Sediment budgets indicate Pleistocene base level fall drives erosion in Minnesota's greater Blue Earth River basin

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Abstract

Minnesota River (MNR) tributaries are some of the most turbid in the state; many are impaired for turbidity under the Clean Water Act. Suspended sediment affects ecology and economics from headwater streams to Lake Pepin, where much of it is deposited. This project created sediment budgets for the greater Blue Earth River basin (GBERB), a group of MNR tributaries with some of the highest sediment loads. A sediment budget is a way to understand the movement of sediment though a watershed that can help landowners, land managers and other interested parties allocate resources to effectively reduce sediment loads.

Our budgets use historic aerial photos and lidar-derived digital elevation models to delineate source extents and measure bluff and channel erosion rates in ArcGIS; these data were combined with upland and ravine erosion rates measured in the Le Sueur watershed. We explored sediment budget sensitivity to adjustments for sediment storage, bluff vegetation state, sedimentology, erosion rate extrapolation methods and higher-precision bluff extent delineations.

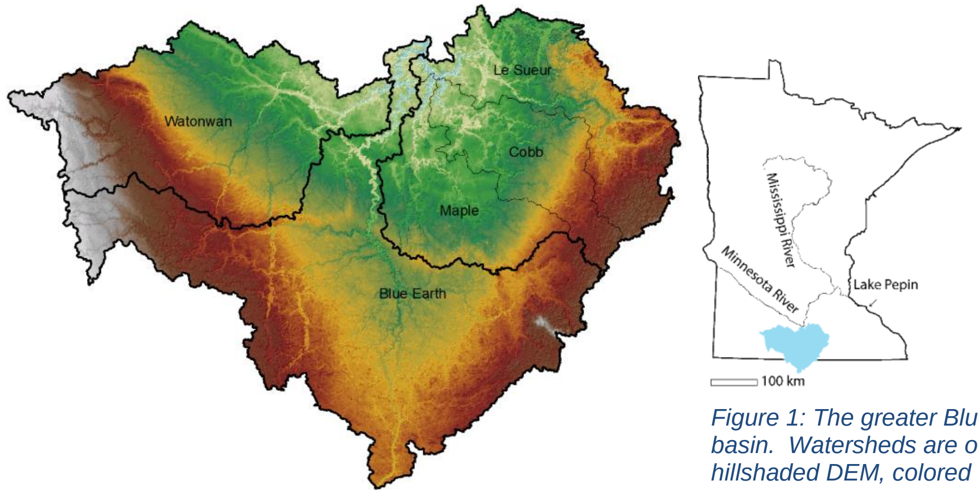

Figure 1: The greater Blue Earth River basin. Watersheds are overlain on a hillshaded DEM, colored by elevation.

Tributaries of the Minnesota River are adjusting to a profound (70m) base level fall at the end of the Pleistocene. About half of the GBERB sediment load comes from reaches below knickpoints where response to base level fall drives erosion of near-channel features like bluffs. Budgets are not sensitive to bluff erosion rate extrapolation techniques and we found no statistically significant correlations between decadal bluff retreat rates and parameters such as bluff vegetative cover, slope, size, aspect, sediment texture or stream power. There is little in-stream sediment storage in the GBERB: accommodation space primarily occurs on floodplains and in lakes, but these features are scarce due to base level fall and agricultural practices. Surficial sediment in the GBERB is composed primarily of homogeneous glacial tills and load estimates have little sensitivity to adjustments for the different bulk density and texture of glaciolacustrine and glaciofluvial sediments. It is important to construct an accurate inventory of bluff extents: A poorly-managed but plausible inventory increased the sediment budget by about 15%. These results will be useful in constructing sediment budgets for other MNR tributaries and in managing the GBERB.

Shapefiles and data from this project are available through the University of Minnesota Digital Conservancy and the U-Spatial Data Locker. Please contact the authors: bevisma@gmail.com or kgran@d.umn.edu

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Introduction: Turbidity, human history and base level fall in the GBERB

High total suspended solids (TSS) have long generated interest in the greater Blue Earth River basin (MPCA et al., 2009). 80-90% of the sediment in Lake Pepin comes from the Minnesota River (MNR) basin, an area that comprises just 1/3 of its drainage area (Kelley and Nater, 2000). Up to 50% of the sediment load in the MNR comes from the GBERB, which makes up just 9% of the basin (Wilcock, 2009). High suspended sediment loads in the GBERB are responsible for turbidity, sedimentation and water quality problems, which negatively impact ecology, recreation potential and human health along the rivers and downstream (MPCA et al., 2009). Many rivers in the GBERB are impaired for turbidity according to Section 303d of the Clean Water Act.

Rivers draining intensively row-cropped farmland often transport large amounts of sediment suspended in the water column (Simon and Rinaldi, 2000). Conversion of native perennial vegetation to cropland increases sediment loads (Blann et al., 2009). Improved management practices following the Dust Bowl led to decreasing sediment yields in many agricultural watersheds (Knox, 2006). However, work in the MNR indicates that despite better management of erosion at the field scale, watershed erosion rates have not changed in the last century (Belmont et al., 2011). In contrast to decreasing erosion rates elsewhere, sedimentation rates in Lake Pepin have remained constant over the last 65 years (Engstrom et al., 2009).

A shift from upland to near-channel sediment sources (such as bluffs, banks and ravines) sustains high sediment loads on the Le Sueur and throughout the MNR basin (Belmont et al., 2011). The shift is concomitant with higher discharge and changing agricultural practices. In the last 70 years, discharge increased in the Minnesota River Basin over all measured streamflow parameters (Novotny and Stefan, 2007). Complicated changes in discharge seasonality, agricultural practices and sediment sources have led to debate about whether climate change, agriculture in general, or specific agricultural practices have more influence on increased discharge. Increased discharge is of interest because it is widely understood that high flow events are primary drivers of near-channel erosion and discharge is often non-linearly correlated to erosion volume (Wolman and Miller, 1960; Knighton, 1998; Mitchell et al., 2014; Cho, 2015). Recent analysis of land-use changes and the seasonality of precipitation and discharge found that more than 50% of increased discharge from the GBERB and other MNR watersheds is due to agricultural drainage (Schottler et al., 2013). These hydrologic changes set the stage for permanent change to flow duration curves and hydrographs, and more erosive streams and storms (Schottler et al., 2013).

The shift from upland to near-channel sediment sources reflects a primary difference between the MNR and other Corn Belt watersheds. MNR tributaries were subject to dramatic Pleistocene base level fall. Base level fall in the GBERB and MNR basin was caused by drainage of glacial Lake Agassiz through glacial River Warren at the end of the Pleistocene (Clayton and Moran, 1982; Matsch, 1983). Glacial Lake Agassiz was a large proglacial lake that formed as the Laurentide ice sheet retreated to the north of the continental divide (Figure 2, Upham 1890). At 13.4k calendar years ago (11.5k radiocarbon years B.P.), meltwater issued from glacial Lake Agassiz through a low in the Big Stone Moraine near the modern Minnesota-South Dakota border (Fenton et al., 1983; Teller and Clayton, 1983). The resulting glacial River Warren channel is the valley of the modern Minnesota River.

Figure 2: The maximum extents of glacial Lakes Agassiz and Minnesota with regard to the modern GBERB. Note: these lakes were present at different times. Figure modified from Jennings, 2007

Glacial River Warren played an important role in shaping the GBERB. The river scoured 65m below the till surface at the mouth of the Blue Earth River, initiating channel incision towards the lower base level. Incision moves upstream on GBERB channels as a knickpoint (Gran et al., 2009). Currently, the knickpoint is 35-64 km upstream of the MNR on the three major GBERB tributaries: the Blue Earth, Watonwan and Le Sueur (Figure 3).

Knickpoints divide the basin into two distinct regions. Below knickpoints, channel gradients are steep, channels are deeply incised below the upland surface, and they flow through narrow valleys lined in bluffs and ravines. Above knickpoints, streams flow through a low-gradient landscape dominated by agricultural fields. The steep landscape below knickpoints is the result of watershed adjustment to knickpoint migration. Water and sediment gauges on the Le Sueur River indicate a significant rise in suspended sediment loads as the channel passes through the incised zone where near-channel sediment sources are abundant (MPCA et al., 2009). Many studies have documented the prevalence of near-channel sediment sources in the Le Sueur and GBERB (Thoma et al., 2005; Belmont et al., 2011; Lenhart et al., 2012; Day et al., 2013; Kessler et al., 2013). Fluvial adjustment of the GBERB to base level fall appears to prime the river for high near-channel erosion rates (Gran et al., 2009). Results from this project indicate that other GBERB channels have similar patterns of sediment loading and suggest this similarity extends to other MNR tributaries.

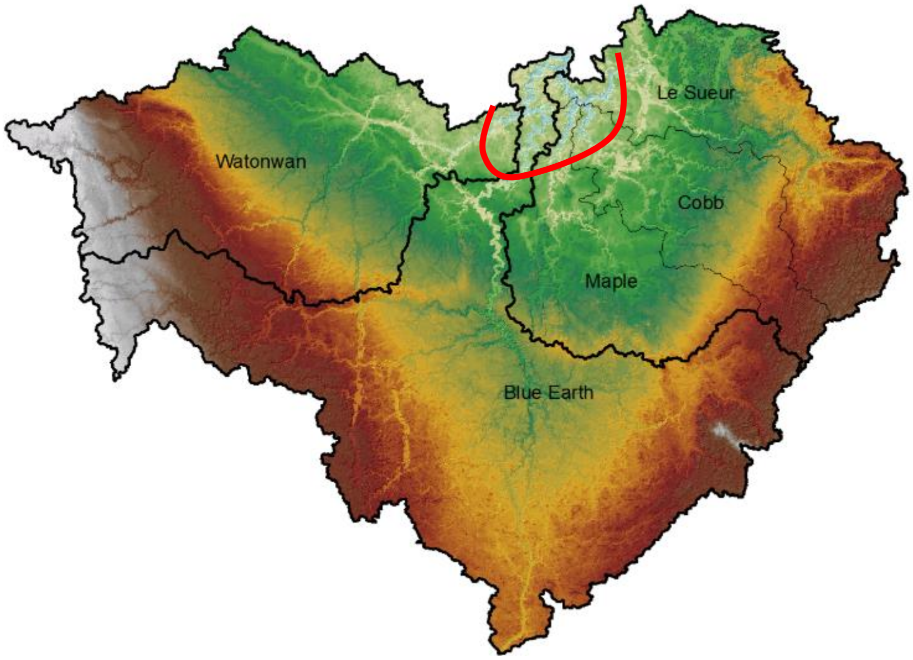


Figure 3: Approximate location of knickpoints in the GBERB.

Background

The Le Sueur Sediment budget

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 (Equation 1).

$$\text{out} = \text{in} - \text{storage} \tag{1}$$

A sediment budget could rely on empirical models, cartographic surveys, theoretical knowledge or many other methods to obtain data about sediment inputs. A mass-balance relationship provides a powerful check on calculated sediment inputs and outputs. It is well understood that the fate of most sediments eroded on the landscape is not to flow out at the river mouth, but to be stored in the watershed as alluvium or colluvium (Wolman, 1977; Walling, 1983; Walter and Merrits, 2008). Sediment budgets have been instrumental in efforts to understand fluvial sediment load from the global scale to sediment transport at the reach scale (Gilbert 1917; Syvitski and Milliman, 2007).

Work on the Le Sueur River measured erosion and sediment delivery rates from four primary sediment sources (Equation 2). The project converted total sediment load to only the fine (silt and clay) sediment load in order to compare estimated loads against suspended sediment gauge records (Belmont et al., 2011). The practice is continued here. For brevity, all mentions of sediment load in this document refer only to the fine sediment load. Estimated sediment load supplied from bluffs, streambanks, ravines and uplands matched the measured Le Sueur River suspended sediment load within 5% (Figure 4; Belmont et al., 2011).

$$Qs = Bl + Ba + R + U - Fp \tag{2}$$

In Equation 2, Qs is suspended sediment discharge, Bl is sediment from bluffs, Ba is sediment from banks, R is sediment from ravines, U is net sediment from uplands and Fp is in-channel deposition. The bank term, Ba, is the sum of sediment eroded by channel migration (Ba_M), incision (C) and widening (Ba_W). Many sediment sources are assumed to be minor and are not explicitly considered in the budget. Such sources include sediment from landscape disturbance like fire or clearing, sediment from urban areas, construction, road runoff and aeolian sediment. Sediment from these sources is lumped with other sources.

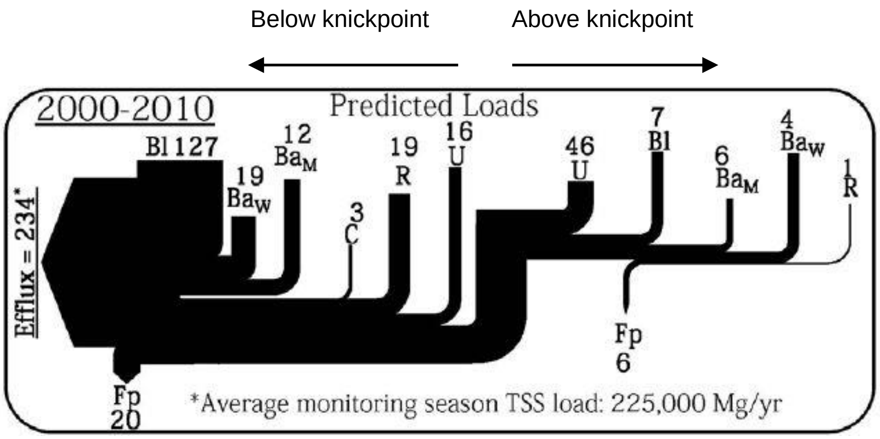


Figure 4: Estimated annual fine sediment loads for the modern Le Sueur River (from Belmont et al., 2011). Sediment sourced above the knickpoint to the right, below on the left. Bl = bluffs, R = ravines, U = uplands, C = channel incision Ba_M = bank meandering contributions Ba_W = bank widening contributions, Fp = floodplain deposition.

Greater Blue Earth River watersheds share similar geologic history and have similar geomorphology. The landforms that supply sediment to the Blue Earth and Watonwan Rivers are similar to the landforms that supply sediment to the Le Sueur River, and similar methods were used to construct sediment budgets. It was important to understand the components of the Le Sueur budget before constructing Blue Earth and Watonwan budgets. The following is an introduction to the primary sediment sources and sinks.

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 can be impressive features: the largest have nearly vertical faces up to 70m high and 500m long, and they line about 50% of the lower parts of GBERB valleys. Bluffs are most often composed of till, but when they are not the full height of the valley they are capped with thin layers (usually < 3m) of alluvial sediment (Day et al., 2013). Such bluffs are strath terraces and record the incisional history of GBERB channels (Gran et al., 2009). Many bluffs in the GBERB are recently stranded terraces and stand just a few meters above the modern channel and floodplain. In contrast to banks, bluffs are out of reach of typical annual floods and purely erosional features.

Bluff erosion is primarily driven by fluvial incision, sapping, and freeze thaw (Day et al., 2012). Toe erosion occurs when a stream channel migrates into a bluff toe. Erosion of the bluff toe oversteepens the bluff face and reduces support for material above leading to mass wasting (Thorne and Tovey, 1981). Aspect is well-correlated to bluff retreat rates along some tributaries of the Le Sueur, suggesting the importance of freeze-thaw to bluff erosion (Day et al., 2013). Bluffs composed of overconsolidated tills appear to be more resistant to fluvial erosion than normally-consolidated bluffs (Gran et al., 2011), but overconsolidated bluffs have joint patterns that may make them more susceptible to frost wedging (Day et al., 2013). Sediment that erodes from a bluff will often collect in a fan at the bluff toe. This material is less dense and less cohesive than its parent material, and probably does not remain in place for long. Even low flows are able to easily entrain such material (Simon et al., 2000). The erodibility of colluvial bluff toes and of bluff parent material is influenced by moisture content. Higher flows that saturate channel materials are strongly correlated with high bluff erosion in the Le Sueur and in other watersheds (Kesel and Baumann, 1981; Day et al, 2012; Neitzel, 2013). Sapping, or erosion by groundwater seeping from the face of a bluff, is visible on GBERB bluffs. Groundwater flow from the bluff face increases pore pressure and can cause erosion at and below the seep (Kessler et al, 2013).

Vegetation can play a role in stabilizing river banks (Gran and Paola, 2001; Lenhart et al., 2013). But bluffs in the GBERB are generally too tall for tree roots to have any influence on erosional processes near the channel (Day et al., 2013). If a bluff has been spared from lateral channel migration for decades, it will trend towards a gentle angle of repose. Often inactive bluffs have dense tree cover on their slopes right down to the channel. However, even in this seemingly stable configuration, bluffs become rapidly steepened again when the river resumes migration into their toes. Day and others (2013) found little correlation between modern vegetation cover and decadal-scale bluff retreat rates on the Le Sueur River.

Streambanks

Banks are the boundaries of channel networks which are low enough that the river can overtop them during floods. Near-channel sediment sources erode by a variety of mechanisms, but are fundamentally driven by excess energy on the banks (Ikeda et al., 1981). Erosion occurs when bank sediments cannot resist the force of water in the channel. High bedload supply, low bank strength and high stream power promote lateral migration and can lead to high erosion rates (Seminara, 2006).

Channels in the GBERB are divided by the 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, 2012). But any incision is slow relative to reaches where incision is driven by adjustment to base level fall. In channels that are not incising, bank erosion on the outside of meander bends is balanced by deposition on the floodplain, making net sediment flux from migration in the reach zero (Lauer and Parker, 2008). Banks above the knickpoint are primarily alluvial in nature, composed of reworked floodplain sediment.

Below the knickpoints, channels in the GBERB are incising rapidly (Gran et al, 2009; 2013). This has implications for the movement of sediment in the channel. First, channel incision itself becomes a sediment source. Incision in the 13.4 ka following the existence of glacial River Warren is recorded by strath terraces lining GBERB channels (Gran et al., 2013). 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 only recently become important. Flows have increased in many Minnesota agricultural watersheds in the last-half century. When annual discharges increase, channel geometry changes in order to move more water. Channels may widen, deepen, straighten or steepen to accommodate higher discharge rates. MNR tributaries have widened over the years 1975–2009 to accommodate increased annual discharge relative to the period from 1940–1974 (Gran et al., 2011; Schottler et al., 2013).

Ravines

Ravines are steep, deep, incised gullies at the tips of the channel network. Ravines connect the uplands to the river valleys, and are often formed by ephemeral streams with only seasonal discharge. Such sites in the GBERB 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 GBERB 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. In dry years ravines are responsible for as little as 2% of the Le Sueur sediment budget (Gran et al., 2011). However, ravine loads are very nonlinear. In a wet year, ravines can be responsible for as much as 15% of the Le Sueur sediment yield. They can have very high sediment load concentrations and can locally add a lot of sediment to the system. Sandbars at ravine mouths, probably deposited during spring floods, can persist in GBERB channels throughout the summer.

Uplands

Eighty percent of the GBERB is low-gradient upland areas cultivated in row-crop agriculture. Upland-derived sediment is eroded by wind, precipitation impact, overland flow and concentrated flow in rills and gullies. European settlement of the GBERB in the 19th century marked the beginning of tall grass prairie and wetland conversion to agricultural land use. Prior to settlement, isolated wetlands were abundant on the flat, hummocky glacial landscape. Wetlands were drained starting at the time of settlement to create farmland and improve agricultural productivity (Belmont et al., 2011). Historically high corn prices promoted a recent intensification of agriculture, agricultural drainage, and land use conversion in the basin and elsewhere (Wright and Wimberly, 2013). Artificial drainage has important positive agricultural effects on the GBERB uplands. GBERB soils are rich in silt and clay (USDA, 2012). Water infiltrates slowly into these soils and crop conditions can be improved by moving water off the landscape more quickly. Tiled fields are ubiquitous in the basin because they increase crop yields. Pattern tile networks often empty into open ditches, which are artificial extensions or modifications of the natural channel network. The addition of drainage ditches to the Blue Earth watershed has increased the length of stream networks by about 25% since the time of European settlement (McKay et al., 2013). Nearly 20% of the area of the modern GBERB was once a wetland but has been drained (Schottler, 2012).

Generally speaking, agricultural uplands with or without substantial artificial drainage have low sediment delivery ratio; that is; they deliver just a fraction of eroded soil to channel networks (Quade, 2000; Lenhart, 2008; MPCA et al., 2009). 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., 2012). Some aspects of agricultural drainage, particularly drain tiles, may further reduce surface soil erosion on agricultural fields. Increased hydraulic conductivity in tiled fields reduces overland flow and erosion at low precipitation rates. However, widespread surface and subsurface drainage affect the volume and timing of water leaving the uplands and entering channels, thereby extending the influence of upland areas on GBERB sediment loads to erosion of downstream near-channel sources (Schilling and Helmers, 2008; Schottler et al., 2013). Changing agricultural practices have reduced sediment derived directly from GBERB uplands, but have simultaneously increased discharge and made streams more erosive.

Storage

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). 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 GBERB budget presented here adds estimates of sediment storage in lakes. Storage on fields is lumped into the uplands term by including only the upland sediment that reaches channels in the budget.

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., 2011). We therefore expect that lakes high in the Blue Earth watershed may be very efficient sediment traps. However, most lakes in the GBERB have been drained for agricultural purposes (Table 1; Schottler et al., 2013). The limited extent of lakes in the basin means that the total amount of sediment trapped may be low.

Table 1: Characteristics of GBERB watersheds

	Watonwan	Blue Earth	Le Sueur
knickpoint distance upstream (km)	35	64	35-40
area (km^2)	2,262	4,054	2,878
maximum incision below upland surface (m)	40	70	75
discharge (mean annual cfs, 1941-2012) [a]	415	1148	583
water yield, cfs/km^2/yr	0.18	0.28	0.20
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) MPCA et al., 2009; b) Fry et al., 2011; c) Schottler, 2012; d) McKay et al., 2013

Glacial geology and independent variables that affect erosion rates

The layout of the GBERB follows broad-scale trends that affect both sediment stability and the forces that drive erosion. Surficial geology, climate and stream morphology change in the basin over thousands of years and tens of kilometers. Many of these large-scale trends were investigated as potential predictors of bluff erosion rates. Additionally, this project explores how adjustments for lake storage, bluff sediment texture, and bluff vegetation affect load estimates. Many of the hydrologic and sedimentology variables affecting the amount of sediment eroded from GBERB channels are closely related to the glacial geology of the basin. This section addresses many of the variables that affect bluff erosion rates.

The landscape of the GBERB was created by the downwasting of the Des Moines lobe of the Laurentide Ice Sheet (Jennings et al., 2011). Relatively homogenous clay-loam and silt-loam glacial diamicton (tills) are up to 60m thick in the GBERB (Meyer et al., 2012), and many are overconsolidated (Jennings, 2007; Jirsa et al., 2010). Till stratigraphy is primarily capped by the Altamont member of the New Ulm Formation, but most of the Le Sueur watershed is covered in fine-texture glacio-lacustrine sediments related to glacial Lake Minnesota (Figure 2, Figure 5). Glacial Lake Minnesota was a very short-lived (c.50 years) supraglacial and proglacial lake (Jennings, 2007). The sediments draped over existing topography, creating a smooth modern land surface. Sediments in the southern part of the lakebed reach 6m thick, but in most places, the sediments average 2m thick. When the Des Moines lobe retreated to the point where it was no longer able to impound glacial Lake Minnesota, proto-GBERB rivers drained it away to the north (Jennings, 2007). In areas not inundated by glacial Lake Minnesota, ground moraine creates a hummocky land surface. A complex of Altamont terminal moraines forms the boundary of the GBERB.

In the western GBERB (the Blue Earth and Watonwan watersheds) surficial geology is coarser, reflecting a number of different glacio-fluvial processes (Jennings et al., 2012). Tunnel valleys mark subglacial channels that drained water from underneath the ice lobe. The depressions left by the tunnel valleys are often occupied by modern lakes. Where these channels exited the glacier they deposited sediment in large, coarse fans. The north branch of the Watonwan River has unusually high sand and gravel content, since it occupies a formerly-braided meltwater stream channel (Jennings, 2010).

