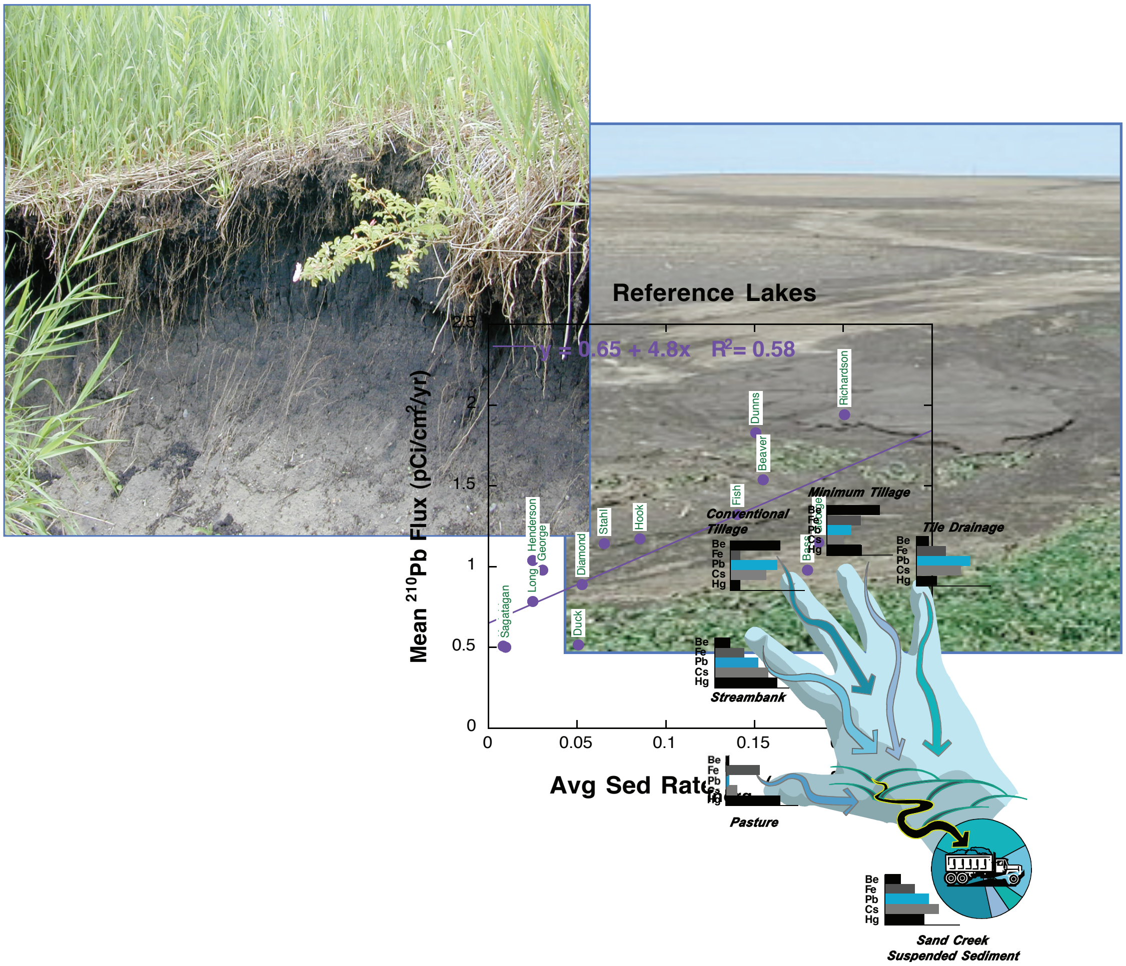
Fingerprinting Sources of Sediment in Large Agricultural River Systems



Shawn P. Schottler, Daniel R. Engstom, Dylan Blumentritt
St. Croix Watershed Research Station: Science Museum of Minnesota

Fingerprinting Sources of Sediment in Large Agricultural River Systems

Final Report

In fulfillment of the requirements for the objectives outlined in the following:

Sediment Source Apportionment to the Lake Pepin TMDL Project CFMS # A94798
Minnesota Pollution Control Agency, 520 Lafayette Road North
St. Paul Minnesota, 55155

Carver County Turbidity Workplan with the Minnesota Pollution Control Agency.
Carver County Government Center,
600 East Fourth Street, Chaska MN 55318-2158

Redwood Cottonwood Rivers Control Area
1241 E. Bridge Street Redwood Falls, MN 56283
State of Minnesota Grant Agreement, Section 319-06 Non-point Source Management
CFMS Agreement No. A95087.

Brown- Nicollet Water Quality Board
322 S. Minnesota Ave. St. Peter MN 56082

Upper Mississippi River Source Water Protection Project
City of St. Cloud, Public Utilities
400 2nd St. South, St. Cloud MN 56301

August 1, 2010

Principal Investigators: Shawn Schottler, Daniel Engstrom and Dylan Blumentritt
St. Croix Watershed Research Station16910 152nd St. North
Marine, MN 55047 schottler@smm.org

Co-investigators: Carrie Jennings[1.] and Laura Triplett[2]
1. Minnesota Geological Survey, St. Paul, MN
2. Gustavus Adolphus College 800 W. College Ave., St. Peter, MN 56011

Acknowledgements

A sincere thank you is extended to all individuals who assisted with collecting suspended sediment samples. Chuck Regan of the MPCA spearheaded this effort. During storm events and weekends Chuck visited numerous sampling sites and collected 10-20 liter water samples and used his home to settle the "mud" and do the initial decanting of water. His efforts were critical to the success of this project. We want to thank all other water managers, technicians and MPCA staff who assisted with sample collection. Without all their dedication and Herculean effort this project would have been lacking in event based source apportionment measurements.

Understanding the link between glacial history and the erosion potential of a watershed is an important aspect of interpreting sediment fingerprinting results. Carrie Jennings of the Minnesota Geological Survey was instrumental in fostering our knowledge of the glacial history of the Minnesota River basin. We thank her for the many hours of fieldwork assistance, and for imparting a real understanding of why the watersheds look and behave the way they do.

We also want to thank Scott Matteson and Rick Moore of Minnesota State University-Mankato. Scott efficiently provided sediment load and yield data for most of the tributaries and Rick took the time calculate the surface areas of several tributaries. Both of these efforts were critical to completing this project.

During the course of the several studies that are summarized in this report, we received numerous comments and advice from many people with extensive experience in the Minnesota River watershed. Their insights and suggestions guided the outcome of these projects. We are grateful for their contributions, and the stimulation to think critically about sediment transport processes.

Table of Contents

List of Tables and Figures

Figures

Tables

Executive Summary.

Lake Pepin and many of the tributaries in the Lake Pepin watershed are impaired for turbidity and excess sediment. The purpose of this project was to use radioisotope fingerprinting to quantify the relative importance of different erosion sources as contributors to the total sediment load. Specifically this study was aimed at separating the contribution of field erosion from non-field erosion sources. Source apportionment was compared and contrasted in multiple tributaries to the Minnesota River, at sites along the mainstem of the river, and in the sediments accumulated in Lake Pepin. This report summarizes the findings from five detailed studies conducted on the greater Lake Pepin watershed. Any one study offers a site-specific estimate of the importance of field and non-field erosion sources. These site-specific results are more enlightening when placed in context with the results of other systems. Thus, this report combines the results of multiple projects into a single presentation, offering the reader a chance to view a basin-wide assessment of erosion sources as predicted by radiometric fingerprinting. By contrasting the watersheds, the importance of different erosion processes emerges.

From a simple two-source perspective, this study successfully addressed the central question and the results show that non-field sources contribute the majority of the sediment burden. This observation of non-field sources dominating sediment loading was true for all tributaries studied and for Lake Pepin. This finding requires that future management strategies will need to focus on mitigating non-field sources and more importantly address the mechanisms that have caused non-field erosion to increase over time. The latter is a critical knowledge gap, brought to the forefront by this research. Significant findings from the studies are summarized below.

Utility of radioisotopes for sediment fingerprinting

The atmospherically deposited radioisotopes, ^{210}Pb and ^{137}Cs were successfully used to discriminate between field and non-field sources. A new method, employing reference lakes, in agricultural watersheds, was developed to ascertain a watershed scale field fingerprint for each tracer. Implementation of this method brought to light the need to correct for direct atmospheric inputs of ^{210}Pb to lake and river surfaces when using this isotope as sediment source tracer.

Relative contribution of field versus non-field erosion

Field versus non-field contributions were assessed in 15 tributaries to the Minnesota River, the River itself, the South Fork Crow River, and Lake Pepin. Non-field sources contribute 60-85% of the sediment entering the Minnesota River. The South Fork of the Crow River had largest field contribution with about half of the sediment coming from field sources. Lake Pepin, which integrates the tributary inputs, currently receives about 65% of its sediment from non-field sources.

Field and non-field sediment loads and yields

While the different watersheds were similar in their percentages of non-field contributions, they are very different in their non-field sediment yields and loading. Not unexpectedly, non-field loads were greatest in the large, and steeply incised watersheds of the Blue Earth-LeSueur watershed. Yields of non-field sediment varied by nearly 500 kg ha^{-1} yr^{-1} among watersheds whereas, field derived sediment yield was less variable, ranging by only 150 kg ha^{-1} yr^{-1} among watersheds. Non-field yields in steeply incised watersheds with eroding bluffs, regardless of watershed size, were uniformly greater than 300 kg ha^{-1} yr^{-1}. The Seven Mile Creek watershed, which is incised but absent of large bluffs had yields of 200 kg ha^{-1} yr^{-1}. Non-field yields in less incised watersheds or watersheds with lower rainfall were less than 100 kg ha^{-1} yr^{-1}. Taken in combination, this means that if we want to understand and mitigate sediment impairments, we need to understand and mitigate the processes that drive non-field erosion. Sediment delivery to agricultural rivers is the result of both land form and land use. Understanding this linkage with respect to non-field loading is especially salient in the Lake Pepin watershed.

Increases in non-field erosion.

Sediment cores from lake Pepin provided an opportunity to examine trends in sediment loading over time. New cores collected in 2008 confirm the accumulation rates estimated in 1996 and show that non-field loading is currently 5X greater than background rates. This shows that while the sources of non-field sediment are natural features, the rate at which they are eroding has accelerated in the last 100 years and implies that rivers have become more erosive over time.

Changes in other systems supporting the Lake Pepin findings.

Sediment cores from Miller Lake and the Redwood Reservoir support the findings from Lake Pepin. Miller Lake (Carver County, MN) integrates sediment inputs from upper Carver Creek, which drains an agricultural watershed that is not incised. Total sediment delivery to the lake has increased by ~ 4X since 1870 and non-field inputs have increased by nearly 2.5X over this same time period. These changes are smaller than those observed in Lake Pepin and likely reflect the magnitude of change expected from a non-incised watershed. The sediment archive in Miller Lake substantiates the conclusion that non-field erosion has increased since European settlement. The Redwood Reservoir (Redwood Co, MN) integrates sediment from a larger riverine system in western Minnesota. A sediment core from the Redwood Reservoir showed nearly an identical relative change in accumulation rate as that observed in Lake Pepin over the same time periods. Sediment inputs to the Redwood Reservoir are also dominated by non-field sources.

Additional work

This study confirms that non-field sources currently dominate sediment loading and that the rate of non-field erosion has increased significantly. The mechanism driving this change is unknown but is likely related to changes in river hydrology. Quantifying the importance of bluffs, ravines and streambanks and understanding the mechanism for each source is imperative for shaping sediment and turbidity management strategies. Further work needs to be done to understand if and how rivers have become more erosive over time and verify temporal trends found in Lake Pepin. Additional studies should examine historical changes in non-field contributions in riverine systems. Comparing and contrasting non-field inputs in watersheds with different landform and land-use may be one of the best methods to understand the drivers of field and non-field erosion.

Introduction

This study sought to answer a straightforward question: what percent of the sediment in Minnesota River system and Lake Pepin is derived from erosion of agricultural fields and how much is from non-field sources? From a management standpoint this is a critical question, as best management practices need to be targeted at the source of the sediment. It has often been assumed that agricultural fields are the dominant source of the sediment, yet large, eroding, non-field sources such as bluffs, streambanks and ravines are visually obvious along the rivers. The studies presented here used two radioisotopes to fingerprint and apportion sources of sediment in Lake Pepin and its tributary basins. Suspended sediments were used to obtain event-based snapshots of source apportionment, while backwater depositional sites were used to get an integrated assessment of different source contributions. Sediment cores from Lake Pepin and the Redwood Reservoir provided an opportunity to estimate how sources have changed over time. This final report combines the findings from five studies. Any one study provides only a partial analysis. The comparison and contrasting of the different tributaries coupled with the historic trends offered by Lake Pepin provide a more complete account.

It is the understanding of sediment sources in concert with erosion processes and mechanisms that make the study of Lake Pepin and it's tributaries so unique. This study focused on Lake Pepin and it's watershed (Fig. 1), not because its sediment impairment is larger or more critical than other impaired waters, but because of the unique characteristics of the system and the opportunity to advance the understanding of erosion processes in a large agricultural watershed. Lake Pepin is an almost singular study site. It is a natural impoundment on a major river system. Approximately 80% of all sediment entering Lake Pepin, today and historically, comes from the Minnesota River (Kelley and Nater, 2000, Meyer and Schellhaass, 2002) and a few select tributaries on the Mississippi River. The land use in the Minnesota River watershed is nearly 90% agriculture with the majority as row-crop agriculture. This means that the sediments in Lake Pepin are an archive of the erosion history of a major agricultural river system.

Figure 1. Major watersheds contributing to Lake Pepin

Furthermore, the sediments in Lake Pepin represent a temporally and spatially integrated record of the erosion processes of a large Midwestern agricultural watershed. Few places in the world offer such an opportunity to understand the effect of watershed-scale land use on sediment erosion.

But the story in Lake Pepin is more than just the effect of changing land use on changing sediment loads; it is also the story of landform. Lake Pepin and the Minnesota River watershed have been shaped by a distinct glacial history. The large ravine and bluff complexes and migrating knick points common in many of the tributaries are a direct result of a catastrophic and exceptional postglacial event. Lake Pepin may be the only place where sediments from an agricultural watershed and tributaries with large eroding bluffs are integrated into a single chronologically intact archive. It is the attempt to understand the linkage between land form and land use that make Lake Pepin scientifically important; and it is the comparison of sediment sources and yields among the many tributaries which helps unravel this erosion story.

Lake Pepin and Minnesota River Basin Geologic Context

The Lake Pepin watershed is comprised of three large river systems that drain the southern half of Minnesota and parts of adjoining Wisconsin and the Dakotas (123,000 km^2): the St. Croix, Minnesota, and headwater Mississippi rivers (Fig. 1). The Minnesota River joins the Mississippi in St. Paul and 40 km downstream is the confluence with the St. Croix River. Each basin is thickly mantled in glacial deposits from the most recent ice lobes of the Laurentide Ice Sheet (LIS). However, because the ice lobes were sourced in different areas, the glacial sediment varies in lithology.

The deposits of the Superior lobe of the LIS cover what is now the St. Croix River basin and much of the headwaters Mississippi basin. The Superior lobe incorporated the iron-stained clastic rock fragments of northern Minnesota and crystalline rocks of the Canadian Shield giving its till a reddish brown color and sandy loam matrix texture. In contrast, the Minnesota River and western portions of the headwaters of the Mississippi drain glacial deposits left by the Des Moines lobe of the LIS. The Des Moines lobe was sourced in the limestone and shale of the eastern Dakotas and Manitoba, which makes its sediment gray and carbonate-rich with a loam to clay loam matrix texture. The Minnesota and adjacent S. Fork of the Crow River watersheds are dominated by the low relief loamy glacial till deposited during multiple phases of the Des Moines lobe between approximately 14,000 and 12,000 radiocarbon years before present (^{14}Cybp)(Clayton and Moran, 1982). In some Minnesota tributary watersheds (e.g. Le Sueur, Chippewa), the till is mantled by up to 3 m of alternating beds of glacio-lacustrine silt and clay that were deposited in short-lived proglacial lakes. In other tributary watersheds, the till surface is inset with deposits of broad, sandy, meltwater streams that flowed along the margins of the retreating Des Moines lobe (Redwood, Cottonwood and Watonwan rivers) (Jennings, 2010), giving the modern rivers occupying those channels a sandier substrate to erode. Overall, the fine-grained, nutrient-rich parent material of the Minnesota River basin, coupled with a level to gently undulating topography make for a highly productive, if poorly drained, agricultural landscape.

As the LIS retreated into Canada, a large pro-glacial water body, glacial Lake Agassiz, covered much of northwestern Minnesota and portions of Manitoba and Ontario (Upham, 1890, 1895; Matsch 1972,1983). The southern outlet of Lake Agassiz created a valley that was 45 m deep at its mouth and 70 m deep near Mankato and conveyed glacial meltwater to the Gulf of Mexico by way of the Mississippi River. This high discharge river, known as glacial River Warren, flowed intermittently over much of the nearly 6,000 year life of Lake Agassiz (Breckenridge et al. 2004).

Rivers in the Middle Minnesota basin, which had been low-gradient streams of glacial meltwater origin, became stranded above the master stream when the initial incision occurred, 11,500 ^{14}C ypb (approximately 13,500 calendar years ago) (Clayton and Moran, 1982; Matsch, 1983). Knick points that originated from this sharp drop in base level immediately began eroding headward and are today expressed as bedrock waterfalls located within 5 to 10 km of the confluence on several major tributaries and as less pronounced slope discontinuities as far as 35 km upstream in tributaries draining more easily eroded glacial deposits. As a result, all of the tributary watersheds in the middle Minnesota River are now comprised of two main zones that vary somewhat in their extent because of the local geology: 1) a relatively low-relief upper zone that is unaffected by knickpoint migration; and 2) a high-relief lower zone where the river is at grade with the Minnesota River (Fig. 2). This lower reach is characterized by bluffs along the valley walls, conditions favorable for ravine formation, flights of terraces that reflect the history of incision of the stream, and new knick points on tributaries to the incised reach. Knick points continue their headward movement today wherever the water that powers their migration continues to be supplied.

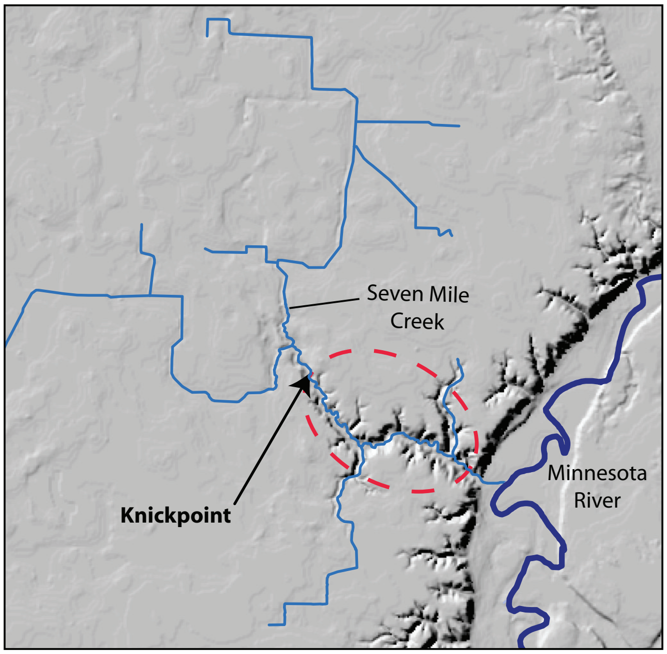


Figure 2. Hillslope model showing the Seven Mile Creek drainage system as it enters the Minnesota River. The area inside the red circle is the incised portion of the watershed, resulting from Glacial River Warren downcutting that began 13,5000 RCYBP and continues today.

As Lake Agassiz drained and its River Warren outlet was abandoned, the Chippewa River of northwestern Wisconsin began depositing its sediment load in the Mississippi River valley and created a natural riverine impoundment, Lake Pepin. This is a fortunate "accident" of geologic history, because the sediments in Lake Pepin record the erosion history of much of Minnesota over the last 10,000 years. This depositional basin provides a unique opportunity to determine natural "background" rates of sediment and nutrient loading and to track erosion brought about by land-use changes that began with European settlement in the region more than 150 years ago.

Historically and currently about 80% of the sediment that is deposited in Lake Pepin comes from the Minnesota River basin (Kelley et al 2006, Kelley and Nater, 2000). A recent analysis of sediment cores taken from Lake Pepin indicates that sediment accumulation rates have increased almost an order of magnitude from pre-European settlement (c. 1830) to 1996 (Engstrom et al. 2009). During this time over 90% of the Minnesota River basin was converted from native prairies and wetlands to agricultural land use (primarily row-crop). As stated earlier, this makes Lake Pepin an ideal system in which to study the erosion processes of large agricultural watersheds, especially in the context of their different geologic settings.

