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Mr. Robert Finley
Regional Manager, Watersheds, MPCA
12 Civic Center Drive, Suite 2165
Mankato, MN 56001

robert.finley@state.mn.us

May 26, 2012

RE: The South Metro Mississippi River Total Suspended Solids (TSS) TMDL Study.

Mr. Finley:

The undersigned petitioners include residents, landowners and farmers of the State of Minnesota. We support the long term objective of improving water quality, and are concerned that the proposed South Metro Turbidity TMDL fails to achieve this objective. Further, we are concerned that inadequate understanding of the cause and effect relationships between natural and man-induced water quality impacts will lead to misdirection of scarce resources. As local stakeholders, we have an interest in the protection and management of local soil and water resources.

Matters of Concern

The undersigned petitioners find that the draft South Metro Total Suspended Solids TMDL report fails to properly account for "natural background" levels as required by the Minnesota Clean Water Legacy Act (CWLA) (MS 114D.15, subdivision 10); as well as, the Natural Water Quality section (7050.0170) of the MN Chapter 7050 rules. "Where background levels exceed applicable standards, the background levels may be used as the standards for controlling the addition of the same pollutants from point or nonpoint source discharges in place of the standards."

The Minnesota CWLA (MS 114D.15, subdivision 10) states that "*Natural background' means characteristics of the water body resulting from the multiplicity of factors in nature, including* *climate and ecosystem dynamics, that affect the physical, chemical, or biological conditions in a water body, but does not include measurable and distinguishable pollution that is attributable to human activity or influence.*" In section 6.6 of the South Metro TMDL, a level of 10% of the existing TSS was used to represent natural background. A 10% number is invalid to use for several reasons. The 10% was based on estimated Lake Pepin sedimentation rates in 1830 compared to recent decades.

The 1830 point of reference clearly does not account for *climate and ecosystem dynamics*, as is required by the Minnesota CWLA. For example, there are different ecosystems present in the watersheds today compared to 1830 and there have been changes in climate (more rainfall in recent decades). There was no evidence provided in the TMDL that indicates sedimentation rates in Lake Pepin directly translate to the sediment load in the South Metro Mississippi River in recent times compared to the 1830 time frame. The Engstrom study that is being referenced also indicates that sedimentation rates in the early part of the 20th century were significantly less than the 1950 to 1980 time frame. However, McHenry and others (McHenry i.e., 1980, Water Resources Bulletin 16) found that sedimentation rates had declined from the 1895-1954 time frame compared to post 1954. Dr Satish Gupta (Natural vs Anthropogenic Factors Affecting Sediment Production and Transport from the Minnesota River Basin to Lake Pepin, January 2011) in his report indicated that "sediment production in the Minnesota River Basin may not be drastically different now than before European settlement in 1850". These major scientific discrepancies with the South Metro TMDL must be resolved. Other researchers have also shown significant differences with the Engstrom study.

A study done by Dr. Satish Gupta (Kessler, Gupta i.e., Journal of Environmental Quality, 2012) indicates that most of the sediment load from the Blue Earth River to the Minnesota River is from bluffs and banks. The Blue Earth River contributes about 50% of the TSS load to the Minnesota River. The processes responsible for this bluff and bank erosion are the same physical processes that have been occurring since the Minnesota River was formed, and therefore, are part of the natural background contributions. The MPCA made no attempt to divide the load allocation into subcomponents in the South Metro TMDL report. The report provided no measurable and distinguishable evidence that the non-point source load was anything other than natural background.

The South Metro Mississippi TSS TMDL study also fails to properly account for the components that contribute to turbidity. Dr. Robert Megard, MN River Turbidity Technical Advisory committee, raised the issue that the organic fraction of the TSS can be a much greater contributor to turbidity than the mineral fraction (May 1, 2009, U of Minnesota, Water Quality Seminar). A 2010 U. S. Geological Survey (USGS) technical Report on pools in the Upper Mississippi River showed that the volatile suspended solids (VSS) had substantially more impact on turbidity than non-volatile suspended solids (NVSS) (Giblin, USGS Technical Report 2010-T001). The VSS impact on turbidity was about 15 times greater than the NVSS on a weight basis. The VSS effect found in the USGS study is similar to what Megard determined for the South Metro stretch of the Mississippi.

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The petitioners ask that the MPCA properly determine the natural background levels of the load allocation, as well as determine load allocations that properly account for the impact of volatile suspended solids on the turbidity measurements. The petitioners also request the load allocations be determined using measurable and distinguishable evidence as is established in the Minnesota Clean Water Legacy Act.

Proposed Actions

The undersigned petitioners request that MPCA hold contested case hearing in this matter.

The MPCA must grant a party's petition to hold a contested case hearing if it finds that:

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Witnesses in this matter shall include the undersigned witnesses and other expert witnesses to be named later.

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We respectfully request that the MPCA to provide the information herein requested at the earliest convenient opportunity. Please contact Mike Youngerberg in our office at 507-388-1635 to make the necessary arrangements.

Kurt Kruger

Kurt Kruger
President

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New ULM MN 56073

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May 26, 2012

RE: The South Metro Mississippi River Total Suspended Solids (TSS) TMDL Study.

Mr. Finley:

The undersigned petitioners include residents, landowners and farmers of the State of Minnesota. We support the long term objective of improving water quality, and are concerned that the proposed South Metro Turbidity TMDL fails to achieve this objective. Further, we are concerned that inadequate understanding of the cause and effect relationships between natural and man-induced water quality impacts will lead to misdirection of scarce resources. As local stakeholders, we have an interest in the protection and management of local soil and water resources.

Matters of Concern

The undersigned petitioners find that the draft South Metro Total Suspended Solids TMDL report fails to properly account for "natural background" levels as required by the Minnesota Clean Water Legacy Act (CWLA) (MS 114D.15, subdivision 10); as well as, the Natural Water Quality section (7050.0170) of the MN Chapter 7050 rules. "Where background levels exceed applicable standards, the background levels may be used as the standards for controlling the addition of the same pollutants from point or nonpoint source discharges in place of the standards."

The Minnesota CWLA (MS 114D.15, subdivision 10) states that "*Natural background' means characteristics of the water body resulting from the multiplicity of factors in nature, including climate and ecosystem dynamics, that affect the physical, chemical, or biological conditions in a water body, but does not include measurable and distinguishable pollution that is attributable to human activity or influence.*" In section 6.6 of the South Metro TMDL, a level of 10% of the existing TSS was used to represent natural background. A 10% number is invalid to use several reasons. The 10% was based on estimated Lake Pepin sedimentation rates in 1830 compared to recent decades.

The 1830 point of reference clearly does not account for *climate and ecosystem dynamics*, as is required by the Minnesota CWLA. For example, there are different ecosystems present in the watersheds today compared to 1830 and there have been changes in climate (more rainfall in recent decades). There was no evidence provided in the TMDL that indicates sedimentation rates in Lake Pepin directly translate to the sediment load in the South Metro Mississippi River in recent times compared to the 1830 time frame. The Engstrom study that is being referenced also indicates that sedimentation rates in the early part of the 20th century were significantly less than the 1950 to 1980 time frame. However, McHenry and others (McHenry i.e., 1980, Water Resources Bulletin 16) found that sedimentation rates had declined from the 1895-1954 time frame compared to post 1954. Dr Satish Gupta (Natural vs Anthropogenic Factors Affecting Sediment Production and Transport from the Minnesota River Basin to Lake Pepin, January 2011) in his report indicated that "sediment production in the Minnesota River Basin may not be drastically different now than before European settlement in 1850". These major scientific discrepancies with the South Metro TMDL must be resolved. Other researchers have also shown significant differences with the Engstrom study.

A study done by Dr. Satish Gupta (Kessler, Gupta i.e., Journal of Environmental Quality, 2012) indicates that most of the sediment load from the Blue Earth River to the Minnesota River is from bluffs and banks. The Blue Earth contributes about 50% of the TSS load to the Minnesota River. The processes responsible for this bluff and bank erosion are the same physical processes that have been occurring since the Minnesota River was formed, and therefore, are part of the natural background contributions. The MPCA made no attempt to divide the load allocation into subcomponents in the South Metro TMDL report. The report provided no measurable and distinguishable evidence that the non-point source load was anything other than natural background.

The South Metro Mississippi TSS TMDL study also fails to properly account for the components that contribute to turbidity. Dr. Robert Megard, MN River Turbidity Technical Advisory committee, raised the issue that the organic fraction of the TSS can be a much greater contributor to turbidity than the mineral fraction (May 1, 2009, U of Minnesota, Water Quality Seminar). A 2010 U. S. Geological Survey (USGS) technical Report on pools in the Upper Mississippi River showed that the volatile suspended solids (VSS) had substantially more impact on turbidity than non-volatile suspended solids (NVSS) (Giblin, USGS Technical Report 2010-T001). The VSS impact on turbidity was about 15 times greater than the NVSS on a weight basis. The VSS effect found in the USGS study is similar to what Megard determined for the South Metro stretch of the Mississippi.

Total suspended solids in the South Metro Mississippi River are dominated by the NVSS fraction; however, the VSS clearly dominates light penetration, and therefore, turbidity measurements. The South Metro Mississippi River TSS TMDL has failed to account for this

important component of the TSS and the outcome is an erroneous load allocation, and therefore, implementation activities which will not be effective.

The petitioners ask that the MPCA properly determine the natural background levels of the load allocation, as well as, determine load allocations that properly account for the impact of volatile suspended solids on the turbidity measurements. The petitioners also request the load allocations be determined using measurable and distinguishable evidence as is established in the Minnesota Clean Water Legacy Act.

Proposed Actions

The undersigned petitioners request that MPCA hold contested case hearing in this matter.

The MPCA must grant a party's petition to hold a contested case hearing if it finds that:

A. There is a material issue of fact in dispute concerning the matter pending before the agency;
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Issues to be addressed by contested case hearing:

The undersigned petitioners request the MPCA address the legal requirements of the South Metro Mississippi River Turbidity TMDL under the US Clean Water Act and the Minnesota Clean Water Legacy Act, including the load allocations, evaluation of natural background conditions and natural background standards.

Witnesses in this matter shall include the undersigned witnesses and other expert witnesses to be named later.

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The undersigned petitioners estimate that it will require two full days to adequately address these matters.

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In preparing for contested case, and pursuant to the Minnesota Government Data Practices Act (MS 13.01) the undersigned petitioners request MPCA provide an opportunity at the earliest convenient date to inspect and review the following data connected with the development of the South Metro Mississippi River Turbidity TMDL report.

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Address 655 MONTANA AVE BENSON MN. 56215
Signature Anthony Hughes

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Geomorphic evolution of the Le Sueur River, Minnesota, USA, and implications for current sediment loading

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ABSTRACT

There is clear evidence that the Minnesota River is the major sediment source for Lake Pepin and that the Le Sueur River is a major source to the Minnesota River. Turbidity levels are high enough to require management actions. We take advantage of the well-constrained Holocene history of the Le Sueur basin and use a combination of remote sensing, field, and stream gauge observations to constrain the contributions of different sediment sources to the Le Sueur River. Understanding the type, location, and magnitude of sediment sources is essential for unraveling the Holocene

Gran, K.B., Belmont, P., Day, S.S., Jennings, C., Johnson, A., Perg, L., and Wilcock, P.R., 2009, Geomorphic evolution of the Le Sueur River, Minnesota, USA, and implications for current sediment loading, *in* James, L.A., Rathburn, S.L., and Whittecar, G.R., eds., Management and Restoration of Fluvial Systems with Broad Historical Changes and Human Impacts: Geological Society of America Special Paper 451, p. XXX–XXX, doi: 10.1130/2008.2451(08). For permission to copy, contact editing@geosociety.org.

development of the basin as well as for guiding management decisions about investments to reduce sediment loads.

Rapid base-level fall at the outlet of the Le Sueur River 11,500 yr B.P. triggered up to 70 m of channel incision at the mouth. Slope-area analyses of river longitudinal profiles show that knickpoints have migrated 30–35 km upstream on all three major branches of the river, eroding 1.2–2.6 × 10^9 Mg of sediment from the lower valleys in the process. The knick zones separate the basin into an upper watershed, receiving sediment primarily from uplands and streambanks, and a lower, incised zone, which receives additional sediment from high bluffs and ravines. Stream gauges installed above and below knick zones show dramatic increases in sediment loading above that expected from increases in drainage area, indicating substantial inputs from bluffs and ravines.

INTRODUCTION

The Minnesota River drains 43,400 km^2 of south-central Minnesota (Fig. 1), a landscape dominated by agricultural land use. The Minnesota River carries a high suspended sediment load, leading to the listing of multiple reaches as impaired for turbidity under Section 303d of the Clean Water Act. Analyses of sediment cores from Lake Pepin, a naturally dammed lake on the mainstem Mississippi River, serving as the primary sediment sink for the Minnesota, St. Croix, and upper Mississippi River systems, indicate that sediment loads into Lake Pepin have increased tenfold since the onset of European settlement in the mid-1800s, from a background of ~75,000 Mg yr^{-1} to ~900,000 Mg yr^{-1} (Engstrom et al., 2008). Of this sediment load, the vast majority (85%–90%) comes from the Minnesota River (Kelley and Nater, 2000).

To help restore clean water and improve ecosystem functionality in the Minnesota River and Lake Pepin, a large-scale effort is under way to lower sediment loading to the system. This involves targeting the dominant sources of sediment to the system, which are poorly constrained. Our research focuses on establishing an integrated sediment budget in one of the major tributaries of the Minnesota River, the Le Sueur River, in an effort to better define the source locations and transport processes for sediment entering the Minnesota River. Once source locations are well defined, best management practices can be targeted toward reducing the sediment load coming from these areas.

The first phase of our sediment budget involves bracketing the range of sediment volumes that have been eroded through time to compare current sediment loading with historic and Holocene average rates. Recent changes in both land use and hydrology in

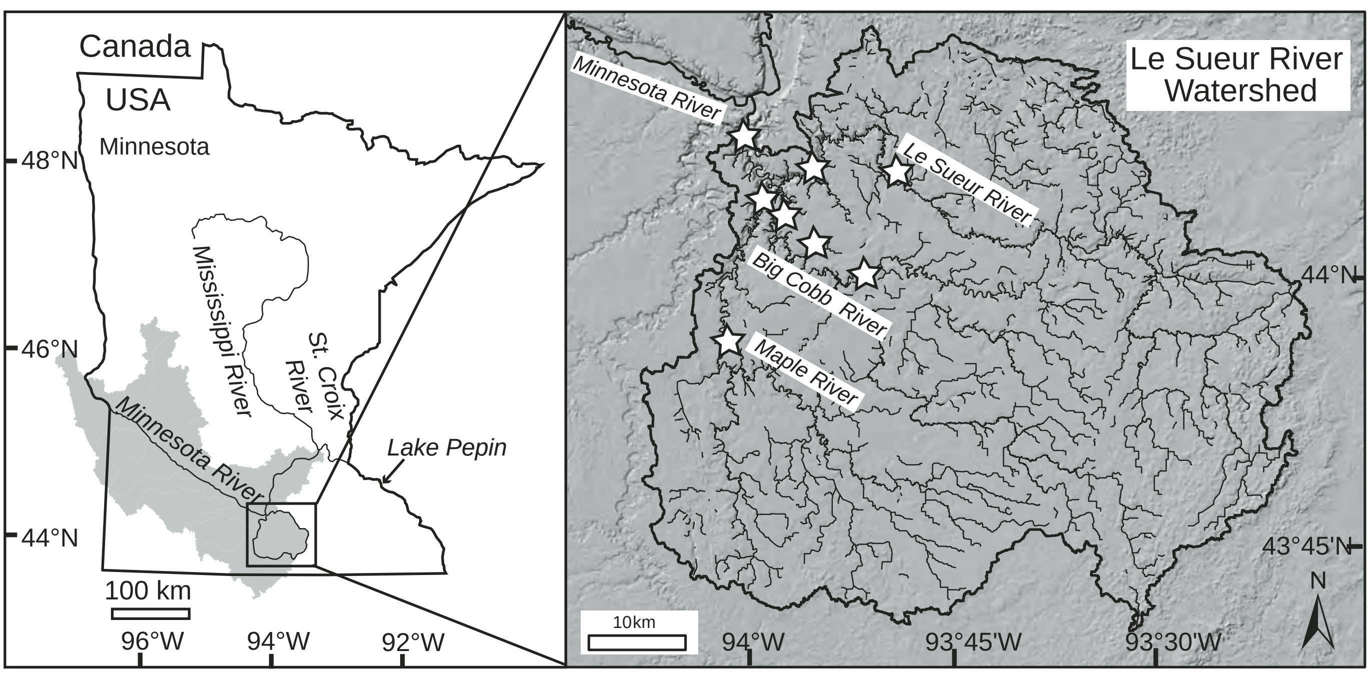

Figure 1. Location map showing Le Sueur River watershed in south-central Minnesota, USA. The shaded area on the state map indicates the extent of the Minnesota River basin. Stars on the inset watershed map on the right indicate locations of gauging stations.

the system may be exacerbating erosion in certain parts of the landscape, resulting in the observed increase in sediment loading to Lake Pepin in the past 170 yr. The next phase involves setting bounds on the relative magnitude and proportion of sediment coming from each primary sediment source to determine which sources are currently important contributors of sediment to the Le Sueur River.

BACKGROUND

The Le Sueur River drains north and west to the Minnesota River in south-central Minnesota (Fig. 1). It covers 2880 km^2 of primarily agricultural land use (87%), the vast majority of which is in row crops (>90%) (Minnesota Pollution Control Agency [MPCA] et al., 2007). There are no major urban areas, although the municipality of Mankato is expanding into the northern part of the watershed. The Le Sueur River has three main branches: the Maple River, the Big Cobb River, and the mainstem Le Sueur. The three branches come together within a span of 3 km, ~10 km upstream of the Le Sueur confluence with the Blue Earth River. The Blue Earth flows into the Minnesota River 5 km downstream from the junction with the Le Sueur River.

Modern sediment-gauging efforts indicate that ~24%–30% of the total suspended solids (TSS) entering the Minnesota River come from the Le Sueur River, making it a primary contributor to the mainstem Minnesota and Lake Pepin (MPCA et al., 2007). This is a disproportionate sediment contribution relative to the Le Sueur watershed area, which constitutes a mere 7% of the Minnesota River basin. From 2000 to 2006, TSS measured at the mouth of the Le Sueur River ranged from 0.9 to 5.8×10^5 Mg yr^{-1} (mean = 2.9×10^5 Mg yr^{-1}) (MPCA et al., 2007; MPCA, P. Baskfield, 2007, personal commun.) (Table 1). Annual flow-weighted mean concentrations of TSS from 2000 to 2006 ranged from 245 to 918 mg L^{-1} (mean = 420 mg L^{-1}) (MPCA et al., 2007; MPCA, P. Baskfield, 2007, personal commun.). Target values set by the MPCA in this region are 58–66 mg L^{-1} (McCollor and Heiskary, 1993).

The lower reaches of the Le Sueur, Maple, and Big Cobb Rivers are currently incising. Knickpoints are migrating upstream along major tributaries, leading to high relief in the lower, incised portion of the watershed. At the mouth of the Le Sueur, the channel is incised 70 m in a valley up to 800 m wide. High bluffs border many of the outer bends along the channel, and steep ravines snake into the uplands. This is in stark contrast to the low-gradient to flat uplands, which occupy most of the watershed area.

The basin is underlain by tills, glacial outwash, and ice-walled lake plains with a thin mantle of glaciolacustrine silts and clays covering 65% of the upland surface. The river is currently incising through the layered Pleistocene tills and the underlying Ordovician dolostone bedrock. Bedrock outcrops have been observed along the channel in patches within 15 km of the mouth.

The high relief in the lower Le Sueur River Valley is the result of knickpoint migration through the basin. These knickpoints originated from a sharp drop in base level on the mainstem Minnesota River during the catastrophic draining of glacial Lake Agassiz. As the Laurentide ice sheet retreated from the Midcontinent at the end of the last glaciation, meltwater from the wasting ice was impounded by a low moraine dam in western Minnesota and formed glacial Lake Agassiz. It eventually covered much of western Minnesota, eastern North Dakota, Manitoba, and western Ontario (Upham, 1890, 1895; Matsch, 1972). The only outlet for much of this time was to the south through glacial River Warren, the valley now occupied by the Minnesota River. River Warren incised older tills and saprolite, and in places exposed resistant rock in the valley floor (Matsch, 1983), creating a valley that was 45 m deep at its mouth and 70 m deep near Mankato, 300 km downstream.

The initial incision was ca. 11,500 radiocarbon yr B.P. (rcbp) (Clayton and Moran, 1982; Matsch, 1983). The valley was occupied until ~10,900 rcbp. Two other outlets were used between 10,900 and 10,300 (Thorleifson, 1996) and between 10,000 and 9600 rcbp (Lowell et al., 2005) during which time the southern outlet was not used. River Warren was reoccupied after 9600 rcbp and finally lost glacial lake discharge by 8200 rcbp. Preexisting tributaries such as the Blue Earth and Le Sueur Rivers were low-gradient streams of glacial-meltwater origin that were stranded above the master stream when the initial incision occurred 11,500 rcbp. Knickpoint migration continues today, with bedrock waterfalls within 5–10 km of the confluence on several major tributaries. In the Le Sueur River the record of incision following glacial River Warren is manifested in >400 terrace surfaces spread throughout the lower basin. Knickpoints are expressed as slope discontinuities evident on all three major branches of the river, and they have propagated approximately the same distance upstream on each branch.

The glaciolacustrine deposits blanketing much of the Le Sueur River watershed were deposited in glacial Lake Minnesota, which drained shortly before the initial carving of the Minnesota River valley. These deposits are composed of highly erodible silts and clays. Given the fine-grained, erodible soils of the Le Sueur

TABLE 1. TSS LOADS IN LE SUEUR RIVER, 2000–2006

	2000	2001	2002	2003	2004	2005	2006§	Mean
TSS* (Mg)	5.8×10^5	4.2×10^5	1.1×10^5	8.6×10^4	4.1×10^5	2.7×10^5	1.5×10^5§	2.9×10^5
FWMC† (mg/L)	918	355	318	245	475	356	270§	420

Note: 2000–2005 data from Minnesota Pollution Control Agency (MPCA et al., 2007).
*TSS—total suspended solids.
†FWMC—flow-weighted mean concentration.
§2006 data from MPCA (P. Baskfield, 2007, personal commun.), preliminary.

River watershed and the high relief in the basin, the watershed is primed to have high suspended-sediment loads relative to other watersheds in the basin, and it is susceptible to erosion driven by changes to the landscape following the arrival of settlers of European descent in the mid-1800s.

The presettlement landscape of the Le Sueur River was dominated by prairie vegetation that covered two-thirds of the basin, with hardwoods in the river valleys and the northeastern corner of the watershed. Wet prairie and open lakes occupied at least 15% (Marschner, 1974), and possibly as much as one-third, of the watershed area (Minnesota Department of Natural Resources, 2007). Two major changes to the landscape have occurred in the past 200 yr: conversion of original prairie to agriculture, and alterations to the basin hydrology. Land cover in the basin is now primarily row crops (currently 87% cropland; MPCA et al., 2007), with lakes and wetlands covering only 3% of the watershed area. Hydrologic alterations include draining wetlands, connecting previously closed basins to the drainage network, ditching small tributaries, and tiling agricultural fields to ensure rapid drainage of surface, vadose, and, in some places, groundwater. The hydrologic alterations are both pervasive and dynamic. Nearly all farm fields have artificial drainage, and the depth, density, and capacity of drainage have generally increased over time (Water Resources Center, 2000). Little documentation exists for these progressive hydrologic changes. Superimposed on these direct changes to the hydrologic system are indirect changes from climate change in the last ~50 yr, including statewide increases in mean annual precipitation, to number of days with precipitation and number of intense rainfall events per year (Novotny and Stefan, 2007). These changes are, in turn, superimposed on the template of the geomorphically evolving, incised channel network that was initiated by deep, rapid incision in the Minnesota River Valley.

METHODS

This research effort focused on sediment loading to the Le Sueur River over multiple temporal and spatial scales, with the goal of identifying sources, fluxes, and sinks in the evolution of the drainage system and its response to human alteration. Most of the work on the volume of Holocene erosion was done through analyses of digital topography, including high-resolution topography acquired through LiDAR (light detection and ranging) in Blue Earth County. This data set covers ~30% of the total watershed area, including all of the area below the major knickpoints. Holocene erosion volumes are compared with 2000–2006 sediment loads measured at stream gauges as a comparison of current rates versus background rates. Both of these erosion measures are compared with the signal of deposition at Lake Pepin over the past 400 yr from Engstrom et al. (2008).

Sediment sources to the Le Sueur River include upland-derived sediment, high bluffs, terraces, and ravines. Major sediment sources are shown in Figure 2. The primary sediment sources above the knick zone include upland-derived sediment and sediment eroded from streambanks owing to lateral migration of channels. Normally, streambanks are not a net source of sediment because the sediment eroded is balanced by deposition on floodplains. However, because the river is migrating into terraces and high bluffs, erosion from these features can lead to net sediment contributions to the channel from stream migration. Most of the terraces are below the major knick zone, but there are smaller terraces throughout the basin, remnants of the passage of the upper knickpoint through the system. Through and below the major knick zones, ravines and bluffs have become important sediment contributors. Information on total sediment flux was derived from paired gauging stations above and below the knick zones on major tributaries. Analyses of historical air photos from 1938 to 2003 help constrain channel migration patterns and dynamics. These data combine to determine which sediment sources are significant components of the modern sediment budget.

LiDAR Analyses

We extracted river longitudinal profiles from 30 m SRTM (Shuttle Radar Topography Mission) data obtained from the U.S. Geological Survey and analyzed the relationship between local channel gradient and contributing drainage area (see Wobus et al., 2006) along the entire river profile using the Stream Profiler utility (www.geomorphtools.org) with a 3-m contour, a 1-km smoothing window, and an empirically derived reference concavity of 0.45 (Fig. 3). Slope-area analyses were conducted on each of the three mainstem channels to find major slope discontinuities (see Fig. 3B). In a graded system, the slope-area relationship should increase monotonically throughout the entire fluvial portion of the watershed. The sharp discontinuities evident in the slope-area plot highlight the locations of knickpoints.

We estimated the mass of sediment that has been excavated over the past 11,500 yr from the incised, lower reaches of all three branches of the Le Sueur River. To calculate the missing mass, we hand-digitized polygons delineating the incised portion of the river valleys using the 3-m resolution aerial LiDAR digital elevation model (DEM) (Fig. 4). Precision in this process was enhanced by overlaying the DEM with a semitransparent hill shade and using a multiband color scheme for the DEM, which we manipulated to depict most effectively small differences in the elevation range of interest. The valley walls are generally strikingly clear and easy to trace using this technique. Valley polygons were split into 3-km-long reaches. We then converted each of those polygons to grids, attributing a paleosurface elevation value to each cell in the grid. The mass removed was determined by subtracting the current topography from the paleosurface.

To generate minimum and maximum estimates of the mass of excavated sediment, we used two different paleosurface elevations. Our maximum estimate assumed that the watershed was initially a planar glacial lake bed with a paleosurface elevation of 327 m above sea level for all valley polygons, consistent with the average elevation of the surrounding, low-gradient uplands in this area. Our minimum estimate assumed a different paleosurface elevation for each 3-km valley reach consistent with the elevation of the highest terraces mapped in that reach. These elevations are the highest levels that we know were occupied by the river in the past 11,500 yr.

Using the same approach, we hand-digitized all 95 ravines (considering only those with a planar area of an incised valley >0.5 km^2) and calculated the mass of material that has been excavated by ravines as a result of ravine incision and elongation only. The paleosurface elevation of each ravine was determined using the average of 10 upland-surface elevations surrounding the ravine.

Volumes of sediment removed were converted into mass using a bulk density of 1.8 Mg m^{-3} (Thoma et al., 2005). To

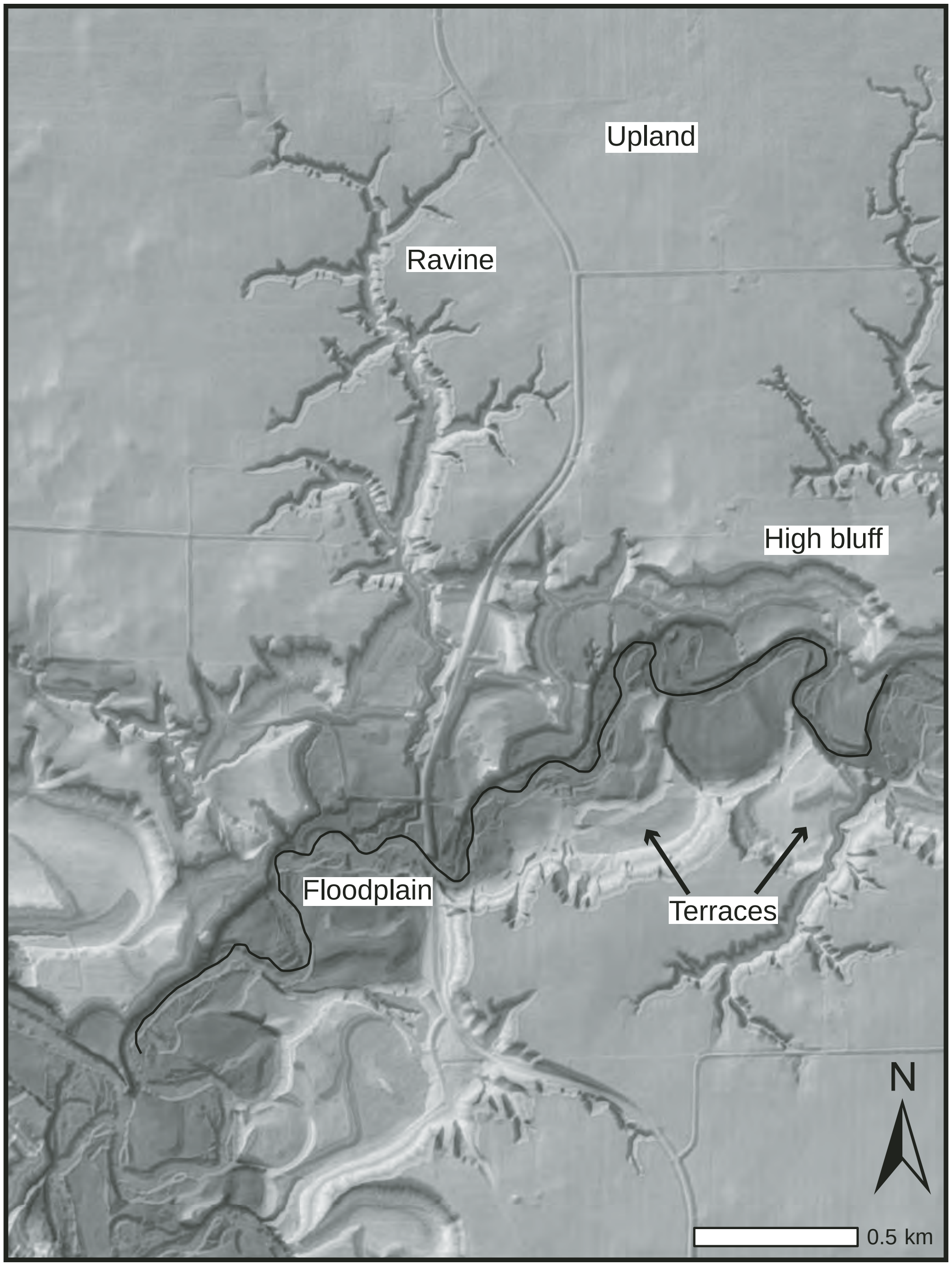

Figure 2. Primary sediment sources in the Le Sueur River watershed include uplands, ravines, high bluffs, and terraces. Shown here is a merged LiDAR digital elevation model (DEM) and a slope map of the lower Le Sueur River with different source areas labeled. Relief is ~70 m from river valley to uplands. LiDAR—light detection and ranging.

compare with TSS measurements, we assumed that only the silt and clay fractions (65% of the total mass) move downstream as suspended load. This mass could then be compared with the inorganic fraction of TSS from modern gauging efforts.

We mapped fluvial terrace surfaces from the 3 m aerial LiDAR DEM, using a semitransparent hill shade to enhance visual precision (Fig. 5). The criterion used to delineate terrace surfaces was visual observation of undissected, planar (<1 m of relief) surfaces within the incised river valley that are >2 m above the river water-surface elevation from the LiDAR data set. This relief criterion excluded floodplain surfaces where active deposition is still occurring.

Historic Rates of Channel Migration

Aerial photographs from 1938 and 2003 were used to constrain short-term river migration rates. The 1938 photos were georeferenced in ArcGIS. At least seven stable control points were selected and matched in each photo, fit with a second-order polynomial function, and rectified after a total root mean square error (rmse) <0.5 was achieved. Channel banks were digitized by hand in ArcGIS. In cases where vegetation obscured the channel edge, the bank was estimated assuming a width consistent with adjacent up-downstream reaches. To calculate channel migration rates, we used a planform statistics tool described in Lauer and Parker (2005) (available at http://www.nced.umn.edu/Stream_Restoration_Toolbox.html). This tool maps the center line of the channel based on the user-defined right and left banks. The program then compares the center line of the 1938 channel with the 2003 channel center line using a best-fit Bezier curve. The overall georeferencing error was ±4.5 m, although individual images varied around this average.

To estimate the potential net contribution of sediment eroded through lateral migration, bank heights were calculated

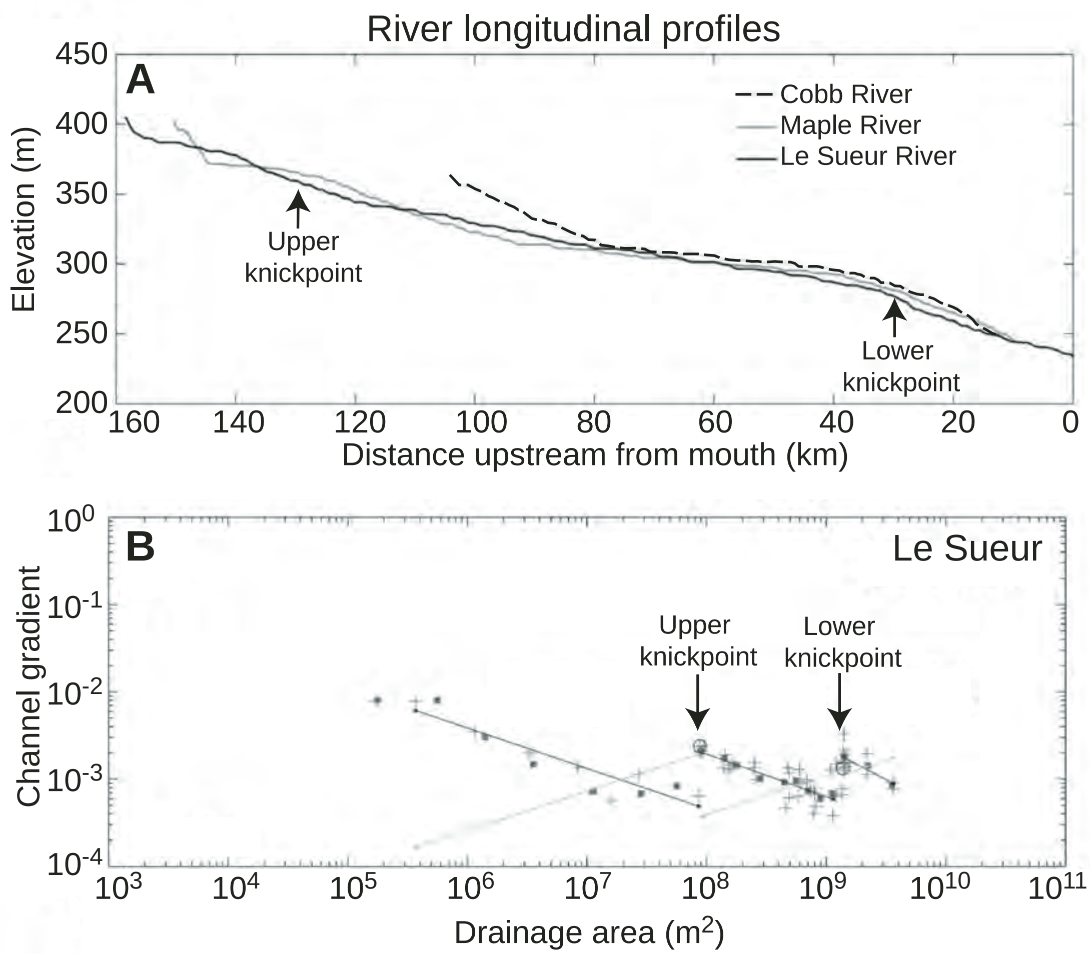

Figure 3. (A) Longitudinal elevation profiles of the Le Sueur River and its two primary tributaries, the Cobb and Maple Rivers, extracted from a 30 m DEM. The locations of the two knickpoints delineated on the Le Sueur River branch using the slope-area analysis in plot B are shown. (B) Analysis of local channel gradient and contributing drainage area of the Le Sueur River longitudinal profile, after smoothing with a 1-km moving window and sampling every 3 m drop in elevation. The discontinuities in the slope-area relationship indicate the locations of two knickpoints. Both data sets were extracted using the stream profiler tool available at geomorphtools.org.

along a profile line adjacent to the top of the banks in 2003. Bank elevations were averaged every 100 m, and reach-average channel elevations were subtracted to get bank heights. Since channels both erode and deposit on their floodplains, resulting in no net gain or loss of sediment, we removed areas with elevations at or below the floodplain elevation, leaving only banks in terraces and bluffs. This methodology gives a measure of the potential net flux of sediment into the channel from channel migration into these higher surfaces. Floodplain heights were measured off the LiDAR DEM at 25 different sites along the mainstem Le Sueur River. The average floodplain height was 1.8 m ±0.5 m in the lower 25 km and 1.0 ±0.1 m from 25 to 75 km upstream. We measured volumes of sediment potentially entrained from terraces and bluffs along the lower 73.6 km of the mainstem Le Sueur River and then extrapolated to the rest of the mainstem Le Sueur, Maple, and Big Cobb Rivers, a total of 410 river km, to get a measure of the potential net volume of sediment that would be eroded into the channel from lateral migration into terraces and bluffs. These volumes were converted to mass using a bulk density of 1.8 Mg m^{-3}, and to potential suspended sediment load assuming a silt-clay content of 65% of the total sample.

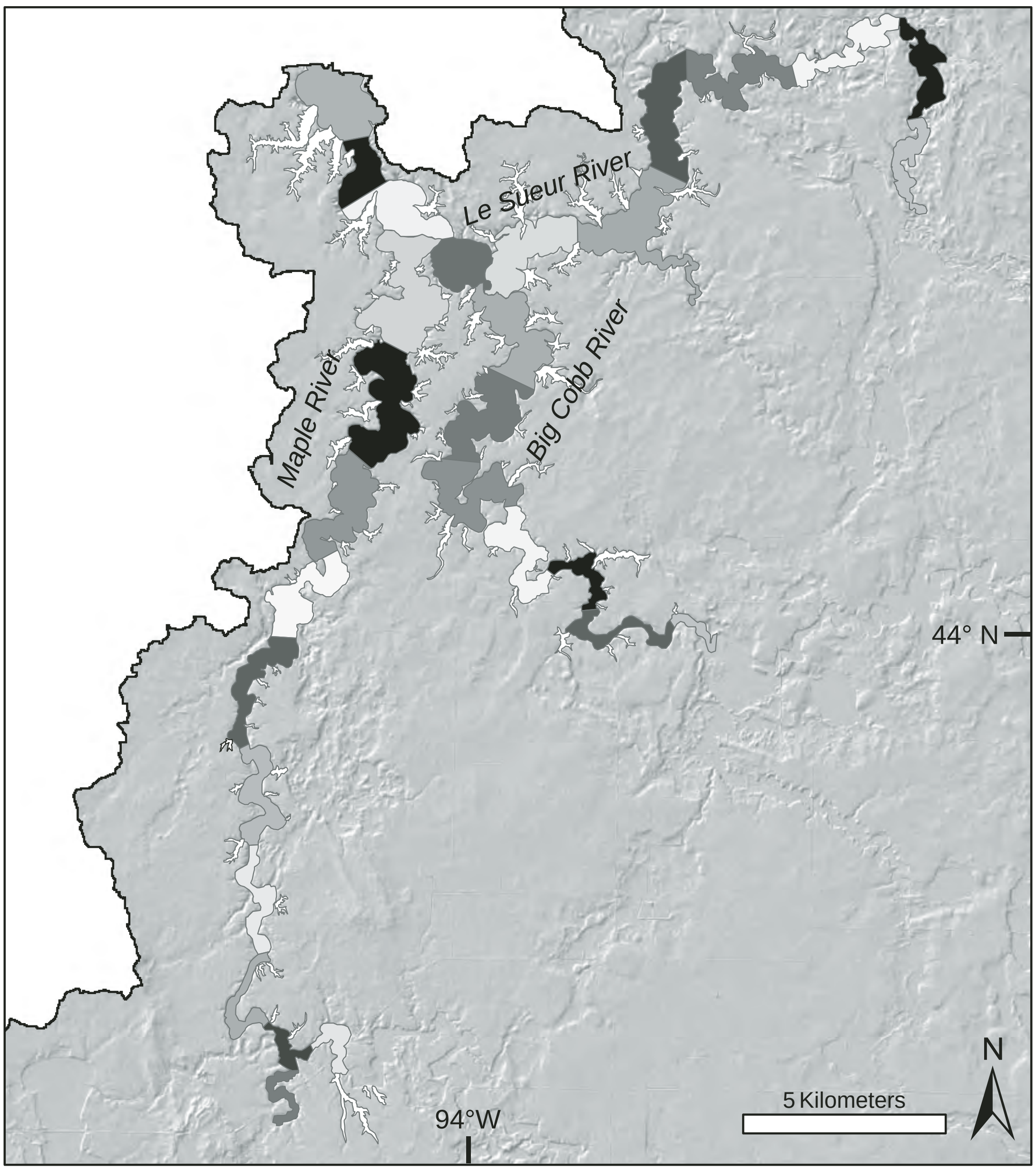

Figure 4. Valley and ravine polygons used to determine sediment mass excavated in the past 11,500 yr, overlain on the LiDAR DEM.

Gauging Data

Modern sediment fluxes were calculated through continuous-flow gauging at nine stations in the Le Sueur River watershed by the MPCA (Fig. 1; Table 2). Approximately 30–40 grab samples were collected and processed by the MPCA throughout the year at each of these gauging stations and analyzed for TSS. Individual samples were converted into flow-weighted mean sediment concentrations by agency staff using the U.S. Army Corps of Engineers' FLUX program. Data from 2000 to 2005 were reported in MPCA et al. (2007). Data from 2006 come from the MPCA (P. Baskfield, 2007, personal commun.) and include preliminary data from gauges in their first year of operation.

