Collaborative for Sediment Source Reduction: Greater Blue Earth River Basin – Sediment Budget for Greater Blue Earth Basin

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The Collaborative for Sediment Source Reduction (CSSR) project was funded by a series of four grants, each covering a different aspect of the entire project. The primary goal of CSSR was "*To identify a consensus strategy for reducing sediment loading in the Greater Blue Earth watershed using a decision framework that incorporates the best available scientific information, accounts for uncertainty, and provides a model for decision making throughout the Minnesota River Basin*". This report only covers objectives 3 and 4 funded by the Minnesota Department of Agriculture grant. These objectives focused on developing a full sediment budget for the Greater Blue Earth River watershed (objective 3) and assembling information on management options, costs, and efficiencies to support the decision analysis model. A full report will be made available upon completion of the entire project in fall 2016.

This report is submitted on behalf of the entire CSSR research group:

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CLEAN WATER LAND & LEGACY AMENDMENT

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Objective 3: Develop sediment budget for the GBE watershed

This goal of this objective was to extend a sediment budget compiled in the Le Sueur watershed to the entire Greater Blue Earth River (GBER) watershed. The sediment budget was developed for fine sediment only (silt and clay) on an annual timescale for modern conditions and pre-settlement conditions. Below we describe the basic framework for the sediment budget; methods used to inventory sediment sources, measure and extrapolate erosion rates, incorporate sediment sinks, and compile the final sediment budget; and then present the budget results. All input files are available as ArcGIS shapefiles and will be included with this report. The sediment budget is in an attached Excel spreadsheet. This sediment budget was used in the construction of a decision analysis model known as MOSM (Management Options Simulation Model). Much of the work here was conducted by Martin Bevis, as part of his Master's degree at the University of Minnesota Duluth. The text presented here on the modern sediment budget is revised directly from his thesis (Bevis, 2015), and the reader is directed there for more details on the modern sediment budget in the GBER watershed (Bevis, 2015; http://hdl.handle.net/11299/170661).

Background

Fundamentally, a sediment budget is based on the mass-balance relationship that sediment inputs to a channel must equal sediment outputs, minus any change in storage. The GBER watershed sediment budget builds off of the sediment budget created for the Le Sueur watershed as part of an MPCA-funded project (Gran et al., 2011; Belmont et al., 2011). Work on the Le Sueur River watershed measured erosion and sediment delivery rates from four primary sediment sources. The project converted total sediment load to fine sediment load in order to compare estimated loads against total suspended solids (TSS) loads determined from measurements at gauging stations (Gran et al., 2011; Belmont et al., 2011). Estimated sediment load supplied from bluffs, streambanks, ravines and uplands coupled with deposition in floodplains matched the measured Le Sueur River TSS load for 2000-2010 within 5% (Belmont et al., 2011).

The budget we developed for the GBER watershed takes the same general form as the Le Sueur watershed budget, but includes the potential for sediment to be deposited in lakes, too. Equation 1 captures the basic form of the GBER sediment budget, giving the predicted sediment load, Q_s, as

$$Q_s = Bl + Ba + R + U - Fp - L \qquad (1)$$

where *Bl* is sediment eroded from bluffs, *Ba* is sediment eroded from banks, *R* is sediment eroded from ravines, *U* is net sediment from uplands, and the two sinks, *Fp* and *L*, refer to the sediment mass deposited in floodplains (*Fp*) and in lakes (*L*). Additional sediment sources are assumed to be minor compared to these four sources and are not explicitly considered in the budget. Such sources include sediment from landscape disturbances like fire, urban runoff, construction, road contributions and aeolian deposition.

Components of the budget

Bluffs

Bluffs are the source of about half the suspended sediment in the Le Sueur River (Belmont et al, 2011; Day et al., 2013). Bluffs here are defined as steep features lining the river channel that exceed the height of a typical bank. In contrast to banks, bluffs are out of reach of typical annual floods and are purely erosional features. Bluffs can be impressive features: the largest have nearly vertical faces up to 70m high and 500m long, and they line about 50% of the channels in the lower reaches of GBER watershed valleys. Bluffs are most often composed of glacial till, although bluffs in former glacial Lake Minnesota deposits are topped by several meters of glaciolacustrine silts and clays, and bluffs on strath terraces are generally capped with 2-3 m of alluvial sediment (Day et al., 2013). Till layers may contain interbedded glaciofluvial sand and gravel deposits. Some bluffs near the mouth of the Blue Earth and Le Sueur Rivers are composed of Paleozoic bedrock.

Streambanks

Banks are the boundaries of channel networks that are low enough for the river to overtop them during floods. Net sediment loading from banks differs depending on the geomorphic regime. Channels in the GBER watershed are divided by knickpoints into two fundamentally different systems. Above the glacial River Warren-induced knickpoints is a landscape that channel incision has not yet reached. Here, channels are in a state of dynamic equilibrium with the surrounding landscape. These channels may be widening and adjusting to changes in discharge, like Elm and Center Creeks (Lenhart et al, 2011b), but any incision is slow relative to downstream reaches where incision is driven by adjustment to base level fall. In channels that are not incising, bank erosion on the outside of most meander bends can be balanced by deposition on the floodplain, making net sediment flux associated with migration in the reach zero (Lauer and Parker, 2008). Banks above the knickpoint are primarily alluvial in nature, composed of reworked floodplain sediment although there are some places where channels are cutting into till.

Below the knickpoints, channels in the GBER watershed are incising rapidly (Gran et al, 2009; 2013). This has implications for the erosion and deposition in the channel. First, channel incision itself becomes a sediment source. In addition, because the river is downcutting through the landscape below the knickpoints, meander migration is not balanced by floodplain deposition. Incision deepens the channels to the point that floodwaters are not able to access the floodplain, and sediment is transported downstream rather than deposited back onto floodplains.

Channel widening is a further source of channel-derived sediment that has recently become important. Flows have increased in many Minnesota agricultural watersheds in the last-half century (Lins and Slack, 1999; Novotny and Stefan, 2007; Lenhart et al., 2011a; Schottler et al., 2013; Zhang and Schilling, 2006). When annual discharges increase, channels may widen, deepen, straighten or steepen to accommodate higher discharge rates. Minnesota River tributaries have widened substantially to accommodate increased annual discharge from the mid-1900s to the present (Schottler et al., 2013; Lenhart et al. 2011b).

Ravines

Ravines are steep, deep, incised gullies at the tips of the channel network. Ravines connect the uplands to the river valleys, and are usually formed by ephemeral streams with seasonal discharge. Such sites in the GBER watershed display a diverse array of sizes and relief. Erosion in ravines proceeds by a combination of fluvial and hillslope processes. Channel incision and migration leads to oversteepened slopes and mass wasting. Ravines are narrow and deep, and there are often bluffs in ravines. Seeps may occur on steep or near-vertical slopes.

Ravine discharges and sediment loads in the GBER watershed are highly variable. Some ravines connect directly to the channel network, and some discharge onto terraces. When ravines discharge onto terraces, whatever sediment load they carry is dropped as steep ravine slopes transition to nearly flat terrace tops. Ravine discharges also vary seasonally. Since most of the discharge in a ravine comes from the upland above it, flow depends on seasonal variation in precipitation, infiltration and evapotranspiration. Ravines are most active in the spring, when the upland landscape has little or no crop cover and may quickly route precipitation to ravines. Ravines often dry up in mid-summer when crop evapotranspiration is highest and precipitation is low.

Sediment from ravines is a small fraction of the Le Sueur budget, even though they can have very high sediment load concentrations and can locally add a lot of sediment to the system. In dry years ravines were responsible for as little as 2% of the Le Sueur sediment budget (Gran et al., 2011). In the wettest year monitored, ravines were responsible for as much as 15% of the Le Sueur sediment yield.

Uplands

Ove eighty percent of the GBER watershed is composed of low-gradient upland areas in primarily row-crop agriculture. Upland-derived sediment is eroded by wind, precipitation impact, overland flow and concentrated flow in rills and gullies in addition to erosion within the ubiquitous ditch networks. Agricultural uplands in the GBER watershed have low sediment delivery ratios; that is; they deliver just a fraction of eroded soil to channel networks (Quade, 2000; Lenhart, 2008; MPCA et al., 2009). In many watersheds, 5-10 times the amount of upland-sourced sediment that reaches the watershed outlet is stored on fields before it ever reaches a channel (Walling, 1983; Beach 1994; DeVente et al., 2007). A study on the Blue Earth River tributaries Elm and Center Creeks found just 8-13% of eroded field sediment reached the Blue Earth River (Lenhart et al., 2011b). Given the complexity of erosion, in-field deposition, and ditch maintenance, the "upland" term in the sediment budget is a net term that includes both upland erosion and deposition. This approach differs slightly from the MOSM model, in which field erosion rates are calculated directly from RUSLE and then reduced via a sediment delivery ratio.

Storage

Storage on floodplains and in lakes can further decrease the amount of the total eroded sediment that reaches watershed outlets (Trimble, 1999; Verstaeten and Poesen, 2000). Storage estimates in the original Le Sueur budget included an estimate of sediment storage on floodplains. The GBER watershed budget presented here adds estimates of sediment storage in lakes. Previous observation of sediment yields above and below lakes on Elm Creek (a tributary joining the Blue Earth near Winnebago) found that 90% or more of sediment entering a lake is trapped there (Lenhart et al., 2009). Although there are isolated incidents of increased turbidity downstream of lakes with carp present (personal communication, J. Finlay), it is not known how widespread this phenomenon is and thus this process is not included in the sediment budget. Here, we have treated lakes as sinks, and have expanded the budget to include storage in lakes, mediated by a site-specific trapping efficiency. Most of the sediment trapped in lakes was likely generated from upland erosional processes, as most of the lakes with high trapping efficiencies are located high in the watersheds.

Methods

Subwatershed delineations and gauging network

The GBER watershed sediment budget was compiled as a series of three budgets for the Watonwan, Blue Earth, and Le Sueur Rivers. Characteristics of each major HUC-8 watershed are given in Table 1. The Le Sueur basin was further subdivided into the Le Sueur, Cobb, and Maple; and the upper Blue Earth was divided into two branches: Elm Creek and the upper Blue Earth subbasin. Other subdivisions were based on geomorphic regime, separating out areas above, within, and below the knickzone (Figure 1). Where possible, these divisions were made at the location of stream gauges, so that budget predictions of sediment load could be compared with TSS loads determined by the Minnesota Pollution Control Agency (MPCA) and their partners. By separating out subwatersheds based on geomorphic regime, we also ensure that bluff erosion rates, in particular, are only extrapolated to sources in similar geomorphic settings.

***Table 1:** Characteristics of GBER watersheds*

	Watonwan	Blue Earth	Le Sueur
knickpoint distance upstream (km)	35	64	35-40
area (km^2)	2,262	4,054	2,878
discharge (mean annual cfs, 1941-2015) [a]	400	1133	590
discharge (mean annual cms, 1941-2015) [a]	11.3	32.1	16.7
annual runoff, in/yr	6.2	9.8	7.2
Annual runoff, mm/yr	158	250	183
Land Use			
percent of landscape in row crops [b]	86	85	82
depressional areas lost, % of watershed area [c]	na	17	18
percent of watershed likely tiled [c]	46	46	47
percent of channels ditched [c]	8	28	23
Lakes			
area lakes (km^2) [d]	31.2	49	66.8
number of lakes	463	737	408
lake area as percent of watershed area	1.4	1.2	2.3

sources: a) USGS (waterdata.usgs.gov); Watonwan is missing annual Q data between 1946-1976; b) Fry et al., 2011; c) Schottler, 2012; d) McKay et al., 2013. Table modified from Bevis (2015)

Estimated sediment budgets on the Le Sueur River are well constrained by a group of seven gauges (Table 2). TSS loads on the Blue Earth and Watonwan Rivers were monitored by a single long-term gauge near the mouth on each river (Figure 1, Table 2). Additional upstream gages exist, but the record of TSS load data was too short to be used in the current sediment budget. The main gauge on the Blue Earth is located just downstream from Rapidan Dam. Downstream of Rapidan, the Blue Earth River has incised into the Paleozoic bedrock (Prk) and flows in a narrow, deep valley. The knickzone on the Blue Earth extends upstream from this gauge approximately to the town of Vernon Center. We consider this reach to be below the knickpoint. We further subdivided the area of the Blue Earth basin above the knickpoint at the town of Winnebago, in part because the knickpoint on the Blue Earth River is more diffuse and this part of the channel is different compared to the far upstream reaches. Because of the existing body of work on Elm Creek (Lenhart, 2005; Lenhart et al., 2009; 2011), we separated out calculations for Elm Creek in our sediment budget.

