Identifying sediment sources in the Minnesota River Basin

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Minnesota Pollution Control Agency

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Minnesota River Sediment Colloquium
June 30, 2009, Revised Aug. 10, 2010

Contents

Primary author

| Peter Wilcock | Johns Hopkins U/NCED | wilcock@jhu.edu |

Colloquium committee

| Pat Baskfield | MPCA | pat.baskfield@state.mn.us |
Patrick Belmont	NCED	belmont@umn.edu
Adam Birr	MDA	Adam.Birr@state.mn.us
Pete Cooper	NRCS	peter.cooper@mn.usda.gov
Dan Engstrom	SCWRS	dre@smm.org
Carrie Jennings	U of M/MGS	carrie@umn.edu
Richard Kiesling	USGS	kiesling@usgs.gov
Scott Matteson	MSU	scott.matteson@mnsu.edu
David Mulla	U of M	mulla003@umn.edu
John Nieber	U of M	nieber@umn.edu
Chuck Regan	MPCA	chuck.regan@pca.state.mn.us
Shawn Schottler	SCWRS	schottler@smm.org

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Introduction

The Minnesota Pollution Control Agency is supporting and collaborating with researchers to conduct studies to identify and quantify sediment sources within the Minnesota River Basin. This report summarizes that on-going work, describing the context and different sediment sources, and summarizing current understanding. Many of the streams and rivers in the Minnesota River watershed exhibit high levels of turbidity, which impairs the ecosystem of the Minnesota River, as well as the Mississippi River and Lake Pepin (Figure 1). The primary components of turbidity in the Minnesota River are suspended solids, of which sediments, silts and clays, are the main contributors. An effective plan to reduce turbidity in the Minnesota River requires identification of the principal sources of sediment, including their location, rate, and erosion mechanism.

Figure 1
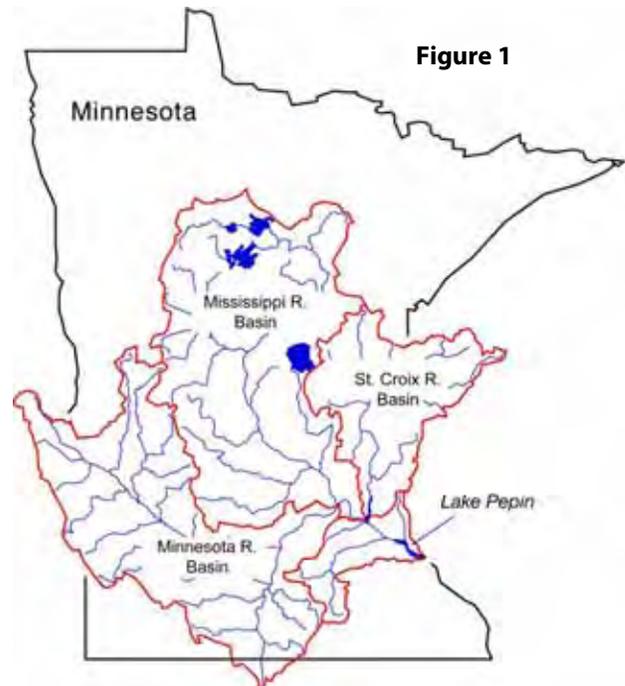
The landscape

The Minnesota River Basin is thickly mantled by glacial deposits remaining from large ice sheets that occupied the region as recently as 12,000 years ago. Relief in much of the basin is modest. ranging from nearly flat former lake beds to the rolling topography of glacial moraines. The steepest topography is found immediately along the Minnesota River. Toward the end of the last glacial period, Lake Agassiz, a very large lake fed by glacial meltwater, covered 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, which flowed in the valley now occupied by the Minnesota River. The large volume of meltwater from Lake Agassiz, including occasional extreme floods, carved a valley much larger than would be associated with a river the size of the Minnesota. Importantly, the lake drainage also caused the River Warren to cut through the glacial sediment and, in places, the underlying bedrock, by as much as 70 meters, producing steep valley slopes and initiating incision in tributary streams.

The initial river incision occurred approximately 11,500 years before present (Clayton and Moran, 1982; Matsch, 1983). Prior to the incision, tributaries to the ancestral Minnesota River were low-gradient streams of glacial meltwater origin. With the downcutting of River Warren, these streams were stranded above the master stream and began to cut deeper valleys (Figure 2). On a geologic time scale, this incision is just getting underway and is readily visible in air photos in portions of the basin along the Minnesota River (Figure 3). As the tributary rivers downcut, incision of their tributaries together with erosion of the valley sides increases the supply of sediment to the river. The portions of
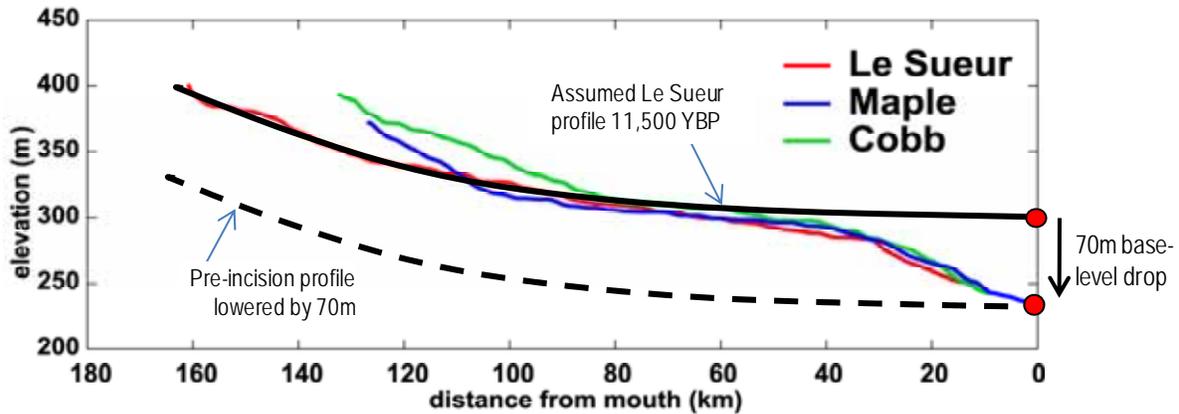
Figure 2. Long profile of the three main rivers in the Le Sueur River Watershed. Incision of the ancestral Minnesota River has triggered downcutting in its tributaries over the past 11,500 years. Downcut areas are associated with steep bluffs and ravines. Adjustment of the river network occurs over geologic time scales.

the Minnesota River Basin undergoing the most rapid incision are indicated on maps showing ground slopes (Figure 4-next page). The presence of the valley incision divides the Minnesota River Basin into an upper zone receiving sediment primarily from field, ditch, and stream erosion and a lower, incised zone, which receives additional sediment from high bluffs and ravines.

