

Timing and pattern of valley excavation, Le Sueur River, south-central Minnesota, USA

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Abstract

Strath terraces of the Le Sueur River, south central Minnesota, preserve the record of river incision. A combination of airborne LiDAR (light detection and ranging) and terrace dating through optically-stimulated luminescence (OSL) and radiocarbon methods were used to construct a conceptual model of valley excavation during the Holocene and late Pleistocene from lateral and vertical incision. The river is responding to approximately 70 meters of base level fall that occurred 13,400 years ago (11,500 radiocarbon years before present), when glacial River Warren carved the Minnesota River valley. The carving of the Minnesota River valley led to widespread incision on Minnesota River tributaries as knickpoints propagated upstream from the main stem Minnesota River.

As the knickpoint moved up the Le Sueur River, hundreds of terrace surfaces were formed. These terraces are strath terraces carved into glacial tills, with alluvial deposits overlying planed-off till surfaces. Observations from dating terrace alluvium indicate that the river underwent relatively continuous incision, which is ongoing today. The incision model derived from terraces ages was coupled with valley geometry measured from LiDAR data to determine how valley excavation rates have changed through time. Results from this conceptual model indicate that valley excavation has been relatively constant through time. When this background valley excavation rate was compared with the modern sediment load, it was determined that the modern sediment load is 4-5 times greater than the average Holocene sediment load. This demonstrates

that the post-settlement load is greater than the pre-settlement load and should guide the management of this basin to focus on the anthropogenic changes to the basin.

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1. Introduction

Terrace flights along the Le Sueur River in south-central Minnesota contain the preserved record of river incision over the Holocene and late Pleistocene. This study focuses on creating a conceptual and quantitative model of valley excavation over the Holocene and late Pleistocene by systematic mapping and dating of depositional ages on strath terraces. The incision model is coupled with high-resolution digital elevation models (DEMs) derived from aerial LiDAR (Light Detection and Ranging) to constrain volumes of sediment removed through valley excavation. The estimated volumes were converted to sediment loads to compare to the modern load values, allowing comparisons between long-term pre-settlement sediment loads and modern sediment loads on this sediment-rich, turbidity-impaired river.

Today, the Le Sueur River (LSR) is actively incising through a series of stacked tills overlying bedrock. This incision is related to the carving of the Minnesota River valley 13,400 cal. yr. B.P. (11,500 rcbp), which triggered up to 70 meters of base level fall on tributary channels (Clayton and Moran, 1982; Matsch, 1983). The Minnesota River valley was carved as a result of the drainage of glacial Lake Agassiz through glacial River Warren (Matsch, 1982; Thorleifson, 1996). As base level fell during the flooding event, it created knickpoints that propagated upstream on tributaries like the LSR (Gran, et al., 2009). As the LSR incised, terraces were created and many were preserved.

The LSR watershed covers 2880 km² (~1112 mi²) of south-central Minnesota and is a prime contributor of high sediment loads to its downstream confluent river systems;

the Minnesota River and the subsequent Mississippi River. The LSR watershed comprises about seven percent of the Minnesota River basin, yet it contributes approximately 24-30% of the total suspended solids (TSS) (MPCA, et. al., 2007). These relatively high sediment loads negatively impact water quality and the overall integrity of the local and downstream systems. Depositional records downstream in Lake Pepin indicate that most of the sediment deposited there was derived from the Minnesota River (Kelley and Nater, 2000), and the rate of deposition has increased by a factor of ten over pre-settlement deposition rates (Engstrom et al., 2009). The erosional history in the Le Sueur River may help provide insight into determining the pre-settlement rate of erosion to compare with modern erosion rates and with the downstream record in Lake Pepin.

A combination of field work and GIS analyses were used to determine the incision history of the LSR valley. Field work involved mapping terraces, collecting sediment for grain size distributions, and collecting materials to be dated using optically-stimulated luminescence (OSL) and radiocarbon techniques. The field-mapped terraces were used to confirm digitally-mapped terraces. Grain size distributions were collected from terraces to determine if sedimentologic competencies changed through time. The dated material was used to give terraces a numeric depositional age and develop a chronology for valley incision.

GIS analyses on aerial LiDAR data were used to digitally map terraces, calculate volumes of sediment removed through established time periods, and create profiles of the valley history. By combining the mapped terraces and ages, volumes of sediment removed through time were calculated and used to derive an annual load. The annual

load was converted to the silt and clay fraction to compare with modern TSS loads.

Valley profiles were created through time to create a conceptual framework for how the LSR watershed developed as the knick point propagated upstream. The results show that sediment loads from valley excavation in the LSR watershed had a relatively constant mean volume through time, with a potential dip in the mid-Holocene dry period followed by a rise. Pre-settlement erosion rates of fine-grained sediment from valley excavation alone were 4-5 times lower than the modern TSS load.

2. Background

The LSR watershed is 2880 km². Three main rivers drain the watershed: the mainstem LSR, the Maple River, and the Big Cobb River. The LSR flows into the Blue Earth River and subsequently the Minnesota River. The Maple and the Big Cobb Rivers flow into the LSR within 3 km of each other approximately 10 km upstream from the confluence of the Blue Earth and Le Sueur Rivers (Figure 2-1). The basin is characterized by an area of high relief along the lower reaches of all three rivers, and an area of gentle to rolling terrain throughout the rest of the basin (Figure 2-2). The flatter terrain is a result of the last glaciation which shaped this region's landscape. The area of high relief is a result of an incising river system responding to knickpoint migration due to a change in local base level.

2.1 Geological Setting

Ordovician dolostone bedrock and Pleistocene glacial tills underlie the basin, with outcrops visible towards the mouths of the rivers. The surficial deposits consist of glacial tills, glacial outwash, and features such as ice-walled lake plains located in the eastern portion of the basin (Figure 2-3) (Jennings, 2010). A thin layer of glaciolacustrine silts and clays cover the western two-thirds of the basin, which is about sixty-five percent of the upland surface (Jennings, 2010). The tills of the area range from 41-68% silt-clay and the glaciolacustrine sediments are 61-97% silt and clay (Carrie Jennings, correspondence). The minimum age of the surficial deposits is around 12,000 rcbp (Johnson et al., 2011; Ruhe and Scholtes, 1959).

The incision history of the LSR is influenced by the region's extensive glacial history. Towards the end of the last glaciation, the Laurentide ice sheet was retreating from the Midwest. A low moraine dam formed as a result of the retreat, trapping the meltwater and forming glacial Lake Agassiz (Upham, 1890; Upham, 1895; Clayton and Moran, 1982; Fisher, 2005). Due to the size of glacial Lake Agassiz there were other outlets present that were occupied through the course of the lake's existence (Fisher, 2005). The southern outlet of the lake was through glacial River Warren, which is now occupied by the Minnesota River (Matsch, 1982; Thorleifson, 1996).

The initial incision was around 11,500 rcbp (Clayton and Moran, 1982; Matsch, 1983). Glacial River Warren's valley was occupied until about 10,900 rcbp. The two other outlets were used between 10,900 - 10,300 rcbp (Thorleifson, 1996) and 10,000 and 9,600 rcbp. Glacial River Warren was not occupied again until after 9,600 rcbp 11,500 BP and lost the discharge from glacial Lake Agassiz by 8,200 rcbp (Thorleifson, 1996).

Glacial Lake Minnesota covered approximately two-thirds of the LSR watershed, and was created during the retreat of the Des Moines Lobe (Hobbs and Goebel, 1982). Rather than one single lake, glacial Lake Minnesota most likely was a series of combined water bodies trapped by an ice dam. Stratigraphically, the glacial lacustrine drape seems to only record about 20 years of sedimentation (Patterson, 2003). Because of the presence of glacial Lake Minnesota covering much of the watershed, the initial condition in the watershed is assumed to be a relatively planar surface. River valleys developed in this planar surface following the drainage of glacial Lake Minnesota, shortly before glacial Lake Agassiz carved what is now the Minnesota River valley. Material from

glacial Lake Minnesota sediments have been dated at $10,070 \pm 80$ rcbp, which shows that the lake was potentially occupied until the draining of glacial Lake Agassiz (Carrie Jennings, correspondence).

The result of the draining of glacial Lake Agassiz through glacial River Warren was a 70 m deeply incised valley in the vicinity of Mankato (Gran et al., 2009, Matsch, 1983). Tributaries that existed previous to the incision event, such as the LSR, were left stranded above the base level set by the initial incision event 13,400 calendar yr BP (11,500 rcbp). This base level fall led to knick points that can be seen on long profiles of all three rivers 25-35 km upstream of the mouth as slope discontinuities (Figure 2-5).

2.2 Climate

Multiple climatic changes have occurred in the Le Sueur watershed throughout the Holocene. To assess those changes climate proxies, lake core data have been studied. Very little data exist specifically in the LSR watershed, so the climate information has been adapted from regional studies in northern Iowa and central Minnesota that suggest a transitional period from the early Holocene –mid Holocene (Chumbley et al., 1990, Anderson, 1993; Dean 1997; Wright et al. 1998, 2003; Hu et al. 1999; Denniston et al., 1999; Dean et al., 2002; Camill et al. 2003). For this study, the Holocene climate has been broken up in to three time periods: early (13,400-9,000 cal yr bp), middle (9,000-4000 cal yr bp), and late (4,000 cal yr bp).

During the late Pleistocene/early-Holocene (13,400-9,000 cal yr bp) glaciers had retreated, but the region was still affected by the cooler climate. According to Webb and

Bryson (1972), the region was 4.4°C colder, moister, and cloudier than the modern climate. More snow was present during the winter months. Conditions during this time could also be described as similar to cold boreal and subarctic conditions.

The mid-Holocene (9,000-4,000 cal yr bp) experienced changes to the global airstreams. During this time, the Pacific air stream was blocked off from the region. This was also a time of elevated solar isolation in which temperatures were higher than present day (Berger and Loutre, 1991). With the changes in airstreams and elevated solar isolation the Le Sueur watershed most likely began to develop drier more arid conditions (Berger and Loutre, 1991; Wright et al. 1998).

The late-Holocene (4,000 cal yr bp-present) climate transitioned to the current conditions we have today. Over the past 50 years there has been an increasing trend in precipitation, the number of days with precipitation, and the number of intense rainfall events (Novotny and Stefan, 2007; Belmont et al., 2011a). With the increase in precipitation and precipitation events there has also been an increase to the stream flows of the Minnesota River Basin (Novotny and Stefan, 2007; Lenhart et al. 2011).

2.3 Land Use History

Climate has had a large impact on vegetation within the LSR watershed. The dominant landcover before the influence of humans was that of prairies and wet prairies (Marschner, 1930, Minnesota Department of Natural Resources, 2007) (Figure 2-6). Hardwood forests covered the river valleys and the northeastern portion of the watershed (Marschner, 1930) (Figure 2-6).

Two main changes occurred to the basin as it was being settled over the last two hundred years. The first was the conversion of original prairie to agriculture. The second involves the alteration of the basin's hydrology through artificial drainage. The basin hydrology changes included draining of the wetlands, creating a large public and private ditch network and the installation of tile drainage systems. Approximately 86% percent of the basin is now cropland, primarily row crops such as corn and soybeans (Water Resources Center, 2009a). According to the Water Resources Center (2007) of Minnesota State University in Mankato, Minnesota, almost all of the farm fields have artificial drainage which has increased the depth, density, and capacity of drainage over time.

During the 1850's, Euro-Americans began to migrate from the east to the plains of Minnesota. Areas close to the river bottoms began to be settled first in which small farms were created. The 1862 Homestead Act initiated free land to those who would inhabit the tall-grass-prairie and wet prairie landscapes (Risjord, 2005). The first farmers harvested small plots of wheat because the native prairie plants had massive root wads which made it difficult to clear the land. The wet prairies were left for the small herds of cattle to graze during the summer months.

