Stream Corridor Sediment Budget for Watershed Sediment Source Apportionment for the Forested Little Fork River, Minnesota

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Abstract

Excess sediment is a leading cause of habitat degradation in rivers and streams in the United States. Sediment can also serve as a vector for phosphorus (P), which may drive harmful algal blooms in downstream waters. The Little Fork River in northern Minnesota provides a disproportionate source of sediment to the Rainy-Lake of the Woods Basin and has been a focal point for monitoring and management by the Minnesota Pollution Control Agency (MPCA) over the past decade. To address excess sediment and associated P in the Little Fork, the U.S. Geological Survey (USGS) is working in collaboration with MPCA, Koochiching Soil and Water Conservation District, North St. Louis and Itasca Soil and Water Conservation Districts, and University of Minnesota-Duluth to delineate sources of sediment and sediment-bound P for the Little Fork basin using geochemical sediment fingerprinting and sediment budget techniques. Data collection for this project commenced in 2021, with the collection of rapid geomorphic assessment (RGA) data to support sediment budget development, and the collection of sediment samples to support geochemical fingerprinting. In this paper we describe results for a stream corridor sediment budget including estimates of sediment contributions from eroding valley sides, terraces, banks, and ravines, along with storage estimates of soft (fine-grained) streambed sediment deposition. Initial sediment budget estimates, considered to be accurate within an order of magnitude, indicate that there is approximately 130,000 megagrams/year (Mg/yr) of corridor erosion and a total of 840,000 Mg of soft streambed sediment deposition. About 50% of the erosion is estimated to be from headwater steep-sloped channels in ravines, especially those that intersect the valley sides of the Little Fork downstream of its confluence with the Sturgeon River. In contrast, most of the soft streambed sediment deposition is in headwater gentle-sloped channels surrounded by wetlands with beaver activity. The soft sediment to erosion ratio for the basin is 5. This ratio suggests there is an average of approximately 5 years' worth of stored sediment sourced from upstream erosion. This simple ratio does not account for

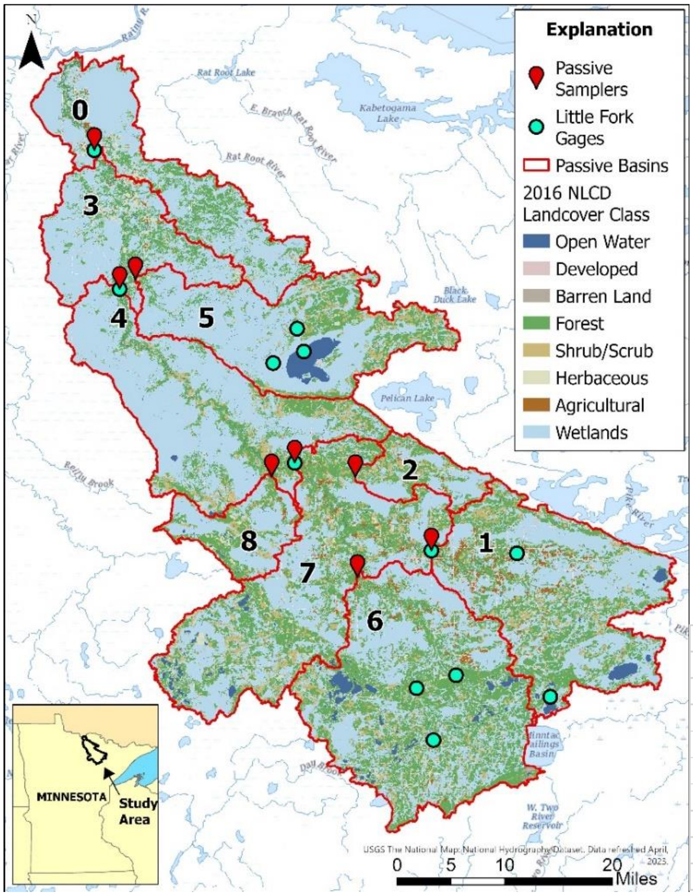
the spatial variability in the location of relatively high erosion rates and high soft sediment deposition. These estimates will be used to compliment geochemical fingerprinting apportionments of upland sources of sediment and sediment-bound P from mature and recently harvested forests, agricultural fields, wetlands, and roadways, and the stream corridor.

Introduction

The Little Fork River has been identified as a major source of sediment to downstream waters even though the basin is mainly comprised of wetlands and forests (Figure 1). Six reaches of the mainstem Little Fork River have been listed as impaired for aquatic life under the U.S. Environmental Protection Agency (EPA) 303(d) rule due to high total suspended solids (TSS). Four of the six reaches have Total Maximum Daily Load (TMDL) regulations under development based on characterization of sediment loading conditions (Minnesota Pollution Control Agency [MPCA] 2011; 2016). In order to meet TSS load allocations for the Little Fork, reductions in TSS concentrations of 45-85% will be needed for the highest flow conditions experienced by the basin (MPCA 2016). Previous studies provided a detailed understanding of the geomorphic characteristics in the basin and delineated stream corridors most sensitive to erosion (Gran et al. 2007). The Little Fork and its tributaries have approximately twice the water yield of streams in neighboring basins, possibly due to differences in land cover and land use histories (Anderson et al. 2006).

The Little Fork basin is known to supply a disproportionate amount of sediment to the Rainy River and Lake of the Woods (MPCA 2021). Lake of the Woods is eutrophic due to being enriched by nutrients, and more details describing its P source can be found from the MPCA (2021). Comparison of monitoring data from the MPCA's Watershed Pollutant Load Monitoring Data Viewer (MPCA 2019) for Little Fork River at Little Fork against the downstream gage at Rainy River at Manitou (72% of the total Rainy River drainage basin), revealed that the Little Fork basin comprises 9.7% of the drainage area at this point but contributes an annual average of 39.7% of the TSS, 19.9% of the total phosphorus (TP), and 15.7% of the dissolved orthophosphate (DOP). Information describing the dominant sources of sediment and sediment-bound P is needed to help guide development of the sediment TMDL and to work toward reducing these disproportionate impacts. Identification of the major sources of sediment generating the impairment is a critical first step in the TMDL process (EPA 1999).

