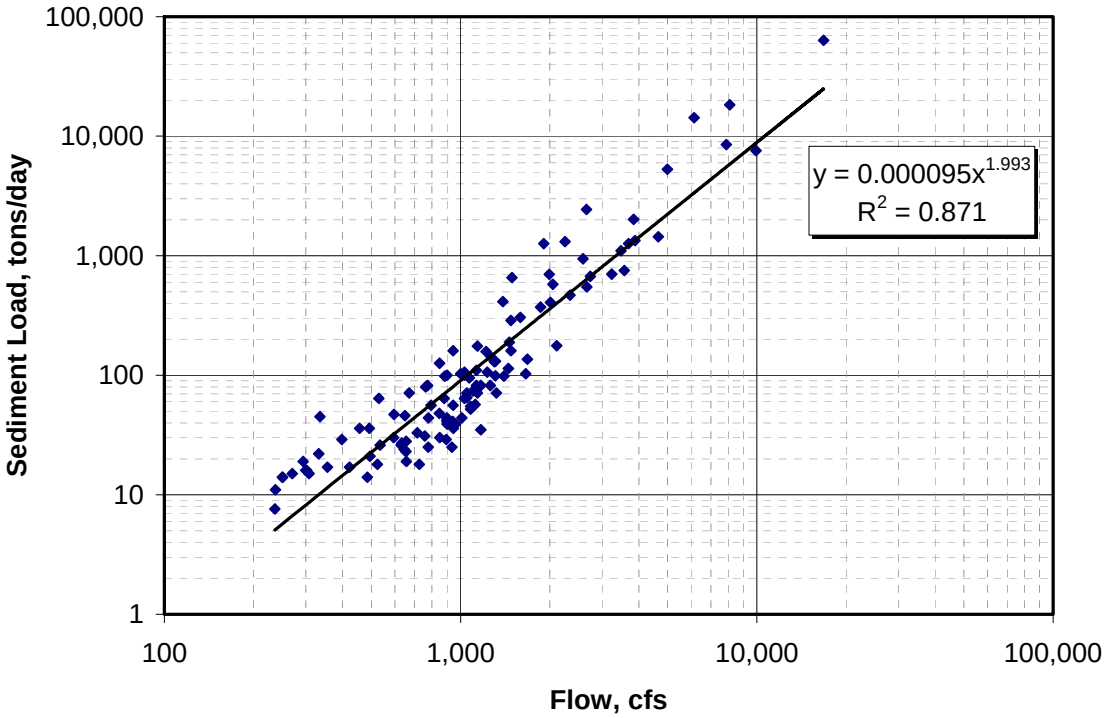

Figure 4 Ontonagon Main Stem Sediment Rating Curve (USGS Gage 04040000).

Table 2 Sediment Size as a function of flowrate at gage 04040000.

Flow, cfs	Data points	Silt/Clay Fraction, %	Sand Fraction, %
Q < 1,030	60	100	0
1,030 < Q < 2,250	57	94	6
2,250 < Q < 4,990	18	90	10
4,990 < Q < 8,100	5	85	15
8,100 < Q < 16,800	2	66	34
Q > 16,800	0	50	50

Although sediment data was not collected when flows exceeded 16,800 cfs, the flow in the period of record did exceed this value several times, and therefore the sand/clay fraction patterns were extrapolated in the final row of Table 2.

Suspended sediment loads as a function of clay and sand were calculated for the period of record at USGS gage 04040000 by combining the regression obtained from the sediment rating curve and the fraction of clay and sand as a function of flowrate. The calculated

annual suspended sediment loads include data from 1942-2008, and are summarized in Table 3.

Table 3 Annual Suspended Sediment Load Summary.

	Total Sediment Load, tons/year	**Clay Load, tons/year**	**Sand Load, tons/year**
Average	156,300	136,000	20,300
Maximum	364,200	285,500	78,700
Minimum	35,300	34,100	1,200

Dredging records Dredging records may be used as a component in the sediment delivery equations; however, caution should be applied if using dredge data to determine bed or total sediment loads directly. Dredge records reflect the amount of material removed from a navigation channel, not necessarily the amount of material that has been deposited in the channel. Moreover, littoral sediment is also included in the dredge records, which may result in overestimating fluvial sediment yields.

