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**ARTICLE** *in* ENVIRONMENTAL SCIENCE & TECHNOLOGY · AUGUST 2011

Impact Factor: 5.33 · DOI: 10.1021/es2019109 · Source: PubMed



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Environmental Science & Technology

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# Large Shift in Source of Fine Sediment in the Upper Mississippi River

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*Supporting Information*

**ABSTRACT:** Although sediment is a natural constituent of rivers, excess loading to rivers and streams is a leading cause of impairment and biodiversity loss. Remedial actions require identification of the sources and mechanisms of sediment supply. This task is complicated by the scale and complexity of large watersheds as well as changes in climate and land use that alter the drivers of sediment supply. Previous studies in Lake Pepin, a natural lake on the Mississippi River, indicate that sediment supply to the lake has increased 10-fold over the past 150 years. Herein we combine geochemical fingerprinting and a suite of geomorphic change detection techniques with a sediment mass balance for a tributary watershed to demonstrate that, although the sediment loading remains very large, the dominant source of sediment has shifted from agricultural soil erosion to accelerated erosion of stream banks and bluffs, driven by increased river discharge. Such hydrologic amplification of natural erosion processes calls for a new approach to watershed sediment modeling that explicitly accounts for channel and floodplain dynamics that amplify or dampen landscape processes. Further, this finding illustrates a new challenge in remediating nonpoint sediment pollution and indicates that management efforts must expand from soil erosion to factors contributing to increased water runoff.

## INTRODUCTION

Sediment and turbidity are leading causes of impairment in U.S. rivers and streams[1,2] and remedial action requires identification of the sources and mechanisms of sediment supply. Despite extraordinary efforts, sediment remains one of the most difficult non-point-source pollutants to quantify for several reasons.[3−7] Erosion is typically episodic and highly localized. Erosion mechanisms are strongly nonlinear, and their rates are contingent on multiple factors including climate, geology, and land use history.[8,9] Eroded sediment may exit the watershed quickly or be stored for very long periods.[10,11] Finally, the accuracy of current methods for estimating sediment yield from agricultural watersheds has been challenged[4,8,12] because most estimates are based on empirical models of soil erosion and require a scalar reduction factor to estimate sediment yield as a fraction of erosion. Few studies provide evidence to constrain this reduction factor, and available observations indicate diverse and highly nonlinear scaling with drainage area.[7,8]

**Received:** June 4, 2011
**Accepted:** August 31, 2011
**Revised:** August 30, 2011

  

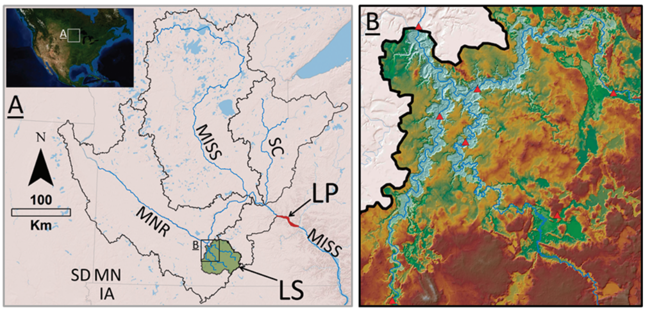


**Figure 1.** Inset A shows the Lake Pepin (LP) watershed within the upper Midwest, composed of the Minnesota (MNR), upper Mississippi (MISS), and St. Croix River (SC) watersheds. Inset B shows lidar topography data for the incised portion of the Le Sueur watershed (LS), including the locations of gaging stations on all three main branches.

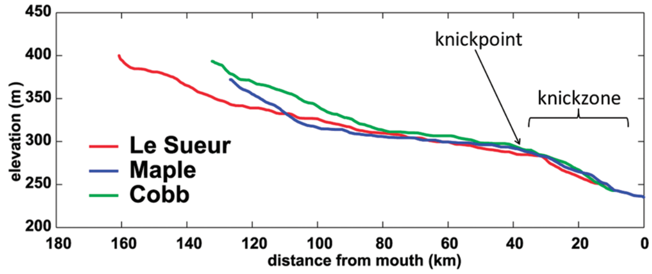


**Figure 2.** Longitudinal profiles of the Le Sueur River (red) and its two main tributaries, the Maple (blue) and Cobb (green) rivers. The locations of the knickpoint, approximately 40 km from the mouth in all three branches, as well as the knickzone, or reach of active incision, are indicated.

