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Watershed

Draft Little Fork River Watershed Restoration and Protection Strategy Report Update 2026

MINNESOTA POLLUTION CONTROL AGENCY

CLEAN WATER LAND & LEGACY AMENDMENT

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Key terms and abbreviations

1W1P	One Watershed, One Plan
BMP	best management practice
BWSR	Board of Water and Soil Resources
DNR	Minnesota Department of Natural Resources
e. coli	Escherichia coli
EPA	U.S. Environmental Protection Agency
F-IBI	fish community-based Index of Biological Integrity
HUC	Hydrologic Unit Code
IBI	index of biological integrity
IWM	intensive watershed monitoring
LFRW	Little Fork River Watershed
LOW	Lake of the Woods
mg/L	milligrams per liter
MT/Yr	Metric Tons per year
M-IBI	macroinvertebrate community-based Index of Biological Integrity
MPCA	Minnesota Pollution Control Agency
MS4	municipal separate storm sewer system
N	Nitrogen
NLF	Northern Lakes and Forest
NPDES	National Pollutant Discharge Elimination System
P	Phosphorus
SCL	Sturgeon Chain of Lakes
SDS	state disposal system
SID	Stressor identification
SWCD	Soil and Water Conservation District
10X	Ten times (chemistry samples collected on 10 dates)
TALU	tiered aquatic life uses
TMDL	total maximum daily load
TP	total phosphorus
TSS	total suspended solids

USGS	United States Geological Survey
WHAFF	Watershed Health Assessment Framework
WID	Water Body Identification (e.g., 09030005-612)
WPLMN	Watershed Pollutant Load Monitoring Network
WRAPS	Watershed Restoration and Protection Strategy

Executive summary

The authors acknowledge that the lands of the Little Fork Watershed are the historical lands of the Bois Forte Band of Chippewa. The South Central/East portions of the watershed contain Bois Forte Reservation lands. The watershed and surrounding lands have spiritual and personal significance for the ancestral and contemporary Bois Forte people that have gathered and preserved traditional knowledge for centuries. We honor and respect their past and continued relationship to this area: its land, water, air, and beings. We also recognize them as a sovereign nation and their continued treaty rights. We acknowledge the privileges accommodated in accessing tribal lands and sharing information with tribal community members. Miigwech (Thank you).

The State of Minnesota has adopted a Watershed Approach for managing water quality for each of the 80 major watersheds in the state. Each major watershed undergoes surface water monitoring and assessment and has the opportunity for a Watershed Restoration and Protection Strategy (WRAPS) revision. The Little Fork River Watershed (LFRW) first underwent intensive watershed monitoring (IWM) in 2008, with the initial WRAPS report approved in 2017.

The *Little Fork River WRAPS Report Update 2026* is a revision of the 2017 *Little Fork River WRAPS Report* and summarizes water quality findings from the second round of IWM (MPCA 2021), stressor identification (SID; MPCA 2024a), water quality research projects, and studies. The goals of this updated WRAPS Report are to:

1. Highlight differences and trends in watershed conditions over the last 10 years.
2. Share updated surface water quality resources, information, and tools for watershed stakeholders as they plan and implement best management practices (BMPs).
3. Provide updated recommendations for prioritizing and targeting implementation in various areas of the watershed.

The LFRW is a complex, heavily forested watershed with relatively few anthropogenic influences affecting water quality. The watershed, the largest subwatershed of the Rainy River on the U.S. side, is over 1,800 square miles (sq mi), but has less than one person per sq mi and contains less than 1% of developed land use.

Overall, water quality conditions have not significantly changed in the LFRW since 2008, when the initial watershed-scale analysis was conducted. The lakes in the watershed continue to come close to the level of impairment, holding their own and still meeting standards. The river and stream network continues to be a challenge as large portions of the watershed don’t meet the statewide standard for turbidity and TSS but still have biological communities that meet exceptional use designations.

The *Little Fork River WRAPS Report Update 2026* presents a comprehensive framework for enhancing the ecological health of the watershed, promoting tailored BMP opportunities to build resilient ecosystems. Developed by local partners and the Minnesota Pollution Control Agency (MPCA), this report outlines strategies for mitigating pollutants by focusing on the Sturgeon Chain of Lakes (SCL) Subwatershed for protection and addressing sedimentation throughout the stream network for restoration. These targeted efforts will foster resilient ecosystems capable of withstanding current and future environmental stresses. This report provides essential information for local government and conservation groups and related stakeholders who are committed to the stewardship of the LFRW. By following the recommendations set forth in this report, collective efforts can drive meaningful restoration and protection, ensuring the sustainability of this vital natural resource for current and future generations. For further consultation or to engage in collaborative efforts related to these strategies, please contact Itasca, Koochiching, or Northern St. Louis County SWCD offices or the MPCA.

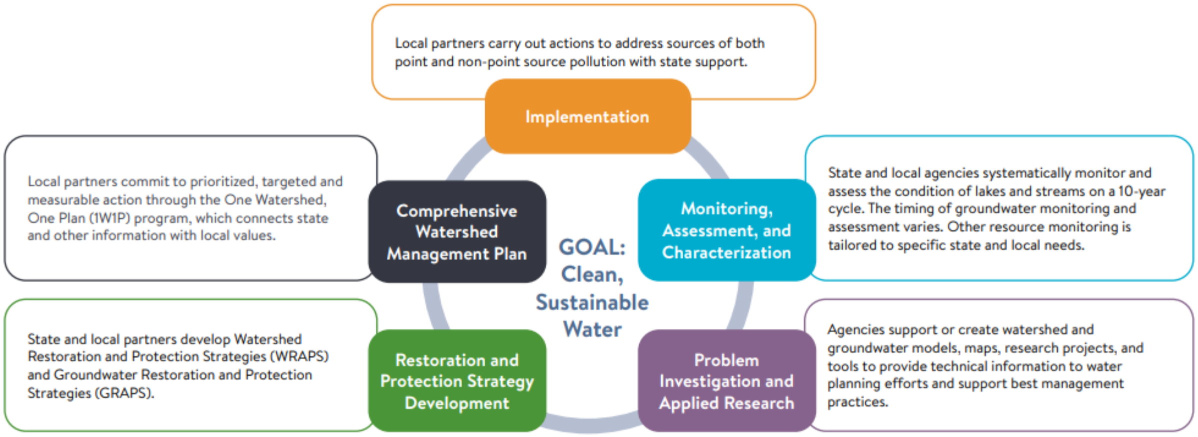
Figure 1. Upstream view of Little Fork River from Hwy 65 bridge.

1. Watershed approach

Minnesota has adopted a watershed approach to address the state's 80 major watersheds. The Minnesota Watershed Approach incorporates water quality assessment, watershed analysis, public participation, planning, implementation, and measurement of results into a 10-year Cycle that addresses both restoration and protection.

Along with the watershed approach, the MPCA developed a process to identify and address threats to water quality in each of these major watersheds (Figure 2).

Figure 2. Minnesota's Watershed Approach to monitoring, assessing, strategizing restoration and protection, plan development, and project implementation to restore and protect Minnesota's water quality.



Local partners carry out actions to address sources of both point and non-point source pollution with state support.

State and local agencies systematically monitor and assess the condition of lakes and streams on a 10-year cycle. The timing of groundwater monitoring and assessment varies. Other resource monitoring is tailored to specific state and local needs.

Agencies support or create watershed and groundwater models, maps, research projects, and tools to provide technical information to water planning efforts and support best management practices.

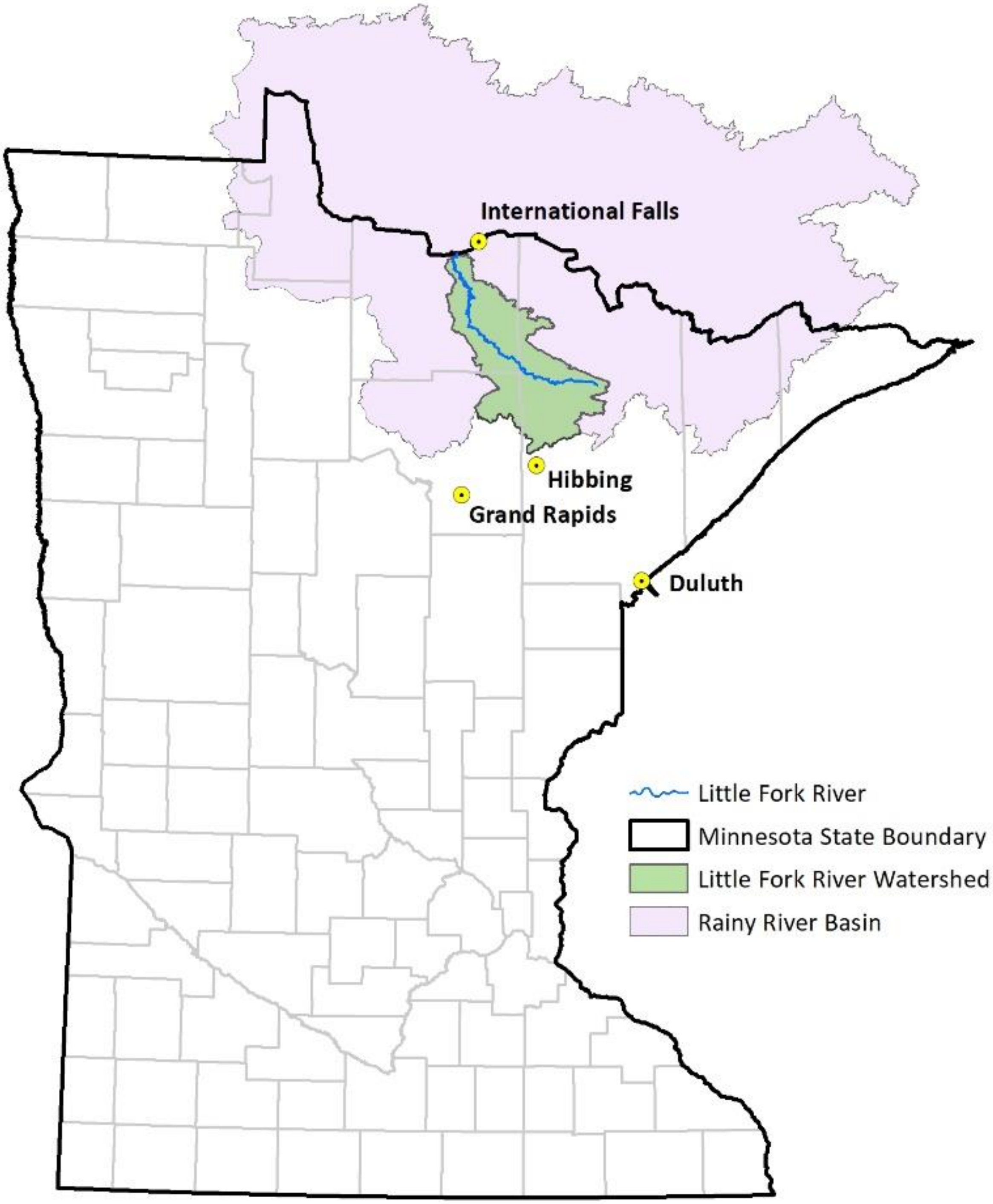
State and local partners develop Watershed Restoration and Protection Strategies (WRAPS) and Groundwater Restoration and Protection Strategies (GRAPS).

Local partners commit to prioritized, targeted and measurable action through the One Watershed, One Plan (1W1P) program, which connects state and other information with local values.

This process is called WRAPS development. The WRAPS reports have two parts: impaired waters have strategies for restoration, and waters that are not impaired have strategies for protection. The first WRAPS cycle went from 2008 through 2016. This report is from 2018 through 2026.

Waters not meeting state standards are listed as impaired, and total maximum daily load (TMDL) studies are developed for them and a TMDL is written. The TMDLs are incorporated into the WRAPS reports. In addition, the watershed approach process facilitates a more cost-effective and comprehensive characterization of multiple water bodies and overall watershed health, including both protection and restoration efforts. A key aspect of this effort is to develop and use watershed-scale models and other tools to identify strategies for addressing point and nonpoint source pollution that will cumulatively achieve water quality targets. For nonpoint source pollution, the WRAPS report informs local planning efforts, but ultimately the local partners decide what work will be included in their local plans.

Figure 3. Location of the LFRW within Minnesota and the Rainy River Basin.



2. Watershed background and description

The LFRW is one of the largest major watersheds in Minnesota. It drains 1,843 sq mi and is in a remote portion of the Rainy River - Lake of the Woods (LOW) Basin (Figure 3). The watershed is remote with sparse road access in many locations. It is common to have stream sections spanning more than 30 miles between crossings and there is one stream section that is over 50 miles between road crossings. It is the largest U.S. tributary, by volume, of the Rainy River, which separates United States from Canada. The headwaters of the Little Fork River begin in Lost Lake, approximately 6 miles West Northwest of Tower, Minnesota, and flows north approximately 160 miles through a heavily forested and wetland landscape to the Rainy River.

A total of 16 Hydrologic Unit Code -12 scale (HUC; for more information on HUC please see U.S. Geological Survey [USGS] Hydrologic Unit of the United States webpage) subwatersheds comprise the LFRW (Figure 5). They range in size from 111 to 680 km^2 (43 to 262 mi^2). The watershed is sparsely populated and spans three counties- Itasca, Koochiching, and St. Louis, and Bois Forte Band of Chippewa tribal lands. In addition, the Bois Forte Band of Chippewa and Grand Portage Band of Lake Superior Chippewa have hunting, fishing, and gathering rights in the 1854 Ceded Territory, which includes the headwaters of the LFRW (Figure 6). A small portion of the SW LFRW is in the 1855 Treaty Area, where Leech Lake and Mille Lacs Bands of Chippewa preserved hunting and gathering rights.

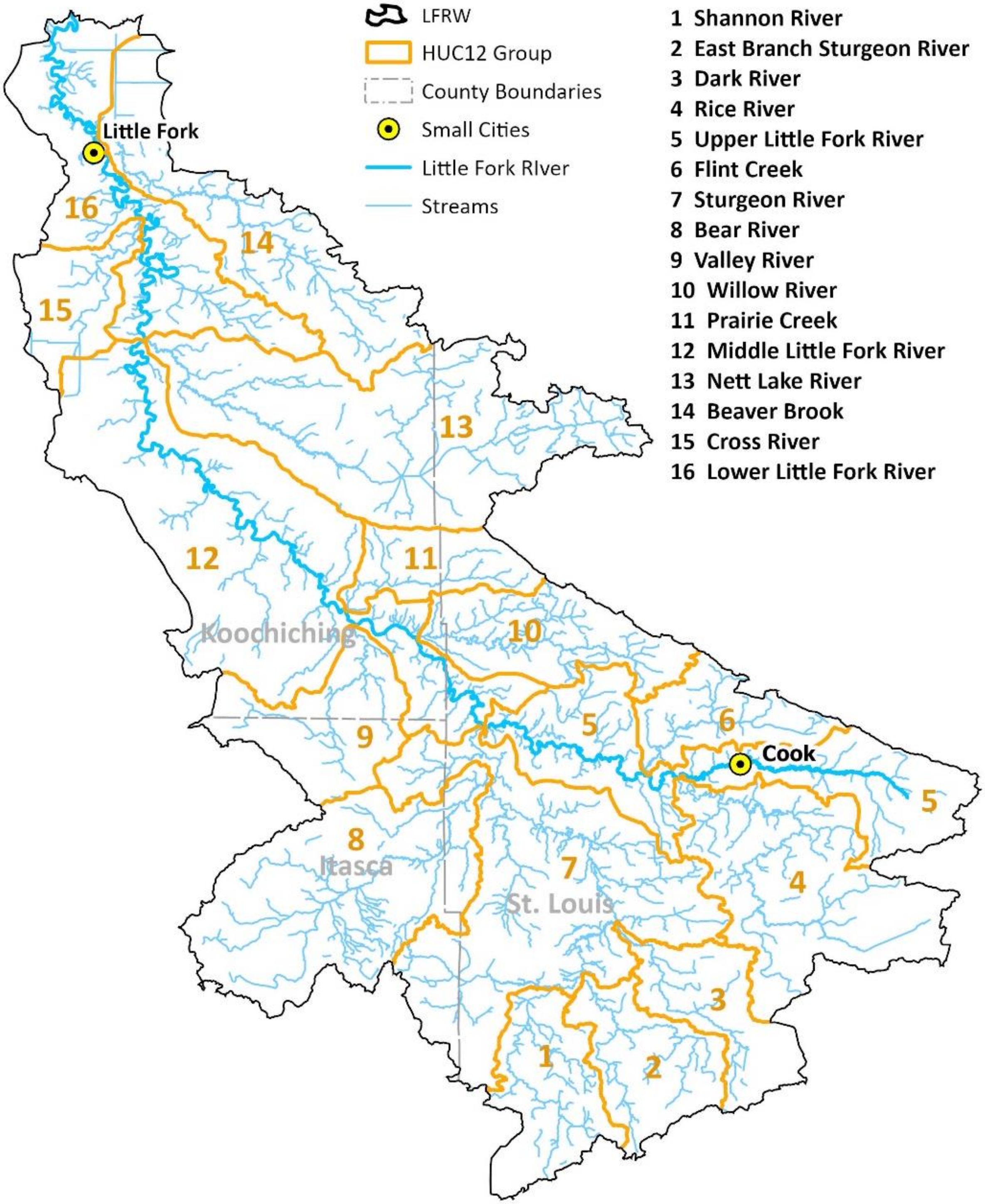
Fifty-two percent of the land in the watershed is publicly owned, including several state forests. Private and corporately owned land makes up 44% of the watershed, and the Bois Forte Band of Chippewa Reservation land makes up the remaining 4% of the watershed.

Portions of four state forests, five state wildlife management areas, and the Chippewa National Forest are all part of the LFRW. McCarthy Beach State Park is also located on Sturgeon and Side Lakes in the headwater lake region.

Prior to intensive logging beginning in the 1890s, the LFRW contained considerable areas of mixed red and white pine forest. During the time of extensive logging (1890s to 1937) the river served as an important means of transporting the harvested logs downstream to the Rainy River, where several sawmills were located. Land use in the LFRW has remained steady for many years, with iron ore mining, forestry, and tourism/recreation dominant land uses. The main communities in the LFRW include Cook (population 523), Little Fork (population 543) and Nett Lake (population 297) along with many smaller communities. More detailed land use and LFRW background information can be found in the Cycle 1 Little Fork River Watershed Restoration and Protection Strategy Report.

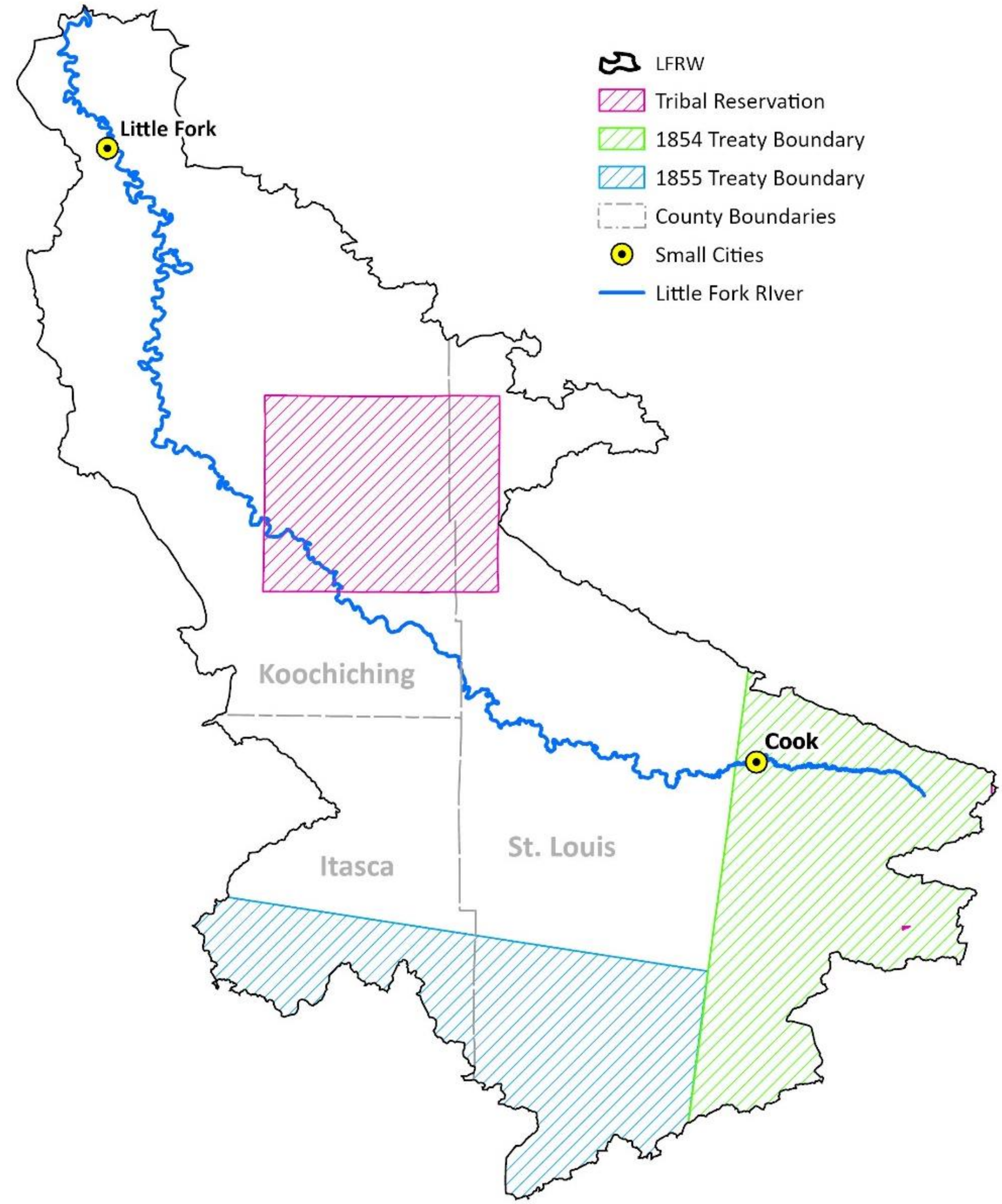
Figure 4. A winter view upstream from the Silverdale bridge.

Figure 5. The HUC-12 scale subwatersheds of the LFRW.



Partnerships and cooperation are strong within this watershed among the Itasca, Koochiching, and North St. Louis Soil and Water Conservation Districts (SWCD), the Bois Forte Band of Chippewa, and state partners. The work is supported by effective communication, active information sharing, and a continued interest in strengthening partnerships and coordination. Although the Bois Forte Band faces capacity challenges due to its remote location, they remain invested in pursuing future projects that address watershed concerns.

Figure 6. Tribal lands (Reservation and treaty) in the LFRW.



The partnership decided to focus on one priority restoration and one protection priority in this report. This will help the few staff at the local level develop actions to accomplish their work. Extremely high concentrations of sediment and resulting turbidity and TSS impairments in the stream network, became the focus for the partners in the restoration aspect of the report. Local conservation partners identified SCL as the protection focus of this report.

3. Assessing water quality

The MPCA and local partners monitored water quality conditions in lakes, rivers, and streams within the LFRW in 2008-2009 and again 10 years later in 2018-2019 to assess whether water bodies meet water chemistry standards protective of aquatic life (AQL), aquatic recreation (AQR), and aquatic consumption uses (AQC), and if conditions had changed between the two time periods. The overall goal of these assessments is to ultimately determine which waters are healthy, need protection, or are polluted and require restoration.

The first round of monitoring in 2008-2009 revealed a mix of healthy headwater lakes, widespread sediment issues in numerous riverine systems, very good to excellent biological communities in both streams and lakes, and a willing and able mix of local government partners dedicated to working on the LFRW. The second round of monitoring found much the same as the first round and trends were similar.

Overall, monitoring results have shown little to no change in water quality within LFRW streams and lakes over the past decade. Despite high levels of sediment in the stream system, the LFRW continues to support thriving aquatic communities. The condition of fish and macroinvertebrate communities within the Little Fork stream network as measured by the fish or macroinvertebrate index of biotic integrity (FIBI or MIBI), has largely remained the same since 2008. The various lakes in the LFRW remain healthy as well; however, climate change signals and increased human pressures have fostered increasing warmer conditions and at times enough to form harmful algal blooms. The presence of extensive forests and numerous wetlands, combined with the low amount of human land disturbance, maintains the excellent condition of aquatic communities. However, challenges remain in protecting the lakes in the headwaters of the system.

Figure 7. Deadmans Rapids in low water condition, Koochiching County, MN.

Should you be interested in water quality data for select rivers and lakes in the watershed, beyond what is mentioned in this report, see the MPCA Water Data Viewer.

3.1 Streams

Assessment decisions for the LFRW Cycle 2 monitoring data were made in 2020. There were 36 Water Body Identifications (WIDs) assessed for AQL use and 16 WIDs were assessed for AQR use. Sampling locations are shown in (Figure 9). Of the assessed WIDs for AQR, one (Flint Creek 09030005-588) was determined to not be supporting AQR due to *Escherichia coli (E. coli;* bacteria). Among the WIDs assessed for AQL use, three were found to be not supporting AQL, and seven others were either inconclusive or had insufficient information to make an assessment. The Rice River was taken off the impaired waters list because the most recent data collected in 2018 strongly indicate that this stream supports AQL. The 2012 and 2015 sampling for this stream were conflicting in their interpretation, and an additional sample was needed to ensure the correct biology is present in the stream. Assessment results for streams are shown in Figure 10 and Figure 8. For more information, please see Little Fork River Watershed assessment and trends update.

Three new stream WIDs were found to have biological impairments (i.e., do not meet AQL use standards) during Cycle 2 and include: Johnson Cr - 679 (F-IBI and M-IBI), Gilmore Cr - 594 (MI), and Timber Cr - 630 (M-IBI). Johnson and Gilmore Creek impairments were investigated and determined to be EPA category 4D (Natural Background) and 4C (nonpollutant stressor) respectively, meaning a TMDL is not needed. The “natural background” designation was due to beaver impoundments and wetlands causing low dissolved oxygen leading to reduced biological diversity. The “nonpollutant” stressor in Gilmore Creek was determined to be low oxygen due to beaver activities and a low gradient flow pathway.

Timber Creek was determined to be impaired for AQL, with reduced sensitive macroinvertebrate taxa, due to elevated specific conductivity (high ionic concentration) and low dissolved oxygen; the latter may be partly natural due to wetland headwater habitat. The ionic composition is due to the presence of alkalis, alkaline earth compounds, major cations, and major anions, which collectively determine the total ionic salinity of the water. This is assessed in the field with a probe that measures conductivity (the water's ability to conduct electricity), indicating the presence and concentration of dissolved ions. There is a taconite mine tailings basin that is adjacent to Timber Creek. The reissued National Pollutant Discharge Elimination System (NPDES)/State Disposal System (SDS) Permit through the MPCA's Industrial Division will include requirements to further evaluate the tailings basin and its discharges and will include monitoring and/or limits, as necessary, as required by state and federal regulations to restore Timber Creek. For a complete identification of impaired water bodies for all pollutants in the Little Fork Watershed, please see the Minnesota's impaired waters list.

Figure 8. MPCA staff Jesse Anderson and Nolan Baratono conducting a geomorphic survey on the Little Fork near Samuelson Paek, Koochiching County, MN.

Figure 9. Biological and multiple-visit chemistry monitoring sites used in the stream assessment process for the IWM Cycle 2 effort for the LFRW.

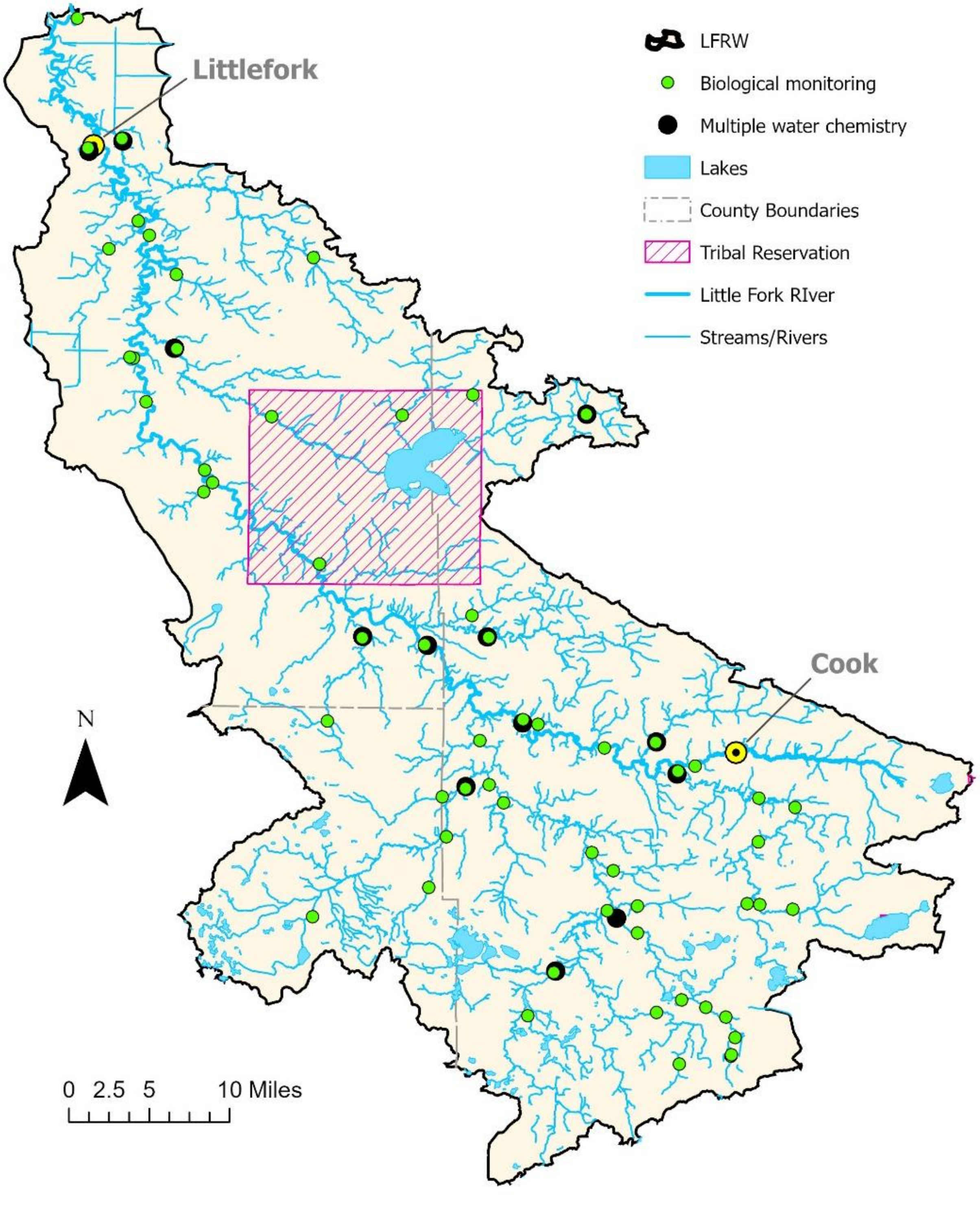


Figure 10. Stream assessment results for AQL uses.

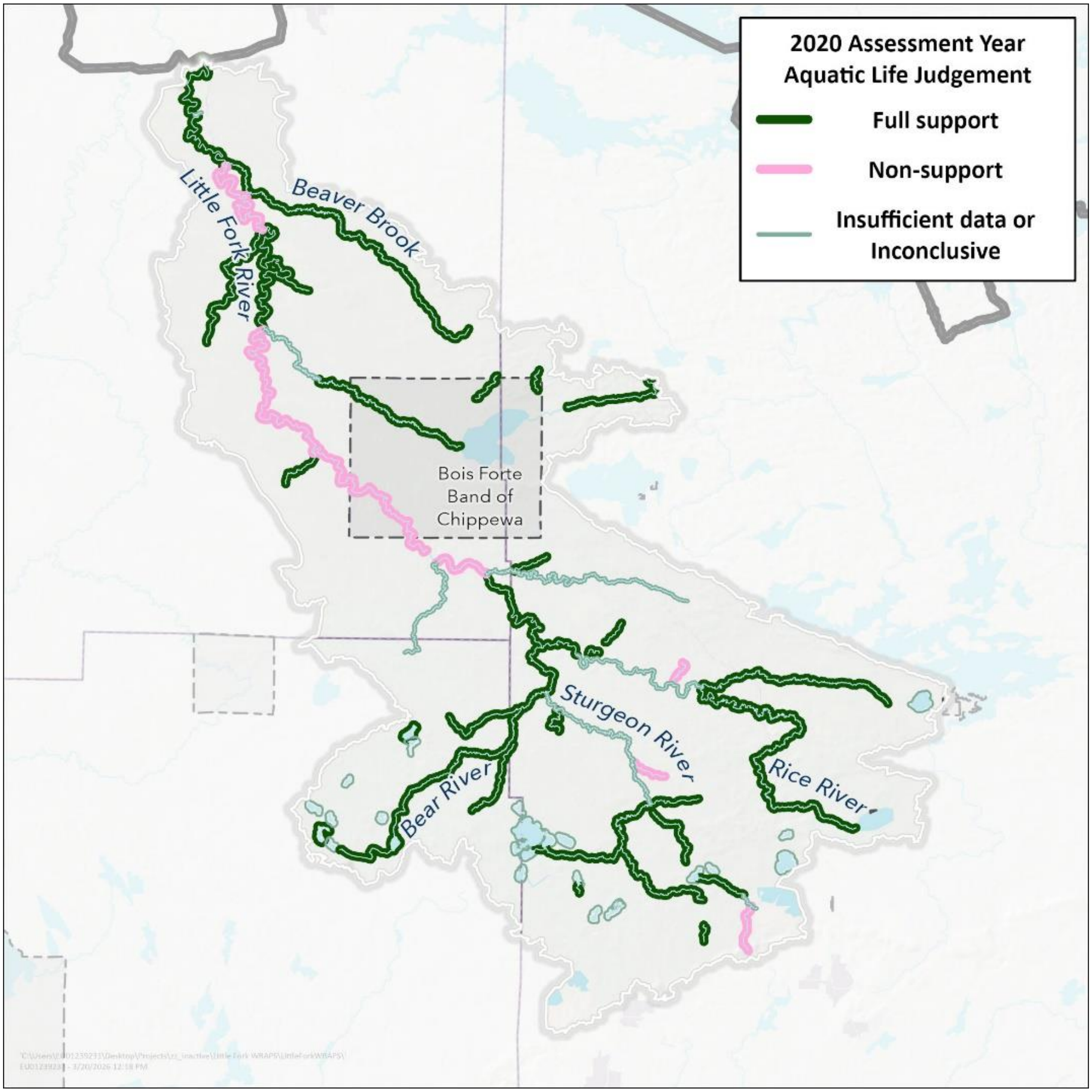
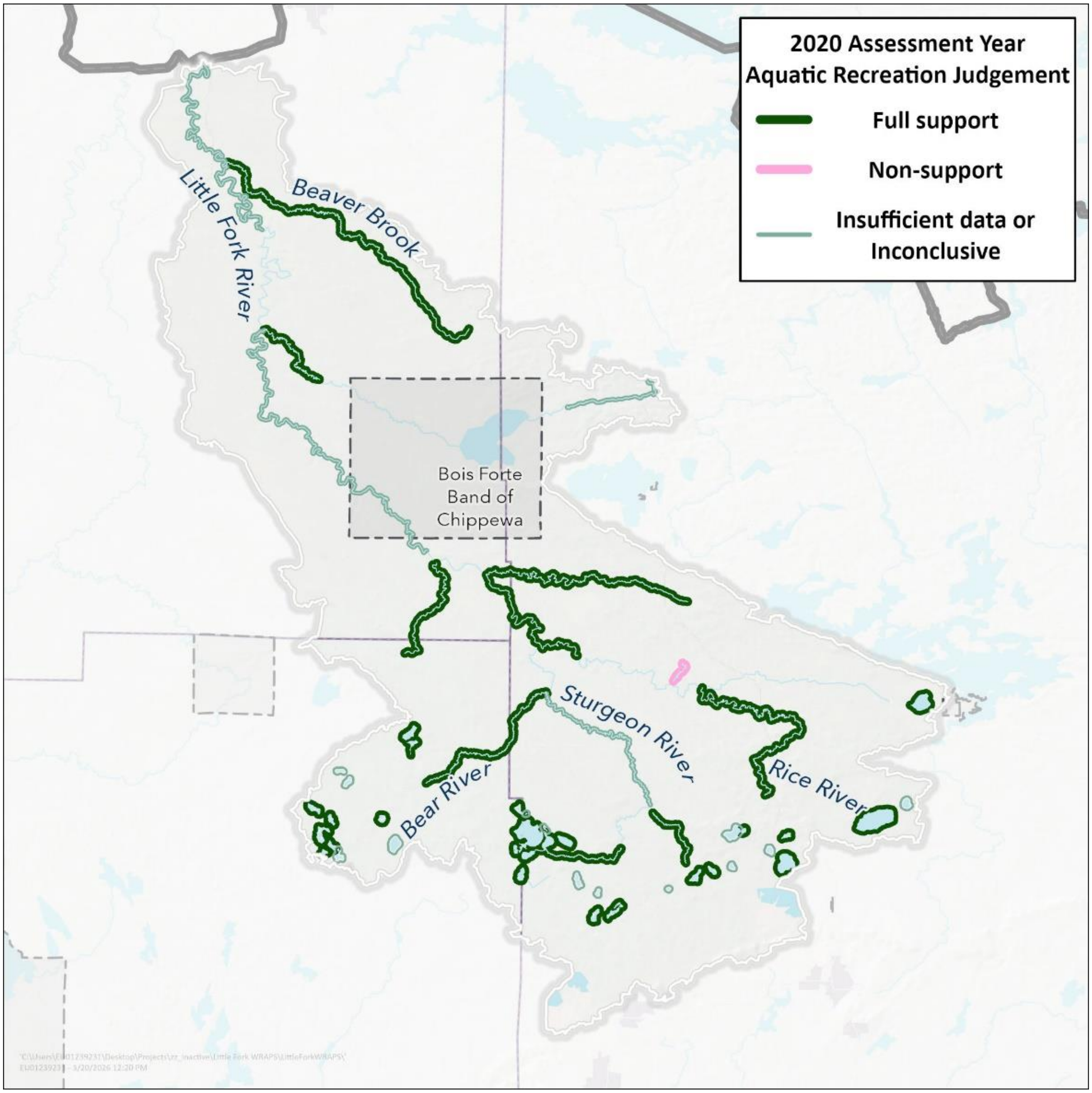


Figure 11. Stream assessment results for AQR uses.