As the price of the cattle increased, it became economically feasible for framers to raise larger herds of cattle. The small family farm became more focused on being able to produce meat for the general population and focused their field efforts towards producing cattle feed. With the advancement of farming technologies, the root wads were easier to break up, and farmers began to expand their fields. The innovation of subsurface

drainage began in the 1880's (Lawes, 1882; Magdalene, 2004) and continues in practice today.

Tiling was one of the major methods of decreasing standing water. Tiling consists of a series of subsurface drainage pipes. Initial tiles were made of clay pipes. They are now mostly constructed of flexible perforated PVC (polyvinyl chloride) pipe.

The most dominant soil type in LSR watershed agricultural fields is a silty loam. For this soil texture, the University of Minnesota Extension recommends tile spacing of 45-50 feet apart and depths of 3.3-4.0 feet. For this region, tiles are typically placed in a parallel or herringbone pattern and usually discharge into a county ditch or county tile lines. In some instances, a surface inlet is placed in depressional areas to aid drainage. Most tiles within agricultural fields are privately owned, making it difficult to document the total amount. The result of the installation of tiles has impacted the drainage of the watershed. The tiles act as macropores underground allowing for water to flow more easily to its outlet (Blann et al., 2009). This results in once internally-drained wetlands being connected to the main river channels of the LSR watershed.

2.4 Modern Sediment Loads

Due to the abundance of silts and clays, high relief in the lower part of the basin, and anthropogenic influences to the land, the LSR watershed is susceptible to high suspended sediment loads. According to current gaging efforts by the Minnesota Pollution Control Agency (MPCA) approximately 24-30 percent of total suspended solids (TSS) flowing in to the Minnesota River come from the LSR watershed. The average

TSS load at the mouth of the Le Sueur River during the monitoring season from 2000-2010 was 225,000 Mg/yr (WRC and MPCA, 2009; MPCA, unpublished data; Gran et al., 2011a).

Just south of where the Minnesota River empties into the Mississippi is Lake Pepin, a naturally dammed lake, which acts as sediment sink (Figure 2-1). Lake Pepin is currently filling in at a rate that is approximately ten times greater than the natural pre-settlement background rate (Engstrom et al., 2009). The majority of the sediment in Lake Pepin can be traced back to the Minnesota River Basin (Kelley and Nater, 2000). It is still unclear how erosional changes in the LSR may link to this 10-fold depositional increase within the whole of the Minnesota River basin.

2.5 Terrace Formation and Basin Evolution

The LSR is a geomorphically young basin evolving through time following a base level fall at the mouth. There are competing models regarding how basins evolve through incision, network extension, and integration. One goal of this study is to develop a conceptual model of how the LSR watershed evolved using terraces to constrain channel incision patterns at different points in time.

Terraces are classified by how they form, and the formations are influenced by allogenic and/or autogenic factors (Erkens et al., 2008; Hancock and Anderson, 2002). A strath terrace is a cut terrace and represents a time when the channel and the transported material are in direct contact with the underlying bedrock (Wegmann and Pazzaglia, 2002). The majority of the LSR terraces are strath terraces cut into glacial till.

Terraces are preserved due to a drop in base level. In many places, terraces are paired and exist in discrete terrace sets representing a time of relative stability when valleys widened and channels ceased to incise (Pazzaglia et al, 1993). Other terraces may form through lateral migration accompanying ongoing incision and thus are not found in terrace sets (Finnegan and Dietrich, 2011).

We describe the driving forces behind terrace creation as either allogenic or autogenic. Allogenic refers to controls outside of the basin which includes tectonic uplift, changes in base level and climate. Autogenic controls are internally-driven changes within the system itself, such as meander migration and cutoff. The factors that influence the LSR will be further discussed in the discussion.

Terraces form a useful tool in understanding the pattern and driving forces that lead to channel incision and basin evolution since they record specific points in time when the river was at a higher elevation. In the LSR watershed, terraces were formed in response to an initial base level fall with knickpoints propagating up through the newly-forming drainage network.

Laboratory experiments and numerical models provide additional insight into how new drainage networks evolve following base level fall. Parker (1977) and Hancock and Willgoose (2002) conducted similar experimental models of basin evolution following a fall in base level. The base level was dropped incrementally over time for both experiments. Both found that as a basin developed and expanded, the sediment flux was high initially; then exponentially decreased through time.

Hasbargen and Paola (2002) found a different result. In their experiment, base level was dropped continuously instead of dropping base level in a step-wise fashion like Parker (1977) and Hancock and Willgoose (2002). Results showed that as base level dropped the amount of sediment transported through the mouth of the modeled watershed increased through time. As time progressed, the drainage network became fully integrated, and even though base level continued to lower, the sediment flux reached a steady state, fluctuating over a small range.

These sets of experiments show opposite trends in sediment flux as the landscape evolves from base level fall. The competing processes of knickpoint migration and drainage integration lead to different potential trajectories for sediment flux through time. Either the channel incised rapidly at first, releasing a pulse of sediment that then decays through time, or the channel incised steadily, releasing increasing volumes of sediment as the network expands, finally stabilizing once the network is fully integrated.

It is also possible that allogenic controls on incision drive the pattern of sediment evacuation from the basin. The terraces record this incision history and the relationship between terrace height and age varies between the different scenarios. Figure 2-7 displays four possible scenarios relating terrace height and age to patterns of basin evolution: A) demonstrates a slow knickpoint migration in the beginning, speeding up over time, B) shows a type of external change to the basin, i.e climate related, C) represents a constant rate of knickpoint migration and incision, and D) represents a rapid incision early on in the basin's formation, slowing down as time progressed.

Understanding the incision history has great implications in understanding modern sediment loads. It is possible to determine the average rate of erosion within the valley from the time of incision by glacial River Warren to the present (Gran et al., 2009, 2011a). The modern TSS loads are much greater than this average background rate of sediment erosion from the valley (Gran et al., 2011b). However, this does not explain how modern sediment loads compare to pre-settlement loads, just to the average Holocene rate of erosion. To establish the relationship between modern loads and pre-settlement loads, one must investigate the LSR's past which includes the river's incision history. For example, if the excavation of the valley is slow initially, increasing with time, then a higher modern sediment load would fit in with the scenario. If the opposite occurred where the valley was eroded quickly in the beginning with sediment loads decreasing over time, then the change from pre-settlement to modern sediment loads would be even higher. Lastly, if valley incision is relatively constant, then the expected pre-settlement loads should match the average background rate throughout the Holocene and late Pleistocene.

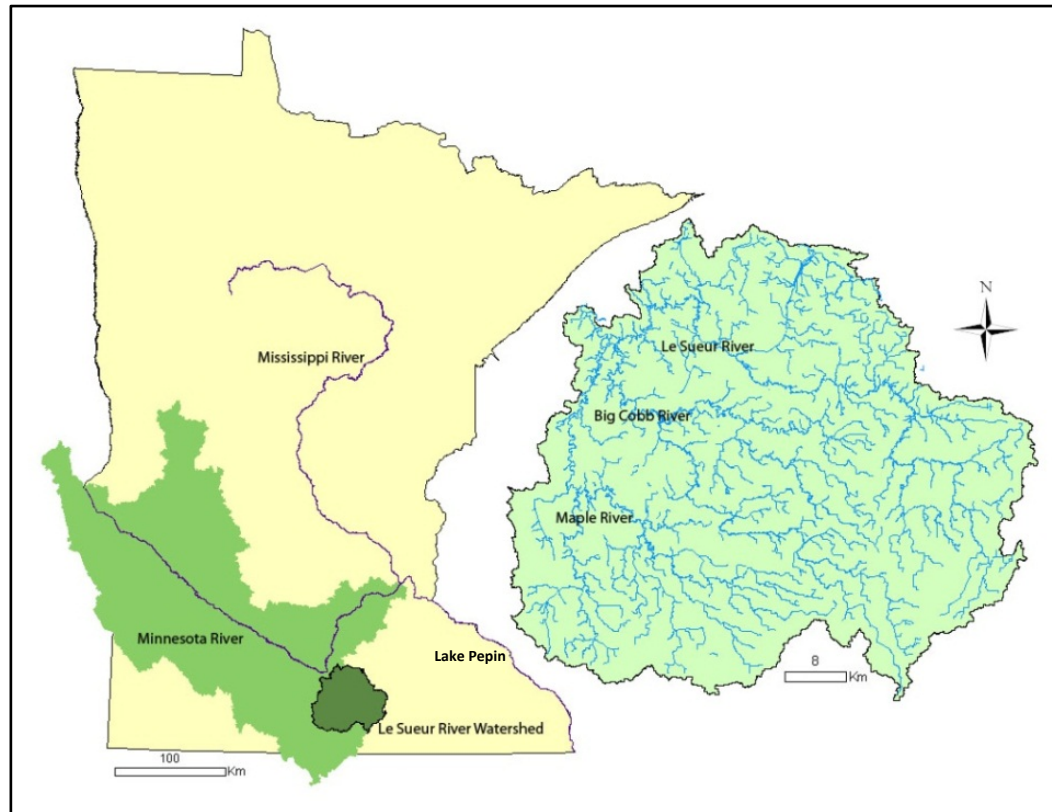


Figure 2-1. Location map of the Le Sueur River Watershed, with major tributaries (Le Sueur River, Big Cobb River, and Maple River) in relation to the Minnesota and Mississippi Rivers. The location of Lake Pepin is also noted.

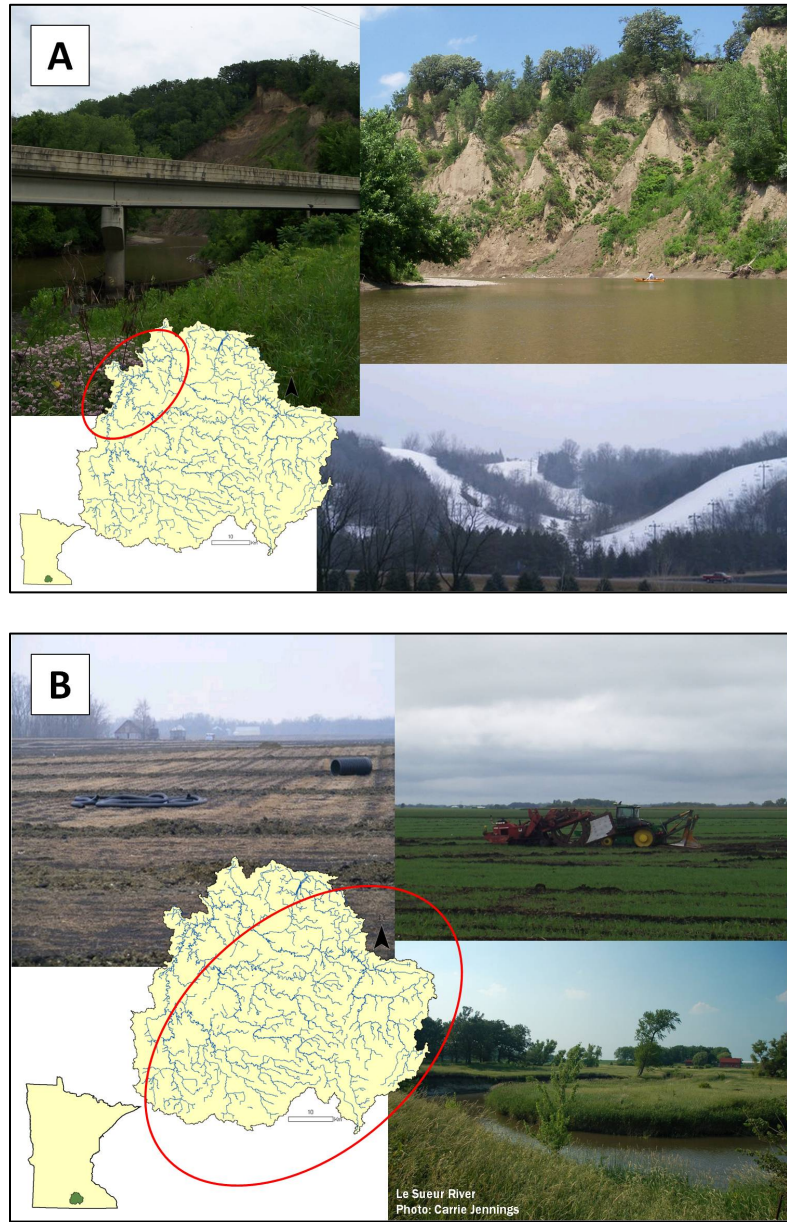


Figure 2-2. A) Images of the lower basin within the knick zone. Notice the steep bluffs along the river. B) Images of the upper basin, above the knick zone, comprised primarily of relatively flat surfaces that have been converted for agricultural purposes.