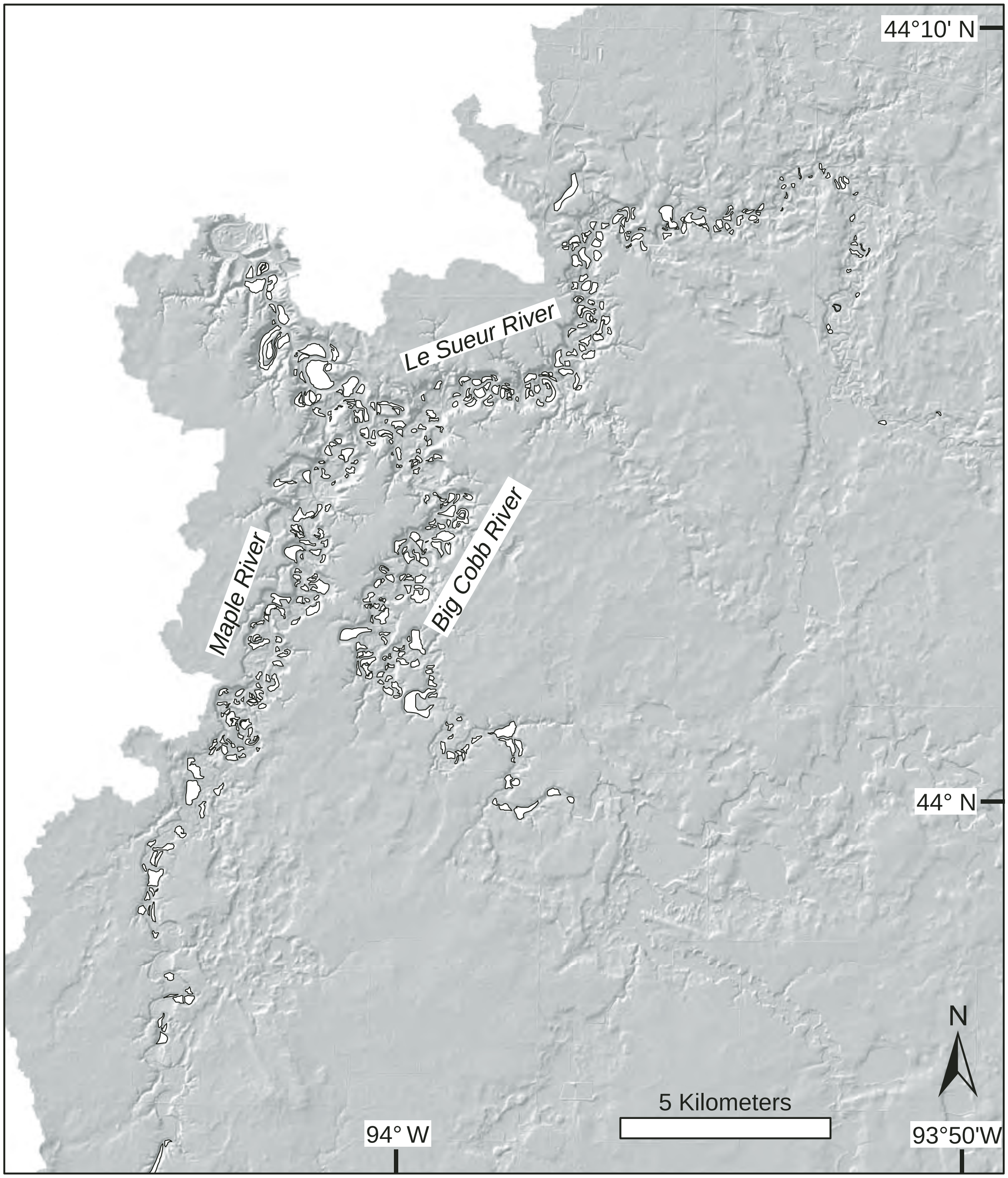

Figure 5. Terraces mapped in the lower Le Sueur River watershed, overlain on top of the LiDAR DEM. Only terraces >2 m above the channel were mapped, to exclude active floodplains.

TABLE 2. GAUGING STATIONS IN THE LE SUEUR RIVER WATERSHED

Station	Location	Years of operation*	Drainage area (km^2)
LS1	Le Sueur R. at Red Jacket, BE County Rd. 66	1939–	2880
LS2	Le Sueur R., BE County Rd. 90	2006–	1210
LS3	Le Sueur R. at St. Clair, BE County Rd. 28	2007–	870
LC	Little Cobb R., BE County Rd.	1996–	336
BC	Big Cobb R., BE County Rd. 90	2006–	737
LM	Lower Maple R., BE County Rd. 35	2003–	878
UM	Upper Maple R., BE County Rd. 18	2006–	780
BD[†]	Beauford Ditch, Minnesota Highway 22	1999–	18

*As of 2008 these stations are currently in operation.
[†]BD site was a former U.S. Geological Survey gauging site in operation from 1959 to 1985.

To compare modern TSS loads with volumetric estimates of sediment removed over the Holocene, we removed the estimated organic fraction of the TSS. Samples were also analyzed for total suspended volatile solids (TSVS). Using TSVS as a proxy for the organic content of TSS, estimates of the organic content of TSS samples from the Le Sueur River in 1996 ranged from 16% to 34% (Water Resources Center, 2000). We adjusted the average TSS load from 2000 to 2006 by this amount to compare inorganic fractions only.

RESULTS

Until glacial River Warren incised and widened the ancestral Minnesota River Valley, the Le Sueur River watershed contained a series of low-gradient, ice-marginal meltwater channels and a relatively flat glacial lake bed masking former channels. Most of the current river-valley topography formed in the time since 11,500 yr B.P. Terraces in the lower valley record the history of incision (Fig. 5). On all three branches, knickpoints have migrated 30–35 river km upstream from the confluence with the Blue Earth River (Fig. 3), an average knickpoint migration rate of 3.0–3.5 m yr^{-1} over the past 11,500 yr. A second knickpoint is seen between 120 and 140 river km upstream on all three branches, indicating an average upstream migration rate of 10.9–12.6 m yr^{-1}. These exceptionally high migration rates speak to the poor strength of the underlying till and glaciolacustrine sediments at the surface. The elevation drop associated with the upper knickpoint appears to be relatively minor. Most of the relief in the basin is related to migration of the lower knickpoint.

The mass of sediment evacuated from incision since the initial base-level drop was used to determine an average yield per year (Table 3), broken down by sediment removed from the major river-valley corridor versus sediment removed by ravines still present along the valley walls for each of the three major channels in the Le Sueur River watershed. Sediment removed from the valley was probably removed through a combination of lateral erosion into bluffs and streambanks, erosion by ravines no longer present because they were consumed by lateral valley erosion, and vertical channel incision.

The amount of sediment excavated probably varied through time as the channel incised and the network expanded. Some studies of newly forming drainages have shown high rates of sediment evacuation early, diminishing through time (Parker, 1977; Hancock and Willgoose, 2002). Other studies have found the opposite, with lower rates of erosion initially, increasing until the drainage network was fully established (Hasbargen and Paola, 2000). The Le Sueur River is still very much in transition. It is in the early stages of channel incision and knickpoint migration, but in the latter stages of drainage development, particularly following anthropogenic alterations to the drainage network. Other fluctuations in the sediment load probably occurred during the well-documented mid-Holocene dry period, ca. 5–8 ka B.P. (Grimm, 1983; Webb et al., 1984; Baker et al., 1992; Webb et al., 1993; Geiss et al., 2003), which intermittently slowed sediment contributions from the Minnesota River to Lake Pepin (Kelley

TABLE 3. MASS EXCAVATION FROM VALLEYS AND RAVINES

	Valley excavation (minimum estimate)		Valley excavation (maximum estimate)		Ravine excavation	
	Mass (Mg)	Flux* (Mg yr^{-1})	Mass (Mg)	Flux* (Mg yr^{-1})	Mass (Mg)	Flux* (Mg yr^{-1})
Maple	2.6×10^8	2.3×10^4	6.4×10^8	5.6×10^4	4.0×10^7	3.5×10^3
Cobb	1.6×10^8	1.4×10^4	4.3×10^8	3.7×10^4	4.2×10^7	3.7×10^3
Le Sueur	5.9×10^8	5.2×10^4	1.3×10^9	1.2×10^5	1.4×10^8	1.2×10^4
Total	1.0×10^9	8.8×10^4	2.4×10^9	2.1×10^5	2.2×10^8	1.9×10^4

*Fluxes are average rates over the past 11,500 yr.

at al., 2006). Averaging over all of the variability during the last 11,500 yr results in the average sediment export from the incised portion of the Le Sueur River Valley and ravines as 1.1–2.3 × 10^5 Mg yr^{-1}, equivalent to a suspended load (silt and clay fractions only) of 0.7–1.5 × 10^5 Mg yr^{-1}. The average annual suspended sediment load was probably higher, given the contribution of fine sand to the suspended load during peak-flow events.

Modern sediment fluxes at the mouth of the Le Sueur River measured from 2000 to 2006 are listed in Table 1. The annual TSS flux for these seven years ranged from 0.86 to 5.8 × 10^5 Mg yr^{-1}, with an average of 2.9 × 10^5 Mg yr^{-1}. The inorganic fraction (66%–84% of TSS) was therefore ~1.9–2.4 × 10^5 Mg yr^{-1} on average from 2000 to 2006. These values are 1.3–3.4 times higher than the Holocene average rate, considering only silt and clay fractions.

Spatial variations in sediment loading become apparent when we compare the 2006 results from gauges positioned above and below the major knickpoints on two of the main branches (Table 4). On the Maple River the drainage area increases very little from the upper gauge to the lower gauge (a 13% increase), but the TSS load increases by a factor of 2.8. From the gauge on the Little Cobb River to the gauge farther downstream on the Big Cobb River, the drainage area increases by a factor of 2.2, but TSS increases by an order of magnitude. Processes on the uplands do not change markedly from the upper watershed to the lower watershed. The primary difference is that the lower watershed includes contributions from bluffs and ravines. If we assume that upland sediment yields do not change appreciably from upstream to downstream, we can use the yield at the upper basin as a measure of upland erosion. These yields are 9.8 Mg km^{-2} on the Maple and 11.2 Mg km^{-2} on the Big Cobb. Applying these yields to the drainage areas at the lower gauges, we end up with a mass of sediment that cannot be accounted for by upland erosion and get a measure of the potential importance of ravine and bluff erosion. On the Maple River the excess sediment amounts to 14,000 Mg or 61% of the total sediment load. On the Big Cobb the excess sediment is 25,000 Mg or 74% of the total sediment load. The role of bluff and ravine erosion compared with the total sediment budget in the Le Sueur River watershed is substantial and must be accounted for in the sediment budget.

To determine the relative importance of streambank erosion from lateral migration, we measured the potential volume of sediment that would be removed from lateral migration into high bluffs and terraces using average lateral migration rates from aerial photographs. Along the Le Sueur mainstem, channels moved an average of 0.2 m yr^{-1} between 1938 and 2003, with much of the movement concentrated on mobile bends. Given the current channel configuration and near bank elevations, this migration would lead to an average of 130 Mg river km^{-1} yr^{-1} of material entering the channel from lateral migration into terraces and high bluffs. If this rate is applied on all three mainstem rivers, the potential net sediment flux to the channel is ~4.4 × 10^4 Mg yr^{-1}, or 2.7 × 10^4 Mg yr^{-1} of silt and clay, should migration rates continue at the same pace.

DISCUSSION

The Le Sueur River currently has a very high suspended-sediment load. TSS loads measured on the Le Sueur River are an order of magnitude higher than current standards set by the MPCA (MPCA et al., 2007). Sedimentation records from Lake Pepin indicate that deposition rates are an order of magnitude higher than presettlement deposition rates (Engstrom et al., 2008), and by extrapolation we might assume that the Le Sueur River had an order of magnitude increase in erosion rates over presettlement background rates as well. However, when comparing sediment volumes removed in the Le Sueur River, averaged over the past 11,500 yr, with gauging records from 2000 to 2006 at the mouth of the Le Sueur River, the increase appears more modest: an increase of 1.3–3.4 times over the Holocene average background rate rather than a tenfold increase.

The major modern sources of sediment to the mainstem channels include ravines eroding through incision, elongation, and mass wasting; bluffs eroding through mass wasting as a result of fluvial undercutting and sapping; upland erosion on agricultural fields (particularly in spring prior to closure of the row-crop canopy); and streambank erosion above and beyond the volume involved in floodplain exchange. The Le Sueur River has been involved in two major changes to the landscape that have affected erosion from these sources: conversion of original prairie and forests to agriculture, and alterations to the basin hydrology that have increased overall peak flows (Novotny and Stefan, 2007).

Clearing and continued use of land for agriculture probably only affected erosion from upland sources directly. Changes in basin hydrology and climate, which led to higher discharges, could have increased erosion from streambanks and bluffs through channel widening and potentially higher rates of lateral channel migration. An increase in discharge in the large ravines could have increased erosion significantly. These landscape features have high channel and side slopes and are particularly sensitive

TABLE 4. TSS DATA FROM PAIRED GAUGES IN 2006*

	Maple		Cobb	
	Upper	Lower	Upper	Lower
Drainage area (km^2)	780	878	336	737
TSS[†] (Mg yr^{-1})	7.9 x 10^3	2.2 x 10^4	4.0 x 10^3	3.3 x 10^4
TSS[†] yield (Mg km^{-2})	9.9	25.4	11.8	45.4

*Data from MPCA (P. Baskfield, 2007, personal commun.), preliminary.
[†]TSS—total suspended solids.

portions of the landscape. In many cases, drainage-tile outlets empty directly into ravines, increasing peak flows dramatically. Observations from the field indicate that headcuts in ravines are highly active, particularly where ravine tips are eroding into glaciolacustrine sediments. Field observations during storm flows in ravines have found water running clear in low-intensity storms and very muddy in high-intensity storms, possibly indicating a threshold response in sediment flux from ravines, once overland flow is generated.

Paired gauges on the mainstem channels give us some insight into the relative importance of bluff and ravine erosion versus upland erosion. Gauges installed on the upper and lower Maple River and on the Big Cobb and Little Cobb Rivers provide a basis for estimating sediment contributions from bluff and ravine erosion. The upper gauge receives sediment primarily from upland fields, smaller tributaries and ditches, and streambank erosion into low terrace surfaces. The lower gauge contains additional sediment derived from ravines and erosion of high bluffs. The observed increase in TSS, above and beyond that expected from an increase in drainage area or discharge, indicates that bluffs and ravines are playing a significant role as sediment sources to the lower reaches. If the TSS yield from the watershed measured at the upper gauge is applied to the increase in watershed area above the lower gauge, the remaining TSS load provides an estimate of the contribution from ravines, banks, and bluffs. For the Maple and Cobb Rivers in 2006, 61%–74% of the sediment was potentially derived from these non-upland sources. Previous studies in the neighboring Blue Earth River have estimated that bank and bluff erosion alone account for 23%–56% of TSS load (Thoma et al., 2005) and 31%–44% according to Sekely et al. (2002). Ongoing work by S. Schottler and D. Engstrom (personal commun., 2008) indicates that >75% of the suspended sediment at the mouth of the Le Sueur River was derived from non-field sources, including ravines, bluffs, terraces, and stored floodplain sediments.

Assessments of stream-migration rates on the mainstem Le Sueur River, coupled with bank and floodplain elevations, indicate that stream migration on the three major branches of the Le Sueur River could potentially contribute 2.7×10^4 Mg yr^{-1} of suspended sediment as a net source to the channel not balanced by floodplain deposition. This volume is 11%–14% of the average TSS load at the mouth of the Le Sueur River. Because the channel is incised, and channel migration occurs into these high surfaces, not just into floodplains, a significant mass of sediment can be contributed to the channel above and beyond the amount deposited on the floodplain.

CONCLUSIONS

The Le Sueur River has a well-constrained geomorphic history that can be used to understand the current sediment dynamics of the system. A major knickpoint migrating through the Le Sueur River network divides the watershed into two main regions: above the knick zone, where the watershed is dominated by low-gradient agricultural uplands composed of glaciolacustrine and till deposits, and below the knick zone, where high bluffs and steep-sided ravines are added to the system. Gauging efforts indicate a significant rise in sediment load as rivers move through the lower reaches of the channel, below the knick zone, highlighting the importance of bluffs and ravines as sediment sources in the lower watershed. In addition, channel-migration studies indicate that streambank erosion from channel migration may contribute a significant volume of sediment to the overall TSS load that is not lost to floodplain deposition owing to the presence of high terraces and bluffs along the channel edge.

Sediment loads are high in the Le Sueur River, an order of magnitude higher than MPCA target values. Records from Lake Pepin indicate an order of magnitude increase in deposition, a rise that should be mirrored in the Le Sueur River, a major contributor of sediment to the Minnesota River and ultimately to Lake Pepin. However, calculations of sediment removed from the valley since base-level fall 11,500 yr B.P. indicate that modern sediment loads are only 1.3–3.4 times higher than the average load over the past 11,500 yr, even when grain-size variations and organic content are accounted for. This Holocene average rate assumes a linear progression of erosion through time, and the history of valley incision and erosion is more complicated than this. Efforts are ongoing to determine terrace ages in the lower Le Sueur River Valley to better constrain the history and evolution of incision and thus of sediment flux from the basin. Unraveling terrace histories will help resource management by better constraining presettlement sediment yields as well as by shedding light on the pattern and style of landscape evolution in an incising system.

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Lidar Quantification of Bank Erosion in Blue Earth County, Minnesota

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Sediment and phosphorus (P) transport from the Minnesota River Basin to Lake Pepin on the upper Mississippi River has garnered much attention in recent years. However, there is lack of data on the extent of sediment and P contributions from riverbanks vis-à-vis uplands and ravines. Using two light detection and ranging (lidar) data sets taken in 2005 and 2009, a study was undertaken to quantify sediment and associated P losses from riverbanks in Blue Earth County, Minnesota. Volume change in river valleys as a result of bank erosion amounted to 1.71 million m^3 over 4 yr. Volume change closely followed the trend: the Blue Earth River > the Minnesota River at the county's northern edge > the Le Sueur River > the Maple River > the Watonwan River > the Big Cobb River > Perch Creek > Little Cobb River. Using fine sediment content (silt + clay) and bulk density of 37 bank samples representing three parent materials, we estimate bank erosion contributions of 48 to 79% of the measured total suspended solids at the mouth of the Blue Earth and the Le Sueur rivers. Corresponding soluble P and total P contributions ranged from 0.13 to 0.20% and 40 to 49%, respectively. Although tall banks (>3 m high) accounted for 33% of the total length and 63% of the total area, they accounted for 75% of the volume change in river valleys. We conclude that multitemporal lidar data sets are useful in estimating bank erosion and associated P contributions over large scales, and for riverbanks that are not readily accessible for conventional surveying equipment.

Sediment and phosphorus are major causes of surface water impairment throughout the world. The presence of suspended sediments in rivers and lakes increases turbidity, which limits light penetration and plant growth for aquatic organisms. In addition, suspended sediments have also been shown to negatively impact aquatic organisms at multiple life stages (Newcombe and Jensen, 1996). Similarly, sediment-attached phosphorus has often been linked to eutrophication of water bodies, which can lead to fish kills. One such example of a fish kill occurred in Lake Pepin, a floodplain lake on the Mississippi River about 80 km southeast of St. Paul (Fig. 1), during the drought of 1988. Sediment-attached phosphorus is widely believed to be the cause of the fish kill.

The Minnesota River Basin (MRB; Fig. 1) has several major water bodies that are listed as impaired due to the presence of excess sediments. Monitoring studies by the Metropolitan Council Environmental Services from 1976 to 1992 have shown that the water quality of the Minnesota River is worse than that of the Mississippi and St. Croix rivers near the Twin Cities of St. Paul and Minneapolis, MN (Meyer and Schellhaass, 2002). United States Geological Survey monitoring studies have shown that sediment loads in the Minnesota River at Mankato are highly variable, ranging from 0.2 to 3.3 million Mg yr^{-1} from 1968 to 1992 (Payne, 1994). About 55% of these sediments and 46% of the water flow in the Minnesota River at Mankato originates from the Greater Blue Earth River Basin (GBERB; Fig. 1), a relatively flat area with 54% of the land having <2% slope and 93% of the land <6% slope.

The GBERB and MRB have been extensively tile drained with numerous surface and side inlets that allow the transport of surface sediments to ditches, and subsequently to streams and rivers (Thoma et al., 2005b; Ginting et al., 2000). There has been controversy on the extent of sediment contributions from agricultural fields compared to stream banks from the MRB. In 1994, Minnesota Pollution Control Agency (MPCA) suggested that bank erosion could not be >25% of the sediment

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Abbreviations: ASPRS, American Society of Photogrammetry and Remote Sensing; DEM, digital elevation model; ΔDEM, subtracted digital elevation models; GBERB, Greater Blue Earth River Basin; GPS, global positioning system; IDW, inverse distance weighted; IMU, inertial measurement unit; LD_{min}, minimum level of detection threshold; lidar, light detection and ranging; MnDOT, Minnesota Department of Transportation; MRB, Minnesota River Basin; OK, ordinary kriging; NN, natural neighbor; RMSE, root mean square error; RTK, real-time kinetic; TIN, triangulated irregular network; TSS, total suspended solids.

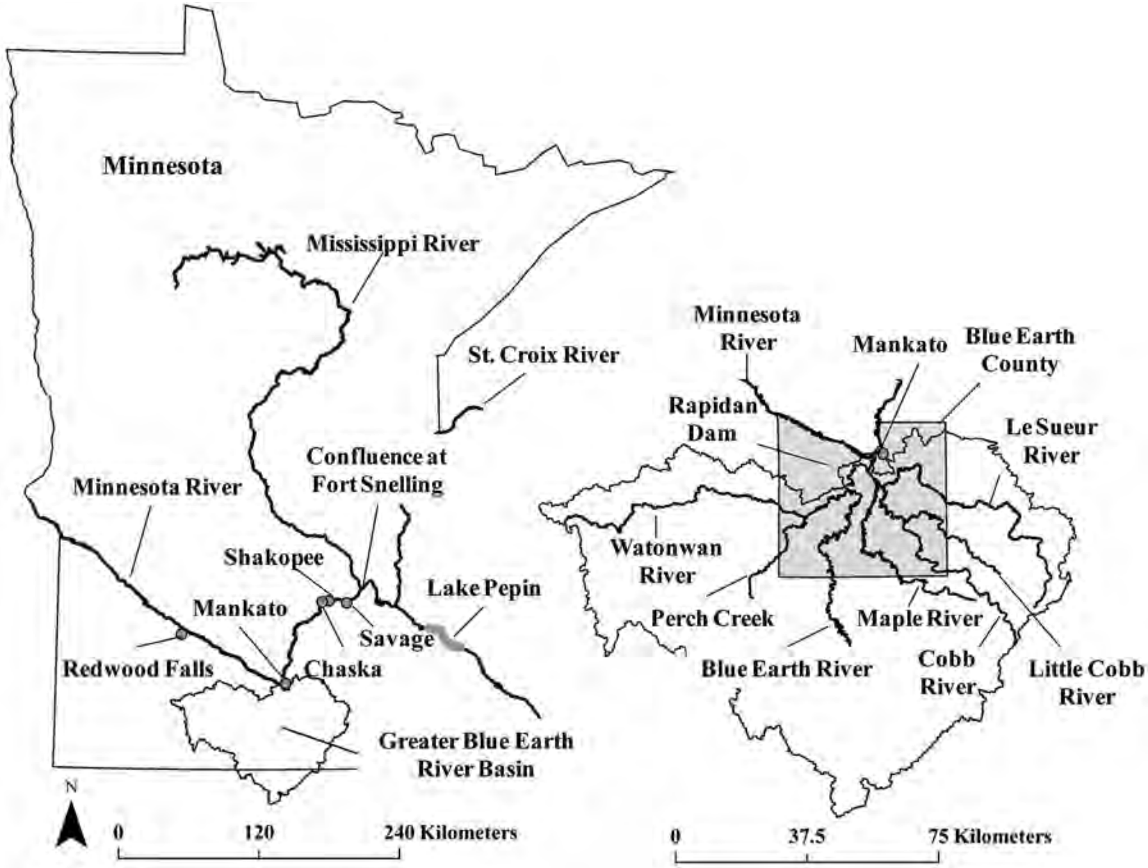

Fig. 1. A map of Minnesota showing the location of various rivers in Blue Earth County within the Greater Blue Earth River Basin.

load in the Minnesota River (MPCA, 1994). However, Payne (1994) showed that 39% of the sediment load in Redwood River between Seaforth and Redwood Falls, MN, originated from riverbanks over a 1-wk period. Using the rating curve for period without rainfall and the flow data for all periods, Gupta and Singh (1996) estimated that riverbank contributions in the Minnesota River at Mankato varied from 48 to 55% of the total sediment load for water years 1990–1992. These authors assumed that if there was no rainfall in the basin for 10 d (recession limb of the hydrograph) then most of the sediments in the river were from bank erosion. The major limitation of Gupta and Singh (1996) analysis is that it does not include catastrophic failures due to floods or seepage during or shortly after rainfall events. Their analysis only considers the sediment contribution due to fluvial erosion for a given flow level and thus significantly underestimates bank erosion.

By conducting ground surveys of seven banks using a total-station surveying instrument, Sekely et al. (2002) estimated that 36 to 48% of the sediments in the Blue Earth River originated from bank erosion. These authors used bank area as a surrogate variable to extrapolate their measurements on seven stream banks to the entire river. However, this analysis does not account for the variations in bank failure mechanisms through space and time (i.e., not every bank fails every year and the bank failure mechanism on a given bank is not the same every time). In other words, area of the bank has little to do with bank erosion/failure mechanisms and thus should not be used as a surrogate to extrapolate estimates from a few banks to the full length of the reach. This approach was recently adopted by Wilcox (2009) using the tall bank (bank with >3-m relief) erosion rates measured on the Le Sueur and the Maple rivers with ground-based light detection and ranging (lidar) and aerial photographs. However, using area as a surrogate variable to extrapolate along the entire length of a river channel has the same limitations as that of Sekely et al. (2002).

Using multitemporal airborne lidar scans over 56 km of the Blue Earth River, Thoma et al. (2005a) calculated that riverbank contributions from that portion of the river varied from 23 to 56% of the measured total suspended load between 2001 and 2002. The efforts by Thoma et al. (2005a) differed from others in that it characterized the full length of a reach, thus eliminating the need for extrapolation.

Recently, lidar data have become more widely available (Notebaert et al., 2009; Perroy et al., 2010). An airborne lidar scan is collected by sending thousands of laser pulses to the ground each second from a lidar instrument, typically attached to an aircraft, and recording the travel time for their returns. Normally, multiple returns are recorded for each laser pulse with the last being the ground. A global positioning system (GPS) and inertial measurement unit (IMU) record the aircraft's position and attitude (roll, pitch, and yaw), respectively. The combination of laser return times, GPS-derived position, and IMU information allows for the precise estimation of horizontal and vertical positions of objects on the ground. Laser returns from vegetation and other objects, such as buildings, can be removed from the data set to obtain ground positions for constructing a "bare earth" digital elevation model (DEM). Airborne lidar data of a river valley taken at two different times provide an estimate of the change in the volume of the valley as a result of bank erosion, sloughing, and accretion (Thoma et al., 2005a).

Typically, surveying companies assure their lidar data have root mean square errors (RMSE) less than 1 m horizontal and 0.15 m vertical positioning, conforming to the guidelines (Flood, 2004) set by the American Society of Photogrammetry and Remote Sensing (ASPRS). Data accuracy varies depending on aircraft elevation, aircraft speed, laser pulse rate, and laser footprint. Hodgson and Bresnahan (2004) presented an error budget model, along with detailed background information, that covers the potential sources of error in lidar data. In addition, several investigators have examined the accuracy and uncertainty of developing DEMs from elevation surveying data in fluvial systems (Bowen and Waltermire, 2002; Lane et al., 2003; Notebaert et al., 2009; Perroy et al., 2010; Wheaton et al., 2010). Bowen and Waltermire (2002) found that areas with large topographic relief tend to have lower vertical accuracy in steep riparian corridors, primarily due to horizontal positioning limitations (lower horizontal accuracy). This lower vertical accuracy in turn could lead to a higher degree of uncertainty in quantification of valley volume change in steep terrain. As such, a variety of methods have been adopted to account for uncertainty in DEMs (Wheaton et al., 2010). A minimum level of detection threshold (LD_{min}) is frequently applied to examine uncertainties between actual elevation changes and noise (Fuller et al., 2003). Values falling below the threshold level are generally discarded, while the values above the threshold are considered real. Threshold levels can be set based on the results of accuracy tests, such as those described in the guidelines outlined by the ASPRS (Flood, 2004).

In addition to errors from data collection and varying topography, the manner in which data are processed can also have a significant impact on the accuracy of DEMs derived from lidar data (Hodgson and Bresnahan, 2004). Several efforts have been made to identify the best spatial interpolation techniques for generating DEMs from lidar data (Lloyd and Atkinson, 2002; Bater and Coops, 2009; Guo et al., 2010). Liu (2008) has given a review on the limitations of several interpolation techniques such as inverse distance weighted (IDW), natural neighbor (NN), triangulated irregular network (TIN), spline, ordinary kriging (OK), and universal kriging for generating DEMs from lidar data. Generally, the results identifying the best spatial interpolation technique have been inconsistent, and often depend on the specific lidar data collection method, and how and where the data were applied. For instance, Guo et al. (2010) found IDW, NN, and TIN to be the most efficient methods for generating DEMs from lidar, but found kriging methods to provide the most accuracy. On the other hand, Bater and Coops (2009) found NN as the best spatial interpolation technique for generating lidar-derived DEMs. Studies have also shown that as lidar data density increases, the accuracy differences among spatial interpolation techniques for generating DEMs diminishes (Bater and Coops, 2009; Guo et al., 2010). Currently, no studies have been reported that quantify the effect of different interpolation techniques on lidar-based change detection calculation.

The objective of this study was to quantify sediment and associated phosphorus contributions from bank erosion/sloughing along several rivers in Blue Earth County using airborne lidar. Characterization of phosphorus contributions from bank erosion is included because of its impact on water quality of Lake Pepin on the Mississippi River. Blue Earth County was selected for this study because the lidar data from an earlier scan were available for this county and also the GBERB contributes over half of the sediment load to the Minnesota River at Mankato (Payne, 1994). In this paper, we also report the accuracy and uncertainties of using airborne lidar over steep terrains, examine how different spatial interpolation techniques affect lidar-based DEM change detection calculations of stream bank erosion, and explore the sensitivity of using limited soil characterization to estimate fine sediment and associated phosphorus contributions from bank erosion.

Materials and Methods

Study Area Description

The geological setting of Blue Earth County is well described by Bennett and Hurst (1907) and Wright (1972a,b). Gran et al. (2009) has provided more specific details on the geology of the Le Sueur River watershed. Briefly, the area was glaciated during the Wisconsin glaciations approximately 12,000 yr before present. The area predominately consists of fine-textured, carbonate-rich buff-colored glacial tills deposited by the Des Moines Lobe. In some places the till is as thick as 80 m. Due to compaction at the time of deposition, the bulk density of the till often exceeds 1.6 Mg m^{-3}. As the Des Moines Lobe retreated, Glacial Lake Minnesota occupied the region depositing up to 1 m of lacustrine sediment on top of the till. After glaciation and drainage of Glacial Lake Minnesota, river incision began. River bottoms commonly contain thin (<2 m) deposits of alluvium. The surface soils are black loam to fine clays with high organic matter content derived from prairie grasses native to the region. In most untilled soils, organic matter is generally concentrated in top 15-cm depth.

Blue Earth County, Minnesota, lies in the GBERB and contains many rivers that are deeply incised with steep and unstable banks. The county is relatively flat with 71 and 93% of the land <2% and <6% slopes, respectively. Blue Earth County also has the most rivers of any county in Minnesota. The major waterways include the Blue Earth, Le Sueur, Watonwan, Maple, Big Cobb, and Little Cobb rivers, and Perch Creek (Fig. 1). The Watonwan River and Perch Creek are tributaries of the Blue Earth River, whereas the Maple, Big Cobb, and Little Cobb rivers are tributaries of the Le Sueur River. The Le Sueur River converges into the Blue Earth River before it joins the Minnesota River at Mankato. For this study, 496 km of rivers including the Minnesota River at the northern edge of the county were investigated. Table 1 lists the length of each river analyzed in this study. These lengths are based on the centerline of the river channel. Some of the sloughing banks are as tall as 50 m (Fig. 2) and in some places the valley is as wide as 1.5 km. Lack of vegetation on the banks, exposed tree roots, accumulation of the fallen material at the toe, and presence of dead trees in the rivers are some of the indications of active bank sloughing along these rivers. Most of these rivers are lined with tall trees or shrubs, and access to these banks is primarily through the river with a canoe. Generally, the tall banks are

Table 1. River length and the length and area of tall (>3 m high) and short (<3 m high) banks for each river in this study in Blue Earth County, Minnesota. Sum of tall plus short bank lengths will be greater than the river length, as we are considering both sides of the river and river length corresponds to the center line of the river channel.

River	River length	Tall bank length	Tall bank area	Short bank length	Short bank area
	——— km ———		km^2	km	km^2
Blue Earth	103	100	2.14	125	0.82
Watonwan	41	29	0.60	56	0.33
Perch Creek	32	11	0.19	63	0.35
Le Sueur	71	69	1.00	77	0.38
Maple	80	49	0.79	110	0.38
Big Cobb	87	29	0.40	122	0.59
Little Cobb	32	8	0.13	44	0.24

sheer cliffs with slopes as high as 80 degrees (Fig. 2). Surveying these banks with conventional surveying equipment such as a total station is dangerous, laborious, time consuming, and for most practical purposes infeasible. Remote sensing techniques, such as lidar, provide a unique tool to quantify bank sloughing/erosion safely and quickly.

Lidar Data

With the exception that the calculations were done with a geographic information system software, the procedures used to calculate volume change from two lidar data sets were similar to those of Thoma et al. (2005a). The data processing utilized three data products (bare earth points, hydrologic breaklines, and 0.6-m contours) derived from the lidar data sets and delivered by the data vendors. The following text briefly describes the features of the two lidar data sets used in this study.

2005 Lidar Data Set

The first lidar data set was obtained by Optimal Geomatic, Inc., Huntsville, AL, with an Optech (Toronto, ON, Canada) ALTM 3100 lidar system flown at 1836 m above ground using a laser pulse rate of 70 kHz. The data were collected during four flights over two collection periods, 13–14 Apr. 2005 and 23–24 Apr. 2005, with a footprint of 0.45 m and an average of 1 data point m^{-2} during leaf-off conditions. Raw lidar data were processed by the vendor using proprietary software to produce bare earth points, hydrologic breaklines, and 0.6-m contours. The accuracy of their data was checked by the Minnesota Department of Transportation (MnDOT) using ground truth data with a total of 351 points collected with real-time kinetic (RTK) GPS over a variety of land covers. Points included 204 open terrain, 41 tall weeds and crops, 13 brush lands and low tree, and 93 urban areas. The reported fundamental vertical accuracy was ±0.24 m. Fundamental vertical accuracy is calculated as $RMSE_{(z)} \times 1.96$ and refers to the confidence interval at 95% significance (Flood, 2004).

Fig. 2. A steep tall bank actively sloughing along the Le Sueur River in Blue Earth County, Minnesota. Accumulated material at the toe is from past bank sloughing from above. Lack of vegetation on part of the bank indicates active sloughing nature of this bank.

2009 Lidar Data Set

The second lidar data set was obtained by Aero-Metric, Inc., Sheboygan, WI, using an Optech (Toronto, ON, Canada) ALTM Gemini system flown at 1200 m above ground with a laser pulse rate of 45 kHz. Data were collected on 28 Apr. 2009 and 2–3 May 2009 during leaf-off conditions with a 0.9-m footprint and average of 1.25 data points m^{-2}. Raw lidar data were processed by the vendor using proprietary software and included the generation of bare earth points, hydrologic breaklines, and 0.6-m contours. The vendor also collected ground elevation data for 106 points using static and RTK GPS techniques for an accuracy assessment over a variety of land covers. Points included 26 hard surfaces (roads, parking lots, etc.), 20 shortgrasses, 20 tallgrasses/weeds, 20 brushes, and 20 woods. The fundamental vertical accuracy reported for this scan was ±0.17 m.

Lidar Data Processing

Volume Change and Mass Wasting Calculations

The vendor-generated bare earth points in both data sets were spatially interpolated to an Environmental Systems Research Institute (Redlands, CA) ArcGIS 9.3 terrain file of a common extent using the breaklines and contours as hard and soft control lines, respectively. Terrain files data structure provides an efficient way to manage large data sets of bare earth points, breaklines, and contours to create TINs. Due to the large lidar data sets, terrain files were selected as a balance between processing efficiency and accuracy. Next, each terrain file was converted to a DEM grid with a 0.76-m spatial resolution (hereafter referred to as *user DEMs*). The above data processing resulted in county-wide bare earth user DEMs with the same spatial alignment for both years of lidar data. In this study, we define riverbanks as the area between the breakline of the river and the top of the riverbank. The highest water mark indicated by the breaklines in the two scans was used to define the bottom of the bank. Since the lidar systems used in collecting the data for this study could not penetrate water surfaces, all areas below the high-water mark were eliminated from bank

Table 2. Mean fine sediment (silt + clay), bulk density, soluble P, and total P in samples representing various parent materials along riverbanks in Blue Earth County, Minnesota. Number within parentheses represents the number of samples.

Parent material	Silt + clay	Bulk density	Soluble P	Total P
	%	Mg m^{-3}	——— mg kg^{-1}	———
Till	56.3 (27)	1.82 (27)	0.46 (22)	408.8 (24)
Lacustrine	67.3 (5)	1.48 (5)	0.74 (5)	556.2 (5)
Alluvium	52.5 (5)	1.49 (4)	0.73 (3)	558.6 (5)

erosion calculations. The top of the bank was manually digitized using a combination of aerial imagery (2005 and 2009), hillshade models, and slope grids. Hillshade models and slope grids were calculated for both 2005 and 2009 using the user DEMs. The 2005 aerial imagery was collected in unison with the 2005 lidar data, while the 2009 aerial imagery was collected from 4 Apr. 2009 to 6 May 2009 by Blue Earth County. This riverbank identification procedure was performed for each river examined. The user DEMs were then subtracted from each other, creating a county-wide grid showing elevation change from 2005 to 2009.

The riverbanks in the county-wide elevation change grid were identified as the zones for net elevation change calculations. The net elevation change for each river was calculated from the subtracted DEMs (ΔDEM) for all riverbank zones using a summary zonal statistic in ArcGIS. This net elevation change for each river was then multiplied by the spatial extent (area) of the riverbank zones, resulting in a net volume change. Next, net volume change was multiplied with the mean bulk density of a given parent material (Table 2) to calculate mass wasting. These mass wasting values were in turn multiplied with fine content (silt + clay), soluble P, and total P concentrations (Table 2) to calculate fine sediment, soluble P, and total P losses as a result of bank erosion/sloughing.

In addition to the above calculations, further analysis was also undertaken to quantify the extent (volume basis) of soil loss from tall (>3-m relief) and short (<3-m relief) stream banks in Blue Earth County, Minnesota. This classification was chosen to be consistent with previous literature (Gran et al., 2009). Gran et al. (2009) defined tall banks as bluffs and short banks as stream banks. Bluffs in our and Gran et al. (2009) studies are not rock outcrop but glacial deposits, mainly tills. Tall banks were identified using a 10-m by 10-m moving window analysis in ArcGIS. Areas identified as tall banks were manually inspected to ensure the accuracy of the moving window classification. Remaining areas (<3-m relief) were considered short stream banks. Extent of volume loss (erosion) from tall and short stream banks was expressed as a percentage of the total volume change for each river.

Lidar Data Accuracy

Fundamental vertical accuracies in the lidar data outlined earlier were the results of accuracy analysis performed on the raw data provided by the vendor. In addition, we also conducted two accuracy analyses on the user DEMs. In the first accuracy analysis, 78 of the 2005 MnDOT hard surface points, collected with an RTK GPS unit, were compared against the corresponding points in the 2005 and 2009 user DEMs. This was done to ensure data accuracy in user DEMs across years. Bias in the elevation estimates for the 2005 and 2009 user DEMs were evaluated by comparing the mean vertical errors in the data sets using a paired *t* test with a null hypothesis that the vertical errors were equal to zero.

The second accuracy assessment involved testing the vertical accuracy of points on steep terrains. This was done because a large proportion of the volume change in our study area was on steep terrains (>10% slope). The procedure involved subtracting elevations of 124 points representing a variety of land covers on steep terrains between 2005 and 2009 user DEMs. The points were taken on areas with slopes ranging from 4 to 77% and included wooded (26 points), road (77 points), grass (6 points), tallgrass (9 points), and a restored bluff (6 points) land covers. These areas were stable and known to have zero elevation change between 2005 and 2009. Differences in elevation between the 2005 and 2009 user DEMs at the selected points were summarized as measurement errors in the lidar data. A paired *t* test was performed between the elevations of the 2005 user DEM and 2009 user DEM found at the 124 steep terrain points with the null hypothesis that the mean difference between their elevations was equal to zero.

Elevation Error Analysis

An additional uncertainty analysis was conducted to determine how various levels of elevation errors in steep terrain could have impacted the net volume change estimates in this study. A series of LD_{min} (0.00, 0.08, 0.15, 0.23, 0.3, 0.46, 0.61, and 0.91 m) were applied to the ΔDEM following methods similar to those developed by Fuller et al. (2003). At each interval, values beneath the minimum threshold (for both erosion and deposition) were removed from the ΔDEM. The net change in volume estimates were then recalculated at each interval for all rivers, and the results were compared to the original volume change to determine whether or not significant change in the volume occurred at various LD_{min}; a potential indicator of possible uncertainty on steep terrains.

Spatial Interpolation Error Analysis

A sensitivity analysis was conducted on one bank (Fig. 3) to see how various spatial interpolation techniques for generating DEMs from lidar data affect volume change estimates for riverbank erosion. The techniques tested were IDW (Bartier and Keller, 1996), OK (Cressie, 1990), NN (Sibson, 1981), regularized spline, and regularized spline with tension (Mitasova and Hofierka, 1993). For all techniques, the number of points used for each local approximation was 12. The IDW was run with 2, 4, and 6 exponent power options. These power options control the weight of the surrounding points on the interpolated value. Higher exponent values give less weight to points further away from the local interpreted value. The OK was applied with spherical, circular, exponential, Gaussian, and linear semivariogram models. Briefly, the procedure for this sensitivity anal sisinvolved first generating DEMs for both 2005 and 2009 lidar data sets for each spatial interpolation

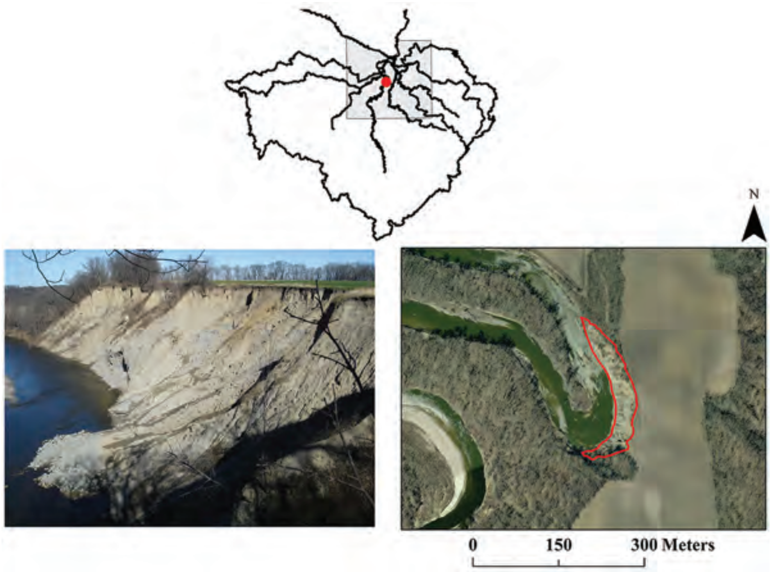

Fig. 3. Pictures of a bank in Blue Earth County, Minnesota, used in sensitivity analysis of volume change calculations with various spatial interpolation techniques in construction of digital elevation models.

technique using the bare earth point files provided by the vendors and then calculating the net volume change between 2005 and 2009 DEMs. Using summary statistics, the resulting volume change from various interpolation techniques was then compared to the volume change calculations from the terrain to raster technique used for the whole study area.

