Landscape evolution, valley excavation, and terrace development following abrupt postglacial base-level fall

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ABSTRACT

Many high-latitude fluvial systems are adjusting to base-level changes since the last glaciation. Channels that experienced base-level fall may still be incising, often through glacial diamictons (tills). These tills can be quite competent, behaving more like weak bedrock than unconsolidated sediment, and erode at a fast pace, thus providing a unique opportunity to test models of channel incision and knickpoint migration in transient systems. Here, we integrate light detection and ranging (LiDAR) topography, strath terrace chronology, and numerical modeling to determine knickpoint migration and incision history of the Le Sueur River in central Minnesota, USA. Results indicate that the Le Sueur River is best modeled as a detachment-limited channel, with downstream coarsening related to lag clasts from tills playing a critical factor in longitudinal profile development.

The Le Sueur River meanders as it incises, so we coupled the best-fit incision model to a meander model to determine valley excavation history. The excavation history was used to determine a natural background erosion rate, prior to land-use changes associated with settlement and agricultural expansion in the mid-1800s. We compared background fine sediment (silt and clay) erosion rates with historic decadal-average annual suspended loads. Results show that modern fine sediment contributions from sources associated with valley excavation are three times higher than modeled presettlement loads. Recent changes in hydrology associated with land use and climate change have increased flows in rivers, leading to higher sediment loads, not just from field erosion, but from increased bank and bluff erosion in the deeply incised valleys.

INTRODUCTION

Many channels experience a lowering of base level, either from tectonic uplift, sea-level fall, or local events that trigger channel rerouting or incision. The way in which a river responds to a base-level fall depends on the rate and pattern of the signal, the processes of river incision, and the material through which the channel is incising. Often, base-level fall is transmitted upstream through the propagation of knickpoints, particularly when incision is occurring through a competent substrate (i.e., Bishop et al., 2005; Crosby and Whipple, 2006; Berlin and Anderson, 2007). Although many studies of incisional landscapes have occurred in mountainous environments, where rivers incise through bedrock driven primarily by tectonic uplift, few have been conducted in the vast northern continental interiors, where base-level fall is driven by widespread changes resulting from the end of the last glaciation. Many rivers in these interior postglacial landscapes are still adjusting to new base-level conditions, from deposition or incision by meltwater and glacial ice. These rivers are in transition, as base-level changes propagate upstream and drainage networks integrate and expand. Although these landscapes can be challenging to model, they can also offer opportunities to investigate incision and landscape evolution in young, transient, evolving systems.

One of the challenges of developing accurate models of knickpoint migration and channel incision is that of equifinality: Multiple models may yield the same result, especially in a steady-state system. Predicting transient response is more discriminating (Whipple, 2004), yet compared to the abundance of studies that assume steady state, there are comparatively few studies published that focus on transient profile evolution (i.e., Howard and Kerby, 1983; Stock and Montgomery, 1999; Whipple et al., 2000; Hancock and Anderson, 2002; van der Beek and Bishop, 2003; Crosby and Whipple, 2006; Berlin and Anderson, 2007; Finnegan et al., 2007; Hilley and Arrowsmith, 2008). If both transport-limited and detachment-limited models yield similar results in steady-state conditions, then studying a system that is still in a transient response remains, as stated by Whipple (2004) "the underexploited, critical test."

The Le Sueur River in south-central Minnesota (Fig. 1) is undergoing a transient response to the initial carving of what is now the Minnesota River valley ca. 13.4 k.y. B.P. (ka) (11,500 ^{14}C yr B.P.) (Shay, 1967; Clayton and Moran, 1982; Matsch, 1983; Lepper et al., 2007; Belmont, 2011). This well-dated event was a glacial outburst flood, which led to incision of 65 m near the mouth of the Le Sueur River, triggering a knickpoint that has been migrating upstream ever since. The knickpoint is now expressed as a knick zone covering the lower 35–40 km above the mouth of the Le Sueur River and its two major tributaries. The record of incision is preserved in individual terrace landforms throughout the knick zone on these three channels. Because the initial conditions are well known, and the timing and magnitude of incision are well constrained, the situation is ideal for testing numerical models of channel incision and valley evolution for till-based channels. These models can, in turn, yield insight into the history of valley excavation and thus sediment evacuation in the Le Sueur throughout the

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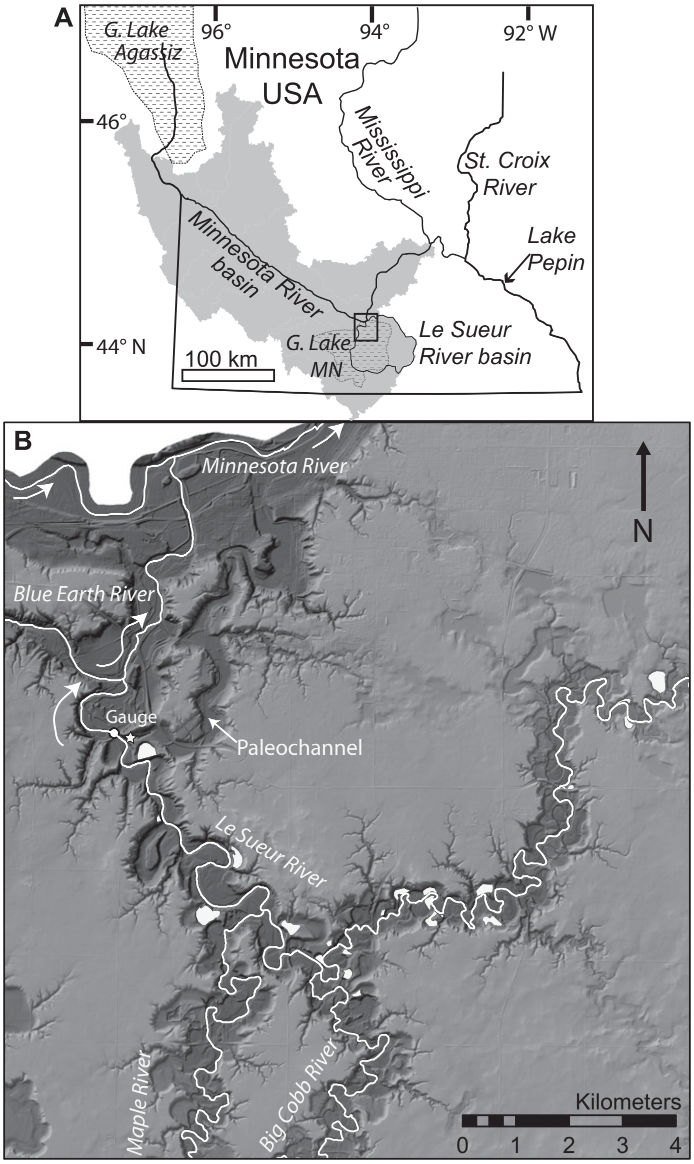

Figure 1. (A) Map showing location of Le Sueur River with respect to the Minnesota, Mississippi, and St. Croix Rivers and the past locations of Glacial Lakes Agassiz and Minnesota. (B) Inset map showing the lower Le Sueur River and its two major tributaries, the Maple and the Big Cobb Rivers. The Le Sueur joins the Blue Earth River just north of the gauge site, ~5 km upstream from where the Blue Earth River joins the easterly flowing Minnesota River. Locations of terraces where samples were collected for optically stimulated luminescence (OSL) and ^{14}C dating are in white. The star marks the location where OSL samples were collected within the paleochannel. The gauge at Red Jacket (USGS #05320500) is shown as a white circle.

Holocene, giving us a natural "presettlement" rate of erosion from this basin.

The Le Sueur River and reaches on the lower Minnesota River are impaired with respect to turbidity, per section 303d of the U.S. Environmental Protection Agency's Clean Water Act. The turbidity impairment is due primarily to excess suspended sediment, one of the leading causes of water-quality impairments nationwide (Palmer et al., 2000; U.S. Environmental Protection Agency, 2012). One of the challenges facing management agencies is determining the portion of the fine sediment load that is derived from human modifications of the landscape above and beyond the natural geologic rate of erosion. Studies of modern sediment sources indicate that erosion from channel incision and migration dominates the sediment budget in the Le Sueur River (Gran et al., 2011b; Belmont et al., 2011b). Knowing if (and how) these erosion rates have increased over natural background rates is particularly important for agencies responsible for managing water quality in the greater Minnesota River basin.

Here, we used a combination of field observations, digital elevation model (DEM) analyses, strath terrace chronology, and numerical modeling to explore channel incision and knickpoint propagation in the Le Sueur River and to test two models of channel incision in an unusually well-constrained system. We sought to quantify model sensitivity in the Le Sueur River to assumptions about the rate and pattern of channel meandering as well as to external controls, including climate change and stream capture. By synthesizing all of the data, we constrain the valley evolution and channel incision history of the Le Sueur River during the late Pleistocene and Holocene, allowing comparison between presettlement natural, background erosion rates and elevated modern suspended sediment loads.

BACKGROUND

Sudden base-level fall can trigger knickpoints that propagate upstream, transmitting the signal of base-level fall to the upper watershed. In transport-limited systems, knickpoints tend to diffuse as they move upstream, while many detachment-limited systems can maintain a steeper knickpoint form that moves upstream as a kinematic wave (Begin et al., 1980; Gardner, 1983; Whipple and Tucker, 2002). Although these two end members predict different transient responses to base-level fall, the resulting steady-state channel profiles are indistinguishable. In incising systems, knickpoint migration can be the dominant mechanism of channel erosion (i.e., Seidl and Dietrich, 1994; Wohl et al., 1994; Stock and Montgomery, 1999; Hasbargen and Paola, 2003), and so an understanding of what drives knickpoint migration and how the channel will respond is critical in understanding the evolution of transient systems.

Accurate modeling of valley evolution during base-level fall must account for not only channel incision but also lateral migration. Lateral migration rates are commonly argued to reflect the overall ratio between sediment supply and transport capacity. As sediment supply increases, the bed can become covered with sediment, decreasing vertical incision rates and increasing lateral planation rates, resulting in the development of strath terraces (Bull, 1990; Hancock and Anderson, 2002; Fuller et al., 2009; Wegmann and Pazzaglia, 2009). One of the consequences of lateral migration in an incising system is that channel migration into hillslopes can destabilize those features, trigger failure, and increase local erosion rates. Thus, the balance between vertical incision and lateral planation not only affects valley morphology and strath terrace development, but it also affects volumetric erosion rates in the incising system.

Physical experiments of erosional response to base-level fall show conflicting results depending on how base-level fall was accomplished. Experiments by Parker (1977) and Hancock and Willgoose (2002) showed that mass eroded following instantaneous base-level fall starts high and then declines rapidly through time. Alternatively, experiments by Hasbargen and Paola (2000) found the opposite result: Erosion steadily increased until it reached steady state, at which point, erosion fluctuated about a constant mean. In the first two cases, base-level fall was sudden, while in the third case, base-level fall was more gradual and continued throughout the length of the experiment. As it is widely recognized, base-level signals can evolve and, in particular, diffuse as they travel upstream. Despite a common downstream trigger, parts of a basin proximal to the outlet may see relatively rapid base-level lowering rates, while distal upstream locations may experience more gradual rates. Thus, it is difficult, a priori, to predict the shape of a curve relating sediment flux out of a basin to base-level fall history.