This study is applying sediment fingerprinting and sediment budget techniques described in Gellis et al. (2016) and Gorman et al. (2017) to estimate potential upland and riparian corridor sources of sediment and sediment-bound P in the Little Fork. Sediment fingerprinting has become a standard EPA-approved method for sediment source delineation (Gellis et al. 2016; Gorman et al. 2017). Multiple lines of evidence can be used to validate sediment fingerprinting estimates of source contributions, and sediment budgets are commonly used (Gellis et al. 2016). Sediment budgets can be developed using a combination of methods including aerial photograph interpretation, models for channel migration, and/or physical measurements of streambank and valley wall erosion from across a representative set of sites to estimate contributions from stream corridor sediments to overall sediment loading (Gran et al. 2011, Belmont et al. 2011, Gellis et al. 2016). Measuring soft sediment deposition can be used to quantify the instream storage portion of the budget (Fitzptarick et al. 2019).



ID	Subbasin Name
0	Little Fork River Mouth
1	Little Fork River nr Linden Grove, TH73
2	Willow River at CTY 75 nr Greaney, MN
3	Little Fork River at Littlefork, MN
4	Little Fork River nr Littlefork, MN65
5	Nett Lake River near UT 63 nr Littlefork, MN
6	Sturgeon River at CTY 107 nr Meadow Brook, MN
7	Little Fork River nr Silverdale, MN65
8	Valley River near Rauch, MN

Figure 1. Location of the Little Fork River study area with suspended sediment passive sampler sites, streamgages, and major land-cover classes from the National Land Cover Dataset (NLCD) [Dewitz 2019, showing subbasins and National Hydrologic Dataset (NHDPlus) delineation of the stream network (U.S. Geological Survey 2018)]

Starting in 2021, the USGS in collaboration with MPCA, Koochiching Soil and Water Conservation District, North St. Louis and Itasca Soil and Water Conservation Districts, and University of Minnesota-Duluth began a study to delineate sources of sediment and sediment-bound P for the Little Fork basin using geochemical sediment fingerprinting and sediment budget techniques. The project includes complimentary data sets to derive a better understanding of sources and sinks of sediment and sediment P in the Little Fork basin to assist TMDL related management actions. This paper focuses on the first phase of the project which concentrated on assembling a stream corridor sediment budget for eroding valley sides, terraces, banks, and ravines, as well as storage of soft sediment. The soft sediment deposition is thought to be mainly composed of silt and clay sized particles, as well as some fine-grained sand. A second report, planned for 2024, will focus on the sediment source apportionment results from the geochemical fingerprinting phase of the study.

Study Area

The Little Fork River drains 4,848 km^2 (MPCA 2016) before joining the Rainy River and flows northwest to Lake of the Woods and north through Canada. Much of the basin was intensively logged in the late 1800s and early 1900s, and timber harvest remains one of the primary economic activities in the basin (Drache 1983, Pollard 1975, Anderson et al. 2006). The basin's surficial geology is characterized by Rainy Lobe glacial deposits in the southern extent of the basin (adjacent to the Mesabi Iron Range), and large areas of Koochiching Lobe glacial deposits (Minnesota Geological Survey 2021). Exposures of Lake Agassiz sediments extend from the west, and the northeastern edge of the basin is characterized by scoured bedrock uplands (Minnesota Geological Survey 2021). A large portion of the basin is part of the Nett Lake Reservation tribal lands belonging to the Bois Forte Band of Chippewa (MPCA 2016). Land cover across the basin is largely comprised of forests and wetlands (Dewitz 2019). The basin has 37% forest cover and includes 18% deciduous, 6% evergreen, and 13% mixed forest. Woody wetlands cover 40% of the basin, and emergent herbaceous wetland covers 6%. The basin has less than 2% developed land and 2% is agricultural use, mostly for pasture/hay (1.6%) with a small amount in cultivated crops. As much as 19% of the wetlands may be peat deposits (Hobbs and Goebel 1982).

Methods

Field-Based Rapid Geomorphic Assessments

Field-based rapid geomorphic assessments (RGAs) form the framework for the sediment budget analyses and include measurements of valley side, terrace, bank, and ravine erosion and soft streambed sediment deposition. Data were collected at 46 reaches in the summer and fall of 2021 during extreme drought conditions using methods described in Fitzpatrick et al. (2019) and Blount et al. (2022). Reaches for the RGAs were selected to represent a range of slope, valley types, stream order, and channel sizes. The reaches included ephemeral and perennial channels. Ravines are typically developed along steep slopes of entrenched valley sides and were included in this assessment. Ravines will typically have punctuated sections of gully or channel erosion at knickpoints along a longitudinal continuum (Fryirs and Brierley 2013). The stream network and its physical characteristics were initially described for reconnaissance of RGA potential locations using an overlay of streamlines used in the HSPF model and lidar-based digital elevation (DEM) model data (Minnesota IT Services Geospatial Information Office 2018). The Little Fork outlet and select subbasin outlets were chosen for data collection, passive suspended sediment samplers for sediment fingerprinting, and RGA development because the MPCA has measured TSS and streamflow at these locations (Figure 1).

Erosion characteristics of valley sides, terrace cuts, and banks were quantified by measuring the length and height of erosion along both sides of the channels for the entire reach length. Collection of additional data included visual estimates of texture and origin of the sediment (i.e., glacial, glaciolacustrine, alluvium). Lateral recession rates were estimated using the indicators described in the Wisconsin Natural Resources Conservation Service (2016) bank erosion calculator while in the field. Lateral recession rates ranged from 0.009 meters/year (m/yr) for slight (some bare spots but no signs of active erosion) to 0.18 m/yr for very severe (bare bank with vegetative overhang, many fallen trees, and drains or culverts eroding). Loads were computed using a volume-weight conversion. The volume-weighted conversion was determined for each eroding section based on the described texture of the eroding material, and from published general dry density values (Wisconsin NRCS Streambank Erosion Prediction guide 2016). These loads were compared to the MPCA's stream TSS loads. Additionally, materials described as till in the field were assigned a volume-weight conversion based on reported dry density values for glacial or glaciolacustrine till deposits in other regional studies (Thoma et al 2005, Hall 2016). The volume weight conversions ranged from a low of 353 kg/m^3 for organic soils to high of 1,990 kg/m^3 for glaciolacustrine till. The estimated total weight of annual valley side, terrace, and bank erosion at each reach was divided by the reach length to obtain a rate of erosion per km that could be applied to the broader network. This approach was taken because the conversion factors applied were based on visual estimates of eroding sediment texture rather than measurements of density.