The recent geologic history of the Minnesota River Basin leaves it primed to be a large source of sediment. Agricultural development over the past 150 years has acted to greatly increase that sediment supply. The incised zone, although relatively small in area, can supply large

Figure 3. Aerial image (Google Earth) showing uplands, ravines and bluffs along an incised portion of the Blue Earth and Le Sueur Rivers.

amounts of sediment from erodible glacial deposits in a setting of steep slopes and incising river channels. In the low relief upland zone, erosion rates are generally smaller, but the area is very large and rates of soil erosion have increased many times over since European settlement due to the development of row-crop agriculture throughout the watershed (Mulla and Sekely, 2009). The challenge in determining sediment sources in the Minnesota River Basin is to evaluate sediment yield from upland field sources in the context of other sources driven by incision of the stream network. Which sources dominate? Which produce the most turbidity? Which are most treatable? This document summarizes efforts to define the balance between field and other sediment sources.

Sediment sources

In order to define management actions to reduce sediment loading, it is necessary to not only determine the location of erosion, but the mechanism by which sediment is eroded and introduced

into the stream system. The major sources of sediment can be grouped into four broad categories: fields, ravines, bluffs, and streambanks (Figure 5).

Approximately 65% of the land in the Minnesota River Basin is used for annual row cropping. Sediment sources include erosion from sheet and rill flow, gully development, and enlargement of drainage ditches. Agricultural fields in the watershed have extensive networks of subsurface and surface drainage. Intakes to drainage tiles are another sediment source and the increased runoff rates promoted by artificial drainage can increase erosion from flow through the watershed network. Sediment yield from agricultural land has been the

Figure 4. Map indicating regions of large valley slopes along portions of the Le Sueur, Blue Earth River and Minnesota Rivers.

subject of intense research for many decades and a range of models have been developed to estimate this source of sediment. Despite the extensive experience developed in estimating sediment yield from agricultural land, uncertainties in estimating sediment yield at the mouth of agricultural watersheds remain very large. One of the primary sources of uncertainty concerns the deposition of field-derived sediment before it reaches the stream, causing sediment delivery rates to be smaller than field erosion rates. We can constrain this uncertainty by using multiple sources of information, including information from stream gauges.

Tall hillslopes, or bluffs, are common along incised portions of the Minnesota River and its tributaries (Sekely et al., 2002; Thoma et al., 2005). Bluffs can be very large, more than 50m in height and 100s of m in length along the stream. Bluff erosion is driven by river erosion at the toe, which triggers slope failure by grain fall, slumping, gullying, and block fall. The rate of bluff erosion is also influenced by the layering of material properties such as strength, hydraulic conductivity, and grain size, the orientation of the bluff, and the amount of groundwater supply which can determine seepage paths and pressures near the surface of the bluff. Bluffs that contribute the most sediment to the river are tall, wet, actively undercut by the stream, bare of vegetation, and composed of
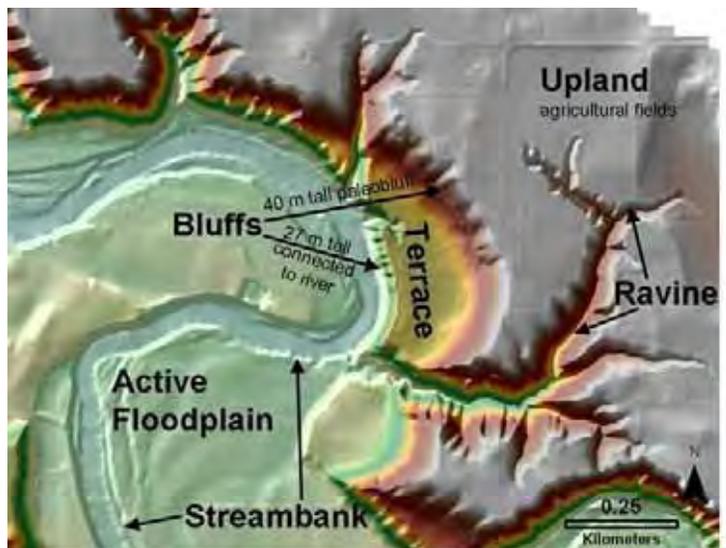

Figure 5. Digital elevation model of a portion of the Le Sueur River watershed, showing the primary sources of sediment.

weaker sediment layers. There is some indication that the rate of bluff erosion is proportional to the size of the bluff, although the range of observed bluff erosion rates is very large. Only a portion of bluff sediment is composed of fine grained materials that contribute to turbidity in the river water. Analysis of topographic data for the Minnesota River Basin indicates that more than half of the large bluffs in the Minnesota River Basin are located in the Blue Earth and Le Sueur watersheds south of Mankato (Figure 4). Control of bluff erosion ultimately requires protection of the slope toe against future erosion and retreat. Bluffs can continue to erode and supply sediment to the river for decades after toe protection; drainage control and slope revegetation are important factors in limiting further erosion. In developing a sediment budget to estimate the overall contribution from bluffs, the challenges are to determine the rates of bluff erosion and their controls, to identify all actively eroding bluffs, and to develop a reliable means of assigning erosion rates to all bluffs in the watershed.

In the incised portion of the Minnesota River Basin, small steep valleys, termed ravines, cut through the bluffs, connecting the broad, flat uplands to the incised river channel below. Ravines vary widely in size, shape, relief, and proximity to the Minnesota River. Unlike bluffs, ravines erode by a combination of hillslope and river processes. Although net erosional, ravines can store as well as erode sediment. Ravines exhibit a close coupling between hillslope and channel processes: incision of the channel in the bottom of the ravine triggers slope erosion by grain fall and slumping. Although the ultimate cause of ravines is the drop in elevation between the uplands and the incised mainstem channel, the immediate driver of erosion is the volume and rate of water discharged to the ravine, which can be increased by discharge from upland drainage systems. At their upper end, ravines may have sharp vertical cliffs or gentler forested hillslopes. Ravine channels can grade into smaller features termed gullies, which serve as the upper end of the ravine channel and are often controlled by grade and bank control measures.   Some larger ravines store large quantities of sediment in the valley bottom. Under conditions of increasing water discharge, such ravines may shift from storing to releasing sediment and may become some of the largest individual sources of sediment within the Minnesota River Basin.   Analysis of topographic data for the Minnesota River Basin indicates that ravines are found primarily along the valley walls of the Minnesota River and in the more deeply incised portions of the Blue Earth, Le Sueur, and Cottonwood watersheds. In developing an estimate of the sediment delivered from ravines, the challenges are to determine the rates of erosion from ravines and their controls and to develop a reliable means of identifying the ravines that produce the most sediment throughout the watershed.