Overview of Radiometric Fingerprinting

Quantifying the relative and absolute contributions of different sediment sources to riverine loads has proven to be a difficult task, but one that is paramount to efficiently allocating resources to land management/soil erosion practices. Several studies (Whiting et al., 2005; Walling et al., 2002; Collins and Walling 2002; Schottler and Engstrom, 2002; Brigham et al., 2001; Walbrink and Murray, 1996; He and Owens, 1995) have used atmospherically deposited radioisotopes as tracers to discriminate between sediment sources in small watersheds. Walling and Woodward (1992) first presented the use of “radiometric fingerprints” as tracers of suspended sediment sources for two basins in the United Kingdom (UK). Subsequent studies (He and Owens, 1995; Collins et al. 1997; Schottler and Engstrom, 2002) have successfully used radioisotopes in tandem with other geochemical tracers to separate field from non-field erosion in small watersheds. The underlying premise of these studies is that soils with differing land use and exposure to the atmosphere will have unique signatures of radioisotopes. Naturally occurring radioisotopes such as ^{210}Pb and ^{137}Cs, are enriched in cultivated soils through atmospheric deposition. In contrast, streambanks, ravines and near channel bluffs (Fig. 3) have minimal exposure to atmospheric inputs and have had much greater time for decay losses are depleted in these tracers. Thus, suspended sediment eroded from fields should have much higher activities (i.e. concentration) of ^{210}Pb and ^{137}Cs than suspended sediment eroded from non-field sources. Comparing the tracer signature of soils from different sources with the signature of suspended sediment in rivers permits the contribution of each erosion source to be calculated.

This study employed the sediments accumulated in closed-basin lakes, surrounded by agricultural land use as an archive of the field source fingerprint. This fingerprint was then compared to two types of riverine sediments to determine the relative contribution eroded from agricultural fields. Comparison of source fingerprints to total suspended sediments (TSS) collected during flow events from tributaries provided an event-based estimate of source apportionment. Short sediment cores were collected from backwater depositional sites and provided a recent temporally and spatially averaged estimate of sediment sources. Surface intervals from sediment cores collected from Lake Pepin in 1996 and 2008 provided an integrated watershed-scale estimate of the contribution of field and non-field sediment sources.

Note that radioactive decay is analogous to concentration. In this report, the terms concentration and activity are interchangeable and have radioactive decay units of pCi/g. Measured concentrations of ^{210}Pb are a combination of mineralogical supported ^{210}Pb and meteorically deposited ^{210}Pb. Supported ^{210}Pb can be determined explicitly by gamma spectrometry, by measurement of the ^{214}Pb daughter products. Meteoric, or excess ^{210}Pb is determined by subtracting supported ^{210}Pb from total ^{210}Pb. All future references to ^{210}Pb in this report are for excess ^{210}Pb.

Definition of Sediment Sources

This project quantified contribution to suspended sediments from two general erosion environs: upland cultivated fields and non-field sources. It is important to specify what is included in the definition of each of these source types. The reference lakes and edge of field samples, which were used to define the agricultural field fingerprint, receive sediment eroded from row-cropped fields and potentially minor amounts from forested soils, pastures with perennial cover, and via wind erosion from more distant field areas. The signature in the

Figure 3. Field and non-field sources of sediment in the greater Lake Pepin watershed. Clockwise from upper left: field erosion in Blue Earth County; large ravine in Seven Mile Creek watershed; bluff erosion along Le Sueur River, and streambank erosion on the upper Le Sueur River. Ravines, bluffs and streambanks are operationally defined as non-field because they all have negligible concentrations of ^{210}Pb and ^{137}Cs and thus do not have unique radioisotopic fingerprints. Fields are enriched in these isotopes through precipitaton.

reference lakes can result from sheet, rill and shallow gully erosion processes. The fingerprint measured in the lakes and field samples is thus a temporal and spatial integration of these processes and represent inputs of shallow sediments from agricultural watersheds. Field sediment is operationally defined as the upper 20 cm, which is the approximate mixed depth due to cultivation.

The definition of non-field is nominally any eroded sediment from a source that has not been exposed to the atmosphere for ~100 years or more. Sediment from large bluffs, sloughing or undercutting banks, and large gullies eroding to the rivers will all yield similar fingerprints. Since each of these sources receive minimal or no atmospheric inputs, they will all have negligible concentrations of the radioisotope tracers. Thus, in the final analysis it is not possible to distinguish among each of the different non-field sources using these fingerprinting methods.

Sediments that were eroded from upland/fields, deposited in ravines or streambanks and then re-eroded are referred to as legacy sediments. The fingerprinting method, which uses tracers with half-lives of 20-30 years, cannot distinguish between legacy field sediments and "true" non-field sediments. In other words, we are defining non-field sediments as any sediment that has not been exposed to atmospheric deposition within the last ~75 -100 years. While separating "legacy" from non-field may be of interest geologically, it would seem to have less bearing on the intent of this study. Upland/field soils that were eroded 75-100 years ago and emplaced in river channels are now functioning as streambanks. Management practices to mitigate contribution from these sources should be independent of determining if the sediment/streambank is 75 or 7500 years old.

Determination and Confirmation of Field Fingerprint

Although the theoretical basis of traditional radiometric fingerprinting is sound, generating a spatially integrated and representative fingerprint of the upland/field source over a large watershed is cumbersome. Traditional methods use direct sampling of field soils, an approach that is complicated by the fact that topographic highs and lows in fields will have different activities of ^{210}Pb and ^{137}Cs due to soil redistribution and changing exposure to rainfall. In addition ^{210}Pb and ^{137}Cs transport and concentration is a function of particle size. Methods that employ direct sampling or passive edge of field collectors will collect size fractions that are coarser than the sediments that reach receiving waters. These samples have diluted radioisotope concentration and some type of correction must be made to relate the field values to the riverine values.

This study used a modification of the traditional fingerprinting method to define the field signature: it employed closed basin "reference" lakes to efficiently calculate an integrated upland fingerprint for the entire Lake Pepin watershed. Reference lakes had no riverine or perennial channelized inputs, and had watersheds with extensive row-crop agriculture (Fig. 4). Thus, it can be assumed that sediment inputs to these lakes are dominated by erosion of field soils. Furthermore, these lakes integrate watershed scale upland erosion processes such as sheet, rill and shallow gully erosion. Sediments accumulated in these lakes represent a temporal and spatial archive of the field erosion fingerprint.

While the reference lakes represent an efficient means to define a basin-wide field fingerprint, the task is more difficult than simply collecting lake sediment and measuring the radioisotope concentration. Both ^{210}Pb and ^{137}Cs can enter the lake either on eroded field sediment or by direct deposition from precipitation. The challenge in using reference lakes is in separating the atmospheric from watershed contributions. This task was accomplished by modeling concentration and fluxes in each lake and optimizing the set of equations for a unique solution.

Figure 4. Bean Lake in Cottonwood county Minnesota. A typical reference lake with no river or ditch inflow and a large portion of its immediate watershed in row-crop agriculture.

Sediment cores were collected from 30 reference lakes, and ^{210}Pb and ^{137}Cs fluxes, inventories and concentrations were determined for each core by alpha and gamma spectrometry. Sediment composition for each core was determined by loss-on-ignition. All measurements were normalized to the fraction of inorganic matter to remove dilution effects produced by in- lake production of organic matter and carbonate precipitates. Atmospheric and field-eroded inputs of each tracer were modeled to compare predicted inventories and concentrations to measured values. A set of four equations was developed to describe ^{210}Pb concentrations and inventory in any core. Because concentration profiles of ^{137}Cs can be influenced by diffusion within the sediment column, rather than model surface concentration of ^{137}Cs, the whole core inventory was used, thereby negating variation due to in-situ diffusion. The set of equations is described below. Using this approach removes the need to correct for particle size, because the range of particle sizes encompassed by the cores overlaps with the particle sizes in suspended sediments and depositional sites.

Sediment accumulation rates and radioisotope fluxes/inventories require knowledge of chronology for each core. Chronology was determined for each lake using the ^{210}Pb constant rate of supply (CRS) dating method. Cesium-137 and sediment composition provide independent means to validate the CRS model chronology. Cesium was released to the atmosphere by above ground nuclear bomb testing, with major inputs beginning ~1955 and peaking just prior to cession in 1963 (Robbins et al. 2000). CRS modeled dates were anchored to the independent dating markers of 1955, 1963 established by the onset and peak concentration of ^{137}Cs respectively, and to 1940, defined by an abrupt bulk-density increase associated with the desiccation of these shallow lakes during 1934-1938 drought. Present-day, core-site specific, sediment accumulation rates were calculated from the total dry inorganic mass accumulated from 1985 until the date of coring. Total inventory of ^{210}Pb was calculated by summing the ^{210}Pb inventory at each core interval from 1955 to present and decay correcting to the date of coring. The period of direct ^{137}Cs deposition was relatively brief (1955-1963) and was treated as a “pulse” input. If inputs are considered a pulse, losses by decay in the core and decreases in field sediment concentration are equivalent. Total ^{137}Cs inventory at the time of coring is simply the sum of ^{137}Cs inventory at each interval from 1955 to present. Because lakes were cored over a period of several years, total inventory for all cores were decay corrected to reflect a common date, 2007. It should be noted that radioisotope inventories are based on total accumulation since 1955, a date that was established independently of the CRS dating model, and therefore sediment flux and ^{210}Pb and ^{137}Cs inventories are independent in the optimization model.

Expressions of Radioisotope Inventories and Concentration in Reference Lake Cores

$$\text{PbInv}_i = (\text{AtmPb x yrs x FFPb}_i) + (\text{CDM}_i \text{ x Pb}_{\text{field}}) \qquad \text{eqn 1.}$$

$$\text{CsInv}_i = (\text{AtmCs x FFCs}_i) + (\text{CDM}_i \text{ x Cs}_{\text{field}}) \qquad \text{eqn 2.}$$

$$\text{PbSurf}_i = ((\text{AtmPb x FFPb}_i)/\text{OSRsurf}_i) + \text{Pb}_{\text{field}} \qquad \text{eqn 3.}$$

$$\text{Ratio} = \text{Pb}_{\text{field}}/\text{Cs}_{\text{field}} \qquad \text{eqn 4.}$$

For Any Lake (i)

Measured (known) Values:

PbInv$_i$: Inventory (pCi/cm^2) of ^{210}Pb to core site average since 1955
CsInv$_i$: Total inventory (pCi/cm^2) of ^{137}Cs in core.
PbSurf$_i$: Concentration (pCi/g) of ^{210}Pb in surface interval of core.
CDM$_i$: Observed (measured) cumulative dry mass of sediment g/cm^2 (average 1965- present)
OSRsurf$_i$: Observed sediment accumulation rate at surface of core, g/cm^2-yr
Yrs: number of years of atmospheric deposition e.g. 1955 to 2007 =52

Variables (Unknowns)

AtmPb: Atmospheric flux rate of ^{210}Pb; same for all lakes, pCi/cm^2-yr
AtmCs: Total atmospheric input of ^{137}Cs, pCi/cm^2; same for all lakes
FFPb$_i$: Focusing factor of ^{210}Pb, unitless; different for each lake
FFCs$_i$: Focusing factor of ^{137}Cs, unitless; different for each lake
Pbfield: Concentration of ^{210}Pb (pCi/g) on incoming sediment to lake
Csfield: Concentration of ^{137}Cs (pCi/g) on incoming sediment to lake
Ratio: Ratio of Pb to Cs on incoming particles; assumed to be constant.

Sediment and radioisotope focusing are important parameters in this model. Focusing is the preferential movement of sediment or an isotope to the core site. The unit-less focusing factor (FF) relates the enrichment or depletion at the core site to the whole lake average. Regions of a lake that are suitable for sediment coring usually have FF greater than one. FF for particle reactive radioisotopes such as ^{210}Pb and ^{137}Cs should be similar to the focusing of sediment but they do not have to be the same.

Several parameters in the optimization model can be constrained, which aids in finding a unique solution. The atmospheric deposition rate of ^{210}Pb has been measured continuously over a five-year period at two NADP sites in Minnesota (Lamberton and Marcell), the results of which yield a volume-weighted average flux of 0.45 (+/- 0.05) pCi cm^{-2} yr^{-1} (C. Lamborg and D. Engstrom, unpublished) and are supported by measurements of atmospheric inputs to Minnesota and Wisconsion lakes (Engstom et al. 2004) Studies of numerous other lakes in Minnesota have shown that focusing of ^{210}Pb to a core site, even in lakes with steep-sided basins, seldom exceeds 3.5 (Engstrom et al. 2007). Most lakes in this study were shallow with generally flat bottoms, such that $FFPb_i$ can be safely assumed to be less than 3.5. Less is known about the focusing of ^{137}Cs, but it is likely similar to ^{210}Pb. Constraints applied to the model equations above were as follows:

a) $0.4 < AtmPb < 0.50$ pCi/g
b) $1 < FFPb_i < 3.5$
c) $1 < FFCs_i < 7.0$

The set of equations was applied to 30 reference lakes, resulting in 120 equations describing 64 unknown variables. In this model, Pb_{field} and Cs_{field} are constant among lakes. This over-determined set of equations was optimized by minimizing the sum of the squares of the residuals in the Excel "Solver" function. Current optimized results estimate the field fingerprint of ^{210}Pb at 2.32 pCi/g and ^{137}Cs at 0.36 pCi/g.

The set of equations above can be optimized in an alternate manner, where Pb_{field} and Cs_{field} are allowed to vary for each lake. In this method, the model is not expressly over-determined, but because of the tight constraints to several parameters, it still converges to a unique solution. Solving the model with incoming concentrations different for each lake, the optimized results estimate the mean field fingerprints of ^{210}Pb and ^{137}Cs at 1.88 (+/- 1.6) pCi/g and 0.38 (+/- 0.32) pCi/g respectively. These results were chosen for subsequent source apportionment calculations presented in this study. This approach to optimizing the model has the advantage of directly showing the variability in concentration of ^{210}Pb and ^{137}Cs on eroded sediments entering each lake. The high standard deviation about the mean is evidence that the variability of concentrations on eroded sediments is large. This is not unexpected given the variability of erosions processes and site characteristics. It also illustrates the need for fingerprinting methods to have a sampling strategy that will capture this variability.

Confirmation of the Field Fingerprint.

Given the variability of the source fingerprint, it is useful to have some confirmation of the mean fingerprinting values estimated from the model. To test the validity of the reference-lake derived fingerprints, we collected samples from several unique sites that are likely to contain only field sediments. The samples described below, and summarized in Table 1, are from a few such locations scattered throughout the Minnesota River watershed and from discrete flow events. Although they represent a limited spatial and temporal context, they provide a reasonable comparison to the results estimated from the sediments achieved in the reference lakes.

Beauford Ditch, Blue Earth County, Minnesota.

Beauford Ditch drains into the Cobb River, a tributary to the LeSueur River in east central Blue Earth County. The ditch is less than three km long at the point it crosses the sampling site at Highway 22. The ditch drains an intensive agricultural area, and its short length means that there is little potential for streambanks or other non-field inputs to comprise a significant proportion of the sediment load. Sediments in the ditch should be locally representative of field-eroded material. Suspended sediment samples were collected after three precipitation events in 2007 and 2008

Other Ditch Samples

Six additional samples were collected from agricultural ditches after a rain event on May 30, 2008. Suspended sediments were collected from County Ditch 13, Nicollet County; County Ditch 1, Blue Earth County; and four unnamed ditches in Waseca and Steele Counties. Ditches were less than two km long at the point they were sampled and were visually inspected to confirm that they did not have eroding banks that could produce a non-field signature.

Direct Field Runoff

A sudden and intense rain event occurred while sampling the ditches on May 30th. This event produced significant edge of field runoff that was easily sampled in adjacent road ditches and grassed waterways. Five suspended sediment samples were collected from edge of field runoff near Mapleton, Minnesota during and following the rain event. These samples are unquestionably field-eroded sediments.

Figure 5. Coring Belle Pond near St. Peter Minnesota. Earthen dam constructed in 1969 is visible in center-right of photo. All sediment in this impoundement is from post-1969 field erosion.

Belle Pond – Seven Mile Creek Watershed, Nicollet County.

While searching for suitable reference lakes, a unique site that provides validation for the ^{137}Cs fingerprint was located. In 1969 an earthen berm was constructed as an erosion control structure at the head of a large ravine, near Seven Mile Creek. This dam created a small pond of less than 10 hectares (Fig. 5). The pond receives inputs from field runoff and does not have any perennial, channelized inputs. Sources of sediment to the pond are thus similar to the inputs to the reference lakes, but because the pond was not present until 1969, it received negligible direct atmospheric inputs of ^{137}Cs. This means that the only inputs of

^{137}Cs to the pond are from eroded sediments, and thus the concentration measured in those sediments is the field erosion signature. The agricultural watershed delivering sediments to the pond is small, but nonetheless represent a temporally, and spatially integrated fingerprint. A fingerprint for ^{210}Pb cannot be estimated in the same manner, as the pond continues to receive direct atmospheric inputs of this isotope.

Table 1. Activities of radioisotopes from various reference systems used to confirm the fingerprint for field sediments estimated from the reference lakes. The field fingerprint from reference lakes is shown for comparison. All activities were normalized to fraction inorganic matter. Cs-137 values were decay normalized to 2007. Numbers in parentheses are one standard about the mean.

Reference Site	^{210}**Pb** (pCi/g)	^{137}**Cs** (pCi/g)
Beauford Ditch	2.11 (1.01)	0.20 (0.06)
Other Ag Ditches	2.22 (0.58)	0.35 (0.15)
Edge of Field Runoff	1.55 (0.59)	0.30 (0.09)
Belle Pond		0.31 (0.10)
Average of Confirmation sites	**1.96 (0.36)**	**0.29 (0.06)**
Estimate from Reference Lakes (Pb$_{field}$, Cs$_{field}$ vary for each lake)	**1.88 (1.6)**	**0.38 (0.32)**

Because each of the samples above represents actual sediments in transport, the concerns about particle size and spatial heterogeneity, which plague direct field-soil sampling, are minimized. If a sufficient number of such sites could be sampled over several events from various locations in the watershed, it would likely provide the best estimate of the field erosion fingerprint. Results from the ditches, edge of field runoff, and Belle Pond agree very well with one another and the estimates derived from the reference lakes. Averaging the samples, the mean fingerprints for ^{210}Pb and ^{137}Cs are 1.96 (s.d. 0.36) and 0.29 (s.d. 0.06), respectively. These results are within 25% of the reference-lake model results, and thus the fingerprints for field sediment obtained from the model appear reasonable and can be used as spatially and temporally robust reference values.

Source Apportionment Model

A simple mixing model, employing the source fingerprints, was used to calculate contributions from field and non-field sources. A two-source model is sufficient for tributaries in the Minnesota River watershed where the overwhelming majority of soils that receive atmospheric deposition are in similar land use—row crop agriculture. Source apportionment can be described as:

$$Csed_i = \%f(Cf_i) + \%nf(Cnf_i) \qquad \text{eq. 5.}$$

Where $Csed_i$ is the concentration of tracer(i) (excess^{210}Pb or ^{137}Cs) in a sediment core interval or TSS sample, Cnf_i is the mean concentration of tracer (i) in a non-field source, Cf_i is the mean concentration (e.g. fingerprint) of tracer (i) from field sources, determined from reference lakes, *%nf* is the percent contribution from non-field, and *%f* is the percent contribution from field sediment. The mixing model must also satisfy the conditions;

$$\%f_i + \%nf_i = 1 \qquad \text{eq. 6.}$$

and

$$0 \leq \%nf_i, \%f_i \leq 1 \qquad \text{eq. 7.}$$

Since non-field sources have negligible ^{137}Cs and ^{210}Pb concentration and can be treated as zero, the relative contribution from field (*%f*) is simply the concentration ratio of tracer (i) on a riverine sediment sample ($Csed_i$) to the field source fingerprint (Cf_i):

$$\%f_i = Csed_i/Cf_i \qquad \text{eq. 8.}$$

Field source fingerprints for $\mathrm{Pb_{field}}$ and $\mathrm{Cs_{field}}$, determined from the reference lake model, equal 1.88 and 0.38 respectively and were substituted for Cf_i in equation 8. Source apportionment for any riverine sample was calculated independently using each tracer. Estimates from the two tracers were averaged (eq. 9) and the standard deviation (i.e. range) of source apportionment for the combined tracers was calculated by propagating the error of the individual estimates (eq. 10)

$$\mathrm{Y = 1/2(A/B + C/D)} \qquad \text{eq. 9.}$$

where

Y is the relative contribution from field source based on both tracers
A = $\mathrm{C_{sedPb}}$, the measured concentration on ^{210}Pb on any riverine sediment sample
B = field fingerprint of ^{210}Pb; $\mathrm{Pb_{field}}$ = 1.88 pCi/g
C = $\mathrm{C_{sedCs}}$, the measured concentration of ^{137}Cs on riverine sediment sample
D = field fingerprint of ^{137}Cs; $\mathrm{Cs_{field}}$ = 0.38 pCi/g

And

$$\sigma_Y^2 = \frac{A^2}{4B^2}\left(\frac{\sigma_A^2}{A^2} + \frac{\sigma_B^2}{B^2}\right) + \frac{C^2}{4D^2}\left(\frac{\sigma_C^2}{C^2} + \frac{\sigma_D^2}{D^2}\right) \qquad \text{eqn 10}$$

Standard deviation of the mean source fingerprints were 1.66 for ^{210}Pb and 0.32 for ^{137}Cs. Error terms for riverine measurements were either the standard deviation of multiple TSS samples from a monitoring site or the standard deviation of several intervals from a depositional site core.