Fieldwork and Laboratory Analysis

For conversion of volume change estimates from lidar analysis to mass wasting and then fine sediment losses, 26 soil samples representing materials of various depths and origins were collected from the study area. Because of the difficulty of taking soil samples from tall sheer cliffs, samples were taken from accessible banks, fallen material at the toe of the riverbanks, and road cuts. During sampling of road cuts, efforts were made to sample areas representing mid- to upper depths of tall banks that are otherwise difficult to sample.

These samples were characterized for bulk density and particle size distribution using the clod method (Grossman and Reinsch, 2002) and the hydrometer method (Gee and Or, 2002), respectively. These samples were also analyzed for soluble P with water using a 1:10 ratio (Kuo, 1996) and total P via microwave acid digestion (USEPA, 1981). Soluble P and total P analysis was done by the Soil Testing Laboratory at the University of Minnesota. Since lacustrine and alluvium materials generally represent <2-m depth of the bank, their contributions to the total sediment loads from most tall banks will be minor. We combined our data on particle size analysis, bulk density, soluble P, and total P with the database from Thoma et al. (2005a). Table 2 lists the mean values of fine sediment (silt + clay), bulk density, soluble P, and total P in bank samples by parent material.

Sediment loads for the Blue Earth and Le Sueur rivers were obtained from the Water Resources Center at Minnesota State University, Mankato, MN (Scott Matheson, personal communication, 2010). These data represent the measurements at the USGS water gauging stations near the mouth of these rivers. The data for the Blue Earth River represented the contributions from the Blue Earth and Watonwan rivers plus Perch Creek, whereas the data for the Le Sueur River represented the contributions from the Le Sueur, Maple, Big Cobb, and Little Cobb rivers. Percent contributions of sediment, soluble P, and total P from riverbanks to river loads were calculated by dividing the fine sediment (silt + clay), soluble P, and total P loss estimates from the lidar calculations with the respective measured values of total suspended solids, soluble P, and total P loads at the gauging stations. We also report the estimated value of fine sediment, soluble P, and total P losses due to bank erosion from the Minnesota River touching the northern boundary of Blue Earth County.

Results and Discussion

Accuracy Assessment of Lidar

The fundamental vertical accuracy ($RMSE_{(z)} \times 1.96$) at 95% confidence interval for the 2005 and 2009 scans when tested against the 2005 MnDOT hard surface points corresponded to ±0.20 and ±0.14 m, respectively. The corresponding fundamental vertical accuracy between the 2005 and 2009 user DEMs was ±0.25 m. The 2005 user DEM underestimated the actual terrain elevation, based on the 2005 MnDOT hard surface points by 0.029 m ($P = 0.01$), whereas the 2009 user DEM overestimated the actual terrain elevation by 0.032 m ($P < 0.01$). The comparison of mean vertical error between the 2005 and 2009 user DEMs resulted in an average difference of 0.06 m ($P < 0.01$), with the 2009 user DEM producing higher elevation estimates than the 2005 user DEM. This average difference between user DEMs is less than the typical fundamental vertical accuracy (±0.15 m) that vendors guarantee in their processed lidar data.

The differences in elevation determined from 2005 and 2009 user DEMs for points of varying steepness in parks and roads of Blue Earth County, Minnesota, are shown in Fig. 4 as a function of percent slope. The average difference in elevation was −0.009 m with a minimum difference of −0.291 m and a maximum difference of 0.303 m. Except for a few outliers, difference in elevation between 2005 and 2009 user DEMs was about same (±0.2 m) irrespective of the slope. The differences in elevation between the two scans showed a fundamental vertical accuracy of ±0.19 m at a 95% confidence level; a value slightly higher than ±0.15-m fundamental vertical accuracy specification typically promised by lidar vendors for a single lidar data set.

Volume Change in River Valleys

Changes in the volume of river valleys as a result of bank erosion from 2005 to 2009 for several rivers in Blue Earth County, Minnesota, are shown in Fig. 5. The greatest volume change in the river valley occurred for the Blue Earth River followed by the Le Sueur River, the Maple River, the Watonwan River, the Big Cobb River, Perch Creek, and the Little Cobb River. This trend in volume loss follows the trends in tall bank area over the scanned rivers' kilometers (Table 1): the Blue Earth River > Le Sueur River > Maple River > Watonwan

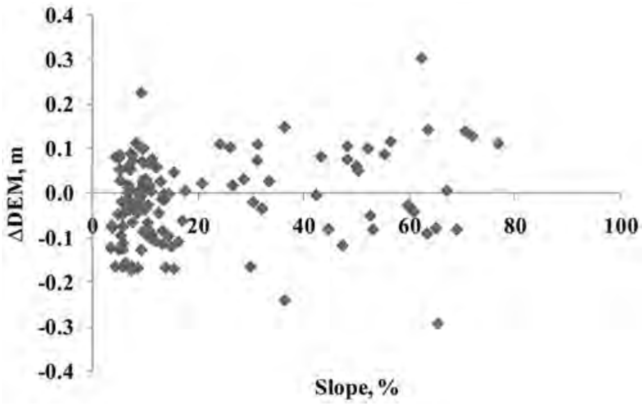

Fig. 4. Distribution of elevation difference between 2005 and 2009 user digital elevation models (DEMs) plotted as a function of slope for the 124 steep terrains points taken on various land covers in Blue Earth County, Minnesota. All of the points were stable locations known to have zero change in elevation between 2005 and 2009.

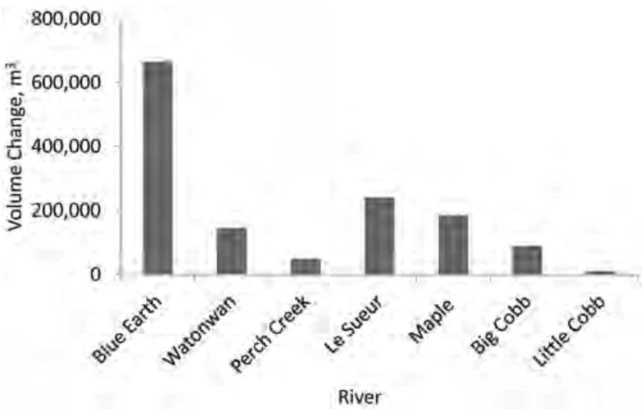

Fig. 5. Change in volume of river valleys as a result of bank erosion/sloughing from 2005 to 2009 for various rivers in Blue Earth County, Minnesota.

River > Big Cobb River > Perch Creek > Little Cobb River. Volume change estimates for the Maple, Big Cobb, and Little Cobb rivers are somewhat conservative because in some sections there were insufficient lidar data due to high water levels in the 2005 scan and thus these submerged banks were removed from the bank erosion calculations. Removal of submerged banks also implies that the lidar analysis in this study does not account for erosion losses from the riverbed. Volume change as a result of bank erosion/sloughing in tributaries of the Blue Earth and the Le Sueur rivers amounted to 1.39 million m^3 from 2005 to 2009. Corresponding volume change in the Minnesota River at the northern edge of Blue Earth County equaled 321,571 m^3 over 4 yr.

Contributions from Tall vs. Short Banks

Percent contributions to volume change estimates from tall (>3-m relief) and short (<3-m relief) banks for each river in Blue Earth County are shown in Fig. 6. When summed over all rivers, tall and short banks, respectively, contributed 75 and 25% of the calculated volume change from the lidar scans. However, the tall banks account for only 33% of the total length and 63% of the total area along all rivers investigated (Table 1). This further indicates that tall banks, while occupying a small portion of the river lengths in Blue Earth County, are the key producers of sediment in rivers of GBERB. Contributions from short (<3-m relief) banks may be conservative because during the analysis it was quite evident that point bars were forming from the deposition of suspended sediments on the inside of meanders. Although depositional point bars are likely composed of sediments from all sources (fields, ravines, and short and tall banks), this analysis discounted 100% of the point bar deposition from the areas defined as short banks.

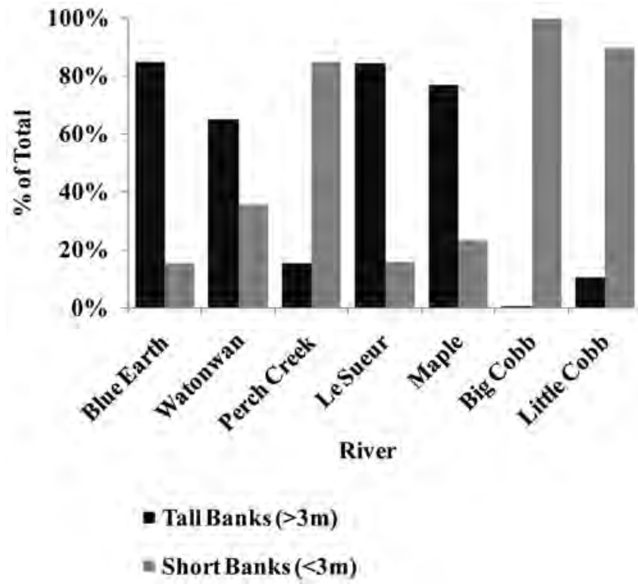

Fig. 6. Proportion of soil volume lost due to bank erosion from tall (>3 m high) and short (<3 m high) banks between 2005 and 2009 along various rivers in Blue Earth County, Minnesota.

LD_{min} Uncertainty Analysis

The results of the LD_{min} uncertainty analysis on net volume change from all riverbanks except along the Minnesota River at the northern edge of the county are shown in Fig. 7. These results show that at LD_{min} values < 0.46 m, the volume change slightly increases with an increase in LD_{min}. Comparatively, at LD_{min} values > 0.46 m there is a decrease in volume change with an increase in LD_{min}. These results are expected considering that a larger portion of small elevation changes are attributed to deposition and thus deletion of areas with small changes in elevation results in an increase in volume change. Conversely, a majority of large elevation changes are the result of erosion and thus deletion of areas with large elevation changes results in a decrease in volume change. Percent error in volume change corresponded to 0.25, 1.5, 3.3, 4.9, 5.4, 2.6, and −10% for LD_{min} values of 0.08, 0.15, 0.23, 0.30, 0.46, 0.61, and 0.91 m, respectively.

Overall, the results in Fig. 7 indicate that the removal of data within ±0.91 m has little impact on net volume change estimates for the rivers analyzed in this study. This suggests that the majority of sediments are derived from areas with large elevation changes (>0.91 m in ΔDEM). Comparing these results with the range of error values (−0.291 to 0.303 m) in the steep terrain accuracy assessment indicates that the range of error in steep terrain is below the threshold level that would have a significant impact on the net volume change calculations. This

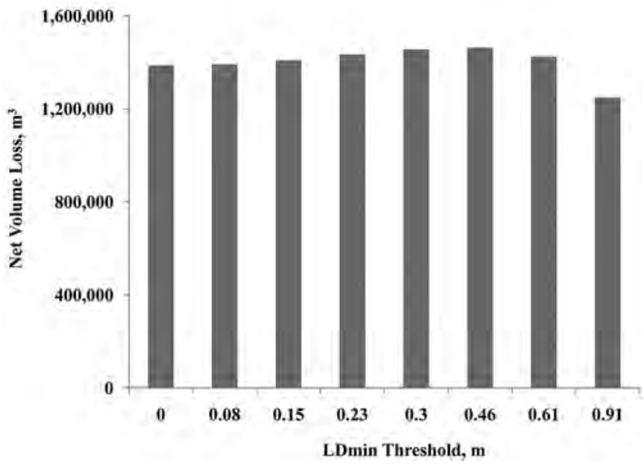

Fig. 7. Variation in net volume loss due to bank erosion from all rivers except along the Minnesota River at the northern edge of Blue Earth County, Minnesota, at various threshold levels of LD_{min} in the uncertainty analysis.

further increases the confidence in lidar quantification of sediment production as a result of mass failure of riverbanks.

Spatial Interpolation

The results of the spatial interpolation sensitivity analysis on one bank are given in Table 3. The volume loss calculations for all interpolation techniques varied between 10,933 and 13,143 m^3 with an average value of 11,719 m^3 and a standard error of 202 m^3. This is <2% standard error in volume calculations due to spatial interpolation. The calculation from the terrain to raster technique resulted in volume loss of 11,543 m^3, a value close to the average value for all the techniques. These results suggest that the terrain to raster technique used for this study performs similarly to other spatial interpolation techniques used in the literature. It is likely that the high data density provided by the lidar data sets in our study reduced the error between different spatial interpolation techniques, a result similar to the findings of other studies (Bater and Coops, 2009; Guo et al., 2010). For the purposes of this study, we concluded that terrain to raster was a suitable spatial interpolation technique for quantifying volume loss from riverbanks of Blue Earth County using lidar-derived DEMs.

During the review of the manuscript, a question was raised whether a 0.76-m spatial resolution might be too fine for lidar data that were collected with an average 1 point m^{-2}? In other words, some of the grid cell values may be derived wholly from interpolated values rather than data points. We hypothesize that if a 0.76-m cell size induced a significant error in our net volume calculations, we would have seen notable differences among the spatial interpolation techniques. Since the above analysis shows minimal differences between interpolation techniques, we concluded that 0.76 m is appropriate for this investigation.

Table 3. Sensitivity analysis of volume loss calculations for one bank using various techniques for interpolating lidar data to construct digital elevation models.

Spatial interpolation method	Volume loss	Difference from terrain to raster
	m^3	%
ArcGIS 9.3 Terrain to Raster	11,543	—
Inverse Distance Weighted, Exp. of 2	11,060	−4
Inverse Distance Weighted, Exp. of 4	11,240	−3
Inverse Distance Weighted, Exp. of 6	11,346	−2
Ordinary Kriging Circular	11,332	−2
Ordinary Kriging Exponential	11,941	3
Ordinary Kriging Gaussian	10,933	−5
Ordinary Kriging Linear	11,448	−1
Ordinary Kriging Spherical	11,448	−1
Natural Neighbor	12,539	9
Spline Regularized	13,143	14
Spline with Tension	12,656	10

Characteristics of Stream Bank Sediments

Using lidar data to estimate bank erosion and the contributions of sediment, soluble P, and total P from banks to river loads requires the conversion of volume change (Fig. 5) to mass-wasting-associated losses. For these conversions, representative values of bulk density, soluble P, and total P for bank materials are important. As previously mentioned, accurately characterizing riverbank materials in the entire study area, both spatially as well as with depth, was not practical. Since the riverbanks in Blue Earth County consist of varying materials, mass wasting and fine sediment losses were calculated by parent material. Table 2 lists the average bulk density and fine sediment of glacial till, glacial lacustrine, and alluvium samples collected along riverbanks in the county. This is based on the combined database both from this study and from Thoma et al. (2005a). As expected, the bulk density of the tills is much higher (1.82 Mg m^{-3}) than that of lacustrine (1.48 Mg m^{-3}) or alluvium (1.49 Mg m^{-3}) materials. This is primarily because tills generally occur at deeper depths buried under a large amount of overburden material including thick ice during the ice age. Fine sediment contents were generally higher in lacustrine soils (67.3%), followed by nearly equal amounts in tills (56.3%) and alluvium (52.5%) materials.

Mean fine sediment content for tills calculated in this study (56.3%) is slightly lower than the 65% value used by Gran et al. (2009) in their calculations for bank sediment contributions in the Le Sueur River Basin. Gran et al. (2009) had >300 samples in their database for particle size distribution and they applied the average value to much deeper depths when calculating geologic erosion over thousands of years. No literature values are available for bulk density, soluble P, and total P for bank materials in Blue Earth County to compare with our database. Gran et al. (2009) used bulk density value of 1.82 Mg m^{-3} from Thoma et al. (2005a). This bulk density value represents an average of 11 samples. The bulk density for tills in the combined database (Table 2) also equaled 1.82 Mg m^{-3}. We use this value in our calculations.

To address the issue of variation with soil depth, we also obtained particle size analysis at various depths for five coring sites in Blue Earth County from the Minnesota Geological Survey (Alan Knaeble and Gary Meyer, personal communication, 2011). Table 4 lists maximum depth of sampling, number of samples for silt + clay measurement, mean values of silt + clay to that depth, number of samples for bulk density measurement, and depth-weighted mean bulk density at each of the five coring sites. The maximum sampling depth of measurements varied from 12.5 to 51.6 m. Since silt + clay contents were measured on random samples, these values represent ordinary means. Comparatively, bulk density was measured on two representative samples for each depth section; thus, mean values were depth weighted. Averaged over all soil depths at five coring sites (N = 133), silt + clay content corresponded to 55.6%, a value close to the mean value of 56.3% in our database. We used these additional sources of data in our sensitivity analysis to provide a likely range of sediment, soluble, P, and total P contributions from riverbank sloughing to river loads.

Fine Sediment, Soluble Phosphorus, and Total Phosphorus Losses

Table 5 lists the estimated fine sediment, soluble P, and total P contributions from bank erosion from various rivers as a proportion of the measured values (Table 6) at the mouth of the Blue Earth River below Rapidan Dam, or at the mouth of the Le Sueur River before it joins the Blue Earth River. These values are calculated for various parent materials from volume change in Fig. 5 and the corresponding silt + clay, soluble P, and total P contents in Table 2. As stated earlier, contributions for the Blue Earth River, the Watonwan River, and Perch Creek are relative to USGS water gauge measurements for the Blue Earth River, whereas contributions for the Le Sueur, Maple, Big Cobb, and Little Cobb rivers are relative to the measurements for the Le Sueur River. As expected, fine sediment, soluble P, and total P contributions from bank erosion follow the trends of volume change for various river valleys (Fig. 5). The combination of higher density and lower fine content in tills, or lower density and higher fine content in lacustrine soils resulted in only small differences (<12%) in the total fine sediment losses for various parent materials in a given river system (Table 5). Fine sediment losses followed the trend: till > lacustrine > alluvium.

Depending on the parent material, combined fine sediment losses from the Blue Earth River, the Watonwan River, and Perch Creek within Blue Earth County varied from 48 to 63% of the total suspended solids (TSS) measurements at the mouth of the Blue Earth below Rapidan Dam. Similarly, combined fine sediment losses from the Le Sueur, Maple, Big Cobb, and Little Cobb rivers within Blue Earth County varied from 61 to 79% of the TSS measurements at the mouth of the Le Sueur River before it joins the Blue Earth River. Higher proportion of sediment losses from bank erosion in the Le Sueur River Basin relative to the Blue Earth River Basin are likely (i) due to greater length of the rivers analyzed in the Le Sueur River Basin (270 km) compared with the Blue Earth River Basin (176 km), and (ii) because the measured sediment loads at the mouth of the Le Sueur River were lower than at the mouth of the Blue Earth River over the study period (Table 6). Fine sediment contributions from the Minnesota River touching the northern edge of Blue Earth County corresponded to 82,380, 80,079, and 62,891 Mg yr^{-1} for the till, lacustrine, and alluvium parent materials, respectively.

Both soluble P and total P losses followed the trend: alluvium > lacustrine > till. Combined soluble P losses from the Blue Earth River, the Watonwan River, and Perch Creek varied from 0.16 to 0.20% of the measured value at the mouth of the Blue Earth River, whereas the corresponding total P losses ranged from 40 to 45% of the measured value. Depending on the parent material, combined soluble P losses from the Le Sueur River, the Maple River, the Big Cobb River, and the Little Cobb River varied from 0.13 to 0.17% of the measured value at the mouth of the Le Sueur River. Corresponding total P losses ranged from 44 to 49% of the measured values. Soluble P and total P losses for the Minnesota River at the northern edge of the county varied from 67.3 to 88.1 kg yr^{-1} and 59.8 to 66.9 Mg yr^{-1}, respectively.

Table 4. Mean and standard deviation of silt + clay content and bulk density of soil samples from various depths at five Minnesota Geological Survey coring sites in Blue Earth County, Minnesota. Mean silt + clay content represent ordinary means whereas mean bulk density refers to depth-weighted mean. N_1 is the number of samples for silt + clay content, whereas N_2 is number of samples times two replications for bulk density at each coring site.

Core	Max. depth	N_1	Silt + clay	N_2	Bulk density
	m		%		Mg m^{-3}
SC5	12.5	7	63.9 ± 24.5	20	1.94 ± 0.16
SC5A	27.2	18	46.3 ± 19.8	32	1.92 ± 0.20
SC6	82.2	32	52.3 ± 19.4	142	1.85 ± 0.14
SC7	67.2	44	66.3 ± 22.3	122	1.95 ± 0.14
SC8	51.6	32	47.5 ± 19.2	84	1.97 ± 0.15

Table 5. Fine sediment, soluble P, and total P losses as a percentage of the measured values at the mouth of the Blue Earth River (Blue Earth River, Watonwan River, and Perch Creek) or the Le Sueur River (Le Sueur River, Maple River, Big Cobb River, and Little Cobb River). The losses were estimated for each of the three parent materials using specific fine sediment content, bulk density, and soluble P and total P contents.

River	Sediment losses			Soluble P losses			Total P losses		
	Till	Lacustrine	Alluvium	Till	Lacustrine	Alluvium	Till	Lacustrine	Alluvium
	%								
Blue Earth	48.8	47.4	37.2	0.12	0.16	0.16	31.3	34.4	34.7
Watonwan	10.7	10.4	8.2	0.03	0.03	0.03	6.8	7.5	7.6
Perch Creek	3.6	3.5	2.7	0.01	0.01	0.01	2.3	2.5	2.5
Le Sueur	36.1	35.1	27.6	0.06	0.08	0.08	20.0	22.2	22.4
Maple	27.9	27.1	21.3	0.05	0.06	0.06	15.5	17.1	17.3
Big Cobb	13.6	13.2	10.4	0.02	0.03	0.03	7.5	8.3	8.4
Little Cobb	1.7	1.5	1.2	0.003	0.004	0.004	0.9	1.0	1.0

Table 6. Annual suspended solids, soluble P, and total P measured at the mouth of the Blue Earth and the Le Sueur rivers for the study period (2005–2009).

River	Sediment	Soluble P	Total P
	Mg yr^{-1}	kg yr^{-1}	Mg yr^{-1}
Blue Earth	216,145	191.1	166.2
Le Sueur	132,824	117.5	102.1

Because these rivers extend past Blue Earth County into the neighboring counties, it is likely that bank sloughing also occurred along these rivers in the neighboring counties. This would suggest that our estimates of volume change and, in turn, bank erosion are somewhat conservative. It is also likely that some of the sediments are settling in floodplains and not necessarily making it to the mouth of these rivers as well as to the confluence with the Minnesota River. The other sources of sediment in Blue Earth County are agricultural fields and near channel ravines. Although relatively flat, agricultural fields do contribute some sediment to rivers through surface and side inlets. The level of erosion in near-channel ravines and subsequent sediment transport to rivers has not been documented yet, and should be the focus of future studies.

Sensitivity Analysis of Fine Sediment, Soluble Phosphorus, and Total Phosphorus Losses

We also ran sensitivity analyses for sediment, soluble P, and total P contributions from bank sloughing using the estimate of fine sediment content (65%) and bulk density (1.82 Mg m^{-3}) from Gran et al. (2009) and mean fine sediment content and depth-weighted bulk density measurements on samples from five Minnesota Geological Survey soil coring sites (Table 4). We used our measurements of soluble P and total P (Table 2) for till in both these sensitivity runs.

Table 7 shows the comparison of sediment, soluble P, and total P contributions as a proportion of the measured values for three databases. Using values from Gran et al. (2009), estimates of fine sediment contributions to TSS loads corresponded to 73 and 92% of measured values at the mouth of the Blue Earth River and the Le Sueur River, respectively. Corresponding soluble P contributions from bank erosion for the two rivers equaled 0.18 and 0.16% of the measured values, and total P contributions at 44 and 49% of the measured values.

Using the mean silt + clay content and depth-weighted bulk densities for five Minnesota Geological Survey coring sites, contributions of fine sediment from bank erosion varied from 55 to 79% for the Blue Earth River and from 69 to 100% for the Le Sueur River. Corresponding contributions for soluble P and total P from riverbank sloughing varied from 0.16 to 0.17% and 41 to 43%, respectively, of the measured values for the Blue Earth River and 0.14 to 0.15% and 45 to 48%, respectively, of the measured values for the Le Sueur River. Using the till measurements, our estimates for sediment (63 and 79%), soluble P (0.16 and 0.13%), and total P (40 and 44%) contributions from riverbank erosion/sloughing at the mouth of the Blue Earth River and the Le Sueur River (Table 6) are within the range of values obtained with databases of Gran et al. (2009) or five coring sites of the Minnesota Geological Survey. This further suggests that the soil samples collected and analyzed in this study provide estimates of bank erosion contributions within the range of estimates calculated using soil characterization data from other investigations.

Conclusions

The results from this study show that bank erosion/sloughing is the primary source of sediments in rivers of Blue Earth County. As much as 1.71 million m^3 of soil sloughed from banks of rivers in the county from 2005 to 2009. Tall banks (>3 m high) accounted for 75% of the volume change in river valleys even though they represented only 33% of the total length and 63% of the total area. Conversion of lidar-measured volume change into mass wasting and then fine sediment loss suggests that as high as 63 and 79% of the measured TSS loads at the mouth of the Blue Earth River and the Le Sueur River, respectively, may be from riverbank erosion/sloughing. Sensitivity analysis with additional databases showed that the range of losses calculated in this study could

Table 7. Estimated bank sloughing contributions of sediment, soluble P, and total P to corresponding total loads at the mouth of the Blue Earth and the Le Sueur rivers for various values of silt + clay content and the bulk density in river banks. Silt + clay content for Minnesota Geological Survey (MGS) cores refer to ordinary mean, whereas the bulk densities are depth-weighted values over the length indicated in Table 4. Sediment, soluble P, and total P estimates reported for this study correspond to the till parent material.

Source	Silt + clay	Bulk density	River	Sediment	Soluble P	Total P
	%	Mg m^{-3}			%	
This study	58.8	1.82	Blue Earth	63.1	0.16	40.4
			Le Sueur	79.3	0.13	43.9
Gran et al., 2009	65.0	1.82	Blue Earth	72.8	0.18	44.4
			Le Sueur	91.5	0.16	48.6
MGS-SC5	63.9	1.94	Blue Earth	76.2	0.17	42.7
			Le Sueur	95.8	0.15	46.8
MGS-SC5A	46.3	1.92	Blue Earth	54.6	0.16	42.3
			Le Sueur	68.7	0.15	46.3
MGS-SC6	52.3	1.85	Blue Earth	59.4	0.16	40.7
			Le Sueur	74.7	0.14	44.6
MGS-SC7	66.3	1.95	Blue Earth	79.3	0.17	42.9
			Le Sueur	99.7	0.15	46.9
MGS-SC8	47.5	1.97	Blue Earth	57.5	0.17	43.4
			Le Sueur	72.3	0.15	47.5

be further refined with characterization of fine sediment content, bulk density, soluble P, and total P from additional bank sites in the basin. We conclude that multitemporal lidar scans are useful for estimating bank erosion over large scales and for riverbanks that are not readily accessible for conventional surveying equipment. This method has an advantage over empirical methods that use areas as a surrogate to extrapolate limited measurements to the full length of a river. An added advantage of this technique is in helping to identify banks that are a major source of sediments in a given river system.

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Evaluation of Light Penetration on Navigation Pools 8 and 13 of the Upper Mississippi River

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Preface

The Long Term Resource Monitoring Program (LTRMP) was authorized under the Water Resources Development Act of 1986 (Public Law 99–662) as an element of the U.S. Army Corps of Engineers' Environmental Management Program. The LTRMP is being implemented by the Upper Midwest Environmental Sciences Center, a U.S. Geological Survey science center, in cooperation with the five Upper Mississippi River System (UMRS) States of Illinois, Iowa, Minnesota, Missouri, and Wisconsin. The U.S. Army Corps of Engineers provides guidance and has overall Program responsibility. The mode of operation and respective roles of the agencies are outlined in a 1988 Memorandum of Agreement.

The UMRS encompasses the commercially navigable reaches of the Upper Mississippi River, as well as the Illinois River and navigable portions of the Kaskaskia, Black, St. Croix, and Minnesota Rivers. Congress has declared the UMRS to be both a nationally significant ecosystem and a nationally significant commercial navigation system. The mission of the LTRMP is to provide decision makers with information for maintaining the UMRS as a sustainable large river ecosystem given its multiuse character. The long-term goals of the Program are to understand the system, determine resource trends and effects, develop management alternatives, manage information, and develop useful products.

This report supports Task 2.2.3 as specified in Goal 2, Monitor Resource Change, of the LTRMP Operating Plan (U.S. Fish and Wildlife Service, 1993). This report was developed with funding provided by the LTRMP.

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Conversion Factors and Abbreviations

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L), and concentrations of turbidity are given in nephelometric turbidity units (NTU).

A nanometer (nm) is equal to 10^{-9} m (a billionth of a meter).

Abbreviations used in this report

LTRMP	Long Term Resource Monitoring Program
NTRU	nephelometric turbidity ratio units
NTU	nephelometric turbidity units
NVSS	nonvolatile suspended solids
PAR	photosynthetically active radiation
RM	river mile
R^2	coefficient of determination
SAV	submersed aquatic vegetation
TSS	total suspended solids
UMESC	Upper Midwest Environmental Sciences Center
UMRCC	Upper Mississippi River Conservation Committee
UMRS	Upper Mississippi River System
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VSS	volatile suspended solids

Evaluation of Light Penetration on Navigation Pools 8 and 13 of the Upper Mississippi River

By Shawn Giblin, Kraig Hoff, Jim Fischer, and Terry Dukerschein

Abstract

The availability of light can have a dramatic affect on macrophyte and phytoplankton abundance in virtually all aquatic ecosystems. The Long Term Resource Monitoring Program and other monitoring programs often measure factors that affect light extinction (nonvolatile suspended solids, volatile suspended solids, and chlorophyll) and correlates of light extinction (turbidity and Secchi depth), but rarely do they directly measure light extinction. Data on light extinction, Secchi depth, transparency tube, turbidity, total suspended solids, and volatile suspended solids were collected during summer 2003 on Pools 8 and 13 of the Upper Mississippi River. Regressions were developed to predict light extinction based upon Secchi depth, transparency tube, turbidity, and total suspended solids. Transparency tube, Secchi depth, and turbidity all showed strong relations with light extinction and can effectively predict light extinction. Total suspended solids did not show as strong a relation to light extinction. Volatile suspended solids had a greater affect on light extinction than nonvolatile suspended solids. The data were compared to recommended criteria established for light extinction, Secchi depth, total suspended solids, and turbidity by the Upper Mississippi River Conservation Committee to sustain submersed aquatic vegetation in the Upper Mississippi River. During the study period, the average condition in Pool 8 met or exceeded all of the criteria whereas the average condition in Pool 13 failed to meet any of the criteria. This report provides river managers with an effective tool to predict light extinction based upon readily available data.

Background

Solar radiation affects the productivity and metabolism of aquatic ecosystems (Wetzel, 2001). A large portion of the biological energy production in lakes and rivers is a result of energy derived from solar radiation used in photosynthesis. The extinction of light in aquatic ecosystems is a function of the properties of water, particles suspended in the water, and dissolved and colored compounds in the water. In unproductive systems dissolved compounds play an important role in light extinction. Turbidity and phytoplankton abundance play a larger role in light extinction in more productive aquatic systems (Wetzel, 2001). Light extinction can exhibit considerable spatial and temporal variation within a given system. Weather, season, water quality, biological activity, ice cover, snow cover, flow regime, and vegetation density all can affect the amount of light available for photosynthetic activity.

The availability of light can have a dramatic affect on macrophyte and phytoplankton abundance and distribution in virtually all aquatic ecosystems. In turn, the abundance of macrophytes can affect the amount of nursery habitat for fish, invertebrate abundance, and water quality (Korschgen and others, 1997; Janecek, 1988). *Vallisneria americana* Michx. is considered an important resource for waterfowl and fish within the Upper Mississippi River System (UMRS) (Korschgen and others, 1997). Periodic declines of *Vallisneria* within the UMRS have had a negative effect on ecosystem health (Kimber and others, 1995). Light availability is a major factor affecting *Vallisneria* abundance, growth, and reproduction on the UMRS (Kimber and others, 1995; Doyle, 2000; Kreiling and others, 2007). Recent emphasis on the effect of light regime on submersed aquatic vegetation (SAV) in the UMRS has prompted researchers and river managers to relate commonly available light-penetration indicators (e.g., turbidity, Secchi depth, and total suspended solids (TSS)) to light extinction (Upper Mississippi River Conservation Committee, 2003).

The purpose of this study was threefold: (1) to develop relations between frequently measured water-quality parameters and light extinction, (2) to gage how tributary water quality affects light extinction in the UMRS, and (3) to determine what fraction of the suspended load, volatile versus nonvolatile, contributes more to light extinction in the river. Monitoring programs, including the Long Term Resource Monitoring Program (LTRMP), often measure factors that affect light extinction (nonvolatile suspended solids, volatile suspended solids, and chlorophyll) and other correlates of light extinction (turbidity and Secchi depth), but rarely do they directly measure light extinction. Developing relations between water-quality parameters and light extinction will provide river managers with additional tools to identify problems within the system.

Methods

In Pool 8 of the Upper Mississippi River, five transects consisting of three sites each were established on the main channel. The Black River, La Crosse River, Root River, and Coon Creek each were sampled at one location to monitor the tributaries to Pool 8. Transects were established at Minnesota Island (River Mile (RM) 701.1), Riverside Park immediately downstream of the La Crosse River (RM 698), immediately downstream of the Root River (RM 693.5), Horseshoe Island (RM 687.8), and immediately upstream of Lock and Dam 8 at Genoa, Wisconsin (RM 679.5, fig. 1). In Pool 13, four transects consisting of three to five sites each were established on main- and side-channel sites. The Maquoketa River, Apple River, Plum River, and Elk River each were sampled at one location to monitor the tributaries to Pool 13. The transect locations for Pool 13 were directly downstream of each tributary at RM 548.5, 545.1, 536.6, and 528.3 (fig. 2). All transects were perpendicular to the main channel. Transects were selected to measure the effect of tributaries and to detect whether lateral or longitudinal light gradients exist within the pools. Sites were sampled weekly from May 6 to July 16, 2003.

Data were collected at every site for turbidity, Secchi depth, transparency tube, and underwater photosynthetically active radiation (400 to 700 nm). Turbidity and Secchi depth information was obtained using standard LTRMP protocols (Soballe and Fischer, 2004). Turbidity was analyzed with a Hach 2100P turbidimeter (Hach Company, 1995) and reported in nephelometric turbidity units (NTU). The 2100P uses a tungsten-filament lamp light source, 90-degree detection angle, and multiple detectors with ratio compensation. The 2100P does not have the option of turning the ratio compensation off. With ratio compensation on, the instrument's microprocessor calculates a ratio of signals from each detector. For this reason, 2100P values are sometimes reported as nephelometric turbidity ratio units (NTRU). However, turbidity values are expressed as NTU for this report. The Hach 2100P was checked daily with low, medium, and high NTU Gelex Secondary Standards. The Hach 2100P turbidimeter was calibrated quarterly using Hach StablCal Stabilized Formazin Turbidity Standards.

The transparency tube was a clear, plastic tube 120 cm long marked in 1-cm increments with a small Secchi pattern painted on the bottom. Water was collected from 0.20 m below the surface and poured into the tube until the pattern disappeared. Readings were taken in the shade and recorded to the nearest centimeter (U.S. Environmental Protection Agency, 2006).

Samples for TSS and volatile suspended solids (VSS) were collected at one site per transect per sampling episode and at all tributaries according to LTRMP standard procedures (Soballe and Fischer, 2004). Suspended solids were determined gravimetrically following standard methods (Greenburg and others, 1992). TSS and VSS laboratory analysis was done at the U.S. Geological Survey Upper Midwest Environmental Sciences Center (UMESC) Water Quality Laboratory in La Crosse, Wisconsin. Nonvolatile suspended solid (NVSS) values were calculated by subtracting VSS from TSS.

Photosynthetically active radiation (PAR) was measured in micromoles s^{-1} m^{-2} using two LI-192SA Underwater Quantum Light Sensors and an LI-1000 datalogger (LI-COR, Inc., 2006). Calibration was done before and after sampling by holding the sensors side by side outdoors and recording three 10-second averages. A correction factor was applied to one cell to ensure both cells yielded the same response under identical light exposure. All underwater-light measurements were done between 1000 and 1500 hours. Both sensors were placed on a single pole and were positioned 90 degrees apart. The sensors were deployed over the side of the boat or from shore so that the upper sensor was approximately 0.25 m below the water surface and the lower sensor was 0.75 m below the water surface. The lower sensor was placed at 0.5 m in La Crosse River and Coon Creek when depth was insufficient. Sensors were held as close to horizontal as possible and placed to avoid shadows. The sensors were allowed to stabilize for 20 to 30 seconds and three 10-second readings were recorded for each site and later averaged. Light-extinction coefficient was calculated as

$$k = [\ln(Io)- \ln(Iz)]/z,$$

where

k	is light-extinction coefficient (1/m),
Io	is surface or upper light measurement,
Iz	is light measurement at depth z, and
z	is depth interval between Io and Iz.

The depth of 1 percent of surface light ($z_{I1\%}$) was calculated as

$$(z_{I1\%}) = \ln(100)/k.$$

Results and Discussion

Conditions During the Study Period

In 2003, discharge at Dam 8 was slightly above the recent average for May and July and slightly below average for June (table 1). Discharge at Dam 13 was slightly above average for May, below average for June, and near average for July (table 1). Based on LTRMP data for 1994–2002, main channel turbidity and TSS in 2003 were near average for Pool 8 and above average for Pool 13 (table 2). Substantial differences in water quality between Pools 8 and 13 (table 2) translated into differences in light-extinction measurements between the pools (table 3).

Figure 1. Navigation Pool 8 of the Upper Mississippi River. (Location of sampling sites for the light penetration study in red.)

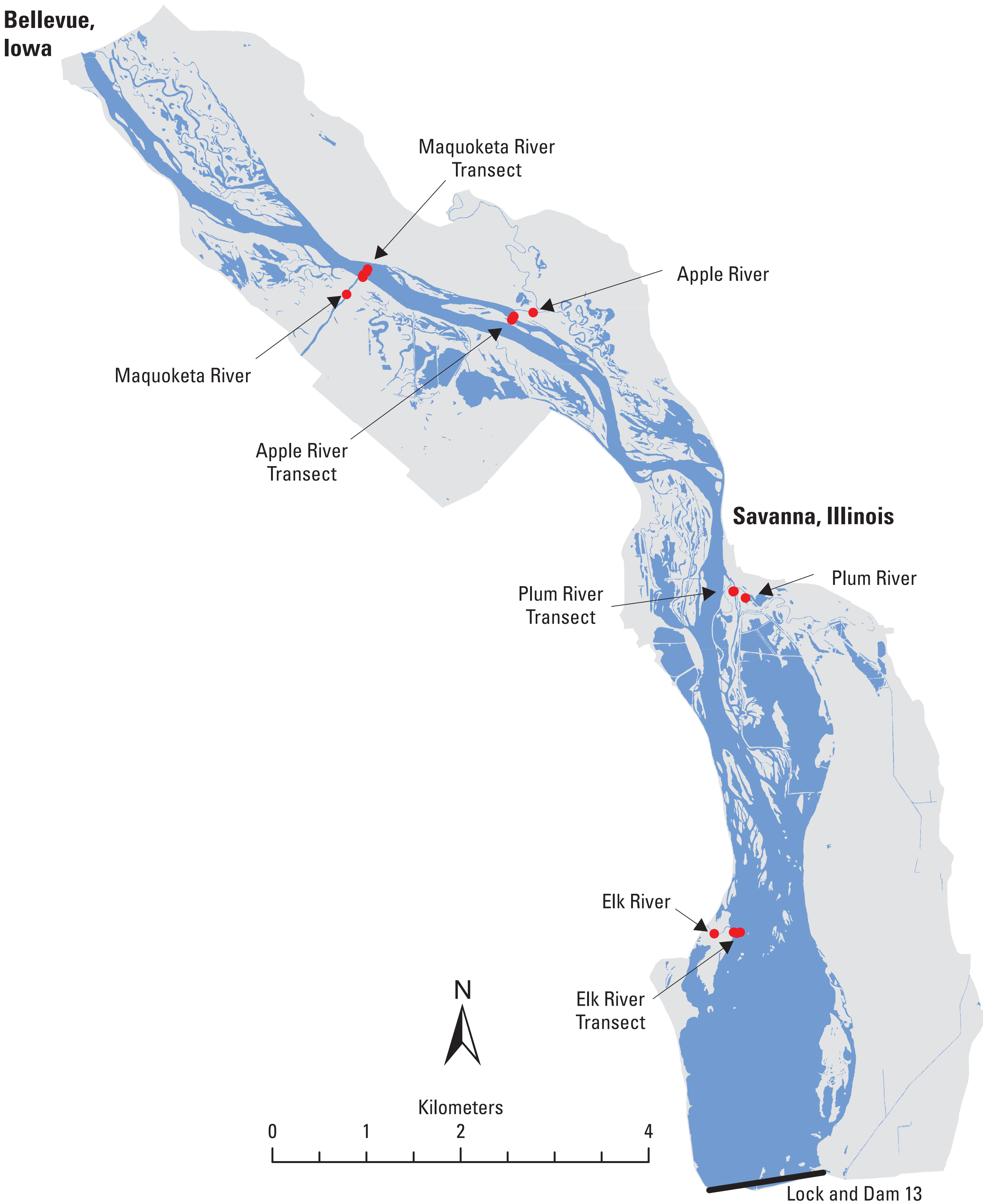

Figure 2. Navigation Pool 13 of the Upper Mississippi River. (Location of sampling sites for the light penetration study in red.)

Table 1. Average discharge for Dams 8 and 13 for 2003 compared to recent averages based on U.S. Army Corps of Engineers data.

[Data are reported in cubic feet per second]

Time period	Dam 8		Dam 13	
	1983–2002	2003	1986–2002	2003
May 6–May 31	64,922	81,392	89,732	109,986
June	52,603	46,743	75,614	60,828
July 1–July 16	55,273	62,650	76,098	76,366

Table 2. Average total suspended solids and turbidity for the study period compared to 1994–2002. The average for 1994–2002 is from Long Term Resource Monitoring Program sampling in the main channel during late July and early August of each year.

[TSS, total suspended solids; mg/L, milligrams per liter; NTU, nephelometric turbidity units]

Location and parameter	1994–2002 average	2003 study average
Pool 8 TSS (mg/L)	21.1	23.4
Pool 8 turbidity (NTU)	15.1	14.9
Pool 13 TSS (mg/L)	35.1	56.3
Pool 13 turbidity (NTU)	25.7	37.2

Table 3. Summary of average water-quality and light-extinction variables for 2003.