To supplement dredge volumes recorded by USACE, a sample of pre- and post-dredging bathymetric survey data was used to calculate actual volumes of fluvial material deposited in the navigation channel. For several pairs of years, a post-dredging survey taken in the spring was established as a baseline condition, and the pre-dredging survey taken the following spring was used to calculate sediment accumulation (an example is shown in fig. 5). These surveys were converted to Triangular Irregular Networks (TIN) and the volume between the surfaces was calculated. This analysis extended only to the portion of the channels where fluvial material deposited, which removed littoral sources. The calculated volumes are, on average, 25% less than the dredge records. Annual dredge records are summarized in Table 4.

Table 4 Annual Volumes Dredged from Ontonagon Harbor and Navigation Channel.

	Total Sediment Dredged, yd^3/year	**Total Sediment Dredged, ton/year**	**Fluvial Sediment Dredged, yd^3/year**	**Fluvial Sediment Dredged, ton/year**
Average	59,000	76,000	44,000	57,300
Maximum	162,000	211,000	122,000	158,000
Minimum	10,200	13,300	7,660	9,960

The gradation of the dredge material is over 99% sand, based on historic grain size distribution data. Moreover, gradations of the dredge material are uniform with average grain sizes of D_{85} = 0.50mm; D_{50} = 0.31mm; and D_{15} = 0.20mm.

Bed Load Sediment Data Data associated with bed load transport are not available for the Ontonagon River; however, the dredge data may be used to close the sediment yield budget. Based on gradations in the harbor, the majority of fine suspended sediment is

wash load and is transported through the navigation channel and discharged to Lake Superior. Therefore, the only portion of suspended sediment that is deposited in the navigation channel is the sand fraction (approximately 20,300 tons/year). The remaining sediment in the dredge and bathymetric records must be from bed load transport, which equates to approximately 37,000 tons/year.