The AQR impairment on Flint Creek, 09050003-588 was investigated by MPCA watershed scientists. Several locations have been sampled at various flow regimes to understand and potentially isolate the sources. It is believed that sources of *E. coli* may be entering the stream from cattle operations adjacent to the stream segment -588. More work is required to isolate the exact areas, and then opportunities for BMP installations can be discussed. More information can be found in the Little Fork River Watershed Stressor Identification Report and the Little Fork River Total Maximum Daily Load Report.

In 2018, Minnesota adopted changes to its water quality standards (Minn. R. chs. 7050 and 7052) that establish a Tiered Aquatic Life Uses (TALU) framework for rivers and streams. This rule amendment affected Class 2 (AQL) standards. The EPA approved the TALU framework rule in late 2018, resulting in several Little Fork River stretches being moved into the highest tier of protection, the "Exceptional Use" tier of the TALU classification framework. This presented interesting challenges for the LFRW, as often when excess sediment input occurs, the AQL becomes less diverse and declines in health.

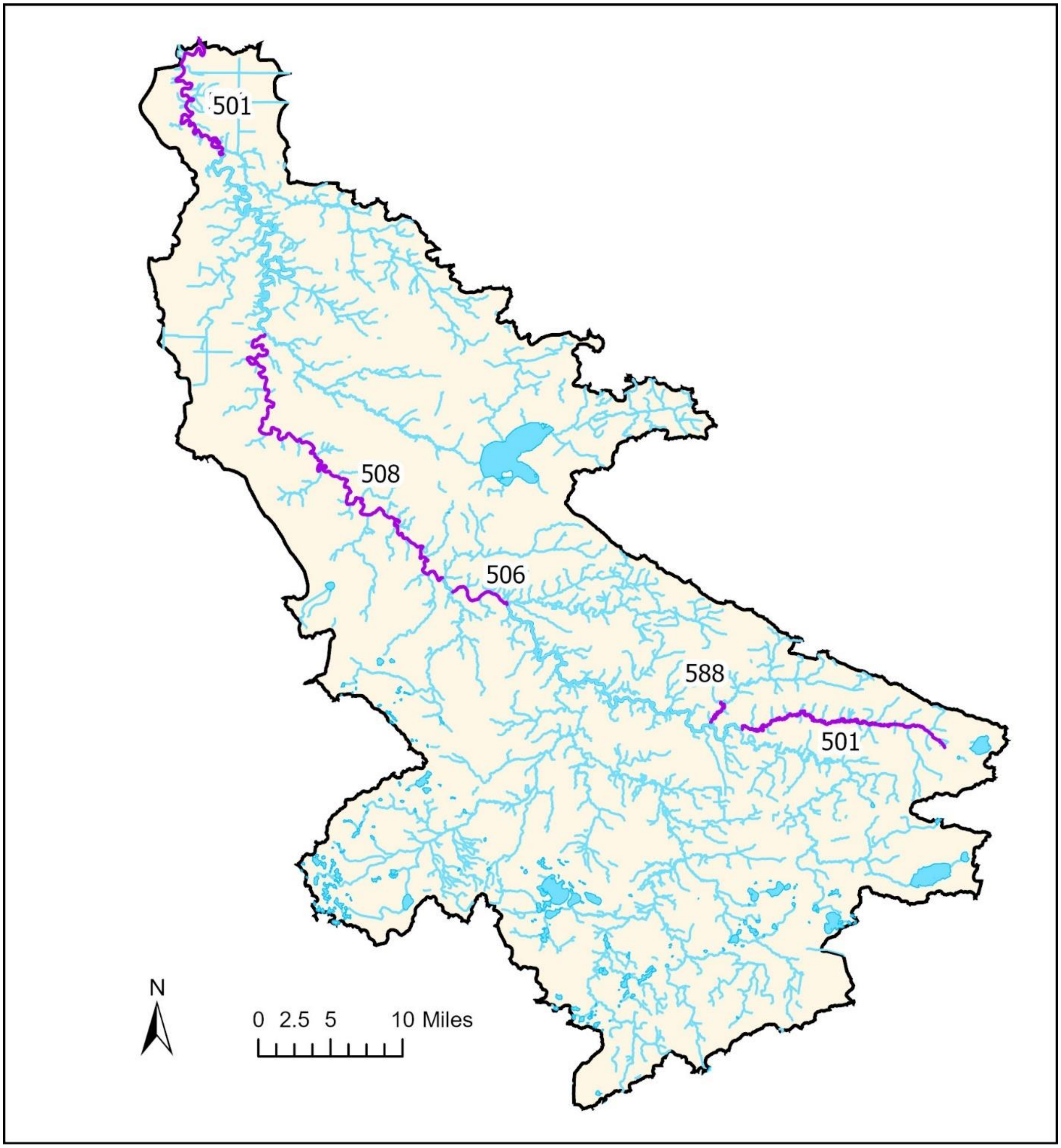
The Little Fork River watersheds' aquatic communities meet and often far exceeded the standards designed to protect AQL. In fact, over 50% of the stream fish communities sampled scored in MPCA's Exceptional classification range. Over 76 miles of the Little Fork River and 38 miles of the Sturgeon River have been designated as Exceptional Use waters because of the high quality of the fish and macroinvertebrate communities (Figure 12). Other exceptional waters include the lower 14 miles of the Nett Lake River and portions of the Bear and Shannon Rivers.

Figure 12. LFRW WIDs that attain the biological threshold of being classed as Exceptional Use within MPCA's TALU standards framework.

The LFRW is somewhat unique in that the heavy sediment loads it carries do not impact the biotic communities (macroinvertebrates and fishes). As an example, over 50 miles of the main stem of the Little Fork River are impaired by TSS and yet meet MPCAs Exceptional Use category for the [Tiered Aquatic Life Uses---MPCA](). The Little Fork River sediment loads are often three to four times the State TSS standard of 15mg/L for this ecoregion (Figure 13).

To better understand the sources of and drivers of heavy sediment loads in Flint Creek Watershed, additional geomorphological work was conducted by Minnesota Department of Natural Resources (DNR) on the middle WIDs of Flint Creek. For more information on that work please see [Little Fork River Watershed Stressor Identification Report]().

Figure 13. Map of the TSS impaired WIDs of the LFRW.



Past studies have been completed by various agencies on the sediment loads in the Little Fork River. These provide a good context for understanding sediment in this system:

- Application of Dimensionless Sediment Rating Curves to Predict Suspended-Sediment Concentrations, Bedload, and Annual Sediment Loads for Rivers in Minnesota (2020)

  Provides consistent and reliable sediment data that are needed by federal, state, and local government agencies responsible for monitoring water quality, planning river restoration, quantifying sediment budgets, and evaluating the effectiveness of sediment reduction strategies.

- Suspended-sediment concentrations, loads, total suspended solids, turbidity, and particle-size fractions for selected rivers in Minnesota, 2007 through 2011 (2014)

  The U.S. Geological Survey, in cooperation with the MPCA, established a sediment monitoring network in 2007 and began systematic sampling of suspended-sediment concentrations, total suspended solids (TSS), and turbidity in rivers across Minnesota to improve the understanding of fluvial sediment transport relations.

- Effect of Historical Logging on Geomorphology, Hydrology, and Water Quality in the Little Fork River Watershed (2006)

  Extensive stands of pine and pulpwood were historically logged from the 1890s to 1937. This study was designed to further document the turbidity and sediment concentrations in the mainstem of the Little Fork River from the Rainy River confluence to the headwaters, and to provide information needed to determine the scope and likely sources of turbidity impairment for the upcoming TMDL study.

- Little Fork River Channel Stability and Geomorphic Assessment - Final Report (2007)

  This geomorphic study of the LFRW served to (1) support the weight of evidence that the history of logging was the mechanism responsible for the stream's impairment; (2) determine the causes of the river's present-day instability.

- Suspended sediment in Minnesota streams (1986)

  Suspended-sediment samples were collected by the U.S. Geological Survey from 115 sites on Minnesota streams since October 1960. Data from 42 sites were sufficient for characterizing sediment concentrations and yields.

As stated, the Little Fork River is the largest of the four major rivers in the U.S. portion of the Rainy River-LOW Basin. Because phosphorus (P) binds to sediment particles, the loads of sediment originating from the LFRW are of concern in relation to the need to decrease P loading to LOW (Figure 14). The LOW has an EPA-approved TMDL study for AQR due to Excess Nutrients, which calls for a 37% reduction in P coming out of the LFRW. After learning of the sediment loading issues in the Cycle 1 WRAPS, as well as the Little Fork River Watershed Monitoring and Assessment Report, the MPCA, local partners at Itasca SWCD, Koochiching SWCD, and North St. Louis SWCD, and the USGS began examining sediment throughout the watershed. Work as part of Cycle 2 was focused on sediment sources, transport, temporary storage, and export. This also included evaluating the relationship between sediment and biologically available P bound to sediment upon entering LOW.

Figure 14. The confluence of the sediment-laden Little Fork River flowing into the Rainy River at Pelland, MN on April 26, 2022.

Challenges remain in reducing sediment and P loading to the Rainy River, and ultimately to LOW. Understanding the basic sediment budget and sources of fluvial sediment has been difficult due in part to the watershed size and remoteness, and the complexity of these issues. Intensive land uses, such as cultivated agriculture, are nearly absent in the watershed, at only between 100 and 500 acres of the 1800 sq mi watershed. Mining lands account for less than 1% of land use, and urban lands only account for 2% of the landscape.

3.2 Lakes

Lakes are abundant in LFRW and provide important base flow to the headwaters of several Little Fork River tributaries, such as in the Sturgeon, Bear, and Dark River subwatersheds. There are 165 lakes in the watershed, and most are in the southwest portion. Located in the lake-rich headwaters region, the SCL is the protection focus of this report.

The MPCA and local county SWCD partners monitored 28 lakes in the watershed, ranging in size from 77 acres (Kelly Lake) to 1920 acres (Big Rice Lake). Results overall indicate an abundance of high-quality lakes, with 26 of 28 lakes meeting regional eutrophication standards for total phosphorus (TP), algae (chlorophyll-*a*), and Secchi transparency. The remaining two lakes, Shannon and Bear, did not meet standards; these lakes periodically have high P and chlorophyll-*a* concentrations, and low Secchi transparency. Both lakes are shallow lakes with abundant wetlands in their watersheds; in these settings, it is common for shallow lakes to naturally exceed water quality standards and have low water clarity.

Nine lakes were also sampled and assessed for AQL in the Cycle 2 LFRW IWM using a process developed by the DNR for the lake fish community. Four of the nine lakes were not assessable, as metrics for that type of lake had not been developed (Button Box, Lost, Sand, and Fourteen lakes). Two lakes had insufficient data (Beatrice and Little Bear lakes), and three lakes were fully supporting AQL (Bear, Thistledew, and Owen lakes) and these three also attained Exceptional Use status (Figure 15). Like for flowing waters, these fish communities reflect the cumulative effects of natural and human-caused influences on a lake's contributing watershed (a.k.a., lakeshed). Overall, fish diversity was low relative to many other watersheds within Minnesota. This is likely caused by the geology of the area, where there is generally low alkalinity and low inter-lake connectivity, which could make colonization difficult for some fish species. A total of 25 fish species were captured in the lakes during fish IBI sampling. Six of these species are considered intolerant to anthropogenic stressors within the watershed (e.g., blackchin shiner, blacknose shiner, Iowa darter, mimic shiner, rock bass, smallmouth bass) while two species are considered tolerant to these stressors (e.g., black bullheads and fathead minnows).

The largest lake in the watershed, Nett Lake, is located entirely within the boundaries of the Nett Lake Reservation of the Bois Forte Band of Chippewa and therefore was not sampled or assessed by the MPCA. This 7,400-acre shallow lake contains extensive stands of wild rice and is a very important cultural resource for Tribal members. The lake is believed to be the largest wild rice body in the United States. The Bois Forte Department of Natural Resources and Ecological Resources Department continuously monitors water quality on this lake and adjacent streams.

Figure 15. Location of the three lakes assessed as having TALU Exception Use level fish communities.

The focus for protection in the LFRW is the SCL, a small headwater lake system in the southwest portion of the watershed. This small system of connected lakes (Big Sturgeon, West Sturgeon, South Sturgeon, Little Sturgeon, and Side Lake) and two nearby lakes (Perch and Beatrice) all are currently meeting water quality parameters for recreation use. However, the ability for these lakes to maintain this "unimpaired" status will require the greater Sturgeon Lakes community to be vigilant, in addition to concrete conservation actions taken by the community landowners.

4. Priority Focus Areas

Based upon the work conducted in Cycle 1, and in consideration of local partner priorities and interests, as well as community surveys, addressing the high sediment loading challenges in the Little Fork River and its tributary network, and protection of the Sturgeon Lakes area have been identified as priority focus areas for the LFRW in the coming years. This does not mean that there are no other water quality issues or challenges in the watershed; this is just the current focus. There are still several stream impairments for *E. coli*, a recreational use impairment, and many other areas for protection consideration. These *E. coli* impairments are certainly more approachable restoration opportunities than the sediment restoration challenges. The following sections focus on the protection (SCL) and the restoration (sediment issues in the stream network) priorities of the watershed. For information on other water quality opportunities outside of the two focus areas, please see Chapter 8 of this report.

4.1 Sturgeon Lakes Subwatershed Protection Priority

The Sturgeon River Subwatershed in the southwestern portion of the LFRW contains five interconnected lakes, the SCL (Figure 17). This popular resort/recreational area also includes two additional unconnected lakes in proximity to the Surgeon Chain, Perch, and Beatrice. The SCL area straddles the Itasca/St. Louis County line and has local government representation in two townships, one in each county. This subwatershed is the focus of protection efforts in the LFRW.

Most of the lakes in the SCL need further protection for cold water species present in the lake, lake whitefish and cisco. Protecting coldwater fish habitats in Minnesota lakes is a priority and new standards to protect these habitats have been drafted. For more information please see: Development of water quality standards to protect coldwater lake habitats in Minnesota (December 2025).

To learn more about coldwater habitat protection needs in applicable lakes, view the DNR presentation on YouTube Ciscos - Minnesota lakes' keystone fish species (approx. 1 hour). The presentation explains how the warming climate is putting a “summer squeeze” on the area within the lake that these fish can survive in during the summer months. When there is a long ice-free season and hot summer temperatures, oxygen can become depleted in the colder, deeper part of the lake in the summer months because the warm upper layer that exchanges oxygen from the atmosphere does not mix with cold water on the bottom due to water density differences. This puts thermal stress on coldwater fish species because they must move out of the cold water to seek oxygen. As more nutrients (P) enter the lake, production of algae increases, and the more algae blooms there are. The more algae that dies and sinks to the bottom, the more it uses up the cisco’s oxygen, as bacteria consume oxygen during their decomposing of the dead algae.

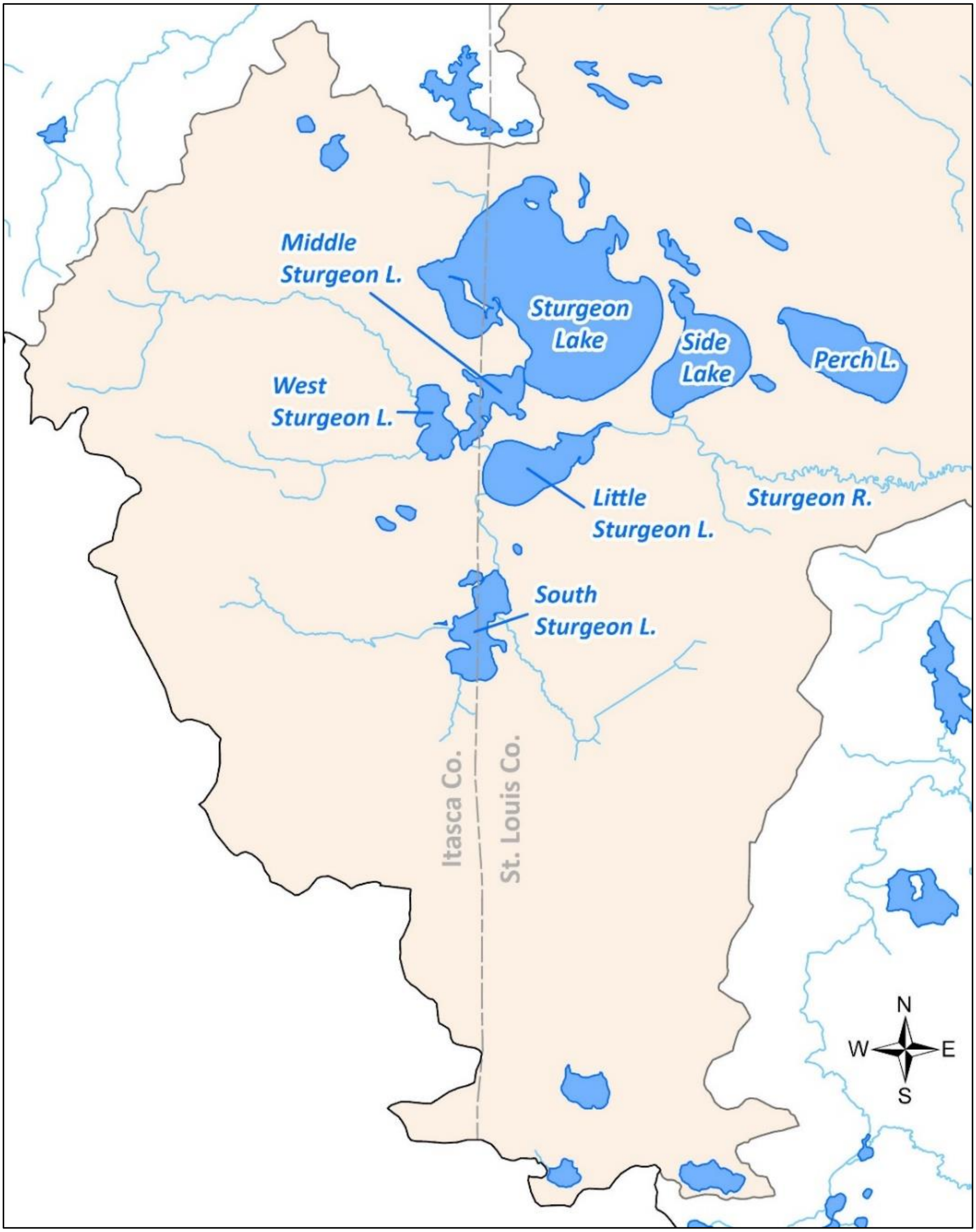
The DNR has developed a tool called Watershed Health Assessment Framework (WHAF). This tool helps citizens and water quality professionals understand, manage, and protect Minnesota's watersheds as complex, interconnected natural systems. In the WHAF tool for lakes, a lake health score is used; if you would like more information on how these scores were derived, please see the DNR WHAF Lake Health Scores webpage.

Citizen volunteers have worked for many years collecting water quality data on the SCL. These efforts have established long-term water transparency data records that have been very helpful in developing a better understanding of their water quality. Three of the lakes (Sturgeon, West Sturgeon, and Little Sturgeon) have statistically significant declining trends in transparency. A nearby high-quality lake, Beatrice, with 30 years of citizen-collected transparency data, also has a declining trend. The cause is likely not associated with anthropogenic land use change, as Beatrice Lake has limited shoreland development and a very small watershed that is mostly forested. Climatic changes are the likely cause of declining transparency. Chapter 0 provides more information on climate change.

implications in the LFRW. Over the decades, the reduction in clarity within these lakes has generally been less than one foot per decade. Perch Lake is the only lake in the Chain that has increasing clarity. Keeping these lakes in their un-impaired condition is a high priority for residents, MPCA, and local conservation partners at North St. Louis SWCD and Itasca SWCD.

Figure 16. Typical ravine in the lower Little Fork River main stem.

Figure 17. The SCL and other lakes in close proximity within their HUC-12 subwatershed boundaries (tan-shaded area).



Sturgeon River

The Sturgeon River main stem, originating out of the SCL, flows east. This WID (09030005-527; 12 miles long) of the river has excellent water quality and is supporting AQL and AQR uses, meeting Northern Lakes and Forest (NLF) ecoregion expectations. However, this stretch of river is listed as impaired for Wild Rice Production due to sulfate and AQC due to mercury in fish tissue. Wild rice and local fish are culturally critical to the Bois Forte community, who historically and currently harvest wild rice and fish in the area. Water quality challenges with mercury and sulfate are difficult to address, often expensive to reduce, and are typically beyond the capacity of local partners to address. The MPCA is developing plans with industrial permit holders in the region to address these issues. For more information on mercury impairments in waters of the state please see Mercury and Water Quality. For more information on sulfate impairments and the MPCA approach to this issue, please see Protecting wild rice waters.

Shannon River and Lake (69093901)

Downstream from the Chain of Lakes approximately 4.5 river miles, the Shannon River enters the Sturgeon River. The Shannon flows approximately 14 miles from its headwaters, through Shannon Lake to the Sturgeon River. The upper Shannon River does not have recent biological data and has few water quality data points. The lower WID of the Shannon River supports exceptional fish and macroinvertebrate communities. Three intolerant macroinvertebrate taxa were collected during sampling, including two sensitive species of caddisflies (*Neureclipsis* and *Oxyethira*). An intolerant fish species (lamprey ammocetes) was captured during both fish sampling visits made in 2018 along with numerous insectivorous taxa and lithophilic spawners (blackside darter, golden redhorse, common shiner). This robust fish community is present even though this WID has been severely impacted by beavers and has a low gradient.

Moving upstream, Shannon Lake is a 133-acre warmwater lake with three miles, over 90%, of undeveloped shoreline. This lake does not meet water quality standards for recreation, as these lakes periodically have high phosphorus and chlorophyll-*a* concentrations, and low Secchi transparency. The lake is approximately two miles upstream from the mouth of the Shannon River and has many species of fish such as walleye, perch, northern pike, and others. Compared to other lakes in the watershed, Shannon Lake ranks below average in water quality and biology, and average in hydrology. The DNR WHAF score for this lake is a C+. The lake is rated as sensitive to P addition and scores in the “high protection” category, according to the DNR Lakes of Phosphorus Sensitivity Significance.

Sturgeon Lake Chain

A short water quality summary was developed for each of the major lakes in the SCL protection area as follows:

Sturgeon Lake (69093901)

Often referred to locally as “Big” Sturgeon, it is the largest lake in the system at slightly over 1,500 acres, with a mean depth of 26 ft, maximum depth of 80 ft, and just over 10 miles of shoreline. This lake meets recreational water quality standards. The lake also features a popular swimming beach at McCarthy Beach State Park and contains many warmwater fish species as well as cisco and lake whitefish, two coldwater species that are important prey for some gamefish like walleye. Most of the lake, 85%, is inside French Township in St. Louis County, and the western 15% of the lake is in Bearville Township in Itasca County.

Compared to other LFRW lakes, Sturgeon ranks average in water quality, biology, and hydrology. The DNR WHAF score for this lake is a B. While this lake has outstanding biology, it is highly sensitive to phosphorus loading and possesses average hydrological scores.

West Sturgeon Lake (69093903)

West Sturgeon is 117 acres, with a mean depth of 16 ft, a maximum depth of 31 ft, and 2.2 miles of shoreline. The lake has many warmwater fish species as well as the coldwater species cisco. West Sturgeon is entirely in Bearville Township of Itasca County.

Compared to other LFRW lakes, West Sturgeon ranks average in water quality, biology, and hydrology. The DNR WHAF score for this lake is a B. Water quality wise, this lake is very sensitive to P and scores in the “highest protection need” category. The biology in the lake is above average, with high quality plant and animal community features. Hydrologically the lake scores as average with high lakeshed health scores.

As with Sturgeon Lake above, West Sturgeon Lake is a candidate for protection. New standards to protect the coldwater habitat portions of the lake are proposed.

South Sturgeon Lake (31000300)

South Sturgeon is 204 acres and is very similar in size and water quality as West Sturgeon. It has a mean depth of 24 ft, a maximum depth of 43 ft, and 3.7 miles of shoreline. This lake meets recreational water quality standards. The lake has a NE-SW alignment, with the southwestern part of the lake in Itasca County and the northeastern part of the lake in St. Louis County, at 44% and 56% respectively. The lake has a variety of warmwater fish species as well as the coldwater species cisco.

Compared to other lakes in the watershed, West Sturgeon ranks average in water quality, biology, and hydrology. The MN DNR WHAF score for this lake is a B. It is rated sensitive to P and scores in the “higher protection needs” category compared to other lakes in the watershed, according to WHAF. Like Sturgeon and West Sturgeon lakes, it is a candidate for protection of coldwater habitat. New standards to address the coldwater habitat portions of the lake are proposed.

Little Sturgeon Lake (69129000)

With 3.6 miles of shoreline, Little Sturgeon Lake has a maximum depth of 22 ft and is just over 270 acres in size. It is of similar size and water quality to other lakes. This lake meets recreational water quality standards. The lake contains an assembly of warmwater species such as walleye, perch, northern pike, and others. There are no cisco or whitefish present. The lake is entirely in St. Louis County and French township.

Compared to other LFRW lakes, Little Sturgeon ranks average to just below average in water quality, just above average for biology, and high/above average for hydrology The DNR WHAF score for this lake is a B. Water quality wise, this lake is sensitive to P and scores in the “high protection” category compared to other lakes in the watershed. The overall biology in the lake is above average, with quality plant and animal community features. Hydrologically the lake scores average and has high lakeshed health scores.

Side Lake (69093300)

Located just downstream from Little Sturgeon, Side Lake is about 368 acres with 4 miles of shoreline and has a maximum depth of 32 ft. This lake meets recreational water quality standards. It is connected to the other lakes in the SLC by the Sturgeon River. The lake site entirely within St. Louis County and French Township, and much of the shoreline is part of McCarthy Beach State Park. The lake has a variety of warmwater fish species as well as the coldwater species cisco.

Compared to other LFRW lakes, Side Lake ranks above average in water quality, biology, and hydrology. The DNR WHAF score for this lake is an A+. Water quality wise, this lake is sensitive to P and scores in the “highest protection” category compared to other lakes like it in the watershed. Overall biology in the lake is high, and hydrologically the lake scores very well with high lakeshed health scores.

As with other lakes in this subwatershed, Side Lake is also a candidate for protection of its coldwater habitat. New standards to address the coldwater habitat portions of the lake are proposed.

Perch Lake (69093200)

Located very close to the SCL but not connected to it is 344-acre Perch Lake, which has over 3 miles of shoreline, a mean depth of 12 ft, and a maximum depth of 21 ft. It is located entirely in St. Louis County’s French Township. This lake meets recreational water quality standards. Perch lake has a variety of warmwater species such as perch, walleye, northern pike and others.

Compared to other lakes in the watershed, Perch Lake ranks slightly above average in water quality, biology, and hydrology. The DNR WHAF score for this lake is an A. Water quality wise, this lake is sensitive to P and scores in the “highest protection” category compared to other lakes like it in the watershed. The overall biological communities in the lake are very healthy, with quality plant and animal community features. Hydrologically the lake scores very well with high lakeshed health scores.

Beatrice Lake (31005800)

Featuring over 4 miles of shoreline, mean depth of 11 ft, and a maximum depth of 28 ft, this 124-acre lake has a very small lakeshed area and is often referred to as a seepage lake (one without an outlet, or inlet). This lake meets recreational water quality standards. The lake is almost entirely in Itasca County with only 6% in St. Louis County. Compared to other lakes in the watershed, Beatrice Lake ranks slightly above average. The DNR WHAF score for this lake is an A. Water quality wise, this lake is sensitive to P and scores in the “highest protection” category compared to other LFRW lakes. The overall biology in the lake is high and hydrologically the lake scores very well with high lakeshed health scores.

Protection Strategies for the Sturgeon Subwatershed

- Identify and assist landowners with opportunities to improve shoreline and near-shore waters for improved water quality
- Offer technical assistance to Sturgeon Chain of Lakes community members/owners to implement BMP projects on their property to improve water quality
- Develop and implement a grant program for septic repair/replacement
- Continue to support and grow the Sturgeon Chain of Lakes Citizen Lake Monitoring Program

- Offer grant programs or cost share opportunities for BMP projects for lakeshore landowners

The entire subwatershed is sensitive to P inputs. Historically, these water bodies have met water quality standards but usually fluctuate just above the impairment threshold or just below the impairment threshold every year. In conversations with local conservation partners and community members, harmful algal blooms seem to be happening more frequent than the historical frequency of every three to five years, and are usually happening every year since 2015. With anticipated further changes in climate, this subwatershed of lakes and streams are vulnerable to changes that may push these lakes into recreationally impaired status, and possibly impaired for their coldwater status. Once a lake is determined to be impaired, it is difficult and expensive to reverse. This is why it is important to highlight this subwatershed as a priority for protection in the LFRW.

The SCL community is aware of and actively involved in the health of their lake system. The active Sturgeon Chain of Lakes Association, established in 1999, has six different committees to address various challenges in the lakes. These programs and the Association are staffed by dedicated volunteers.

In 2021, the local conservation partners and Sturgeon Chain of Lakes Association developed a small survey to understand those water quality attributes that are most important to local citizens in the subwatershed. The top five issues on the minds of residents regarding water quality include (in order): Water levels, aquatic invasive species, algae blooms, erosion, and septic systems. Half the respondents to the survey feel the SCL water quality is getting worse, and half the respondents indicate the water quality is about the same as it has always been. This indicates there is room for education in the community about water quality issues and potential solutions. For more information, the survey can be viewed in Appendix C.

The MPCA, North St. Louis SWCD, and Itasca SWCD staff toured the SCL and nearby stream sections in late summer 2023. Observations revealed several opportunities to work with local landowners to implement conservation practices on the landscape. Of note were:

- Opportunities to develop better buffering between the lawns and the lake through native plantings.
- Opportunities to partner with landowners to educate about the conservation practices that could apply to their property (DNR Score the Shore: a citizen shoreline description survey, Itasca County SWCD Lake Stewardship and other programs).
- Opportunities to inspect, upgrade, repair, or replace septic systems that are not functioning effectively.
- Opportunities to educate local landowners about basic lake ecology and living on a lake sustainably.
- Opportunities to grow the volunteer citizen lake monitoring in the subwatershed.

In summary, the Sturgeon River Subwatershed is a healthy, vibrant watershed system and community. Water quality has largely been unchanged for the past 25 years. However, with climatic changes more recently occurring and those anticipated in the coming years, this subwatershed's lakes may be in danger of falling into impaired status, reducing their recreational desirability.

4.2 Little Fork Sediment Restoration Priority

AQL impairments due to excessive sediment or turbidity are a chronic water quality issue in the majority of LFRW's stream network. This near-wilderness river system is situated on the southeastern portion of the Glacial Lake Agassiz lakebed, formed thousands of years ago from deposits of silt, clay, and sand. This downstream transport of sand, silts and clays has resulted in several AQL impairments based upon excess sediment or turbidity in both the Little Fork River's main stem and several of its tributaries.

In 2017, the *Little Fork River Watershed Restoration and Protection Strategy Report* identified several WIDs that were impaired by turbidity (this standard changed to TSS in 2014). Local partners had little knowledge of the source of the sediment or the contributing factors to high sediment loads. The first report recommended that an intensive sediment study be conducted to better understand the erosion, storage, transport, and sources of fluvial sediments in the stream network.

Staff from the Koochiching, Itasca, and North St. Louis SWCDs partnered with the University of Minnesota-Duluth, MPCA, and USGS to intensively study sediment dynamics in the watershed system. This research focused on the relationship between sediment, P delivery to the Rainy River, and the resulting contribution to algal blooms in LOW.

The research questions developed by the local team include:

- What are the sources of sediment?
- Where are the sediment sources?
- How much is eroded, stored, and transported?
- Do the sources change seasonally?

It was determined that a sediment budget and sediment fingerprinting could be very useful tools to understand these complex dynamics in the Little Fork Watershed system. A sediment budget would determine how much sediment enters the watershed system and how much is stored in the system. The fingerprinting component would determine the soil types that the sediment originated.