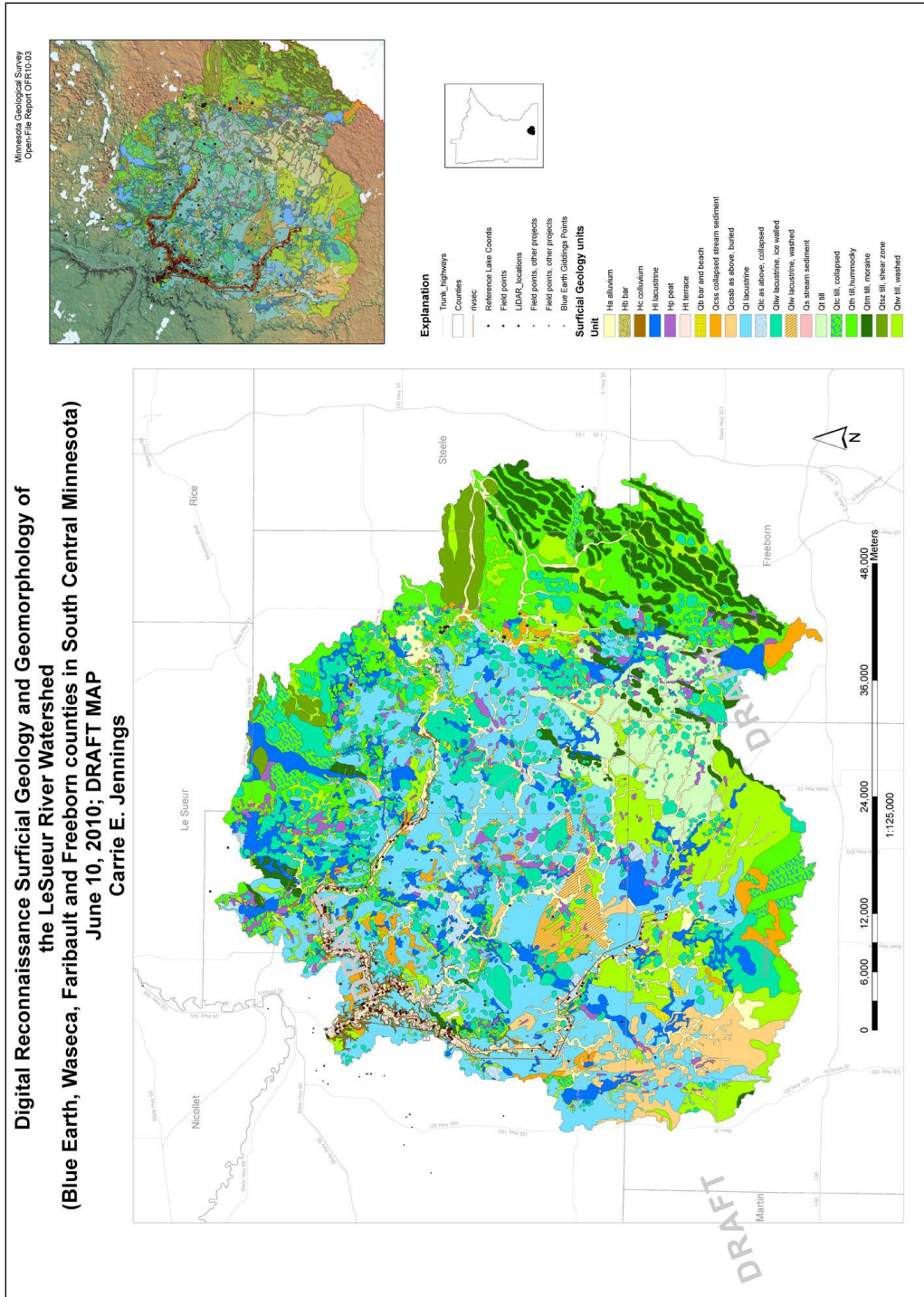


Figure 2-3. Surficial geologic map of Le Sueur water shed (after Jennings, 2010).



Figure 2-4. Location map of glacial lakes during the last glaciation at their maximum extent, including glacial Lake Agassiz (after Teller et al., 1983) and glacial Lakes Benson and Minnesota (after Hobbs, and Goebel, 1982) (from Jennings, 2007).

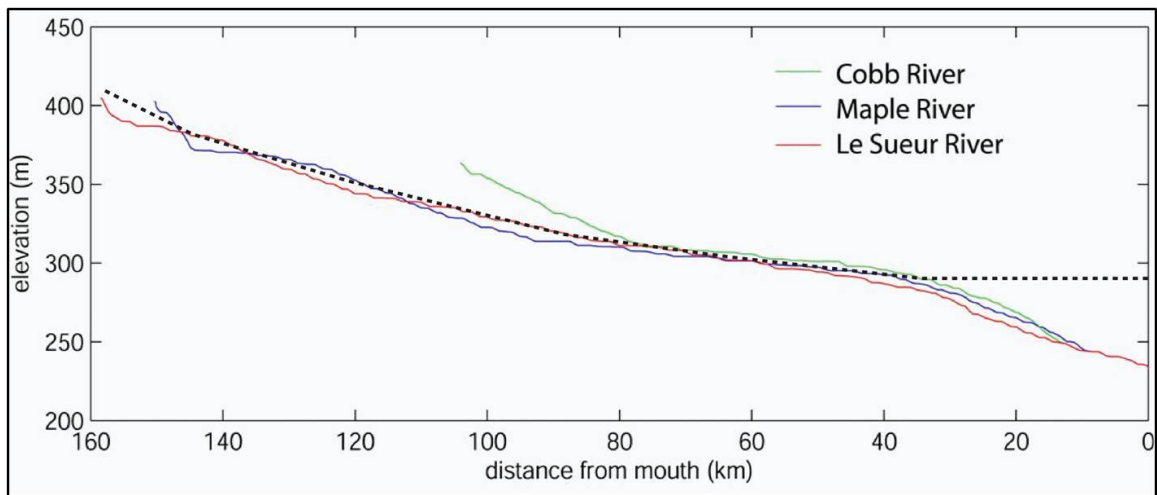


Figure 2-5. Long profiles of all three rivers of the Le Sueur River Watershed. The dashed black line indicates the graded profile that might have developed if the base level had not fallen.

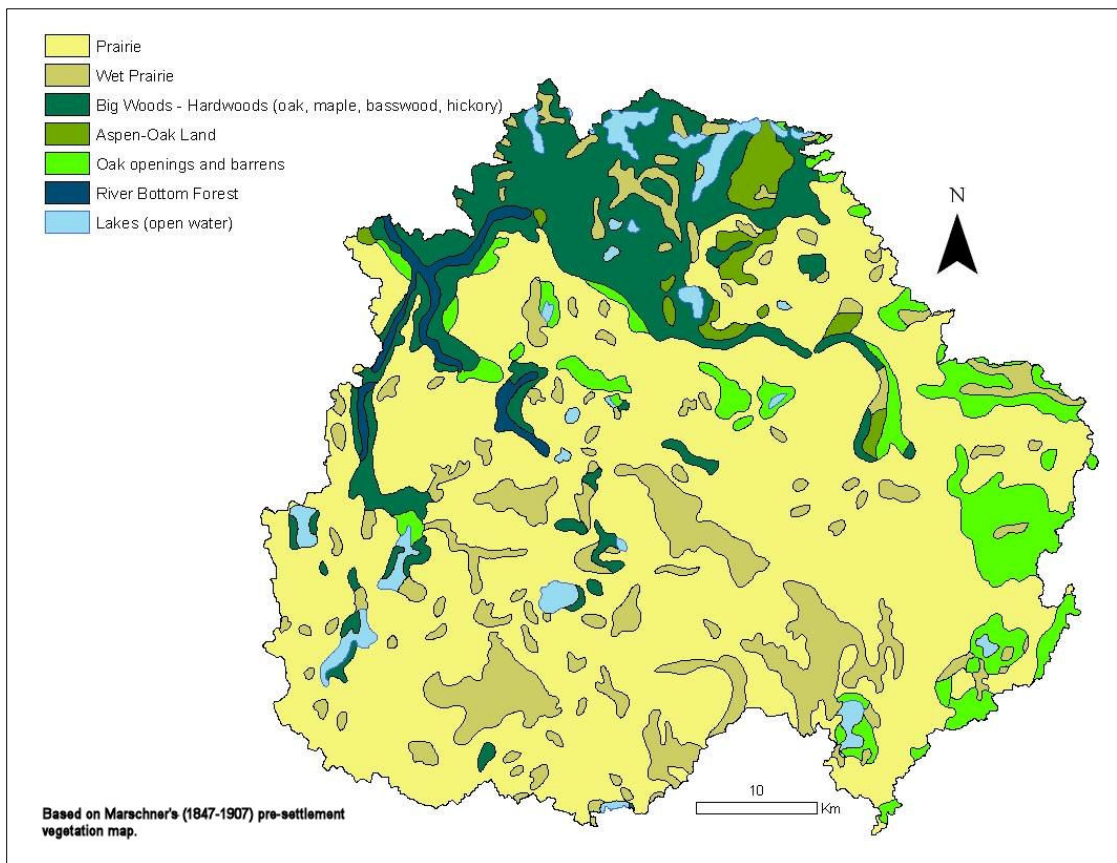


Figure 2-6. Pre-settlement land cover of the Le Sueur watershed, based on Marschner's (1847-1907) pre-settlement vegetation map of Minnesota.

