Little Fork River Channel Stability and Geomorphic Assessment

Final Report

Submitted to the MPCA

Impaired Waters and Stormwater Program

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Introduction

The Little Fork River heads in the Vermillion Range, flowing north to the Rainy River. The 1843 mi^2 watershed consists primarily of forest and wetlands and is sparsely populated. The first stands of timber were logged from the 1890s through 1937, including log drives on the mainstem channel up until 1937. Logging continues to the present, representing the primary industry in the area.

In 2002, water quality measurements at the Minnesota Pollution Control Agency (MPCA) monitoring site in Pelland showed turbidity values exceeding water quality standards. Further study on the channel was initiated to determine the scope and severity of the turbidity problem (Anderson et al., 2006). This study indicated that high turbidity was widespread on the Little Fork River, extending at least 142 RM (river miles) upstream from the Rainy River. The high turbidity is predominantly suspended sediment.

Anderson et al.'s (2006) analysis of historic stream gage records indicates systematic changes in the 1.5-year discharge event independent of climate over the past 80 years. These trends are inferred to be the result of land use changes from historic logging that increased the 1.5-year flood flow. Since the end of the first wave of logging, the 1.5-year flow discharge has stabilized and subsequently decreased, but the heightened discharge of flood events from the early 1900s may have destabilized the channel, leading to the current high turbidity levels. Historic log drives may have enhanced channel disturbances. Based on the weight of evidence, the MPCA has attributed current high suspended sediment loads to the effects of historic logging leading to channel disturbance and long-term channel adjustment.

The Minnesota Pollution Control Agency (MPCA, Client) has requested this geomorphic study of the Little Fork River Watershed to: (1) support the weight of evidence that the history of logging was the mechanism responsible for the streams impairment; (2) determine the causes of the river's present day instability (vertical degradation of the river channel, and or aggradation of the floodplain).

Objectives:

This project was comprised of six main objectives designed to develop a better understanding of the geomorphology of the Little Fork River and its watershed and how historic changes in land use may have affected the hydrology and processes within the basin. These objectives were

1) Establish a geomorphic classification for the Little Fork River watershed
2) Analyze historic landscape changes
3) Study near-channel floodplain/terrace surfaces to determine if they are still hydraulically connected to the mainstem channel
4) Determine if a wave of sediment was released and deposited onto the floodplain during historic land clearing
5) Assess historic changes in the mid-channel island at the confluence with the Rainy River
6) Analyze historic gaging records to look for bankfull flow discharges and depths, and how they relate to near-channel terrace/floodplain elevations

Each objective was written up in a stand-alone technical memo, compiled here as chapters. These are followed by a summary of the entire report.

Background

Geomorphic history of Little Fork watershed:

The Little Fork River flows north to the Rainy River, draining 1843 mi^2. It originates in the Vermillion Iron Range, flows through gently rolling uplands, and ends in part of the Glacial Lake Agassiz plain. Basin relief is minimal, from a maximum elevation of 1867 ft on the range to 1076 ft at the mouth of the Little Fork River. From the mouth of the Sturgeon River at RM 111 to the confluence with the Rainy River, the average gradient is 0.00027. Much of the elevation drop occurs in bedrock knickpoints, rapids and waterfalls, with very low gradient reaches in between.

The geomorphic history of the Little Fork River valley is inextricably linked to the post-glacial history of the area. Following the last glacial retreat through the area, between 11.1 – 11.4 ka BP (before present) (Thorleifson 1996; Elson 1967), much of the lower Little Fork River basin was covered by Glacial Lake Agassiz. This lake extended across much of central Canada with the southern end extending into northern and western Minnesota. The maximum extent of the lake has been mapped by Teller et al. (1983) as extending into the central portion of the Little Fork River basin, potentially reaching as far south as the confluence with the Sturgeon River. Surficial geology maps show lake clays and silts either from Lake Agassiz or other glacial lakes extending halfway up the Sturgeon River subwatershed and covering most of the upper Little Fork River subwatershed near Cook (Helgeson et al., 1976). Glacial Lake Agassiz's legacy to the area includes heavy clay deposits found along much of the mainstem channel below more recent fluvial sediments. These clays were reached in several of the cores collected for this project. Lake Agassiz did not occupy the Little Fork basin for long. A compilation study by Thorleifson (1996) indicates that Lake Agassiz likely retreated from the Little Fork basin by 10.9 ka BP, although the downstream end may have been reoccupied by the southern end of the lake at 9.9 ka BP. Additional studies show that Lake of the Woods to the west was completely isolated from the retreating Lake Agassiz by 9 ka BP (Yang and Teller, 2005).

