Sediment Accumulation in the Floodplain of Lower Minnesota River Watershed

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LOWER MINNESOTA RIVER WATERSHED DISTRICT

Executive Summary

The main objective of this work was to provide a direct assessment of sediment accumulation in the floodplain of the Lower Minnesota River Watershed to better document how sedimentation in this reach has changed as a result of changes in flow and sediment supply in the post-settlement period. The method selected was to core floodplain lakes, analyze the fossil pollen and non-pollen palynomorphs (spores and charcoal) archived in the mud collected from the floor of the lake, and correlate the major ecological shifts as indicated by pollen assemblages to dated horizons in nearby lakes. The correlation method was chosen over directly dating the sediment as a cost-saving measure. Indications of land disturbance, cultivation, erosion and flooding helped further constrain the interpretations of the ages of horizons.

If all of the interpreted horizons are correct, and linear sedimentation rates accurately reflect the lake history, sedimentation rates were ~1 cm/year from 1860 to 1910, more than doubled reaching an average of 2.44cm/y from 1950 to 1993, and declined but remain 50% above the background rate at 1.4 cm/y from 1993 to 2018. However, dated profiles for many Minnesota lakes (Engstrom, 2007) suggests that both over- and underestimates of sedimentation rates are possible with the linear interpolation method used here to estimate post-1850 accumulation rates in Rice Lake. Comparison of the linear sedimentation rates to rates for two nearby lakes suggests Rice Lake rates are up to 44% greater. The cores taken for this project have been archived and could be dated at some future time to get more precise estimates of the change in sedimentation rate.

Introduction

The Minnesota River occupies a deep and broad valley created by the drainage of glacial Lake Agassiz approximately 13,400 years ago (Clayton and Moran, 1982; Matsch, 1983). The tributaries to the Minnesota are still adjusting their gradients to this change and delivering sediment to the Minnesota River as they excavate their valleys (Gran et al., 2009). The Minnesota River does not have the capacity to carry away all of the sediment delivered to it by its tributaries and therefore the valley has been filling in since shortly after it was created (Wright, 1990). The rate of sediment accumulation varies spatially, with climate, and with other factors that affect watershed hydrology and the hydrologic cycle—e.g. ground cover and artificial drainage.

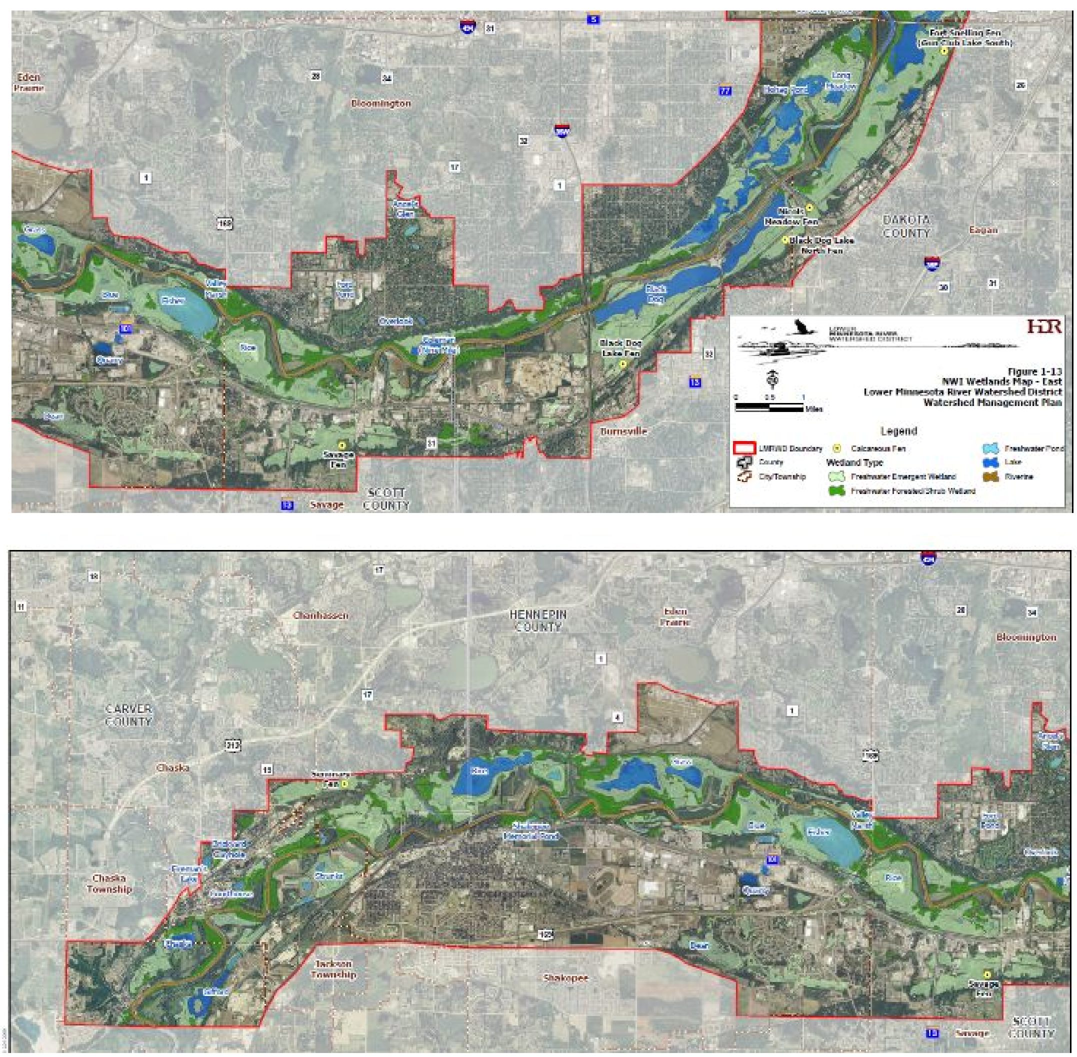
Changes in river flow have been documented by gauging efforts (Wilcock et al., 2009; Groeten et al., 2016). The intensification of agriculture and agricultural drainage have increased peak flows in rivers at certain times of the year, and changing rainfall patterns have also increased flows (Schottler et al., 2013). As a result, rivers have widened significantly, nick points on tributaries have retreated more rapidly, and meander migration rates have increased (Belmont et al., 2011). All of these changes have led to increased sediment delivery by the tributaries, erosion on the main-stem river, and greater in-channel sediment loads.

Lake Pepin, a riverine lake on the Mississippi River downstream of the confluence of the Minnesota, St. Croix and Mississippi rivers archives the combined record of changes in these three watersheds. It is filling in almost ten times faster than pre-settlement rates (Engstrom et al., 2009). High sediment-loading watersheds within the Minnesota River basin have been identified as the primary sources (e.g. Gran et al., 2009; Groeten et al., 2016) and estimates of the changes in run-off ratio in agricultural vs. non-agricultural watersheds modeled (Schottler et al., 2013).

The Minnesota is a net-depositional system with a significant fraction of the high sediment loads contributed by tributaries. The relatively unconfined valley allows flood waters to spread out broadly. The 14.7-mile-long reach of the Minnesota River between Chaska and Minneapolis is dredged for navigation through a collaborative arrangement between the Saint Paul District of the U.S. Army Corps of Engineers and the Lower Minnesota River Watershed District.

Of primary concern is how this reach been impacted by increases in flow and sediment load. That has not yet been fully quantified, however, gauging data and dredging history begin to tell the story of this altered river system. The perception is that in-channel sediment loads are greater resulting in greater volumes of dredged material and increased expense and difficulty of disposing of the dredge spoils.

Figure 1. Lower Minnesota River Watershed District



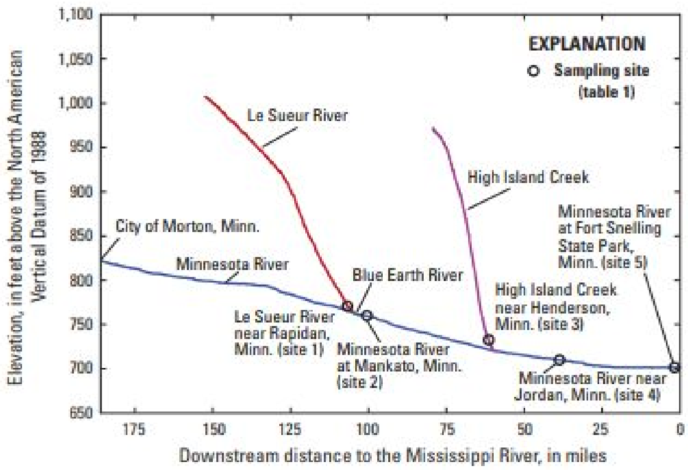


Figure 2. Stream gradients along the Minnesota River (from Morton to Fort Snelling State Park, Minnesota) and three tributaries (Le Sueur River, Blue Earth River, and High Island Creek).