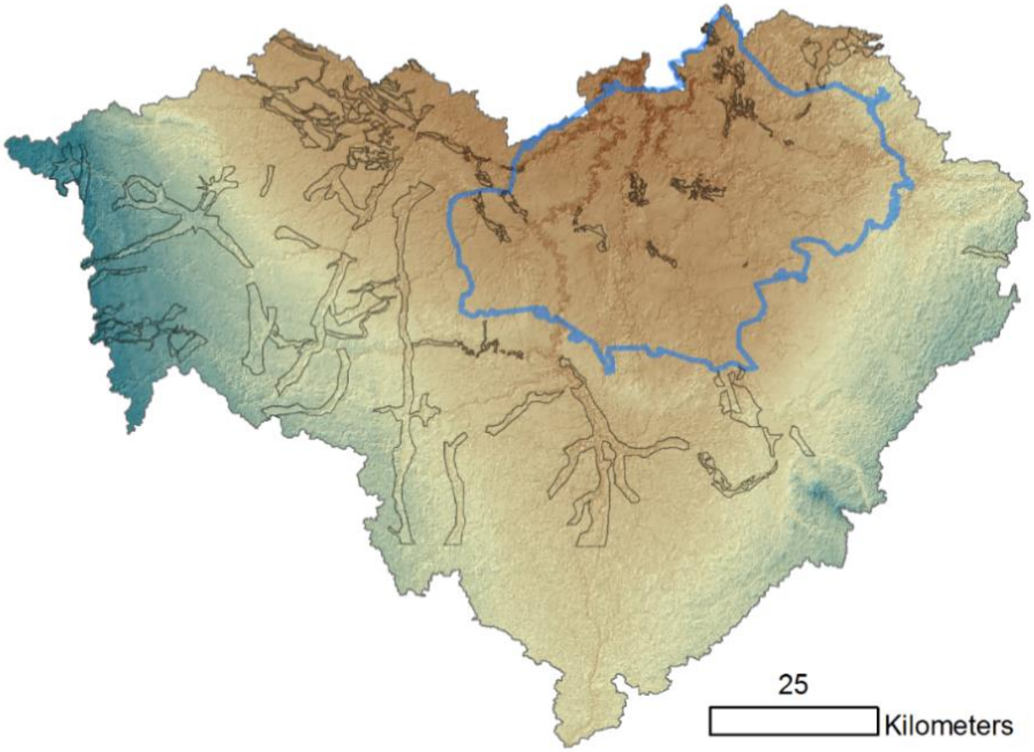


Figure 5: Quaternary sediments in the GBERB: tunnel valleys and outwash channels (black), approximate extent of glacial Lake Minnesota sediments (blue). Tunnel valleys also visible on topography in Figure 1. Blue Earth and Watonwan Rivers often follow glacial outwash channels and tunnel valleys.

Above Winnebago, the Blue Earth River and most of its tributaries follow outwash channels for a portion of their lengths (Figure 5). It appears that the Blue Earth River follows the course of a tunnel valley downstream of Winnebago. When the river turns northeast, the valley continues its trend northwest into the Watonwan watershed, where the Watonwan follows it, too. These surficial sediments are an important part of the western GBERB, and a primary contrast to the eastern GBERB, where the surficial geology is dominated by glacial Lake Minnesota sediment. Glacio-fluvial sediments have the highest concentrations of coarse sediment (sand and gravel) in the basin and may be an important source of bedload to upstream reaches on the Blue Earth and Watonwan (Table 2).

Table 2: 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.

Methods

Gauges, subwatersheds and load

The GBERB sediment budget is divided into subbasins for two primary reasons: first, in order to compare budget-estimated sediment loads with calculated total suspended solids (TSS) loads at river gauging stations. The total TSS load is calculated from daily discharge data and grab samples with the Army Corps of Engineers FLUX program by the Minnesota Pollution Control Agency (MPCA) and partner agencies. The second reason we use subbasins is in order to extrapolate bluff erosion rates within similar geomorphic settings. Subwatersheds were defined based on broad drivers of fluvial erosion. Primarily, divisions were made at channel confluences and knickpoints (Figure 6, Figure 7). Fundamentally, channel reaches below knickpoints are affected by knickpoint incision, while reaches above knickpoints are not, so this technique means rates are only extrapolated to sources with similar geomorphic setting. Previous work in the basin found that when bluffs are grouped according to their location relative to knickpoints, average subwatershed erosion rates increase downstream (Day et al., 2013).

Estimated sediment budgets on the Le Sueur River are well constrained by a group of seven gauges. Loads on the Blue Earth and Watonwan rivers are monitored by a single gauge on each river (Figure 6). The gauge on the Blue Earth is located just downstream from Rapidan Dam. Downstream of Rapidan Dam, 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 to the town of Vernon Center. We consider this reach to be below the knickzone. Because the basin is so big, we further divided the area of the Blue Earth basin above the knickpoint at the town of Winnebago. Because of the existing body of work on Elm Creek, we also separated calculations for that river (Lenhart et al., 2010).

On the Watonwan, the Garden City gauge is fortuitously located at the knickpoint. However, there is no gauge measuring knickzone loading on the Watonwan; the gauge at Rapidan measures discharge from the Watonwan watershed and the Blue Earth watershed. MPCA-published loads for the Blue Earth are determined by subtracting the load at the Garden City 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.

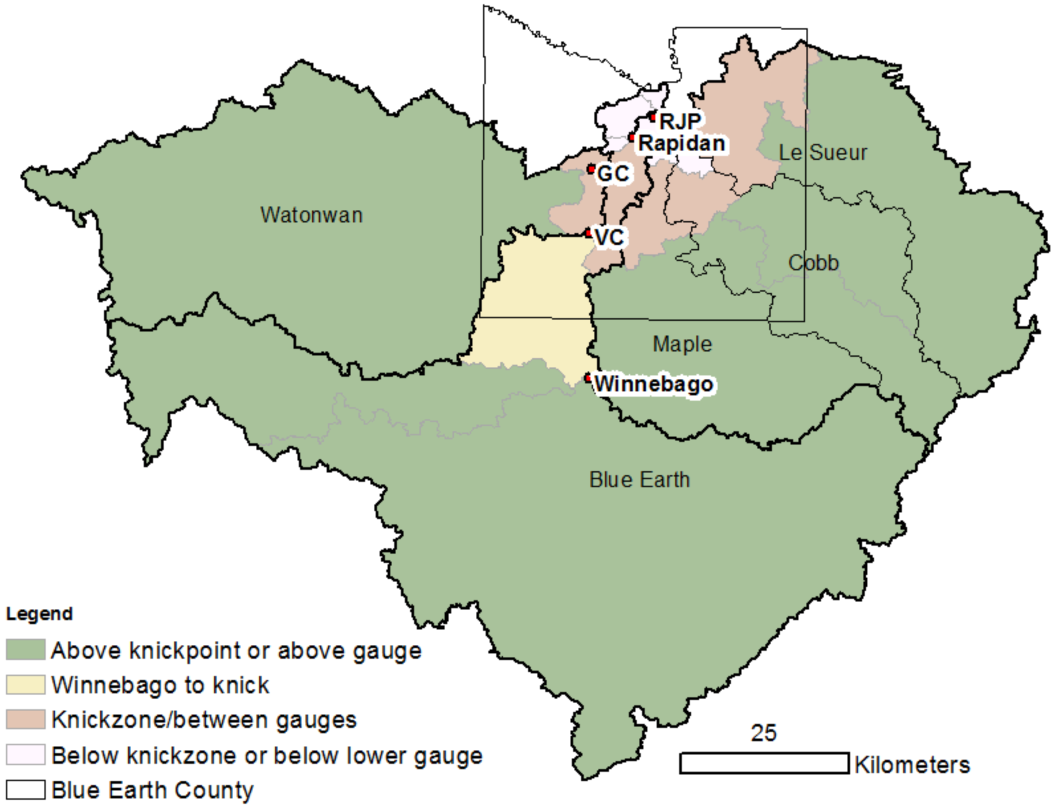


Figure 6: Subwatersheds based on geomorphic domain in the GBERB. Abbreviations for locations referenced in the text are: RJP: Red Jacket Park, GC: Garden City, VC: Vernon Center. Knickpoints are located at boundary of pink and green subwatersheds.

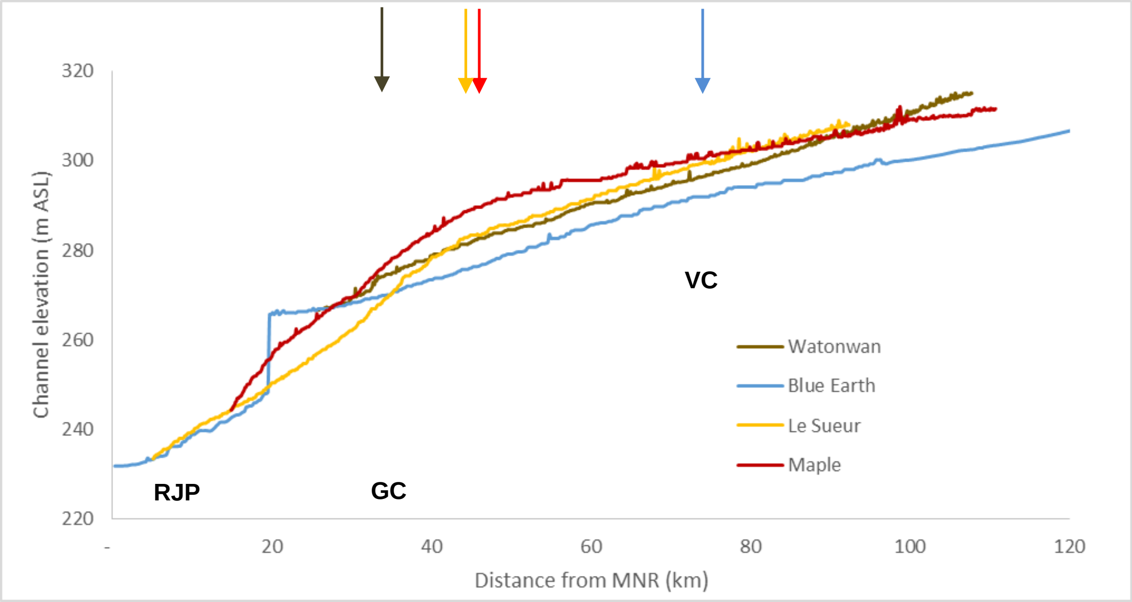


Figure 7: GBERB channel long profiles. Knickpoints generated by late-Pleistocene base level fall (location indicated by arrows) separate downstream zones of incision from relatively unaffected upstream reaches. In Figure 6, knickpoints are at the boundary between pink and green watersheds. Locations of Red Jacket Park, Vernon Center, and Garden City also shown in Figure 6. The Rapidan Dam is clearly visible on the Blue Earth long profile.

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, and 4) calculate volume and mass of fine sediment eroded.

Define and identify GBERB bluffs

To define GBERB bluffs, Esri ArcGIS was used to identify tall, steep features in the basin. 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 in the GBERB. DEMs were obtained from the University of Iowa GIS library and theMinnesota 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. Many features were then removed from the results of this simple query, because sediment eroded from steep off-channel features will be trapped on floodplains, so it is not appropriate to include these bluffs in the sediment budget. Other steep features are accounted for differently (e.g., ravines).

Off-channel bluffs were first removed by applying a buffer around the active channel. This step removed features that were not within 100m of GBERB channels larger than Strahler stream order 3 or within 30m of channels of stream order 3 or lower. Then a buffer was used to exclude features for which no part was within 30m of the manually traced centerlines created to measure streambank meander migration. Bluffs along ditches (as defined in the United States Geological Survey National Hydrology Database) were also excluded from the sediment budget. Ditches are subject to routine dredging and maintenance. Bluff sediment eroded into ditches is removed frequently and therefore does not enter main channels and become part of the total sediment load reaching the mouth. 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).

Finally, manual methods were used to cull the bluff inventory. The first coarse run through the watershed primarily focused on deleting entire bluffs that were not connected to modern channels but persisted following automated exclusions. This step also deleted a lot of features from lakeshores. The final step primarily trimmed parts of bluff polygons that were not on active channels rather than entire bluffs.

Figure 8 is an example of how some bluffs in the original budget were trimmed from the revised budget. Bluff A was excluded from this budget because it overlaps bedrock outcrops. Half of bluff B was excluded because it is not directly connected to the active modern channel. In this case, a cross section taken normal to the channel revealed a 30m wide floodplain separating the northern part of the feature from the channel.

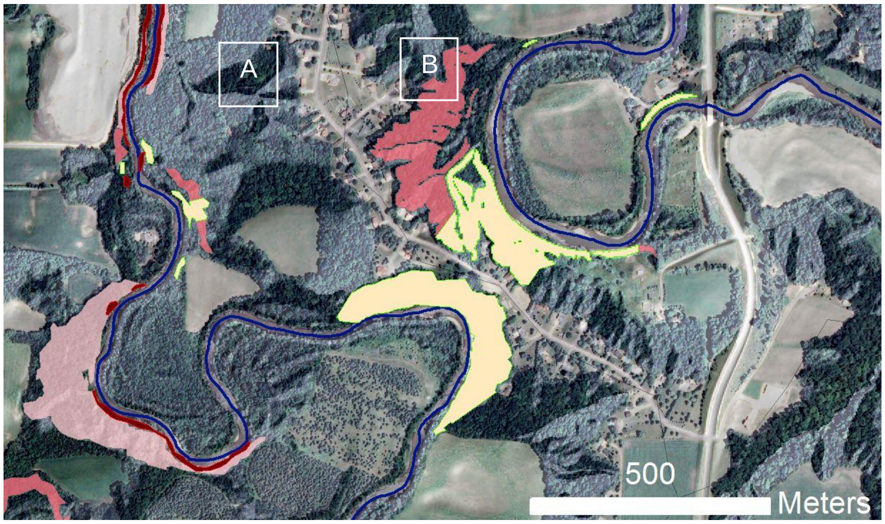


Figure 8: Original budget bluffs, pink, and revised budget bluffs, tan. Bedrock outcrops are dark brown/red. Bluffs or parts of bluffs in the original Le Sueur budget that were excluded from the revised budget were excluded primarily because bluffs were composed of bedrock (A), or bluffs were not connected to the active channel (B). 2008 NAIP aerial photo overlying a 3m hillshade. Image location is just upstream from confluence of Maple (left) and Le Sueur Rivers (right). Road on right side of image is County Highway 16.

Physical attributes were collected from the bluffs that remained following trimming. Bluff surface area is 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). Surface area is further used here to calculate average local erosion rates. Day et al., (2013) defined surface area (SA) as bluff length (l) multiplied by maximum bluff height (h). Day et al., (2013) measured bluff length and height manually to find surface area, but we use map area (A) and average bluff slope (θ) to find surface area (Equation 3). Map area is the projection of bluff face to a horizontal plane and is calculated easily in ArcGIS attribute tables. Average bluff slope is the average of the slopes of each raster cell within the bluff shapefile, and was calculated using the *slope* and *zonal statistics as table* tools.

$$SA = A * \tan \theta \quad (3)$$

Figure 9 shows the parameters required to calculate surface area, which is the projection of the sloped bluff face onto a vertical plane.

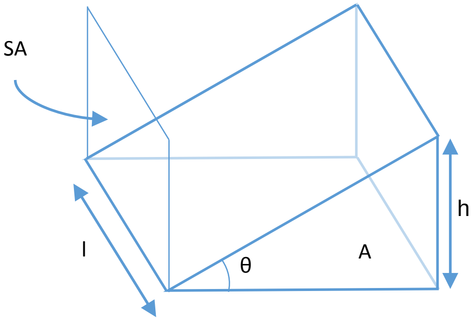


Figure 9: A schematic drawing illustrating bluff surface area (SA) and the parameters used to calculate it. Height (h), average bluff slope (θ) and area (A) are calculated with tools in ArcGIS and used to calculate length (l) and surface area.

For this study maximum height is the relief within each bluff feature, measured using the ArcGIS tool *zonal statistics as table* and a 3m DEM. Bluff surface area was divided by height to define bluff length (Equation 4).

$$l = SA/h \tag{4}$$

Other attributes that affect the mass of suspended sediment supplied from bluffs were collected from geologic maps and aerial photographs. These attributes include bluff stratigraphy, vegetation cover, and bluff material properties. Surficial geology maps were used in ArcGIS to identify bluffs containing Quaternary alluvium (Jennings, 2010; Jennings et al., 2012). Pleistocene alluvium in the GBERB 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 GBERB; 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 the GBERB 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 give 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 GBERB. These units are on average 3m thick in the GBERB (Meyer and Lively, 2012; Gran et al., 2009).

Measure crest retreat and toe migration rates

Bluff crest and toe migration are 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 are measured over the longest timescale possible with the photographs available. Retreat rates measured over shorter timeframes are overwhelmed by georeferencing and tracing error (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 are 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 10). In this case, we model the volume of bluff sediment eroded as a triangular prism (Equation 5).

$$V_{E(away)} = CRR/2 * h * l \qquad (5)$$

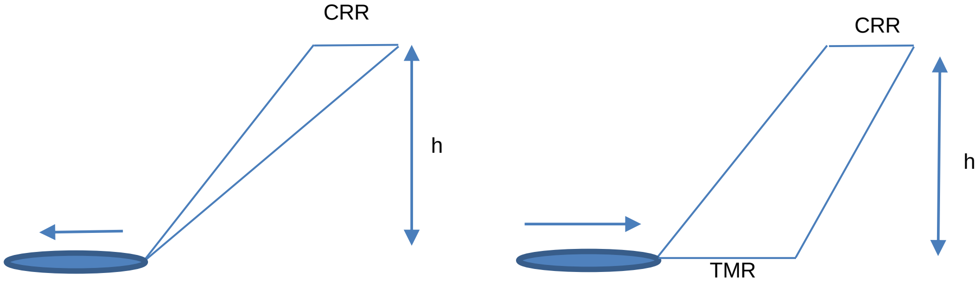


Figure 10: Schematic cross sections of eroding bluffs. When a channel is migrating away from a bluff, erosion volume is modeled as a triangle. The crest may retreat, but the toe is pinned. When a channel is migrating toward a bluff, erosion volume is modeled as a trapezoid. The crest and toe may both retreat at different rates.

Because the volume eroded is the erosion rate multiplied by bluff surface area, Equation 5 describes the erosion rate when the river is migrating away from a bluff (E_{away}) as:

$$E_{away} = CRR/2 \qquad (5b)$$

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:

$$V_{Etoward} = (CRR+TMR)/2*h*l \qquad (6)$$

and

$$E_{toward} = (CRR+TMR)/2 \qquad (6b)$$

To combine Equations 5b and 6b into an average bluff retreat rate, we need to know how often the river migrates into the bluff and how often the river migrates away. While we recorded channel migration direction at all the studied bluffs, we reason a priori that over long time scales the river is no more likely to migrate toward a bluff as it is to migrate away from a bluff. Our study was designed to examine only bluffs that are connected to the channel, and when channels migrate away from bluffs, they become disconnected from the river. Channel migration into bluffs is therefore over-represented in our data. Rather than use observed migration direction, we assume that channels spend half the time migrating toward any given bluff, and half the time migrating away. Thus:

$$E = E_{away}/2 + E_{toward}/2 \qquad (7)$$

Substituting Equations 5b and 6b into 8 gives:

$$E = (½CRR)/2 + (½(TMR+CRR))/2 \tag{8}$$

which is equal to:

$$E = (2CRR + TMR)/4 \tag{9}$$

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

$$V_E = SA*(2CRR + TMR)/4 \tag{10}$$

or

$$V_E = SA*E$$

Interpolate and extrapolate bluff erosion rates

Measured bluff erosion rates are applied to bluffs on which it was not possible to measure crest and toe retreat distances. 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 11).

$$E_{interpolate} = \Sigma V_E/\Sigma SA \tag{11}$$

A 3 km radius was used because it minimizes accidentally sampling data from adjacent channels (Figure 11).

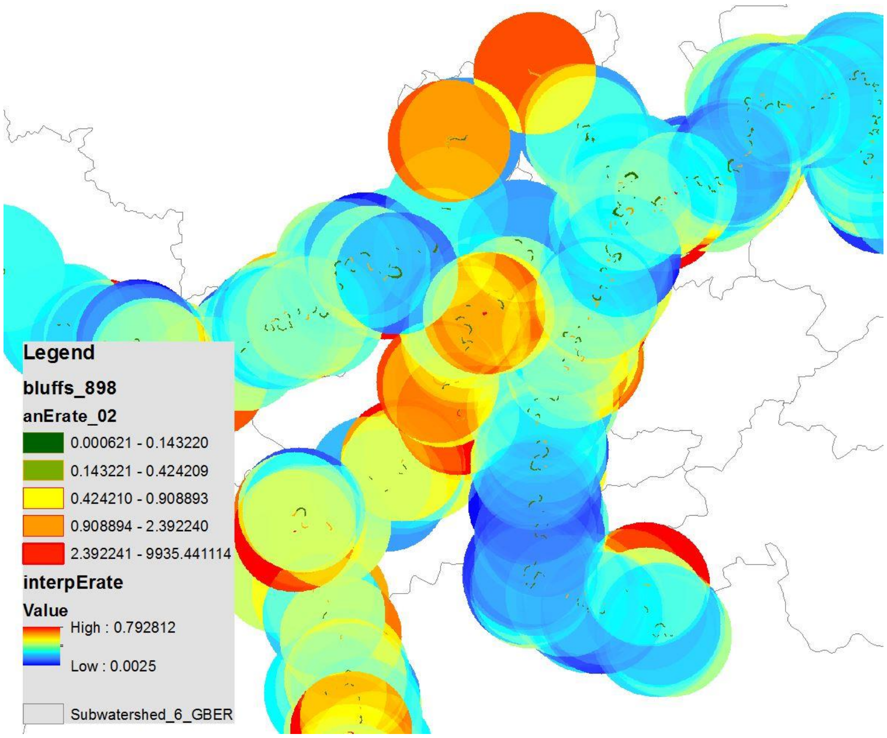


Figure 11: Interpolated bluff erosion rate in the GBERB is calculated as $E_{interpolate} = \Sigma V_E / \Sigma SA$ *of bluffs within a 3 km radius. This local erosion rate is illustrated here: warm colors represent a high rate and cool colors are low rates. Bluffs with measured erosion rates are also shown.*

For bluffs that are far away from bluffs with measured E, we must extrapolate rates. The simplest E to extrapolate is an average basin, watershed or subwatershed rate. However, even average rates from subwatersheds high in the GBERB are biased towards measurement of large (downstream) bare bluffs, so we devised a way to correct for these effects. We determined extrapolation rates based on the vegetation characteristics of measured bluffs. Because we believe that vegetation cover is indicative of current bluff stability, and that the small, upstream, heavily-vegetated bluffs may behave differently than the large downstream bluffs, it may be more appropriate to extrapolate rates that take the vegetation state of the measured bluffs into account. We defined long-term, vegetation-specific erosion rates in each subwatershed using bluffs with measured erosion rates and their vegetation state in 2010. Such an analysis can benefit from a space-for-time substitution that uses the spatial distribution of vegetated bluffs to represent a bluff's temporal vegetation characteristics. Appendix 1 is a discussion of space-for-time substitution in this context. A detailed discussion of constructing and extrapolating vegetation-specific erosion rates is included in Appendix 2.

Calculate erosion volume and convert to mass

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 2).

Surficial units in the GBERB 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 (see Figure 5).

Sand depth was determined using data from the sand distribution model in the Blue Earth County geologic atlas (Meyer and Lively, 2012). The authors mapped surficial sand depth by interpolation from well boring logs. To find alluvial unit thickness for this project, we simply averaged the sand depth of the units selected above, and applied this mean depth to surficial sand throughout the GBERB. Average Pleistocene alluvium depth in Blue Earth County is 3m. We expanded our analysis of alluvium to include Holocene terraces because their alluvial caps are nearly the same thickness as Pleistocene alluvium (Gran et al., 2011). 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 GBERB (Table 2).

Bluffs were considered to contain Pleistocene alluvium if any part of the bluff feature fell within 20m of mapped Pleistocene alluvial unit. We used search criteria to select bluffs that overlapped Holocene terrace alluvium. No search distance was used for terrace alluvium because terrace features are more precisely mapped and usually distinguishable on 3m DEMs. Bluffs that were partially but not primarily on terraces were manually removed from this group. Alluvium on the modern floodplain was excluded from the analysis because this material is accounted for in the banks section of the budget. If a bluff was proximal to both Holocene terraces and Pleistocene alluvium (which six bluffs were), adjustments were made for only the most prevalent alluvium, determined with visual comparison of surficial geologic maps and feature shapefiles.

Banks

To determine sediment supply from banks, channel extents were traced by hand on 2008 and 1938/9 aerial photos as far upstream as possible. Banks were traced on aerial photos viewed at about 1:2,500 scale. Channels are lined by either banks or bluffs: traced channels along bluff toes were used to calculate bluff erosion rates. Traced channels not adjacent to bluffs are considered banks.

Sediment supply from banks is 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). Similar data, collected previously for the Le Sueur and Maple was also used in this project (Belmont et al., 2011). From traced banklines, *Planform Statistics* interpolated 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. I used *Planform Statistics* to create buffers 5m 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.

For erosion from a channel reach to be considered in the budget, it must meet specific criteria. Erosion from meander migration in channels above the knickpoints is balanced by floodplain deposition and not included in the budget. The method cannot calculate sediment supply from channel reaches that have shortened via meander cutoff over the period of investigation, and these reaches were manually identified and excluded. 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 are 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). Data are exported from ArcGIS and tabulated in a spreadsheet.

Widening rates were calculated from the traced banklines. Channel areas in 1938 and 2008 were divided by the associated reach length to obtain average widths, which are divided by 70 years to obtain annual widening rate. For figures and 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).