STUDY AREA

The Le Sueur River watershed in south-central Minnesota was reset by the last glaciation (marine isotope stage 2). During the Last Glacial Maximum, the entire watershed was covered by the Des Moines lobe of the Laurentide ice sheet. As the ice retreated to the north, an ice-marginal lake formed, known as Glacial Lake Minnesota (Jennings, 2007) (Fig. 1). Glacial Lake Minnesota covered the western two-thirds of the Le Sueur watershed, depositing up to 3 m of glaciolacustrine silts and clays on the surface and leaving behind a very low-gradient surface. Underlying these silts and clays, there lie up to 60 m of stacked tills with interbedded glaciofluvial sands (Jennings, 2010). Most of the tills dissected by the modern channels were deposited by the Des Moines lobe and include the Upper and Lower Heiberg Members and the Moland Member. Deeper valleys reach into older tills, including the Wisconsinan-age Traverse des Sioux Formation, deposited by the Rainy lobe, as well as pre-Wisconsinan tills of the Good Thunder Formation. Most of these till units contain ~35% sand and ~65% silt and clay, with a slightly higher sand content in the Moland Member and Traverse de Sioux Formation (Meyer et al., 2012). All of these till formations contain <10% gravel (Meyer et al., 2012), and many are overconsolidated as a result of compaction and dewatering from thick glacial ice (Boulton, 1976). Isolated outcrops of poorly consolidated Paleozoic sandstones are found in patches in the lower 8 km of the Le Sueur River, overlain by glacial deposits. A paleochannel connecting the Le Sueur River directly to the Minnesota River (Fig. 1) contains outcrops of a Paleozoic dolostone capping the sandstone.

Since the last glaciation, regional climate has experienced several major excursions. The region was ice free by the early Holocene, but still experienced a cooler climate, with cold boreal and subarctic conditions (Webb and Bryson, 1972). From 8–9 ka to 4–5 ka, a time referred to as the mid-Holocene dry period, the region became warmer and drier (Chumbley et al., 1990; Laird et al., 1996; Dean, 1997; Wright et al., 2004; Yu et al., 1997; Dean et al., 2002; Camill et al., 2003), followed by a return to cooler, moister conditions. Over the past 50 yr, precipitation has increased, including the number of days experiencing precipitation and the number of intense rainfall events (Kunkel et al., 1999; Seeley, 2003). The increase in precipitation correlates with an increase to stream flows of the Minnesota River basin (Novotny and Stefan, 2007; Lenhart et al., 2011a).

Native vegetation in the Le Sueur watershed was primarily prairie and wet prairie with hardwood forests lining the river valleys and the northeastern corner of the watershed (Marschner, 1930; Minnesota Department of Natural Resources, 2007). Recent vegetation changes have been dramatic: ~86% of the basin is now covered by row-crop agriculture (Musser et al., 2009), most of it on very low-gradient upland terrain.

One of the biggest impacts to this river system occurred at the end of the last glaciation, 13.4 ka (11,500 ^{14}C yr B.P.), when Glacial Lake Agassiz first drained through its southern outlet (Shay, 1967; Clayton and Moran, 1982; Matsch, 1983), carving the valley now occupied by the Minnesota River. Glacial Lake Agassiz was a massive proglacial lake that formed along the Minnesota–North Dakota border, eventually covering much of south-central Canada (Upham, 1890, 1895; Thorleifson, 1996). After this initial draining of Lake Agassiz, outflows occupied the valley discontinuously until 12.83 ka (10,800 ^{14}C yr B.P.) and again before 10.62 ka (9400 ^{14}C yr B.P.) (Fisher, 2003).

The initial incision event started knickpoints migrating upstream on tributaries flowing into what is now the Minnesota River valley (Gran et al., 2009, 2011a; Belmont et al., 2011b). The modern longitudinal profiles of the Le Sueur River and its major tributaries, the Maple and the Big Cobb, show that knickpoints have migrated ~35–40 km upstream on each channel (Fig. 2), creating steep channel gradients in the zone below the knickpoints all the way to the mouth of the Le Sueur. Channel gradients are twice as high in the knick zone (0.0015), and valley relief increases, reaching 65 m at the mouth of the Le Sueur. In the knick zone on the Le Sueur River, bluffs line ~31 km of channel, with an additional 46 km of bluffs lining its two main tributaries (Day, 2012). Bluffs erode through a combination of toe erosion through fluvial abrasion and shear, sapping from groundwater, and freeze-thaw processes that weaken till material (Day et al., 2013). Many of these tills behave like weak bedrock. They are overconsolidated, able to maintain near-vertical slopes for tens of meters, and can even fail in blocks along fracture planes.

The record of river incision is recorded in terraces throughout the valley of the Le Sueur and its two major tributaries (Fig. 1). These strath terraces are carved into consolidated tills, with a thin overlying veneer of alluvium (Fig. 3). The alluvial cap is almost uniformly 2–3 m thick and typically contains channel deposits overlain by finer overbank alluvium. The terraces are unpaired, suggesting that incision occurred steadily, rather than in punctuated intervals, through lateral planation and terrace abandonment via river incision (Davis, 1902).

Additional evidence of incision lies near the mouth of the Le Sueur River. A 9.4-km-long abandoned paleochannel (Fig. 1) connects the Le Sueur River valley directly to the Minnesota River, bypassing the Blue Earth River, to which the Le Sueur is now a tributary. The upstream end of the paleochannel is truncated at an elevation of 264 m, 25 m above the current Le Sueur River at that location, indicating that 25 m of incision has occurred since the paleochannel was abandoned. The incision that followed this stream capture event represents a distinct second period of local base-level fall early on in the incision history of the Le Sueur River.

Within the Le Sueur and Maple River channels, cross-sectional measurements reveal that standard hydraulic geometry applies to channel width and depth, with both parameters increasing downstream (Belmont, 2011). However, bed grain size also increases in the downstream direction, with notable coarsening within the knick zone (Fig. 4). The main source of coarse-grained material (gravel, cobbles, and boulders)

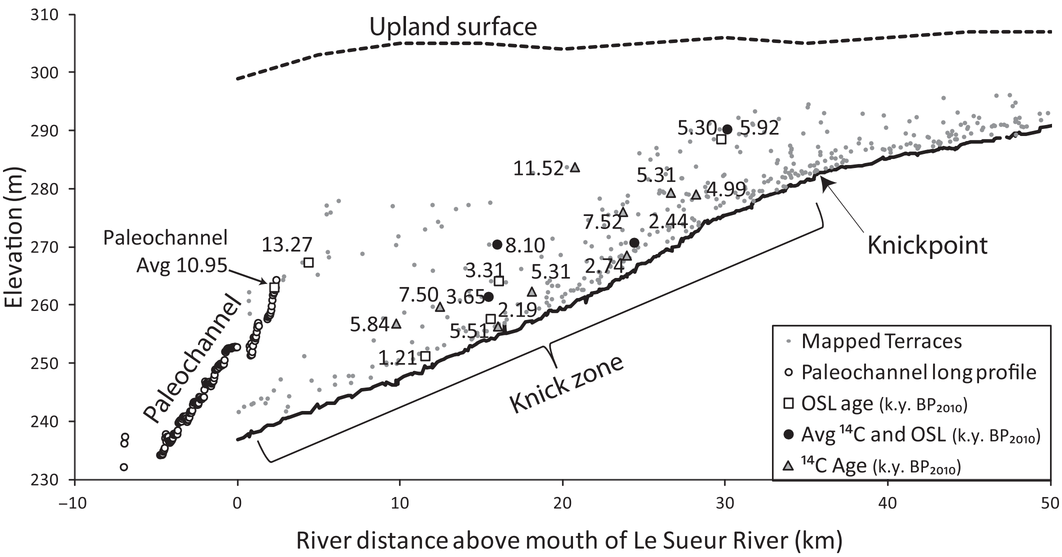

Figure 2. Longitudinal profile of the main stem Le Sueur River. Distance upstream is relative to the mouth of the Le Sueur at the confluence with the Blue Earth River. The paleochannel long profile is indicated in open circles. The upland surface is shown on the top. All terraces are marked on the figure, with dated terraces labeled as to dating methodology and age. OSL—optically stimulated luminescence.

in the Le Sueur River is the glacial tills through which the river is incising. The greater the valley incision depth, the more gravel is available to downstream reaches. Thus, upper reaches above the knickpoint contain primarily sand, silt, and clay, while the median grain size increases to 22 mm in the lower reaches of the knick zone, where incision depths are greatest. Floodplain widths are greatest in the upper basin, decreasing sharply within the knick zone to the point where the river lacks a true geomorphic floodplain through much of the lower basin (Belmont, 2011).

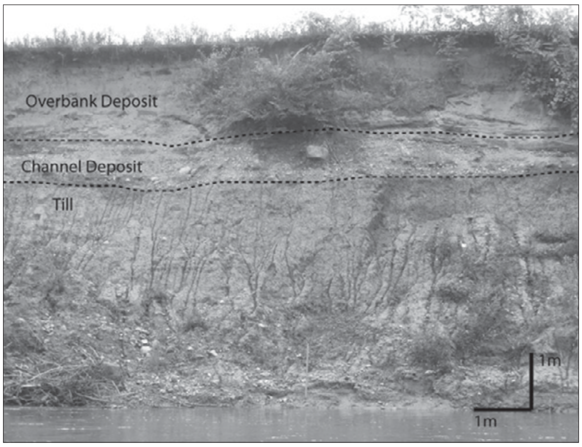

Figure 3. Photo showing a typical strath terrace in the Le Sueur River. Overbank alluvium covers channel deposits on top of planed-off glacial till.

METHODOLOGY AND RESULTS

Valley morphology was analyzed from high-resolution light detection and radar (LiDAR) data, with age control on a series of terraces provided by radiocarbon and optically stimulated luminescence (OSL) dating. These data provide constraints for the two numerical models we employ to explore the mechanics of channel incision and knickpoint propagation in the Le Sueur River valley. We then use the modeling results to refine the channel incision and valley excavation history and compare modeled rates of erosion with modern sediment loads. We first present the methodology and results of the valley geomorphology and geochronology, and then explain the methodology and results from the numerical modeling.

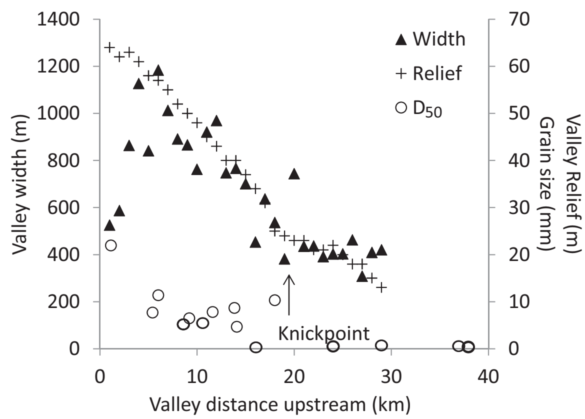

Figure 4. Valley distance upstream of mouth of the Le Sueur River versus valley relief, valley width, and median grain size. The knickpoint is located 20 valley km (35–40 river km) upstream from the mouth.

Valley Characterization and Age Control

Methods

The Le Sueur knick zone is in Blue Earth County, Minnesota, where high-resolution airborne LiDAR data from 2005 are available. Optimal Geomatics, Inc., acquired the LiDAR data for Blue Earth County with a horizontal root mean squared error (RMSE) of 1 m and a vertical RMSE of 0.15 m. Most of the geographical information system (GIS) analyses detailed here utilized a 3 m DEM derived from the LiDAR data. Along the main stem Le Sueur River, valley-top widths were measured every kilometer from the LiDAR DEM. We also extracted a longitudinal profile of both the Le Sueur River and the upland surface along the length of the river valley. The upland surface is very flat here, with elevations varying between 295 and 310 m above mean sea level (amsl) along the entire 40 km length of the lower channel that incises into the former Glacial Lake Minnesota bed. Outside of the glacial lake bed, upland elevations rise slightly in the upstream direction.

We calculated the total volume of material eroded from the Le Sueur River valley using the LiDAR DEM. Each of the three main river valleys (Le Sueur, Big Cobb, and Maple) was subdivided into 5 km reaches. Along each reach, the average upland elevation was determined. We then found the volume missing between that elevation and the modern topography of the valley in ArcGIS. These valley volumes were summed to obtain a total volume eroded during excavation of the Le Sueur River valley (Gran et al., 2009). This measure assumes no incision of the Le Sueur River valley prior to base-level fall from the draining of Glacial Lake Agassiz. In a second more conservative estimate, we allowed for some incision prior to this event, and calculated the volume of material eroded from the highest terrace to the modern valley bottom using the same techniques, but setting the upper elevation to be that of the highest terrace along each 5 km reach. This provides a minimum volume of sediment eroded due to valley excavation since base-level fall (Gran et al., 2009).