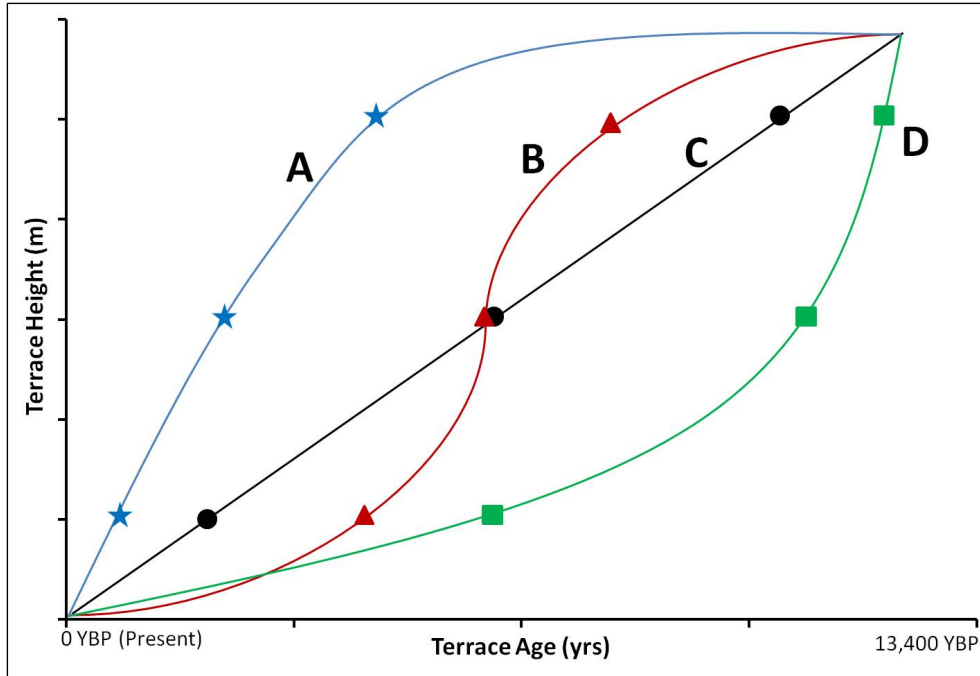


Figure 2-7. Varying models of how the terrace age could relate to terrace height based on knickpoint migration through time. The points on each line represent what the heights of terraces of different ages could be. A) Demonstrates a slow knickpoint incision in the beginning, speeding up over time. B) Shows a type of external change to the basin, i.e. climate related. C) Represents a constant rate of knickpoint incision. D) Represents a rapid incision early on in the basin's formation, slowing down as time progressed.

3. Methods

A combination of GIS (geographic information systems) analyses, field work, and depositional age constraints were used to understand the incision history of the Le Sueur River. Shapefiles of terraces and valley volumes through different time periods were developed using GIS. Field work was conducted to verify mapped terraces, collect material for OSL (optically-stimulated luminescence) and radiocarbon dating techniques, and sample for grain size distributions to determine any sedimentologic changes in competency through time. These approaches were combined to simulate LSR valley morphologies throughout the Holocene and late Pleistocene.

3.1 Terraces

Terraces give a snapshot of the Le Sueur River through time. A terrace is a remnant floodplain that was stranded due to river incision. Knowing the depositional age of sediments on a specific terrace gives you a known elevation of the channel at a discrete point in time. Therefore, terraces can be used to help determine incision history. Terraces were mapped in the field and by remote-sensing techniques using airborne LiDAR data to determine the extent of terraces throughout the valley. GIS was used to measure attributes including terrace height and location. Selected terraces were dated to determine ages. Terrace attributes and ages were combined to derive an age model for the whole system.

3.1.1 Mapping

Processed airborne LiDAR data were acquired through Blue Earth County, Minnesota. The data were converted to a one-meter DEM from which hillshade and slope files were created. Only the portion of the river in Blue Earth County was mapped due to LiDAR data availability, but the entire knickzone and thus the vast majority of terraces in the watershed are in Blue Earth County. Figure 3-1 shows an example of landforms that can be identified using the DEM. Terraces were also mapped throughout the basin using 1:24000 topographic maps, which were used to help guide field work.

Terraces were defined using the following criteria: 1) located within the river valley; 2) a generally flat surface with undulations no greater than 5 m, 3) one side with a steep slope, and 4) > 1-2 m above the river channel, which is the approximate floodplain height above the channel. Meander cutoffs meeting this criterion were mapped as terraces. If a terrace was found to have an undulation of greater than 5 m, it was either discarded or the polygon was modified to fit the criterion and checked again. A subset of terraces was field checked.

Terrace height was measured with respect to the local river elevation. The terraces were divided into three categories for consistency: 1) adjacent to stream, 2) set back from the stream, and 3) in a meander bend but set back from stream. For each terrace an upstream and downstream river elevation were recorded and averaged. The average river elevation was subtracted from the average terrace elevation to get a terrace height. Confirmed terrace locations and elevations were plotted with reference to the modern stream elevation as a proxy for river kilometer.

3.1.2 Grain Size

Terrace deposits generally consist of a coarse channel deposit lying directly on top of planed-off till and overlain by finer-grained overbank alluvial deposits (Figure 3-2). Channel deposits on terraces were collected for grain size to determine if there were any measurable changes in competence of the river over time. Forty samples were collected within the knick zone along the Le Sueur River from County Road 41 to County Road 66 (Figure 3-3). The sample sites were accessed by canoe.

At each terrace site, the upper and lower boundaries of the channel deposit were identified. A two-gallon Ziploc[®] bag was filled with a representative sample of the upper portion of the channel deposit. Stratigraphy was logged including contacts between overbank deposits, channel deposits, and till (Figure 3-2). This was repeated for all terraces that have exposures along the selected reach, for a total of 40 terraces sampled.

Samples were sieved in the field. Samples that contained shells were noted, and the shells were picked out and saved for future radiocarbon dating. Each sample was first weighed, then sieved through a 16 mm, 8 mm, and 4 mm sieve. Sediment that was less than 4 mm was weighed and a split was taken. The split was sent to the Limnological Research Center at the University of Minnesota-Twin Cities. Samples were run through the laser diffractometer to obtain percents of sand, silt and clay. The percents were then applied to original weight of less than 4 mm in order to come up with a full-grain size distribution.

3.1.3 Dating

Field reconnaissance canoe trips were held to select terraces for dating based on three factors: 1) accessibility, 2) exposure, and 3) available materials. An ideal terrace for sampling was easy to access by canoe or car, had all three stratigraphic units visible (till, channel material, and overbank deposits), and contained material suitable for dating. This included either in-situ gastropods or bivalves for radiocarbon dating or fine-grained quartz sand in overbank deposits for OSL dating.

Nine terrace samples were sent to the Utah State University Luminescence Laboratory in Logan, Utah, to be dated using OSL. Three of the samples were also radiocarbon dated. OSL is a technique that measures a buried quartz or feldspar grain's last exposure to sunlight, thus providing a depositional age. It can be used on fluvial materials where there is insufficient material for other dating techniques. The Utah State University laboratory processed the samples using the single-aliquot regenerative-dose procedure (Murray and Wintle, 2000, 2003; Wintle and Murray, 2006).

One major assumption is that the luminescence signal gets reset to zero by an appropriate period of exposure to light prior to deposition (Wallinga, 2002). This may not always be achieved in some fluvial deposits because grains are exposed to varying amounts of light during transport (Wallinga, 2002). If the sediment has incomplete zeroing, referred to as "partial bleaching", then the age may be overestimated. Four samples were identified as being partially bleached. The single-aliquot technique can identify whether or not a sample is partially bleached before the end process. A minimum

age model can be used by the laboratory to calculate the ages of all samples, decreasing the error.

The field procedure for collecting samples was adapted from Joel Pederson of Utah State University. At each selected location the vertical stratigraphy was logged, noting contacts between the till, channel deposits, and overbank deposits. OSL samples were collected around 30 cm above a known channel deposit, or about 1 m above the till line (Figure 3-2).

Using a small garden shovel, 6-8 cm of sediment were excavated and cleared off. A 10-12 inch metal conduit was used to collect the samples of sediment. This was to ensure that none of the sediment was exposed to light. Using the shovel, sediment was scraped away from the conduit and collected in a Ziploc[®] bag to measure the dose rate during analysis. A film canister of sediment was also collected at each site to test for water content. The metal conduit was removed from the hole and capped with duct tape to seal the sediment in place.

Thirteen samples were dated using radiocarbon techniques. Two terraces ('W', 'V') had datable material in an upper and lower channel deposit. The upper date was used for the terrace age. Terraces were selected based on the amount of bivalve and gastropod material found at each site (Figure 3-4). At many terrace sites the material collected for grain size distributions contained shells. These shells were sieved and picked out of the sediment sample with tweezers. Any sand grains were removed from the shells using deionized water. The shells were placed into a labeled foil packet. Each packet was placed in its own Ziploc[®] and sent to Beta Analytic Inc., in Miami, Florida,

for radiocarbon analyses using AMS (Accelerator Mass Spectrometry) techniques. Beta Analytic ran an acid etch preparation on the shells prior to AMS analyses to derive a measured age (BP) for the samples. A 2-sigma calibration was used in the conversion of BP results to calendar ages, which were then compared with the OSL results.

3.1.4 Age Model

An age model was created from the dated terraces and their corresponding heights. No relationship was found between terrace age and distance upstream or between incision rate (terrace height divided by terrace age) and distance upstream. Plotting terrace sets as elevation over channel versus age determined that terraces throughout the basin incised at similar rates, and that this rate did not change appreciably through time.

Two age models were considered that related height above bed to age of terrace formation, with continuous incision. In the first, a single incision rate was applied through time. Thus,

$$T(age) = \frac{h}{r}$$

where $T(age)$ is the terraces age in years, r is the incision rate in m/yr, and h is the height of the terrace above the river bed in meters. In the second age model, the incision rate was allowed to change after a determined height (or age) was reached. This accounted for the possibility that incision rates may have changed through time. For instance, if rates were high initially and then slowed, the two-phase model would allow

for a fast rate early on, changing to a slower rate. It does not allow for a continuously changing rate. The two-phase model takes the form of

$$T(\text{age}) = \frac{h}{r}, \text{ if } h < bh$$

$$T(\text{age}) = \frac{h_1}{r_1} + \frac{h_2}{r_2}, \text{ if } h > bh$$

where $T(\text{age})$ is the terrace age in years, r is the incision rate in m/yr, h is the height of the terrace above the river bed in meters, b is the fraction of height above the channel where the change of rate occurs, h_1 is the height, h_2 is the terrace height at the break point, r_1 is the rate of initial incision, and r_2 is the rate of incision after the break point.

An iterative solver function was used to determine the best fit rates and the best break point so as to best fit the modeled heights with actual heights (or modeled ages vs. actual ages). A one-break model was chosen as the model to use when determining the age. Rate one, $r_1 = 2.25 \text{ m/ka}$, was used until the break, which was calculated to be at 6.85 ka. After the break rate two was applied, $r_2 = 1.46 \text{ m/ka}$. The age model was used to model the age of all terraces. The age model was not fit to the upper surface, as it was not an alluvial surface.

3.2 Valley Development through Time

Terraces are the archives to determine a temporal history for the LSR which includes incision and valley excavation. The incision history involves the down-cutting

of the valley and the excavation history involves the amount of material removed from the valley, a process that incorporates both vertical incision and lateral migration. Coupling the terrace data and with valley extents and valley volumes through time was used to determine these histories. Using dated terraces mapped from LiDAR, surfaces were created to represent the river valley at different points in time. These surfaces correspond to isolated snapshots of terrace creation formed during a more-or-less continuous descent to the modern valley. These are not based upon episodic events that are seen in tectonically active regions, because the terraces in the Le Sueur River valley are not found in sets.

The river valley, including the mapped terraces, was broken up in to 5 km segments from mouth to the top of the knick zone, 35 river km upstream. This distance covered the extent of terrace development. Observations of terrace height, age, and location were used to determine the relative elevation and age bracket for the extent of each valley surface. Six surfaces were selected to represent the valley extent through time. The surfaces selected were named T₀, T₁, T₂, T₃, T₄, and T₅ (“T” meaning terrace surface at certain times). T₅ represents the oldest surface and T₀ the youngest, or the modern floodplain. A shapefile for each surface was manually delineated and created for each 5 km section.