Starting in 2021, over 120 discreet upland soil samples were collected across the watershed to compile a record of the various soil types and land uses. Land use types included mature forest, clear cut/disturbed forest, wetland, agricultural fields, and unpaved roads. Soil samples were also collected from near-channel sites of gullies/ravines, headwaters streambanks, and mainstem riverbanks within the impaired WIDs. In addition, the team developed a method to sample the high waters of spring runoff in this large river system using a pump and barrel syphoning system developed by team members. Lastly, summer 2021 was a dry year, resulting in extended periods of very low stream flows. The low water conditions allowed exceptional conditions to conduct more than 30 Rapid Geomorphic Assessments (RGA) and install eight passive suspended sediment samplers in the streams co-located at river gages. However, low water did not transport much sediment in the 2021 open water season, and the river nearly broke its 80-year history of record for lowest flow.

The open water season of 2022 allowed for more normal spring runoff and flows for the year. Sediment samples were obtained at spring runoff flows, several rain events, and low water flows. In addition, upland sampling gaps from 2021 were identified and re-sampled. Together with some samples collected in 2021, the river sediment samples collected in 2022 were of adequate volume for the fingerprinting component.

The complement of water samples, RGA, and land soil samples allowed for a full examination of the amount of sediment in the system being transported and stored (budget) and an indication of source apportionment of the sediment collected in-stream (fingerprinting). Additionally, the study used MPCA WPLMN data in conjunction with the data collected at the study's eight gaged sites. The MPCA WPLMN program is a partnership including state and federal agencies, Metropolitan Council Environmental Services, state universities, and local partners across Minnesota.

Since 2007, the network of partners has collected data to understand long-term trends and observe changes over time. Passive sediment samplers were set at four sites on the main stem of the Little Fork River, and four others set on tributaries (Willow River, Valley River, Nett River, and Sturgeon River). Below is a high-level summary of the results of the sediment budget and fingerprinting studies. Greater detail can be found in the two peer-reviewed scientific papers developed as an output of this work. For further information on the methods, results, discussion, and conclusions, as well as suggestions for future work please see Appendix A (Sediment budget paper) and Appendix B (Sediment fingerprinting paper).

4.3 Key Sediment Budget Findings

Initial sediment budget estimates, considered to be accurate within an order of magnitude, indicate that there is approximately 130,000 MT (1 MT equals 2204 lbs) of corridor near-channel erosion and a total of 840,000 MT of soft streambed sediment deposition. About 50% of the erosion is estimated to be from short, steep-sloped channels in ravines, especially those that intersect the valley sides of the Little Fork River downstream of its confluence with the Sturgeon River. In contrast, most of the soft streambed sediment deposition are in headwater low-gradient channels surrounded by wetlands and containing beaver impoundments. The soft sediment to erosion ratio for the basin is five. This ratio suggests there is an average of approximately five years' worth of stored sediment in stream channels sourced from upstream erosion. This simple ratio averages spatial variability in locations of relatively high erosion rates versus areas of high soft sediment deposition. These estimates were used to complement the fingerprinting apportionments of sediment from the six identified upland sources.

As stated earlier, erosion rates were highest along the Little Fork River mainstem and adjacent ravines that intersect its valley sides, downstream of its confluence with the Sturgeon River (Mile 114: DNR Canoe Trail). The sediment budget approach used in this work indicated that erosion in ravines, mapped using the 10-m Digital Elevation Models' extended network, may account for approximately 50% of the total budget. The resulting GIS-based maps developed for this project 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. To see the detailed stream network, erosion rates for ravines, and the sediment mapping tool developed to assist local partners, please see Appendix F.

Of the total corridor erosion (130,000 MT/yr) nearly 39,000 MT/yr was from the fine-grained silt and clay portion of the load. Of the four tributaries studied with annual TSS data, the fine-grained portion of erosion comprised the majority of the TSS. The soft sediment deposition estimates suggest that overall, the Little Fork River temporarily stores sediment. If all erosion stopped from the corridor and uplands, it would take approximately five years or more, depending on floods, to evacuate all the soft, deposited sediment from the streambed. This is a highly conservative estimate of time for evacuation of this sediment, given the large amount of soft sediment stored in headwater beaver-impounded WIDs, and it is likely that all 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.

For more information on sediment budgeting methodology and findings please see Appendix A.

4.4 Key Sediment Fingerprinting Findings

Sediment fingerprinting was significant in understanding the basic land types and apportionment of the originating sources of fluvial sediment. Those land types include stream channel, bank, gullies/ravines, harvested forest lands, dirt/gravel roads, agriculture lands, and mature forest lands. These sources can change seasonally and with differing stream flow regimes. Sediment was collected from four stream locations on the main stem and from four tributaries (Willow, Valley, Nett, and Sturgeon). For easy reference the Little Fork River State Water Trail was used to describe locations in this section.

In the most downstream portions of the Little Fork main stem (Mile 114: DNR Canoe Trail), the dominant sediments are from stream channel, banks, and ravines, with very small amounts detected from harvested forest types and banks (Figure 18 and Figure 19). This typically occurs at all stream flow regimes. As one moves upstream to the Little Fork at Hwy 65 (Mile 59: DNR Canoe Trail), dominant sediments are still from stream channels, banks, and ravines, however there are also small signals from dirt roads, harvested forest, and a small amount from agricultural land.

Figure 18. Typical stream bank erosion along the Little Fork mainstem.

Figure 19. Mile 34.5 of the Little Fork Canoe Trail showing bank failure.

Upstream portions of the Little Fork main stem reveal changes in sediment sources. The Silverdale site (Mile 100: DNR Canoe Trail) reveals a switch to a more diverse set of sources including dirt roads, harvested forest, and agriculture, in addition to ravines and eroding banks. The sediment apportionment is relatively equal among those five sources. Continuing to the most upstream main stem gage, at Linden Grove (Mile 127: DNR Canoe Trail), the sources change to the majority coming from agricultural settings and dirt roads, with small amounts deriving from forested area.

The Nett River is a medium size tributary of the Little Fork, having a drainage area of 217 sq mi., and with an impoundment at the headwater lake, Nett Lake. The headwater lands and first four to six miles of stream belong to the Bois Forte Band of Chippewa. Fingerprinting of sediment from early spring run-off to mid-June in the Nett River revealed sediment sources from ravines and recently harvested forest lands. As flows naturally decline in mid-summer to low flows of the fall, sediment sources change to include banks, ravines, harvested forest lands, dirt/gravel roads and agricultural lands.

Valley and Willow rivers are smaller tributaries to the Little Fork, encompassing 73 and 74 sq mi drainage areas respectively. In the Valley River's Watershed, ravines and harvested forest lands account for most of the sediment with smaller amounts deriving from dirt/gravel roads and agricultural lands in early summer (run-off through July). However, for the lower flow periods of late summer and fall, the sources switch to mostly agricultural land and dirt/gravel roads, along with ravines. The Willow River has a similar pattern of sediment sources and seasonality.

The Little Fork River's valley contains numerous natural ravines adjacent to the main stem of the river. Generally, ravines are defined as steep-sided or V-shaped valleys that are larger than gullies but smaller than canyons. They may contain perennial or intermittent streams but are typically formed when moving water incises and erodes a channel into the underlying material.

Informing sedimentation restoration strategies for the Little Fork Watershed

- Develop further understandings of sediment in the Little Fork system.
  - Identify ravines and prioritize them for sediment contributions to the system.
  - Prioritize, target and measure sediment savings from various BMP opportunities to treat erosion and effectiveness in the Little Fork main stem and impacted tributaries.
  - Explore a pilot project for a ravine system(s), understand causation of ravine(s), sediment transport, and treatments for sediment control.
- Identify landscape level opportunities for upland BMP treatments in watershed.
- Identify habitat improvement opportunities with DNR and other groups for fisheries spawning, rearing, and other life-stage habitat needs.
- Educate landowners and raise awareness of erosion issues and what they can do on private property in the LFRW.
- Identify data gaps needed and explore implementing Site Specific Standards for TSS in LFRW.

Ravines are the product of focused runoff flowing down the valley walls causing a specific area of streambank erosion. There are many ravines in the system with small watersheds (often < 5 sq mi) and involving small numbers of landowners that could be used as a pilot BMP study or for detailed ravine studies to try to identify causes of these highly erosive ravines. For more information on the sediment fingerprinting project please see Appendix B.

Further investigation of ravines is warranted to find local opportunities suitable for BMP treatments to reduce erosion and sediment transfer to the river's water. BMP applications in agricultural lands, working forest lands, and dirt/gravel roads are identifiable and have a long history of successes statewide. Ravines and banks can be targeted as they often are large, localized sources of sediment contributions. Application of BMPs in these instances can help stabilize a specific ravine; however, at a system-wide scale, they are not an option for fully reducing sediment to meet water quality standards; the cost would be prohibitive. BMPs to address banks and bluffs are also good investments to protect infrastructure; however, like ravines, are not an option for controlling enough sediment to meet water quality standards, again, due to cost.

Attenuating the flows by creating water storage has often been used in heavily dominated agricultural lands but is not as practical in heavily forested landscapes such as the LFRW. There may be opportunities to store water using small BMPs at pasture edges where more runoff can occur than from forest lands. This may be particularly helpful where a gully is also present.

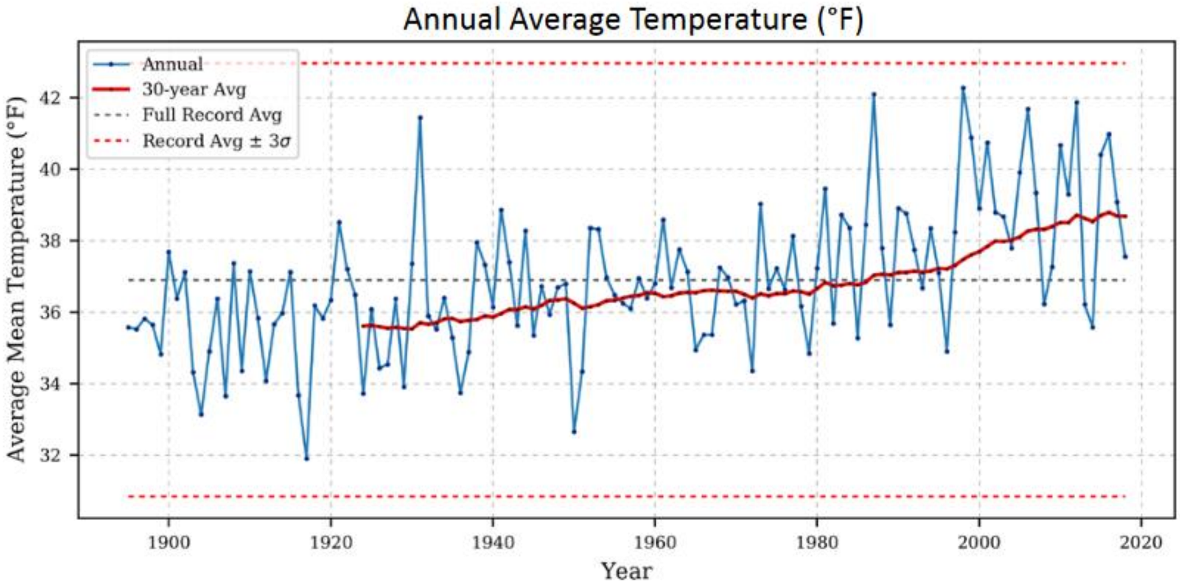
In conclusion, there are sediment BMP opportunities in the upper reaches of the Little Fork River and possibly in the lower reaches. In addition, costs and benefits of projects will need to be examined very closely as the amount of sediment in the system is extremely high. See Section 7 for summary recommendations.

Figure 20. MPCA staff Mike Kennedy and North St. Louis County Soil and Water District staff measuring a large ravine in the lower Little Fork Watershed.

5. Climate Change

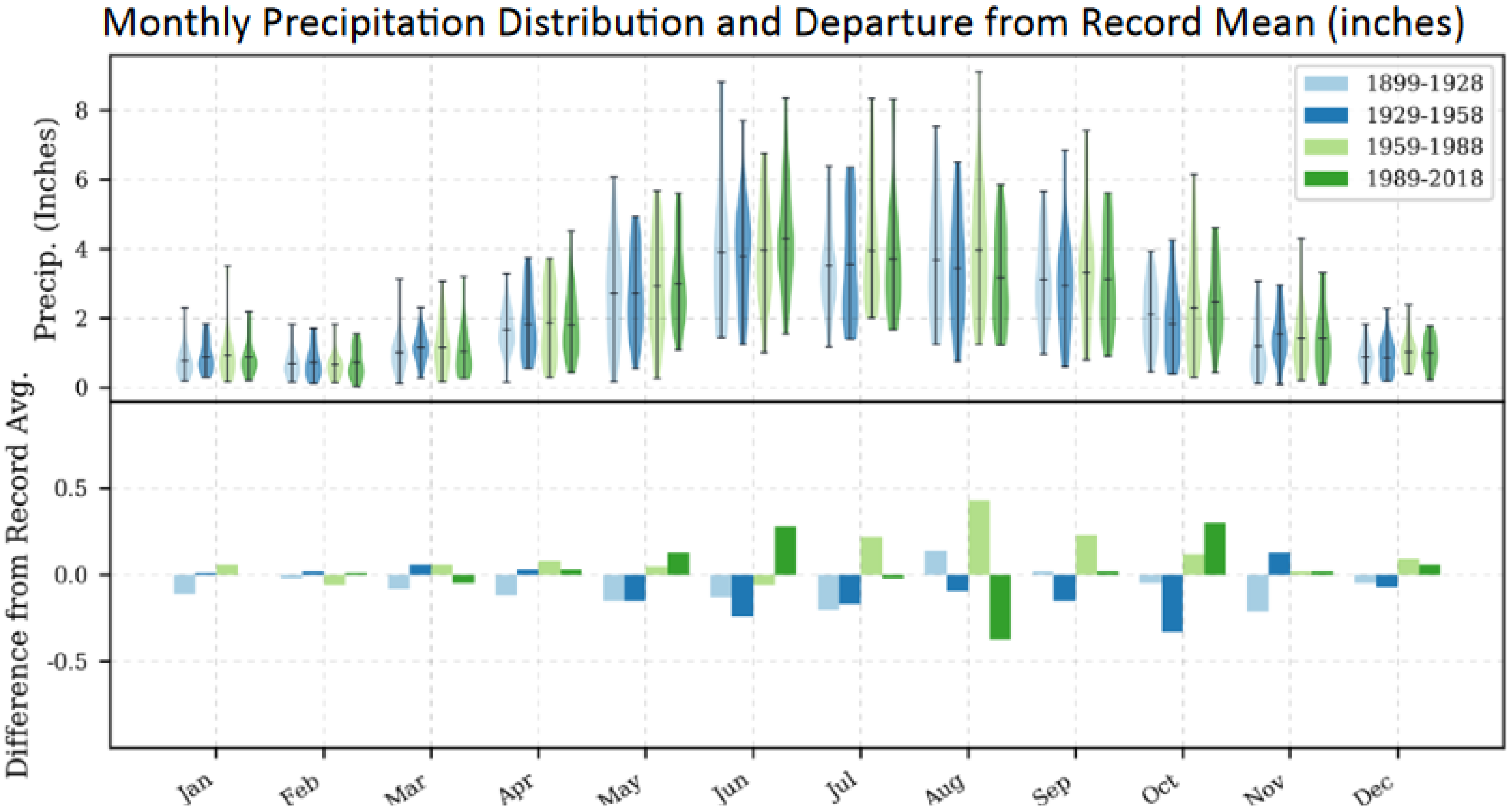
The *Climate summary for watersheds: Little Fork River Report (DNR 2019)* shows that annual average temperatures in the LFRW have increased over the last century and that most years during the past three decades have been warmer than average (Figure 21). Monthly average temperatures in the LFRW peak in July, and winter temperatures on average have increased over time.

Figure 21. Annual Average Temperature in the LFRW (DNR, 2019).



Annual precipitation has also shown an upward trend across the watershed. Monthly precipitation is typically highest in May and June and increases in precipitation in recent years were most pronounced in June to August (Figure 22). The frequency of one to three inch rain events has increased in general in Minnesota, along with the size of the heaviest rainfall of the year. Minnesota has experienced an increase in devastating, extreme rainstorms, covering large swaths of land. Climate projections indicate these big rains will continue increasing into the future.

Figure 22. Monthly precipitation distribution and departure from record in the LFRW (DNR, 2019)



Statewide lake data collected by the DNR, MPCA, and local partners shows that the climate trends described above have already impacted lakes throughout the state and region. According to MPCA's Climate Change and Minnesota's Surface Waters Viewer, lake surface temperatures have warmed during all seasons throughout Northern Minnesota. During the summer growing season (June through September), lakes in northern Minnesota are, on average, warmer now than they were 50 years ago. Additionally, warmer winters have resulted in about 10 or more fewer days of ice coverage on average for lakes throughout the northern region since the mid-1970s.

Reduced ice coverage, higher year-around water temperatures, and more intense and frequent precipitation events can result in significant impacts to lakes and lake users, including but not limited to (MPCA 2021):

- Overall increase in flow, sediment, and nutrient loading from the lake drainage area.
- Longer periods of stratification and anoxia resulting in increased internal P recycling.
- Longer open water and growing season for algae and cyanobacteria blooms.
- Larger fluctuations in lake level from year to year.
- Potential for increased densities of aquatic invasive plants, such as curly-leaf pondweed (CLP) and Eurasian watermilfoil (EWM).
- Decreases in walleye (which prefer summer water temps at 65˚F to 70˚F) in smaller, warmer lakes.
- Potential for more fish kills as fish are squeezed into smaller zones of sufficient oxygen.
- Shortened season for safely recreating on ice-covered lakes.

Changes in the LFRW climate are happening, and local citizens and governmental organizations need to address these changes by incorporating climate resiliency planning for infrastructure repair and replacement. As county, city, and townships replace culverts, bridges, stormwater treatments and other important infrastructure it is important to accommodate new trends in temperature and precipitation into the effort. Homeowners also should be aware of these changes and build them into future landscape planning as well.

For a more detailed overview of climate changes for north central Minnesota (LOW, Beltrami, Koochiching, Itasca, Cass, and Hubbard Counties) please see the University of Minnesota Climate Adaptation Partnership.

6. Environmental Justice

The LFRW community spans portions of three counties in North Central Minnesota, Itasca, Koochiching, and St. Louis. A mainly rural, heavily forested area, which has lost year-round population in the past 50 years, but gained seasonal recreational properties, many of which are on rivers or lakes. Major drivers of economic activity in the LFRW are dominated by tourism and the forest products industry. All three counties are below the national per capita income range and of the 87 Minnesota counties rank 29th (St. Louis), 36th (Koochiching), and 59th (Itasca) (United States Census Bureau, 2023/2024).

Not all communities in the LFRW have good access to internet resources. This is certainly a limiting factor in communicating and sharing information and work in the watershed. To this end, the MPCA and local conservation partners are very strategic in planning meetings in the watershed at times and locations that are easy to attend. Often attendance is better in person than online in this watershed, and many attendees have been “regulars” at meetings since WRAPS work began in 2008.

Bois Forte Band of Chippewa have one of their major land holdings in the watershed at Nett Lake. Nett Lake is a small community that straddles the St. Louis County and Koochiching County border and has a population of 183 people on 1.7 sq mi. Twenty percent of the population is below the poverty line with an average household income of $35,000 per year. The MPCA and local partners have consulted the Band’s Natural Resource Department for advice on meetings at Nett Lake about the LFRW. Band members and staff have been key partners in Little Fork River Watershed water quality work, but with limited capacity.

Local partners have learned that having a meeting in the lower portions of the watershed and then repeating the same meeting in upper portions of the watershed have been most successful. Offering an opportunity to hold a special meeting on Nett Lake is the best way to build involvement and capacity with the Bois Forte Band.

A special focus of this report is the protection efforts in the SCL, surrounding the unincorporated area of Side Lake. To understand the community aspects of the Side Lake area, local partners used the EPA Environmental Justice Screening Tool. Using a 10-mile radius around Side Lake revealed several sociodemographic factors that may be of interest in working with community members on water quality issues. With the center of a 10-mile radius at Side Lake, there are approximately 1,762 people in the identified area of 314 sq mi. The demographic results in this area of interest (10 sq mi radius around Side Lake) are contained in Figure 23 and Figure 24.

Figure 23. Graphic of the 10-mile radius around Side Lake, Minnesota (the central community in the SCL protection project area) indicating several social dimensions of the community.

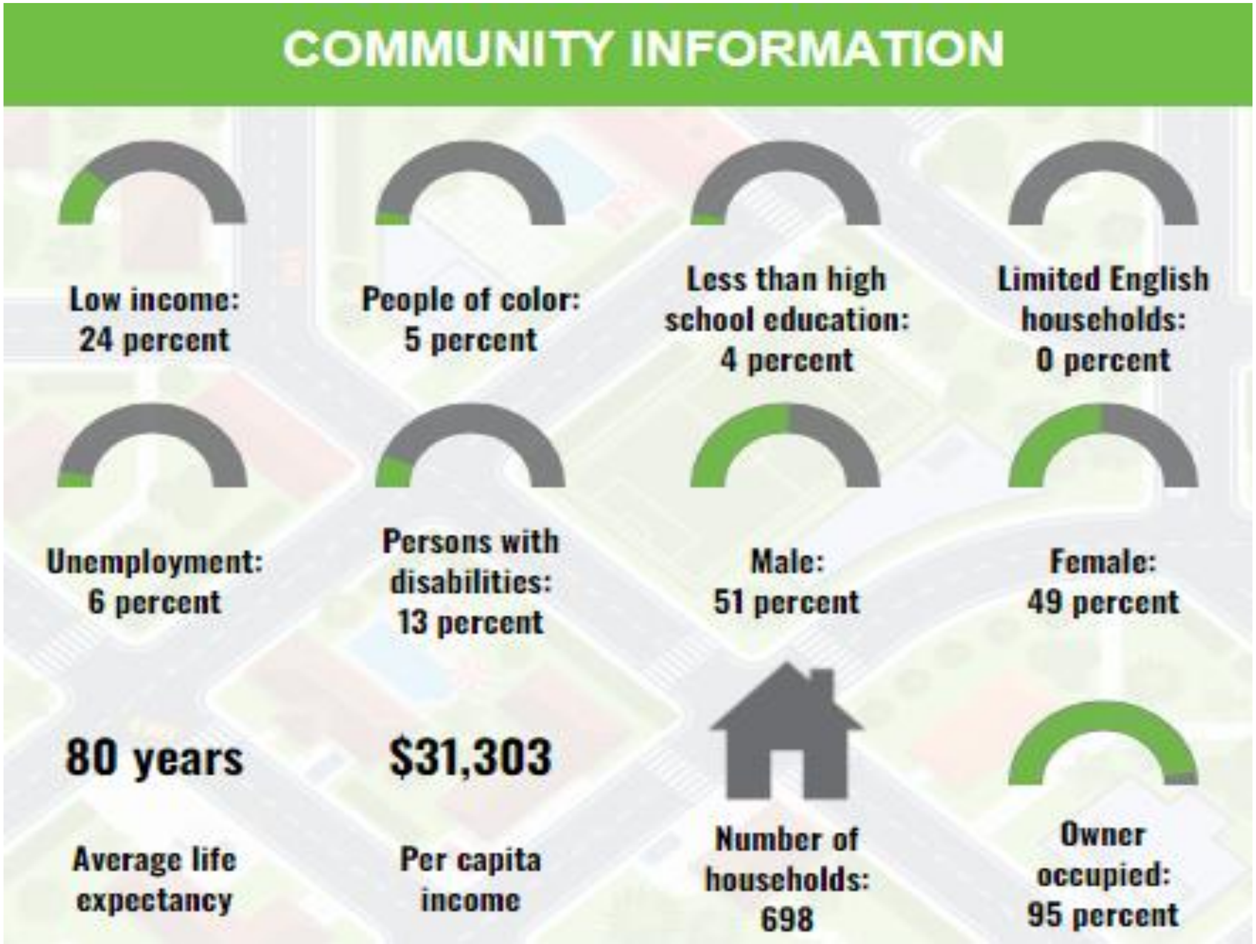


Figure 24. Six key socio-economic indicators of the Side Lake, Minnesota protection project area.

Socioeconomic Indicators	Value	State Average
People of Color	5%	20%
Low Income	24%	23%
Unemployment Rate	6%	4%
Limited English Speaker Households	0%	2%
Less than High School Education	3%	7%
Broadband Internet	14%	11%

The MPCA and local conservation partners have been highly attentive to the specific socio-economic needs of the Side Lake focus area. Efforts are centered on educating the public, developing technical assistance, and fostering active collaboration to protect the water quality of this vital resource. Data indicates that while community members within the SCL protection area often have low income levels, internet service remains accessible to most residents. However, most of the year-round residents are retired and do not prefer learning about the watershed in an online format, and prefer learning in person, according to survey work the partners have conducted. To better serve this community, the partnership intends to host more frequent in-person meetings in the headwater regions, ensuring that information regarding water quality is distributed effectively without placing an undue burden on residents.

In the broader LFRW, the partnership is committed to a strategy that reduces the travel burden for its low-income residents, who often face long drive times and high fuel costs to attend central meetings. This approach includes scheduling more frequent in-person sessions in both the headwaters and lower watershed areas to ensure equitable access to information. Furthermore, at the request of the Bois Forte Commissioner of Natural Resources, the partnership will hold special meetings dedicated to the Bois Forte Band. This tailored engagement ensures that critical water quality data reaches all corners of the community while respecting the time and resources of local members.

Figure 25. Fielder Landing, Mile 44.5 of the Little Fork River Canoe Trail

7. Goals to Meet Water Quality Standards and Fully Support Uses

Water quality goals for the LFRW are varied and include focus areas of biology integrity and sediment control.

Biological integrity of the Little Fork River system is high, with good and exceptional quality fish and macroinvertebrate populations despite excessive sediment loads. Over 76 miles (48% of the entire 160-mile flow length) of the Little Fork River have been designated as exceptional use waters, which are those having fish and macroinvertebrate communities that are like the communities that existed before European settlers inhabited the region. Maintaining and increasing the number of miles in the exceptional use category is a top priority.

Sediment control is a challenge. It remains to be seen if BMPs can effectively reduce the concentrations of TSS in the Little Fork stream system. However, there are proven BMP opportunities in the small urban centers, upland forest and agricultural lands of the watershed and according to the fingerprinting work, as discussed in Section 4.

Continued work to identify the "root causes" of the extensive ravine systems throughout the watershed, but especially downstream of the Nett River confluence in the lower Little Fork River will be key to understanding if BMPs can reduce the sediment in the system below the 15 mg/l standard.

Short term goals for sediment in the watershed include:

- Reduce sediment inputs at upper watershed gages of Valley, Willow, Sturgeon River, Linden Grove, and Silverdale. Fluvial sediment samples indicated agricultural, harvested forest, and roads dominated the sediment sources throughout all flow regimes of the open water season in this part of the watershed.
- Conduct a full investigation and develop an understanding of the lower watershed ravines that contribute to the sediment load.
- Conduct a full examination of data to assess the need for and development of Site-specific water quality standards for sediment, if it is determined that the statewide standard is not appropriate for this situation.

Long-term goals are:

- Increase or maintain biological integrity and function in the LFRW, inclusive of wetlands, streams, and lakes.
- Special protection focuses and efforts are especially needed in the SCL as these lakes have historically been very close to the impairment threshold for many years and may lose their cold water assemblage of fish.

Local citizens and watershed community members are encouraged to continue to engage and assist in monitoring the lakes and streams in the LFRW, as they have for many years. This data has been instrumental in water quality work over the past 10 years and will be important into the future.

8. Restoration and Protection

It is important to improve or maintain water quality in the LFRW. It is more cost effective to fix smaller manageable issues before they manifest into larger ones that are cost prohibitive. Restoring water resources that have become impaired is costly, difficult, and can take long periods of time. While this report focuses exclusively on the priorities of local conservation managers of Itasca, Koochiching, and North St. Louis SWCDs, other water quality opportunities also exist in the watershed. See Table 1 below for all the impaired waters in the LFRW.

Tools have been developed to assist the local water quality partners in developing action plans to address maintaining the high-quality waters across the watershed, to examine the lakes of the watershed, and to assist in examining streams.

8.1 Stream Prioritization

The stream protection and prioritization tool is designed to generate a prioritized list of streams, see Table 2. The list is based on the results of water quality assessments, the level of risk posed from near shore areas, the level of risk posed from the contributing watershed, and the level of protection already in place in the watershed. The tool utilizes state-wide coverages; therefore, additional local information must be weighed including factors such as forest management practices, potential development trends, and mining impacts.

The process is limited to streams that have water quality assessments that include fish and/or macroinvertebrates (bugs), and the streams must be meeting water quality standards – i.e., they are considered to be fully supporting of AQL. The first step considers how close these communities are to being impaired or degraded.

The second step looks at near shore (riparian) risks to healthy stream communities. This includes the presence of steep slopes, percent altered streams, percent wetland loss, road density, population density, population change, feedlots, septic system density, and a variety of land use categories (percent agriculture, percent row crop, percent impervious surface, percent undeveloped).

The analysis of the data indicates that road density and disturbed land use (cultivated and urban uses) can best predict impacts or changes in stream biological health. These same risks are then also evaluated for the larger, upstream watershed.

The third step evaluates the existing level of protection of the near shore areas and upstream watershed. To complete this step, analysis of lands in public ownership or with public easements on private lands is conducted.

A prioritized list of streams is then generated for the entire watershed. The list may then be further prioritized by splitting out, or separately considering, modified streams (ditches), general use streams (good biology and habitat), and exceptional streams (best biological communities and habitat). One can easily identify the Stream Priority Class as well as their Priority Ranking. For more information on how to use and understand this tool please visit MPCA Prioritization and Trophic State Index Tool.

8.2 Lake Prioritization

The lake protection and prioritization tool generates a prioritized list for protection and restoration, see Table 3. The analysis is based on MPCA's water quality assessment results, the estimated amount of clarity lost if P is added, the amount of land use disturbance, lake size, and what is known about current trends in water quality. The tool utilizes state-wide coverages; therefore, additional local information including local priorities, values and land use information such as forest management practices, potential development activities and/or mining impacts need to be considered. The process is limited to lakes that have completed water quality assessments and that are currently meeting water quality standards – i.e., they are considered fully supporting for AQL. The first step considers how much lake clarity would be lost with an increase of 100 pounds of P to the lake. This is also known as the lake's P sensitivity.

The second step considers the significance of this sensitivity – i.e., the likelihood that this increase in P would occur. Factors considered include the percentage of disturbed land use (cultivated and urban uses), the amount of surface area of the lake, the current P concentration and loading to the lake, and the proximity of the lake to the impairment threshold. Information on declining trends in water quality are also considered.

The third step for lakes is a prioritized list of lakes, each with a P load reduction target. The target is calculated as a 5% reduction in predicted P loading (pounds/year) for any given lake. The target is not regulatory; it is intended to give local groups a value to aim for, in lieu of maintaining current P levels. This provides a way to measure progress over time for a given lake; estimated load reductions in P can be tracked as new practices are implemented.

Tables, maps, and spatial data (via DNR's WHAF) are created for use in prioritization activities. The lakes and streams are ranked and prioritized. For lakes, the top 25th percentile is the high (A) priority, 50th to 75th percentile is medium (B) priority, and the bottom half of the lakes are the lower (C) priority.

It is important to note that these prioritization tools are considered a starting point. Additional factors should be considered when evaluating the provided lists, and ultimately more decisions will be made at the local water management planning levels. For example, what local or regional priorities impact the list? Are areas under development pressure? Is there land use conversion planned? Perhaps a particular area has mining, logging, or other practices that are not found statewide, and local maps will provide better information. And finally, are there opportunities to "stack" environmental benefits by choosing lake or stream protection strategies that achieve multiple objectives such as habitat preservation or open space protection (in addition to water quality protection).

Local knowledge of surface water resources is key to utilizing any prioritization tool. For example, knowing those lakes or streams that have active associations that are engaged in water quality improvement can add weight to other data. Local governments may have information as to what lands are most at risk for development, or what areas may be at risk due to noncompliant septic systems, land use violations, or filled or degraded wetlands.

Below is a partial list of data sets that could be considered when prioritizing surface waters.

- Land use/Land cover
- Groundwater depth
- Land ownership private vs. public
- Impervious surface coverage
- National Wetland Inventory
- Flow direction
- Index of Biological Integrity scores (fish and invertebrates)
- State permitted sites (NPDES-CSW, municipal separate storm sewer system [MS4], IS)
- Petroleum cleanup sites
- Restorable wetlands inventory
- Invasive species observations
- Cumulative forest change
- Public water supplies
- Census blocks
- Tribal lands
- DNR native plant communities
- Trout streams
- Wild rice locations
- Lakes of biological significance (DNR)
- Topography and soils

In addition to these available datasets, local knowledge can be of use for identifying the following considerations:

- Potential implementation partners
- Problem areas (eroding bluffs, shorelines, degraded areas)
- Future development plans
- Illicit discharge locations
- Local values
- Historic activities
- Social capital and leadership for project implementations

If additional context, background information, or data for any of these water bodies is desired, please contact the Watershed Project Manager in the MPCA Northeast Regional Office.

