Estimating Bedload Sediment Delivery to the Great Lakes from Sixty Michigan Rivers

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Introduction

Watershed sediment delivery is the total amount of sediment accumulated within a watershed and delivered to the river outlet over a particular timeframe. Estimation of watershed sediment delivery involves an understanding of the complex processes of soil erosion, sediment transport, and sediment deposition (Barkach JH, 2021; Garcia, 2008; Gray and Simoes, 2008; MacArthur et al., 2008; MacArthur et al., 2008; Alighalehbabakhani et al., 2017; and, USACE, 1995, 2008, 2015). The purpose of this research was the development of an empirical equation using regression analysis to predict bedload sediment delivery to the river outlet of 60 Michigan rivers and five sub-watersheds.

Soil erosion at the watershed scale involves transport of sediment entrained in overland surface water flow to the river system as well as erosion of the bed and banks of the river (formation of gullies, river bank failure, and mass wasting). The transport of sediment by water forms the bed and banks of the river, and changes the slope of the river through aggradation (raising of the river bed) and degradation (deepening of the river bed). Sediment depositional areas (e.g. sinks) within the watershed include sediment deposited onto floodplains and in the bed and banks of the river, upland and aquatic wetlands, as well as sediment deposited in natural lakes and manmade reservoirs that trap sediment before it reaches the river outlet (USACE, 2008).

Figure 1. Examples of Deposition and Erosion Within a Fluvial System, Two Hearted River (61); Aerial Photograph Grand River Outlet (14) at Lake Michigan Following a Large Storm Event, April 22nd, 2013 (Beaver M, 2013)

Estimation of watershed sediment delivery integrates the effects of river flow, topography, surficial geology, and land use. Excessive sedimentation can significantly reduce reservoir capacity, affect the water quality of rivers and impoundments, adversely affect biological communities, and accumulate in navigation channels affecting the use of harbors and require frequent maintenance dredging (USACE, 1995). An example of sediment discharge from the Grand River (14) to Lake Michigan following a large storm event is shown in Figure 1.

USACE Great Lakes maintenance dredging of federal navigation channels averaged approximately 2.4 million cubic meters of sediment each year. Of the 60 Michigan rivers included in this research, 30 of these rivers discharge to USACE-Detroit District maintained harbors or navigation channels (see Figure 2). Prediction of bed load sediment delivery at the river outlet was the focus of this research and is the portion of the bed material load that travels within a few grain diameters of the river bed and moves by rolling, sliding, and saltating along the bed of the river.

Initial research was conducted to compare empirical watershed sediment delivery estimates using two fundamentally different approaches (Barkach JH et al., 2020): the 2010 Great Lakes regional trend line that was developed by the USACE (USACE, 2010) and the global BQART sediment delivery equation that was developed Syvitski and Milliman (2007). The USACE 2010 Great Lakes regional trend line (USACE, 2010) is based on sediment delivery estimates from 61 watersheds located throughout the Great Lakes basin, these include 13 USACE 516(e) models and 48 Great Lakes reservoirs from the Subcommittee on Sedimentation Reservoir Sedimentation (RESSED) database (USGS, 2014). Using these data, the USACE (2010) developed an area-based watershed sediment delivery regression equation for the Great Lakes watershed where:

$$Qs = 177.6A^{0.77} \tag{1}$$

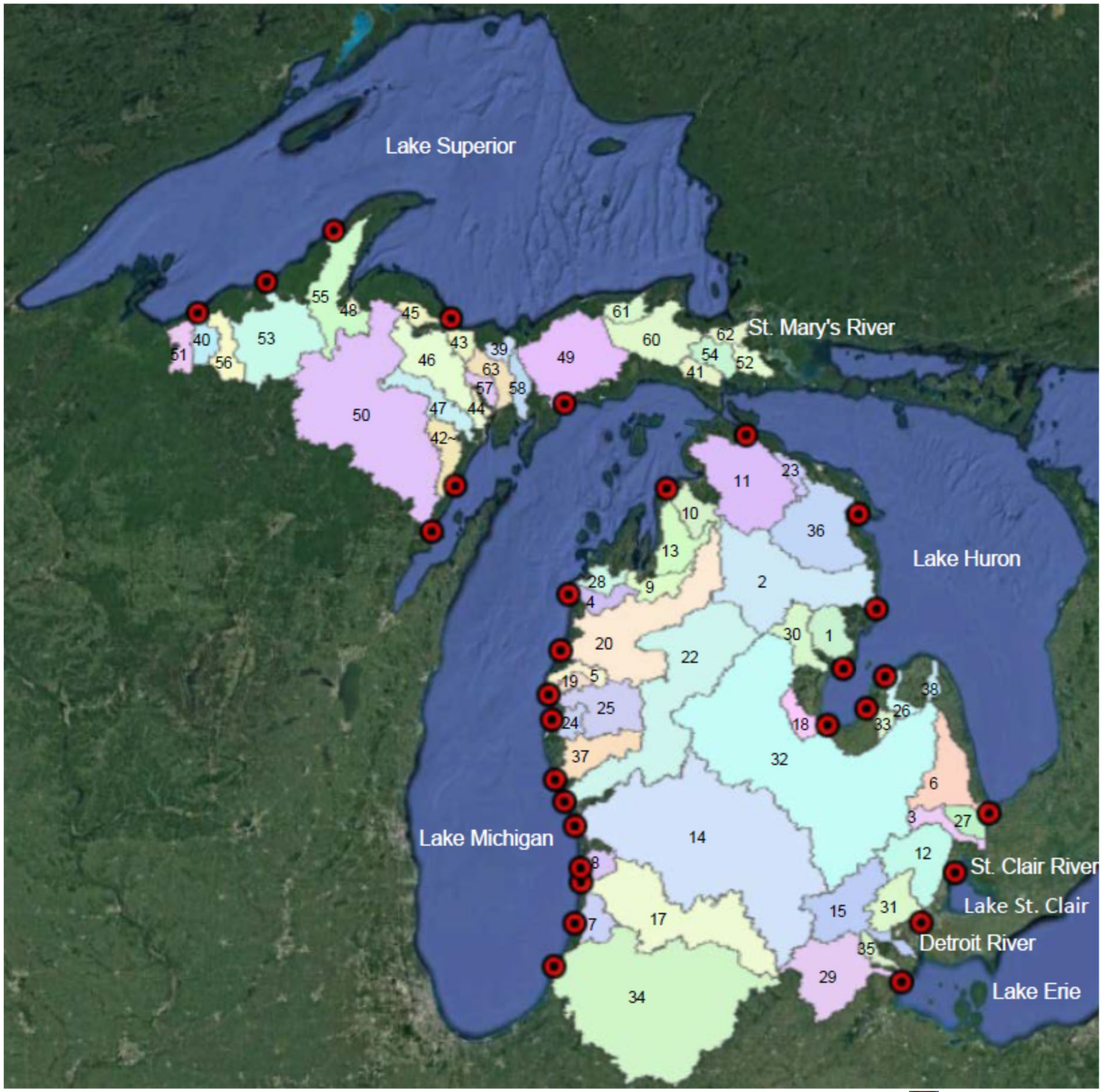
Qs = Watershed Sediment Delivery (metric tonnes/year)
A = Watershed Area (square kilometers)

The USACE (2010) Great Lakes regional trend line is an empirical equation, and as such, is most applicable to estimating watershed sediment delivery within the Great Lakes basin. With respect to the USACE (2010) Great Lakes regional trend line, the high correlation between watershed area and watershed sediment delivery (R^2=0.78) appears to be reflected in the high correlation (R^2=0.95) between watershed area and mean annual river flow for the 60 watersheds included in this research (Barkach JH et al., 2020).