We wanted to compare long-term valley excavation rates to modern sediment loads. Because modern suspended sediment loads are often determined through measurement of total suspended solids (TSS), we recast the volume of sediment removed into a mass of fine sediment removed. TSS measurements sample only the suspended sediment and washload fractions, which are composed primarily of silt and clay in the Le Sueur. Thus, we converted volume of eroded till into mass of fine sediment using a bulk density of 1.8 Mg/m^3 from bluffs in the Blue Earth River basin (Thoma et al., 2005) and a fraction silt and clay of 65% determined from measurements of tills in the Le Sueur River basin (Gran et al., 2011b). We did not include the fraction of material >2 mm in size, which averaged only 3% by volume for all measured till samples ($n = 35$).

Within the valley itself, we mapped terrace remnants using the LiDAR DEM (Johnson, 2012) and then calculated a terrace height above channel as the difference between the mean terrace elevation and river elevation averaged from the upstream and downstream ends of the terrace.

To obtain terrace ages, we collected 22 samples from terrace sediments, including nine samples of overbank alluvium on terraces, for optically stimulated luminescence (OSL) dating, and 13 samples of freshwater mollusks and gastropods for radiocarbon dating. An additional three OSL samples were collected from the paleochannel near the mouth of the Le Sueur River (Fig. 1) to better constrain the timing on the stream capture event that led to the abandonment of the channel. The Utah State University OSL Laboratory analyzed the OSL samples, and Beta Analytic, Inc., processed the radiocarbon samples.

OSL is a technique that measures the time since a quartz or feldspar grain was last exposed to sunlight, thus giving a depositional age for the sediment. It has been used successfully to determine depositional ages of fluvial sediments (Olley et al., 1999; Lian and Roberts, 2006; Vandenberghe et al., 2007; Rittenour, 2008). At each OSL sampling site, we logged vertical stratigraphy, noting contacts between the till, channel deposits, and overbank deposits, and collected OSL samples from the overbank alluvium ~30 cm above a known channel deposit, or ~1 m above the till surface. To ensure none of the sample was exposed to light, we removed the outer 6–8 cm of sediment and inserted a 30 cm opaque metal conduit into the alluvium to collect samples for dating. Additional samples were collected to measure dose rate during analysis and water content at the site.

The Utah State University Luminescence laboratory analyzed OSL samples using the single-aliquot regenerative-dose procedure (Murray and Wintle, 2000, 2003; Wintle and Murray, 2006) on small aliquots of quartz sand (see Supplemental Data for more information[1]). One major assumption in OSL dating is that the luminescence signal is reset by exposure to light prior to deposition, which may be problematic in fluvial environments (e.g., Wallinga, 2002). If sediment has incomplete zeroing, referred to as "partial bleaching," then the age may be overestimated due to the incorporation of residual signal from the previous burial history. As a number of samples displayed evidence of partial bleaching, we used a minimum age model for each sample (Galbraith et al., 1999) to calculate the OSL ages.

Thirteen radiocarbon samples were pretreated with an acid etch prior to analysis via accelerator mass spectrometer (AMS) at Beta Analytic, Inc., with one sample large enough to analyze with standard radiometric techniques. We collected samples from channel deposits on terraces at the base of the overbank alluvium, containing primarily bivalve mollusks with some freshwater gastropod shells. Samples were sieved, and shells were handpicked with tweezers and washed with deionized water. On two terraces (TV and TW), we collected two samples: one from the channel deposits and one higher up in the overbank alluvium. For modeling purposes, we used the older ages as terrace ages.

We calibrated radiocarbon ages to calendar yr B.P. (yr B.P.) using the Pretoria calibration procedure (Talma and Vogel, 1993) with the INTCAL09 calibration database (Reimer et al., 2009). Because ^{14}C ages before present are relative to 1950 and OSL ages are relative to 2010, we shifted all of the ^{14}C ages to be relative to 2010 instead by adding 60 yr to each of the calendar yr B.P. ages. The new calibrated ^{14}C data are all reported as $B.P._{2010}$ for clarity. On four terraces, both ^{14}C and OSL data were available, and the results were averaged. Uncertainties were calculated as the square root of the sum of the squares of individual uncertainty ranges.

Results

The Le Sueur River valley rim is up to 1200 m wide near the mouth, decreasing in width upstream, with a width of 400 m just above the knickpoint. Width narrows near the mouth of the channel, downstream of the paleochannel in a reach that contained some of the only bedrock outcrops in the basin (area between the mouth and 8 km upstream). Likewise, relief is highest at the mouth (65 m), decreasing with distance upstream (Fig. 4). Estimates of the volume of sediment removed from the Le Sueur River valley range from 3.3×10^8 to 7.2×10^8 m^3 (minimum: volume removed below the highest local terrace; maximum: volume removed below the local upland elevation of 300–310 m amsl; Gran et al., 2009). Combining all three main tributaries of the Le Sueur watershed gives a total erosional volume of 5.6×10^8 to 1.3×10^9 m^3 (Gran et al., 2009).

In the lower Le Sueur, Big Cobb, and Maple River valleys, 512 terrace remnants were mapped (Fig. 2). The vast majority of these terraces are along the knick zone. There has been <11 m of incision of the valley above the knickpoint resulting in terrace creation in the upper basin.

Dated terrace ages range from 1.21 ± 0.40 k.y. $B.P._{2010}$ to 13.27 ± 1.59 k.y. $B.P._{2010}$, with heights between 2.0 m to 25.9 m above bankfull channel elevations. Elevation data from which heights are extracted have a vertical accuracy of ±0.15 m, but estimates of height above the channel have an increased uncertainty, estimated at ±1 m, given variability in both channel and terrace surface elevations. Terrace ages, elevations, and locations are given in Table 1, with additional information on ^{14}C and OSL results in a supplemental data repository (Tables DR1–DR3 [see footnote 1]). There is a weak linear

[1]GSA Data Repository item 2013327, supplemental OSL and ^{14}C data, is available at http://www.geosociety.org/pubs/ft2013.htm or by request to editing@geosociety.org.

TABLE 1. TERRACE AND PALEOCHANNEL DEPOSITIONAL AGES

Terrace name	Distance upstream (km)	Terrace height (m)	Terrace elevation* (m)	Sample type	Conventional radiocarbon age† (k.y. B.P.)	Calibrated age† (cal k.y. B.P.$_{2010}$)	OSL age§ (k.y. B.P.$_{2010}$)	Final age# (k.y. B.P.$_{2010}$)
LS-TC-1	4.35	25.9	267.4	OSL			13.27 ± 1.59	13.27 ± 1.59
LS-16-00	9.74	9.10	256.9	^{14}C	5.03 ± 0.05	5.84 ± 0.12		5.84 ± 0.12
LS-TZ-1	11.53	2.0	251.3	OSL			1.21 ± 0.40	1.21 ± 0.40
LS-08-01	12.43	9.90	259.8	^{14}C	6.51 ± 0.05	7.50 ± 0.12		7.50 ± 0.12
LS-TV-1**	15.42	7.7	261.5	OSL, ^{14}C	3.09 ± 0.04	3.36 ± 0.09	3.94 ± 0.47	3.65 ± 0.24
LS-TY-1	15.55	3.8	257.7	OSL			2.19 ± 0.46	2.19 ± 0.46
LS-TR-1	15.95	16.5	270.5	OSL, ^{14}C	7.63 ± 0.05	8.51 ± 0.09	7.68 ± 0.66	8.10 ± 0.33
LS-22-06	16.00	2.30	256.4	^{14}C	4.71 ± 0.05	5.51 ± 0.13		5.51 ± 0.13
LS-TX-1	16.05	9.8	264.2	OSL			3.31 ± 0.36	3.31 ± 0.36
LS-22-04	18.08	5.30	262.4	^{14}C	4.58 ± 0.05	5.31 ± 0.21		5.31 ± 0.21
LS-90-05	20.73	24.06	283.8	^{14}C	9.95 ± 0.06	11.52 ± 0.23		11.52 ± 0.23
LS-90-03	23.69	11.71	276.1	^{14}C	6.58 ± 0.07	7.52 ± 0.13		7.52 ± 0.13
LS-90-01	23.92	3.89	268.6	^{14}C	2.62 ± 0.05	2.74 ± 0.17		2.74 ± 0.17
LS-TW-1**	24.38	5.83	270.8	OSL, ^{14}C	2.33 ± 0.04	2.38 ± 0.15	2.49 ± 0.56	2.44 ± 0.29
LS-41-10	26.63	10.19	279.4	^{14}C	4.57 ± 0.05	5.31 ± 0.20		5.31 ± 0.20
LS-TP-1	28.18	7.54	279.1	^{14}C	4.33 ± 0.04	4.99 ± 0.10		4.99 ± 0.10
LS-TK-1	29.73	13.86	288.6	OSL			5.30 ± 0.60	5.30 ± 0.60
LS-41-01, LS-TL-01	30.10	15.21	290.3	OSL, ^{14}C	5.26 ± 0.07	6.14 ± 0.18	5.70 ± 0.61	5.92 ± 0.32
Paleo1				OSL			11.37 ± 1.51	11.37 ± 1.51
Paleo2				OSL			10.73 ± 1.14	10.73 ± 1.14
Paleo3				OSL			10.75 ± 1.20	10.75 ± 1.20

Note: Data are modified from Johnson (2012).
*Terrace tread elevations.
†Conventional and calibrated radiocarbon ages are reported with 2σ uncertainty. Calibrated ages are adjusted to B.P. 2010 (before present, adjusted with present = calendar year 2010).
§OSL—optically stimulated luminescence ages, with respect to calendar year 2010 (see Data Repository for details [text footnote 1]).
#When both OSL and ^{14}C ages were measured, the final age reported is the average between OSL and ^{14}C ages.
**Terraces ‘V’ and ‘W’ had two units dated using the radiocarbon technique. The upper unit was used to assign a terrace age.

relationship between terrace height above the modern channel and terrace age (Fig. 5), with considerable scatter. Interesting details lie in the scatter. For instance, there are six terraces that lie between 5 and 6 k.y. B.P.$_{2010}$ in age, at a range of heights above the channel. A comparison of Figure 5 with Figure 2 shows that these terraces are spread over a distance of 20 km along the channel, indicating that incision rates are not steady through time along the entire knick zone.

There are two “gaps” in the vertical distribution of terrace elevations that are noteworthy (Fig. 2). The first is at the top of the section, in the lower valley. The flat upland surface lies at an elevation of 300–305 m throughout the lower 20 km of channel, yet the highest preserved terraces in this reach are only 280 m in elevation, representing a gap of ~20–25 m. The second gap in preserved terraces is present only along the lowermost 10 km of channel. No terraces are preserved between ~10 and 20 m height above the channel (Fig. 2). The terraces above this gap have two dates, 13.27 k.y. B.P.$_{2010}$ and 11.52 k.y. B.P.$_{2010}$, while the highest dated deposit below this gap has an age of 8.10 k.y. B.P.$_{2010}$ (Figs. 2 and 5). No terraces were preserved in the gap. A longitudinal profile of the upper terraces correlates well with the upstream end of the abandoned paleochannel (Fig. 2). Three OSL samples collected from within this paleochannel have an average burial age of 10.95 k.y. B.P.$_{2010}$, suggesting the paleochannel was active from 13.5 k.y. B.P.$_{2010}$ to 10.95 k.y. B.P.$_{2010}$, after which it was abandoned (Belmont et al., 2011a). The implications of this paleochannel on the history of valley excavation are explored in the discussion section.