Soft fine-grained streambed sediment volumes were estimated from field measurements of the length, width, and average thickness of soft sediment deposits along the entire reach (Fitzpatrick et al. 2019; Blount et al. 2022). Soft sediment thickness was measured using a light two-finger push on a meter stick and subtracting the depth of sediment penetration from the water depth. A conservative estimate of a volume-weight conversion of 800 kg/m^3 was applied because of the high water content, based on soft sediment samples from Wisconsin and national estimates for deposited fine-grained sediment (Peppler and Fitzpatrick 2018).

Samples of the eroding sediment and soft sediment deposition were collected along the RGA reaches using methods described in Fitzpatrick et al. (2019) and Blount et al. (2022) and were submitted for laboratory analyses of geochemistry, particle size, sediment-bound P, and organic carbon content for use in the sediment fingerprinting component of the study. These samples were wet sieved to the less than 63-micron fraction, giving a rough estimate of the fine-grained (silt and clay) proportion of eroding and depositing sediment for each RGA reach.

Stream Network and Segment-Scale Geomorphic Characteristics

A stream network was delineated using 1/3 arc second DEM data from the National Elevation Dataset program (USGS 2018) at a 0.02 km^2 stream definition threshold to capture both perennial and ephemeral channels in the basin. The stream definition threshold was determined based on the lowest threshold that captured all the ravine channels included in the RGAs. The resulting stream network increased in size by about 4 Strahler (1957) stream orders from the National Hydrologic Dataset (NHD) Plus stream network (McKay et al. 2012). A stream order of 1 in NHDPlus had a stream order of 4 in the extended network and the Little Fork main stem increased from a stream order of 6 in NHDPlus to 9 in the extended network. This increased the cumulative length of potential channel and riparian network in the Little Fork from 2,970 km to 30,800 km.

The delineated stream network was split into 60-meter (m) segments for network-wide analysis of drainage area, channel slope, stream order, and valley side slope. The dataset includes segments shorter than 60 m that make up 12% of the total network. These shorter segments occur due to splitting at stream confluences and the termination of short drainage lines. The 60-m segment length was selected to provide detailed characterization of abrupt changes in channel slopes, valley width, and short lengths of meander bends that intersect with the valley sides, which are common in rivers in young post glacial landscapes.

To assess the slope of the adjacent valley sides, buffers were generated at four times the bankfull width of each segment, with a minimum width of 30 m. The first step in generating these buffers was to estimate average bankfull width for each 60-m segment in the network. This was achieved by developing a power trendline with least squares fit between the median drainage area (A) and average measured bankfull width ([W_{bf}] Equation 1). The development of this equation incorporated data from 43 of the 46 RGA reaches, excluding three of the RGA reaches due to ditching, beaver impoundment, and missing bankfull measurements. The equation obtained was used to estimate the bankfull width for each 60-m segment in the network:

$$W_{bf} = 1.54A^{0.405} (R^2 = 0.91) \tag{1}$$

Zonal statistics were derived from the buffers generated using four times the W_{bf} for each segment, and a 1/3 arc second slope grid to determine the 90th percentile of slope values. Segments with a 90th percentile value above a 15% slope were categorized as having "steep" valley sides (confined or partially confined valley type) or as a ravine.

Channel slope was calculated by extracting the elevations for the upstream and downstream vertices of each segment from the 1/3 arc-second DEM and dividing by the geometric length of the segment feature in a geographic information system (GIS). The channel slopes grouped into categories of <0.1%, 0.1-0.3%, 0.3-1%, 1-2%, 2-4%, 4-8%, and >8%. These categories were based on channel classifications previously adapted for northern Minnesota (Montgomery and Buffington 1997; Fitzpatrick et al. 2006). Approximately 12.8% of the stream network had negative slope values. The negative slopes were replaced with a value of "0" if the segments intersected a lake or pond in the Minnesota Department of Natural Resources Hydrography Dataset (2022) (0.5%). Segments within 100 m of the Minnesota Department of Transportation roads shapefile were given an adjusted slope of "0", likely representing a culvert passage under a road embankment (1.6%). Slopes between -0.1% to 0% were given an adjusted slope of "0" (1.5%). A negative slope was replaced with the slope of the next downstream segment, if positive (7.8%). The remaining 0.49% of segments with negative slopes were put into a "negative slope" category.

Constructing a Stream Corridor Sediment Budget

The RGA-based corridor erosion and soft bed sediment deposition results were extrapolated to all segments in the delineated stream network based on similar characteristics of channel size (stream order), channel slope, presence of steep valley sides or ravines, and proximity of reach measurement. There were approximately 150 segment types possible based on 9 stream orders, 7 channel slope categories, and presence/absence of steep valley sides. About 50 of the segment categories had less than 10 km of channel length. About 13,600 km, or 44% of the stream network consisted of channels with a stream order of 1, slopes less than 2%, and no steep side slopes. These segments were in open water or flat extensive wetland areas with no expression of channels on aerial photographs or the detailed state lidar-derived DEM and were assigned erosion and soft sediment deposition values of "0".