The Syvitski and Milliman (2007) BQART equation was developed from a database of 488 global rivers whose watersheds cover 63% of the earth's surface. The global BQART equation was validated for rivers that have mean annual flows greater than 30 cubic meters/second (Cohen et al., 2011; Syvitski JPM, 2019). The average annual flow rate of the Michigan rivers included in this research is 22 cubic meters/second, and range in size from 1.0 cubic meters/second (Days River; 44) to 132.5 cubic meters/second (St. Joseph River; 34). The BQART equation estimates annual suspended sediment load that will discharge to a receiving water body at mean annual river flow. The Syvitski and Milliman (2007) BQART equation for watersheds with annual mean basin temperatures >2°C follows:

$$Qs = wBQ^{0.31}A^{0.5}RT \tag{2}$$

Qs = watershed sediment delivery, millions of metric tonnes (MT) per year
w = 0.0006 for units of million metric tonnes/year (MT/yr)
B = geologic and human influence factor, calculated value
Q = mean annual river flow, cubic kilometers/year
A = watershed area, square kilometers
R = relief, kilometers
T = mean basin temperature, °C



Watershed Reference Number	River	U.S. Army Corps of Engineers Harbor or Navigation Channel
1	Au Gres River	Point Lookout Harbor
2	Au Sable River	Au Sable Harbor
3	Belle River	NA
4	Betsie River	Frankfort Harbor
5	Big Sable	NA
6	Black River (East)	Black River
7	Black River (West)	South Haven Harbor
8	Macatawa River	Holland Harbor
9	Boardman	NA
10	Pine River	Charlevoix Harbor
11	Cheboygan River	Cheboygan Harbor
12	Clinton River	Clinton River
13	Elk River	NA
14	Grand River	Grand Haven Harbor
15	Huron River	NA
17	Kalamazoo River	Saugatuch Harbor
18	Kawkawlin River	NA
19	Lincoln River	NA
20	Manistee River	Manistee Harbor
22	Muskegon River	Muskegon Harbor
23	Oqueoc River	NA
24	Pentwater River	Pentwater Harbor
25	Pere Marquette River	Ludington Harbor
26	Pigeon River	Caseville Harbor
27	Pine River	NA
28	Platte River	NA
29	River Raisin	Monroe Harbor
30	Rifle River	NA
31	Rouge River	Rouge River
32	Saginaw River	Saginaw River
33	Sebewaing River	Sebewaing River
34	St. Joseph River	St. Joseph Harbor
35	Stoney Creek	NA
36	Thunder Bay River	Alpena Harbor
37	White River	White Lake Harbor
38	Willow Creek	NA
39	Au Train	NA
40	Black River (Gogebic)	Black River Harbor
41	Carp River	NA
42	Cedar River	Cedar River Harbor
43	Chocolay River	NA
44	Days River	NA
45	Dead River	Presque Isle Harbor
46	Escanaba River	NA
47	Ford River	NA
48	Falls River	NA
49	Manistique River	Manistique Harbor
50	Menominee River	Menominee Harbor
51	Montreal River	NA
52	Munuscong River	NA
53	Ontonagon River	Ontonagon Harbor
54	Pine River	NA
55	Portage River	Keweenaw Waterway
56	Presque Isle River	NA
57	Rapid River	NA
58	Sturgeon River	NA
60	Tahquamenon River	NA
61	Two Hearted River	NA
62	Waiska River	NA
63	Whitefish River	NA

Figure 2. Location of 60 Michigan Watersheds and Associated USACE Harbors   - USACE Maintained Harbor or Navigation Channel

The variable B of the BQART equation accounts for characteristics of the watershed and human influence. The variable B is calculated as follows (Syvitski and Milliman, 2007):

$$B = IL\,(1\text{-}Te)Eh \qquad (3)$$

L = basin-wide lithology factor (see Figure 5 of Syvitski and Milliman, 2007)
Te = sediment trapping efficiency of dams and lakes within the watershed
Eh = human influence soil erosion factor (see Figure 7 of Syvitski and Milliman, 2007)
I = glacial erosion factor, where I = (1 + 0.09 Ag),
Ag = area of the drainage watershed with ice cover as a percentage of the total drainage area of the watershed

The 60 watersheds addressed in this research are underlain by unconsolidated glacial deposits including glacial outwash plains, glacial till, ice contact and lacustrine deposits; for this reason, a basin-wide lithology factor L=2 was utilized (Barkach JH et al., 2020). Natural lakes and manmade reservoirs trap sediment before the sediment can reach the river outlet. With respect to Michigan, the 60 watersheds included in this research contain 2,345 dams located within these 60 watersheds. In the Great Lakes region, the small dams are often located in the edges of the watershed where relief is greatest (near glacial moraines and outwash deposits) in contrast to the large dams that are typically located in series along the main stems of the larger rivers. Based on discussions with Dr. Syvitski, the average sediment trapping efficiency (Te), used to calculate the average (1-Te) value in Syvitski and Milliman's (2007) global database of 488 rivers (0.8) was used for this research (Barkach JH et al., 2020).

The human influenced soil erosion factor (Eh) addresses anthropogenic factors such as urbanization, deforestation, agricultural practices, and mining activities which can increase watershed sediment delivery to a river outlet (Syvitski and Milliman, 2007). With respect to the 60 watersheds included in this research, the human influence soil erosion factor (Eh) was set to 1 for all watersheds with exception of watersheds with high population densities (>200/square kilometer) where Eh was set to 0.3 including the Macatawa River, the Rouge River, the Clinton River, and the Huron River (Barkach JH, 2021). With respect to the BQART equation, the glacial erosion factor (I) ranges from 1 (0% ice cover) to 10 (100% ice cover). Since there are no glaciers in Michigan, the glacial erosion factor was set to I=1 representing 0% ice cover (Syvitski and Milliman, 2007).