Numerical Modeling

Methods

To better understand the dominant pattern and style of channel incision in the Le Sueur, we used two different numerical models to simulate incision from the time of base-level fall 13.5 k.y. B.P.$_{2010}$ to the present. The system is very well constrained. The timing of initial base-level fall is well dated. We have ages on 19 terraces that help constrain channel location throughout the past 13.5 k.y., and the modern long profile gives us the location of the channel now. The initial channel is set at the elevation of Glacial Lake Minnesota (300 m amsl) at the mouth and given a slope equivalent to the slope of the channel above the knick zone.

We first simulated channel evolution with a one-dimensional (1-D) numerical model using two different approaches, per Howard (1994). In the first approach, we modeled the channel as a detachment-limited system, in which bed-load sediment flux is less than capacity. Here, erosion occurs in proportion to stress above a critical threshold required to initiate motion of coarse sediment armoring the river bed. The critical threshold is thus higher than critical values for noncohesive sediment transport:

$$dz/dt = k(\tau* - \tau c*),\ \tau* > \tau c*, \qquad (1)$$

$\tau*$ is the Shields stress, $\tau c*$ is the critical Shields stress, z is elevation, t is time, and k is a constant. The Shields stress (Shields, 1936) was calculated as

$$\tau* = \tau/(\rho_s - \rho)gD_{50}, \qquad (2)$$

where ρ_s is the sediment density, ρ is water density, g is gravity, τ is the shear stress, and D_{50} is

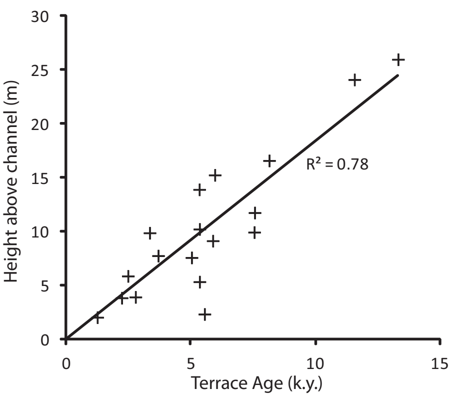

Figure 5. Terrace height above the channel vs. depositional age as recorded by either optically stimulated luminescence (OSL) or ^{14}C. The correlation coefficient is 0.88 (p < 0.000001), with R^2 = 0.78 for a linear regression forced through the origin.

gdS by combining hydraulic geometry relationships developed for the Le Sueur for depth, *d*, with channel slope, *S*, output from the model. Sediment density was assumed to be 2650 kg/m^3.

In the second approach, we modeled the channel as an alluvial transport-limited system, in which erosion is proportional to the divergence of the downstream sediment flux (e.g., Howard, 1994):

$$dz/dt = i(-dQ_t/dx) \quad (3)$$

Here, *i* is an intermittency factor that describes the proportion of the year during which transport occurs, and *x* is distance along the channel. Sediment flux is approximated with the relationship for bed-load sediment transport capacity per unit width of channel, Q_t, following Fernandez-Luque and van Beek (1976).

In both incision equations, we used grain size and hydraulic geometry data derived from 55 (26 Maple and 29 Le Sueur) field-surveyed cross sections (Belmont, 2011). Modern hydraulic geometry relationships for field-measured width, *w*, and depth, *d*, were developed as a function of upstream drainage area, *A*, and assumed constant throughout the Holocene.

$$w = 1.02A^{0.50} \quad (4)$$

$$d = 0.53A^{0.21} \quad (5)$$

We recognize that this is an oversimplification that does not take into account climate change that occurred during this time period. Bankfull discharges on the Upper Mississippi River likely dropped by as much as 30% during the mid-Holocene dry period, with stormier periods increasing discharge 10%–15% (Knox, 1985). However, we start with the simplest case and later incorporate some of the major climatic shits to determine their importance on overall patterns and rates of valley evolution.

Currently, channel-bed grain-size distributions show a nonlinear downstream-coarsening pattern (Fig. 4). As the channel incises through glacial sediments and erodes perched terraces, coarse material becomes available for downstream reaches. For the modeling efforts, we used two different grain-size assumptions. In the first, we assumed grain size was spatially and temporally steady at the current average median grain size, or D_{50}, of 10 mm. For the second scenario, grain size coarsened with increased incision, per the following equation:

$$D_{50} = k_d(z_0 - z), \quad (6)$$

where k_d is a constant related to the concentration of coarse material in the till, z_0 is the initial elevation, and *z* is the elevation of the river at a point in time and space. Grain size started with a D_{50} of 2 mm, as the Le Sueur River is currently a sand-bedded channel above the knick zone, and evolved through time, leading to the downstream coarsening evident today.

We ran four initial sets of simulations, using both the detachment-limited model and the transport-limited model, with either constant grain size or evolving grain size (Table 2). The runs were conducted using a Monte Carlo approach to determine the parameters that best fit (1) terrace age–elevation history and (2) the current river profile. In general, for a combination of either *k* and k_d or *i* and k_d, there is a straightforward linear relationship between the variables, such that for a given *k* or *i*, there is a given k_d that minimizes the misfit in the predicted terrace age–elevation history and a different linear relationship that minimizes the misfit in the final river elevation profile. Combining these two relationships allowed us to find a unique combination of *k* or *i* and k_d that minimized the misfit for both the terrace age–elevation history and the final river elevation, thus yielding the best-fit kinematic model for the Le Sueur River.

The best-fit kinematic model derived here assumes that external controls like climate remain stationary throughout the Holocene. However, the well-documented mid-Holocene dry period affected much of the region, causing warmer and drier conditions in the Le Sueur watershed. The resulting decrease in discharge during the mid-Holocene dry period could potentially have affected longer-term channel evolution in the Le Sueur. To assess the role of this climatic excursion on valley excavation, we modeled the mid-Holocene dry period by decreasing channel depth 25% during the period 9 k.y. to 5 k.y. B.P.$_{2010}$. This time frame covers a range of published dates on the temporal extent of the mid-Holocene dry period in this region (Chumbley et al., 1990; Laird et al., 1996; Dean, 1997; Wright et al., 2004; Yu et al., 1997; Dean et al., 2002; Camill et al., 2003). Fewer studies have examined the hydrologic impact of this climatic excursion, but Knox (1985) found that bankfull floods in the Upper Mississippi River decreased by 20%–30% during the mid-Holocene dry period, so we chose to model our depth reduction at 25%.

A second potentially important external control involves a channel capture related to the paleochannel linking the lower Le Sueur River directly to the Minnesota River (Fig. 1). From our OSL dating, we know the paleochannel was abandoned after 10.95 k.y. B.P.$_{2010}$, when the Blue Earth River captured the Le Sueur. The base-level fall associated with this capture event should have led to a renewed burst of incision on the main stem Le Sueur River. Thus, perhaps base-level fall on the lower Le Sueur River is best modeled as a two-phase event rather than a single episode of base-level fall. To test this idea, we conducted an additional series of runs simulating base-level fall as two discrete drops in elevation rather than one. In this case, the first drop of 36 m occurred at 13.5 k.y. B.P.$_{2010}$, and the remaining 29 m drop occurred at 10.3 k.y. B.P.$_{2010}$ (based on a preliminary age for the paleochannel, later revised to 10.95 k.y. B.P.$_{2010}$).

The next modeling challenge was to transform the 1-D incision results into 3-D valley excavation estimates to constrain the evolution of sediment flux through the Holocene. Results of the 1-D model were used to determine the incision history, but the incision model is not necessarily a good indication of the 3-D excavation of the valley. Consider that as the Le Sueur incises, it also meanders and therefore widens its valley. As the Le Sueur valley widens, the river is less likely to encounter bluffs. However, as the valley deepens, the bluffs become taller, and thus the amount of sediment generated when the river

TABLE 2. ONE-DIMENSIONAL (1-D) MODEL RUN PARAMETERS AND RESULTS

Run parameters			Results	
Channel type	Grain size	Other	Long profile RMSE (m)	Terrace RMSE (yr)
Detachment-limited	Downstream coarsening		2.4	1995
Detachment-limited	Constant		10.9	2821
Transport-limited	Downstream coarsening		4.3	2698
Transport-limited	Constant		5.0	2797
Detachment-limited	Downstream coarsening	Mid-Holocene dry period (9–5 k.y. B.P.$_{2010}$), depth reduced 25%	2.2	2122
Detachment-limited	Downstream coarsening	Two-phase incision, 36 m at 13.5 k.y. B.P.$_{2010}$, 29 m at 10.3 k.y. B.P.$_{2010}$	3.7	2397

Note: RMSE—root mean square error.

does encounter a bluff increases. In addition, the rate of meandering itself may increase with local shear stress and thus the slope of the incising channel (Finnegan and Dietrich, 2011). In this case, as the knickpoint propagated into the Le Sueur catchment, it could have increased channel migration rates. However, because the knick zone appears to have lengthened as it propagated upstream, the local slopes within the knick zone should have decreased through time. Thus, we expect a tradeoff between the length of channel with enhanced migration rates and the magnitude of this enhancement. All of this makes it challenging to translate results from the 1-D incision model to predictions of sediment flux.

In order to explore the sensitivity of the valley excavation history to both the efficiency and pattern of channel meandering on the Le Sueur, we coupled a kinematic model for river meandering (Howard and Knutson, 1984) to the best-fit vertical incision model described earlier using the approach of Finnegan and Dietrich (2011), but with lateral migration rates coupled to local channel slope. This allowed us to model an incising, meandering system like the Le Sueur River. The way in which the strength of the migration rates is coupled to slope and the efficiency of lateral erosion affects both the total widening of the valley and the magnitude of the increase in widening downstream of the knickpoint. We did not exhaustively explore this parameter space, but instead sought parameters that generated downstream increases in valley width that were similar to what is observed on the Le Sueur.

Currently, meander migration rates are ~2–3 times higher below the knickpoint than above (Gran et al., 2011b), roughly consistent with the slope difference across the knickpoint. This indicates that an assumption of a linear relationship between bend migration rate and slope is reasonable. That said, we found that using a linear relationship between slope and τ or $\tau*$ resulted in valleys that widened downstream far more than is observed on the Le Sueur. We found through trial and error that coupling migration rates to $\tau*^{1/4}$ resulted in downstream valley widening comparable with the Le Sueur (Fig. 6). Although this is ad hoc, we emphasize that our goal here is primarily to create a generalized geometric model for the excavation of the Le Sueur, and not to simulate the details of lateral erosion processes. That said, we note that there can be a strong connection between weathering and lateral erosion (Montgomery, 2004). Thus, a possible explanation for the weaker than expected coupling between channel stress and lateral erosion on the Le Sueur may arise from the role that weathering (and thus not channel hydraulics) plays in rendering the till detachable by fluid stresses.

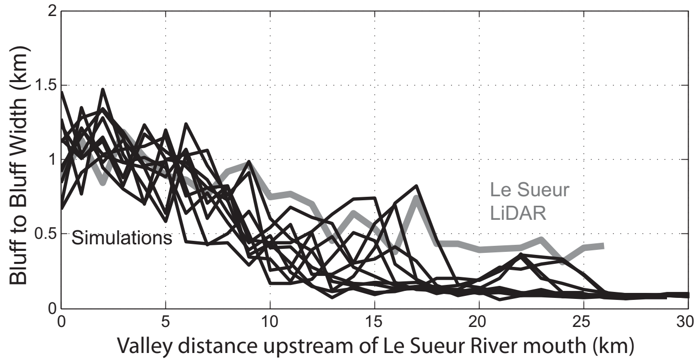

Figure 6. Valley distance upstream vs. valley width. Both measured valley widths from light detection and ranging (LiDAR) data (gray line) and the resulting valley widths from 10 runs of the three-dimensional (3-D) kinematic meandering and incision model (black lines) are shown. These runs were based on the detachment-limited, downstream-coarsening incision model.