[cm, centimeter; NTU, nephelometric turbidity units; TSS, total suspended solids; mg/L, milligrams per liter; VSS, volatile suspended solids; m, meter]

Measurement	Pool 8	Pool 8 tributaries	Pool 13	Pool 13 tributaries
Secchi depth (cm)	64.10	57.79	36.44	40.67
Transparency tube (cm)	42.88	38.33	22.48	26.53
Turbidity (NTU)	14.89	22.83	37.22	27.11
TSS (mg/L)	23.42	49.75	56.26	32.13
VSS (mg/L)	5.82	8.74	11.41	7.31
Light extinction coefficient (m^{-1})	2.85	3.50	4.84	3.65
1 percent of surface light (m)	1.66	1.51	1.02	1.44

Historical Comparisons

Light-extinction data collected by the Wisconsin Department of Natural Resources at Lock and Dams 8 and 9 for 1988–98, that did not account for surface reflection, yielded an average light-extinction coefficient of 4.21 m^{-1} (J. Sullivan, unpub. data, 2007). Sullivan also collected data from Lock and Dams 8 and 9 during 2003–06 that yielded average light-extinction coefficients of 2.79 and 2.84 m^{-1}, respectively. An evaluation of light extinction in Pool 8 during 1983–84 yielded an average light-extinction coefficient of 4.08 m^{-1} (Korschgen and others, 1997). Another evaluation of light extinction (not accounting for surface reflection), conducted on Lake Onalaska in Pool 7 during the summer of 1990, showed an average light-extinction coefficient of 4.64 m^{-1} (Kimber and others, 1995). Examination of the data indicated increased light penetration in the UMRS in recent years. LTRMP data show that average concentrations of suspended solids in Pool 8 decreased appreciably during 1994–2002 (Johnson and Hagerty, 2008).

Comparisons of Water-Quality Parameters to Light Extinction

The small amount of light-extinction data available for the Upper Mississippi River have motivated researchers to develop regression models to predict light extinction based upon commonly collected water-quality parameters. In the majority of the regression analyses we conducted, nonlinear regression achieved higher R^2 values than linear regression. Data from Pool 8, Pool 13, and selected tributaries were combined to predict light extinction from TSS, transparency tube, turbidity, and Secchi depth (table 4). Data also were analyzed only from sites where all variables were measured to determine which of the four variables showed the highest proportion of variability in light extinction. Turbidity explained the highest proportion of variability among the four variables, whereas TSS explained the least proportion of variability (table 4). Data from Pools 8 and 13 also were segregated by pool and into tributary and main channel groups to compare regressions (table 5). These analyses revealed a greater correlation for the main channel sites than the tributary sites when data from both pools were combined.

Table 4. Regression between light-extinction coefficient (m^{-1}) (dependent variable) and water-quality parameters (independent variable). Data are combined for Pool 8 and tributaries and Pool 13 and tributaries.

[N, number of measurements; R^2, coefficient of determination; TSS, total suspended solids; mg/L, milligrams per liter; cm, centimeter; NTU, nephelometric turbidity units]

Independent variable	N	Equation	R^2
TSS (mg/L)	157	$y= 0.794x^{0.4241}$	0.676
Transparency tube (cm)	360	$y= 45.85x^{-0.7502}$	.823
Turbidity (NTU)	360	$y= 0.6973x^{0.5336}$	.822
Secchi depth (cm)	370	$y= 72.84x^{-0.7849}$	.788
Transparency tube (cm)[a]	157	$y= 42.95x^{-0.7375}$	.752
Turbidity (NTU)[a]	157	$y= 0.7152x^{0.5163}$	.769
Secchi depth (cm)[a]	157	$y= 63.44x^{-0.7557}$	.720

[a] Only sites with TSS data are included.

Table 5. Regression between light-extinction coefficient (m^{-1}) (dependent variable) and water-quality parameters (independent variable). Data are segregated for Pool 8 and Pool 13 tributary and main channel.

[R^2, coefficient of determination; TSS, total suspended solids; mg/L, milligrams per liter; cm, centimeter; NTU, nephelometric turbidity units]

Independent variable	Equation	R^2
Pool 8 and 13 tributaries TSS (mg/L)	$y= 0.9954x^{0.3524}$	0.564
Pool 8 and 13 main channel TSS (mg/L)	$y= 0.5149x^{0.5534}$	.879
Pool 8 with tributaries TSS (mg/L)	$y= 1.0444x^{0.3197}$	.620
Pool 13 with tributaries TSS (mg/L)	$y= 0.6023x^{0.5231}$	.786
Pool 8 main channel TSS (mg/L)	$y= 0.9512x^{0.3491}$	.629
Pool 13 main and side channel TSS (mg/L)	$y= 0.4402x^{0.5989}$	.804
Pool 8 and 13 tributaries transparency tube (cm)	$y= 43.811x^{-0.7567}$	.643
Pool 8 and 13 main channel transparency tube (cm)	$y= 46.157x^{-0.7471}$	.893
Pool 8 with tributaries transparency tube (cm)	$y= 49.425x^{-0.765}$	.701
Pool 13 with tributaries transparency tube (cm)	$y= 63.275x^{-0.8602}$	.758
Pool 8 main channel transparency tube (cm)	$y= 29.345x^{-0.6267}$	.515
Pool 13 main and side channel transparency tube (cm)	$y= 50.488x^{-0.7757}$	.846
Pool 8 and 13 tributaries turbidity (NTU)	$y= 0.762x^{0.4855}$	.653
Pool 8 and 13 main channel turbidity (NTU)	$y= 0.6821x^{0.5456}$	.888
Pool 8 with tributaries turbidity (NTU)	$y= 0.8085x^{0.4742}$	.674
Pool 13 with tributaries turbidity (NTU)	$y= 0.7096x^{0.5325}$	.765
Pool 8 main channel turbidity (NTU)	$y= 0.812x^{0.4713}$	.571
Pool 13 main and side channel turbidity (NTU)	$y= 0.8579x^{0.4862}$	.831
Pool 8 and 13 tributaries Secchi depth (cm)	$y= 55.799x^{-0.7358}$	.587
Pool 8 and 13 main channel Secchi depth (cm)	$y= 78.21x^{-0.7984}$	.867
Pool 8 with tributaries Secchi depth (cm)	$y= 117.49x^{-0.8985}$	.721
Pool 13 with tributaries Secchi depth (cm)	$y= 69.37x^{-0.7735}$	.653
Pool 8 main channel Secchi depth (cm)	$y= 64.626x^{-0.7561}$	.560
Pool 13 main and side channel Secchi depth (cm)	$y= 59.305x^{-0.7162}$	.750

Regressions also were developed relating light-extinction coefficient to TSS, transparency tube, turbidity, and Secchi depth data for each pool, including tributaries (table 5; figs. 3–6). The regressions for transparency tube, turbidity, and Secchi depth versus light extinction for Pools 8 and 13 were strong and similar during the study period. The regression for TSS versus light extinction, however, revealed substantial differences between Pools 8 and 13 when the tributaries were included. In addition, regressions were developed among all water-quality variables to estimate what the value of the dependent variable would be based on an independent variable value (e.g. estimated TSS based upon known turbidity; table 6). The regressions for TSS versus transparency tube and Secchi depth were weaker than the other regressions.

Comparison of various relations can reveal the value in predicting real-time environmental conditions within the river. Cole (1979) found that multiplying the Secchi depth by 2.7 to 3.0 provides a good estimate of the depth at which 1 percent of surface light penetrates (compensation point), delimiting the lower depth of the photic zone. A factor of 2.66 was derived using the data collected during this study (fig. 7). A similar relation was developed for transparency tube readings (fig. 8). In this case, a factor of 4.03 times the transparency tube reading provided an estimate of the compensation point. Nonlinear regression revealed an even stronger correlation for both of these relations. The equation for 1 percent of surface light versus Secchi depth is

$$(y = 2.3484x^{0.7849},\ r^2 = 0.788).$$

The equation for 1 percent of surface light versus transparency tube is

$$(y = 3.1788x^{0.7502},\ r^2 = 0.823).$$

Comparison of Results to Proposed Water-Quality Criteria

The Water Quality Section of the Upper Mississippi River Conservation Committee (UMRCC) has proposed water-quality criteria to sustain submersed aquatic vegetation in the UMRS (Upper Mississippi River Conservation Committee, 2003; table 7). During the study period the average condition in Pool 8 met all the criteria, whereas the average condition in Pool 13 failed to meet any of the criteria (table 7). Using regressions from table 4, the value at which each of the water-quality parameters met the UMRCC recommended light-extinction coefficient of 3.42 m^{-1} was 49.2 cm for Secchi depth, 31.3 milligrams per liter (mg/L) for TSS, 19.7 NTU for turbidity, and 31.8 cm for transparency tube. This indicates that the recommended TSS criteria of 25 mg/L may be too low, and a value nearer 30 mg/L may be more appropriate. The UMRCC light criteria did not include transparency tube data as a potential metric. Using regression data from table 4, a transparency tube measurement of roughly 32 cm corresponds to the recommended light-extinction coefficient of 3.42 m^{-1}.

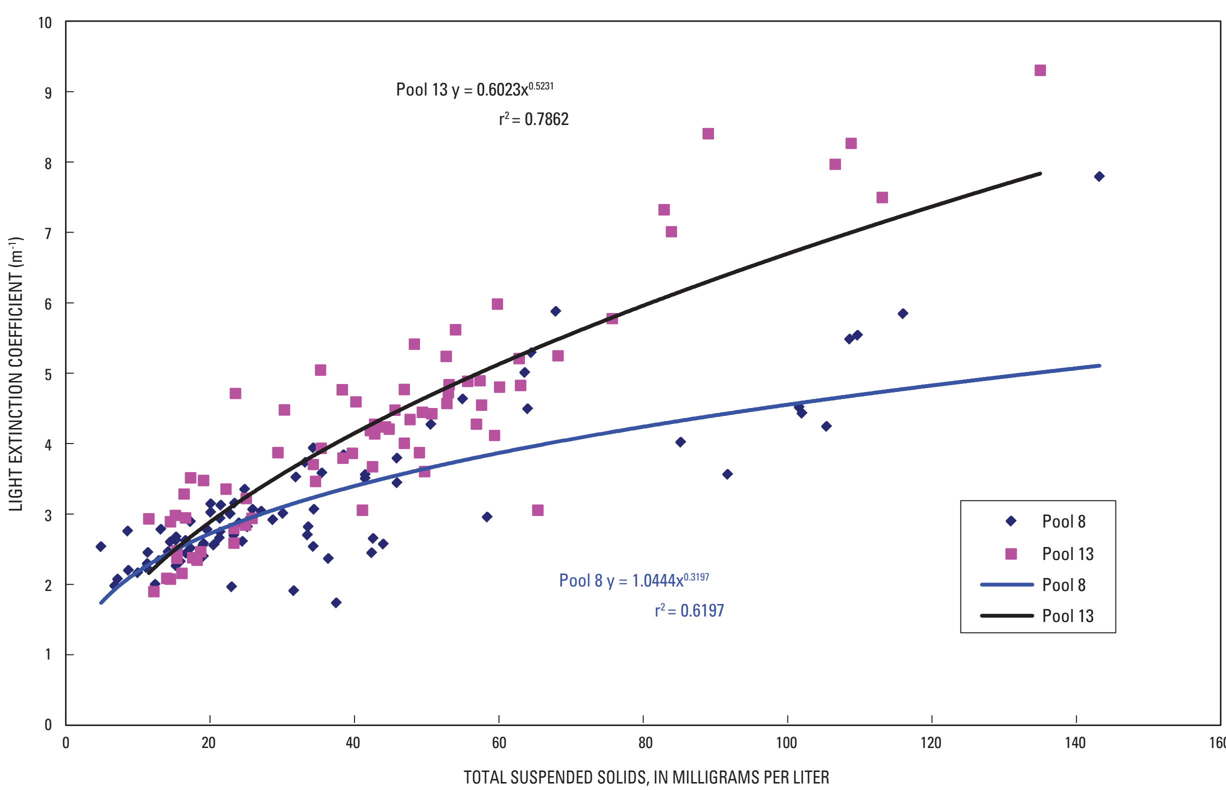

Figure 3. Relation between light-extinction coefficient and total suspended solids from Pools 8 and 13 (pool and tributary sites combined), Upper Mississipppi River, May 6 to July 16, 2003.

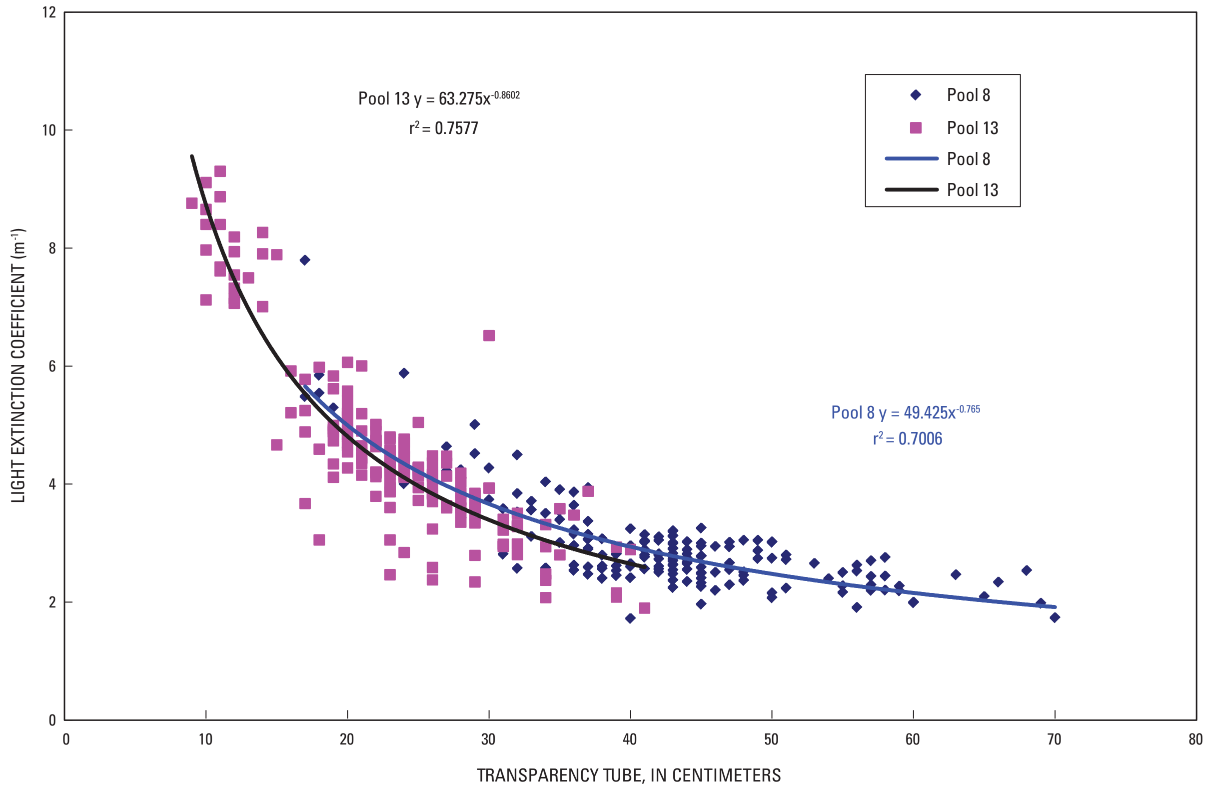

Figure 4. Relation between light-extinction coefficient and transparency tube from Pools 8 and 13 (pool and tributary sites combined), Upper Mississipppi River, May 6 to July 16, 2003.

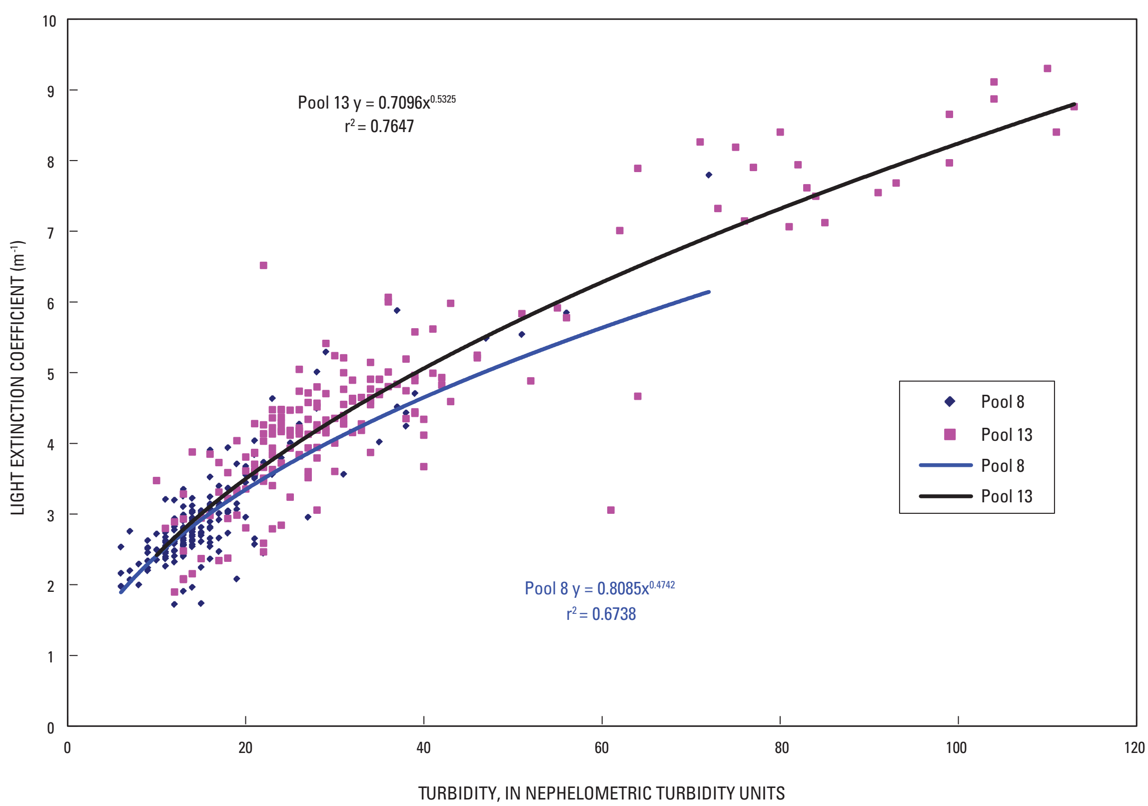

Figure 5. Relation between light-extinction coefficient and turbidity from Pools 8 and 13 (pool and tributary sites combined), Upper Mississipppi River, May 6 to July 16, 2003.

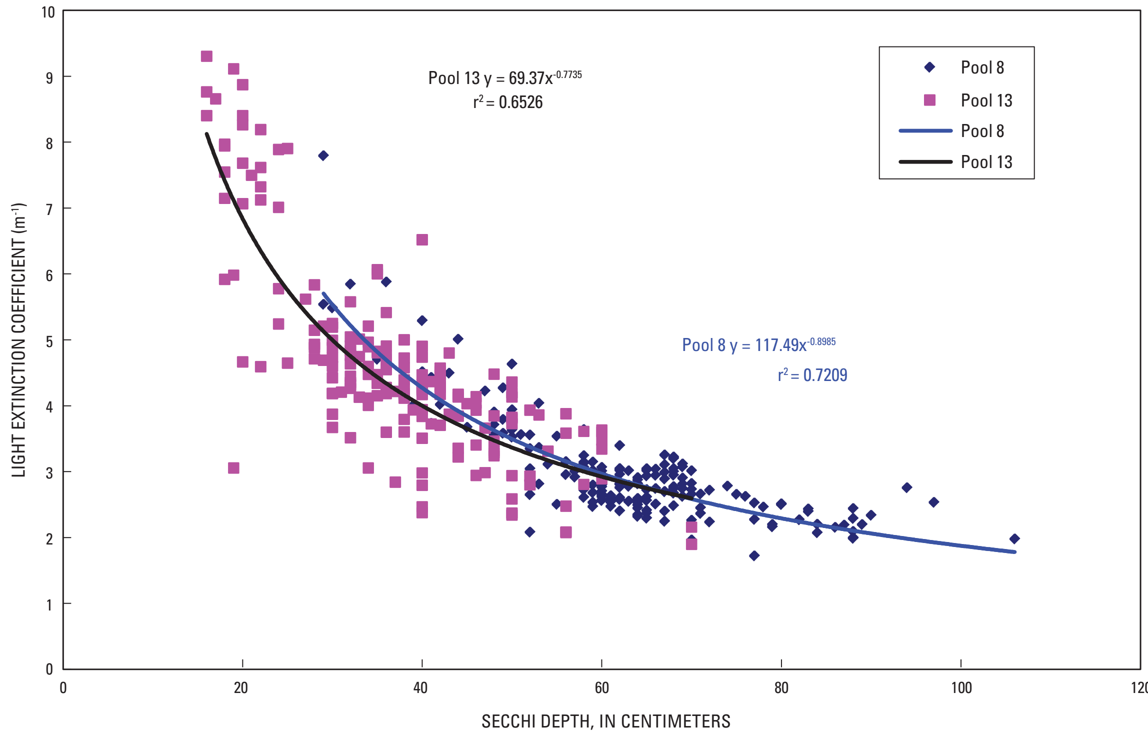

Figure 6. Relation between light-extinction coefficient and Secchi depth from Pools 8 and 13 (pool and tributary sites combined), Upper Mississipppi River, May 6 to July 16, 2003.

Table 6. Relation between water-quality parameters for 2003 study using data combined from Pool 8, Pool 13, and tributaries.

[R^2, coefficient of determination; N, number of measurements; cm, centimeter; TSS, total suspended solids; mg/L, milligrams per liter; NTU, nephelometric turbidity units]

Independent variable	Dependent variable	Equation	R^2	N
Transparency tube (cm)	Secchi depth (cm)	y= 1.3361x+6.6764	0.898	360
Transparency tube (cm)	TSS (mg/L)	$y= 2627x^{-1.29}$	.613	157
Transparency tube (cm)	Turbidity (NTU)	$y= 2073.5x^{-1.3458}$	.894	360
Secchi depth (cm)	Transparency tube (cm)	y= 0.6722x-1.1867	.898	360
Secchi depth (cm)	TSS (mg/L)	$y= 5179.1x^{-1.3225}$	.575	157
Secchi depth (cm)	Turbidity (NTU)	$y= 4900.4x^{-1.4149}$	.876	360
TSS (mg/L)	Transparency tube (cm)	$y= 158.32x^{-0.4749}$	.613	157
TSS (mg/L)	Secchi depth (cm)	$y= 211.54x^{-0.4344}$	.575	157
TSS (mg/L)	Turbidity (NTU)	$y= 1.3159x^{0.8006}$	.834	157
Turbidity (NTU)	Transparency tube (cm)	$y= 228.69x^{-0.6646}$	.894	360
Turbidity (NTU)	Secchi depth (cm)	$y= 309.84x^{-0.6193}$	.876	360
Turbidity (NTU)	TSS (mg/L)	$y= 1.332x^{1.0421}$	.834	157

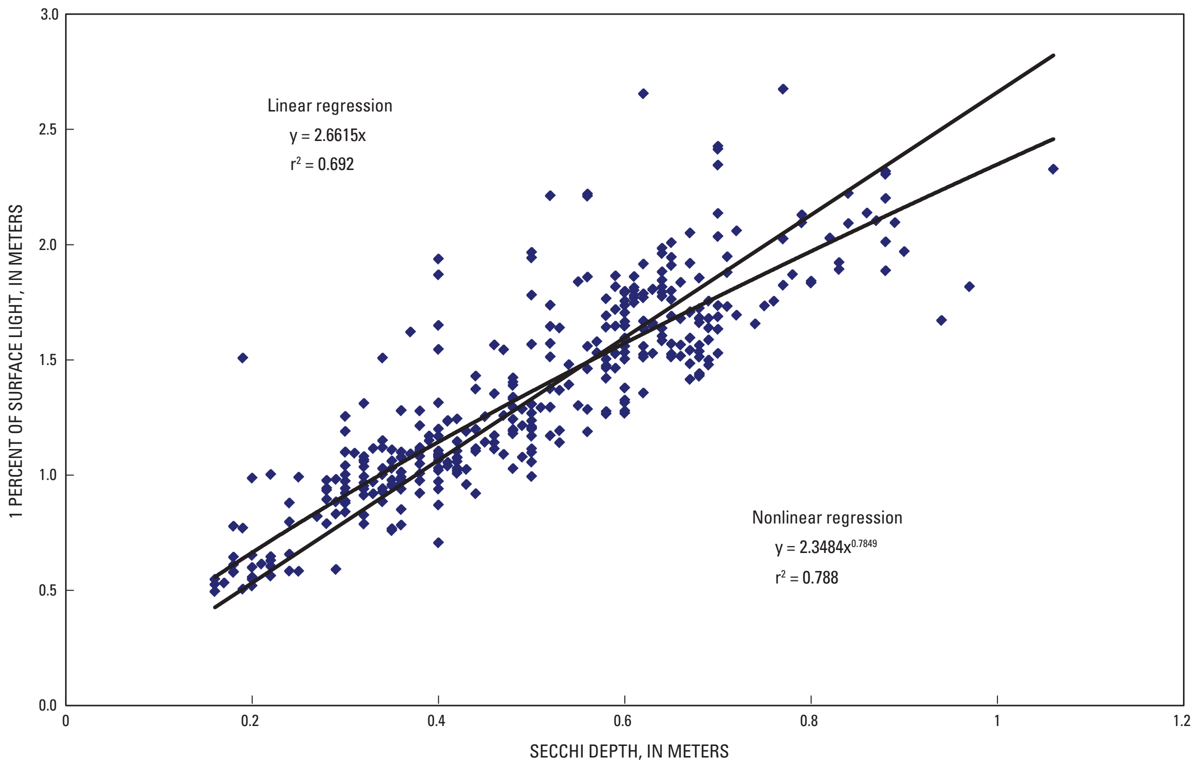

Figure 7. Relation between 1 percent of surface light and Secchi depth from Pools 8 and 13 (pool and tributary sites combined), Upper Mississipppi River, May 6 to July 16, 2003.

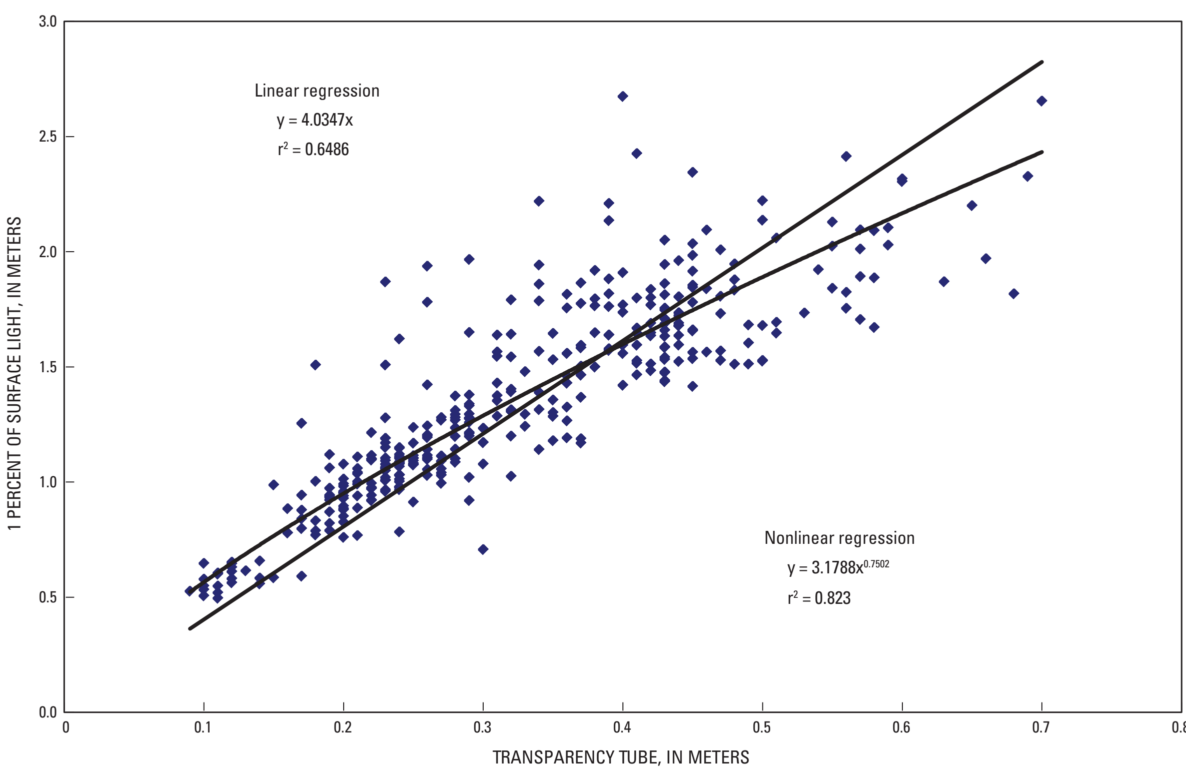

Figure 8. Relation between 1 percent of surface light and transparency tube from Pools 8 and 13 (pool and tributary sites combined), Upper Mississipppi River, May 6 to July 16, 2003.

Table 7. Comparison of Upper Mississippi River Conservation Committee recommended water-quality criteria (UMRCC, 2003) to main channel data from Pools 8 and 13 for May 6 to July 16, 2003.

[cm, centimeter; TSS, total suspended solids; mg/L, milligrams per liter; NTU, nephelometric turbidity units; ≤, less than or equal to; ≥, greater than or equal to]

	Light extinction coefficient (m^{-1})	Secchi depth (cm)	TSS (mg/L)	Turbidity (NTU)
UMRCC recommendation	≤ 3.42	≥ 50	≤ 25	≤ 20
Pool 8—main channel average	2.85	64.1	23.4	14.9
Pool 13—main channel average	4.84	36.4	56.3	37.2

Effects of Tributaries on Light Extinction

Water quality within the Upper Mississippi River is dependent upon the water quality of the tributaries feeding the system (Wasley, 2000). The degree that water quality is affected is a function of the discharge and concentration of suspended sediment of the tributary relative to the UMRS. The LTRMP monitored water quality in the tributaries of Pools 8 and 13, including data on TSS, turbidity, and Secchi depth. Based on this study, the average light-extinction coefficient of the tributaries to Pool 8 was higher than the Pool 8 main channel, whereas the average light-extinction coefficient of the tributaries to Pool 13 was lower than the Pool 13 main channel. Within Pool 8, the Black River had a lower light-extinction coefficient, and the La Crosse River, Root River, and Coon Creek had a higher light-extinction coefficient than the main channel (fig. 9). Scheffe's multiple-comparison procedure (Zar, 1984) indicated that light extinction in the main channel was significantly different than the La Crosse River and Coon Creek at the 0.05 level during the study period. Within Pool 13, the Elk, Apple, and Plum Rivers had lower light-extinction coefficients, and the Maquoketa River had a higher light-extinction coefficient than the main channel (fig. 10). Scheffe's multiple-comparison procedure indicated that light extinction in the main channel was significantly different than the Apple and Elk Rivers at the 0.05 level during the study period.

Tributaries can affect water quality laterally across the Mississippi River (Houser, 2005). Data collected during this study showed an east to west gradient of light penetration in Pool 8 with light penetration being slightly deeper on the east side of the main channel (fig. 11). The data point for the Root River Transect, Site 1, is suspect owing to two light-penetration observations that were extremely low for observed TSS, turbidity, and transparency tube values from the same site visit. The east to west gradient can be partially explained by the incomplete mixing of water from the Black River. Analysis of LTRMP fixed-site sampling data for 2000–05 (during the same months as the study period) indicated that a high proportion of NVSS settled out upstream in Lake Onalaska as the Black River traveled through the lake from Pool 7 into Pool 8 (fig. 1). The concentration of VSS also declined (at a slower rate) and remained lower downstream of Lake Onalaska than that found in the main channel in Pool 8 (table 8). The loss of NVSS at a faster rate than VSS likely was the result of faster sinking rates of NVSS, which is consistent with observations at Lake Pepin (Megard, 2006a). Although the La Crosse River had a high light-extinction coefficient, the Black River discharge was many times greater than the La Crosse River, resulting in lower light extinction on the east side of the Mississippi River downstream of the La Crosse and Black Rivers (table 9). Turbidity generally was higher in the west side of the river relative to the east side with the Root River and Genoa Transects showing the most pronounced gradient (fig. 12). In Pool 13, lateral gradients in turbidity were less pronounced. The only pattern was an increase in main channel turbidity on the west side of the main channel where the turbid Maquoketa River empties into the Upper Mississippi River. The lack of pattern likely was the result of the relatively small flow contribution of three of the four tributaries entering Pool 13 relative to the Upper Mississippi River (table 9).

A weak longitudinal light-penetration gradient was observed for Pool 8 with an increase in light-extinction coefficient downstream. Although this trend was statistically insignificant, the lack of significance likely can be attributed to small sample size. High light-extinction values of the tributaries discharging to lower Pool 8 and wave-induced sediment resuspension owing to long wind fetch likely contributed to this trend. The poorest area for light penetration in Pool 8 (west side of the Genoa Transect) is scheduled for rehabilitation to reduce sediment resuspension. Data collected during this study indicate that management efforts are being directed effectively to an area in the pool with high concentrations of suspended sediment.

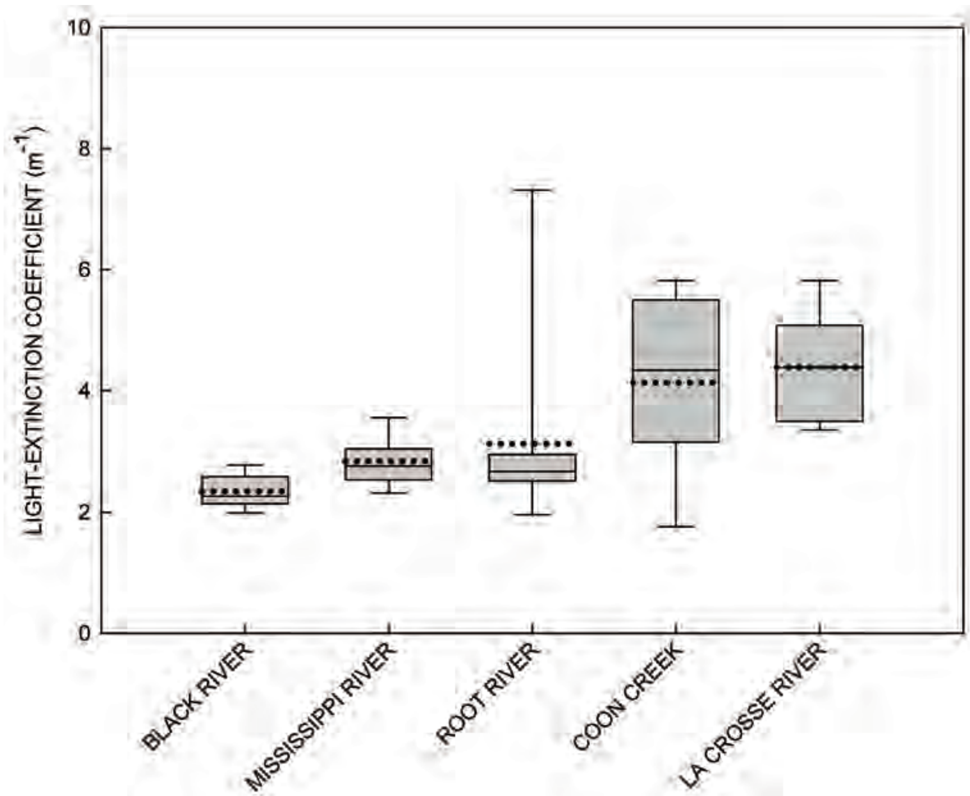

Figure 9. Pool 8 light-extinction summary. The solid line inside the box is the median. The upper and lower ends of the box are the 25th and 75th percentiles. The whiskers denote the 10th and 90th percentiles. The dotted line is the average for each site.

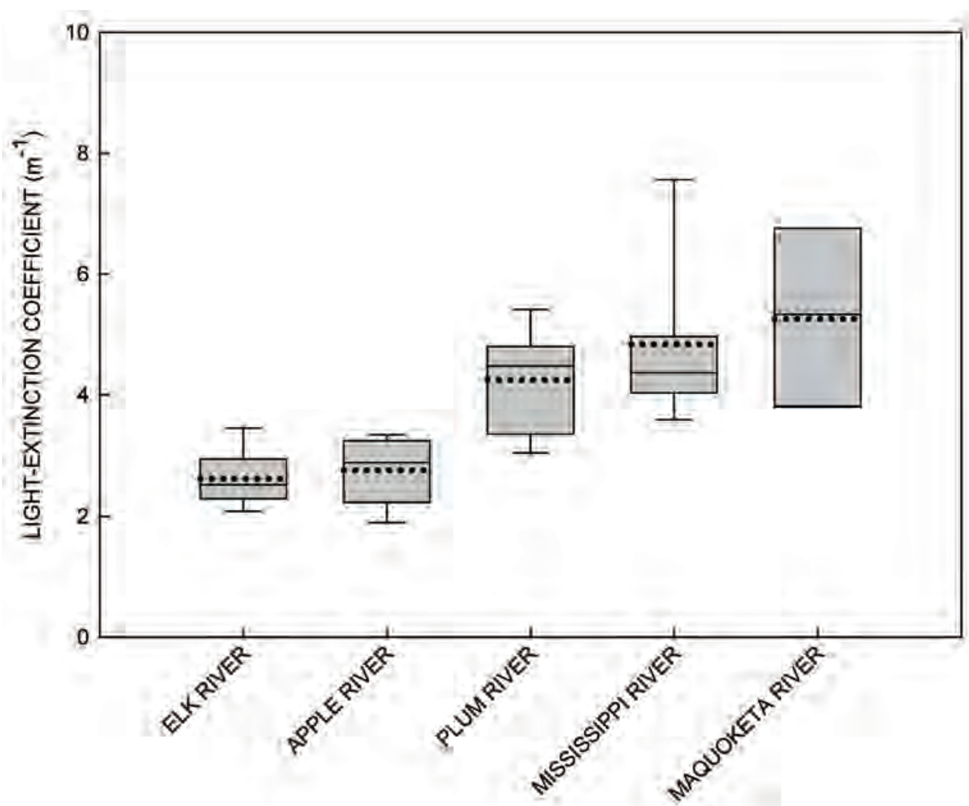

Figure 10. Pool 13 light-extinction summary. The solid line inside the box is the median. The upper and lower ends of the box are the 25th and 75th percentiles. The whiskers denote the 10th and 90th percentiles. The dotted line is the average for each site.

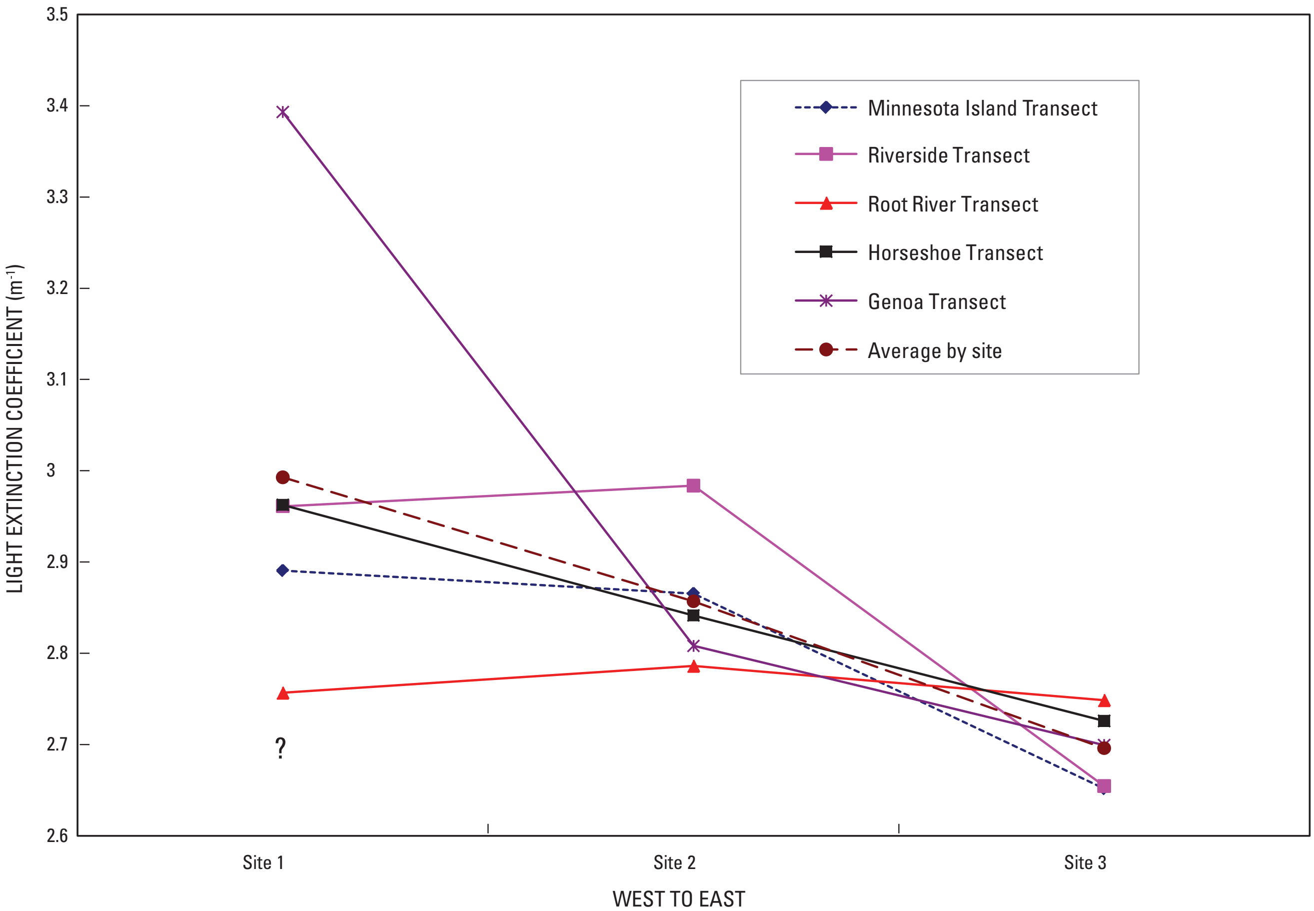

Figure 11. Mississippi River Pool 8 average light-extinction coefficient by transect. The question mark indicates this data point is suspect.

Table 8. Comparison of average water-quality characteristics of the Black River upstream and downstream of Lake Onalaska compared to the main channel of the Mississippi River in Pool 8. Data are from May 6 to July 16 from 2000 to 2005.

[NTU, nephelometric turbidity units; TSS, total suspended solids; mg/L, milligrams per liter; VSS, volatile suspended solids]

	Turbidity (NTU)	TSS (mg/L)	VSS (mg/L)
Black River upstream of Lake Onalaska (BK 14.2M)	16.4	23.1	5.9
Black River downstream of Lake Onalaska (BK 01.0M)	6.1	7.4	4.4
Mississippi River in upper Pool 8 (M 701.1D)	16.8	23.9	5.8

Table 9. Average discharge for the Mississippi River and tributaries for 1970–2000 based on U.S. Geological Survey data.