Study Area

The reach of the Minnesota River within the Lower Minnesota River Watershed District (Fig. 1) is wider than upstream reaches and has a lower gradient (Fig. 2). This change in valley slope and geometry leads to a slowing of the river and accumulation of sediment under natural conditions. For each of the four years analyzed in a recent USGS report, there

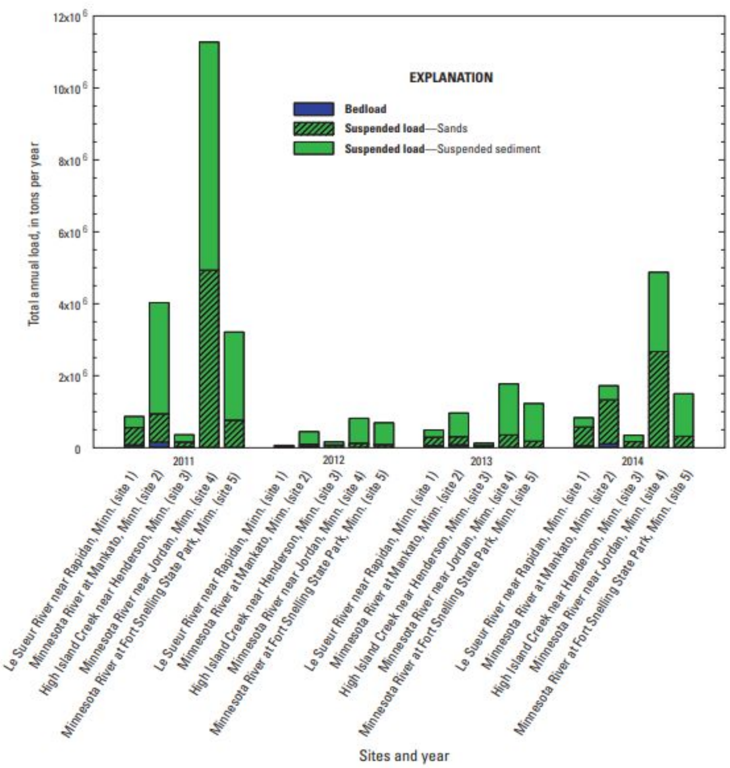


Figure 12. R-LOADEST loads at five sites in the lower Minnesota River Basin, calendar years 2011 through 2014.

Figure 3 Sediment in the Lower Minnesota River Basin, 2011-2014. Groeten et al., 2016

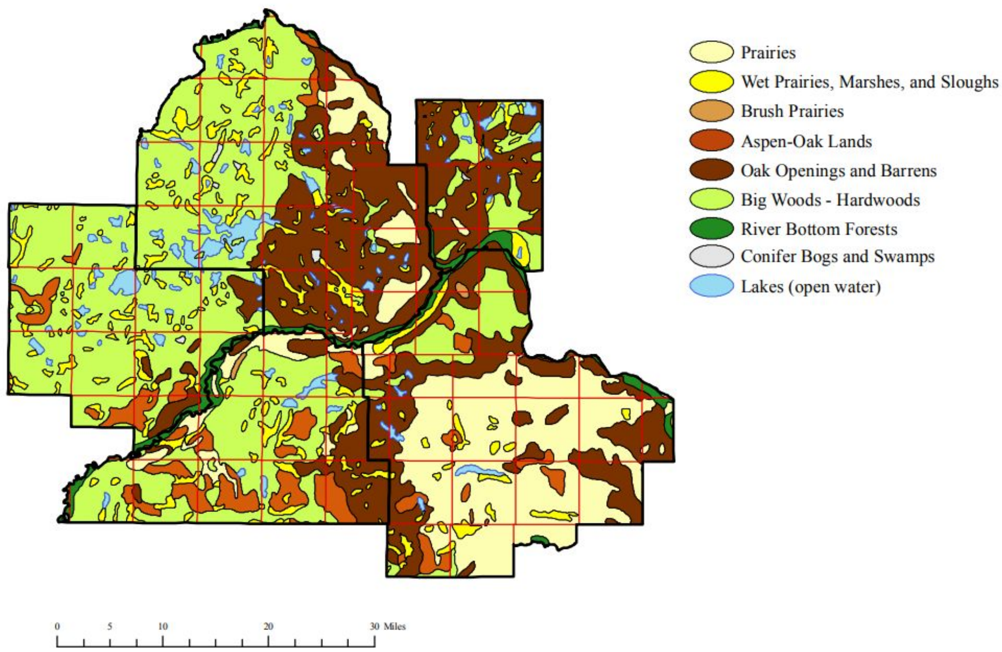
is more sediment coming into this reach than leaving it (Fig. 3., Groeten et al., 2016). On average, 200 tons of sediment per mile will accumulate in the channel, levees and floodplain.

Figure 4. The volume of material in such a truck are distributed in each mile of the Lower Minnesota River on average each year. ***https://commons.wikimedia.org/wiki/File:200_Ton_Truck.JPG***

Exactly how the sediment is distributed across the width of the valley is not known. However, stable floodplain lakes that exist behind the natural levees are where the record of sedimentation events is archived. Lakes also archive airborne and river-transported pollen and plant macrofossils. These become fossils deposited with that sediment that can be linked to landscape and climate changes both locally and regionally and may be used to date changes in sediment accumulation.

Vegetation

At the time of the Public Land Survey (1853-1856), Scott and Hennepin county's vegetation included upland deciduous forest, wetland, prairie, and oak openings and barrens (Figure 5a, Biological Report No. 89, MN DNR 2007). According to the Public Land Survey data, the majority of Hennepin County was heavily forested except for large swaths of prairie and oak openings or barrens mostly along the Minnesota River valley. There is a high probability that fire-dependent plant communities such as prairie and oak openings and barrens were managed locally with the use of fire by Native Americans. Early topographic maps show the distribution of wetlands and forest in 1901 (Figure 5b).



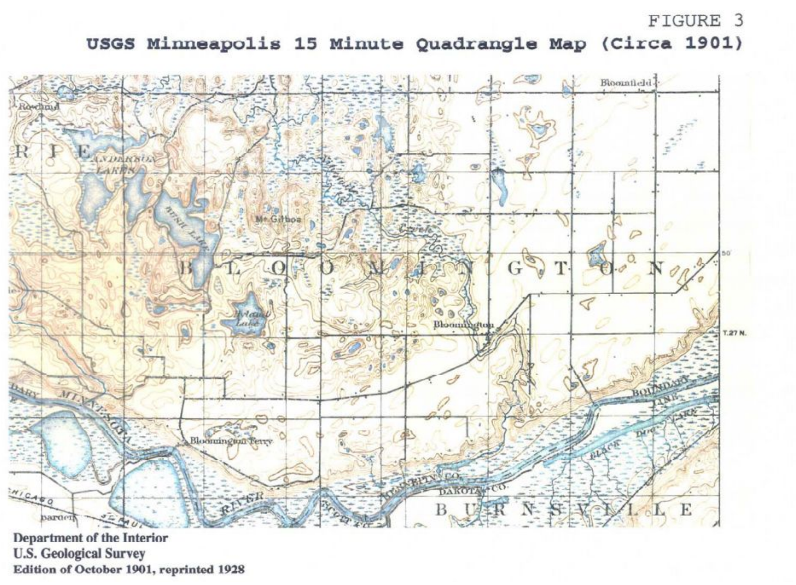


Figure 5.(a) Native Vegetation https://files.dnr.state.mn.us/eco/mcbs/maps/mnriver_map1.pdf (b) Wetland distribution from the USGS 1903 topographic map.

Very little of the original vegetation remains. Modern floodplain lakes are surrounded by forests of silver maple subtype with a tall, open super-canopy of cottonwood above a continuous canopy of silver maple. Other trees that are found within the canopy include basswood, American elm, green ash, and peach-leaved willow. The flooded wetlands around the lakes are dominated by river bulrush, cattails, lake sedge, wild rice, burr reed, bluejoint grass, and rice cutgrass. Other common plants are broad-leaved arrowhead, water plantain, sweet flag, water parsnip, wild mint, and American water-horehound. Corn fields appear on the south side of the Minnesota River.

Human history influences the landscape

The area has been home to Native Americans for over 12,000 years (Gibbon, 2012). Burial mounds in Memorial Park in Shakopee date back approximately 2,000 years. Locations of encampments and farming villages of Native Americans were documented and visited by early European explorers (e.g. Featherstonhaugh, 1847) and the archaeological record supports the utilization of freshwater resources and the relative stability of the lakeshores of floodplain lakes.

Shakopee, the closest town to Rice Lake, was designated as Scott County seat in 1853. In 1860 a railroad was built and the population reached 1,138, and then almost doubled between 1910 and 1912 reaching a population of 2,302. Other events in the settlement history of the region that might impact the sediment accumulating in the Minnesota River floodplain include a great fire in the Minnesota River valley in 1879; expansion of Minneapolis and suburban development throughout the early to mid 1900's; a major flood in 1965; the completion of Highway 169 in 1996; and protection of the Minnesota River Valley National Wildlife Refuge and associated restoration efforts.

Methods

Lakes store histories of both local and distal land-use and climate change and combine a history of erosion, sedimentation, vegetation, fire (charcoal) as well as development in the area. The inorganic and organic sediment archived in a floodplain lake enters through its tributaries and during flood events on the Minnesota River. Sediment can also be airborne. Changes in mineral properties are interpreted as a change in sediment source; changes in the amount of sediment accumulated over time can be interpreted as the result of erosion and flood events in the watershed. The duration of flooding may also impact sediment accumulation. Wind-blown pollen can be far-traveled or originate in immediate proximity to the lake; this is in part dependent on the type of pollen. For example, pine can be very far-traveled. Organics can also originate within the lake by the growth and death of organisms that inhabit it.