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). It is beyond the scope of this study to improve on the established Le Sueur incision rate or attempt to define unique incision rates for other GBERB channels, so the Le Sueur rate was used (1.2mm/a below knickpoints, no incision above knickpoints; Belmont et al., 2011). Moreover, channel incision rate is unlikely to vary much between GBERB channels, because the channels have incised over the same time period to create a network of channels similar in long profile elevation.

Ravines

Ravine sediment source extents are traced by hand, based on break in slope on 3-meter DEMs. For this study, as in the Le Sueur River sediment budget, ravines must have more than 10,000 square meters of incised area to be included in the budget. We estimated that this threshold selects at least 85% of all ravine area. To calculate the sediment supply rate from ravines to GBERB channels, we used rates measured on the Le Sueur from discharge and sediment load (Belmont et al., 2011). The Le Sueur yield was applied to other ravines in the GBERB based on incised area

Uplands

Upland sediment source extent is 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 ^{10}Be and ^{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, 2012). 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. Thus, the upland erosion rate should be considered a measure of effective sediment delivery to channels. Calculated yield was applied to upland sediment supply areas throughout the watershed. Samples for suspended sediment fingerprinting in the Blue Earth and Watonwan are currently being analyzed by colleagues at Utah State University, and should be available in early 2015. Until that time, our budgets apply greater Le Sueur watershed upland sediment yields to the Blue Earth and Watonwan watersheds.

Storage on floodplains

The amount of floodplain storage in the Le Sueur budget was calculated differently for reaches above, within and below knickzones. Within the knickzone, floodplain extent is very limited (Belmont, 2011), so the budget included no storage. Above the knickzone, where banks are in dynamic equilibrium, sediment eroded from banks via channel migration is stored on floodplains. Below the knickzone, gauged loads at the downstream end of the Le Sueur knickzone was equal to gauged load at Red Jacket Park near the mouth of the Le Sueur, in spite of measured 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. To estimate storage from aggradation on the Blue Earth below the knickzone (i.e., below the confluence with the Watonwan) we calculated a “storage yield” below the knickzone of the Le Sueur, then applied it to the Blue Earth reaches below the knickzone. Storage yield below the knickzone of the Le Sueur is 530 Mg of mud stored per channel kilometer per year.

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 estimated storage of bluff sediment within the Blue Earth knickzone. Cross sections of Watonwan floodplains were not included in the study. We assume that the floodplain geometry on the Watonwan behaves like that of the Blue Earth so we estimated storage of bluff sediment within the Watonwan knickzone. 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 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, which are functions of lake geometry and watershed runoff characteristics (Verstaeten and Poesen, 2000). This project estimates 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 12. Though simple, when compared with more complex methods, Brown's curve has provided accurate results when used on watersheds of similar size to the GBERB (Butcher et al., 1992).

$$\mathrm{TE} = 100*(1-\frac{1}{1+0.0021\mathrm{D}\frac{\mathrm{C}}{\mathrm{W}}}) \qquad (13)$$

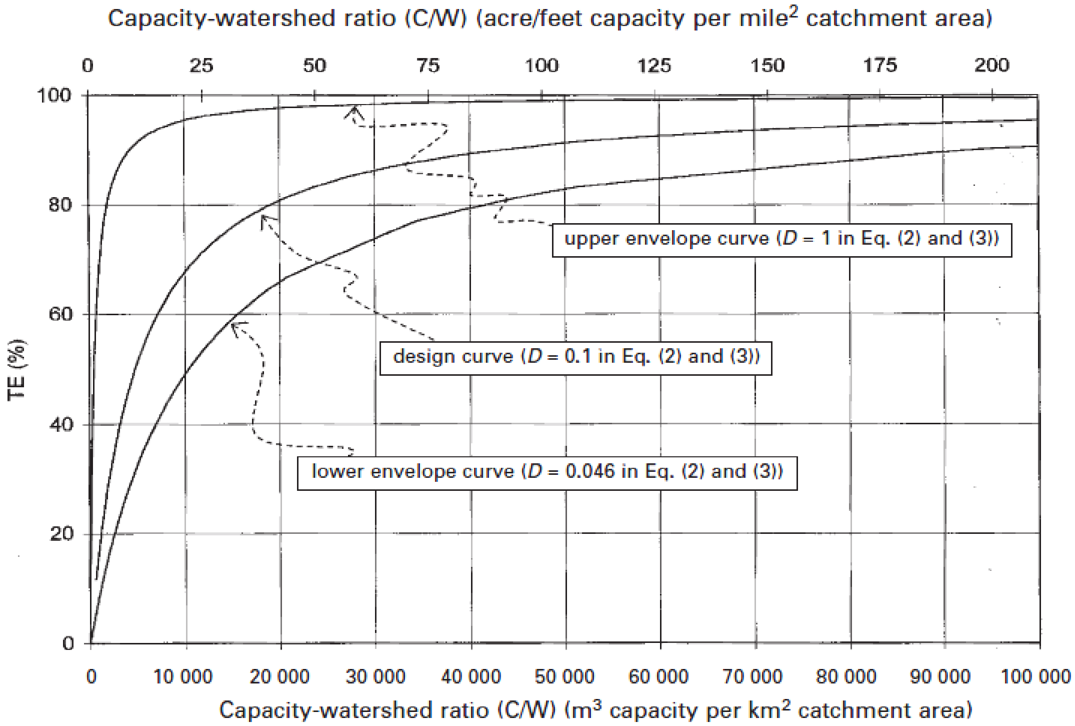


Figure 12: Relationship between CW ratio and trapping efficiency. The median estimated C/W of the largest lake basins in the GBERB is 75,000 m^2/m^3. Figure from Brown, 1943.

We automated estimates of lake trapping efficiency in ArcGIS to estimate unique TE for all GBERB lakes. This was done with a 10m resolution DEM. The automated method used *zonal statistics* to identify the largest flow accumulation value within National Hydrology 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 12, 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 GBERB is about 2m. The sediment budget draws on these data to include sediment storage in every GBERB lake. While Rapidan Dam on the Blue Earth River might be expected to trap sediment, its reservoir is already full of sediment. The reservoir has little storage capacity even for water, and this impoundment has a trapping efficiency of near zero.

Results

Bluff extents

Topographic criteria initially identified bluff extent of about 13 million square meters in the GBERB. Around 80% of the extent identified by the initial search was removed to create the final group of bluffs included in the budget (Table 3). The Blue Earth has the largest bluff extent, followed by the Le Sueur and Watonwan. Figure 13 and Table 3 show how each refining step affects total bluff extent. The final bluff extent in this table includes only bluffs that are immediately adjacent to active channels, not counted as ravines in the budget, and composed of unconsolidated sediments.

Of the steps taken to reduce the initial extent of steep features in the GBERB to only active bluffs, the largest reduction was achieved simply by searching within a set distance of NHD stream lines (Table 3, line 2). Abbreviations used in tables and figures are AB: above, UG: upper gauge, BL: below, LG: lower gauge, KP: knickpoint, and KZ: knickzone. Bluff extent was reduced by nearly as much by excluding bluffs outside a buffer from traced bank lines (Table 3, line 3). This step had no effect above Winnebago on the Blue Earth, where little channel length was traced (Figure 13). Excluding ravine areas and bedrock bluffs primarily reduced the extent of bluffs in the downstream channel reaches. Excluding steep features on ditches primarily reduced extents in the upper portions of the watershed.

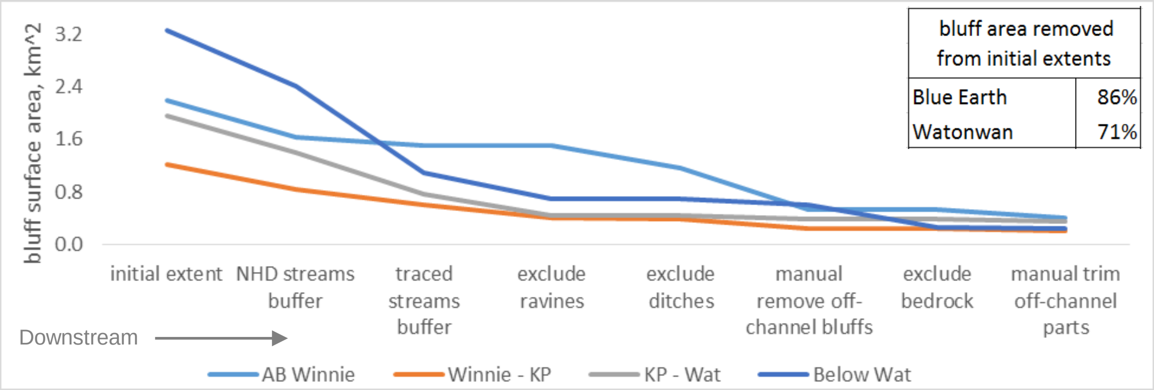


Figure 13: Bluff extents on the Blue Earth River. Subwatersheds are split at Winnebago, the knickpoint, and the confluence with the Watonwan. Plot shows how bluff extent decreases with each refining step.

Table 3: Bluff extent following each refinement

	Bluff surface area (m^2)	LeSueur								
		Maple			Cobb			LeSueur		
		AB UG	BTWN gauges	BL LG	AB UG	BTWN gauges	BL LG	AB UG	BTWN gauges	BL LG
1	initial extent	75,780	216,501	82,351	209,428	242,546	114,178	890,995	286,948	266,473
2	NHD streams buffer	70,258	207,741	81,258	163,136	142,932	101,591	607,646	267,046	264,935
3	traced streams buffer	70,258	207,741	81,258	163,136	142,932	101,591	607,646	267,046	247,639
4	exclude ravines	70,258	207,741	81,258	163,136	142,932	101,591	607,646	267,046	247,639
5	exclude ditches	70,258	207,679	81,258	158,246	142,932	101,591	547,964	267,046	247,639
6	manual remove off-channel bluffs	65,965	207,659	81,224	77,513	142,932	101,591	370,606	267,015	247,272
7	exclude bedrock	65,965	187,177	47,890	77,513	142,932	101,591	370,606	267,015	209,282
8	**manual trim off-channel parts**	**57,584**	**183,139**	**38,618**	**57,733**	**109,764**	**60,799**	**225,132**	**213,321**	**152,218**
9	total area removed from initial	18,196	33,362	43,733	151,695	132,782	53,379	665,863	73,627	114,255

	Bluff surface area (m^2)	Blue Earth				Watonwan		GBER
		AB Winnie	Winnie - KP	Knickzone	Below KZ	Above GC	In KZ	total
1	initial extent	2,191,982	1,229,555	1,967,125	3,254,034	1,427,167	442,416	12,775,453
2	NHD streams buffer	1,636,407	844,235	1,392,926	2,409,037	1,160,774	390,044	9,739,966
3	traced streams buffer	1,513,947	602,321	764,176	1,089,970	1,074,094	243,894	7,177,649
4	exclude ravines	1,511,682	405,796	437,548	701,818	1,055,662	243,894	6,245,647
5	exclude ditches	1,159,891	396,389	437,548	701,818	1,034,259	242,583	5,797,101
6	manual remove off-channel bluffs	544,381	250,902	393,236	605,820	560,083	122,027	4,038,226
7	exclude bedrock	544,381	250,902	393,236	269,326	560,083	122,027	3,609,926
8	**manual trim off-channel parts**	**405,634**	**217,533**	**348,257**	**253,496**	**431,392**	**112,128**	**2,866,756**
9	total area removed from initial	1,786,348	1,012,022	1,618,868	3,000,538	995,775	330,288	9,908,697

key to figure and table text	
AB	above
BL	below
KP	knickpoint
UG	upper gauge
LG	lower gauge

Bluff distribution throughout the GBERB is roughly correlated to subwatershed size. The large subwatersheds in the Blue Earth and Watonwan basins typically have more bluff surface area than the smaller Le Sueur subwatersheds. Bluff frequency (bluff surface area per channel length) is one way to normalize these data (Figure 14). Bluff frequency has consistent trends in the basin (Figure 15). On each GBERB channel, bluff surface area is near zero above the knickpoint, but increases rapidly below the knickpoint.

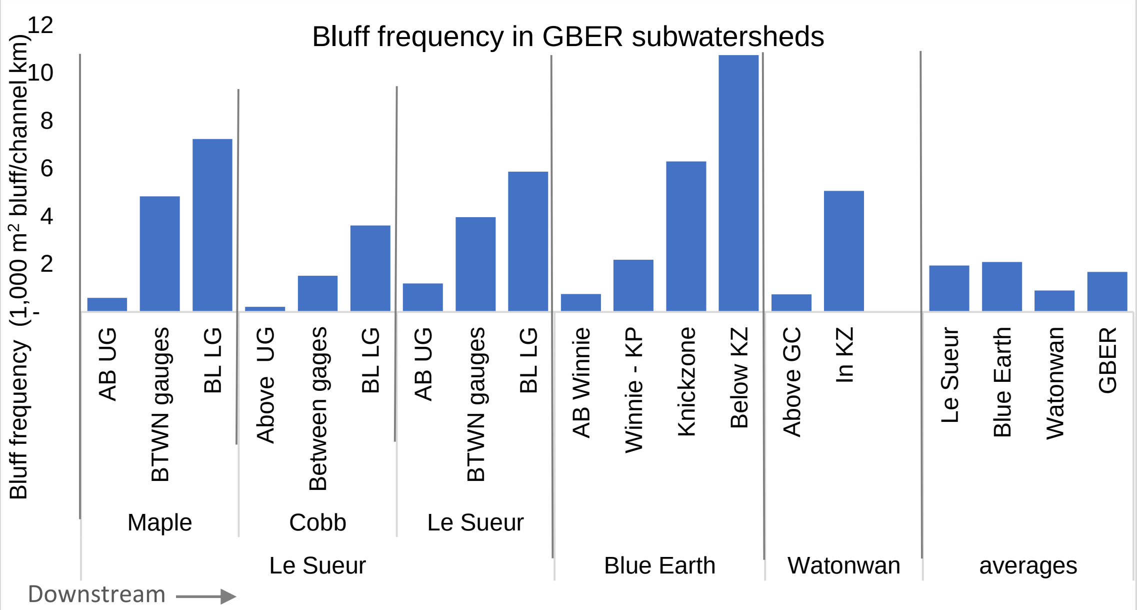


Figure 14: Bluff frequency increases downstream on each watershed in the GBERB. (bluff surface area per channel length; m^2/km) For this figure, channel length is mainstem channel length from the National Hydrography Dataset. Bluff surface areas include bedrock.

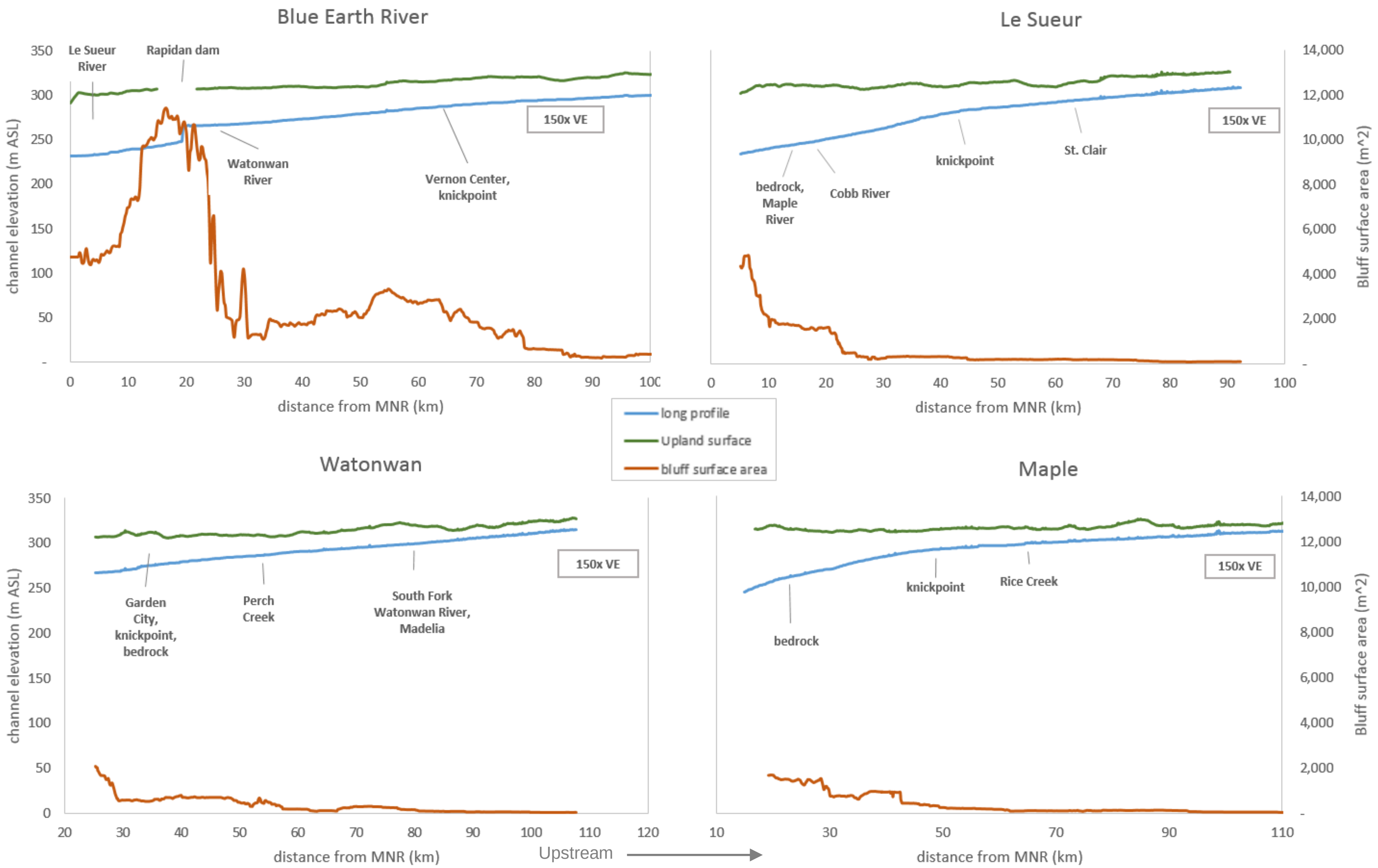


Figure 15: Bluff surface area, including bedrock bluffs, plotted with GBERB channel long profiles. Surface area as plotted here is the sum of bluff surface area within a circle of 3 km radius.

Bluff crest retreat rates and channel migration rates

Retreat and migration rates are highly variable along GBERB channels (Figure 16). Where GBERB channels flow in bedrock channels they often migrate more slowly than channels composed of till or alluvium. For example, compare channel migration rates on the Blue Earth River below the Rapidan Dam to rates above the dam (Figure 16). Bedrock is more resistant to erosion than alluvium, and slows channel incision and migration (Montgomery, 2004; Montgomery et al., 1996). Bedrock channels and bedload are both abundant below GBERB knickzones, so the influence of these features on channel migration is complicated on these reaches. Nonetheless, the effects of both bedrock and bedload are still visible below knickpoints. 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 most 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 Watonwan, channel migration rates may be slowed by bedrock. We normalized channel migration rates to channel width as a surrogate for discharge (Figure 17), because channel width in the Le Sueur basin changes with the square root of basin area (Gran et al., 2013). On a gross scale, discharge is fundamentally controlled by basin area, so normalizing channel migration rates to channel width is a way to investigate the effect of discharge on migration rates. Channel migration rate remains highest on the Blue Earth River following normalization.

Retreat and migration rates have similar trends on each river: our channel migration and bluff retreat rate measurements compliment measurements made previously on the Le Sueur, Maple and Cobb Rivers (Day et al., 2013). Measured bluff erosion rates averaged within each subwatershed are given in Figure 18, and behave like the crest retreat and toe migration rates.

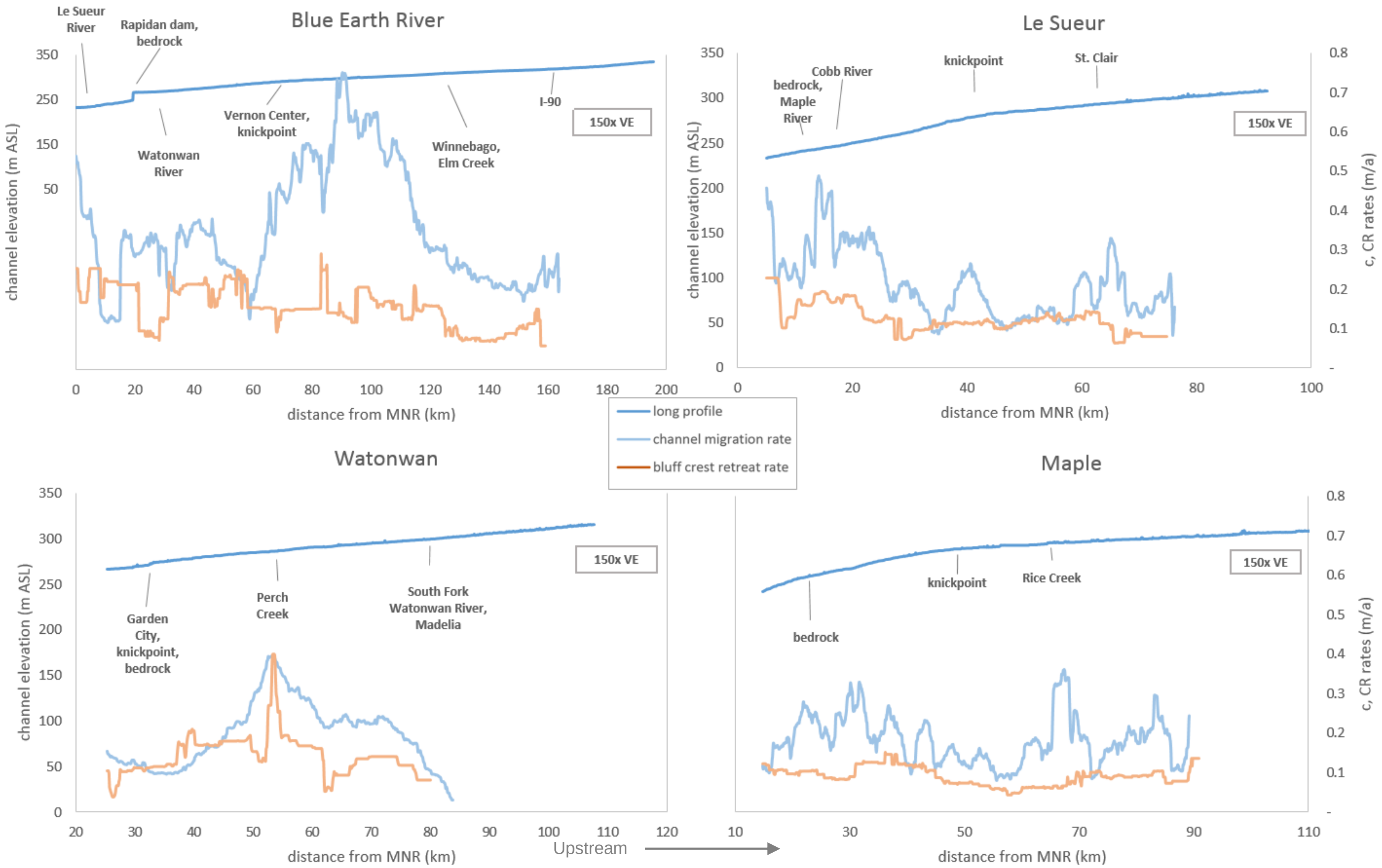


Figure 16: Bluff crest retreat and channel migration rates, smoothed over a 3 km radius. Channel migration rates include bluffs, banks and bedrock reaches, but not reaches that avulsed or were shortened from 1938 to 2008.

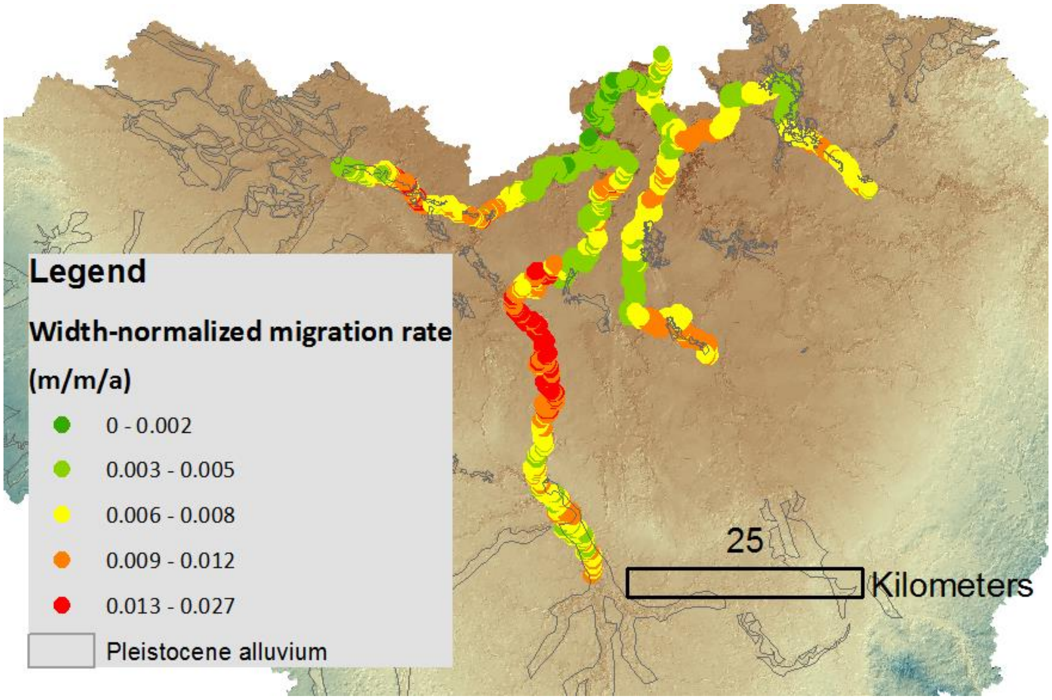


Figure 17: GBERB annual channel migration rates normalized to channel width for comparison across watersheds. High channel migration rates often occur in Pleistocene tunnel valleys and outwash channels (outlined in grey; not shown but believed to exist on the reach of the Blue Earth with the highest migration rates).