For segments of the same category as multiple RGAs, either an average erosion rate and soft sediment deposition amount was assigned, or the results from the RGA in closest proximity or within the same subbasin were assigned. For RGA reaches that contained multiple segments in different categories, the RGA data were applied to the segments that most reflected the channel slope and steep valley sides observed in the field. After initial assignment of the RGA data, the segment assignments were manually re-adjusted where needed to reflect spatial variability among subbasins, local geologic anomalies, or qualitative data describing erosion including photos that were collected with the RGAs. Spatial adjustments were made for ravines along the Little Fork for stream order 9 that had higher erosion rates than ravines along the perennial tributaries. Soft sediment volumes were highly variable depending on beaver dam and related impoundment features and thus an average volume was applied based on RGAs with similar stream order and slope classes. The adjusted segment categorical values were then multiplied by the cumulative segment lengths in each category and summed to estimate the total erosion of sediment from valley sides, terraces, banks, and ravines and soft sediment deposition. Estimates of total erosion and soft sediment deposition were also calculated for the fine-grained material for comparison to TSS load results and using the low to high range of volume-weight conversions to demonstrate uncertainty in the final calculations.

Estimates of erosion and soft sediment deposition for the segments were further summarized into categories based on a combined channel slope and steep valley side slope referred to as the “Slope Class” and size. Strahler stream orders of 1 to 4 were considered headwaters, stream orders 5 to 7 were perennial tributaries, and stream orders 8 and 9 were the main stems of the Little Fork and Sturgeon Rivers. For the sediment budget summary, the small percentage of segments that still had the “negative channel slope” category were grouped into erosion and soft sediment deposition estimates for channel slopes from 0-1%.

There are many sources of uncertainty in sediment budget estimates, and this application to the stream corridor for erosion and soft sediment deposition is no exception. However, the lower level of precision can be justified by providing possible answers to questions about relative location of sediment sources and storage that help with land management decisions across a large basin (Reid and Trustrum 2002). Uncertainty can be introduced with the field based RGAs and propagate with how field data are collected, measured, and applied to the stream network. The uncertainty with field measurements includes measuring areas of erosion, field identification of soft sediment thickness and extent, visual identification of texture, categorical estimates of lateral recession rates, and the timing of the measurements relative to large floods or droughts. Additional uncertainty is inherent in the automation of a more detailed stream network based on flowlines generated from a 10-m DEM, and calculation of channel and side slope categories. Furthermore, the application of the RGA-based reach results for erosion and deposition to the 60-m segments required a level of geomorphology technical experience and familiarity with the basin and field conditions resulting in a combined automated and manual approach. An example of the uncertainty in volume-weight conversion factors is when the lowest and highest volume-weight conversion factors for the observed textures across all RGAs were applied to the erosion rates. Similarly, as one measure of uncertainty in the total weights for soft sediment deposition a value of half (400 kg/m^3, similar to organic soils) and double (1,600 kg/m^3, similar to the high end of the unsaturated bank materials) the estimated volume-weight conversion was applied to the soft sediment volumes. Given there are multiple sources of uncertainty, the sediment budget approach still helps provide spatial representation of the stream corridor sources of sediment contributing to TSS loads.

Results and Discussion

The RGA results for stream corridor erosion and soft sediment deposition illustrate the variability in corridor sources and sinks across the basin (Figure 2). For reaches with only streambank erosion and without eroding valley sides or terraces, erosion rates ranged from 0 to just over 50 Mg/km. For reaches with valley side or terrace mass wasting in addition to eroding streambanks, erosion rates were similar or up to an order of magnitude higher, with a maximum of almost 1,000 Mg/km on a Little Fork mainstem reach. Some of the highest erosion rates, along with the most variability, were from stream orders 3, 5 and 9. Stream order 8 was limited to only 50 km of stream segments and was represented by the Sturgeon and Little Fork upstream of their confluence. Soft sediment deposition was also variable and ranged from no soft sediment at 12 RGA reaches to almost 1200 Mg/km at a beaver impounded reach along a stream order 5 tributary to the Sturgeon River. For contrast, another RGA reach had the same stream order (5) and channel slope of <0.1%. This RGA had failed beaver dams and soft sediment of 30 Mg/km and was on a tributary to the Valley River. For soft sediment deposition, the two RGA reaches of stream order 8 varied by an order of magnitude. The Little Fork reach had almost 700 Mg/km whereas the Sturgeon River reach had less than 10 Mg/km. Field observations showed both reaches had beaver activity as well.

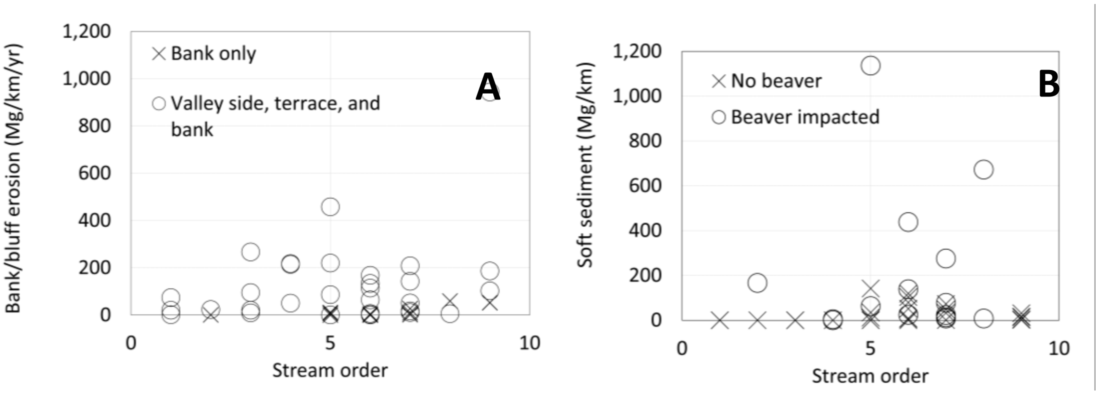
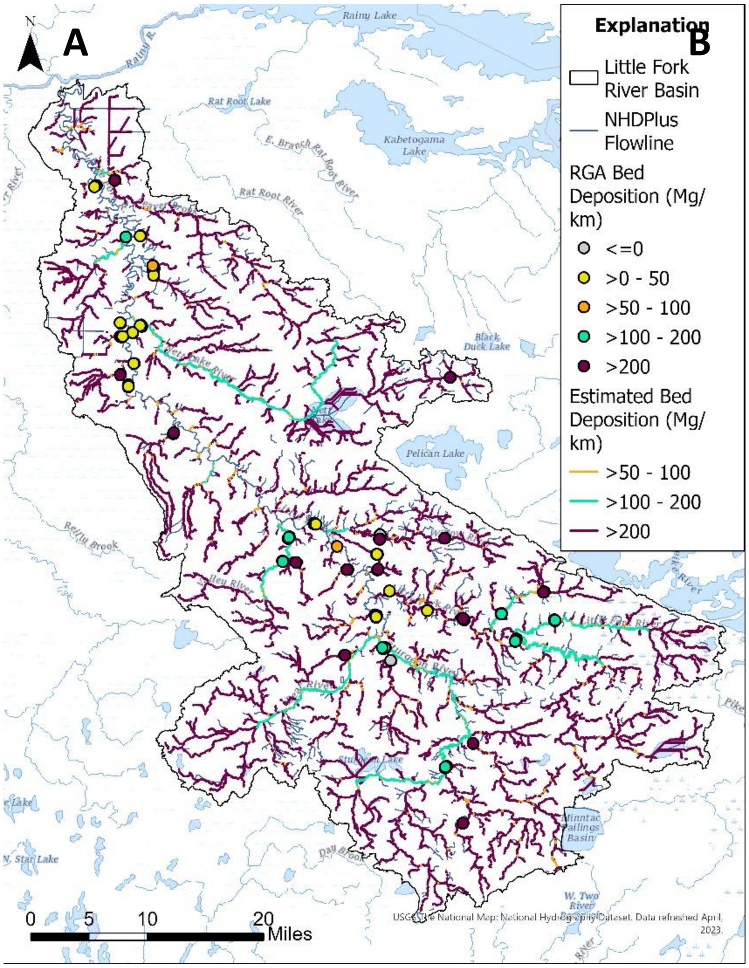