Beach lines from Lake Agassiz provide a useful measure of differential post-glacial rebound of the land surface across northern Minnesota and southern Ontario (Teller et al., 1983). Post-glacial rebound is highest in the northeast, diminishing towards the southwest. In the Little Fork River basin, estimates of post-glacial rebound from the differential uplift of the lower Campbell beach line are approximately 50 m at the mouth of the basin, diminishing to 34 m in the headwaters using isobases 5 to 4.25 (Yang and Teller, 2005; Teller et al., 1983). Most of this uplift occurred early in the Holocene. Uplift rates in the last 1000 years have slowed to approximately 0.59 mm/yr in the south and 0.87 mm/yr in the north, a differential of only 0.28 mm/yr (Yang and Teller, 2005). Although this is small differential, it is causing regional lakes to tilt slowly to the southwest, inundating southern shorelines. Lake gage records on the Lake of the Woods, at the end of the Rainy River, indicate current relative vertical changes of 1 mm/yr from north to south (Tackman et al., 1999).

The effects of these post-glacial regional events on the Little Fork River may be subtle in comparison to more recent anthropogenic effects, but they are still a piece of the geomorphic history of the basin. In particular, the differential uplift in the Little Fork

River could lead to more incision in the lower half of the basin and a general reduction in basin slope through time. The current slope between the Sturgeon River confluence at RM 111 and the confluence with the Rainy is 0.00027. Without the ~ 8 meters of differential uplift (about half of the estimated 16 meters throughout the entire basin), the slope of the channel would have been 0.00032, an increase of 18%. The continued shift of Lake of the Woods towards the south could cause levels in the Rainy River to rise slightly through time, although this would only affect the Little Fork River if it was close enough to Lake of the Woods to feel the backwater effects from that confluence.

Geomorphic processes:

The lower half of the Little Fork River is underlain by glacial lake clays which can affect slope and bank stability in the area. Much of the fluvial sediment is composed of fine sand, silt, and clay, generating cohesive banks. Here we review some of the dynamics that lead to slope and bank failures in cohesive channels with reference to incised channels.

In the Little Fork River, two primary observations can be made about the channel along much of its length downstream of Hannine Falls. First, the channel appears to be entrenched into its paleofloodplain. Second, slope and bank failures are apparent throughout the system. Many of the banks are vegetated with grasses, with trees more prevalent farther up the slope. Bank slopes are convex upwards but steep, often with vertical cutbanks near the water's edge (see Figure 0.1). Bank erosion happens both through erosion of individual grains near the toe of the bank as well as though large block failures that result as the bank oversteepens or is undercut. These larger failures include slumps and rotational failures that extend up the entire valley slope as well as localized bank failures (see Figure 0.1, 0.2).

Figure 0.1: Photo showing the convex upwards banks with cutbanks near the water surface. This photo was taken during low flow at the Bois Forte site (RM 88), looking downstream.

Figure 0.2: Large rotational failures and slumps extending up to the top of the slope break on the outside of a bend.

Bank failures can be described as planar or rotational. Planar fractures and failures are more common but less disruptive to the overall slope in terms of loss of land. Rotational failures tend to occur along only the highest banks (Simon et al., 2000). Planar failures along the bank can occur along any critical failure plane and include slab failures from fluvial undercutting of the bank and pop-out failures along the base of the bank due to excess pore-water pressures (Simon et al., 2000). Failures are more likely to occur on the recessional limb of a flood event as saturated banks lose the confining pressure from elevated flood waters (Simon and Hupp 1987; Thorne 1990; Simon et al., 2000).

The top of the glacial lake clays that underlie much of the mainstem Little Fork River could provide a ready critical failure plane as infiltrating groundwater pools on the surface of low permeability clays. This mechanism for generating bank and slope failures has been recognized in other parts of the Glacial Lake Agassiz basin. The Red River of the North has experienced numerous rotational and planar failures in areas where the channel cuts through glacial lake clays, particularly where the river cuts through the competent Sherack Formation overlying the more deformable Huot or Brenna Formations (Harris, 2003). By incising a river valley through these cohesive sediments, lateral confining pressures are reduced, leading to slumping towards the river. Roads and buildings overlying the area exacerbate the problem by increasing the vertical load. This may be what is happening near the Silverdale Bridge and on County Road 77 on the left bank where the road comes close to the channel and slumping is common.