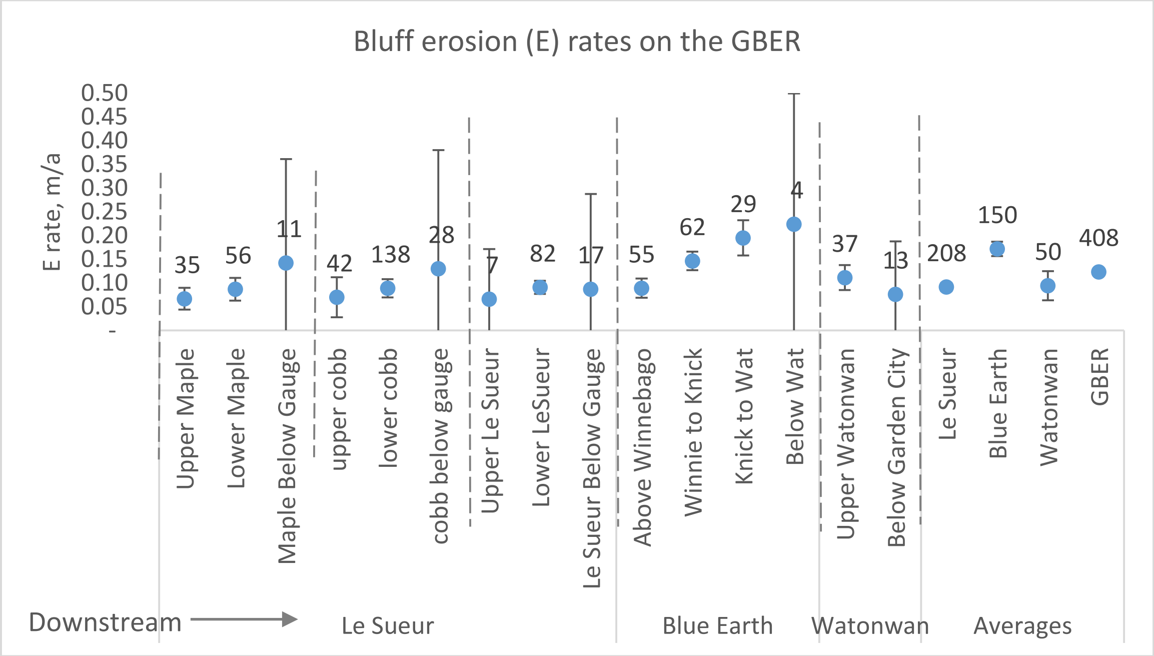


Figure 18: Average measured E rates in each GBERB subwatershed, calculated as a linear regression average of bluff surface area and volume eroded from each subwatershed. Uncertainties are the standard deviation of average subwatershed measured E values. Numbers above each point are the number of measurements in each group.

Potential predictor variables

Bluff geometry and bluff erosion rates are highly variable along channels. We found no meaningful relationships between erosion rates and potential predictor variables measured on individual bluffs (Appendix 3). Fundamental drivers of erosion that shape these landforms, like climate, knickpoint migration, and surficial geology change over long spatial and temporal scales. But regressions between variables averaged over 70 years and circles of 3 km radius did not have meaningful correlations either. Plotting erosion rate and bluff frequency data this way did help us understand watershed-scale patterns of channel migration rates and bluff frequency, but averages made over larger scales (subwatershed or watershed) are required to find any difference between erosion rates and channel material (Figure 19 and Figure 20). Nonetheless, uncertainty remains high even at this large scale.

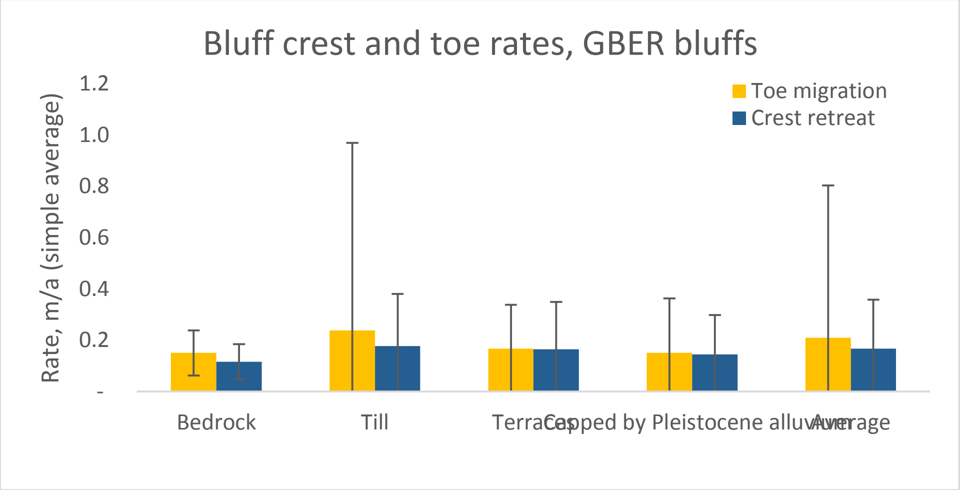


Figure 19: Bluff crest retreat and toe migration distances, from all measurements available in the GBERB, sorted by bluff type.

Across the GBERB, bedrock bluffs retreat slightly slower than bluffs composed of till (Figure 19). Terraces and other bluffs capped with alluvium have intermediate rates that are similar to rates on till bluffs. It can be difficult to draw conclusions from bluff data grouped together across GBERB tributaries or along the length of an entire river because such comparisons do not account for how erosive forces like discharge change along a river. The large standard deviation of such averages is an indication of how variable local rates are, and illustrates the problem of grouping bluffs this way (Figure 19). Grouping data more finely, by subwatershed, helps reduce this problem; but often there are not enough measurements in a single watershed to allow robust comparisons of how different variables affect erosion rates (Figure 18). Channel migration rates have the highest data density, so are the best data to analyze at high resolutions. We collected the most channel migration data on the Blue Earth River, but large variation, as shown by the standard deviation bars in Figure 20, can still be an issue. Figure 20 shows channel migration rates analyzed within Blue Earth River subwatersheds. These data are split in two ways: between banks and bluffs and between bedrock channels and alluvial or till channels. Bank migration rates are always higher than bluff rates within the same subwatershed, and channels migrate faster in unconsolidated material than in bedrock.

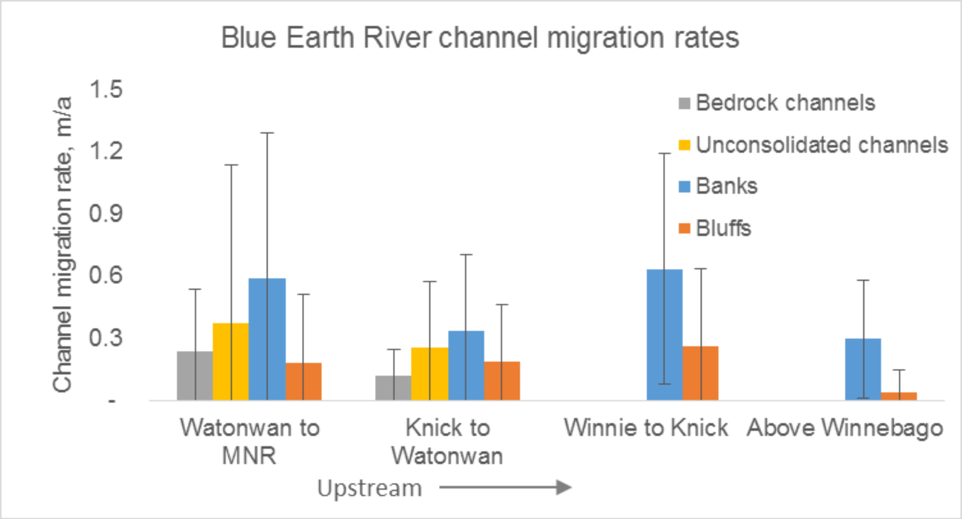


Figure 20: Channel migration rates on the Blue Earth River.

Interpolation and extrapolation of measured erosion rates

We measured erosion rates on just 408 of the nearly 3,500 bluffs in the final GBERB budget (Table 4, Figure 21). This small number of bluffs accounts for about 1/3 of the surface area of GBERB bluffs and about 40% of the annual volume of sediment eroded from GBERB bluffs. More bluffs, and a larger proportion of bluffs, were measured in the Le Sueur watershed than the Blue Earth or Watonwan. Most bluffs on which erosion rates were measured are close to the mouth of the GBERB, while extrapolation bluffs were congregated upstream. Interpolation bluffs are within 3 km of measured bluffs by definition, so are also primarily in downstream areas. 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 is 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. Because we interpolate and extrapolate erosion rates to 2/3 of the bluff surface area in the GBERB, it is important that we understand exactly how an average erosion rate for extrapolation is constructed.

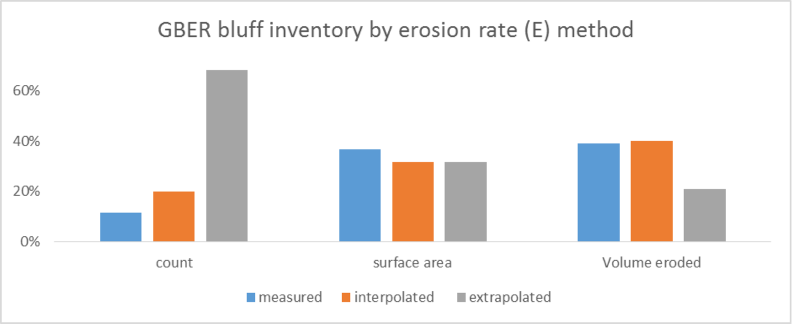


Figure 21: Number, surface area and volume eroded from measured, interpolated and extrapolated bluffs.

Table 4: Count, extent and volume eroded using vegetation-specific extrapolation for GBERB bluffs

measured, interpolated and extrapolated bluff extents		LeSueur								
		Maple			Cobb			LeSueur		
		AB UG	BTWN	BL LG	AB KZ	in KZ	BL LG	AB UG	BTWN	BL LG
count of measured bluffs		35	56	11	-	-	-	7	82	17
count of interpolated bluffs		18	26	2	-	18	35	15	74	21
count of extrapolated bluffs		36	-	-	165	54	-	425	-	-
SA of measured bluffs	m^2	36,873	154,659	37,416	-	-	-	9,767	144,024	62,515
SA of interpolated bluffs	m^2	11,066	28,480	1,202	-	29,626	60,799	20,061	69,297	89,703
SA of extrapolated bluffs	m^2	9,645	-	-	57,733	80,138	-	195,304	-	-
Ve from measured bluffs	m^3/a	2,721	13,470	5,322	-	-	-	705	13,074	5,449
Ve from interpolated bluffs	m^3/a	763	2,700	128	-	2,450	6,682	1,537	5,819	12,644
Ve from extrapolated bluffs	m^3/a	747	-	-	3,283	5,075	-	10,311	-	-

measured, interpolated and extrapolated bluff extents		Blue Earth				Watonwan		GBER	
		AB Winnie	Winnie - KP	Knickzone	Below KZ	Above GC	In KZ	total	percent
count of measured bluffs		55	62	29	4	37	13	408	12%
count of interpolated bluffs		113	129	90	51	81	26	699	20%
count of extrapolated bluffs		838	8	-	6	843	-	2,375	68%
SA of measured bluffs	m^2	63,639	121,523	122,220	106,709	98,309	90,786	1,048,440	37%
SA of interpolated bluffs	m^2	57,852	93,754	226,037	105,867	90,864	21,342	905,950	32%
SA of extrapolated bluffs	m^2	284,143	2,256	-	40,920	242,219	-	912,358	32%
Ve from measured bluffs	m^3/a	5,653	17,798	23,821	23,891	10,933	6,898	129,735	39%
Ve from interpolated bluffs	m^3/a	6,365	15,892	40,145	21,737	14,807	1,529	133,199	40%
Ve from extrapolated bluffs	m^3/a	16,883	196	-	9,589	24,164	-	70,248	21%

The average erosion rate in a subwatershed, when measured, interpolated and extrapolated bluffs are considered is called the subwatershed erosion rate (E_S). E_S is not necessarily equal to the average measured erosion rate (E). In the original Le Sueur budget extrapolated erosion rates were modified by consideration of vegetation, aspect and short-term rates measured with terrestrial lidar. In the revised budget, vegetation and local interpolation rates affected how measured erosion rates were extrapolated. Following extrapolation, E_s can be twice the average measured E rate (Appendix 4). In spite of this increase, the volume of sediment eroded in the revised budget is less than in the original budget because many bluffs were trimmed.

Mass erosion rate: accounting for sediment texture, bulk density and storage

To summarize all the ways erosion rates are modified, we construct average mass erosion rates (E_m) for each subwatershed (Figure 22). A mass erosion rate is simply the mass of mud eroded from each bluff or subwatershed divided by surface area to account for different bluff surface areas in each subwatershed. Subwatershed E_m rates are based on E_s rates and also include adjustments for bulk density and texture. Mass erosion rates in this figure also include the effect of lake and floodplain storage. Like E and E_s, mass erosion rates increase downstream in GBERB watersheds. On the Blue Earth, E_m rates near the mouth are about twice as high as rates higher in the watershed (Figure 22). 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 22, subwatershed mass erosion rates are plotted alongside bluff frequency. Bluff frequency and E_m rate follow a remarkably similar trend, which was also seen in the original Le Sueur budget. 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 23).

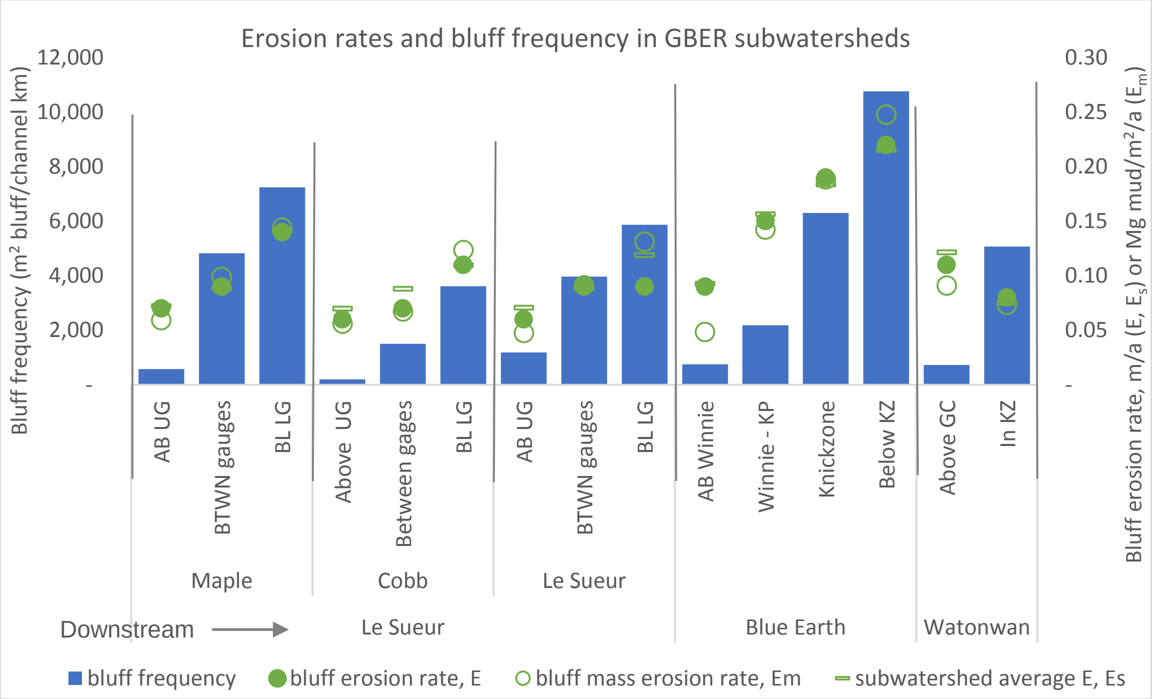


Figure 22: Bluff frequency (blue bars) and erosion rates (green dots) follow remarkably similar trends in the GBERB. Bluff frequency is bluff surface area per channel length (m^2/km). Average measured erosion rate (E m/a), the average of all measured and extrapolated rates in a subwatershed (E_s, m/a), 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.

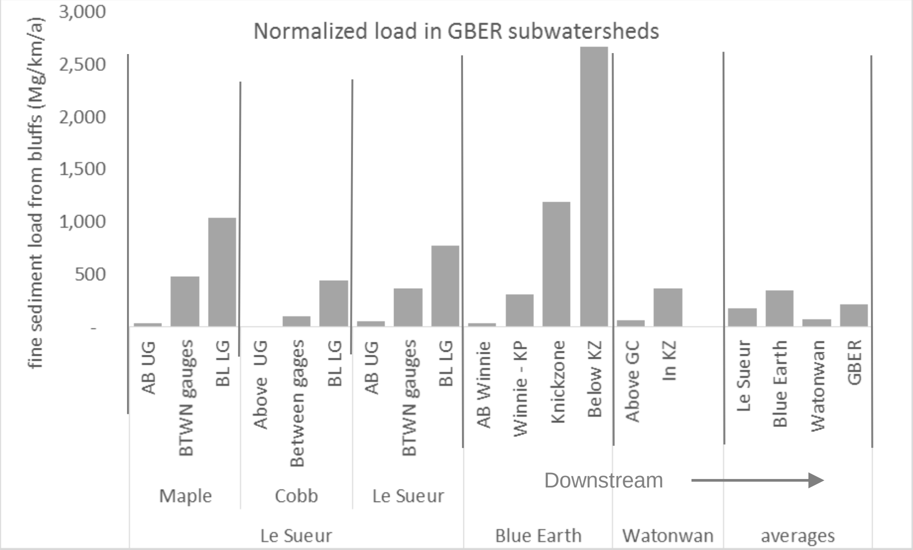
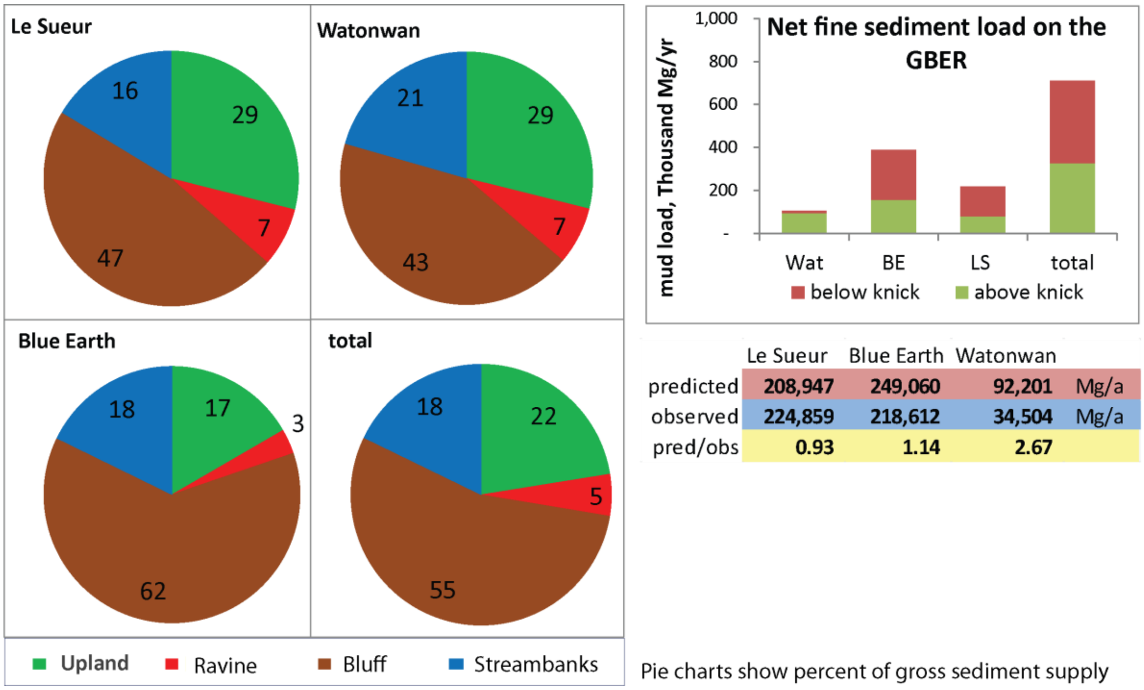


Figure 23: Bluff load normalized to channel length for subwatersheds in the GBERB. Load accentuates the trends seen in its components, rates and extents. Here load includes erosion from bedrock bluffs and the effects of storage.

GBERB sediment budgets

Fine sediment load from bluffs was combined with fine sediment load from other sediment source landforms in the GBERB to estimate sediment loads. Detailed sediment accounting is included as a collection of spreadsheets in Appendix 5, while general results are presented here. As in the original Le Sueur budget, bluffs are the source of most of the suspended sediment in the GBERB (Figure 24). About half the suspended sediment in the GBERB is sourced below knickpoints. Our estimated budgets closely match the MPCA-gauged loads on the Blue Earth and Le Sueur Rivers, but the Watonwan may require further revision. Note that the values in the histograms and table differ because the histogram is an estimate of load at each channel mouth, while the table gives loads at the downstream gauges.



	Le Sueur	Blue Earth	Watonwan	
predicted	208,947	249,060	92,201	Mg/a
observed	224,859	218,612	34,504	Mg/a
pred/obs	0.93	1.14	2.67	

Pie charts show percent of gross sediment supply

Figure 24: Summary of the GBERB sediment budget. Pie charts show the gross contribution (in percent) from each sediment source at the mouth of each river. Histograms give the net estimated suspended sediment load at the mouth of each GBERB channel. About half of the suspended sediment load comes from the 7% of the watershed below knickpoints. Table at right give net fine sediment load from the GBERB channels at the downstream gauges (Red Jacket, Rapidan, and Garden City). Numbers in red are loads estimated from the sediment budget; numbers in blue are loads measured at the gauges.

The effect of additional budget steps on load estimates

When the results of each budget construction step are converted to load, they are easier to compare. The columns on the left side of Figure 25 show how different extrapolation and interpolation methods affect GBERB budget loads. Loads are normalized to the estimate of our “best” extrapolation method, which uses interpolation and vegetation-specific extrapolation of subwatershed average E rates (Column E). However, fine sediment load from GBERB bluffs calculated with the vegetation-specific extrapolation method (Column E) is within a few percent of loads calculated with other interpolation and extrapolation methods. Moreover, the different extrapolation methods used in this project produce a fine sediment load of about 323,000 Mg/a from GBERB bluffs (note that these extrapolation methods do not include fine sediment from bedrock bluffs). The only outlier is when interpolation is used with extrapolation of GBERB average E rates (Column C). These results make sense: E rates measured in different parts of the GBERB are different (Figure 18). Rates measured downstream are typically highest, while measured E rates decrease upstream. Watershed and basin average rates are somewhere in the middle. Though not shown in Figure 18, interpolated rates are higher than subwatershed and basin average rates, because measured bluffs are primarily downstream where rates are high, and interpolation bluffs are by definition close to the measured bluffs. When measured rates are interpolated, the volume or mass of sediment is higher than when subwatershed or basin average E rates are used to extrapolate to all untraced bluffs. Similarly, since extrapolation bluffs are primarily upstream where measured rates are low, when basin-average E rates are extrapolated (Column C) to them instead of subwatershed E rates (Column D), load from bluffs increases. Conversely, if the GBERB average E rate is applied to interpolation bluffs, load from bluffs decreases (Column A). Pairing interpolation with extrapolation of GBERB average E rate thus selectively picks the highest possible rates for each unmeasured bluff, and therefore results in a higher fine sediment load estimate (Column C). The load resulting from vegetation-dependent extrapolation technique (Column E) is 2% less than extrapolation that does not account for vegetation (Column D).