[UMR, Upper Mississippi River; data are in cubic feet per second]

River	Discharge	River	Discharge
Black River[a]	2,111	Maquoketa River[a]	1,259
La Crosse River[a]	469	Apple River[a]	217
Root River[a]	1,047	Plum River[a]	235
Coon Creek[a]	60	Elk River[c]	42
UMR at Winona, Minnesota (Pool 6)[b]	34,290	UMR at Clinton, Iowa (Pool 14)[b]	54,000

[a] Data from Wasley (2000).

[b] U.S. Geological Survey (USGS) gaging station data for 1970–2000.

[c] USGS gaging station data for 1995–97.

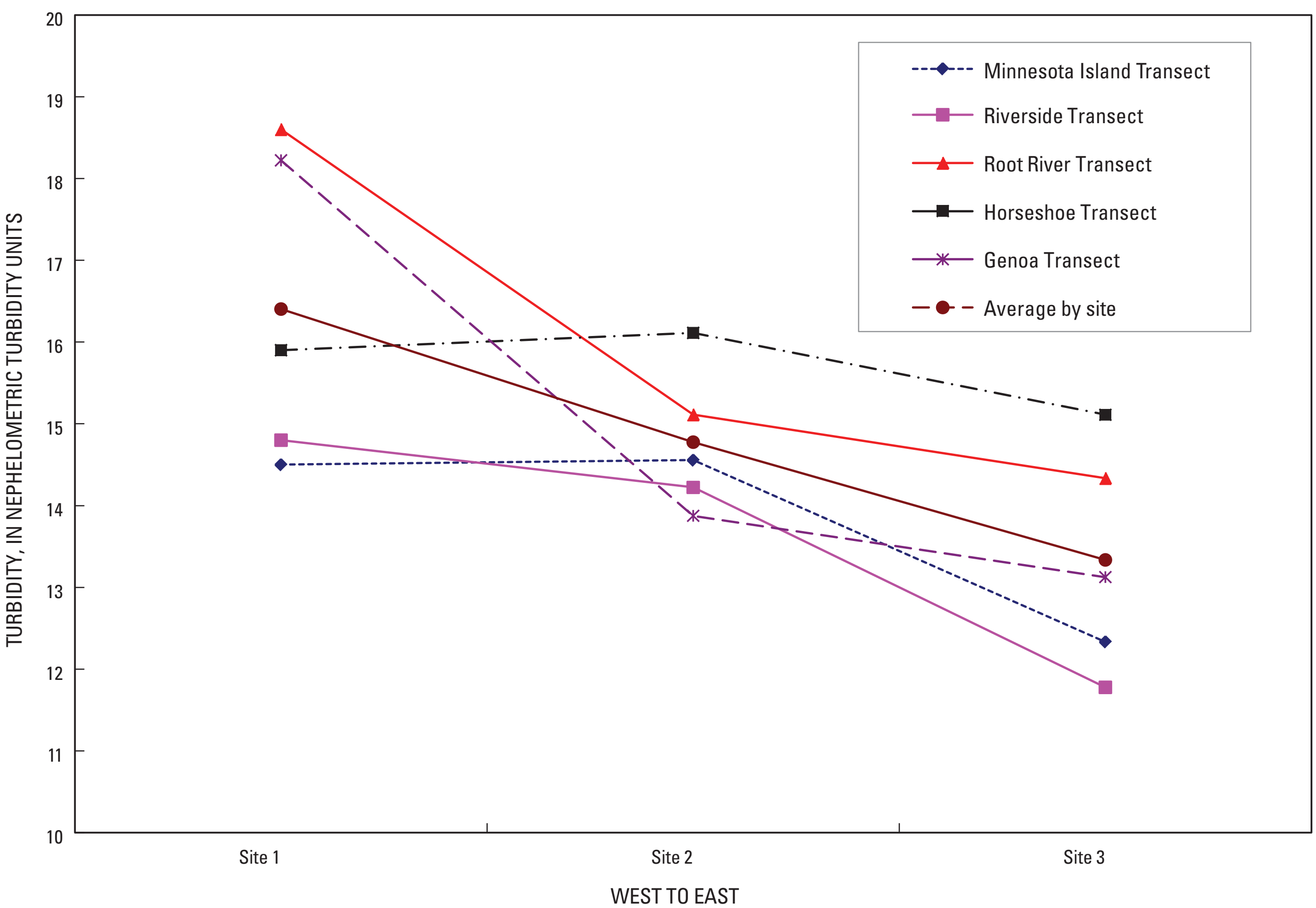

Figure 12. Mississippi River Pool 8 average turbidity by transect.

Effects of Composition of Suspended Solids on Light Extinction

The light-scattering properties of suspensoids in lentic systems tend to vary depending upon the proportion of organic (VSS) and inorganic (NVSS) particles in suspension (Megard, 2006a). Generally, organic suspensoids scatter light more strongly than inorganic suspensoids (Megard, 2006b). Multiple linear regression of data collected during this study resulted in the following equation:

Light-Extinction Coefficient (m^{-1}) = 1.0961
+ 0.2497 (VSS mg/L) + 0.0167 (NVSS mg/L)
R^2 = 0.808.

This equation supports the theory that VSS is a greater light attenuator proportionally than NVSS; however, NVSS tends to occur at higher concentrations in the UMRS. The average concentration of VSS was 8.2 mg/L, and the average concentration of NVSS was 31.5 mg/L during the study period. Based on the regression equation above, on average, the concentration of VSS accounts for 56 percent of light extinction and NVSS accounts for 14 percent. The intercept estimates background extinction owing to unmeasured variables, including dissolved organic carbon, which on average accounts for 30 percent of light extinction.

The different effects of the contribution of NVSS and VSS to light extinction may illustrate the differences between Pools 8 and 13 in the relation of TSS to light extinction (fig. 3). During the study period, Pool 13 had a higher average concentration of VSS (a greater light attenuator) and therefore, a higher light-extinction coefficient. This response was more pronounced at higher concentrations of TSS and may account for some of the disparity between Pools 8 and 13 at concentrations of TSS exceeding 80 mg/L (table 10). It also is likely that variability in the proportion of TSS that is comprised of VSS is a cause for the weak relation between TSS and light extinction. All of the Pool 8 values greater than 80 mg/L were from Coon Creek and Root River, and five of the seven Pool 13 observations were main channel sites. This indicates that there may be important differences in TSS makeup between tributaries and the main channel that are affecting light extinction.

The effects of seasonal light penetration on vegetation and fish within the Upper Mississippi River remain poorly understood; however, this report presents river managers with tools to predict light extinction based upon commonly collected water-quality variables, thereby providing opportunities to further investigate these unknown effects. Transparency tube, Secchi depth, and turbidity all showed strong relations with light extinction and can be used to effectively predict light extinction. TSS did not show as strong a relation to light extinction. This report also provides some insight into the effect that VSS and NVSS are having on light penetration in the Upper Mississippi River and its tributaries. We expect the general relations and principals presented in this report to apply to other parts of the UMRS as well as other river systems. Utilizing relations presented in this report in conjunction with biological indicators of light penetration, such as SAV, represents important tools in understanding light dynamics within the UMRS (Sullivan and others, 2009). The light regime on the Upper Mississippi River has wide-ranging ramifications that affect the overall health of the ecosystem, and we have illustrated that readily available data can be used to predict light extinction

Table 10. Comparison of total suspended solids, volatile suspended solids, nonvolatile suspended solids, and percentage volatile suspended solids for Pools 8 and 13.

[N, number of measurements; TSS, total suspended solids; mg/L, milligrams per liter; VSS, volatile suspended solids; NVSS, nonvolatile suspended solids; k, light extinction coefficient (m^{-1}); tributary data included; only values greater than 80 mg/L TSS are included]

	N	TSS (mg/L)	VSS (mg/L)	NVSS (mg/L)	Percentage VSS	k
Pool 8 average	9	107.04	12.34	94.7	11.42	5.05
Pool 13 average	7	102.76	16.51	86.24	16.26	7.97

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Long Term Resource Monitoring Program—**Evaluation of Light Penetration on Navigation Pools 8 and 13 of the Upper Mississippi River**

The Long Term Resource Monitoring Program (LTRMP) for the Upper Mississippi River System was authorized under the Water Resources Development Act of 1986 as an element of the Environmental Management Program. The mission of the LTRMP is to provide river managers with information for maintaining the Upper Mississippi River System as a sustainable large river ecosystem given its multiple-use character. The LTRMP is a cooperative effort by the U.S. Geological Survey, the U.S. Army Corps of Engineers, and the States of Illinois, Iowa, Minnesota, Missouri, and Wisconsin.

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Natural vs. Anthropogenic Factors Affecting Sediment Production and Transport from the Minnesota River Basin to Lake Pepin

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The pictures on the front page are slumping banks on the Le Sueur River (left panel) and the Blue Earth River (right panel). Pictures in the sequence show the catastrophic failure of the bank in little over a month. Left panel picture was taken from Pictometry Corporation.

This research project was partially supported with funds from the Minnesota Corn Research and Promotion Council and the Minnesota Soybean Research and Promotion Council. Although we are releasing this report, we will be continuously updating it as we find additional data and information in the literature about past landscape conditions.

EXECUTIVE SUMMARY

Sediments are a major water quality impairment for the Minnesota River and its tributaries. Sediments from these rivers are transported downstream to the Mississippi River at St. Paul and then on to Lake Pepin, a large floodplain lake on the upper Mississippi River about 80 km south of St. Paul. Based on sediment cores taken from this lake, researchers have suggested that European settlement in the area and the subsequent cultivation and drainage of agricultural lands are the primary reasons for increased rates of sedimentation since 1830. The objectives of this study were: (1) to quantify sediment contributions from bank erosion/sloughing from several rivers in Blue Earth County, MN, and (2) investigate the role of both natural and anthropogenic factors on increased rates of sedimentation in Lake Pepin. LiDAR (Light Detection And Ranging) scans taken in 2005 and 2009 were used to quantify bank erosion along several rivers in Blue Earth County, MN. Volume change of river valleys measured from these scans showed that bank erosion/sloughing is the major source of sediment to the rivers in this county, as well as to the Minnesota River at Mankato. Fine sediment losses from river banks varied from 56 to 86% of the measured total suspended loads at the gauging stations. Field and laboratory observations showed that bank sloughing is primarily a result of bank instability caused by soil wetness and due to the lateral movement of rivers over time. Bank failure occurs, not only at the base, but also higher up in the middle and near the top of the bank. Increased wetness in the middle or top of the bank is due to seepage from a perched water table, while river water uptake by capillary action increases the wetness at the base. Other mechanisms of bank failure include freezing and thawing, wetting and drying, pore water pressure build up, undercutting, and rapid decrease in river water level compared to water outflow from banks during the recession hydrograph. Since the soils along the river banks have not changed drastically in the last 300 years, and most water in the basin is derived from precipitation, we suggest that consistent with precipitation trends, sediment production in the Minnesota River Basin may not be drastically different now than before European settlement in 1850. We support this finding with qualitative and quantitative descriptions of river conditions from historic documents, as well as turbidity measurements taken by the United States Geologic Survey (USGS) in early 1900s.

As early as 1835, travelers' logs indicated that the Blue Earth River was "loaded with mud" and was the cause of turbidity of the Minnesota River. Subsequent writings in 1850s described the Minnesota River at Fort Snelling as "turbid" and as a "dirty little creek". USGS measurements in 1904-1905 showed that turbidity of the Minnesota River at Mankato went as high as 600-800 ppm (equivalent silica concentrations) during spring. In 1906-1907, turbidity of the Minnesota River at Shakopee in equivalent silica concentration was 330 ppm as compared to <33 ppm for the Mississippi River at Minneapolis. Minnesota's oldest available aerial pictures taken in 1937-38 (Dust Bowl Era) also show a turbid Blue Earth River at Mankato, MN, turbid Minnesota River at St. Paul, MN, and turbid Mississippi River at Prescott, WI, similar to present day conditions, thus supporting the hypothesis that these rivers have been muddy/turbid prior to European settlement.

We also show that early cultivation (pre-1850s) was somewhat primitive with wooden plows attached with metal tips and metal plates, which would have resulted in shallow cultivation. Although a variety of plows started becoming available in 1860, cultivation was still only 4-5 inches deep. The farm papers constantly criticized the farmers for shallow cultivation during this period. The papers suggested that deeper cultivation will alleviate drought. In the

1870s, steam plows started becoming available, but they were too expensive for many farmers to afford. A majority of agricultural crops from 1850-1900 were small grains, hay, and flax that provided soil with good cover. A row crop like corn was grown on a small proportion of land and that too in 3 or 5 year rotation with small grain and hay. Corn grown in rotation with oats and hay produces much less soil erosion than continuous corn. Since there was plenty of land, the producers also did not have a need to drain wetlands. In addition, wetlands produced wild hay that was preferred for draft animals. Major tile drainage efforts in the Minnesota River Basin began around 1900. Since sedimentation rates in Lake Pepin continuously increased from 1830 on, even though there was limited number of people living in the state (state population in 1850 was 6,077 people), we conclude that early cultivation and tile drainage could not be the major reasons for increased rates of sedimentation in Lake Pepin starting in 1830.

Drainage activities picked up after World War I with the rise in commodity prices. Although some counties in the Minnesota River Basin increased their land area in drainage enterprises anywhere from 20 to 60% for the period 1910-1940, this was also a relatively dry period and thus sediment production and transport would have been small. Even though corrugated plastic tile became available for agricultural drainage in 1967, records show that tile drainage was still done with clay or cement tiles until the late 1970s. Initially, plastic tiles were often used to replace aging old clay and cement tiles that had disintegrated and/or were filled up with sediments. Over time, new areas were also brought under tile drainage; however, no new open water wetlands in agricultural landscape have been drained since 1985 as required by law. Although surface inlets have been used to remove excess water since the early days of drainage enterprises, recent efforts have been to replace them with subsurface drainage. In addition, some surface inlets have been replaced with rock inlets or French Drains and some have been moved from the center to the edge of fields, due to the difficulty of working around them with large machinery. These edge of the field inlets along with surface inlets that are still in some depressional areas provide some sediment transport from agricultural lands to the Minnesota River and its tributaries.

Along with agricultural activities, the climate, the land use, and the geomorphology of the region have also undergone changes. We document that (1) the Minnesota River channel has gone through major modifications starting in 1892, (2) precipitation amount and intensity has increased since 1940, and (3) there has been an increase in impervious surfaces, especially in the portion of the seven county metro area (30% in 2002) contributing to the Minnesota River. Since sediment cores in Lake Pepin reflect integrated effects of both sediment production and transport, we conclude that increased sedimentation rates in Lake Pepin may be due to increased rates of transport as a result of straightening, widening, and deepening of the channel between Chaska and Fort Snelling; building of levees near Mankato and Henderson on the main channel and along the Blue Earth River; a trend of increased precipitation starting around 1940; and increased flow from impervious surfaces in the Minnesota River Basin.

At the end of the last glacial retreat (+11,000 years ago BP), the northern extent of Lake Pepin started in St. Paul. This lake has been filling up since that time. The delta in the Mississippi River has been moving down stream. We believe some portion of recent higher sedimentation rates measured from core samples taken from Lake Pepin may be an artifact of the deltas position as well as the shrinkage of lake volume. Since sediment cores taken from Lake Pepin are a repository of many effects, we further conclude that lake cores data, by themselves, are insufficient to single out sources (fields or banks), physical processes (bank failure or river migration), or agricultural management practice (cultivation or drainage) as the cause of recent increased sedimentation, especially from a large basin such as the Minnesota River Basin. We suggest that regulatory agencies undertake focused research on developing techniques that can more accurately measure the impact of channel modifications, impervious surfaces, climate variation, natural landscape processes (seepage and lateral channel movement), and the migrating river delta on lake cores data to quantify the role of landscape modifications (cultivation) and agricultural drainage on sediment production in the Minnesota River Basin.

INTRODUCTION

Sediment is one of the major causes of surface water impairment throughout the world. The presence of suspended sediments in rivers and lakes increases turbidity which limits light penetration and in turn plant growth for aquatic organisms. Suspended sediments also directly affect the functioning of aquatic organisms by covering spawning areas and impacting gill functions. The Minnesota River Basin (MRB, Fig. 1) has several major water bodies that are impaired due to presence of sediments and thus increased turbidity. Monitoring studies by the Metropolitan Council Environmental Services (MCES) from 1976-1992 have shown that the water quality of the Minnesota River is worse than that of the Mississippi and St. Croix Rivers near the Twin Cities of St. Paul and Minneapolis, MN (Meyer and Schellhaass, 2002). Sediment loads in the lower Minnesota River at Fort Snelling were twenty-six times greater than that in the St. Croix River and four times greater than that in the Mississippi River. According to the MCES, these numbers translate to approximately 0.6 million Mg y^{-1} (95 18-Mg truckloads per day) of total suspended solids transported by the Minnesota River at Fort Snelling (Fig. 1). United States Geological Survey (USGS) studies show that sediment loads in the Minnesota River at Mankato are highly variable ranging from 0.2 to 3.3 million Mg per year from 1968 to 1992 (Payne, 1994). Over 55% of these sediments and 46% of the water flow in the Minnesota River at Mankato originates from the Greater Blue Earth River Basin (GBERB, Fig. 1), a relatively flat area with 54% of the land less than 2% slope and 93% of the land less than 6% slope (Fig. 1).

There are many streams in GBERB that are deeply incised with steep and unstable banks (Fig. 2). These streams include the Blue Earth, Le Sueur, Watonwan, Maple, Cobb, and Little Cobb Rivers (Fig. 1). The Watonwan River is a tributary of the Blue Earth River whereas the Maple, Cobb, and Little Cobb Rivers are tributaries of the Le Sueur River. The Le Sueur River converges into the Blue Earth River before it joins the Minnesota River at Mankato. Geological settings of the Le Sueur River Watershed are described in Gran et al. (2009). Measurements from 2000 to 2008 at the mouth of the Le Sueur River and the Blue Earth River (before their confluence) showed an average sediment load of 225,000 Mg and 294,000 Mg, respectively (Scott Matheson, Personal Communication, 2010). Maximum and minimum sediment loads over this period were 526,000 Mg in 2006 and 173,000 Mg in 2000 for the Blue Earth River, and 494,000 Mg in 2000 and 73,000 Mg in 2003 for the Le Sueur River.

At a broader scale, the MRB like the GBERB is also relatively flat. Thirty-three and 74% percent of the land in MRB is <2 and <6% slope, respectively. Both the MRB and GBERB have been extensively tile drained with numerous surface and side inlets that allow the transport of surface sediments to ditches, and subsequently to streams and rivers. There has been controversy on the extent of sediment contributions from agricultural fields compared to stream banks from the MRB. Based on a mass balance of sediments in one reach, Payne (1994) estimated that 25% of the sediment load in the Minnesota River was from bank erosion. Subsequently, Gupta and Singh (1996) estimated that the river bank contributions in the Minnesota River at Mankato were 48-55% of the total sediment load for water years 1990-1992, based on the use of rating curves for periods with and without rainfall. They assumed that if there was no rainfall in the basin for 10 days (recession limb of the hydrograph) then most of the sediments in the river were from bank erosion.

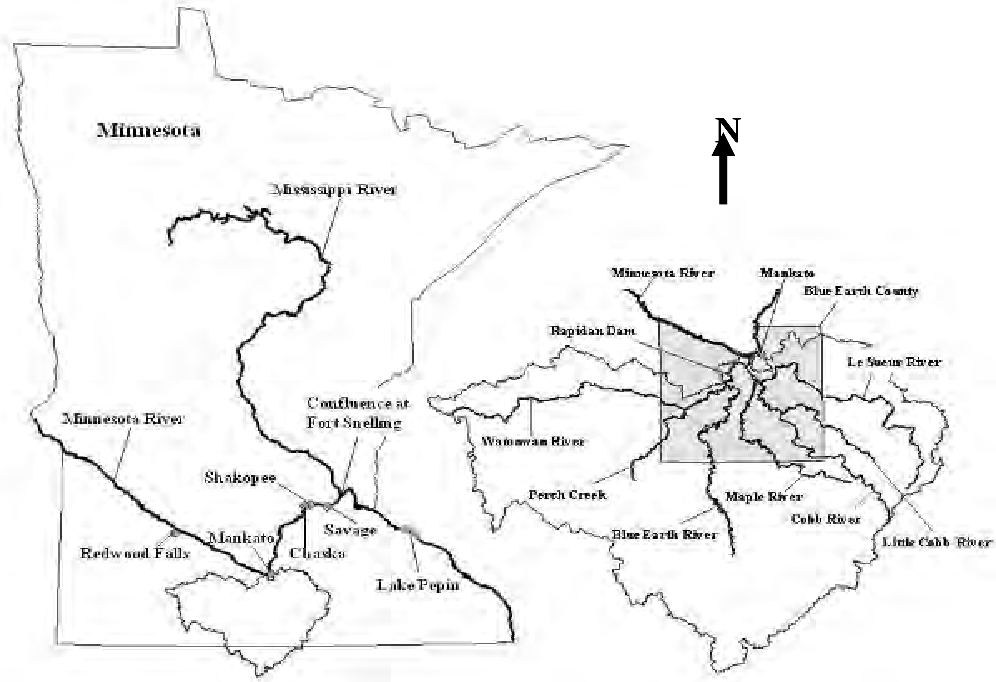


Figure 1: A map of Minnesota showing the location of various rivers in Blue Earth County within the Blue Earth River Watershed.

Figure 2: A picture of the sloughing banks along the Blue Earth River in Minnesota. Photograph taken by David Thoma around 2001.

One limitation of Gupta and Singh (1996) analysis is that it does not include sediment contributions from bank erosion as a result of direct raindrop impact above the waterline for a given flow regime. Furthermore, this analysis also does not include catastrophic failures as well as contributions from seepage induced bank failure which may occur during or shortly after rainfall events. This analysis only considers the sediment contribution due to bank scour below the water line for a given flow level and thus significantly underestimates bank erosion especially if the major cause of bank sloughing is bank failure. Recently, the Minnesota Pollution Control Agency (MPCA, 2010a) has tested a similar approach to estimate stream bank erosion. The process involves first estimating stream bank erosion based on sediment concentration-flow relationship for the recession limb of the hydrograph and then estimating ravines and field erosion through subtraction. The results from this method indicated that approximately 1/3 of the contributions are from each source; bank, ravine, and upland erosion. Since bank erosion is underestimated through the use of this procedure, ravine and field erosion estimates are much higher. This method has the same limitations as that of Gupta and Singh (1996).

By conducting ground surveys of seven banks using a total-station surveying instrument, Sekley et al. (2002) estimated that 36-48% of the sediments in the Blue Earth River originated from bank erosion. These authors used bank area as a surrogate variable to extrapolate their measurements on seven stream banks to the entire river. However, this analysis does not account for the variations in bank failure mechanisms through space and time (i.e. not every bank fails every year and the bank failure mechanism on a given bank is not same every time). Bank area has little to do with bank erosion/failure and cannot be used as a surrogate to extrapolate estimates from a few banks to the full length of the reach. This approach was recently adopted by Gran et al. (2009) and Wilcox (2009) using the bluff erosion rates measured on the Le Sueur and the Maple Rivers with ground-based LiDAR survey and aerial photographs. However, these analyses using area as a surrogate variable to extrapolate across the entire extent of a river channel have the same limitations as that of Sekley et al. (2002).

Using multi-temporal airborne Light Detection And Ranging (LiDAR) scans over 35 miles of the Blue Earth River, Thoma et al. (2005) calculated that river bank contributions were as high as 56% of the measured total suspended load between 2001 and 2002. The efforts by Thoma et al. (2005) differed from others in that it characterized the full length of a reach eliminating the need for extrapolation or limited sampling.

Based on radiometric finger printing of sediments, Schottler et al. (2010) estimated that non-field source contributions in various streams entering the Minnesota River ranged from 60% to 85% of the sediment measured downstream. Non-field sources include river banks, ravines and gullies. One limitation of this method is that it does not directly measure sediment production from river bank erosion, but estimates it from a sediment sample that integrates both sediment production and sediment transport processes. Since the effect of transport processes in small watersheds is negligible, the finger printing technique has mostly been recommended and used in small watersheds. In large watersheds, such as the MRB, sediment transport processes can have a significant impact thus reducing the certainty in partitioning the source of sediments. Factors affecting sediment transport processes include the channel morphology (width, depth, and sinuosity), the length of drainage ditches along its path, presence or absence of levees, and extent of impervious surfaces (roads, parking lots, and roof tops) in the watershed.

Sediments from the MRB have been identified as a major source of sediments in Lake Pepin, a large floodplain lake (103 km^2) on the upper Mississippi River about 80 km south of St.

Paul, MN (Kelley and Nater, 2000). The filling of Lake Pepin with sediments results not only in volume loss for navigation but also in increased algal growth and subsequent eutrophication, resulting in impacts on fish and other aquatic life. Based on fallout cesium-137, McHenry et al. (1980) estimated a sedimentation rate of 2.5 cm yr^{-1} in upper reaches of Lake Pepin. From bathymetric survey data, Maurer et al. (1995) estimated a volume loss of 21% between 1897 and 1986. Using isotopic and pollen analysis on sediment cores from Lake Pepin, Engstrom et al. (2009) showed that the rate of lake filling has steadily increased since 1830. In the upper reaches of the lake, these authors estimated sedimentation rates of >3 cm yr^{-1} from 1990-1996. Averaged over the entire lake (25 sediment cores) the sedimentation rate for 1990-1996 was 1.6 cm yr^{-1} as compared to <0.2 cm yr^{-1} in 1830. These authors attributed increased sedimentation rates in Lake Pepin since 1830 to the onset of European settlement in Minnesota, but more specifically to cultivation of land and tile drainage in the MRB (Engstrom et al., 2009; Balogh et al., 2009).

Using the radiometric finger printing technique, Schottler et al. (2010) also characterized the sources of sediments in Lake Pepin. Based on ^{210}Pb concentrations in lake sediments in 2007, the authors estimated sediment contributions from field and non-field sources to Lake Pepin at 35% and 65%, respectively. Further, assuming that all inputs including the proportion of sediment delivered to Lake Pepin since 1500 have remained constant (combined trapping efficiency since 1500 is same as in 2007), these authors estimated that sediment contributions from fields corresponded to 32%, 59%, 65%, >100%, and >100% for periods 1996, 1967-1996, 1940-1967, 1890-1940, and 1830-1890, respectively. These authors also assumed that there was no field contributions pre-1830. There are several concerns about this analysis. First, we know there have been significant changes in river systems (dredging, straightening, widening, levee construction, additional flow from impervious surfaces, and additional flow due to higher precipitation, presence of lock and dams, etc.) contributing to Lake Pepin and thus one cannot assume the same trapping efficiency or delivery ratio for all periods from 1500 to 2007 (pre-1830, as well as from 1830 to 2007). Second, it is unlikely that all the sediments (100%) in 1830-1890 and 1890-1940 came from fields. As we know, there is significant bank sloughing occurring due to natural processes (Thoma et al., 2003) and thus it is highly unlikely those bank failure processes were absent prior to 1940. The assumption that 100% of the sediment load was coming from river banks for the pre-1830 period is arbitrary and lacks any scientific basis. It is highly unlikely that fields/uplands did not contribute any sediment pre-1830. Third, >100% contributions are physically impossible. It appears that the authors are force fitting their data to a pre-conceived notion of sediment sources without regard to changed sediment transport processes.

In the South Metro Total Maximum Daily Load (TMDL) report to the United Sates Environmental Protection Agency, MPCA (2010b) has selectively included 1940 and 2010 calculations from Schottler et al. (2010). However, they leave out Schottler et al. (2010) calculations that show >100% sediment contributions from fields for the periods 1830-1890 and 1890-1940. In this manuscript we will show that trappings efficiencies (delivery ratio) must have changed from 1830 to present because of channel modifications, as well as increases in impervious surfaces in the basin and varying climate. The channel modifications include dredging, straightening, widening, and deepening of the Minnesota River and the building of levees at Mankato and Henderson.

The objectives of this study were (1) to quantify sediment contributions from bank erosion/sloughing along several rivers in the Blue Earth County using airborne LiDAR, and (2) to investigate the role of both natural and anthropogenic factors on increased rates of sedimentation in Lake Pepin. Blue Earth County was selected for the LiDAR study because an earlier LiDAR scan was available for Blue Earth County and the GBERB contributes over half of the sediment load to the Minnesota River at Mankato (Payne, 1994).

LiDAR APPLICATION IN FLUVIAL RESEARCH

Recently, LiDAR data has become more widely available, increasing its use in fluvial research (Thoma et al., 2005; Heritage and Hetherington, 2007; Milan et al., 2007; Cavalli et al., 2008; Jones et al., 2008; Notebaert et al., 2008; Perroy et al., 2010) and multi-temporal change detection studies (Woolard and Colby, 2002; White and Wang, 2003; Thoma et al., 2005; Rosso et al. 2006; Dewitte et al., 2008; Vepakomma et al. 2008, 2010). An airborne LiDAR scan is collected by sending thousands of laser pulses to the ground each second from a LiDAR instrument typically attached to an aircraft and recording the travel time for their returns. Normally, multiple returns are recorded for each laser pulse with the last being the ground. A global positioning system (GPS) and inertial measurement unit (IMU) record the aircraft's position and attitude (roll, pitch, and yaw), respectively. The combination of laser return times, GPS derived position, and IMU information allows for the precise estimation of horizontal and vertical positions of the objects on the ground. Laser returns from vegetation and other objects can be removed from the data set to obtain the ground positions for building a "bare earth" digital elevation model (DEM). The LiDAR scans of a river valley taken at two different times provide an estimate of the change in the volume of the valley as a result of bank erosion, sloughing and accretion (Thoma et al., 2005).

Typically surveying companies assure their LiDAR data products have root mean square errors (RMSE) less than 1 m horizontal and 0.15 m vertical positioning. Data accuracy varies depending on factors such as aircraft elevation, aircraft speed, laser pulse rate, and laser footprint. Recently, several investigators have examined the accuracy and uncertainty of digital elevation models (DEMs) used in fluvial systems (Bowen and Waltermire, 2002; Lane et al., 2003; Notebaert et al., 2009; Perroy et al., 2010; Wheaton et al., 2010). Bowen and Waltermire (2002) found that areas with large topographic relief tend to have lower vertical accuracy in steep riparian corridors, primarily due to horizontal positioning limitations (lower horizontal accuracy). This lower vertical accuracy in turn could lead to a higher degree of uncertainty in quantification of valley volume change in steep terrain.

As such, a variety of methods have been adopted to account for uncertainty in DEMs (Wheaton et al. 2010). A minimum level of detection threshold (LD_{min}) is frequently applied to examine uncertainties between actual elevation changes and noise (Fuller et al. 2003). Values falling below the threshold level are generally discarded, while the values above the threshold are considered real. Threshold levels can be set based on the results of accuracy tests, such as those described in the guidelines defined by the American Society for Photogrammetry and Remote Sensing (Flood, 2004). In this paper, we also characterize the accuracy and uncertainties in the quantification of stream bank erosion/sloughing from errors in vertical accuracy of the LiDAR scans.

MATERIALS AND METHODS

LiDAR Data

With the exception that the calculations were done in Geographic Information System (GIS) software, the procedures used to calculate volume change from two LiDAR scans were similar to those of Thoma et al. (2005). The data processing utilized three data products (bare earth points, hydrologic breaklines, and 0.6 m contours) delivered by the data vendors. The following text briefly describes the features of the two LiDAR scans used in this study.

2005 LiDAR Scan: The first LiDAR scan was done by Optimal Geomatic, Inc., Huntsville, AL with an Optech ALTM 3100 LiDAR system flown at 1836 meters above ground using a laser pulse rate of 70 kHz. The data was collected during 4 flights over two collection periods, April 13-14, 2005 and April 23-24, 2005, with a foot print of 0.45 meters and an average of 1 data point per m^2 during leaf off conditions. Raw LiDAR data was processed by the vendor using proprietary software to produce bare earth points, hydrologic breaklines, and 0.6 m contours. The accuracy of their data was checked by the Minnesota Department of Transportation (MNDOT) using ground truth data with a total of 351 points collected with real time kinetic (RTK) GPS over a variety of land covers. Points included 204 open terrain, 41 tall weeds and crops, 13 brush lands and low tree, and 93 urban areas. The reported fundamental vertical accuracy was ±0.24 m. Fundamental vertical accuracy is calculated as $RMSE_{(z)}$ x 1.96 and refers to the confidence interval at 95% significance (Flood, 2004).

2009 LiDAR Scan: The second LiDAR scan was done by Aero-Metric, Inc., Sheboygan, WI using an Optech ALTM Gemini system flown at 1200 meters above ground with a laser pulse rate of 45 kHz. Data was collected on April, 28 2009 and May 2-3, 2009. Raw LiDAR data was processed by the vendor using proprietary software and included the generation of bare earth points, hydrologic breaklines, and 0.6 m contours. The vendor also collected ground elevation data for 106 points using static and RTK GPS techniques for an accuracy assessment over a variety of land covers. Points included 26 hard surfaces (roads, parking lots, etc.), 20 short grasses, 20 tall grasses/weeds, 20 brushes, and 20 woods. The fundamental vertical accuracy reported was ±0.17 m.

Fieldwork and Laboratory Analysis

Twenty-three soil samples were collected from several river banks representing materials of various origins. These included 14 samples representing glacial tills, 5 samples representing glacial lacustrine and 4 samples representing alluvium deposits. These samples were characterized for bulk density and particle size distribution using the clod method (Grossman and Reinsch, 2002) and the hydrometer method (Gee and Or, 2002), respectively. Average bulk density and fine contents (silt +clay) of three major parent materials were used to convert LiDAR estimated volume change to mass wasting (bank erosion) and then to fine sediment (silt+clay) loss. The bank samples were also analyzed for soluble P using (1:10) 0.01 M $CaCl_2$ solution (Kuo, 1986) and total P via microwave acid digestion (USEPA, 1981). Soluble and total P analysis was done by the Soil Testing Laboratory at the University of Minnesota. These values were then used with mass wasting estimates to calculate soluble P and total P contributions from bank materials.

LiDAR Processing and Analysis

LiDAR Processing: The vendor generated bare earth points in both scans were spatially interpolated to a triangulated irregular network (TIN) of a common extent using the breaklines and contours as hard and soft control lines, respectively. Next each TIN was converted to a DEM grid with a 0.76 meter spatial resolution (hereafter referred to as user DEMs). This resulted in county wide bare earth user DEMs for each year of LiDAR data with the same spatial alignment. River banks for this study were defined as the area between the breakline of the river and the top of the river bank. The highest water mark indicated by breaklines in two scans was used to define the bottom of the bank. In this study, 2005 breaklines represented the highest water mark for all rivers in the study area. Since the LiDAR systems used in collecting the data for this study could not penetrate water surfaces, all areas below the high water mark were eliminated from bank erosion calculations. The top of the bank was manually identified using a combination of aerial imagery (2005 and 2009), hillshade models, and slope grids. Hillshade models and slope grids were calculated for both 2005 and 2009 using the user DEMs. This river bank identification procedure was performed for each river examined. The user DEMs were then subtracted from each other creating a county wide grid showing elevation change from 2005-2009.

LiDAR Analysis: The defined riverbanks were used as the zones for net elevation change calculations. The net elevation change for each river was calculated from the subtracted DEMs (ΔDEM), mentioned above, for all river bank zones using a summary zonal statistic in ArcGIS. This net elevation change for each river was then multiplied by the spatial extent (area) of the river bank zones, resulting in a net volume change. Next, net volume change was multiplied with the average bulk density to calculate mass wasting. The mass wasting values were in turn multiplied with fine content (silt+clay) and soluble P and total P concentrations for each parent material to calculate fine sediment, soluble P and total P losses as a result of bank erosion/sloughing.

Sediment loads for the Blue Earth and Le Sueur Rivers were obtained from USGS water gauging stations (Scott Matheson, Personal Communication, 2010). The gauge readings for the Blue Earth River represented the contributions from the Blue Earth, Perch Creek, and Watonwan Rivers; whereas the gauge reading for the Le Sueur River represented the contributions from the Le Sueur, Maple, Cobb, and Little Cobb Rivers. The contribution of river banks to river sediment load was estimated by dividing the fine sediment loss estimates from this study by the total observed sediment loads at the gauging stations. Soluble P and total P losses are reported as absolute values.

In addition to the above calculations, further analysis was also undertaken to compare the extent of volume change between bluffs and banks. Bluffs were identified using a 10 m x 10 m moving window analysis in ArcGIS and were defined as areas with at least 3 m of relief. Areas identified as bluffs were manually inspected to insure the accuracy of the moving window classification. Remaining areas (< 3 m relief) were considered stream banks. Volume change for bluffs and banks were calculated as percent of the total volume change for each river.

LiDAR Accuracy: The LiDAR data accuracies stated above were the results of accuracy analysis performed on the data provided by the vendor. In addition, we also conducted two accuracy analyses on the user DEMs. In the first accuracy analysis, 78 of the 2005 MNDOT hard surface points were compared against the corresponding points from the 2005 and 2009 user DEMS. This was done to insure data accuracy in user DEMs across years. Since a large proportion of the volume change in this study area was on steep terrains (>10% slope), the second assessment involved testing the vertical accuracy of points on steep terrain. Following the guidelines defined by the American Society for Photogrammetry and Remote Sensing (Flood, 2004), the procedure involved subtracting elevations of 124 points representing a variety of land covers on steep terrains in parks and roads between 2005 and 2009 DEM. These points were known to have no change in elevation from 2005-2009. The points were taken on areas with slopes ranging from 4% to 77% and included wooded (26 points), road (77 points), grass (6 points), tall grass (9 points), and a restored bluff (6 points) land covers.

Uncertainty Analysis: In addition to the accuracy assessments, an uncertainty analysis was also conducted to determine if the potential for higher elevation errors in steep terrain could have a significant impact on the net volume change estimates in this study. A series of LD_{min} were applied to the ΔDEM following methods similar to those developed by Brasington et al. (2000). At each interval, values beneath the minimum threshold (for both erosion and deposition) were removed from the ΔDEM. The net change in volume estimates were then recalculated at each interval for every river, and the results were compared to the original volume change to determine whether or not significant change in the volume occurred at various LD_{min}; a potential indicator of possible uncertainty on steep terrain.

RESULTS AND DISCUSSION

Accuracy Assessment of LiDAR

A series of comparisons of elevation of bare hard surfaces in the study area at the locations where MnDOT measurements were taken are shown in Fig. 3. These comparisons are between estimates from 2005 user DEM and the measurements made by MnDOT (Fig. 3a), between estimates from 2009 user DEM and the measurements made by MnDOT (Fig. 3b), and then between the estimates from 2009 and 2005 user DEMs. In all cases, the slope of the relationship is close to 1 thus suggesting that LiDAR estimated DEM values for bare hard surfaces were fairly close to the true elevation values. Fundamental vertical accuracy ($RMSE_{(z)}$ x 1.96) at 95% confidence interval for the 2005 and 2009 scans corresponded to ±0.20 m and ±0.14 m, respectively. The corresponding fundamental vertical accuracy between the 2005 and 2009 user DEMs was ±0.25 m.

The frequency distribution of differences in elevation determined from 2005 and 2009 user DEMs for points of varying steepness in parks and roads of the Blue Earth County, MN are shown in Fig. 4. The differences in elevation between the two scans showed a fundamental vertical accuracy of ±0.19 m at a 95% confidence level. The elevation differences show near normal distribution with 2005 DEM elevations slightly higher than 2009 DEM elevations.

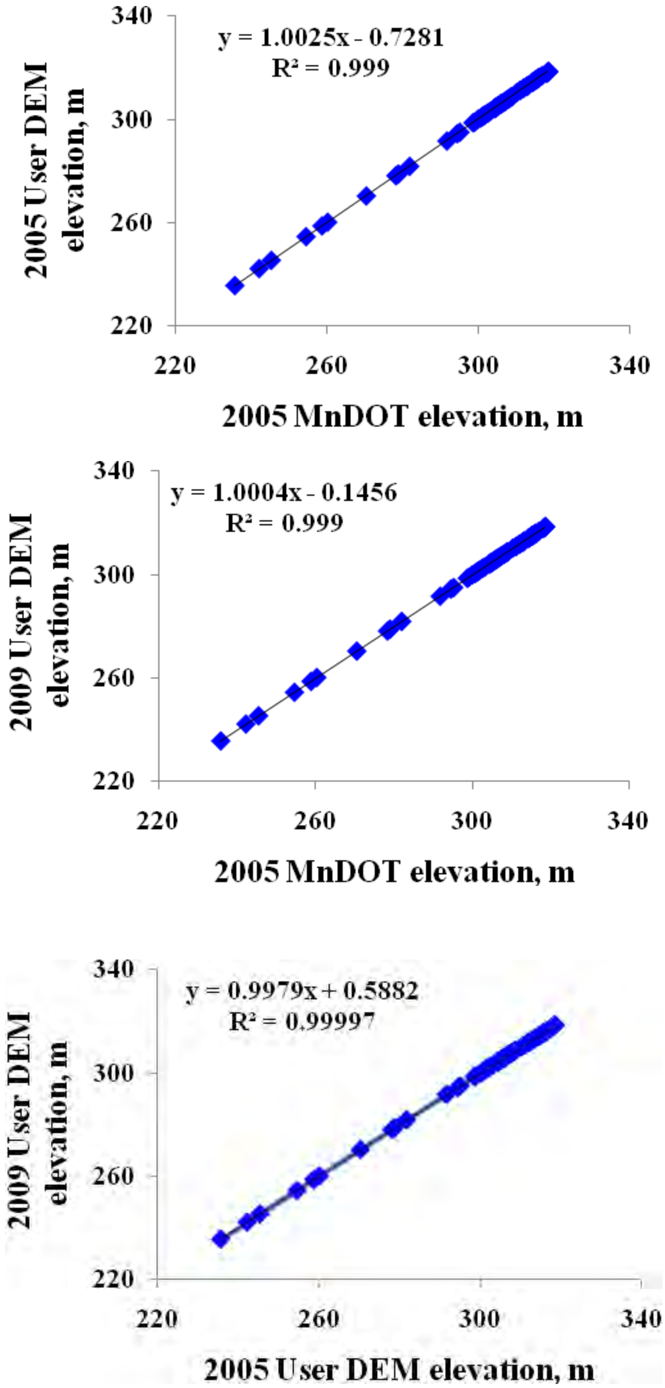


Figure 3: Accuracy assessment of the LiDAR data on flat surfaces: (a) Relationship of elevation between 2005 user DEM and 2005 measurements made by the Minnesota Department of Transportation (MnDOT), (b) Relationship of elevation between 2009 user DEM and 2005 measurements made by the MnDOT, and (c) Relationship of elevation between 2009 user DEM and 2005 user DEM.