Accurate identification of sediment sources and erosion rates are needed to understand and manage the landscape sediment routing system[13] and related biogeochemical processes.[14] The reliability of sediment source estimates can be improved by using multiple, overlapping methods of measurement within the strong constraint of a mass balance, or sediment budget.[15] A sediment budget is a useful tool for evaluating landscape change and sediment yield.[10,16−19] The scope and accuracy of sediment budgets depend strongly on the availability of information for earlier conditions in a watershed. For example, historical information such as photos, maps, and field studies have been used to provide reliable information on previous conditions in order to close a sediment budget over a time period long enough to average over stochastic temporal variability. This approach is strengthened by a suite of new research tools that allow precise dating of land surfaces, geochemical identification of sediment provenance, and high-resolution measurement of topography using airborne and terrestrial lidar.[20,21]

The waters of the Upper Mississippi River (UMR) and its major tributaries have been listed as impaired for turbidity by the U.S. Environmental Protection Agency. Turbidity, eutrophication, and sedimentation have been identified as urgent problems for Lake Pepin, a natural lake on the Mississippi River of exceptional recreational and popular importance (Figure 1). Coring records examining the past 500 years indicate that sedimentation rates in Lake Pepin may have increased by as much as an order of magnitude over the past 150 years.[22] Of the sediment delivered to Lake Pepin, past and present, 80% to 90% derives from the Minnesota River Basin (MRB), despite the fact that the MRB comprises only a third of the drainage area.[22,23] The relatively high sediment yield of the MRB stems from a combination of Quaternary landscape history and human land and water management. Land cover in the basin has shifted from poorly drained tall-grass prairie and wetlands[24] to 78% row crop agriculture[25] over the 150 yr period of increased sedimentation, suggesting that the change in land use underlies the increase.[26]

The 2880 $km^2$ Le Sueur River watershed produces the highest sediment yield (73.5 $Mg/km^2$) of any Minnesota River tributary, accounting for as much as 30% of the Minnesota River sediment load.[26] The Le Sueur landscape is naturally primed for rapid geomorphic change and large sediment supply. The geologic substrate is a 60 m thick package of semiconsolidated, but soft, fine-grained (67% silt and clay, 33% sand, <1% gravel and boulders) tills and glaciofluvial sands.[27] Glacial Lake Agassiz drained catastrophically through the proto-Minnesota River 13,400 years ago, incising the Minnesota River valley up to 70 m near the mouth of the Le Sueur.[28,29] This incision was experienced by the Le Sueur as a drop in local base level causing a knickpoint, or a sharp increase in channel gradient, at the mouth of the Le Sueur. The knickpoint has propagated 40 km up the Le Sueur River network,[30,31] leading to rapid vertical incision (∼5 m/ka) producing valleys with steep river gradients (0.002 m/m), actively eroding bluffs, and ravines. We refer to this expanding, incised reach of the channel network as the knickzone, and the upstream propagating head of the knickzone where the slope discontinuity is observed as the knickpoint (Figure 2).

Prior to settlement, the landscape was dominated by tall-grass prairie and wetlands.[24] Above the knickpoint the channel network was poorly connected with many areas that drained internally to wetlands and ponds within the watershed. Beginning in the 19th century, an expanding network of surface ditches and subsurface conduit has drained the wetlands and uplands, allowing development of agriculture.[32] Beginning in the 1940s, changes in technology and markets led to consolidation of smaller farms into larger operations. These changes are perceived to have initially resulted in more intense and severe agricultural practices, which have more recently evolved into more careful and precise agricultural management.[33] However, little quantitative information has been collected to constrain the magnitude of these effects on historical erosion and sediment delivery. Presently, row crops cover as much as 92% of the uplands in the basin.[25]

The investment required to reduce sediment loading and other nonpoint-source water quality problems is enormous. As an indication, a substantial down payment was made in 2008 when Minnesotans passed a state constitutional amendment that will raise over \$3.5 billion in tax revenue over 25 years for the purpose of protecting and restoring water, wildlife, and cultural resources.[34] Effective use of the portion of these funds dedicated to reducing sediment pollution will require accurate identification of sources and mechanisms of sediment supply. This issue is controversial, particularly in determining the role of historic and contemporary agricultural practice versus natural erosion processes.[35] The stakes are high; management choices will have political, social, and financial implications as well as environmental consequences.