The occurrence of numerous bank and slope failures generally indicates an on-going instability or adjustment in the system (Simon et al., 2000). A theoretical model for channel evolution in an incised system has been developed by the U.S. Geological Survey that may be applicable to the Little Fork River system (Simon, 1989) (see Figure 0.3). The system starts in its premodified condition (Stage I). Due to imposed disturbance to the system (Stage II) (channelization, urbanization, increased peak flows, etc.), the channel incises (Stage III). Degradation leads to high, unstable banks which collapse, widening the channel (Stage IV). As banks fail, widening continues. Meanwhile, the increased sediment load leads to aggradation in the channel bottom (Stage V). Eventually, a new equilibrium condition is reached with newly constructed bankfull benches set within the old floodplain, now stranded as a terrace (Stage VI).

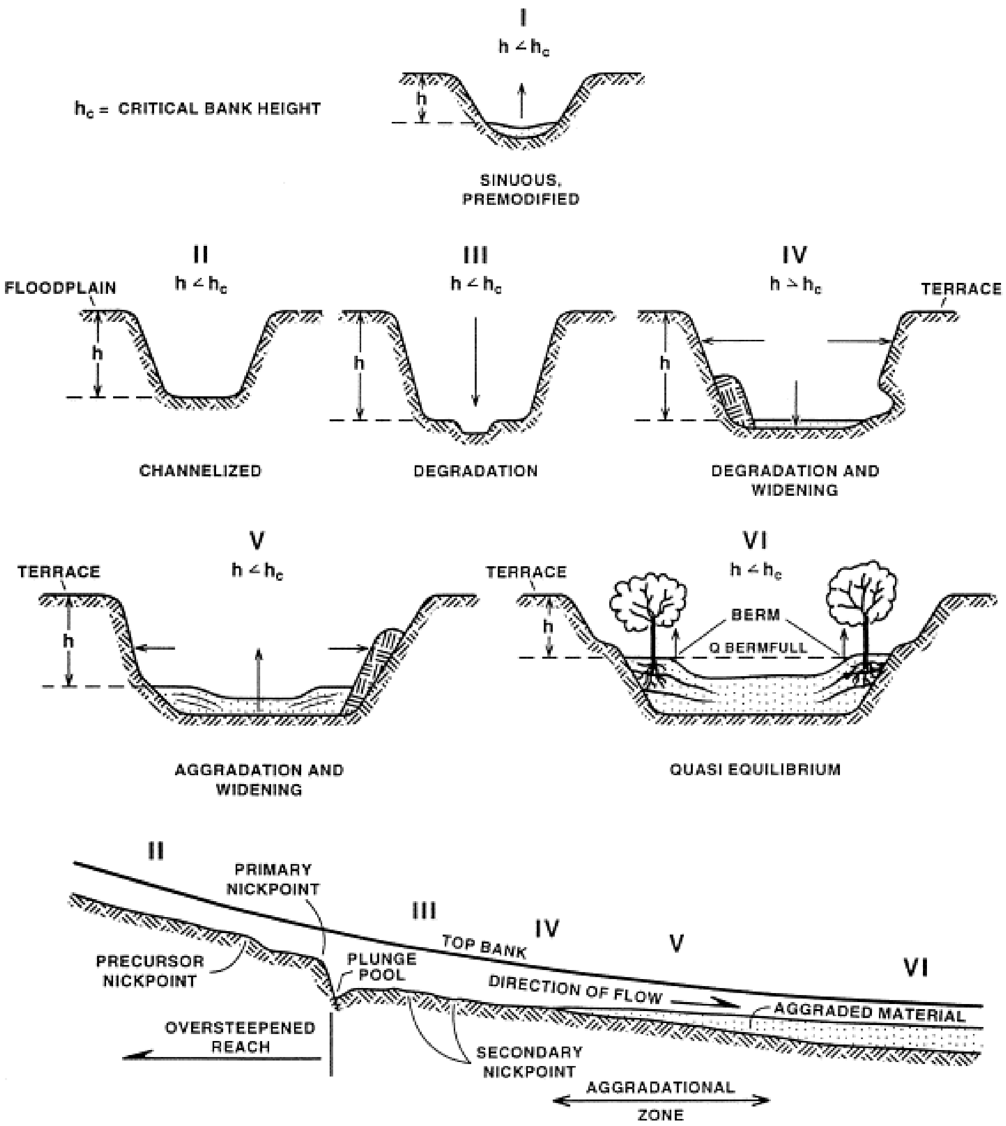

Figure 0.3: Simon's channel evolution model. (From Doyle and Shields (2000))

This model is designed to track channel evolution at a single location through time or at a single time throughout the length of the channel. If a knickpoint is migrating upstream leading to degradation, then the lower reaches of the channel will have the knickpoint pass through them first, starting the degradation, widening, and aggradation cycle. Thus it is possible to have the upper reaches of a basin undisturbed, degrading reaches downstream of the primary knickpoint, and aggrading reaches in the lowermost portion of the basin all at the same time.

