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
INTRODUCTION

The Minnesota River drains 43,400 km² 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 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 $1.2 - 2.6 \times 10^9$ 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.

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 km² 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 x 10³ Mg yr⁻¹ (mean = 2.9 x 10² 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>
<thead>
<tr>
<th>TABLE 1. TSS LOADS IN LE SUEUR RIVER, 2000–2006</th>
</tr>
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<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>TSS* (Mg)</td>
</tr>
<tr>
<td>2000</td>
</tr>
<tr>
<td>5.8 x 10⁵</td>
</tr>
<tr>
<td>FWMC (mg/L)</td>
</tr>
<tr>
<td>918</td>
</tr>
</tbody>
</table>

Note: 2000–2005 data from Minnesota Pollution Control Agency (MPCA et al., 2007).
* TSS—total suspended solids.
† FWMC—flow-weighted mean concentration.
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% (Marhsner, 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 km²) 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...
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.
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>
<thead>
<tr>
<th>Station</th>
<th>Location</th>
<th>Years of operation</th>
<th>Drainage area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS1</td>
<td>Le Sueur R. at Red Jacket, BE County Rd. 66</td>
<td>1939–2006</td>
<td>2880</td>
</tr>
<tr>
<td>LS2</td>
<td>Le Sueur R., BE County Rd. 90</td>
<td>2006–2007</td>
<td>1210</td>
</tr>
<tr>
<td>LS3</td>
<td>Le Sueur R. at St. Clair, BE County Rd. 28</td>
<td>2007–2008</td>
<td>870</td>
</tr>
<tr>
<td>LC</td>
<td>Little Cobb R., BE County Rd.</td>
<td>1996–2006</td>
<td>336</td>
</tr>
<tr>
<td>BC</td>
<td>Big Cobb R., BE County Rd. 90</td>
<td>2006–2007</td>
<td>737</td>
</tr>
<tr>
<td>LM</td>
<td>Lower Maple R., BE County Rd. 35</td>
<td>2003–2006</td>
<td>878</td>
</tr>
<tr>
<td>UM</td>
<td>Upper Maple R., BE County Rd. 18</td>
<td>2006–2006</td>
<td>780</td>
</tr>
<tr>
<td>BD†</td>
<td>Beauford Ditch, Minnesota Highway 22</td>
<td>1999–2007</td>
<td>18</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Table 3. Mass Excavation from Valleys and Ravines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valley excavation (minimum estimate)</td>
</tr>
<tr>
<td>Mass (Mg)</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Maple</td>
</tr>
<tr>
<td>Cobb</td>
</tr>
<tr>
<td>Le Sueur</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

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.
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 × 10⁵ Mg yr⁻¹, equivalent to a suspended load (silt and clay fractions only) of 0.7–1.5 × 10⁵ 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 × 10⁵ Mg yr⁻¹, with an average of 2.9 × 10⁵ Mg yr⁻¹. The inorganic fraction (66%–84% of TSS) was therefore ~1.9–2.4 × 10⁵ 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 on 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 × 10⁵ Mg yr⁻¹, or 2.7 × 10⁵ 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*

<table>
<thead>
<tr>
<th>Drainage area (km²)</th>
<th>Maple Lower</th>
<th>Upper Lower</th>
<th>Cobb Lower</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>780</td>
<td>878</td>
<td>336</td>
</tr>
<tr>
<td>TSS¹ (Mg yr⁻¹)</td>
<td>7.9 x 10⁵</td>
<td>2.2 x 10⁵</td>
<td>4.0 x 10⁵</td>
</tr>
<tr>
<td>TSS¹ yield (Mg km⁻²)</td>
<td>9.9</td>
<td>25.4</td>
<td>11.8</td>
</tr>
</tbody>
</table>

*Data from MPCA (P. Baskfield, 2007, personal commun.), preliminary. ¹TSS—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× 10^6 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 pre-settlement sediment yields as well as by shedding light on the pattern and style of landscape evolution in an incising system.

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