Methods

This research utilized a series of geospatial data sets including digital terrain models, watershed boundaries, soil type, surficial geology, and land use that are readily available through the State of Michigan (2020) Geographic Information System (GIS) Open Data Portal. In addition, the Michigan Department of Environment, Great Lakes, and Energy (EGLE), Hydrologic Studies and Dam Safety Unit provided mean annual river flow and recurrence interval flow calculations for all 60 watersheds and five sub-watersheds, and provided contributing watershed areas for 45 of the 60 watersheds. If a contributing watershed area was not available, then the total watershed area was utilized. The USACE-Detroit District provided extensive dredging data extending back to the early- to mid-1960's for 30 watersheds that were incorporated into this research as well as guidance regarding current estimates of future dredging and dredging backlog data for each harbor and navigation channel.

The 60 Michigan rivers included in this research encompass a total watershed area of 128,043 square kilometers; 119,622 square kilometers are located within in the State of Michigan and 8,421 square kilometers extend into adjoining States (see Figure 2). Land use data was obtained from the 2011 version of the National Land Cover Database (USDA, 2011). With respect to watersheds that extend outside of the State of Michigan, GIS data from the U.S. Department of Agriculture Geospatial Data Gateway and the U.S. Geological Survey National Map Viewer were used.

The maximum and average watershed relief for each river and sub-watershed represent the maximum and average topographic elevation subtracted from the receiving water elevation at the point where the river discharges to the Great Lake, Great Lake connecting channel, or reservoir (five sub-watersheds). With respect to the Great Lake surface water elevations used in this research, the receiving water elevation represents the long-term average elevation from 1918 to 2018.

With respect to the five sub-watershed basins, the receiving water elevation of the corresponding reservoir was provided by the EGLE Hydrologic Studies and Dam Safety Unit. With respect to rivers that discharge to Great Lakes connecting channels such as the St. Clair River (Pine River, 27; Belle River, 3; and Black River-East, 6) and the Detroit River (Rouge River, 31), the receiving water elevation at the river outlet was calculated using the water surface slope of the connecting channel between the adjacent Great Lakes.

Of the 60 watersheds evaluated, eight watersheds are divided into major sub-basins typically defined by glacial moraines (EGLE, 2019). These rivers (and watershed reference number) include: Au Gres River (1), Au Sable River (2), Pine River (10), Grand River (14), Saginaw River (32), St. Joseph River (34), Menominee River (50), and Portage River (55). For these eight rivers, the maximum elevation of the watershed was calculated from the area-weighted maximum elevations of the individual sub-basins (Barkach JH et al., 2020).

The river slopes were calculated one of two ways. Using the USGS (1984) methodology, the slope of the main river channel is calculated from the difference in the streambed elevations between points 10 percent and 85 percent of the distance along the main river channel from the river outlet to the watershed basin divide, divided by 0.75 times the channel length. River slopes estimated by Wayne State University were calculated in a two-step process. First, the difference between the surface water elevation of the most upstream USGS gage within the watershed and the receiving water elevation (or reservoir surface water elevation for five sub-watersheds) was determined. This difference in elevation was then divided by the channel length between the USGS gage and the river outlet to arrive at the calculated river slope. The water surface elevation at the USGS gage was calculated by adding the average USGS (2020) gage depth to the elevation of the USGS gage. If the average river gage depth was not available, then the elevation of the USGS gage was utilized.

The slopes of the 60 Michigan rivers and five sub-watersheds that were evaluated in this research are relatively small and reflect Michigan's glacial heritage. Low gradient rivers (0.001 to 0.0001) are common in Michigan and throughout the Great Lakes basin. The multiple glacial advances within the Great Lakes basin resulted in watersheds underlain by a complex sequence of glacial moraines, ice contact deposits, glacial outwash plains, and glacial lake bed deposits (Bent PC, 1971; Flint RF, 1971). Michigan's extensive glacial heritage has resulted in relatively small differences in topography at the watershed scale in comparison to the elevation of the receiving water (the corresponding Great Lake or Great Lakes connecting channel, or reservoir).

The Hydrologic Studies Program of the Michigan Department of Environment, Great Lakes, and Energy (EGLE, 2016) developed a system to automate runoff Curve Number (CN) calculations by creating a set of GIS lookup tables used to identify each soil-land use combination and its associated watershed runoff CN. In conjunction with this research, 3,879,772 individual curve number polygons were created encompassing the 60 watersheds that were included in this research. The watershed curve numbers utilized in this research represent the portion of the watershed located within the State of Michigan. Fifty three of the 60 watersheds (and all five sub-watersheds) are located entirely within the State of Michigan; exceptions include the River Raisin (29), St. Joseph River (34), Black River (40), Menominee River (50), Montreal River (51), Ontonagon River (53), and Presque Isle River (56).

Mean basin precipitation and temperature for the watershed of each Great Lake was compiled by the NOAA Great Lakes Environmental Research Laboratory (GLERL, 2020) utilizing the methodology developed by Hunter TS et al.. (2015).

Radiometric Dating of Sediment Cores, Five Reservoirs

This research included re-evaluation of reservoir sediment accumulation rates based on radiometric dating using ^{137}Cs and ^{210}Pb for five reservoirs that are sub-watersheds of the Au Sable River (2), Boardman River (9), Grand River (14), Huron River (15), and St. Joseph River (34). Radiometric testing of sediment cores to determine reservoir sedimentation rates was completed at the following dams (Wayne State University, 2017): Mio Dam (2A), Au Sable River; Brown Bridge Dam (9A), Boardman River; Webber Dam (14A), Grand River; Ford Dam (15A), Huron River; and Riley Dam (34A), St. Joseph River.

In conjunction with this research, Dr. Mark Baskaran, Wayne State University re-evaluated the ^{137}Cs and ^{210}Pb radiometric data for all sediment cores in all five reservoirs utilized in this research. With respect to the ^{137}Cs radiometric data, a sediment core was selected to recalculate annual reservoir sediment delivery to the reservoir if there was good definition of the 1963 ^{137}Cs peak. With respect to the ^{210}Pb cumulative mass depth, a sediment core was selected to recalculate annual sediment delivery to the reservoir if the plotted radiometric data was linear. An example of a sediment core that was selected based on the characteristics listed above is shown in Figure 3 (Sediment Core RD6, Riley Dam, St. Joseph River).