On the Watonwan, the Garden City (GC) gauge is fortuitously located near the knickpoint. The knickzone portion of the Watonwan is relatively short, and is captured by the gauge at Rapidan on the Blue Earth River. MPCA-published loads for the Blue Earth are determined by subtracting the load at the GC gauge from the load at Rapidan and thus loads at Rapidan include sediment from the knickzone of the Watonwan. The Blue Earth reach below the Rapidan gauge is ungauged, as is the reach of the Le Sueur below the gauge at Red Jacket Park (RJP).

Table 2: *Gage locations in Greater Blue Earth River basin with Q and TSS annual loads available*

Gage #	Gage Description	TSS annual loads available	Lat	Long
30092001 (05320000)	Blue Earth at Rapidan	2000-2013	44.095556	-94.109167
31051001 (05319500)	Watonwan at Garden City	2000-2013	44.046389	-94.195278
32077002* (05320500)	Le Sueur near Rapidan/Red Jacket	2000-2013	44.109722	-94.041667
32076001	Le Sueur at County Road 8	2006-2013	44.084694	-93.98875
32079001**	Le Sueur at St. Clair	2007-2012	44.083056	-93.854722
32062001	Maple at County Road 18	2006-2013	43.93500	-94.070833
32072001	Maple at CSAH 35	2003-2013		
32071001	Big Cobb at County Road 16	2006-2013	44.04725	-94.000611
32069001** (05320270)	Little Cobb	2000-2012	43.996667	-93.908333
	Additional gages with Q and TSS not used in budget due to limited records			
30025001 (05318270)	Blue Earth at Winnebago	2013	43.769417	-94.19525
31028001	Watonwan at La Salle	2013***	44.05675	-94.503722

**Gage (3207701) moved upstream following major flood*

***Decommissioned in 2012; St. Clair gage was reinstated in 2015.*

**** TSS samples and Q measurements are also available for 2000-2002, but not QA/QC'd TSS loads*

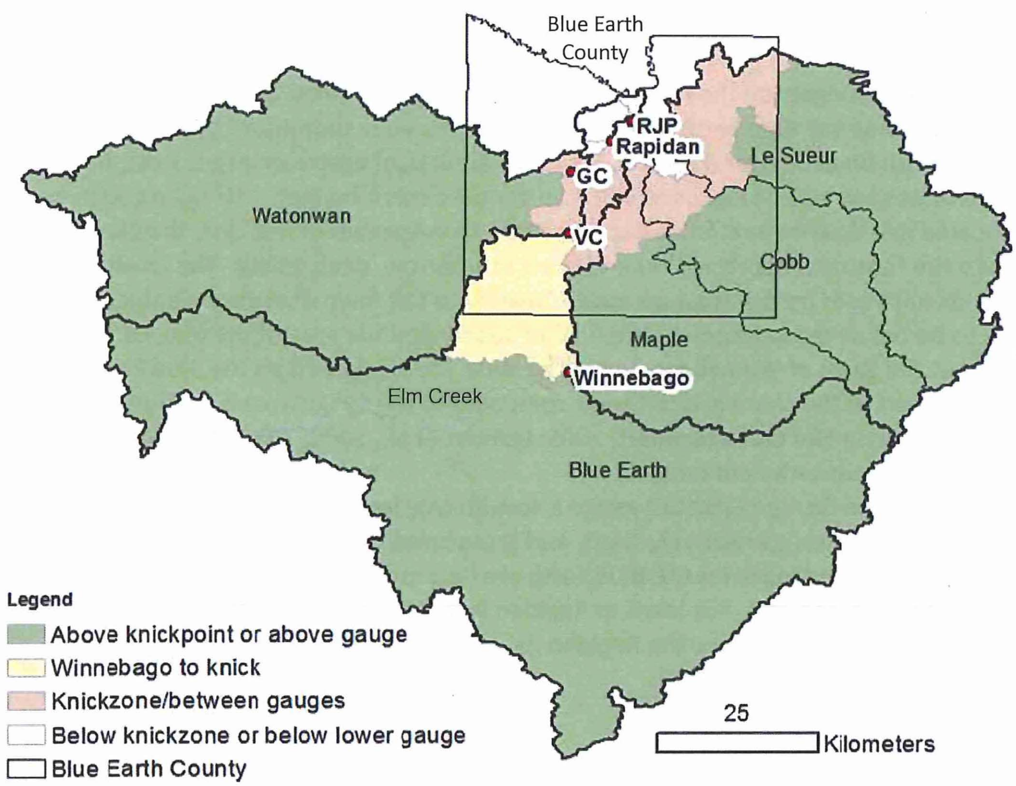

Figure 1: *Subwatersheds based on geomorphic domain in the GBER watershed. Abbreviations for locations referenced in the text are: RJP: Red Jacket Park, GC: Garden City, VC: Vernon Center. Knickpoints are located at boundary of pink and green subwatersheds. Figure from Bevis (2015).*

Sediment source delineations and erosion rate measurements:

Bluffs

The basic procedure to calculate suspended sediment load eroded from bluffs was to 1) define and measure bluff extents, 2) measure erosion rates where possible, 3) extrapolate measured rates to bluffs on which rates were not measured within a subwatershed, and 4) calculate volume and mass of fine sediment eroded. Because bluffs were the dominant contributor of fine-grained sediment in the Le Sueur budget (Belmont et al., 2011), extra care was taken to evaluate different methods for interpolating and extrapolating measured bluff retreat rates to those bluffs that were not measured directly (see Bevis (2015) for more detail).

To define bluffs in the GBER watershed, lidar-derived three-meter-resolution DEMs from 2005 for Blue Earth County, 2012 for other Minnesota counties, and 2008-2011 in Iowa were used to delineate bluffs. DEMs were obtained from the University of Iowa GIS library and the Minnesota geospatial information office. Vertical accuracy of these DEMs is typically about 15 cm. From a DEM of the basin, features with more than three meters of relief in a nine-by-nine meter square were selected. Following the automated delineation procedure, the bluff inventory was cleaned up to leave only bluffs directly adjacent to channels. Off-channel bluffs were removed by applying a buffer around the active channel. This step removed features that were not within 100m of channels larger than Strahler stream order 3 or within 30m of channels of stream order 3 or lower. A buffer was then used to exclude features for which no part was within 30m of manually-traced channel centerlines. Bluffs along ditches (as defined in the United States Geological Survey National Hydrography Database) were also excluded. Any remaining bluffs not adjacent to a mainstem channel were removed manually. Digitized Minnesota Geological Survey (MGS) data were used to identify bluffs in the watershed composed of bedrock, primarily Oneota Dolomite and St. Peter Sandstone (Steenberg, 2012). Although these bedrock bluffs were not removed from the inventory, they were identified so that users of the sediment budget could choose to include them or not.

Bluff attributes were measured from 1m LiDAR-derived data including bluff surface area, height and length. Bluff surface area was used to calculate the annual volume of material eroded from bluffs, in keeping with precedent set in previous studies in the basin (Sekeley et al., 2002; Belmont et al., 2011; Day et al., 2013). Bluff stratigraphy, vegetation cover, and bluff material properties were collected from geologic maps and aerial photographs. Surficial geology maps were used in ArcGIS to identify bluffs containing Quaternary alluvium (Jennings, 2010; Jennings et al., 2012). Pleistocene alluvium in the GBER watershed was deposited by meltwater from the final retreat of the Des Moines lobe of the Laurentide ice sheet, and primarily occurs as outwash channels, tunnel valleys, outwash fans, and deltas. The occurrence of Pleistocene alluvium varies systematically across the GBER watershed; it is most common in the northwest and least common in the southeast (Jennings et al., 2012). Holocene alluvium caps terraces formed by the incision of channels in response to late-Pleistocene base level fall (Gran et al., 2009). Terraces are most common in the lower reaches where incision is greatest. We gave these Quaternary alluvial units special consideration when converting volume of sediment eroded to mass because they are the thickest, most widespread alluvial units in the GBER watershed. These units are on average 3m thick in the GBER watershed (Meyer and Lively, 2012).

Bluff crest and toe migration rates were calculated by measuring the difference in location between a feature traced on aerial photos from 1938/9 and 2008. Georeferenced aerial photographs from 1938, 1939 and 2008 were used throughout this project. The 1938/9 airphotos were downloaded from the University of Minnesota Borchert Library website and georeferenced by hand in ArcGIS using a first-order polynomial transformation. At least eight control points were used for each photo, placed on building corners, or roads and property lines if buildings were not available, with points as close to the channels as possible. Of the recent photographs available at the outset of this project, the National

Aerial Imaging Program (NAIP) aerial photos from 2008 best suited the needs of this work. This year was chosen over newer photographs because the sun was at a higher angle in the 2008 photos and discharge was within channel banks. Shadows and floodwaters make bank and bluff delineation difficult or inaccurate.

Bluff erosion rates were measured over the longest timescale possible with the photographs available. Retreat rates measured over shorter timeframes are overwhelmed by georeferencing and tracing errors (Day et al., 2013; Belmont et al., 2011). Bluff crest retreat rates were measured wherever it was possible in the watershed. Rate measurements require good resolution of bluff features on aerial photos from both times. It was easier to see bluff crests and toes on large bluffs with sparse vegetation, so our measurements may be biased towards bare bluffs close to the mouth of the watershed.

Toe and crest retreat distances were combined with the time between photos to calculate a long-term average bluff erosion rate for each bluff with measurement of both retreat distances. To do so, we created a conceptual model of how bluff crests and toes retreat over time, then substituted the measured distances into the expression to calculate erosion rates for individual bluffs. We conceptualized bluff erosion occurring in two different ways, discriminating between times when a channel migrates toward and away from a bluff. When a river migrates away from a bluff, only the bluff crest will retreat (Figure 2). In this case, we model the volume of bluff sediment eroded as a triangular prism (Equation 2).

$$V_{E(away)} = CRR/2 * h * l \qquad (2)$$

where, $V_{E(away)}$ is volume of bluff sediment eroded, CRR is crest retreat rate, h is bluff height, and l is the length of the modeled bluff.

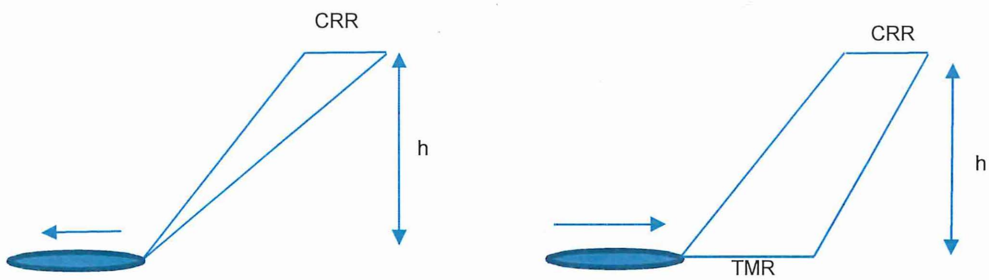

Figure 2: *Schematic cross sections of eroding bluffs. When a channel is migrating away from a bluff, erosion volume is modeled as a triangle. The crest may retreat, but the toe is pinned. When a channel is migrating toward a bluff, erosion volume is modeled as a trapezoid. The crest and toe may both retreat at different rates. CRR is the crest retreat rate, TMR is the Toe migration rate and h is the height of the bluff. Figure from Bevis (2015).*

Because the volume eroded is the erosion rate multiplied by bluff surface area, Equation 3 describes the erosion rate when the river is migrating away from a bluff (E_{away}) as:

$$E_{away} = CRR/2 \qquad (3)$$

When a channel migrates towards a bluff, the base of the bluff may retreat as well as the crest. This situation can be modeled like a trapezoid, where:

$$V_{Etoward} = (CRR+TMR)/2*h*l \qquad (4)$$

and

$$E_{toward} = (CRR+TMR)/2 \qquad (5)$$

To combine Equations 3 and 5 into an average bluff retreat rate, we assume the river spends equal amounts of time migrating into and away from a bluff over long timescales, so the long-term erosion rate, E is taken as:

$$E = E_{away}/2 + E_{toward}/2 \quad (6)$$

Substituting Equations 3 and 5 into 6 and simplifying gives:

$$E = (2CRR + TMR)/4 \quad (7)$$

And thus, the volume eroded (V_E) from one bluff with measured crest and toe retreat rates is

$$V_E = SA*(2CRR + TMR)/4 \quad (8)$$

or

$$V_E = SA*E. \quad (9)$$

Measured bluff erosion rates are applied to bluffs on which it was not possible to measure crest and toe retreat distances via interpolation and extrapolation. To interpolate erosion rates, we used locally-measured bluff erosion rates. The ArcGIS tool *focal statistics* was used to measure the surface area (SA) and volume eroded (V_E) for all bluffs within a 3 km radius of each bluff with measured E (Equation 10).

$$E_{interpolate} = \Sigma V_E/\Sigma SA \quad (10)$$

For bluffs that are too far away from bluffs with measured E, rates were extrapolated based on the measured subwatershed E rate.