In this study, we combine multiple, independent lines of evidence to evaluate sediment sources to the UMR. We use geochemical fingerprinting from Lake Pepin sediment cores to interpret erosional history at the landscape scale and to record shifts in the proportion of sediment derived from soil erosion vs near-channel sources. For the purposes of this paper we use the term 'soil erosion' to refer to removal of sediment from the vast and relatively flat upland terrestrial surface via sheet wash, shallow gully erosion, and wind erosion. The term 'near-channel erosion' is used to refer to processes of channelized fluvial erosion including incision and undercutting of bluffs, banks, and ravines. We also use a sediment budget for the Le Sueur River, a primary contributor of sediment to the Minnesota River, to identify sediment source location and mechanism. We compare the sediment budget constrained for the time period 2000−2010 with the same averaged over the entire Holocene to provide context for the modern rates under current land use and environmental conditions. The sediment budgets are established for silt and clay (<62 $\mu$m), which is the primary contributor to turbidity and deposition in Lake Pepin. Key to our approach is the use of multiple, redundant sources of information to constrain each component of the budget, including aerial lidar analyses, repeat terrestrial lidar scans, geochemical fingerprinting, radiocarbon and optically stimulated luminescence dating, air photo analyses, field surveys, and extensive water and sediment gaging. Details on methods and development of the sediment budgets are presented in the Supporting Information.

## ■ METHODS

**Sediment Budgets.** The Holocene sediment budget was primarily constrained through analyses of high resolution (1 m) lidar topography data and dating of strath terraces. We hand-digitized polygons of the incised valley and ravines independently. The upper extent of the modern knickzone was defined by the location of discontinuities in log−log plots of local channel gradient versus contributing drainage area for each of the three main tributaries using the Stream Profiler Tool (available for free download from www.geomorphtools.org). Over 600 strath terrace surfaces were mapped from aerial lidar and field surveys. Optically stimulated luminescence and Carbon-14 analyses of terrace alluvium confirmed the timing of initial incision and constrained rates of incision throughout the Holocene. To compute the mass of material in the incised valley and ravines we divided the valley polygons into 3 km sections and assumed a flat surface with an elevation consistent with surrounding topography. Volumes of sediment removed were converted into a mass using a bulk density of 1.8 g/cm$^3$ and 67% silt and clay and were divided by 13,400 years to obtain the long term average rate of mass flux from the knickzone.[29]

Each component of the 2000−2010 sediment budget was constrained using multiple lines of information. Annual sediment loads were computed by the Minnesota Pollution Control Agency for all seven gaging stations in the Le Sueur River basin using US Army Corps of Engineers FLUX program. Flow and sediment data were available for all years (2000−2010) for the gage at the mouth of the watershed. Average 2000−2010 loads were computed for each of the tributary gages based on available data (3−9 years depending on the tributary), with missing tributary data estimated relative to the gage at the mouth of the watershed (see the Supporting Information).

Bluff erosion rates were constrained over a decadal time scale from air photo analyses. A total of 451 bluffs were identified from air photos, and their crests were manually digitized for multiple years between 1938 and 2005. Bluff toe retreat was independently estimated by measuring channel meander migration rate near the toe using the Planform Statistics Tool available online from the National Center for Earth-surface Dynamics Stream Restoration Toolbox (http://www.nced.umn.edu/content/tools-and-data). Additionally, bluff-related sediment sources were constrained by three years of repeat terrestrial laser scanning covering a wide range of hydrologic years including intermediate, dry, and wet years for 2008, 2009, and 2010, respectively. An Optech ILRIS-3$_6$D, ER Terrestrial Lidar Scanner from the Lidar Lab at Western State College of Colorado was used to scan 12 bluffs at resolutions varying from 1700 to 10,000 points per m$^2$. Polyworks metrology software (InnovMetric, Quebec City, Canada) was used to align scans, convert point cloud data to TINs, and digitally remove vegetation. An extensive error analysis was conducted to constrain error due to instrumentation, alignment, TIN creation, erroneous points, and assumptions made differencing scans from multiple years.[36] Volumetric bluff erosion rates were computed as the product of bluff height, length, and retreat rate and converted to mass flux using a bulk density of 1.8 g/cm$^3$ and 67% silt and clay.