Ten simulations were run with the full 3-D kinematic meandering model. In all 3-D simulations, we used the 1-D elevation profiles generated by the best-fit 1-D model to determine the elevation coordinates for the meanders. Thus, we implicitly assumed that the process of meandering itself, although locally capable of either increasing or decreasing vertical incision rates (Finnegan and Dietrich, 2011), nevertheless did not influence the evolution of the long profile on the scale of the entire modeled reach. In addition, because the best-fit 1-D model was the detachment-limited model, our approach implicitly assumed detachment-limited erosion. There is no feedback between the height of eroded bluffs and the rate of lateral migration, as might be expected in a system where significant bed load is added to the river during lateral channel motion. Observations on the Le Sueur indicate that, volumetrically, the majority of eroded bluff material goes quickly to suspended or wash load. Coarse material liberated through incision and migration into glacial tills affects modeling solely through an increase in D_{50} of the bed.

Results

The best-fit 1-D model from the four base options was the detachment-limited model with downstream coarsening (Table 2; Fig. 7). Both elements were important in matching both the modern long profile and the measured terrace ages. The transport-limited model incised too rapidly at the start of the simulation and too slowly toward the end of the simulation and was unable to maintain a discrete knick zone, while the detachment-limited model without downstream coarsening ended up with too steep of a knick zone moving upstream as a kinematic wave. Table 2 shows RMSE values associated with the fit of both the modern long profile and the measured terrace ages. The detachment-limited model with downstream coarsening had the lowest RMSE in both cases.

The best-fit 1-D incision model was then used for two runs that included additional external forcings. Neither adding in the mid-Holocene dry period nor the two-stage incision pattern improved the RMSE fit of the detachment-limited, downstream-coarsening model significantly

Figure 7 (*on following page*). Results from the one-dimensional (1-D) incision models and comparison between predicted and measured terrace ages, with a 1:1 line for reference for detachment-limited system with downstream coarsening (A) and with constant grain size (B). (C–D) Resulting longitudinal profiles at 1000 yr increments for the same two sets of runs (A with C; B with D). (E–H) The same sets of comparisons are shown for transport-limited systems with downstream coarsening (E, G) and for transport-limited systems with constant grain size (F, H). (I, K) Results from the detachment-limited, downstream-coarsening base model but with a reduction in flow during the mid-Holocene dry period. (J, L) The same detachment-limited, downstream-coarsening base model, but with a two-stage drop in base level. The first drop of 36 m occurred at 13.5 k.y. B.P.$_{2010}$, and the second drop of 29 m occurred at 10.3 k.y. B.P.$_{2010}$. RMSE—root mean square error.

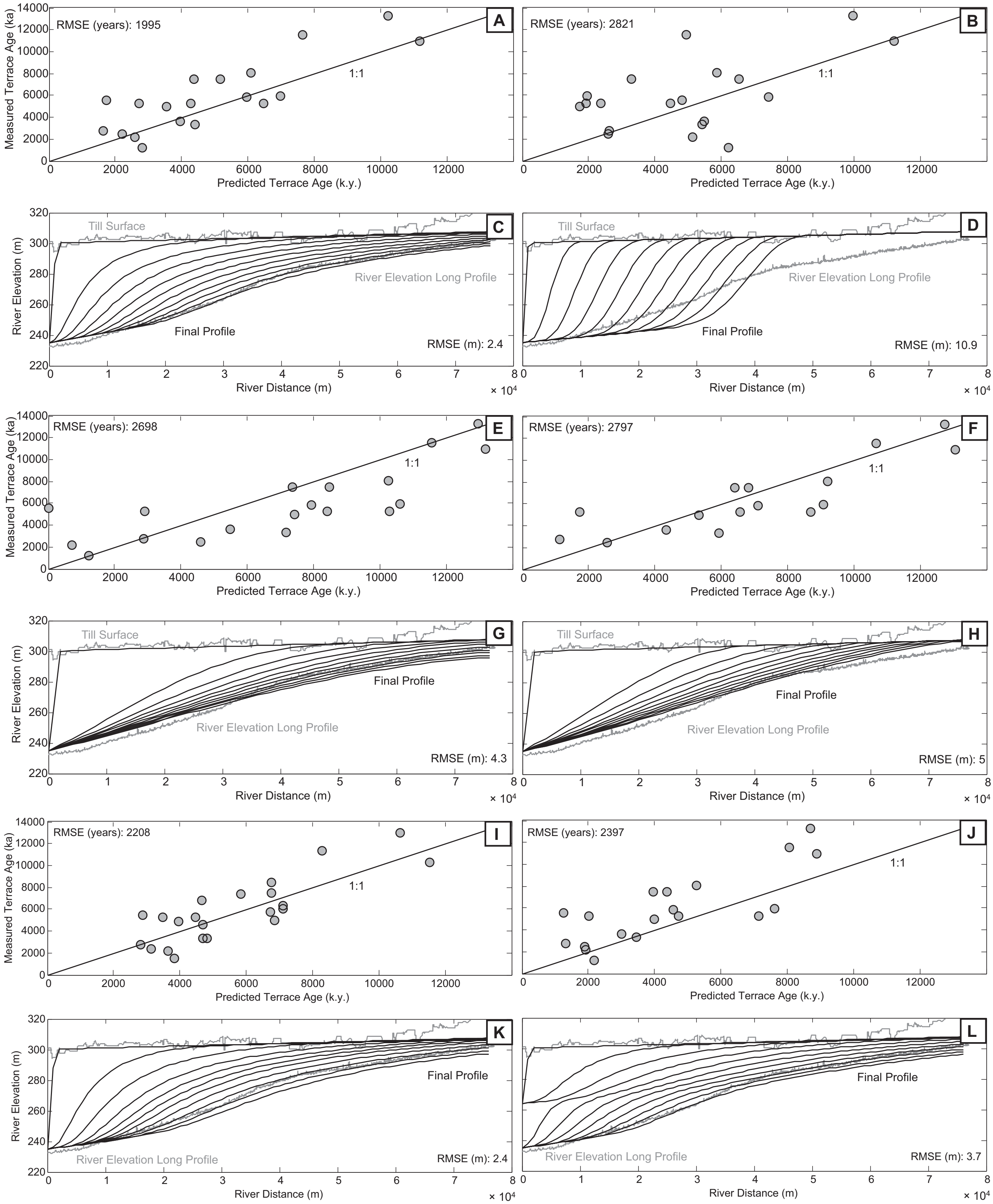
A
RMSE (years): 1995
1:1
Measured Terrace Age (ka)
Predicted Terrace Age (k.y.)
B
RMSE (years): 2821
1:1
Predicted Terrace Age (k.y.)
C
Till Surface
River Elevation Long Profile
Final Profile
RMSE (m): 2.4
River Elevation (m)
River Distance (m)
× 10^4
D
Till Surface
River Elevation Long Profile
Final Profile
RMSE (m): 10.9
River Distance (m)
× 10^4
E
RMSE (years): 2698
1:1
Measured Terrace Age (ka)
Predicted Terrace Age (k.y.)
F
RMSE (years): 2797
1:1
Predicted Terrace Age (k.y.)
G
Till Surface
Final Profile
River Elevation Long Profile
RMSE (m): 4.3
River Elevation (m)
River Distance (m)
× 10^4
H
Till Surface
Final Profile
River Elevation Long Profile
RMSE (m): 5
River Distance (m)
× 10^4
I
RMSE (years): 2208
1:1
Measured Terrace Age (ka)
Predicted Terrace Age (k.y.)
J
RMSE (years): 2397
1:1
Predicted Terrace Age (k.y.)
K
Final Profile
River Elevation Long Profile
RMSE (m): 2.4
River Elevation (m)
River Distance (m)
× 10^4
L
Final Profile
River Elevation Long Profile
RMSE (m): 3.7
River Distance (m)
× 10^4

Figure 7.

(Fig. 7; Table 2). Such changes led to predominantly worse fits to the data. Thus, we believe these external forcings are second-order effects, and we proceeded using the detachment-limited, downstream-coarsening, single-incision-event model as the base incision model in our 3-D modeling effort.

In the best-fit 1-D model, incision rates averaged over the lower 80 km of channel showed a rapid decline from 8 mm/yr to 4 mm/yr in the first 700 yr. Subsequently, the decline in incision rate was fairly steady down to 1.3 mm/yr at present (Fig. 8A). Runs designed to incorporate a stream capture event at 10.3 k.y. B.P.$_{2010}$ showed a sharp increase in incision rates following both base-level fall events, but there was little change in modern incision rates compared to the best-fit 1-D model with a single base-level fall (Fig. 8B). Because the rate of change in incision rate was low after a rapid adjustment period immediately post–base-level fall (<1 k.y.), the difference between both scenarios was minimal by the end of the run, over 10 k.y. later.

To convert incision rates to valley excavation rates, results from the 3-D incision and meandering model were compiled. The model was run until valley width patterns in the numerical model matched those found in the Le Sueur River valley (Fig. 6). Figure 9 shows the resulting elevations due to incision and lateral migration along a 40-km-long valley for three model runs. Ten runs were completed, all showing a rise in volume excavated over the first 3.5 k.y., followed by a slow decline over the Holocene (Fig. 10). Volumes were tracked nondimensionally in the model and then converted back to actual volumes based on the average volumetric erosion rate over the 13.5 k.y. history. Remarkably, the model-predicted volumetric erosion rate from valley excavation after 13.5 k.y. of run time (40,000 m^3/yr) is within 5% of the average volumetric erosion rate over the entire 13.5 k.y. period (42,000 m^3/yr) as determined from LiDAR analyses. This model prediction can be viewed as an estimate of the natural background rate of erosion from valley excavation, averaged over century time scales, and excluding additional forcings from land-use change or recent climate change. This volumetric erosion rate is a conservative estimate, incorporating the volume of sediment removed from the highest terrace to the modern floodplain along the length of the knick zone.

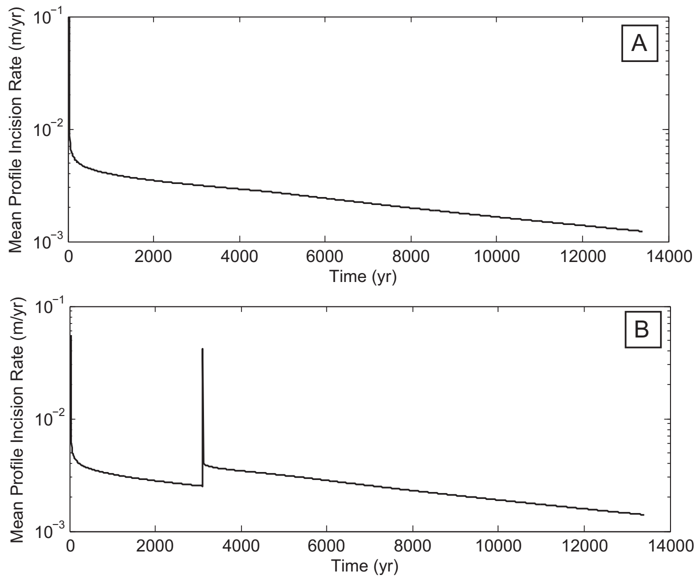

Figure 8. (A) Incision through time as predicted by the best-fit one-dimensional (1-D) incision model with detachment-limited, downstream-coarsening conditions. (B) Incision through time as modeled by the detachment-limited, downstream-coarsening model, but with base-level fall accommodated in two steps, with the first drop of 36 m at 13.5 k.y. B.P.$_{2010}$ and a second drop of 29 m at 10.3 k.y. B.P.$_{2010}$.

DISCUSSION

Long Profile Evolution

The Le Sueur River is incising and evolving as a detachment-limited system. The 1-D numerical models show that an alluvial-based transport-limited approach simply cannot capture the morphology of the modern long profile, and the channel is best simulated as a detachment-limited system. The transport-limited model is based on flux divergence, which is strongest at the slope break at the top of the knick point, where incision is overestimated. The result is a channel that evolves too quickly and loses the distinctive slope break at the knickpoint still visible today. The detachment-limited model focuses incision instead in areas of high slope rather than in areas with rapidly changing slopes. The end result is that a distinct knickpoint can be maintained much longer.