We measured erosion rates on just 408 of the nearly 3,500 bluffs in the final GBER budget. This small number of bluffs accounts for about 1/3 of the surface area of bluffs and about 40% of the annual volume of sediment eroded from bluffs in the GBER watershed. More bluffs, and a larger proportion of bluffs, were measured in the Le Sueur watershed than the Blue Earth or Watonwan. Of the bluffs on which we were not able to measure erosion rates, about 700 were within 3 km of measured bluffs, which makes up about 1/3 of the surface area and accounts for 40% of the annual volume of sediment eroded. The final group of bluffs contains extrapolation bluffs, which are greater than 3 km from bluffs with measured rates. About 2/3 of the bluffs were in this group by count, but they are responsible for only 20% of the annual volume of sediment eroded from bluffs in the watershed. Extrapolation bluffs account for the final 1/3 of bluff surface area.

To calculate the volume of sediment eroded from a bluff, the erosion rate (measured, interpolated, or extrapolated) was multiplied by bluff surface area. The volume of sediment eroded was converted to mass of silt and clay-size sediment (i.e., that which becomes suspended sediment) based on sediment bulk density and texture of till, outwash and Holocene alluvium (Table 3).

Table 3: *Sediment texture and bulk density data*

	bulk density	percent fines*	mass mud/volume sediment
Till	1.8 Mg/m^3	0.65	1.17 Mg mud/m^3 till
Holocene alluvium (Hal)	1.3 Mg/m^3	0.5	0.65 Mg mud/m^3 Hal
Pleistocene alluvium (Pal)	1.3 Mg/m^3	0.31	0.40 Mg mud/m^3 Pal

*silt and clay. Bulk density from Thoma et al., 2005; textures from Jennings, 2010 and Belmont et al., 2011.
Table from Bevis (2015).

Bluffs capped by Quaternary alluvium had a portion of their thickness treated as alluvium in terms of bulk density and texture and the rest was considered to be till. Surficial units in the GBER watershed were identified in ArcGIS using surficial geology maps of Blue Earth County and the middle Minnesota River watershed (Jennings, 2010; Jennings et al., 2012). These maps were constructed from 1:90,000 and 1:250,000 aerial photos. Alluvial units selected included surficial and shallowly-buried sediments from streams, fans, deltas and beaches, which are Pleistocene alluvium; and terrace deposits, which are Holocene alluvium. Sand depth was determined using data from the sand distribution model in the Blue Earth County geologic atlas (Meyer and Lively, 2012). We averaged the sand depth of the units selected above, and applied this mean depth (3m) to surficial sand units throughout the GBER watershed. Where Quaternary alluvium was mapped on bluffs, we altered the bulk density and texture of a three-meter-high band of bluff sediment in our calculations according to published sediment density and texture in the GBER watershed (Table 3).

Vegetation can play a role in stabilizing river banks (e.g. Hupp and Simon, 1991; Millar, 2000; Erskine et al., 2012; Lenhart et al., 2013; Gurnell, 2013), but bluffs in the GBER watershed are generally too tall for root strength to influence erosional processes near the toe. Inactive bluffs may have significant vegetative cover on their slopes, however, but it is more a sign of recent inactivity than a predictor of future stability. Day et al. (2013) found no correlation between modern (2005) vegetation cover and long-term decadal-scale bluff retreat rates from 1938-2005 on bluffs lining the Le Sueur River. There is the potential for bias, however, towards measurement of bluff retreat rates on unvegetated bluffs as they are easier to delineate. To account for this possibility, vegetative cover was noted on all bluffs where it could be determined from recent aerial photographs, and a method was developed for determining differential erosion rates for vegetated vs. unvegetated bluffs within a given subwatershed. The methodology for this is covered in detail in Appendix 2 of Bevis (2015). The sediment budget spreadsheet was constructed with a function that allows the user to extrapolate bluff retreat rates considering vegetation cover.

Banks

Sediment supply from stream banks was split into three components: 1) bank sediment derived from meander migration, 2) sediment derived from channel widening, and 3) sediment sourced from channel incision. Sediment supply rate from meander migration was determined using the method of Lauer and Parker (2008). The method is based on the assumption that on a stream in dynamic equilibrium, cutbank erosion is balanced by floodplain deposition. If a channel is incising, it is reflected in the difference in elevation between the eroding and depositing banks. Sediment export due to meander migration on incising channels is therefore equal to the volume of sediment eroded on the part of the cutbank that is higher than the opposite bank. The ArcGIS plugin *Planform Statistics* was used to determine channel migration rate from 1938 to 2008 on the Blue Earth and Watonwan Rivers (Lauer and Parker, 2008), following the same procedure used on the Le Sueur River (Belmont et al., 2011). Channel banks were traced on 2008 and 1938/9 aerial photographs extending as far upstream as possible. Traced channels adjacent to bluffs were not considered as they are part of the bluff portion of the sediment budget. From traced banklines, *Planform Statistics* interpolates a channel centerline based on nodes spaced every 20m. The tool then compares the 1938 and 2008 centerlines in order to calculate mean annual migration rate at each node. *Planform Statistics* was also used to create 5m buffers outside of the banklines. The tool splits the buffers into boxes with lines normal to the channel centerline at each node. The *zonal statistics as table* tool in ArcGIS was used to extract mean bank height in each buffer box from the one meter resolution DEM.

When a channel is migrating towards the higher bank, the annual volume of eroded sediment is the product of the difference in bank height, reach length on the 2008 centerline, and migration rate.

Sediment volumes were converted to mass using a bulk density of 1.3 Mg/m^3 and a silt and clay composition of 50% (Belmont et al., 2011) (Table 3). Above the knickpoint, where incision is not occurring, channels were assumed to be in dynamic equilibrium with cutbank erosion balanced by floodplain deposition over time.

Widening rates were calculated from the traced banklines around a series of bends throughout tributaries to the lower Minnesota River. Channel surface areas in 1938 and 2008 were divided by the associated reach length to obtain average widths, which were divided by 70 years to obtain annual widening rates (Gran et al., 2011). For calculations involving modern channel width in the greater Le Sueur watershed, we used a flow accumulation layer and the hydraulic geometry relationship $w = 1.02A^{0.50}$ (width (w) in meters, upstream basin area (A) in square kilometers; Gran et al., 2013). Channel widening rates were only applied to channels order 4 and higher. Air photo resolution limited the measurement of channel widening to these larger channels, and lacking direct evidence of systematic widening in the smaller channels, we did not include it in the sediment budget.

The incision rate calculated for the Le Sueur is based on a record of incision preserved in fluvial terraces and kinematic modeling (Gran et al., 2009, 2011, 2013). Channel incision rate is unlikely to vary much between GBER channels, because the channels have incised the same depth over the same time period to create a network of channels similar in long profile elevation, so the Le Sueur rate was used (2.6 mm/a below knickpoints, no incision above knickpoints; Gran et al., 2013).

Ravines

Ravine sediment source extents were digitized manually, based on break in slope on 3-meter LiDAR-derived DEMs. For this study, as in the Le Sueur River sediment budget, only ravines with area > 10,000 m^2 are included in the budget. We estimated that this threshold selects at least 85% of all ravine area based off of a comparison with all ravine areas in the lower Le Sueur watershed. To calculate the sediment supply rate from ravines to GBER channels, we used erosion rates based on monitoring season TSS yields measured on 4 ravines in the lower Le Sueur (Belmont et al., 2011). TSS loads were calculated and compared with TSS loads on the Le Sueur over the same monitoring period. A positive relationship was found between TSS load and incised ravine area (Belmont et al., 2011). As part of this project, an additional two years of data were collected from a subset of the original ravines, but the data were not complete enough to be used for additional annual load calculations. The Le Sueur yield (0.00022 $Mg/yr/m^2$ of incised ravine area (Gran et al., 2011; Belmont et al., 2011)) was applied to other ravines in the GBER watershed based on incised area.

Uplands

Upland sources cover all of the area that is not a near-channel sediment source or a lake. In the Le Sueur, upland supply rates were determined using sediment fingerprinting paired with loads at upstream gauges. Sediment fingerprinting uses meteoric Beryllium-10 (^{10}Be) and Lead-210 (^{210}Pb) isotopes produced in the atmosphere to differentiate between sediment derived from near channel sources and upland-sourced sediment (Belmont et al., 2011; Schottler et al., 2010). Sediment fingerprinting for the Le Sueur budget was conducted at the upper gauges where load is less affected by near-channel sources. Because samples were collected on mainstem channels, the upland erosion rates in the Le Sueur budget already account for deposition on fields prior to sediment delivery to channels as well as erosion, deposition and dredging in ditch networks or lakes. Thus, the upland erosion rate determined from sediment fingerprinting should be considered a measure of net sediment delivery to channels from exposed upland surfaces. Calculated yield was applied to upland sediment supply areas throughout the watershed. Sediment fingerprinting data were used in conjunction with TSS loads from the upper gages on the Maple River and the Le Sueur River to determine upland yields as part of the Le

Sueur River sediment budget (Belmont et al., 2011), with the upland yield derived from the Maple applied to the Cobb River basin as well given their similar surficial geology.

Beryllium-10 and ^{210}Pb are both naturally-occurring tracers that are delivered to soil surfaces via atmospheric deposition (Willenbring and Von Blanckenburg, 2010; Belmont et al., 2014). Specifically, ^{10}Be is produced when high-energy cosmic rays interact with oxygen atoms in the atmosphere and is subsequently delivered to Earth's surface, where it adsorbs to soil particles within the top meter of the soil profile. Lead-210 is part of the decay chain of naturally-occurring Uranium-238 and is delivered to Earth's surface via rainfall or dry deposition and adsorbs to soil particles within the top few centimeters of the soil profile. These specific tracers were selected because they have significantly different half-lives, 1.4 million and 22.3 years for ^{10}Be and ^{210}Pb, respectively. Generally, upland sediment contains high concentrations of both tracers. Bluff sediment exhibits very low concentrations of both tracers. Sediment that is eroded from uplands and temporarily deposited in floodplains, which is subsequently re-mobilized by bank erosion, is deficient in ^{210}Pb after 50-60 years because of its short half-life, but ^{10}Be concentration remains essentially unchanged.

Upland yield data from the Le Sueur and Maple Rivers were augmented with additional fingerprinting samples from the Beauford Ditch, Blue Earth River near Rapidan and the Watonwan River at Garden City. The sediment fingerprinting data were used in conjunction with TSS loads at these two gage sites to determine upland yields. Additional samples were collected from upland, bluff and bank source areas to constrain the geochemical signature of each source. Suspended sediment samples were collected by a combination of staff from the Belmont Lab at Utah State University, the Water Resources Center at Minnesota State University, Mankato, and the Triplett Lab at Gustavus Adolphus College. Samples were dried and split for analysis of grain size, ^{10}Be concentration at Purdue University PRIME Lab, and ^{210}Pb activity at the St. Croix Watershed Research Station.