On the Little Fork River, we saw evidence of degradation-induced bank collapse and failure leading to channel widening. Waves of incision are propagating up tributary channels and ravines. In parts of the channel, collapsed slump blocks are being reworked into a bankfull bench at a new level set into the former floodplain. Unlike Simon's model, however, these observations are not set up in a smooth pattern from upstream to downstream. Because of bedrock control along the channel, numerous knickpoints may have propagated up the mainstem, creating different amounts of incision, bound by bedrock grade control on either end. The uppermost part of the basin, above Hannine Falls (RM 121), does appear to still be accessing the floodplain and is basically still in Stage I. Downstream near the confluence with the Sturgeon River (RM 111), the channel appears to have already built a bankfull bench on failed slump blocks, which would equate with Stage VI. However, further downstream, from RM 111 to 87 the channel reaches its most incised portion, with numerous bank failures, perhaps representing Stage IV. Although the evolution model is a useful way to look at future trajectories of individual reaches, it does not appear to represent the Little Fork River system longitudinally, perhaps due to the complexity of local base level controls.

Ice dynamics & log drives:

Two additional features of the Little Fork River that may contribute to channel and bank erosion and deposition are ice jams and log drives. While the scientific literature is fairly rich with studies of the effects of ice jams on channel hydrology, studies of the geomorphic effects on channels are sparse. Ice jams can increase the stage of a river rapidly without an increase in discharge, inundating floodplain and terrace surfaces. Ice flows can have damaging effects on exposed vegetation, scouring trunks and removing vulnerable trees. Ice and ice jams may also affect on channel morphology. Smith and Pearce (2002) found bowl-shaped scour holes on floodplains associated with turbulence around grounded ice blocks. They also attribute gullying on the downstream end of tight meander bends to ice jams leading to flow rerouting across the neck of the meander. The gullies form as the flow re-enters the channel. Earlier work by Smith (1979) investigated the role of ice jams on channel enlargement.

Many of the effects of log drives and log jams on channel geomorphology mirror the effects of ice and ice jams, especially in the Little Fork River where log drives were timed to coincide with the spring break-up and thaw. Logs would be piled up on the ice awaiting the thaw and then catch a ride downstream as the ice broke up (Polllard, 1975; MN Historical Society, 2002). Logs were also piled in rollways adjacent to the channels which were then released into the flow under optimal discharge conditions (Pollard, 1975). The addition of logs to a system already affected heavily by ice during the spring break-up may not affect the geomorphology of the channel in a substantial way. Logs and ice would have similar effects on vegetation, leading to scarring or removal of exposed trees. Logs did get caught in banks, to be pried out by crews after the spring flood ended, and this could increase erosion on those banks. Log impacts on banks are most likely to occur on the downstream end of bends, where velocities are highest and the flow changes direction sharply. Rollways can also disturb the banks, especially if vegetation was removed in order to clear a path to the channel (Adams, 2006). Often, log drives use splash dams to increase peak discharges, and these can really alter the hydrology of the system and thus lead to incision or widening, but this was likely not done on the Little Fork River. River "cleaning" or the removal of snags, boulders, etc. may have been done to some degree, but this may be less important geomorphically on a large river like the Little Fork than on a smaller river.

Overall, log drives can have devastating effects on some channels, especially if splash dams are used to greatly increase peak flows, and channels are cleared of debris, rocks, and other features that may impede flow. The increased discharge can widen or incise the channel, and clearing can have lasting effects on the channel and its biota. On the Little Fork River, however, log drives were likely not a dominant control on channel geomorphology. Log drives coincided with ice break-up and normal spring floods, and logs and ice may have had similar effects on bank and vegetation scour and on rapid changes in stage during jams. Likely the change in hydrology associated with large-scale clearing of forest cover in the uplands had a greater impact on the channels than did the log drives.

Chapter 1
Geomorphic Classification of the Little Fork River Watershed

Objectives:

Understanding the broader geomorphic context of the Little Fork River and its watershed should help focus management efforts where they are needed and where they have the best chance of succeeding. To better understand the geomorphic context, it helps to break the watershed and the river down into sections with similar characteristics leading to similar patterns of erosion and deposition. The main objective of chapter 1 was to create a broad geomorphic classification of the Little Fork River using existing GIS coverages, air photos, topographic data, and locations of incised vs. aggraded channel sections. Spatial analyses of these data were coupled with in-field observations and a flyover of the channel to develop a geomorphic classification of the mainstem Little Fork River.