Figure 2. RGA results for a) corridor erosion and b) soft sediment deposition [Mg, megagram; km, kilometer; yr, year]

Application of RGA erosion and deposition results to the full stream network are shown in table 1 with spatial distributions on a per km basis shown in Figure 3. Segments were grouped into three categories: headwaters (Strahler stream order 1-4), perennial tributaries (stream order 5-7), and mainstems (stream order 8-9). A large portion of the headwater channels are likely ephemeral since they were not mapped as part of the NHDPlus stream network. Channel slope categories were combined into three categories for summarizing the results – gentle (< 1%), moderate (1-2%), and relatively steep (≥2%). Mainstem segments were mainly gentle slopes, except for a few moderate to steep channel slopes with steep valley sides. Of the 28,000 km of headwater segments, 870 km had steep valley sides and are representative of the ravine tributaries, which had some of the highest erosion rates across the whole network, particularly those that are tributaries to mainstem channels. The steep-sided headwater segments comprised 31% of the headwater total lengths but potentially contribute 83% of erosion from headwaters. In contrast for soft sediment deposition, the steep sided headwater segments contribute only 3% of the soft sediment deposition from headwaters. Headwaters with no steep valley sides and gentle slopes comprised over 50% of soft sediment deposition in the basin. The highest amounts of bed sediment deposition, on a per km basis, were in gentle sloped perennial tributaries with no steep valley sides.

Table 1. Summary of segment erosion rates, bed deposition, and deposition to erosion ratios for headwaters, perennial tributaries, and mainstems for the extended Little Fork stream network [%, percent; <, less than; >, greater than; km, kilometer; Mg, megagram]

Stream Level	Valley Sides	Channel Slope	Total Length	Erosion		Bed Deposition		Deposition : Erosion
(Units)	Steep (>15%)	%	km	Mg/year	Mg/km/year	Mg	Mg/km	Years
Headwaters	No	< 1	23,000	1,600	0	400,000	17	250
Headwaters	No	1-2	2,500	160	0	11,000	5	69
Headwaters	No	> 2	1,800	12,000	7	1,800	1	0
Headwaters	Yes	< 1	620	3,600	6	15,000	25	4
Headwaters	Yes	1-2	190	10,000	53	960	5	0
Headwaters	Yes	> 2	880	52,000	60	730	1	0
Perennial Tributaries	No	< 1	1,100	8,400	7	170,000	150	20
Perennial Tributaries	No	1-2	36	77	2	1,500	41	20
Perennial Tributaries	No	> 2	12	59	5	630	51	11
Perennial Tributaries	Yes	< 1	340	12,000	35	35,000	100	3
Perennial Tributaries	Yes	1-2	42	5,700	140	1,800	42	0
Perennial Tributaries	Yes	> 2	20	4,300	210	860	43	0
Mainstem	No	< 1	22	1,300	58	1,500	70	1
Mainstem	No	1-2	0	2	22	3	35	2
Mainstem	No	> 2	0	0	0	0	0	0
Mainstem	Yes	< 1	220	22,000	100	14,000	63	1
Mainstem	Yes	1-2	5	470	93	54	11	0
Mainstem	Yes	> 2	1	140	97	5	4	0
Total			**30,789**	**133,807**		**654,842**		