Storage on floodplains

The amount of floodplain storage in the Le Sueur budget was calculated differently for reaches above, within and below knickzones. Above the knickzone, where banks are in dynamic equilibrium, deposition rates were set accommodate the sediment eroded from banks via channel migration, thus maintaining dynamic equilibrium. Within the knickzone, floodplain extent is very limited (Belmont, 2011) since channels are actively incising, so the budget included no floodplain storage. Below the knickzone, floodplain deposition rates were calculated based on observations that the summed loads from gauges at the downstream end of the Le Sueur knickzone (Maple, Big Cobb, and Le Sueur) were equal to the gauged load at Red Jacket Park near the mouth of the Le Sueur, in spite of sediment supply in the intervening reach. The estimated load from bluffs in the reach between the lower gauges and Red Jacket must therefore be stored on floodplains in this reach (Belmont et al., 2011). This gives a rate of mass storage below the knickzone estimated at 530 Mg of mud stored per channel kilometer per year. To estimate storage from aggradation on the Blue Earth below the knickzone (i.e., below the confluence with the Watonwan) this "storage yield" below the knickzone of the Le Sueur was applied to the Blue Earth reaches below the knickzone.

To determine where bluff and bank sediment could be stored on Blue Earth and Watonwan floodplains, we compared cross-sections of the Blue Earth and Le Sueur floodplains (Belmont, 2011). While floodplains within the knickzone are very small or non-existent on the Le Sueur and its tributaries, floodplains in the knickzone of the Blue Earth are similar to Le Sueur floodplains above the knickzone, so we included storage of bluff sediment within the Blue Earth knickzone. Cross sections of Watonwan floodplains were not included in the study as most of the Watonwan lies above the knickzone. We assume that the floodplain geometry on the Watonwan within the knickzone behaves like that of the Blue Earth. We therefore estimated the amount of sediment trapped on floodplains in all subwatersheds except for reaches in the Le Sueur knickzone. To do so, our spreadsheets "stored" a 2m-high band of eroded bluff sediment on floodplains in the same way bank sediment above knickpoints is stored on floodplains.

Storage in lakes

The ability of a waterbody to trap sediment (i.e., trap efficiency, TE) depends on characteristics of the inflowing sediment and the retention time of the waterbody, functions of lake geometry and watershed runoff characteristics (Verstaeten and Poesen, 2000). This project estimated storage in lakes based on the ratio of waterbody capacity and watershed area (Brown, 1943). In this relationship (Equation 13), trap efficiency is defined as a function of reservoir storage capacity (C, in m^3); watershed area (W, in km^2); and an empirical form factor (D, ranging from 0.046 –1). Curves demonstrating the effect of the form factor are shown in Figure 3. Though simple, when compared with more complex methods, Brown's curve has provided accurate results when used on watersheds of similar size to the GBER watershed (Butcher et al., 1992).

$$TE = 100*(1-\frac{1}{1+0.0021D\frac{C}{W}}) \quad (11)$$

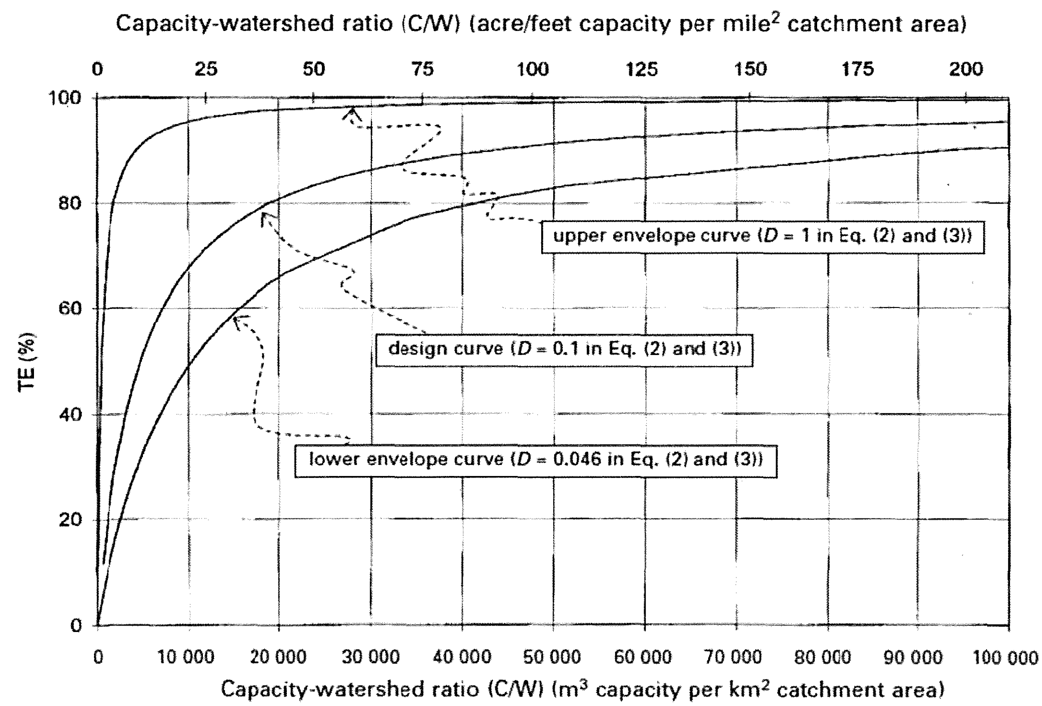

Figure 3: *Relationship between C/W ratio and trapping efficiency. The median estimated C/W of the largest lake basins in the GBER watershed is 75,000 m^3/km^2. Figure from Brown, 1943.*

We automated estimates of lake trapping efficiency in ArcGIS to estimate unique TE for all lakes in the GBER watershed. This was done with a 10m resolution DEM. The automated method used *zonal statistics* to identify the largest flow accumulation value within National Hydrography Dataset waterbodies, then a raster algebra statement using a threshold to select the raster cell with the highest flow accumulation value within the lake. These cells were used as pourpoints to delineate "lakesheds" with the *watershed* tool. Lakeshed areas were paired with lake volumes, and trapping efficiency was calculated using the relationship between lake volume and watershed area described in Equation 13. We used the middle curve in Figure 3, where D = 0.1. Lake capacity was estimated using a linear regression between lake volumes from Minnesota Department of Natural Resources bathymetry data and lake surface area. Average lake depth in the GBER watershed is about 2m. The sediment budget draws on these data to include sediment storage in every lake. While Rapidan Dam on the Blue Earth River might be expected to trap sediment, its reservoir is already full of sediment. The reservoir currently has little storage capacity even for water, and thus the impoundment has a trapping efficiency near zero.

Holocene Sediment Budget

A Holocene sediment budget was constructed to apportion sediment based on pre-settlement conditions. The estimated Holocene budget in the Blue Earth and Watonwan Rivers was heavily based on extensive research in the Le Sueur basin (Gran et al., 2013). There, terrace ages were used to constrain a numerical model of valley growth over the last 13,500 years. The model showed that in the absence of large-scale changes in climate and land use such as were experienced in the last 200 years, the mass of sediment derived from valley excavation (bluff and bank erosion) was 47,000 Mg/yr of silt and clay, which is slightly less (within 5%) than the mean export rate based solely on total valley volume removed in 13,500 years and 3 times lower than the predicted modern fine sediment load associated with bank and bluff erosion.

To determine valley excavation rates in the Blue Earth River, the valley volume was measured using lidar data. A polygon was fit to 5km-long valley reaches, and the missing mass determined between the upland surface and the modern valley bottom. Volumes from all of the valley reaches were summed and converted to mass of fine sediment using bulk density and grain size distributions for till (Table 3). The Blue Earth River pre-settlement rate was taken to be 95% of the mean, assuming the pattern of erosion in the Blue Earth River was the same as in the Le Sueur River over the past 13,500 years.

Pre-settlement ravine erosion rates are less constrained. The total volume of material removed from ravines in the Blue Earth River watershed was summed, converted to Mg of fine sediment, and divided by 13,500. These pre-settlement loading rates were then compared with modern estimates of ravine loads and found to be ~50% of modern loads. Upland contributions were assumed to be negligible given the prairie vegetation and low-relief or zero relief over much of the upland area. Streambank meandering and incision components were considered with bluff erosion as part of the valley excavation portion of the budget. River widening was assumed to be zero. Floodplain and lake deposition is relatively unconstrained and thus reductions in depositional sinks were made commensurate with reductions in primary erosional sources contributing to them.

Results

Bluff extents, migration rates, and erosion rates

Bluffs are primarily found below the knickpoint, with bluffs increasing in size near river mouths. To normalize bluff extent data to different basin areas, we calculated bluff frequency (bluff surface area per channel length). Bluff frequency has consistent trends in the basin: On each GBER channel, bluff surface area is near zero above the knickpoint, but increases rapidly below the knickpoint (Figure 4).

Retreat and migration rates are highly variable along channels in the GBER watershed (Figure 5), but follow similar trends on each river. Where channels flow in bedrock reaches they often migrate more slowly than channels bounded by till or alluvium. For example, channel migration rates on the

Blue Earth River below the Rapidan Dam are much lower than rates above the dam (Figure 6). On the Le Sueur, channel migration rates rise near confluences with the Cobb and Maple Rivers, then decrease below the Maple River, where bedrock is more prevalent. Migration rates rise near the confluence with the Blue Earth. Channel migration rates on the Blue Earth River follow a similar trend: directly below Rapidan Dam, where the channel is primarily bedrock, migration rate is very low, but as confluences with the Le Sueur and then Minnesota Rivers near, migration rate increases. Below the knickpoint on the Watonwan, channel migration rates may be slowed by bedrock. We normalized channel migration rates to channel width as a surrogate for discharge, because channel width on major rivers in the Le Sueur basin changes with the square root of basin area (Gran et al., 2013). Normalized migration rates remain highest on the Blue Earth River (Figure 6).

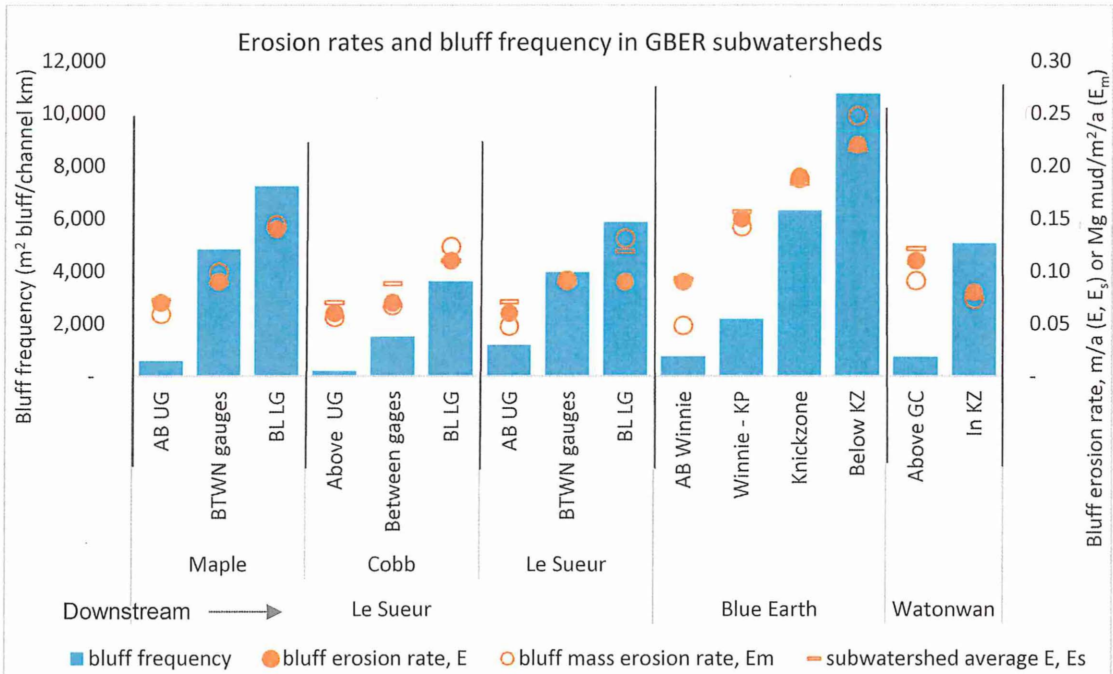

Figure 4: *Bluff frequency (blue bars) and erosion rates (orange dots) follow remarkably similar trends in the GBER watershed. Bluff frequency is bluff surface area per channel length (m^2/km). Average measured erosion rate (E m/a), the average of all measured and extrapolated rates in a subwatershed (E_s, m/a), and mass erosion rate (E_m, Mg mud/m^2/a) are similar in each subwatershed. Upstream is to the left, bedrock bluffs are included in bluff frequency. Figure from Bevis (2015).*