Summary of Findings:

The river was partitioned into six sections, based on observations from air photos, a fly-over, and topographic characteristics. These subdivisions overlap with previous subdivisions by Anderson et al. (2006), with further breakdown in the central portion of the watershed. Section I encompasses the area above Hannine Falls at rivermile (RM) 121. Below Hannine Falls (Section II), the channel becomes entrenched. Below the Sturgeon River confluence at RM 111 (Section III), the valley and river are tightly coupled, and the potential for erosion due to mainstem incision or widening are greatest. Downstream of RM 87 (Section IV), the valley widens, providing room for channel migration. The valley further widens in Section V (RM 59), and valley widths and channel sinuosity reach their peak. Section VI covers the channel downstream of the city of Littlefork (RM 20), where the Little Fork River is affected by backwater effects from the Rainy River.

Methods:

A geomorphic classification of the mainstem Little Fork River was accomplished through a combination of spatial analyses of existing topographic datasets and aerial photography in a GIS framework, observations from the ground at select points along the mainstem channel, and a flyover of the mainstem channel in Fall 2006.

The initial classification is based partly on a previous classification by Anderson et al. (2006), separating the mainstem into three zones based on channel and valley conditions. These three subdivisions were A) upstream of Hannine Falls (RM 121), B) from Hannine Falls downstream to the town of Littlefork (RM 20), and C) downstream of the town of Littlefork to the confluence with the Rainy River. The initial split at Hannine Falls separates the entrenched lower basin from the upper basin. The split at Littlefork separates the stretch of channel subjected to backwater effects from the Rainy River from the unaffected middle section. The upper and lower sections are maintained, and the middle portion of the channel (RM 20 to RM 121) is subdivided into four different subsections, described in more detail in the next section.

Mainstem subdivisions are based on both spatial analyses and observations. The observations come from ground observations at accessible sites along the mainstem channel and a low-altitude flyover in Fall 2006. During the flyover, features such as the presence or absence of depositional features like sandbars and the degree and style of bank erosion as visible from the air were noted.

Spatial datasets used in the classification include a 30-m resolution digital elevation model (DEM), a 30-m resolution land use/land cover map derived from 1995-96 Landsat Thematic Mapper imagery, a 1:100K surficial geology/geomorphology map, 1:100K hydrology datasets, major watersheds as defined by the U.S. Geological Survey hydrologic unit codes, and color aerial photographs from 2003 from the Farm Services Administration. All of these files were obtained from the Minnesota DNR Data Deli website (http://deli.dnr.state.mn.us), and further documentation can be obtained there. A list of spatial datasets used is located in Appendix A.

Aerial photographs from 2003 were used to digitize channel edges along the mainstem channel. These features were digitized from RM 0 to RM 117 by L. Engel, and extended to RM 124 by K. Gran. The DEM was used to derive a slope map, used in conjunction with the DEM to map out the extent of the valley bottom along the mainstem channel. The valley edge was delineated by the presence of steep slopes. In the lower third of the basin, there were a number of places where no obvious steep embankment existed and the valley side slope away from the channel was more gradual. These locations were addressed on a case-by-case basis, looking to other information like aerial photographs for evidence of floodplain features (like scroll bars). Because of the entrenched nature of the mainstem, some places had short steep embankements along the channel coupled with clear fluvial landforms adjacent to the channel with a second slope break at a greater distance. These fluvial landforms are relict, having formed under an older hydrologic regime. Because of these complexities, I have less certainty about the location of the mapped valley wall in the lower third of the basin. Overall trends in channel and valley characteristics should still hold.

Quality control issues arise in overlaying datasets generated from the 30-m DEM with those generated from the 1-m resolution 2003 aerial photographs. In particular, the DEM appears to be offset 1-2 pixels from the aerial photograph. Thus, the channel banks digitized off of the aerial photographs do not always align perfectly with the valley as digitized off of the 30-meter DEM, particularly in places where the valley abuts the channel walls. Once again, trends in valley and channel widths and proximities should still hold.

River miles were digitized by hand from the DNR canoe map to maintain consistency with other publications. Subwatersheds for each section were based primarily on the Minnesota hydrologic units database, with slight adjustments to subdivide the basins based on the new mainstem classification scheme. There were two places requiring a new watershed boundary (upstream of RM 121 and upstream of RM 87), and these were digitized by hand using the DEM for topography.

At each river mile, I calculated the distance to both the right bank and left side of the channel and the valley wall, using the NEAR command. Summing these two values gives a measure of the channel width and the valley width. However, given the use of the NEAR command, the widths reported are not necessarily straight-line distances from bank to bank or wall to wall (they may change direction from one side to another). In addition, given the highly sinuous nature of both the channel and the valley, there may be instances where the nearest valley wall is not perpendicular to the channel at that point.