To get an absolute chronology of events would require a way to date the material that accumulated in the lake. However, it is also possible to use marker horizons of known age to date intervals in a lake core. To avoid the expense of procuring dates on the material in our cores, we compared the sediment and vegetation records of these lakes to well-dated records from 3 lakes in Hennepin and Carver counties (Fig. 6). This approach provides a comparative chronological scale to assess changes in the sedimentation rates in the floodplain lakes (Fig. 7).

Figure 6. Location of Rice and Coleman lakes, and nearby, dated lakes, Mitchel and Round used for reference.

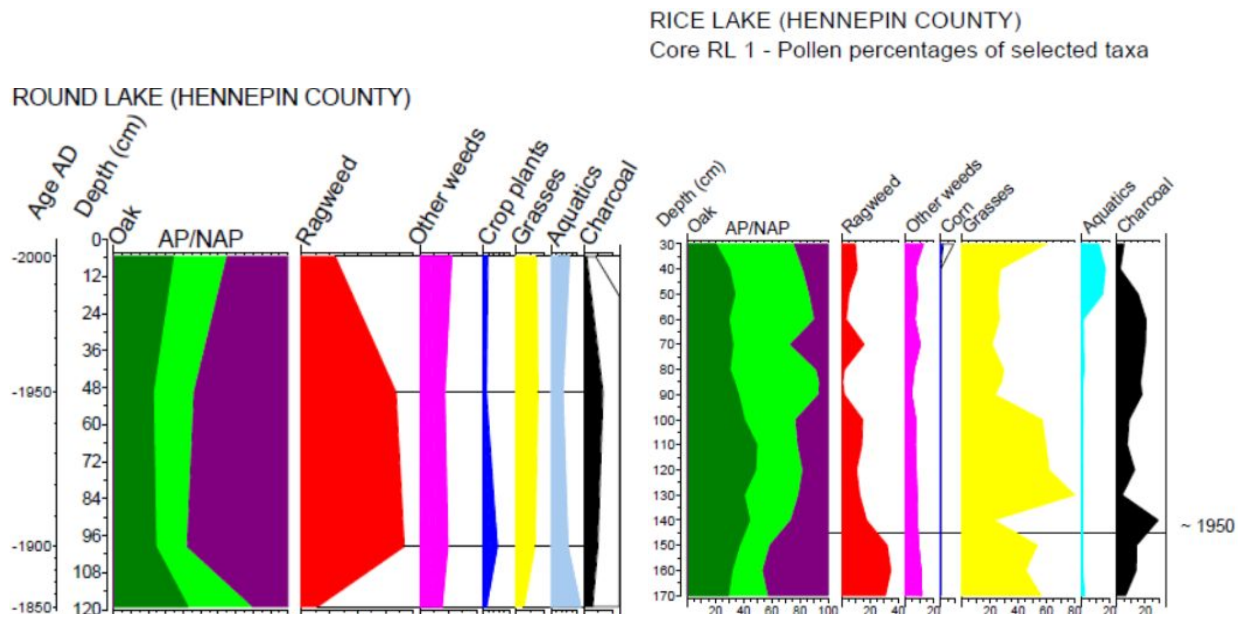


Figure 7. Dated pollen accumulation records from lakes to be used for comparison. Lotus, Mitchell and Round have dated pollen stratigraphy and are close enough to Rice and Coleman lakes in the floodplain for correlation.

Fieldwork

Two lakes located in the floodplain of the Lower Minnesota, Rice and Coleman lakes, were selected to assess historic changes in sediment accumulation rates based on pollen-correlated core intervals. The lakes were selected after reviewing the available information on depth, ownership and access to the floodplain lakes in the lower Minnesota River valley and following site visits during late summer 2017. During the visits vegetation samples were also collected to assist with identification of plant micro-remains remains found in the core. Lake properties are summarized in Table 1.

Figure 8a. Location of Coleman Lake behind a levee on the Minnesota River.

Figure 8b. Rice Lake core locations collected in the fall of 2017 (blue). One more deeper core was taking during January of 2018 (yellow).

Table 1. Summary of core characteristics and and lake morphometry.

Lake	Lake Surface Area (acres)	Max lake depth (cm)	Core	Lake depth (cm)	Core recovery (cm)	Hydrologic sources
Coleman Lake	114	185?				Nine Mile Creek, groundwater, Minnesota River overflow
			CL-1	160	151.5	
			CL-2	165	117	
			CL-3	184	114.5	
			CL-4	174	113	
			CL-5	159	110	
			CL-6	170	82	
			CL-7	185	102.5	
Rice Lake	517	91				Bluff Creek and intermittent surface drainage, groundwater, Minnesota River overflow
			RL-1	80	170	
			RL-2	75	118	
			RL-3	77	120	
			RL-4	80	114.5	
			RL-5	79	119	
			RL-6	70	93.5	
			RL-8B	ice to the bottom	377.5	

Fourteen sediment cores were recovered along two transects in the studied lakes (Figure 8) in the fall of 2017 and February 2018. Cores were named and numbered in accordance with LacCore protocols, and are curated at the University of Minnesota facility.

Laboratory work by LacCore, U of M

All cores were scanned every 5 mm for their physical properties (p-wave velocity, gamma-ray density and magnetic susceptibility) using a GEOTEK™ multi-sensor core logger. The cores were subsequently split, photographed and described by macroscopic structure and texture and by microscopic composition. Weighed subsamples were taken from regular intervals throughout the cores for loss-on-ignition (LOI) analysis to determine bulk density and dry weight percent of organic matter, carbonate minerals, and non-carbonate mineral matter. Sediment subsamples were heated at 105°C to determine dry density, then sequentially heated to 550°C and 1000°C to determine organic matter and carbonate mineral content from post-ignition weight loss, respectively. The bulk sediment measurements of magnetic susceptibility (MS) reflect the concentration of magnetizable mineral phases in the sediment, often viewed as reflecting the concentration of clastic mineral material and interpreted as a signal of erosional intensity on the sediment-contributing landscape.

In both lakes a reference core was chosen for detailed pollen analysis and for establishing a pollen stratigraphy. For these cores sediment samples for pollen analysis were taken every 10 cm, whereas for the rest of the cores only two samples from near-basal material were taken for correlation with the main core.

Pollen preparation follows the classical chemical method, including acetolysis (Faegri and Iversen, 1989). Pollen percentages are based on the pollen sum of arboreal pollen, including trees and shrubs (AP) and non-arboreal pollen (NAP), excluding spores of *Bryophyta* and *Pteridophyta* and pollen of aquatic plants. grass pollen was also excluded because of overrepresentation (over 100 pollen grains per sample). At least 200 to 300 terrestrial pollen grains were identified to the lowest possible taxonomic level with keys of Reille (1992; 1998), Beug (2004), and the pollen reference collection at the University of Minnesota. Charcoal particles larger than 20 µm interpreted as an indicator of regional fires (Tinner and Hu, 2003) were also counted. Non-pollen palynomorphs were identified according to van Geel and others (1989). Both charcoal and non-pollen palynomorphs are presented as percentages of the main pollen sum. Analysis of the pollen data was done using the program *Tilia* 1.5.11 (Grimm 2011), which calculated percentages and created graphics.

Results

Organic sedimentary material in cores collected in this setting may include algal matter produced within the lake itself, local vegetation from lake margins and the surrounding floodplain, and the organic component of sediment transported down the Minnesota River. Carbonate mineral sediment includes both a carbonate component of the Minnesota River sediment load derived from carbonate-bearing sedimentary rocks incorporated in the glacial sediment, and carbonate sediment produced through biochemical precipitation within the lakes. Non-carbonate mineral matter may include locally eroded silt and sand from the immediate watershed, but in this setting will be primarily derived from upstream erosion of glacial sediment in the watershed of the Minnesota River and its tributaries.

Sediment in Coleman Lake

Silty carbonate mud and diatomaceous carbonate mud are the dominant sediment types represented in our core collection. The changes in sediment composition are more pronounced in the upper 30-40 cm of the cores. There the siliciclastic fraction increases from 40-60% to up to 85% and the magnetic susceptibility (MS) shows a distinct increase. The amount of carbonate mineral matter increases to 40% between 30 and 60 cm. The organic component remains low (10-15%) with the exception of core CL-6 where it has a maximum of 50% at 75 cm.
Well-defined maxima in magnetic susceptibility are observed between 100 and 120-130 cm in core CL-1,CL-2, CL-3 and CL-7 (Figure 9).

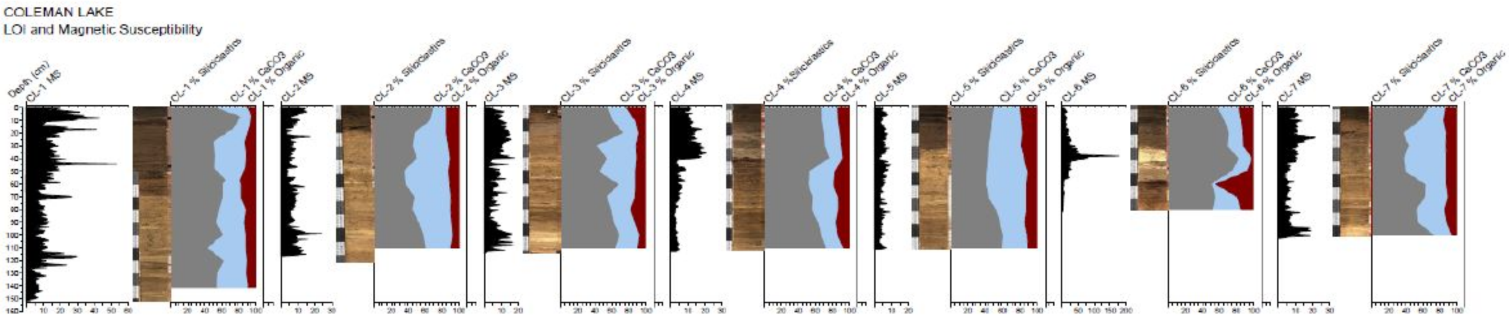


Figure 9. Alignment of Coleman Lake cores with magnetic susceptibility, organic and inorganic carbon and images of core surface.