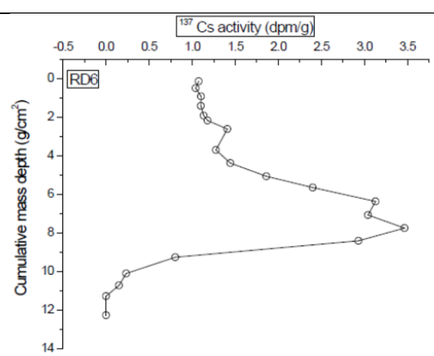
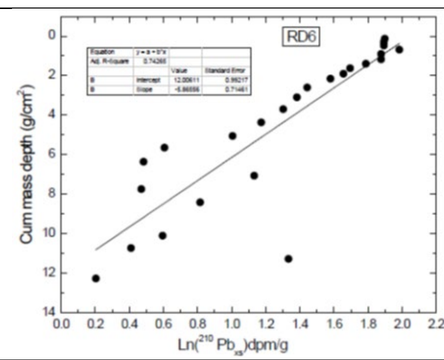
	
Vertical profile of ^{137}Cs activity plotted against cumulative mass depth (Riley Dam RD6, from Figure 3-14; Wayne State University, 2017)	Vertical profile of Ln(^{210}Pbxs) plotted against cumulative mass depth. (Riley Dam RD6, from Figure 3-78; Wayne State University, 2017)

Figure 3. Radiometric Data, Sediment Core RD6, Riley Dam (34A), St. Joseph River

Comparison of the re-calculated reservoir sedimentation accumulation rates for these five reservoirs to prior published results (Alighalehbabakhani et al., 2017; Wayne State University, 2017) reveals that all three rates are very similar with respect to Webber Dam (14A, Grand River) and Riley Dam (34A, St. Joseph River), and within a factor of two with respect to Mio Dam (2A, Au Sable River), Brown Bridge Dam (9A, Boardman River), and Ford Lake Dam (15A, Huron River). With respect to this research, the average annual rate of sediment accumulation within these five reservoirs served as the dependent variable in the subsequent regression analysis (see Table 1).

Table 1. Reservoir Sedimentation Rates of Five Sub-Watersheds Using ^{137}Cs and ^{210}Pb Ra Dating

Dam	Wayne State University (2017) metric tonnes/yr	Alighalehbabakhani et al (2017a) metric tonnes/yr	Annual Sediment Accumulation Rate, Revised metric tonnes/yr
2A, Mio Dam, Au Sable River	20,000	5,000	9,500
9A, Brown Bridge Dam: Boardman River	2,000	2,000	1,100
15A, Ford Lake Dam, Huron River	13,000	7,000	12,000
14A, Webber Dam: Grand River	18,000	16,000	19,000
34A, Riley Dam: St. Joseph River	4,000	4,000	4,500

USACE Navigation Channel Maintenance Dredging Data, 1964-2019

In conjunction with this research, the USACE-Detroit District provided extensive harbor and navigation channel maintenance dredging data. Of the 60 rivers included in this research, USACE maintained navigation channels and harbors are located at the outlets of 30 of these rivers (see Figure 2). Detailed USACE dredging records extend back to the early- to mid-1960's and provide important data regarding the rate of sediment accumulation in these federally defined navigation channels over time. Because maintenance dredging can only be conducted within the defined limits of a federal navigation channel (USACE, 2010), the USACE-Detroit District's dredging data was used in this research to estimate the average annual volume of fluvial sediment that has accumulated in the federal navigation channel since federal maintenance dredging commenced.

With respect to USACE maintenance dredging, two types of sediment are removed, littoral sediment originating from coastal movement of sediment outside of the harbor and navigation channel, and fluvial sediment originating from the river. With respect to USACE dredging data, reference to an outer harbor dredging event refers maintenance dredging in front of the harbor inlet. Inner harbor maintenance dredging is predominantly fluvial sediment that is transported by the river system.

Littoral sediment includes sediment transported by longshore currents originating from the lake shoreline and lake bed sediment resuspended by waves. Because most USACE maintenance dredging projects have historically not separated outer harbor (littoral sediment) from inner harbor (fluvial sediment) sediment, caution is required when evaluating USACE dredging data (USACE, 2010a). A total of 867 USACE maintenance dredging events encompassing 65,424,279 cubic yards of dredged sediment were considered in this research.

Each of the 30 harbors and associated navigation channels were evaluated by both USACE-Detroit District and Wayne State University to determine if the associated USACE-Detroit District dredging data represents either primarily fluvial or littoral sediment, or a combination of both. Other harbor and river specific considerations were also evaluated to determine whether or not a particular harbor was either retained or excluded from this research of fluvial sediment delivery to the river outlet. Of the 30 harbors evaluated, 12 harbors were retained and 18 harbors were excluded. In most instances, harbors were retained in this research if 80-90% of the dredged sediment was determined to be fluvial.

Review of average annual dredging volumes removed by the USACE since initiation of maintenance dredging in comparison to the USACE-Detroit District dredging forecasts (USACE, 2021c) revealed a marked decrease in the rate of sediment accumulation requiring maintenance dredging for 9 of the 12 harbors and navigation channels that were selected for this research. Based on analysis of the USACE dredging data, the decrease in average annual dredging of the USACE navigation channels and harbors started to appear during the early 1990's depending on the watershed. At the suggestion of the USACE-Detroit District, the potential impact of the U.S. Department of Agriculture's (USDA's) Conservation Reserve Program (CRP) and the State of Michigan's implementation of Non-Point Source Best Management Practices during the early 1990's were evaluated.

In Michigan, the Conservation Reserve Program began in 1986 and 29.9 square kilometers were initially enrolled in the program. In 1993 and 1994, the area subject to the Conservation Reserve Program peaked at 1,342 square kilometers and has declined since (see Figure 4). During the early 1990's, the State of Michigan initiated programs to foster control of Non-Point Source pollution and prepared a series of Best Management Practices to control sediment discharge to rivers and streams and were widely distributed to communities (MDEQ, 1992).

To further evaluate the potential impact of the Conservation Reserve Program enrollment as well as the implementation of sediment Best Management Practices within the State of Michigan to reduce sediment loading to rivers and streams, an assessment of the 4-year rolling average of annual dredged sediment was completed on three USACE harbors and navigation channel: USACE Monroe Harbor, River Raisin (29); USACE Rouge River (31) Navigation Channel; and the USACE Saginaw River (32) Navigation Channel. Review of 4-year rolling averages of dredged sediment reveals that the 1993 date of peak Conservation Reserve Program participation in Michigan appears to largely coincide with the decrease in the volume of dredged sediment for these three navigation channels (see Figure 4; Barkach JH, 2021).

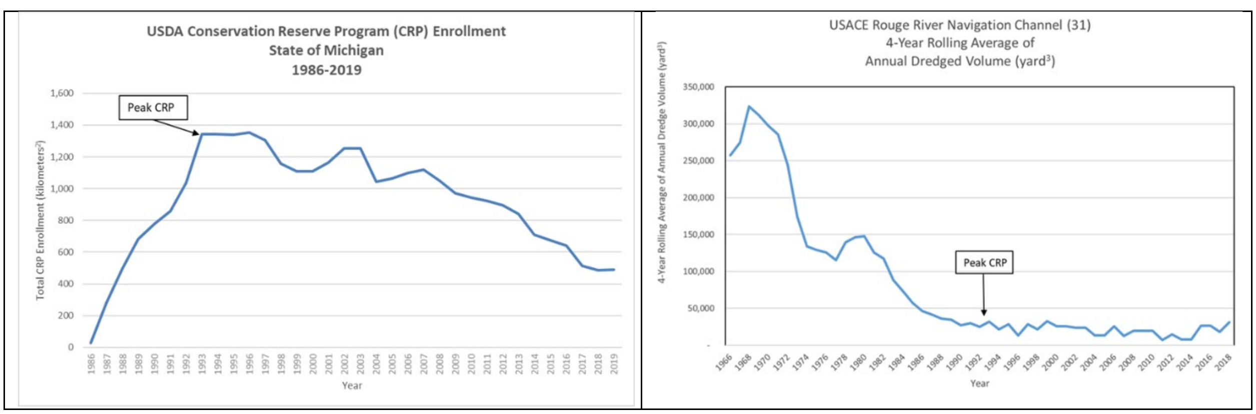


Figure 4. USDA (2021) Conservation Reserve Program Enrollment, State of Michigan, 1986-2019; USACE Rouge River Navigation Channel (31), 4-Year Rolling Average of Annual Dredged Volume