The data are still presented to show variations throughout the basin in channel width, valley width, and channel to valley width ratios. Once again, the trends are still significant, even though individual values may have discrepencies. Channel widths are based on banks digitized by hand off of 1-m resolution aerial photographs. Uncertainty in the width measurements are ~5-10 m. The valley widths come from valley bottom edges digitized from 30-m resolution slope maps and DEMs. Uncertainties in the valley bottom measurements range from 60 - 120 m (2-4 pixels) in the upper basin. In several reaches of the lower basin, where valley walls were less apparent, the error on individual measurements could be much higher. No field checking was done of these measurements for this report.

Sinuosity was calculated for each mainstem subdivision. Sinuosity is a ratio of channel length to valley length over a given length of stream. It is highly sensitive to the distance over which it is calculated. I digitized in a mid-valley line, with points spaced approximately every 100 - 250 m. The channel distance for each mainstem subdivision was compared to the valley distance using this derived route. The results must be interpreted carefully, because the valley is highly sinuous (thus a channel:valley ratio of 1 indicates that the channel and valley follow the same path rather than indicating that the channel is “straight”). A low sinuosity indicates that the channel and valley curve together, and a higher sinuosity indicates that the channel migrates more freely within the valley. If a “straight-line” approach is taken for the entire channel system, tracking the mainstem channel over distances of 5-10 km, the overall sinuosity for the lower 124 RM is 2.

In addition to the derived slope map, DEMs were also used to determine the erosion index throughout the basin. The erosion index (EI) is a unit stream power-based measure of fluvial erosion potential often used to model in-channel bedrock incision rates (e.g. Whipple and Tucker, 1999). Unit stream power is the product of the unit weight of water (density (ρ) times gravity (g)), slope (S) and unit discharge (total discharge (Q) divided by the channel width (w)). Thus, erosion potential (E) as a function of unit stream power can be expressed as

$$E \propto \rho g (Q / w) S$$

Because channel width varies as a function of discharge, $w = c_1 Q^b$, and discharge varies as a function of area (A), $Q = c_2 A$, the above equation can be rewritten in terms of drainage area:

$$EI = K A^{(1-b)} S$$

K incorporates the above coefficients as well as the effects of varying bedrock and substrate erodibility. The value of b is still debated, but many landscape evolution models use $b = 0.5$ (e.g. Rodriguez-Iturbe and Rinaldo, 1997).

Essentially, the EI gives an indicator of the sensitive areas of the basin that hold the greatest chance of fluvial erosion. It is common for mainstem channels to have high EI values, because discharge and upstream area are greatest there. Deviations from this can be significant, as they may indicate hot spots of erosion. An EI map was created for the Little Fork River watershed, using *b* = 0.5, and upstream drainage areas and local slopes computed off of the 30-m DEM. The EI was calculated for the entire drainage basin, although it is only applicable to areas eroding primarily through concentrated flow (not hillslope erosion).

Results:

The Little Fork River starts in the bedrock uplands, enters an entrenched zone around RM 121, passes through a constrained valley below the Sturgeon River confluence, then widens downstream, starting around RM 87 (Table 1.1). Valley widening continues through the town of Littlefork, after which the river enters a depositional zone due to backwater influences from the Rainy River. In this downstream reach, the channel widens and the slope drops considerably (Table 1.1, 1.2). In terms of bank and channel erosion, the middle portion of the river downstream of the Sturgeon River (Section III) is likely the most sensitive portion of the basin to changes in channel width or bed elevation. The channel and valley are so tightly coupled that there is very little room for the channel to move laterally without eroding into the valley wall. Any erosion of the valley sides or channel incision in this reach will propagate rapidly up gullies and tributaries. There is little floodplain or valley bottom to buffer the effects of channel incision, widening, or migration. Once the valley bottom opens up, the channel is able to migrate more freely, widen, or incise, without as much effect on tributaries and gullies.

Anderson et al. (2006) classified the channel into three main subdivisions: (1) upstream of Hannine Falls (RM 121), (2) from Hannine Falls to the town of Littlefork (RM 20), and (3) downstream from the town of Littlefork to the confluence with the Rainy River. The primary criteria used were the degree of entrenchment and the backwater effects from the Rainy River. Downstream of Hannine Falls, the channel becomes entrenched. Downstream of the town of Littlefork, the channel experiences backwater effects from the Rainy River and is strongly coupled to that system. This is the only part of the basin that appears to be dominated by deposition under the current hydrologic regime.