Streambank erosion supplies sediment directly into the river, although the *net* contribution of sediment from streambanks and the floodplains behind them is not easily apparent. The net sediment contribution depends on the balance between streambank erosion and sediment deposition along the river's edge and on the floodplains adjacent to the river. This compensating deposition is too often neglected in determining the sediment budget of a valley bottom. The *net* sediment contribution from channel migration will be the balance between the volume eroded on one side and volume deposited on the other side. There may also be differences in grain size between eroding and depositing banks. The overall sediment balance for the valley bottom must also include deposition of sediment on the floodplains. Because of this compensating difference between erosion and deposition, we analyze streambanks separately from stream bluffs, which are purely erosional features. We distinguish between streambanks and bluffs by the presence of a depositional floodplain surface behind the streambanks. In developing an estimate of the net contribution from streambanks, the challenges are to determine rates of channel migration, channel enlargement, and floodplain deposition along the river valley channels in order to determine the net contribution of sediment from stream erosion and deposition.

Quantification – methods to determine mechanisms, rates and locations

Erosion rates are hard to determine precisely. Erosion occurs via a variety of mechanisms and the type and rate and location of erosion depends on a wide number of factors, including soil or sediment strength, vegetation, land slope, and local runoff. Erosion is generally episodic – an eroding site may show no activity most of the time and erode rapidly during short, intense events. Erosion also varies spatially – over the year, most eroded sediment is likely to come from a small fraction of the land in a watershed. Given this variability in space and time, it is difficult to reliably extrapolate erosion observed at one location to another. To develop reliability in our estimates of erosion, we depend on multiple methods and work to corroborate different, independent lines of evidence.

Stream gauging

Stream gauging provides the most direct and reliable evidence of erosion rates from a watershed. Although gauging requires effort and expense, much of what we know about sediment sources in the Minnesota River Basin comes from stream gauging. An extensive array of gauges has been operated in the Minnesota River by different local and state agencies and watershed projects. For example, 76 gauges were in operation in the period 2002-2006. Stream gauges generally consist of two separate operations. One involves periodic measurements of the rate of water flow, or discharge, and the river water level. From this information, a relationship between water level and discharge is developed and a continuous record of water level record is used to provide a continuous estimate of water discharge. The second operation involves periodic sampling of suspended solids. A relation between total suspended solids (TSS) and water discharge is developed and the continuous flow record is then used to estimate the TSS load over the period of record. Stream gauges on tributaries to the Minnesota are generally operated from spring through fall and removed during winter. The TSS loads are therefore seasonal, although little transport is presumed to occur during frozen conditions in the winter.

The gauge network identifies the total amount of sediment carried by the mainstem river as well as sediment contributions from the principal subwatersheds. Although gauging provides a measure of the amount of sediment passing a river station, it cannot provide information about individual sources. However, in seven tributary watersheds, multiple gauges are operated with gauges above and below the incised lower parts of the river valleys. Comparison of the loads at the upstream and downstream gauges helps to not only isolate the amount of sediment produced in these steepened parts of the watershed, but also provides a constraint on the sediment produced by the abundant bluffs and ravines found in these locations.

Local measurement of sediment erosion and storage

Erosion at local sites can be measured through direct surveys or by changes measured on aerial photographs taken at different times. Field measurements of erosion, particularly in ravines and bluffs, allow contributions from individual sources to be determined. Because such erosion rates vary strongly in time (one large event might move more sediment than the total over many years), it can be difficult to reliably extrapolate local erosion rates to longer time periods. Comparison of air photos taken at different times allows erosion to be measured over longer time periods, but generally with less precision than local measurements in the field. For both bluffs and ravines, erosion rates vary widely from place to place as a function of a range of factors, so a basis for extrapolating measured rates to larger areas is needed. Because many factors control the rate of erosion, it is important to constrain these extrapolations with other evidence, particularly from gauge records and geochemical fingerprinting.

Sediment fingerprinting

In recent decades, "radiometric fingerprints" and other geochemical tracers associated with sediment have been used to separate overland (field) erosion from non-field erosion (stream banks, bluffs, ravines, gullies) (Walling and Woodward, 1992, He and Owens,1995; Collins et al. 1997; Schottler and Engstrom, 2002). Atmospheric deposition of radioisotopes such as ^{210}Pb and ^{137}Cs enrich soils at the earth's surface. When eroded, these materials carry a radiometric "fingerprint", whereas sediments derived from deeper materials, such as by erosion of bluffs and ravines, have minimal exposure to atmospheric inputs and are thus depleted in these tracers. Comparing the tracer signature of field and non-field sources with the signature of suspended sediment in rivers permits the contribution of each erosion source to be calculated. The radioisotopes used in the Minnesota River Basin are closely affiliated with finer grain sizes (silts), making them useful for tracking the sediment sources that contribute to turbidity.

The radioisotope concentration in soils can vary widely, making it difficult to develop a reliable reference condition for the field. To address this problem, the St. Croix Watershed Research Station has developed a new method, utilizing closed basin lakes to efficiently generate a temporally and spatially integrated upland fingerprint. ^{210}Pb and ^{137}Cs fluxes and concentrations were measured in 30 reference lakes. Atmospheric and field eroded inputs of each tracer were modeled to compare predicted fluxes and concentrations to measured values. Optimizing the inputs to the model generates an estimate of the field fingerprint of ^{210}Pb (2.85 +/- 1.05 pCi/g) and ^{137}Cs (0.6 +/- 0.25 pCi/g). Samples from 30 non-field sites (bluffs, gullies, and ravines) had negligible concentrations, so the non-field fingerprint is taken to be zero.

TSS samples and sediment cores from fluvial depositional areas (backwaters, reservoirs, floodplain ponds) along major tributaries and the main-stem of the Minnesota River have been collected and analyzed for radioisotope tracers. TSS samples provide an event based measure of source apportionment, whereas core samples can provide a signature integrated over a longer time period. A simple ratio of fluvial to source fingerprints is used to calculate contributions from field and non-field sources.

Sediment budgets

A powerful tool for identifying sediment sources is a sediment budget. This is a mass balance – not unlike a checkbook – in which the difference between inputs and outputs must equal any changes in storage. We use a sediment budget to evaluate and constrain erosion estimates from various methods. For example, if we use field and air photo observations to estimate the annual amount of sediment eroded and deposited within a subwatershed, that net difference (input – output) should equal the amount of sediment passing a gauge at the mouth of the watershed. If the match is poor, we have some clues for improving our estimates of sediment sources and sinks. If we have closed the budget as best as possible, any remaining discrepancy gives an indication of the uncertainty in the combined estimates of erosion and deposition. In general, we try to bring as many lines of evidence together as possible – in effect, closing the budget for any time period or watershed scale for which sediment information is available. The evidence varies from the very large scale (e.g. evacuation of sediment from the Minnesota River watershed over the last 11,500 years, or changes in sediment delivery to Lake Pepin over the last 150 years) to much smaller scales (e.g. the increase in sediment loading over a storm between two gauges that closely bracket the incised zone on a stream).

Findings

A. Most of the sediment delivered to Lake Pepin is delivered from the Minnesota River Basin and the rate of this supply has increased ten-fold over the past 150 years.