3.2.1 Valley Profiles

Valley profiles were created by making a 3D line for the right valley wall of each time horizon surface. The lines were then graphed through 3D Analyst in Arc GIS, and

the data exported to a spreadsheet. The data were smoothed using a 600 point running average. Ravines and tributaries entering the channel were observed as abrupt dips in the graph. If an elevation fell below one standard deviation of the surface elevation it was removed from the dataset. The data were normalized between 0 and 1 to create a common starting and ending point for all of the data.

3.2.2 Excavation Volumes

Constructing valley volumes excavated through time involved extracting and measuring the missing mass in the valley between time horizon surfaces (T_n and T_{n+1}). The valley snapshots through time were used in conjunction with high-resolution LiDAR elevation data to determine volumes excavated in the time between each valley surface. The modern valley was subtracted from the reconstructed valley to determine the volume removed since the river was at the elevation represented by that time horizon. By comparing the volume differences between time horizons, the volumes excavated during that time period could be determined. For example the volume differences of T_5 and T_4 represented the volume excavated between those two time periods.

In order to determine a height and width the LiDAR DEM data were used. An average elevation was determined for each of the time horizon surfaces by averaging four elevation points along the length of the time horizon surfaces. The average elevation was used to create a raster file for each time horizon surface. The next step involved determining the difference between the volumes of each surface. The modern elevation which is the 3 m DEM was subtracted from the time surface horizon rasters ($T_{1, 2, 3...}$).

The number of pixels that represented the difference between the time horizons was summed. The summation of pixels was multiplied by the pixel dimensions and by 5 km (the river distance of the measured section) to get a volume. The difference in ages between terrace surfaces was determined from the age model, and then the volumes were binned in 1000-year time intervals.

The LSR valley is forming through down-cutting while incising, therefore the valley width is wider at the top of the valley than at the bottom. A width adjustment correction was applied to the calculated volumes to account for the fact that the volumes would have been re-distributed between the time horizons as the river kept incising. This study assumes that the width of the modern floodplain stayed relatively constant through time. Working up from the bottom, the width of T_1 (W_{T1}) was compared with the width of the modern floodplain, W_{T0} . If $W_{T1} > W_{T0}$, then the additional widening was declared to have occurred during the time period after T_1 had formed. The fraction of the W_{T1} attributable to widening after T_1 had formed was calculated as

$$\frac{W_{T1} - W_{T0}}{W_{T1}}$$

and multiplied by the total volume excavated between T_2 and T_1 . This gives the volume that likely came out during the time period between T_1 and T_0 formation rather than between T_2 and T_1 . This volume was then redistributed down to the time between T_1 and T_0 . This same pattern was repeated on up the valley, by comparing W_{T2} to W_{T1} and to W_{T0} and redistributing volume eroded to later time periods. Figure 3-5 shows an illustration to demonstrate what the valley volumes may have looked like with and without width adjustments.

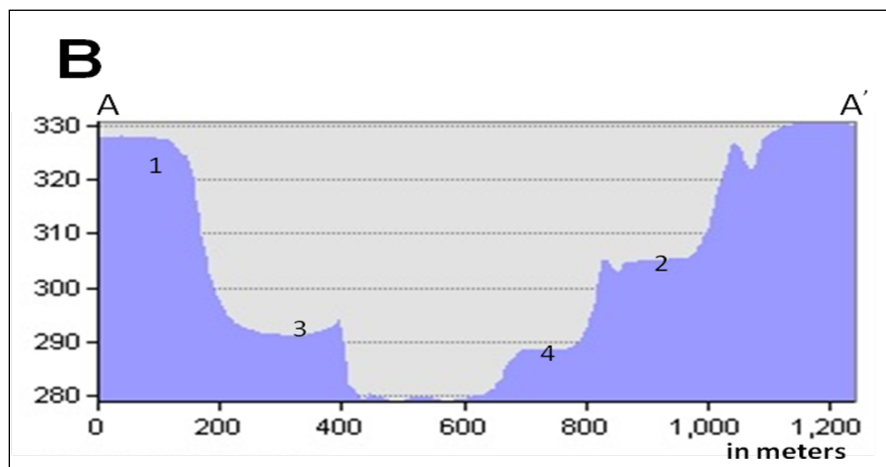
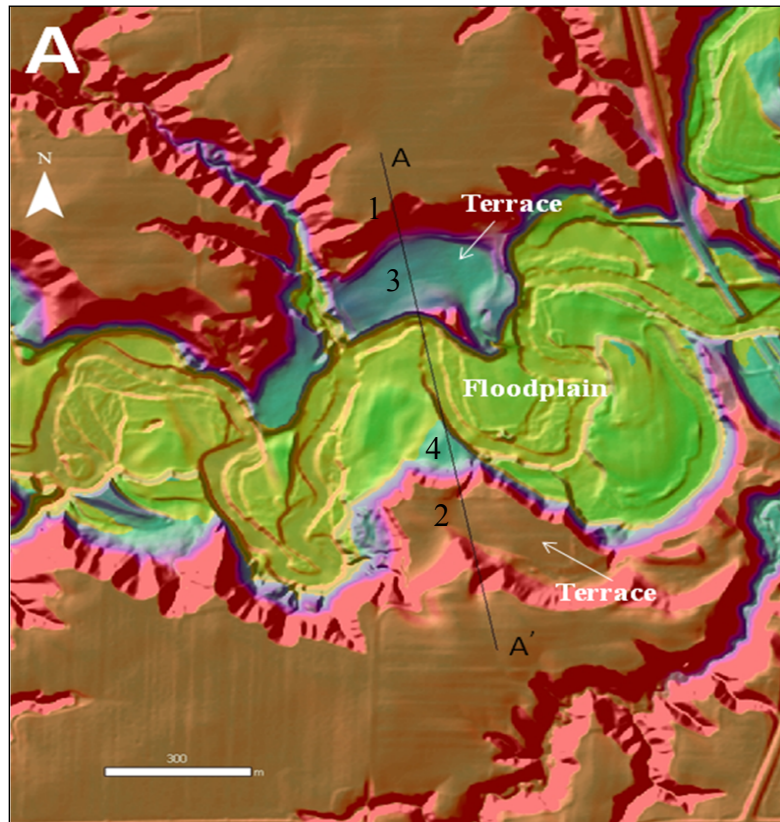


Figure 3-1. A) Example of LiDAR DEM at three meter resolution of the lower Le Sueur River. Terraces and floodplains are easily identified. B) Example of cross-section in meters across the river valley. Notice that in this cross-section there are likely three different terraces of varying ages. Number “1” represents the initial surface.

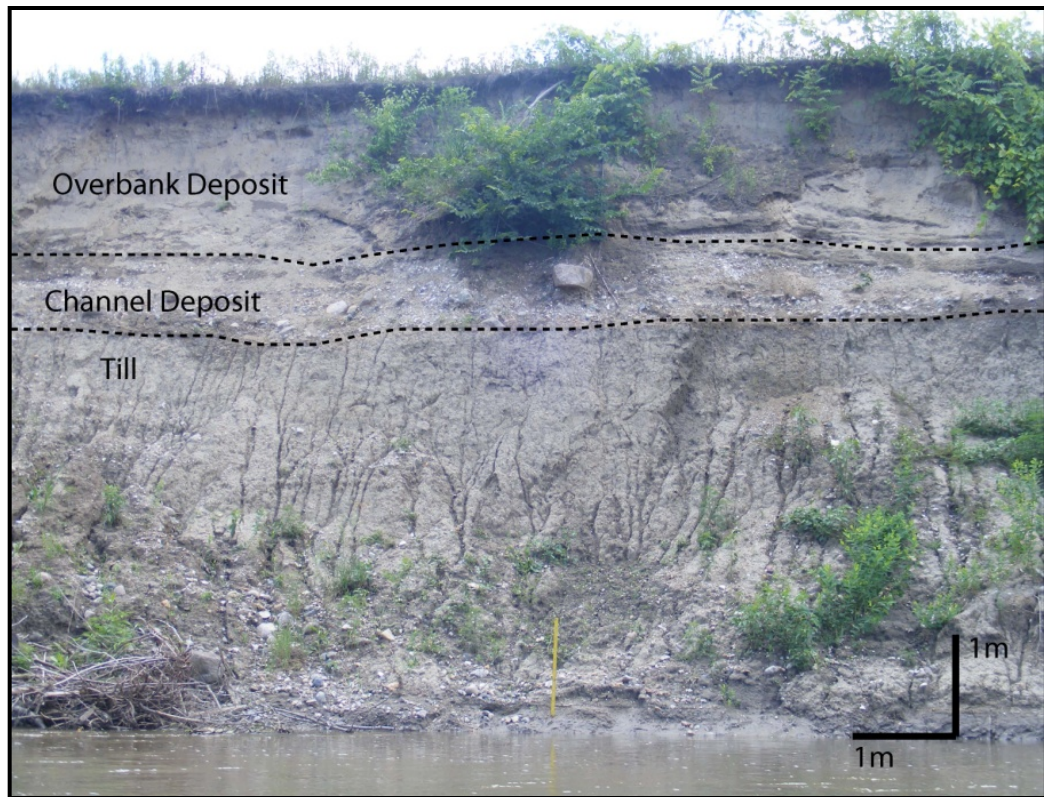


Figure 3-2. Example of strath terrace stratigraphy along the river. Samples for dating were taken either right above the channel deposit (OSL), or within the upper portion of the channel deposit (radiocarbon).

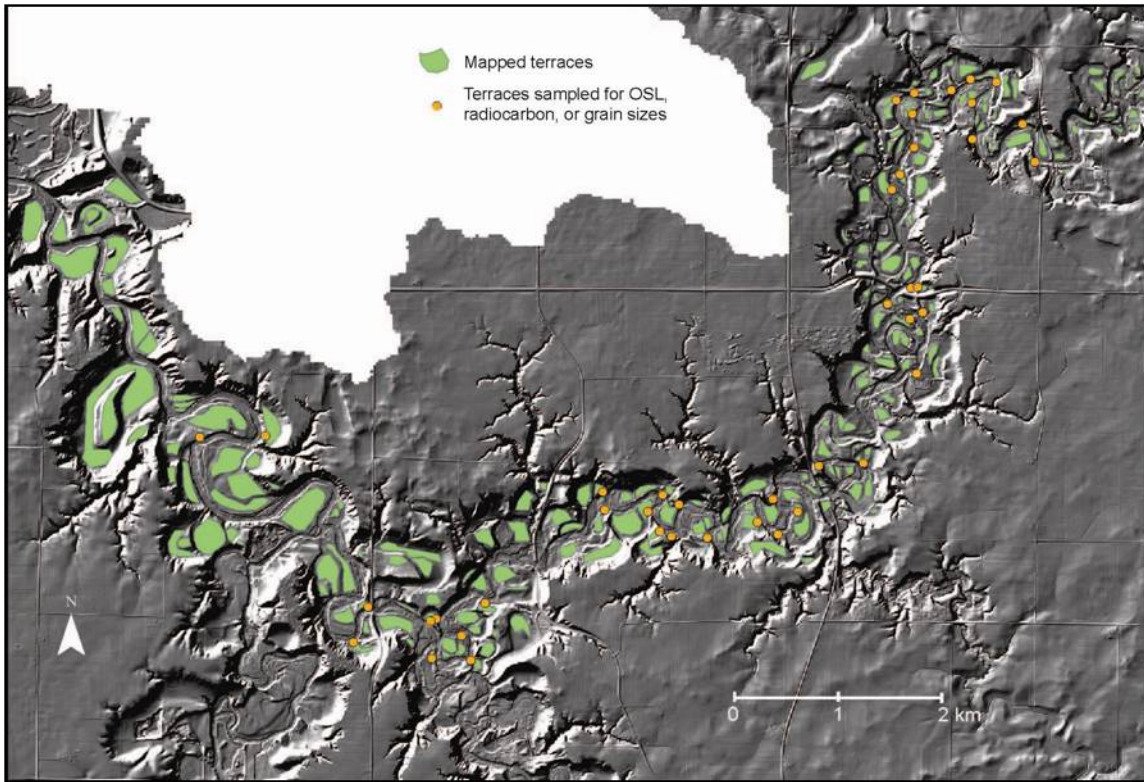


Figure 3-3. A sampling of mapped terraces for about 35 km of the Le Sueur River. The green shapes represent mapped terraces. The orange dots indicate locations that were sampled for OSL, radiocarbon, grain size distributions, or a combination of both methods.