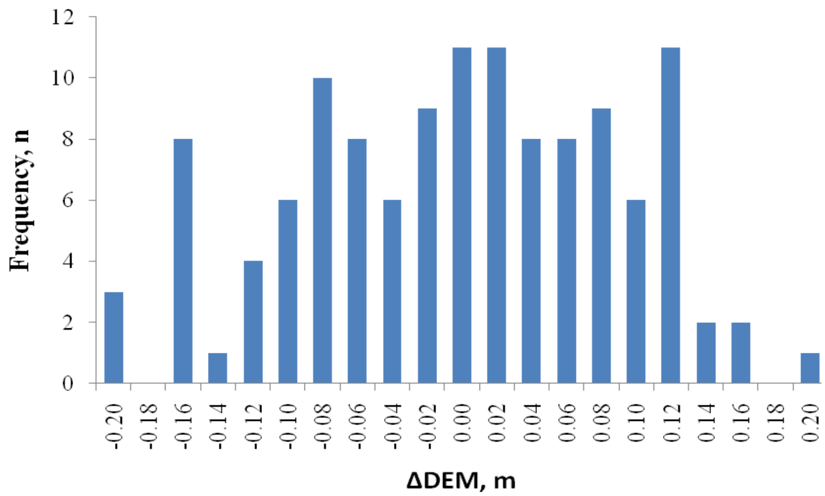


Figure 4: Distribution of elevation difference between 2005 and 2009 user DEMs for various points on steep terrains in parks and roads of the Blue Earth County, Minnesota.

Volume Change in River Valleys

Changes in the volume of river valleys as a result of bank erosion from 2005 to 2009 for several rivers in Blue Earth County, MN are shown in Figure 5. The greatest volume change in the river valley occurred for the Blue Earth River followed by the Le Sueur River, the Maple River, the Watonwan River, the Big Cobb River, the Perch Creek, and the Little Cobb River. Volume change estimates for the Maple, the Big Cobb and the Little Cobb rivers are somewhat conservative because in some sections where the LiDAR data points were insufficient or where they were underwater during 2005 scans, bank erosion calculations were not performed. Volume change in the Minnesota River at the northern edge of Blue Earth County corresponded to 321,571 m^3 from 2005 to 2009.

Mass Wasting and Fine Sediment Losses

Volume change calculations were converted to net mass wasting and then to fine sediment losses by multiplying them with the bulk density, and then again multiplying them with proportion of the fine sediment present in a given parent material. Since the river banks in Blue Earth County consist of varying materials, mass wasting and fine sediment losses were calculated for three major parent materials. Table 1 lists the average bulk density and particle size distribution of glacial till, glacial lacustrine, and alluvium samples collected along river banks in the county. As expected, the bulk density of the tills is much higher (1.83 Mg m^{-3}) than that of lacustrine or alluvium material (1.49 Mg m^{-3}). This is primarily because tills generally occur at deeper depths buried under a large amount of overburden material including thick ice during the ice age. Fine sediment contents were generally higher in lacustrine soils followed by nearly equal amounts in tills and alluvium materials. This combination of higher density and lower fine content in tills, or lower density and higher fine content in lacustrine soils did not result in large differences (<9%) in the total fine sediment losses for various parent materials in a given river system (Fig. 6). Fine sediment losses followed the trend: till> lacustrine>alluvium.

Fine sediment losses in Fig. 6 are plotted as the proportion of the total suspended solids (TSS) measured at one of the two gauging stations: (1) at the mouth of the Blue Earth River below Rapidan Dam, or (2) at the mouth of the Le Sueur River before it joins the Blue Earth River. Percent fine sediment losses for the Blue Earth River, the Watonwan River and the Perch Creek are relative to USGS water gauge measurements for the Blue Earth River below Rapidan Dam, whereas the fine sediment losses for the Le Sueur, the Maple, the Big Cobb, and the Little Cobb Rivers are relative to the measurements at the mouth of the Le Sueur River.

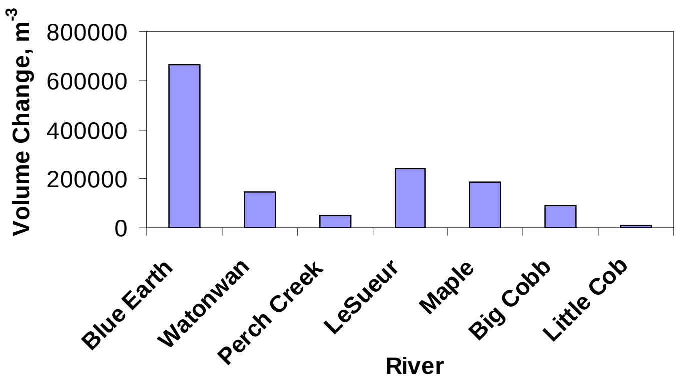


Figure 5: Change in volume of river valleys as a result of bank erosion/sloughing from 2005 to 2009 for several rivers in the Blue Earth County, MN.

Table 1: Mean particle size distribution, bulk density, soluble P, and total P in soil materials representing various parent materials along the river banks in Blue Earth County, MN.

Parent Material	N[¶]	Sand %	Silt %	Clay %	Bulk density, Mg m^{-3}	Soluble P mg kg^{-1}	Total P mg kg^{-1}
Till	14	39.45	27.32	33.23	1.83	0.21	400.4
Lacustrine	5	32.71	31.70	35.59	1.48	0.24	556.2
Alluvium	4	39.60	33.30	27.20	1.50	0.37	503.4

[¶] N=Number of samples

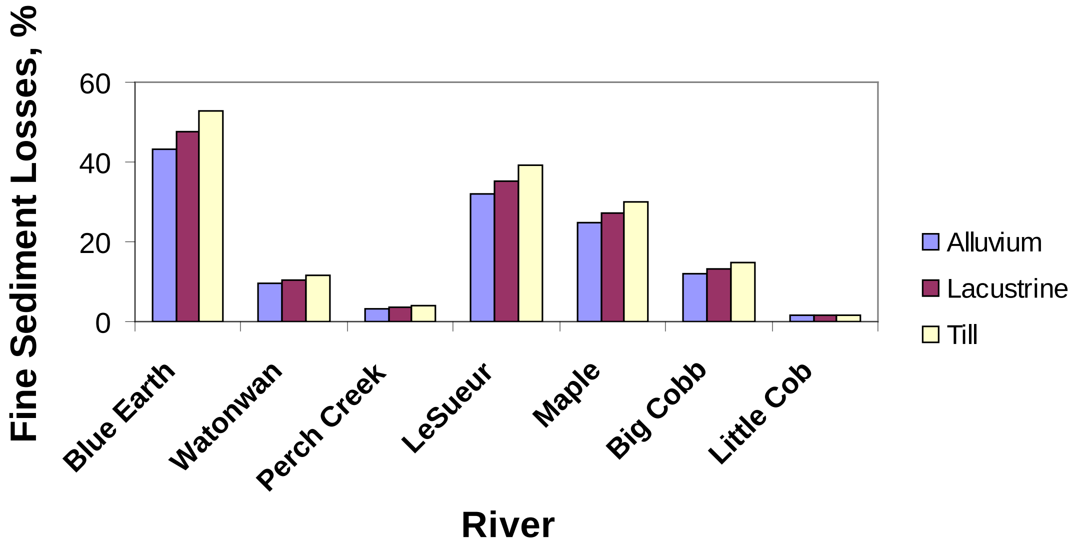


Figure 6: Fine sediment losses as a percentage of measured TSS at the mouth of the Blue Earth River (Blue Earth River, Watonwan River, and Perch Creek) or the Le Sueur River (Le Sueur River, Maple River, Big Cobb River, and Little Cobb River). Fine sediments losses were estimated for each of the three parent materials using specific bulk density and specific fine sediment contents.

Depending upon the parent material combined fine sediment losses from the Blue Earth River, Watonwan River, and Perch Creek varied from 56% to 68% of the TSS measurements at the mouth of the Blue Earth below Rapidan Dam. Similarly, combined fine sediment losses from the Le Sueur, the Maple, the Big Cobb and the Little Cobb Rivers varied from 70 to 86% of the TSS measurements at the mouth of the Le Sueur River before it joins the Blue Earth River. Since these rivers extend past Blue Earth County into the neighboring counties, it is likely that some sloughing of the banks along these rivers in the neighboring counties also occurred. This would suggest that our estimates (56 to 86%) of bank erosion for these rivers are likely an underestimate. Fine sediment contributions from the Minnesota River touching the northern edge of Blue Earth County corresponded to 88,905 Mg yr^{-1}, 80,273 Mg yr^{-1}, and 72,961 Mg yr^{-1} for the till, lacustrine and alluvium parent materials, respectively.

Soluble P and Total P Losses

The soluble P and total P losses associated with bank sloughing for various rivers in the Blue Earth County are shown in Figs. 7 and 8. Generally, soluble P losses followed the trend: alluvium> lacustrine> till. Comparatively, total P losses associated with bank erosion/sloughing follow the trend: lacustrine>alluvium>till. Combined soluble P losses from the Blue Earth River, the Watonwan River and the Perch Creek varied from 77 to 126 kg y^{-1} depending upon the parent material. Corresponding total P losses ranged from 157 to 177 Mg y^{-1}. Depending upon the parent material, combined soluble P losses from the Le Sueur River, the Maple River, the Big

Cobb River, and the Little Cobb River varied from 44 to 77 kg y^{-1}. Corresponding total P losses ranged from 96 to 109 Mg y^{-1}. Soluble P losses from the Minnesota River at the northern edge of the county varied from 29 to 47 kg y^{-1} and the corresponding total P losses ranged from 59 to 66 Mg y^{-1}.

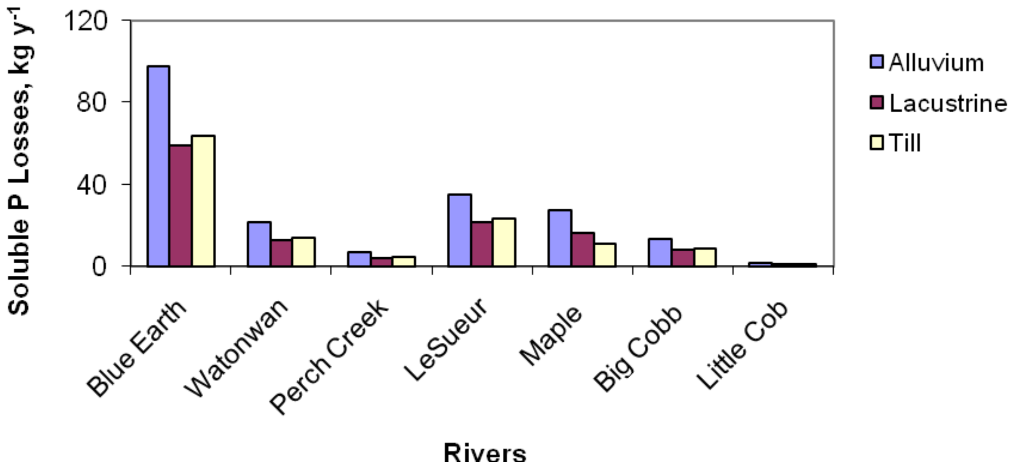


Figure 7: Soluble P losses associated with bank erosion/sloughing from various rivers in the Blue Earth County, MN as a function of three parent materials.

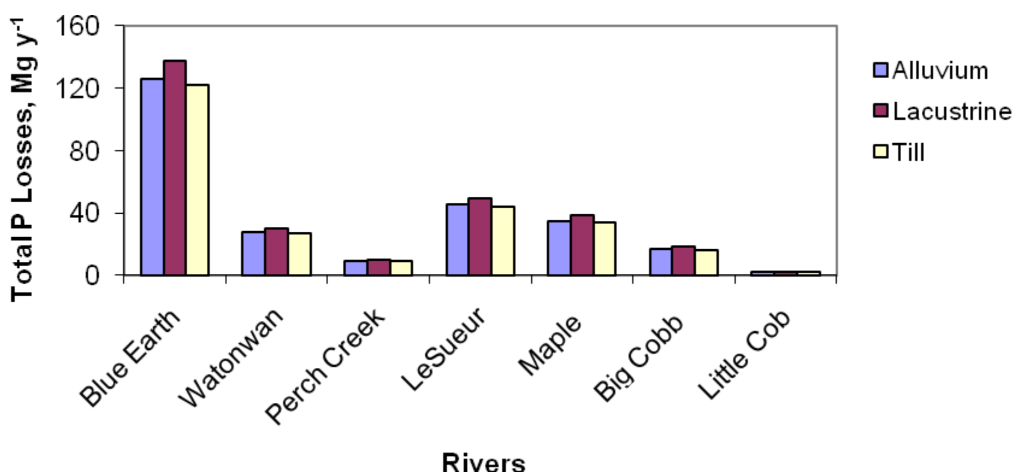


Figure 8: Total P losses associated with bank erosion/sloughing from various rivers in the Blue Earth County, MN as a function of three parent materials.

Contributions from Bluffs vs. Banks

Percent contribution to volume change estimates from bluffs (> 3 meters high) and banks (< 3 meters high) for each river in Blue Earth County are shown in Fig. 9. When summed over all rivers, bluffs and banks, respectively, contributed 75% and 25% of the calculated volume change from the LiDAR scans. This further indicates that tall bluffs are the key producers of sediment from river erosion processes in GBERB. Contribution from smaller (<3 meters high) banks may be a conservative estimate because during the analysis it was quite evident that point bars were forming from the deposition of suspended sediments on the inside of meanders. Although depositional point bars are likely composed of sediments from all sources (fields, ravines, banks, and bluffs), this analysis discounted 100% of the point bar deposition from the areas defined as banks (<3 meters high).

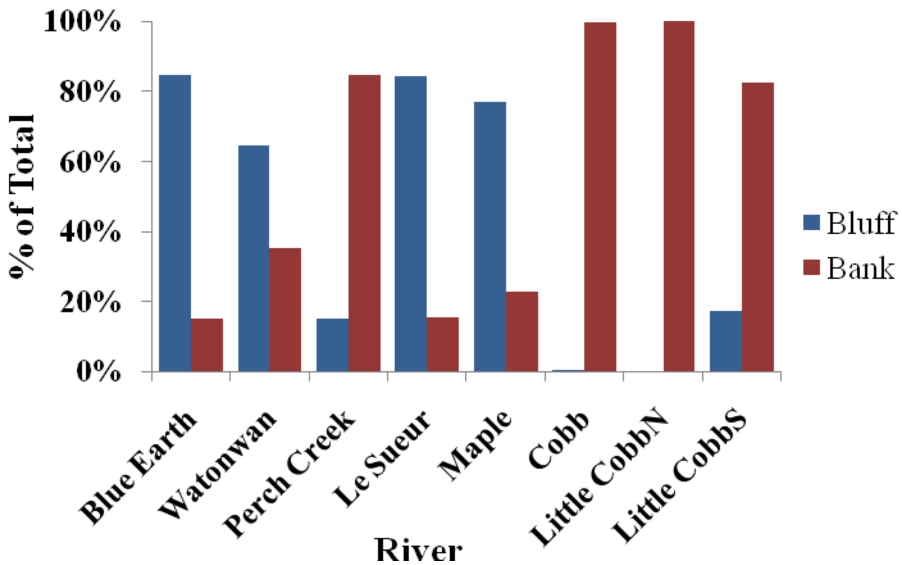


Figure 9: Proportion of the volume change in bluffs (>3m) and banks (<3m) between 2005 and 2009 along various rivers in the Blue Earth County, MN.

LD_{min} Uncertainity Analysis

The results of the LD_{min} uncertainty analysis on net volume change from banks of all the rivers in this study are shown in Fig. 10. These results show that at lower values of LD_{min} (0.46 m), the volume change slightly increases whereas at higher LD_{min} values there is a decrease in volume change. A larger portion of small elevation changes are attributed to deposition and thus deletion of areas with small elevation changes results in an increase in volume change. Conversely, a majority of large elevation changes are the result of erosion and thus deletion of areas with large elevation changes results in a decrease in volume change.

Overall, the results in Fig. 10 indicate that the removal of data within ± 0.91 m has little impact on net volume change for the rivers analyzed in this study. This suggests that the majority of sediment come from areas with large elevation changes thus increasing the confidence that LiDAR is an effective tool for quantification of sediment production in areas with tall banks such as Blue Earth County, MN.

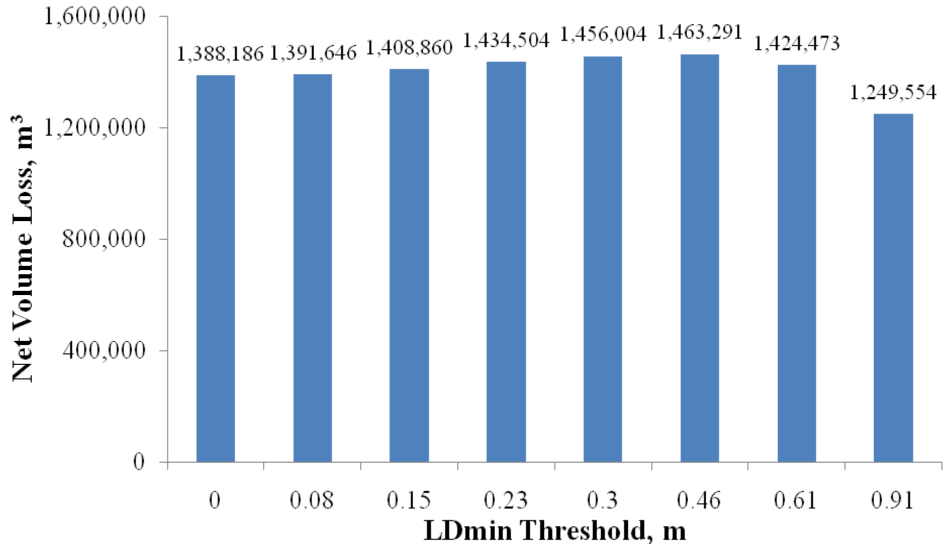


Figure 10: Variation in net volume loss for various levels of LD_{min} threshold in the uncertainty analysis for all rivers in Blue Earth County, MN.

MECHANISMS OF BANK FAILURE

Although bank materials in the MRB are generally high in fine contents and have a higher density than surface soils in agricultural landscape (Thoma et al., 2003), they are not very strong when wet. Two experiments were designed to evaluate these materials when they come in contact with water. In the first experiment, approximately 1 m x 1 m area adjacent to the top edge of a bank on the Le Sueur River was bermed and then continuously ponded for about 15-20 minutes. This experiment was conducted in August 2005 when the soil was relatively dry and there were several cracks at the surface. Piezometer readings showed water quickly moved from the surface to about 2.5 m depth and then ponded there for some time, conditions similar to perch water table conditions. Within a short period, water started leaking through a horizontal layer at the base of the bank (2.5-2.7 m depth). In about 15-20 minutes, the bank failed as a rotational block (Fig. 11), about 60-90 cm back from the edge with about 2 tons of soil sloughing (video-supplemental material). The top of the bank with grass roots was still in place. Except for a small channel at the base, there was little water seepage from the face of the bank. The bank failure occurred because of an increased weight of wet soil and increased pore water pressure in the soil that acted against the soil's cohesive forces (Casagli et al., 1999). Tensiometer data showed that bank failure occurred at saturation when matric suction went to zero or negative. The next experiment examined the impacts of water coming in contact with bank materials. In this experiment, small soil clods taken from various river banks were brought in contact with about 1 cm of standing water. The dry clods soaked up the water by capillary action and within one to two hours disintegrated. The degree of disintegration, from the development of cracks to chunks falling off to a soupy mass, varied for different bank materials. An example of a clod that showed the most drastic change in its configuration after coming in contact with water is shown in Fig. 12.

Additional visual field observations also suggest that during the rising limb of the hydrograph capillary action forces water into the bank and when the river recedes, the banks slump due to the lack of pressure from the river water, as well as wet weight of the soil (Fig. 13). The slumped materials are subsequently taken away by river flow causing the top of the bank to slough and in some cases adjoining banks to fail as a collateral damage.

Figure 11. Picture of the bank along the Le Sueur River after a rotational failure due to pore water pressure build up behind it.

Perched water table conditions indicated by the presence of seepage spots are another dominating factor causing bank sloughing in the area (Fig. 14). Seepage-induced bank failure is due to liquefaction of the soil or increased pore water pressure. Additional factors causing bank failure include freezing and thawing, wetting and drying, and undercutting of river banks. During early spring when soils are still frozen, the authors have observed soil material rolling off the banks facing the sun. It appears that the top few centimeters of the materials often thaw out faster than the bottom and slide down due to lack of binding with the frozen base.

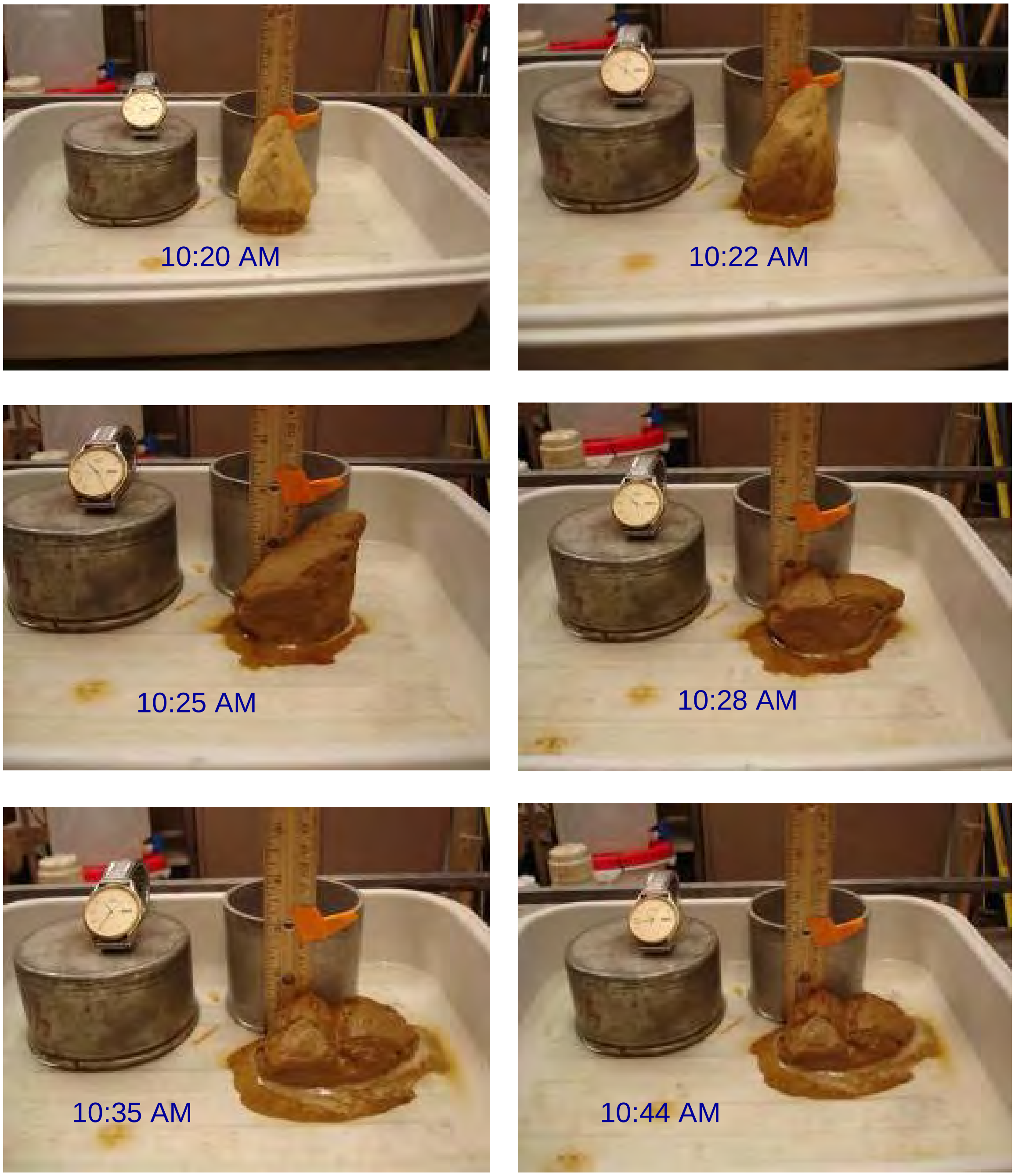


Figure 12: Time series pictures of a clod showing its disintegration when placed in shallow water.

Figure 13. A picture of the slumping bank along the Blue Earth River, MN. The slump is caused by detachment of the bank bottom due to low soil strength and heavy wet soil during recession hydrograph.

Figure 14. Seepage from banks along the Le Sueur River (Fig. 14a, photograph taken by Scott Salsbury, spring 2010) and the Blue Earth River (Fig. 14b). The seepage that caused bank failure in Fig. 14 b started in the middle of the bank.

An additional source of sediment is from the lateral migration of rivers. Comparisons of photographs over time have shown drastic movement of the river in the basin. The authors observed that much of this migration occurs during large flows from high precipitation or snowmelt events with ice jams. As an example, Fig. 15 shows the movement of a reach of the Blue Earth River from 1938 to 2009. Some of this is a cumulative effect of bank failure and some is due to river migration. Along the given transect, the river has moved 120 m, an equivalent of 1.7 m per year. The figure also shows the cutoff of an oxbow. During the movement of these rivers, a substantial quantity of sediment is taken out from the river banks. An example of this phenomenon was also observed in September 2010 on the Maple River near Good Thunder. The area received about 25 cm of rain in one day resulting in large river flow that took out the road connecting the bridge over the river, as well as part of the peninsula (Fig.16). Sometimes several bank failure mechanisms act in unison on a single bluff, thus exacerbating sediment production. Recently, Hansen et al. (2010) concluded that overall sinuosity (river length/valley length) of the Minnesota River has reduced from 1.5 to 1.3 since 1855 and the width of the channel has increased from 70 to 104 m since 1938.

Suggestions have also been made that planting trees on banks such as in Figs. 13 and 14 would help stabilize these banks and thus reduce the sediment load in the Minnesota River. Figure 15 shows that a large portion of the bank in Fig. 14b was under forest in 1938, but the trees failed to prevent bank sloughing. Similar observations were noted for other banks after superimposing the 2009 breaklines on aerial photographs taken in 1938.

Based on visual observations, it appears that the catastrophic failure of river banks is continuously occurring in GBERB. Figure 17 shows a sequence of photographs of a bank along the Blue Earth River. Figure 17a shows some debris at the base of the bank on 27 May 2010. The reason for the presence of this debris is not clear. However, this failure does not appear to be due to river water reaching the top of the pillar or seepage from the back. The owners of the land moved to this property around 1996 and at that time they could walk up to the tip of the standing pillar in Fig. 17b (close up in Fig. 17c) from where this picture was taken. A subsequent picture (Fig. 17d) shows that in little over a month, the pillar fell apart. There was some rain and slightly windy conditions in the area during that period (28 June-5 August, 2010).

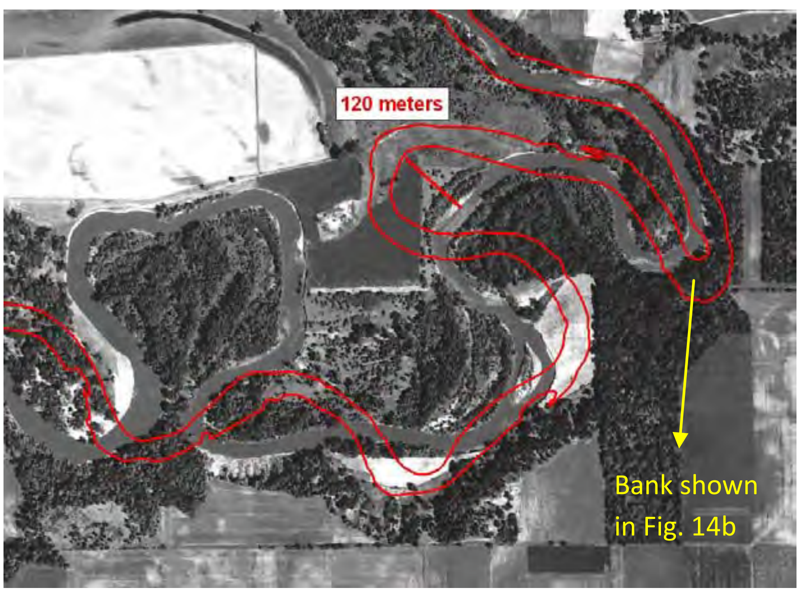


Figure 15: 2009 position (Red Line) of a reach of the Blue Earth River on 1938 photograph showing the extent of river movement between 1938 to 2009. Present day path has cut off the oxbow present in the 1938 photograph. Channel migration at the transect is about 120 m over 61 years.

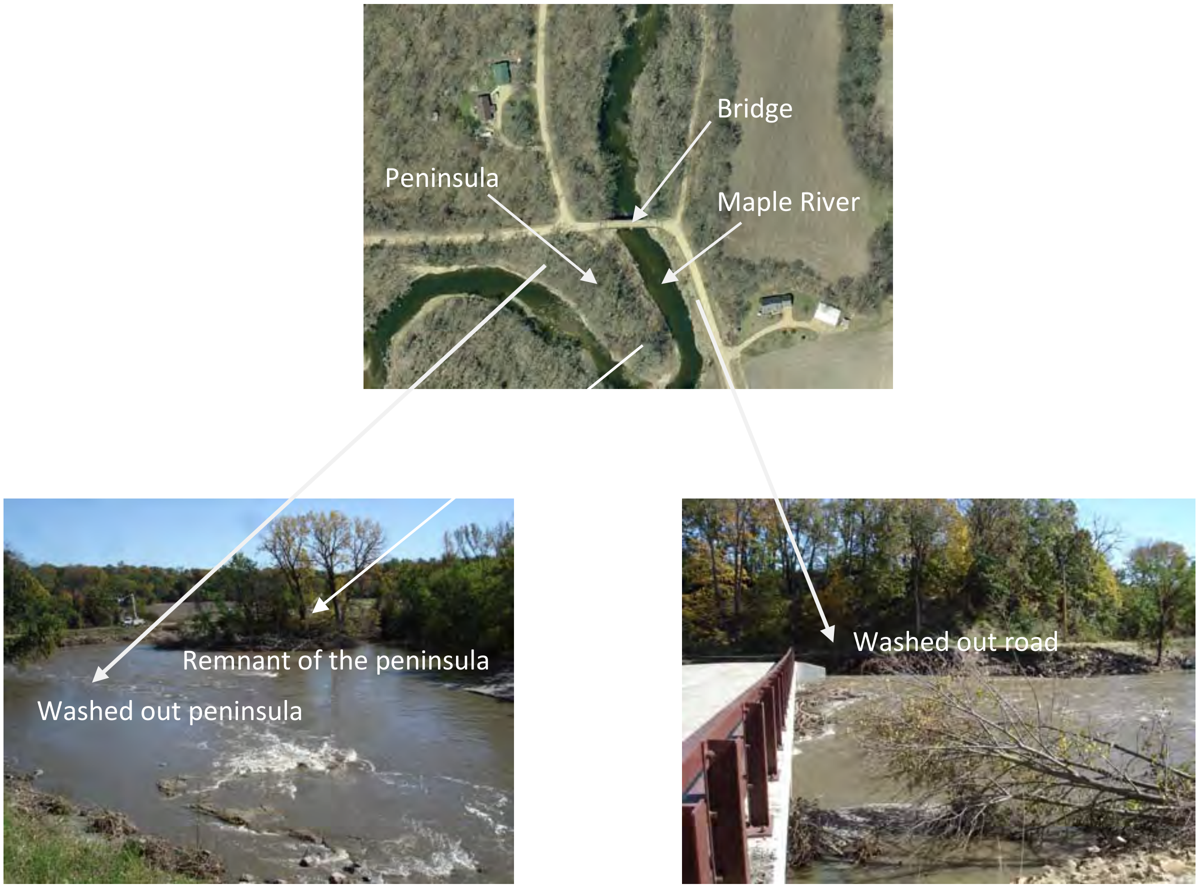


Figure 16: A peninsula in the Maple River near Good Thunder. The peninsula as well as road connecting the bridge washed out due to heavy rainfall (25 cm in a day) in the area in September 2010.

The bank failure mechanisms described above in combination with LiDAR measurements of significant bank erosion (56% to 86% of the measured values) would suggest that sediments in the Minnesota River and its tributaries are mainly coming from river banks and the bank failure mechanisms are primarily controlled by natural factors such as the material properties and precipitation (presence of free water either through seepage or from capillary action along the river). The material properties have not changed drastically in the last 200-300 years because of the slow pace of soil formation processes. On the other hand, precipitation has varied somewhat over this period. Figure 18 shows the probabilities of annual precipitation in the MRB for the periods 1891-1939 and 1940-2003. Except for the return period of about 1.1 years (>97% probability), all other annual precipitations have increased by as much as 10 cm during the period 1940-2003 as compared to 1891-1939. For a site with longer precipitation record such as at St. Paul, MN (Fig. 19), the differences in annual precipitation between 1940-1999 and 1859-1939 are consistently higher for all return periods (>1 year). Johnson et al. (2009 a,b) showed that mean annual flow and sediment loads in the Minnesota River at Fort Snelling closely followed the precipitation trends in the MRB from 1976 to 2003 (Fig. 20).

The above observations on weak bank materials when wet in combination with increased trends in precipitation suggest that, consistent with precipitation, sediment production in GBERB and more widely in the MRB is likely a natural phenomenon involving bank erosion/sloughing and must have been going on even before European settlers came to the area.

Figure 17: A series of picture showing catastrophic failure of a bank along the Blue Earth River. Dates these photographs were taken are 27 May 2010 (Fig. 17a), 28 June 2010 (Fig. 17b, c), and 5 August 2010 (Fig. 17d).

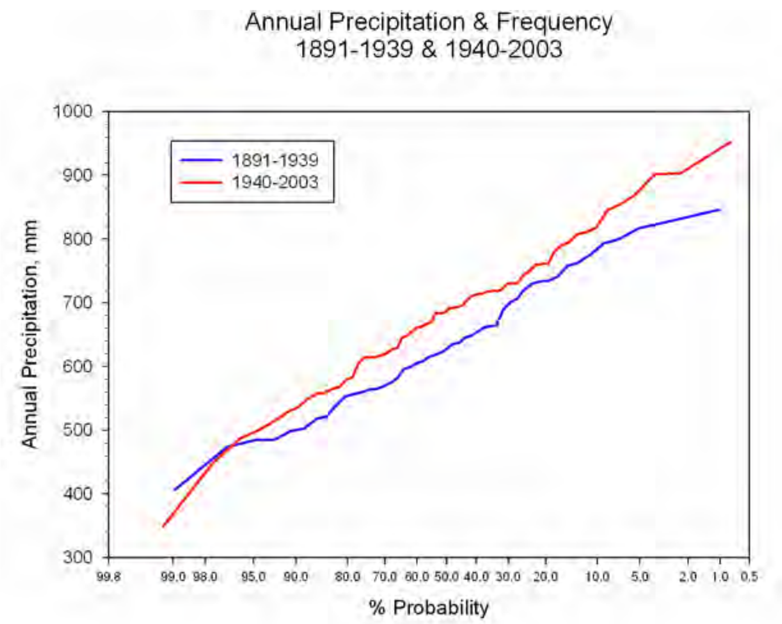


Figure 18: Annual precipitation at various probabilities in the Minnesota River Basin for the periods 1891-1939 and 1940-2003.

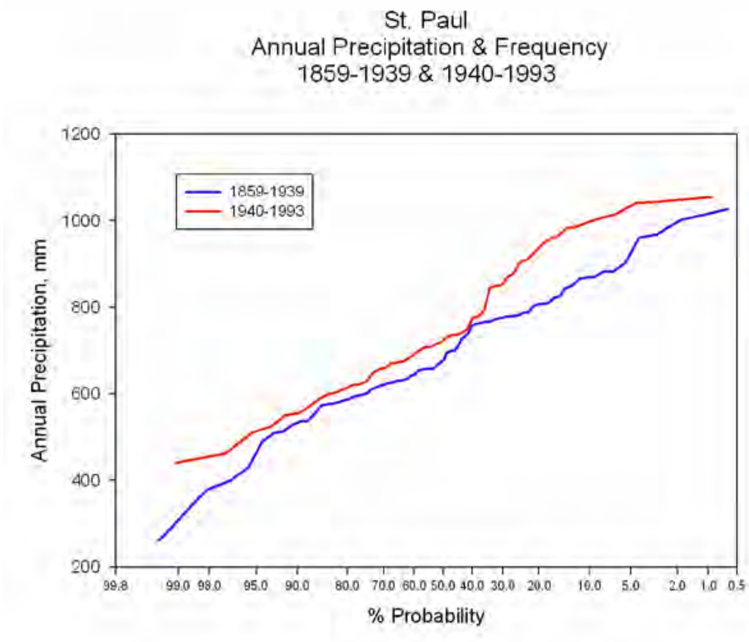


Figure 19: Annual precipitation at various probabilities in St. Paul for the periods 1859-1939 and 1940-1993.

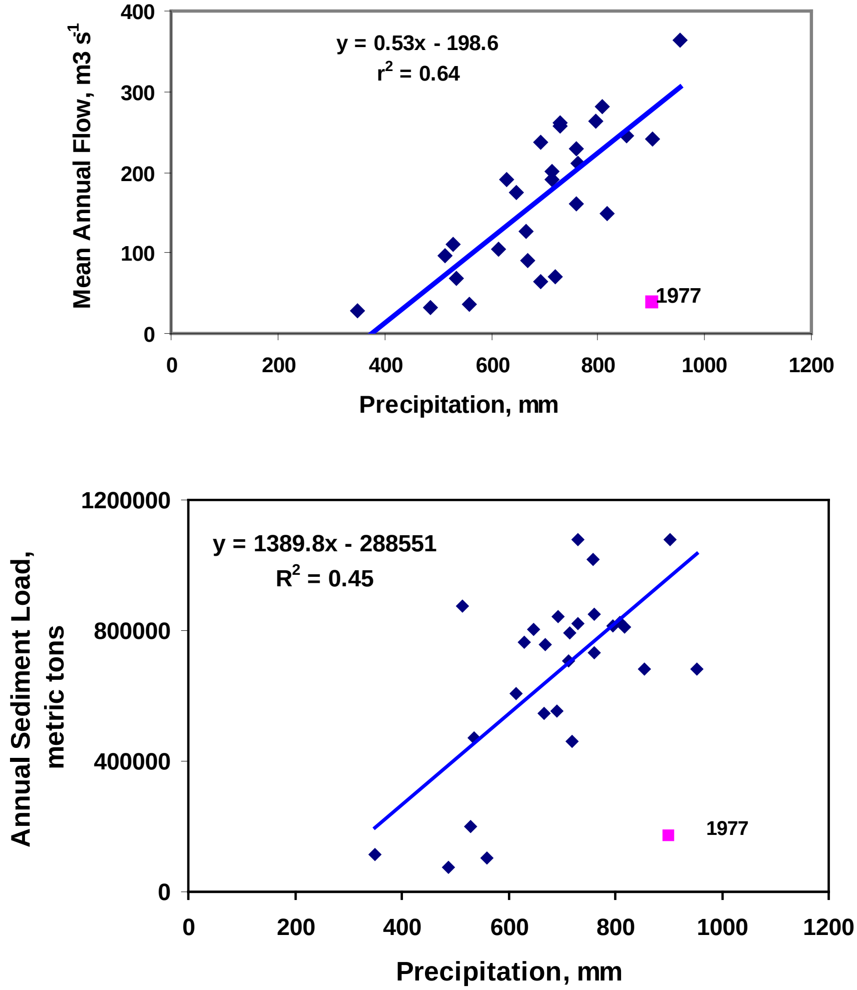


Figure 20: Relationships between mean annual flow and sediment load in the Minnesota River at Fort Snelling as a function of precipitation for the period 1976-2003 (Johnson et al., 2009 a). Data point for 1977 is an outlier and is not included in the regression.

FACTORS AFFECTING THE FILLING OF LAKE PEPIN

As stated earlier, Kelly and Nater (2000) have shown that the Minnesota River and its tributaries are the major contributor of sediment to Lake Pepin. Recently, Engstrom et al. (2009) and Balogh et al. (2009) have suggested that the increased rates of sedimentation in Lake Pepin since 1830 are due to the onset of European settlement in Minnesota and more specifically due to cultivation and tile drainage of agricultural lands in the MRB. In this section, we are presenting alternative explanations to their assertions by presenting multiple levels of evidence: (1) the Minnesota River and its tributaries have historically been sediment laden, (2) total population of Minnesota was small (6,077) in 1850 and could have not caused the increased sedimentation in Lake Pepin between 1830 to 1850, (3) earlier cultivation tools were somewhat primitive and could not have resulted in large sediment loads, (4) even after the availability of a variety of plows in 1850-1870s, soil cultivation was relatively shallow (4-5 inches deep), (5) earlier settlers did not drain wetlands because there was plenty of land for settling and because they preferred wild hay growing in wetlands for their draft animals, (6) most of the cultivated area was under small grains which provided good soil cover thus small to minimal erosion, and (7) the limited area that was in row crops, like corn, was typically in a 3 to 5 year rotation with oats and meadow and would have resulted in minimal soil erosion. We further show that increased sediment loads to Lake Pepin in recent years may be due to significant changes in sediment transport processes in river channels (such as dredging, straightening, widening, and building of levees) in combination with increased flow due to increased impervious surfaces (roads, parking lots, roof tops) and higher precipitation. We also raise the question whether pre-1830 sedimentation rates measured by Engstrom et al. (2009) in core samples are the true historic rates because of the presence of a delta in the Mississippi River that is moving downstream towards the present day Lake Pepin.

In brief, we are posing a question: to what extent are the increased sedimentation rates in Lake Pepin attributable to natural processes and in-stream modifications versus agricultural activities including land conversion and artificial drainage in the Minnesota River Basin? The discussion below is divided into three periods: Pre-1910, 1910 to 1940 and from 1940 to Present. Figure 21 shows a timeline of various activities related to agricultural drainage, channel modifications and historical travelers' logs. We also provide the timeline of precipitation variation during these periods, as well as rates of sedimentation in Lake Pepin presented by Engstrom et al. (2009).

Pre-1910:

Minnesota was declared a United States Territory in 1849 and a state in 1858. Census data show a total population of 6,077 in 1850 which increased to 172,023 in 1860 and then 1.75 million by 1900 (Dole and Wesbrook, 1907). As stated earlier, the MRB is relatively flat with 33% of the land <2% slope and 74% of the land <6% slope. Similarly, the GBERB is even flatter than the MRB with 54% and 93% of the land <2% and <6% slope, respectively. Since significant soil erosion from agricultural fields is generally associated with basins that have steeper slopes, cursory analysis would suggest that large sediment loads in the Minnesota River and its tributaries could not be coming from agricultural fields in the MRB (0.2 to 3.3 million Mg per year from 1968 to 1992) or in the GBERB (0.14 to 0.77 Million Mg per year from 2000 to 2008).