Lake Pepin, a natural impoundment on the upper Mississippi River, provides a repository that records the erosion history of the agricultural watersheds of Minnesota (Figure 1). High-resolution dating of 25 sediment cores from Lake Pepin shows a tenfold increase in sediment loading to the lake since the advent of Euro-American settlement (from 79,000 t/yr before c. 1830 to 876,000 t/yr during the 1990s; Engstrom et al., 2009). An analysis
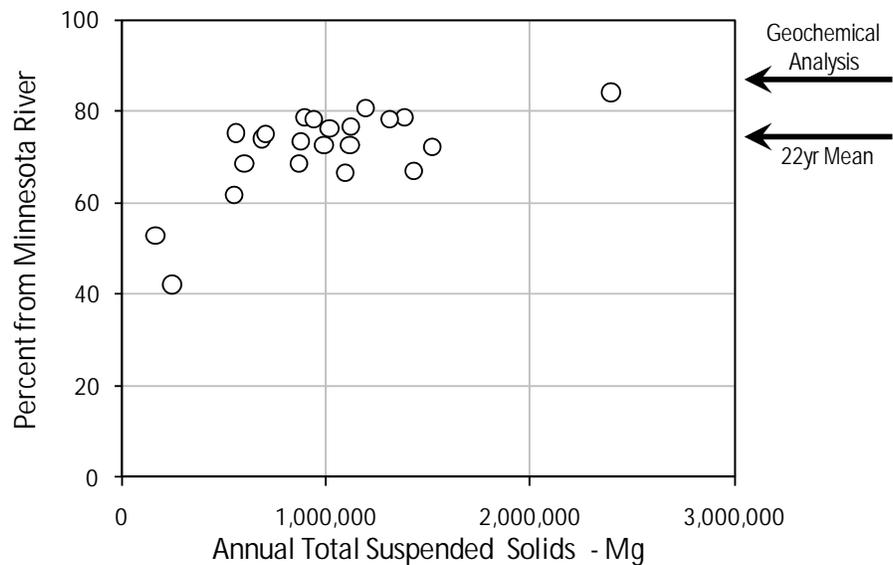

Figure 6. Percentage of TSS delivered to Lake Pepin from the Minnesota River Basin as a function of annual loading to Lake Pepin in metric tons. Data from stream gauging records from 1985 to 2006, compiled by MPCA. Also shown are the mean Minnesota River contribution (74%) and an estimate developed by comparing the geochemical composition of sediments in Lake Pepin with that of source materials in the contributing watershed (87%; Kelly and Nater, 2000). These independent estimates provide strong evidence that most of the sediment entering Lake Pepin is derived from the Minnesota River Basin.

of the chemical constituents of the sediment delivered to Lake Pepin indicate that between 80% and 90% of the sediment entering Lake Pepin comes from glacial deposits located predominantly in the Minnesota River Basin (Kelley and Nater, 2000). This estimate is supported by gauging records that indicate that, over a 22 year period, 74% of the sediment entering Lake Pepin derives from the Minnesota River Basin (Figure 6).

The record of sediment delivery from the Minnesota River over the past 150 years provides a useful context for modern estimates of sediment erosion. Models and methods for estimating modern sediment erosion should be demonstrated to be consistent with plausible changes in erosion that could be driven by changes in land use and climate over the same time period.

B. Some subwatersheds contribute most of the sediment to the Minnesota River.

A small number of watersheds contribute disproportionately large volumes of sediment to the Minnesota River. Figure 7 shows TSS yields from major tributaries to the Minnesota during 2005-2007. Sediment yield, in lbs/acre, indicates which watersheds produce the most sediment per unit area. Locations with the highest yield may be the most favorable for sediment reduction actions. Tributaries in the lower portion of the Minnesota River Basin, generally entering the Minnesota between Mankato and the Twin Cities have larger yields compared to tributaries entering upper portions of the Minnesota River. Sediment load depends on both yield and drainage area. A table of

sediment load in kilograms is inset in Figure 7. The Blue Earth and Le Sueur watersheds combine both large area and large yield and contribute more sediment to the Minnesota River than any other tributary. The Minnesota River valley is deeply incised in this reach, producing steep, incised valleys in tributaries.

Two gauges on the Minnesota River, one at Judson and the other at St Peter, nicely illustrate the increased loading in this region. Even though the drainage area increases by only 34% as one moves downstream from Judson to St Peter, the TSS loading increases by a much larger amount. For a five year period starting in 2002, the TSS load was 1.8 million tons at Judson and 5.4 million tons at St. Peter, a 300% increase. Nearly all of the increased load can be attributed to the TSS supply from the Blue Earth and Le Sueur Rivers, which discharge into the Minnesota between the two gauges. The 2002-2006 TSS load of these rivers was measured as 3.2 million tons.

Although stream gauging can show which tributaries provide the most sediment, determining the proportion of the total Minnesota River sediment load due to each tributary involves some complications. Sediment from ungauged tributaries must be included in determining proportions. Also, some of the sediment supplied from tributaries can be stored before leaving the Minnesota River Basin. Because of deposition, particularly along the broad valley of the Minnesota River, the mainstem record provides a measure of the total load passing each gauge; it does not indicate the total amount of sediment produced within the watershed.

Minnesota River Basin
2005-2007 Total Suspended Solids
Average Monitoring Season Yield (lbs/acre) and Load (kg)

Stream Name	TSS Yield (lbs/acre)	TSS Load (kg)
Lac Qui Parle	40	11,131,749
Chippewa	50	27,198,833
Dry Weather	45	1,374,654
Hawk	51	7,537,789
Yellow Medicine	71	13,747,476
Redwood	83	15,241,083
Beaver	26	711,808
Cottonwood	169	64,157,587
Little Cottonwood	153	7,547,115
Watonwan	149	36,863,082
Blue Earth	636	288,199,445
Le Sueur	508	163,730,873
Seven Mile	161	1,719,276
Rush	342	40,002,883
High Island	297	20,527,380
Sand	271	18,328,947