Riverine Samples

The premise of radiometric source apportionment is to compare concentration of selected tracers such as ^{210}Pb and ^{137}Cs in riverine suspended sediments, to the concentrations in erosion sources. Several types of riverine samples were collected for comparison.

Impoundments and backwater depositional areas along the river were used as natural collectors to generate a temporally and spatially representative sample of riverine suspended sediment. Short sediment cores were collected from four depositional sites on the mainstem of the Minnesota River, from two sites along the South Fork of the Crow River, and from eleven sites on tributaries to the Minnesota River. All backwater sites were nearly at the same elevation as the river and receive suspended sediment inputs during most flow events. Cores were sectioned into 2-cm intervals, freeze-dried and archived at the SCWRS. Loss-on-ignition (LOI) was completed on the samples to determine the relative fraction of organic, carbonate and inorganic material. The uppermost intervals, which are assumed to represent sediments deposited within the last five years, were analyzed by alpha and gamma spectrometry to determine ^{210}Pb and ^{137}Cs activities.

Suspended sediment from individual flow events were collected to investigate the seasonal and flow related variability in source apportionment. Minnesota Pollution Control Agency (MPCA) staff collected TSS samples from 27 flow events in 16 tributaries during 2007 and 2008. Ten- to 20-liter grab samples were collected and the sediments isolated by settling and decanting. LOI was preformed on a sub-sample, and all subsequent radioisotope measurements were normalized to fraction inorganic matter. A list of all suspended sediment samples and associated source apportionment is shown in Appendix 1.

Sediments accumulated in the upper end of Lake Pepin provide an integrated estimate of sediment source inputs from the entire Minnesota River basin. Sediment coring of Lake Pepin is described in a later section. The lake was cored in 1996 and again in 2008. Surface intervals from these two coring campaigns were used to estimate corresponding source apportionment for the preceding decade. Dated cores from Lake Pepin offer a unique opportunity to examine historical changes in source apportionment, but the calculations are complicated by atmospheric inputs of ^{210}Pb directly to the river surface, and changing sediment accumulation rates. A discussion of historical changes in sediment sources to Lake Pepin is presented later in the report.

Particle Size and Direct Atmospheric Deposition Corrections.

Two factors can complicate the direct comparison of source fingerprints to riverine samples. One is particle size. Both ^{137}Cs and ^{210}Pb can be preferentially transported on fine-grained particles. Thus, sediments with a high specific surface area (smaller grain size) will be enriched in radioisotopes over coarser sediments with less surface area per volume. All suspended samples with sufficient sample mass, and three samples from each reference lake and depositional site were analyzed for particle size by laser diffractometry. Specific surface areas for reference lakes ranged from 7000 -12,000 m^2/m^3. Riverine suspended sediments and depositional sites ranged from 6800 to 11,500 m^2/m^3. Because “particle size” of the reference sites overlaps with that of the riverine samples, a size correction was considered to be unnecessary. Two depositional samples collected from the Blue Earth River and the Chippewa River Reservoir had specific surface areas less than 6000 m^2/m^3 and were excluded from the results.

Atmospheric deposition of ^{210}Pb to the river surface and subsequent sorption onto riverine sediments is a larger concern. (Note: cesium has not been present in precipitation since the 1970s.) Samples collected from some riverine depositional sites had ^{210}Pb concentrations two to three times larger than the source fingerprint, clearly demonstrating that they were enriched by direct atmospheric deposition. Depositional sites along the mainstem of the Minnesota River, where surface area of the upstream river plus tributaries is large, were the most affected. For these sites, ^{210}Pb could not be used as a tracer and only ^{137}Cs was used. Although the surface area of the tributaries is small compared to that of the mainstem, direct atmospheric contributions cannot be ignored.

Table 2. Estimated average enrichement of ^{210}Pb to suspended sediments by direct deposition to the river surface.

River	Surface Area (ha)	Inorganic Sed. Load (tons/yr)	Avg. ^{210}Pb added by atm. (pCi/g)
LeSueur River at Red Jacket (includes Maple and Cobb Rivers)	647	185882	0.16
Upper Le Sueur R. at St. Clair	138	28431	0.22
Cottonwood River	483	64513	0.34
Redwood River	266	16576	0.72
Watonwan River	242	29442	0.37
Chippewa River	505	20420	1.05
Blue Earth above Rapidan	588	186660	0.14
Blue Earth near mouth includes Watonwan	830	216102	0.17
Yellow Medicine River	231	9250	1.12
Sourth Fork Crow River	234	21300	0.49
Minnestoa River and major tributaries Lac qui Parle to Redwood Falls	1130	181825	0.29
Minnestoa River plus major tributaries Lac quiParle to New Ulm	2259	198401	0.53
Minnestoa River plus major tributaries Lac qui Parle to Judson	2743	238470	0.52
Minnestoa River plus major tributaries Lac qui Parle to St. Peter	4824	668752	0.32

Atmospheric enrichment of ^{210}Pb is a function of the surface area of the water body and the sediment load. In rivers with large surface areas and low sediment loads, direct atmospheric deposition of ^{210}Pb can be the major source of the measured concentration. Flux rates from atmospherically dominated lakes and long-term measurements from two sites in Minnesota, show the annual atmospheric deposition rate of ^{210}Pb to be 0.45 pCi cm^{-2} yr^{-1}. The surface area of several major tributaries was estimated by dividing the river into 20 to 30 segments and multiplying each length by an appropriate mean width (Moore, personal communication, 2009). Sediment loads from 2000 through 2008 were averaged to estimate the mass of particles available to dilute/adsorb the atmospheric deposition (MSU Water Resources Center, 2009; Metropolitan Council, 2005). The average concentration of ^{210}Pb contributed by the atmosphere ($Conc_{atm}$) to any sample was then estimated as:

$$Conc_{atm} = 0.45 \text{ x } (SA_{trib}/SL_{trib}) \qquad \text{eq. 11.}$$

where SA_{trib} is the surface area of the river and SL_{trib} is the annual sediment load. A summary of estimated surface areas, measured average sediment loads, and calculated concentration supplied by the atmosphere is presented in Table 2. These atmospherically-supplied ^{210}Pb concentrations were subtracted from each corresponding riverine sample. For rivers such as the LeSueur, where sediment loads are high, the atmospheric correction is minimal. In large rivers with lower sediment loads, such as the Chippewa and Yellow Medicine, the atmospheric contribution to the measured ^{210}Pb concentration is significant. Source apportionment results, which are detailed in a later section, show that with this correction, relative contributions predicted by ^{210}Pb and ^{137}Cs agree fairly well, and confirm that with no correction, ^{210}Pb would consistently over predict contributions from field sources. This is an important observation that should be considered in all fingerprinting studies utilizing atmospherically deposited tracers.

Lake Pepin Sediment Re-coring and Accumulation Rates

A major project to study Lake Pepin infilling was done in 1996 (Engstrom et al. 2009). This work was extremely useful for understanding the historical sediment delivery trends, which provided information about how land-use changes have affected erosion in the watershed. The study utilized a total of 25 sediment cores from Lake Pepin (Fig. 6). The elongated lake was divided into five sub-basins, with a five-core transect taken from each. Ten "primary" cores were selected, two from each sub-basin, and dated in detail with ^{210}Pb, ^{137}Cs, ^{14}C and other chronostratigraphic markers (Engstrom et al. 2009). From the dated cores, it was possible to calculate whole-basin sediment accumulation rates for the depositional zone in Lake Pepin.

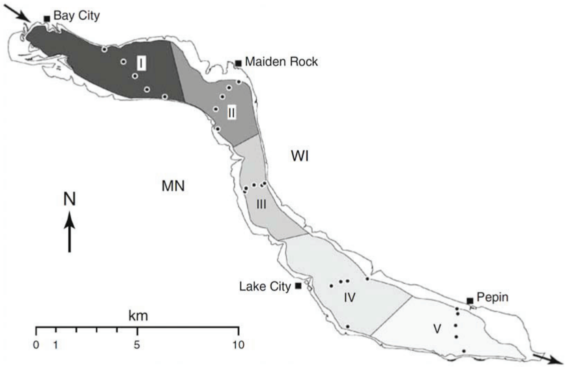


Figure 6. Five transects and 25 coring sites in Lake Pepin.

It had been more than a decade since that work was completed, and current, more up-to-date information was needed to make management decisions regarding turbidity issues and sediment loading. This update was accomplished in a re-coring effort in 2008. To efficiently assess recent sediment accumulation rates without recreating the entire 1996 procedure, an alignment method for overlapping the magnetic susceptibility profiles of the 1996 cores and the 2008 cores was developed. This re-coring method calculated current sediment accumulation independent of the original CRS dating model, and provided confirmation of the 1996 estimates.

Method

In the summer of 2008 each of the 10 primary core locations were revisited to determine the most recent trends in Lake Pepin sediment accumulation. The locations were reproducible to within several meters using the differentially-corrected GPS coordinates recorded in 1996. Following collection, each core was split into two halves. One half was scanned for magnetic susceptibility at the Limnological Research Center at the University of Minnesota and then stored in the LACORE core repository. The other half was taken to the St. Croix Watershed Research Station and sectioned at two-centimeter intervals. An aliquot of wet sediment was used for loss-on-ignition (LOI) analysis, and the remainder was freeze-dried. Several intervals from the top portion of each core were measured for ^{210}Pb and ^{137}Cs for sediment fingerprinting work.

Figure 7. Sediment cores from Lake Pepin.

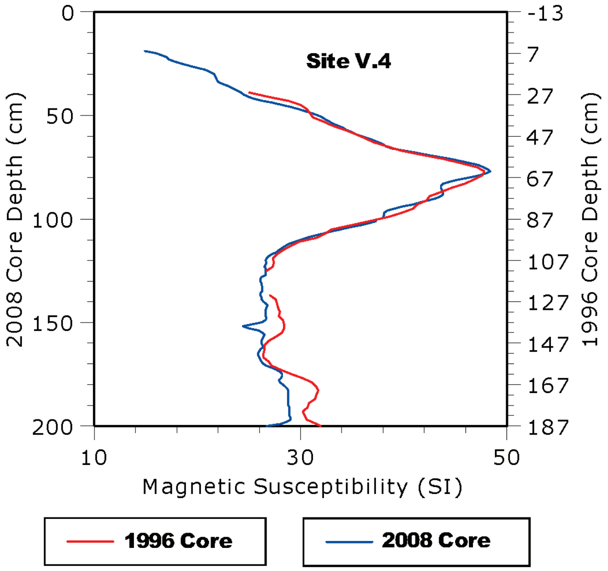


Figure 8. Overlapping magnetic susceptibilty profiles of cores from 1996 and 2008 to determine amount of new sediment added between coring times.

A major obstacle in determining the amount of new sediment at any core location is accounting for compaction and dewatering of sediment that was once at the sediment-water interface, but is now buried by newer sediment. Since each core has different amounts of new sediment, there will be varying degrees of compaction. We used a method that takes this compaction issue into account. First, the cores were aligned using the prominent features in magnetic susceptibility (Fig. 8) and the linear amount of new sediment was determined. From the tie point, which is at a depth below the effects of recent compaction, the amount of dry mass, as established from LOI measurements, is determined in both the original core and the new core at each location. The amount of new sediment is then simply the difference in the masses.

Results

Sedimentation rates decrease incrementally from the upstream end of Lake Pepin to the downstream end. The sediment accumulation rate, normalized to the inorganic fraction, is 20.7 kg m^{-2} yr^{-1} in the northern portion of the lake basin where the Mississippi River enters, and decreases to 4.5 kg m^{-2} yr^{-1} in the lower-most portion of the lake near the Chippewa River delta. The average whole-basin total accumulation rate from 1996-2008 was 772,400 metric tons/yr. This is a slight decrease from the 1990-1996 rate, but is consistent with the overall historic trend (Fig. 9). The most likely explanation for the decrease is the recent low-flow years in comparison with the 1990-1996 period.

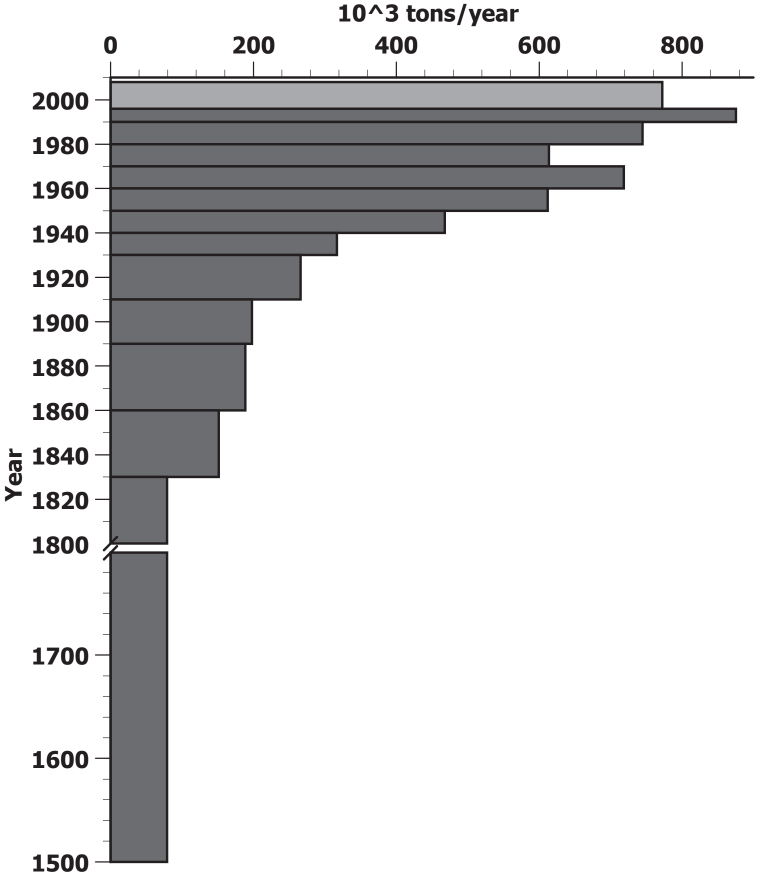


Figure 9. Whole lake, total sediment accumulation rate for Lake Pepin. Light gray bar is the recent rate calculated from the 2008 re-coring effort, and is calculated independently of the original CRS dating model.

Source Apportionment Results

Event based source apportionment

Concentrations of radioisotopes in suspended sediment samples were used to estimate event-based field and non-field loading to different tributaries. Concentrations of ^{210}Pb and ^{137}Cs were measured on individual samples as described earlier, and ^{210}Pb concentrations were corrected for direct atmospheric contributions. Measured concentrations were compared to the field fingerprint (eq. 8) to give an estimate of the field contributions. Estimates based on ^{210}Pb and ^{137}Cs were averaged (eq. 9) and the standard deviation about the mean calculated from equation 10. Appendix 1 shows relative contribution from field and non-field sources for all event based TSS samples. Tributaries with sufficient samples to estimate an average source apportionment are summarized in Figure 10.

As was expected, event samples showed a wide range in source apportionment results. Average field contributions were estimated for rivers where more than five samples were collected during non-snow melt runoff. In all these tributaries, fields contribute on average less than 50% of the sediment. In steeply incised watersheds such as the LeSueur, Blue Earth, Maple, and High Island creek field erosion contributes less than 25% of the sediment. In less incised watersheds such as the Watonwan and South Fork of the Crow, fields contribute up to half of the sediment load.

The contrast between the Watonwan and the LeSueur rivers is notable. Both rivers have samples from over 20 events (Appendix 1) covering a wide range of flow or runoff characteristics. On average the Watonwan receives about 60% of it sediment load from non-field sources, while the LeSueur is over 80% from non-field. The Watonwan is also more variable, and has some samples in which field sources contributed more than two-thirds of the load. In contrast, the LeSueur consistently shows fields to contribute less than one-third of the sediment (based on average of ^{210}Pb and ^{137}Cs apportionment), and only one event shows fields contributing more than 50%.

Appendix 1 shows source apportionment predicted from ^{210}Pb and ^{137}Cs individually. Generally, the predicted contributions agree fairly well, but results based on ^{210}Pb are often higher than estimates generated from ^{137}Cs. This is likely the result of an under-correction of direct atmospheric contributions of ^{210}Pb to the river surface. Direct atmospheric inputs were estimated for each tributary and represent an average annual correction. Some samples, especially if the sediment load in the river is small, could reflect high contributions from recent rainfall events. This occasional deviation between ^{137}Cs and ^{210}Pb source apportionment estimates illustrate the importance of correcting for atmospheric contributions as well as having multiple fingerprinting tracers.

Event-based source apportionment results offer only a snapshot of the erosion process. Insufficient sample numbers and a lack corresponding flow-weighted mean sediment concentrations precluded calculation of annualized estimates for each erosion source. Even so, the overall number of samples, the similarities between events, and the comparison between several tributaries provide a useful assessment of the relative importance of field and

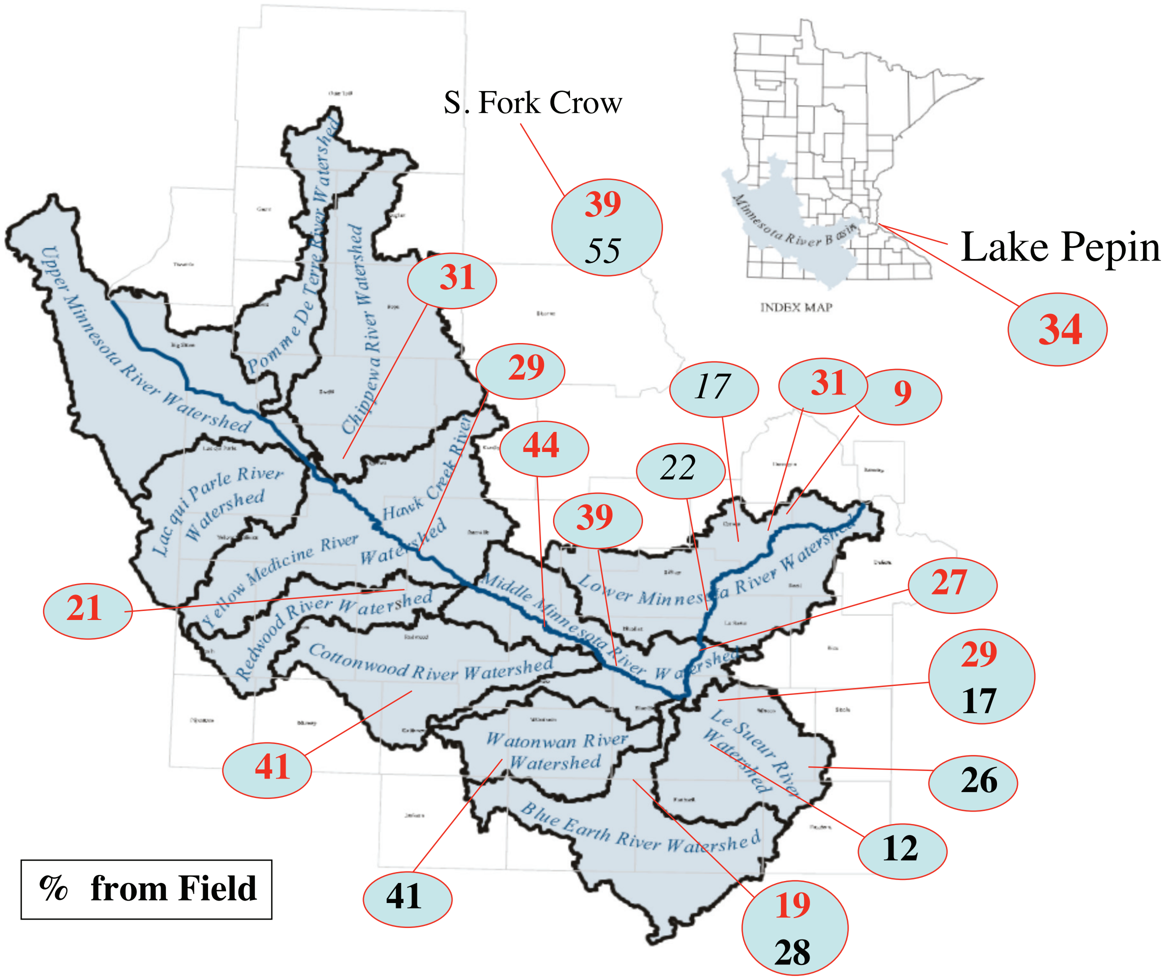


Figure 10. Percentage of sediment from field sources in different tributaries. Numbers in red are results from integrator sites, numbers in black are averages from flow events.

non-field sources. Unless the samples grossly and systematically missed events that carried a large contribution from fields, it is clear than non-field sources dominate sediment loading.