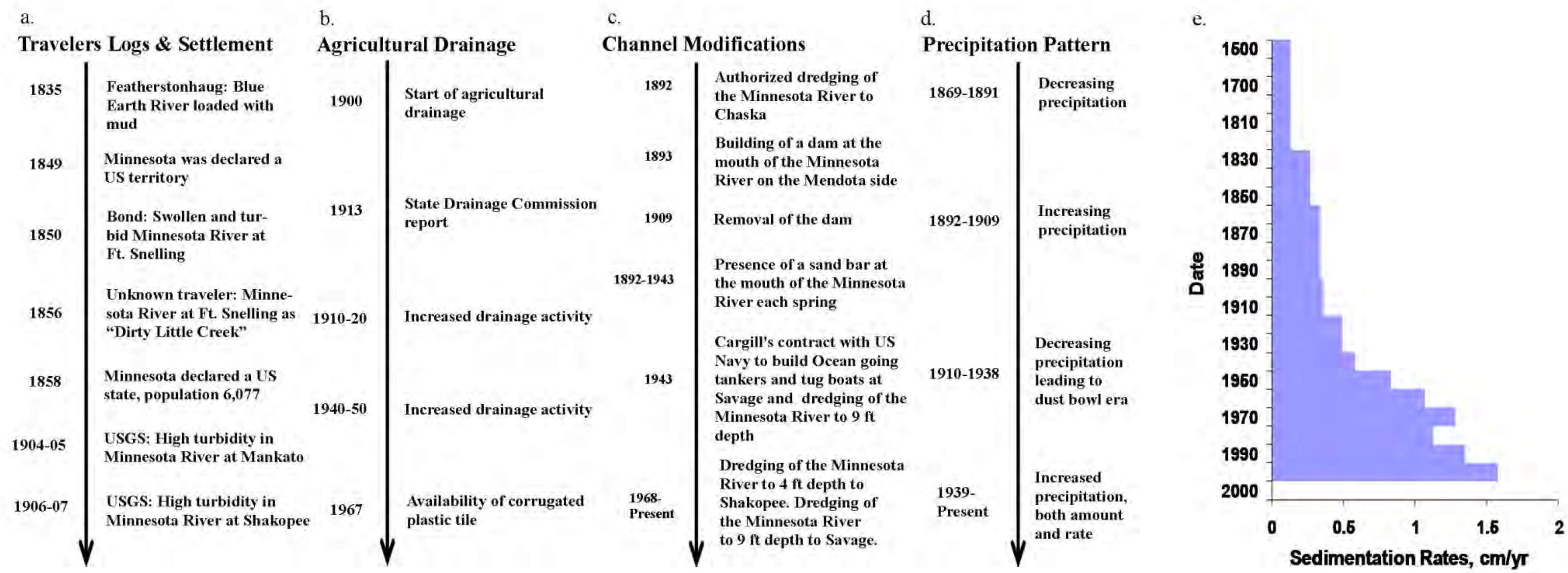


Figure 21: Timelines of historic travelers logs, settlement in Minnesota, agricultural drainage activities, channel modifications, precipitation patterns, and the rates of sedimentation in Lake Pepin. Rates of sedimentation in Lake Pepin are taken from Engstrom et al., 2009 and re-drawn.

Historic River Water Quality: There have been several qualitative and quantitative descriptions of the water quality of the Minnesota River and its tributaries prior to 1910. For example, G.W. Featherstonhaugh, a well known geologist of his time, recorded on 22 September 1835 that the Blue Earth River was "…loaded with mud of a blueish colour, evidently the cause of the St. Peters being so turbid" (Featherstonhaugh, 1847). St. Peters is the previous name for the Minnesota River. The author mentioned a rain event occurring in the area at that time and also noted that half of the water volume in the Minnesota River at Mankato was coming from the Blue Earth River. Featherstonhaugh's observations about the Blue Earth River being muddy and the cause of the Minnesota River being turbid while representing half of its volume are similar to USGS findings in recent times (Payne, 1994). The important implications of Featherstonhaugh's observations are that there was limited agriculture in 1835 (land was mostly under prairie grass) and thus high levels of turbidity or sediment load, especially during the fall in the Blue Earth River, must be from tall river banks noted in his travel log. Featherstonhaug (1847) also noted that on 26 September 1835 between New Ulm and Redwood Falls, upstream from the confluence of the Blue Earth and the Minnesota Rivers, the Minnesota River was shallow (30 cm deep) and "beautifully transparent" with countless mussels stuck in white sand that he could select by baring his arm as he went upstream in his canoe. Shallowness and transparency reflect the low flow conditions typical of the fall in the MRB due to dry weather. The authors of this report also observed somewhat transparent water conditions in a shallow Blue Earth River on 18 August 2010. The authors were also able to pick up mussels from the bottom of the shallow Blue Earth River (Fig. 22). Although the Minnesota River between New Ulm and Redwood Falls is not completely transparent at present times, its TSS concentration (turbidity) is lower than downstream TSS, especially after the confluence with the Blue Earth River in Mankato (Payne, 1994).

Several other pioneers have also noted the turbid nature of the Minnesota River in the 1850s. Bond (1857) reminisced about the events and excitements of the celebrated voyage on the steamboat Yankee day after day as he and 100 other St. Paul citizens ascended up the "swollen and turbid" Minnesota River in 1850. An Assistant Surgeon at Fort Ridgley (between Redwood Falls and Mankato) in 1856 noted that Minnesota River was somewhat yellow and turbid with a muddy bottom (Hasson, 1856). A traveler coming from St. Croix River in 1856 wrote in his diary that Minnesota River at Fort Snelling was "a dirty little creek" (Jones, 1962). Other similar descriptions of poor water quality of the Minnesota River and its tributaries are recorded in other historic travelers' logs.

Although there are limited quantitative measurements of turbidity in the Minnesota River in earlier times, the USGS measurements (Dole and Wesbrook, 1907) in January 1904 to May 1905 show that turbidity (in equivalent standard silica concentration) of the Minnesota River at Mankato, MN varied from 10-40 mg L^{-1} with a peak at 400 mg L^{-1} (Fig. 23). These authors also reported that turbidity values during spring freshets (a flood resulting from heavy rain or a spring thaw, Wikepedia, 2011) in other years went as high as 600 to 800 mg L^{-1}. Similar measurements on the Minnesota River at Shakopee in 1906-1907 (Fig. 24) showed peak turbidity (in equivalent silica concentration) to be as high as 330 mg L^{-1} in mid July 1907 (Dole, 1909). This value of turbidity appears to be disproportionately high considering that January thru July 1907 precipitation for the Minnesota River Basin was much below normal (381 mm vs. 487 mm for 30 year normal).

Figure 22: A picture of a mussel specimen observed in a shallow Blue Earth River on 18 August 2010.

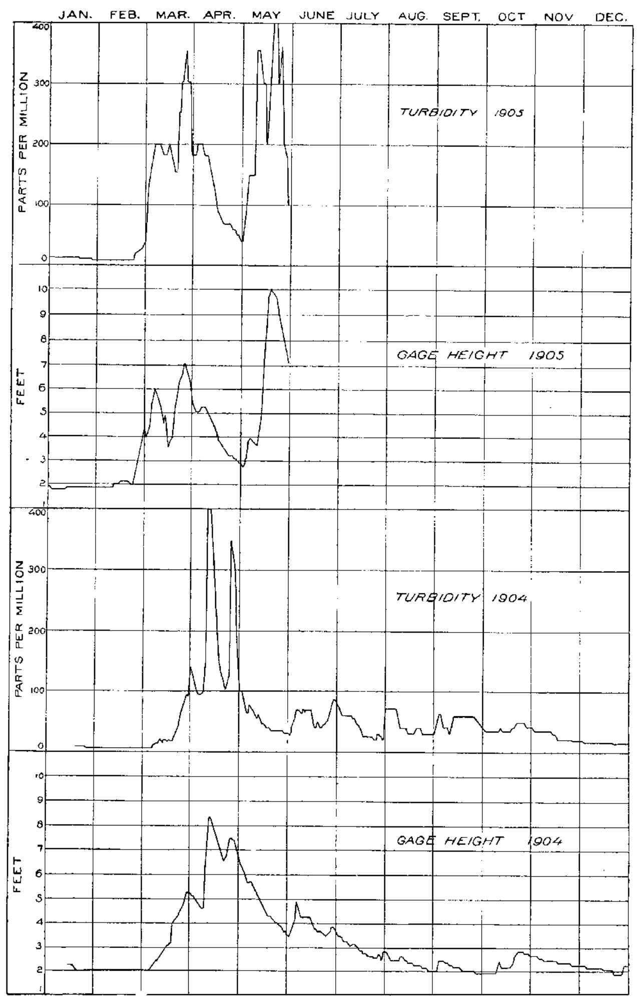


Figure 23. USGS measurements of turbidity in equivalent silica concentration and gauge height of the Minnesota River 1904-1905 at Mankato, MN (Taken from Dole and Wesbrook, 1907).

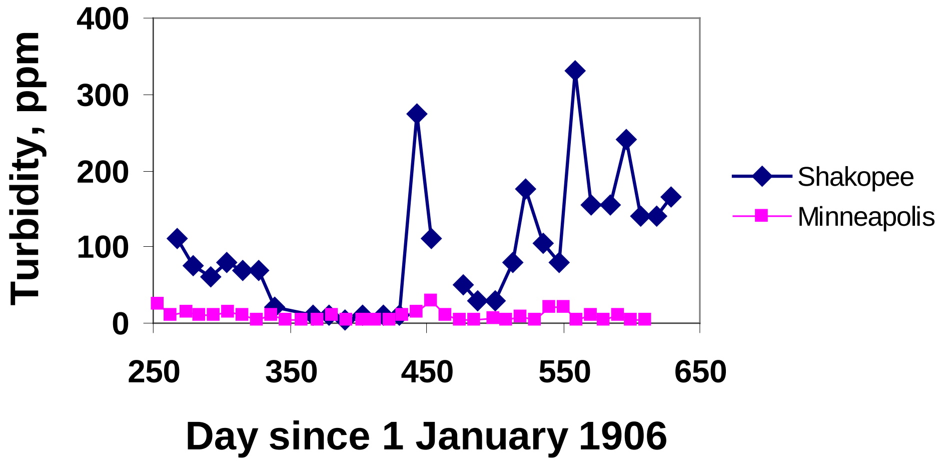


Figure 24: USGS measurements of turbidity in equivalent silica concentration at Shakopee, MN on the Minnesota River and on the Mississippi River at Minneapolis, MN in 1906-1907. (Data taken from Dole, 1909). Precipitation in the Minnesota River Basin in 1906 and 1907 corresponded to 74 and 58 cm, respectively.

Historic Agricultural practices: Arguments have also been made that prairies were plowed when European settlers came to the area resulting in more soil erosion, greater sediment loads in rivers, and thus higher rates of sedimentation in Lake Pepin starting in 1830 (Engstrom et al., 2009; Schottler et al., 2010). Earlier cultivation tools were generally primitive. In the 1840s, most plows were made of wood, but in some cases a metal tip or strap-iron covered the moldboard plow to reinforce wooden parts (Jarchow, 1949 ; Lettermann, 1966). The iron or steel moldboard plow appeared on the scene in 1850s, and was called the sod or prairie-breaking plow. Sometimes, as many as 10 yokes of oxen were required to pull this plow (Jarchow, 1949). These earlier wooden and iron plows would not scour in rich prairie soils and the farmer had to carry paddles to clean the plowshare frequently (Jarchow, 1949). By 1860, cast iron plows were numerous and the scouring steel moldboard plow made by John Deere was also available in Minnesota. However, earlier steel plows were often brittle and tended to warp (Jarchow, 1949). During this decade, several plow and agricultural implement manufacturing companies also started making these plows in Minnesota. Plow improvements included the hardening of cast iron, which improved its wearing capacity, as well as scouring ability. Although a variety of plows started becoming available in 1860, cultivation was still only 4-5 inches deep (Jarchow, 1949). The farm papers constantly criticized the farmers for shallow cultivation during this period. The papers suggested that deep cultivation will alleviate drought problems. In 1870s, steam plows started becoming available but they were too expensive for many farmers to afford.

Considering these primitive plowing tools on land that is fairly flat (Fig. 25), it is highly unlikely that large sediment loads in the MRB rivers in earlier times were due to the initial cultivation of the prairies. Furthermore, substantial area in earlier times was planted to small grains (wheat, oats, and barley), tame (cultivated) and wild hay, flax, and rye (Table 2), all crops known to provide better soil cover than corn and as such, are less conducive to soil erosion. In 1910, areas in small grain, cultivated hay, wild hay, and corn in Blue Earth County corresponded to 26.9%, 6.2%, 6.2%, and 13.7% of the total county area, respectively (Burns, 1954). This suggests that it was unlikely that the turbidity of the rivers in the area from 1850-1910 was due to the initial cultivation of the prairies. Furthermore, for the first half of 20th century, corn was frequently grown in a three year rotation (Barewald, 1989) or a five year rotation (Dr. Vern Cardwell, Professor of Agronomy, University of Minnesota, Personal communication, 2010) with hay and small grains, such as oats or barley. Oats and hay were needed for feeding of dairy and draft animals. The Universal Soil Loss Equation (USLE) demonstrates well that soil loss is substantially lower from corn in a rotation with oats and hay, than from corn grown continuously or corn-soybean rotation. For example, "the crop/vegetation and management factor" (C)-value in USLE for a fall-tilled moldboard-plowed field in the Midwestern United States is 0.071 for corn-oats-hay-hay-hay compared to 0.12 for corn-oats-hay and 0.48 for continuous corn (Wischmeier and Smith, 1972). This translates to soil erosion reduction of 75% and 85% for three year and five year rotations, respectively. This analysis would suggest that the role of corn (a row crop) in sediment production prior to 1910 as suggested by agencies (Rott, 2007) and shown by regression analysis (Mulla and Seekley, 2009) would be rather minimal.

Figure 25: A view of the flat landscape in the Minnesota River Basin showing two "potholes": the one in the foreground with wet soil and the one in the background with ponded water. Picture taken by David Thoma.

Table 2: Crop land statistics for Blue Earth County from 1860-1910 (Adopted from Burns, 1954)

	---Year---					
	1860	1870	1880	1890	1900	1910
% of Land In Farms	15	58	76	85	94	93
% of Farmland in Crops	-	32.1	46.0	42.8	58.9	62
	---Area, acres---					
Wheat	(21,513)¶	(725,879)	96,660	75,997	156,610	85,509
Hay (Tame)	-	-	-	38,723	33,040	30,564
(Wild)	-	-	-	20,000	21,968	30,514
(All kind)	(8,636)	(18,994)	57,365	58,723	54,008	61,078
Oats	(22,838)	(467,575)	21,766	35,528	39,746	43,732
Corn	(72,700)	(198,060)	21,636	42,319	44,214	67,157
Flax	-	-	24,114	14,137	6,321	924
Barley	(476)	(35,146)	3,029	4,148	5,210	2,580

¶ Number in parenthesis are in bushels or tons

Historic Drainage Practices: The MRB is part of the pothole region of the Upper Midwest and is generally flat. Potholes are small depressions with slight inward gradient (Fig. 25) and are generally not hydrologically connected to each other at the soil surface (Haan and Johnson, 1967). Soils in the basin have high clay content (>30%) which in turn results in their lower permeability to water infiltration and its subsequent downward movement (Thoma et al., 2005). Reduced soil permeability in turn creates perched water table conditions in the landscape leading to standing water in agricultural fields after snowmelt and spring rains. To overcome problems associated with ponding and perched water table conditions, farmers have installed surface and subsurface tile drainage systems that remove and transport water from agricultural fields to surface waterways (ditches and streams).

Tile drainage of agricultural land in the MRB started around 1900 with the construction of County and Judicial ditches. According to the Minnesota Drainage Commission (Ralph, 1913a,b), a total of 4,226 kilometers of ditches were completed or under construction by 1912 in 26 of the 37 counties of the MRB (Fig. 26). These drainage ditches were organized as drainage enterprises. The commission reported that 191,012 ha in the basin benefited or will benefit from these ditches, an area equal to 4.4% of the total area in 26 counties. The corresponding area for the Blue Earth County was 4,452 ha, or 2.2% of its total area.

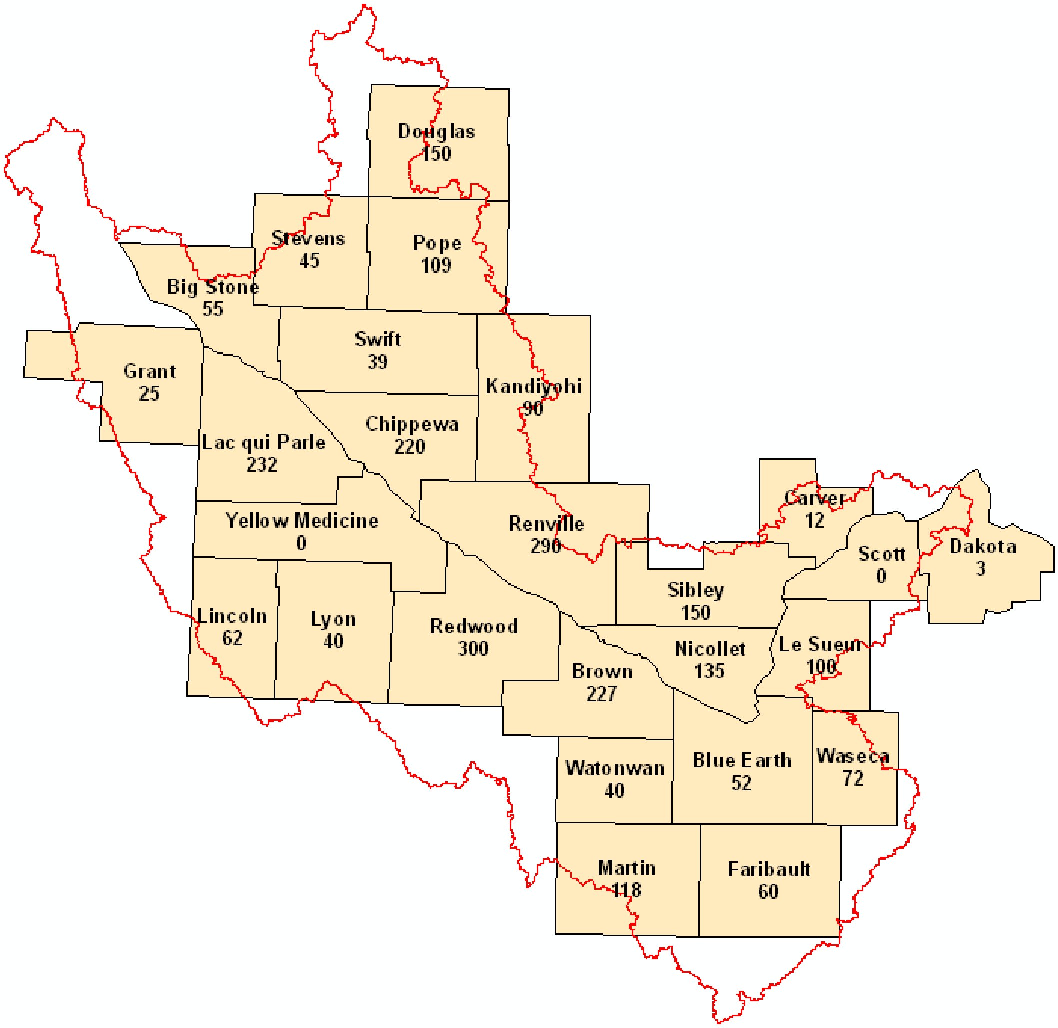


Figure 26: Distribution of miles of County and Judicial ditches in 26 counties of the Minnesota River in 1912. Data taken from Minnesota Drainage Commission Reports (1913).

Based on Census data, Burns (1954) reported that 1% and 6% of the land area in Blue Earth county was within the drainage enterprise in 1900 and 1910, respectively. While studying the modification of wet prairies in Southern Minnesota, Moline (1969) concluded that prior to 1910, settlers regarded the wet areas indifferently and did not see the need to drain partially because there was enough area for settlement and partially the wet ground produced higher yields of wild hay. There was no cost associated with raising wild hay and it provided decent feed for both dairy and draft animals (Burns, 1954; Moline, 1969). It was only after World War I (after 1918), when prices of commodities started to increase and more sophisticated drainage technology became available that draining wet areas was economically beneficial to farmers (Moline, 1969). The author concluded that full scale drainage did not start until about 50-60 years after the initial settlement thus weakening the criticism the settlers from earlier periods were the culprits of wetland drainage. These observations are consistent with the observations of others on the development of agriculture in the state. For example, Jarchow (1949) in the History of Minnesota Agriculture to 1885 recorded that earlier settlers were more concerned with issues involving mechanization, such as development of plows, drills, rakes, and harvesting and threshing equipment with some efforts going into the development of dairy industry. There is no mention of drainage in this writing.

Both historic travelers' logs, as well as USGS measurements indicate that the Minnesota River and its tributaries were turbid in earlier times, including the period before the European settlers came to the territory and also before the installation of drainage networks in the basin. These observations are consistent with our LiDAR calculations showing high proportions of the sediments in Blue Earth County rivers are from bank erosion/sloughing. This further suggests that the majority of sediment production in the basin is due to bank sloughing and is primarily controlled by natural processes such as soil properties, landscape slope, and precipitation. Agricultural statistics as well as the history of agriculture also indicates that it was unlikely that the turbidity of the rivers in the area from 1850-1910 was due to initial cultivation of the prairies. This gives rise to the following question: What are the reasons for very low rates of sedimentation in Lake Pepin from 1500-1830s and a slightly higher rates from 1830 to 1910 as measured by Engstrom et al. (2009) using core samples (Fig. 21)?

Sediment Settling in the Minnesota River Valley: One reason for very low rates of sedimentation in Lake Pepin from 1500-1830s is likely due to the flat landscape of the Minnesota River valley from Mankato to St. Paul. In 1823, Major Long wrote that the Minnesota River is very serpentine and has sluggish currents (Jones, 1962). The serpentine nature of the river along with the flatness of the Minnesota River Valley (about 11 cm drop per km from Mankato to Fort Snelling, Dole and Wesbrook, 1907) is conducive to a significant amount of fine sediments settling out in the channel or in the valley. Regression analysis of grab samples for TSS concentrations (Metropolitan Council data, Cathy Larson, Personal Communication, 2010) from Jordan to Fort Snelling shows this part of the Minnesota River is an efficient sediment trap (Fig. 27). For every kilometer downstream from Jordan, there was a decrease in TSS concentration of 0.73 mg/L for the period 1976-2007. Some of this decrease in TSS concentration may be dilution by storm water from impervious surfaces in portions of the seven county metro area contributing to the Minnesota River.

Mass balance of sediment loads in the Minnesota River at St. Peter, Jordan, and Fort Snelling shows that as much 118,990, 80,371, 38,619 Mg of sediments drop out per year between St. Peter and Fort Snelling, St. Peter and Jordan, and Jordan and Ft. Snelling, respectively, for the period 2000 to 2008 (Fig. 30). Sediment dropout rates between St. Peter and Ft. Snelling and St. Peter and Jordan equal 16% and 12% the sediments measured in Minnesota River at St. Peter. The corresponding rate between Jordan and Ft. Snelling equal 6% of the sediments measured at Jordan. This analysis shows that there is a large variation in the amount of settling or pick up for different reaches over different years (Fig. 28). The Metropolitan Council has also suggested that the lower 64.4 km of the Minnesota River is a deposition zone for TSS with annual retention of 22-39% from 2004-2006 (Larson, 2010). During this period, this reach also retained 5 to 11% of the phosphorus load. According to Army Corps of Engineers, 19,500 cubic yards of material was dredged every year from 1970 to 2009 between Fort Snelling and Savage. A majority of these sediments were removed from miles 0-1.1, 10.7-11.2, and 11.8-12.4 (USACE, 2010). Considering these recent dredging rates, it seems likely that the sediment dropout rate in the lower Minnesota River prior to 1892 would have been higher since the river channel was still meandering and had not been dredged, widened, and straightened. In other words, a significant amount of sediments from earlier times likely did not reach present day Lake Pepin.

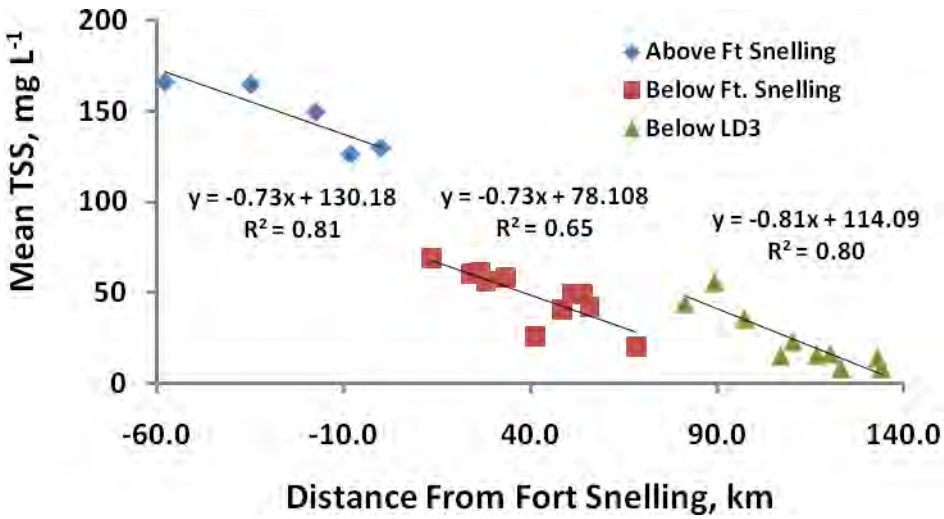
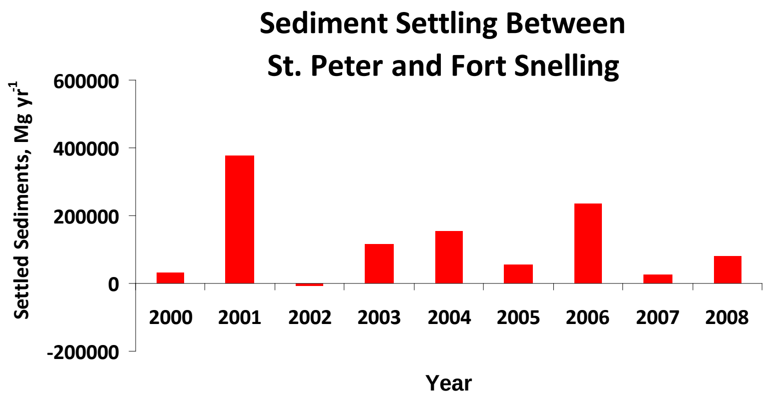


Figure 27: Change in mean TSS concentration as a function of distance between Jordan to Lock and Dam 3 along the Minnesota and the Mississppi Rivers. Each point is average of several data points. TSS concentrations are from grab samples collected by Metropolitan Council Environmental Services. Because of variable number of data points, data was averaged at each location. Fort Snelling is mile 0. Above Ft. Snelling refers to Minnesota River from Jordan to Ft. Snelling. Below Ft. Snelling refers to Mississippi River at Lock & Dam (LD) 2 and 3. Below LD3 refers to Lake Pepin. Decrease in concentration in the Minnesoat River is mainly due to settling with some dilution from impervious surfaces whereas decrease in concentration at LD2 and LD3 is due to both settling as well as dilution from the Mississippi and the St. Croix Rivers.

a



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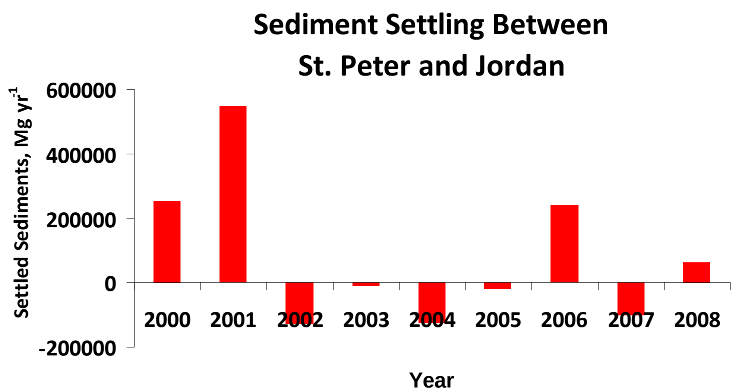

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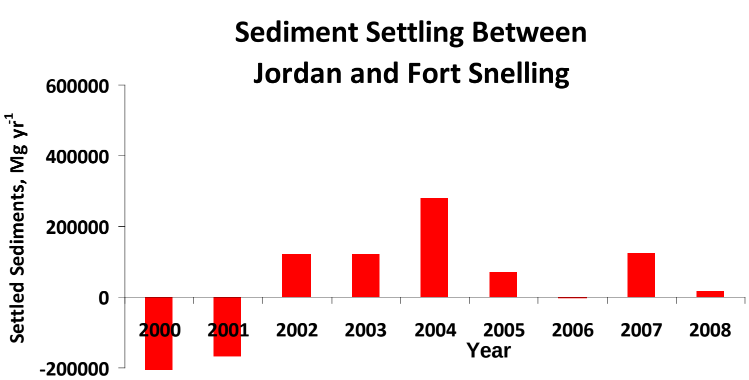


Figure 28: Sediment settling between (a) St. Peter and Fort Snelling, (b) St. Peter and Jordan, and (c) Jordan and Fort Snelling for the period 2000-2008.

Factors Affecting Earlier Sedimentation in Lake Pepin: Sediment core data show a constant sedimentation rate in Lake Pepin for the period 1500 to 1830 (Engstrom et al., 2009). One possibility for this constant rate may be the position of the delta in the Mississippi River that Schoolcraft (1855) noted in his travel log. In pre-settlement times, the delta was so far upstream that it did not affect the transport of fine particles to present day Lake Pepin. According to Zumberge (1952) Lake Pepin started in St. Paul, MN some 11,000 years ago when Glacial Lakes Agassiz and Duluth stopped draining south. These authors reported that Lake Pepin has been filling with sediments over time leading to its present day position south of Red Wing. Blumentritt et al. (2009) calculated the delta migration rate of 7.7 m yr^{-1} to 12.8 m yr^{-1} from 1500 to 5200 years before present. We suggest that higher sedimentation rates in Lake Pepin from 1830 to 1910 relative to 1500 to 1830 may to a certain extent be an artifact of the migration of the delta downstream. In other words, sedimentation rates during 1500-1830, as measured in present day Lake Pepin, are lower because larger quantities of sediment dropped out further upstream near earlier delta positions. If this analysis holds, it implies that earlier sedimentation rates, based on core samples from a transect in present day Lake Pepin, would be much lower and thus comparison of rates based on core samples at a given location may not be appropriate unless sediments from earlier times that have settled upstream are also accounted for in core samples. In other words, there may be a strong influence of the delta position and that effect needs to be teased out before core data can be used to further partition effects of agriculture practices, channel modifications, impervious surfaces, and climate on rates of sedimentation in Lake Pepin.

In 1892, the Army Corps of Engineers was first authorized to maintain a four-foot channel in the Minnesota River from Fort Snelling to 25.6 river mile in Shakopee (Merritt, 1979). Although this dredging took place, it would have had negligible effects on facilitating greater movement of fine sediments past the mouth of the Minnesota River (at Fort Snelling) to Lake Pepin because of the construction of a dam at the mouth of the Minnesota River (Fig. 29) in 1893 (Merritt, 1979). Both the dam construction and dredging was done to increase water levels in the Minnesota River for leisure excursion boats after a dry period from 1869 to 1890 (Fig. 30). A side channel near Fort Snelling facilitated the entry of the excursion boats. Although it was a leaky dam, the precipitation in the area started to increase after its construction leading to flooding of towns such as Savage, Shakopee, and Chaska, upstream of the Minnesota River at Fort Snelling (Merritt, 1979). As a result of this flooding, the dam was removed in 1909. It is well understood that the presence of a dam would result in some deposition of fine sediments behind it and thus lessen the transport of sediments to downstream locations.

The authors of this report have also looked at a few logs of the soil cores taken by the Minnesota Department of Transportation (MnDOT) during construction of bridges over the Minnesota River. These core data show a presence of fine sediments at various depths in the Minnesota River Valley. A core log taken below the I-494 bridge (8 April 1963) near the Minneapolis/St. Paul International Airport shows fine sediments at various depths to bedrock at about 48 m depth (Fig. 31). The shallowest presence of fine sediment was at a 4.9-m depth. The authors have also found a similar presence of fine sediments in MnDOT core logs for the Bloomington Ferry Bridge. The above observations suggest that one reason for lower sedimentation rates in Lake Pepin prior to 1830 may be related to the flatness of the Minnesota

River valley, as well as a lack of dredging and straightening of the Minnesota River; conditions conducive for sediment settling in the Minnesota River valley.

Figure 29. Pike dam at the mouth of the Minnesota River (1893-1909). Picture taken from Merritt, (1979).

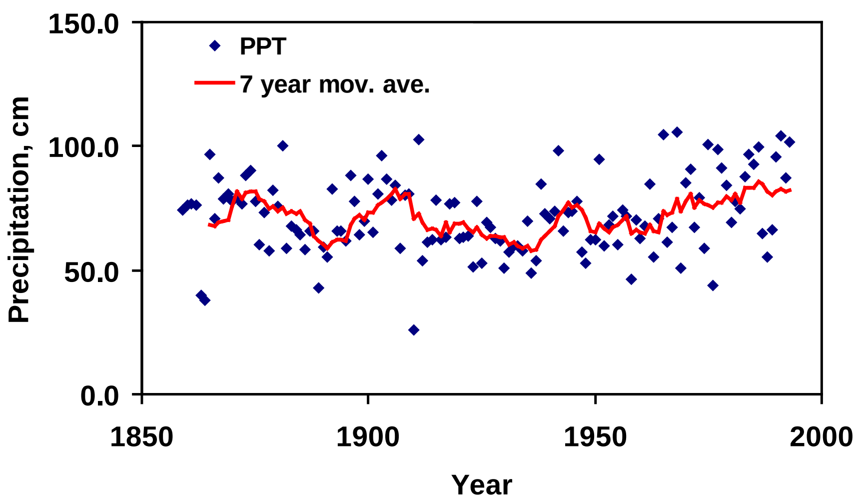
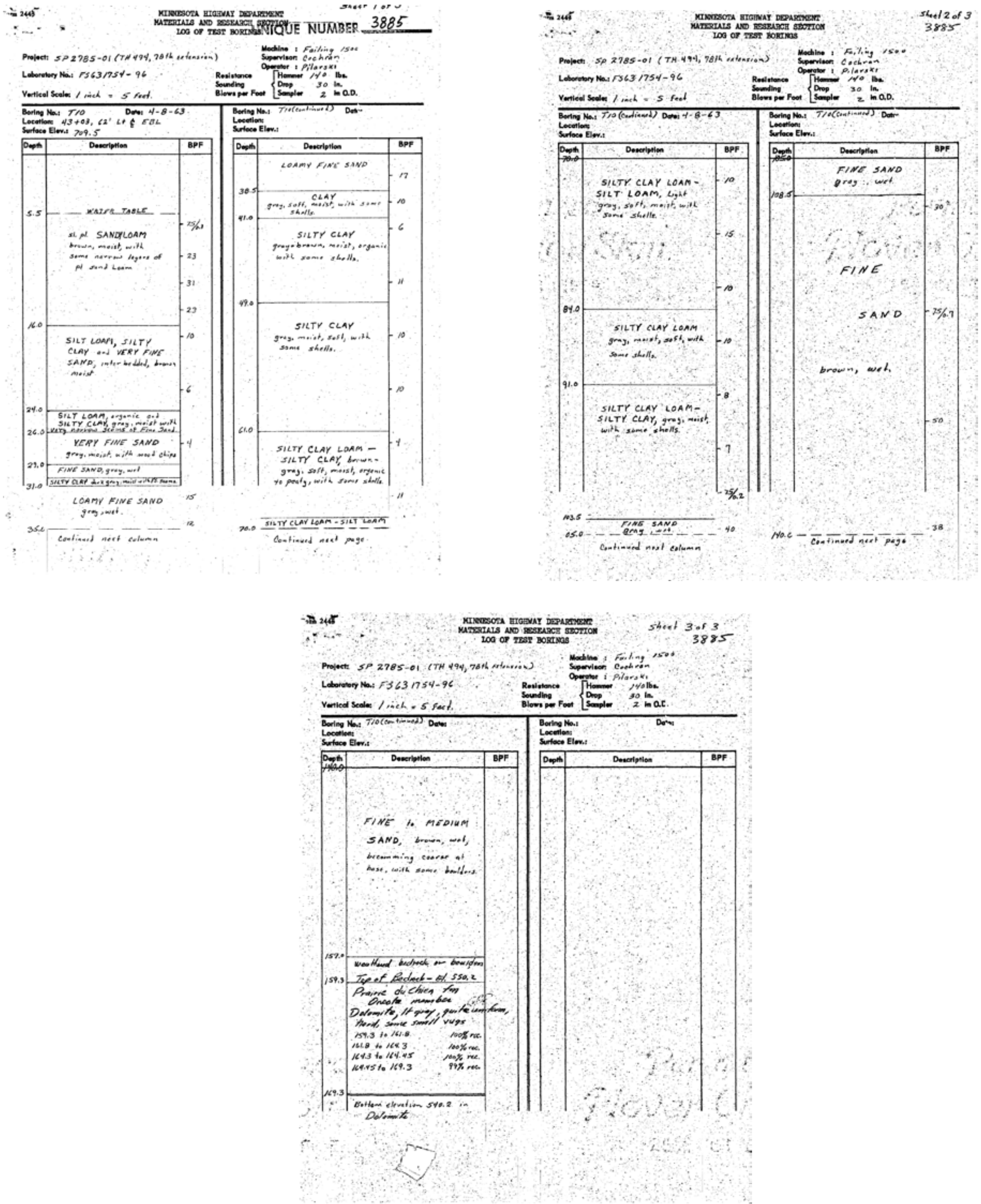


Figure 30: Trends in precipitation in St. Paul, MN from 1859-1993 (Data complied by Tom St. Martin).



MINNESOTA HIGHWAY DEPARTMENT
MATERIALS AND RESEARCH SECTION
LOG OF TEST BORINGS

UNIQUE NUMBER 3885
Sheet 1 of 3

Project: SP 2785-01 (TH 494, 78th extension)
Laboratory No.: FS63 1754-96
Vertical Scale: 1 inch = 5 feet.
Machine: Failing 1500
Supervisor: Cochran
Operator: Pilarski
Resistance Sounding Blows per Foot: Hammer 140 lbs. Drop 30 in. Sampler 2 in O.D.

Boring No.: T10 Date: 4-8-63
Location: 43+03, 62' Lt ℄ EBL
Surface Elev.: 709.5

Depth	Description	BPF
5.5	WATER TABLE	75/6.3
	sl. pl. SANDY LOAM brown, moist, with some narrow layers of pl. sand Loam	23, 31, 23
16.0	SILT LOAM, SILTY CLAY and VERY FINE SAND, inter-bedded, brown, moist	10, 6
24.0	SILT LOAM, organic and SILTY CLAY, gray, moist with very narrow seams of Fine Sand	
26.0	VERY FINE SAND gray, moist, with wood chips	4
29.0	FINE SAND, gray, wet	
31.0	SILTY CLAY dark gray, moist with some	
	LOAMY FINE SAND gray, wet.	15, 12
35.0	Continued next column	

Boring No.: T10 (continued)

Depth	Description	BPF
	LOAMY FINE SAND	17
38.5	CLAY gray, soft, moist, with some shells.	10
41.0	SILTY CLAY gray-brown, moist, organic with some shells.	6, 11
49.0	SILTY CLAY gray, moist, soft, with some shells.	10, 10
61.0	SILTY CLAY LOAM — SILTY CLAY, brown-gray, soft, moist, organic to peaty, with some shells.	4, 11
70.0	SILTY CLAY LOAM - SILT LOAM	
	Continued next page	

MINNESOTA HIGHWAY DEPARTMENT
MATERIALS AND RESEARCH SECTION
LOG OF TEST BORINGS
Sheet 2 of 3
3885

Project: SP 2785-01 (TH 494, 78th extension)
Laboratory No.: FS63 1754-96
Vertical Scale: 1 inch = 5 feet
Machine: Failing 1500
Supervisor: Cochran
Operator: Pilarski
Resistance Sounding Blows per Foot: Hammer 140 lbs. Drop 30 in. Sampler 2 in O.D.

Boring No.: T10 (continued) Date: 4-8-63

Depth	Description	BPF
70.0	SILTY CLAY LOAM - SILT LOAM, Light gray, soft, moist, with some shells.	10, 15, 10
84.0	SILTY CLAY LOAM gray, moist, soft, with some shells.	10
91.0	SILTY CLAY LOAM - SILTY CLAY, gray, moist, with some shells.	8, 7, 75/6.2
103.5	FINE SAND gray, wet	
105.0	Continued next column	40

Boring No.: T10 (continued)

Depth	Description	BPF
105.0	FINE SAND gray, wet	
108.5	FINE SAND brown, wet.	30, 75/6.7, 50
140.0	Continued next page	38

MINNESOTA HIGHWAY DEPARTMENT
MATERIALS AND RESEARCH SECTION
LOG OF TEST BORINGS
Sheet 3 of 3
3885

Project: SP 2785-01 (TH 494, 78th extension)
Laboratory No.: FS63 1754-96
Vertical Scale: 1 inch = 5 feet.
Machine: Failing 1500
Supervisor: Cochran
Operator: Pilarski
Resistance Sounding Blows per Foot: Hammer 140 lbs. Drop 30 in. Sampler 2 in O.D.

Boring No.: T10 (continued)

Depth	Description	BPF
140.0	FINE to MEDIUM SAND, brown, wet, becomming coarser at base, with some boulders.	
157.0	weathered bedrock or boulders	
159.3	Top of Bedrock - el. 550.2 Prairie du Chien fm Oneota member Dolomite, lt gray, quite uniform, hard, some small vugs. 159.3 to 161.8 100% rec. 161.8 to 164.3 100% rec. 164.3 to 164.45 100% rec. 164.45 to 169.3 99% rec.	
169.3	Bottom elevation 540.2 in Dolomite	

Figure 31. A log of test boring below the I-494 bridge in the Minnesota River Valley near the MSP International airport. The log was made by Minnesota Department of Transportation on 8 April 1963.

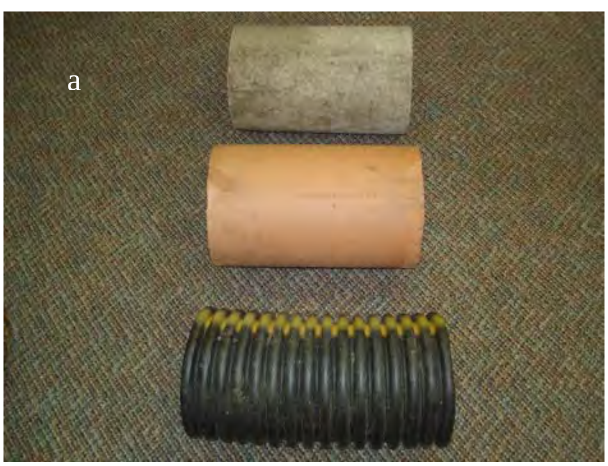
1910 to 1940

Drainage: From 1910 to 1940, Minnesota saw a sharp growth in drainage of agricultural lands. Based on Census data, Burns (1954) reported that 6%, 26%, 32%, and 32% of the land area benefited from agricultural drainage in Blue Earth County for each subsequent decade from 1910 to 1940 (Table 3). As a percent of farmland, the corresponding numbers were 26%, 26%, and 32% for each decade starting in 1920. The author noted that maximum drainage activities in Blue Earth County occurred from 1910 to 1920. Subsequently, depression and war years brought an end to the construction of drainage enterprises and these activities resumed only after the 1950s (Burns, 1954). Areas under wild hay also increased the most between 1900 and 1920, the active drainage period. The reason for this increase in area under wild hay is not apparent. Tiles used during this period were short clay or cement pipes (Fig. 32) that were laid in a trench end to end with small gaps in between, allowing drainage water to enter the tiles. Gap between the neighboring pipes was not that precise and often lead to filling of these tiles with sediment (Don Gass, Personal Communication, 2010)

Table 3: Percent of the land area in drainage enterprise in Blue Earth County, MN from 1900 to 1950.