Based on these findings, the post-1993 USACE maintenance dredging data were utilized in this research to estimate the average annual rate of fluvial sediment delivery to the river outlet and was calculated by (see Table 2): (1) averaging the post-1993 USACE dredging data (1993 to 2019), (2) adding in the USACE estimate of dredging backlog through December 2019, and (3) adjusting volume dredged to remove the estimated littoral component. Using the post-1993 dredging data to estimate the average annual rate of sediment delivery to the river outlet resulted in annual rates that were very similar to the USACE (2020) dredging forecasts for 9 of the 11 watersheds, exceptions include: Black River-East (6) and the Saginaw River (32). The USACE-Detroit does not prepare a dredging forecast for Manistique River (49) so this comparison was not available.

To convert the average annual volume of dredged sediment to metric tonnes, USACE pre-dredge sediment quality data were utilized. USACE pre-dredge sediment quality samples are collected prior to dredging and represent composite samples of the dredge cut. Based on analysis of the pre-dredge sediment quality data, a total of 752 pre-dredge sediment samples were collected from the Inner harbor of 27 USACE harbors and navigation channels; the geometric mean of 69 pounds/cubic feet of sediment was utilized to convert the average annual volume of sediment dredged to metric tonnes (Barkach JH, 2021).

Assessment of Fluvial Depositional Areas, Upland and Aquatic Wetlands, Natural Lakes and Manmade Reservoirs

In conjunction with the calculation of watershed runoff Curve Numbers, assessment of depositional areas using the Michigan Resource Information System (MIRIS), Land Use/Cover Polygons (MDNR, 1978) was used to calculate the percentage of the watershed covered in aquatic wetlands, upland wetlands, natural lakes and manmade reservoirs.

The percentage of the watershed covered in manmade reservoirs was calculated from the EGLE (2020) dam inventory. Of the 2,607 dams located in Michigan, 262 are located in the drainage areas of the Great Lakes ("Lake drainage areas") and are not assigned to one of the 60 Michigan watersheds and were excluded from this research. Of the remaining 2,345 dams located in Michigan, 1,378 dams are located on the rivers that drain the 60 watersheds and five sub-watersheds, and include FERC dams (dams regulated by the Federal Energy Regulatory Commission), hydropower dams, retired hydropower dams, farm ponds, and private and recreational dams (Barkach JH, 2021; EGLE, 2020). The remaining dams are not located on rivers, rather they are used for other purposes such as: water supply for industrial purposes (e.g. mining, agriculture), stormwater retention ponds, wastewater lagoons, tailing or debris ponds, and water level control structures; because these structures, are not located on the river where their presence could impact watershed sediment delivery to the river outlet, these 967 dams excluded from this research.

Results and Discussion

This research involved development of an empirical equation that can be utilized as a statistical model to describe the relationship between bedload sediment delivery to the river outlet and significant watershed characteristics using step-wise regression analysis to identify predictive variables. The dependent variable is the annual watershed sediment delivery to the river outlet for 12 rivers based on USACE-Detroit District dredging data (see Table 2; highlighted green in Table 4) and for five sub- watersheds using ^{137}Cs and ^{210}Pb radiometric dating (see Table 1;

Table 2. Comparison of Estimates of Annual Fluvial Sediment Delivery: Since 1st Recorded Dredging Event and Post-CRP, and Adjusted to Removal Fluvial Sediment

				USACE Detroit District Forecast Dredging (March 2020)[3]						USACE Fluvial Sediment Delivery Since Peak CRP		
Watershed Reference Number	River	USACE Average Annual Dredging Since Base Event[4] (Including Backlog Through Dec 2019, Minus Channel Deepening) (yard^3)	Sediment Delivery to the River Outlet Based on Dredging Data and Removal of Littoral Component (yard^3)[1]	Forecast Dredging, Outer Harbor (yard^3)	Forecast Dredging - Low Estimate (yard^3)	Forecast Dredging - High Estimate (yard^3)	Forecast Dredging - Low Estimate (years)	Estimated Dredging - High Estimate (years)	Annual Forecast Dredging, Geometric Mean of Low and High Estimates (yard^3)	Dredging Base Year, Peak CRP	Annual Fluvial Sediment Delivery Since Peak CRP (yard^3)[2]	Average Annual Sediment Delivery Since 1993, Specific Weight of 69 lbs/ft^3 (tonnes/year)[2]
1	Au Gres River	**11,952**	**10,757**		20,000	20,000	5	6	**3,651**	1993	**5,156**	**4,400**
6	Black River - East	**11,151**	**11,151**		15,000	35,000	5	10	**3,240**	1991	**12,809**	**11,000**
8	Macatawa River	**66,885**	**23,410**	**35,000**	45,000	65,000	2	4	**19,121**	1993	**20,486**	**17,000**
12	Clinton River	**10,450**	**9,405**		20,000	20,000	3	5	**5,164**	1992	**10,678**	**9,000**
14	Grand River	**87,512**	**17,502**	**35,000**	20,000	40,000	2	4	**10,000**	1993	**11,566**	**10,000**
29	River Raisin	**129,030**	**69,780**		90,000	135,000	1	2	**77,942**	1992	**73,351**	**62,000**
31	Rouge River	**80,084**	**80,084**		50,000	60,000	2	5	**17,321**	1993	**25,625**	**22,000**
32	Saginaw River	**446,042**	**401,438**	**180,000**	50,000	100,000	2	3	**28,868**	1992	**223,740**	**190,000**
34	St. Joseph River	**70,210**	**17,552**	**40,000**	30,000	60,000	2	4	**15,000**	1993	**14,071**	**12,000**
49	Manistique River	**6,948**	**13,190**		-	-	-	-	**NA**	NA	**13,190**	**11,000**
50	Menominee River	**4,525**	**8,599**		25,000	50,000	5	10	**5,000**	NA	**8,599**	**7,300**
53	Ontonagon River	**53,651**	**40,239**		40,000	40,000	1	1	**40,000**	1993	**35,359**	**30,000**