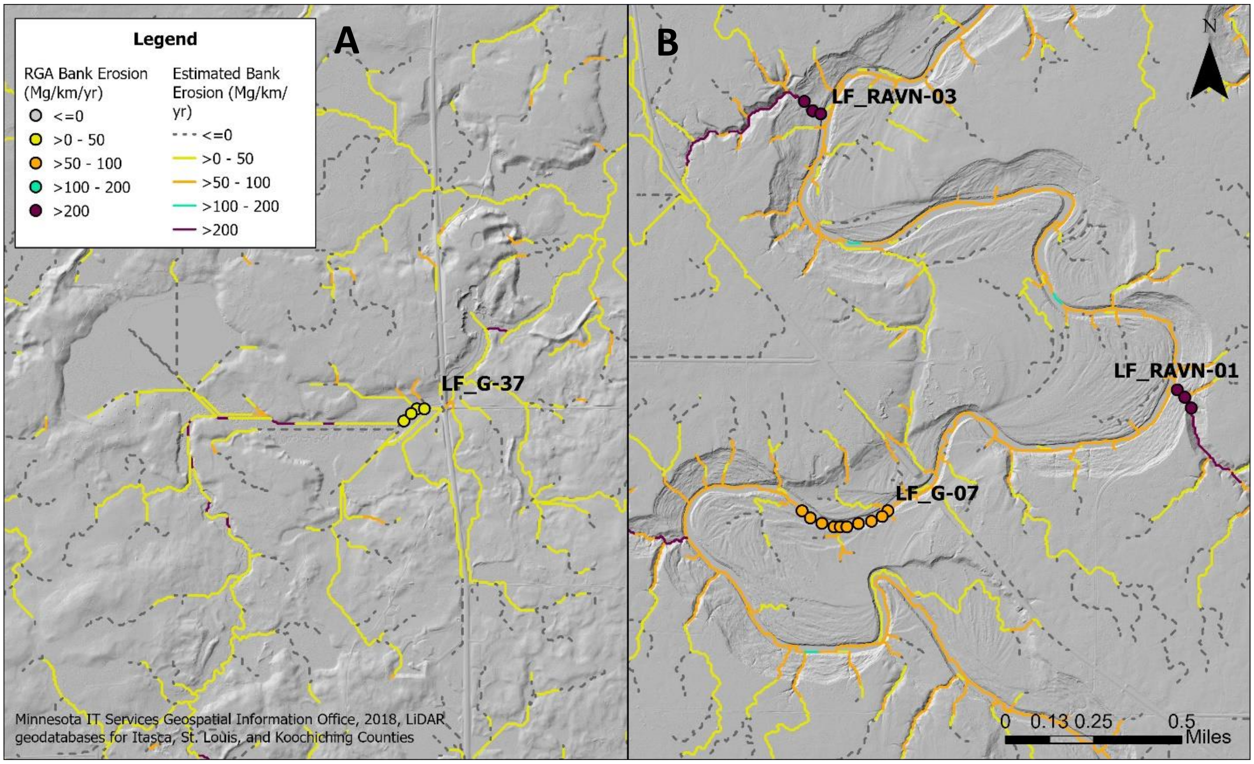


USGS The National Map: National Hydrography Dataset. Data refreshed April, 2023.

Figure 3. Mapped distribution of 60-m segments with a) corridor erosion and b) soft sediment deposition relative to RGA results. Segments with erosion rates less than 50 Mg/km/yr and deposition rates less than 50 Mg/km have been masked to improve visualization of segments with higher rates due to the high density of the study's delineated stream network.

Examples of spatial differences in erosion rates for headwater segments are shown in Figure 4. The dashed gray lines in Figure 4A denote relatively flat segments with 0 or gentle slopes with no erosion, many of which have no surface expression in the hillshade background. In contrast, the ravine segments that feed into the mainstem have relatively steep channel slopes and valley side slopes and high erosion (Figure 4B). Erosion rates are highest where ravine segments intersect the valley side of the mainstem. For reference, one ravine with the smallest drainage area of 0.02 km^2 had a discontinuous channel with an average width of 0.45 m and produced 20.8 Mg/km/yr of erosion, while the ravine with the largest erosion rates had a drainage area of 6.92 km_2, an average width of 3.4 m, and produced between 300 and 460 Mg/km/yr.

The most heavily eroding ravine drains into a section of the Little Fork mainstem which had the highest erosion rate of all the RGA reaches estimated of 1,000 Mg/km/yr (Figure 5). These reaches were on a large meander in the Little Fork mainstem, which generally runs southeast to northwest (Figure 5). A large change in the valley and channel meander pattern might reflect a change in the lithology, landform, or underlying bedrock that cause the river to change its general direction because these features may be more resistant to erosion (Fryirs and Brierley 2013). This stretch of the river is surrounded by a remote area with no access points, which made it difficult to determine how far upstream and downstream to apply the higher erosion rate. The channel slope through this section was not noticeably different than upstream or downstream, but subtle differences may have been lost within the resolution of the 10-m DEM used to calculate the segment slopes. However, steep valley side slopes were observed on both sides of the river throughout the reach. This stretch of the river has an actively incising section (Gran et al. 2007) and may represent an active knickpoint propagating upstream. The channel width of the river was slightly narrower here than upstream or downstream, and the RGA reach had almost continuous erosion along both banks, which was unique to this RGA reach. This might indicate that the erosion is enhanced through the narrow channel by the heavy ice flows that are common during spring ice break up. This location was also an important landing area in lumber-related log drives on the river, which continued into the 1930s, decades later than many other rivers in the region (Pollard 1975, Anderson et al. 2006). The last log drive in 1937 contained 30,000 cords of pulpwood and 13 million feet of pine logs. Historical photographs show the logs spanning the channel up to the top of the banks and terraces (Anderson er al., 2006). The proximity of the nearby tributary ravine with high erosion further supports the hypothesis of upstream propagation of a knickpoint in this zone. Perhaps this section of the Little Fork represents a combination of knickpoint propagation, narrow channel due to post-glacial lithology and landforms, and ice-breakup related erosion. This stretch with the highest mainstem erosion rates may be extended using the more detailed analysis of the geomorphology of the mainstem in Gran et al. (2007) where they noted an actively eroding stretch for 39 km downstream of the confluence with the Sturgeon River. Gran et al. (2007) also noted that the valley width was less through this stretch compared to downstream.