Table 1. Impaired water bodies of the Little Fork River Watershed (Denotes nontraditional pollutant).**

Water body name	Water body description	Water body type	Year added to list	AUID or WID	Use class	County	HUC-8	Watershed name	Affected designated use	Pollutant or stressor	Year TMDL plan approved
Dark**	Lake or Reservoir	Lake	2024	69-0790-00	2B	St. Louis	09030005	Little Fork River	Wild Rice Production	Sulfate	TBD
Lost**	Lake or Reservoir	Lake	2014	69-0581-00	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2014
Thistledew**	Lake or Reservoir	Lake	2012	31-0158-00	2B	Itasca	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2013
Perch**	Lake or Reservoir	Lake	2012	69-0932-00	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	
Side**	Lake or Reservoir	Lake	2010	69-0933-00	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2010
Pfeiffer**	Lake or Reservoir	Lake	2002	69-0671-00	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
Auto**	Lake or Reservoir	Lake	2002	69-0731-00	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
Sand**	Lake or Reservoir	Lake	2002	69-0736-00	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
Little Bear**	Lake or Reservoir	Lake	1998	31-0156-00	2B	Itasca	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2008
Little Sand**	Lake or Reservoir	Lake	1998	69-0732-00	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	TBD
Dark**	Lake or Reservoir	Lake	1998	69-0790-00	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	TBD

Water body name	Water body description	Water body type	Year added to list	AUID or WID	Use class	County	HUC-8	Watershed name	Affected designated use	Pollutant or stressor	Year TMDL plan approved
Fourteen**	Lake or Reservoir	Lake	1998	69-0793-00	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
Leander**	Lake or Reservoir	Lake	1998	69-0796-00	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2008
Clear**	Lake or Reservoir	Lake	1998	69-0799-00	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2008
LONG (MAIN BASIN)**	Lake or Reservoir	Lake	1998	69-0859-01	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2008
LONG (NORTH BASIN)**	Lake or Reservoir	Lake	1998	69-0859-02	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2008
Sturgeon**	Lake or Reservoir	Lake	1998	69-0939-01	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
Middle Sturgeon**	Lake or Reservoir	Lake	1998	69-0939-02	2B	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
West Sturgeon**	Lake or Reservoir	Lake	1998	69-0939-03	2B	Itasca	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
Gilmore Creek	Unnamed cr to Unnamed cr	Stream	2022	09030005-594	2Bg	St. Louis	09030005	Little Fork River	Aquatic Life	Benthic macroinvertebrates bioassessments	TBD
Johnson Creek	T60 R18W S6, south line to north line	Stream	2022	09030005-679	1B, 2Bdg	St. Louis	09030005	Little Fork River	Aquatic Life	Benthic macroinvertebrates bioassessments	TBD

Water body name	Water body description	Water body type	Year added to list	AUID or WID	Use class	County	HUC-8	Watershed name	Affected designated use	Pollutant or stressor	Year TMDL plan approved
Flint Creek	Unnamed cr to Unnamed cr	Stream	2022	09030005-588	2Bg	St. Louis	09030005	Little Fork River	Aquatic Recreation	Escherichia coli (*E. coli*)	TBD
Johnson Creek	T60 R18W S6, south line to north line	Stream	2022	09030005-679	1B, 2Bdg	St. Louis	09030005	Little Fork River	Aquatic Life	Fish bioassessments	TBD
Flint Creek	Unnamed cr to Unnamed cr	Stream	2022	09030005-588	2Bg	St. Louis	09030005	Little Fork River	Aquatic Life	Total suspended solids (TSS)	TBD
Little Fork River	Headwaters to Rice R	Stream	2010	09030005-502	2Bg	St. Louis	09030005	Little Fork River	Aquatic Life	Turbidity	2018
Little Fork River	Willow R to Valley R	Stream	2010	09030005-506	2Bg	Koochiching	09030005	Little Fork River	Aquatic Life	Turbidity	2018
Little Fork River	Prairie Cr to Nett Lake R	Stream	2010	09030005-508	2Bg	Koochiching	09030005	Little Fork River	Aquatic Life	Turbidity	2018
Sturgeon River**	Headwaters (Little Sturgeon Lk 69-1290-00) to E Br Sturgeon R	Stream	2024	09030005-527	2Bg	St. Louis	09030005	Little Fork River	Wild Rice Production	Sulfate	2007
Little Fork River	Beaver Bk to Rainy R	Stream	2006	09030005-501	2Bg	Koochiching	09030005	Little Fork River	Aquatic Life	Turbidity	2018
Little Fork River**	Beaver Bk to Rainy R	Stream	1998	09030005-501	2Bg	Koochiching	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
Little Fork River**	Headwaters to Rice R	Stream	1998	09030005-502	2Bg	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007

Water body name	Water body description	Water body type	Year added to list	AUID or WID	Use class	County	HUC-8	Watershed name	Affected designated use	Pollutant or stressor	Year TMDL plan approved
Little Fork River**	Rice R to Beaver Cr	Stream	1998	09030005-503	2Bg	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
Little Fork River**	Beaver Cr to Sturgeon R	Stream	1998	09030005-504	2Bg	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
Little Fork River**	Sturgeon R to Willow R	Stream	1998	09030005-505	2Bg	St. Louis	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
Little Fork River**	Willow R to Valley R	Stream	1998	09030005-506	2Bg	Koochiching	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
Little Fork River**	Valley R to Prairie Cr	Stream	1998	09030005-507	2Bg	Koochiching	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
Little Fork River**	Prairie Cr to Nett Lake R	Stream	1998	09030005-508	2Bg	Koochiching	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
Little Fork River**	Nett Lake R to Cross R	Stream	1998	09030005-509	2Bg	Koochiching	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007
Little Fork River**	Cross R to Beaver Bk	Stream	1998	09030005-510	2Bg	Koochiching	09030005	Little Fork River	Aquatic Consumption	Mercury in fish tissue	2007

Table 2. Stream Prioritization for water quality opportunities in LFRW streams.

AUID or WID	Use Class	Stream Name	TALU	Priority Rank	Stream Priority Class
09030005-603	2B	Shannon River	Exceptional	6.5	A (High priority)
09030005-562	2A	Unnamed creek (Valley River Tributary)	General	9	A (High priority)
09030005-672	2B	Nett Lake River	General	9	A (High priority)
09030005-665	2B	Unnamed creek	General	11	A (High priority)
09030005-668	2B	Unnamed creek	General	14	B (Medium priority)
09030005-514	2B	Sturgeon River	Exceptional	15	B (Medium priority)
09030005-597	2B	McNiven Creek	General	15	B (Medium priority)
09030005-666	2B	Unnamed creek	General	15	B (Medium priority)
09030005-671	2B	Unnamed creek	General	15	B (Medium priority)
09030005-677	2B	Unnamed creek	General	16	B (Medium priority)
09030005-599	2B	Shannon River	General	16.5	B (Medium priority)
09030005-613	2B	Flint Creek	General	16.5	B (Medium priority)
09030005-627	2B	Paavola Creek	General	16.5	B (Medium priority)
09030005-667	2B	Alango Creek	General	16.5	B (Medium priority)
09030005-568	2A	Venning Creek	General	17	B (Medium priority)
09030005-662	2B	Unnamed creek	General	17	B (Medium priority)
09030005-517	2B	Rice River	General	18	B (Medium priority)
09030005-518	2B	Beaver Creek	General	18	B (Medium priority)
09030005-524	2B	Sturgeon River	General	18	B (Medium priority)
09030005-633	2B	Boriin Creek	General	18	B (Medium priority)
09030005-669	2B	Unnamed creek	General	18	B (Medium priority)

Table 3. Lake Prioritization for water quality opportunities in LFRW lakes.

Lake ID	Lake Name	LBCA Index	Sensitivity Index	LPSS Protection Priority	Lake Acres	Mean Secchi (m)	Mean TP (ug/L)	Watershed Acres
31-0058-00	Beatrice	Higher	50	A (High priority)	124	4	15	574
31-0284-00	Raddison	Highest	75	A (High priority)	204	5	8	903
31-0290-00	Napoleon	Higher	79	A (High priority)	138	5	11	273
31-0292-00	Owen	Higher	32	A (High priority)	268	4	15	1,372
69-0669-00	Big Rice	High	2	A (High priority)	1,917	1	32	11,719
69-0799-00	Clear	Higher	50	A (High priority)	139	3	16	439
69-0932-00	Perch	Highest	47	A (High priority)	344	4	11	876
69-0933-00	Side	Highest	28	A (High priority)	368	4	17	760
69-0939-01	Sturgeon	Highest	9	A (High priority)	1,585	4	10	11,240
69-0939-03	West Sturgeon	High	8	A (High priority)	117	1	18	11,240
31-0155-00	Horsehead	High	64	B (Medium priority)	70	3	15	317
31-0156-00	Little Bear	High	44	B (Medium priority)	131	3	13	1,237
31-0157-00	Bear	High	2	B (Medium priority)	344	1	34	13,466
31-0158-00	Thistledew	Higher	38	B (Medium priority)	326	5	9	2,862
31-0298-00	Walters	High	20	B (Medium priority)	127	2	18	2,936
31-0299-00	Kelly	High	45	B (Medium priority)	70	3	11	2,276
69-0612-00	Little Rice	High	10	B (Medium priority)	182	0	30	2,951
69-0731-00	Auto	High	72	B (Medium priority)	97	4	11	593
69-0736-00	Sand	High	7	B (Medium priority)	779	3	25	3,533
69-0859-01	Long	High	17	B (Medium priority)	259	2	15	4,137
69-0912-00	Dewey	High	21	B (Medium priority)	201	3	10	7,503
69-0923-00	Hobson	High	96	B (Medium priority)	67	4	10	329

9. Strategies

It is important to use information gathered during this second Cycle of watershed monitoring to help support implementation efforts by local partners in the LFRW. The MPCA is required by the Clean Water Legacy Act to monitor and assess waters in the state and then develop strategies to restore waters that do not meet standards. State agencies work closely with local partners who specialize in implementing BMPs that can help mitigate many of these impaired waters, as well as protecting high value lakes and streams, through the One Watershed, One Plan (1W1P) framework.

The LFRW is a remote, healthy watershed with two main focal points in water quality - sedimentation and protection of high-quality headwater lakes. These two priorities have been the focus of the three SWCDs that comprise the watershed, Itasca, Koochiching, and North St. Louis, in partnership with state agencies and USGS.

The state program, 1W1P, is administered by Minnesota Board of Water and Soil Resources (BWSR) and funded by the Clean Water Fund. It is designed to provide comprehensive local watershed planning, which also triggers funding to implement locally led projects to address water quality.

The LFRW 1W1P planning process began in Spring 2025. Information from this report, especially regarding the priority focus areas, will continue to be used to help develop and implement conservation projects within the watershed. The online desktop sediment erosion and deposition tool, developed specifically for the LFRW, will be used to scope landscape level projects for restoration and protection. Information collected from the monitoring and assessment, problem investigation and characterization, as well as research findings from the extensive sediment studies add detail to priority efforts. County and SWCD staff are encouraged to contact MPCA staff to further inquire about chemical or biological data that can help in identifying priority areas to consider for future water quality project implementation.

9.1 Sedimentation

While Sections 4 and 7 above discuss findings of scientific research on sedimentation in the LFRW, questions still remain. The sources of fluvial sediment in the stream network vary through the open water season; however, most of the sediment found in the streams is derived from the channels and banks and near-shoreline ravines. What is causing this? Is it downcutting of the stream bed? Is it glacial rebound? What are the drivers of the near-shore ravines? There are hundreds of small, medium and large ravines on the main stem, each with very small drainage areas of 3 to 5 sq mi. When one examines the land use changes in these small ravine watersheds, not much has changed in 50 years. What is the cause of these erosion situations along the main stem of the Little Fork?

As local partners continue to better understand the sediment issues, there are still questions that remain. Is the 15ug/L an appropriate standard for the Lake Agassiz soil types, which are found throughout the watershed? Can BMPs create declining trends in sediment loads in the stream system and attain 15ug/L standard? Is it appropriate for a site-specific standard? What data is needed to conduct a site-specific standard for the Little Fork stream network?

The MPCA recommends continuing to develop understanding of ravine formation, identifying BMP treatments that may be effective to mitigate the sediment in the river and attain the standard. The

MPCA also recommends a complete review of all sediment and flow data to understand the gaps in data that is needed to develop a site-specific standard for this river system.

9.2 Headwater Lakes and Streams Protection

Headwater lakes and streams protection in the Little Fork River will focus on two subwatersheds, the Sturgeon Lake and Sturgeon River Units (09030005-0301 and 09030005-0308 respectively), see Figure 17. Together they represent over 100 sq mi of headwater streams and lakes.

The SCL, located in western St. Louis and eastern Itasca Counties, drains an area of 31,000 acres or 48 sq mi. The watershed unit contains the headwaters of the Sturgeon River and is the LFRW's largest tributary. Originating from many small tributaries within the George Washington State Forest, the Sturgeon River begins at the outlet of Sturgeon Lake and flows in an easterly direction to its confluence with the Shannon River. Both the Sturgeon and Shannon rivers flow through predominately forested land cover with wetlands interspersed throughout. Other land uses in the subwatershed include barren/mining in the southwest portion and rangeland land use, although limited, in the southeast portion of the subwatershed. There are no named tributaries to the Sturgeon or Shannon Rivers in the watershed.

This subwatershed unit has 30 lakes greater than 10 acres and forms the headwaters of the Sturgeon River. The SCL are likely the most developed lakes in the LFRW. Local property owners have worked with DNR Fisheries and Itasca County to model shoreland development sensitivity and proper siting of septic systems. Recent data indicate that lakes within the SCL have excellent water quality; however, it is in a declining trend. Headwater and seepage lakes, such as Beatrice and Side, have lower TP and chlorophyll-*a* concentrations because watershed sources of nutrients are low. Flowage lakes, such as Little Sturgeon, with much larger drainage areas, have higher TP and chlorophyll-*a* concentrations (and lower transparencies) but results are within NLF criteria and reflective of natural watershed characteristics.

The Sturgeon River Subwatershed Unit, immediately downstream of the Sturgeon Lake Subwatershed Unit, is in western St. Louis County and drains an area of 33,793 acres or 52 sq mi. The Sturgeon River is the largest tributary to the Little Fork River. Within this subwatershed unit, the Sturgeon River flows in a general northeast direction until its confluence with the Dark River, where it then turns and flows northwest to its confluence with the Bear River.

The Sturgeon River, along with its tributaries, flow through an undeveloped forest and wetland dominated landscape with scattered agricultural practices (mostly pasture and hay lands) in the eastern portion of the watershed. The named tributaries to the Sturgeon River in this watershed unit are Sand, Gilmore, Paavola, and Murray creeks. The water chemistry monitoring for this watershed unit is represented by the pour point station 08RN003 on the Sturgeon River at the County Road 107 Bridge, upstream of the confluence with the Bear River.

Local partners have held several community meetings in the Side Lake Community, each having excellent attendance and participation. Local community members are interested in working to protect the high-quality waters of the SCL. The MPCA recommends an intensive effort to provide technical assistance and guidance for local landowners, especially waterfront, to implement conservation BMPs and practices to mitigate excess nutrients from entering any of the lakes in the headwaters area. Native plantings, erosion control efforts, rain gardens, water bars on yard trails, erosion control mulch, and not maintaining a lawn adjacent to the lake water are all effective BMP opportunities.

The Itasca County Lake Challenge (see Appendix E) has been an effective tool in the past to use as a discussion item and assistance tool. Use of that tool along with available cost-share programs and grant opportunities for landowners collectively can impact local water quality in the lake system. In addition, continuing to develop effective volunteer lake monitoring, through a certified lab, is a very effective approach in assisting the MPCA with understanding the lakes.

Lastly, the lakes in this small Chain of Lakes have heavy visitation in the summer months through rentals of private cabins, or state park visitation. Partnering with the McCarthy Beach State Park to develop education programming for summer use has been discussed and should be pursued further.

10. Monitoring Plan

Data from five monitoring programs will continue to be collected and analyzed for the LFRW, as summarized below:

1. ***Intensive Watershed Monitoring*** collects water quality and biological data throughout each major watershed for the first two years of each 10-year Watershed Approach cycle. This work is scheduled for its third iteration in the LFRW in 2028. This data provides a periodic but intensive "snapshot" of water quality throughout the watershed.
2. The ***Watershed Pollutant Load Monitoring Network*** intensively collects pollutant samples and flow data to calculate daily sediment and nutrient loads on either an annual or seasonal (no-ice) basis. This program began in 2012 and there are five sites in the LFRW (Linden Grove, Meadow Brook, Little Fork at Hwy 210, Little Fork at Hwy 65, and Silverdale).
3. The ***Volunteer Water Monitoring Program*** is a network of volunteers who collect monthly lake and river transparency readings. More than a dozen data collection locations are monitored in the LFRW. This data provides an ongoing record throughout much of the watershed.
4. Ongoing **Local Monitoring Efforts** of several lake associations and individuals that collect volunteer water quality data in Itasca and St. Louis County. Volunteer stream or lake monitoring is always encouraged in the LFRW. The Sturgeon Chain of Lakes Association and Side Lake volunteers have provided valuable data to MPCA and local partners for many years. We encourage growth and further volunteer monitoring. To learn more about volunteer opportunities please visit Volunteer Water Monitoring Program.
5. **WRAPS** identified local monitoring needs in addition to the ongoing efforts of Koochiching, Itasca, and North St. Louis SWCD and the MPCA. Moving forward, the three SWCD districts will need pre-project data collection to ensure BMP treatments are effective in reduction of pollutants.

In addition to the above five monitoring programs and efforts that can be deployed in the watershed, several monitoring opportunities are described in the 2025 *Little Fork Watershed Stressor Identification Report* (MPCA 2025), they include:

- Gilmore Creek (09030005-594) needs additional TSS samples to determine if TSS is a stressor on the macroinvertebrate community in that area.
- Flint Creek (09030005-612, -588, -574) - DNR maintains geomorphic work in this system, re-visiting monuments and measurements from 2001 and 2011 survey work on the two WIDs above and below U.S. Hwy 53, preferably every three to five years.
- Timber Creek (09030005-630) - Analysis of biological and chemistry monitoring sites from NPDES/SDS Permit at US Steel-MinTac.

11. Public participation

Public participation has been robust in the LFRW during the past 6 years. Over 100 one-on-one communication opportunities happened as we conducted field work over the course of the summers of 2020 and 2021. Fact sheets (See Appendix D) were developed and distributed by local partners, MPCA, and USGS staff during our field work seasons of 2020 and 2021.

In Winter/Spring of 2021 local partners and MPCA undertook an extensive boat tour of the chain of lakes noting opportunities to develop partnerships with landowners to develop localized BMPs on the lakeshore. One theme emerged in that work, and it was the need for technical assistance in “how” residents can be better lakeshore stewards. The SCL Challenge (See Appendix E) was developed as a version of the Itasca Lake Challenge, to help develop further interest and educate landowners on the various benefits to the lake and humans.

In the Fall of 2022, local partners and MPCA staff held several local in-person information meetings focused on the sediment challenges in the watershed and the protection strategies, which were citizen co-developed in the SCL area (Table 4, Figure 26, and Figure 27).

Table 4. Dates, location and attendance of public meetings held in the LFRW.

Date	Location	Attendance
9-22-2022	Little Fork	10
10-4-2022	Effie	5
10-5-2022	Cook	5
2-13-2023	Bearville Township	6
2-13-2023	French Township	20

Figure 26. MPCA Project Manager, Mike Kennedy, speaking to Cook, Minnesota community members.

Figure 27. Itasca SWCD Water Resource Specialist, Matt Gutzman, explains excess sedimentation to a community member in Little Fork, Minnesota.

In Fall 2023/Winter 2024 Itasca and North St. Louis SWCD developed a small community survey to learn of interests in water quality protection in the SCL. The focus of the survey was to gather information on what issues were important to residents as it relates to “living on the lake”. The top five results of a ranking question indicated the following respondents as “most important issue”:

- Water Levels
- Aquatic Invasive Species
- Property Taxes
- Algae Blooms
- Erosion

For the results of the survey, please see Appendix C.

Public notice for comments

An opportunity for public comment on the draft WRAPS report was provided via public notice in the *State Register* from April 27, 2026, through May 27, 2026. There were [xx] comments received and responded to because of the public comment period.

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Appendix A - Sediment budget paper

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 which may in turn play a role in driving harmful algal blooms in downstream waters. The Little Fork River in northern Minnesota is 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 phosphorus in the Little Fork, the MPCA identified a need for improved understanding of the sources of sediment and sediment bound phosphorus to the basin. In order to address this question, the U.S. Geological Survey is working in collaboration with MPCA, Koochiching Soil and Water Conservation District, and North St. Louis Soil and Water Conservation District to delineate sources of sediment and sediment bound phosphorus for the Little Fork Watershed using geochemical sediment fingerprinting and sediment budget techniques. Data collection for this project commenced in 2021, with the collection of rapid geomorphic assessment data to support sediment budget development, and the collection of sediment samples to support geochemical fingerprinting. In this paper we describe results for the sediment budget for the stream corridor including estimates of sediment contributions from eroding valley sides, terraces, banks, and ravines and estimates of storage of soft fine-grained sediment. Initial results from the corridor sediment budget indicate that there is approximately 130,000 Mg/yr of corridor erosion and a total of 840,000 Mg of soft sediment stored in channels, most of which is in headwater gentle sloped channels surrounded by wetlands with beaver activity. The soft sediment to erosion ratio is 6.4, suggesting that there is about 6 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 distribution. These estimates will be used to compliment the geochemical fingerprinting apportionments of upland sources of sediment and sediment-bound phosphorus from mature and recently harvested forests, agricultural fields, wetlands, and roadways as well as erosion along the stream corridor.

Introduction

The Little Fork River (has been identified as a major source of fine-grained sediment to downstream waters even though the watershed 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 EPA's 303(d) rule due to high turbidity or below threshold fish populations. Four of the six reaches have TMDL regulations under development. As part of the TMDL process a watershed model, the Hydrologic Simulation Program, Fortran (HSPF) was developed and revealed that 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 have provided detailed understanding of the geomorphic character in the basin and delineated stream corridors most sensitive to erosion (Gran et al. 2007), explored effects of land use history on hydrology and found that 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), and characterized sediment loading conditions and initiated the development of the TMDL (Minnesota Pollution Control Agency 2011; 2016).

Though the Little Fork basin only comprises approximately 7% of the 26,930 mi^2 Rainy River basin drainage area, it supplies a disproportionate amount of sediment to downstream Rainy River and eutrophic Lake of the Woods (for details describing Lake of the Woods phosphorus source see MPCA 2019). Comparison of monitoring data from the MPCA's Watershed Pollutant Load Monitoring Data Viewer (accessed September 25, 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), reveals that the Little Fork basin comprises 9.65% of the drainage area at this point but contributes an average of 39.7% of the total suspended solids (TSS), 19.9% of the total phosphorus (TP) and 15.7% of the dissolved orthophosphate (DOP) annually. Information describing the dominant sources of sediment and sediment-bound phosphorus 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 (U.S. Environmental Protection Agency 1999). This study is estimating potential upland and riparian corridor sources of sediment and particulate-bound phosphorus in the Little Fork by building off a previous geomorphic assessment of the Little Fork (Gran et al. 2007) and applying sediment fingerprinting and sediment budget techniques described in Gellis et al. (2016) and Gorman et al. 2017).

Sediment fingerprinting is a widely used method that employs geochemical and physical properties to tie fluvial sediment (from suspension or in channel storage) back to erosional sources in the landscape (Gellis et al. 2016). Many different geochemical tracers may be used (fallout radionuclides 137Cs, 210Pb, 7Be; stable isotopes of carbon and nitrogen; color; magnetism; mineralogy), but the most widely used tracers are elemental concentrations. The use of elemental fingerprints has been thoroughly researched (see Miller et al. 2015 for an extensive list of references where the use of major elements, rare earth elements, and trace metals were explored) and has been used to inform management actions for reduction of sediment loading (Miller et al. 2015, Cashman et al. 2018, Fitzpatrick et al. 2019).

Furthermore, 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. Sediment budgets are commonly used and 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). Measures of deposited fine-grained bed sediment are also often obtained to quantify the instream storage portion of the budget.

The Little Fork basin has not been listed as impaired for phosphorus, but exceedances for flow weighted mean phosphorus concentrations from 2007 through 2009 for a standard under development has raised MPCA's interest in further characterization (MPCA, 2011). Between 23% and 42% of flow weighted mean total phosphorus measured at the Little Fork at Littlefork, MN between 2007 and 2009 was in dissolved from, demonstrating that across flow regimes most of the measured total phosphorus exists in particulate form (MPCA, 2011). The particulate portion may be comprised of a combination of sediment bound and biologically bound forms.

Starting in 2021, the U.S. Geological Survey in collaboration with MPCA, Koochiching Soil and Water Conservation District, and North St. Louis Soil and Water Conservation District began a study to delineate sources of sediment and sediment bound phosphorus for the Little Fork Watershed 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 watershed 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 fine-grained streambed sediment. Part of the sample collection for the fingerprinting portion of the study involved collecting suspended sediment passive samplers at eight subbasins throughout the watershed (Figure 1).

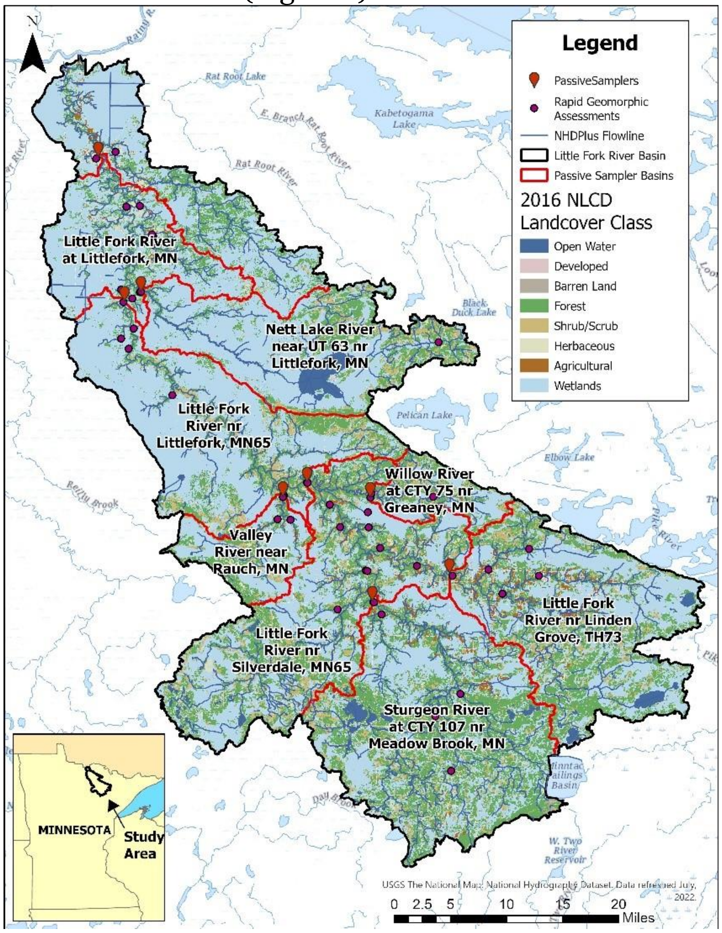


Figure 1. Location of the Little Fork River study area with major land-cover categories [Dewitz, 2019].

Study Area

The Little Fork River Watershed drains 1,872 square miles (Minnesota Pollution Control Agency, 2016) before joining the Rainy River and flowing northwest to Lake of the Woods and north through Canada. This remote watershed is characterized by the Northern Lakes and Forest and Northern Minnesota Wetlands ecoregions. Much of the watershed was intensively logged in the late 1800s and early 1900s, and timber harvest remains one of the primary economic activities in the basin to present day. Surficial geology in the basin 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 into the basin from the west, and the northeastern edge of the basin is characterized by scoured bedrock uplands (Figure 1). A large portion of the basin is part of the Nett Lake Reservation tribal lands belonging to the Bois Forte Band of Chippewa (Minnesota Pollution Control Agency, 2016). Land cover across the basin is largely comprised of forests and wetlands. Forests cover a combined 37% of the basin, with 18% deciduous, 6% evergreen, and 13% mixed forest. Woody wetlands cover 40% of the basin, and emergent herbaceous wetland covers 6%. Less than 2% of the basin is considered developed and 2% is under agricultural use, mostly for pasture/hay (1.6%) with a small amount in cultivated crops (Figure 2, data from Minnesota Geospatial Commons, 2019). Based on data from the Minnesota Geological Survey, as much as 19% of the wetlands delineated by NLCD data set 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. (2016; 2019) and Blount et al. (2022) and will be published in Fitzpatrick et al. (in review). Reaches for the rapid geomorphic assessments were selected to represent a range of slope, valley types, stream order, and channel sizes along a stream network longitudinal continuum. The reaches included ephemeral and perennial channels. Ravines included in this assessment are typically developed along steep slopes of entrenched valley sides. 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 model data (Minnesota IT Services Geospatial Information Office, 2018).

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. Additional data collected included visual estimates of texture and origin of the sediment (i.e. glacial, glaciolacustrine, alluvium). While in the field annual lateral recession rates were estimated using the indicators described in the Wisconsin Natural Resources Conservation Service (2016) bank erosion calculator. To convert annual volumes to loads for later comparison with stream suspended sediment loads, a volume-weight conversion was determined for each eroding section based on the described texture of the eroding material and the general dry density values published by the Wisconsin NRCS Streambank Erosion Prediction guide (2016).

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 and Hall 2016). 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 kilometer that could be applied to the broader network.

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. 2016; 2019; Blount et al. 2022). Soft sediment thickness was measured using a light 2-finger push on a meter stick or sounding rod 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).

Stream Network and Segment-Scale Geomorphic and Stream Corridor Characteristics

A stream network was delineated using 1/3 arc second digital elevation model data from the National Elevation Dataset program (U.S. Geological Survey, 2018) at a 0.02 km^2 stream definition threshold to capture both perennial and ephemeral channels in the basin. The network was delineated using ArcHydro Pro Tools and followed the workflow for completely dendritic terrain with unknown stream locations described in the ESRI Technical Paper “Arc Hydro Overview of Terrain Pre-processing Workflows” (2019). The stream definition threshold was determined based on the lowest threshold that captured all the ravine channels included in the rapid geomorphic assessments (Figure 2). The resulting stream network increased in size by about 4 Strahler stream orders from the NHDPlus stream network (Figure 2; McKay et al. 2012). A stream order of 1 in NHD had a stream order of 4 in the extended network the Little Fork main stem increased from a stream order of 6 in NHD to 9 in the extended network (Figure 2). 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 segments for network-wide analysis of drainage area, channel slope, stream order, and valley side slope. The dataset includes segments shorter than 60 meters that make up 12 percent of the total network. These shorter segments occur due to splitting at stream confluences and the termination of short drainage lines. The 60-meter segment length was selected to provide detailed characterization of abrupt changes in channel slopes and valley width and short lengths of meander bends that come in contact 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 regression between the median drainage area (A) and average measured bankfull width (W_{bf}). The development of this regression 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 regression equation obtained was used to estimate the bankfull width for each 60-meter segment in the network:

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

Zonal statistics were derived from the buffers generated using four times the bankfull width 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 15% rise were categorized as having "steep" valley sides (confined or partially confined valley type) or ravine.

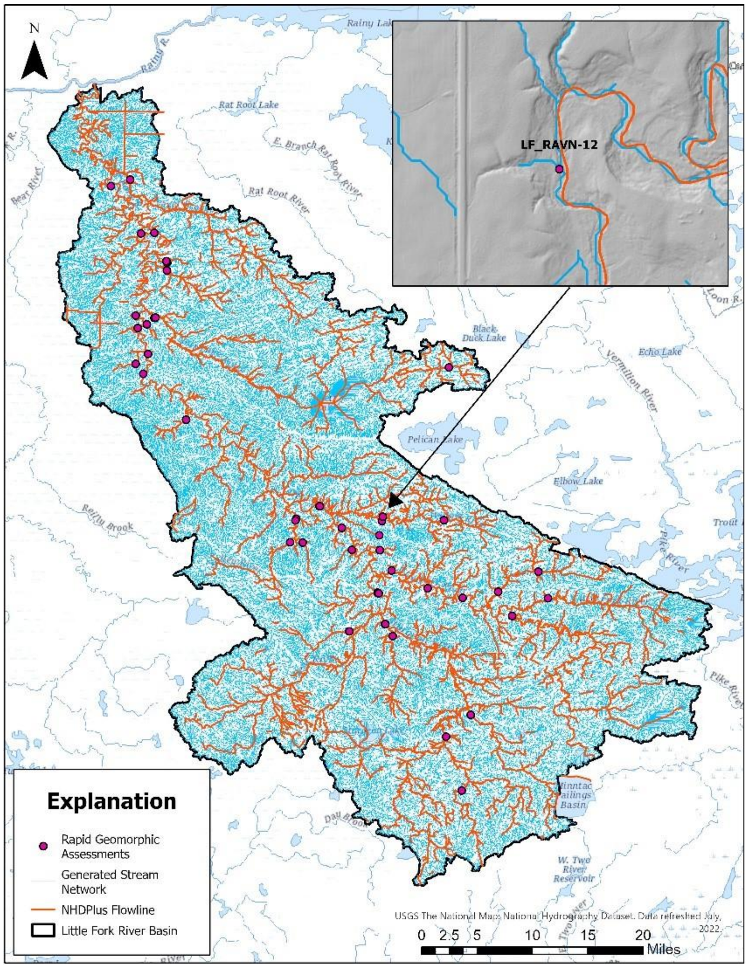


Figure 2. Comparison of extended flow network derived from 10-m digital elevation model data and NHDPlus streamlines with inset showing flowline for 1st order ravine (RAVN-12) with smallest watershed area for rapid geomorphic assessments.

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 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 0.45% of the stream network had negative slope values due to a range of factors but many related to the DEM not being hydro-enforced at road-stream crossings. To address the negative channel slopes, an adjusted channel slope field was created, and the following schema was applied to negative channel slope values:

a. Segments that intersect DNR Lake/Pond waterbodies were given an adjusted slope of 0
b. Segments with negative slope between 0 and -0.1 were given and adjusted slope of 0

c. Segments with negative slope Negative segments that were within 100 m of the MNDOT roads shapefile were given an adjusted slope of 0
d. If the slope of the next downstream segment was positive, the next downstream slope was used as the adjusted slope
e. If the next downstream slope of a segment was between 0 and -0.1, it was given an adjusted slope of 0
f. Remaining negative slopes were left as they were and put into a “negative slope” category.

Characteristics of the riparian corridor for each segment were also collected from publicly available geospatial datasets including forest disturbance (Minnesota DNR, 2021), surficial geology (Minnesota Geological Survey, 2021), glacial lobe (Minnesota Geological Survey, 2021), depth to bedrock (Natural Resources Conservation Service, 2021), presence of peat (Minnesota Geological Survey, 2021), soil unit (Natural Resources Conservation Service, 2021), and land use classifications (U.S. Geological Survey, 2016). Buffers were generated for riparian analysis using the same process as described for the valley side slope analysis at 8-times the estimated bankfull width with a minimum of 60 m across. These riparian buffers were then used to tabulate the percentage of intersection between features within the geospatial datasets and the riparian corridor of each stream segment. These characteristics were then used to further inform and refine the application of bank erosion and bed deposition rates to the stream network.

Constructing a Stream Network Scale Stream Corridor Sediment Budget

The RGA-based corridor erosion and soft bed sediment results were applied to the 60-m segments based on similar channel size (stream order), channel slope categories, presence of steep valley sides or ravines, land cover in the riparian corridor, 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 segment categories that contained multiple RGAs, either an average was assigned to a segment, or the results from the RGA in closest proximity or within the same sub-watershed were assigned. For RGA reaches that contained multiple segments in different categories, the RGA data was applied to the segment category 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 re-adjusted if needed due to spatial variability among subbasins, local geologic anomalies, or qualitative data and photos 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 impoundment features and thus an average volume was used for segment categories where beaver activity was likely. The adjusted segment categorical values were then multiplied by the cumulative segment lengths in each category and summed to estimate the total annual load of sediment from valley side, terrace bank and ravine erosion and soft bed sediment volume.

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 segments in the "negative channel slope" category were grouped into the results for channel slopes from 0-1%.

Stream Corridor Sediment Budget

The RGA results for stream corridor erosion and soft sediment deposition illustrate the variability in corridor sources and sinks across the watershed (Figure 3). For erosion, reaches without eroding valley sides or terraces had from 0 to just over 50 Mg/km. For those that had valley side or terrace mass wasting, 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 observed in stream orders 3, 5 and 9. Stream order 8 was limited to 50 km in the watershed and 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 reaches to almost 1200 Mg/km at a beaver impounded reach of stream order 5. In the same stream order of 5 and channel slope of <0.1% another RGA reach had much beaver activity with failed dams and soft sediment of 30 Mg/km. For soft sediment the two reaches of stream order 8 were quite different, with the Little Fork reach having almost 700 Mg/km whereas the SturgeonRiver reach had less than 10 Mg/km. Field observations show both reaches had beaver activity as well.