Temporally Integrated Source Apportionment

Backwater depositional sites, which integrate the temporal and flow specific variation embedded in the event samples, were used to estimate current annual contributions (Fig. 11). Sediments accumulated in riverine backwater sites – Miller Lake, Lake Pepin, and several reservoirs –provide a proxy for flow-weighted sediment-source apportionment. Average concentrations of ^{210}Pb and ^{137}Cs at each integrator site are shown in Table 3. For comparative purposes, source apportionment estimates used each tracer individually (eq. 8) Overall, estimates for the two tracers were similar and help confirm the precision of the method. Individual tracer estimates were averaged and the confidence interval calculated (eq. 9 and 10). Finding riverine depositional sites that acted as suitable sediment collectors was difficult

Figure 11. Examples of riverine, backwater depositional sites that integrate suspended sediments from multiple flow events. Top photo is a depositional site on the S. Fork Crow River just above the confluence with N. Fork Crow River near Rockford Minnesota. Bottom photo is depositional site along Blue Earth River, two miles west of Vernon Center Minnesota.

and limited our ability to assess the variation within an individual tributary watershed. It is reassuring that similar tributaries have similar results. And, in the South Fork of the Crow River, two backwater systems, approximately 25 km apart, yielded nearly identical source-apportionment estimates (Table 3).

Similar to the event samples, integrator sites showed that on an annual basis, non-field sources contribute the majority of the sediment. Tributaries in the upper portion of the Minnesota River basin receive about 30-40% of their sediment from field sources, while tributaries in the

Table 3. Summary of isotope concentrations and source apportionment results from temporally and spatially integrated riverine depositional sites. Because of unknown amounts of atmospherically deposited ^{210}Pb, only ^{137}Cs was used for source apportionment in Lake Pepin and Miller Lake (Upper Carver Creek).

Location	Description	Excess ^{210}Pb (pCi/g)	^{137}Cs (pCi/g)	% from field based on ^{210}Pb	% from field based on ^{137}Cs	Average % from Field
Chippewa River	Reservoir at Montevideo	0.53	0.13	28%	34%	**31** (+/- 20)%
Redwood River	Reservoir at Redwood Falls	0.29	0.1	15%	26%	**21** (+/- 17)%
Beaver Creek	Recent Deposits of Sediment in Shallow Backwater	0.29	0.13	15%	34%	**25** (+/- 21)%
Cottonwood River	Backwater Depositional Site above New Ulm	0.91	0.13	48%	34%	**41** (+/- 27)%
Blue Earth River	Two backwater sites about 3 miles downstream of Vernon Center	0.48	0.05	26%	13%	**19** (+/- 13)%
Blue Earth River	Reservoir at Rapidan	0.11	0.03	6%	8%	**7** (+/- 7)%
Le Sueur River	Shallow pool behind natural levee, below confluence with Cobb R.	0.63	0.09	34%	24%	**29** (+/- 19)%
Upper Carver Creek	Surface Sediments from Miller Lake		0.22		58%	**58** (+/- 13)%
Carver Creek	Low head dam near mouth	0.2	0.01	11%	3%	**7** (+/- 8)%
Bevens Creek	Low head dam near mouth	0.28	0.19	15%	50%	**31** (+/- 24)%
Little LeSueur Creek	Low head dam near mouth	0.11	0.05	6%	13%	**10** (+/- 10)%
S. Fork Crow River	Backwater Pools near Confluence with N.Fork Crow	0.63	0.17	34%	45%	**39** (+/- 27)%
S. Fork Crow River	Backwater Pools near Watertown	0.68	0.16	36%	42%	**39** (+/- 31)%
Minnesota River at Granite Falls	Reservoir below Granite Falls Minnesota	0.55	0.09	29%	24%	**26** (+/- 21)%
Minnesota River below Granite Falls	Backwater Depositional Site	0.6	0.1	32%	26%	**29** (+/- 23)%
Minnesota River above New Ulm	Backwater pool just upstream with confluence with Cottonwood River	0.95	0.14	51%	37%	**44** (+/- 28)%
Minnesota River below New Ulm	Floodplain Lakes near Courtland, MN	0.82	0.13	51%	34%	**39** (+/- 27)%
Minnesota River above St. Peter	Backwater Depositional Site at Kasota MN ~10 upstream of St. Peter	0.46	0.11	24%	29%	**27** (+/- 18)%
Lake Pepin 1997	Surface Intervals from four cores from upper end of the lake		0.14		37%	**37** (+/- 11)%
Lake Pepin 2007	Surface Intervals from four cores from upper end of the lake		0.13		34%	**34** (+/- 4)%

middle and lower portions of the basin receive less than 30% from fields (Fig. 10). Similar to the TSS results, the South Fork Crow River is one of the watersheds were field contributions were largest. Backwater sites along the mainstem of the Minnesota River act as integrators of all upstream inputs. The four mainstem sites (Table 3) support the findings from the individual tributaries and confirm that non-field sources dominate inputs to the River.

Loads and Yields of Non-field and Field Sediment

Comparing percentages of field and non-field contributions leaves the impression that the various watersheds are more or less similar. This is not the case. Comparing field and non-field sediment loads and yields reveals dramatic differences among the watersheds. Field and non-field percentages estimated above were multiplied by measured annual inorganic loads and yields to give a mass balance comparison among the watersheds (Fig. 12 and 13). Except for the Watonwan, LeSueur and Upper LeSueur rivers, percentages estimated from integrator site were used for this calculation. Annual average sediment loads, based on five to eight years of monitoring, were available for most of the tributaries (MSU-Water Resources Center, 2009; Metropolitan Council, 2005). Total loads were corrected to inorganic load by subtracting the fraction of volatile suspended solids (VSS). VSS measurements did not accompany every measurement, so an average VSS fraction of 12% was applied to all samples. No measurements are available to correct for the amount of calcium carbonate produced *in situ* in the rivers, although it can be assumed that this is a small portion of the non-volatile suspended sediment. Yield data were calculated by simply dividing annual inorganic load by the entire watershed area above the monitoring site.

Loading from non-field sources dominates sediment inputs to the Minnesota River and is greatest in the Blue Earth-LeSueur watershed (Fig. 12). Total sediment load delivered by each tributary varies as a result of watershed size, with most of the variability accounted for by non-field sources. Field loading ranges by only about 30,000 tons/year among watersheds, as compared to non-field loads which range by 157,000 tons/year. On average the Blue Earth and LeSueur Rivers contribute over 50% of the annual sediment load to the Minnesota River (MSU Water Resources Center, 2009). And because three-fourths of the sediment in these rivers comes from non-field sources, the load from non-field sources is very high.

Comparing sediment yields helps remove the variability caused by differences in watershed size. In general, yields of field sediment are relatively similar among watersheds, while non-field yields vary by a factor of five (Fig. 13). Yields of field-derived sediment encompass a range of only 150 kg ha^{-1} yr^{-1}, while non-field yields cover a range of over 500 kg ha^{-1} yr^{-1}. The greater range in non-field yields, as compared to field yields, makes sense given the differences in land form among tributaries. Across the basin the lands in row-crop agriculture are generally similar; what is different among the watersheds is the near-channel land topography. Tributaries in the middle and lower Minnesota basin, such as the LeSueur, Blue Earth rivers, and Carver and Bevens creeks, have regions where the rivers flow through steeply incised “canyons”. The steeply incised reaches have migrating knick points, unstable slopes, and connect to a network of major ravines. Given the geography of these rivers, it is not surprising that they have high yields of non-field sediment and that these yields are much higher than those from tributaries that flow through less incised topography (Fig. 13). This suggests that sediment delivery from cropland is less variable across the watersheds than are inputs related to land form/geology.

Sediment yield is a function of precipitation patterns and runoff. Watersheds such as the Chippewa and Redwood could have reduced yields because they are in the western portions of the Minnesota watershed with lower rainfall and higher evapo-transpiration. However, Upper Carver Creek and the Watonwan, South Fork of the Crow, and Cottonwood rivers also have lower non-field yields but have similar climate to the contrasted steeply incised watersheds.

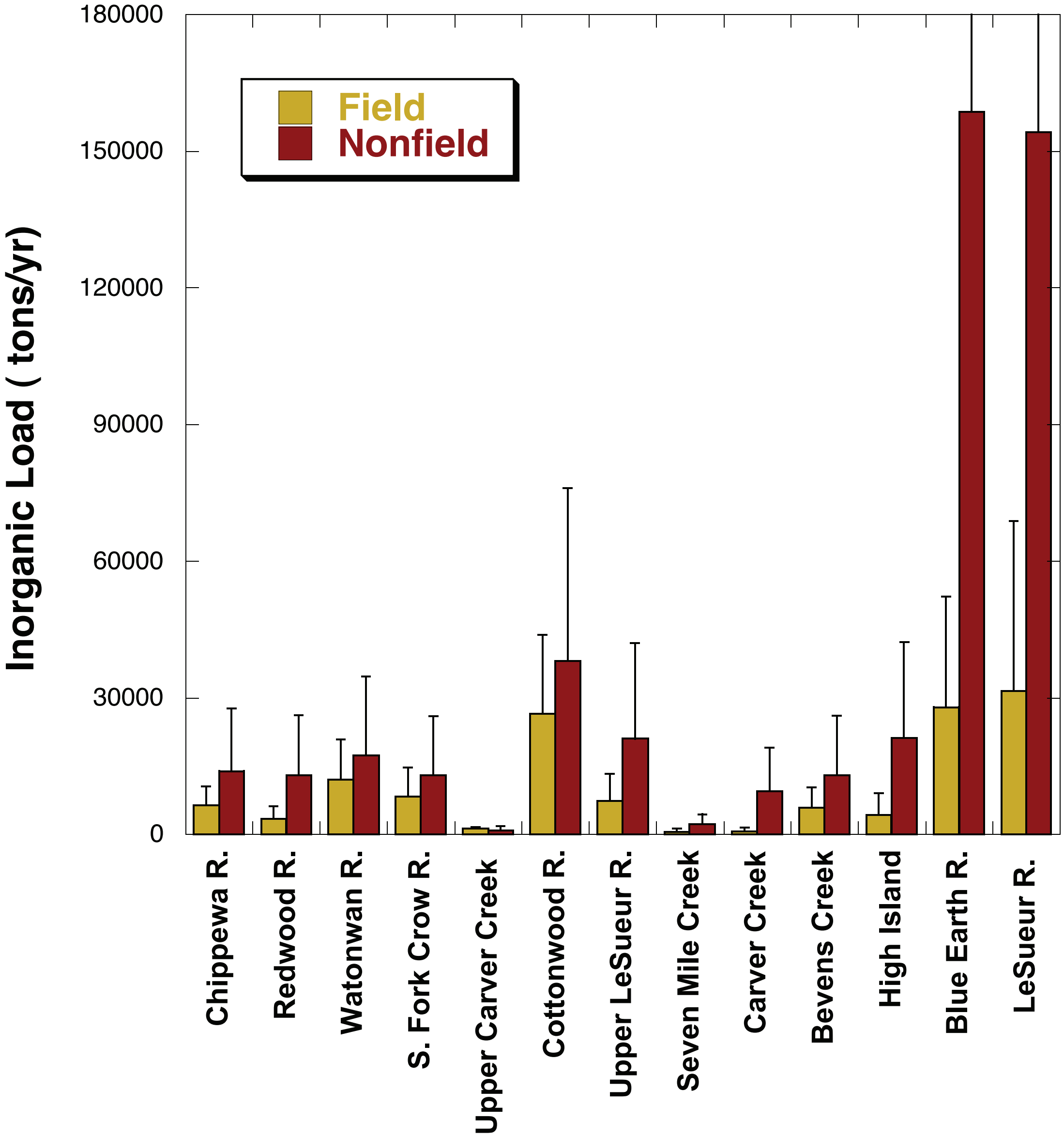


Figure 12. Comparison of field and non-field sediment loads throughout the Lake Pepin watershed.

Normalizing yields to runoff depth would provide a useful comparison. However, this parameter was not available for all watersheds in this study. Yields normalized to runoff depth are the same as flow weighted mean sediment concentration (FWMSC).

Within the groupings of steeply incised and less incised, the non-field yields are relatively uniform. The watersheds of Seven Mile Creek and the Upper LeSueur River are intermediate to these groupings. Seven Mile Creek is incised but does not have bluffs directly connected to the stream channel, and the lower portion of the watershed is armored by bedrock. It is a system dominated by several large ravine complexes, and the yields may define the

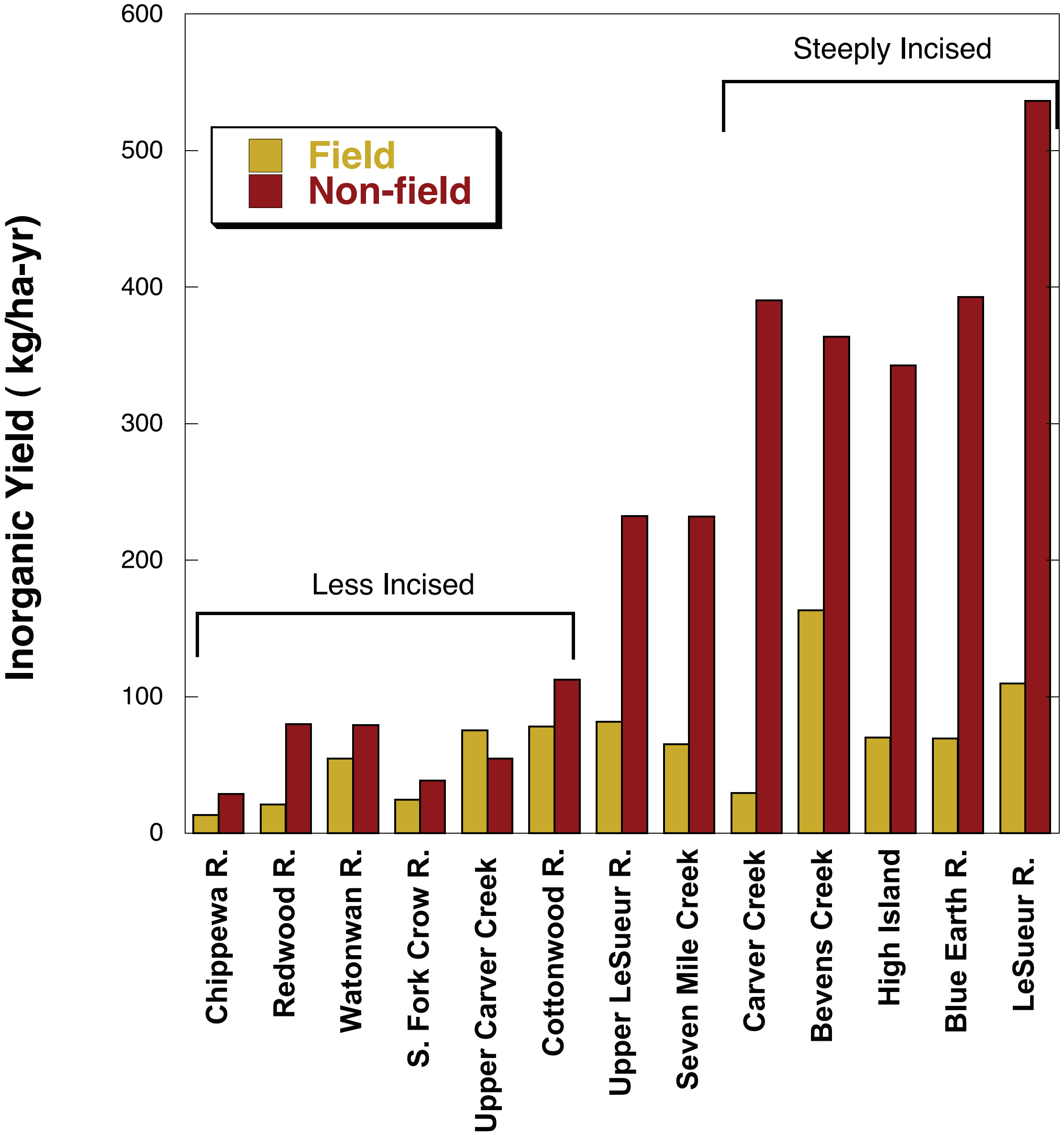


Figure 13. Comparison of field and non-field sediment yields in sub-basins of the Lake Pepin watershed

amount of sediment expected from a steeply incised system with no bluff contribution. It is a single watershed so this conclusion is tentative, but the comparison provided by Seven Mile Creek is unique. The upper LeSueur watershed, which is not steeply incised, is the most anomalous. Total yields measured in this watershed are known to be large, and if our source apportionment results are accurate, the non-field yields are noticeably larger than those of other watersheds in the "less incised" category. The source apportionment estimates for the Upper LeSueur are based on only six TSS samples, and it is possible that the field contribution is underestimated. Further study is warranted on the different soil types, topography, and land use which contribute to higher than expected non-field yields in the upper LeSueur River.

Discussion

The comparative presentation of non-field yields may be the single most instructive outcome of this study. It demonstrates that whichever processes govern non-field erosion are the processes that most influence sediment yields and loads. Until the sources and mechanisms driving non-field erosion are understood, it will be difficult to efficiently mitigate sediment impairments. Because of geologic history, non-field sources such as bluffs and large ravines are natural and prevalent features in some watersheds. Consequently these watersheds are predisposed to high erosion rates. However, it would be highly inaccurate to label this phenomenon as natural. Post-settlement increases in sediment accumulation rates in Lake Pepin, the Redwood Reservoir (discussed below) and numerous lakes in agricultural watersheds (Engstrom et al. 2007) clearly show that rates of sediment erosion have increased substantially over the past 150 years. Coupling these observations with the non-field sediment yields determined in this study, demonstrates that the rate of non-field erosion must also have increased. The features and potential for non-field erosion may be natural, but the rate is not. Why have non-field erosion rates increased; have rates increased proportionally in all systems; and have our rivers become more erosive? Has the hydrology of the watersheds changed and if so why? These are critical questions that bear directly on environmental management and policy. Some watersheds such as Carver Creek, Seven Mile Creek, and the South Fork of the Crow River may not be major contributors to sediment load, but contrasting their yields hints at mechanisms and geologic factors that are important to answering these questions. The information shown in Figure 13 highlights the importance of gathering information on multiple watersheds, and is the reason results from several studies were combined into this single report.

Watershed Scale Integrated Source Apportionment: Lake Pepin.

Lake Pepin integrates the erosion history of a large agricultural basin. Sediment cores from the lake offer a unique opportunity to examine both the present day integrated contribution of field and non-field sources on a large watershed scale, and to estimate how these contributions may have changed over time. Source apportionment in Lake Pepin is complicated by direct deposition of ^{210}Pb, both to the upstream river surface and the lake itself. These direct inputs negate the ability to estimate source apportionment by ^{210}Pb, and require estimates to be based on ^{137}Cs solely. Atmospheric deposition of ^{137}Cs reached negligible rates in the 1970s and thus today ^{1317}Cs enters the lake only on eroded particles. In lakes with slow sediment-accumulation rates or highly organic sediments, surface concentrations of ^{137}Cs can be enriched by remobilization of peak inputs within the sediment column, as was the case for many of the reference lakes. However, in the upper end of Lake Pepin, sediment accumulation rates are very high and sediments are less than 15% organic matter. It is therefore reasonable to rule out diffusion and assume that the measured ^{137}Cs concentration represents the concentration on incoming soil particles. If ^{137}Cs were slightly enriched due particle size in Pepin sediments relative to the reference lakes, it would mean that our prediction of field contributions is slightly over-estimated.

Sediments accumulated in the upper end of Lake Pepin have similar particle size (specific surface areas) to cores from the reference lakes and were used for source apportionment estimates. Sediments in the middle and lower end of Lake Pepin are finer than those in the reference lakes and may have radioisotope concentrations that are enriched by preferential deposition of fine-grained particles. Cesium-137 was measured in four cores from the two uppermost transects. Surface samples from 1996 and 2007 were analyzed by gamma spectrometry and ^{137}Cs concentrations for two transects were averaged for each time period. Relative contribution from field sources was again calculated by comparing the measured value to the field reference fingerprint (eq. 8).

Contributions from field-eroded sediments to Lake Pepin in the periods around 1997 and 2007 are similar to results obtained throughout the Minnesota River basin (Table 3, Fig 10). In the last two decades about one-third of the sediment entering Lake Pepin was derived from field erosion. In other words, two-thirds of the sediment was derived from non-field sources. Given that Lake Pepin receives over 80% of its sediment load from the Minnesota River, it is reassuring that the source-apportionment estimates for the lake are similar to the estimates in the Minnesota River. While this observation does not validate the accuracy of the results, it does help confirm the consistency of the method as applied to both small and large watersheds.

Estimates of Historical Trends in Lake Pepin Source Apportionment

The elegance of Lake Pepin sediment cores is that they provide an opportunity to examine historical trends in sediment inputs. There are other natural lakes in Minnesota that receive inputs from rivers, but none integrate the processes of such a large agricultural basin. In addition, Lake Pepin is the only natural lake that is downstream of the bluff features so common in the greater Blue Earth River basin. It's unique glacial history, position in the Mississippi basin, and watershed land use make Lake Pepin of singular significance to examine the changes in field versus non-field erosion over time. Unfortunately, unraveling historical changes in source apportionment is complex and uncertain.