Based on an analysis of channel and valley widths, valley wall height and slope, presence/absence of active floodplain environments, depositional features, and observations, I recommend a further subdivision of the middle portion of the channel into four sections, bringing the total number of mainstem sections to six:

I. Upper basin, upstream of Hannine Falls (RM 121)
II. Hannine Falls to confluence with Sturgeon River (RM 111)
III. Confluence with the Sturgeon River to RM 87, just downstream of the oxbow
IV. RM 87 to RM 59, upstream of the Dentaybow canoe launch
V. RM 59 to the town of Littlefork (RM 20)
VI. Littlefork to the confluence with the Rainy River (RM 0)

These subdivisions were based primarily on changes in the mainstem valley that affect bank erosion and sediment inputs to the mainstem. They were originally determined from a combination of airborne observations and spatial analyses of channel and valley size, valley topography, and valley wall slopes. In addition to the criteria used to make the subdivisions, other data are used to describe channel, valley, and watershed characteristics for each section and the watershed that contributes to it.

Tables 1.1 and 1.2 summarize basic channel and valley parameters for each reach. Section III, which has the most confined channel also maintains a fairly steep section slope of 0.0004, however, much of elevation drop occurs at rapids and waterfalls (see Figure 1.1). The channel slope overall drops as the valley widens and the channel has more room to move across the valley bottom. The slope drops significantly between sections V and VI, which affects the depositional environment seen in section VI leading to visible sand bars forming.

Brief descriptions for each subdivision are given below, followed by basin-scale descriptions of downstream variations in channel and valley features, land use/land cover, surficial geology, topography, and erosion potential.

Table 1.1: Section sinuosity and slope

Section	RM[1] (start)	RM (end)	Sinuosity[2] (CL/VL)	Section Slope[3]
I	124+	121	1.3	0.00051
II	121	111	1.2	0.00036
III	111	87	1.2	0.00040
IV	87	59	1.3	0.00025
V	59	20	1.8	0.00024
VI	20	0	1.5	0.00014

[1] RM refers to river mile, according to the official Department of Natural Resources canoe map.

[2] Sinuosity was calculated as channel length over valley length for the entire section. The valley length was determined from a mid-valley line, with points digitized approximately every 100 – 250 meters.

[3] Slope here refers to the elevation loss over channel length for the entire section. Actual channel slopes are generally lower, as much of the elevation loss occurs at knickpoints (rapids and waterfalls). In calculating section slope, Section I ended at the top of Hannine Falls, and Section II started at the bottom of the falls.

Table 1.2: Channel and valley widths

Section	Valley Width (m)			Channel Width (m)	Width Ratio[1] (VW/CW)			n[2]
	Min	Avg	Max	Average	Min	Avg	Max	
I	63	71	84	28	2.0	2.5	3.2	3
II	42	120	304	24	1.3	5.4	14.0	10
III	56	168	412	38	1.2	4.6	10.8	24
IV	115	334	525	38	4.2	9.1	13.8	28
V	58	616	1979	41	1.2	16.6	54.2	39
VI	71	425	984	61	1.4	7.2	18.4	20

[1] The width ratio is the valley width over the channel width. It was calculated at each river mile marker, and minimum, maximum, and averages are taken from that dataset.

[2] n refers to the number of mile markers where data were collected.

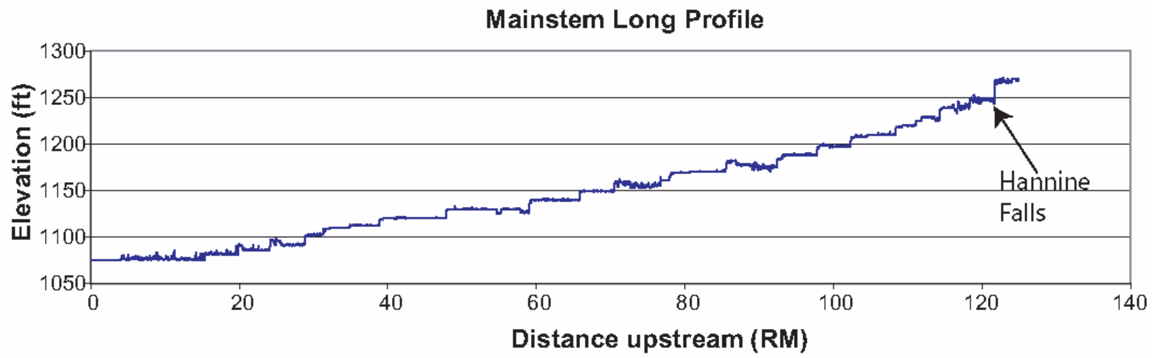

Figure 1.1: Long profile of the Little Fork mainstem. These data were extracted from the 30-m DEM at ~50 meter intervals. Much of the jaggedness comes from interpolations that cross over elevation lines (1-foot contours). However, most of the stair-step pattern is real and represents rapids and waterfalls. Between RM 124 and RM 20, there are 11 rapids listed by the Minnesota DNR on their state canoe route map.