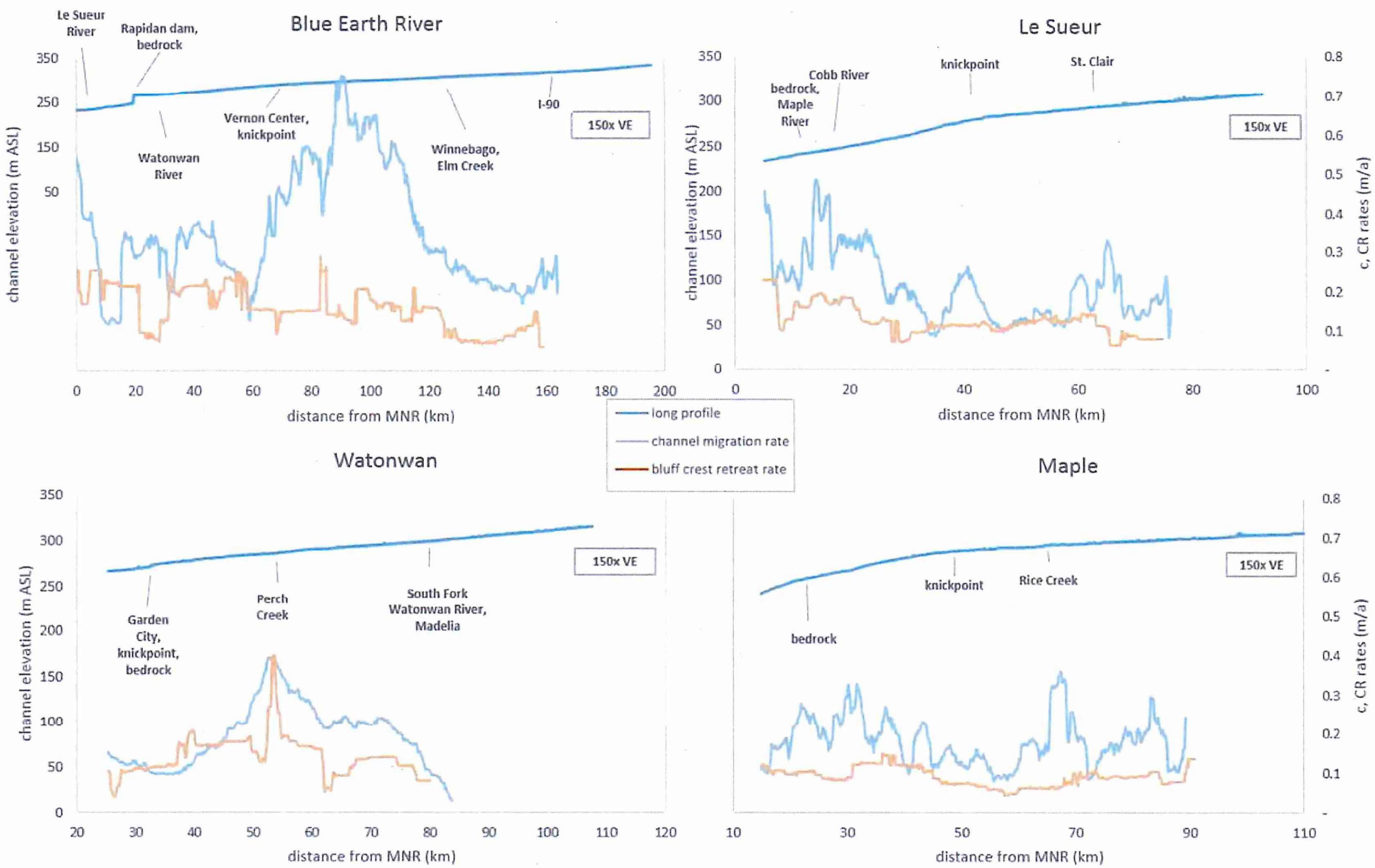

Figure 5: *Bluff crest retreat and channel migration rates, smoothed over a 3 km radius. Channel migration rates include bluffs, banks and bedrock reaches, but not reaches that avulsed or were shortened from 1938 to 2008. Long profiles have 150x vertical exaggeration. Figure from Bevis (2015).*

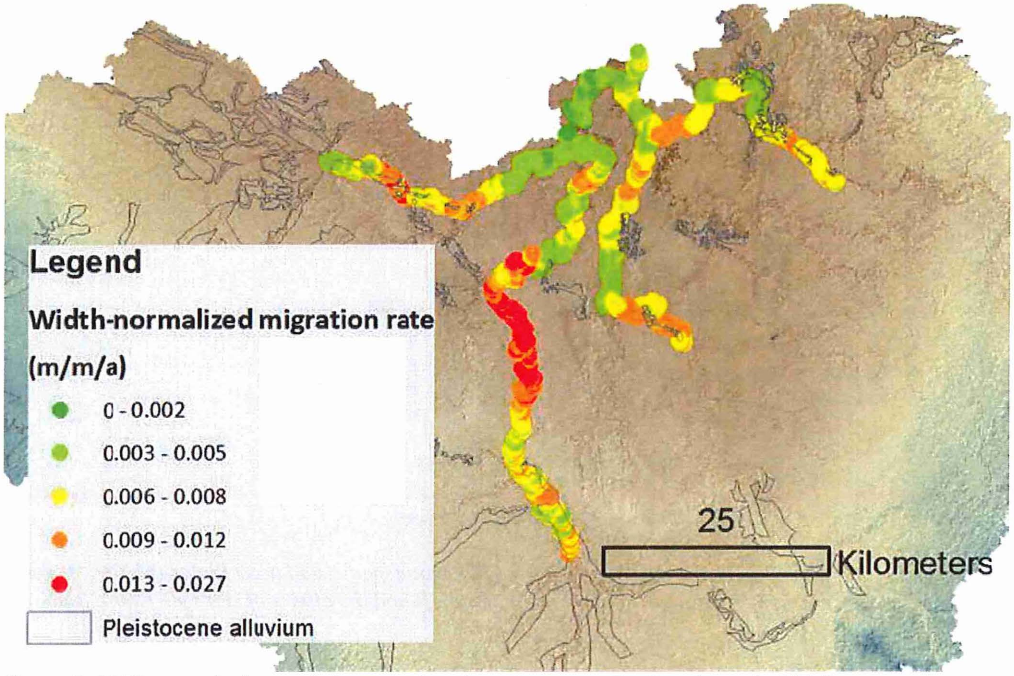

Figure 6: *GBER watershed annual channel migration rates normalized to channel width for comparison across watersheds. High channel migration rates often occur in Pleistocene tunnel valleys and outwash channels (outlined in grey; not shown but believed to exist on the reach of the Blue Earth with the highest migration rates). Figure from Bevis (2015).*

Bluff extent and retreat rates were used to calculate volumetric (E) and mass erosion rates (E_m) (Figure 4). A mass erosion rate is simply the mass of mud (silt and clay) eroded from each bluff or subwatershed divided by surface area to account for different bluff surface areas in each subwatershed. Subwatershed E_m rates include adjustments for bulk density and texture. Mass erosion rates in this figure also include the effect of lake and floodplain storage. Like E, mass erosion rates (E_m) increase downstream in GBER watersheds. On the Blue Earth, E_m rates near the mouth are about twice as high as rates higher in the watershed (Figure 4). Average E_m rates on the Blue Earth River are just under twice the average E_m rates on the Le Sueur and Watonwan. Note also that E_m rates closely follow E rates, but are reduced by storage on lakes high in watersheds, and changed by interpolation downstream. In Figure 4, subwatershed-averaged mass erosion rates are plotted alongside bluff frequency. The product of E_m and extent is load. When load is normalized to stream length, the along-channel trend in each subwatershed is even stronger (Figure 7).

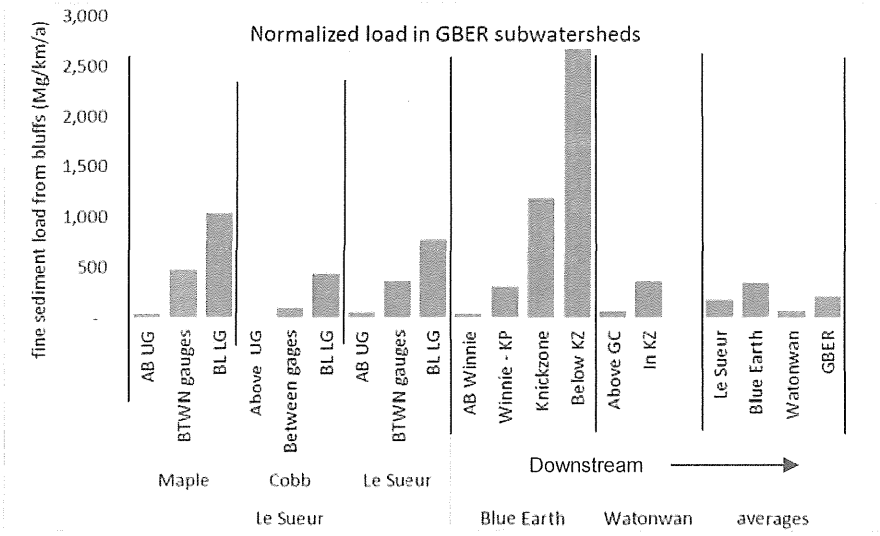

Figure 7: Bluff load normalized to channel length for subwatersheds in the GBER watershed. Load accentuates the trends seen in its components, rates and extents. Here load includes erosion from bedrock bluffs and the effects of storage. Figure from Bevis (2015).

Upland Sediment Fingerprinting

Our fingerprinting sampling strategy sought to expand existing datasets for sediment sources and gages in the Le Sueur watershed, while also expanding to additional sites within the Le Sueur, Blue Earth and Watonwan watershed. Samples collected in locations where we had existing data showed generally consistent concentrations for both ^{10}Be and ^{210}Pb. Adequately constraining source area fingerprints is challenging due to the spatial variability in tracer delivery rate, potential for mixing of sediment spatially and vertically within the soil profile, differences in grain size and carbon content. Nevertheless, source area concentrations were found to be fairly consistent. Bluff samples analyzed as part of this and previous studies average 0.12 x 10^8 atoms/g for ^{10}Be and were consistently found to be devoid of ^{210}Pb. Banks, which are alluvial deposits that consist of a mixture of upland and bluff sediments, averaged 0.80 x 10^8 atoms/g for ^{10}Be and were also consistently found to be devoid of ^{210}Pb. Uplands were found to be more variable, as is expected from the wide range of land use and erosional histories throughout the study area. Including previous upland ^{10}Be samples as well as new samples collected as part of this study and as part of a complementary study conducted by St. Croix Watershed Research Station, upland ^{10}Be concentrations averaged 2.7 x 10^8 atoms/g for ^{10}Be. Excluding St. Croix samples, the average ^{10}Be concentration of upland sources is 2.4 x 10^8 atoms/g. Figure 8 shows average concentrations of each of the tracers for suspended sediment samples and Table 4 shows average results interpreted for source apportionment. Percent upland plus bank are computed from ^{10}Be samples using a simple unmixing model between upland and bluff concentrations. Percent upland minus bank are computed from ^{210}Pb results using a simple unmixing model between upland and bank sources. These numbers should be viewed as preliminary until related projects at Utah State University and St. Croix Watershed Research Station are completed and upland fingerprints have been better constrained.