Net local bank erosion rates were computed using the method of Lauer and Parker,[37] which computes net, local sediment flux from bank erosion as a function of a measured meander migration rate and the difference in elevation between opposing channel banks. To perform this calculation we used the Planform Statistics Toolbox. Meander migration rates were measured from historic air photo analysis (1938−2005), discretizing the channel every 20 m, and bank elevations were extracted from 1 m aerial lidar (source: Blue Earth County Environmental Services) using a 10 m buffer on each bank. Bank contributions from channel widening were computed by digitizing banks from historic air photos (1937−2009), identified by vegetation line, for multiple years and over 14 reaches, each approximately 10 meander bends in length. Width change was converted to volumetric change by computing average depth from a basin-specific downstream hydraulic geometry relationship and assuming that depth remains constant as the channels widen at the observed rate. Volumetric bank erosion rates were converted to mass flux using a bulk density of 1.5 g/cm$^3$ and 50% silt and clay.

We used airborne lidar to map ravine locations throughout Blue Earth County and compared historical air photos from 1938 and 2005 to identify recent changes in ravine tip locations. Ravine loads were measured using autosamplers to capture storm events for three monitoring seasons on up to four ravines. Loads were extrapolated to other ravines throughout the watershed based on incised area measured from aerial lidar. See the Supporting Information for data and additional explanation of methods.

**Geochemical Fingerprinting.** We conducted sediment fingerprinting[38,39] using naturally occurring radiogenic tracers Beryllium-10 ($^{10}$Be), Lead-210 ($^{210}$Pb), and Cesium-137 ($^{137}$Cs) measured in suspended sediment samples collected at multiple gages within the Le Sueur watershed as well as from Lake Pepin sediment cores. In brief, $^{10}$Be and $^{210}$Pb are produced in the atmosphere, delivered via rainfall and dry deposition, and are adsorbed to the outside of soil particles within the top 150 and 5 cm of the soil profile, respectively.[40,41] Thus, both tracers exhibit relatively high concentrations in sediment eroded from the soil surface and low concentrations in bluff material, which has experienced relatively little exposure to the atmosphere. Cesium-137 was delivered from atmospheric deposition primarily from nuclear testing in the 1950s and 1960s,[41,42] and the concentration is also high in upland soils and low in near-channel (bluff, ravine, bank) sediment.


dx.doi.org/10.1021/es2019109 |Environ. Sci. Technol. XXXX, XXX, 000–000

Because these tracers are radioactive and have very different half-lives (1.4 million yr, 22.3 yr, and 30 yr for $^{10}Be$, $^{210}Pb$, and $^{137}Cs$, respectively) their concentrations change during transport and storage in the channel-floodplain network.[43−46] Specifically, $^{10}Be$ decay is negligible over the time scales in which channel transport and floodplain storage occur. However, some additional $^{10}Be$ is added to sediment during floodplain storage. In contrast, $^{210}Pb$ and $^{137}Cs$ decay over floodplain residence times (assumed to be $10^2-10^3$ yr), and therefore the upland signature of these tracers is diluted to a degree that depends on the rate of channel floodplain exchange. In this way, $^{10}Be$ fingerprinting provides an upper constraint and $^{210}Pb$ and $^{137}Cs$ provide minimum constraints on the percentage of sediment derived from uplands. Determining a unique solution for sediment apportionment based on combined $^{10}Be$, $^{210}Pb$, and $^{137}Cs$ data is not possible at this time for a number of reasons, including number of samples available, insufficient constraints on the variability of atmospheric delivery rates, and the lack of independent constraints on channel-floodplain exchange activity. Therefore, we compute source apportionment for suspended sediment samples based on $^{10}Be$ results using a two end-member unmixing model (bluffs: $[^{10}Be] = 0.07\ (\pm.01) \times 10^8$ atoms $g^{-1}$; uplands: $[^{10}Be] = 2.0\ (\pm.36) \times 10^8$ atoms $g^{-1}$). Suspended sediment samples were also analyzed for $^{210}Pb$ and $^{137}Cs$ by alpha and gamma spectroscopy. We collected a total of 28 suspended sediment samples from the Le Sueur River and tributaries during the 2009 field season. Sample activity for $^{210}Pb$ was corrected for direct deposition, and sediment apportionment for both $^{210}Pb$ and $^{137}Cs$ were computed based on an extensive data set from 30 reference lakes to constrain the upland tracer signature, described in detail by Schottler et al.[47] See the Supporting Information for data and additional explanation of methods. Additional raw data and GIS shapefiles are available from the corresponding author upon request.