Using ^{137}Cs to estimate source contributions from surface sediments collected in 1996 and 2008 is straightforward. No decay correction of ^{137}Cs is necessary and there are no direct inputs from the atmosphere. This is not true for earlier time periods, making ^{137}Cs only useful for surface intervals. While deposition directly to the river surface eliminates the use of ^{210}Pb to estimate source apportionment, we can look at changes in ^{210}Pb concentration over time to estimate the relative changes in source inputs. If all inputs have remained constant over time, the decay corrected concentration of ^{210}Pb should be constant throughout the core.

Decay corrected ^{210}Pb concentrations have decreased in recent decades (Table 4); the question is, does this reflect a change in the source of sediment to the lake?

Concentrations of ^{210}Pb on Lake Pepin sediments is a function of the relative contribution from field inputs, direct deposition to the river surface and the total amount of sediment in the river. Atmospheric deposition is constant, but the concentration resulting from atmospheric deposition is dependant on the sediment load. Sediment, especially non-field sediment, acts as a diluent of atmospheric deposition. If sediment loads are small, atmospheric deposition creates a larger concentration on particles as compared to periods with high sediment loads, i.e. dilution. Thus, the increases in decay corrected ^{210}Pb concentrations observed in older sediments (Table 4) could be the result of either a greater percentage of field-eroded sediments, or a smaller sediment load in the river. Since we know that sediment loading to Lake Pepin was indeed less in the past, the question is: are the changes in sediment load enough to explain the changes in measured ^{210}Pb concentrations?

The annual load of ^{210}Pb entering the upper end of Lake Pepin can be described as:

$$\text{Pbm} \times \text{Sp} = \text{X} \left[(\text{Sf} \times \text{Pb}_f) + (\text{Atm} \times \text{SA})\right] \qquad \text{eq. 12}$$

where Pbm is the concentration of ^{210}Pb measured on sediment in the upper transects of the lake and Sp is the total load of sediment entering the lake. Sf is the total amount of sediment eroded from fields that enters the river system annually. Pb_f is the concentration of ^{210}Pb on these particles. Atm is the estimated annual areal atmospheric deposition rate of ^{210}Pb (0.45 pCi/cm^2-yr), and SA (cm^2) is the combined surface area of the rivers upstream of Lake Pepin. In combination these terms represent the total load of ^{210}Pb entering the river system, but only a fraction of this ultimately reaches Lake Pepin. X, describes the fraction of the total load that reaches the lake and is directly related to the combined sediment trapping efficiency (%trap) of the tributaries to Lake Pepin:

$$\text{X} = 1 - \%\text{trap} \qquad \text{eq. 13}$$

Equation 13 can be simplified by dividing through by Sp and distributing X to become:

$$\text{Pbm} = (\text{X} \times \text{S}_f \times \text{Pb}_f)/\text{Sp} + (\text{Atm} \times \text{SA} \times \text{X})/\text{Sp} \qquad \text{eq. 14}$$

The percentage from field sediment is recognizable in the first part of eq. 14 as:

$$(\text{X} \times \text{S}_f)/\text{Sp} = \%\text{f} \qquad \text{eq. 15}$$

We can also assume that Atm and SA, have been constant over time and thus express the second part of eq. 14 as:

$$(\text{Atm} \times \text{SA} \times \text{X}) = \text{Z} \qquad \text{eq. 16}$$

With these two simplifications equation 14 can be rewritten:

$$\mathrm{Pbm}_i = (\%f_i \text{ x } \mathrm{Pb}_f) + Z_i/\mathrm{Sp}_i \qquad \text{eq. 17}$$

Equation 17 describes the measured ^{210}Pb concentration at any time interval in Lake Pepin. Pbm_i and Sp_i are measured decadal averages (Fig. 9 and Table 4), and only $\%f_i$ and Z_i are unknown.

Measured concentrations of ^{210}Pb (Pbm) need to be decay corrected to a common date, e.g. the date of coring. Decay correction is sensitive to the difference between the total ^{210}Pb concentration and supported ^{210}Pb values. The older a sample is, the smaller the difference between total and supported ^{210}Pb, and thus greater uncertainty in decay correcting the concentrations. Decay correction is also dependant on precisely knowing the age of any interval. Again, the older the sample, the greater the sensitivity to uncertainty in age estimates. These two criteria limit decay correcting ^{210}Pb concentrations to intervals younger than 1940.

A better method is to decay the total inventory of ^{210}Pb between two well-anchored dates, and divide this by the cumulative dry mass for this period. This provides a robust, average, decay corrected ^{210}Pb concentration. In the initial coring of Lake Pepin, specific dates were assigned to magnetic features that were common to all cores. These dates were verified by ^{137}Cs and pollen profiles. The ^{210}Pb inventory between these markers is decay corrected by:

$$\mathrm{Inv}_{decay} = (\mathrm{A1}-\mathrm{A2})/\exp(-k \text{ x } td) \qquad \text{eq. 18}$$

Inv_{decay} is the decay corrected inventory for the time period of interest, A1 is the total ^{210}Pb inventory below a dating marker; A2 is the total inventory below the next (older) dating marker; k is the decay constant for ^{210}Pb; and td is the number of years for decay correction. Because ^{210}Pb is an exponential decay, td is calculated as:

$$td = yr_{core} - yr_{Al} - ti \qquad \text{eq. 19}$$

Where yr_{core} is the date of coring, yr_{Al} is the date associated with marker defining the top of A1 and ti is the additional number of years needed to decay the inventory defined by:

$$ti = \frac{1}{k} \times \ln\sqrt{A1/A2} \qquad \text{eq. 20}$$

The decay corrected inventory is then divided by the cumulative inorganic dry mass between the dating markers to give a decay corrected ^{210}Pb concentration for that time period (Table 4)

To minimize the effect of direct deposition to the lake surface only the two transects (four cores) from the uppermost portion of the lake were used. Decay corrected ^{210}Pb concentrations were calculated for the four cores and averaged. Concentrations measured in surface intervals were assigned to the date of coring. Table 4 shows the decay corrected concentrations and average inorganic sediment loading during the known time intervals

Given these decay corrected concentrations, we can return to eq. 17 and estimate changes in field contributions (%f_i) over time. One way to assess changes in %f_i, is to use current source apportionment estimates (%fi ~ 0.35), our reference value for Pbf (1.88 pCi/g) and solve equation 17 for Z at 2007. We can then assume that Z_i does not change over time and solve eq. 17 for %f at each time interval (Table 4).

Table 4. Estimated changes in the relative contribution from field sediment to Lake Pepin based on changes in the decay corrected ^{210}Pb concentrations and sediment loads over time. These modeled estimates assume that upstream trapping of sediment has remained proportionally constant over time. Historical field percentages greater than 100% suggest that current trapping efficiencies may be greater than past rates

Date	Inorganic Sediment Load "*Sp*" (1000'sTons/yr)	Measured or Decay Corrected ^{210}Pb Concentration (pCi/g)	% field
2007	594	2.16	35
1996	673	1.93	32
1967-1996	566	2.71	59
1940-1967	476	3.12	65
1890-1940	205	7.84	>100
1830-1890	137	16.9	>100
Pre-1830	63		0

When we do this, the relative contributions from fields are predicted to have been larger in the past, becoming the dominant source prior to 1940. This model exercise predicts contribution from fields exceeding 100% in the periods older than 1940. This suggests that either Zi is not constant or our decay correction of Pbm is slightly off. Older dates are highly sensitive to the date of decay correction and could easily vary the estimated concentration of Pbm by +/-25%. It is also likely that trapping efficiency of sediments and ^{210}Pb has changed over time, thus Zi is not a constant. If current trapping efficiency were larger today than in the past, this would have the effect of reducing the percent from field in older time periods. Given that field inputs are unreasonably large prior to 1940 suggests that trapping efficiency has increased post-1940.

While this exercise does have significant uncertainty and assumes trapping of ^{210}Pb to be constant over time, it is the best estimate available on how sediment sources have changed. The model is anchored in 2007 source apportionment estimates and predicts field contribution for 1996 to be 32%. This is similar to the estimate of 39% generated using ^{137}Cs concentrations, and helps verify the utility of the exercise. The predicted changes in source apportionment over time need to be viewed within the context of their uncertainty, but nonetheless strongly suggest that the relative contribution from fields were larger in the past.

Estimates of Changes in Field and Non-field Loads to Lake Pepin

Decadal estimates of inorganic sediment loads from each source can be readily calculated by multiplying the relative fraction from each source by the whole lake accumulation rates describe earlier. For the periods 1996 and 2007, where relative source apportionment is

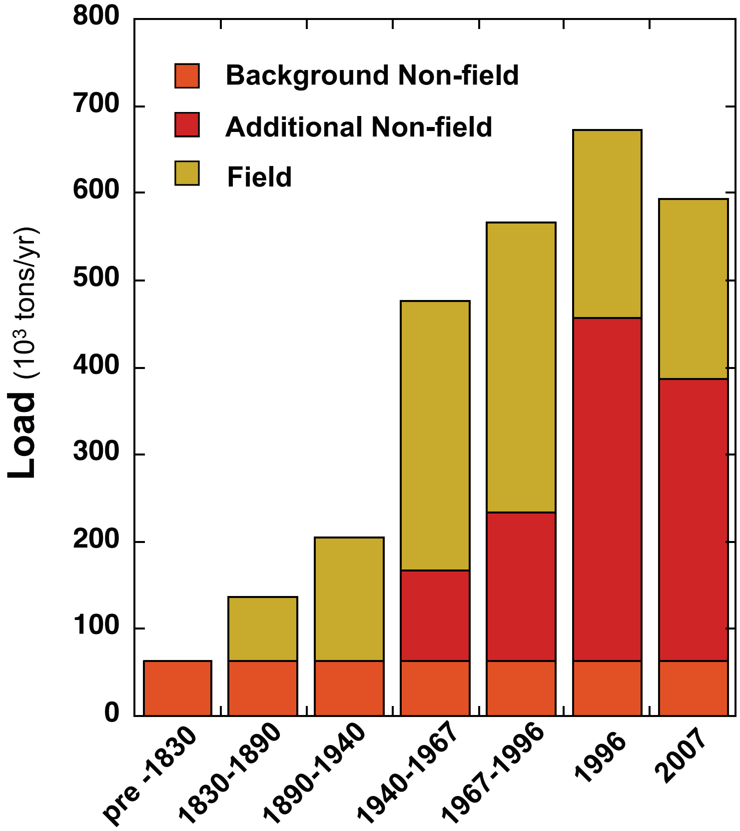


Figure 14. Estimate of changes in inorganic field and non-field loading to Lake Pepin over time based on changes in ^{210}Pb concentrations. Results assume that upstream sediment storage has remained constant. Changes in ^{210}Pb concentrations could also be satisfied with sediment storage increasing in recent time periods. Both estimates require current inputs of non-field loading to be at least 4X greater than background conditions.

explicitly estimated from ^{137}Cs measurements, this is a straightforward calculation. For earlier time periods we must rely on the source apportionment estimates generate in the model exercise above. Figure 14 shows historical estimates in field and non-field loading to Lake Pepin. Loading prior to 1830 is defined as the natural background load, and assumed to be dominated by non-field sources. This load exists during all time periods. For periods where the model predicted greater than 100% contribution for field sources, the background load was subtracted from the total load, and the remainder expressed as field load.

It is not surprising that field loads show a dramatic increase over time as the watershed is converted to agriculture (Fig. 14), but what is striking is how non-field loads have increased. Loading from fields rises steadily after 1830, reach peak contributions after the1940s and remain roughly constant or slightly decreasing until the present. Figure 14 suggests that current field contributions may have decreased by one-third, but it is difficult to know if this trend is real. What is surprising is the major increase in non-field loads in the past 70 years. During the period 1940 to present, when field loads were roughly constant or decreasing, non-field loads increase from by nearly 5X as compared to background rates.

Estimates for periods older than 1996 carry with them the uncertainty created in the historical source apportionment model, above. The loads shown in Figure 14 should not be viewed as precise estimates, but rather used to illustrate the general magnitude of changes in source loading. The result of this exercise are uncertain, but the trend and general magnitude of change is difficult to refute. The estimates in Figure 14 need further examination, both in Lake

Pepin and in other agriculture systems.

The calculate 5-fold increase in non-field loading is not based on uncertain decay corrections or varying accumulation rates . The current sediment load to Lake Pepin is known, and current source apportionment is based on measured values of ^{137}Cs (and confirmed by results from many watersheds). This allows the direct calculation of current non-field loading. Compared to the pre-settlement loading rates, which were based on calibrated ^{14}C measurements with low uncertainty (Engstrom et al. 2009), it is unequivocal that non-field loading has increased over time. The magnitude of increase could be less than 5X, but assembled data clearly show that the rate of non-field inputs is much greater today than it was prior to 1830. This raises the question, why have non-field loads steadily increased especially since 1940? Are the trends in Lake Pepin similar to changes that have occurred in other large agricultural basins? Can the trends and magnitude of change be verified? Until the mechanisms causing the change in non-field loading are understood, it will be difficult to accurately and efficiently implement the necessary BMPs to reduce sediment loads

Trends in Sediment Loading in the Carver-Bevens Creeks Watershed.

Changes in sediment accumulation rates and source apportionment were examined in the Carver Creek watershed and compared to current source apportionment in the adjacent Bevens Creek watershed. These systems provide a comparison to the current and historical estimates observed in Lake Pepin. Miller Lake, which integrates inputs from upper Carver Creek, is an important comparison, because it archives the processes of a riverine system in an agricultural watershed that is not incised. Carver and Bevens creeks are tributaries to the lower Minnesota River that outlet in Carver County, Minnesota. Both creeks have been identified as having high-suspended sediment yields, averaging greater than 400 kg ha^{-2} yr^{-1} (Metropolitan Council, 2005), and both have watersheds dominated by row-crop agriculture with areas that are transitioning to rural-residential uses. Radioisotope fingerprinting was used to quantify the relative importance of different erosion sources as contributors to the total suspended load in each watershed. The lower portion of both creeks is steeply incised with a nick zone that is migrating upstream. Miller Lake is a natural impoundment in the upper portions of the Carver Creek watershed. Sediment cores from the lake provided an opportunity to compare source apportionment in the incised and non-incised reaches of an agricultural watershed.

Carver and Bevens Creeks: Sampling and Methods

A lake and two low-head dams (Fig. 15 and 16) were used as sites to collect temporally and spatially integrated samples of suspended sediments. Miller Lake is a 140-acre lake in the upper Carver Creek watershed. Carver creek drains an area of about 43,000 acres before it empties into Miller Lake. The creek outlets from the lake and subsequently flows through a steeply incised region before flowing into the Minnesota River. Miller Lake essentially records the erosion history of an agricultural, non-incised watershed. Fine-grained sediments trapped behind low head dams on the lower reaches of Carver and Bevens creek were sampled and presumed to represent the annual suspended sediment composition. The low head dams (sediment traps) are in the incised portion of the watershed, near the confluence with the Minnesota River and integrate the sediment loading/composition entering the Minnesota River. Surface samples (0-2 cm) of sediment cores collected in Miller Lake and the two impoundments were used to estimate source apportionment. These samples represent the temporally and spatially integrated sediment accumulated over the past 1 to 5 years. Relative contributions from field and non-field sources were determined according the methods described earlier.

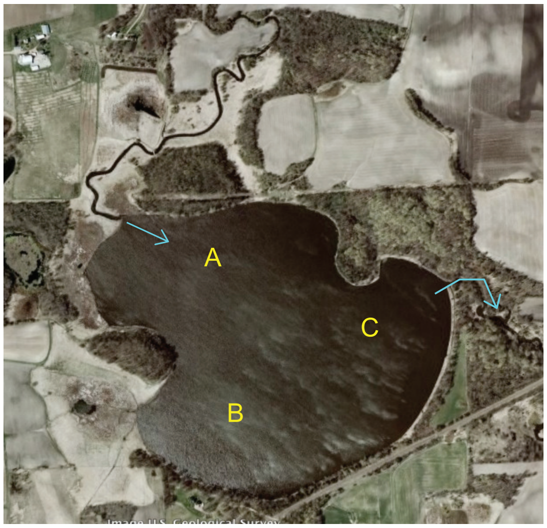


Figure 15. Coring locations in Miller Lake, Carver county, MInnesota. Carver creek enters the lake on the northwest side and outlets to the east.

Sediment cores from Miller Lake provide a record of historical changes in sediment loading and sources in the upper Carver Creek watershed. (Note: conformable, undisturbed sedimentation was not present in the low head dams, thus no sediment cores could be take from those sites.) Three sediment cores were collected from Miller Lake in September 2007 (Fig. 15). All cores were collected from depositional areas of the lake. A four-meter long core was collected in the depositional area on the inlet side of the lake. A 1.6-m long core was collected from an area of the lake furthest from the inlet, and a 2.5 long core was collected from the depositional area of lake near the outlet.

Figure 16. Sediment sampling low-head dam on Bevens creek. Surface sediments were used to assess temporally integrated source apportioment.

Once the cores were collected, the top 30 cm was extruded in the field and stored in polypropylene jars. The top 10 cm was sectioned in 2-cm intervals, and 4-cm intervals thereafter. The remaining, un-sectioned portion of the core was taken to the Limnological Research Center (LRC) at the University of Minnesota-Twin Cities, where the core was split lengthwise, photographed, and magnetic susceptibility was measured. One half of the core was archived in the National Lacustrine Core Repository (LacCore) at the LRC. Once these whole-core analyses were completed, the core was transported to the St. Croix Watershed Research Station (SCWRS) where it was then sectioned into 4-cm intervals. LOI was performed on each depth interval for the entire core, and then the samples were freeze-dried. Lead-210 was measured using alpha spectrometry, ^{137}Cs was measured using gamma spectrometry, and grain size was measured with a laser diffractometer (3 samples).

Lead-210 and ^{137}Cs activity profiles are shown in Figure 17. Cores A and C show well defined ^{210}Pb profiles and a clear ^{137}Cs peak. Cesium-137 was present in rainfall as a result of above ground nuclear bomb testing which ceased in 1963. Thus, the peak activity of ^{137}Cs is used to anchor the year 1963 in the sediment chronology. In Core B, ^{210}Pb activity declines abruptly to background levels at ~20 cm, yet below this ^{137}Cs is still present. This indicates that core B has a truncated sediment record and is not useable for dating or interpretation. Chronology was determined for cores A and C applying the constant rate of supply model to the ^{210}Pb depth profiles and anchoring the model to the 1963 ^{137}Cs marker.

Source Apportionment Carver and Bevens Creeks: Field versus Non-field Contributions

Source apportionment was done for the 0-2 cm intervals of cores A and C, and surface grab samples from the low-head dams on Carver and Bevens creeks (Table 3). Relative values of source apportionment were applied to average loading and yield data for all three sites to estimate the annual load and yield from field and non-field sources. Source apportionment estimation was presented earlier and is summarize in Table 3.

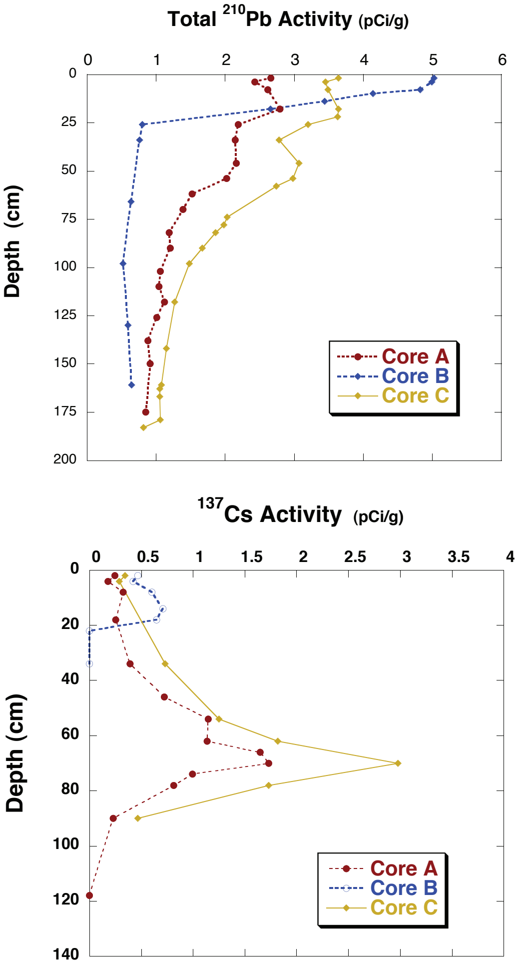


Figure 17. Pb-210 and ^{137}Cs concentration profiles for three Miller Lake cores.

Relative contributions of field versus non-field sediment near the outlets of Carver and Bevens creek are similar to results obtained throughout the Minnesota River watershed, with non-field sources contributing greater than 70% of the load. While total loads in Carver and Bevens Creeks are small compared to large tributaries such as the Blue Earth and LeSueur, their sediment yields are similar (Fig. 13).

Source apportionment in upper Carver Creek (from Miller Lake cores) is somewhat different than lower Carver Creek. About half of the sediment delivered to Miller Lake is predicted to be from field erosion. While this may not seem large, it is greater than the other sites analyzed in the Minnesota River basin. The outlets of Carver and Bevens creek have received inputs from the steeply incised portions of their watershed and the sediment load is dominated by input from these non-field areas. Miller Lake is above the nick point of Carver Creek and receives proportionally more sediment from field sources.