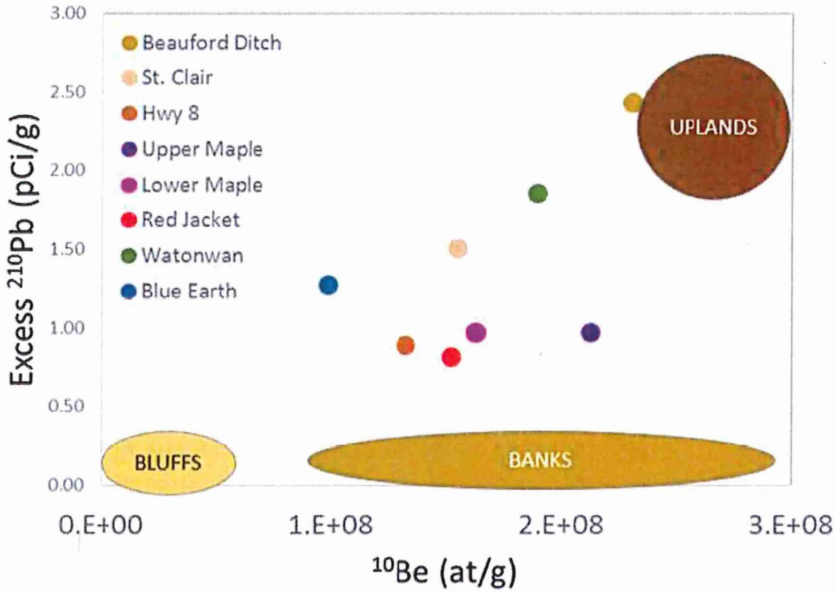

Figure 8. *Results from sediment fingerprinting analyses. Large circles indicate the range of tracer concentrations found in source areas. Small dots indicate the average concentration of each tracer measured in suspended sediment samples.*

Table 4. *Average sediment fingerprinting samples from source areas and suspended sediment samples. These values are preliminary pending completion of related projects.*

Summary Table	Avg ^{10}Be (at/g)	Avg ^{210}Pb (pCi/g)	% Upland + Bank	% Upland-Bank
Uplands	2.39E+08	2.43		
Bluffs	1.19E+07	0.00		
Banks	8.03E+07	0.00		
Beauford	2.30E+08	2.43	101	100
St. Clair	1.55E+08	1.51	68	62
Hwy 8	1.32E+08	0.89	58	37
Red Jacket	1.52E+08	0.82	67	34
Upper Maple	2.12E+08	0.97	93	40
Lower Maple	1.63E+08	0.97	72	40
Watonwan	1.89E+08	1.86	83	77
Blue Earth	9.88E+07	1.27	43	52

Ravines

Ravine loads were taken directly from loads measured in a series of 4 ravines in the Le Sueur River basin. Differences in the relative importance of ravine loads were therefore driven primarily by ravine area. The Le Sueur watershed has a greater density of ravines compared to the rest of the GBER watershed; the incised ravine area in the Le Sueur watershed was approximately the same as in the Blue Earth and Watonwan watersheds combined. The Watonwan watershed had quite a large area of ravines found in the far upper basin, associated with high relief in that region and not associated with the knickzone. It is possible that these ravines erode at a significantly different rate than the ones monitored in the lower Le Sueur River, but we currently have no data on the rates of erosion there. We consider this to be a source of uncertainty in our Watonwan ravine load estimates and could be one reason why sediment loads predicted in the Watonwan are consistently higher than loads measured at the Garden City gage.

Streambanks and Floodplain Deposition

Under the sediment budget for the Greater Blue Earth River basin, streambanks appear to be a much more important source of sediment compared with the earlier Le Sueur River sediment budget (Gran et al., 2011; Belmont et al., 2011). The main reason has to do with how sediment loads are reported in the GBER watershed budget. Here, we separate out sources and sinks. Thus, although streambanks account for approximately 20-30% of the total budget in terms of source contributions, much of that sediment is deposited in floodplains. Estimated floodplain deposits in the Watonwan almost completely match streambank contributions (70-80%), while on the Blue Earth River, floodplain deposition accounts for approximately 40% of the total streambank-sourced loads. On the Le Sueur River, floodplain deposition accounts for approximately half of the total streambank-sourced loads, with most of the floodplain capacity coming in below the knickzone. When net streambank contributions are considered (streambank erosion minus floodplain deposition), the fraction of sediment derived from streambanks is only 15% of the total sediment budget for the GBER watershed.

GBER watershed sediment budgets

The GBER sediment budget shows similar results to the Le Sueur sediment budget with a predominance of near-channel sediment sources in the total fine sediment load. Detailed sediment accounting is included on an accompanying Excel spreadsheet, while general results are presented here. The spreadsheet allows the user to include or exclude bluffs in bedrock reaches. In addition, the user can consider vegetation cover as a factor in extrapolating bluff retreat rates or not. Although work by Day et al. (2013) in the Le Sueur watershed found no correlation between long-term decadal-scale erosion rates and vegetation cover, it is frequently discussed as a potential control on bluff erosion and may be more important in other watersheds. Thus, the user is able to consider vegetation cover as a factor in erosion rates or not. Upland yields are set by fingerprinting data that are still considered preliminary pending completion of a related project. Because of this, ranges of upland % determined from fingerprinting data are included on the budget front page and the user is able to adjust the percent within the specified range. The median values are used in the results shown in Table 5 and Figure 9.

For comparison with observed TSS loads, the user can compare the predicted loads from the budget to observed loads from a range of timescales (2000-2013, 2000-2010, and 2007-2012). The benefit of the shorter timescale (2007-2012) is that all gages were operating during the entire time period, so all loads are based on FLUX calculations made from direct sampling. In the Le Sueur subwatersheds, 2007-2012 had noticeably lower TSS loads (72-88% of longer time periods), although TSS loads are more comparable in the Blue Earth and Watonwan (96-105%). For longer time periods, data had to be adjusted for some of the gages (data were adjusted based on the relative loads from a mouth gage (Red Jacket on Le Sueur subwatersheds and Rapidan for Blue Earth and Watonwan Rivers) between the time period of actual gaging vs. the time period of averaging. The time period of 2000-2010 was used in the original Le Sueur budget, and the time period 2000-2013 represents the most up-to-date TSS load data available as of June 2016.

Comparing predicted loads with 2000-2013 data, the total fine sediment load on the Watonwan and Blue Earth Rivers is best predicted when vegetation cover is considered (see Table 5). In general, bare bluffs composed a larger proportion of the measured bluffs than extrapolated bluffs, and when this is the case, erosion rates that considered vegetation cover were lower. The best fit scenario for the Le

Sueur was the scenario in which all bluffs were included and vegetation cover was not included as a factor. Under all scenarios, the majority of the fine sediment was derived from near-channel erosion of bluffs and streambanks (60-78% over all different bluff scenarios).

Bluffs in the Blue Earth watershed contribute more sediment to the river than Le Sueur bluffs, primarily because there is more bluff surface area in the Blue Earth watershed, but also because erosion rates are higher. Figure 7 shows channel migration rates throughout the GBER, with the highest migration rates present on the Blue Earth River. The Watonwan has a relatively higher proportion of sediment derived from banks than other GBER watershed rivers, primarily because the other major sources (bluffs and uplands) are not as high. The rate of channel sediment supply from the Watonwan is not significantly different than on other GBER watershed channels. The Watonwan has little incised channel length, and meander migration rates are only a little higher than rates on the Le Sueur. Widening is in line with widening measured on other GBER watershed channels.

Upland sediment yields as determined from preliminary sediment fingerprinting data give yields of 1.4×10^{-5} $Mg/m^2/yr$ (124 lbs/acre) on the upper Le Sueur watershed, 1.3×10^{-5} $Mg/m^2/yr$ (113 lbs/acre) on the Watonwan watershed, and 2.2×10^{-5} $Mg/m^2/yr$ (218 lbs/acre) in the Blue Earth watershed. Although the range in sediment fingerprinting data can appear quite large (for ex. Upper Maple is 0.4 – 0.93 % upland with preliminary fingerprinting data), the impact on the overall sediment budget is not large. Varying the upland fingerprints from the lowest to the highest resulted in a variability in the total sediment load at the mouth gage of ± 4% on the Le Sueur, ± 3% on the Blue Earth, and ± 1% on the Watonwan. Changes in upland yields to the channel are mediated in part by commensurate changes in lake storage in the uplands.

Storage is a significant portion of the budget. Values listed above for each source are gross contributions. Storage then removes fine sediment from the river prior to the gage at the mouth. On the Blue Earth and Le Sueur Rivers, the fraction stored varied between 23-26%. On the Watonwan, the fraction stored was much higher: 44-48%. The Watonwan gage is located near the knickpoint, so the geomorphic regimes where source contributions are high and sinks less abundant (i.e. the knickzone) are not as extensive on the Watonwan above the gage.

The budget is set up to display sources relative to each other in a series of pie charts (Figure 9A). Magnitudes of sediment contributions are displayed in a bar graph for each major watershed, broken down by geomorphic regime (above vs. below knickpoint) (Figure 10). It is important to note that the pie charts in the GBER sediment budget show a comparison of sediment sources only, without including depositional volumes. To illustrate the difference between source comparisons and net (source – sink) comparisons, Figure 9B has net sediment loads plotted for each source. Since most of the sediment deposited in lakes is derived from upland sources, lake depositional volumes were removed from upland source loads. Similar to the original Le Sueur River budget, we also removed floodplain deposits from streambank erosional volumes.

Table 5: *Example sediment budget predictions and observations for major HUC-8 watersheds*

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Predicted via sediment budget, Le Sueur River (Mg/yr silt and clay)				
	Exclude bedrock bluffs	Include bedrock; Do not consider vegetation cover	Exclude bedrock; Consider vegetation cover	Include bedrock; Consider vegetation cover
Uplands	41,016	41,016	41,016	41,016
Ravines	20,009	20,009	20,009	20,009
Bluffs	110,843	117,286	67,835	74,278
Streambanks	46,592	46,592	46,592	46,592
(Lakes)*	(16,002)	(16,059)	(10,792)	(10,849)
(Floodplains)*	(26,367)	(26,367)	(25,260)	(25,260)
Total Predicted	176,091	182,477	139,401	145,787
Observed at Red Jacket gage (Average TSS load, Mg/yr)				
2000-2013	211,860	211,860	211,860	211,860
2000-2010	229,762	229,762	229,762	229,762
2007-2012	186,553	186,553	186,553	186,553
Predicted via sediment budget, Watonwan River (Mg/yr silt and clay)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Exclude bedrock bluffs	Include bedrock; Do not consider vegetation cover	Exclude bedrock; Consider vegetation cover	Include bedrock; Consider vegetation cover
Uplands	27,612	27,612	27,612	27,612
Ravines	9,886	9,886	9,886	9,886
Bluffs	55,043	55,043	27,662	27,662
Streambanks	29,221	29,221	29,221	29,221
(Lakes)*	(13,802)	(13,802)	(12,842)	(9,552)
(Floodplains)*	(23,463)	(23,463)	(21,132)	(21,132)
Total Predicted	84,497	84,497	63,697	63,697
Observed at Garden City gage (Average TSS load, Mg/yr)				
2000-2013	34,515	34,515	34,515	34,515
2000-2010	34,842	34,842	34,842	34,842
2007-2012	35,696	35,696	35,696	35,696
Predicted via sediment budget, Blue Earth River (Mg/yr silt and clay)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Exclude bedrock bluffs	Include bedrock; Do not consider vegetation cover	Exclude bedrock; Consider vegetation cover	Include bedrock; Consider vegetation cover
Uplands	98,531	98,531	98,531	98,531
Ravines	9,342	9,342	9,342	9,342
Bluffs	152,997	152,997	130,088	130,088
Streambanks	107,352	107,352	107,352	107,352
(Lakes)*	(29,066)	(29,066)	(25,572)	(25,572)
(Floodplains)*	(44,497)	(44,497)	(43,147)	(43,147)
Total Predicted	294,659	294,659	276,593	276,593
Observed at Rapidan gage minus Watonwan contributions (Average TSS load, Mg/yr)				
2000-2013	205,994	205,994	205,994	205,994
2000-2010	224,732	224,732	224,732	224,732
2007-2012	215,932	215,932	215,932	215,932