	1900	**1910**	**1920**	**1930**	**1940**	**1950**
	--------------------Area %---------------------					
¶Blue Earth County	1	6	26	32	32	36
§Minnesota	-	-	17	21	21	21

¶County Auditor's records, §U.S. Census of drainage, 1940, 1950



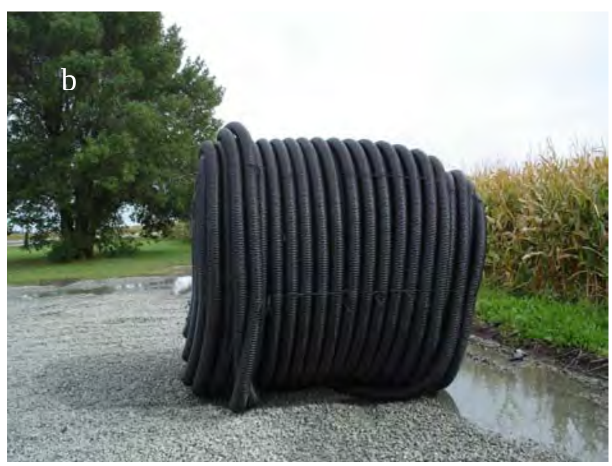


Figure 32: A sample of cement, clay, and plastic tiles used for tile drainage (Fig. 32a). Cement and clay tiles were usually a foot long and were mostly used prior to 1980s. Plastic tile comes in one long roll many feet in length (Fig. 32b).

There is a lack of written information on the layout of tile lines on farms prior to 1910. Here are some recollections of Dr. Wally Nelson, Superintendent of the Southwest Research and Outreach Center at Lamberton, MN. Wally was raised on a farm in Redwood County and his was the first farm in the county that installed tile drains, around 1915. He recollected that earlier tile lines were generally a single tile line from an outlet to a depression. This was because tiles were manually laid (hand dug) and both labor and clay tiles were added expense on the farm. An open cast iron pipe connected to a subsurface tile line carried the surface water from the depression to a drainage ditch. This "open inlet" would often get plugged with debris such as straw and cobs thus slowing or blocking the flow of water. These inlets had to be manually cleaned to allow the depressions to drain.

Using Census data, Moline (1969) estimated the area in drainage enterprises corresponded to 11%, 27%, and 35% of the land area in 13 counties of the MRB for each decade from 1920 to 1940, respectively. The counties included Blue Earth, Brown, Chippewa, Fairbault, Kandiyohi, Lac Qui Parle, Martin, Nicollet, Redwood, Renville, Sibley, Swift, and Yellow Medicine. The corresponding numbers for the State of Minnesota were: 18%, 22%, and 22% of the total land area.

Burns (1954) showed a few examples of tile layout on a small number of farms in Blue Earth County during this period. Tiles were generally 15 to 30 cm diameter, made out of clay or concrete, and mostly laid as widely spaced laterals where needed. Roe and Ayers (1954) also showed a couple of examples of laid tile in Iowa, Minnesota, and North Dakota farms in 1910-20s. Most early tile drainage was limited to wet areas.

Based on the above reports, one would expect that cast iron surface inlets would have transported some upland sediment to ditches. However, 1910 to 1940 was also a relatively drier period that culminated into the drought of the thirties and Dust Bowl years of 1930 to 1938 (Fig. 30). Thus, given the drier climate of the period and limited area under drainage, sediment loads from these early drainage surface inlets would likely have been smaller.

Channel Modifications: Dredging and straightening of the Minnesota River was significant during the 1910-1940 period. Merritt (1979) reported that a sand bar would form each spring from 1893-1943 at the mouth of the Minnesota River with about 0.45 m of water at the mouth and a 1.8 m deep channel running 24 miles upstream. As part of the Congressional authorization in 1892 to maintain a four-foot channel to Shakopee (25.6 miles upstream of the Minnesota and Mississippi Rivers confluence), the Army Corps of Engineers kept the mouth of the Minnesota River open by annually dredging (Merritt, 1979). It is likely that some of the fines were removed from the channel during dredging. However most significantly, the channel dredging likely facilitated the movement of fine sediments downstream and thus contributed to higher sediment loads in Lake Pepin. Dredging and straightening of the Minnesota River channel is similar to the construction of drainage ditches in the MRB. Both facilitate the flow of water and associated sediments downstream, and in both cases, there is some settling of sediments along their path. Since the dredged area of the Minnesota River channel is closer to Lake Pepin, it likely has a more direct impact on sedimentation rates in Lake Pepin compared to drainage ditches in the MRB over 200 km upstream. As mentioned previously, it is also likely that the migration of the delta towards present day Lake Pepin contributed to the increased rates of its filling measured by Engstrom et al. (2009).

Historic River Water Quality: Turbid conditions of rivers as evident from the turbidity contrast between different rivers at their confluences, even during the Dust Bowl period, further suggest that the primary source of sediment in rivers of the MRB is derived from river bank erosion driven mainly by natural processes. The earliest aerial photographs of Minnesota landscapes that include rivers were taken by the USDA in 1937 and 1938. These photographs show that the Blue Earth River was more turbid than the Minnesota River at Mankato (Fig. 33a), the Minnesota River was more turbid than the Mississippi River at Fort Snelling (Fig. 33b), and the Mississippi River was more turbid than the St. Croix River at Prescott, WI (Fig. 33c). These conditions are similar to those described by Featherstonhaugh in 1835 for the Blue Earth and Minnesota Rivers confluence, similar to the condition described by Bond (1957) at Fort Snelling in 1950, and similar to the turbidity contrast that appears in a picture of the Mississippi River and St. Croix River confluence taken on 2 June 2004 (Fig. 1 in Engstrom, 2009). Within the GBERB, 1938 aerial photographs showed that the Blue Earth River was more turbid than the Watonwan River (Fig. 34a). However, there was no difference between the Le Sueur River and the Blue Earth River at their confluence in 1938 (Fig. 34b).

Historical photographs also demonstrate the seasonal influence on turbidity. Photographs taken from 1937and 1938 to present times (Figs. 35, 36, 37, 38) also show similar turbidity differences between the rivers depending upon the month the photographs were taken. Photographs taken in early spring (April, May, June and July and sometimes in August) show contrasting turbid conditions at rivers confluences, whereas photographs taken in September, October and November rarely show these differences. This may also explain why Featherstonhaugh, on 26 September 1835, observed shallow and transparent water in the Minnesota River upstream of Mankato: river flows in fall are generally low unless there is a major storm in the area.

Row Crops: Annual row crops such as corn and soybeans have also been blamed for increased sediment loads and thus turbidity in rivers of the MRB (Rott, 2007, Mulla and Seekley, 2009). Although corn became an important crop starting in 1900, it was not until the 1950s when development of new hybrids that matured faster and were better adapted to cooler weather conditions that it was possible to profitably raise corn north of the Minnesota River (Baerwald, 1989). In 1907, Dole and Westbrook reported that Minnesota was number the #1 wheat growing state in the US but corn was extensively grown in the counties bordering Iowa border. As mentioned earlier for first half of 20th century, corn was frequently grown in rotation with hay and small grain (Baerwald, 1989) and thus field erosion would have been much lower than in present day continuous corn or corn-soybean rotations. These observations further suggest that the role of corn in sediment production prior to 1950 would have been relatively small.

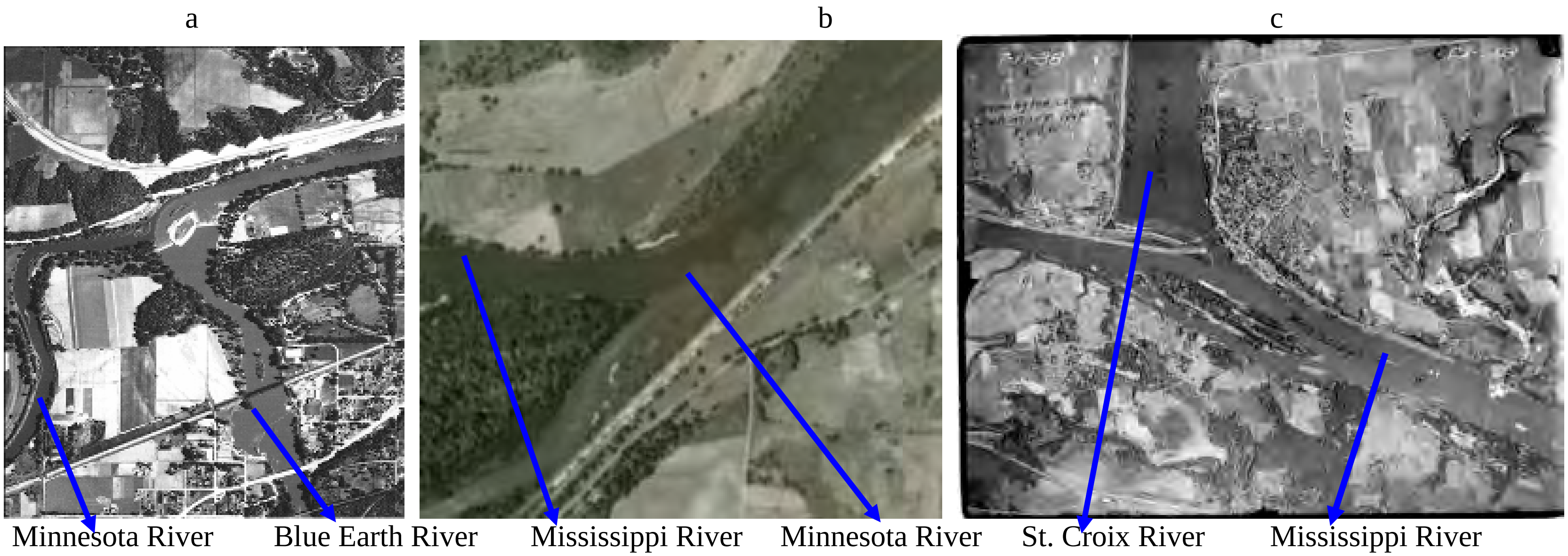


Figure 33. Aerial photographs of the confluence of various rivers in 1937-1938. Figure 33a. The turbid Blue Earth River joining the Minnesota River at Mankato, MN in 1938. Figure 33b. The turbid Minnesota River joining the Mississippi River at Fort Snelling, MN on 30 June 1937. Figure 33c. The turbid Mississippi River meeting the St. Croix River at Prescott, WI on 11 July 1938. These photographs were taken by USDA.

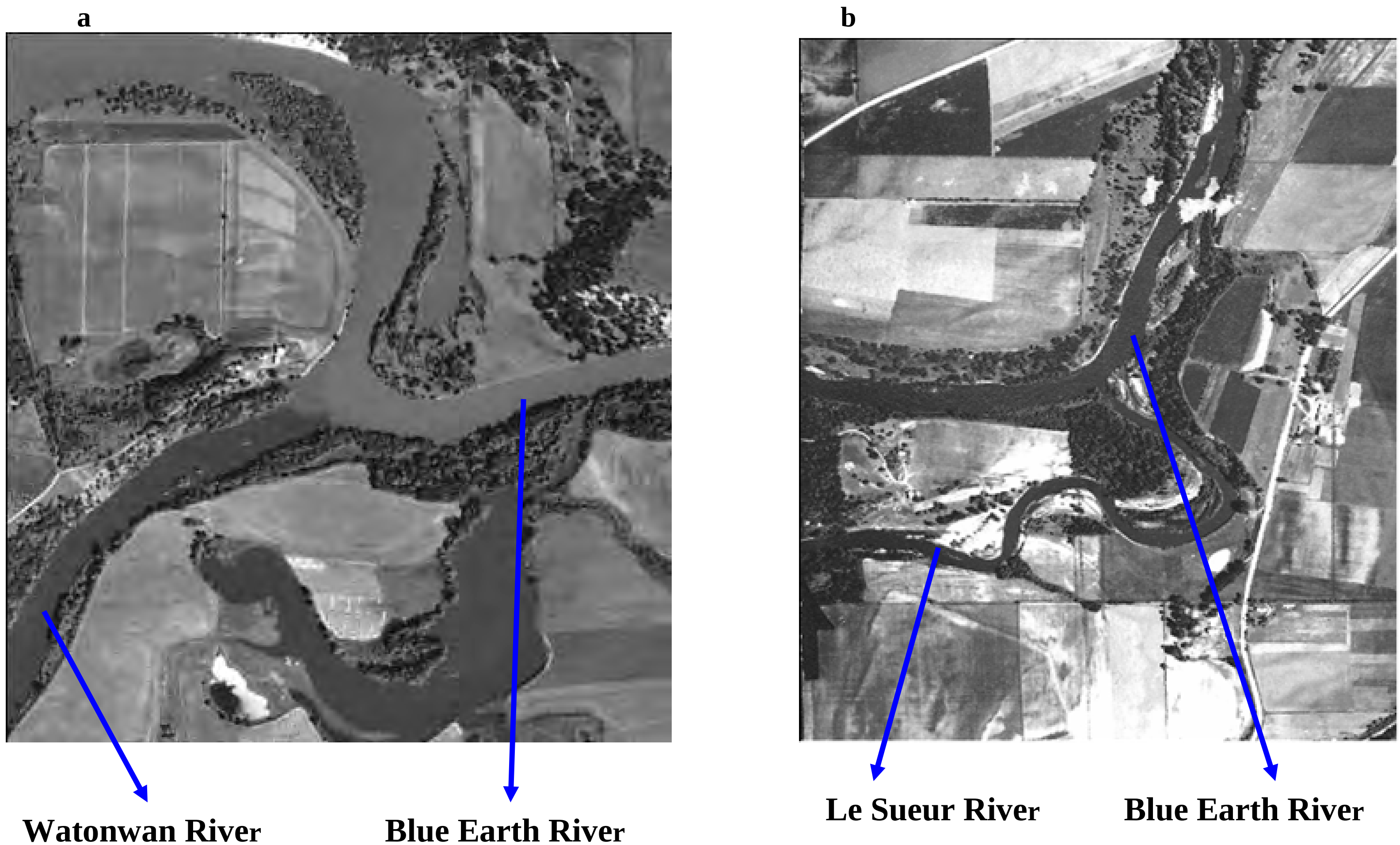


Figure 34. Photographs of the confluence of three rivers in the Blue Earth County in 1938. The Watonwan joining the Blue Earth River past Garden City, MN (Fig. 34a). The Le Sueur River joining the Blue Earth River near Mankato, MN (Fig. 34b). These photographs were taken by USDA.

30 June 1937 | 25 June 1940 | 10 May 1957

Figure 35. Aerial pictures of the confluence of the Minnesota River with the Mississippi River at Fort Snelling, MN. These pictures show Minnesota River was turbid as early as 1937. These photographs were taken by USDA.

22 September 1937

11 July 1938

Figure 36. Aerial pictures of the confluence of the Mississippi River with the St. Croix River at Prescott, WI in 1937 and 1938. These pictures show Mississippi River was turbid as early as 1938. These photographs were taken by USDA.

28 October 1949

1 June 1957

15 July 1964

Figure 37. Aerial pictures of the confluence of the Mississippi River with the St. Croix River at Prescott, WI in 1949, 1957, and 1964. These photographs were taken by USDA.

Figure 38. An aerial pictures of the confluence of the Mississippi River with the St. Croix River at Prescott on 1 May 1960. Picture taken by the Minnesota Department of Conservation and now stored at the Minnesota Historical Society. The plastic corrugated tile line currently used for tile drainage was introduced in 1967.

1940-Present

The period between 1940-present has been shown to have the largest increase in sedimentation rates in Lake Pepin (Fig. 21). It appears that higher sedimentation rates in Lake Pepin from 1940-present may be attributable to a combination of sediment production and sediment transport factors i.e. (1) increased precipitation resulting in more bank failure as well as in more lateral migration of the tributaries resulting in more sediment production, and (2) transport changes including dredging, widening, and straightening of the Minnesota River channel; increased impervious surfaces; and construction of levees along the main channel and the tributaries resulting in increased water and sediment transport.

Drainage: The building of drainage enterprises stopped during the depression and World War II years, but these activities resumed again in the 1950s (Burns, 1954; Moline, 1969) and thus, with the availability of steam and tractor power, patterned (parallel) tile systems with narrowly spaced laterals became more common. In 1950, the land area in drainage enterprise in Brown, Fairbault, LeSueur, Martin, Nicollet, Waseca and Watonwan counties, counties adjoining Blue Earth

County, were 23%, 56%, 23%, 60%, 34%, 15%, and 23%, respectively (Burns, 1954). The length of ditches in 13 MRB counties increased from 2,160 miles to 4,312 miles from 1920 to 1960 and the corresponding length of tile increased from 3,274 to 6,378 miles (Moline, 1969).

The third period of increased drainage activity in the area appears to be during 1970s and 1980s when corrugated plastic tubing was made available for agricultural drainage. Fouss (1974) reported that research on corrugated plastic tubing as an agricultural subdrain began in 1965 and by 1967 the tube was commercially fabricated in the USA. This led to the development of a whole new industry for installing drainage pipes in agricultural fields (Fouss, 1974). Initially, although some new lands were drained using the corrugated plastic tubing, the new tubing primarily replaced many of the old clay and cement tiles that had degraded over time (Don Gass, Tile installer since 1940, Personal Communication, 2010). Using Quade et al. (1980) data, Prince (1997) showed that drained land in four counties (Blue Earth, Le Sueur, Nicollet and Brown) of south central Minnesota showed little change from 1971 to 1978. Percent drained land corresponded to 50.4%, 43.5%, 59.4%, and 48.2% in 1971 as compared to 39.9%, 46.7%, 58.9%, and 45.9% in 1979 for Blue Earth, Le Sueur, Nicollet, and Brown Counties, respectively. Drained land estimates in 1971 were based on a survey by the USGS, whereas 1979 estimates of Quade et al. (1980) used county ditch maps.

Initially there was some reluctance in the use of plastic tubing for tile drainage mainly because of the concerns whether or not it could withstand frost pressure during winter (Don Gass, Personal communication, 2010). Because of this concern, when tile lines were first installed in 1971 at the Southwest Research and Outreach Center in Lamberton, MN, 4,600 m of clay rather than plastic tile was used. Prior to 1970s, drainage in agricultural lands was mostly localized to wet areas on the farm. Because of increases in commodity prices since the 1970s, potential for higher crop yield from drained areas, and relatively less expensive cost of installing perforated plastic tile, additional areas on individual farms in the MRB have been brought under tile drainage. However as required by law, drainage of open water wetlands in agricultural field stopped in 1985 (Roger Ellingson, Tile Line Installer, Ellingson Companies, Personal Communication, 2010).

During the period from 1940-1985, there has been some installation of surface inlets in depressional areas. However, recent research suggests that the quantities of sediment reaching the streams from these inlets will be low, because much of the surface sediments settle out either in the fields (Ginting et al., 2000) or in the ditches along the way (Slattery et al., 2002; Leece et al., 2006). Ginting et al. (2000) showed that depressions in fields often get inundated due to back-pressure from the main drainage line connecting a series of fields. This back-pressure prevents the drainage of down slope fields until the upstream fields have been drained (Fig. 39). Inundated pools around surface inlets provide sediment sinks, resulting in less loss of surface soil to ditches. Furthermore, the gentle gradient of open ditches facilitates additional settling of fine particles. Counties and watershed districts periodically clean these ditches and put the sediment on the side of the ditch to increase berm heights (Roe and Ayers, 1954).

In recent years, there has been a trend in the complete removal of surface inlets or moving them to the edge of the field (Roger Ellingson, Ellingson Companies, Personal Communication, 2010). This is mainly due to the difficulty of maneuvering big heavy machinery around the inlets. Efforts have also been made to replace surface inlets with rock inlets or French Drains. However, statistics on the extent of these modifications are not readily available.

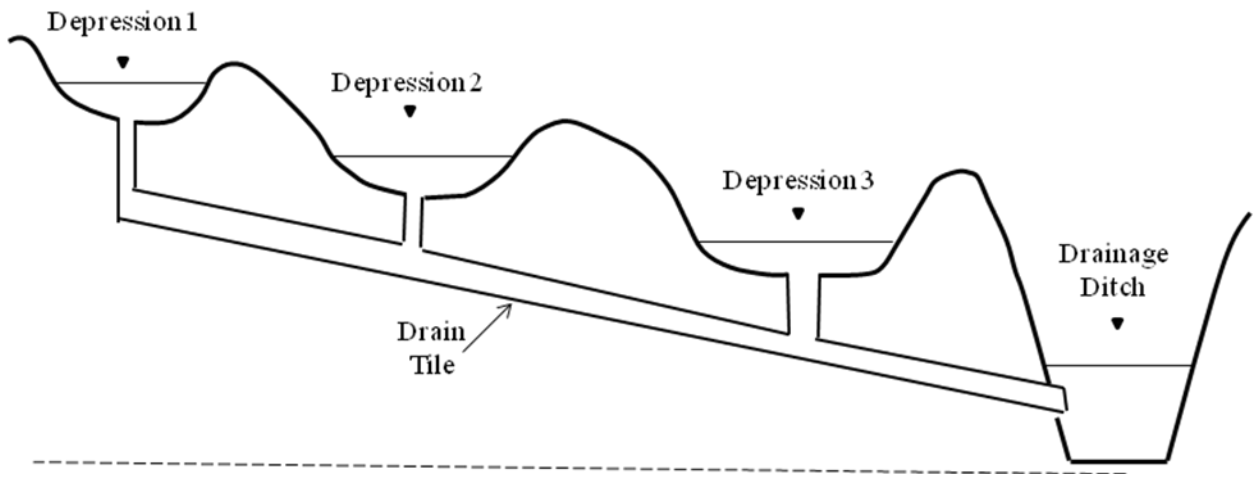


Figure 39: A schematic of various depressions hydraulically connected to each other through a mainline in the Minnesota River Basin. Each depression represents a field. Because of slightly higher elevation, depression #1 will empty first and then depression #2 and depression #3. This allows some settling of sediments around surface inlets depressions #2 and #3 (Modified from Campbell and Johnson, 1975)

Channel Modifications: There are several notable activities concerning dredging of the Minnesota River starting in 1940. In 1943, Cargill obtained a US Navy contract to build ocean going tankers and tugboats at Savage (Merritt, 1979; Marks, 2010). The facility produced 18 auxiliary oil and gas carriers and 4 tugboats and employed 3500 people during peak production (Marks, 2010). As part of this contract, the Army Corps of Engineers was required to maintain a nine-foot deep channel to mile marker 13.0 (Savage). Merritt (1979) stated that after 1943, this channel filled in over time and in 1968, the nine-foot channel was re-dredged to mile marker 14.7. It is likely that some of the fine sediment that settled in the channel (and also in the valley during floods) in between the dredging periods may have moved when the channel was dredged in 1968. Since 1968, the channel has been maintained at a nine-foot depth from Fort Snelling to Shakopee (about 26 miles upstream) by the Army Corps of Engineers. The goal of dredging is to deepen the channel so that all the water stays within a restricted cross-section rather spread over a large area (flood plains) with relatively shallow depth. From Stokes law it is well understood that particles settle faster (less time) in shallow rather than deep water (Chow et al., 1988) due to reduced settling depth and slower water velocities. Narrower-deeper channels (more water per unit cross-section area) are likely to carry larger sediment loads than wider-shallow channels.

Channel straightening and levee construction has also occurred on the Minnesota River and its tributaries. The timelines of these modifications are not readily available, but they appear to be after the 1940s (based on historical and recent photographs). Historic travelers' logs mention the Minnesota River being serpentine, tortuous or meandering (Major Long, 1823; Henry Thoreau, 1861, both cited by Jones 1962; Featherstonhaugh, 1847; Hasson, 1856). However, the present day Minnesota River is fairly straight between Mankato and Fort Snelling. As mentioned earlier, Hansen et al. (2010) concluded that overall sinuosity (river length/valley length) of the Minnesota River has reduced from 1.5 to 1.3 since 1855. As an example, aerial photographs from 1957 and 1980 show that the Minnesota River was straightened just above Fort Snelling (Fig. 40). Many similar in-channel modifications also exist in tributaries of the MRB. The presence of bends (tortuosity) in a river slows the movement of sediments and is thus conducive to sediment deposition (Leopold, 1994). In contrast, the straightening of rivers facilitates the downstream movement of fine particles (Leopold, 1994).

Levees have also been built in two areas between Fort Snelling and Mankato to control floods: downstream from the junction of the Minnesota River with the Blue Earth River at Mankato (Fig. 41ab) and near the town of Henderson (Fig. 41b). There is also a levee on the Blue Earth River near Le Hillier, Mankato (Fig. 41c). Levees eliminate river-floodplain interactions and thus force higher sediment loads to downstream locations.

Impervious Surfaces: With the increase in population since 1940, there has also been an increase in impervious surfaces such as roof tops, malls, parking lots, and roads. An analysis of satellite data from Sawaya et al. (2003) and Bauer et al. (2007) shows that proportion of land surface that is impervious to varying degrees in the MRB was 6% for the whole basin, 13% for the area between Mankato and Twin Cities in 2000, and 30% for the portion of 7 metro counties contributing to Minnesota River in 2002 (Table 4). In 1986, the corresponding number for the 7 metro counties was 20%. The increase of impervious surfaces since pre-settlement times would have likely resulted in increased flow as well as sediment transport in the Minnesota River.

Table 4: Percent area under impervious surfaces in the whole Minnesota River Basin (MRB), MRB from Mankato to Fort Snelling, and MRB in Metro. The data was estimated from maps produced by Sawaya et al. (2003) and Bauer et al. (2007).

Location	Year	Impervious surface, %
Whole Minnesota River Basin	1990	4
	2000	6
Minnesota River Basin between Mankato and Ft. Snelling	1990	8
	2000	13
Minnesota River Basin in Metro	1986	20
	1991	24
	1998	27
	2002	30

10 May 1957

August 1980

Figure 40: Two pictures of the confluence of the Minnesota River with the Mississippi River at Fort Snelling and Pike Island showing the area where channel has been straightened.

Figure 41. Levees along the Minnesota River at (a) Makato, and (b) Henderson and (c) along the Blue Earth River at LeHiller, Mankato.

Trends in Precipitation: Increased precipitation is another probable cause for higher sedimentation rates in Lake Pepin in recent years. Since about 1940, precipitation in the MRB has been on an upward trend (Fig. 42). At some individual locations, there has been a substantial increase in precipitation. For example, 30-year annual precipitation at Waseca has increased from 70 cm from 1921-1950 to 88 cm from 1971-2000 (Seeley, 2009). There are several years when annual precipitation has exceeded the 90th percentile starting around 1960 (Fig. 42). In addition, the intensity of the storms in recent years has also increased. Zandlo et al., (2008) noted that the number of > 5.1 cm precipitation events in Minnesota have increased from 1 to 1.5% of the annual precipitation events during the last 30 years. Large storms are likely to result in higher river flows as well as higher sediment loads, which likely leads to greater sediment transport to Lake Pepin (Johnson et al., 2009a). Since similar precipitation amounts and intensities occurred from 1895 to 1905 (Zandlo et al., 2008) and since sedimentation rates in Lake Pepin were 1/5 of today, it has been suggested that precipitation effects are likely minimal to absent (MPCA, 2010b). This observation will only hold if one is considering soil erosion from a landscape. However, this will not be the case if one is considering river flow and associated sediment transport processes. Since there is more impervious area now than in 1895 to 1905, recent higher precipitation amounts and intensities will result in higher river flows and thus likely higher sediment transport.

Figure 43 shows a comparison of flow probabilities for the Minnesota River at Fort Snelling for the periods 1976-2003 vs. 1939-1975. At probabilities <75% (return period >1.8 yrs), there is substantial increase in flow in the Minnesota River for the period 1976-2003. This is expected since at lower probabilities, there is higher precipitation and generally wet years will proportionally lead to more runoff and in turn more stream flow. As shown by Johnson et al. (2009), there is a strong relationship between flow and sediment load in the Minnesota River at Fort Snelling (Fig. 44). This would suggest that some of the increased sediment transport in the Minnesota River, and in turn increased sedimentation in Lake Pepin, is likely due to increased flow as a result of recent increases in precipitation in combination with increased impervious surfaces, building of levees, and channel modifications.

Drainage Effects on Soil Erosion: Although the presence of surface inlets has increased the delivery of field sediment to rivers, it is also likely that subsurface tile drainage has reduced some surface sediment losses. Istok and Kling (1983) showed that increases in tile drained area has the effect of reducing surface runoff and associated soil erosion by increasing the soils capacity to hold water from subsequent rainfall events. In the Universal Soil Loss Equation (USLE), drainage is part of the Erosion Control Practice (P) factor. Bengston and Sabbagh (1990) showed that in the hot and humid climate of Louisiana there was a 40% reduction in P value and in turn 40% reduction in soil loss from the presence of subsurface drain. The authors attributed lower quantities of soil loss to drier surface soils and less runoff created by lowering the water table with subsurface drainage. Since seepage is one of the major mechanisms for bank failure, it is also likely that subsurface drainage has reduced some seepage and thus resulted in less bank failure compared to earlier times.

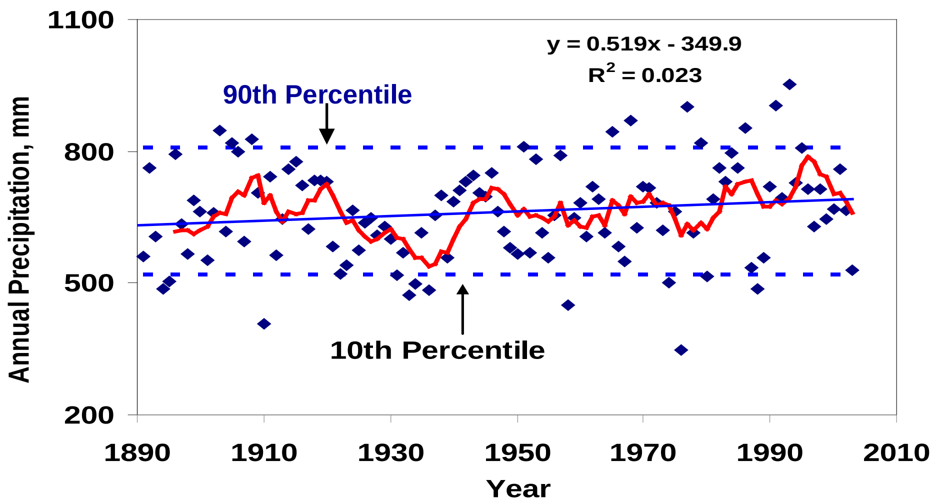


Figure 42: Trends in precipitation in the Minnesota River Basin from 1890-2003. Red line is a seven year moving average and straight-line is a fitted linear trend. Two dashed lines represent the 10th and 90th percentile. In recent years, precipitation has exceeded the 90th percentile. However, there has also been years when it is below 10th percentile and thus making the average change not statistically significant. However, it is the wet years that are important for generating large quantity of runoff and in turn river flow and thus carrying sediments downstream.

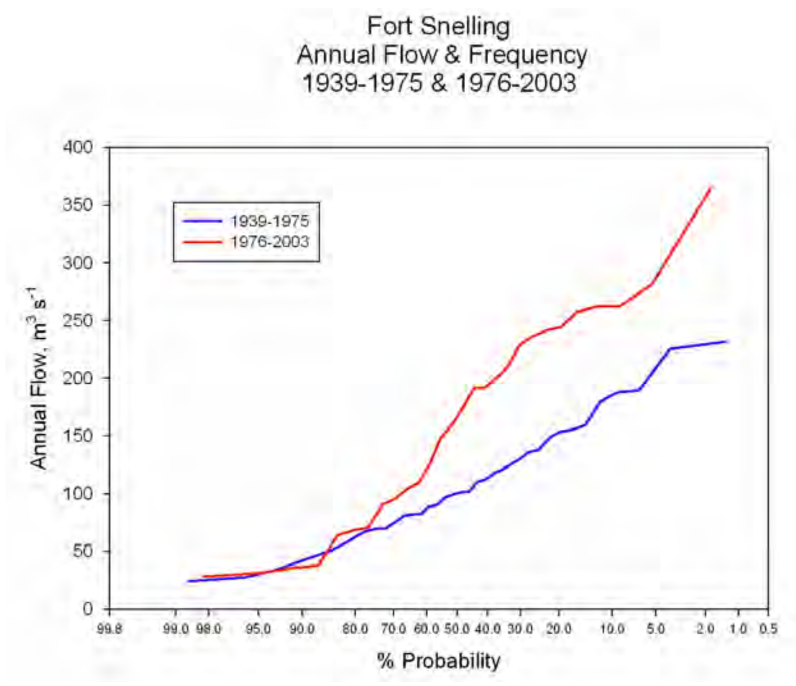


Figure 43. A comparison of probabilities of mean annual flow in the Minensota River at Fort Snelling for the periods 1940-2003 and 1939-1975.

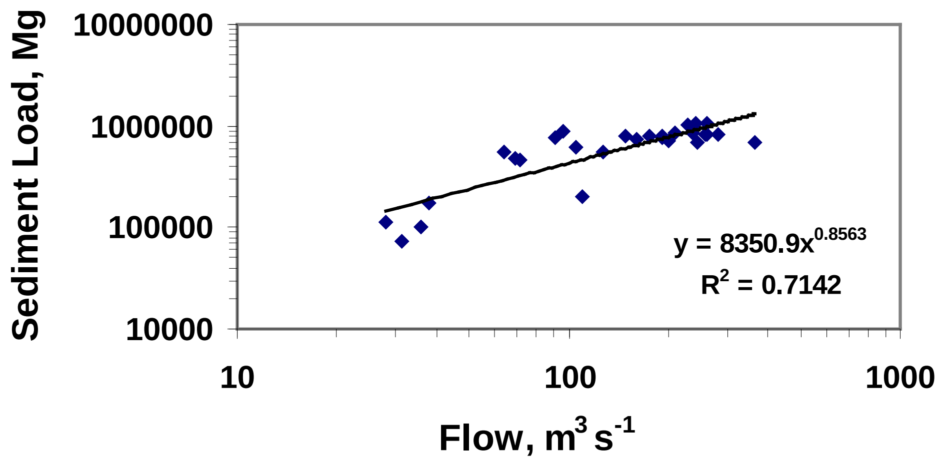


Figure 44: Realtionship between sediment load and flow in the Minnesota River at Fort Snelling for the period 1976-2003.

Introduction of Soybeans in Crop Rotation: Recently, Schilling (2005) has suggested that base flows in Iowa Rivers have increased and cannot be explained by increased precipitation in the area. He suggested the possibility that this may be due to reduced evapotranspiration from soybeans and thus more tile flow. This observation has been used in Minnesota by some to suggest that river flow increases and thus increased sediment loads are partially due to the adoption of soybeans in crop rotation. According to Baerwald (1989), crop rotations started to change slowly in 1950s with oats and barley being replaced with soybeans. In Blue Earth County, there were no soybeans grown prior to 1940. In 1940 and 1950, soybean acreage corresponded to 1.3% and 11.5% of the total land area, respectively (Burns, 1954).

As shown in 1937-38 aerial pictures (Figs. 33-37), many of the rivers in the MRB were turbid even before any of the area was brought under soybean cultivation. Thus increased sediment load in the Minnesota River and its tributaries, as well as increased rates of sedimentation in Lake Pepin from 1940-present cannot be attributed solely to the adoption of soybeans in the crop rotation. One should also note that in pre-settlement times large tracks of prairies naturally burned (Featherstonhaug, 1847; Jones, 1962) and thus, under those conditions, there would have been some decrease in evapotranspiration in the area. Since Native American practiced shifting cultivation in pre-settlement times, they also burned tracts of prairies. Furthermore from 1850 to 1900, there was substantial harvesting of trees in the three watersheds contributing to Lake Pepin which would have also resulted in substantial decrease in evapotranspiration and possibly higher flows. Similarly, with increases in population there has been significant conversion of prairie land to housing, roads, and parking lots. That would have also contributed to decrease in evapotranspiration. We suggest that until the effects of increased precipitation, dredging, straightening, and levee construction have been teased out of river flows, it will be difficult to argue that the inclusion of soybeans in corn-soybean crop rotations is one of the main reasons for increased turbidity of the Minnesota River and its tributaries or increased rates of sedimentation in Lake Pepin.

Partitioning Source of Sediments in Lake Pepin: As discussed earlier, sediment dropout rates in the Minnesota River Valley vary over time (Fig. 28). This would suggest that Schottler et al. (2010) assumption of the same combined sediment trapping efficiencies (delivery ratio) between 1830 to 1996 as in 2007 for the MRB to Lake Pepin may not be correct. This means that this assumption along with their other assumptions has likely resulted in incorrect partitioning of Lake Pepin sediments between field and non-field sources prior to 2007. For example, their estimates of >100% contributions from fields for the periods from 1830 to 1890 and then 1890 to 1940 is physically impossible. Knowing that bank sloughing is primarily controlled by bank material properties and precipitation, there must have been some bank sloughing going on during these periods and thus it is highly unlikely that 100% of the sediments came from field sources, especially from 1830-1850. Total population for the state in 1850 was 6,077 and it is highly unlikely that all of this population was living in the MRB and cultivating a large enough area to have such large loads coming to Lake Pepin. These authors also assumed that all of the pre-1830 sediment load of 63,000 Mg per year in Lake Pepin was coming from non-field sources (Schottler et al., 2010). This is arbitrary and without scientific basis, leaving an impression that the authors are force fitting the data to a pre-determined outcome. Knowing that agriculture was somewhat primitive and drainage pathways were not yet fully developed, a constant rate of 74,000 Mg per year from field sources (over and above pre-1830 loads of 63000 Mg per year assumed to be coming from non-field sources) for the periods of 1830 to 1890 is also arbitrary and lacks a scientific basis.

Delta Effect: Part of the increased sedimentation rate (measured as depth) in Lake Pepin is likely due to the shrinking size of the lake as a result of a delta that is moving down stream. One can visualize this phenomenon assuming Lake Pepin is more like a long bath tub (Fig. 45). For the same amount of sediment delivered at the mouth of the lake, sedimentation rates at a fixed point will increase as the volume of the lake shrinks (Fig. 45a, b, c). Since most of the coarse sediments settle at the mouth of the lake, the rate of increase will be much higher at upper end of the lake. This may partially explain why earlier rates of sedimentation are lower than the recent rates and why this effect is much more noticeable at the upper end of the lake than the lower end.

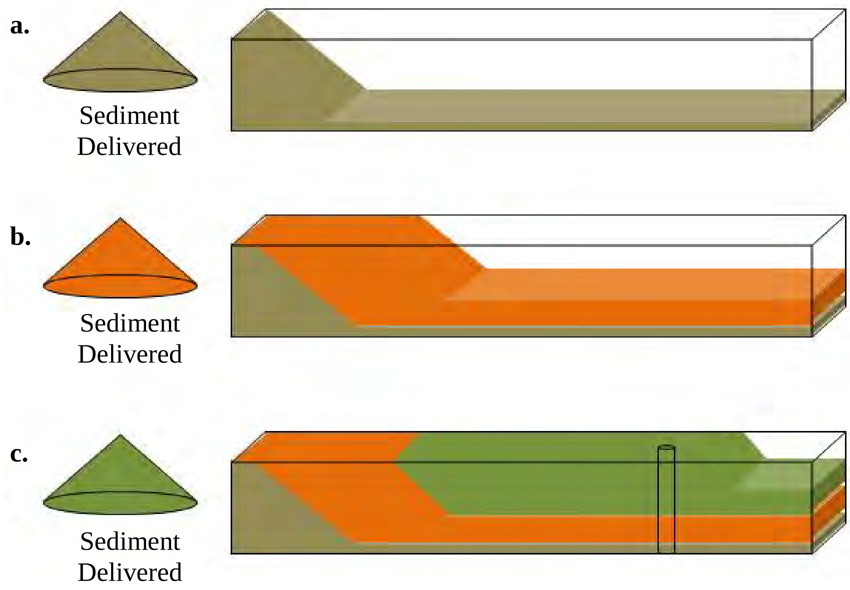


Figure 29: A schematic showing how the same amount of sediment will increase the sedimentation rate in a lake that is shrinking due to the movement of a delta. Different colors indicate different times (t_1, t_2, t_3). A core taken from a set-up shown in Fig. 29 c will show smaller sedimentation rates for earlier times (t_1, t_2) even when the amount of sediment delivered was the same.

CONCLUSIONS

Sediment is a major water quality impairment for the Minnesota River and its tributaries, and around the world. Sediment is transported downstream to the Mississippi River at St. Paul and in turn to Lake Pepin, a large natural floodplain lake on the upper Mississippi River about 80 km south of St. Paul. Settling of European immigrants in the area and more specifically, cultivation and tile drainage of agricultural lands, have been labeled as significant causal factors for the increased sedimentation in Lake Pepin. The LiDAR study described herein showed that a vast majority of the sediment in various rivers of Blue Earth County are coming from bank sloughing. Further field observations and laboratory experiments indicated that soil and slope instabilities along with lateral migration of these rivers are the likely causes of bank mass failures. Since the underlying properties and processes controlling bank failure have not changed drastically in these landscapes over the last 200-300 years, we conclude that these river banks were failing at a similar intensity, consistent with precipitation, even before the immigrants came to the area in 1850. We support this finding both by qualitative descriptions of historic travelers' logs and quantitative measurements of turbidity made by USGS in early 1900s. We further show that drainage practices between 1900 to 1940 could not have been the cause of the increased sediment load in the Minnesota River and thus increased sedimentation in Lake Pepin, because there was a relatively small amount of row crops in the basin and that too either in 3 or 5 year rotation with oats and hay, limited drainage mainly from depressional areas constructed primarily with single tile lines, and somewhat drier climate from 1910 to 1940.

The Lake Pepin sediment cores are a record of past conditions and as such, they represent both sediment production as well as sediment transport processes in the basin. We show that sediment transport has been influenced by both natural and human factors over the recent history of the MRB. This includes channel modifications (straightening, widening, dredging, levee building), increased impervious surfaces (roads, parking lots, and roof tops), and increased trends in precipitation. We suggest that increased sedimentation in Lake Pepin may be the result of changed sediment transport processes. We further suggest that earlier sedimentation rates measured from core samples may have been affected by the position of delta that is moving downstream. We conclude that Lake Pepin core data, integrating three large watersheds; Minnesota River, Upper Mississippi River, and the St. Croix River; cannot be used by itself to single out sediment production sources (field vs. non-field) or a specific agricultural management practice (cultivation or drainage) as the cause of increased sedimentation. We suggest that further work be undertaken on developing techniques that can tease out the impacts of channel modifications, impervious surfaces, climate variations, natural landscape processes (seepage and lateral channel movement), and the migrating river delta from lake cores data in order to quantify the role of landscape modifications (cultivation) and agricultural drainage on sediment production in the Minnesota River Basin. We also suggest that concerted efforts over several climate cycles should be made to quantify bank erosion/sloughing with LiDAR for all rivers in the Minnesota River Basin. The LiDAR analysis is not only useful in quantifying the extent of bank erosion but it can also identify banks that are the major source of sediments in the basin.

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