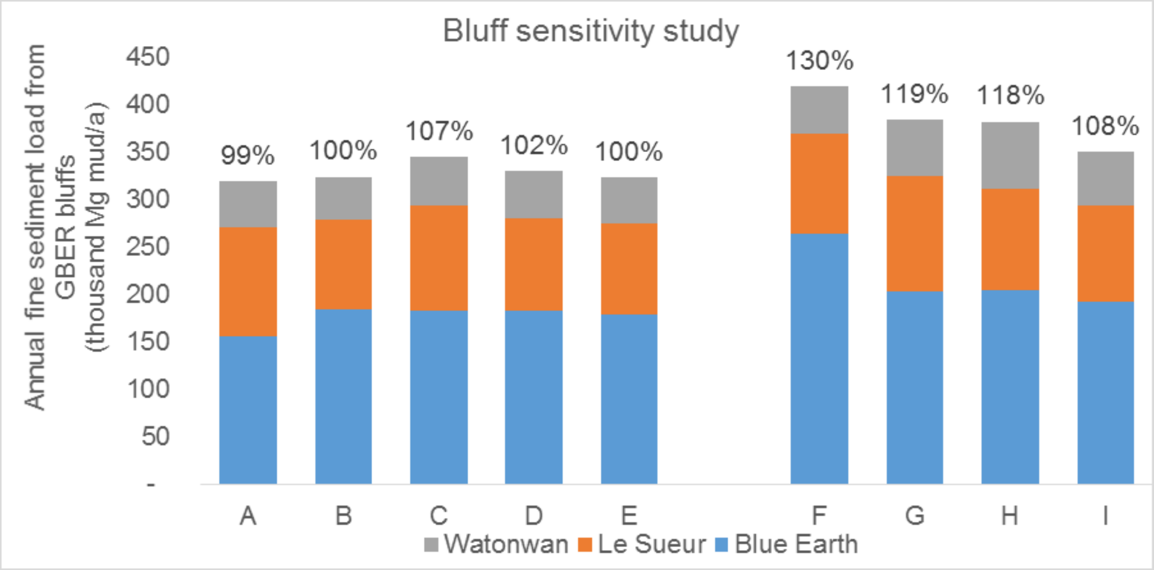


Figure 25: Load from bluffs in the GBERB, systematically excluding one calculation step to illustrate the effect of each step. Scenarios A-E show the effect of different extrapolation methods: A extrapolates the basin-average E with no interpolation, B extrapolates subwatershed average E rates with no interpolation, C extrapolates basin average E with interpolation where possible, D extrapolates subwatershed average E with interpolation, and column E extrapolates vegetation specific erosion rates and uses interpolation. Column F adds bedrock bluffs, G includes the extents trimmed in the final step of extent revisions, H excludes storage of floodplains and in lakes, I does not adjust texture and bulk density for glaciofluvial sediment.

The right side of Figure 25 shows the sensitivity of fine sediment load from bluffs to refinement. Each value in Figure 25 represents an individual scenario where one calculation step is excluded but all other steps are completed in order to illustrate the effect of each step. Inclusion of bedrock bluffs (Column F) has the largest effect on estimated load from bluffs, followed by re-adding the extents trimmed by the final step of the bluff extent revision process (Column G; Figure 13). These results make sense because all bedrock bluffs are near the mouth of the watershed, where measured rates and bluff extents are highest. When extents near the mouth of the basin are excluded from budget estimates, the estimated load decreases more than when extents are removed elsewhere in the watershed.

Storage of fine sediment from bluffs in lakes and on floodplains has an effect on estimated loads similar to the re-addition of trimmed bluff extents (Column G). Both storage (Column H) and adjustments to texture and bulk density (Column J) affect the Watonwan and Blue Earth disproportionately more than the Le Sueur. Three percent of fine sediment eroded from bluffs is trapped in the Le Sueur watershed, compared to 8% in the Blue Earth and 5% in the Watonwan.

Blue Earth and Watonwan channels often follow Pleistocene tunnel valleys (Figure 5). Altering the texture and bulk density of eroded sediment according to the occurrence of Pleistocene alluvium primarily affected fine sediment load from these watersheds and reduced the budget by about 15,000 Mg/a (Column J). Holocene alluvium is present in terrace bluffs, which exist below GBERB knickpoints, primarily in the Le Sueur watershed. Adjustments for Holocene alluvium reduced budget loads by 10,000 Mg/a, primarily in the Le Sueur watershed. Overall, adjusting load estimates for the texture and bulk density of alluvium in bluffs reduced the final budget load from bluffs by less than 10%, about half the effect on budget loads of the other adjustments we investigated. Bluff extents are the largest source of uncertainty in our results and are about 15% of total budget load.

Discussion

Knickpoints, bluff extents and erosion rates in a geologic context

Blue Earth and Watonwan knickpoints are very diffuse compared to Le Sueur knickpoints (Figure 7). The Blue Earth knickpoint has incised farther upstream than the Watonwan and Le Sueur; it appears to be moving faster. In regions responding to base level fall, knickpoint migration rate can be affected by channel discharge, substrate, and the influence of bedload on the balance of vertical channel incision to lateral migration rates (Wobus et al., 2006; Turowski, 2012). The observation that the Blue Earth knickpoint is farther upstream than other GBERB knickpoints suggests that discharge may influence knickpoint migration in the GBERB. Rivers with higher discharge have higher erosional energy with which to erode and move sediment. Along with channel slope, discharge is the primary property determining a stream’s erosional energy in shear stress and stream power equations (Knighton, 1998). The Blue Earth has much higher discharge than other channels in the GBERB (Table 1). To test the idea that knickpoint position may be related to discharge, we normalized stream length to the square root of basin area (Figure 26). Broadly, long-term average discharge is a function of precipitation rate and basin area. Normalizing long profiles to basin area is thus a way to see if knickpoints move in proportion to discharge. The knickpoints on the Le Sueur, Maple and Blue Earth are in almost exactly the same place when displayed this way. This suggests that discharge has a strong influence on knickpoint migration rate in these watersheds. The knickpoint on the Watonwan is steep and farther downstream than knickpoints on the other rivers. Transient knickpoints related to base level fall can temporarily steepen and pause their upstream movement when they encounter changes in substrate erodibility (Wobus et al., 2006; Turowski, 2012). Bedrock channels often are more difficult to erode than alluvial channels, and have lower rates of vertical incision and lateral migration (Turowski, 2012). Bedrock primarily outcrops in the lower reaches of GBERB channels (Steenberg, 2012). We have observed bedrock in the Watonwan channel near Garden City, though outcrops are not mapped there by the Minnesota Geological Survey. The Watonwan knickpoint has encountered bedrock in the channel, and it appears to be stuck there. The resistant bedrock will continue to slow upstream knickpoint migration until it is eroded. The distance knickpoints have traveled up GBERB channels may be also be related to watershed position relative to the Minnesota River. The Watonwan is located 25 km from the confluence with the MNR, so the base level fall it experienced was both smaller and more recent than other GBERB channels.

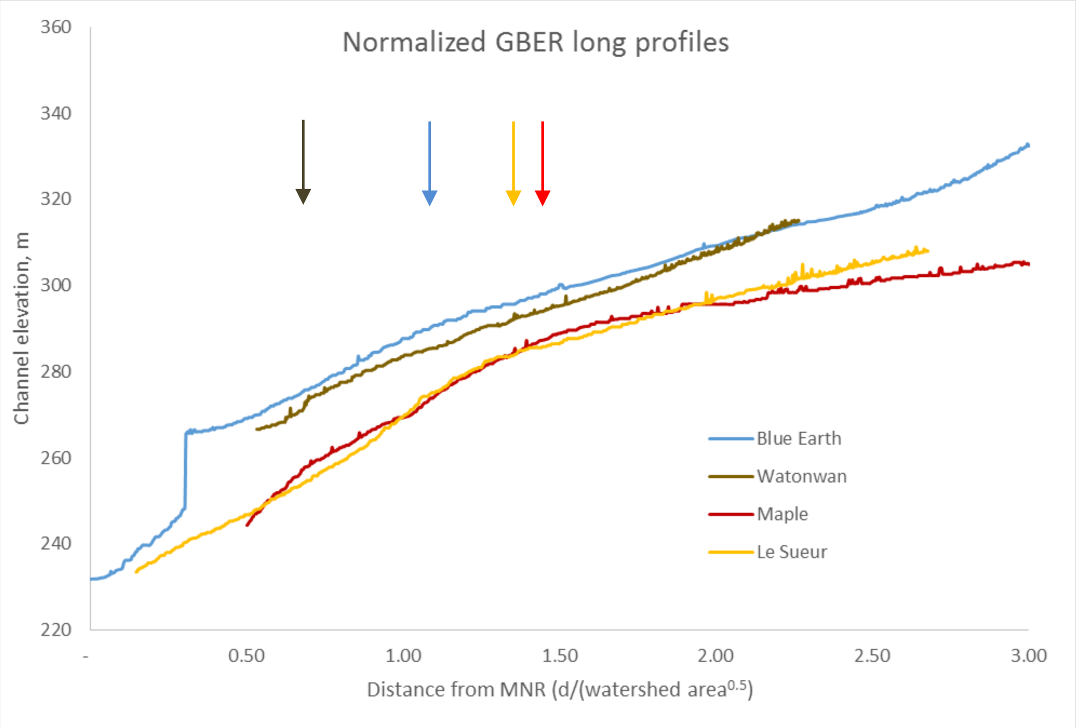


Figure 26: Channel long profiles normalized to basin area illustrate the primary importance of long-term average discharge and bedrock on knickpoint migration in the GBERB. When channel length is normalized to the square root of basin area, knickpoints have migrated similar distances except where slowed by bedrock.

Incision through GBERB tills is detachment-limited, just as on many bedrock channels (Gran et al., 2013). Detachment-limited streams, in contrast to transport-limited streams, only erode their beds when they are able to detach clasts (Turowski, 2012). Tills in the GBERB behave like weak bedrock likely because 1) they are often overconsolidated and 2) large clasts eroded from the till concentrate in the channel as incision progresses and armor channels (Gran et al., 2013). Blue Earth and Watonwan channels may also source coarse material from outwash channels.

In an incising system, vertical channel incision and lateral migration rates are often considered opposed to each other, and the balance between them related to coarse sediment supply (Bull, 1979). When bedload is moving downstream, it acts like “tools” that erode the bed. If there is little sediment supply, a stream has no tools with which to incise or migrate. Incision rates are highest when channels are able to transport large clasts downstream: the bed is eroded by collisions with the bedload (Turowski, 2012). When the amount of bedload available exceeds the transport capacity of the channel, bedload is deposited in point bars. As point bars disrupt flow in the channel, more sediment is deposited, the bars grow larger, the channel is forced towards the outer bank, and the bank erodes (Dietrich et al., 1979). If there is too much sediment supply for the river to transport, the bed becomes armored and channels can’t incise. This has been deemed the “cover” effect. In the GBERB, bedload is primarily sand and finer gravels, while larger clasts are relatively immobile and armor the bed (Gran et al., 2013). Often, when a bed is armored, lateral migration increases relative to vertical incision (Wegman and Pazzaglia, 2009).

Bluff frequency (bluff surface area per channel length) in the GBERB increases with distance downstream of knickpoints. On the Blue Earth, for example, bluff frequency is ten times larger downstream than upstream (Figure 22). Because bluff frequency is so high below knickpoints, bluff extent within a watershed is roughly related to knickzone length. The highest bluff frequency in the GBERB is on the Blue Earth River below the Rapidan Dam, an area with similar depth of incision below the upland surface to the lower Maple and Le Sueur, yet bluff frequency is nearly twice as high (Figure 15). High bluff frequency on this reach may be due to the narrow valley. Belmont (2011) noted valleys below Rapidan are only half as wide as on the lowest reaches of the Maple. The channel is more frequently in contact with bluffs on this narrow valley. We found that bluffs line 97% of the channel below Rapidan Dam, while only 54% and 40% of the channel on the lowest reaches of the Le Sueur and Maple, respectively, are lined in bluffs (Appendix 5). The narrow Blue Earth channel and thus the high bluff frequency below Rapidan could be due to the prevalence of bedrock on this reach. Incising channels frequently narrow when they flow through resistant substrates (like bedrock) in order to generate the erosive energy required to keep pace with local incision rates in less resistant bed materials (Finnegan et al., 2005). If migration rates are lower in bedrock, then valleys will be narrower (Figure 20).

Channel migration rates appear to be affected by some of the same variables that influence knickpoint migration rates and bluff frequency. Channel migration rates are high in the areas of the GBERB with the highest discharge: the lowest alluvial reaches of the Blue Earth and Le Sueur Rivers. Meander migration rate has been positively correlated with the erosive power of river channels, and therefore can be higher on larger channels (Nanson and Hicken, 1986). Channel migration rate often is high near confluences, like the confluence of Perch Creek and the Watonwan, or Rice Creek and the Maple River (Figure 16). This may be due to the influx of bedload from tributary channels, which can deposit and divert channels laterally (Turowski, 2012). Bedload near the mouth of the Le Sueur and Maple is also sourced from deep incision into the relatively homogenous tills, which excavates and concentrates coarse sediment in proportion to the volume of till removed (Gran et al., 2013).

The highest migration rates in the GBERB are on the Blue Earth, near Vernon Center (Figure 17). Between Winnebago and the knickpoint, the Blue Earth River flows through a Pleistocene outwash channel. It is possible that sand sourced from the outwash drives high channel migration rates (Figure 17). Alternatively, sand sourced from the bluffs in the reach could be the source of bedload, creating a positive feedback cycle between meander migration and bluff erosion. Modern channels have cut far below thin surficial glacio-fluvial sediment into the underlying till, and adjusting budget estimates for differences in sediment bulk density and texture has little effect on load (Figure 25). However, outwash may affect fine sediment load via its effect on channel processes. This hypothesis could be strengthened by field work to characterize bedload and bedload sources in the Blue Earth and Watonwan Rivers.

Bluff frequency and erosion rates

Bluff frequency and erosion rates are both highest closest to channel outlets, where channels have been most affected by base level fall. However, the effects of base level fall and knickpoint migration on bluff erosion rates are obscured by the effects of other variables related to a complex mix of channel dynamics, surficial geology, and watershed hydrology (Appendix 3). Erosion rate trends are not as strong as trends in bluff frequency. On the Blue Earth, E rates near the mouth are about 5 times higher than rates higher in the watershed, while bluff frequency is 10 times higher (Figure 15). Bluff frequency follows similar patterns in all GBERB watersheds (Figure 15), while E rates are highly variable along a channel and must be averaged over large distances to see any patterns (Figure 21 and Figure 18). Because rates are so variable along a channel, it takes a lot of E rate measurements to generate an average E rate with low uncertainty.

Measured E rate uncertainty is low at the watershed scale, but uncertainties remain high at subwatershed scale (Figure 18). Fundamentally, a lack of measurements below knickzones drives high E rate uncertainty there. Facing such a problem, one might normally make more measurements to lower uncertainty but we measured as many crest retreat rates as possible. Working with the data available, the trends we found within watersheds have a common pattern. E rates increase downstream in all watersheds, and in the original and revised Le Sueur budgets. Physical drivers for higher channel migration rates, such as confluences, bedload inputs and discharge also increase downstream. With these trends in mind, we wonder how far upstream bluff erosion rates continue to decrease and if they asymptotically approach a minimum. No such minimum exists in our data, but we wonder if more upstream measurements, were they possible, would lower upstream bluff E rates. Regardless, measured erosion rates are very low upstream and bluffs extents are low there, so load from bluffs above knickpoints is small overall (Figure 22).

We used locally averaged erosion rates to search for ways erosion rates are related to bluff and channel geometry (Appendix 3). The lack of correlation between erosion rates and the geometry of bluffs and banks at the individual bluff or local scale suggests that the stochastic variation in bluff geometry and erosion rates overwhelm trends at less than the subwatershed scale. At the subwatershed scale, we found some basic differences between channel migration rates in bedrock and till, and channel migration rates in bluffs and banks (Figure 19). Even comparisons at this scale need to be made carefully, because variables we suspect affect erosion rates (like channel slope, discharge and surficial geology) vary over similar scales.

The balance between length scales low enough such that driving forces may be considered reasonably constant and length scales long enough to provide low measurement uncertainty seems to be the subwatershed scale. Migration rates vary unpredictably between about 5 and 50 cm/a. We cannot predict a value within this range for an individual bluff. Averages of more individuals produce lower uncertainty (Figure 18). Therefore, we advocate averaging rates over areas no smaller than subwatersheds. This finding has implications for extrapolation methods. If, as we suggest, migration rates vary so much (and in the case of bluff crest retreat rates, are so sparse) that it is difficult to meaningfully average them at smaller than subwatershed scales, then interpolation is an unreliable extrapolation technique. Fundamentally, there are too few crest retreat measurements to generate reliable averages at the scale of a 3 km radius.

Bluff erosion rates, even at a watershed scale, are highly variable and difficult to explain. But at scales as small as the local reach, clear trends exist in bluff frequency, which are in part related to base level fall and knickpoint migration. Regardless of erosion rate trends, lack thereof, or which rate we chose to use in a budget, sediment load normalized to channel length is always higher below knickpoints on the basis of bluff frequency alone.

Much attention has been paid to the Le Sueur watershed because it has the highest yield of any MNR tributary watershed. However, yield can be a deceiving way to look at erosion where near-channel sediment sources like bluffs are concerned. Near-channel sources on the Blue Earth generate about as much fine sediment as the entirety of the Le Sueur watershed. While the load from near-channel sources is likely due in part to the high discharge sourced from its vast watershed area, that same large watershed area makes Blue Earth sediment yield lower than yield in the Le Sueur. It may be more appropriate in watersheds where sediment load is dominated by near-channel sediment sources to normalize load to channel length. If bluff load is looked at in this way, Blue Earth load exceeds the Le Sueur. We call bluff surface area normalized to channel length “bluff frequency.” Accurate bluff frequency figures require an accurate inventory of bluff extents, a task to which much energy has been committed in the GBERB.

Budget sensitivity study

Results of our sensitivity study show that it is important for MNR sediment budgets to get bluff extents right. Bluff erosion rates are very high relative to erosion rates of other landforms in the basin (2 orders of magnitude larger than ravine erosion rates and 10^4 times greater than upland supply rates; Appendix 5). When bluff rates are applied to other landforms in the basin or bluffs that are disconnected from channels, sediment load is overestimated. Accurate measurement of bluff extent is therefore a very important component of GBERB sediment budgets.

The method to calculate bluff surface area was automated in the revised budget for a few reasons. First, heavy vegetation cover made it impossible to extend traced channel centerlines far enough upstream to reach many of the bluffs in the revised budget, making it impossible to include all of the upstream reaches with the original method. Moreover, developing an automated scheme in ArcGIS streamlined calculation of bluff length. Because the revised surface area calculations directly relate surface area to map area, the method requires that bluff polygons be accurately trimmed to exclude bluffs or portions of bluffs that are set back from the active channel. The revised method creates consistency between bluff shapefiles and the surface areas in the budget. In contrast, a bluff polygon in the original budget was allowed to be longer than the length of the bluff recorded in the budget (GIS shapefiles from this project are available through the U-Spatial Data Locker. Please contact the authors for more information: bevisma@gmail.com or kgran@d.umn.edu).

Though automated searches removed a lot of bluff extent from the initial inventory, we manually evaluated whether or not each remaining bluff in the watershed was on an active channel. This was the most important and time-consuming work in the bluff trimming process and was done in ArcGIS using the bluff shapefile and 2008 NAIP aerial photographs (Table 3, lines 6 and 8). These were the difficult features to trim, a process that was made no easier by the preceding automated searches. The final manual trimming removed 743,000 m^2, which is about 20% of the final extent. While this is only 7% of the total surface area that was trimmed by automated searches, it represents a 20% change in the fine sediment load from bluffs, or about 10% of the total GBERB load estimated in the budget. While it was certainly useful to run automated searches to cull steep features from the group of bluffs, the importance of the final manual deletion and trimming cannot be overstated.

Initially we thought it prudent to exclude bedrock bluffs for load calculations because they have different texture and bulk density than till and they erode at slower rates. However, we recognize that bluffs that are composed in part of bedrock make up a large portion of bluff surface area in the Blue Earth watershed. The bedrock portion of these bluffs is usually less than 50% of total bluff height, and they are capped by unconsolidated sediments. While rates may be lower and texture different than unconsolidated bluffs, bedrock bluffs still contribute sediment to the GEBR. With this uncertainty in mind, the budget user can select to include or exclude bedrock bluffs in our sediment budget spreadsheet (Appendix 5). This feature makes it easy to understand how trimming bedrock or off-channel extents affects estimated fine-sediment load. At this point, bedrock bluffs are assigned the same texture and bulk density as till bluffs. This binary approach should be considered a sensitivity study and defines a range of possible loads derived from bedrock bluffs. The actual load likely lies somewhere between these end members, so the end members are one way to define budget uncertainty related to bedrock bluffs, a large portion of overall budget uncertainty.

In some basins, in-stream sediment storage far exceeds sediment load (Trimble, 1999). The sediment budget we created includes estimates of bluff sediment stored on floodplains similar to the way in which bank sediment is stored there. Because the Blue Earth has more bluff surface area than the Le Sueur and because sediment is stored on floodplains in the Blue Earth knickzone, much more bluff sediment was stored on floodplains in these watersheds (Figure 25). Due to increased relief as the western part of the Watonwan rises up towards the Coteau des Prairies, this watershed has more upstream bluffs than the other GBERB watersheds. We estimate relatively little (only 4,000 Mg/a of fine sediment) storage of bluff sediment in lakes. This is likely because most GBERB lakes are high in the watershed, while most bluffs exist on lower reaches. Overall, about 45,000 Mg/a of fine sediment from bluffs is stored in GBERB lakes and on floodplains (Figure 25). This is equal to nearly 20% of the final estimate of annual mud load from bluffs when bedrock bluffs are excluded or 11% of the final load when bedrock bluffs are included. Much more upland sediment is stored in lakes than bluff sediment. As a rough check on our estimate, we back-calculated the average mass of sediment stored in lakes per year. It is very low: 0.5 kg/m^2 of lake area. To put this number in context, that is approximately 0.3 mm of sediment, if the sediment were to have the same density as till. Such a figure might be thought of like varve thickness and is a very low accumulation rate (Hu et al., 1999).

Load from uplands and the amount of upland sediment trapped in lakes were estimated using yields calculated from sediment fingerprinting work on the Le Sueur. Future researchers may choose to combine estimates of upland erosion (like the revised universal soil loss equation) with estimates of on-field storage and these estimates of lake trapping efficiency. Such a combination would be an independent check of upland sediment supply estimates made with sediment fingerprinting and TSS loads (Belmont et al., 2014).

In the GBERB, about 20-30% of all sediment that enters channels is stored on floodplains (Figure 4, Appendix 5). This is in contrast to Coon Creek, where perhaps the best-known fluvial sediment budget in existence indicates that at times over 90% of sediment entering channels was stored on floodplains (Figure 27; Glanz, 1999; Trimble 1999, 2009). Coon Creek is geographically proximal but in a much different geologic setting than the GBERB. Coon Creek is located in the driftless region of Wisconsin, a landscape that was unglaciated in the last glaciation. Hillslopes contain highly erodible loess. Unlike floodplains below knickpoints in the GBERB, floodplains in the driftless region are quasi-equilibrium features. Work in the Coon Creek watershed began with channel transects in 1938. Resurveys over three decades starting in 1974, combined with floodplain coring and historic photographs enabled quantification of channel and floodplain changes (Trimble, 2009). The research found that upper tributaries on Coon Creek began incising in response to forest clearing by European settlers for farming and grazing, from about 1852-1938. The loess was washed down into the main valleys of Coon Creek, where it was stored on the wide floodplains as "post-settlement alluvium." Only a small fraction of the eroded sediment reached the mouth of the river, so sediment load at the mouth remained within 3% of the level during initial land-clearing (Figure 27). So much sediment was deposited that Coon Creek could not reach the floodplains, leaving the river entrenched. The once-floodplains became stranded fill terraces. As the river carves a new floodplain inset within the fill terraces, it erodes the alluvium stored during the erosional peak, but enough storage remains available that sediment load at the mouth remains the same. Sediment input from uplands was fundamentally a pulse from initial clearing. The sediment pulse, and erosion thereafter, has been buffered by storage on floodplains. Sediment delivery from Coon Creek to the Mississippi River has remained stable since initial land clearing, despite wide variation in supply and storage rates within the Coon Creek watershed.