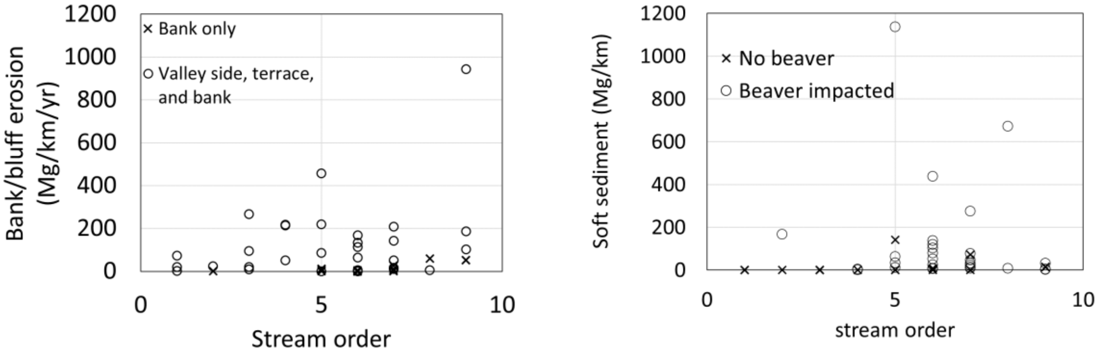


Figure 3. Rapid geomorphic assessment results for a) corridor erosion and b) soft sediment deposition.

Application of RGA results to the full stream network is shown in table 1 with spatial distributions on a per km basis shown in Figure 4. Segments were grouped into three categories: headwaters (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 had almost all 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 (Figure 5). 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 have only 3% of the soft sediment deposition. Headwaters with no steep valley sides and gentle slopes comprised over 50% of soft sediment deposition in the watershed. The highest amounts of bed sediment deposition, on a per km basis, were in gentle sloped perennial tributaries with no steep valley sides. Soft sediment deposition rates for the perennial tributaries represent an average of the range in RGA reach based rates in beaver-caused impoundments relative to more flowing channels between impoundments.

Table 1. Summary of segment side slope, channel slope, and stream order categories with cumulative stream length

Stream Level	Valley sides	Channel Slope	Total Length	Erosion		Bed Deposition	
(Units)	Steep (>15%)	%	km	Mg/year	Mg/km/year	Mg	Mg/km
Headwaters	No	Gentle	23036	1560	2	435080	882
Headwaters	No	Moderate	2533	161	1	18053	118
Headwaters	No	Steep	1772	11779	311	1852	121
Headwaters	Yes	Gentle	616	3612	130	12572	659
Headwaters	Yes	Moderate	191	10068	259	457	10
Headwaters	Yes	Steep	874	52279	1013	74	4
Perennial Tributaries	No	Gentle	1119	6571	112	314281	2467
Perennial Tributaries	No	Moderate	36	73	10	3665	305
Perennial Tributaries	No	Steep	12	59	184	359	135
Perennial Tributaries	Yes	Gentle	341	12205	333	30445	1474
Perennial Tributaries	Yes	Moderate	42	5689	304	404	34
Perennial Tributaries	Yes	Steep	20	4262	1401	511	136
Mainstem	No	Gentle	22	1266	335	451	209
Mainstem	No	Moderate	0	2	62	3	49
Mainstem	No	Steep	0	0	0	0	0
Mainstem	Yes	Gentle	217	22310	677	13418	592
Mainstem	Yes	Moderate	5	467	158	74	24
Mainstem	Yes	Steep	1	136	264	17	27
Total			30837	132497	5555	831716	7247

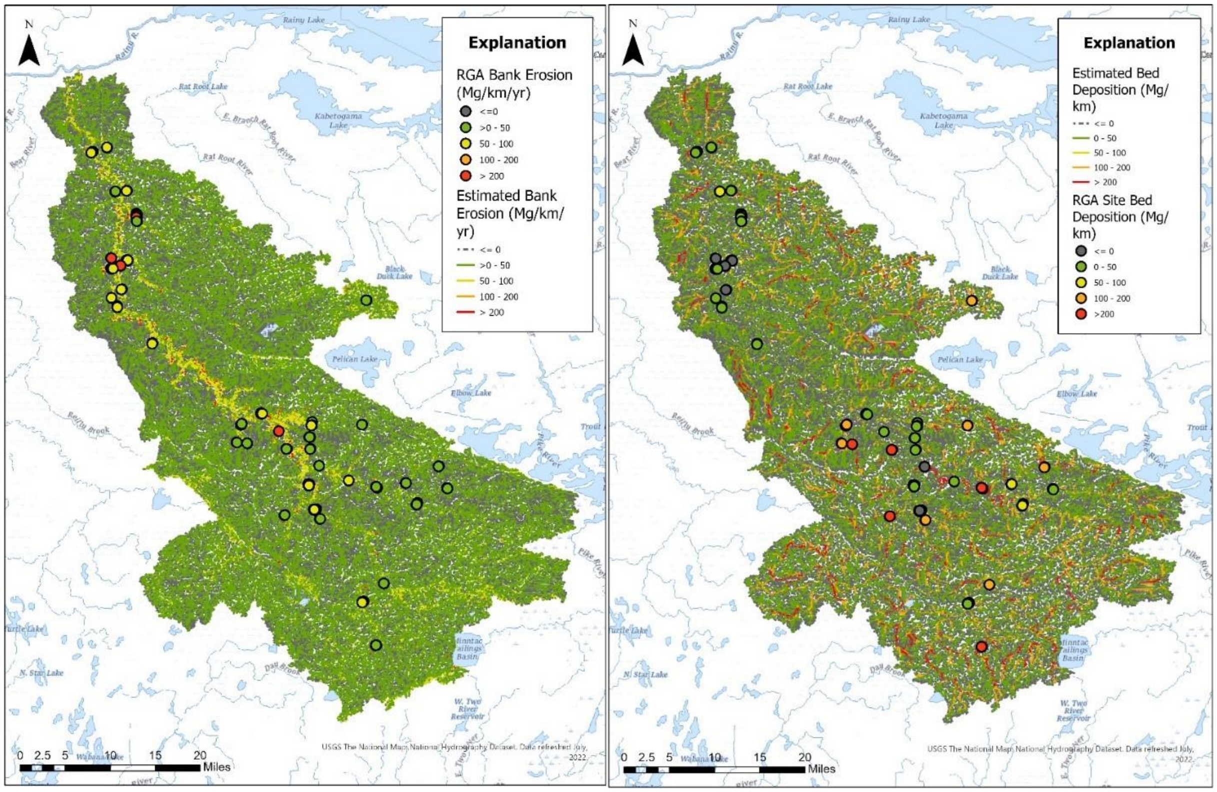


Figure 4. Mapped distribution of segments with a) corridor erosion and b) soft sediment deposition relative to rapid geomorphic assessment results

Examples of differences in erosion rates for headwater segments are shown in Figure 5. The dashed lines in the figures represent segments of stream order 1 with no steep slopes and no surface expression. These segments have gentle slopes and are representative of connector segments through lakes and ponds or flat-lying wetland areas. In contrast are headwater segments that feed into the mainstem. Erosion rates are highest where they intersect the valley side of the mainstem as shown in Figure 5B. For reference, one ravine site 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 pof of erosion, while the ravine with 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.

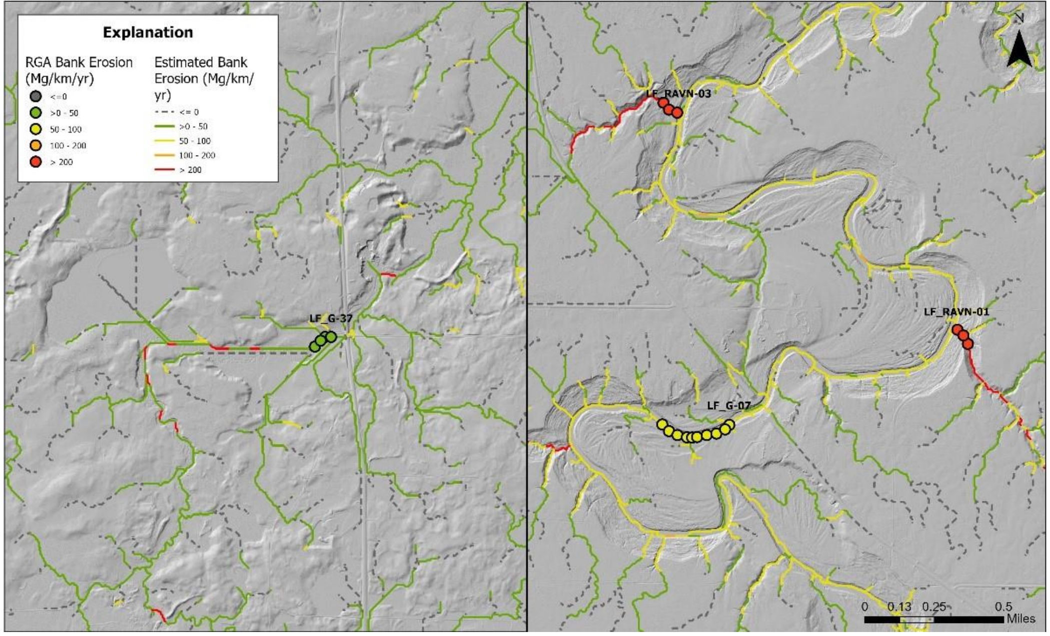


Figure 5. Examples of corridor erosion rates for low stream orders in headwater lowlands and ponds, and b) ravines with steep side slopes along the main stem of the Little Fork, along with rapid geomorphic assessment results.

The most heavily eroding ravine drains to a section of the Little Fork mainstem which had the highest erosion rate of all RGA reaches measured, 1,000 Mg/km/yr (Figure 6). These reaches were on a large meander in the Little Fork mainstem, which generally runs southeast to northwest (Figure 6). Typically, a large change in the meander pattern like this reflects a change in the lithology, landform, or underlying bedrock that cause the river to change its general direction where the intersecting land is more resistant to erosion. This stretch of the river is in a remote area with no access points, which made it difficult to determine how far upstream and downstream to apply the higher 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. This stretch of the river is in an actively incising section (Gran et al. 2007) and may represent an active knickpoint propagating upstream. The channel width of the river is slightly narrower here than upstream or downstream, and the RGA reach had almost continuous erosion along both banks. This might indicate that the erosion is enhanced through the narrow channel by the heavy ice flows that are common during spring break up. This location was also an important landing area in 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. The coincidence of the nearby tributary ravine with high erosion further supports the hypothesis of upstream propagation of a knickpoint in this zone. Perhaps this segment represents a combination of a knickpoint propagation, narrow channel because of post-glacial lithology and landforms, and ice-breakup caused erosion. This stretch with the highest mainstem erosion rates may be extended using Gran et al. (2007) more detailed analysis of the geomorphology of the mainstem 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.

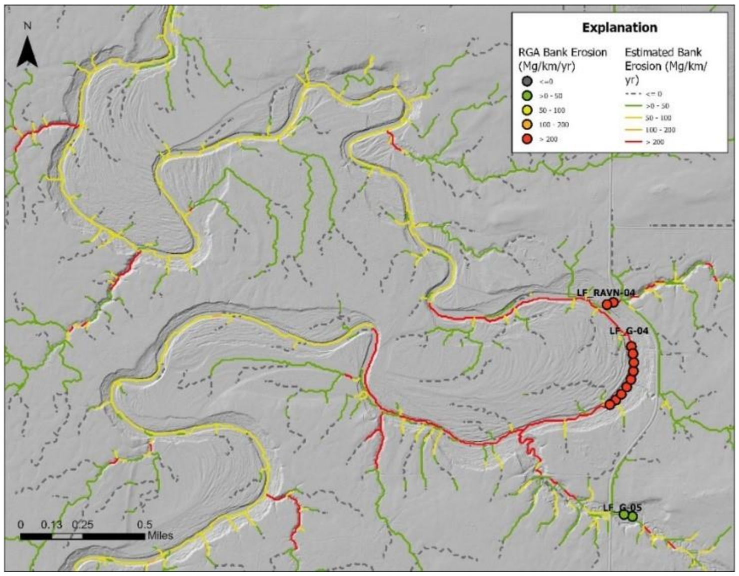
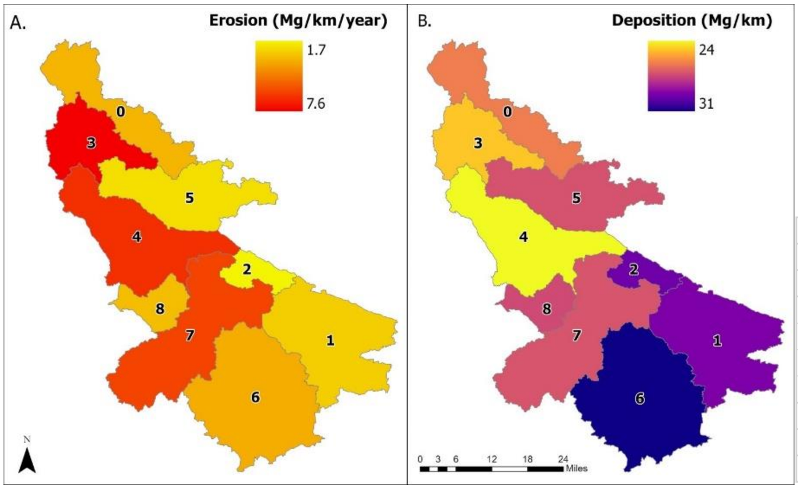


Figure 6. Example of Little Fork main stem with notably higher RGA erosion rates than rest of main stem sites and approximated segments along the same meander bend that were assigned a corresponding higher erosion rate.

Individual subbasin and cumulative totals for the Little Fork for erosion and soft sediment deposition reflect subbasin size and their location in the watershed (Figure 7, Table 2). For example, the Willow River (2) and Nett Lake River (5) have the least erosion because of gentle sloped channels and bedrock close to the surface. Similarly, the Little Fork upstream of the confluence with the Sturgeon River flows through bedrock uplands with little valley entrenchment (Gran et al., 2007). The lower sections of the Little Fork (3, 4, and 7), have common eroding valley sides and terraces that generate high erosion rates. Overall, cumulative erosion in the Little Fork was estimated at 130,000 Mg/yr, including all sediment size classes. Most of the riparian zones along the channels are wetlands and forest. The Little Fork near Linden Grove (1) has the most agricultural land cover in the riparian corridor of 5%. These subbasin outlets have suspended sediment samplers where suspended sediment has been collected for geochemical sediment fingerprinting.



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

Table 2. Summary of corridor erosion and soft sediment deposition with selected riparian land cover characteristics for the Little Fork watershed and its subbasins

	Entire Little Fork River Watershed	Little Fork River Mouth (0)	Little Fork River at Littlefork (3)	Little Fork River nr Littlefork (4)	Little Fork River nr Silverdale (7)	Little Fork River nr Linden Grove (1)	Willow River (2)	Nett Lake River (5)	Sturgeon River (6)	Valley River (8)
Drainage Area (km^2)	4,726	435	355	676	779	721	128	548	913	172
Stream Length (km)	30,837	2,857	2,380	4,806	4,856	4,564	801	3,868	5,577	1,128
Total Erosion (Mg/yr)	132,497	9,293	18,186	31,173	29,075	12,115	1,381	8,710	19,158	3,406
Total Deposition (Mg)	837,360	73,932	58,162	113,319	130,238	132,322	23,434	103,952	171,478	30,523
Per km Erosion (Mg/km/yr)	4	3	8	6	6	3	2	2	3	3
Per km Depostion (Mg/km)	27	26	24	24	27	29	29	27	31	27
Per km^2 Erosion (Mg/km^2/yr)	28	21	51	46	37	17	11	16	21	20
Per km^2 Deposition (Mg/km^2)	177	170	164	168	167	183	183	190	188	177
Riparian Land Cover										
Wetlands		56	55	52	46	50	49	63	43	56
Forest and Shrub		37	38	41	45	40	46	30	48	38
Agriculture + Herbaceous		3	3	3	4	5	3	1	3	4

For soft sediment, the Sturgeon River has the most stored sediment on a per km basis followed by the Upper Little Fork (Figure 7, table 2) the Willow River. The entire watershed has approximately 837,000 Mg of soft sediment stored in the channels, with a he soft sediment to erosion ratio of 6.4, suggesting that there is about 6 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 distribution. For example, some ravines had high erosion rates but no to little soft sediment deposition, indicating that eroded materials are readily transported downstream, especially the silt/clay portion that is transported in suspension during high flows.

Discussion and Conclusions

This initial corridor sediment budget for erosion and deposition for the Little Fork watershed is a first attempt at using a national publicly available 1/3 arc second DEM that recognizes and attributes small ephemeral channels in ravine settings that could be a large contributor to suspended sediment loads during runoff events. The GIS-based results are most useful for showing areas of concern that can be followed up with more site-specific field reconnaissance for targeting management concerns. The RGA data provide field validation of the range in erosion and deposition. Although at a relatively coarse resolution, with known problems with hydrologic dams at road-stream crossings or over-representation of non-existent channels in wetlands, we were comfortable that we captured ravine channels and represented the distribution of channel slopes and the presence of steep valley sides adjacent to the channels. The loads estimates offered by this sediment budget represent a time averaged approximation of the contributions of eroding near channel features, and also represent all sediment sizes present in the valley sides, terraces, or banks, including coarse materials that are less readily transported and move more slowly through the network than fine sediments that move in suspension as part of wash load. The watershed erosion estimates do not account for storage in the channel, and the soft sediment deposition estimates suggest that overall, the Little Fork stores sediment, and that if all erosion stopped, it would take roughly 6 years or more, depending on floods, to evacuate all the soft sediment from the channel bed. Of course, this is an unreasonable assumption but gives an idea of the possible lag times between management actions and quantifiable reductions in suspended sediment concentrations at monitoring sites. This estimate of eroding volume is larger than measured TSS at loads at the network of gages on the Little Fork and its tributaries. However, these raw erosion volumes are valuable in identifying the relative influence of distinct parts of the stream network on downstream sediment loading. Furthermore, when the results of sediment total phosphorus (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.

In summary, erosion rates are highest along the Little Fork mainstem and adjacent tributaries that intersect valley sides, downstream of its confluence with the Sturgeon River. Next steps involve validating procedures and results with complimentary sediment fingerprinting-based apportionments for upland and stream corridor erosion sources. The stream network segment-based erosion and deposition rates can be used for general identification of areas that maybe of concern in the development of management strategies for the meeting the TMDL for the Little Fork. Site specific management actions require a higher resolution data set and additional site investigations.

Acknowledgments

The rapid geomorphic assessments involved intensive fieldwork in rocky, steep sections of rivers and brushy hidden ravines in remote locations. The field work was greatly assisted by Sam Soderman, Phil Norvitch, Mike Kennedy, Jesse Anderson, Andy Kasun, and Karen Gran. Meg Haserodt assisted with GIS analysis and building of the detailed stream network. Funding was provided by the Minnesota Pollution Control Agency and the U.S. Geological Survey Cooperative Match Program.

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Appendix B – Sediment fingerprinting paper

Contents lists available at ScienceDirect

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Near-channel erosion as a driver of watershed-scale sediment and phosphorus loading in a forested sub-watershed of Lake of the Woods

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ABSTRACT

The Little Fork River, a forested watershed in northern Minnesota, United States, is a disproportionate contributor of sediment and phosphorus to Rainy River and Lake of the Woods. Sources of sediment and sediment-bound phosphorus to the Little Fork were investigated using complementary lines of evidence in the form of geochemical sediment fingerprinting and a stream-corridor sediment budget that included harvested forest and ravines, in addition to upland forest and agriculture, roads, and streambanks. Near-channel ravine and streambank sources comprised 95–100 % of streambed sediment and 79–100 % of suspended sediment at the river mouth, while tributaries had up to 50% of suspended sediment from upland sources including harvested forest, agriculture, and roads. Repeat suspended-sediment sampling at eight sites showed more source variability among sites than across events. Ravine erosion was the watershed's largest contributor to downstream sediment and sediment-bound phosphorus loading, while streambed sediment had a larger streambank source. Near-channel erosion also contributed phosphorus, though with less labile and redox-sensitive forms than forest and agricultural soils. In contrast to observations from agricultural settings, suspended-sediment phosphorus concentrations were elevated above some, but not all sources. The effects of watershed size, glacial history, land cover, and variable temperature and precipitation on runoff generation and peak streamflow are important considerations for mitigating near-channel loss of sediment and phosphorus in the Little Fork. These results suggest that management of sediment and phosphorus export from the Little Fork could incorporate context for location in the watershed, geomorphic setting, and runoff characteristics.

1. Introduction

Sediment is a globally important pollutant and has been identified as one of the most common causes for the degradation of stream biological integrity (Gellis et al., 2016). Excess sediment in river systems can decrease light, bury benthic habitat (Minnesota Pollution Control Agency (MPCA), 2015), impact fish health (Newcombe and Jensen, 1996), and serve as a vector for nutrients and contaminants (Ongley, 1996). Sediment is commonly a vector for phosphorus (Baker, 2018; Correll, 1998; Kreiling et al. 2023), a vital nutrient which occurs naturally in soils and sediment in a variety of mineral and organic forms. Phosphorus can become elevated on sediment due to adsorption in environments where dissolved phosphorus is abundant and the sorptive capacity of sediment is high, generating high sediment-bound phosphorus (sedP) (Kreiling et al., 2023; Records et al, 2016; Withers and Jarvie, 2008). Excess phosphorus has long been understood to be a critical contributor to the proliferation of algae in fresh waters (Schindler and Fee, 1974), and thus the sources of phosphorus in a

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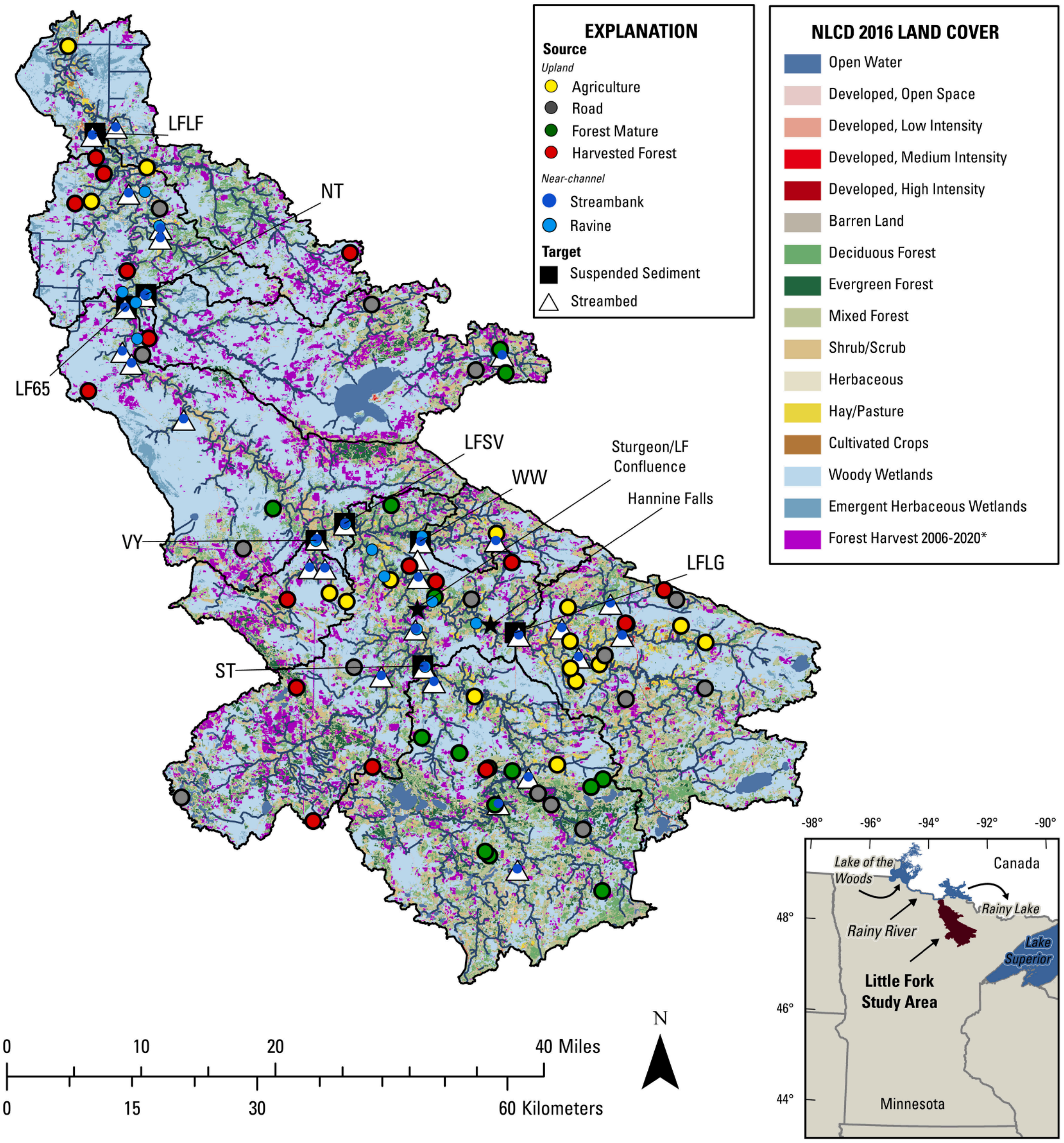
watershed are important considerations for management of algal blooms in receiving waters.

The Little Fork River, a forested tributary to the Rainy River in northern Minnesota, United States (Fig. 1), has sediment-related impairments (Anderson et al., 2006) and is a disproportionate contributor to sediment and phosphorus loading to downstream Rainy River and Lake of the Woods (Hargan et al., 2011). Lake of the Woods experiences seasonal eutrophication and severe harmful algal blooms (Binding et al., 2023) that produce algal toxins including the hepatotoxin microcystin and neurotoxins anatoxin-a and cylindrospermopsin (Zastepa et al., 2023), deplete hypolimnetic dissolved oxygen (MPCA, 2021), and cause anoxia (Heathcote et al., 2023). Blooms have occurred on Lake of the Woods for over a century, especially in the shallow, turbid southern basin which is underlain by deposits from glacial Lake Agassiz (Pla et al., 2005). Hargan et al. (2011) determined that between 45 % and 75 % of the new inputs of phosphorus to Lake of the Woods are derived from the Rainy River. Though phosphorus loads from Rainy River have decreased in recent decades, harmful algal blooms in Lake of the Woods persist (James, 2017). Studies suggest that Lake of the Woods phosphorus is driven not only by present-day loading from Rainy River but also the legacy of phosphorus stored in lakebed sediment that is supplied via internal loading (Alam et al., 2020; Edlund et al., 2014; Edlund et al., 2017; James, 2017). Though volumetrically the Little Fork River comprises only 8 % of total streamflow of the Rainy River, it contributed an average of 41 % of the suspended sediment and 21 % of the total phosphorus annual load from 2010 to 2022, with 88 % of the phosphorus in particulate form, suggesting a strong relation to sediment export. To address concerns about sediment within the Little Fork and its role as a loading source to Rainy River and Lake of the Woods, total maximum daily load (TMDL) regulations were established by the state of Minnesota, and work is underway to meet a benchmark of 15 mg/L total suspended solids (TSS) (MPCA, 2017). To meet these objectives,



Base from U.S. Geological Survey and Minnesota Department of Natural Resources, digital data 1:650,000, variously data, NAD 1983 UTM Zone 15N Transverse Mercator
*Harvested Forest 2006-2020 from Forest Disturbance layer, Minnesota Department of Natural Resources.

Fig. 1. Little Fork River watershed study area showing locations of sample collection. Suspended-sediment target sample collection occurred at passive samplers. Streambed target samples were collected at rapid geomorphic assessment sites. Source sediments were collected from uplands representing forest, harvested forest, agriculture, and road sources. Near-channel source samples including bank and ravine sediments were collected at rapid geomorphic assessment sites. Land cover from the National Land Cover Dataset (NLCD) 2016 (Dewitz, 2019) and a forest disturbance layer called “Most Recent Fast Forest Disturbances in Minnesota Version 4.0” (Vogeler et al., 2019) are shown, as well as the location of the watershed within the state of Minnesota. For site short names, see Table 1.

additional information is needed regarding sediment sources in the watershed.

Previous investigations have linked the large sediment loads from the Little Fork to glacial history (Gran et al., 2007) and land use change (Anderson et al., 2006). The lower Little Fork is entrenched within its valley with incision propagating up tributaries and ravines, causing slump blocks and channel widening, perhaps in part due to differential uplift following glacial retreat (Gran et al., 2007). In addition to glacial history, ice dynamics and historical log drives also may have played a role in shaping the Little Fork (Gran et al., 2007). The Little Fork River watershed was extensively logged from the late 1890s to 1937 (Anderson et al., 2006) and has active logging to present day. Evaluation of geomorphic data, climate records, and stream gage data indicate that the 67 % annual exceedance probability flood, frequently interpreted as "bankfull" or channel forming flow, had an initial increase until the late 1930s and then a decline to present (Anderson et al., 2006). These streamflow changes were found to be independent of the concurrent changes in annual precipitation, and it was hypothesized that the increase in flood size in the early 1900s was related to forest harvest and its impact on the hydrology and geomorphology of the watershed. Declines in bankfull flows occurring later in the record were hypothesized to be related to the regeneration of forest and subsequent reductions in annual runoff (Anderson et al., 2006).

A recent sediment budget for the Little Fork stream network estimated ravine and streambank erosion rates of 39,000 megagrams per year (Mg/yr) for fine-grained (silt and clay) sediment (Fitzpatrick et al., 2023; Sterner et al., 2025). The Little Fork experienced an average annual suspended sediment loading rate of over 58,400 Mg (measured as TSS) from 2010 to 2022 (data from Watershed Pollutant Load Monitoring Network Data Viewer (MPCA, 2024)), suggesting that, on an order of magnitude scale, ravine and streambank erosion could account for a majority of the suspended sediment load of the Little Fork watershed. This sediment budget found that the Little Fork channel network has 190,000 Mg of fine-grained soft sediment in storage, suggesting that resuspension of streambed sediment may cause a lag in seeing the downstream benefits of management practices for suspended sediment load reduction, measured as TSS by water-quality management agencies.

In response to the need for more detailed information regarding sediment sources in the Little Fork, this study employed geochemical sediment fingerprinting, a complementary line of evidence to the stream-corridor sediment budget, to describe sediment and sedP sources from both the near-channel (ravines and streambanks) and uplands. Additionally, contributions of sedP erosion to phosphorus loading and sedP storage in the channel network were assessed by development of a complementary sedP budget, and the potential bioavailability of sedP associated with source sediment and fluvial target sediment was explored. To further support TMDL development and supplement past research in the Little Fork, sediment fingerprinting and studies of sedP were used to investigate the following questions:

- Are near-channel ravine and streambank erosion the largest sources of suspended sediment in the forested Little Fork watershed? Are ravines or streambanks larger sources?
- Do uplands contribute to watershed scale sediment loading? Which upland land cover generates the largest masses of eroded sediment?
- Do sources of suspended sediment vary with season, storm magnitude, and streamflow, or spatially throughout the watershed?
- Do sources of suspended sediment in this forested, post-glacial watershed differ from sources in agricultural or urban settings?
- Do sources of stored streambed sediment vary from headwaters to mainstem?
- How does sedP vary among sediment sources and how does it compare to suspended and streambed sediment? Does fluvial sediment show enrichment in phosphorus relative to sources?
- Where are hotspots for sedP introduction within the stream corridor?

Based on prior studies we hypothesized that near-channel erosion would contribute the largest volumes of sediment and sedP moving through the watershed as suspended sediment and being stored within the network as bed sediment.

2. Study area

The Little Fork River watershed spans 4848 km^2 (MPCA, 2017) and flows north from the Laurentian Divide in northeastern Minnesota to the Rainy River at the border with Canada. The Rainy River drains east to Lake of the Woods before becoming the Winnipeg River and flowing north to Hudson Bay in Canada. The Little Fork River is part of the U.S. Environmental Protection Agency's (EPA) Northern Lakes and Forests and Northern Minnesota Wetlands Ecoregions (MPCA, 2017; Omernik and Gallant, 1988) and is characterized by vast expanses of wetland and forest, much of which were logged in the late 1800s and early 1900s (Anderson et al., 2006). The Little Fork watershed had an average annual precipitation of 26.8 in. (68 cm) from 1989 to 2018, with an average of 2.6 in. (6.6 cm) from December to February, 5.9 in. (15 cm) from March to May, 11.2 in. (28.4 cm) from June to August, and 7 in. (17.8 cm) September to November (Minnesota Department of Natural Resources (MN DNR), 2019). Average annual temperatures ranged from 27.6 °F to 49.7 °F (−2.4 to 9.8 °C) from 1989 to 2018 (MN DNR, 2019). Land cover in the Little Fork includes woody wetlands (51 %) and forests (29 %), with smaller portions of shrub/scrub (7 %), emergent herbaceous wetland (5 %), grassland/herbaceous (2 %), developed (2 %), agriculture (1 %), and open water (2 %) (Dewitz, 2019). Approximately 10 % of the watershed was harvested from 2006 to 2020 (Vogeler et al., 2019), the 15 years preceding this study. Statewide mapping for Minnesota indicates as much as 19 % of the watershed was mapped as peat deposits (Hobbs and Goebel, 1982), and all-hydric soils (i.e., soils where the entire mapping unit meets the definition of being formed under saturation, flooding, or ponding; Federal Register, 1994) delineated by the Natural Resources Conservation Service (NRCS) Web Soil Survey comprise 40 % of the watershed (NRCS, 2023) and were present across many categories of land cover. Soil parent material generally consists of glacial till, glacial lake, or glacial lake-modified silt or clay or sand associated with glacial outwash, ice-contact deposits, or paleo beach-bar deposits (Helgesen et al., 1976).

The Little Fork's present-day geomorphology reflects its glacial history as well as changes in land cover that have occurred over time. The last glacial advance through the area that is now the Little Fork River Watershed occurred from 11.1 to 11.4 ka BP (before present) (Thorleifson, 1996; Yang and Teller, 2005). Prior to this, much of the lower Little Fork River watershed was part of the eastern extent of glacial Lake Agassiz, a glacial lake that covered much of central Canada and northwest and north central Minnesota, which is understood to have retreated from the Little Fork watershed around 10.9 ka BP and from Lake of the Woods by 9 ka BP (Gran et al., 2007). The glacial lacustrine signature of glacial Lake Agassiz, other glacial lakes (Gran et al., 2007), and of reworked glacial tills can be seen in the banks of the Little Fork River as exposures of thick glacial lacustrine clay. These deposits are overlain by more recent fluvial sediment. The very low permeability of the glacial clays underlying fluvial deposits may lead to bank instability where water pools at the contact between these clays and overlying coarser fluvial units, which may influence erosion (Gran et al., 2007).

3. Methods

3.1. Sample collection

Geochemical sediment fingerprinting requires establishment of a sediment chemistry dataset with samples representing the sediment sources in the watershed and the fluvial sediment sinks or "targets." Fluvial target samples are the samples for which sediment fingerprinting evaluates the relative proportions from different sediment sources. For this study, target samples included streambed and suspended sediment. This study collected source and target samples during the ice-free season from April to October 2021 and 2022, an extremely dry year followed by a very heavy precipitation year.

Source sediment categories were selected based on land cover and proximity to the stream corridor, and included near-channel streambanks and ravines, upland mature forest, recently harvested forest (logged in the preceding 2 years), agriculture, and roads (Fig. 1). Roads included a mix of gravel, dirt, and paved roads. Sampling locations for upland sources were selected using a combination of the National Land Cover Dataset (NLCD) 2016 (Dewitz, 2019) and Minnesota DNR's Most Recent Fast Forest Disturbance Layer filtered to depict harvested forest from 2019 to 2020, the 2 years preceding sample collection (Vogeler et al., 2019). Polygons were created from each land cover of interest, and a random point distribution was generated for each land cover type, with approximately 15 samples in each land cover category (Sterner et al., 2025). Wetlands, which comprise greater than half of the land cover in the watershed, were initially explored as an upland source, but due to their extensive thick sphagnum moss, peat, and other vegetation, adequate sediment recovery for analysis was not possible. Thus, areas of peat and wetland were excluded from the analysis using the NLCD Woody Wetlands, Emergent Herbaceous Wetlands, and open water categories, and the "All Hydric" soil class from the NRCS Web Soil Survey (NRCS, 2023) to represent inundated soils and peatland. This reduced the potential contributing area for sediment by about 57 %, more than 2500 km^2.