A detailed look at source apportionment in Carver versus Bevens creek provides further evidence of field inputs entering Miller Lake. Bevens

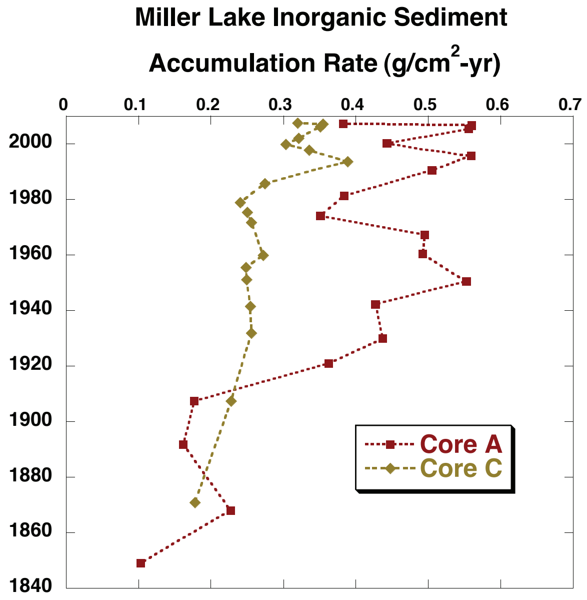


Figure 18. Inorganic sediment accumulation rates near the inlet (A) and outlet (C) basins of Miller Lake.

creek shows 31% from field inputs, while Carver shows less than 10% from field. This may simply be the result of Miller Lake trapping the major load of field sediment such that loading below Miller Lake is nearly 100% non-field. Bevens creek on the other hand has no major sediment trap, and field sediments are a proportionally large fraction of the sediment reaching the mouth. If the field and non-field load trapped in Miller Lake were added to the loading data in the lower Carver creek, the overall source apportionment would predict 20% from field sources, similar to Bevens creek.

It is also possible to use cores A and C look at changes in source apportionment over time. Direct atmospheric inputs of ^{137}Cs varied from the 1950s through the early 1970s and thus ^{137}Cs is not suitable for examining changes in temporal trends in source apportionment. Lead-210 is also difficult because it has both atmospheric and field inputs to the lake. These inputs can be expressed as:

$$\mathrm{Conc}_{\mathrm{core}} = \mathrm{AtmDep}/(\mathrm{MSR}/\mathrm{FF}) + \mathrm{Pb}_{\mathrm{field}} \qquad \text{eq. 21}$$

where $\mathrm{Conc}_{\mathrm{core}}$ is the decay-corrected total concentration (pCi/g) of ^{210}Pb in a core interval, AtmDep is the annual average atmospheric deposition rate (pCi cm^{-2} yr^{-1}), FF is the core specific sediment focusing factor and $\mathrm{Pb}^{\mathrm{field}}$ is the concentration of ^{210}Pb on incoming particles from field erosion.

Given the number of unknown variables, equation 21 cannot be solved uniquely. However, at a core site, it can be assumed that FF, AtmDep and $\mathrm{Pb}_{\mathrm{field}}$ are constant over time. Thus, if the relative importance of field has not changed over time, the ratio of $\mathrm{Conc}_{\mathrm{core}}$ (eq. 21) at two time periods should be near unity. If the concentration ratio at two time periods has changed, then the relative input from field/non-field must have changed proportionally. This method is highly sensitive to decay correcting ^{210}Pb measured at historic intervals. Only the 1963 peak provides a date with enough certainty to permit this calculation. Ratios of concentrations in 1963 and present were estimated for cores A and C using atmospheric deposition rates of 0.3 to 0.5 pCi cm^{-2} yr^{-1}, FF as described below, and the measured decade-specific, sediment-accumulation rates (Fig. 19). Equation 21 was expressed using the different combinations of variables and known values for 2007 and 1963. The ratio of 2007 to 1963 ranged from 0.9 to 1.04 for core A and 0.83 to 0.9 for core C. These ratios suggest that relative source apportionment has remained essentially unchanged from 1963 to present. Over this same time period, the fraction from non-field inputs to Lake Pepin is predicted to have increased by 1.5X

Upper Carver Creek Sediment Accumulation Rates and Loading: A comparison to Lake Pepin

Inorganic sediment accumulation rates for cores A and C from Miller Lake are shown in Figure 18. Core A shows about a five fold increase in sediment accumulation rates since ~1850 and the onset of European settlement. Core C shows a more subtle increase with about a 2-fold increase since 1870. Sediment dates could not be determined prior to 1870 in core C. Given that 1870 is after European settlement, it is likely that sediment accumulation rates in core C had already increased by this time. Core A, near the inlet from Carver Creek, shows a ~2.5 fold rise in accumulation rate between 1900 and 1925. This change coincides with major hydrologic changes and drainage alteration in upper Carver Creek c. 1920 (Aamodt, 2009 personal communication).

Core specific sediment accumulation rates are useful for showing historical changes and relative comparisons but do not directly define whole lake sediment loading. Sediments are focused at different rates in different parts of the lake. Deep basins generally have greater sediment focusing than areas that are shallow and morphologically flat-bottomed. In a lake with an outlet it is also necessary to know trapping efficiency to calculate sediment loading.

Carver County Land and Water Services has been measuring flow and suspended sediments (TSS) upstream and downstream of Miller Lake since 1997. It is possible to construct a comparative sediment mass balance from these data, and also estimate trapping efficiency. Data from Carver County are shown in Table 5. Based on the 12 years of gauging and TSS data just upstream of Miller Lake, an annual load of 4600 tons entering the lake is predicted. Mass balance data from the inlet and outlet stations are highly variable and even show that some years the lake is a net producer of inorganic sediment. This improbable outcome is likely the result of an insufficient number of samples used to calculate loading. If the suspect years are removed from the data set, a trapping efficiency of >67%

Table 5. Sediment mass balance for Miller Lake based on stream monitoring data collect by Carver County, SWCD

Year	Inorganic sediment load into Miller Lake (tons)	Inorganic sediment load out of Miller Lake (tons)	Sediment Stored in Miller Lake (tons)	Trapping Efficiency
1997	6332	1165	5168	82%
1998	1688	711	977	58%
1999	23634	4869	18765	79%
2000	255	25	230	90%
2001	125	87	38	
2002	2362	1186	1177	50%
2003	4875	757	4118	84%
2004	2496	4533	-2037	
2005	12125	7879	4247	35%
2006	389	374	14	
2007	856	384	472	55%
2008	524	155	369	70%
Avg. Tons/yr	**4638**	**1844**	**2795**	**67%**

is predicted. This is a reasonable estimate for a lake the size and shape of Miller Lake.

Whole lake sediment loading can be estimated from sediment accumulation rates in cores A and C by the following relationship:

$$\text{Load}_{yr} = (\text{MSR}/\text{FF}) \times \text{SA}/\text{TE} \qquad \text{eq. 22}$$

where Load_{yr} is the total amount of inorganic sediment (kg) entering the lake each year, MSR is the measured sediment accumulation rate at a core site (g cm^{-2} yr^{-1}), FF is the sediment focusing factor, SA is the lake surface area (cm^2) and TE is the sediment trapping efficiency for the lake. Miller Lake has surface area of 140 acres. Using reasonable estimates of 1.25 to 2 for FF and a trapping efficiency of 70%, annual sediment loads of 1400 to 3200 tons/yr entering the lake are predicted from cores A and C. These values represent the minimum and maximum range of estimates. Thus, 3200 tons/yr is an upper limit and is significantly smaller than the 4600 tons/year estimated from TSS loading data. Based on this comparison, it appears that the stream–gauge sediment mass-balance is overestimating loading to the lake by at least 30%.

An alternate way to calculate loading from the cores is to use the total mass of sediment accumulated since some well defined dating maker Such as the ^{137}Cs peak (1963). Dividing the cumulative dry mass since 1963 by the number of years (44), the average accumulation rates for cores A and C were 0.49 and 0.30 g cm^{-2} yr^{-1}, respectively. Applying the same FF and trapping efficiency as before, the average annual sediment load over the past four decades is 1200 to 3000 tons. These estimates are only slightly less than current rates. Given that accumulation rates have increased in recent decades, this outcome was expected. This approach validates the sediment accumulation rates calculated by the ^{210}Pb dating method and helps anchor the upper limit of annual loading to the lake at less than 3200 tons/yr.

Using equation 22, focus corrected sediment accumulation rates from cores A and C were averaged and used to calculate whole-lake loading to Miller Lake at several periods in the past (Fig. 19). The largest increase in loading to the lake occurred in the time period around 1920. This is consistent with the hypothesis that hydrologic/drainage alterations in the upper Carver Creek watershed during this period changed sediment delivery. Loading to the lake in the decades after these alterations is relatively constant with rates increasing by ~15% in recent years. Careful examination of when and what type of drainage alterations were implemented in the watershed should be done to see if the hypothesized link between sediment delivery and watershed hydrology can be confirmed. Understanding the mechanism for the sediment loading increase in the early 20th century may be useful for instituting management practices to reduce current sediment loading.

Overall, sediment delivery from the upper Carver creek watershed has increased by 4X since 1870. This compares to about 9X increase in Lake Pepin over the same time period. Similarly if we multiply the non-field percentage determined for Miller Lake by the current load, and ratio this to the 1870 loading rate, we see that non-field inputs have increased by~ 2X. Again this is about half the magnitude of change calculated for Lake Pepin. The observation that both systems show a post-European settlement increase in non-field loading, helps confirm the concept that conversion of the native landscape to row-crop agriculture not only results in increased sediment erosion, but also increased non-field erosion.

The smaller relative increase in the upper Carver system is probably the result of differences in watershed landform. Lake Pepin integrates many different watersheds, with the largest loads coming from steeply incised tributaries. Miller Lake integrates inputs from a less incised agricultural watershed. The observation that relative increases in Miller Lake are about half that of Lake Pepin may reflect the proportional changes to be expected from non-incised versus incised watersheds.

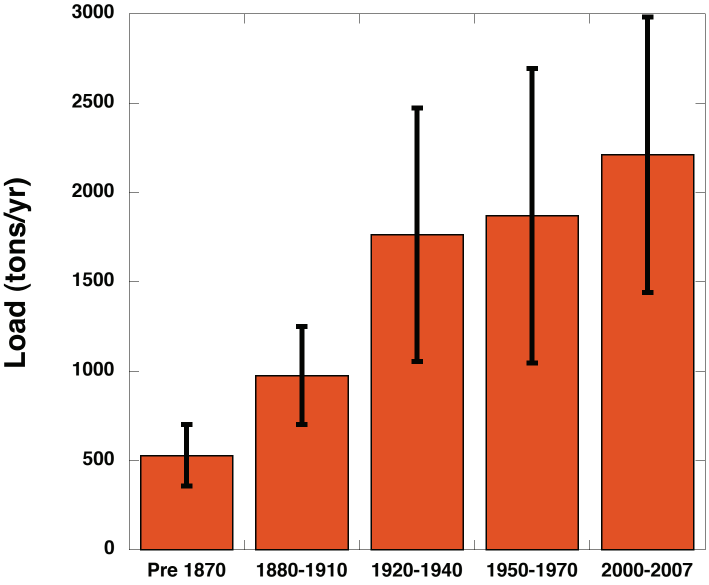


Figure 19. Historical changes in sediment accumulation rates in Miller Lake. The current relative contribution from non-field sources is ~58% (Table 3), which means that current non-field loading is about 1200 tons/yr. This is 2X the pre-1870 rate, confirming that non-field erosion rates have increased.

Carver and Bevens Creek: Summary

Sediment loads at the outlet of Carver and Bevens creek are dominated by erosion of non-field sources such as ravines, streambanks and bluffs with only 10-30% of the sediment derived from erosion of field source. Annual loading of sediment from Carver and Bevens Creeks is much smaller than loads from other watershed, but the yields are similar to other incised tributaries in the middle and lower Minnesota River watershed. Non-field sediment yields are 5-9 times greater than yields of eroded field sediment. Annual non-field sediment load (tons/yr) and yields (kg ha^{-1} yr^{-1}) in lower Carver Creek are 5 to 6 times greater than upper Carver Creek, highlighting the contributions from the steep portions of the watershed. Sediment accumulation rates in Miller Lake near the inlet from Carver creek show a ~2.5 fold increase between 1900 and 1920. This change coincides with major hydrologic changes and drainage alteration in upper Carver Creek

It is important to restate the observations from the Lake Pepin source-apportionment, that while the non-field sources dominate sediment loading, the rate is not “natural”. The processes and sources of non-field erosion may well have existed in the past, but the rate at which they are eroding is not. Cores from Miller Lake show that sediment delivery from Upper Carver Creek has increased four fold since 1870 and that non-field erosion has doubled. These results support the observed trends in Lake Pepin but also demonstrate that the impact of land use changes in a non-incised agricultural watershed are proportionally smaller than the changes in the incised watersheds contributing the majority of sediment to Lake Pepin. Further investigation is needed to understand the linkage between land use, land form and climate that are driving the increases in non-field erosion and clarify why rivers have become more erosive.

Redwood Reservoir: Sediment Sources and Rates in a Western Minnesota Watershed

Redwood Lake was created by damming of the Redwood River in 1902 (Fig. 20). The lake is now 3 m deep on average with a sediment infill up to 8 m. The sediment filling the lake is a unique archive that documents over 100 years of erosion history in the Redwood watershed. The reservoir provides a complementary site to Lake Pepin, useful for understanding the post-settlement sediment transport history in the upper portion of the Minnesota River watershed.

In September of 2006 a 5.6 meter sediment core was taken from the lower portion of the Redwood Reservoir (Fig. 21), approximately 300 meters upstream of the dam. Several analyses were performed on the sediment to determine the nature and source of deposition. Once the core was collected, the top 94 cm were immediately extruded in the field and placed in polypropylene sample jars. The remaining, un-sectioned, portion of the core was taken to the Limnological Research Center (LRC) at the University of Minnesota-Twin Cities where the core was split lengthwise, photographed, and magnetic susceptibility was measured. One half of the core remains archived in the National Lacustrine Core Repository (LacCore) at the LRC. The working half of the core was then transported to the Large Lakes Observatory at the University of Minnesota-Duluth where elemental analysis was performed using x-ray fluorescence (XRF). Once these whole-core analyses were completed, the core was transported to the St. Croix Watershed Research Station (SCWRS) where it was then sectioned into 4-cm intervals, each interval placed in two sample jars, one for pollen analysis at the LRC and the other for radioisotope analysis at the SCWRS. Lead-210 was measured using alpha spectrometry, ^{137}Cs was measured using gamma spectrometry, and grain size measured with a laser diffractometer (5 samples) on the freeze dried

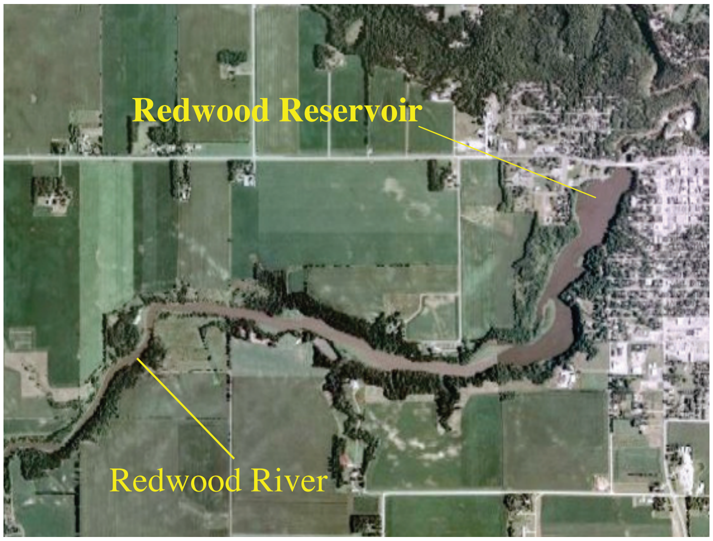


Figure 20. Redwood reservoir at Redwood Falls, Minnesota

Figure 21. Coring the Redwood Reservoir.

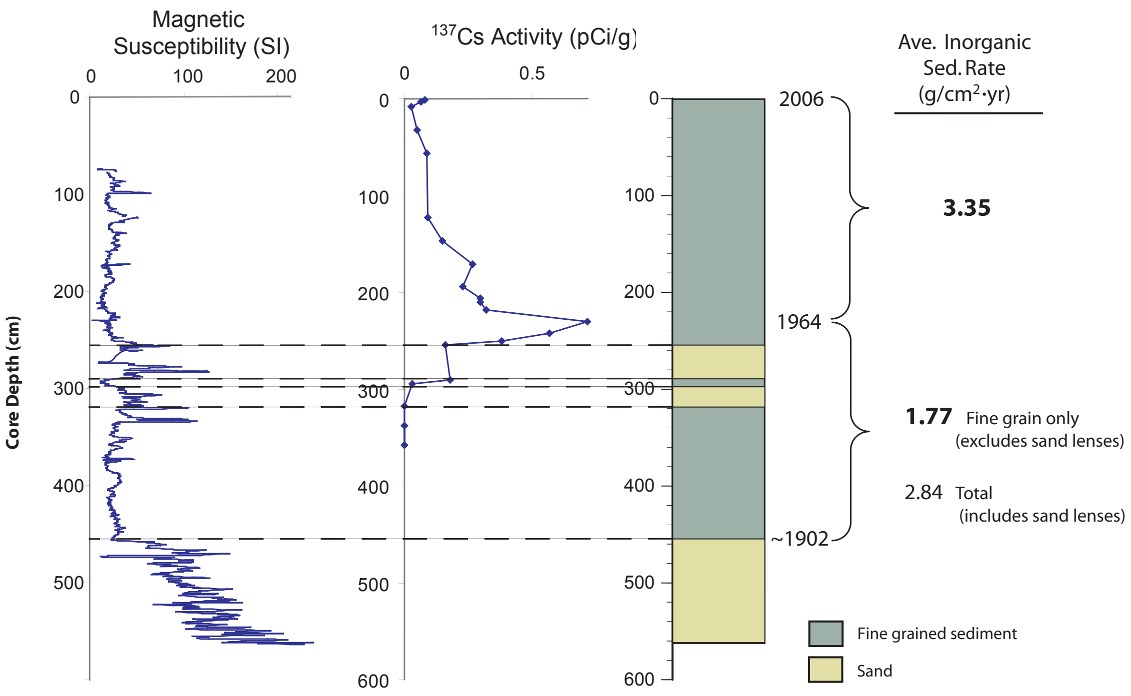


Figure 22. Magnetic susceptibility, ^{137}Cs activity profile and sediment accumulation rates in the Redwood Reservoir. Sand lenses determined by loss-on-ignition, and grain size are shown with tie lines. Sand lenses were excluded from source apportionment to allow comparison to TSS samples, other integrator sites and Lake Pepin.

samples.

Sediment chronology for this core was only possible using three dating markers. Dating by ^{210}Pb was unsatisfactory because episodic deposition of sediment violates the assumption of a constant rate of ^{210}Pb supply necessary to the dating model. The Redwood dam was built in 1902 and is represented in the sediment core where the sandy riverine deposits transition to fine-grained lake sediments at approximately 450 cm. This lithologic change is consistent with the magnetic susceptibility profile (Fig. 22). The 1963/64 dating marker was determined from the ^{137}Cs peak, which marks the year after the nuclear test ban treaty went into effect. Sediment in uppermost intervals is assumed to have been recently deposited.

Sediment accumulation rates were calculated from cumulative dry mass for the two time periods, 1902 to 1963, and 1963 to 2006. In the 1902- 1963 time period, there are two thick sand layers, which may be a result of high flow events that carried coarse-grained sediment to this portion of the basin. For understanding sediment erosion processes as it relates to suspended material carried in the river, it is the fine-grained sediments that are relevant. The total sediment accumulation rate for the early time period is 3.5 g cm^{-2} yr^{-1}. However, when the event-based sand layers are excluded, the inorganic accumulation rate is only 1.77 g cm^{-2} yr^{-1}. The average accumulation rate from 1964 to 2006, which does not contain any thick sand lenses, is 3.35 g cm^{-2} yr^{-1}.