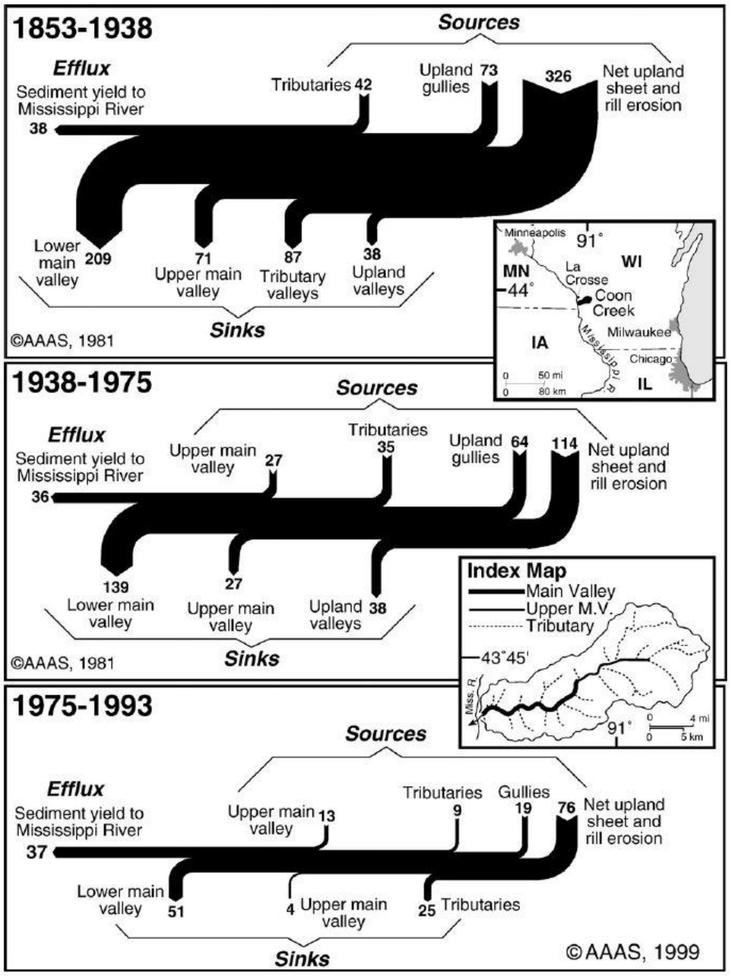


Figure 27: Sediment budgets for Coon Creek, Wisconsin, 1853 to 1993 (Trimble, 1999). Values are annual averages for the periods in 10^3 Mg/year.

These storage rates reflect a fundamental difference between the two watersheds: the Blue Earth is a young, incising river with no loess while Coon Creek is a relatively mature river with extensive floodplains. Incising channels cut narrow channels with steep valley walls. Small floodplains, little sediment accommodation space and low storage rates in the GBERB are logical results of incision, while Coon Creek's old, wide valleys have plenty of room in which to store sediment. Modern load on both Coon Creek and the Blue Earth is primarily sourced from near-channel features, but the composition of the sources is different. Coon Creek is eroding terraces composed primarily of reworked post-settlement alluvium, but bluffs in the GBERB are made of mostly till parent material. The sediment budgets of streams like Coon Creek were fundamentally altered by the addition of large volumes of post-settlement alluvium (Walter and Merrits, 2008). But in the GBERB, the volume of post-settlement alluvium is minor compared to the reservoir of parent material the river continues to excavate through. About 20% of the sediment that enters channels is stored in the GBERB (Figure 25), which is significant. However, most of the storage happens in lakes and on floodplains above knickpoints (Appendix 5).

Differences between GBERB watershed sediment budgets

Uplands and bluffs are the primary sources of suspended sediment in all GBERB watersheds and are deserving recipients of the research energy put towards understanding their erosion rates. Banks and ravines together make up about 20% of the budget on GBERB channels (Figure 24). Ravines supply the smallest amount of fine sediment to GBERB channels. The Le Sueur receives proportionally twice as much sediment from ravines than other GBERB channels and there is more ravine surface area on the Le Sueur than on the Blue Earth or Watonwan. While we can’t say definitively why this is the case, it may be related to differences in surficial geology. Glacial Lake Minnesota sediment and the fine glacial tills that dominate the Le Sueur watershed may be more cohesive and able to hold steep slopes better than the coarser Blue Earth sediments. Lower channel migration rates in the Le Sueur may allow ravines more time to develop before they are washed out or widened by migrating channels. Bedrock on the Blue Earth could also armor it from ravine development. It could also be simply a matter of watershed shape: there may not be enough catchment area along the narrow lower Blue Earth to create enough runoff to initiate ravine growth with similar frequency to the Le Sueur.

Banks supply slightly more fine sediment to the GBERB sediment budget than ravines. The Watonwan has a relatively higher proportion of sediment derived from banks than other GBERB rivers, but the rate of channel sediment supply is not significantly different than on other GBERB 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 GBERB channels (Appendix 5). Simply put, the high proportion of fine sediment derived from banks on the Watonwan is because the river has low supply from bluffs and uplands, making supply percentage from banks appear higher.

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. However, yield (fine sediment discharge per watershed area) is higher on the Le Sueur than the Blue Earth. Looking at this information in the context of the GBERB sediment budget can help predict likely upland erosion rates. The Blue Earth is larger than the Le Sueur, so a similar upland erosion rate would result in much higher load than was measured by the MPCA. We can therefore conclude that upland erosion rates must be lower on the Blue Earth than on the Le Sueur. Our estimated load from the Blue Earth nearly matches the measured load at Rapidan when we use the upland supply rates from the Maple and Cobb. Maple and Cobb upland supply rates are lower than the Le Sueur rate because they have lower relief (Figure 1). We suspect that sediment fingerprinting will find similar upland supply rates in the Blue Earth watershed. A greater extent of glaciofluvial surficial geology in the Blue Earth watershed may be responsible for the low upland erosion rates we suspect. Coarser soils have less fine sediment to contribute to our fine sediment budget and higher infiltration rates, which result in less overland flow and less energy available to erode and transport sediment.

Fine sediment load in the Watonwan River is overestimated by a factor of two in our sediment budget (Figure 24). We suspect that sediment fingerprinting will indicate sediment supply rate from the Watonwan uplands is lower than other GBERB channels. Coarse surficial geology and drier climate in the Watonwan watershed could explain low upland supply rates. Notice, however, that to bring estimated loads in line with measured loads, upland sediment supply would need to be nearly completely eliminated. This is unlikely to be the case. Alternatively, it may be that measured loads are systematically low on the Watonwan, but the MPCA has confirmed their confidence in the gauging methodology and data for the Watonwan (Pat Baskfield, MPCA, personal communication). If the gauge data are accurate, and overestimation cannot be explained with uplands alone, then there could be a problem with bluff loads. We have no reason to doubt the crest retreat and channel migration data collected on the Watonwan. While bluff extents and erosion rates are in line with other GBERB tributaries, the Watonwan does have the highest proportion of bluffs above the knickzone of any GBERB tributary. It could be that bluffs high in the watershed erode more slowly than bluffs near the knickpoint or that we are underestimating storage rates, but we lack measurements to test this hypothesis. If all bluffs above the confluence of the north and south branches of the Watonwan are excluded from the budget, gross load from bluffs above Garden City is 37,000 Mg/a, and the difference between our estimated and the MPCA's measured loads is halved. This simple scenario was made using the budget spreadsheet and shapefiles included in Appendix 5. The scenario represents an extreme case and is probably not realistic, but it illustrates that for estimated load to equal measured load, large reductions must be made. These reductions are too large to come from a single source. Most likely, supply rate from bluffs and uplands will be reduced significantly before the Watonwan budget is balanced.

Management implications

Our work shows that bluffs are huge sediment sources, in all GBERB watersheds. If an immediate reduction in fine sediment load is required, stabilizing a large bluff might do so, but this would be a short-term solution that does not address the root causes of high bluff erosion rates throughout the watershed. More comprehensive fine sediment management will require more comprehensive information of watershed sediment sources and erosion rates, but a useful budget for other MNR tributaries may not require undertaking measurements to the extent that was done for this project.

GBERB sediment budgets can be the basis of predictions about fine sediment budgets for other MNR tributaries. Bluffs and uplands are the primary sediment sources in all GBERB watersheds. We expect the same to be true for other MNR tributaries, and suggest that these sediment sources be the primary focus of budget construction on MNR tributaries outside the GBERB. To roughly construct a sediment budget for another MNR tributary watershed, we might initially assume that sediment sources supply fine sediment at proportions similar to what was observed in the GBERB: that is, banks might supply 20% of the load; ravines, 5%; with the other 75% of the fine sediment load distributed between bluffs and uplands.

Estimated load from bluffs is sensitive to careful delineation of bluff extents and less sensitive to energy spent trying to precisely extrapolate erosion rates or adjust for sediment storage, texture and bulk density. We urge researchers interested in identifying major sources of suspended sediment on other MNR tributaries to first delineate bluff extents in those watersheds. Creating an accurate inventory of bluff extents is not a small task: some aspects of creating this inventory were automated in this project, but much of the work was completed manually. However, an accurate inventory of bluff extents is useful for informing management decisions. With an accurate inventory of bluff extents, upland extents are, at first pass, simply the remaining watershed area (though ravines comprise a small part of the watershed area, too). Sediment fingerprinting results can be added to bluff and upland extents and gauged sediment load to estimate upland and bluff sediment supply rates. These rates should be compared with GBERB rates to check for accuracy. Extents and approximate erosion rates could be used in the same way this budget is being used: to target management actions on the sediment sources from which erosion is easiest to reduce.

Of course, a comprehensive budget would also measure unique crest retreat rates, channel migration rates, ravine supply rates and storage. Day et al. (2013) suggest that rates should be measured on 30–40% of bluffs to keep extrapolation error below 20%. We add that spatially distributed E rates are useful for understanding along-channel trends. We see two ways one might compare or export our E rates to other MNR watersheds: at the watershed or subwatershed scale. In spite of higher uncertainty at the subwatershed scale, bluff E rates do increase downstream on most watersheds (Figure 18), and we think extrapolation of subwatershed averages is appropriate. If subwatersheds are set up based on geomorphic regimes, then subwatershed-average rates should be used in the appropriate area relative to knickpoints. Coarse glacio-fluvial surficial geology appears to be common in the western MNR tributary basins (Jennings, 2010). Initial River Warren incision below the upland surface appears to be less in the western MNR tributary basins. Both of these factors could decrease knickzone length by decreasing incision in western GBERB tributaries. We expect bluff extent to decrease when moving westward, because smaller knickzone will likely result in less bluff extent. Initially, we expect watershed bluff E rates in other MNR watersheds to scale very roughly with upland area, as we saw in the GBERB (Figure 16). Overall, lower bluff extents resulting from smaller knickzones likely produce less load from bluffs, and may be one of the reasons total yield decreases upstream in the MNR valley. A drier climate also likely reduces water yield, discharge, bluff erosion rates and frequency.

Conclusions

Sediment budgets presented here were motivated by high turbidity throughout the MNR basin. The incisional history of the Le Sueur River demonstrates that Pleistocene base level fall is a powerful driver of valley excavation on MNR tributaries (Gran et al., 2009; 2013). But modern conditions can affect erosion rates, too. Belmont and others (2011) showed that sediment load from the Le Sueur has increased about four times over the Holocene average. A numerical model of valley excavation based on a history of incision recorded by strath terraces adds that modern valley excavation (primarily achieved by bluff erosion) is three times higher than the Holocene average (Gran et al., 2013). Increased sediment load and the shift to near-channel sources in historic times are overprinted by rising discharge in Minnesota's rivers in the last half of the 21st century relative to the first half (Novotny and Stefan, 2007). This is an unsurprising correlation, since discharge is a primary component of the shear stress a river exerts on its banks and thus a river's ability to erode near channel sources.

This project focused primarily on load from bluffs in the GBERB because bluffs are the source of about 60% of all the fine sediment that makes its way out of the basin. Uplands supply the next greatest share, about 20% of the fine sediment load. Banks and ravines account for the remaining 20%. Load from bluffs is a function of bluff extent and erosion rate. Bluff extents are more variable across watersheds than bluff erosion rates, and careful work is required to accurately delineate extents for a budget. Bluffs are largest and most frequent below GBERB 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 appear to be increased by bedload and slowed by bedrock. Bedload is concentrated in GBERB 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. Even though coarse sediment can affect channel migration rates, adjustments for differences in sediment texture and bulk density from different sources have little effect on load estimates. Contemporary bluff vegetation state has little correlation with long-term bluff erosion rates. About 20% of sediment eroded in the GBERB is stored on floodplains and in lakes: a rather small amount relative to budget uncertainties, and much less than in other watersheds (Trimble, 1999; Walter and Merrits, 2008). Various different methods of bluff erosion rate interpolation and extrapolation resulted in similar fine sediment load from GBERB bluffs, suggesting that elaborate extrapolation techniques are not worth the extra effort. We advocate extrapolating subwatershed-scale bluff erosion rates. Fine sediment load from bluffs is primarily a function of bluff extent and erosion rate; other factors have minor effects. The budget presented here uses upland fine sediment supply rates from the Le Sueur watershed and is fairly accurate on the Blue Earth as constrained by gauged sediment loads. These results will be further improved by the pending addition of sediment fingerprinting results for the Blue Earth and Watonwan rivers.

We attempted to identify variables that could predict bluff erosion rates in other MNR tributary watersheds. Over various scales, including regressions between data on single bluffs, local averages over a 3 km radius, and subwatershed averages, no trends were found between bluff erosion rate and bluff slope, bluff aspect, bluff size, radius of channel curvature, channel slope, watershed area upstream, or between bluff toe migration and crest retreat rates. The lack of correlation between potential predictor variables and bluff erosion rates suggest that bluff failure is a complicated stochastic process, the average rates of which must be measured over long spatial and temporal scales (Day et al., 2013).

Belmont and others (2011) concluded their work detailing the Le Sueur sediment budget by invoking regional relevance, noting that the similar land use and geologic history means that streams throughout the Minnesota River Valley may also be producing increased modern sediment loads derived primarily from near-channel sources. Through sediment budgeting, we have shown that the Blue Earth and Watonwan Rivers derive their loads from the same sediment sources as the Le Sueur, and in similar proportions.

Though we do not (yet) have a Holocene baseline against which to compare our budgets, as a modern erosion al hotspot, the GBERB could be considered the heart of a management problem. Our work supports the hypothesis Belmont and others (2011) suggested, but it does not answer the implied societal question: what, if anything, is to be done about high near channel erosion rates and increased sediment load? To those wishing to address high sediment load in the GBERB, we submit that the GBERB has derived its load primarily from bluffs throughout most of the Quaternary, so modern GBERB erosion and sediment loading rates are increases to an inherently rapid process (Engstrom et al., 2009; Belmont et al., 2011; Gran et al., 2013). Reducing bluff erosion to pre-settlement levels would be a difficult enough task in any environment, but in the GBERB, some of the processes that drive high near channel erosion rates are accelerating. Unless land managers change course, changing climate and agricultural practices will continue to drive hydrologic changes including higher discharges in the GBERB and MNR basin (Novotny and Stefan, 2007; Blann et al., 2009; Schottler et al., 2013). As these changes occur, we should expect to see migration rates increase and further accelerate bluff erosion. Without addressing hydrologic changes in the basin, rates of bluff erosion will continue to be high. But, land managers who wish to decrease sediment load in the GBERB should also note that fluvial adjustment to base level fall continues to drive bluff creation, erosion and sediment loading in the basin. Management efforts to decrease load should recognize that bluffs are the primary source across the basin and that bluffs have been highly active for thousands of years.

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Appendix 1: Space for time substitutions and local averages

To investigate how channel migration and bluff erosion rates change across the GBERB, we plotted rates averaged at local and subwatershed scales. Variables that change systematically over long spatial scales, like channel slope, are often averaged over short length scales to reduce local noise and emphasize large-scale trends. Channel migration rate is influenced by the erosive power of flowing water and bank erodibility. Components of bank erodibility and stream power such as channel slope, sediment supply, bank material properties and discharge change over long length scales and have along-channel trends. Therefore channel migration rate should, too, and we think it is appropriate to average over reach scales. We use this approach to find reach-averaged values for parameters like bluff size, relief, and channel slope. Similarly, temporal averages are used to smooth fluctuations in a stochastic system.

When rates are episodic, characteristic averages are usually obtained by measuring rates over long timescales, thus incorporating times of both erosion and stability (Sadler, 1981). The relationship between measured erosion rates and the length of time period over which the rate is measured decreases as a negative power function, so that the difference in rates measured at progressively longer periods approaches zero. In the GBERB, the difference between bluff erosion rates measured over 70 years and rates measured over longer periods approaches zero (Kessler et al., 2013). In cases where behavior is constant across space and time, the meaning of rates measured over long timescales can be expanded by combination with spatial averages. Substitution of spatial data for temporal data is called ergodic reasoning. Space-for-time substitutions are commonly used in geomorphology to describe landscape evolution. For example, observation of similar, spatially distributed features of different ages (like fault scarps) is often substituted for long-term observation of single features (e.g., Colman and Watson, 1983). It is more rare for geologists to do as we propose here, which is a direct substitution of spatial averages for temporal averages. For example, to find an average bluff erosion rate, we could measure the erosion rate on one bluff over a time scale long enough to smooth variability into a characteristic average. This might take 100 years. But if the variables that control bluff erosion rates are relatively constant over a distance of 5 km, then it is statistically equivalent to measure erosion rates on 100 bluffs in a 5 km reach for one year.

As long as the behavior of the subject is the same across space and time, an ergodic approach is appropriate (Paine, 1985). The variables that affect rates of channel migration and bluff failure change across tens of kilometers and thousands of years in the GBERB, a scale we believe is long enough to allow smoothing measurements over a few kilometers.

Appendix 2: Extrapolation of vegetation-specific erosion rates

Bluff erosion rates are easiest to measure on large, bare bluffs. This may bias measured rates towards bluffs that are recently active, potentially creating an artificially high erosion rate for extrapolation. Adjustments were made to account for the measurement bias in a process we call vegetation-specific extrapolation. The first step is to use the information we have to define possible bare and vegetated erosion rates on measured bluffs. This can be done using data from the whole watershed, subwatershed, or single bluffs. First, we modified Equation 10 to allow different erosion rates for bare and vegetated bluffs.

$$V_E = E_b * SA_b + E_v * SA_v \tag{14}$$

Equation 14 was populated with data (the erosion volumes, surface areas and 2010 vegetation state) from the bluffs on which we measured erosion rates (Table 5), and then solved for a range of paired solutions for E_b and E_v (Figure 28). In this construction, V_E is the annual volume eroded from bluffs with measured rates, and is therefore a known, constant value. Equation 14 defines a range of bare and vegetated erosion rates that are possible if erosion rate is a function of vegetation state. To limit this range of possible rates, we began by discarding all rate pairs for which E_v is greater than E_b, because bare bluffs likely erode faster than vegetated bluffs. We further reduced the range of possible erosion rate pairs by excluding pairs where the bare bluff erosion rate is larger than short term erosion rates, because short term erosion rates on the GBERB and in general are higher than rates measured over longer timescales (Kessler et al., 2013; Sadler, 1982). A short-term bare bluff erosion rate of 20 cm/a was measured with terrestrial lidar on the Le Sueur (Day et al., 2013). Note that this method pertains only to extrapolation bluffs. It is unnecessary to adjust for vegetation on bluffs with measured or interpolated rates, because measured rates implicitly account for the long-term effects of vegetation.

Table 5: Inputs to Equation 14 for subwatersheds requiring extrapolation of bluff erosion rates

Vegetation study inputs		LeSueur				Blue Earth			Watonwan
		Maple	Cobb		LeSueur				
		AB UG	AB KZ	in KZ	AB UG	AB Winnie	Winnie - KF	Below KZ	Above GC
total Vlost, measured	m^3/a	2,721	3,426	26,544	705	5,653	17,798	23,891	10,933
VolLost, interpolated	m^3/a	763	2,300	10,969	1,537	6,288	15,892	21,737	14,807
SA veg, measured	m^2	33,197	39,281	125,796	6,084	28,843	71,271	100,803	47,927
SA bare, measured	m^2	3,676	7,359	172,887	3,683	34,796	50,252	5,906	50,382
SA veg, extrapolation	m^2	8,108	246,319	59,362	183,422	240,511	1,821	40,920	156,990
SA bare, extrapolation	m^2	1,537	17,422	20,776	12,941	43,632	435	-	85,229
measured bluffs, bare	%	10%	16%	58%	38%	55%	41%	6%	51%
extrap. bluffs, bare	%	16%	7%	26%	7%	15%	19%	0%	35%

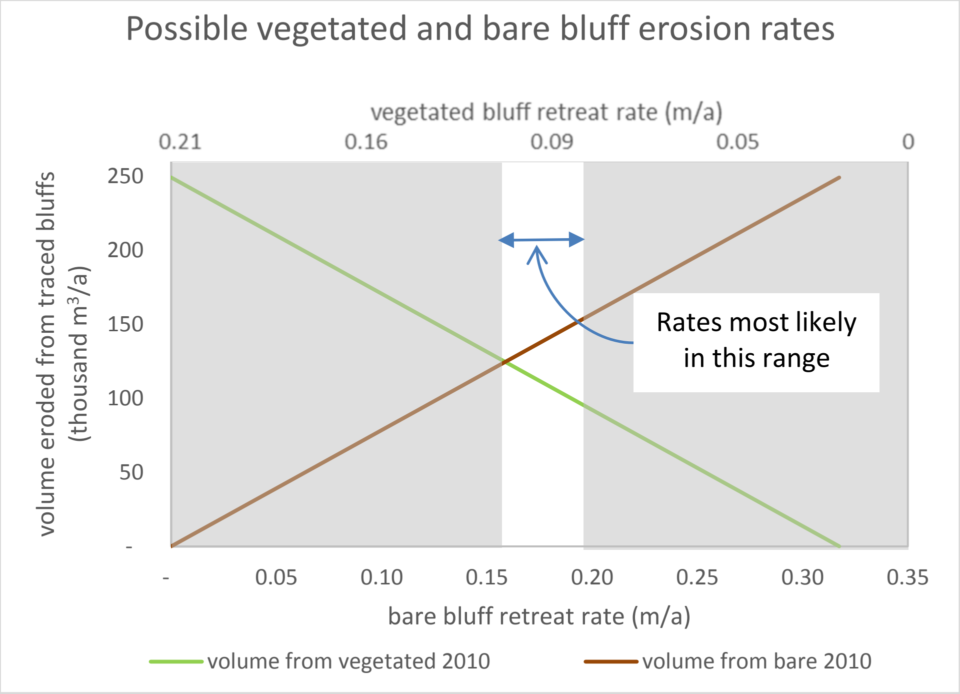

Figure 28: Possible vegetated and bare bluff erosion rates based on volume eroded from all GBERB bluffs with measured rates. By definition, the total erosion volume from each rate pair is constant (250,000 m^3/a). Vegetated bluff erosion rate values are at a maximum when bare bluff erosion rate is lowest. E_b is likely greater than E_v, and E_b is likely less than 0.2 m/a, a short-term E_b (Day et al., 2013).

The simplest way to apply selected rate pairs to extrapolation bluffs is according to vegetation state in 2010. However, vegetation state in 2010 is not necessarily indicative of vegetation cover over 70 years. An approach that may better represent long-term trends in the watershed is to extrapolate rates E_b and E_v to bluffs in proportion to each bluff's temporal vegetation probability (Figure 29).

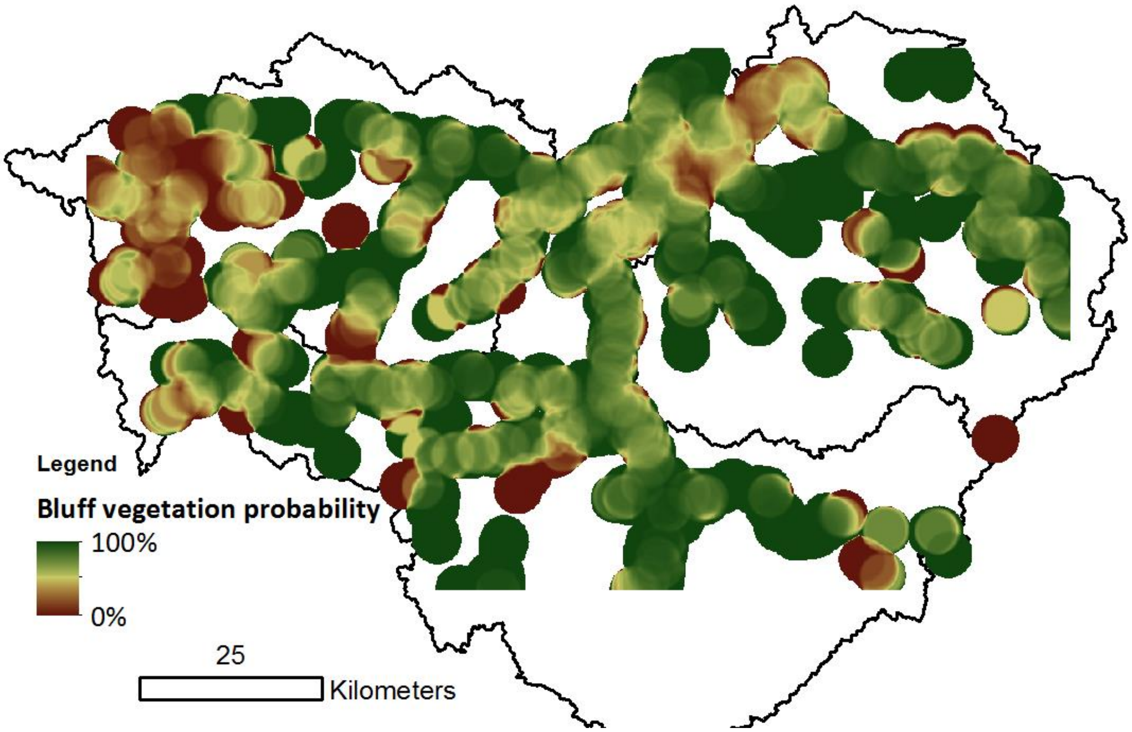

Figure 29: The fraction of bluffs that are vegetated within a 3 km radius of each GBERB bluff. This spatial probability of vegetation may be similar to the portion of time that a bluff is vegetated over decades or centuries.