For near-channel sources, a distribution of sampling locations was selected at channel reaches where rapid geomorphic assessments (RGAs) surveys were conducted. These RGAs provided measures of channel geometry and quantification of erosion and deposition rates for representative reaches throughout the network and were conducted as part of a stream-corridor sediment budget assessment (Fitzpatrick et al., 2023; Sterner et al., 2025). Samples were collected from eroding streambanks and ravines as composites for each category from multiple locations along each RGA reach. Both categories included mass-wasting terraces and valley sides, and the ravine category included v-shaped gullies with no bed deposition if present. Reaches included perennially wet or flowing segments mapped as part of digital state or national hydrography data sets. Ravine reaches had smaller tributary feeder channels that were typically steep and ephemeral with confined valleys, some of which were not part of the existing hydrography data sets and thus were delineated as part of an extended hydrologic network created as part of the sediment budget development (Fitzpatrick et al., 2019). The RGA locations were chosen based on slope, stream order, and position within the channel network to represent the range of conditions present and to allow for extrapolation of measured streambank erosion along perennial reaches and the mainly ephemeral ravine-features connecting uplands to perennial reaches. Source sediment samples were collected using plastic trowels to avoid metals contamination and scraping the top 2–5 cm of soil or sediment into a plastic bag following methods described in Fitzpatrick et al. (2023). Two streambank samples were excluded from the fingerprinting analysis, LF-41 due to low sample mass and LF-23 due having been collected entirely from a small area (0.5 m × 1 m) of eroding bank that would have overrepresented a very small eroding feature (Sterner et al., 2025).

In addition to the source sediment sample set, fluvial "target" samples including streambed and suspended sediment were collected. We collected soft, fine-grained streambed sediment from depositional zones, where present, in the RGA reaches (Fitzpatrick et al., 2023; Sterner et al., 2025). Although not part of the RGA reach selection process, beaver (*Castor canadensis*) activity was noted as extensive across the watershed, and the visual presence of beaver activity was documented as part of the RGAs. Notably, some RGA reaches were in actively beaver-impounded waters. Suspended sediment was collected at eight sites (Fig. 1; Table 1, Table 2) using one of two methods based on season and streamflow (Table 2). During ice-out and high water, water was pumped into 100-L plastic barrels using a high-capacity pump at the streamside and allowed to settle for 3–5 days before syphoning and centrifuging. With suspended-sediment concentrations peaking around 300 mg/L during these events, large volumes (~90 L) of river water were needed to obtain adequate suspended sediment for analysis. These pumped samples represent a single day of peak snowmelt or high-water conditions (Table 2). Potential contamination from metal parts within the pump was evaluated using a suspended-sediment blank consisting of powdered quartz in deionized water at a ratio representative of high TSS (~250 mg/L) for the Little Fork River, and elements showing concentrations above the background concentration on the quartz were removed from analysis. During low water, passive samplers (Phillips et al., 2000) were used for integrated suspended-sediment collection over the span of approximately 1 month at each of the gaged and ungaged locations (Table 1, Table 2).

Table 1
Monitoring locations for suspended-sediment sample collection, stream flow, and load monitoring. Sites listed from north to south, downstream to upstream on the Little Fork River. Latitude and longitude are provided in ESM Table S3 and Sterner et al. (2025).

Station Name	Sub-watershed Short Name	Rapid Geomorphic Assessment Reach	Drainage Area, Cumulative (km^2)
Little Fork River at Littlefork, MN	LFLF	LF-01	4300
Nett Lake River near UT 63 near Littlefork, MN	NT	LF-06	550
Little Fork River near Littlefork, MN65	LF65	LF-07	3400
Valley River near Rauch, MN	VY	LF-16	170
Little Fork River near Silverdale, MN65	LFSV	LF-15	2500
Willow River at CTY 75 near Greaney, MN	WW	LF-18	130
Little Fork River near Linden Grove, TH73	LFLG	LF-26	720
Sturgeon River at CTY 107 near Meadow Brook, MN	ST	LF-32	910

Samples were transported on ice and stored frozen until processing and analysis. To enable direct application of suspended-sediment source apportionment results to measured-TSS loads at the monitoring locations with stream gages, all samples were sieved to less than 63 μm to isolate the silt and clay fraction, which is the fraction most commonly moving in suspension and measured as TSS load (Gray et al., 2000). A prior study of Minnesota rivers showed that suspended sediment in the Little Fork had a median of 92 % finer than 63 μm (Tornes, 1986). Sediment was wet-sieved through polyester sieves, avoiding any contact with metal to prevent contamination of the sediment's elemental signature. TSS loads were measured and computed by the MPCA in partnership with Koochiching and North St. Louis Soil and Water Conservation Districts. Results of sediment source apportionment for suspended sediment collected as part of this study (as described above) were applied to these TSS loads. These TSS loads were accessed via the MPCA's Watershed Pollutant Load Monitoring Network Data Viewer (MPCA, 2024) and via personal communication by MPCA staff for 2021 and 2022 (Kelli Nerem, MPCA, 14 December 2023). For three tributaries that did not have load monitoring during the study period, results are presented as percent source apportionment rather than applied to TSS load.

Table 2

Suspended-sediment sample collection matrix listed by sampling site short name, showing sampling method by month during which samples were collected for each of eight sites. Sample method is abbreviated as PM for pumped sample, TB for passive sampler tube, FC-TB for fall composite passive sample, SC-TB for summer composite passive sample, −PM for pumped sample with insufficient material for analysis, −TB for passive sample with insufficient material for analysis, and – for no sample. Pumped samples were collected on a single day, and the resulting sediment source apportionment was applied to the load for that single day, presented in Fig. 4. Passive samples (TB) were collected over the course of a month, or 2 months in the case of fall and summer composite samples. The month of collection is listed. Sub-watershed short names are explained in Table 1.

Event	LFLF	NT	LF65	VY	LFSV	WW	LFLG	ST
Mar-21	PM	−PM	PM	−PM	PM	−PM	–	−PM
Apr-21	PM	PM	PM	PM	PM	PM	–	−PM
Jul-21	TB	TB	TB	TB	TB	−TB	TB	TB
Oct-21	TB	−TB	TB	–	−TB	−TB	TB	−TB
Apr-22	PM	PM	PM	PM	PM	PM	PM	PM
Jun-22	PM	PM	PM	PM	PM	PM	PM	PM
Jul-22	–	TB	TB	TB	TB	SC-TB	TB	TB
Aug-22	–	TB	TB	TB	TB	SC-TB	TB	TB
Sep-22	TB	FC-TB	TB	FC-TB	TB	−TB	−TB	TB
Oct-22	TB	FC-TB	TB	FC-TB	−TB	−TB	−TB	TB

3.2. Sample analysis

All sediment samples were analyzed for a suite of 49 elements, particle size, organic matter percent, and loosely bound (readily bioavailable) phosphorus. Elemental analysis was carried out via Inductively Coupled Plasma-Optical Emission Spectrometry-Mass Spectrometry following multi-acid digestion of the sediment samples at the U.S. Geological Survey's (USGS) Geology, Geophysics, and Geochemistry Science Center (USGS, 2019). Organic matter percent was evaluated via loss on ignition by the University of Minnesota Research Analytical Lab (Combs and Nathan, 1998). Particle size was evaluated using laser diffraction by Dr. Nic Jelinski's lab at the University of Minnesota. Sediment fingerprinting used the median grain size (D_{50}) of the less than 63-μm-sieved sample as a single metric for statistical evaluation. All samples were run in triplicate to address small sample masses, results were evaluated to remove outliers from replicates, and replicate results were averaged. Seven samples had insufficient material and were not analyzed for particle size or organic matter percent: six fluvial target suspended sediments and one mature-forest sample. A representative average from within the same source or target group was used for particle size and organic matter percent for these samples. Differences in median phosphorus concentration, D_{50}, and organic matter percent across source and target sediment categories were explored using Wilcoxon Rank Sum tests and were evaluated for statistical significance using an alpha level of 0.05, and where a negative location difference estimate indicated the median value for "x" in the test was lower than "y". Select source and suspended-sediment samples also underwent sequential extraction of phosphorus and analysis of loosely bound, iron- and aluminum-bound, mineral-bound, and recalcitrant organic phosphorus following the methods of Engstrom and Wright (1984) and Psenner and Puckso (1988).

3.3. Statistical methods for sediment source apportionment

Sediment fingerprinting methods use sediment geochemistry to determine the sources of sediment in a fluvial "target" sample—typically a suspended sediment or streambed sediment sample. These methods use stepwise linear discriminant function analysis (DFA) to determine the group of elements or "fingerprint" that differentiate sources. Sediment fingerprinting for Little Fork River suspended and bed sediment was carried out using the Sediment Source Assessment Tool (SedSAT) tool (Gorman Sanisaca et al., 2017) with all recommended default settings and 1000 Monte Carlo iterations. Correction factors were applied to elemental concentrations on source sediment based on the particle size (D_{50}) and organic matter percent of the fluvial sample as these two factors influence elemental chemistry (Gorman Sanisaca et al., 2017). Source verification testing was used to evaluate the effectiveness of the sediment fingerprints in differentiating sources by running source sediment samples as though they were fluvial target samples. Apportioned results were averaged by source sample across fluvial samples as each fluvial sample has a unique set of fingerprints for source categories. Those samples with >50 % of the sample classified as the correct source were considered correctly classified. The mixing model used to determine sediment source apportionment also produced an error term using equation 7 in Gorman Sanisaca et al., 2017. This error term was optimized by SedSAT to provide minimum error.

Sediment fingerprinting and sediment budget methods have become part of the EPA's suite of tools used for sediment source identification (Gellis et al., 2016). Results of apportionment are presented in comparison to land cover characteristics from the National Land Cover Dataset (NLCD) (Dewitz, 2019) and forest disturbance data (Vogeler et al., 2019) that were summarized by sub-watershed and within the riparian buffer of each RGA reach where streambed and bank samples were collected.

3.4. Stream corridor sediment-bound phosphorus budget

Near-channel contributions to phosphorus loading were evaluated following methods used in a previously published corridor sediment budget (Fitzpatrick et al., 2023; Sterner et al., 2025). This involved applying sedP concentration data from sediment samples collected for fingerprinting during the 2021 RGAs (which were sieved to less than 63 μm) to estimated bulk sediment loads (including all particle sizes) from streambank and ravine erosion and to masses of bulk soft-streambed-sediment deposition measured at those RGA reaches. Reach-based estimates for sedP erosion and deposition at the RGA sites were then extrapolated across the network using methods from Fitzpatrick et al. (2023) to obtain a bulk sedP estimate for the channel corridor. Previous studies indicate phosphorus preferentially binds to smaller particles (Stone et al., 1995) and is overall higher on smaller grain sizes (Kozyrev et al., 2023); thus, sieved sediment of <63 μm is likely to contain a majority of the phosphorus, making this a high estimate of potential contributions of the stream corridor to phosphorus loading.

As part of the underlying sediment budget development, the stream network was expanded in a geographic information system using 1/3 arc second digital elevation model data from the National Elevation Dataset program (USGS, 2018) at a 0.02-km^2 stream definition threshold to capture both perennially flowing and ephemeral channels in ravines and gullies that were not delineated as part of the existing hydrography data sets, but which were identified as important sediment sources during project-based reconnaissance efforts (Fitzpatrick et al., 2023, Sterner et al., 2025). This expanded network added four stream orders to those derived from the National Hydrologic Dataset (NHD) Plus stream network (McKay et al., 2012). The channel network was then broken into short segments of 60 m or less which were grouped by stream order, channel slope, and valley side slope. Channels with stream orders of 1–4 were grouped into headwaters. Perennial tributaries were assigned stream orders 5–7. The mainstems of the Sturgeon and Little Fork rivers, with stream orders of 8 and 9 were grouped as mainstem. Fitzpatrick et al. (2023) discusses sources of uncertainty in this form of sediment budget.

4. Results

4.1. Sediment fingerprinting

Sediment fingerprinting analysis leveraged elemental chemistry with correction factors for D_{50} and organic matter percent. Of the 49 elements analyzed, five were removed from the sediment fingerprinting analysis—two (selenium and tellurium) because their results were below the detection limit for nearly all samples, and three (arsenic, molybdenum, and tin) because a pump blank showed concentrations above the maximum concentration measured on the powdered quartz used in the test. The removal of these elements reduced errors on the sediment fingerprinting apportionment for 73 % of the fluvial target samples. Stepwise DFA leveraged the remaining 44 elemental tracers to distinguish sources of suspended and streambed sediment (Electronic Supplemental Materials (ESM) Table S1). The tracers with the highest mean percent of source samples independently discriminated by the tracer included strontium (Sr), phosphorus (P), iron (Fe), magnesium (Mg), sodium (Na), barium (Ba), tungsten (W), lithium (Li), and titanium (Ti) (Table 3). Strontium had both the highest mean percent of source samples differentiated and the most occurrences of being the top discriminant tracer (Table 3).

Source verification test results averaged by source sample showed a range of success at classifying sources (ESM Fig. S1). Near-channel sediments had the most samples with less than 50 % of the sample correctly classified on average, and most of these were confused for other near-channel sources, though some were confused for upland sources. Bank sediment had eight of 27 samples with less than 50 % classified as bank source. Of these, bank was still the largest percentage on average for all but two; two were outweighed by ravine source, two had ravine as the second largest percentage, three had agriculture, and one had road source (ESM Fig. S1). Ravine sediment had five of 16 samples with less than 50 % correctly classified on average, three were equaled or outweighed by the average percent apportioned to banks, and one was outweighed by agriculture source signature (ESM Fig. S1). Upland sediment showed less confusion between sources and tended to confuse upland samples for other upland source types. Samples from agriculture had all but one correctly classified, one sample 30 % harvested forest signature on average. Samples from harvested forest had two of 12 with less than 50 % correctly apportioned, one had ravine, and one had agriculture as the second largest source. Mature forest samples all had >75 % of the apportionment as the correct source on average (ESM Fig. S1). Mixing model errors are presented alongside apportionment results (ESM Table S2).

4.2. Sediment source apportionment

Sediment source apportionments from geochemical sediment fingerprinting revealed strong spatial patterns in suspended sediment and streambed sediment source across the watershed. Near-channel ravine and streambank sediment comprised a majority of the source in the lower mainstem with ravine comprising almost the entire source signature at the watershed outlet, eclipsing upland sources which were the largest proportion of source at the farthest upstream locations, especially upstream of the confluence of the Little Fork and Sturgeon rivers. Seasonal and runoff-related variability was also observed within sites, particularly at upstream sites, but both suspended and streambed sediment had stronger spatial variability than temporal. A complete table of sediment source apportionments for all fluvial samples is given in ESM Table S2.

Land cover in the watershed is relatively uniform and rich in forest and wetlands, with 57 % of the watershed in woody and herbaceous wetlands and open water (Dewitz, 2019), leaving only 43 % of the watershed potential contributing area for runoff generation and erosion. Agricultural and developed land use at the farthest downstream point in the watershed, Little Fork River at Littlefork, MN (LFLF) USGS site 05131500, were 1 % and 2 %, respectively, and increased to 3 % at the farthest upstream site Little Fork River nr Linden Grove, TH73 (LFLG) USGS site 05129915 (ESM Table S3). Harvested forest cover logged from 2006 to 2020 is high in the lower watershed (10 % at LFLF) and lower upstream (5 % at LFLG) (ESM Table S3). While these sub-watershed-scale variations in land cover are small compared to variation in sediment source, riparian land cover at the monitoring sites shows larger variability across sites (ESM Table S4), sometimes in parallel and sometimes in contrast with variation in sediment source. Sediment-source apportionments tended to be larger than sub-basin land cover percents, and variable relative to local-riparian land cover. Complete land cover statistics for each sampling location are given by cumulative sub-watershed (ESM Table S3) for the riparian buffer at 8 × channel width for each RGA reach (ESM Table S4), and for each RGA sub-watershed non-cumulatively (ESM Table S5). The land cover statistics most relevant to the sources observed are presented as context for the sediment source apportionments.

4.3. Suspended-sediment sources along the mainstem Little Fork and Sturgeon rivers

Suspended sediment collected during the 2021 and 2022 open water seasons at a network of passive sampler and stream gage locations represent a range of hydrologic conditions (Fig. 2; USGS, 2024) from high (~90th percentile) snowmelt flows in April 2021 to historic low flows in summer 2021 to near record high flows (>95th percentile) during snowmelt in April 2022 at the watershed outlet gage, LFLF. However, the proportion of sediment sources across these seasons and hydrologic conditions remained relatively consistent at each location,

Table 3

Summary of top tracers from stepwise discriminant function analysis (DFA) that discriminated sediment sources across target samples. Tracer DFA Rank is based on "mean Pi", which is the average percent of source samples independently discriminated by a given tracer. A DFA Rank of 1 is given to the highest value of mean Pi for each fluvial sample apportionment. Units for Mg, Na, and Ti (*) are percent; others are mg/kg (parts per million).

Tracer	DFA Rank High	DFA Rank Low	Mean Pi	Count of DFA Rank of 1	Agriculture	Bank	Forest Harvested	Forest Mature	Ravine	Road
Sr	1	9	0.52	28	125–214	154–297	93.4–265	144–253	158–233	234–854
P	1	8	0.50	19	490–1850	500–1080	560–1620	720–1210	660–850	650–1700
Fe*	1	9	0.49	12	1.91–3.3	2.31–4.05	1.62–2.69	1.79–2.71	2.49–3.96	1.57–8.16
Mg*	2	10	0.48	0	0.637–1.085	0.667–2.698	0.415–0.811	0.382–0.795	1.061–2.755	0.535–2.097
Na*	1	9	0.48	7	0.657–1.274	0.766–1.728	0.284–1.655	0.439–1.535	0.763–1.357	1.519–2.879
Ba	1	18	0.47	1	311–602	436–622	346–631	353–681	420–552	410–947
W	1	16	0.46	2	0.5–6	0.6–1.2	0.5–1.1	0.5–2.3	0.6–1.3	0.7–92.9
Li	1	13	0.45	5	23.3–53.5	25.8–50	12.4–36.7	16–31.9	23.1–47.2	12.4–45.6
Ti*	1	15	0.45	1	0.175–0.36	0.248–0.342	0.189–0.329	0.151–0.407	0.241–0.332	0.177–0.443

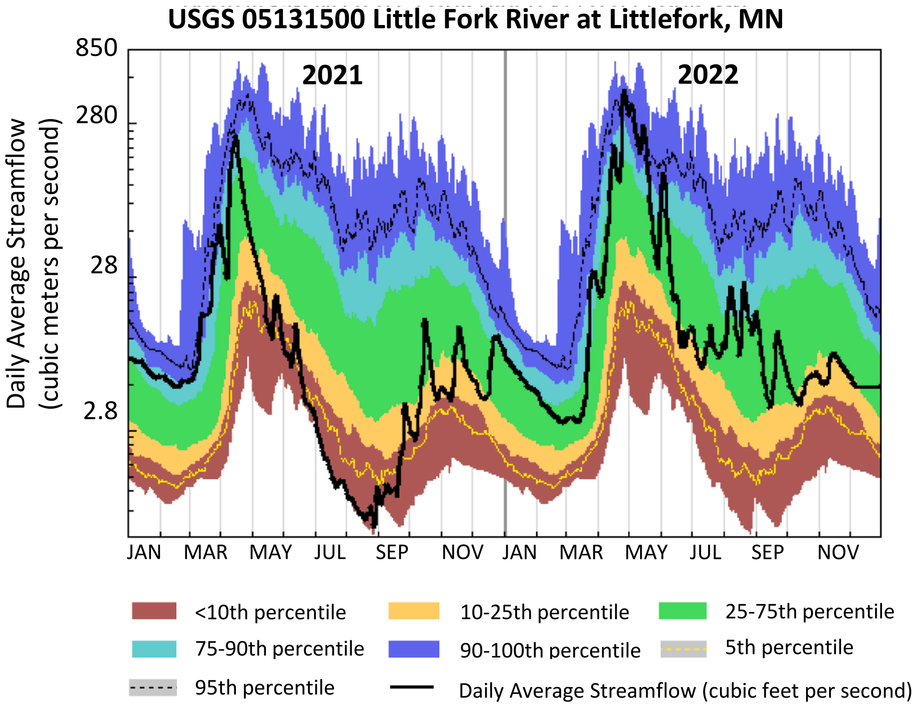


Fig. 2. Streamflow hydrograph for the study period at Little Fork River near Littlefork, MN65 (LFLF), with flow percentiles representing the full 105 years of available record. Plotted using USGS Water Watch (USGS, 2024).

with the farthest downstream site (LFLF) having 84–100 % near-channel sediment across events including almost entirely ravine source signature across events at the watershed outlet, and the farthest upstream site (LFLG) having 29–100 % upland sediment across events, with gradation in between and more upland influence at upstream sites (Fig. 3, ESM Table S2).

The farthest downstream site near the watershed outlet, LFLF, which represents 91 % of the total watershed area and had the highest TSS loads (>8300,000 kg), which occurred on a single day of peak snowmelt in April 2022, had 100 % ravine-derived sediment across events for all but the April 2021 snowmelt event, which had 16 % harvested forest signature (Fig. 3). In contrast, the April 2022 snowmelt event that generated flows in the 95th percentile of a more than 100-year long record (Fig. 2, Fig. 3) had 100 % ravine source. This location is within the lower watershed, downstream of the confluence of the Little Fork and Sturgeon rivers, which was demonstrated by prior study (Fitzpatrick et al., 2023; Sterner et al., 2025) to have steeper side slopes and the highest stream corridor erosion rates in the watershed. This part of the stream corridor with its steep, heavily eroding near-channel also had highly altered land cover within the riparian corridor, including 45 % developed and 21 % agriculture (ESM Table S3) (Dewitz, 2019). The sub-watershed had low developed (2 %) and agriculture (1 %) land cover (Dewitz, 2019), but some of the highest harvested forest land cover (10 %, Vogeler et al., 2019) in the watershed. Developed land cover likely indicates roads are present and is referenced here in relation to road source. These types of alteration may have hydrologic impacts on runoff and peak flow generation, relating to streambank and ravine erosion.

Upstream, suspended sediment shows progressively larger proportions of bank source, and eventually larger proportions from upland sources (Fig. 3). Little Fork River nr Littlefork, MN65 (LF65, 3400 km^2) USGS site 05131400, which represents 72 % of the total watershed area and had 95 % of the TSS load measured at LFLF (>7,900,000 kg) during the study's largest event in April 2022, also showed a predominance of ravine source across events, though with some variability. During the April 2021 snowmelt event, suspended sediment had 77 % ravine and 12 % bank source. The April 2022 event, which had more than twice the TSS load of the 2021 event, had nearly identical total near-channel source proportions but a shift to more bank source than in 2021 (30 % bank, 60 % ravine in 2022) and small proportions from uplands. Over all events, the signature ranged from 60 to 100 % ravine, 0 to 30 % bank, and upland proportions of 21 % or less, typically dominated by road and harvested forest. Land cover in LF65 sub-watershed was very similar to LFLF, with 2 % developed (which may be related to roads), 2 % agriculture (Dewitz, 2019), and 9 % harvested forest (Vogeler et al., 2019). The riparian buffer included some alternation (1 % developed, 13 % agriculture, 0 % harvested forest) but less than downstream.

Upstream from LF65, Little Fork River nr Silverdale, MN65 (LFSV, 2500 km^2) USGS site 05131323 showed more variation in the proportions from near-channel and uplands than the downstream sites, with samples from 2022 also showing substantially more bank influence, and more sediment from upland sources, especially agriculture and road. Here ravine source comprised 5–71 % and streambank source comprised 0–57 % of apportioned suspended sediment. Upland sources were heavy in road (11–30 % across events) and agriculture (0–32 %), with both sources present in all sampled events, and all but one event having agriculture as a source. During the largest loading event sampled (snowmelt in April 2022), LFSV had 68 % near-channel (57 % bank and 11 % ravine) and 32 % upland sediment, with road sediment as the most abundant upland source (20 %). The TSS load at LFSV during the largest loading events (3,000,000 kg TSS on a single day of peak snow melt in April 2022) represents approximately one third of the total mass measured at the watershed outlet gage LFLF (8,300,000 kg TSS) but comprises 54 % of the drainage area, indicating two thirds of the sediment exported from the system is sourced within the downstream 46 % of the watershed. Land cover in the riparian buffer at the LFSV RGA reach included 11 % developed and 9 % agriculture (Dewitz, 2019), and while the riparian buffer did not have harvested forest, the sub-watershed had 8 % harvested forest (Vogeler et al., 2019).

The two farthest upstream sites with TSS load data—LFLG (720 km^2) and Sturgeon River at CTY 107 near Meadow Brook, MN (ST, 910 km^2) USGS site 05131190—have a wider variety of sources and greater influence of uplands than their downstream Little Fork mainstem counterparts. The TSS loads at LFLG and ST each represent closer to one

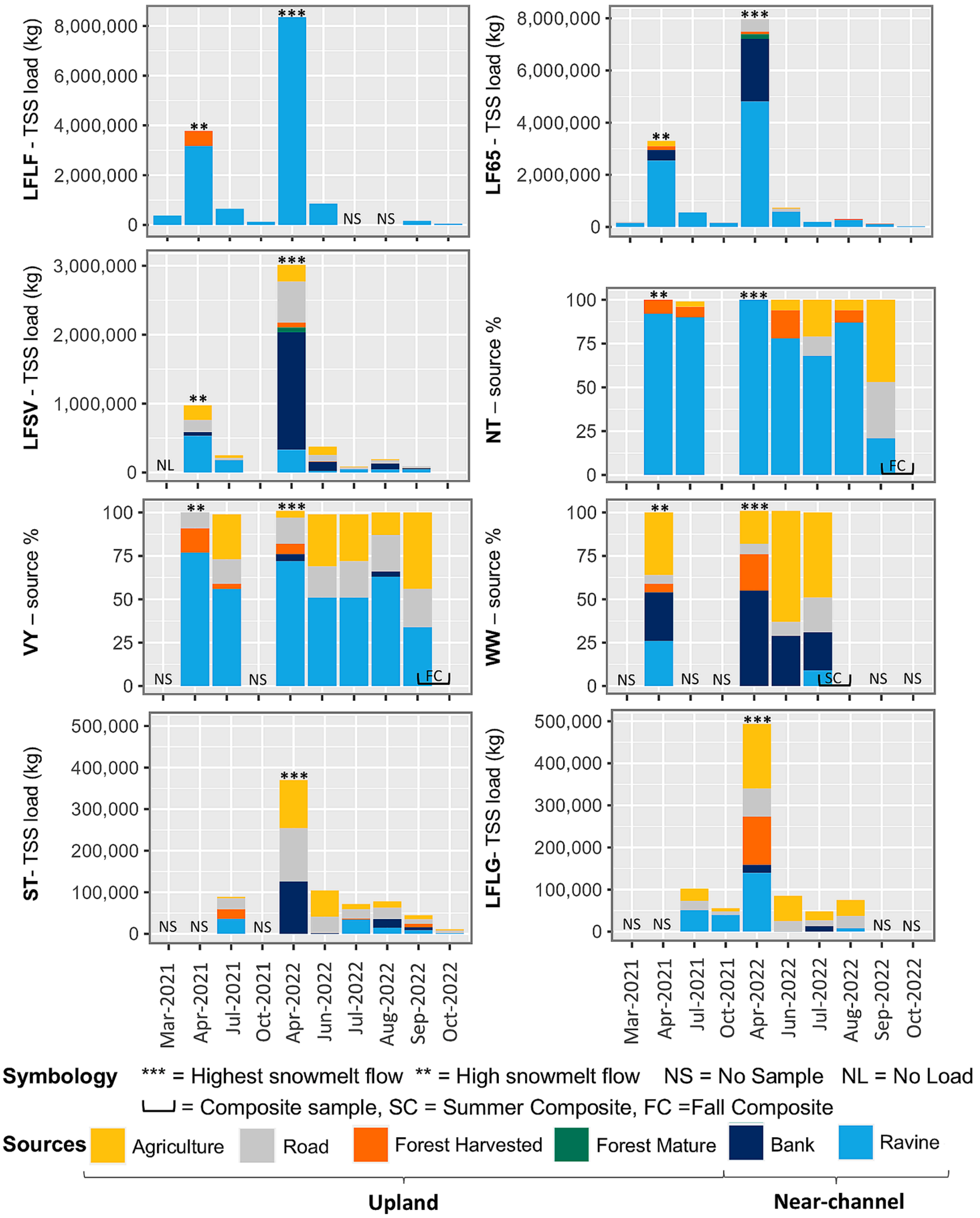


Fig. 3. Suspended-sediment apportionment applied to total suspended solids loads at gaged locations on the Little Fork and Sturgeon rivers and suspended-sediment source apportionment for un-gaged perennial tributaries to the Little Fork River. Date symbology includes ** where collected under high flow snow melt conditions, *** where collected under extreme high flow snow melt conditions, –ns where there was no sample due to the samplers being compromised, –nl where no load data were available for application of source apportionment. Samples with low mass that were composited from multiple months prior to analysis are indicated with a bracket and SC denoting summer composite or FC denoting fall composite. Sampling method details are available in Table 2.

sixteenth of the total export at the watershed outlet, where LFLG had just over 490,000 kg TSS and ST had 370,000 kg on the day of peak snow melt in April 2022. The two sites have some similar temporal patterns—both had sediment almost entirely comprised of agriculture and road sources in June 2022—and both had approximately 30 % near-channel sediment during the largest loading event in April 2022, though the upland type varied between sites during that event. Notably, LFLG had a large proportion of harvested forest (23 %) during the April 2022 event while ST had a notable road source (35 %), but both had agriculture source proportions around 30 %. Across events, both had overall larger proportions from agriculture than downstream sites, corresponding to land cover within the drainage watershed and local riparian area. The LFLG site had agriculture as its biggest upland contributor of suspended sediment (14–71 %), with road second (13–39 %), and both were present in every sample. Harvested forest was only identified as a source at LFLG during the largest loading event in April 2022. Land cover in the sub-watershed at LFLG has the highest percentage of agriculture of any sub-watershed (3 %) but lower harvested forest land cover (5 %) than downstream. Notably, the site had an area of harvested forest in the riparian corridor less than 250 m upstream of the monitoring site. At the ST site, the upland signature had consistent contributions from roads (24–54 %) and variable but sometimes very high agricultural inputs (4–60 %) and sporadic harvested forest influence (0–26 %). The ST site has high developed (15 %) and agricultural (11 %) land cover in its riparian buffer within the sampled reach. In the case of both agriculture and road source at these sites, land cover percent did not equal or exceed the percent of suspended sediment sourced from that land cover; however, these sites had both higher percent developed and percent agriculture land cover and higher proportions of sediment from those sources than downstream sites.

4.4. Suspended-sediment sources in perennial tributaries to the Little Fork

Three un-gaged perennial tributaries to the mainstem Little Fork River—Nett Lake River near UT 63 nr Littlefork, MN (NT, 550 km^2), Valley River near Rauch, MN (VY, 170 km^2), and Willow River at CTY 75 nr Greaney, MN (WW, 130 km^2) (Fig. 1)—had source apportionments that varied seasonally. These tributaries were un-gaged during the time of this study, but their seasonal flow distribution mirrors the gaged sites based on simulated HSPF flows shared via personal communication from MPCA staff (Mulu Fratkin, MPCA, 15 January 2025) generated using the HSPF model that supports the TMDL (MPCA, 2017). Source apportionments at these un-gaged locations vary seasonally. These locations had a similar spatial pattern to the sites with TSS load monitoring, where NT, a tributary to the lower Little Fork River within the entrenched section of the Little Fork and downstream of a large lake, had near-channel ravines as the largest source across storm events (21–100 %, Fig. 3), while near-channel sediments were smaller proportion of source at upstream VT and WW. The NT site had smaller contributions from harvested forest, agriculture, and roads (Fig. 3). One sample at NT showed large agriculture apportionment (47 % in a fall composite sample from 2022, Fig. 3), despite having no agricultural landcover in the NLCD data set (ESM Table S3); however, this sample occurred during fall low-flows and had very low mass, and source verification testing showed some confusion between near-channel ravine and bank sample and agriculture sample apportionment (ESM Fig. S1). The NT sub-watershed had the highest footprint of harvested forest of any sub-watershed (15 %; Vogeler et al., 2019). Nett Lake is more than 40 km upstream of the NT sampling location and serves as a sink for sediment within the upper reaches of the NT sub-watershed.

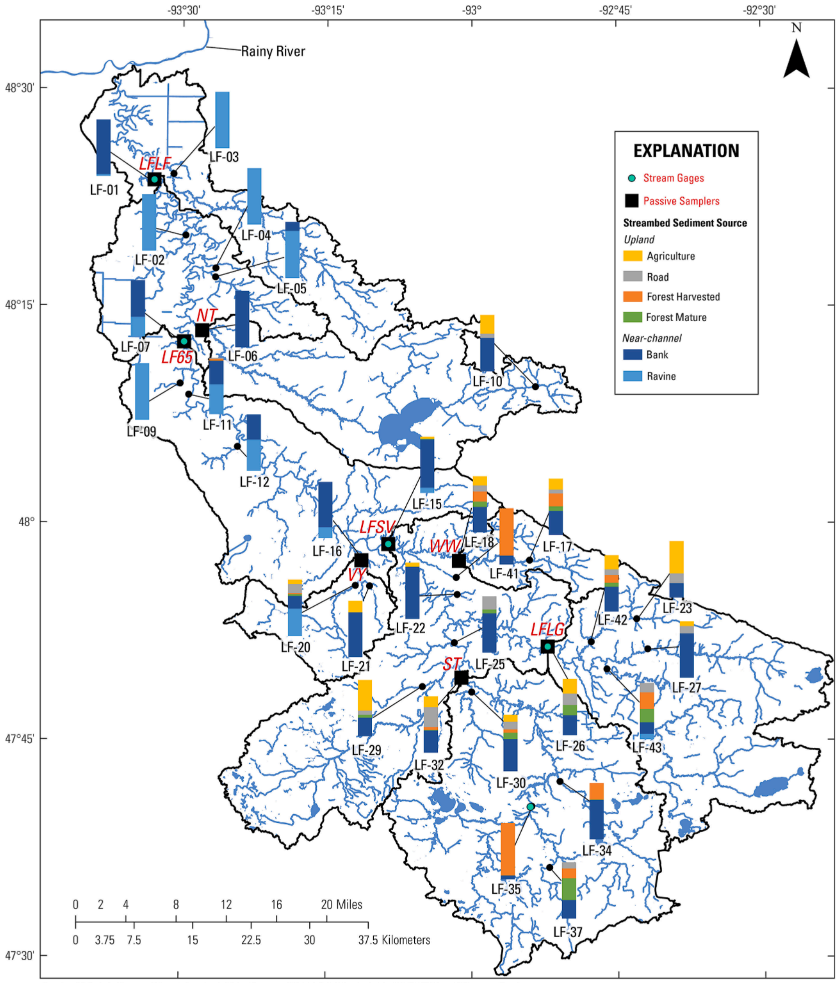
Farther upstream at VY and WW, near-channel sources comprised lower proportions of source, contributing 34–77 % and 32–55 % of source, respectively (Fig. 3), with more influence of uplands than NT and more variability across events. The VY and WW differed in their near-channel sources. The WW, which joins the Little Fork from the east, had nearly all bank signature (except for the April 2021 event which was almost evenly split with ravine), whereas VY, which joins from the west, had nearly all ravine across events (Fig. 3). The east side of the watershed is characterized by outcropping bedrock which may limit ravine development in the WW. Source signatures for suspended sediment from VY showed predominance of near-channel sediment with harvested forest and road signature during snowmelt events (April 2021 and 2022). The relative influence of upland source categories also varied between VY and WW. Upland sediment at VY had consistent presence of road source (9–22 %) and agriculture (0–44 %) and more sporadic presence of sediment from harvested forest (0–14 %). The VY sub-watershed has little agriculture and developed land cover (both 1 %) but has the second highest harvested forest cover of any sub-watershed (14 %). The most abundant upland sources from WW were agriculture (19–64 %) and road (5–20 %), and the largest event in the Little Fork watershed, snowmelt in April of 2022, had 21 % harvested forest. Land cover within the WW sub-watershed has 2 % agriculture and 2 % developed (related to road source) and 11 % harvested forest.