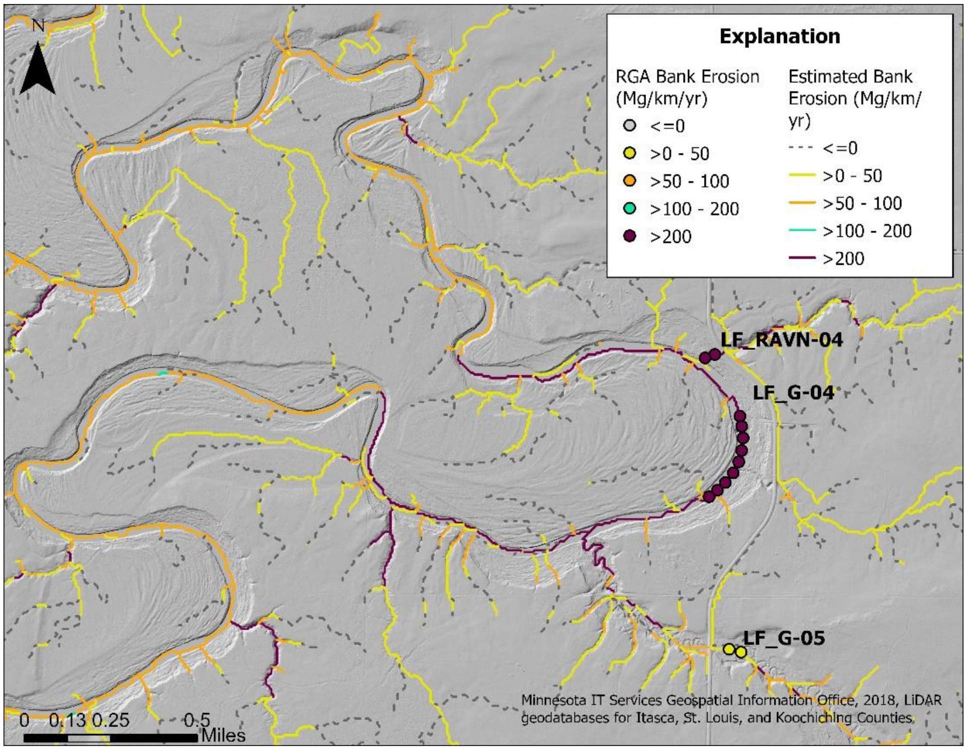


Minnesota IT Services Geospatial Information Office, 2018, LiDAR geodatabases for Itasca, St. Louis, and Koochiching Counties

Figure 4. Examples of corridor erosion rates for a) low stream orders in headwater lowlands and ponds, and b) ravines with steep side slopes along the main stem of the Little Fork, along with RGA results

Overall, cumulative erosion in the Little Fork was estimated at 130,000 Mg/yr, including all sediment size classes, with the highest erosion rates below the confluence of the Little Fork and

Sturgeon Rivers (Table 1). Parsing these results by slope and stream order category showed that ravines (stream orders 1 - 4 with >15% slopes) contribute 66,000 Mg/yr, nearly 50% of the total erosion. Ravine erosion rates were also highest below the confluence of the Little Fork and Sturgeon Rivers where the Little Fork valley was the most developed morphologically. Evaluating the proportion of total basin erosion comprised of fine sediment (silt and clay), we found that this comprised an estimated 39,000 Mg/yr or 30% of the total estimate of eroded material (Table 2).



Minnesota IT Services Geospatial Information Office, 2018, LiDAR geodatabases for Itasca, St. Louis, and Koochiching Counties.

Figure 5. Example of Little Fork main stem with notably higher RGA erosion rates than rest of main stem sites and approximated segments along the same meander bend that were assigned a corresponding higher erosion rate

Evaluation results included an uncertainty measure in the corridor sediment budget estimates by using high and low values of the sediment volume to weight conversions and showed that total erosion rates ranged from 39,000 to 200,000 Mg/yr (Table 2). Total soft sediment deposition was 660,000 Mg, or about 5 times that of erosion, an overall indication that there is more sediment stored than eroded and transported through the basin. The estimates using the low and high volume-weight conversion varied by an order of magnitude from 330,000 to 1,300,000 Mg of soft sediment deposition. Limiting the total amount by the silt and clay portion only resulted in an estimate of soft sediment deposition of 190,000 Mg.

Table 2. Summary of erosion estimates calculated as a measure of uncertainty, obtained using high and low volume to weight ratios. Erosion volume for the fine-grained (silt and clay) portion of eroded material is also presented [Mg, megagram]

	Total	Silt and clay portion only	Total low volume-weight ratio	Total high volume-weight ratio
Erosion (Mg/year)	130,000	39,000	35,000	200,000
Soft sediment deposition (Mg)	660,000	190,000	330,000	1,300,000

Individual subbasin and cumulative totals for the Little Fork for erosion and soft sediment deposition reflected subbasin size and their location in the basin (Figure 6, Table 3). For example, the Willow River (2) and Valley River (8) had the least subbasin erosion because of small subbasin size. They contributed 2 and 3 Mg/km/yr. The Nett Lake River (5) had a larger subbasin area but also contributed about 2 Mg/km/yr likely because of its gently sloped channels and bedrock close to the surface. Similarly, the Little Fork near Linden Grove, upstream of the confluence with the Sturgeon River (1), flows through bedrock uplands with little valley entrenchment (Gran et al. 2007), whereas the lower sections of the Little Fork (3, 4, and 7), have eroding valley sides and terraces and had high erosion rates (8, 6, and 6 Mg/km/yr).

Average annual TSS load over the available period of record for the farthest downstream gage on the Little Fork was 60,000 Mg/yr spanning 2007-2019 (MPCA 2023) (Table 3). In comparison, the fine (silt and clay) erosion was 36,000 Mg/yr at the Little Fork streamgage (3). The majority of sediment in transport could be accounted for by the fine material eroding from streambanks, ravines, and other near-channel features on an average annual basis. The proportion of estimated erosion to annual TSS loads increased upstream at the three Little Fork subbasins and Sturgeon River subbasin with TSS load data (Table 3).