TSS Yield (2005-2007)
- 1-50
- 51-100
- 101-200
- >200

Legend
- Minnesota River
- Counties
- Major Watersheds

Map Prepared by: Scott Matteson
Water Resources Center
Minnesota State University, Mankato
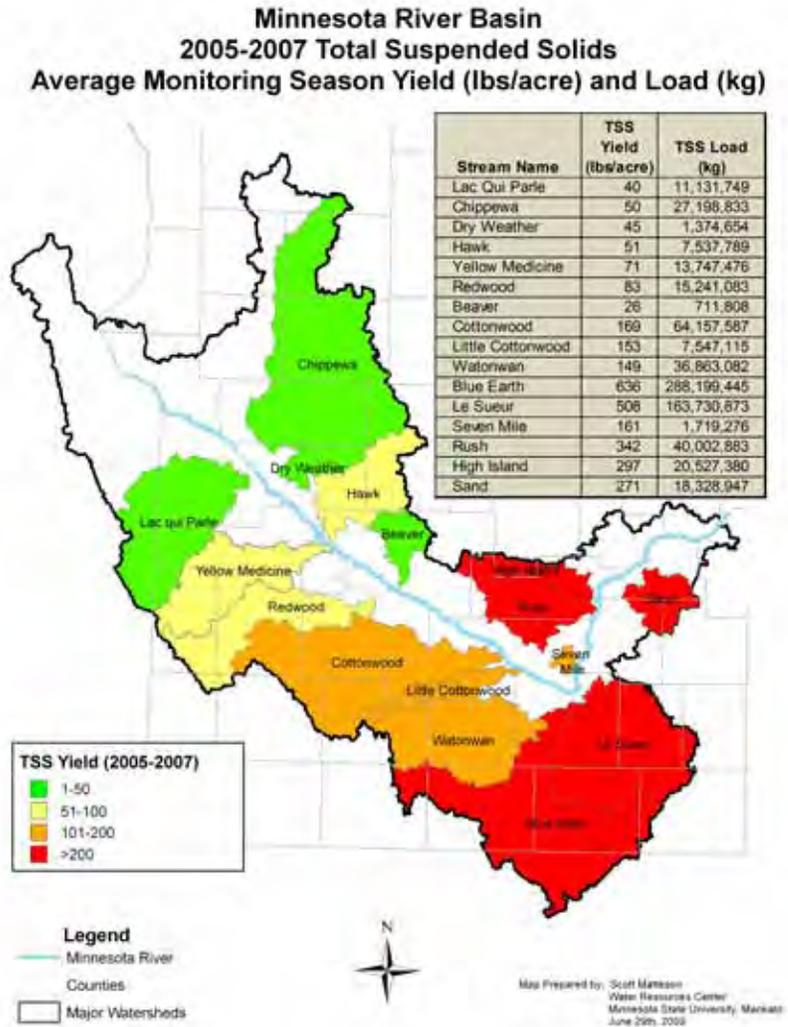June 29th, 2009

Figure 7. Map of Minnesota River Basin showing annual TSS yield (lbs/acre). Total annual TSS load in kg is given in the inset table. Locations not colored did not have available information.

C. Sediment source location within subwatersheds

The sediment sources within tributaries, including those with large sediment yield, are not evenly distributed. A likely region for increased sediment supply is the lower incised reaches of tributaries (Figure 2). Here, tall bluffs and ravines can augment sediment supply from fields and streambanks. Also, greater relief between field and stream can accelerate runoff and its associated erosion. An

increase in sediment supply has been documented in seven watersheds with pairs of stream gages that approximately bracket the lower incised reach. In general, the upper gauge records erosion from fields and streambanks, whereas the lower gauge records an increased input from bluffs and ravines. Based on comparison of loads at the upper and lower gauges, 30% to 95% of the sediment yield is picked up in the incised reaches between the gauges, even though the increase in contributing area is generally much smaller (Figure 8). The increase in loading through the incised reaches is particularly large in smaller watersheds entering the Minnesota River from its left bank (Seven Mile Ck, Rush River, High Island Creek), but also quite large in the Maple and Cobb Rivers.
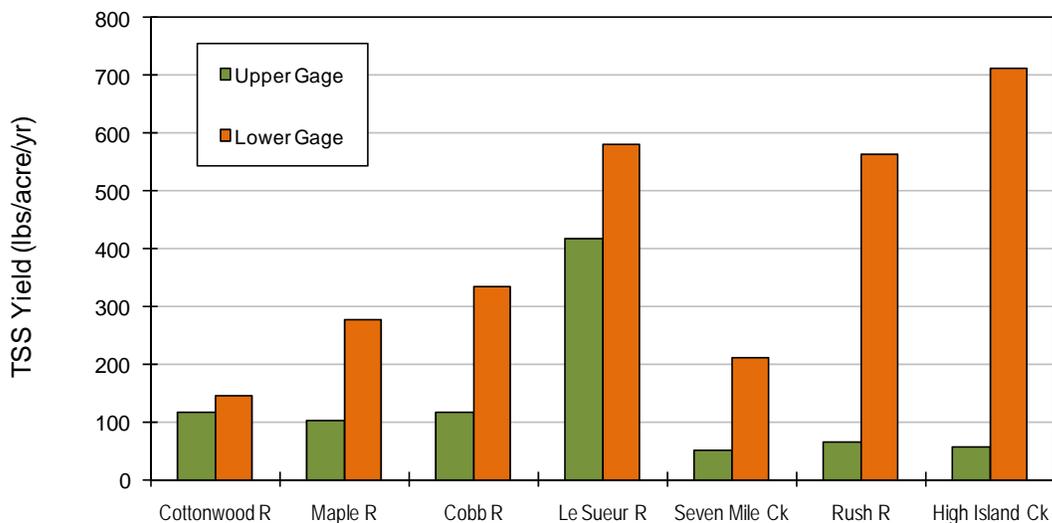

Figure 8. Annual TSS yield at upper and lower gauges in seven watersheds tributary to the Minnesota River. The gauges are located above and below the incised lower portions of the river valleys. Increases in TSS yield are generally much larger than the corresponding increase in drainage area, indicating that disproportionately large amounts of sediment are supplied in the incised reaches between each pair of gauges.

Comparison of Figures 7 and 8 indicate that many of the upstream/downstream gauge pairs have been located on rivers with large TSS yield. The comparison of upstream/downstream gauges clearly indicates that much of the loading occurs as the rivers move through the incised portions of the watershed. The stream gauging provides a direct confirmation of increased loading in these reaches and provides estimates of not just relative contributions, but the sediment delivery rates.

D. Identifying erosion mechanisms

In order to direct restoration efforts, it is necessary to determine not only the regions that contribute the most sediment to the Minnesota River network, but also the specific location and mechanism by which sediment is introduced. This is the most difficult sediment source allocation task. Ongoing research is directed at better defining the dominant sources of sediment in the watershed. The information given here explains the basics of this work and discusses the nature of the anticipated results.