4.5. Streambed sediment sources

Soft, fine-grained streambed sediment stored in perennial channels showed a similar spatial pattern to suspended sediment, with source signatures comprised entirely of near-channel sediment along the downstream, northern Little Fork mainstem and tributaries. Streambed sediment at LFLF and NT had 97 % and 100 % bank sediment source, respectively, while other locations had 100 % ravine source or a mix of bank and ravine (Fig. 4). Streambed sediment from the more southern upstream tributaries showed more influence of a range of upland sources. Streambed sediment had overall more bank source than did the suspended sediment, including at locations where suspended sediment was dominated by ravine signature (LFLF, LF65, and LFSV in Fig. 3; LF-01, LF-07, and LF-15 in Fig. 4). In the more southern upstream tributaries upstream of LFSV, sources in part reflect local land cover, though sediment source apportionments were not equal to land cover percent. One such example is LF-41 Bois Forte Creek, an artificial channel which cuts through a narrow swath of harvested woody wetland that had large slash piles from timber harvest present at the time of sampling, having over 80 % harvested forest signature, despite the forest disturbance layer indicating no harvest in the sub-watershed or riparian buffer. The site with the highest harvested forest signature, LF-35, had 95 % harvested forest source and only 6 % harvested forest land cover within its sub-watershed. The sites with bed sediment with the highest source proportions from agriculture, LF-10 (33 % agriculture source), LF-23 (57 %), and LF-29 (55 %), did not have the highest percent agricultural land cover in their drainage watersheds; in fact, all had less than 1 %, and 0 % in their riparian buffer at the RGA reach. However, sites LF-23 and LF-29 did have pasture within approximately 1 km of the RGA reach and adjacent to the riparian corridor. Several other sites with agriculture as a source of streambed sediment did have high agricultural land cover in their riparian buffer at the RGA reach, including LF-21 (21 % agriculture sediment source, 26 % agricultural land cover in the riparian buffer), and LF-26 (26 % of sediment source, 7 % of riparian land cover) and LF-32/ST (19 % of sediment source, 11 % of riparian land cover). Developed land cover also corresponded to road sources, although like agriculture, apportionment generally outweighed land cover. For example, two sites with high road source apportionments, LF-25 (24 % road) and LF-26 (20 % road) had developed land cover of 0 % and 1 % in their riparian buffers, respectively, and both had 3 % developed in their RGA sub-watersheds and were approximately 3 km downstream of a road crossing. However, bed sediment at LF-32/ST had 35 % road source, the highest of any bed sediment sample, and it also had 15 % developed land cover within its riparian buffer.

4.6. Sediment-bound phosphorus sources and bioavailability

Total sedP concentrations, D_{50}, and organic matter varied between sources and fluvial targets for sediment from the Little Fork River watershed (Fig. 5). Among the sediment sources, agricultural soils showed the largest range in sedP concentration (490–1850 mg/kg) and had the highest maximum concentration; however, roads had the highest median sedP concentration, with harvested and mature forest close behind (Fig. 5). Ravines had the smallest range in sedP (660–850 mg/kg, mean of 750 mg/kg); smaller than banks (500–1080 mg/kg, mean of 728 mg/kg), and overall near-channel ravines and banks had the lowest median sedP concentrations of the sediment sources, statistically lower than road (ravine $W = 18$, $P < 0.001$; bank $W = 37$, $P < 0.001$), mature forest (ravine $W = 24.5$, $P < 0.001$; bank $W = 46.5$, $P < 0.001$), and harvested forest (ravine $W = 62.5$, $P = 0.024$; bank $W = 112$, $P = 0.009$) sources by Wilcoxon Rank Sum test (ESM Table S6). Bank source sedP and fluvial target streambed sedP both varied spatially across the river network (Fig. 6), with the highest concentrations of both occurring in the ST sub-watershed, and some of the lowest concentrations occurring in the LFLG sub-watershed, including at the LFLG site. Low to moderate bank and streambed sedP concentrations were observed in the downstream, more heavily eroding portion of the watershed where near-channel sources comprise the bulk of source apportionments. Sources with higher D_{50} included road, mature forest, and harvested forest, while ravine, bank, and agriculture had smaller mean



Base from U.S. Geological Survey and Minnesota Department of Natural Resources, digital data 1:650,000, variously data, NAD 1983 UTM Zone 15N Transverse Mercator

Fig. 4. Streambed sediment source apportionment map. For site short names, see Table 1.

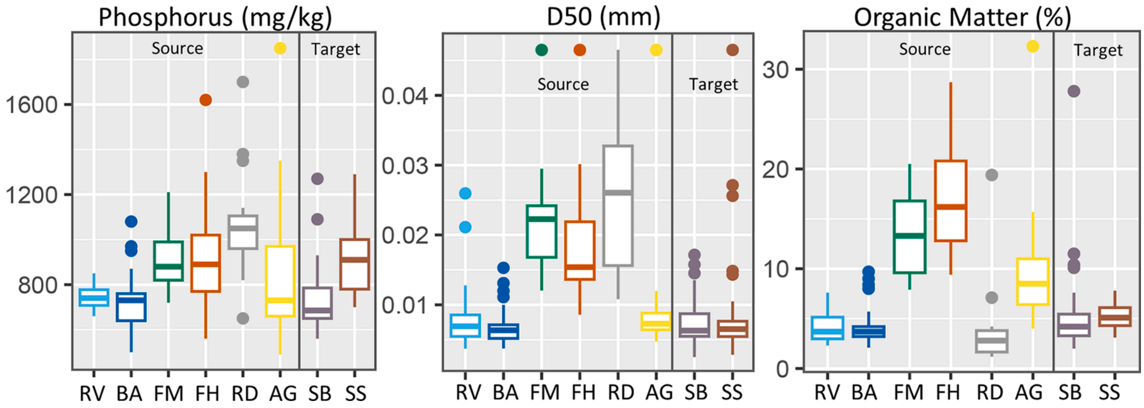
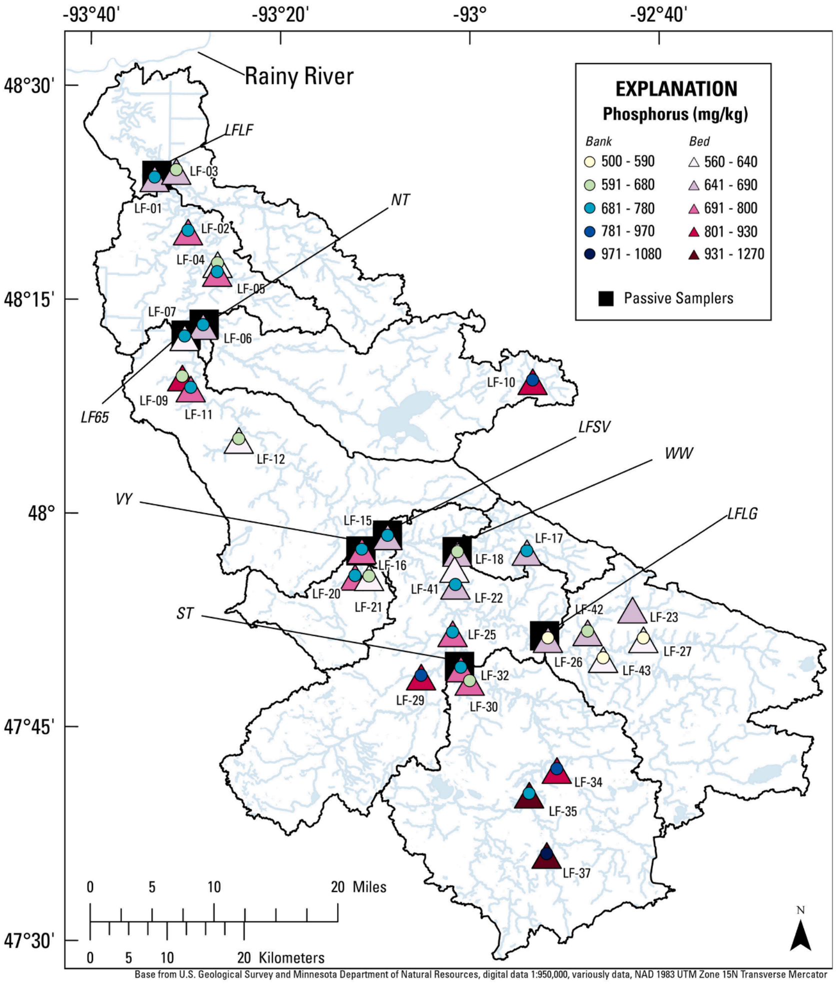


Fig. 5. Box plots for sediment-bound phosphorus concentration (mg/kg), mean sediment particle size (D_{50}, presented in mm), and organic matter percent, showing the interquartile range and median, where outliers were defined as less than and greater than 1.5 multiplied by first and third quartiles, respectively. Sources are abbreviated for ravine (RV), bank (BA), forest mature (FM), forest harvest (FH), road (RD), agriculture (AG), and targets streambed sediment (SB) and suspended sediment (SS).

particle size among the source sediment categories (Fig. 5). Harvested forest had the overall highest percent organic matter with the exception of one outlier sediment from agriculture (Fig. 5). Mature forest organic matter was similar to harvested forest but slightly lower.

SedP varied between streambed and suspended sediment. Streambed sediment had a lower median sedP concentration than any of the source sediment (Fig. 5, statistically significant for road $W = 429$, $P < 0.001$; forest mature $W = 350$, $P < 0.001$; and forest harvested $W = 352$, $P = 0.011$) (Fig. 5, ESM Table S6). Suspended sediment had a modest range (700–1250 mg/kg, mean of 924 mg/kg) and a higher median sedP concentration than the near-channel sources (bank $W = 217$, $P < 0.001$ and ravine $W = 107$, $P < 0.001$) but lower than road ($W = 610$, $P =$



Base from U.S. Geological Survey and Minnesota Department of Natural Resources, digital data 1:950,000, variously data, NAD 1983 UTM Zone 15N Transverse Mercator

Fig. 6. Map of streambed and streambank phosphorus concentrations in mg/kg; for site short names, see Table 1.

0.012) and similar to mature and harvested forest (Fig. 5, ESM Table S6). The LFLF site, which had suspended sediment with a 100 % ravine source apportionment, had a range of 730–1000 mg/kg sedP and a mean of 866 mg/kg. Streambed and suspended-sediment samples had similar D_{50}. Suspended-sediment median D_{50} across samples was slightly higher than for streambed sediments, though it had several high outliers and the difference in median was not statistically significant (Fig. 5, ESM Table S6). Bed sediment had a much higher organic matter percent maximum and range, but suspended sediment had a significantly higher median percent organic matter ($W = 1144$, $P = 0.048$) (Fig. 5, ESM Table S6).

Results of sequential extraction of phosphorus from source sediment revealed that the average proportion of potentially labile phosphorus (loosely bound, iron-bound, and labile-organic-bound) was larger for upland sediment sources (agriculture, mature and harvested forest) than for near-channel sources (bank and ravine) (Fig. 7). Mature forest had

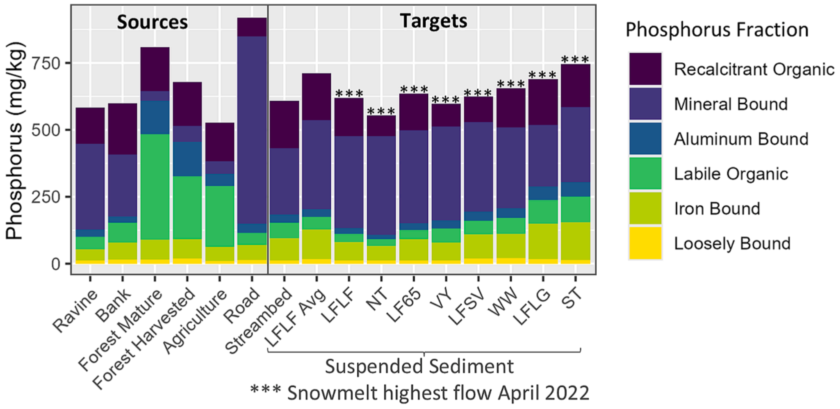


Fig. 7. Sediment phosphorus fractions including average loosely bound, iron- and aluminum-bound, labile organic-bound, mineral-bound, and recalcitrant organic-bound phosphorus fractions for sediment sources and targets, determined by sequential extraction from sediments, presented in mg/kg. For site short names, see Table 1.

the highest average proportion of potentially labile phosphorus (60 %), with agriculture (55 %) and harvested forest (48 %) having slightly lower potentially labile fractions on average. Roads, which consisted of a mix of gravel, dirt, and paved surfaces, had surprisingly high total phosphorus concentrations on average but were shown by the sequential extraction results to be comprised largely of more stable mineral-bound sedP.

Target sediment appeared to follow the source sediment phosphorus fraction results with regards to the most abundant sediment source at each site. Downstream sites on the Little Fork mainstem (LFLF, LF65, LFSV) had lower potentially labile sedP (18 %, 20 %, 26 %, respectively, during the April 2022 snowmelt event, 25 % on average at LFLF) where near-channel sediment was the largest proportional source, which also had lower labile sedP. In contrast, sites upstream (LFLG, ST) had higher fractions of potentially labile sedP (35 % and 34 %, respectively) and higher proportions of upland sediment sources. Although near-channel ravines had lower potentially labile sedP than upland sediment sources, as the primary source of sediment at the scale of the Little Fork watershed, the large particulate phosphorous load (> 6000 kg during the single day of peak snowmelt during the April 2022 snowmelt event) sourced from these features and throughout the stream corridor may contribute redox-sensitive phosphorus relevant to internal loading of phosphorus downstream in the Rainy River and Lake of the Woods (Fig. 8).

4.7. Stream corridor sediment-bound phosphorus budget

Results of a stream corridor sedP budget for the Little Fork reveal similar patterns to the sediment budget (Fitzpatrick et al., 2023; Sterner et al., 2025) with the highest contributions of sedP from near-channel erosion downstream of the confluence of the Little Fork and Sturgeon rivers, especially from ravines and small tributaries along the well-developed, steep valley of the Little Fork (Table 4). The section of the Little Fork watershed with the largest contributions of bulk sedP from stream corridor erosion occurred between LF65 and LFSV (24,000 kg/yr, Table 4). This section did not have the highest bank sediment sedP concentrations (Fig. 6) but did have the some of the highest measured near-channel (bank and ravine) erosion rates. The sedP contribution through this section was 4.9 kg/km/yr while the section between LF65 and the farthest downstream point at LFLF was 5.5 kg/km/yr. This section of the watershed spanning from LFSV to LFLF, which is all downstream of the confluence of the Little Fork and Sturgeon rivers, was identified as the portion of the watershed with largest near-channel sediment contributions (Fitzpatrick et al., 2023; Sterner et al., 2025) and includes many eroding ravines and contributions from VY. Cumulative total stream corridor erosion sedP contributions estimated as part of this corridor budget summed to just under 100,000 kg/yr for the mouth of the Little Fork River, and just under 93,000 kg/yr for the main gage at LFLF (Table 4, Fig. 9). Average annual total phosphorus load at LFLF from 2012 to 2022 was approximately 80,000 kg total phosphorus and 9000 kg dissolved orthophosphate, leaving approximately 71,000 kg of particulate phosphorus load on average per year (MPCA, 2024).

Deposition and storage of sedP, also in parallel with the sediment budget, is greatest in the upstream reaches of the Little Fork and its headwaters and tributaries (Fig. 9). Storage of sedP in streambed sediment was largest in the Little Fork upstream of its confluence with the Sturgeon River (Fig. 9), despite bed sediment sedP concentrations being lower in the LFLG sub-watershed than in the ST sub-watershed (Fig. 6). Large volumes of sedP were estimated to be stored in low-order gently sloping headwater channels, similar to sediment storage (Fitzpatrick et al., 2023; Sterner et al., 2025). Though beaver-impounded and non-beaver-impounded reaches had similar mean sedP concentrations (758 mg/kg and 703 mg/kg, respectively), average masses of sedP in storage within ponded beaver-impounded reaches was an order of magnitude higher than non-beaver-impounded reaches (174 kg/km and 45 kg/km, respectively). Organic matter percent and particle size were also not different between beaver-impounded and non-beaver-impounded bed-sediment categories. The site with the highest bed-sediment sedP concentration (1270 mg/kg) was on the Sturgeon River (LF-35, Fig. 6). This site had overall low sedP storage (approximately 18 kg/km), but a portion of the reach had a beaver-impounded side channel.

5. Discussion

5.1. Stream corridor and upland sources varied from upstream to downstream

Sediment fingerprinting and the previous evaluation of the stream-corridor sediment budget support the hypothesis that near-channel erosion is the largest source of suspended sediment, streambed sediment, and sedP to the Little Fork River across hydrologic regimes, and revealed ravine erosion as the primary source of suspended-sediment export to downstream Rainy River and Lake of the Woods. Despite the

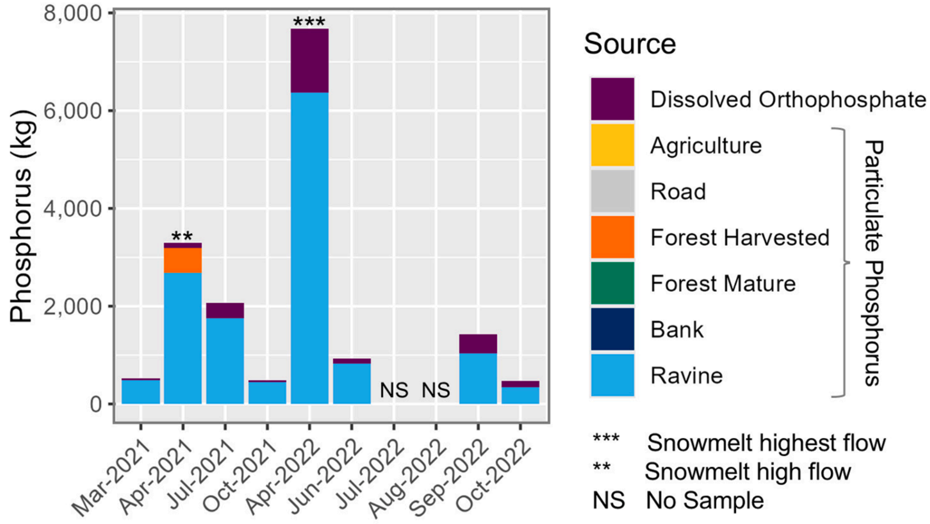


Fig. 8. Apportionment of total phosphorus including dissolved orthophosphate and particulate phosphorus apportioned based on sediment sources for Little Fork at Littlefork (LFLF). LFLF was the only site with available dissolved orthophosphate loads in 2021–2022 with which to calculate a particulate phosphorus load.

Table 4
Stream corridor budget for sediment-bound phosphorus for monitoring locations throughout the Little Fork River watershed, listed by suspended-sediment sampling sub-watershed; sub-watershed short names are explained in Table 1.

Sub-watershed Short Name	Drainage Area, Non-cumulative (km^2)	Stream Length, Non-cumulative (km)	Total Stream Corridor P Erosion, Non-cumulative (kg/yr)	Total P Erosion Yield, Non-cumulative (kg/km/yr)	Total Stream Corridor P Deposition, Non-cumulative (kg)	Total Stream Corridor P Deposition Yield, Non-cumulative (kg/km)	Drainage Area, Cumulative (km^2)	Total Stream Corridor P Erosion, Cumulative (kg/yr)	Average Annual Total Phosphorus Load, 2012–2022 (kg)
Little Fork Basin*	440	2900	6,900	2.4	43,000	15	4700	100,000	–
LFLF*	360	2400	13,000	5.5	37,000	15	4300	93,000	80,000
NT	550	3900	6700	1.7	65,000	17	550	6700	–
LF65*	680	4800	24,000	4.9	71,000	15	3400	73,000	50,000
VY	170	1100	2600	2.3	19,000	17	170	2600	–
LFSV*	780	4800	22,000	4.6	81,000	17	2500	47,000	31,000
WW	130	800	1000	1.3	16,000	20	130	1000	–
LFLG	720	4600	9300	2	82,000	18	720	9300	8900
ST	910	5600	15,000	2.6	102,000	18	910	15,000	8200

* Cumulative including all sub-watersheds listed below

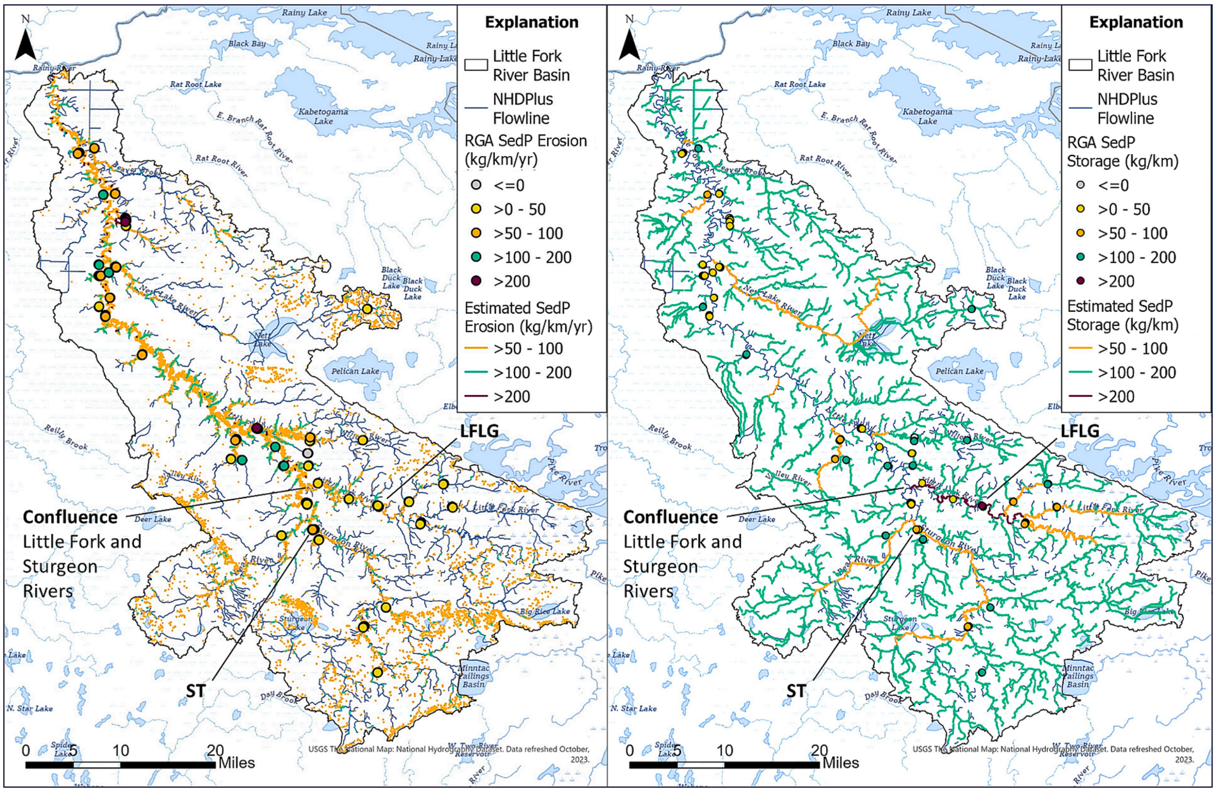


Fig. 9. Map of stream corridor sediment-bound phosphorus erosion and deposition and hotspots within the channel corridor.

large range in flow conditions and TSS loads sampled, source signatures remained relatively consistent at each location, but strong spatial patterns were observed, with larger upland sources in upstream headwaters locations becoming eclipsed downstream by near-channel sediment as watershed drainage area increased (Fig. 3). Though relations between source apportionment and percent land cover were not one-to-one, there were links between the most abundant upland sediment source and the local-riparian or sub-watershed land cover. Roads and agriculture were commonly large sources at headwater locations, and roads often had larger apportionment where the riparian corridor had high developed land cover. Agriculture showed higher apportionment where agricultural land cover occurred in or around the riparian area or had a relatively higher proportion in the sub-watershed, though the largest loading sites were not always in the sub-watersheds with the highest agricultural land cover. Harvested forest tended to be an episodic source and often corresponded to higher flows, with snow melt of 2021 at LFLF as an example. Though a similar signature of harvested forest was not observed in the April 2022 snowmelt at LFLF, it may have been eclipsed by near-channel erosion associated with the larger flows of the April 2022 event, which produced more than double the TSS load of the April 2021 event (Fig. 2, Fig. 3).

Across regions, physiographic provinces, and land cover in the United States, sediment sourcing studies have shown near-channel sources to be large contributors to watershed-scale sediment loading. These include heavily agricultural watersheds of the Central Lowland province in the post-glacial Upper Midwest, including the Le Sueur River, Minnesota (Belmont et al., 2011), West Fork Beaver Creek, Minnesota (Williamson et al., 2014), tributaries to the Fox River, Wisconsin (Apple and Plum creeks; Blount et al. (2022) and Fitzpatrick et al. (2019), respectively), and tributaries to the Maumee River (Black Creek, Indiana, Williamson et al., 2020); glaciated and non-glaciated areas of the central Midwest from South Dakota to Kentucky (Gellis et al., 2017); the Piedmont province of Maryland at Linganore Creek (Gellis and NOE, 2013); the Valley and Ridge province in agricultural and forested Smith Creek, West Virginia (Gellis and Gorman Sanisaca, 2018); and urban sites including Difficult Run in suburban Fairfax County, Virginia (Cashman et al., 2018) and Moores Mill Creek in the southern Piedmont of Alabama (bank and construction site sources; Malhotra et al., 2020). These studies point to the importance of near-channel sediment sources and to runoff generation, peak flows, and fluvial processes in driving spatial and temporal variability in near-channel and upland erosion.

5.2. *Drivers of near-channel erosion in the forested Little Fork River*

The combination of glacial history, bedrock topography, increased runoff from forest harvest, and potential climatic shifts toward more intense rainfall (Environmental Protection Agency, 2016) likely factor into the spatial distribution and predominance of near-channel corridor sources in the Little Fork. The Little Fork has extensive ravine erosion propagating from the mainstem up steep valleys in response to channel incision and post-glacial isostatic rebound (Gran et al., 2007). This type of knickpoint migration and incision from late-glacial base level changes is complex, episodic, and long-lasting (Faulkner et al., 2016). Patterns in runoff and sediment source may also be affected by increased and variable temperatures, snow and ice cover, and succession of extreme drought and extreme floods (Qui et al., 2021), like the extreme low flows of summer 2021 followed by the >95th percentile snowmelt April 2022 event. The Little Fork was overall wetter (increase of 0–0.8 in. (0–2 cm) in precipitation) and warmer (increase of 1.6–1.8 °F (0.9–1 °C)) on average when comparing 1989–2018 to the full record (1895–2018) (MN DNR, 2019). Studies from the broader Rainy River watershed also showed warming from 1910 to 2010 and increased rainfall and runoff during ice-cover conditions spanning November to March, which may induce earlier snowmelt (Greenwood and Eimers, 2023) and affect patterns in ice-out, snowmelt, freeze thaw, and subsequent scour of near-channel features. The Little Fork's clay-rich glacial sediments render it prone to flashiness and sensitive to hydroclimatic change (Greenwood and Eimers, 2023) and to hydrologic effects of landscape alteration (Anderson et al., 2006).

Forest harvest and disturbance have been shown by multiple studies in the region to impact water yield and erosion. In the Little Fork, the predominance of near-channel sources in watershed-scale suspended-sediment loads corresponds well to previous study findings that extensive logging in the Little Fork was correlated to years of increased water yield and initial increased baseflow (Anderson et al., 2006), which in turn increased corridor erosion. Previous studies in the region suggest that clearcutting increases streamflow by 30 to 80 %, and that forested river systems take approximately 12–15 years to recover hydrologically after harvest, potentially doubling peak flows and increasing snow-melt flood peaks during this timeframe (Verry, 1986). Historical clearcutting, change from evergreen to deciduous species, and loss of duff layer following historical fires has also been shown to double peak flows compared to pre-Euro-American settlement for Lake Superior tributaries (Fitzpatrick and Knox, 2000). Increased runoff from uplands, including harvested forest areas, can accelerate knickpoint migration and the development of ravines and gullies. Past work in the Nemadji River watershed found that disturbance from timber harvest in the mid-1800s and a large fire in the late 1800s increased water yield, initiated head-cuts and upstream knickpoint propagation, and generated bank erosion (Riedel et al., 2002), which was the primary source of sediment loads (Riedel et al., 2002). A similar mechanism is likely at play in the Little Fork, where episodic disturbance increases water yield and drives incision in ravines and tributaries downstream of the Sturgeon River confluence (Fig. 1). At the time of our sample collection in 2021, approximately 10 % of the Little Fork watershed had experienced timber harvest in the preceding 15 years, and could have been actively contributing to hydrologic alteration, increased water yield, and streamflow above pre-logging conditions. While ravines were the primary source of suspended sediment across events in the lower Little Fork, the snowmelt event of 2021 had 16 % of the load at LFLF derived from harvested forest. This may reflect the extent of connection between harvested forest areas and ephemeral ravines.

5.3. *Sources of streambed sediment and sediment-bound phosphorus*

Streambed sediment sources had a similar spatial pattern to suspended sediment, with mostly near-channel source in the lower watershed, but had higher streambank apportionment than suspended sediment which had more ravine source, potentially reflecting differences in timing and process of erosion. Ravine erosion is largely ephemeral, occurring only during high runoff events. Streambank erosion, though episodic, may occur much more frequently, as streambanks are in constant contact with river water, experiencing ice-scour, oversteepening from high flows, undercutting, and freeze/thaw processes. Groundwater sapping in banks and valley sides may also accentuate erosion along critical failure planes that may be vulnerable during intense localized rainfall and fluvial erosion (Fitzpatrick et al., 2023; Fox and Wilson, 2010; Gran et al., 2007; Simon and Rinaldi, 2000). In uplands, streambed sediment had larger upland sources, and local land cover of the riparian corridor appeared to be related to source apportionment, although not one-to-one. Drainage area, proximity to the channel, slope, connectivity, and extent of disturbance may influence the relation between local land cover and streambed-sediment source.

While sources and concentrations of streambed sedP varied across the network, hotspots for sedP erosion and storage were driven primarily by the masses of sediment, having high sedP erosion in the lower watershed, and high storage in the upper watershed (Fig. 9), where uplands comprised a majority of the sediment source. While the highest sedP concentrations in streambed sediment were in the ST watershed, the largest masses of stored sedP were in the LFLG sub-watershed (Fig. 9), corresponding to higher stored sediment in headwaters (Fitzpatrick et al., 2023; Sterner et al., 2025). Many headwater channels were bounded by wetlands and peat and affected by beaver activity. With high volumes of stored sedP in beaver-impounded reaches within the Little Fork River network (Fitzpatrick et al., 2023; Sterner et al., 2025), the removal of beaver dams could generate additional releases of previously stored sedP.

5.4. *Phosphorus variability and lability from sources to sinks*

Phosphorus export from the Little Fork to downstream Rainy River and Lake of the woods was largely particulate in form—88 % particulate phosphorus and 12 % dissolved orthophosphate on average from 2012 to 2022—suggesting a strong relation to suspended-sediment export. Sediment fingerprinting apportionment and stream-corridor sedP budget results suggest that sediment fluxes and associated sedP export from the watershed was attributable almost entirely to ravine erosion. Ravines and streambanks had the lowest median sedP concentrations of any of the sources in the watershed except agriculture (Fig. 5, ESM Table S6) and had low labile phosphorus (Fig. 7) relative to forested and agricultural uplands. Suspended sediment had statistically higher median sedP than ravine, bank, and agricultural sediment (Fig. 5, ESM Table S6), but lower than sediment from roads. The higher median sedP of suspended sediment may suggest that suspended sediment is becoming enriched through adsorption of dissolved phosphorus during transport. However, unlike many agricultural basins, the maximum concentrations of sedP on suspended sediment was not higher than all sources; harvested forest and agriculture had higher maximum sedP than suspended sediment. Though high sedP on suspended sediment may also be influenced by particle sorting and higher percent fines, suspended-sediment D_{50} was not significantly smaller than ravine, streambank, or agricultural sediment (Fig. 5, ESM Table S6). Enrichment of suspended sediment with phosphorus has been observed in many post-glacial agricultural and urban settings where dissolved phosphorus inputs to the landscape are high (Baker, 2018; Blount et al., 2022; Fitzpatrick et al., 2019; Grundtner et al., 2014; James and Larson, 2008; Williamson et al., 2024; Williamson et al., 2021), though in many of these cases, the suspended-sediment median and maximum sedP were higher on suspended sediment than any source sediment (Blount et al., 2023; Blount et al., 2022; Fitzpatrick et al., 2019), and maximum suspended-sediment sedP was higher in those basins than in Little Fork (Blount et al., 2022; Fitzpatrick et al., 2019), likely due to higher dissolved phosphorus runoff from agriculture. While there may be sources of dissolved phosphorus within the channel corridor including large peatland complexes and reaches with beaver activity, this watershed lacks the extensive application of fertilizer and manure that are typical of watersheds with intensive agriculture. Forest soils in the Little Fork are rich in phosphorus, especially in labile and redox-sensitive forms (Fig. 5, Fig. 7), and harvested forest soils have lower potentially labile and redox-sensitive phosphorus, suggesting that harvest may contribute to the loss of sedP from forest soils. Previous study in forested watersheds has demonstrated significant increases in phosphorus loss from harvest activities (Hubbard Brook Ecosystem Study, 2024); these losses may depend upon the extent of harvest and proximity to the channel.