Sediment in Rice Lake

All sediment cores comprise alternating silty carbonate mud and diatomaceous carbonate mud with some silt. The siliciclastic material (50-80%) dominates the sediments from Rice Lake. The lowest siliciclastic percentages (up to 50%) are between 390 and 340 cm in core RL-8, where the highest carbonate percentages of up to 40% appear. The inorganic mineral component increases to as much as 80 % between 340 and 300 cm in core RL-8, accompanied by an increase in magnetic susceptibility values. Except for core RL-2, the inorganic mineral fraction decreases in the top 20-40 cm. This decrease is accompanied by an increase in carbonate minerals, and for cores RL -2 and RL-3 an increase in the organic fraction. All cores show high MS in the uppermost 30-35 cm (Figure 5).

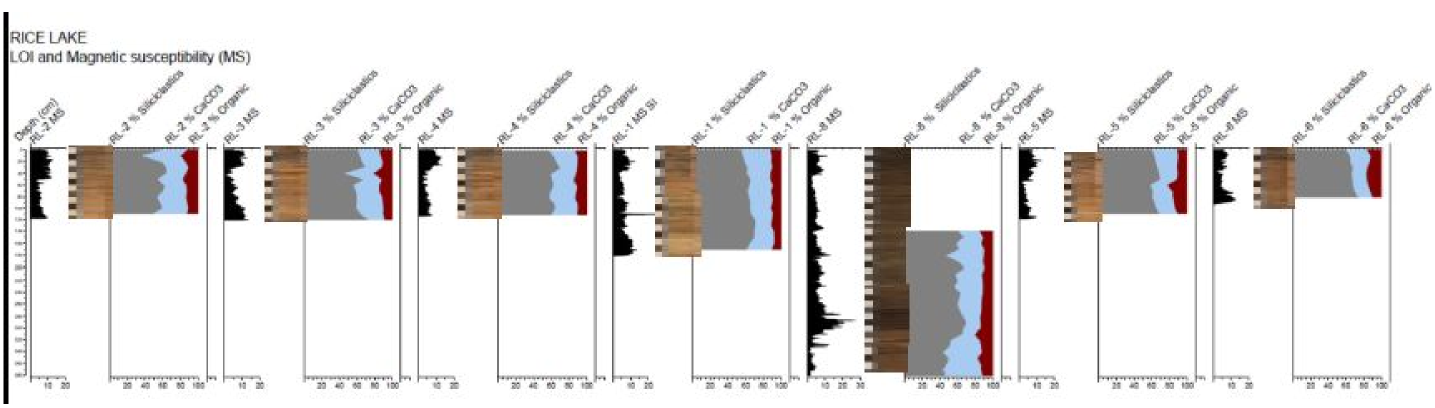


Figure 10. Alignment of Rice Lake cores with records of magnetic susceptibility, organic and inorganic carbon and images of core surface.

Pollen

Representative cores from each lake are discussed in detail. Pollen zones that are statistically determined help frame the ecological history of the lake and region. Key pollen events can then be linked to dated pollen stratigraphy in nearby lakes for which there is chronological control.

Pollen stratigraphy of Coleman Lake

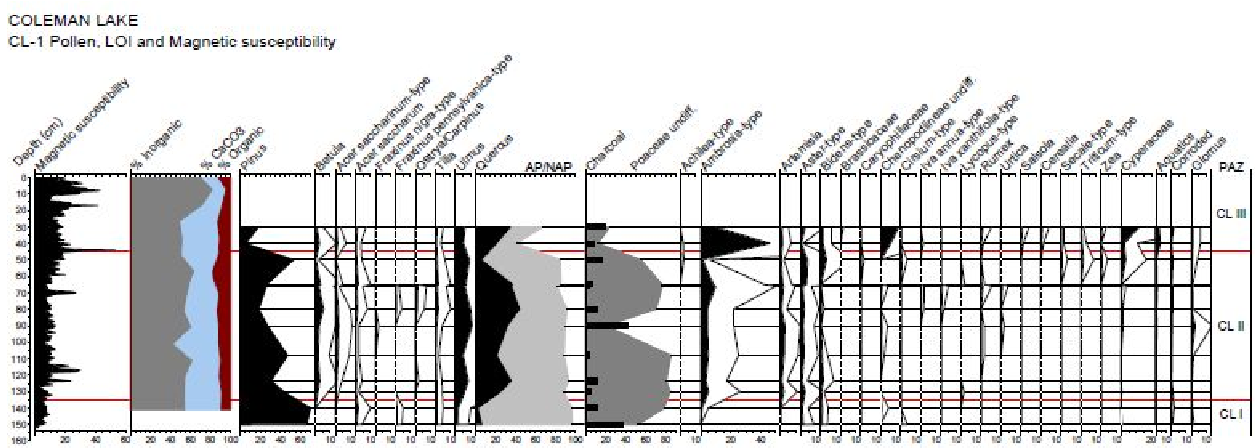


Figure 11. CL-1, representative core from Coleman Lake with pollen counts and zones.

The pollen stratigraphy of core CL-1 is represented with three pollen zones recognized by stratigraphically constrained cluster analysis in CONNISS (Grimm, 1987). Zone CL I is characterized by low taxonomic diversity as few pollen types were found: pine (*Pinus*) pollen up to 80%, grass (Poaceae) pollen (excluded from the pollen sum) up to 80%, and small amounts of oak (*Quercus*), elm (*Ulmus*), ragweed (*Ambrosia)*, wormwood (*Artemisia)* and aster (*Aster*-type). Microscopic charcoal, up to 40% in the lowermost pollen spectrum indicates fire activity in near the lake and involving either wetland vegetation dominated by grasses or more likely nearby prairie fires. The high percentage of pine pollen likely has a long-distance origin facilitated by the treeless vegetation around the lake. In Zone CL II oak and elm are dominant among the tree species. The most distinct feature of Zone CL III is the high peak of *Ambrosia* pollen percentages, up 40% following a sharp decrease in *Quercus* (oak) values (from 40 to 10%).

Pollen Stratigraphy of Rice Lake

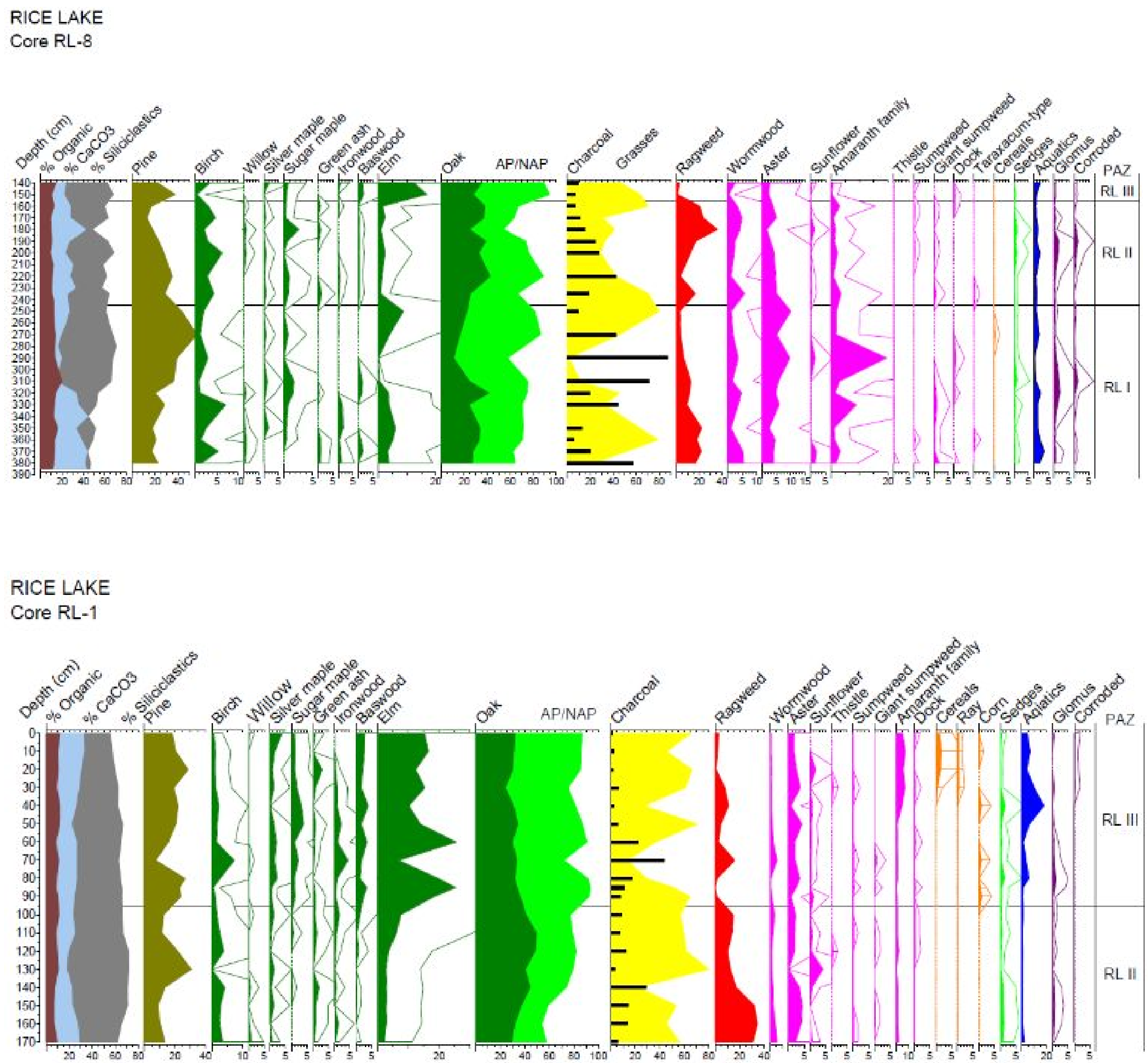


Figure 12. Pollen diagrams from two cores in Rice Lake, RL-8 and RL-1.