## ■ RESULTS AND DISCUSSION

The well-dated incision history and low-gradient postglacial terrain of the Le Sueur watershed[29] allow us to establish an average sediment budget for the Holocene. We used aerial lidar combined with optically stimulated luminescence dating[48] to compute the volume of material excavated from the incised valley and ravines over the Holocene (Figure 3, top panel). Valley excavation produced 60,000 Mg/yr, with 80% from bluff erosion (Bl), bank erosion (Ba), and vertical channel incision (C) and 20% from ravine incision (R). A small amount of deposition (Fp) within the incising valley, equivalent to 5000 Mg/yr, is recorded in strath terraces.[29] Sediment evacuation modeling based on dated terraces suggests that sediment yield was relatively steady over the Holocene.[48] Prior to Euro-American settlement in the early 19th century, sediment supply from the poorly drained, low-gradient uplands of dense perennial grasses and wetlands was assumed negligible relative to that from the incising valley.

We developed a sediment budget for the period 2000−2010 (Figure 3, bottom panel), relying on estimated sediment loads at seven gaging stations, including one at the mouth of the watershed and two on each of the three main branches, with one just upstream from their confluence and the other just above the knickpoint (red triangles in Figure 1). Bluff erosion (Bl) dominates the sediment budget, contributing 26,000 Mg/yr above the knickpoint and 107,000 Mg/yr within the knickzone, with erosion rates more than double the Holocene average.

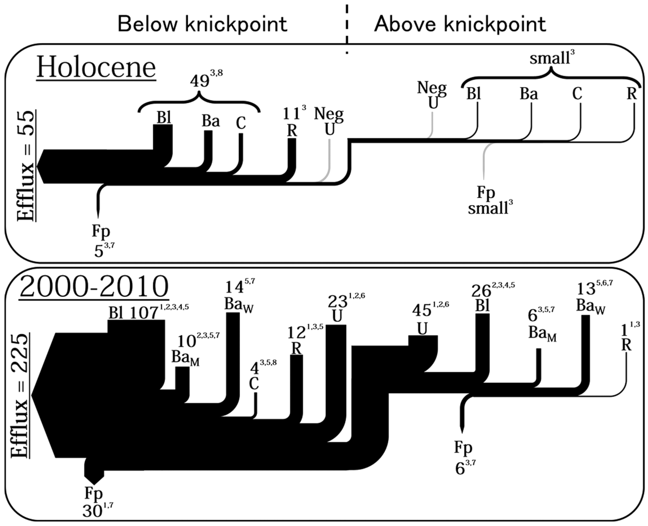


**Figure 3.** Fine sediment budgets (clay + silt) for the Le Sueur River, averaged over Holocene time and over 2000−2010. Values given in $10^3$ Mg/yr. Sediment sources include Bluffs (Bl), Bank erosion resulting from channel migration ($Ba_M$) and widening ($Ba_W$), Channel incision (C), Ravines (R), and Uplands (U). Superscripts indicate methods used to constrain each flux (1: Gaging data, 2: Geochemical tracers, 3: Aerial lidar analysis, 4: Terrestrial lidar scans, 5: Air photo analysis, 6: Numerical modeling, 7: Field surveys, 8: OSL and $^{14}C$ dating).