Figure 3-4. Sample of bivalves and gastropods that were sampled for radiocarbon dating. Samples were collected in the channel deposit of the terrace (Figure 3-3).

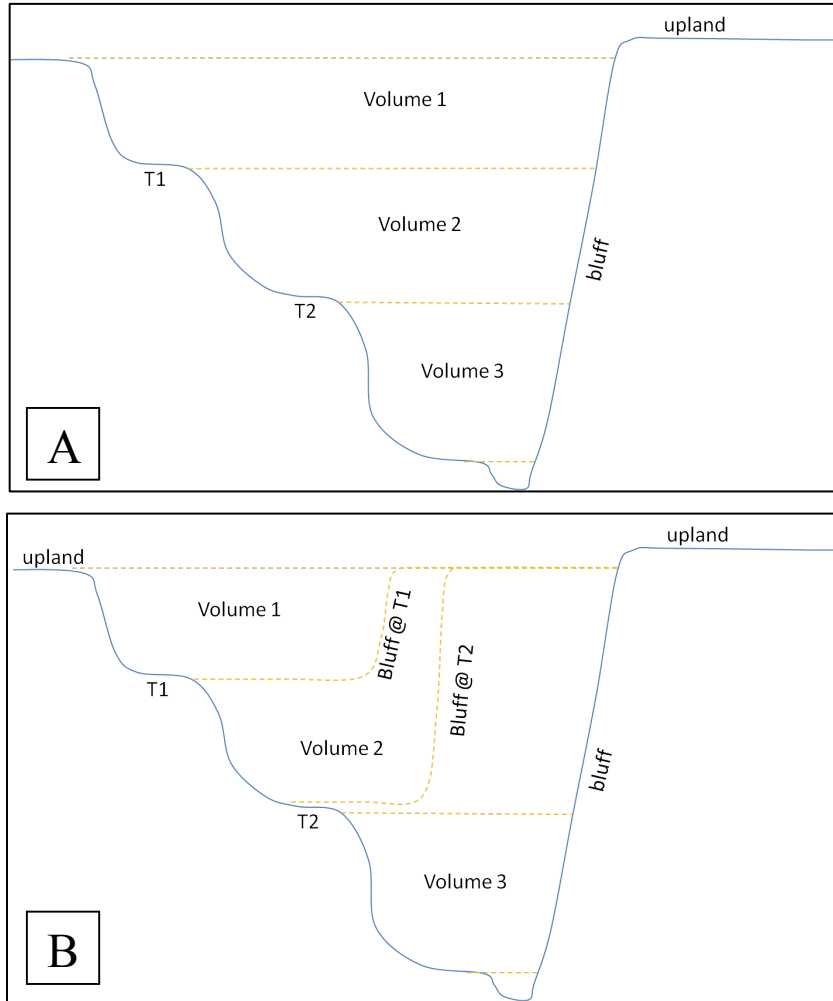


Figure 3-5. Illustration of volumes before (A) and after (B) width adjustments. A) The initial volumes were calculated based on the volume for each time period, with wider valley widths at the top. B) Volumes that have been width adjusted to account for valley widening through time by assuming that the modern floodplain was the same width throughout the entire time of valley incision and excavation and that changes in valley width occurred later by channel migration into tall bluffs.

4. Results

At present, 519 terraces have been mapped using airborne LiDAR. This number includes terraces both above and below the knick point for the mapped portion of Blue Earth County. Approximately 230 terraces were used for this study covering the lower 35 km of the LSR. Terraces in the Maple and Cobb Rivers are not discussed here.

Terrace heights range from 3 m to 34 m (± 3 m of elevations found on a given terrace surface) above the bed with an average height of 5.54 m (± 3 m). Figure 4-1 demonstrates the relationship between the mapped terraces and distance upstream. No distinct pairings of terraces are apparent, and the terraces primarily appear to represent a relatively continuous history of incision rather than periods of stability punctuated by periods of rapid incision (Figure 4-2). A gap is present between the upper surface and the highest terrace, as well as the highest collection of terraces and the group of terraces just below it in the downstream end of the valley.

Forty terraces were sampled for grain size data and analyzed by the Limnological Research Center at the University of Minnesota. Figure 4.3 shows the grain size distribution of terrace materials. The order of the colors from the furthestmost upstream to downstream is as follows: red, orange, green, blue, purple. There is not a distinct correlation between grain size distribution and terrace location. The uppermost reach of terraces (in red) does not differ greatly from terraces downstream. The purple terrace reaches may be slightly finer. Sediment competency of the terraces does not appear to change appreciably through time or location along the river.

Eighteen terraces were dated using a combination of OSL and radiocarbon techniques. The OSL and radiocarbon dates are presented in Table 4-1. Dated terraces range in a height from 2 m to 25.9 m with ages ranging from 1.54 cal kyr +/- 0.23 cal kyr to 13.04 cal kyr +/- 0.94 cal kyr respectively. The average age of the sampled terraces is 5.66 cal kyr. The OSL and radiocarbon dates are comparable as a result of the Le Sueur River being a part of a fresh-water system.

Table 4-1. OSL and Radiocarbon ages for sampled terraces.

Terrace name	Terrace Height (m)	Terrace elevation (m)	Sample Type	¹ OSL Age (cal kyr BP)	² Conventional Radiocarbon Age (rc kyr BP)	² Calibrated Radiocarbon Age (cal kyr BP)	³ Average Date (kyr BP)
C*	25.9	267.4	OSL	13.04±0.94			
Y	3.8	257.7	OSL	2.17±0.38			
X	9.8	264.2	OSL	3.3±0.49			
K*	13.86	288.6	OSL	5.01±0.44			
L*	15.21	290.3	OSL	6.35±0.48			
P	7.54	279.1	C ¹⁴		4.91±0.065	4.86±0.04	
R*	16.5	270.5	OSL, C ¹⁴	7.48±0.5	8.45±0.08	8.41±0.05	7.95±0.5
V [†] *	7.7	261.5	OSL, C ¹⁴	4.57±0.43	3.31±0.085	3.34±0.04	3.96±0.6
W [†]	5.83	270.8	OSL, C ¹⁴	4.02±0.86	2.34±0.02	2.34±0.02	3.18±0.8
Z	2.0	251.3	OSL	1.54±0.23			
LS-90-03	11.71	276.1	C ¹⁴		6.86±0.07	6.85±0.07	
LS-08-01	9.90	259.8	C ¹⁴		6.51±0.05	7.41±0.09	
LS-16-00	9.10	256.9	C ¹⁴		5.03±0.05	5.78±0.13	
LS-22-04	5.30	262.4	C ¹⁴		4.58±0.05	5.26±0.20	
LS-22-06	2.30	256.4	C ¹⁴		4.71±0.05	5.46±0.14	
LS-41-01	15.21	290.3	C ¹⁴		5.26±0.07	6.08±0.18	
LS-41-10	10.19	279.4	C ¹⁴		4.57±0.05	5.25±0.2	
LS-90-01	3.89	268.6	C ¹⁴		2.62±0.05	2.75±0.04	
LS-90-05	24.06	283.8	C ¹⁴		9.95±0.06	11.46±0.23	

¹ OSL = Optically stimulated luminescence ages

² Conventional and calibrated radiocarbon ages are reported with 2 sigma uncertainty.

³ Average between OSL and C¹⁴ ages.

* Terraces high potential for partial bleaching resulting in an overestimation in age.

† Terraces 'V' and 'W' had two units dated using the radiocarbon technique. The upper unit was used to assign a terrace age.

From the combined GIS analyses and dating results, the evolution of the Le Sueur River valley has been broken into 6 time periods: T₀, T₁, T₂, T₃, T₄, T₅. Using these time

periods, Figure 4-4 shows an estimation of where the LSR valley time horizons are located. From that estimate, valley profiles were created (Figure 4-5). The valley profiles demonstrate that there is a gap between the highest surface and the next one down, which is also apparent in the mapped terraces (Figure 4-1). Figure 4-5 also shows that the rollback of incision was more or less continuous.

To calculate volume removed through time, the late Pleistocene and Holocene were broken up into intervals of 1000 years. Once the initial volume was established, it was converted to volume of fines (silt and clay) by multiplying by a bulk density of 1800 kg/m³ (Thoma et al., 2005), and then by percent fines which was 65% (Gran et al., 2009). The resultant volume measurements ranged from 4.99x10⁶ to 1.39x10⁸ Mg of fines per 1000 years.

Unfortunately, the valley is now wide at the top and narrow at the bottom, but the width at the top has likely grown through time. In order to compare volumes of sediment removed through the entire 13,400 year time period, the volume data were width-corrected assuming a constant width through time. This is a reasonable assumption given that incision was likely continuous rather than punctuated in discrete events. The blue shows the data with width adjustments. The adjusted measurements ranged from 1.93x10⁷ to 4.58x10⁷ Mg of fines per 1000 years. The average annual rate for the LSR branch over the past 13,000 years is 3.81x10⁴ Mg/year of fines. Scaling up to include the Maple and the Cobb branches brings the average annual erosion rate up to 5.0x10⁴ Mg/year of fines.