Three pollen zones are also recognized in Rice Lake by stratigraphically constrained cluster analysis in CONNISS (Grimm, 1991). Zone RL I (RL-8), dominated by grasses (up to 80%) and prairie herb types (wormwood, aster species, sunflower and ragweed) reflects the regional pre-settlement wetland and prairie vegetation along with some oak openings registered with oak pollen (25-40%,), elm (up to 10%), sugar maple, silver maple, and birch. The high concentration of charcoal between 270 and 330 cm most probably indicates independent fires near the lake in the wetland and upland forests as shown in the decreased pollen percentages of grasses, oak and fire-sensitive elm and sugar maple. Corroded pollen grains and fungal spores of *Glomus* in the same interval point to increase erosion in the lake catchment. Amaranth species are pioneers and their spread on burned wetland areas is interpreted in this zone, where it reaches its maximum values. An increase in the amount of pine pollen above the charcoal interval indicates openings in the forest canopy facilitating pollen transport. The most characteristic feature for zone RL II (RL-8 and RL-1) is the rise in *Ambrosia* percentages by up to 40%, followed by an increase in the oak pollen from 30 to 50%. In zone RL III (RL-8 and RL-1) the most significant change is the increase in the elm pollen percentages, reaching as high as 30%.

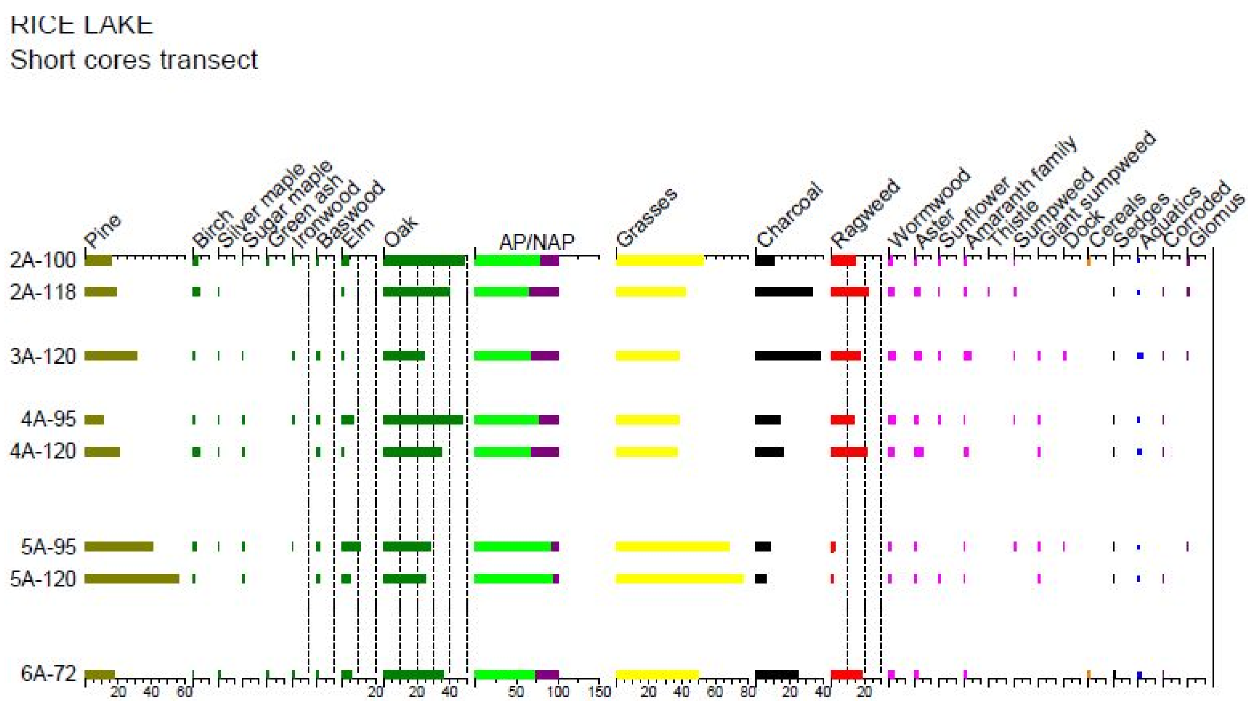


Figure 13. Transect of short cores from Rice Lake and the pollen assemblage at the bottom of each core.

The pollen spectra of the analyzed sediment samples at selected depths in the short cores show analogues with dominant pollen types similar to those at the same depths in core RL-1. This indicates similar sedimentation processes and rates in the different parts of the lakes.

Discussion

The pre-settlement regional vegetation in the study area, reflected in zone RL I in the pollen diagram for core RL-8 from Rice Lake consisted of wetlands, prairies and oak openings. The high charcoal amount in pollen spectra in this zone indicates fires. This is an expected result given the literature documenting the extent of prairies and their fire dependence (Umbanhower, 2004). It is possible that some of the fires had anthropogenic origins because the area was occupied by Native Americans. The charcoal layer in the sediments shows high magnetic properties and an increase in the inorganic noncarbonate mineral component of the sediment as a result of soil erosion after the fires. The sediment of the post-settlement horizon has higher carbonate amounts and in this region that has been correlated to a greater percentage of cultivated acres in the surrounded lake catchment (Umbanhower et. al. 2011).

Almost all cores from Rice and Coleman lakes have distinct magnetic peaks in the top 30-40 cm that could reflect larger and more frequent flooding in the valley since 1993. The changes in the magnetic properties in the cores from Coleman Lake are more pronounced than those in Rice Lake but because of the lack of an absolute chronology and the unclear pollen stratigraphy of the main core CL-1 it is difficult to correlate them to particular flood events. The pollen stratigraphy for Coleman Lake most probably matches the vegetation changes in upper part of Zone RL II and Zone RL III of Rice Lake.

There is a discharge gauging station located on the Minnesota River upstream of the Highway 101 bridge near Jordan. Those records and the record of Highway 101 bridge closures due to flooding help constrain when sediment-laden floodwaters might have inundated Rice Lake. The bridge was closed six times between 1993 and 2011 with closure times varying from several days to several weeks when water elevations exceeded 709.4' (Table 2, Fig. 14; SEH, 2011). Typically, the lakes in the floodplain that we studied are flooded during 10-year recurrence flood events.

Table 1 – Days Highway 101 Crossing Closed During Flood Events 1965 - 2011

Flooding Event	(1) Highway 101 Days Closed
Spring 2011	43
Fall 2010	16
Spring 2010	27
Spring 2001	29
Spring 1997	18
Summer 1993	27
Spring 1969	17
Spring 1965	15

(1) Data for 2010 and 2011 were obtained from MnDOT. Data for 1993, 1997 and 2001 were obtained from the *Trunk Highway 41 Draft Environmental Impact Statement (DEIS)*. Data for 1965-1969 were estimated from historic hydrograph plots and assuming the road is closed for three days beyond the date when the water level dropped below the closure elevation to conduct maintenance and restoration work.

Table 2. Flood events that lead to the closing of Highway 101, near Rice Lake.

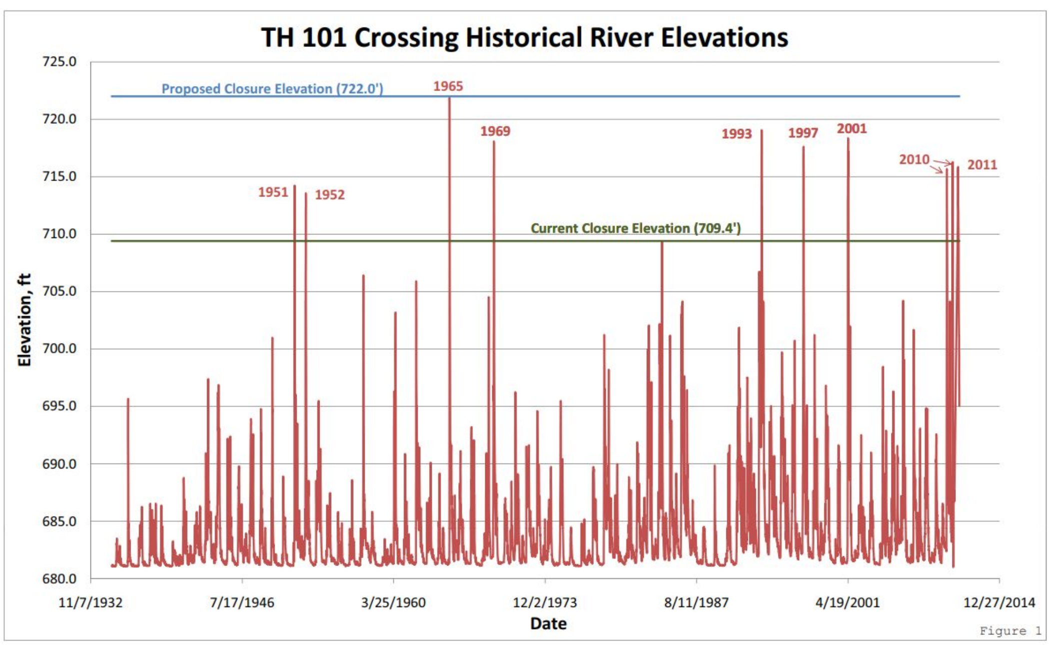


Figure 14. Elevation of the river that results in Highway 101 closure shown in green.