**Lakes and Floodplains are sinks and are subtracted from the 4 source contributions.*

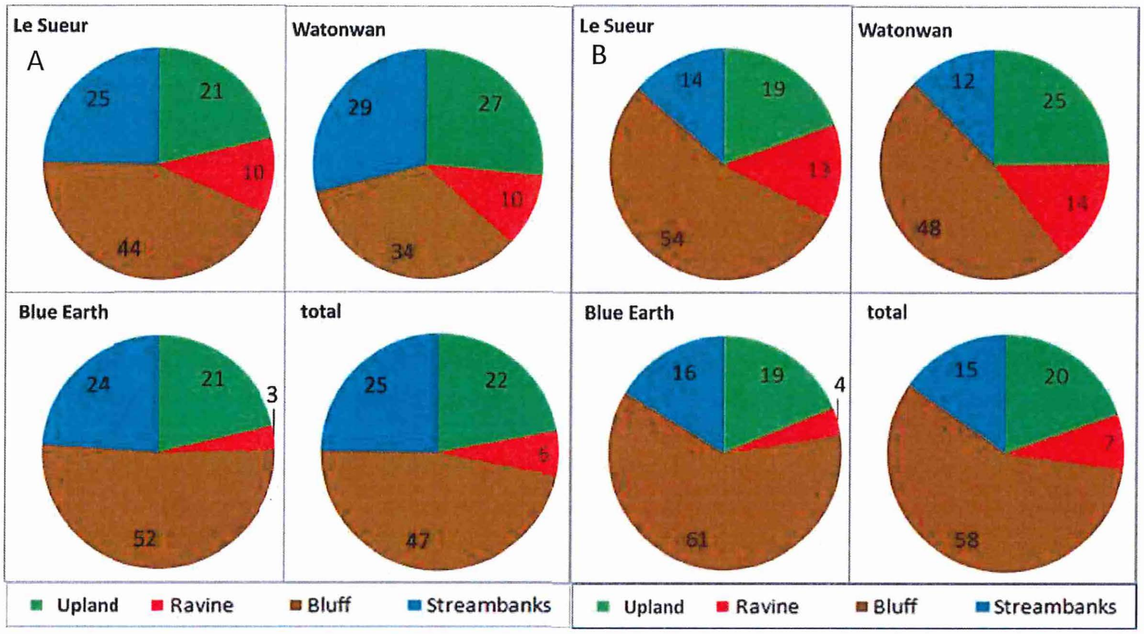

Figure 9: *Pie charts from Scenario 4. On the left (A) are four pie charts showing the break-down of sediment sources in each major watershed, without considering sediment sinks. On the right (B) are four charts illustrating the effects of including both sources and sinks. Here, lake deposition was removed from upland source contributions and floodplain deposition was removed from streambank contributions.*

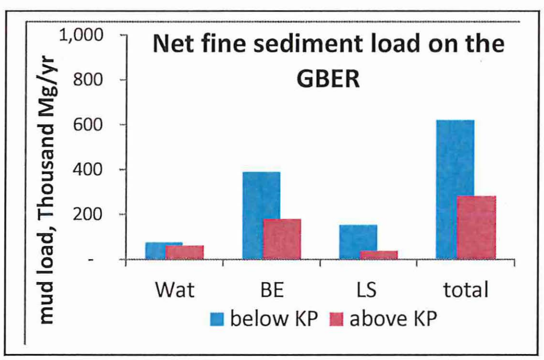

Figure 10: *A chart illustrating the relative net sediment contribution from each major watershed, broken down into sediment derived from different geomorphic regimes (above vs. below knickpoint). Data shown are from Scenario 4.*

Pre-settlement (Holocene) sediment budgets

Much of the Le Sueur and Blue Earth River watersheds were covered by glacial Lake Minnesota which drained shortly before the incision of the Minnesota River valley by glacial River Warren. Because of this, the modern river valleys and ravines carved are into what was once a flat-lying glacial lake bed, now covered by rich agricultural lands. In the Le Sueur River, we were able to measure the volume of material eroded from the valleys of the Le Sueur, Cobb, and Maple Rivers and convert that into fine sediment volumes using bulk density and grain size analyses (Gran et al., 2013). Here, we extended this analysis to the Blue Earth River, where we measured 1.76 x 10^9 Mg of fine sediment removed over the past 13,500, for a mean annual erosion rate of 130,000 Mg/yr of silt and clay.

In the Le Sueur River valley, Gran et al. (2013) used terrace ages coupled with hydraulic geometry and surface grain size data from the modern channel to construct a best-fit incision model for the mainstem Le Sueur. This model was then used to investigate how sediment loads varied through time as the knickpoint migrated upstream and channels incised and migrated laterally, expanding the valley size. The results from the best-fit model indicate that erosion rates increase initially, then slowly decline over time. Interestingly, long-term pre-settlement erosion rates determined from the incisional model indicate that erosion rates today should be quite similar to the mean average annual erosion rate. We assume for now that the Blue Earth River likely eroded in a similar pattern to the Le Sueur River and use the mean average erosion rate as the pre-settlement long-term erosion rate.

The mean annual valley erosion rate in the Blue Earth River over past 13,500 years was 130,000 Mg/yr of silt and clay. Valley erosion is a combination of bluff erosion, bank erosion, and channel incision. Combining the streambank and bluff portions of the sediment budget gives 237,000 – 260,000 Mg/yr under different scenarios for modern conditions. Neither of these calculations includes the effects of deposition. Valley excavation rates have thus increased by only a factor of two on the Blue Earth, compared to a factor of 3 on the Le Sueur.

To compile a Holocene-scale sediment budget for the Blue Earth River, we used the valley excavation data to constrain bluff erosion rates at half of the present rates. Ravine erosion rates were estimated by taking the total volume of sediment removed via ravine erosion, converting it to mass, and taking an average over 13,500 years. The resulting ravine yield is 50% of the modern yield on the Blue Earth and Watonwan, so ravine yields were set to 50% modern rates. Streambank rates are less constrained and were set the same as the Le Sueur River pre-settlement rates (modern rates above the knickzone, 50% modern within the knickzone, and 33% modern below knickzone). Upland erosion rates are assumed to be essentially zero (set to 1% of modern rates) given pre-settlement prairie vegetation and low gradient relief found in most of the Blue Earth watershed uplands. Relative erosion rates, depicted as a fraction of the modern, were set the same in the Watonwan watershed as the Blue Earth watershed. The Holocene sediment budget can be accessed on the "GBER budget" page by toggling the "time frame flag" in cell A55. We used the best-fit bluff scenario for each major tributary (scenario 2 for Le Sueur and 3 for Blue Earth and Watonwan) to compare predictions for Holocene loads vs. modern loads. Comparing predictions of loads at the mouth of the Greater Blue Earth watershed, the predicted Holocene load is 290,000 Mg/yr or 53% of the modern predicted load of 542,000 Mg/yr. At the three gages (Le Sueur, Blue Earth, and Watonwan), the predicted Holocene average load was 238,000 Mg/yr, or 45% of the averaged measured TSS load (2000-2013) of 533,000 Mg/yr.

Summary:

The sediment budget presented here was motivated by high turbidity throughout the Minnesota River Basin (MNR basin), primarily driven by sediment loading. Work in Lake Pepin by Engstrom et al. (2009) shows that fine sediment deposition rates have increased ten-fold since the early 1800s. Most of the fine sediment deposited in Lake Pepin now comes from near-channel sediment sources (Belmont et al., 2011), primarily the high bluffs that line the incised lower valleys of major tributaries (Sekely et al., 2002; Gran et al., 2009; Belmont et al., 2011). The sediment budget developed here for the GBER watershed has comparable results to these earlier studies.

Bluffs are the dominant source of sediment in the GBER watershed. Uplands and streambanks provide the next greatest volumes of sediment, with ravines making up the smallest share of the 4 major sources. It is important to note that the GBER budget presented here separates sources and sinks. Much of the sediment derived from streambanks is balanced by deposition in the floodplain, particularly in the upper watersheds. Most of the sediment deposited in lakes comes from upland erosion, although lake deposition rates are not high enough to trap the majority of the upland sediment.

Most of the work presented here from Bevis (2015) focuses on bluffs because they are such an important source. Bluff contributions are a function of both bluff extent and erosion rate. Because bluff extents are more variable across watersheds than bluff erosion rates, careful work is required to accurately delineate extents for a budget. Bluffs are largest and most frequent below GBER watershed knickpoints; they are smaller and less common upstream. Bluff erosion rates, a function of channel migration and bluff crest retreat rates, are also highest below knickpoints. Channel migration rates were slower (but not zero) where bedrock outcropped along the channel, and higher in locations where higher inputs of bedload material are expected. Bedload is concentrated in GBER watershed channels by erosion of till, at channel confluences, and where glacio-fluvial sediments are present, all of which are common below knickpoints.

We explored sediment budget sensitivity to many potential improvements and adjustments. We found that fine sediment load from bluffs is primarily a function of bluff extent and erosion rate; other factors, like the extent of Pleistocene alluvial deposits, have minor effects only. Even though coarse bedload may affect channel migration rates, adjustments for differences in sediment texture and bulk density from terraces vs. valley bluffs or from glaciofluvial sediments more present in the Watonwan River had little effect on total fine sediment load estimates. Vegetation cover was not an important predictive element: the current bluff vegetation state has little correlation with long-term bluff erosion rates and thus time spent mapping vegetation cover on bluffs was not useful. Different methods of bluff erosion rate interpolation and extrapolation resulted in similar fine sediment load from GBER watershed bluffs, suggesting that elaborate extrapolation techniques are not as useful as detailed work in delineating bluff extent. We advocate extrapolating subwatershed-scale bluff erosion rates. Sediment fingerprinting was useful in obtaining basin-integrated upland sediment yields, and there are differences in upland yields across the GBER watershed. Storage is an important part of the budget, with 20% of the sediment eroded in the GBER watershed is stored on floodplains and in lakes, and should be included in a sediment budget format.

The original Le Sueur sediment budget came within 10% of the average TSS loads at the Red Jacket gage from 2000-2010. In this version of the Le Sueur budget, the total predicted loads declined. More care was taken in this budget to delineate only bluff extents actively along the channel, and bluff trimming to not include portions that were disconnected by floodplains was more aggressive. This budget also extended lidar data analysis into the entire watershed (not just Blue Earth County), and thus some bluff and ravine sources higher up in morainal complexes were included that might not have been in the original budget. Likewise, lake deposition was included. The net effect of all of these changes was to lower the predicted sediment loads on the Le Sueur.

The Blue Earth and Watonwan sediment budgets tended to overpredict sediment loads, with the problem more pronounced in the Watonwan watershed. With the Watonwan River, there are a significant number of ravines and bluffs that lie in the far upper basin. They tend to be much smaller and more vegetated than bluffs further downstream. By using bluff air photo analysis and ravine load monitoring from sites well within the knickzone to determine rates to extrapolate into the far upper watershed, it is likely that these rates were over-estimated. Given that fingerprinting data indicate uplands comprise 77-83% of the total load at Garden City, that leaves very little load left to account for with bluffs and ravines (<7,000 Mg). Most of the streambank contributions are balanced by deposition.

By developing a budget for all three major watersheds in the GBER, we can also examine commonalities and differences between the three basins. Upland rates varied some across the watershed, with the Blue Earth River having higher upland yields than the Watonwan, Cobb, Maple, and Le Sueur Rivers. The Watonwan overall had lower sediment loading than the other two watersheds. In part, this is due to the location of the mouth of Watonwan, far upstream and near the top of the knickzone, leading to a much shorter incised valley length and less sediment derived from bluffs and streambanks.

The sediment budget produced here was intended to both provide information on the dominant sources, sinks, and pathways for fine sediment moving through the Greater Blue Earth River basin, allow for comparisons of some of the differences between the Le Sueur, Blue Earth, and Watonwan Rivers, and provide information to help constrain the Management Options Simulation Model (MOSM). It both provides the framework for MOSM and acts as a check on MOSM results to determine if they are reasonable and scientifically-sound.