i. Sediment fingerprinting indicates contributions from fields vs. other sources

The concentration of radioisotopes in river sediment provides an estimate of the proportion derived from field erosion. Fingerprinting results throughout the Minnesota River Basin indicate that inputs from field sources can vary between 10 to 40% (Figure 9). The fingerprint-derived percent field source in the Blue Earth and Le Sueur watersheds is somewhat smaller than found in watersheds with smaller loads, suggesting that increased supply from bluffs and ravines may dilute the proportion derived from fields. However, the difference in field percentage relative to lower-yield watersheds is
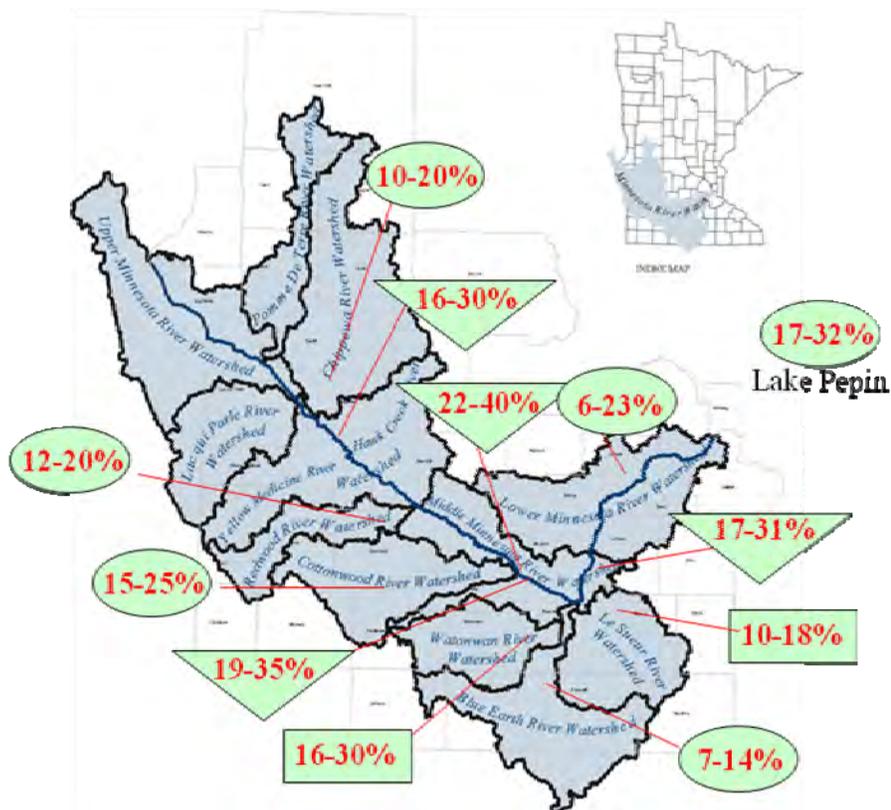

Figure 9. Average percentage contribution of field eroded sediment in the Minnesota Watershed estimated using radioisotope fingerprinting. Source apportionment values are based on the combined results of ^{210}Pb and ^{137}Cs tracers. Estimates based on TSS samples are shown in boxes, estimates from cores at depositional sites are in ovals and triangles. Triangles indicate samples taken from the Minnesota River mainstem. All estimates are for sediments finer than 63um, and are normalized to the inorganic fraction of the sediment composition.

modest compared to the increase in overall loading in these watersheds (Figure 7), suggesting that both field and non-field sediment sources are larger in the Blue Earth and Le Sueur systems.

ii. Sediment budget analysis

Direct measurement and extrapolation of erosion rates from ravines, bluffs, and streambanks can be combined with stream gauging and fingerprinting results to develop a sediment budget for individual watersheds. By using multiple lines of evidence, it is possible to estimate the relative magnitude of different sources and describe the uncertainty in those estimates. The Blue Earth and Le Sueur watersheds have been a particular focus for research on sediment sources. We will use the Maple River, a tributary of the Le Sueur River, to illustrate the development of a sediment budget for identifying source allocations. A stream gauge has been operated near the mouth of the Maple River since 2003, providing six years of TSS records. A second gauge, located close to the upper end of the incised zone, was started in 2006, providing three years of TSS records and a chance to compare changes in sediment loading as the river passes through the lower, incised part of the watershed.

The first step in developing a sediment budget is to estimate the rate at which sediment is supplied from the principal sources. Based on TSS records at various gauges that drain primarily upland portions of the Le Sueur and Blue Earth watersheds, erosion rates can vary between approximately 10 to 50 Mg/km^2. The sources of sediment to these upland gauges are primarily fields, with lesser contributions from streambanks and drainage ditches. On the Maple River, some smaller bluffs and ravines are located above the upper gauge.

Bluff erosion rates have been measured with both ground-based surveys and aerial photography measurements. Sekeley et al. (2002) report annual bluff erosion rates in the Blue Earth watershed of 0.04 Mg/m^2 to 0.15 Mg/m^2 with a median value of 0.078 Mg/m^2 (Figure 10). Work by the National Center for Earth-surface Dynamics indicates bluff erosion rates in the Le Sueur watershed between 0 and 0.4 Mg/m^2 with a median rate of 0.045 Mg/m^2. It is evident from Figure 10 that erosion rates vary widely from bluff to bluff. Developing a better method of estimating sediment contributed from bluffs is a primary focus on ongoing research. The area of actively eroding bluffs has been determined using high-resolution topography developed from airborne laser swath mapping (lidar).

Measurement of ravine erosion was initiated in 2008 in several ravines in the Le Sueur watershed. Preliminary measurements indicate annual erosion rates of order 0-0.0008 Mg/m^2. An upper limit for ravine erosion rates can be estimated using TSS gauging records on Seven Mile Creek near St Peter (Figure 7). Here, valley bluffs are formed partly in sandstone, reducing their rate of erosion. Two gauges are operated on Seven Mile Creek, one immediately above the incised reach and one near the mouth. An upper bound on ravine erosion rates of 0.0019 Mg/m^2 results from attributing all erosion between the gauges to ravines. In the Maple River, the area of ravines has been determined using high-resolution topography developed from airborne laser swath mapping (lidar).

River meander migration rates in the Maple River have been measured using 1938 and 2005 aerial photographs. Stream channel width and height has been surveyed in the field. Net bank erosion, reduced by estimated floodplain deposition results in an annual sediment supply to the Maple River of 0.035 Mg per m of streambank.

Sediment supply from fields, ravines, and bluffs is calculated by multiplying an erosion rate for each source by its area. Sediment supply from streambanks is estimated using a net bank erosion rate multiplied by stream length. These estimates have enormous uncertainty unless constrained by an independent estimate of sediment loading. In the Maple River, this constraint is provided by measured TSS loads at the two stream gauges. For six-year record (2003 - 2008) at the lower gauge, the estimated annual TSS load is 41,300 Mg (after excluding organic solids). The record at the upper gauge is shorter, (2006 - 2008) with an annual TSS load of 7,800 Mg. This value may be smaller than the long-term average because sediment loads were generally small in 2006, 2007, and 2008.