The variability in magnetic susceptibility in the upper portion of Core RLHC17-1A-1P-1 could be related to influx of magnetic grains carried in the river during these flood events.

Ambrosia rise and sedimentation rates

The rise in *Ambrosia* pollen associated with the Euro-American settlement was dated at 1900 AD in Mitchell Lake (102 cm) and 1910 in Round Lake (98 cm). These lakes, located 3-4 miles away from Rice Lake are the closest studied and dated lakes, and are used here for biostratigraphical comparison (Fig. 15).

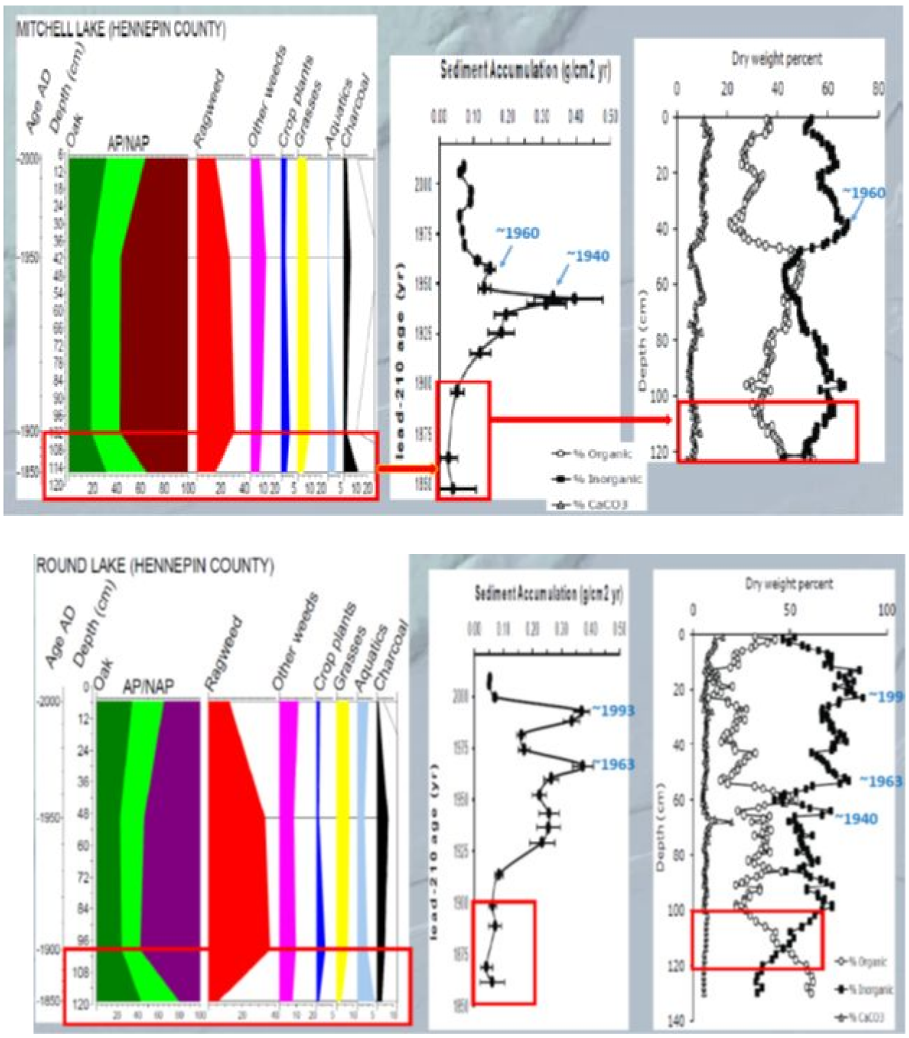


Figure 15. Rise of Ambrosia (ragweed) in nearby (a) Mitchell Lake, and (b) Round Lake, Hennepin County

The rise in *Ambrosia* in both lakes is preceded by an increase in the inorganic content of sediment, as well as a higher charcoal amount (Mitchell Lake) that appears up to 20 cm below the *Ambrosia* rise and it is dated to 1850 when the city of Eden Prairie, the closest populated place, was established. The increase in the inorganic component of sediment most probably marks the settlement horizon whereas the *Ambrosia* rise reflects the time of intensified agriculture in the area about 50 years after the arrival of the first European settlers.

Similar increases in the inorganic component of the sediment occurring one to several centimeters below the *Ambrosia* rise was observed in cores from Crystal Bay, Lake Minnetonka. However, because of the uncertainty in the measurements of the ^{210}Pb activity, the increased inorganic sediment component was accepted as a pre-settlement event (Murtchie, 1985).
There are no other studies in the area where independent age control of the *Ambrosia* rise is provided through pollen analysis performed on ^{210}Pb and ^{137}Cs-dated cores.

In Rice Lake the *Ambrosia* rise occurs at 180 cm (core RL-8) and is accompanied by a peak in the magnetic susceptibility and in the carbonate mineral component. This is above the interval (230 and 190 cm) with higher charcoal concentration and additional indicators of erosion (fungal spores of *Glomus*, corroded pollen grains and very large individual carbonate grains and carbonate aggregates likely formed in soils). This points to intensification of human activity in the area. It is very possible that the settlement horizon in the lake registers at 230 cm and that this horizon correlates to 1850-1860 when the nearby town of Shakopee was established and the first railroad in the region was built. In this case the *Ambrosia* at 180 cm might reflect the farming development facilitated by improved transportation around 1910-1912 when the population in Shakopee almost doubled compared to 1860.

The decrease in *Ambrosia* pollen in Mitchell and Round lakes is dated at 1950 and in the Rice lake pollen diagrams it appears at 140 cm. The pronounced magnetic susceptibility peaks in the top 30-40 cm in all cores from Rice and Coleman lakes might be related to the floods events since 1993.

Taking all of these age interpretations at face value, a linear rate of modern sedimentation for these lakes in the floodplain of the Minnesota River was calculated. If the correlations are correct, sediment accumulation rates for the floodplain lakes are approximately:

- 1.0 cm/y from 1860 to 1910 (Background sedimentation rate)
- 1.0 cm/y from 1910 to 1950 (Rate may be low because of 1930s drought)
- 2.44cm/y from 1950 to 1993 (>2 times background; sediment stored during drought may be contributing to higher rates during this period)
- 1.4 cm/y from 1993 to 2018 (~50% higher than background)

However, ^{210}Pb profiles for many lakes (Engstrom, 2007) suggests that both over- and underestimates of sedimentation rates are possible with this linear interpolation method used here to estimate post-1850 accumulation rates in Rice lake. Comparison of the linear sedimentation rates estimated for Mitchell (0.9cm/y) and Round (0.9cm/y) lakes with ^{210}Pb-corrected sedimentation rates shows that the maximum dated sedimentation rates were 0.95cm/y around 1940 in Mitchell Lake and up to 1.3 cm/y in Round L around 1966. Both Mitchell Lake and Round Lake lie outside the Minnesota River floodplain, and therefore have been subject to changes in sediment mobilization and delivery occurring at the local watershed scale, but not to changes in transport through a major fluvial network such as the Minnesota River.

Summary and Future Work

If all of the inferred time horizons are correct, sedimentation rates peaked at 2.44cm/y from 1950 to 1993 and have decreased to 1.4 cm/y from 1993 to 2018. This would mean that in the last 50 years the valley floor rose 120 cm. According to a recent tabulation (Table 3) (Smith et al., 2018), Chaska only has approximately 4.5 feet (137 cm) of freeboard on their levee. At current sedimentation rates, that will largely be gone within 50 years and this does not take into account the changes in recurrence interval and size of recent floods (Table 4) which may lead to more frequent inundation. There have been significant increases in flow and overbank flooding in the past three decades.