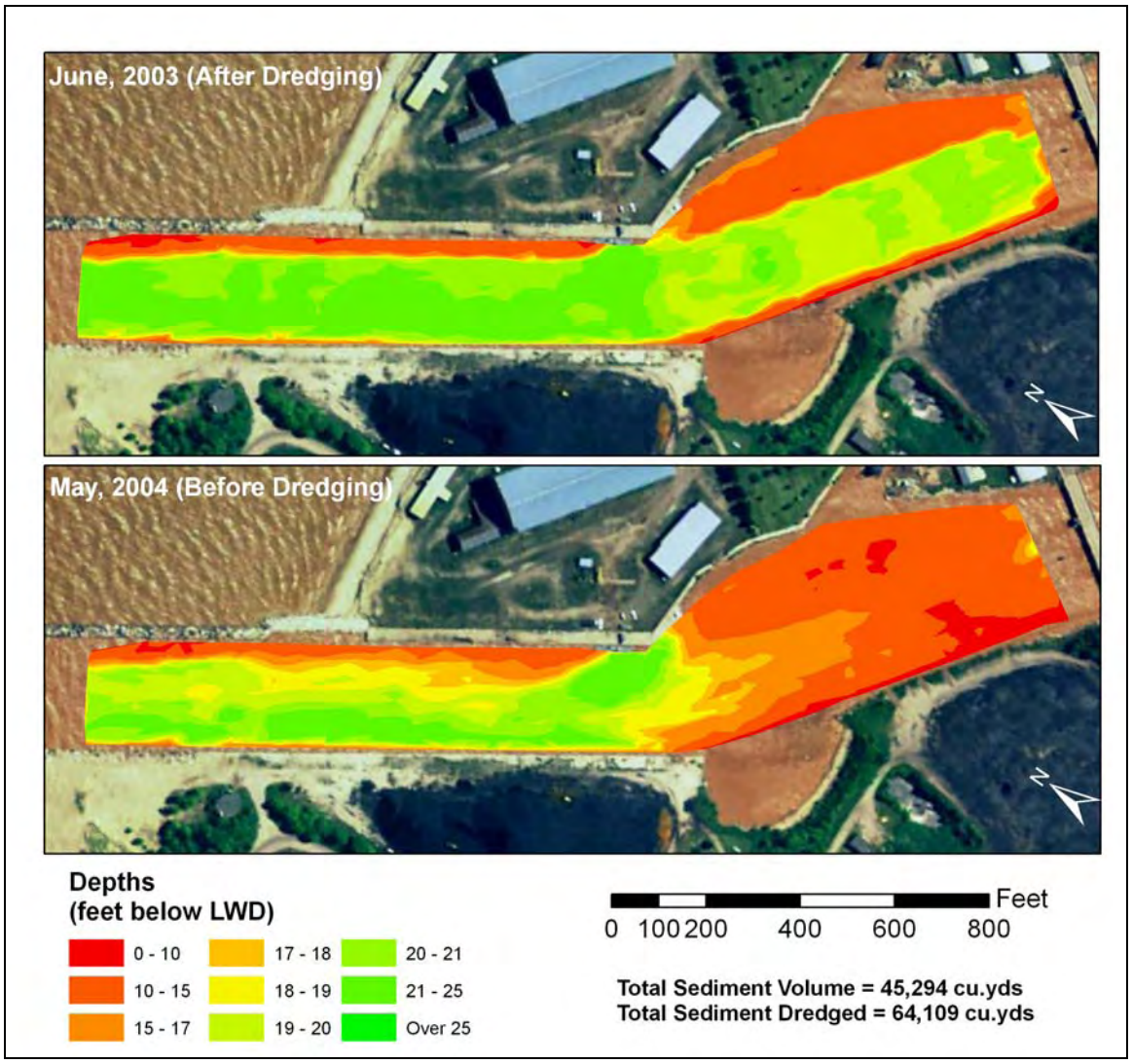

Figure 5 Bathymetry Data of Navigation Channel just following dredging in June, 2003 (above) and just before dredging in May, 2004 (below). Sediment deposits up to nine feet are observed in the navigation channel. A total of 45,294 cubic yards deposited in the navigation channel out of the total 64,109 cubic yards that were dredged.

Modern Sediment Loads The total sediment yields are calculated by summing up the suspended and bed sediment loads, which equate to 193,300 tons per year (fig. 6). This closely matches the expected value of 180,000 tons per year as predicted by the Great Lakes regional sediment yield curve (fig. 7).

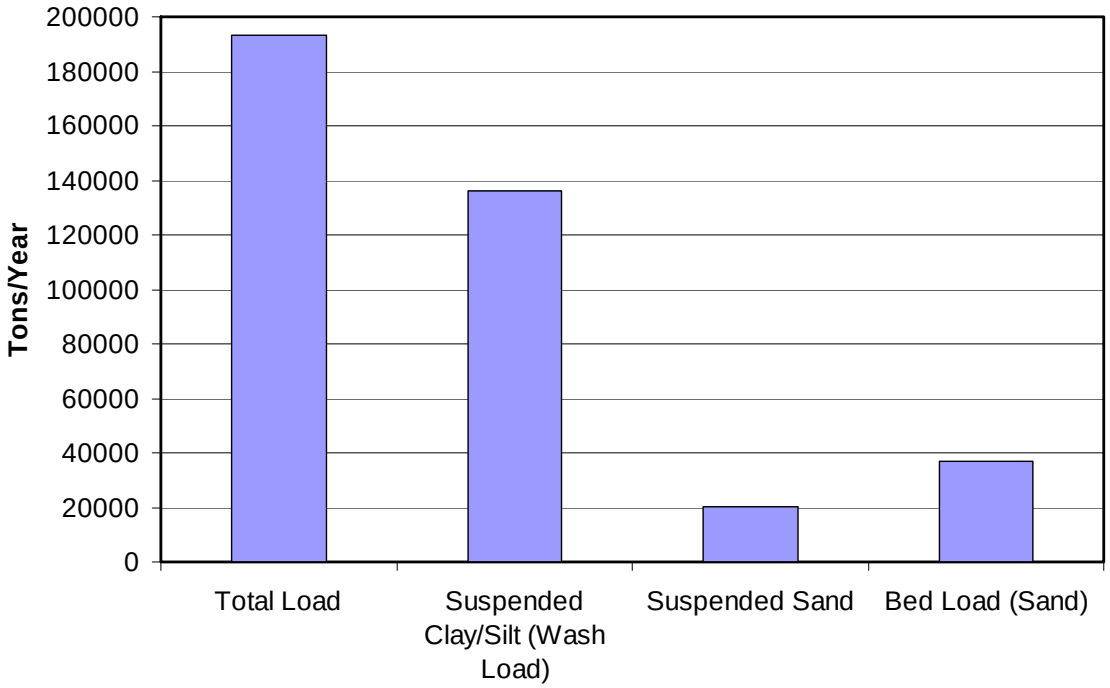

Figure 6 Summary of Modern Sediment Yields.