Ravines comprise only 0.3% of the watershed area but contribute 5% of all sediment, including 1000 Mg/yr above the knickpoint and 12,000 Mg/yr within the knickzone. Based on sediment fingerprinting results, agricultural uplands contribute 45,000 Mg/yr above the knickpoint and add an additional 23,000 Mg/yr within the knick zone. Based on air photo measurements of channel changes since 1938, net bank erosion[37] from meander migration ($Ba_M$) and channel widening ($Ba_W$) contribute 6000 and 13,000 Mg/yr above the knickpoint, respectively, and 10,000 and 14,000 Mg/yr within the knickzone. Channel incision within the knickzone contributes an additional 4000 Mg/yr.

Given the history of agricultural development in the watershed and the legacy of significant valley bottom deposition in areas with a similar history,[10,11] the possibility that the modern sediment budget includes erosion of valley bottom legacy sediment must be carefully considered. Precisely constraining floodplain storage (legacy or otherwise) remains a difficult task in large watersheds. Yet, the importance of floodplain storage should not be understated in development of a watershed sediment budget.[49] In this study, four separate observations, taken together, support the finding that historic and modern floodplain storage is neither large nor changing considerably under current conditions. First and foremost, floodplain storage is expected to be small in incising systems. Within the knickzone, floodplains are relatively narrow[30] and continued, rapid vertical incision limits opportunity for vertical floodplain accretion. Second, we have observed floodplain inundation during multiple events and have mapped small pockets of deposition following a high flow event in September 2010. Specifically, we documented 0−20 cm of localized deposition, typically less than 10% silt and clay, though this grain size fractionation may have been influenced by conditions specific to this event. In any case, our observations indicate that the channel is not unable to access floodplains but also that floodplain storage is not a large number in any part of the channel network. Third, we do not observe large differences in height between eroding and depositing banks above the knickzone, which would otherwise indicate a larger amount of storage having occurred in the past and an ongoing process of net floodplain degradation. Lastly, some overbank deposition occurs behind large woody debris jams above the knickpoint. These debris jams are transient features that appear to form and degrade over annual to decadal time scales. Deposition behind the debris jams appears to be reasonably balanced by bank scour as the channel migrates around the jams. Assuming the frequency and magnitude of these woody debris jams has not changed significantly over recent decades, net sediment storage associated with them has also not changed. While floodplain storage is the least-well constrained number in our modern sediment budget, these observations all suggest that floodplain storage is neither large nor changing significantly from recent decades.

Significant year-to-year variability exists in sediment loading, which translates to variability in contributions from each of the sources. The suspended sediment load for the entire watershed during the driest year (2009) of our monitoring period was a mere 29,000 Mg in contrast to the wettest year (2010), which was 543,000 Mg. Years 2007 and 2008 exhibited intermediate flow, with annual watershed suspended sediment loads of 135,000 and 136,000 Mg, respectively. It was simply fortuitous that the years over which we intensively measured fluxes and erosion rates covered the full spectrum of hydrologic conditions.

Defining uncertainty in sediment budgets is a persistent problem. Budgets are typically assembled using a wide range of information of different types, each with their own uncertainty. These include sediment sources from topographic differencing, sediment flux measured at stream gages, and estimates of the proportion of sediment yield derived from terrestrial vs near-channel sources. Because of the very different nature of these data (sediment supply averaged over large space and time scales, sediment concentration calculated from individual stream samples and extrapolated over time series of flow, and source proportions based on geochemical analyses of individual soil and sediment samples), a formal uncertainty analysis is difficult to define and interpret. Further, the strong constraint of mass balance and the plausible requirement that approximations hold across similar locations and time periods, add certainty to the combined sediment budget that cannot be combined with the uncertainty of individual components in any obvious way.