River Gauge	DEM River Elevation(ft)	5 Yr RI(ft)	10 Yr RI(ft)	25 Yr RI(ft)	50 Yr RI(ft)	100 Yr RI(ft)	Years on Record
Ortonville	966	966.62	967.7	969.22	969.26	969.4	77
Lac Qui Parle	934	935.89	936.8	938.8	940	940.1	68
Montevideo	919	924.8	926.38	929	931	933	106
Morton	822	832.5	832.7	834	835	840	15
Mankato	760	768.12	772.47	775.25	777	778	112
Henderson	725	738.3	739.5	742	744	747	32
Jordan	695	715.9	721.81	723.5	723.65	725	78
Savage	687	711.6	714.6	717	720	724	46
Fort Snelling	687	706.7	709.76	711.5	720	723	9

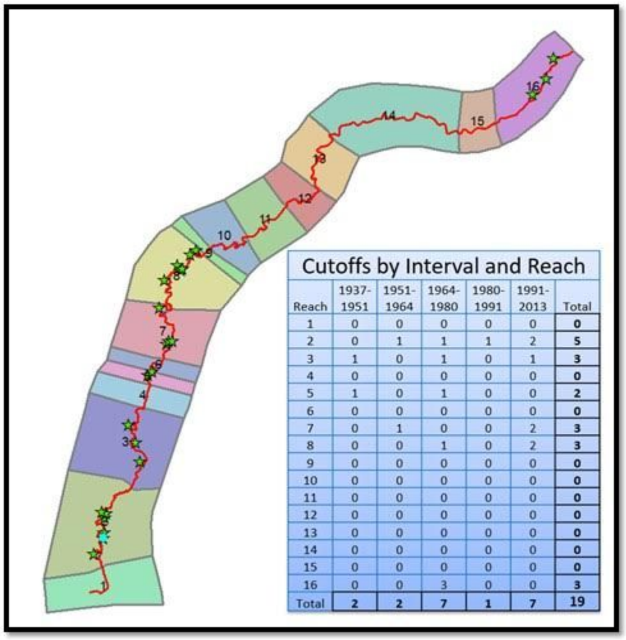
Table 3. Height of five different recurrence intervals and the number of years that stream data was recorded, and elevation of the Minnesota River at each gauge station for the basin DEM. From Smith et al., 2018.

City	Elevation of Flood Control Structure	Design Flood Protection	Sources
Montevideo	938 feet	100-year flood + 3 feet	City of Montevideo, 2011
Granite Falls	912 feet	100-year flood + 3 feet	USACE, 2016
New Ulm	814 feet	100-year flood + 2 feet	USACE, 2016
Mankato	778.14-780.14 feet	100-year flood	USACE, 2016
Henderson	745 feet to 743 feet	170-year + 3 feet	USACE, 2016
Chaska	728.5 feet	100-year	USACE, 2016
Carver	726.5 feet	100-year	Mason, 2011

Table 4. Elevation of flood levees along the Minnesota River and magnitude of flood they are designed to protect against. From Smith et al., 2018.

Dating key horizons in the cores would confirm the interpretations of sedimentation rates. In particular, the assumption that magnetic susceptibility peaks indicate recent flood events, while logical, is a hypothesis that should and could be easily tested. The settlement and other anthropogenic disturbances that are interpreted from pollen, sediment and other aspects of the sediment stratigraphy could be dated to firm up the dates of those changes and refine the assumed linear interpolation method. Comparison of the linear sedimentation rates to ^{210}Pb-based rates for two nearby lakes show rates in these floodplain lakes are up to 44% greater. The cores taken for this project have been archived and could be dated at some future time to get more precise estimates of the change in sedimentation rate. Sedimentation estimates would also be more meaningful if converted via bulk density to mass accumulation rates (e.g. g/cm2/yr) rather than presented as linear accumulation rates.

A 3-year project conducted by the Water Resource Center, Minnesota State University, Mankato funded by DNR Fisheries to explore the construction of a carp barrier was released on July 1, 2018 and may have relevant information on recent changes to the river. Reaches were defined geomorphically to conduct both average- and reach-specific analysis (Libby et al., 2018). The Lower Minnesota River Watershed District is confined to reach 15 and 16.



Reach	1937-1951	1951-1964	1964-1980	1980-1991	1991-2013	Total
1	0	0	0	0	0	0
2	0	1	1	1	2	5
3	1	0	1	0	1	3
4	0	0	0	0	0	0
5	1	0	1	0	0	2
6	0	0	0	0	0	0
7	0	1	0	0	2	3
8	0	0	1	0	2	3
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
15	0	0	0	0	0	0
16	0	0	3	0	0	3
Total	2	2	7	1	7	19

Figure 16. Numbered reaches defined geomorphically by Libby and others. 2018.

Repeat bathymetric surveys of the Minnesota River were conducted for the three-year period of the study and reflect changes in the channel itself. Bathymetry was measured twice during the 3-year study. Sites near Jordan, Chaska, and Shakopee were surveyed in 2015 and 2016 and scouring and aggradation were highly variable. In general, long, straight reaches like the lower reaches of the river have little bathymetric variability. Scour pools are associated with the outside bends of meanders and deeper pools are on tighter bends (Belmont et al., 2018).

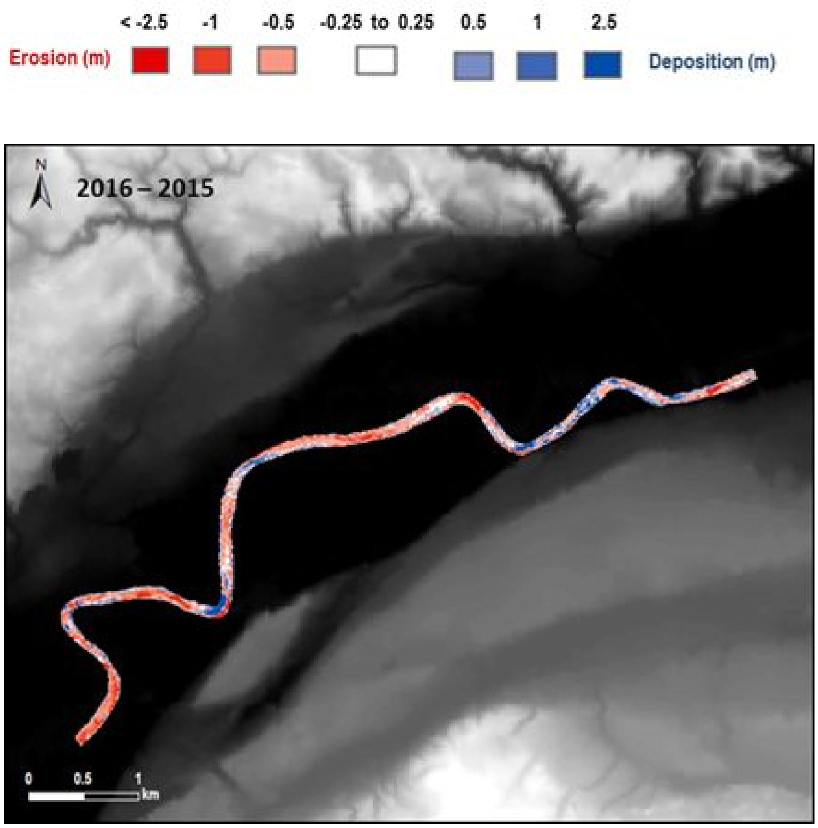


Figure 17. DEM of difference at site I, Chaska, between 2015 and 2016. Erosion is red, deposition is blue, and change below a 25 cm minimum level of change is white, from Belmont et al., 2018.

The reach between Chaska and Shakopee may have limited capacity for meander migration and channel-width adjustment. It has exhibited more extensive channel deepening over the study period compared to upstream reaches which the study authors interpret as erosion (Belmont et al., 2018). However this could reflect dredging activity. Although these changes were documented over a short interval of time, when combined with the longer observations of channel migration, they suggest relative stability of this reach of the river. Nonetheless, we know that reach from Jordan to the confluence is a sediment sink over longer periods (Groeten et al., 2016) and this is in part because of a flattening gradient. It would be best to extend the period of record and compare it with dredging before drawing too many conclusions.

Table 5. Average Annual Channel Migration from Libby et al., 2018

Average Annual Channel Migration by Reach and Interval (m/yr)						
Reach	1937-1951	1951-1964	1964-1980	1980-1991	1991-2013	Average
1	1.07	1.46	0.61	0.45	0.24	0.76
2	1.05	1.37	1.41	1.21	1.39	1.29
3	0.98	0.81	1.00	0.93	0.79	0.90
4	0.35	0.69	0.61	0.89	0.18	0.54
5	1.53	1.98	2.43	1.36	2.01	1.86
6	0.55	0.63	0.74	0.68	0.69	0.66
7	0.89	1.14	0.86	1.33	1.51	1.15
8	1.28	1.13	1.26	1.57	1.75	1.40
9	0.41	0.31	0.53	0.11	0.19	0.31
10	0.84	0.74	0.78	0.90	1.27	0.90
11	0.66	0.33	0.76	1.10	0.39	0.65
12	1.03	1.15	1.32	1.08	1.41	1.20
13	0.39	0.56	0.44	0.48	0.48	0.47
14	0.26	0.38	0.58	0.49	0.27	0.40
15	0.78	0.37	0.54	0.69	0.23	0.52
16	0.40	0.63	0.83	1.39	0.16	0.68
Average	0.77	0.84	0.91	0.99	0.81	0.86
10th Percentile		Quartile 1	Quartile 2	Quartile 3	90th percentile	
0.27		0.48	0.78	1.20	1.45	

< 0.27	>0.27 & <0.48	>0.48 & <0.78	>0.78 & <1.20	>1.20 & <1.45	>1.45

The lower slope is cited as one reason for less channel migration (Libby et al., 2018). Cutoffs upstream have shortened the length overall by 11 to 12 kilometers, thereby steepening the gradient for the Minnesota overall, but not in this reach (Figure 18).