Vegetation state is controlled by some of the same variables that control bluff erosion rates. Bare bluffs are indicative of high recent erosion rates (Day et al., 2013). Conversely, a vegetated bluff is an indication of low recent erosion rates. Vegetation state at one point in time does not indicate the long-term erosion history of a bluff: every bluff studied in the Le Sueur watershed that migrated was bare at some point over a 70-year record of aerial photography (Day et al., 2013), but most are vegetated now. This observation illustrates that the timescale of vegetation change on a bluff is much shorter than the timescale of change for independent variables that affect large-scale erosion rates. Because the timescale of vegetation change on a bluff is much shorter than the timescale of change for independent variables that affect it, we can make an ergodic substitution (Appendix 1). A long-term average vegetation state may better correlate with long-term erosion rate. Using ergodic reasoning, the spatial probability of vegetation should also represent the probability over time that any one bluff in the area is vegetated (Figure 29). Vegetation probability may more accurately represent the percent of the time an individual bluff spends vegetated or bare over long time periods. Vegetation rate pairs and vegetation probability were combined for each bluff to determine annual volume of sediment eroded with Equation 15.

$$V_E = SA * (ProbVeg * E_v + (1- ProbVeg)* E_b) \tag{15}$$

Possible pairs of vegetated and bare bluff erosion rates for Blue Earth bluffs upstream of Winnebago (including Elm Creek) are shown in Figure 30. The green line shows the volume of sediment eroded from vegetated extrapolation bluffs when the rate on the top axis is applied to the surface area of vegetated bluffs. The brown line shows the volume eroded from bare bluffs, when the rate on the bottom axis is applied to bare bluff surface area in the watershed. The yellow line is the total volume eroded from all extrapolation bluffs. For example, if bare bluffs are eroding at 8 cm/a, the paired vegetated rate is 10 cm/a; bare bluffs produce about 3,000 m^3 of sediment per year, and vegetated bluffs produce about 23,000 m^3/a. In the watershed overall, there is much more vegetated bluff surface area than bare surface area, so using high vegetated bluff E rates produces more sediment from extrapolation bluffs than using high bare bluff E rates. Total volume of sediment eroded ranges from about 47,000 m^3/a when high vegetated bluff E rates are used to less than 10,000 m^3/a when low vegetated bluff E rates are used. If we allow that bare bluffs probably erode at a faster rate than vegetated bluffs, we can reduce this range by discarding values to the left of the vertical black line. In these subwatersheds, the median E_v and E_b values in the range where E_v is less than E_b are 0.05 and 0.12 m/a, respectively. Median rate pairs like these were applied to extrapolation bluffs according to each bluff's probability of vegetation (Equation 15). There were very few bluffs with measured rates above Winnebago, which accounts for the wide range of potential erosion volumes shown in Figure 30.

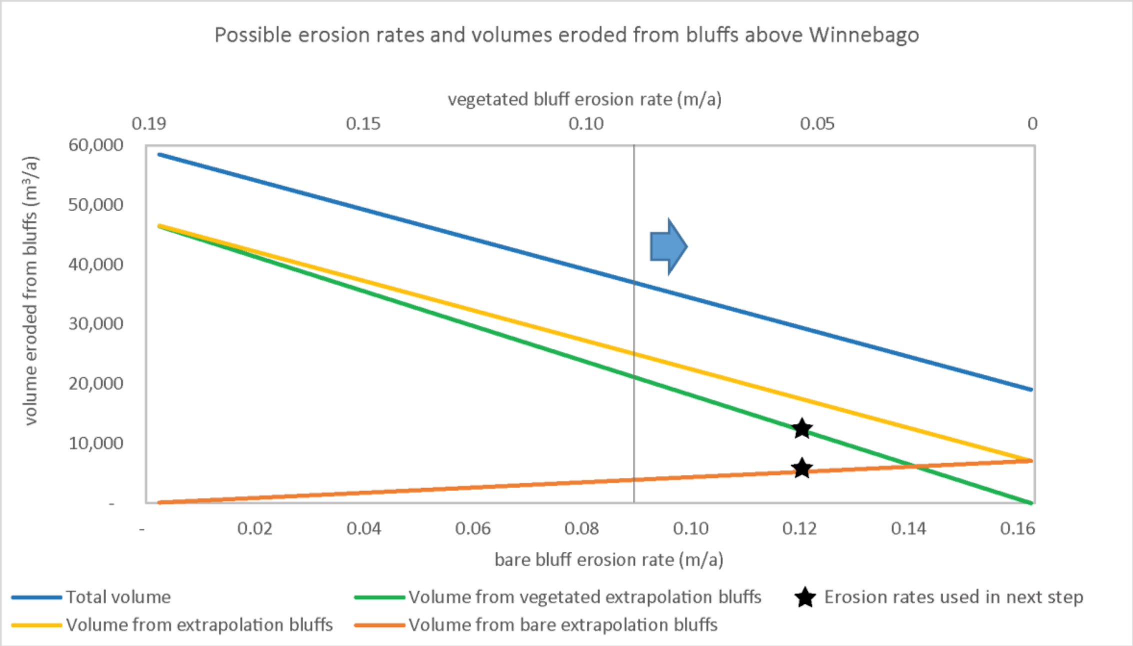

Figure 30: A result from the vegetation-specific E rate extrapolation method: Potential volumes eroded from bluffs above Winnebago, shown as thick blue line. Green line shows corresponding volume eroded from vegetated bluffs to which rates are extrapolated; brown line is volume eroded from bare extrapolation bluffs. Yellow line is the sum of erosion volume from bare and vegetated extrapolation bluffs. Blue line is total volume from all bluffs; in vertical space, the difference between the yellow and blue lines is the volume eroded from measured and interpolated bluffs (which is constant under all extrapolation scenarios). Top axis is vegetated bluff erosion rate correlating to vegetated bluff erosion volume (green line), and the bottom axis is for bare bluffs (orange line). Bare bluff erosion rates are likely higher than vegetated bluff erosion rates. On the plot this occurs to the right of the vertical line. The median E_v and E_b values in the range where E_v is less than E_b (stars) are combined with the probability of vegetation on extrapolation bluffs to calculate load in the final step of the vegetation-specific extrapolation method.

In seven of the 15 GBERB subwatersheds, all budget bluffs had measured erosion rates or had rates interpolated to them. In the other eight subwatersheds, it was necessary to extrapolate erosion rates to bluffs without measured E rates. Table 6 lists the (linear regression) averages of bluff erosion rates in the subwatersheds where rate extrapolation was required. Line one is the subwatershed average of measured bluff erosion rates (without any consideration of vegetation). Rates in lines two and three summarize the first step in constructing vegetation-specific erosion rates: they consider the vegetation state in 2010 of measured bluffs in each subwatershed. These values are the median of all erosion rate pairs in the subwatershed for which $E_b > E_v$ (e.g., the median rates of rate pairs to the right of vertical line in Figure 30). Line 4 gives the proportion of watershed bluff surface area that is vegetated. Line 5 is the result from both steps: it is a back-calculation of the average erosion rates that were actually used. These summary rates account for the vegetation states of bluffs on which rates were measured and bluffs to which rates were extrapolated.

Table 6: Erosion rates for extrapolation

	erosion rates for extrapolation (m/a)	LeSueur				Blue Earth			Watonwan
		Maple	Cobb		LeSueur				
		AB UG	AB KZ	in KZ	AB UG	AB Winnie	Winnie - KP	Below KZ	Above GC
1	average before veg study	0.07	0.07	0.09	0.07	0.09	0.15	0.22	0.11
2	median Eb when Eb>Ev	0.40	0.25	0.12	0.13	0.12	0.25	2.15	0.17
3	median Ev when Eb>Ev	0.04	0.04	0.04	0.04	0.05	0.07	0.11	0.05
4	average probVeg	0.88	0.85	0.75	0.83	0.81	0.91	0.94	0.52
5	"as built" average	0.08	0.06	0.06	0.05	0.06	0.09	0.23	0.10

*Table includes only subwatersheds where extrapolation was necessary.

Bare bluff E rates determined with the first part of the vegetation-sensitive extrapolation method can be extraordinarily high, particularly in subwatersheds where few measured bluffs were bare, like below the knickzone on the Blue Earth (Table 6). But taken together, the two parts of this extrapolation method balance each other. The small extent of bare bluffs below the knickzone on the Blue Earth means that in the second half of the vegetation study the high bare bluff E rate is only extrapolated to a very small area, and the vegetation-specific extrapolation rate is similar to extrapolation rates that do not explicitly account for bluff vegetation state (i.e., compare line one to line five in Table 6). In most subwatersheds, the “as built” rates in line 5 are lower than average erosion rates that do not account for bluff vegetation, because rates were measured disproportionately often on bare bluffs. Where extrapolation rates increased after consideration of bluff vegetation (Upper Maple and Blue Earth below the knickzone), there is very little bare bluff surface area with measured rates (Table 5). Typically, bare bluffs composed a larger proportion of the measured bluffs than the extrapolated bluffs, and when this is the case, vegetation-specific erosion rates decreased. Rates at the bottom of Table 6 are the vegetation-sensitive extrapolation rates. The two parts of the vegetation-specific extrapolation method work together to moderate these rates. Vegetation-specific erosion rates for extrapolation are very similar to the extrapolation rates that do not consider vegetation. Our bias towards measuring bare bluffs does not significantly affect estimated load from bluffs. Vegetation has little effect on long-term bluff erosion rates and our measurement bias for bare bluffs does not significantly affect estimated load. These findings support the suggestion that vegetation has little effect on long-term bluff erosion rates (Day et al., 2013).

Appendix 3: Bluff erosion rates: Potential predictor variables, local variation and the value of local averages

Because we were not able to measure bluff retreat and channel migration rates for all bluffs in the basin we needed to extrapolate erosion rates across tens or hundreds of kilometers. All sediment budgets face this problem to some extent, so this aspect of our project was of special interest. We explored variability in bluff erosion rates in two ways: 1) spatially, to see how similar bluff erosion rates are to other nearby rates, and 2) by comparing erosion and retreat rates against measurements of channel and bluff geometry in an attempt to find variables that could predict bluff erosion rates. An accurate way to predict erosion rates might lower sediment budget uncertainty, and might also be used to construct sediment budgets on other MNR tributaries.

Previous work in the GBERB looked at correlations between erosion rates and potential predictor variables measured on single bluffs and at the subwatershed scale, with mixed results (Day et al., 2013). We extended this analysis by exploring potential predictor variables on three spatial scales: on individual bluffs, on groups of bluffs within circles of 3 km radius, and within subwatersheds. Just as averaging channel slope over a few kilometers is more practical than looking at high-resolution topographic data, we hoped that averaging potential predictor variables and retreat rates over local scales would smooth the effects of local variation and the stochastic nature of bluff failure to make rates more predictable.

Bluff erosion rates and physical characteristics were measured using ArcGIS, and then averages were constructed in a spreadsheet. This task is easy at the subwatershed scale, but local averages are trickier. Initially, we employed the same ArcGIS-based method used to create local E rate averages outlined in the main body of this document, but it became cumbersome to execute for more than a few parameters. Instead, we proceeded with statements based on if/then commands in Microsoft Excel to create averages for each bluff based on the parameters of all bluffs within 3 river kilometers. This method allowed us to quickly create local averages of many measured parameters.

We found poor correlations between potential predictor variables and erosion rates on individual bluffs (Table 7). Local and subwatershed regressions were slightly better correlated in some cases. These findings are similar to results from regressions on individual Le Sueur bluffs (Day et al, 2013; Se Jon Cho, Johns Hopkins University, personal communication). Correlation coefficients indicate that no single potential predictor variable is strongly correlated to bluff erosion (E) rate at any scale. Note that crest retreat and toe migration rate are strongly correlated to E rate; this is because they are the components from which E rates are constructed. E rate is best correlated to upstream watershed area and channel width, but only over long spatial scales. These results make sense, because on typical rivers, width and upstream area are both related to river discharge (Knighton, 1998). On the Le Sueur, previous research found that standard hydraulic relationships hold between channel width, depth and contributing upstream area (Gran et al., 2013). Discharge is a primary component of the shear stress or erosive energy rivers exert on their banks, so it makes sense that higher discharge is associated with higher near-channel erosion rates.

Other variables primarily related to distance from the watershed outlet also correlate relatively well to E rate, including distance upstream, bluff length, bluff surface area, valley relief and radius of channel curvature. Bluffs and bends are longer and larger downstream, and the valley is deeper downstream: these variables are primarily related to location within the watershed, but none are as clearly related to discharge as upstream area. The presence of Pleistocene outwash is somewhat correlated to bluff erosion rates, suggesting that bedload sourced from outwash channels may enhance GBERB channel migration. That the correlation between the presence of outwash features and E rate is not better may be related to our method of noting the presence of glacial alluvium only on bluffs adjacent to mapped glacio-fluvial sediments.

Table 7: Correlations between bluff erosion rates and potential predictor variables at three scales

Correlation coefficents (R^2) between E and potential predictor variables			
	single bluffs	local averages	subwatersheds
Bluff geometry and characteristics			
bluff height	0.01	0.01	0.03
bluff length	0.14	0.03	0.11
bluff surface area	0.01	0.01	0.05
annual volume eroded	0.12	0.05	0.07
mean bluff slope	0.02	0.01	0.01
maximum bluff slope	0.01	0.06	0.07
local vegetation %	0.16	0.01	0.01
bare or vegetated			0.09
bluff aspect			0.03
presence of Pleistocene alluvium			0.09
Holocene alluvium (terraces)			0.16
presence of bedrock			0.10
Watershed position			
valley relief	0.01	0.01	0.01
distance upstream	0.01		0.05
upstream watershed area	0.06	0.29	0.59
stream power	0.01	0.01	0.01
Channel geometry			
channel slope	0.01		
channel width	0.06	0.16	0.43
theta	0.01	0.15	
d theta	0.03	0.09	
r curve	0.01	0.04	0.22
Rates			
channel migration rate	0.69	0.47	0.74
CR rate	0.84	0.86	0.78
E	1.00	1.00	1.00

Bluff vegetation status and aspect do not correlate well with E rate, a finding echoed elsewhere (Day et al., 2013). It is somewhat surprising that we did not find a good correlation between aspect and bluff erosion rate. This result may simply reflect the complicated interaction between the many factors that affect bluff erosion rates; or it might suggest that other processes have greater effect on bluff erosion rates. It is not surprising that vegetation cover is poorly correlated to bluff erosion rates. (Appendix 2). Like vegetation, bluff slope is poorly correlated to E rate. Similarly, bluff slopes relax and decrease following failure, so high slopes do not indicate imminent failure but low slopes are an indication of stability. Colman and Watson (1983) describe a process of similar slope decay for earthquake scarps. The lack of correlation between bluff slopes and E rates suggest that the timing of bluff failure is too episodic and/or too frequent for successful application of a slope-based failure prediction model. Interestingly, channel slope is also poorly correlated to bluff erosion rates. We might expect to see high channel incision rates and low channel migration rates in areas of high channel slope (Turowski, 2012), but how such a situation translates to bluff erosion rates is not clear in these data. High bluff erosion rates occur in areas of low channel slope (between Winnebago and the knickzone on the Blue Earth) and in areas of high slope (the Le Sueur knickzone). Channel slope is thus not understood to be a primary control on bluff erosion rates. Channel slope and upstream watershed area are the components of stream power; the poor correlation between channel slope and bluff erosion rate explains why stream power does not correlate better to bluff erosion rate.

Other statistical methods were used to explore correlations between bluff erosion rates and potential predictor variables, including principal components analysis and multivariate regressions. Results are not presented here because they do not improve our analysis. Bluff erosion rates are primarily influenced by discharge and channel geometry; principal components analysis supports this finding. Multivariate linear and power regressions do not fit the data any better than single variable linear regressions.

Locally averaged parameters are typically better correlated to E rates than parameters measured only on individual bluffs, but subwatershed averages have the best correlation to E rate. This finding may suggest that locally averaged parameters have meaning and smooth some of the stochastic variability in bluff E rates; but nonetheless, no potential predictor variables are closely enough correlated to bluff E rate for use as predictor variables by themselves. This finding supports our endorsement of bluff erosion rate extrapolation at the subwatershed scale.

Erosion and migration rates at local and subwatershed scales

We averaged E rates over local and subwatershed scales (Figure 16 and Figure 18). Figure 31 shows the standard deviation of channel migration rate measurements over the same window in which rates were averaged. The measurements are highly variable along the channel, so standard deviations of the local averages are very high. This may be one reason local interpolation is no better (Table 7) or more useful (Figure 25) than subwatershed extrapolation. Local standard deviation is similar to the geostatistical concept of variance, a comparison of the difference between two measured values and the geographic distance separating the locations where the values were measured. Spatial variation in bluff erosion rates were also investigated using variograms and geostatistical prediction maps. Results from these analyses were not useful and not presented here. Geostatistics does not improve our analyses because individual bluff erosion rates vary more over local scales than average bluff erosion rates vary over subwatershed scales. This is likely because channel geometry affects bluff erosion rates and changes at reach scales.

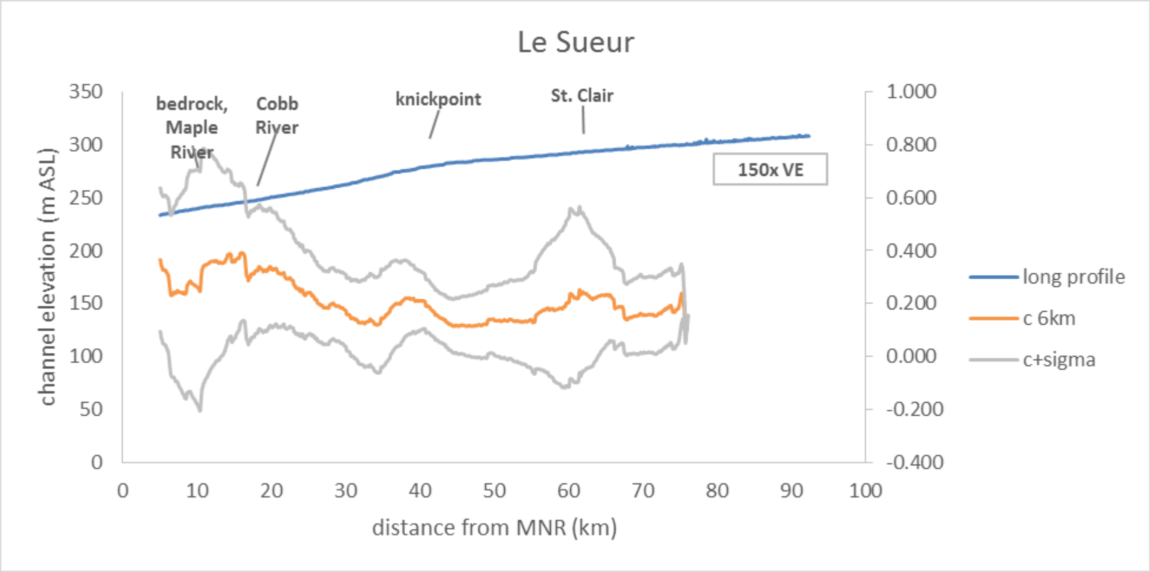

Figure 31: Channel migration rates on the Le Sueur River have very large standard deviations.

However, local averages do have value. Bluff erosion and channel migration rates are so locally variable that without a local smoothing window it is difficult to interpret how factors that might drive erosion rates (like bedrock, bedload, channel slope and discharge) affect erosion and retreat rates (Figure 16 and Figure 17). Locally averaged bluff erosion and channel migration rates plotted along channel are useful for interpreting landscape-scale erosion rate trends related to the presence of bedload and bedrock. However, note that the standard deviation of locally averaged channel migration rates is similar to the average rates themselves (Figure 31, Figure 16). High local variation is a problem with locally averaged rates in general, but bluff E rates in particular, because we have fewer measurements of E rate than channel migration rate.

Bluff erosion and channel retreat rates are influenced by many variables (Wick, 2013). In general, the best correlations between bluff erosion rates and the variables we investigated are related to along-channel bluff location within the GBERB. However, even variables related to along-channel bluff location are not well correlated to erosion rates on any of the spatial scales we investigated. We could not find any single variables that could be used to predict bluff erosion rates a priori. Bluff erosion and channel migration rates themselves are highly variable, and have high along-channel standard deviations. We found that averaging these retreat and erosion rates locally simplifies interpretations of highly variable data and enhanced our understanding of how bedrock and bedload affect bluff erosion and channel migration rates (e.g., Figure 16 and Figure 17). But because bluff erosion rates are so variable at local scales, extrapolating locally averaged erosion rates generates high uncertainties and is meaningless in the context of the GBERB budget. Local averages do not increase sediment budget accuracy because bluff erosion rates vary at similar magnitude on local and subwatershed scales. We therefore advocate extrapolating bluff erosion rates based on bluff location at subwatershed scales.

Appendix 4: Alterations to the original Le Sueur budget: the effect on load estimates of bluff extents and different averaging and extrapolation methods

Bluffs in the original Le Sueur budget were excluded from the revised budget primarily because original bluffs were bedrock or set back from the modern active channel. Figure 32 and Table 8 show how refining steps reduced bluff extent in the Le Sueur watershed.

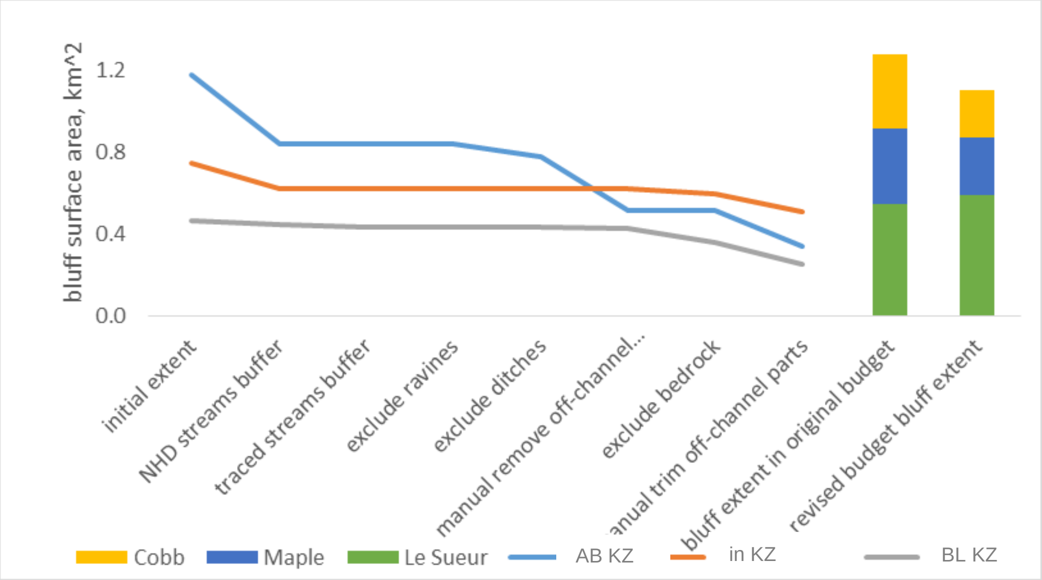

Figure 32: Refining bluff extents in the Le Sueur watershed. Lines show extent in each subwatershed following reduction in each step. Initial extents were taken from the original budget in Blue Earth County; in other counties, initial extents were the results of a topographic criterion. On the right, histogram shows bluff extents in the original and revised Le Sueur budget.

The original budget already excluded bluffs that were along ditches or in ravines, so these steps did not remove any bluff area. Le Sueur bluff extent below the knickzone was reduced by the largest proportion. Many of the bluffs in this area were excluded from the revised budget because they overlapped bedrock outcrops. Overall, most of the bluff extent trimmed from the original Le Sueur budget was trimmed because it was not immediately adjacent to active channels. Total bluff extent in the Le Sueur watershed in Blue Earth County (that is, within the area covered by the original budget) was reduced by about 30% between the original and revised budget (Table 8). However, the addition of bluff extent outside of Blue Earth County made up for some of this reduction, making the revised Le Sueur budget extent (1.01 x 10^6 m^2) nearly 90% of the original Le Sueur budget bluff extent (1.28 x 10^6 m^2) (Figure 32). Of the three Le Sueur subwatersheds, extents on the Le Sueur River increased in the revised budget, while the Cobb and

Maple extents shrunk. This makes sense because a larger fraction of the Le Sueur subwatershed lies outside of Blue Earth County than the Cobb or Maple subwatersheds (Figure 6). Additionally, the upper portions of the Le Sueur subwatershed are steep where they drape up to the Bemis terminal moraine, while the upper reaches of the Cobb and Maple have lower relief and remain primarily within the glacial Lake Minnesota lake plain (Figure 5). Extent on the Cobb decreased the most, maybe because extents were less-carefully trimmed in the initial budget.