Despite the lack of a formal uncertainty analysis, plausible conclusions can be drawn by invoking sediment mass conservation over multiple time and space scales. Values for each component of the sediment budget, drawn from a plausible range based on the uncertainty in each component, are subject to the collective constraint of mass conservation. For example, a sediment source may be judged to be minor if even exceptionally large values (within the measured range of uncertainty) do not produce a significant fraction of the overall mass balance. Further, the plausible range of uncertainty in any individual component may be constrained if exceptionally large or small values of that component require implausible combinations of other components in order to balance the budget. In the end, a weight-of-evidence approach, constrained by the use of multiple lines of evidence, is used to support conclusions regarding sediment sources, fluxes, and sinks. Here we have closed our budget for the 2000−2010 time period by applying a single parameter to adjust all predicted source fluxes as a fraction of their respective uncertainty (see the Supporting Information). This approach provides an objective means to balance the budget in a manner that is sensitive to the estimated uncertainty associated with each of the measurements.

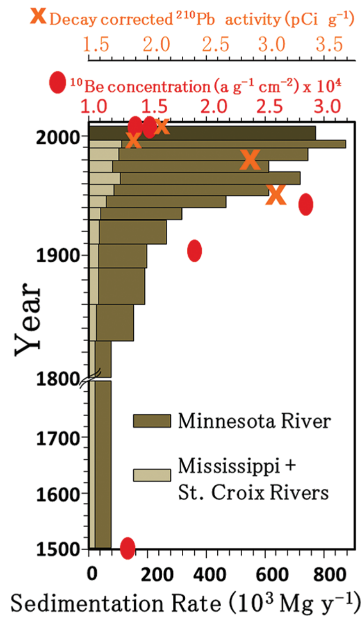


**Figure 4.** Depth profile of Lake Pepin sedimentary record showing sedimentation rate across the entire lake bottom (bottom axis) and concentrations of radionuclide sediment tracers (top axes). Upland soil erosion delivers sediment enriched in both tracers; bluffs and ravines deliver tracer-deficient sediment.

Based on similar topographic history and land use, the sediment supply observed over the past decade on the Le Sueur is likely representative of other tributaries to the Minnesota River, which collectively account for the bulk of sediment contributed to the UMR and Lake Pepin.[23] Sedimentation rates in Lake Pepin (Figure 4) have increased from an apparent 'background' rate of ~80,000 Mg/year prior to 1830 to as high as 850,000 Mg/yr between 1950 and 2008.[22]

We analyzed natural atmospheric fallout nuclides $^{210}$Pb and $^{10}$Be in Lake Pepin sediment cores as tracers that document the relative proportion of fine sediment derived from uplands versus near-channel sources over the past 500 years. Upland sources have high concentrations of both tracers, whereas bluffs and ravines have correspondingly low concentrations ([40,41] see the Supporting Information). Both tracers show similar changes over time (Figure 4, red dots for $^{10}$Be, orange Xs for $^{210}$Pb). The low $^{10}$Be concentration 500 years ago indicates very little upland soil erosion relative to bluff erosion. During the mid-20th century, a sharp increase in $^{10}$Be concentrations indicates a pulse of soil erosion from agricultural fields. In the past three decades, both $^{10}$Be and $^{210}$Pb document a strong shift back toward near-channel sources, consistent with our 2000−2010 sediment budget in the Le Sueur watershed. Because $^{10}$Be and $^{210}$Pb have very different half-lives ($^{210}$Pb 22 years; $^{10}$Be 1.4 million years), the decrease in both nuclide concentrations indicates a real decrease in field sources relative to bluffs and ravines, rather than recent activation of legacy field sediment stored in the valley bottom, which would be depleted in $^{210}$Pb, but not $^{10}$Be. Additionally, measured concentrations from source areas confirm that $^{10}$Be concentration in upland soils remains high and therefore the decrease in $^{10}$Be concentration is not related to prior erosion of nuclide-rich soil, which has been documented in


dx.doi.org/10.1021/es2019109 |Environ. Sci. Technol. XXXX, XXX, 000–000

parts of the Chesapeake Bay watershed.[50] A $^{210}Pb$ apportionment model[47] indicates that the proportion of sediment derived from fields was high in the 1940s-1960s (3.2 pCi $g^{-1}$ ~ 65% field source), remained relatively high through the 1980s (59% field), and then decreased by the mid-1990s (32% to 35% field).