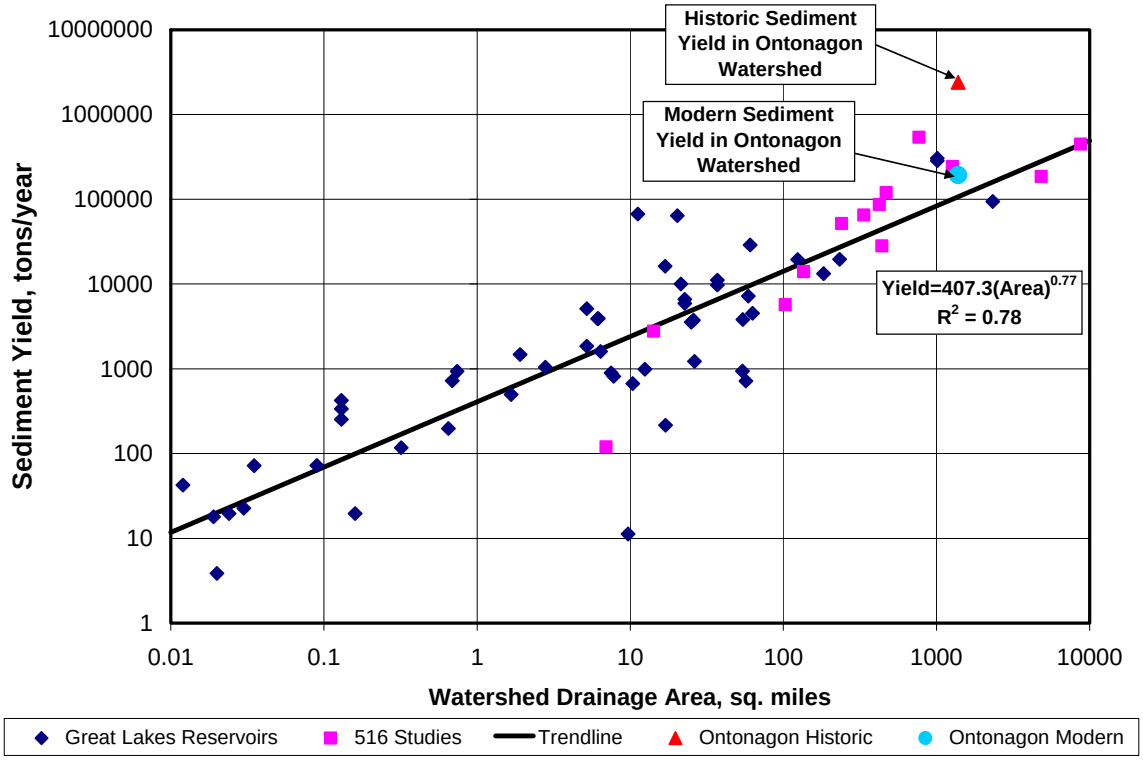

Figure 7 Comparison of Modern Sediment Yields with Historic Yield and other Studies.

IMPACTS TO GREAT LAKES NAVIGATION

The deep-draft navigation channel at the mouth of the Ontonagon River experiences significant sedimentation, which primarily occurs during the peak flows associated with spring runoff. Deposits of over nine feet of sediment occur in the channel and annual dredging is required to maintain the navigation channel. From the years 2000-2008 the average cost to dredge the channel exceeded $350,000 per year.

The primary use of the navigation channel is to facilitate coal delivery to the fiber mill in Ontonagon, which is an essential industry to the local economy. In addition, the harbor upstream of the navigation channel is used for recreational boating and fishing. Under current conditions, sustained dredging is required to maintain these uses.

CONCLUSIONS

Despite stable hydrology in the highly forested Ontonagon Watershed, high sediment delivery rates to Lake Superior and the Ontonagon federal channel persist. This work identifies natural fluvial and geologic factors as the primary cause of high sediment yields, with limited effects due to anthropogenic activities. Due to unstable valley walls and river banks in many locations, upland mitigation techniques are likely not feasible for the purpose of reducing sediment loadings downstream. As an alternative to upland mitigation, USACE has developed and calibrated a HEC-RAS sediment transport model that may be used to analyze impacts that would be associated with channel or harbor modifications. Dredging management scenarios and engineering projects, such as sediment traps, can also be analyzed with the model to determine if dredging frequencies can be reduced. However, navigation channel maintenance is a critical objective in any proposed management alternative.

In addition, this work has identified a process for analyzing historic sediment yields in a previously glaciated watershed, and determined that annual sediment loading rates are decreasing over geologic time scales. This was confirmed through the modern sediment yield analysis, which showed that current sediment yield rates are significantly less than the average annual rates over the past 11,000 years. The analysis utilizing bathymetric survey data in the navigation channel, dredge volume records, suspended sediment loads, and dredge sediment gradations was used as an alternative to developing a watershed wide sediment budget. This method produced sediment loadings that matched the Great Lakes regional sediment yield curve developed from the RESSED database and other USACE 516(e) studies, and has the potential to be replicated in future sediment budget studies.

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