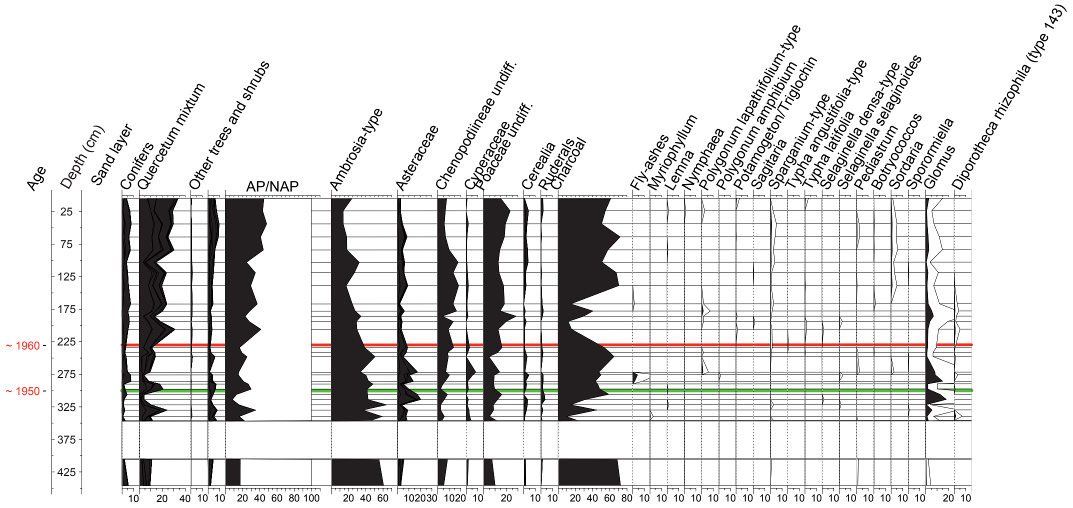


Figure 23. Changes in pollen abundances in the Redwood Reservoir

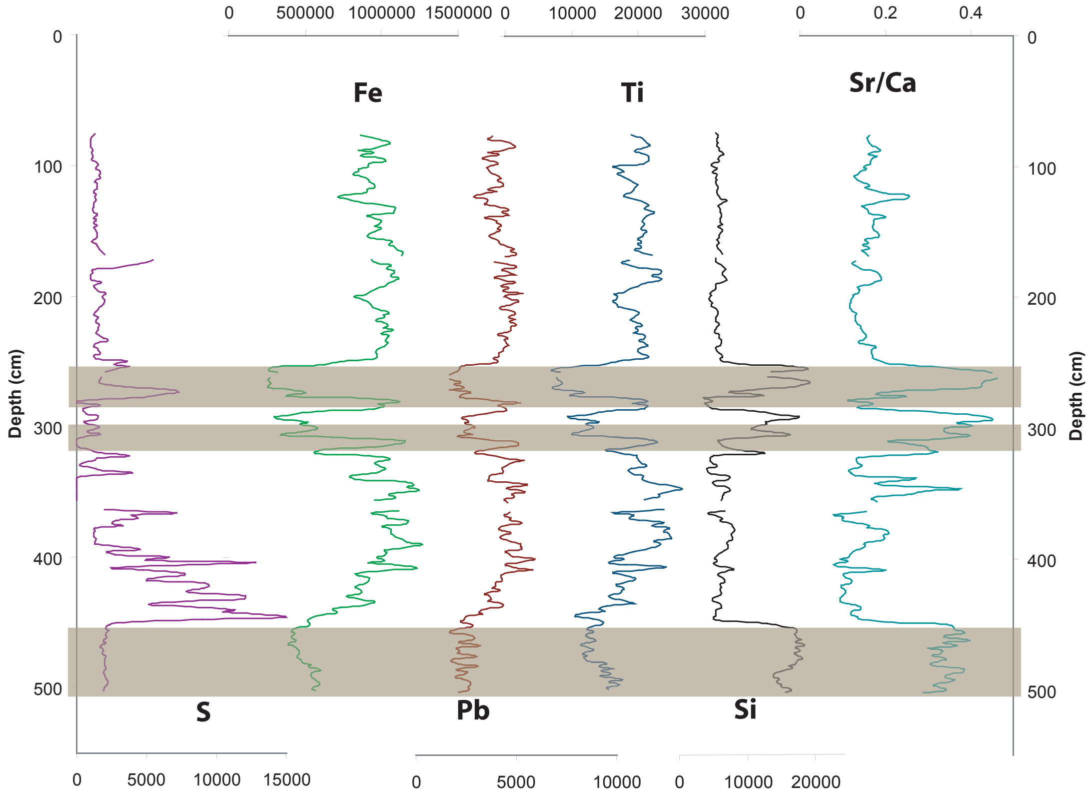


Figure 24. Profiles of selected metals in the Redwood core measured by XFRM

Comparison of the two time intervals shows that sediment delivery to the reservoir has increased by nearly 90% in the past 40 years as compared to the period before 1964. This means that if the reservoir were dredged, and infilling occurred at the current rate, it would take only 80 years to reach current conditions as compared to 104 years (2006-1902). Based on the minimal water depth behind the reservoir it is reasonable to conclude that sediment-trapping efficiency is currently much lower than it was in the period prior to 1964. Thus, the present-day sediment-accumulation rate in a newly created reservoir would be greater than 3.35 g cm^{-2} yr^{-1}, and it would take less than 80 years to reach current conditions.

Table 6. Comparison of changes in sediment accumulation rates in Lake Pepin and Redwood reservoir. Sediment accumulation in the reservoir is highly focused at the core site and thus appear to be much larger than the whole basin (focusing corrected) rates measured for Pepin. It the relative change in rates that is the salient comparison.

	Fine-grained Sediment Accumulation Rate (g/cm^2-yr)	
	Lake Pepin	Redwood Reservoir
1964 to 2007	0.57	3.35
1900 to 1964	0.31	1.77
Relative Change In Rate	+80%	+89%

On a course time scale, the trends in sediment accumulation in the Redwood Reservoir are similar to those observed in Lake Pepin (Table 6). It is not possible to compare absolute accumulation rates, as those in the reservoir core are not corrected for sediment focusing. However, it is instructive to compare the relative change in sediment accumulation rate. Lake Pepin decadal rates can be assembled into the same two time periods as the estimates for the Redwood Reservoir. Remarkably, both systems show nearly the same relative increase in accumulation rate (Table 6), with the period after 1963 nearly double the pre-1963 rates.

The absolute rates in the reservoir appear to be much greater than those in Lake Pepin. This is the result of core specific focusing and should not be construed as higher loading rates in Redwood than in Lake Pepin. Present-day measured sediment loads from the Redwood River are more than an order of magnitude less than loading rates to Lake Pepin, thus there must be high sediment focusing to the Redwood core site.

Some caution is required in making this comparison. Lake Pepin represents a synthesis of multiple cores, while Redwood is a single core. Lake Pepin is a natural lake where trapping efficiency is relatively constant over time, while Redwood is subject to the variability of sediment accumulation patterns (e.g. changes in trapping efficiency) associated with a small reservoir.

Field and non-field sediment contributions to the reservoir were estimated using ^{137}Cs from the upper intervals of the core and the procedures outlined above. Non-field sediments are estimated to comprise 79% (+/- 17%) of the current load (Table 3, Figure 10). This source apportionment is similar to that for other tributaries in the upper Minnesota watershed. Sediments in the upper sections of the core have particle sizes with specific surfaces around 7000 m^2/m^3 which is on the low end of the range observed in the reference lakes and suspended sediments. It is therefore possible that some ^{137}Cs has been preferentially lost on very fine sediments not trapped in the reservoir and that the non-field contribution is slightly overestimated. Only two suspended sediment samples from the Redwood River were available for comparative source apportionment (Appendix 1)

In Lake Pepin we used decay corrected ^{210}Pb inventory over different time intervals to examine to how ^{210}Pb concentrations entering the lake changed and related these changes in concentration to changes in field and non-field inputs. A similar calculation for Redwood shows that average ^{210}Pb concentrations from 1964-2006 were about 1.4 pCi/g and 4.4 during the period 1902-1964. It is tempting to suggest that this decrease in ^{210}Pb is associated with greater relative inputs from non-field sources. However, as discussed above, it is necessary to adjust this concentration for direct atmospheric inputs of ^{210}Pb to the river surface. This correction normalizes to changes in sediment dilution (caused by changes in sediment load) and requires trapping efficiency of the reservoir to be constant over time. Because trapping efficiency has declined as the reservoir has filled, it negates the potential to use ^{210}Pb to predict historical changes in source apportionment.

Profiles of magnetic susceptibility (Fig. 22) and stable Pb (from atmospheric pollution) (Fig. 24) offer a qualitative assessment of how relative source contributions have changed over time. Peaks in magnetic susceptibility are associated with sand layers. When these are removed the profile is nearly uniform, suggesting a constant source of sediment. Field sediments, through atmospheric deposition, should be enriched in stable Pb relative to non-field sediments. Deposition of stable Pb increased steadily from the turn of the century until the 1970s when leaded gasoline was banned. If field sediments dominated inputs, we would expect to see a rise and subsequent decline in the Pb concentration profile. The uniform temporal trend of elemental Pb in the core supports the observation that field sediments are not the dominant source. The uniform profiles in both magnetic susceptibility and stable Pb could result from either a temporally constant proportion of field and non-field inputs, which means loading from both sources has increased over time, or could reflect a system where non-field inputs have always dominated and overwhelmed any changes in the source ratio. If our conclusion is correct, that non-field sources dominate present-day sediment loading, and that loading has doubled over time, the inputs from non-field sources must have increased over time. And if this is true, it underscores the need to understand the source of the non-field sediment and to clarify the possibility that the Redwood River, like other tributaries supplying Lake Pepin, has become more erosive over time.

A Pilot Study to Separate Bluff and Ravine Inputs

A pilot study was conducted, comparing a suite of major and trace-element concentrations in ravine and bluff deposits and surface soils from the watershed of the Le Sueur River, to determine the feasibility of using fingerprinting methods to discriminate among non-field sediment sources. The Le Sueur River contributes a disproportionately high percentage of the sediment load in the Minnesota River, and other investigators have identified ravines and bluffs as the most important sources within the Le Sueur watershed. Elemental composition was determined for whole-sediment and heavy-mineral fractions of nine bluff and twelve ravine samples. Ten elements in the heavy-mineral fraction were statistically distinct as tracers to segregate ravine from bluff contributions. In addition, six suspended sediment samples from the Le Sueur River were analyzed for whole sediment composition, but there was insufficient sample to also measure the heavy mineral composition, and a mixing model could not be applied.

The Le Sueur River near Mankato, MN was chosen for the pilot study because it is a mid-sized watershed that contributes a disproportionately high volume of sediment to the impaired Minnesota River. Bluffs along the Le Sueur River are comprised of glacial till, occasionally overlain by one to three meters of fluvial terrace deposits. The till is from the Des Moines lobe of the Laurentide ice sheet, the last glacier to occupy south-central Minnesota, as well as earlier glacial advances. Because the older glacial advances came from the same general direction as the Des Moines lobe, all tills exposed in these bluffs are fairly similar. The bluffs are vertical to near vertical and are taller than the streambanks, which are active floodplain features defining the “bank full” stream channel. Bluffs contribute to the Le Sueur River’s sediment load via processes of bluff-toe erosion, collapse and retreat.

Ravines are steep fluvial features that connect the upland to the river. In general, ravine processes are poorly understood. Water flow in ravines is transitory, and ravines grow by headward extension, widening and/or deepening depending on hydraulic and geologic conditions. Ravines may contribute to the Le Sueur River’s sediment load by the erosion of parent material resulting from ravine growth, and also by capturing and funneling eroded surface soil from the upland. Ravines develop in the same glacial till that comprises bluffs, so both landforms have identical parent material. However, ravine sediment may differ geochemically from that of bluffs because: (1) fluvial action in ravines selectively transports certain particles; (2) increased weathering in ravines may change the composition of the sediment; and (3) surface soil may be a significant component of transported ravine material and thus impart its unique geochemical characteristics to ravine sediment. If the ravine sediment does differ geochemically from bluff sediment, and if both are distinct from upland (field-derived) sediment, then a mixing model, similar to that used in other studies of sediment-source apportionment, could be applied to the Le Sueur River watershed.

Sample collection

Nine bluffs between St. Clair and the Le Sueur River’s confluence with the Blue Earth River were sampled in July 2008 . Samples were collected from the near-vertical face of each bluff, avoiding slumps, and the weathered, surficial sediment was first removed with a rock hammer to expose relatively “fresh” till.

Twelve ravine samples were collected from two ravines near the County Road 8 bridge, named “Lex” and “Liar”, that are being studied by NCED researchers. Samples were collected from fine-grained depositional features assumed to be in active transport within the ravine. For example, some samples were collected from small "benches" or terraces, 10-30 cm thick, near the base of the ravine walls, and some samples were collected from small fluvial bars on the bottom of the ravines. Two surface grab samples were collected from fields near the sampled ravines. Six suspended sediment samples were collected by the Minnesota Pollution Control Agency and dewatered by settling. Three samples were collected at St. Clair on May 3, 2006, and May 11 and June 6, 2008: two were collected at the County Road 8 crossing south of Mankato on May 11 and June 6, 2008, and one was collected at the Red Jacket Recreational Park south of Mankato, May 21, 2008.

Sample preparation and analysis

Bluff, ravine and field samples were disaggregated by soaking in deionized water and with gentle physical pressure, as necessary. The samples were then sieved for the <63-µm fraction which was analyzed. This size fraction is comparable to the suspended sediment samples, which are composed primarily of silt and clay-sized particles. A 0.25 g (dry mass) aliquot from each source sample was used for analysis of the "whole-sediment" fraction. For suspended-sediment samples, which were short of material, the entire sample was used for "whole sediment" analysis.

The remaining bluff, ravine and field samples were treated to isolate the "heavy-mineral" fraction. First, organic matter was removed by wet oxidation in 40-mL of 30% hydrogen peroxide solution in an 85˚C water bath. Additional peroxide was added in 10-mL increments until the reaction was complete, usually 35-55 minutes. Next, carbonate cement was removed by soaking samples overnight in 35-mL 1M NaOAc solution, then heating the samples to 90˚C in a water bath for 1-2 hours . Third, iron-oxide cement was removed using a sodium dithionite extraction in a 80°C water bath (Soil Survey Investigations Report, 1996). Finally, each sample was immersed in ca. 40-mL of sodium polytungstate solution adjusted to a density of 2.91 g/cm^3, and centrifuged at 5000 rpm for 30 minutes or until the sample had clearly separated into lighter and heavier fractions (Skipp and Brownfield, 1993). Light minerals and excess solution were decanted, and the residual heavy-mineral fraction was rinsed three times with deionized water, air-dried, and powdered with a mortar and pestle.

Whole-sediment and heavy-mineral fractions were each fused with lithium metaborate in graphite crucibles at 1000°C and dissolved in 1M HCl for analysis by inductively coupled plasma optical emission spectroscopy (ICP-OES). U.S. Geological Survey rock standards were used for calibration. Major elements (Al, Ba, Ca, Fe, K, Mg, Mn, Na, P, Si, Sr, Ti) were measured as oxides directly from the fused solution. The major elements were removed from the sample matrix by ion exchange (Dionex strong-acid exchange resin) prior to measuring the trace elements (Ba, Be, Ce, Co, Cr, Cu, Dy, Er, Eu, Ga, Gd, Ho, La, Mn, Nd, Ni, Pb, Pr, Rb, Sc, Sm, Sr, V, Y, Yb, Zn).

Results

Element concentrations in ravines and bluffs were compared using the Mann-Whitney U test to determine whether any could be used to discriminate between the two sediment sources (bluffs and ravines). One ravine sample, R2A, had anomalously high concentrations of all elements in the heavy-mineral fraction and so was treated as an outlier and excluded from the statistical analysis. Of the whole-sediment samples, Ho, P and Zn were statistically significant discriminators at $p<0.05$, but Ho was near its analytical detection limit and so is not considered to be a reliable tracer. In the heavy-mineral fraction, eleven elements were statistically significant discriminators at $p<0.05$: Al, Fe, P, Ce, Cr, Eu, Ga, Gd, La, V and Zn (Table 7), although Gd was near its analytical detection limit and thus is not a reliable tracer. Zn was also significant at $p<0.01$.

The mean and median concentrations of all tracers in the heavy mineral fraction were higher in ravines than in bluffs (Fig. 25). Also, most of those tracers had some overlap of ravine and bluff concentrations, despite their statistical differences, and the concentration of tracers varied more among ravine samples than among the bluff samples.

Tracer concentrations in the two field samples were all more similar to bluffs than to ravines, with the exception of Al, which was closer to the Al concentration in ravines (Table 8). The two potential tracers identified in the whole-sediment fraction were P and Zn. Of these tracers, P concentrations in the field samples were more similar to bluffs than ravines, and Zn concentration in the field samples was intermediate between bluffs and ravines (Table 9). In the suspended sediment samples, P concentration was lowest at Red Jacket (most downstream) and highest at County Road 8, while Zn concentration was lowest at St. Clair (most upstream) and highest at Red Jacket.

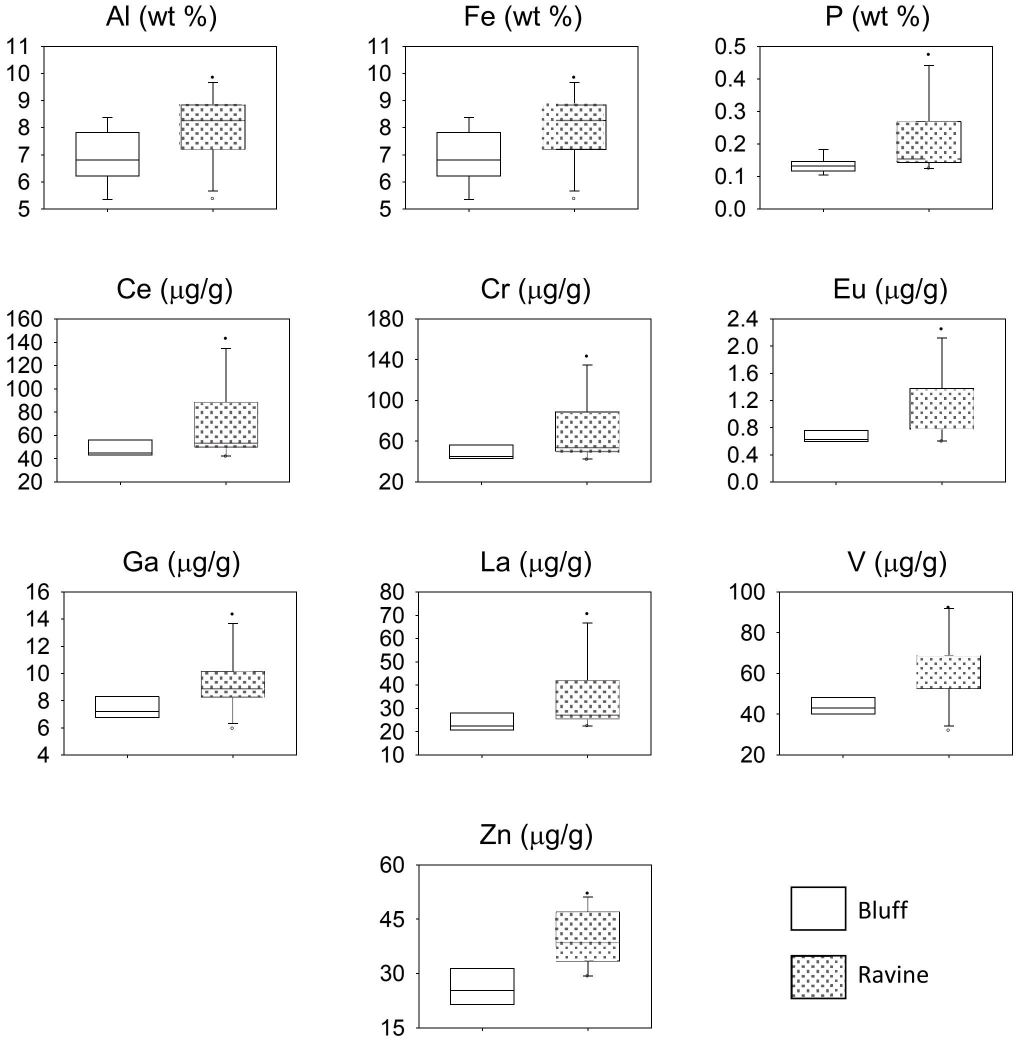
Table 7. P-values of Mann-Whitney U test comparing ravine samples and bluff samples. Values less <0.05 are underlined

Element	Whole sediment p-value	Heavy mineral p-value	**Element**	Whole sediment p-value	Heavy mineral p-value	**Element**	Whole sediment p-value	Heavy mineral p-value
Al	0.464	0.031	**Ga**	0.554	0.033	**Pr**	0.464	0.109
Ba	0.554	0.331	**Gd***	0.862	0.0	**Rb**	0.808	0.075
Be	0.602	0.351	**Ho***	0.041	0.395	**Sc**	0.464	0.310
Ca	0.095	1.000	**K**	0.602	0.456	**Si**	0.148	0.656
Ce	0.754	0.041	**La**	0.345	0.033	**Sm**	0.464	0.129
Co	0.754	0.545	**Mg**	0.095	0.882	**Sr**	0.193	0.112
Cr	0.972	0.020	**Mn**	0.169	0.840	**Ti**	0.554	0.095
Cu	0.508	0.904	**Na**	0.219	0.552	**V**	0.277	0.026
Dy	0.277	0.206	**Nd**	0.148	0.152	**Y**	0.382	0.177
Er*	0.095	0.152	**Ni**	0.247	1.000	**Yb**	0.702	0.091
Eu	0.345	0.016	**P**	0.001	0.020	**Zn**	0.015	0.001
Fe	0.382	0.038	**Pb**	0.058	0.351			

* = element has high analytical uncertainty

Discussion

The concentrations of certain elements are significantly different in the ravines and bluffs of the Le Sueur River watershed and could be used as tracers to discriminate between those two sources in a suspended sediment sample from the river. A mixing model would require



Examples of elements that do not significantly differ between bluffs and ravines:

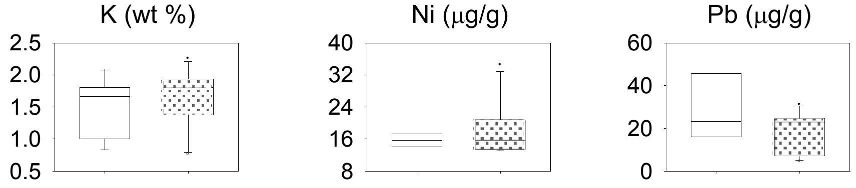


Figure 25. Box plots showing the range of concentrations for the ten tracers that were statistically significant in discriminating between bluff and ravine samples, and for three element that were not discriminatory. Boxed values are the interquartile range and enclose 50% of the data. Median values are marked as a line. Whiskers mark the 10th and 90th percentiles.

at least five tracers in order to quantify the contributions of ravines and bluffs to the suspended sediment in the river, and ten elements in the heavy mineral fraction meet the criteria at $p<0.05$. Only two elements in the whole sediment fraction (P and Zn) could be used as tracers, which is insufficient to construct a mixing model (unless either element had a concentration of zero in one of the sediment sources, which they do not). Therefore, the heavy-mineral fraction must be used. Unfortunately, we did not have sufficient mass of any of the suspended sediment samples to isolate and analyze its heavy-mineral fraction. If this research is continued and expanded, we recommend starting the heavy-mineral separation procedures with at least 10 g of sediment (dry weight). Also, additional field samples or a different method of characterizing field-source composition would be necessary to determine whether surface soils could be differentiated from bluff and ravine using elemental tracers.