Erosion rates of near-channel sources (particularly bluff and streambanks) are sensitive to changes in river discharge. Two recent hydrologic changes, both related to human activity, may be acting to increase discharge and amplify erosion of near-channel sources. First, climate records indicate that mean precipitation has increased in Minnesota, along with an increase in the frequency and magnitude of extreme events.[51,52] Climate models predict a continued upward trend in the 21st century across the midwestern U.S., primarily in the form of more frequent heavy rains.[53] A second important driver is the extensive modification of the channel network with agricultural ditches (25% of the modern network) and subsurface tile drains, particularly over the past 30−40 years.[54] These modifications have increased both the effective drainage area and the efficiency of drainage. Additionally, tile drains are likely increasing infiltration capacity and thereby reducing surface runoff, which would reduce fluvial soil erosion at the expense of increasing flow in the river, consistent with the apparent decrease in upland soil delivery and increase in near-channel erosion observed over the past few decades. However, at present we are unable to deconvolve the influence of tile drains from other land use and climatic factors that are also contributing to changes in hydrology.

The Lake Pepin sediment cores indicate that the rate of sedimentation in the past decade has remained large, even as the sediment supply has shifted from upland to near-channel sources (Figure 4). The Le Sueur 2000−2010 sediment budget (Figure 3, bottom panel) corroborates a dominant near-channel source of recent sediment supply. The combination of Holocene and modern sediment budgets and geochemical fingerprinting of Lake Pepin sediment cores provide strong evidence that the dominant source of persistent large sediment loads has shifted from agricultural soil erosion to amplified near-channel erosion, driven by a combination of changing precipitation and a vastly altered drainage network.

Our results indicate that 70% of sediment contributed to the Le Sueur River during 2000−2010 is derived from the channel network (bluffs, banks, ravines, and channel incision), which comprises less than 1% of the landscape. This finding underscores the need for development of combined watershed erosion and sediment routing models that account for channel adjustments and changes in channel-floodplain storage in response to changes in flow and the amount and type of sediment supply. Such models are imperative for understanding sediment as a water quality metric, especially under nonstationary climate conditions, and for predicting the effectiveness of remedial actions. Such models will be strengthened by increasing availability of high resolution topography data that includes channel bathymetry, providing opportunities for development of 2D and 3D models of flow, erosion, and deposition. Incorporating theory for production and decay of radiogenic tracers associated with the sediment would provide a platform for hypothesis testing and model validation that would allow us to move beyond conventional empirical approaches for prediction of watershed sediment yield.

The research, management, and policy challenges posed by these findings are imposing: both the source and driving mechanism of elevated sediment loads are changing. Effective remediation must now accommodate both erosion and runoff controls. Land and water resource management must develop watershed-scale solutions to mitigate systemic hydrologic amplification of natural erosion processes.

## ASSOCIATED CONTENT

**Supporting Information.** All supporting data used to constrain the Holocene and 2000−2010 sediment budgets, including synthesis of sediment excavation over Holocene time, a summary of modern sediment gaging data on main channels and ravines, air photo analysis of channel widening and channel migration, explanation of sediment fingerprinting sample processing and results, and summary data for air photo and repeat terrestrial lidar analysis of bluff erosion. This material is available free of charge via the Internet at http://pubs.acs.org.

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## ACKNOWLEDGMENT

This work was funded by the National Center for Earth-surface Dynamics NSF EAR 0120914, Minnesota Pollution Control Agency, and Minnesota Department of Agriculture. Additional support was provided by the Utah State University Agricultural Experiment Station (paper #8288), the University of Minnesota Limnological Research Center, and Minnesota Supercomputing Institute. Aerial lidar data were provided by the Environmental Services Department of Blue Earth County, Minnesota. J.K.W. thanks the Alexander von Humboldt foundation for a postdoctoral fellowship. We also thank three anonymous reviewers for constructive comments on the manuscript and Julia Marquard, Noah Finnegan, Caitlyn Echterling, Jenny Graves, Khalif Maalim, Luam Azmera, Ashley Thomas, Bridget Wolfe, Mandy Kinnick, and James Ley for their assistance on the project.

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