The detachment-limited nature of the Le Sueur comes both from consolidated glacial till that occupies the valley walls and bed of the channel in the knick zone as well as the coarse

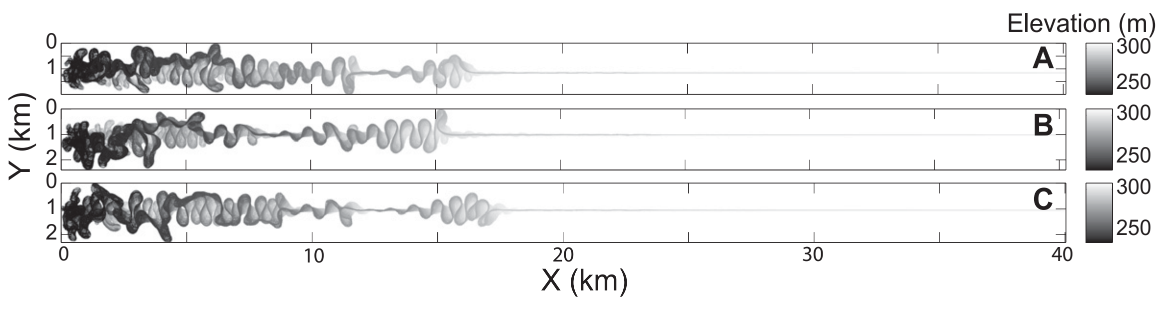

Figure 9. Example runs from the three-dimensional (3-D) numerical model coupling meander migration with the best-fit one-dimensional (1-D) channel incision model. (A–C) Results from three of the 10 different runs.

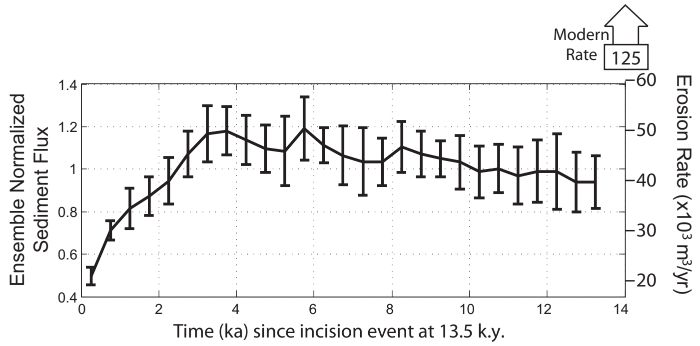

Figure 10. Valley volumes eroded through time as predicted by the three-dimensional (3-D) kinematic meandering model coupled to the best-fit one-dimensional (1-D) incision model. The solid line represents the average of an ensemble of 10 runs, with error bars indicating one standard deviation. Valley volumes are normalized to the average volume eroded over the entire 13.5 k.y. period on the left and reported in m^3/yr on the right.

glacial gravels and boulders that erode out of the till, becoming relatively immobile clasts that must be "detached" before the bed beneath them can mobilize. The nature of the less mobile clasts varies from reach to reach. Some reaches are covered with immobile boulders, while others have gravel armor that is likely mobilized during high flows.

Another striking result to come out of the 1-D numerical modeling is the importance of downstream coarsening on the evolution of the valley. Figure 7 shows the difference in the resulting long profile for model runs with and without downstream coarsening. In the detachment-limited model without downstream coarsening (Fig. 7D), the knick zone remains steep, progressing upstream as a kinematic wave. Once downstream coarsening is added, the bed becomes more difficult to mobilize, slowing erosion in downstream reaches. Faster incision rates on the finer-grained upstream end versus the more-armored downstream end of the knick zone allow the knick zone to lengthen and prevent the knickpoint from maintaining a steeper face as it migrates upstream (Fig. 7C).

These two findings have implications well beyond the Le Sueur River basin. Many rivers in glaciated terrains in the Upper Midwest and central Canada are till-bedded and incising. These rivers are relatively young, occupying valleys that were either carved or re-excavated since the glaciers retreated only 10,000–20,000 yr ago. Because till is usually less cohesive than well-lithified bedrock, however, both vertical incision rates and lateral planation rates can be quite high. In addition, any terraces in these young systems were formed during the time period in which radiocarbon dating can be applied, so age constraints can be readily available. Those who seek to study detachment-limited incision in transient systems may want to turn their attention to these young, till-bedded channels.

Role of Base-Level History and Climate Forcings

In addition to the base-level fall, several other factors influenced the evolution of the Le Sueur River valley, including a significant stream capture event after 10.95 k.y. B.P. The paleochannel profile projects to the upper suite of terraces upstream from its point of entry into the current Le Sueur River valley (Fig. 2), and ages from two terraces dated on or above that elevation all predate the potential capture time. One of the last meltwater pulses from Glacial Lake Agassiz down the Minnesota River valley occurred around 10.3–10.6 ka (Blumentritt et al., 2009; Fisher 2003), which may have helped trigger the stream capture event. Sometime between 10.95 k.y. B.P.$_{2010}$ and 8.1 k.y. B.P.$_{2010}$, the Blue Earth River appears to have captured the Le Sueur River, stranding the paleochannel and initiating more incision on the Le Sueur River. The absence of terraces below the upper suite of terraces near the mouth may be the result of faster incision rates following the capture event (Fig. 8B). Generally, a high vertical incision rate will preclude the formation of lateral strath terraces, since channels do not spend enough time at a given elevation to carve a strath surface. Once incision rates declined enough, terrace formation could resume through lateral meander migration.

Although this stream capture event played an important role in the history of the Le Sueur River and the geometry of the lower valley, it was fairly insignificant in the final valley profile morphology and modern incision rates. Results of the 1-D incision modeling found no better fit between model and data when the system was modeled with a two-stage incision event similar to the initial base-level fall followed by a stream capture 3000 yr later. The lack of a significant difference in the modern incision rate between one-stage and two-stage incision models illustrates how quickly the incisional signal diffuses. The temporal scale is long enough for the signals to converge into a solution that is indistinguishable within the range of uncertainty here. Thus, for modern incision rates specifically, the stream capture event is of secondary importance.

Likewise, although climatic conditions presumably did change appreciably in the basin during the mid-Holocene dry period, it appears they played a secondary role in controlling the overall pattern of incision within the context of incision and knickpoint migration. The mid-Holocene dry period was modeled through a reduction in shear stress and discharge equivalent to a 25% reduction in flow depth from 9 k.y. to 5 k.y. B.P.$_{2010}$. This was not a strong enough perturbation to substantially change the way the system responded to the initial incision event.

Although the mid-Holocene dry period did not appear to alter the overall valley excavation history, it may have played a role in the timing of sediment evacuation from the basin that could not be captured by the models used here. Many studies in basins beyond the glacial margin indicate substantial changes in either channel geometry or depositional rates during the mid-Holocene dry period (Knox, 1985, 2000; Beach, 1994; Bettis and Mandel, 2002). These nonglaciated watersheds have greater relief and drainage density and contain abundant erodible loess deposits, affecting the magnitude of response associated with changes in climate. Patterns seen elsewhere include changes in storage associated with climate change (Bettis and Mandel, 2002; Hudak and Hajic, 2005; Knox, 2006), but because the Le Sueur River lacks a geomorphic floodplain throughout most of the incising knick zone (Belmont, 2011), there is little room to accommodate changes in storage within the main valley. Sediment is mobilized rapidly out of the knick zone, dampening any effects of climate change on incision rates and long profile evolution.

Implications for Management

Modeling results show a pattern of valley excavation where volumetric erosion rates rise rapidly for the first 3500 yr, and then decline gradually up to the present (Fig. 10). Although the actual rates fluctuated by as much as ±20% depending on the model run, the pattern was consistent and the variability quantifiable. The pattern of valley excavation leads to a peak in the volumetric erosion rate around 10 k.y. B.P.$_{2010}$, which then declines ~20% during the Holocene. The tradeoff between less-frequent access to valley walls as valleys widen coupled with higher and higher valley walls through incision led to relatively slow changes in the volumetric erosion rates during the Holocene. The model-predicted annual volumetric erosion rate from valley excavation for presettlement conditions is within 5% of the average annual rate over the entire 13.5 k.y. time period, or an estimated 40,000 ± 6000 m^3/yr. Converting this to a mass of silt and clay yields 47,000 ± 7000 Mg/yr of fine sediment.

From 2000 to 2010, TSS loads at the mouth of the Le Sueur River ranged from 29,000 Mg/yr to 540,000 Mg/yr, with an average load of 225,000 Mg/yr (Gran et al., 2011b; Water Resources Center, 2009). These are TSS loads calculated for the monitoring season only (generally March–November). Annual loads are generally not more than 5%–10% higher because rivers freeze during the winter months. Decadal-averaged modern fine sediment loads are thus 4–5 times higher than model-predicted "presettlement" loads.

Since the estimated presettlement loads include only sediment eroded from valley excavation, but not sediment derived from ravines or upland agricultural field erosion, we must parse out the total historic TSS load into its components. A sediment budget by Gran et al. (2011b) found that the valley excavation processes of bluff erosion, bank erosion, and channel incision account for 65% of the total fine sediment budget on the Le Sueur River, or an estimated 146,000 Mg/yr. Thus, valley excavation rates over the past decade are approximately three times higher than modeled century-scale presettlement erosion rates from valley evolution.

What would cause valley excavation rates to increase threefold over background rates? Most observations point toward a dramatic change in watershed-scale hydrology (Novotny and Stefan, 2007; Belmont et al., 2011a; Lenhart et al., 2011a, 2011b; Schottler et al., 2013). Since the onset of agriculture in the Le Sueur basin, many areas that were internally drained have been connected to the channel network, thus increasing the total drainage area of the Le Sueur basin. At the same time, subsurface drainage tiles have been added to most agricultural fields. These drain tiles act to increase infiltration rates into the subsurface, where water is more rapidly moved through subsurface flow via tile drains into ditches and channels, where it enters the stream network. Since much of the water drained by tiles would have remained in the watershed and been lost through evapotranspiration, most of the water from tile drainage represents a net increase in water volume carried by channels (Schottler et al., 2013). Analyses of flows in the Minnesota River show a dramatic increase in flows across the hydrograph from base flows to peak flows (Novotny and Stefan, 2007), consistent with changes in hydrology seen in the Le Sueur and other major tributaries. Although precipitation also has been increasing, it has not increased enough to account for the change in discharge measured on the Minnesota River (Schottler et al., 2013).

Increased flows associated with changes in land use have been correlated with greater channel widths, indicating higher rates of bank erosion (Schottler et al., 2013). Given the increase in valley excavation rates, the higher flows also appear to be increasing shear along bluff toes as well, thus allowing bluff erosion to proceed at a more rapid rate than presettlement valley excavation modeling suggests. The knick zone appears to be particularly sensitive to these recent changes in hydrology, amplifying the effects of hydrologic changes on sediment loading in the channel. The implications for management of these channels is that focusing on sediment sources at the field scale will not be sufficient to dramatically lower sediment loads in rivers. Excess water in rivers is now driving more rapid erosion of banks and bluffs, and management practices need to address delivery of water to channels, not just sediment.

CONCLUSIONS

The young, incising channel studied here provides a well-constrained natural experiment of a rapidly evolving, transient, detachment-limited system. Because the underlying tills erode like relatively weak bedrock, significant changes can occur over a short time scale, allowing for good constraints on incision rates and patterns of valley excavation. Similar channels elsewhere may provide an opportunity for studying transient detachment-limited channel evolution.

The Le Sueur River in south-central Minnesota provides an example of a till-based channel that is incising following 65 m of base-level fall from the incision of the Minnesota River valley 13.5 k.y. B.P.$_{2010}$. The Le Sueur River is best modeled as a detachment-limited system, in which downstream coarsening also plays a critical role in setting the modern longitudinal profile. Downstream coarsening arises due to incision into glacial tills containing gravels that accumulate as relatively immobile bed load in the channel.