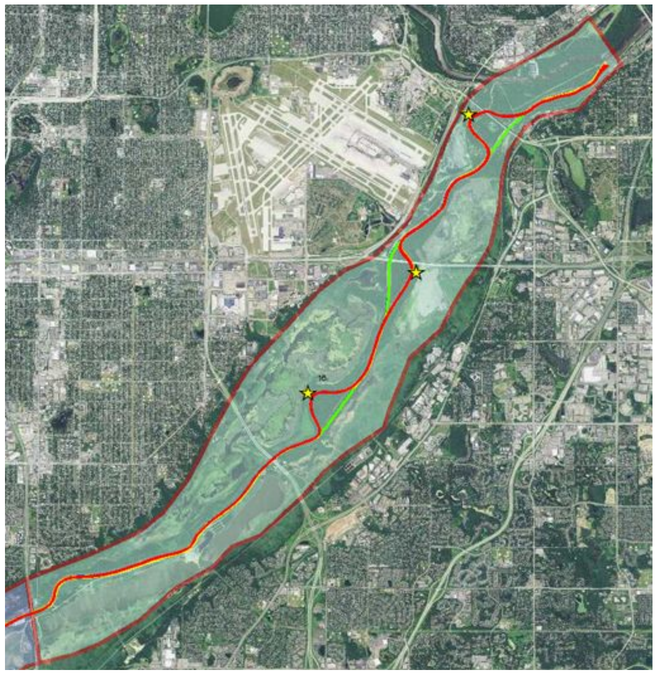


Figure 20. Reach 16 with migration locations(Red = 1937-1951, Orange = 1951-1964, Yellow = 1964-1980, Green = 1980-1991, Blue = 1991-2013) from Libby et al., 2018.

Channel width has also increased more upstream than in the reach managed by the Lower Minnesota River Watershed District. Average channel width in reaches 15 and 16 increased by 38% and 26%, respectively (Figure 19, 20 and Table 6, Libby et al., 2018).

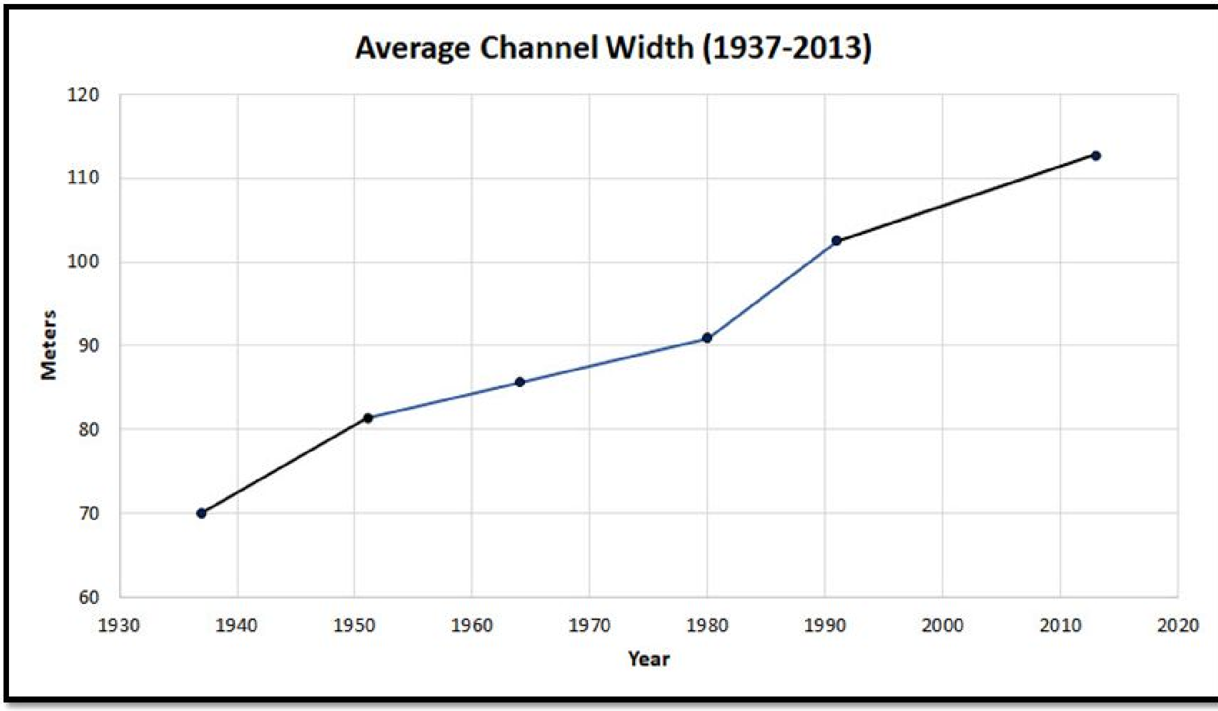


Figure 18. Graphical results for channel width change for all years for the entire river.

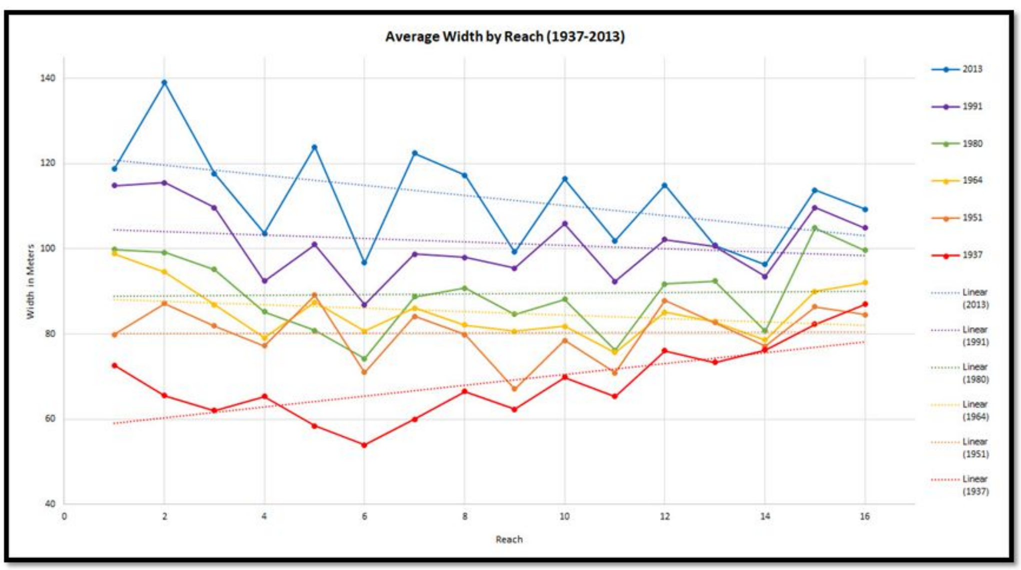


Figure 19. Average channel width for all years by river reach, from Libby et al., 2018

Table 6. Average Channel Width by Reach and Interval

Average Channel Width by Reach and Interval (m/yr)							
Reach	1937	1951	1964	1980	1991	2013	Average
1	72.66	79.91	98.87	99.87	114.90	118.74	97.49
2	65.48	87.20	94.63	99.17	115.58	139.05	100.19
3	62.03	81.92	86.92	95.17	109.72	117.67	92.24
4	65.32	77.21	79.05	85.26	92.41	103.68	83.82
5	58.42	89.17	87.51	80.88	100.98	123.90	90.14
6	53.94	71.01	80.60	74.17	86.84	96.69	77.21
7	60.00	84.20	86.13	88.71	98.82	122.45	90.05
8	66.50	79.83	82.13	90.80	97.98	117.31	89.09
9	62.35	67.10	80.64	84.67	95.48	99.26	81.59
10	69.79	78.45	81.82	88.14	105.90	116.47	90.10
11	65.37	70.87	75.70	76.15	92.39	101.92	80.40
12	76.06	87.86	85.09	91.77	102.20	114.93	92.99
13	73.30	82.69	82.91	92.44	100.63	100.79	88.79
14	76.21	77.18	78.56	80.73	93.55	96.37	83.77
15	82.26	86.37	90.00	104.96	109.72	113.75	97.85
16	86.93	84.51	92.06	99.61	104.94	109.33	96.23
Average	70.05	81.45	85.65	90.89	102.54	112.84	89.50
10th Percentile		Quartile 1	Quartile 2		Quartile 3	90th Percentile	
66.92		78.68	87.36		99.81	114.91	

<66.92	>66.92 & <78.68	>78.68 & <87.36	>87.36 & <99.81	>99.81 & <114.91	>114.91

In summary, the reach of the river managed by the Lower Minnesota River Watershed District is a net sediment sink with a low gradient and uniquely stable channel form and will continue to have an aggrading floodplain which will compromise flood protection in cities near the river within decades under current conditions. Next steps are:

- Firm up the sedimentation rates by dating stored core material. This will also make the work suitable for publication.
- Compare recent LiDAR topography, the MSU study and river cross-sections taken by the Corps of Engineers for the Chaska levee project and other floodplain modeling efforts to determine changes to inundation and flood risk to communities and structures in the LMRWD.
- Work with the Wildlife Refuge on adaptive management strategies for trail locations, road crossings, etc., in the face of increasing flows, flood levels, sediment and dredge volumes.
- Pursue upstream flow management in line with recommendations of the NCED group using the Management Option Simulation Tool (MOSM) in the Le Sueur watershed and similar approaches in other watersheds.

Acknowledgements

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