1. Estimated annual fluvial sediment delivery to the river outlet since the 1st recorded USACE dredging event or the most recent Rivers and Harbors Authorization, including USACE backlog through December 2019 and adjusted to remove littoral sediment.
2. Estimated fluvial sediment delivery, basis: USACE average annual dredging since 1993 (Peak CRP), including backlog through Dec. 2019 and adjusted to remove littoral sediment.
3. For Macatawa River (8), Grand River (14), Saginaw Rive (32), and St. Joseph River (34), the USACE-Detroit District Prepared Prepared Dredging Forecasts for Both the Outer and Inner Harbor. For The Remaining Eight Harbors, the USACE Dredging Forecast Combines The Outer and Inner Harbor Dredging.
4. Base Event, either the 1st dredging event or the most recent Rivers and Harbors Authorization, whichever is later.

highlighted in yellow in Table 4). Eighteen independent variables were evaluated and presented in Barkach JH (2021), these variables include:

- Watershed Area (square kilometer)
- Percent of Watershed, Total Surface Water Area (EGLE, 1978) MIRIS Land Use
- Percent of Watershed, Total Reservoir Pool Surface Area, EGLE (2020) Dam Inventory
- Percent of Watershed, Total Aquatic Wetlands (EGLE, 1978) MIRIS Land Use
- Percent of Watershed, Total Upland Wetlands (EGLE, 1978) MIRIS Land Use
- Mean Annual River Flow (cubic meters/second)
- 1.5-year, 2.0-year, 5-year Recurrence Interval Flows (cubic meters/second)
- Watershed Curve Number (unitless)
- River Slope (meter/meter)
- Relief: Net Watershed Elevation Difference, Maximum Watershed Elevation (meter)
- Relief: Net Watershed Elevation Difference, Average Watershed Elevation (meter)
- Mean Basin Temperature (°C)
- Population Density (people/square kilometer)
- Percent of Watershed, Total Surface Water and Aquatic Wetlands[1]
- Percent of Watershed, Total Wetlands (Upland and Aquatic)[1]
- Percent of Watershed, Total Surface Water and Reservoirs[1]

Note that combined watershed characteristics are identified with a superscript[1]. As discussed in Barkach JH (2021), 42 regressions were completed of natural log transformed dependent and independent variables listed above. Of these 42 regressions, Regression 3-36 provided the best balance of significance (0.014), R^2 (0.538), and relative low p-values for the following independent variables: 1.5 year recurrence interval flow (P-value: 0.002); percent of watershed covered in upland and aquatic wetlands (P-value: 0.149); percent of the watershed covered in reservoirs (p-value: 0.387). Because watershed area is highly correlated with the 1.5-year recurrence interval flow (Barkach JH et al., 2020), watershed area was removed from the regression equation 3-36 without reduction in significance (Barkach JH, 2021). Review of the residual plots reveals that the three independent variables are distributed randomly about zero, and the normal probability plot of Regression 3-36 is linear (Barkach JH, 2021). Bedload watershed sediment delivery Regression 3-36 equation follows:

$$Q_b = EXP(3.901) * EXP(-0.694)LN(W) * EXP(0.150)LN(R) * EXP(0.858)LN(Q1.5) \qquad (4)$$

Q_b – Bedload Watershed Sediment Delivery (tonnes/year)
Q1.5 – 1.5-year Recurrence Interval Flow at the River Outlet (cubic meters/second)
W - Percent of the Watershed Covered in Both Upland and Aquatic Wetlands (EGLE, 1978)
R - Percent of the Watershed Covered in Reservoirs (EGLE, 2020 updated dam inventory)

With respect to the independent variables, 1.5-year recurrence interval flow is the most important (P-value: 0.002), and had consistently lower P-values than either annual mean flow or 2-year recurrence interval flow (Barkach JH, 2021). The 1.5-year recurrence interval flow is associated with "bankfull flow" and is the flow rate where the river performs the most work (e.g. transporting sediment). Due to the strong correlation between watershed area and the 1.5-year recurrence interval flow, the removal of watershed area from Regression 3-36 results in an improvement in significance from 0.031 to 0.014 (Barkach JH, 2021). In conjunction with the 1.5-year recurrence interval flow and the total percentage of watershed covered in wetlands, the percentage of the watershed covered in reservoirs was also determined to be an effective predictor variable of bedload watershed sediment delivery to the river outlet. Although most dams in Michigan are small, they are effective at retaining sediment within the watershed. Bedload sediment delivery estimates using Regression 3-36 are contained on Tables 3 and 4.

Review of Table 3 reveals that the predicted watershed sediment delivery estimates using Regression 3-36 in comparison to the estimated watershed sediment delivery estimates based on USACE dredging data and radiometric dating are within +/- 70% for 13 of the 17 watersheds. The average difference between predicted watershed sediment delivery using Regression 3-36 and the watershed delivery estimates based on dredging data and radiometric dating was -31%. The largest differences based on total metric tonnes between predicted sediment delivery using Regression 3-36 and the watershed sediment delivery estimates based on either USACE dredging data or radiometric dating were noted at the Saginaw River (32), Grand River (14), St. Joseph River (34) and the Menominee River (50).

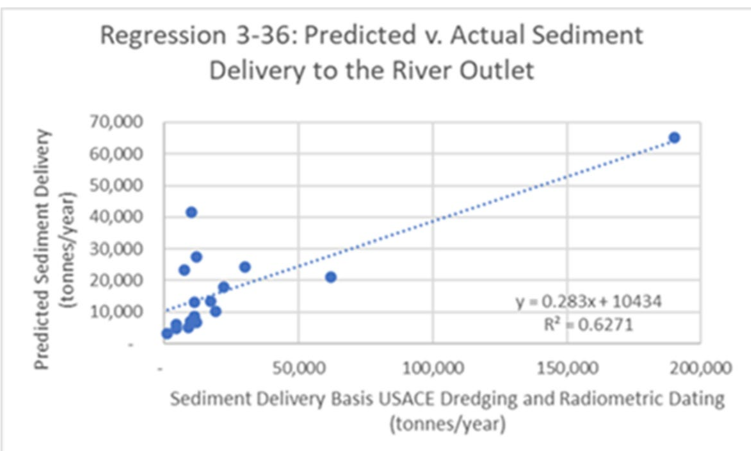
Of these four rivers, the Saginaw River had the largest total difference where the predicted annual watershed sediment delivery using Regression 3-36 is 65,000 metric tonnes per year in comparison to the 190,000 metric tonnes per year based on USACE dredging data. Note, that with respect to the USACE's (2020) annual maintenance dredging forecast of 180,000 metric tonnes for the Saginaw River, 155,000 metric tonnes are forecast for the Entrance Channel located in Saginaw Bay and 25,000 metric tonnes is forecast for the Upper Saginaw River navigation channel (inner harbor). The littoral component of sediment delivery was estimated by USACE (2020) to be 10%, but based on the USACE (2020) dredging forecast, the littoral component could be much larger (Table 2).