By coupling a 3-D kinematic model of meander migration to the 1-D channel incision model, we were able to model valley evolution in the Le Sueur River. Results show that valley excavation rates increased steadily for the first 3500 yr after base-level fall and then declined slowly throughout the Holocene. The model-predicted valley excavation rate is within 5% of the average annual rate over the entire 13.5 k.y. Using the results of the 3-D model coupled with measurements of grain-size distributions and bulk density, we predict the presettlement volumetric erosion rate to be 47,000 ± 7000 Mg/yr of silt and clay.

This presettlement erosion rate was compared to the decadal-average annual TSS load from 2000 to 2010 for the Le Sueur River. Average TSS loads from 2000 to 2010 are 4–5 times higher than presettlement erosion rates. Focusing on the portion of TSS coming from bank and bluff erosion and channel incision (i.e., valley excavation), the modern loads remain three times higher than predicted presettlement loads. Thus, not only have land-use changes increased sediment derived from fields, but erosion rates within the valley itself are increasing. The increased flows in rivers, driven primarily by drainage of the landscape (Schottler et al., 2013), are creating more erosive rivers, dramatically increasing valley excavation rates within the Le Sueur River.

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REFERENCES CITED

Beach, T., 1994, The fate of eroded soil: Sediment sinks and sediment budgets of agrarian landscapes in southern Minnesota, 1851–1988: Annals of the Association of American Geographers, v. 84, p. 5–28, doi: 10.1111/j.1467-8306.1994.tb01726.x.

Begin, Z.B., Schumm, S.A., and Meyer, D.F., 1980, Knickpoint migration due to base level lowering: Journal of the Waterway Port Coastal and Ocean Division of the American Society of Civil Engineers (ASCE), v. 106, no. 3, p. 369–388.

Belmont, P., 2011, Floodplain width adjustments in response to rapid base level fall and knickpoint migration: Geomorphology, v. 128, p. 92–102, doi:10.1016/j.geomorph.2010.12.026.

Belmont, P., Gran, K., Jennings, C.E., Wittkop, C., and Day, S.S., 2011a, Kirk Bryan field trip: Holocene landscape evolution and erosional processes in the Le Sueur River, central Minnesota, *in* Miller, J.D., Hudak, G.J., Wittkop, C., and McLaughlin, P.I., eds., Archean to Anthropocene: Field Guides to the Geology of the Mid-Continent of North America: Geological Society of America Field Guide 24, p. 439–455, doi:10.1130/2011.0024(21).

Belmont, P.B., Gran, K.B., Schottler, S.P., Wilcock, P.R., Day, S.S., Jennings, C., Lauer, J.W., Viparelli, E., Willenbring, J.K., Engstrom, D.R., and Parker, G., 2011b, Large shift in source of fine sediment in the Upper Mississippi River: Environmental Science & Technology, v. 45, no. 20, p. 8804–8810, doi:10.1021/es2019109.

Berlin, M.M., and Anderson, R.S., 2007, Modeling of knickpoint retreat on the Roan Plateau, western Colorado: Journal of Geophysical Research, v. 112, F03S06, doi:10.1029/2006JF000553.

Bettis, E.A., and Mandel, R.D., 2002, The effects of temporal and spatial patterns of Holocene erosion and alluviation on the archaeological record of the central and eastern Great Plains, USA: Geoarchaeology: International Journal (Toronto, Ontario), v. 17, no. 2, p. 141–154.

Bishop, P., Hoey, T.B., Jansen, J.D., and Artza, I.L., 2005, Knickpoint recession rate and catchment area: The case of uplifted rivers in eastern Scotland: Earth Surface Processes and Landforms, v. 30, p. 767–778, doi:10.1002/esp.1191.

Blumentritt, D.J., Wright, H.E., Jr., and Stefanova, V., 2009, Formation and early history of Lakes Pepin and St. Croix of the Upper Mississippi River: Journal of Paleolimnology, v. 41, p. 545–562, doi:10.1007/s10933-008-9291-6.

Boulton, G.S., 1976, The development of geotechnical properties in glacial tills, *in* Legget R.F., ed., Glacial Till: The Royal Society of Canada Special Publication 12, p. 292–303.

Bull, W.B., 1990, Stream-terrace genesis: Implications for soil development: Geomorphology, v. 3, p. 351–367, doi:10.1016/0169-555X(90)90011-E.

Camill, P., Umbanhower, C.E., Jr., Teed, R., Geiss, C.E., Aldinger, J., Dvorak, L., Kenning, J., Limmer, J., and Walkup, K., 2003, Late-glacial and Holocene climatic effects on fire and vegetation dynamics at the prairie-forest ecotone in south-central Minnesota: Journal of Ecology, v. 91, no. 5, p. 822–836, doi:10.1046/j.1365-2745.2003.00812.x.

Chumbley, C.A., Baker, R.G., and Bettis, E.A., III, 1990, Midwestern Holocene paleoenvironments revealed by floodplain deposits in northeastern Iowa: Science, v. 249, no. 4966, p. 272–274, doi:10.1126/science.249.4966.272.

Clayton, L., and Moran, S.R., 1982, Chronology of late-Wisconsinan glaciation in middle North America: Quaternary Science Reviews, v. 1, p. 55–82, doi:10.1016/0277-3791(82)90019-1.

Crosby, B.T., and Whipple, K.X., 2006, Knickpoint initiation and distribution within fluvial networks: 236 waterfalls in the Waipaoa River North Island, New Zealand: Geomorphology, v. 82, no. 1–2, p. 16–38, doi:10.1016/j.geomorph.2005.08.023.

Davis, W.M., 1902, River terraces in New England: Bulletin of the Museum of Comparative Zoology, v. 38, p. 289–345.

Day, S.S., 2012, Anthropogenically-Intensified Erosion in Incising River Systems [Ph.D. dissertation]: Minneapolis, Minnesota, University of Minnesota, 242 p.

Day, S.S., Gran, K.B., Belmont, P., and Wawrzyniec, T., 2013, Measuring bluff erosion part 2: Pairing aerial photographs and terrestrial laser scanning to determine a watershed scale sediment budget: Earth Surface Processes and Landforms, doi:10.1002/esp.3359 (in press).

Dean, W.E., 1997, Rates, timing, and cyclicity of Holocene eolian activity in north-central United States: Evidence from varved lake sediments: Geology, v. 25, p. 331–334, doi:10.1130/0091-7613(1997)025<0331:RTACOH>2.3.CO;2.

Dean, W.E., Forester, R.M., and Bradbury, J.P., 2002, Early Holocene change in atmospheric circulation in the northern Great Plains: An upstream view of the 8.2ka cold event: Quaternary Science Reviews, v. 21, p. 1763–1775, doi:10.1016/S0277-3791(02)00002-1.

Fernandez-Luque, R., and van Beek, R., 1976, Erosion and transport of bed-load sediment: Journal of Hydraulic Research, v. 14, no. 2, p. 127–144, doi:10.1080/00221687609499677.

Finnegan, N.J., and Dietrich, W.E., 2011, Episodic bedrock strath terrace formation due to meander migration and cutoff: Geology, v. 39, p. 143–146, doi:10.1130/G31716.1.

Finnegan, N.J., Sklar, L.S., and Fuller, T.K., 2007, Interplay of sediment supply, river incision, and channel morphology revealed by the transient evolution of an experimental bedrock: Journal of Geophysical Research, v. 112, F03S11, doi:10.1029/2006JF000569.

Fisher, T.G., 2003, Chronology of Glacial Lake Agassiz meltwater routed to the Gulf of Mexico: Quaternary Research, v. 59, p. 271–276, doi:10.1016/S0033-5894(03)00011-5.

Fuller, T.K., Perg, L.A., Willenbring, J.K., and Lepper, K., 2009, Field evidence for climate-driven changes in sediment supply leading to strath terrace formation: Geology, v. 37, p. 467–470, doi:10.1130/G25487A.1.

Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H., and Olley, J.M., 1999, Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia. Part I: Experimental design and statistical models: Archaeometry, v. 41, p. 339–364, doi:10.1111/j.1475-4754.1999.tb00987.x.

Gardner, T.W., 1983, Experimental study of knickpoint and longitudinal profile evolution in cohesive, homogeneous material: Geological Society of America Bulletin, v. 94, no. 5, p. 664–672, doi:10.1130/0016-7606(1983)94<664:ESOKAL>2.0.CO;2.

Gran, K.B., Belmont, P., Day, S.S., Jennings, C., Johnson, A., Perg, L., and Wilcock, P.R., 2009, Geomorphic evolution of the Le Sueur River, Minnesota, USA, and implications for current sediment loading, *in* James, L.A., Rathburn, S.L., and Whittecar, G.R., eds., Management and Restoration of Fluvial Systems with Broad Historical Changes and Human Impacts: Geological Society of America Special Paper 451, p. 119–130.

Gran, K.B., Belmont, P., Day, S.S., Finnegan, N., Jennings, C., Lauer, J.W., and Wilcock, P.R., 2011a, Landscape evolution in south-central Minnesota and the role of geomorphic history on modern erosional processes: GSA Today, v. 21, no. 9, p. 7–9, doi:10.1130/G121A.1.

Gran, K.B., Belmont, P., Day, S., Jennings, C., Lauer, J.W., Viparelli, E., Wilcock, P., and Parker, G., 2011b, An Integrated Sediment Budget for the Le Sueur River Basin: Final Report to the Minnesota Pollution Control Agency, 119 p (unpublished).

Hancock, G.S., and Anderson, R.S., 2002, Numerical modeling of fluvial strath-terrace formation in response to oscillating climate: Geological Society of America Bulletin, v. 114, p. 1131–1142, doi:10.1130/0016-7606(2002)114<1131:NMOFST>2.0.CO;2.

Hancock, G.R., and Willgoose, G.R., 2002, The use of a landscape simulator in the validation of the Siberia landscape evolution model: Transient landforms: Earth Surface Processes and Landforms, v. 27, p. 1321–1334, doi:10.1002/esp.414.

Hasbargen, L.E., and Paola, C., 2000, Landscape instability in an experimental drainage basin: Geology, v. 28, no. 12, p. 1067–1070, doi:10.1130/0091-7613(2000)28<1067:LIIAED>2.0.CO;2.

Hasbargen, L.E., and Paola, C., 2003, How predictable is local erosion rate in eroding landscapes?, *in* Wilcock, P.R., and Iverson, R.M., eds., Prediction in Geomorphology: American Geophysical Union Geophysical Monograph 135, p. 1–10, doi:10.1029/135GM16.

Hilley, G.E., and Arrowsmith, R., 2008, Geomorphic response to uplift along the Dragon's Back pressure ridge, Carrizo Plain, California: Geology, v. 36, p. 367–370, doi:10.1130/G24517A.1.

Howard, A.D., 1994, A detachment-limited model of drainage basin evolution: Water Resources Research, v. 30, p. 2261–2285, doi:10.1029/94WR00757.

Howard, A.D., and Kerby, G., 1983, Channel changes in badlands: Geological Society of America Bulletin, v. 102, p. 233–242.

Howard, A.D., and Knutson, T.R., 1984, Sufficient conditions for river meandering: A simulation approach: Water Resources Research, v. 20, no. 11, p. 1659–1667.

Hudak, C.M., and Hajic, E.R., 2005, Landscape evolution of the Minnesota River valley: Geological Society of America Abstracts with Programs, v. 37, no. 5, p. 8.

Jennings, C.E., 2007, Overview of the Quaternary Geologic History of the Minnesota River, *in* Native Plant Communities and Rare Species of the Minnesota River Valley Counties: St. Paul, Minnesota Department of Natural Resources, Division of Ecological Resources, Minnesota County Biological Survey Biological Report 89, p. 2.1–2.12.

Jennings, C.E., 2010, Draft Digital Reconnaissance Surficial Geology and Geomorphology of the Le Sueur River Watershed (Blue Earth, Waseca, Faribault, and Freeborn Counties in South-Central MN): Minnesota Geological Survey Open File Report 10–03, map, report and digital files at ftp://mgssun6.mngs.umn.edu/pub4/ofr10_03/.

Johnson, A.L., 2012, Timing and Pattern of Valley Excavation, Le Sueur River, South-Central Minnesota, USA [M.S. thesis]: Duluth, Minnesota, University of Minnesota, 53 p.