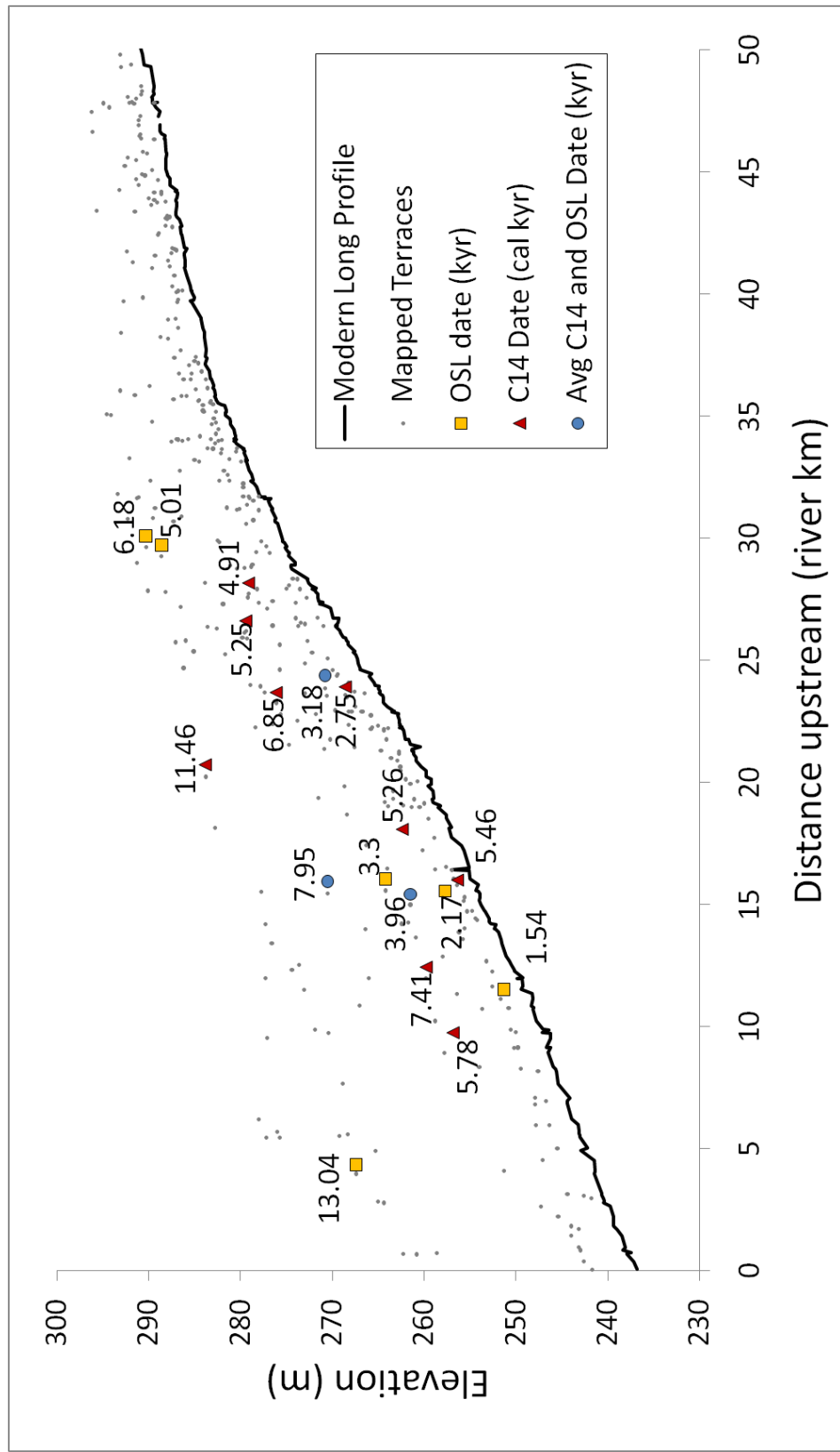


Figure 4-1. Terraces mapped from 1 m airborne LiDAR on the Le Sueur River. Dated terraces are noted in squares (OSL), triangles (C14) and circles (both). Uncertainties are given in Table 4-1. Long profile adapted from Belmont et al., 2011b.

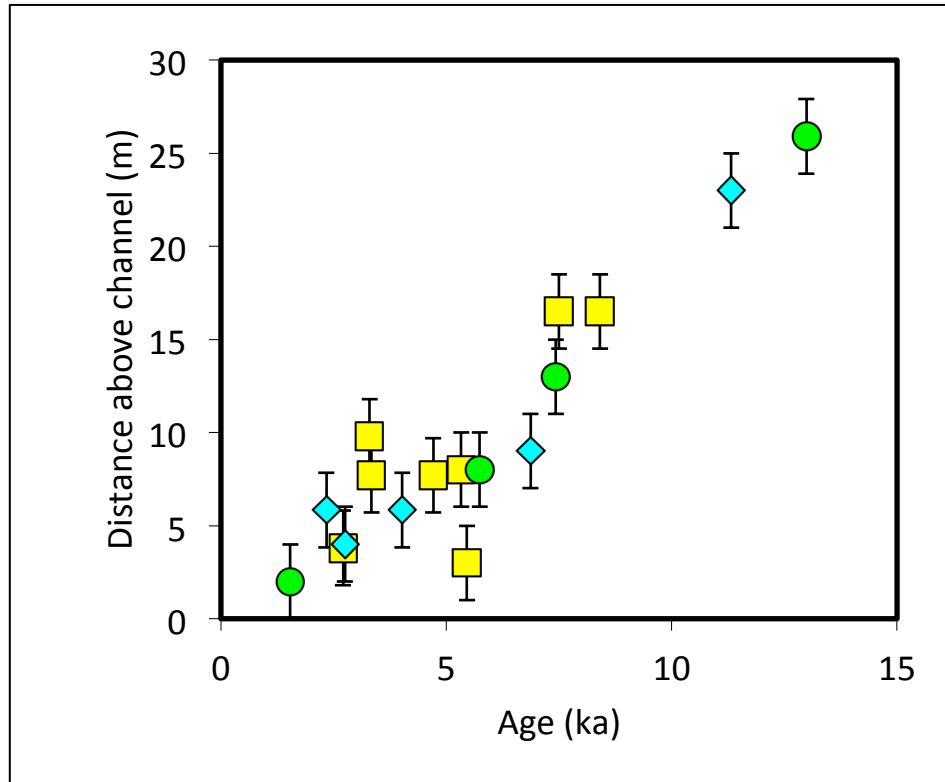


Figure 4-2. Terrace sets in three reaches along Le Sueur River, showing relatively linear increase in elevation above bed with age.

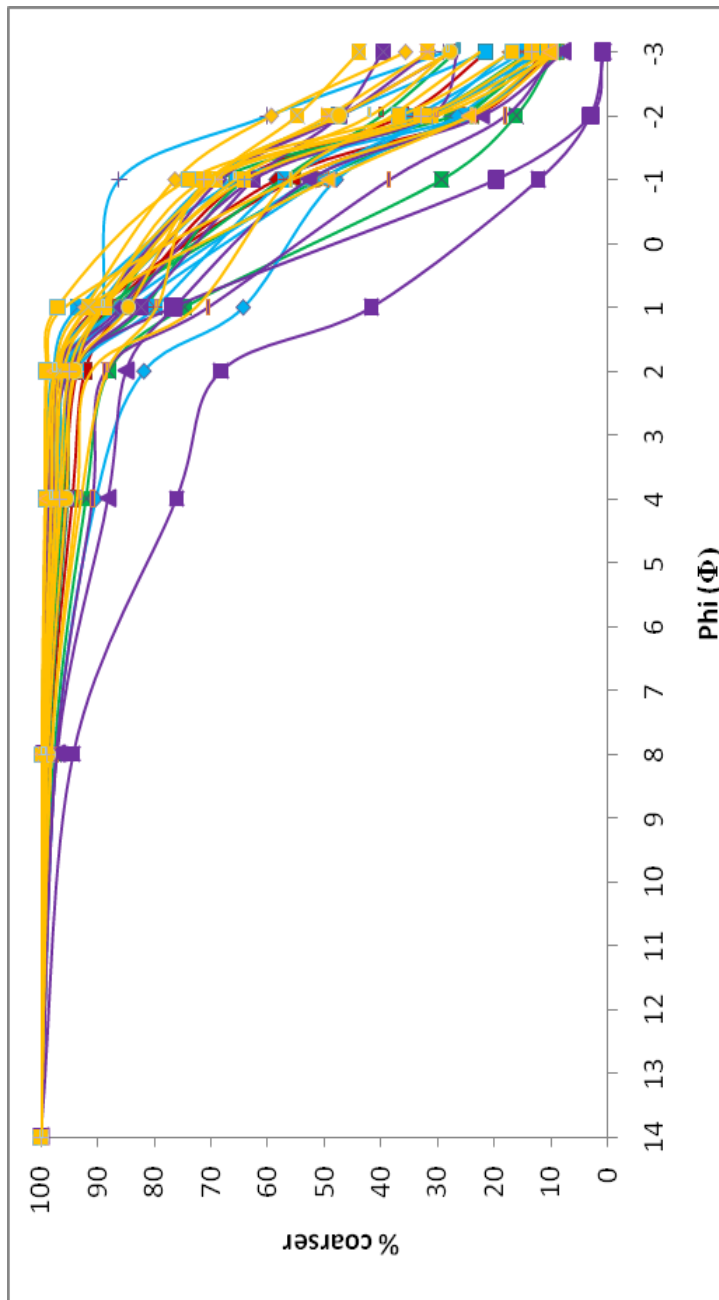


Figure 4-3. Grain Size distributions of 40 LSR terraces. The colors represent different stretches of the Le Sueur River. From upstream to downstream: red, orange, green, blue, purple.

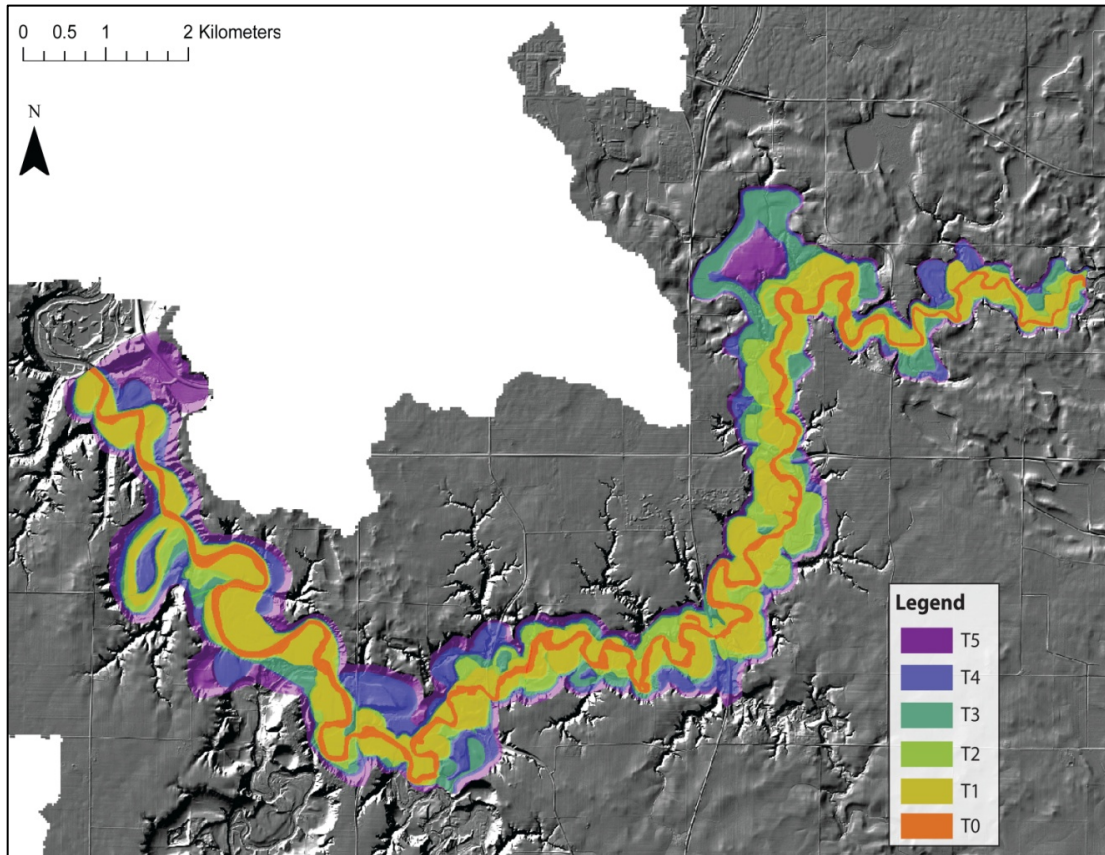


Figure 4-4. Schematic of valley time horizons for a 35 km stretch of river. T5 is the oldest, while T0 is the modern channel with floodplain.