The effect of natural lakes and depositional areas in close proximity to the river outlet on the prediction of watershed sediment delivery is a topic of further research. With respect to the Grand River (14), the predicted annual watershed sediment delivery using Regression 3-36 is 41,000 metric tonnes per year in comparison to the 10,000 metric tonnes per year based on USACE dredging data. With respect to the St. Joseph River (34), the predicted annual watershed sediment delivery using Regression 3-36 is 28,000 metric tonnes per year in comparison to the 12,000 metric tonnes per year based on USACE dredging data. With respect to the Grand River (14) and St. Joseph River (34), the differences are likely due to the presence of large depositional areas near the river outlet. With respect to the Menominee River (50), the large difference in the predicted annual watershed sediment delivery using Regression 3-36 (23,000 metric tonnes per year) in comparison to the 7,300 metric tonnes per year based on USACE dredging data is likely due the close proximity of the Park Mill Dam located six kilometers from the river outlet.

With respect to the Ontonagon River (53), the USACE-Detroit District completed a bathymetric analysis of several pairs of pre- and post-dredging events at the Ontonagon Harbor to estimate the littoral and fluvial components of the sediment removed during USACE maintenance dredging (USACE, 2010). The USACE (2010) created a digital surface using a Triangular Irregular Network (TIN) and then calculating the volume between the surfaces in the area where fluvial sediment was deposited. As shown in Table 3, the estimated watershed sediment delivery using USACE dredging data is 30,000 metric tonnes per year and is in close agreement with the predicted bedload sediment delivery using Regression 3-36 of 24,000 metric tonnes per year.

Table 3. Predicted Sediment Delivery Using Regression 3-36 in Comparison to Estimated Sediment Delivery Using USACE Dredging Data and Radiometric Dating

Watershed Reference Number	River	USACE Harbor	Estimated Watershed Sediment Delivery to the River Outlet (tonnes/year)	Estimated Watershed Sediment Delivery to the River Outlet (tonnes/year/km^2)	Basis	Regression 3-36: Predicted Sediment Delivery to the River Outlet (tonnes/year)	Percent Difference: Regression 3-36 v. Estimated Watershed Sediment Delivery	USACE (2020) Average Annual Dredging Forecast (tonnes/year)	BQART Sediment Load (Qs) (Syvitski and Milliman, 2007) (tonnes/year)	USACE (2010) Great Lakes Regional Trend Line $S_y = 177.6*A^{0.77}$ (A: km^2) (tonnes/year)	USACE 516(e) Study (tonnes/year)
1	Au Gres River	Point Lookout Harbor	4,400	6.99	USACE Dredging Data	4,900	11%	3,100	11,000	25,000	
2A	Au Sable River	NA; Mio Dam	9,500	3.47	Radiometric Dating	7,100	-25%		58,000	79,000	
6	Black River (East)	Black River	11,000	5.98	USACE Dredging Data	13,000	18%	2,700	37,000	58,000	
8	Macatawa River	Holland Harbor	17,000	37.72	USACE Dredging Data	13,000	-24%	16,000	2,000	20,000	
9A	Boardman River	NA; Brown Bridge Dam	1,100	3.54	Radiometric Dating	3,300	200%		10,000	15,000	
12	Clinton River	Clinton River	9,000	4.36	USACE Dredging Data	5,200	-42%	4,400	18,000	63,000	73,000
14	Grand River	Grand Haven Harbor	10,000	0.71	USACE Dredging Data	41,000	310%	8,500	260,000	280,000	250,000
14A	Grand River	NA; Webber Dam	19,000	4.22	Radiometric Dating	10,000	-47%		95,000	120,000	
15A	Huron River	NA; Ford Dam	12,000	5.95	Radiometric Dating	6,700	-44%		16,000	62,000	
29	River Raisin	Monroe Harbor	62,000	22.37	USACE Dredging Data	21,000	-66%	66,000	85,000	79,000	
31	Rouge River	Rouge River	22,000	18.27	USACE Dredging Data	18,000	-18%	15,000	8,900	42,000	
32	Saginaw River	Saginaw River	190,000	11.96	USACE Dredging Data	65,000	-66%	180,000	290,000	300,000	250,000
34	St. Joseph River	St. Joseph Harbor	12,000	0.98	USACE Dredging Data	28,000	133%	13,000	290,000	250,000	76,000
34A	St. Joseph River	NA; Riley Dam	4,500	3.32	Radiometric Dating	6,100	36%		31,000	46,000	
49	Manistique River	Manistique Harbor	11,000	2.90	USACE Dredging Data	8,500	-23%	NA	110,000	100,000	
50	Menominee River	Menominee Harbor	7,300	0.70	USACE Dredging Data	23,000	215%	4,200	290,000	220,000	
53	Ontonagon River	Ontonagon Harbor	30,000	8.37	USACE Dredging Data	24,000	-20%	34,000	140,000	97,000	180,000



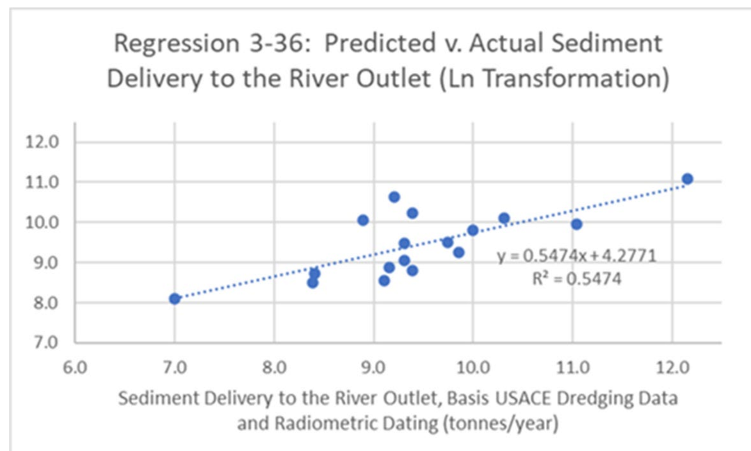


Table 4. Comparison of Regression 3-36 Predicted Bedload Sediment Delivery and Watershed Sediment Delivery Predicted Using the USACE (2010) Trendline and the BQART Equation, Watersheds 1-63