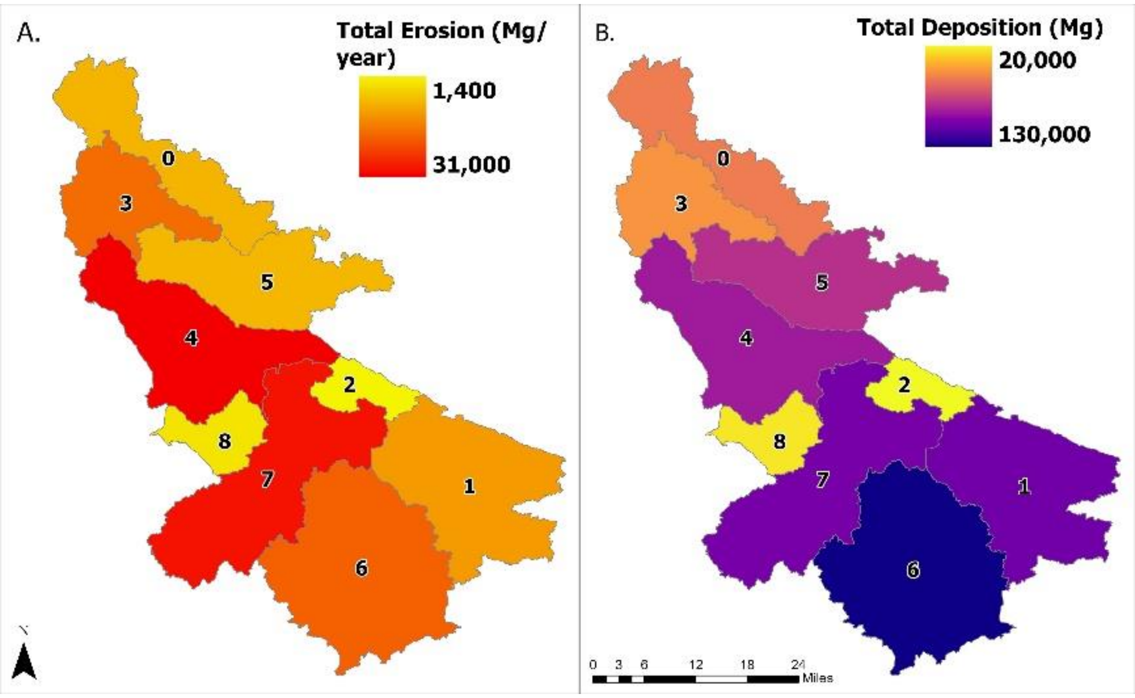


Figure 6. Estimated a) corridor erosion and b) soft sediment deposition totals for eight subbasins in the Little Fork River watershed, Minnesota

For soft sediment deposition, the Sturgeon River had the most stored sediment for the subbasin total and Mg/km basis followed by the Little Fork upstream and downstream of the Sturgeon River (Figure 6, Table 3). The entire basin had approximately 660,000 Mg of soft sediment stored in the channels, with a soft sediment to erosion ratio of 5, suggesting that there is about 5 years' worth of erosion stored as soft sediment in the channels. This simple ratio does not account for the spatial variability in the location of high erosion rates and high amounts of soft sediment deposition. For example, some ravines had high erosion rates but no to little soft sediment deposition, indicating that eroded materials are readily transported downstream.

Table 3. Summary of corridor erosion, soft sediment deposition, and total suspended solids (MPCA, 2023) for the Little Fork basin and its subbasins [ID, identification number; km, kilometer; Mg, megagram; yr, year, -, not available]

ID	Subbasin	Drainage Area (km2)	Cumulative Stream Length (km)	Total Erosion (Mg/yr)	Fine Sediment Erosion	Total Deposition (Mg)	Fine Sediment Deposition (Mg)	Annual Average TSS (Mg/yr)
0	Full Little Fork River Basin	4700	31,000	130,000	39,000	660,000	47,000	-
1	Little Fork River nr Linden Grove, TH73	720	46,000	12,000	3,700	110,000	32,000	2,700
2	Willow River at CTY 75 nr Greaney, MN	130	800	1,400	380	20,000	5,600	-
3	Little Fork River at Littlefork, MN	4300	28,000	120,000	36,000	600,000	170,000	56,000
4	Little Fork River nr Littlefork, MN65	3400	22,000	98,000	28,000	470,000	140,000	33,000
5	Nett Lake River near UT 63 nr Littlefork, MN	550	3,900	8,900	2,700	83,000	24,000	-
6	Sturgeon River at CTY 107 nr Meadow Brook, MN	910	5,600	20,000	5,600	130,000	37,000	3,300
7	Little Fork River nr Silverdale, MN65	2500	1,600	63,000	18,000	360,000	110,000	17,000
8	Valley River near Rauch, MN	170	1,100	3,500	990	24,000	6,800	-

Conclusions and Future Work

In summary, erosion rates were highest along the Little Fork mainstem and adjacent ravines that intersect its valley sides, downstream of its confluence with the Sturgeon River. The sediment budget approach used in this study indicated that erosion in ravines, mapped using the 10-m DEM extended network, may account for approximately 50% of the total budget. The resulting GIS-based maps were useful for showing areas of concern with a high potential for erosion that can be followed up with more site-specific field reconnaissance for more targeted management. The RGA data provided field validation of the ranges in erosion and deposition. Even though the RGA data had a relatively coarse resolution, we were still able to include erosion estimates from ephemeral ravine channels in a stream corridor sediment budget. The erosion estimates represented a time-averaged approximation of the contributions of eroding sediment along the stream corridors and included all sediment sizes present in the valley sides, terraces, or banks, including sands and gravels. Sand and gravel likely move more slowly through the network than silts and clays that move in suspension as part of the wash load. The total erosion estimate was 130,000 Mg/yr, and potentially, 39,000 Mg/yr of the total was from the fine-grained silt and clay portion. Of the four subbasin locations with annual TSS data, the fine-grained portion of erosion ranged from about 60 to 170 percent of the TSS data. The soft sediment deposition estimates suggest that overall, the Little Fork has stored sediment. If all erosion stopped from the corridor and uplands, it would take approximately 5 years or more, depending on floods, to evacuate all the soft sediment from the streambed. Of course, this is a highly conservative estimate of time for evacuation of this sediment, given the large amount of soft sediment stored in headwater beaver-affected reaches, and it is likely that all of the soft sediment would not be resuspended even during floods. However, it provides a sense of the possible lag times between upstream management actions and expected reductions in TSS loads at downstream monitoring sites. Furthermore, when the results of sediment-bound P analyses are complete, they will also be used with these results to estimate corridor contributions to sediment-bound P in transport and deposition within the network. Next steps involve validating procedures and publishing results of the complimentary sediment fingerprinting-based apportionments for upland and stream corridor erosion sources.

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