Knox, J.C., 1985, Responses of floods to Holocene climatic change in the Upper Mississippi Valley: Quaternary Research, v. 23, no. 3, p. 287–300, doi:10.1016/0033-5894(85)90036-5.

Knox, J.C., 2000, Sensitivity of modern and Holocene floods to climate change: Quaternary Science Reviews, v. 19, p. 439–457, doi:10.1016/S0277-3791(99)00074-8.

Knox, J.C., 2006, Floodplain sedimentation in the Upper Mississippi Valley: Natural versus human accelerated: Geomorphology, v. 79, p. 286–310, doi:10.1016/j.geomorph.2006.06.031.

Kunkel, K.E., Andsager, K., and Easterling, D.R., 1999, Long-term trends in extreme precipitation events over the conterminous United States and Canada: Journal of Climate, v. 12, p. 2515–2527, doi:10.1175/1520-0442(1999)012<2515:LTTIEP>2.0.CO;2.

Laird, K.R., Fritz, S.C., Grimm, W.C., and Mueller, P.G., 1996, Century-scale paleoclimatic reconstruction from Moon Lake, a closed-basin lake in the northern Great Plains: Limnology and Oceanography, v. 41, no. 5, p. 890–902, doi:10.4319/lo.1996.41.5.0890.

Lenhart, C.F., Peterson, H., and Nieber, J., 2011a, Increased streamflow in agricultural watersheds of the Midwest: Implications for management: Watershed Science Bulletin, Spring 2011, p. 25–31.

Lenhart, C.F., Verry, E.S., Brooks, K.N., and Magner, J.A., 2011b, Adjustment of prairie pothole streams to land-use, drainage, and climate changes and consequences for turbidity impairment: River Research and Applications, v. 28, p. 1609–1619, doi:10.1002/rra.1549.

Lepper, K., Fisher, T.G., Hajdas, I., and Lowell, T.V., 2007, Ages for the big stone moraine and the oldest beaches of Glacial Lake Agassiz: Implications for deglaciation chronology: Geology, v. 35, p. 667–670, doi:10.1130/G23665A.1.

Lian, O., and Roberts, R.G., 2006, Dating the Quaternary: Progress in luminescence dating of sediments: Quaternary Science Reviews, v. 25, p. 2449–2468, doi:10.1016/j.quascirev.2005.11.013.

Marschner, F.J., 1930, Interpretation of Francis J. Marschner's map of the original vegetation of Minnesota: Based on the notes of the Public Land Survey, 1847–1907: St. Paul, Minnesota, North Central Forest Experiment Station, U.S. Department of Agriculture.

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

Meyer, G.N., Knaeble, A.R., Lusardi, B.A., Jennings, C.E., and Gowan, A.S., 2012, Quaternary Stratigraphy, Plate 4, *in* Runkel, A.C., Meyer, G.N., and Lusardi, B.A., Geologic Atlas of Blue Earth County, Minnesota [Part A]: Minnesota Geologic Survey County Atlas Series, Atlas C-26, 6 plates, 1:100,000 scale.

Minnesota Department of Natural Resources, 2007, Native Plant Communities and Rare Species of the Minnesota River Valley Counties: Minnesota County Biological Survey Biological Report 89.

Montgomery, D.R., 2004, Observations on the role of lithology in strath terrace formation and bedrock channel width: American Journal of Science, v. 304, no. 5, p. 454–476.

Murray, A.G., and Wintle, A.G., 2000, Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol: Radiation Measurements, v. 32, no. 1, p. 57–73, doi:10.1016/S1350-4487(99)00253-X.

Murray, A.S., and Wintle, A.G., 2003, The single aliquot regenerative dose protocol: Potential for improvements in reliability: Radiation Measurements, v. 37, p. 377–381, doi:10.1016/S1350-4487(03)00053-2.

Musser, K., Kudelka, S., and Moore, R., 2009, Minnesota River Basin Trends Report: http://mrbdc.wrc.mnsu.edu/mnbasin/trends/index.html (last accessed May 2013), 66 p.

Novotny, E.V., and Stefan, H.G., 2007, Stream flow in Minnesota: Indicator of climate change: Journal of Hydrology (Amsterdam), v. 334, p. 319–333, doi:10.1016/j.jhydrol.2006.10.011.

Olley, J.M., Caitcheon, G.G., and Roberts, R.G., 1999, The origin of dose distributions in fluvial sediments, and the prospect of dating single grains from fluvial deposits using optically stimulated luminescence: Radiation Measurements, v. 30, no. 2, p. 207–217, doi:10.1016/S1350-4487(99)00040-2.

Palmer, M.A., Covich, A.P., Lake, S., Biro, P., Brooks, J.J., Cole, J., Dahm, C., Gibert, J., Goedkoop, W., Martens, K., Verhoeven, J., and Van De Bund, W.J., 2000, Linkages between aquatic sediment biota and life above sediments as potential drivers of biodiversity and ecological processes: Bioscience, v. 50, p. 1062–1075, doi:10.1641/0006-3568(2000)050[1062:LBASBA]2.0.CO;2.

Parker, R.S., 1977, Experimental Study of Drainage Basin Evolution and its Hydrology Implications [Ph.D. thesis]: Fort Collins, Colorado, Colorado State University, 331 p.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsay, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.S., Talamo, S., Turney, C.S.M., van der Plicht, J., and Weyhenmeyer, C.E., 2009, IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP: Radiocarbon, v. 51, no. 4, p. 1111–1150.

Rittenour, T.M., 2008, Luminescence dating of fluvial deposits: Applications to geomorphic, palaeoseismic, and archaeological research: Boreas, v. 37, p. 613–635, doi:10.1111/j.1502-3885.2008.00056.x.

Schottler, S.P., Ulrich, J., Belmont, P., Moore, R., Lauer, J.W., Engstrom, D.R., and Almendinger, J.E., 2013, Twentieth century agricultural drainage creates more erosive rivers: Hydrologic Processes, doi:10.1002/hyp.9738 (in press).

Seeley, M., 2003, Climate Trends: What Are Some Implications for Minnesota's Air and Water Resources?: http://www.pca.state.mn.us/index.php/air/air/view-category/Page-1/Page-6.html (accessed July 2012).

Seidl, M.A., and Dietrich, W.E., 1994, The problem of channel incision into bedrock: Catena, v. 23, supplement, p. 101–124.

Shay, C.T., 1967, Vegetation history of the southern Lake Agassiz basin during the past 12,000 years, *in* Mayer-Oakes, W.J., ed., Life, Land, and Water: Proceedings of the 1960 Conference on Environmental Studies of the Glacial Lake Agassiz Basin: Winnipeg, Canada, University of Manitoba Press, p. 231–252.

Shields, A., 1936, Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung [Application of similarity principles and turbulence research to bed-load movement]: Mitteilungen der Preußischen Versuchsanstalt für Wasserbau, v. 26.

Stock, J.D., and Montgomery, D.R., 1999, Geologic constraints on bedrock river incision using the stream power law: Journal of Geophysical Research, v. 104, p. 4983–4993, doi:10.1029/98JB02139.

Talma, A.S., and Vogel, J.C., 1993, A simplified approach to calibrating ^{14}C dates: Radiocarbon, v. 35, p. 317–322.

Thoma, D.P., Gupta, S.C., Bauer, M.E., and Kirchoff, C.E., 2005, Airborne laser scanning for riverbank erosion assessment: Remote Sensing of Environment, v. 95, p. 493–501, doi:10.1016/j.rse.2005.01.012.

Thorleifson, L.H., 1996, Review of Lake Agassiz history, *in* Teller, J.T., Thorleifson, L.H., Matile, G., and Brisbin, W.C., eds., 1996, Sedimentology, Geomorphology and History of the Central Lake Agassiz Basin—Field Trip Guidebook B2: Winnipeg, Manitoba, Geological Association of Canada/Mineralogical Association of Canada, Annual Meeting, May 27–29 1996.

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

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

U.S. Environmental Protection Agency, 2012, Water Quality Assessment and TMDL Information, 2011: http://ofmpub.epa.gov/tmdl_waters10/attains_nation_cy.control (accessed 22 June 2012).

Vandenberghe, D., Derese, C., and Houbrechts, G., 2007, Residual doses in recent alluvial sediments from the Ardenne (S. Belgium): Geochronometria, v. 28, p. 1–8, doi:10.2478/v10003-007-0024-z.

van der Beek, P., and Bishop, P., 2003, Cenozoic river profile development in the Upper Lachlan catchment (SE Australia) as a test of quantitative fluvial incision models: Journal of Geophysical Research, v. 108, p. 2309, doi:10.1029/2002JB002125.

Wallinga, J., 2002, Optically stimulated luminescence dating of fluvial deposits: A review: Boreas, v. 31, p. 303–322, doi:10.1080/030094802320942536.

Water Resources Center, Minnesota Pollution Control Agency, 2009, State of the Minnesota River: Summary of Water Quality Monitoring 2000–2008, 37 p, http://mrbdc.mnsu.edu/sites/mrbdc.mnsu.edu/files/public/reports/basin/statemr08.html (last accessed May 2013).

Webb, T., and Bryson, R.A., 1972, Late- and postglacial climactic change in the northern Midwest: Quaternary Research, v. 2, p. 70–115, doi:10.1016/0033-5894(72)90005-1.

Wegmann, K.W., and Pazzaglia, F.J., 2009, Late Quaternary fluvial terraces of the Romagna and Marche Apennines, Italy: Climatic, lithologic, and tectonic controls on terrace genesis in an active orogeny: Quaternary Science Reviews, v. 28, p. 137–165, doi:10.1016/j.quascirev.2008.10.006.

Whipple, K.X., 2004, Bedrock rivers and the geomorphology of active orogens: Annual Review of Earth and Planetary Sciences, v. 32, p. 151–185, doi:10.1146/annurev.earth.32.101802.120356.

Whipple, K.X., and Tucker, G., 2002, Implications of sediment-flux dependent river incision models for landscape evolution: Journal of Geophysical Research, v. 107, no. B2, p. ETG 3-1–ETG 3-20, doi:10.1029/2000JB000044.

Whipple, K.X., Snyder, N.F., and Dollenmayer, K., 2000, Rates and processes of bedrock incision by the Upper Ukaka River since the 1912 Novarupta ash flow in the Valley of Ten Thousand Smokes, Alaska: Geology, v. 28, p. 835–838, doi:10.1130/0091-7613(2000)28<835:RAPOBI>2.0.CO;2.

Wilcock, P., on behalf of the Minnesota River Sediment Colloquium Committee, 2009, Identifying Sediment Sources in the Minnesota River Basin: Synthesis Report for Minnesota River Sediment Colloquium: Report for Minnesota Pollution Control Agency, http://www.pca.state.mn.us/index.php/view-document.html?gid=8099 (last accessed May 2013), 16 p.

Wintle, A.G., and Murray, A.S., 2006, A review of optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration: Radiation Measurements, v. 41, p. 369–391, doi:10.1016/j.radmeas.2005.11.001.

Wohl, E.E., Greenbaum, N., Schick, A.P., and Baker, V.R., 1994, Controls on bedrock channel incision along Nahal Paran, Israel: Earth Surface Processes and Landforms, v. 19, p. 1–13, doi:10.1002/esp.3290190102.

Wright, H.E., Jr., Stefanova, I., Tian, J., Brown, T.A., and Hu, F.S., 2004, A chronological framework for the Holocene vegetational history of central Minnesota: The Steel Lake pollen record: Quaternary Science Reviews, v. 23, p. 611–626, doi:10.1016/j.quascirev.2003.09.003.

Yu, Z.C., McAndrews, J., and Eicher, U., 1997, Middle Holocene dry climate caused by change in atmospheric circulation patterns: Evidence from lake levels and stable isotopes: Geology, v. 25, p. 251–254, doi:10.1130/0091-7613(1997)025<0251:MHDCCB>2.3.CO;2.

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