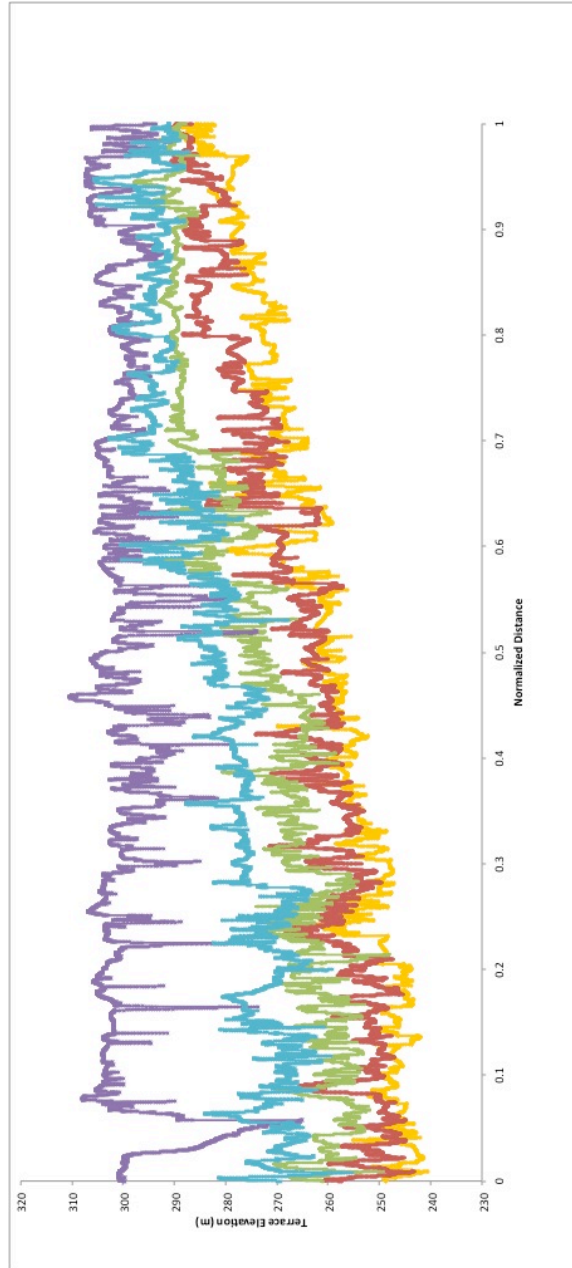


Figure 4-5 Profiles of the valley through time. Purple, blue, green, red, orange, represent different time frames in that order. Purple represents the upland surface, and the orange represents the floodplain. The jagged drops of the lines are where the valley crosses a ravine. The distance was normalized based on 30 km of river.

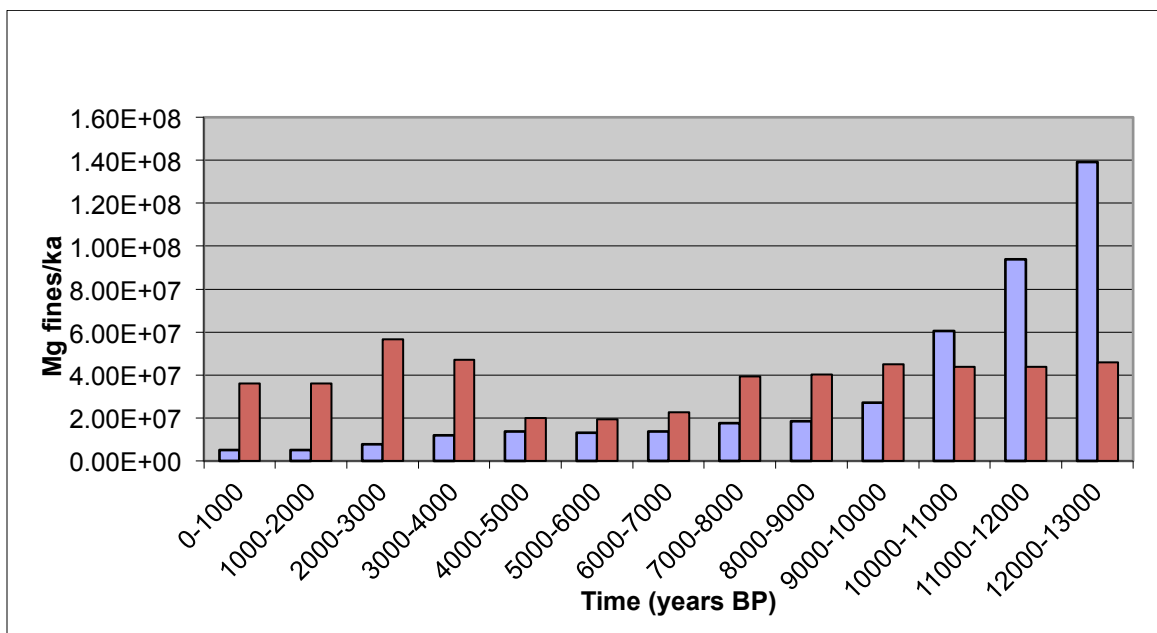


Figure 4-6. Volume of sediment (fines) excavated over 1000 year time intervals for the Le Sueur River Valley. Blue represents data without any adjustments to the valley. Red represents a width correction that was applied. The modern (2000-2010) average TSS load has been calculated at 225,000 Mg/yr (Gran et al., 2011a).

5. Discussion

The conceptual framework for the development of the LSR valley is dependent upon understanding the terraces of the watershed. The formation of the terraces gives insight to the factors that may have driven incision. Terraces were used to reconstruct the valley through time, determine volumes of sediment excavated within the valley, and develop an incision history. The combination of this information has implications for what the pre-settlement sediment loads were on the LSR. These pre-settlement loads can be compared to modern gauging efforts to see how land use changes in the watershed have affected erosion and sediment loading in the LSR.

Terraces of the LSR are unpaired strath terraces. LSR terrace formation was triggered by base level fall (allogenic factor), but individual terraces may have been the result of internal (autogenic) factors. The allogenic (external) factors that impacted the formation of terraces were changes in base level and climate. The LSR did undergo a large change in base level with the draining of glacial Lake Agassiz through glacial River Warren and the resulting knick point can still be seen in a long profile view (Figure 2-5). This base level fall triggered the incision that has formed the terraces. Climate influences are present within this basin as well with a significant climate excursion during the mid-Holocene dry period. The volumes removed through time do seem to dip in this time period though it is hard to make a direct correlation between climate and terrace formation and/or valley excavation. The climatic factors that may drive terrace formation would typically be seen in paired terraces, which are not observed in the LSR basin.

Tectonic uplift, a major allogenic factor in many basins, can be ruled out. The LSR is not in a tectonically active area. Isostatic rebound from intense glacial periods could be considered similar to tectonic uplift and may have some small effect. However, the thickness of the ice and the size of glacial Lake Minnesota within this area were minimal compared to other parts of the state, and the basin lacks paired terraces.

The scattered nature of the terraces points more towards autogenic controls on the formation of the LSR valley. The likely candidates include meander migration and cut-offs, which can be seen in the LiDAR. The meandering and incision of the LSR produced enough sediment that the river experienced lateral migration and down-cutting, which is the most likely cause for the creation of strath terraces. Finnegan and Dietrich (2011) modeled flights of unpaired strath terraces numerically and found that the formation was largely driven by the internal meandering and incising of the river. This may be a good model for incision of the LSR, and recent modeling efforts by Finnegan (summarized in Gran et al., 2011b) indicate that the LSR is best modeled as a meandering bedrock channel.

The lateral migration and down cutting seem to suggest that this basin has an incision history that is continuous and still incising today. Figure 4-2 shows that when there are series of stacked tills in one location, the incision is fairly continuous. The easily erodible nature of the tills allows for lateral migration to take place. The rates of high bluff erosion that have been measured at between 15-20 cm/yr (Day, et al., in review a,b) are further evidence that lateral migration is an on-going process.

Two places that do not necessarily support the idea of continuous incision are apparent in Fig. 4-1. There is a ~35 m gap between the upland surface and the highest terrace. There is also an area between the highest flight of terraces and the terraces below it that appears to be missing preserved terraces. Instead of continuous incision throughout, these gaps may suggest that the incision rate was faster earlier on in the basin's history and then became more continuous as time progressed. During times of rapid incision, vertical incision rates far exceed lateral plantation rates, and strath terraces are not likely to form.

The gap between the upland surface and the highest terrace may be related to the initial change in base level. Prior to the draining of glacial Lake Agassiz, glacial Lake Minnesota drained, and a knick point could have easily cut through the softer lake sediments before being hindered by the till. This may have triggered an initial wave of incision within the basin in which no terraces were preserved.

Another gap can be seen between the highest flight of terraces and the next terraces down, visible only in the most downstream part of the river valley. This gap is most likely linked to a stream capture event. Following the base level fall of the Minnesota River, 13,400 cal. BP, the LSR drained directly into the Minnesota River. This is evident in a paleochannel that is seen in LiDAR. Fluvial sediments within the paleochannel dated using OSL indicate that the mean depositional age was 10,300 yr BP (Meixell et al., 2009; Belmont et al., 2011b). It is suggested that the Blue Earth River, which is just east of the LSR watershed, captured the river after 10,300 yr BP. This

timing corresponds with the described gap. The capture event may have increased the incision until it became adjusted with the existing long profile.

Despite the two gaps, continuous incision is a reasonable model for most of the valley and was the basis for the construction of the age models to help determine volumes of sediment removed. The non-width and width-corrected volumes resulted in vastly different interpretations. The non-width corrected data would suggest that the active floodplain is narrowing through time, which is just not the case. The width-corrected data fits better with the continuous incision and meandering history of the basin.

The volumes that were calculated do not appear to fit with either of the experimental or numerical models described in the background section. This drainage system is not well integrated, meaning that it is a young system, therefore, it is unlikely that it has reached a steady-state condition that Hasbargen and Paola (2000) reached in their experimental model. Parker (1977) and Hancock and Willgoose's (2002) models also do not fit this system. There is not an increase in volume excavated followed by a collapse.

The modeling that Finnegan and Dietrich (2011) did on strath terraces was based on a bedrock channel. Despite the LSR incising through till, this system should be thought of as a bedrock system. Recent numerical modeling efforts by Finnegan et al. (2010), demonstrates a replication of the modern long profile which best matches the terrace ages requires the system to be modeled as a bedrock system with downstream coarsening as seen on the Le Sueur River (Belmont et al., 2011b).

The data in this study and the recent numerical modeling demonstrate a steady sediment load due to the continuous incision. With this assumption, the most reasonable estimate for pre-settlement sediment loading is the Holocene average load. This has been calculated for the Le Sueur, Maple, and Cobb Rivers combined as 50,000 Mg/yr of fines (Gran et al., 2011a,b). The 2000-2010 average sediment load at near the mouth of the LSR (also including the Le Sueur, Maple, and Cobb) is 225,000 Mg/yr (Gran et al., 2011a), which is approximately 4-5 times greater than the average Holocene erosion rate of fines. The Lake Pepin data suggests a ten times increase in deposition, which does not agree with the 4-5 times greater increase in sediment load. Erosion in the LSR valley has increased, but there is not enough of an increase to drive the entire observed depositional increase in Lake Pepin.

6. Conclusion

The LSR valley is a relatively young system that shows not only a unique geomorphic signature in response to a change in base level, but also demonstrates a response to anthropogenic changes to the basin. Strath terraces of the LSR basin have recorded the histories of the basin's adjustment to the change in base level. This creates an opportunity for a conceptual idea of the pre-settlement sediment load. The LSR has experienced a fairly consistent pre-settlement load from valley excavation through time. However, the results demonstrate that the basin is currently carrying a sediment load 4-5 times greater than the pre-settlement load. This suggests that anthropogenic influences have impacted this basin and should be addressed when determining best management practices. The human changes on the hydrology of the system, which appears to be a significant factor within this basin, should be taken into consideration (Belmont et al, 2011a).

Further studies should focus on the other rivers of this basin, the Maple and the Cobb, to determine if a similar pattern of constant sediment loads over time exist, as well as an increase in sediment load post-settlement. On a large basin scale approach, it would be interesting to look at other tributaries of the Minnesota River basin. The histories of these rivers may provide further clues towards basin evolution of a system influenced greatly by changes in base level.

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