Watershed Reference Number	River	USACE Harbor	Predicted Bedload Sediment Delivery, Regression 3-36 (tonnes/yr)	Predicted Bedload Sediment Delivery Regression 3-36 (tonnes/yr/km^2)	Watershed Sediment Delivery, BQART Equation (Syvitski and Milliman, 2007) (tonnes/yr)	Watershed Sediment Delivery, USACE (2010) Great Lakes Regional Trend Line (tonnes/yr)	Percent Bedload: Regression 3-36 as a Percentage of Total Watershed Sediment Delivery (USACE 2010 Trendline)
1	**Au Gres River**	**Point Lookout Harbor**	4,900	7.8	11,000	25,000	19%
2	Au Sable River	Au Sable Harbor	11,000	2.5	140,000	110,000	10%
2A	Au Sable River	NA; Mio Dam	7,100	2.6	58,000	79,000	9%
3	Belle River	NA	10,000	17.2	15,000	24,000	42%
4	Betsie River	Frankfort Harbor	2,100	3.4	22,000	25,000	8%
5	Big Sable	NA	2,400	5.7	15,000	19,000	13%
6	**Black River (East)**	**Black River**	13,000	7.1	37,000	58,000	23%
7	Black River (West)	South Haven Harbor	3,000	4.1	13,000	29,000	11%
8	**Macatawa River**	**Holland Harbor**	13,000	29.5	2,000	20,000	68%
9	Boardman	NA	4,400	7.8	25,000	24,000	19%
9A	Boardman River	NA; Brown Bridge Dam	3,300	10.5	10,000	15,000	22%
10	Pine River	Charlevoix Harbor	8,000	9.9	36,000	31,000	26%
11	Cheboygan River	Cheboygan Harbor	13,000	3.6	110,000	99,000	13%
12	**Clinton River**	**Clinton River**	5,200	2.5	18,000	63,000	8%
13	Elk River	NA	6,700	6.5	44,000	37,000	18%
14	**Grand River**	**Grand Haven Harbor**	41,000	2.9	260,000	280,000	15%
14A	Grand River	NA; Webber Dam	10,000	2.3	95,000	115,000	9%
15	Huron River	NA	7,300	3.2	19,000	68,000	11%
15A	Huron River	NA; Ford Dam	6,700	3.3	16,000	62,000	11%
17	Kalamazoo River	Saugatuck Harbor	11,000	2.1	140,000	130,000	8%
18	Kawkawlin River	NA	5,600	9.6	5,400	24,000	23%
19	Lincoln River	NA	1,400	5.3	4,700	13,000	11%
20	Manistee River	Manistee Harbor	13,000	2.9	230,000	110,000	11%
22	Muskegon River	Muskegon Harbor	15,000	2.3	310,000	150,000	10%
23	Oqueoc River	NA	1,800	4.9	7,500	17,000	11%
24	Pentwater River	Pentwater Harbor	6,300	14.6	11,000	19,000	33%
25	Pere Marquette River	Ludington Harbor	4,800	2.8	70,000	54,000	9%
26	Pigeon River	Caseville Harbor	2,400	6.4	5,100	17,000	14%
27	Pine River	NA	17,000	32.8	9,100	21,000	77%
28	Platte River	NA	1,300	3.6	15,000	17,000	8%
29	**River Raisin**	**Monroe Harbor**	21,000	7.7	85,000	79,000	27%
30	Rifle River	NA	8,000	8.2	42,000	36,000	22%
31	**Rouge River**	**Rouge River**	18,000	14.9	8,900	42,000	43%
32	**Saginaw River**	**Saginaw River**	65,000	4.1	290,000	300,000	21%
33	Sebewaing River	Sebewaing River	13,000	48.9	3,200	13,000	100%
34	**St. Joseph River**	**St. Joseph Harbor**	28,000	2.3	290,000	250,000	11%
34A	St. Joseph River	NA; Riley Dam	6,100	4.5	31,000	46,000	13%
35	Stoney Creek	NA	6,600	20.8	5,200	15,000	44%
36	Thunder Bay River	Alpena Harbor	11,000	3.6	87,000	87,000	13%
37	White River	White Lake Harbor	5,600	4.7	50,000	41,000	14%
38	Willow Creek	NA	1,000	3.9	4,000	12,000	8%
39	Au Train	NA	1,900	6.7	8,000	14,000	14%
40	Black River (Gogebic)	Black River Harbor	9,900	14.9	26,000	26,000	37%
41	Carp River	NA	2,600	6.0	7,400	19,000	14%
42	Cedar River	Cedar River Harbor	1,700	1.7	18,000	36,000	5%
43	Chocolay River	NA	4,300	10.8	22,000	18,000	24%
44	Days River	NA	600	3.9	3,500	8,900	7%
45	Dead River	Presque Isle Harbor	4,100	9.7	27,000	19,000	22%
46	Escanaba River	NA	7,100	3.0	89,000	70,000	10%
47	Ford River	NA	4,300	3.6	39,000	42,000	10%
48	Falls River	NA	2,300	19.9	7,200	6,900	33%
49	**Manistique River**	**Manistique Harbor**	8,500	2.2	110,000	100,000	8%
50	**Menominee River**	**Menominee Harbor**	23,000	2.2	290,000	220,000	11%
51	Montreal River	NA	6,700	9.6	26,000	28,000	24%
52	Munuscong River	NA	5,700	12.2	9,100	20,000	28%
53	**Ontonagon River**	**Ontonagon Harbor**	24,000	6.8	140,000	97,000	25%
54	Pine River	NA	4,000	5.6	10,000	28,000	14%
55	Portage River	Keweenaw Waterway	11,000	4.4	97,000	75,000	15%
56	Presque Isle River	NA	7,000	7.5	50,000	34,000	20%
57	Rapid River	NA	1,900	5.4	6,600	16,000	12%
58	Sturgeon River	NA	1,600	2.9	10,000	23,000	7%
60	Tahquamenon River	NA	4,600	2.2	30,000	64,000	7%
61	Two Hearted River	NA	500	0.9	14,000	22,000	2%
62	Waiska River	NA	2,200	5.7	5,400	17,000	13%
63	Whitefish River	NA	3,100	3.9	22,000	31,000	10%

Note: The watersheds where the dependent variable is the annual watershed sediment delivery to the river outlet based on USACE dredging data are highlighted green, those based on radiometric dating are highlighted in yellow.

The percentage of bedload calculated using Regression 3-36 in comparison to the estimated total watershed sediment delivery estimated using the USACE (2010) Great Lakes Regional Trend Line for all 65 watersheds is presented Table 4. The mean and median values of the percentage of bedload to total watershed sediment delivery are 19.4% and 13.3% and are within the range of 5-20% reported by USGS (2011) and similar to 10% that has been reported by others (MacArthur RC et al., 2008; USACE, 1995).

The predicted bedload watershed sediment delivery to the river outlet and at the corresponding sub-watersheds for the Grand River (14) and St. Joseph River (34) normalized to watershed area are similar (see Table 4). For the Grand River (14) at Grand Haven Harbor and the Weber Dam (14A), the bedload watershed sediment delivery as a function of watershed area is 2.9 tonnes/year/kilometer^2 and 2.3 tonnes/year/kilometer^2, respectively. For the St. Joseph River (14) and the Riley Dam (34A), the bedload watershed sediment delivery as a function of watershed area is 2.3 tonnes/year/kilometer^2 and 4.5 tonnes/year/kilometer^2, respectively. Although these are only two comparisons, Regression 3-36 provides good agreement of predicted bedload sediment delivery within these two sub-watersheds.

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