Objective 4: Establish efficiency and cost of conservation drainage and sediment reduction practices

The goal of this objective was to collect data on management options, cost, effectiveness, and potential spatial extent within the Greater Blue Earth River watershed. The process was iterative in that data were assembled for a wide array of management options, and this list was then reduced based on conversations with stakeholders at semi-annual meetings. For modelling purposes, management options were sorted into categories based on how they physically prevent erosion and/or trap sediment. The final management option (MO) categories used in MOSM are defined in Table 5, along with the primary mechanism through which they reduce erosion. For each of these general categories, installation costs, maintenance costs, and estimated lifespan are noted in Table 6. It was very difficult to find robust data on effectiveness, so we utilize a sliding scale in the MOSM model that allows users to input estimated effectiveness for each management option. Likewise, many MOs, particularly the newer techniques, lacked information on estimated lifespans, and the lifespan will affect annualized costs. We carried out additional research on the effectiveness of water control management options (WCMOs) through detailed simulations using the Soil and Water Assessment Tool (SWAT) model. These are summarized in Mitchell (2015) and Mitchell et al. (*in prep.*) which will soon be submitted for publication and will be presented in the full report.

Table 5: *Description of the major management option (MO) categories used in the MOSM model and the primary function each plays in reducing sediment loading.*

MO Types	Definition	Location of implementation	Example MO	Primary Function in Sediment Reduction
TLMO	Tillage MO	Field	Conservation tillage, reduced tillage	Reduce erosion on fields
AFMO	Agricultural field erosion MO	Field	Grassed water ways	Trap sediment on fields (reduce sediment delivery ratio)
WCMO	Water control MO	Field	Water Retention ponds, wetland restoration	Reduce flow to reduce near-channel erosion Trap sediment on fields
ICMO	In-channel storage MO	Channel	Temporary water storage in ditches	Reduce flow to reduce near-channel erosion
BFMO	Buffer MO	Field near channel	Buffer strips along channels	Trap sediment (reduce sediment delivery ratio)
RAMO	Ravine MO	Ravines	Ravine tip stabilization to reduce branch growth	Reduce erosion from ravines
NCMO	Near-channel MO	Bluffs	Bluff stabilization, toe protection	Reduce erosion from bluffs

Tillage Management Option (TLMO) ALLOCATION				Install range	Install assumptions	Maintenance details
Extent of all farm land (ac)	Install. ($/ac)	Mntnc [$/(ac*yr)]	(yr)			
Conventional till (%)	26	8	1		Costs from 2016 Iowa custom rate survey w/ cost breakdown[9]	
Reduced till (%)	28	11	1			
Conservation till (%)	14	6	1			
Agricultural Field Management Option (AFMO) ALLOCATION						
Extent of all MOs (ft)	Install. ($/ac)	Mntnc [$/(ac*yr)]	Life Span			
Input extent (ft)	3,200	64[7]	10	1,900-4500/acre[3] 2000-3000/acre[4]	35' width	Mow 2x per year. Inspect/seed after heavy rain. Control weeds. Control vermin.
Buffer Strip Management Option (BFMO) ALLOCATION						
Extent of all MOs (ft)	Install. ($/ac)	Mntnc [$/(ac*yr)]	Life Span			
Input extent (ft)	1,000	45[7]	10	500-2000/acre[4] 750-1150/acre[3]		Mowing 2x per year.Remove sediment at upper end of gradient every 2 years.
Water Conservation Management Option (WCMO) ALLOCATION						
Extent of all MOs (ac)	Install. ($/ac)	Mntnc [$/(ac*yr)]	Life Span			
Input extent (ac)	3,000	574[5,7]		6000 (ea)[2] 300-5,300/acre[3] 100-150/ln ft, 12,000-17,000/acre[4]		Inspect embankment/ridge and repair if necessary after heavy rain. Control weeds. Control vermin. Periodically clean channel with heavy equipment.
In-Channel Management Option (ICMO) ALLOCATION						
Extent of all MOs (ft)	Install. ($/ft)	Mntnc [$/(ft*yr)]	Life Span			
Input extent (ft)	250	1.4[7]		1000-3000 (ea) for structure[3] 15,000-20,000 (ea) for rate control weir[4]	cost based on flap gate structure	Grease gate annually. Paint every few years.
Ravine Management Option (RAMO) ALLOCATION						
number of ravine tips	Install. ($/TIP)	Mntnc [$/(tip*yr)]	Life Span			
Input number of tips	6,000	35[7]		1,000-11,500 (ea)[2] 571-2,100/ft; 3,750-60,000 (ea)[1] 1,000-21,000 (ea)[3]		Check for pipe blockage
Near-Channel Source Management Option (NCMO) ALLOCATION						
Extent of all MOs (ft)	Install. ($/ft)	Mntnc [$/(ft*yr)]	Life Span			
Input extent (ft)	200	0.7[7]		11-77/ft[3] 500-1000/ft[4] 26-208/ft[6] 62-226/ft[2]		Inspection, planting shrubs

Table 6: Install and maintenance costs summarized for major MO categories used in MOSM.

[1]*Miller, T.P., J.R.Peterson, C.F. Lenhart, and Y. Nomura. 2012. The Agricultural BMP Handbook for Minnesota. Minnesota Department of Agriculture.*
[2]*Nelson, Paul. July 26, 2016. Personal Communication.*
[3]*USDA-NRCS MN-WI-MI Regional Rates for Environmental Quality Incentive Program (EQIP). 2016. Accessed at http://www.nrcs.usda.gov/wps/portal/nrcs/detail/mn/programs/financial/eqip/*
[4]*Lewandowski, A., Everett, L., Lenhart, C., Terry, K., Origer, M., & Moore, R. (2015). Fields to Streams: Managing Water in Rural Landscapes. Part Two, Managing Sediment and Water.*
[5]*Iowa State University. 2016 Iowa Farm Custom Rate Survey. March 2016. Accessed at https://www.extension.iastate.edu/agdm/crops/pdf/a3-10.pdf*
[6]*Melchoir, Marty. Jan 19, 2014. Personal Communication.*
[7]*Center for Watershed Protection (2004). Stormwater Pond and Wetland Maintenance Guidebook. Accessed at http://www.stormwatercenter.net/Manual_Builder/Maintenance_Manual/pondwetlandguidebookdraft.pdf*
[8]*Ambrosini, K. (2014). Analysis Of Flap Gate Design and Implementations for Water Delivery Systems in California and Nevada. Accessed at http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1125&context=braesp*
[9]*Uri, Noel D. "An evaluation of the economic benefits and costs of conservation tillage." Environmental Geology 39.3-4 (2000): 238-248.*

The spatial extent of areas appropriate for each management option was determined in ArcGIS. The methodology for delineating each MO is summarized below but is covered in more detail in the final CSSR report and in Se Jong Cho's dissertation (in prep, 2016). The text presented here is summarized from Cho's thesis.

The datasets used to delineate spatial extents are listed here, with source information at the bottom of the page:

- 3-m and 30-m Digital Elevation Model (DEM)[1]
- National Conservation Easements Database (NCED)[2]
- Soil Survey Geographic database (SSURGO)[3]
- Identification and classification of wetlands and deep-water habitats of the Contiguous US (CONUS wet polygons)[4].
- National land cover database 2011 (NLCD)[5]
- National hydrography dataset (NHD) blue lines[6]
- University of Minnesota Water Resource Center (WRC) ditch shape file[7]

TILMO: Area available for Tillage Management Options were identified as cultivated crops in NLCD data, excluding areas in conservation easement as shown in NCED data or wet polygons in CONUS data. TILMO act on the landscape by reducing the initial erosion rate on fields through reduced tillage or other conservation tillage practice.

AFMO: Agricultural Field Management Options include treatments designed to trap sediment already eroded from fields and includes practices such as installation of grassed waterways, water and sediment conservation basins (WASCOBs), or terraces. Areas available for AFMOs were delineated by using a stream power index (*SPI*) calculated as

$$SPI = \ln(\alpha * tan\beta) \quad (12)$$

where (α) is upstream contributing area and (β) is slope. Areas with $SPI \geq 7$ were identified as areas susceptible to water erosion on fields. Areas with $SPI \geq 11$ often had existing ditches or channels already in them. Thus, areas with $7 \geq SPI \geq 11$ were used for potential AFMO treatment. Within this range, only areas available for cultivated crops as determined from NLCD data were used, and wet

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[1] USGS The National Map Viewer, http://viewer.nationalmap.gov/viewer/
[2] National public conservation easement map layer is obtained from the National Conservation Easement Database (NCED) https://s3.amazonaws.com/nced/20130911/NCED_metadata_7_01_2012.htm. Phase I completed on July 31, 2011 and predict a nearly complete (>90%) mapping of publicly held easement in Minnesota.
[3] USDA web soil survey, http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm
[4] U.S. Fish and wildlife Service and National wetlands Inventory, http://www.fws.gov/wetlands/
[5] National land cover product created by Multi-Resolution Land Characteristics (MRLC) Consortium obtained from http://www.mrlc.gov/nlcd2011.php
[6] USGS The National Map Viewer, http://viewer.nationalmap.gov/viewer/
[7] WRC ditch shape file received from Paul Davis of the Minnesota Pollution Control Agency on June 24, 2013

polygons in CONUS were removed. Additional area was removed if it was within an existing channel or ditch or if the line length was below a minimum threshold (100 m).

BFMO: Buffer management options were added after the January 2016 stakeholder meeting at the request of stakeholders following a Minnesota state-wide buffer initiative. Unfortunately, at the time BFMO was added to MOSM, the official map of affected waterways was not yet available. Because of this, we created our own for use in MOSM. NHD blue line data were used to identify all natural streams and rivers and manmade streams and ditches. All streams were given a 50 foot buffer, and all NHD blue lines identified as artificial waterways were given a 16.5 foot buffer. There are some differences between this buffer file and the official file released in July 2016.

WCMO and ICMO: Water control management options include any MO designed to hold water back. ICMOs specifically refer to in-channel water control MOs and WCMOs broadly refer to any wetland restoration or temporary water storage basin not in a ditch or channel. Candidate sites for ICMOs included all "public open ditch" lines from the WRC ditch shape file. WCMOs were identified as topographic depressions on 3-m DEM (filled DEM minus raw DEM). Only topographic depressions with high topographic index (*TI*) values were used

$$TI = \ln\left(\frac{\alpha}{tan\beta}\right) \quad (13)$$

Developed land, forest, water, and existing wetlands as determined by NLCD data were removed as were sites on existing wet area polygons in CONUS and sites where existing conservation easements already exist. Finally, WCMO sites < 0.74 acres (3000 m^2) were removed to avoid having numerous sites that would cause significant challenge for producers to work around in fields.

RAMO: Ravine management options were modeled as MOs that provide additional stability to ravine tips, preventing ravine growth. Examples include berms or WASCOBs placed around ravine tips. All ravines were mapped by hand from lidar data, noting the sharp slope break between the low-gradient uplands and the steep ravine walls. Tips were counted and recorded per mapped ravine.

NCMO: Near-channel management options specifically refer to actions that directly stabilize a bank or bluff. In MOSM, only bluffs are considered as these are the primary sources of sediment to the stream. For the sediment budget, bluffs were mapped as areas with > 3m of relief in a 9m x 9m area and then trimmed to only include bluffs immediately adjacent to streams. The area available for NCMO was the same bluff area determined by the sediment budget.

Summary:

The determination of areas where individual MOs could be applied allowed the model to have realistic potential area from which to select treatment areas in different scenarios. These areas were initially mapped in ArcGIS and the shapefiles created were summarized into a series of tables, noting the available MO area in each sediment subbasin within the GBER watershed. It is important to note that these maps do not specify which sites should be used first. In many cases, the user of MOSM can specify which prioritization scheme should be used in selecting various sites (i.e. largest WCMO sites first or sites closest to existing wetlands first), but the model does not provide guidance in terms of placement at scales finer than the subbasin level. There are several new tools in existence now that can be used to look at specific sites at the scale of an individual landowner's property (for example PTMap (HEI 2016), or ACPF (Tomer et al., 2013)), and these can be used in conjunction with MOSM if specific site locations are desired. The strength of MOSM is the ability to integrate all of the different management actions together at the scale of a 9200 km^2 watershed, in real-time, to compare different portfolios of actions across a wide range of possibilities (water retention to buffers to bluff stabilization). More information on the MOSM model itself will be covered in the final report.

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