Evaluation of the Maple River sediment budget indicates that plausible, if relatively large, erosion rates can produce 41,300 Mg annual sediment load at the lower gauge. For example, if relatively large erosion rates are chosen for bluffs (0.078 Mg/m^2/yr) and ravines (0.0019 Mg/m^2/yr), the upland erosion rate needed to produce the observed downstream load is 26.3 Mg/km^2/yr. This combination corresponds to a contribution from fields, bluffs, and ravines of 47%, 39%, and 10%, respectively, with the balance contributed from net erosion of streambanks. This upland erosion rate is large, but within the mid-range of upland erosion rates observed in this area. The percentage derived from the field is considerably larger than observed with fingerprinting (Figure 9). If a smaller field erosion rate of 17.1 Mg/km^2/yr is used (consistent with the estimates derived from the longer record at the lower gauge), a bluff erosion rate 0.137 Mg/m^2/yr is sufficient to produce the TSS loading observed at the lower gauge, giving a field and bluff percentage of 18% and 69%, respectively.   This field percentage is closer to that observed using fingerprinting. The proportions are also consistent with a similar sediment
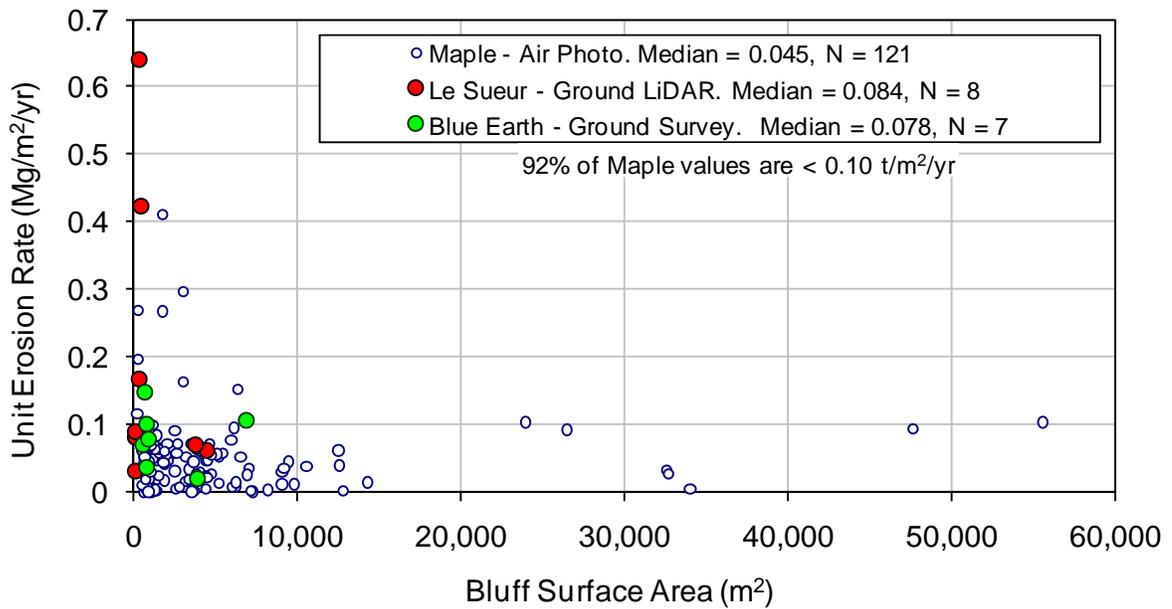
Figure 10. Bluff erosion rates observed in the Le Sueur and Blue Earth watersheds. Erosion rates are estimated for muds only (silts and clays).

budget that estimated upland sediment supply using the SWAT model for the entire Le Sueur watershed. However, a bluff erosion rate of 0.137 Mg/m²/yr is larger than 94% of the measured bluff erosion rates (Figure 10), indicating that either total bluff erosion rates are larger than estimated from field and air photo measurements, or that contributions from field, ravines, or streambanks are larger than estimated. One possibility is that ravines and the fields and gullies adjacent to ravines may contribute more sediment than captured in the calculations above. This is supported by field observations that river turbidity and TSS concentrations can be much larger on the rising limb of floods when muddy flows are observed to discharge from ravines compared to the falling limb of floods when ravine discharge and TSS can be much smaller. Ongoing research is directed toward developing improved understanding of each of these sources and reconciling these independent estimates of sediment supply.

The lower Maple River flows through a deeply incised landscape. In this location, bluff and ravine erosion may exceed that from fields as the dominant sediment erosion mechanism. In watersheds with few or no bluffs, the proportions will be different. Ongoing research is focusing on improving our ability to estimate sediment source apportionments in other locations in the Minnesota River Basin

E. Sediment storage in the lower and middle Minnesota River valley

Storage of eroded sediment along the mainstem Minnesota River can be evaluated using records of TSS load from stream gauging on the mainstem and its tributaries. Mainstem gauging stations operate at Judson, St. Peter, Jordan, and Ft. Snelling. To calculate storage between any pair of these gauges, sediment inputs are added and compared to the output at the downstream gauge. For the entire gauged reach, load at the upstream gauge at Judson is combined with tributary inputs for comparison with the output at the downstream gauge at Ft. Snelling. TSS inputs from ungauged tributaries are estimated by applying the yield of the gauged tributaries to the drainage area of the ungauged tributaries. This was done separately for each year 2000-2005 and for each of the three
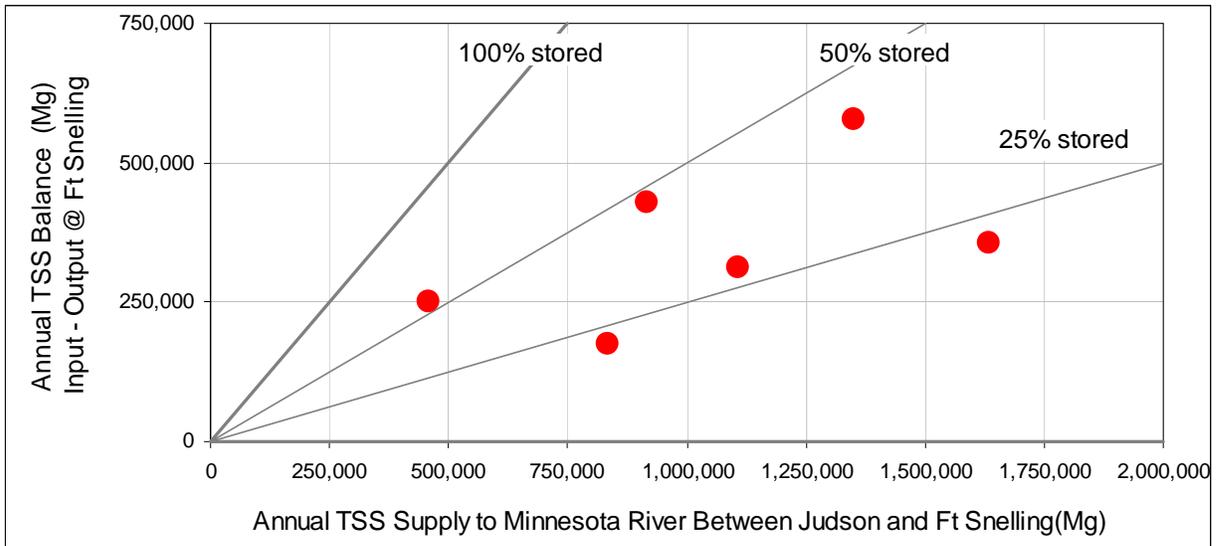
Figure 11. Estimated TSS storage along the mainstem Minnesota River between Judson and Ft. Snelling. Annual input is TSS supply at the Judson gauge and all tributaries between Judson and Ft Snelling. Annual output is the TSS load at Ft Snelling. The annual balance is (input – output) and is plotted as a function of input. Sediment storage is indicated in each year with a six year average storage of 33% of input.

mainstem reaches. Of the total supply of 6.3 million Mg estimated for this six year period, 18% was estimated for ungauged areas or missing data; the remainder was from calculated loads at gages.