Table 8: Bluff extent change on the Le Sueur within Blue Earth County

Le Sueur bluffs in Blue Earth County	LeSueur									
	Maple			Cobb			LeSueur			Le Sueur
(m^2)	AB UG	BTWN gauges	BL LG	AB UG	BTWN gauges	BL LG	AB UG	BTWN gauges	BL LG	total
SD bluffs within BE co	68,614	216,501	82,351	5,780	242,546	114,178	41,717	263,782	239,732	1,275,201
MB bluffs within BE co	54,921	183,139	38,618	3,366	146,815	60,799	34,355	213,321	152,218	887,552
reduction from orig., BECo	13,693	33,362	43,733	2,414	95,731	53,379	7,362	50,461	87,514	387,649
% reduction from orig., BECo	20%	15%	53%	42%	39%	47%	18%	19%	37%	30%

A budget encompassing all suspended sediment contributions from all bluffs in the GBERB requires the extrapolation of measured rates to bluffs on which it was not possible to measure rates. To help us determine how to calculate average bluff erosion rates for extrapolation in our revised budget, we investigated how sensitive mean erosion rates are to averaging methods. Our conceptual model of bluff erosion incorporates the lateral migration rate of the adjacent channel. Erosion rates on bluffs with measured crest and toe retreat rates are affected by how channel migration direction is incorporated into erosion rate, the averaging method, and the bluff extent. When channel migration rate is measured from aerial photographs, a net channel migration direction is also recorded. The original Le Sueur budget incorporated the net migration direction into bluff erosion rate calculations. This was done by applying the volumetric erosion equation matching observed channel migration direction to calculate bluff erosion rate (Equations 5b and 6b; Table 9, line 1). Where it was not possible to record migration direction, a migration direction (toward or away from bluff) was assigned based on ratios of migration direction in the observed data. For example, in the Blue Earth watershed, 65% of the observed migration direction was toward bluffs, so 65% of the unmeasured bluffs were assigned a “toward” migration direction. We chose to use an equal distribution of channel migration direction to calculate bluff erosion rate in our revised budget, because it is a more systematic way of dealing with these unmeasured variables, and because we think it better represents long-term channel behavior. The new method reduces the average Le Sueur watershed bluff erosion rate.

The biggest change came on the Le Sueur below the lower gauge. On this reach, observed channel migration direction was primarily towards bluffs. The revised method effectively increased the frequency at which E was calculated as half the base of a triangle (Equation 5b) at the expense of the frequency at which E was calculated as the average length of the bases of a trapezoid (Equations 6b and 10), therefore reducing the erosion rate (Table 9).

Table 9: Average erosion rates (E) in the greater Le Sueur watershed

	Average subwatershedshed bluff erosion rate (E) (m/a)			Le Sueur						
				Maple			Le Sueur			Le Sueur
				AB UG	BTWN gaug	BL LG	AB UG	BTWN gaug	BL LG	average
1	**SD LS bluffs**	obs. mig. direct'n	simple average	0.06	0.11	0.07	0.06	0.14	0.17	0.12
2	**SD LS bluffs**	MD = 50-50	simple average	0.09	0.10	0.09	0.07	0.11	0.13	0.10
3	**SD LS bluffs**	MD = 50-50	linear regression	0.05	0.08	0.11	0.08	0.12	0.11	0.10
4	**MB LS bluffs**	MD = 50-50	linear regression	0.07	0.09	0.14	0.07	0.09	0.09	0.09

The accuracy of the revised method depends on the rate at which channel migration direction changes. Where small bends move quickly, migration may change direction entirely over 70 years. The revised method makes sense in such a scenario. Where bends are large, like in the knickzones, migration rates may also be high, but migration direction may not change over 70 years. The original method of dealing with migration direction is probably better suited for knickzones, where channel migration direction does not change as quickly. The revised method may be misrepresenting the volume of sediment eroded from some bluffs below the knickpoint, but as differences between the Maple and Le Sueur show, the different method of dealing with migration direction does not uniformly raise or lower individual bluff erosion rates.

Using a linear regression average rather than an arithmetic average to calculate average bluff erosion rates results in the same Le Sueur watershed average erosion rate (Table 9, lines 2-3). However, averages change in the subwatersheds according to the size of bluff on which the rates were measured. In the Upper Maple the average bluff erosion rate decreases from 9 to 5 cm/a, indicating that low rates were measured on large bluffs. Below the lower gauge on the Maple, the opposite is the case: the average bluff erosion rate increases from 9 to 11 cm/a, indicating that high rates were measured on large bluffs. An average calculated with a linear regression, like Equation 11, normalizes rate measurements to the bluff area over which the rate was measured, thereby weighting the average towards measurements on large bluffs. An arithmetic average of bluff erosion rates gives equal weight to each measured bluff rate in the final average. In effect, the simple average biases the result towards rates measured on small bluffs. We think there is no reason that measurements on small bluffs should be given more weight relative to measurements on big bluffs. In fact, we suspect that lower georeferencing error likely makes crest and toe retreat rates more accurate when measured on large bluffs than on small bluffs (Day et al., 2013). We therefore prefer to use linear regressions between volume of sediment eroded from bluffs and bluff surface area and to calculate averages.

In the Le Sueur basin, about 30% of bluff surface area within Blue Earth County was trimmed from the original to the revised budgets, primarily because parts of the original budget bluffs are set back from active channels or composed of bedrock. Because average bluff erosion rates calculated with linear regressions are affected by the surface areas of bluffs considered, the change in bluff surface area between the original and revised budget affects average bluff erosion rates (lines 3 and 4 in Table 9). No new rates were measured in these subwatersheds, so any rate changes between lines 3 and 4 in Table 9 are solely due to different bluff extents. Overall, the Le Sueur watershed average E rate decreases by 1 cm/a. Below the knickzone, subwatershed average E rates change by nearly 50%. Subwatersheds below the knickzone were most affected by excluding bedrock and set-back bluff extents from the budget. The largest change is below the lower gauge on the Maple, where the average rate increased from 11 to 14 cm/yr. There are many bedrock outcrops mapped along channels in this subbasin, so the extent change is due both to removing bluffs that are composed of bedrock and bluff areas that are set back from active channels. The higher rate suggests that bedrock bluffs and bluffs set back from active channels have lower erosion rates than bluffs that are connected to active channels. The second largest change was in the Le Sueur below the lower gauge. Here reducing bluff extent decreased the average erosion rate from 11 to 9 cm/yr. Bluff extent in this subwatershed changed significantly, because many original budget bluffs are composed of bedrock or set back from active channels. The small change reflects the fact that the extents of the measured bluffs did not change very much, and affirms that the measured bluffs met a stringent definition of “bluff” in the original budget. Moreover, E did not change much according to which method of dealing with migration direction was used, which averaging method was used, or which set of extents was used. However, we still advocate for the use of our revised method for bluff rate calculations, because we believe that it is more accurate to use an even distribution of migration directions, averages determined with linear regressions, and a bluff inventory that carefully excludes extents disconnected from active channels.

When all the differences between the construction of E in the original and revised Le Sueur budget are considered together, E rates change most below the knickzones (Figure 33). Rates on the Le Sueur below the lower gauge, for example, decrease by 0.08 m/a. Half of this decrease results from different treatment of migration direction (Table 9, lines 1 and 2). One quarter of this difference results from the use of a linear regression average instead of an arithmetic average (lines 2 and 3), and an additional quarter of the difference is due to bluff trimming (lines 3 and 4). Change on the Maple below the gauge was of similar magnitude but opposite sign. The opposite is true on the Maple below the gauge, where rates steadily increased due to disproportionately high observed channel migration away from bluffs, high rates measured on large bluffs, and extent trimming on off-channel and bedrock bluffs with low E rates.

While average E in the revised budget changes the most below the knickzone, uncertainties are also greatest there. Uncertainties are large in any subwatershed where few bluffs were measured, like below the knickzone and above the knickzone on the Le Sueur (Figure 18). But uncertainties are also large below the knickzone because bluffs of different sizes were measured there. Because we calculate E using a linear regression when bluffs of different sizes (e.g., a long valley bluff and a small terrace bluff) are measured in the same watershed, the standard deviation of E is also large. In subwatersheds where many bluffs were measured (typically within and above the knickzone), average measured E did not change very much between the original and revised budgets (Figure 33). In other words, where many bluffs were measured, changes to a few measured bluffs did not affect the subwatershed averages very much.

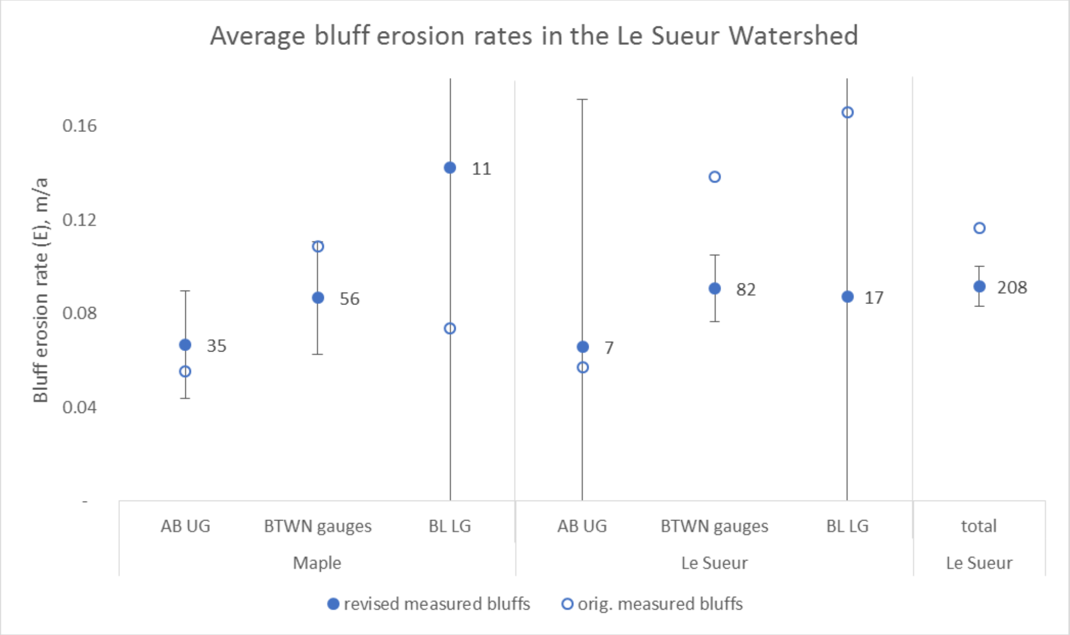

Figure 33: Average measured E rates in each subwatershed of the Le Sueur watershed. Uncertainties from standard deviation of average subwatershed measured E values (liner regression average). Numbers next to each point are the number of measurements in each subwatershed.

The average erosion rate in a subwatershed, when measured, interpolated and extrapolated bluffs are considered, is not necessarily equal to the average rate on bluffs with measured E rates. In the original budget extrapolated erosion rates were modified by consideration of vegetation, aspect and short-term, terrestrial lidar (TLS) rates. In the revised budget, vegetation affected how measured erosion rates were extrapolated, and local interpolation rates are different than the subwatershed average by design. To better summarize the erosion rates used in each version of the budget, and understand the effects of the additional extrapolation methods on bluff erosion rates in the original budget, we back-calculated liner-regression average erosion rates from bluff surface area and the volume of sediment eroded from each bluff (Table 10, lines 3 and 4; Figure 34). Bluff erosion rates in these lines represent the subwatershed average of all erosion rates actually used in the budget (they include measured, interpolated and extrapolated rates). We distinguish these subwatershed rates (E_s) from E rates, which are the average of only measured rates.

Table 10 compares bluffs from the original budget to the revised budget, just in Blue Earth County and including the whole GBERB. The table summarizes bluff surface area (line 1), the linear regression average measured erosion rate (E; line 2), average subwatershed erosion rates (E_s, lines 3 and 4), and the total volume lost using interpolation where possible and vegetation-specific extrapolation (line 5). Line 3 includes only bluffs in the Le Sueur watershed within Blue Earth County, while line 4 considers bluffs throughout the entire watershed. Parts A, B, and C compare differences between the original Le Sueur budget (A), the revised Le Sueur budget within Blue Earth County (B), and the full extent of the revised Le Sueur budget (C). About 1/10 of the bluff surface area in the Le Sueur watershed is outside of Blue Earth County. Rates above the knickzone decreased with the addition of these bluffs, likely because they are highly vegetated.

Table 10: Original and revised budget bluffs in Blue Earth County and including the whole GBERB.*

A	**Original budget Le Sueur Bluffs in BE Co.**		Le Sueur									
			Maple			Cobb			Le Sueur			Le Sueur
			AB UG	BTWN gauges	BL LG	AB UG	BTWN gauges	BL LG	AB UG	BTWN gauges	BL LG	total
1	final surface area	m^2	68,614	216,501	82,351	68,678	179,649	114,178	41,717	263,782	239,732	1,275,201
2	E	m/a	0.06	0.11	0.07	-	-	-	0.06	0.14	0.17	0.12
3	Es, Blue Earth Co.	m/a	0.03	0.08	0.09	<0.01	0.13	0.14	0.10	0.07	0.17	0.10
5	total volume lost	m^3/a	1,983	16,439	7,499	236	23,647	15,527	4,054	18,262	41,880	129,527

B	**Revised budget Le Sueur Bluffs in BE Co.**		Le Sueur									
			Maple			Cobb			Le Sueur			Le Sueur
			AB UG	BTWN gauges	BL LG	AB UG	BTWN gauges	BL LG	AB UG	BTWN gauges	BL LG	total
1	final surface area	m^2	54,921	183,139	38,618	37,051	113,130	60,799	34,355	213,321	152,218	887,552
2	E	m/a	0.07	0.09	0.14	-	-	-	0.07	0.09	0.09	0.09
3	Es, Blue Earth Co.	m/a	0.07	0.09	0.14	0.04	0.07	0.11	0.07	0.09	0.12	0.09
5	vol. eroded, veg extrap	m^3/a	4,103	16,170	5,450	1,566	7,718	6,682	2,447	18,893	18,094	81,124

C	**Revised budget All GBER bluffs**		Le Sueur									
			Maple			Cobb			Le Sueur			Le Sueur
			AB UG	BTWN gauges	BL LG	AB KZ	in KZ	BL LG	AB UG	BTWN gauges	BL LG	total
1	final surface area	m^2	57,584	183,139	38,618	57,733	109,764	60,799	225,132	213,321	152,218	1,098,308
2	E	m/a	0.07	0.09	0.14	-	-	-	0.07	0.09	0.09	0.09
3	Es, Blue Earth Co.	m/a	0.07	0.09	0.14	0.04	0.07	0.11	0.07	0.09	0.12	0.09
4	Es, whole watershed	m/a	0.07	0.09	0.14	0.06	0.07	0.11	0.06	0.09	0.12	0.08
5	vol. eroded, veg extrap	m^3/a	4,230	16,170	5,450	3,283	7,525	6,682	12,553	18,893	18,094	92,881

D	**Revised budget All GBER bluffs**		Blue Earth					Watonwan			GBER
			AB Winnie	Winnie - KP	Knickzone	Below KZ	total	Above GC	In KZ	total	total
1	final surface area	m^2	405,634	217,533	348,257	253,496	1,224,920	431,392	112,128	543,520	2,866,748
2	E	m/a	0.09	0.15	0.19	0.22	0.17	0.11	0.08	0.09	0.12
3	Es, whole watershed	m/a	0.07	0.16	0.18	0.22	0.15	0.12	0.08	0.11	0.12
5	vol. eroded, veg extrap	m^3/a	28,901	33,886	63,966	55,217	181,970	49,904	8,427	58,331	333,182

* Volume of sediment eroded in the original budget was obtained from Day et al., 2013 table V; original bluff surface area is from bluff length and height in the original budget bluff attribute tables.

Extrapolation had a greater effect on subwatershed E_s rates in the original budget than the revised budget. When bluffs are grouped by aspect, average E rates have puzzling trends (Day et al., 2013). Bluff vegetation state had a lot of influence on E rates in the original budget. The original budget explicitly addressed the potential effect of vegetation on suspended sediment load from bluffs when rates measured on bare and vegetated bluffs were extrapolated to bluffs with the same vegetation state. Vegetation state was given additional weight when short-term TLS rates were extrapolated to bare bluffs only. The revised budget also considered the potential effects of vegetation, but only how the vegetation characteristics of the groups of measured and unmeasured bluffs might affect extrapolated E rates. Exploring the potential influence of vegetation in this way had much less of an effect on load.

In the original Le Sueur budget, subwatershed average E_s rates near the mouth are higher than E rates, probably because there is a lot of bare bluff surface area there (Figure 29). Conversely, average rates in subwatershed within and above the knickzone generally decreased following additional extrapolation methods, likely because most bluffs there are vegetated. Average subwatershed E rates decrease on the Maple in the original budget following the addition of extrapolated bluffs, which is likely due to a near lack of bare bluffs on the upper Maple (Figure 29).

In the revised budget, E_s rates were generally only slightly different than E rates (Table 10 B-D, lines 3-5). The only significant difference between E and E_s is an increase on the Le Sueur River below Highway 8 (Table 10C lines 3 and 4). There are no extrapolation bluffs in this subwatershed, and the rate difference comes from a large interpolation bluff near bluffs on which high rates were measured (i.e., the bluff at the mouth of the Le Sueur). Inclusion of this very large bluff increases the subwatershed average (similar findings regarding the importance of single bluffs are noted in Day et al., 2013). Note on this watershed (and others), E rate uncertainty when calculated as one standard deviation of erosion rates within the subwatershed is similar to the E rate itself (Figure 18). This is very high uncertainty, driven by a dearth of measurements in some subwatersheds. Note that uncertainties are lower in watersheds with more measured erosion rates. While not depicted here, uncertainty for local, 3 km-radius averages will be higher than subwatershed values, because even fewer measurements contribute to local averages.

Overall, E rates in both the original and revised budgets decrease slightly when extrapolation bluffs are considered in the subwatershed average. This makes sense, because most extrapolation bluffs are small, vegetated upstream bluffs and we generally measured lower erosion rates on such bluffs. Extrapolation of subwatershed average rates can only affect the overall subwatershed average rate by moving it closer to the average measured rate, because it increases surface area of bluffs with the average watershed rate. On the other hand, rate interpolation to local bluffs on a subwatershed scale in the revised budget could move E_s away from the average measured rate if abnormally high measured rates are interpolated to nearby large bluffs.

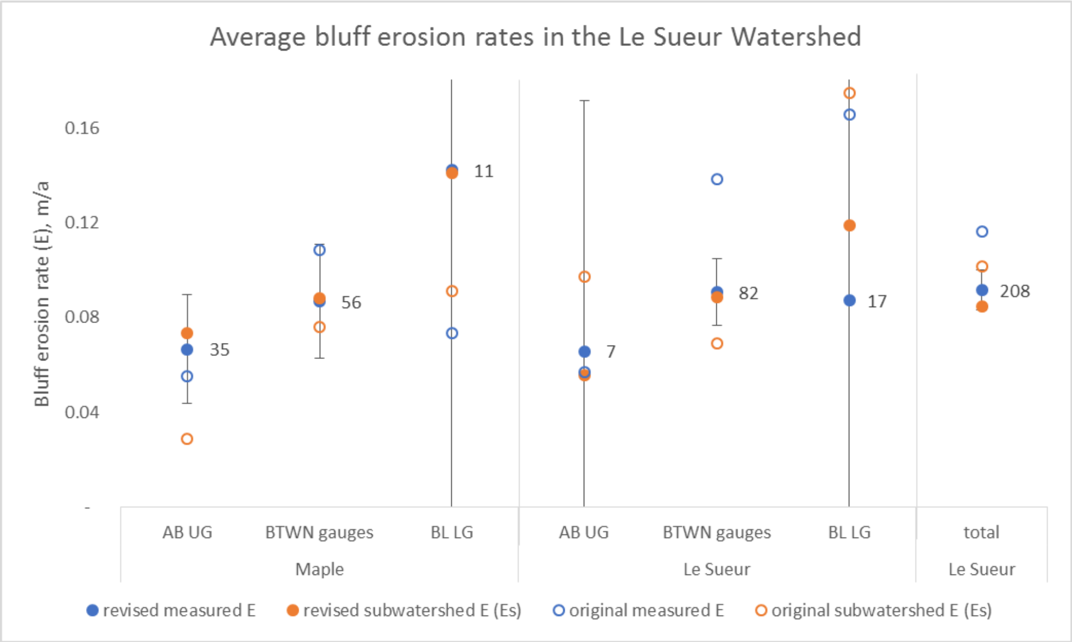

Figure 34: Average bluff erosion rates in the Le Sueur Watershed. Uncertainties from standard deviation of the measured E values in each subwatershed(using a liner regression average).

The volume of sediment eroded (V_E) from each GBERB bluff is the product of its erosion rate and surface area. The volume of sediment eroded from each subwatershed in the Le Sueur watershed is shown in Figure 35. Overall, V_E in the revised budget fell to 93,000 m^3/a from 130,000 m^3/a in the original budget (Table 10). Reductions were primarily located on the Cobb River and below the lower gauge on the Le Sueur. The many differences between the rates and extents in the original and revised Le Sueur budget were discussed previously. When E rates are calculated with the assumption that over 70 years GBERB channels are as likely to migrate left as they are to migrate right (rather than using the observed channel migration direction) measured rates decrease by about 15% (Table 9). Using a linear regression average and trimming the extent of measured bluffs reduced the measured rate by a total of about 10%. Including bluff extents outside of Blue Earth County reduced the average rate a further 10%. These changes combined to make E rates lower in the revised budget than the original budget (Figure 33). But higher sensitivity to bluff vegetation state reduced E_s in the original budget more than in the revised budget, so E_s rates are more similar between budgets than E rates (Figure 34, Table 10). The total rate decrease from the original to the revised budget is 17%. Though bluff extents were added outside Blue Earth County, bluff extents within the county were reduced, particularly below the knickzone, so total extent decreased from the original to revised budget by 14% (Figure 32). The total volume of sediment eroded from bluffs in the revised budget was 29% less than the volume eroded in the original budget (Figure 35).

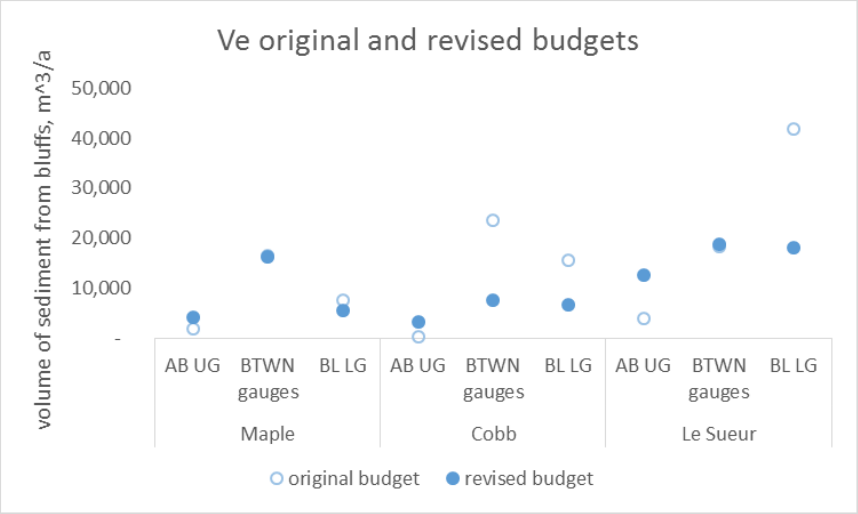

Figure 35: Volume eroded from each subwatershed in the original and revised budget.

Altering the texture and bulk density of bluff sediment reduced the estimated fine sediment load on the Le Sueur by 1%, compared to 4% on the Blue Earth and 2% on the Watonwan. With regard to the original Le Sueur budget, these estimated effects of lake storage, bluff sediment texture and bulk density further increase the difference between the original and revised Le Sueur budgets, but adjusting revised estimates for these factors has much less effect on load than adjustments made to rates and extents.

A bluff erosion rate difference of 25% between the original and revised Le Sueur budgets illustrates how conceptual models of bluff erosion and calculation methods can affect estimated loads (Table 9). This rate difference represents about a 12% difference in the total budget within Le Sueur County, which is similar to other bluff-related uncertainties (Figure 25).

Appendix 5: GBERB sediment budgets

The GBERB sediment budgets are the foundation from which this thesis was constructed. The details are included in a spreadsheet available with this project at the University of Minnesota Digital Conservancy or from the author (bevisma@gmail.com). ArcGIS shapefiles detailing extents and rates for bluffs, banks, ravines, uplands and lakes are also available.