Table 8. Mean concentrations of tracers in the heavy mineral fraction of each sub group. Units of Al, Fe and P are wt% all others are ug/g.

Tracer	Bluff (n=8)	Ravine (n=11)	Topsoil (n=2)
Al	6.99	8.01	8.43
Fe	1.55	1.90	0.98
P	0.13	0.20	0.07
Ce	47.18	69.53	46.88
Cr	52.17	81.01	55.63
Eu	0.66	1.05	0.54
Ga	7.57	9.30	6.58
La	23.20	35.37	25.90
V	46.06	61.18	45.24
Zn	25.94	39.64	20.92

Table 9. Mean concentrations of tracers in whole sediment fraction of each source group.

Tracer	Bluff (n=9)	Ravine (n=11)	Topsoil (n=2)	Suspended sediment, St. Clair (n=3)	Suspended sediment, County Rd. 8 (n=2)	Suspended sediment, Red Jacket (n=1)
P (wt %)	0.14	0.17	0.14	0.19	0.20	0.17
Zn (µg g^{-1})	94.21	132.60	109.93	74.11	101.06	132.20

Ravines not only differ from bluffs, but all tracer concentrations are higher in the ravine samples than in the bluff samples. We do not know enough about the mineralogy of these two sources to explain why that might be so. Future researchers could do a mineralogical analysis of the heavy-mineral fraction to better understand the provenance and transport processes affecting the tracers identified here, particularly the trace elements. Furthermore, the hypothesis that ravine samples differ from bluffs because ravines have a large component of field-derived sediment is not supported by these data. All tracer concentrations in the field samples were more similar to those of bluffs than ravines, with the exception of Al. However, we only analyzed two field samples, and such surface soils are known to be spatially highly variable. Furthermore, in situ field collections are not necessarily representative of the particles that are mobilized and erode from a field into a ravine. Future researchers will need to either analyze many field samples to more completely characterize the variability in the Le Sueur River watershed, or they will have to consider alternate ways to characterize the elemental composition of mobilized field particles. This is important to understand ravine-sediment composition, but also because field-erosion is the third component of riverine suspended sediment (with bluffs and ravines) so it must somehow be included in a mixing model.

Finally, it is interesting to compare the tracers identified in this study with those used by Schottler and Engstrom (2002) to discriminate between field and non-field sediment sources. In that study they did not isolate the heavy mineral fraction, so all data refer to the whole sediment. In both studies, Zn (in the whole-sediment fraction) was a significant tracer at a significance level of $p<0.05$. The fact that Schottler and Engstrom were able to use many other tracers in the whole-sediment fraction indicates that field sources are very different geochemically from non-field sources, while non-field sources (ravines and bluffs) are relatively similar. We had hoped that other elements, for example U, might be useful as tracers, but the ICP-OES was unable to measure U nor others such as Cs, Nb, Th and Zr. Future researchers should consider using ICP - mass spectrometry (ICP-MS) to test whether those could serve as additional tracers.

Recommendations for Future Research

The results from the different studies converge to a common theme: that non-field sources are a critical component of sediment impairments in Lake Pepin and its tributary watersheds. Mitigating these impairments will require an understanding of the driving forces and why sediment delivery has increased in recent decades. With regard to understanding non-field erosion sources and processes, three major knowledge gaps need to be addressed.

1. Quantify bluff, streambank and ravine contributions

The tracers ^{210}Pb and ^{137}Cs only permit the separation of sediments that are exposed to rainfall versus sources that are not significantly exposed to rainfall. In agriculturally dominated watersheds, such as those in this study, this translates into field versus non-field. These sediment source tracers do not discriminate among the different non-field sources such as bluffs, ravines and streambanks. A comparison of results among the different tributaries can be used to infer the importance of the different non-field sources, but a more thorough quantification is warranted. Additional work that directly quantifies contributions from the different non-field sources should be initiated. The importance of the non-field sources is almost certain to vary with the geologic characteristics of the watersheds such that specific non-field sources should be evaluated in multiple tributary watersheds. The pilot study tested in the LeSueur watershed showed promise and should be expanded. Additional meteoric tracers such as ^{10}Be may also be a useful addition.

2. Verify time trends and recent increases in non-field loading.

One of the most important findings of this research is the observation that erosion of non-field sources has increased over time. The comparison of background sediment accumulation rates to current non-field loading rates measured in Lake Pepin provides near-unequivocal evidence that non-field erosion rates have increased. However, this observation should be confirmed in other systems, as the implications for designing management strategies are of great consequence and demand verification. Further quantification on time trends and the magnitude of non-field erosion increases throughout the Minnesota River watershed and Lake Pepin is necessary. Is the increase in non-field erosion happening in all basins, is Lake Pepin unique, and how does the magnitude of increase vary with landform and land use? Lake Pepin is currently the key piece of evidence that erosion of natural features is occurring at an un-natural rate. This finding could potentially impact agriculture practices, and it will become incumbent on watershed mangers to both confirm the Lake Pepin record and compare and contrast it in the many sub-basins of the Minnesota River.

3. Mechanisms causing non-field erosion to increase.

Given that non-field erosion has increased in the last 150 years, the obvious question is, why? Have rivers become more erosive and what is the cause? The increase is largely coincident with conversion of the prairie and big woods landscape to agriculture. But this does not directly describe the mechanism for the increasing non-field erosion. There are a number of practices or climatic factors that could cause an increase in non-field erosion. These include, but are not limited to: increases in runoff due to loss of wetlands, drainage ditches and the connectivity of formerly closed depressions; changes in stream flow due to changes in precipitation; increases in runoff due to conversion of crops with high spring time evapo-transpiration potential (e.g. hay or alfalfa) to crops with low ET in the spring (corn and soybeans); increases in runoff due to intensification of artificial drainage. Studies to examine which mechanism or combination of mechanisms is changing non-field erosion must be conducted. If the mechanisms driving changes in non-field erosion are not elucidated, there is a high risk that large amounts of management funding will be spent in a manner that will not produce measurable improvements in water quality.

References:

Aamodt, G, (2009) Personal Communication. Carver County Minnesota, Environmental Services, 600 East Fourth Street, Chaska Minnesota.

Breckenridge A, Johnson TC, Beske-Diehl S and Mothersill JS 2004. The timing of regional Lateglacial events and post-glacial sedimentation rates from Lake Superior. *Quaternary Science Reviews* 23:2355-2367.

Brigham, M.E., McCullough, C.J., and Wilkinson, P., (2001). Analysis of suspended sediment concentrations and radioisotope levels in the Wild River basin, Northwest Minnesota, U.S.G.S Water Resources Investigations Report 01-4192, 21 p.

Carver County Land and Water Services, (2009). Water quality monitoring program, Data available at http://www.co.carver.mn.us/departments/LWS/wqmp.asp or from Minnesota Pollution Control agency: http://www.pca.state.mn.us/data/edaWater/index.cfm

Clayton, L., and Moran, S.R., 1982, Chronology of late-Wisconsinan glaciation in middle North America: *Quaternary Science Reviews*, 1:55 – 82.

Collins, A.L. and Walling, D.E., (2002). *Journal of Hydrology*, 261:218-244

Collins, A. L., Walling, D. E., Leeks, G. J. L., (1997). *Catena,* 29:1- 27.

Collins, AL, Walling, DE and Leeks, GJL (1998) Use of composite fingerprints to determine the provenance of the contemporary suspended sediment load transported by rivers. *Earth Surface Processes and Landforms,* 23:31-52.

Engstrom D.R., Almendinger J.E. and Wolin J.A. (2009). Historical changes in sediment and phosphorus loading to the upper Mississippi River: mass-balance reconstructions from the sediments of Lake Pepin. *Journal of Paleolimnology* 41:563-588.

Engstrom D.R. Balogh S.J. and Swain E.B., (2007) History of mercury inputs to Minnesota lakes; Influences of watershed disturbance and localized atmospheric deposition, *Limnology and Oceanography*, 52:246-2483

Engstrom D.R., Swain E.B., Henning T.A., Bringham, M.E. and Brezonik P.L., (1994) Atmospheric Mercury Deposition to Lakes and Watersheds, In: Environmental Chemistry of Lakes and Reservoirs, Baker L.A (Editor), ACS series 237, Washington D.C., pp 34-66.

Foster, IDL, Lees, JA, Owens, PN and Walling, DE (1998) Mineral magnetic characterization of sediment sources from an analysis of lake and floodplain sediments in the catchments of the Old Mill Reservoir and Slapton Ley, South Devon, UK. *Earth Surface Processes and Landforms,* 23:685-703.

He, Q., and Owens, P., (1995). Determination of suspended sediment provenance using cesium- 137, unsupported lead-210, In, Sediment and Water Quality in River Catchments, Foster, I.D.L., Gurnell, A.M., Webb, B.W. (Eds.), John Wiley and Sons Ltd., UK, p. 207-227.

Jennings, C.E., (2010), Sediment Source Apportionment to the Lake Pepin TMDL--Source Characterization , Minnesota Geological Survey Open File Report Number 10-01.

Kelley DW, Brachfeld SA, Nater EA and Wright Jr. HE (2006). Sources of sediment in Lake Pepin on the Upper Mississippi River in response to Holocene climatic changes. *Journal of Paleolimnology,* 35:193-206.

Kelley D.W. and Nater E.W, (2000). Historical sediment flux from three watersheds in Lake Pepin, Minnesota, USA. *Journal of Environmental Quality*, 29:561-568.

Kelley, DW and Nater, EA (2000) Source apportionment of lake bed sediments to watersheds in an Upper Mississippi basin using a chemical mass balance method. *Catena*, 41:277-292.

Matsch, C.L. 1972, Quaternary Geology of Southwestern Minnesota, *in* Sims, P.K., G.B. Morey (eds.), Geology of Minnesota: A Centennial Volume: St. Paul, Minnesota Geological Survey, p. 548-560.

Matsch, C.L., 1983, River Warren, the southern outlet of Lake Agassiz, *in* Teller , J.T. and Clayton, L., eds., Glacial Lake Agassiz: Geological Association of Canada Special Paper 26, p. 232 – 244.

Metropolitan Council (2005). 2004 Stream Monitoring and Assessment Report, St. Paul Minnesota. Publication Number 32-05-071.

Meyer, M.L. and Schellhaass, S.M, Sources of phosphorus, chlorophyll and sediment to the Mississippi River upstream of Lake Pepin: 1976-1996. A report for environmental studies of phosphorus. Metropolitan Council Environmental Services, St. Paul, MN.

Minnesota State University-Mankato (MSU) Water Resources Center, (2009) State of the Minnesota River 2000-2008, Minnesota Pollution Control Agency HYSTRA database.

Moore, R., Personal Communication (2009) Minnesota State University-Mankato (MSU) Water Resources Center, Mankato Minnesota.

Robbins J.A., Holmes, C., Halley, R., Bothner, M., Shinn, E., Graney, J., Keeler, G., tenBrink,M., Orlandini, A., and Rudnick, D., (2000) *Journal of Geophysical Research*, 105:28,805-28,821

Schottler, S.P. and Engstrom D.R., (2002). Identification of Sediment Sources in an Agricultural Watershed, Report to the Legislative Commission on Minnesota's Resources, Project W02, ML 1999, Subd 6b, December 30, 2002 St. Paul MN.

Skipp, GL and Brownfield, I (1993) Improved density gradient separation techniques using sodium polytungstate and a comparison to the use of other heavy liquids U.S. Geological Survey Open File Report 92-386 USDot Interior Denver, CO

Soil Survey Investigations Report, (1996) Number 42, U.S. Department of Agriculture.

Upham, W., 1890, Report of exploration of the glacial Lake Agassiz in Manitoba: Geological Survey of Canada. Annual Report 1888 – 89, part E, 156 p.

Upham, W., 1895, The Glacial Lake Agassiz: United States Geological Survey, Monograph 25, 658 p.

Walling, DE (2005) Tracing suspended sediment sources in catchments and river systems. *Science of the Total Environment,* 344:159-184.

Walling, D.E., Russell, M.A., Hodgkinson, R.A., and Zhang, Y., (2002). *Catena*, 47:232-353.

Walling, D.E., Owens, P.N., Graham, J. and Leeks, L., (1999). *Hydrological Processes*, 13:955-975

Walling, D.E., and Woodward, J.C., (1992). Erosion and Sediment Transport Monitoring in River Basins; Proceedings of the Oslo Symposium, August 1992; IAHS Publ. no 210, p. 153-165.

Wallbrink, P.J., and Murray, A.S., (1996). *American Journal of the Soil Science Society*, 60:1201-1208.

Wallbrink, P.J., and Murray, A.S., (1993). *Hydrological Processes*, 7:297-304.

Whiting, P.J., Matisoff, G., Fornes, W., and Soster, F.M., (2005). GSA Bulletin, 117:515-529.

Appendix 1. Summary of source apportionment results for suspended sediment samples collected during flow events. Concentrations of ^{210}Pb are corrected for atmospheric contributions summarized in Table 2. Both Cs and Pb concetrations are nomalized to fraction inorganic sediment.

Location	Excess ^{210}Pb (pCi/g)	^{137}Cs (pCi/g)	% from field based on ^{210}Pb	% from field based on ^{137}Cs	
Le Sueur River near outlet at Red Jacket					
3/20/07	0.24	0.00	13%	0%	
3/21/07	0.00	0.01	0%	2%	
3/24/07	0.35	0.07	18%	19%	
3/28/07	0.39	0.07	21%	20%	
4/1/07	-0.05	0.09	-3%	25%	
4/20/07	0.13	0.02	7%	6%	
5/3/07	0.81	0.00	43%	0%	
5/16/07	0.40	0.00	21%	0%	
5/21/07	1.72	0.09	92%	24%	
5/25/07	0.72	0.10	38%	26%	
7/4/07	0.35	0.01	18%	3%	
8/19/07	0.21	0.00	11%	0%	
8/24/07	0.51	0.10	27%	26%	
8/31/07	0.27	0.02	15%	5%	
10/5/07	0.36	0.06	19%	15%	
5/3/08	0.60	0.08	32%	22%	
5/11/08	0.40	0.01	22%	2%	
5/30/08	0.52	0.04	28%	12%	
6/2/08	0.32	0.06	17%	15%	
6/6/08	0.75	0.01	40%	3%	
6/10/08	0.49	0.05	26%	13%	
6/11/09	0.69	0.08	37%	20%	
Average all events using both tracers					**17** (+/- 20) **%**
Le Sueur River above nick point at St. Clair					
3/24/07	0.71	0.01	38%	3%	
3/28/07	0.58	0.08	31%	22%	
8/19/07	0.96	0.01	51%	3%	
8/24/07	0.80	0.21	43%	56%	
8/31/07	0.73	0.01	39%	2%	
10/5/07	0.30	0.04	16%	9%	
6/11/09	0.74	0.08	39%	22%	
Average all events using both tracers					**26** (+/- 21) **%**
Blue Earth River near Outlet					
3/20/07	0.74	0.07	39%	17%	
3/28/07	0.36	0.12	19%	31%	
5/25/07	0.20	0.06	11%	15%	
8/24/07	0.90	0.11	48%	29%	
6/6/08	0.82	0.12	43%	31%	
Average all events using both tracers					**28** (+/- 20) **%**
Watonwan River near Mouth					
3/18/07	1.08	0.09	57%	23%	
3/19/07	0.62	0.06	33%	15%	

3/21/07	0.98	0.15	52%	40%	
3/23/07	0.58	0.01	31%	3%	
3/25/07	0.56	0.01	30%	3%	
3/28/07	1.42	0.09	75%	23%	
4/4/07	0.47	0.11	25%	28%	
4/6/07	1.16	0.33	62%	87%	
4/9/07	1.00	0.12	53%	31%	
4/22/07	0.51	0.05	27%	12%	
5/4/07	1.55	0.06	82%	15%	
5/17/07	1.25	0.11	67%	28%	
6/22/07	1.64	0.19	87%	50%	
8/19/07	1.31	0.07	70%	19%	
8/20/07	0.97	0.09	51%	25%	
8/21/07	1.12	0.11	60%	28%	
9/12/07	1.00	0.06	53%	15%	
8/28/07	1.54	0.13	82%	34%	
10/11/07	0.94	0.18	50%	46%	
10/22/07	0.70	0.09	37%	25%	
10/24/07	0.82	0.22	43%	59%	
10/30/07	1.04	0.08	55%	22%	
5/30/08	1.34	0.25	71%	65%	
6/10/08	0.36	0.09	19%	24%	
Average all events using both tracers					**41** (+/- 30) **%**
Maple River near confluence with LeSueur R.					
8/19/07	0.35	0.01	19%	3%	
8/24/07	0.41	0.09	22%	25%	
10/5/07	0.20	0.01	11%	2%	
5/11/08	-0.01	0.00	0%	0%	
6/11/09	0.39	0.08	21%	22%	
Average all events using both tracers					**12** (+/- 11) **%**
High Island Creek near Mouth					
3/22/07	0.00	0.01	0%	2%	
3/27/07	0.12	0.01	7%	3%	
3/30/07	0.00	0.05	0%	12%	
4/3/07	-0.06	0.07	-3%	19%	
4/19/07	0.56	0.00	30%	0%	
4/27/07	0.83	0.09	44%	25%	
5/11/07	1.12	0.00	60%	0%	
5/23/07	1.24	0.00	66%	0%	
Average all events using both tracers					**17** (+/- 19) **%**
Chippewa River at Hwy 40					
4/19/07	-0.05	0.06	-3%	15%	
3/28/07	0.57	0.15	30%	40%	
3/27/07	0.47	0.00	25%	0%	
4/1/07	0.40	0.13	21%	34%	
4/12/07	1.03	0.14	55%	37%	
Average all events using both tracers					**26** (+/- 22) **%**
Seven Mile Creek at Outlet					
6/18/06	-0.06	0.01	-3%	3%	
3/14/07	0.80	0.06	42%	15%	

Appendix 1 continued

10/08/07	1.28	0.11	68%	29%	
10/18/07	0.54	0.00	29%	0%	
Average all events using both tracers					**22** (+/- 23) **%**
South Fork Crow River (at Delano)					
5/18/07	1.10	0.21	59%	56%	
5/24/07	0.96	0.15	51%	38%	
6/12/08	1.77	0.19	94%	50%	
S. Fork Crow River (at Co.Rd. 9)					
5/24/07	0.79	0.06	42%	15%	
6/12/08	1.80	0.17	96%	44%	
Average all events using both tracers					**55** (+/- 39) **%**
Upper Maple River at Hwy 18					
6/11/09	1.16	0.13	62%	34%	
Cottonwood River at New Ulm					
5/3/07	0.61	0.21	32%	56%	
6/6/08	1.46	0.15	78%	40%	
Buffalo Creek at Co Rd					
6/12/08	2.08	0.29	111%	77%	
Hawk Creek at Granite Falls					
6/4/07	1.02	0.08	54%	22%	
Big Cobb River at Co Rd 16					
10/5/07	0.53	0.02	28%	5%	
Redwood River at Redwood Falls					
5/4/07	1.72	0.09	92%	25%	
6/4/07	1.24	0.19	66%	50%	
Yellow Medicine River at Granite Falls					
5/4/07	-0.25	0.06	-13%	15%	
6/4/07	0.41	0.05	22%	12%	