Sediment storage between Judson and Ft. Snelling varies between 21% and 55% for each of the six years 2000-2005, with an average storage over the entire period of 33% (Figure 11). By these estimates, of the 6.3 million Mg TSS supplied above Ft Snelling over 2000-2005, 2.1 million Mg were stored along the Minnesota River valley and 4.2 million Mg passed Ft Snelling. Annual values are 1.05 million Mg supplied, 0.35 million Mg stored, and 0.7 million Mg discharged. The reach with the largest sediment storage is between St Peter and Jordan, which stored 26% percent of its sediment supply from 2000-2005.

One consequence of sediment storage is that percent reductions in sediment supply from tributaries will be reduced by sediment storage between source and sink. That is, if management actions were to reduce sediment supply to the river network by, say, 100,000 Mg, we may expect reductions in loading at Ft. Snelling of order 67,000 Mg, or two-thirds of the reduced supply. Another consequence, potentially more important but difficult to evaluate with current information, is that changes in sediment storage along the Minnesota River may play an important role in the sediment delivery from the watershed. Hence, factors that influence changes in sediment storage may have important consequences for changes in sediment delivery from the Minnesota River. One factor that may contribute to the increase in sediment delivered to Lake Pepin over the 20th Century is the development and maintenance of a shipping channel and the construction of levees along the Lower Minnesota River. If these actions have reduced the extent of flooding and flood-related deposition, the proportion of sediment stored in this lower reach would be reduced, leaving a larger fraction of the sediment supply delivered directly to the Mississippi River and Lake Pepin.

Summary of current understanding of sediment sources

Multiple lines of evidence indicate that most of the sediment entering Lake Pepin comes from the Minnesota River Basin and that the rate of sediment supply has increased by approximately an order of magnitude over the 150 years. Widespread agricultural development over that time clearly plays a dominant role in this history, although changes in climate may have also contributed. The geological history of the Minnesota River valley leaves it primed to produce large amounts of sediment – floods from glacial meltwater lowered the Minnesota River valley bottom by as much as 70m about 12,000 years ago and the tributaries draining into the maintstem have been adjusting to this downcutting by carving their own valleys ever since. An extensive series of stream gauges documents that the tributaries that contribute the most sediment to the Minnesota River Basin are those with a deep incised drainage, a large drainage area, and readily eroded soil and sediment. Actions to reduce sediment loading require identification of not only the subwatershed from which the largest amounts of sediment derive, but the specific location and mechanism of large sediment supply. Sediment sources can be grouped into four categories: field, ravine, bluff, and streambank. Stream gages located above and below the incised zone in seven watersheds show that these portions of the tributary watersheds produce a large fraction of the sediment supply, indicating that the bluffs and ravines that predominate in these regions are important sources of sediment.

Further resolution of the location and mechanism of erosion is not a simple task: erosion is generally episodic and locally intense, making direct observation uncertain and extrapolation to large areas difficult. We develop confidence in our estimates by using different methods to develop multiple lines of evidence. Comparison among the different estimates is guided by the strong constraint of mass balance (e.g. the erosion and change in sediment storage in a watershed must equal the total sediment leaving the watershed) and corroboration between multiple lines of evidence (e.g. the proportion of field-derived sediment estimated by sediment fingerprinting should be consistent with the rates used to estimate a sediment budget; the sum of the estimates from individual mechanisms should be consistent with the total load measured at stream gages). Research has focused in the Blue Earth and Le Sueur watersheds, which together may contribute as much as half of the sediment to the Minnesota River, even though they account for only one-fifth of its drainage area. These watersheds contain the majority of the bluffs in the basin as well as many large ravines. Sediment derived from bluffs and ravines may be the largest source of sediment in these watersheds although local observations have not been fully reconciled. In watersheds with fewer bluffs and ravines, the contribution of sediment from non-field sources will be smaller.

Based on stream gauging results, more sediment is delivered to the Minnesota River from its tributaries than is discharged to the Mississippi and Lake Pepin, indicating that sediment storage occurs along the Minnesota River and its wide valley bottom. This is significant because reductions in loading in the tributaries will be reduced by the proportion stored along the Minnesota River and because factors that influence changes in sediment storage along the Minnesota River valley bottom may also play a role in determining sediment supply to Lake Pepin.

Ongoing research

The Minnesota Pollution Control Agency and other local and state agencies continue to invest in research to better understand sediment sources in the Minnesota River watershed. This work is intended to support selection of effective remediation actions and to forecast the water quality benefits of these actions such that wise allocation of public resources can be made. The following is a partial list of ongoing research.

i. Continued monitoring of TSS loads from principal tributaries to the Minnesota River as well as multiple mainstem stations in order to track the response of river water quality to changes in land use, climate, and management actions.

ii. Continued gauging upstream and downstream of incised portions of key watersheds in order to identify the magnitude of bluff and ravine contribution and to test methods for estimating the contribution from different sources within a watershed. These gauges provide a high return in improved understanding of the magnitude, location, and mechanism of sediment supply in the Minnesota River Basin.

iii. Complete sediment budget for the Le Sueur watershed, combining all sources in a model that accounts for the routing and storage of sediment along the rivers, using a mass balance to constrain estimates and define uncertainty.

iv. Complete an inventory of ravines and bluffs for the incised portion of the Minnesota River Basin . Conduct research to measure sediment loads from these features.

v. Use a mass balance to reconcile erosion estimates from different methods, including extrapolation of local erosion rates, different various fingerprinting methods, and gauging records.

vi. Develop a basis for extrapolating sediment budgets from one watershed to another in order better characterize sediment sources throughout the Minnesota River Basin.

vii. Develop a sediment budget for the Minnesota River mainstem in order to identify the magnitude of sediment storage and the factors that control changes in sediment storage. Evaluate possible management actions along the mainstem that may alter the proportion of TSS stored in the river floodplain.

viii. Conduct research to identify the relative roles of changing climatic patterns versus changing land use and land management patterns on sediment delivery from bluffs and ravines.

ix. Explore the role of tile and ditch drainage in changing stream hydrology and the erosive potential of Minnesota River tributaries.

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