5.5. *Implications for management of sediment and sediment-bound phosphorus*

Collaborative study of sediment and sedP sources and storage in the Little Fork River has yielded results that may be helpful in guiding management for suspended sediment and phosphorus load reduction. Near-channel erosion in the lower 46 % of the drainage network (downstream of LFSV) was found to generate two thirds of the sediment exported from the Little Fork to downstream Rainy River and Lake of the Woods, and along with it, large quantities of sedP. A baseline of near-channel erosion is natural, and is linked to channel evolution, the relatively short time since deglaciation, and the flashy nature of the watershed influenced by glacial Lake Agassiz clays (Gran et al., 2007; Greenwood and Eimers, 2023). This flashiness also means that the watershed is potentially sensitive to hydroclimatic shifts and changing land cover in uplands. With extensive present-day logging (10 % of the watershed logged in the 15 years preceding the study), forest management practices to minimize impacts to hydrology may assist with reducing peak flows and associated near-channel erosion (for example, practices outlined by the Minnesota Forest Resources Council and Minnesota Department of Natural Resources, 2014). With the largest source apportionments attributed to ravine erosion, areas where forestry management, agricultural land cover, or road crossings occur surrounding a ravine would be important places to examine runoff generation. Runoff at the rim of ravines that connect harvest areas to the channel network may impact the loss of sediment and phosphorus from both ravines and forested areas. Even with focused management, there may be potential for the benefits to be masked by accelerated erosion from increasing storm magnitude and frequency with climate change, or due to lags in the delivery of sediment and sedP from storage. Beaver-impounded reaches store large amounts of sediment and associated sedP, and thus the removal of beaver dams may have undesirable effects with respect to sediment release from storage and increased bank erosion via associated with the dam release.

Due to the importance of near-channel sediment loading and the influence of this erosion on sedP loss from the channel, addressing the areas with the greatest erosion will address the bulk of phosphorus export. However, upland mature forest had relatively high redox-sensitive and labile phosphorus, while harvested forest had less. This suggests that forestry management in uplands and along steep tributaries to the lower mainstem Little Fork may assist with retaining labile phosphorus, reducing erosion, and ultimately reducing phosphorus export to the Rainy River and downstream Lake of the Woods.

6. Conclusions

Geochemical sediment fingerprinting successfully identified sources of fluvial sediment in the Little Fork River, a large, forested watershed which delivers disproportionate loads of sediment (measured as TSS) and phosphorus to downstream Rainy River and Lake of the Woods.

While suspended sediment exhibited some within-site variation in source with time and hydrologic condition, sediment source was more variable spatially along the river corridor. Near-channel eroding ravines were the largest contributors of suspended sediment at the scale of the watershed, with banks increasing in contribution at sites upstream of the outlet within the incised zone of the river network, while upland sources comprised a larger portion of the suspended sediment in upper mainstem and headwaters (Fig. 3). Upland erosion contributors included harvested forest, though largely episodic, as well as road and agriculture, which had more consistent contributions through time and space across upland headwaters sites. Upland sediment sources were frequently linked to land cover within the drainage or riparian area local to the sampling location. Harvested forest was the only discernable upland source to contribute to sediment loading at the scale of the Little Fork watershed, suggesting that soil losses and runoff from harvested areas contribute to the export of sediment from the Little Fork to Rainy River and Lake of the Woods.

Sediment-bound phosphorus concentrations showed variability among source and target categories, but notably, suspended-sediment sedP was lower than in many urban and agricultural watersheds, and concentrations were elevated above most, but not all source sediment concentrations (Fig. 5, ESM Table S6), suggesting potentially less enrichment via adsorption of dissolved phosphorus compared to what is frequently observed in agricultural settings. In addition to being the primary source of sediment at the watershed scale, ravines and streambanks were also an important source of sedP, and the erosion of ravines can account for a majority of the particulate phosphorus and total phosphorus load from Little Fork River to downstream waters (Fig. 8) and is relevant to management. While near-channel sources of sediment were by far the largest sources of both sediment and phosphorus at the watershed scale, upland sources tended to have higher phosphorus concentrations, and higher labile and redox-sensitive phosphorus concentrations, which also may contribute to phosphorus cycling in the channel network and to downstream phosphorus loading and to internal loading of phosphorus in seasonally eutrophic Lake of the Woods.

In parallel with suspended sediment, source evaluation for streambed sediments showed that the channel corridor dominated the source signal lower in the watershed, with upland sources comprising the bulk of streambed sediment source in the headwaters. The channel network also stores large masses of sedP in the streambed, showing hotspots for phosphorus storage that co-occur with the largest sediment storage locations (Fig. 9), as sediment storage is more variable than phosphorus concentration (Fig. 6). This stored sedP may be vulnerable to later release and induce lags to management practice effectiveness at the scale of the watershed, which is especially important in this forested watershed where a majority of the phosphorus is in particulate form.

The mechanisms driving near-channel erosion in the Little Fork include a mix of natural (glacial and post-glacial history) and anthropogenic (forest harvest, agriculture, road development, climate change) factors that relate to runoff generation and peak flows, which in turn drive erosion in the channel corridor. Due to the importance of this type of erosion to both suspended sediment and sediment-bound phosphorus export from the Little Fork, management could consider this mix of factors in its evaluation of approaches to reducing sediment and phosphorus loads as well as runoff, from the Little Fork to Rainy River and Lake of the Woods.

CRediT authorship contribution statement

Anna C. Baker: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Faith A. Fitzpatrick:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Samuel S. Soderman:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Michael J. Kennedy:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Shelby P. Sterner:** Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Jesse P. Anderson:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Karen B. Gran:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Conceptualization. **Krimson S. Anderson:** Writing – review & editing, Writing – original draft, Software, Formal analysis, Data curation. **Kevin Stroom:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Phil Norvitch:** Resources, Project administration, Investigation, Data curation, Conceptualization. **James D. Blount:** Software, Resources, Investigation, Formal analysis, Data curation. **Matthew E. Gutzmann:** Writing – review & editing, Resources, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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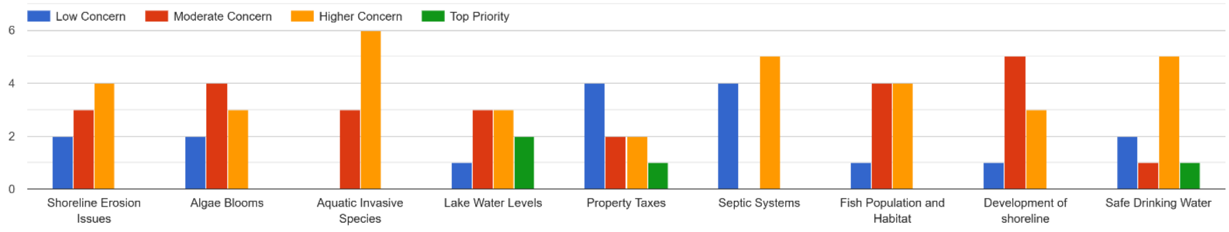
Appendix C – Side Lake Community Survey and Results

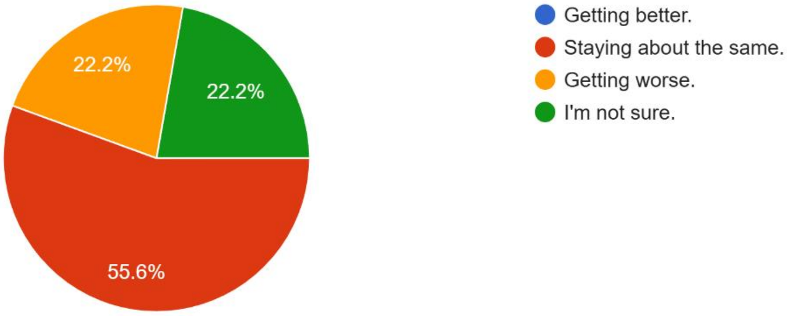
Side Lake WQ Survey Results and Questions

Rank the following issues/concerns on the Sturgeon Chain of Lakes:



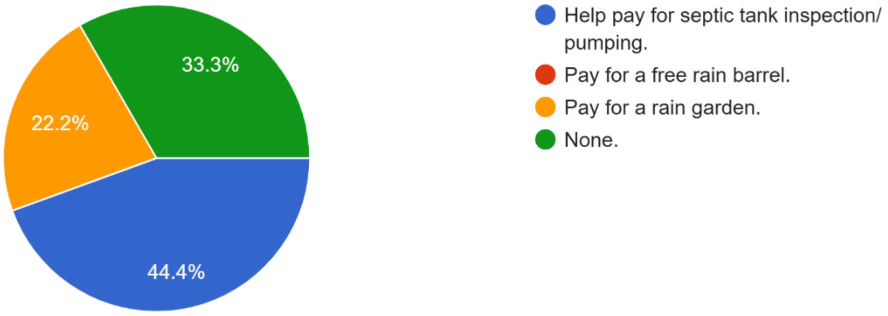
In your opinion, the water quality in the Sturgeon Chain of Lakes is:

9 responses



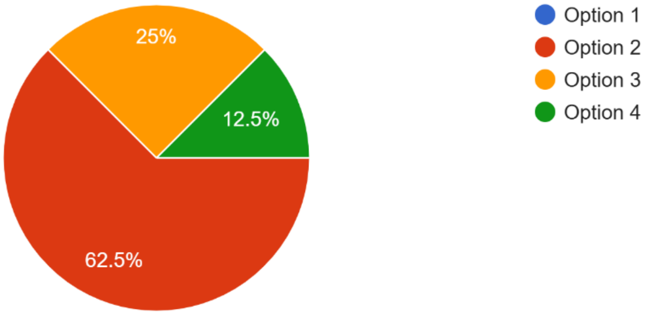
If there was a program to help you pay for a project, which of the following would you most likely be interested in:

9 responses



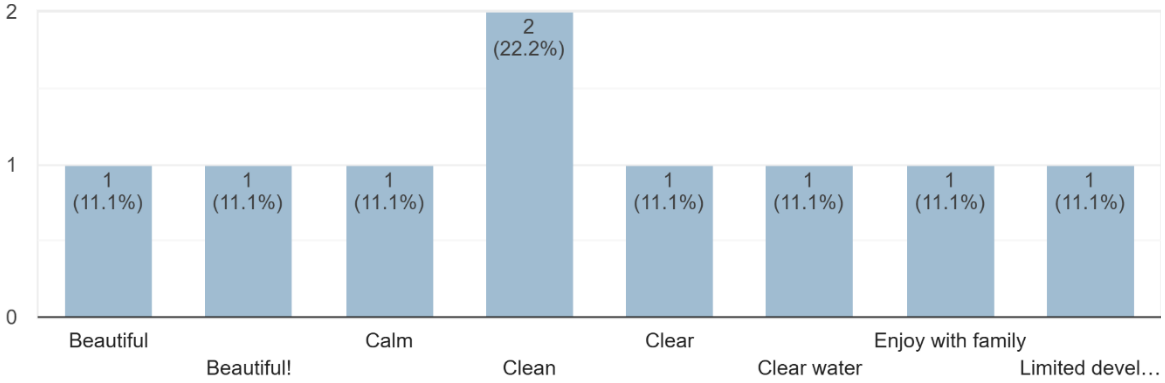
Which of the following photos shows your version of the perfect lake shore?

8 responses



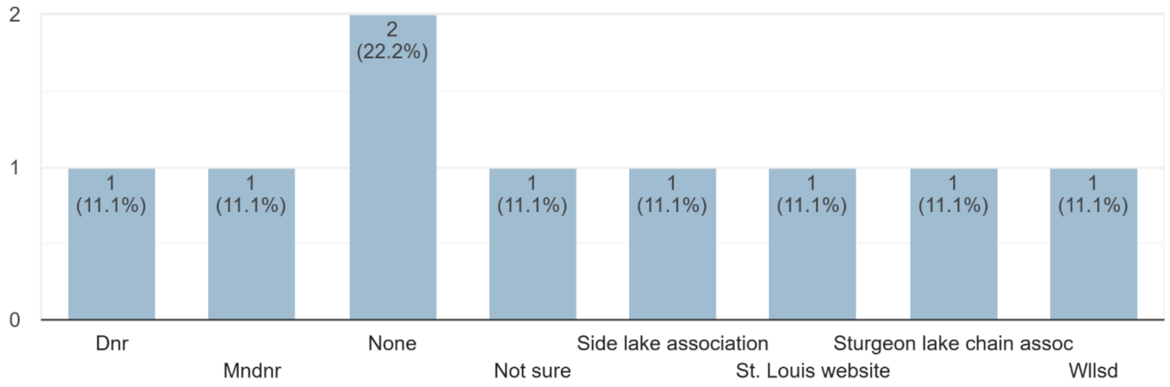
When you think about your favorite lake or stream, what word or phrase comes to mind?

9 responses



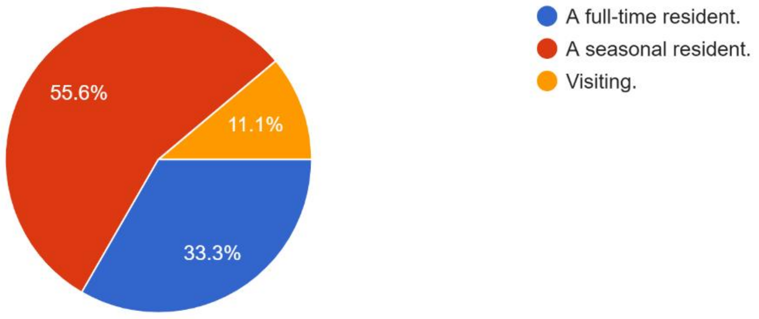
Where do you get your information about water quality in the lakes you visit?

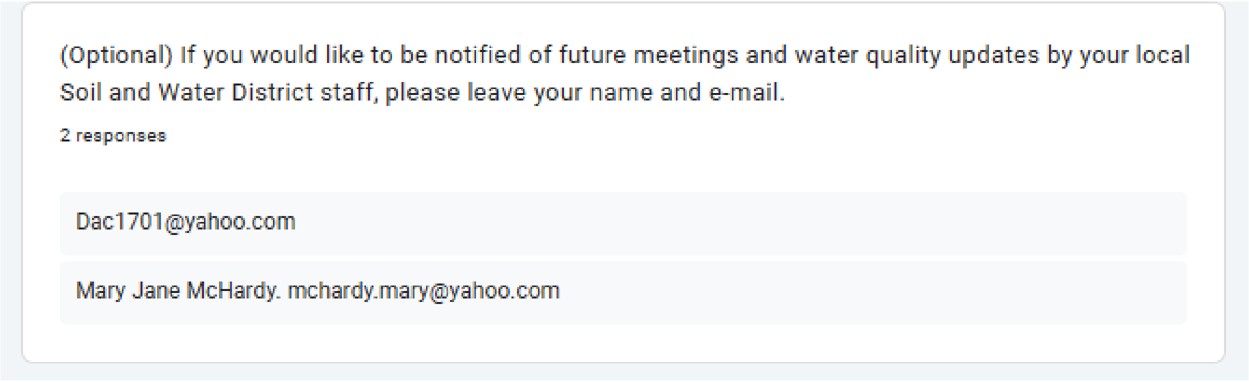
9 responses



I am:

9 responses





(Optional) If you would like to be notified of future meetings and water quality updates by your local Soil and Water District staff, please leave your name and e-mail.

2 responses

Dac1701@yahoo.com

Mary Jane McHardy. mchardy.mary@yahoo.com

Appendix D – Fact sheet

Sediment Fingerprinting - Little Fork River Watershed

What is Sediment Fingerprinting?

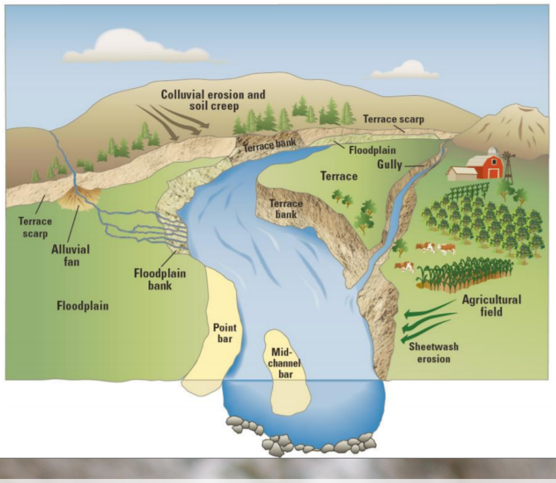
It's a way of finding where the sediment pollution is coming from when the source is not exactly clear.

How is it like a fingerprint?

Imagine a big bag of Skittles dumped all over a yard. Each color in any location has its own unique and identifiable "fingerprint". When it rains, imagine only the yellow and red Skittles running off into a river causing the river to turn colors. When we look at the river sample, we notice that it's the yellow and red Skittles causing pollution and we're able to track down where those are and keep them from running off. With actual sediment, the different types of clay, dirt, silt and other material are made up of very unique characteristics (like a fingerprint) that we can use to help track down where it's coming from and help prevent them from polluting our rivers and streams!

What exactly is sediment pollution anyway?

When it rains, things like dirt, silt, clay, sand, and soil get washed into the rivers and streams which make the river cloudy. This blocks sunlight into the water which prevents vegetation from growing and makes it hard for fish and other water animals to see their food. Sometimes it's easy to see where the sediment is coming from like when storm sewer is dumping water with sand and silt from the road after a storm. Other times, it's harder to locate if the sediment is coming from streambank erosion, forests, or farm fields.



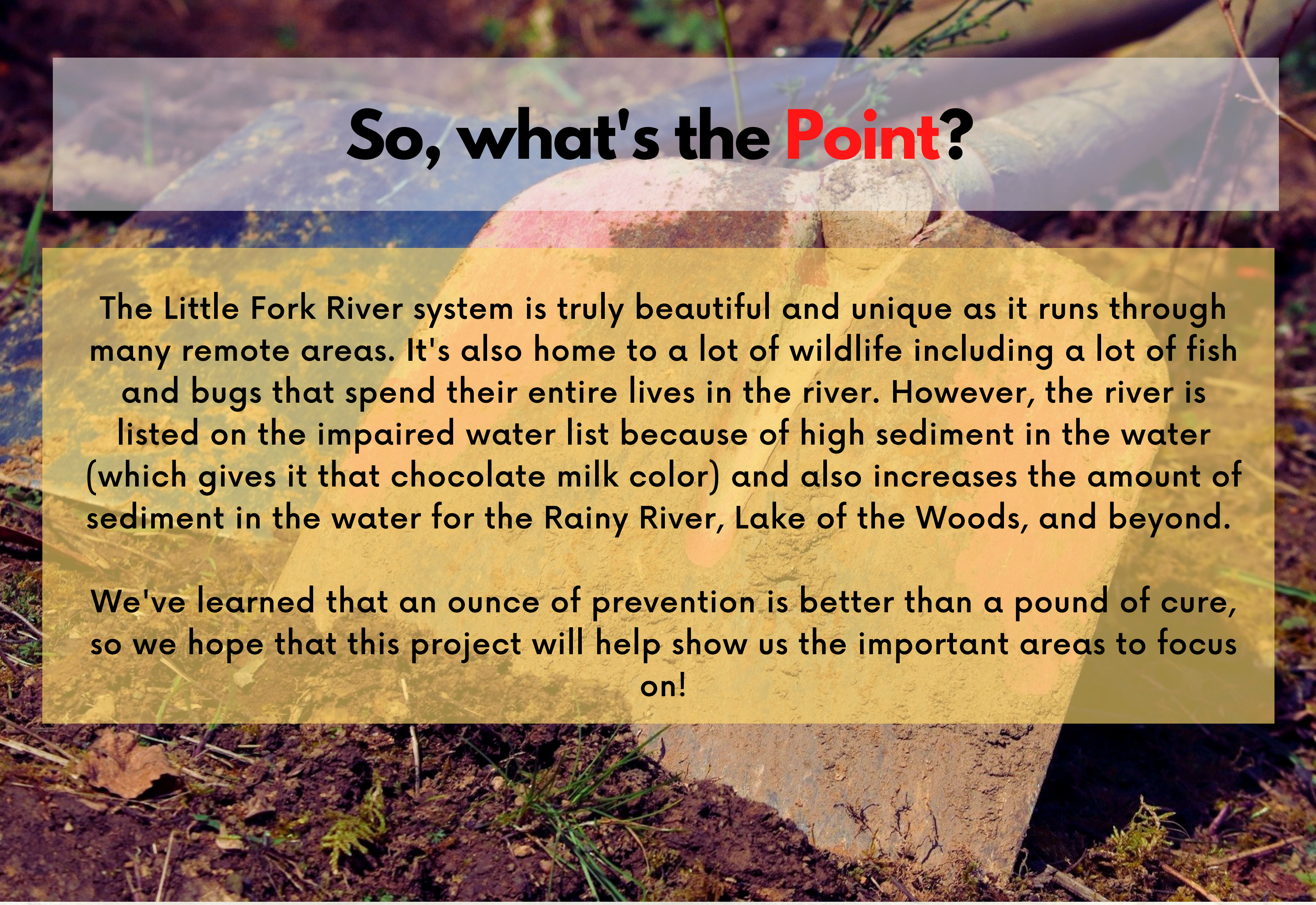
Sources and sinks of sediment in a watershed

Source: EPA, "A Manual to Identify Sources of Fluvial Sediment"

How do you find the sediment that's getting into the river?

We have placed passive sediment samplers at eight locations in the Little Fork River Watershed. These are collecting sediment that is suspended in the water of the river, traveling downstream. Soil samples are also being taken at different places on the ground all across the watershed. The samples are broken down in a lab in order to find their special characteristics, a fingerprint. If we notice some sediment in the river that matches a fingerprint from a sample on the ground, we will know what type of land it's coming from and can try to prevent more of it from running off into the river. The hard part is finding a fingerprint in a huge watershed area!

Passive sediment samplers



So, what's the Point?

The Little Fork River system is truly beautiful and unique as it runs through many remote areas. It's also home to a lot of wildlife including a lot of fish and bugs that spend their entire lives in the river. However, the river is listed on the impaired water list because of high sediment in the water (which gives it that chocolate milk color) and also increases the amount of sediment in the water for the Rainy River, Lake of the Woods, and beyond.

We've learned that an ounce of prevention is better than a pound of cure, so we hope that this project will help show us the important areas to focus on!

If you want to help us solve this mystery, stay tuned for more updates coming soon!

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You can also learn more at: www.koochiching.mn.us/fingerprint

Appendix E – Lake Challenge

The Sturgeon Chain Lake Challenge

Lake ______________ Property Owner________________________ Property #___________ Property Width_____ft. Date____________

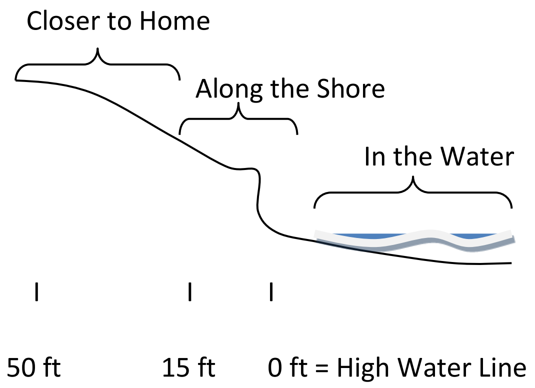
Step 1: **Take a closer look at your site.** **Step 2:** **Note items circled in these two grey columns.** **Step 3:** **Consider the corresponding *Challenge(s)* in this column.** **Step 4:** **Go for it!**

In the Water From the water's edge lakeward	Circle your responses			If you circle items in these two columns, consider a *Challenge*		⇨	**In the Water** ***Challenge* Menu**	**Lake and Human Benefits**	**Relative Cost**	**Time-Effort**	***I'll take this Challenge****
What is the width of the recreation area where aquatic plants have been removed?	No water use	About 10 feet	About 20 feet	About 30 feet	More than 40 feet	⇨	**A Smaller Footprint** Where aquatic plants were removed, allow them to grow back.	Fish, frogs, and other wildlife use plants for nesting, cover and food. Aquatic plants protect your shore from erosion. Native aquatic plants can minimize invasive plants.	0	None	
							Go Fish! Replant aquatic plants (MN DNR no-fee permit required).		$-$$	Some to Moderate	
Are there downed trees ("fish sticks") in the water?	Abundant fish sticks		Some fish sticks		No fish sticks	⇨	**Fish Sticks** Let fallen trees and branches remain along the shore and in the water.	Fish, turtles, water birds and mammals use downed trees for shelter, resting, hunting and food.	0	None	
How many accessories (docks+boats+other) are in the water?	0	1-2	3	4	More than 4	⇨	**Ships Ahoy!** Store on land the water accessories you don't often use.	Increase fish habitat (otherwise limited by water accessories).	0	None	

Along the Shore From water's edge to 15 ft landward of the high water line	Circle your responses			If you circle items in these two columns, consider a *Challenge*		⇨	**Along the Shore** ***Challenge* Menu**	**Lake and Human Benefits**	**Relative Cost**	**Time-Effort**	***I'll take this Challenge****
What width of your shoreline has been altered for lake access, view, recreation, other?	Little or none	About 10 feet	About 20 feet	About 30 feet	More than 40 feet	⇨	**A Smaller Footprint** Reduce this area to a smaller footprint with the following option(s).	80 percent of wildlife in MN depends upon a shoreland of native plants for their survival.	0 - $$$	None to Moderate	
Within this area: a. Describe the tree/shrub cover.	Dense	Many	Some	A few	None	⇨	**Hedge Your Edge** Plant native trees and shrubs along your shore.	Deep roots of native plants resist erosion from ice and wave action. Native plants also filter soil and pollutants from rainwater run-off.	$ - $$	Moderate	
b. What part is lawn or sand blanket?	None	About one quarter	About half	About three quarters	All or nearly all	⇨	**Green Armor Your Shore** Plant native grasses and grass-like plants.		$ - $$	Moderate	
c. What part is mowed or weed-whipped?	None	Only enough for a path	Some	Most	All	⇨	**Bye-Bye Geese** Stop mowing and weed-whipping. Geese avoid tall plants where predators may be lurking.	1.5 pounds of poop per goose per day will not land on your lawn and wash into the lake.	Saves you $$	None	
d. What part is armored with rock?	None	About one quarter	About half	About three quarters	All or nearly all	⇨	**Soft Rock** Install native plants into existing rock.	Plants soften the appearance, filter run-off and provide wildlife habitat.	$ - $$	Moderate	
e. What other hard surfaces exist? (Circle all that exist.)	None		Other?	Boat(s) Sidewalk Dirt path	Road Building Patio	⇨	**Stop the Drop** Remove unnecessary hard surfaces and replant or install pervious surfaces, berms, etc. to capture and filter rainwater.	Reduce rainwater run-off (carrying soil, nutrients and other pollutants) entering the lake by over 80%, and reduce algae in the lake, too!	$ - $$	Moderate	
f. Is there a fire ring or area?	No				Yes	⇨	**Ring of Fire** Move fires and fire rings away from the lake (25 to 50 feet is recommended).	Reduce the phosphorous- and nitrogen-rich ashes carried into the lake by rainwater and wind.	0	Some	
g. What portion of the shore has an ice ridge?	All – Ridge not breeched	Part – Ridge not breeched	None – Natural slope	All/Part – Ridge breeched	All – Ridge regraded	⇨	**No Water Over This Dam** Leave ice ridge in place and create an access over it. Plant a rain garden behind it for added beauty and filter.	An ice ridge across your entire shoreline can capture and filter up to 100% of soil, nutrients and other pollutants in rainwater run-off.	0	None	
h. What length of shoreline is eroding? (continued on back side)	Little to none	About 10 feet	About 20 feet	About 30 feet	More than 40 feet	⇨	**Shore Up Your Shore** Consult with Itasca SWCD to determine which erosion control method is best for your shore. Permit may be required.	For a 100-ft lot, this can reduce the soil entering the lake by about 360 pounds per year and result in about 90 pounds less algae in the lake.	$ - $$$	Some to Great	

Closer to Home 50 feet landward of the high water line (excluding the Along the Shore area)	Circle your responses			If you circle items in these two columns, consider a *Challenge*		⇨	**Closer to Home *Challenge* Menu**	**Lake and Human Benefits**	**Relative Cost**	**Time-Effort**	***I'll take this Challenge****
What average width of this upland area has been altered for access, recreation, view, other?	Little to none	About 10 feet	About 20 feet	About 30 feet	More than 40 feet	⇨	**A Smaller Footprint** Reduce this area to a smaller footprint with the following option(s).	80 percent of wildlife in MN depends upon a shoreland of native plants for their survival.	0 - $$$	None to Great	
In this area a. Describe the amount of trees.	Dense	Many	Some	A few	None	⇨	**Super Filter** Plant native trees, shrubs, ferns, vines, flowers, grasses and/or grass-like plants. They filter run-off, minimize erosion and provide food, shelter and nesting sites for songbirds and other wildlife.	For a 100-ft lot, replacing lawn with a 50-ft forested filter can reduce the soil entering the lake by about 360 pounds per year and result in about 90 pounds less algae in the lake.	$ - $$$	Some to Great	
b. Describe the amount of shrubs.	Dense	Many	Some	A few	None	⇨					
c. What part is covered by lawn or bare soil?	None	About one quarter	About half	About three quarters	All or nearly all	⇨					
d. What part is mowed or weed-whipped?	None	Only enough for a path	Some	Most	All	⇨	**No Mow-Let It Grow!** Stop mowing and allow plants to grow back.	Taller grasses will better filter run-off from your property.	Saves you $300/acre/yr	None	
							Set Your Sights High Raise the blade on your mower to 3 inches.	A longer lawn will also better tolerate stress and limit weeds.	0	None	
e. Is erosion or runoff related to the following? (Circle all that apply.)	Little or None	Stairs Lift	Other?	Sidewalk Path Steps	Road Building Patio/Deck Wall	⇨	**Step it Up!** Modify your foot access to filter rather than funnel rainwater directly to the lake.	Reduce rainwater run-off (as well as the soil, nutrients and other pollutants it carries) entering the lake by over 80%. This will reduce the algae in the lake, too!	0 - $$$	Some to Great	
							Get with the Flow! Modify hard surfaces with water bar, berm, etc. to redirect rainwater to filter into soil rather than flow directly into lake.		0 - $$$	Some to Great	
							Who'll Stop the Rain? Install rain barrel, rain garden, drip trench, etc. to capture and use rainwater.		$ - $$$	Some to Great	

Extra Credit *Challenges*	(Circle those that interest you.)				***I'll take this Challenge****
Pass It On!	**Help a neighbor with a *Challenge* Project** Plant a filter, make a water bar, survey for frogs, etc.	**Tell a neighbor about the *Lake Challenge***	**Tell several neighbors about the *Lake Challenge*** Host a boat tour or back yard party	**Start a "Welcome Aboard " Program** Tell new lake neighbors about the *Lake Challenge*	
Family Fun	**Shoreland Scientist** See what's in your rainwater run-off! *Equipment and training provided. Time: 15 min following each rain event.*	**Fish Count** *Training provided. Time: 1 hour per year*	**Frog and Toad Count** *Training provided. Time: 1 hour per year*	**Other ideas? Please describe!**	



To enroll or seek more information on the

Sturgeon Chain Lake Challenge,

Contact: N. St. Louis SWCD (218) 749-2000

Itasca SWCD (218) 326-5573

***** *or indicate if you've already met this challenge***

Notes:

Appendix F – Little Fork detailed stream order line work with erosion rates

Appendix F

Little Fork Detailed Stream Order Line Work with Erosion Rates

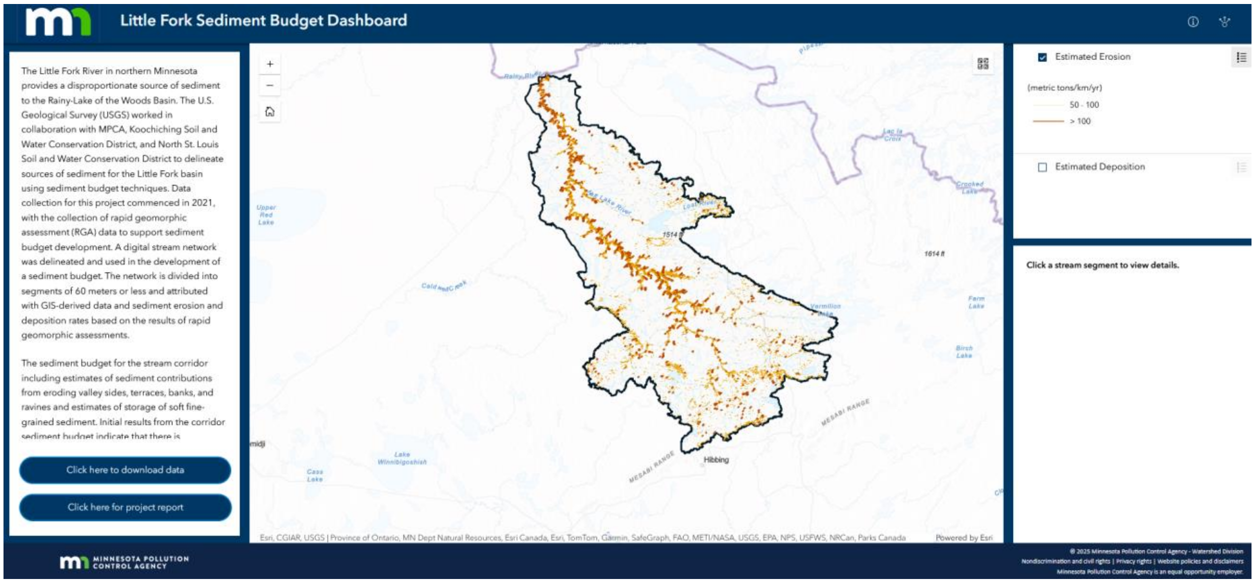
One of the outputs of the extensive sediment work conducted by USGS, MPCA, Itasca, Koochiching, and N. St. Louis SWCD offices, and the graduate students at University of Minnesota Duluth was a detailed GIS layer of the Little Fork stream network. Stream ordering is a method of assigning a numeric order to links in a stream network. This order is a method for identifying and classifying types of streams based on their numbers of tributaries. Some characteristics of streams can be inferred by simply knowing their order. MPCA typically utilizes the Strahler (1957) method of Stream Order.

For example, first-order streams are dominated by overland flow of water; they have no upstream concentrated flow. Because of this, they are most susceptible to non-point source pollution problems and can derive more benefit from wide riparian buffers than other areas of the watershed.

This system works very well and is used in MPCA surface water work. However, in watershed planning with local partners it was apparent when comparing field notes that this system of stream order was not fine enough for us to plan out landscape level understandings of small-scale ravines that had small watersheds (< 8 Sq. miles). With the assistance of the USGS a finer line system was developed off Strahler's' work to four levels smaller than the traditional line work for a given watershed. This enables local partners to study and fully understand the context and setting of these ravines.

One area we are looking at is Fiedler ravine, near the community of Little Fork, approximately 44 miles upstream from Rainy River outlet. In the two maps below, it clearly shows the benefits to local conservation partners in being able to see the details in Figure 2 vs. Figure 1.

Figure 1



The Little Fork River in northern Minnesota provides a disproportionate source of sediment to the Rainy-Lake of the Woods Basin. The U.S. Geological Survey (USGS) worked in collaboration with MPCA, Koochiching Soil and Water Conservation District, and North St. Louis Soil and Water Conservation District to delineate sources of sediment for the Little Fork basin using 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. A digital stream network was delineated and used in the development of a sediment budget. The network is divided into segments of 60 meters or less and attributed with GIS-derived data and sediment erosion and deposition rates based on the results of rapid geomorphic assessments.

The sediment budget for the stream corridor including estimates of sediment contributions from eroding valley sides, terraces, banks, and ravines and estimates of storage of soft fine-grained sediment. Initial results from the corridor sediment budget indicate that there is

☑ Estimated Erosion

(metric tons/km/yr)

50 - 100

> 100

☐ Estimated Deposition

Click a stream segment to view details.

Figure 2