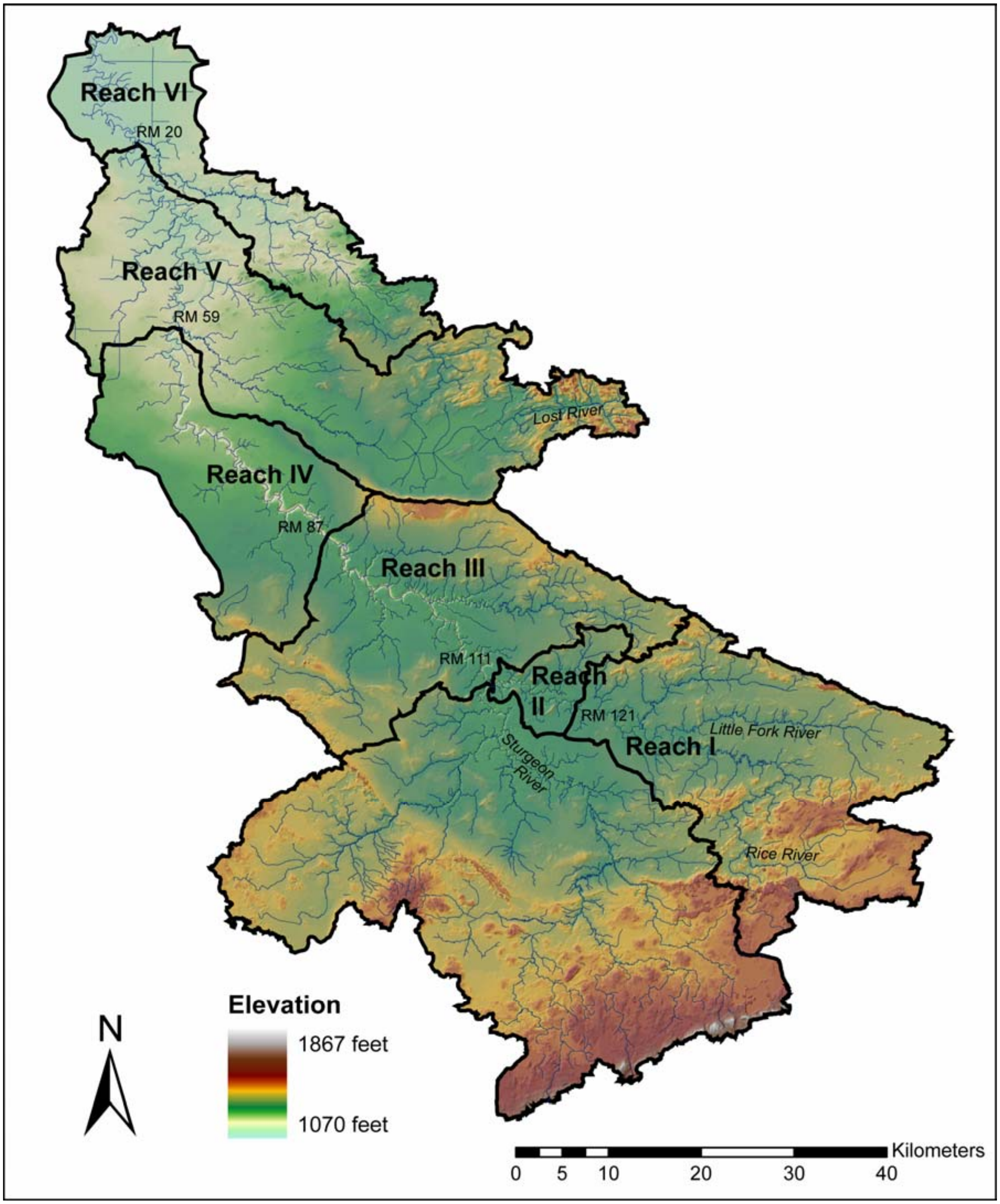

Figure 1.2: Six subdivisions of the mainstem Little Fork River and the additional drainage area added for each reach. The Sturgeon River is shown separately here, but joins the Little Fork River at RM 111, thus contributing to Reach III and below. The watershed subdivisions are overlain on a 30-meter DEM of the watershed.

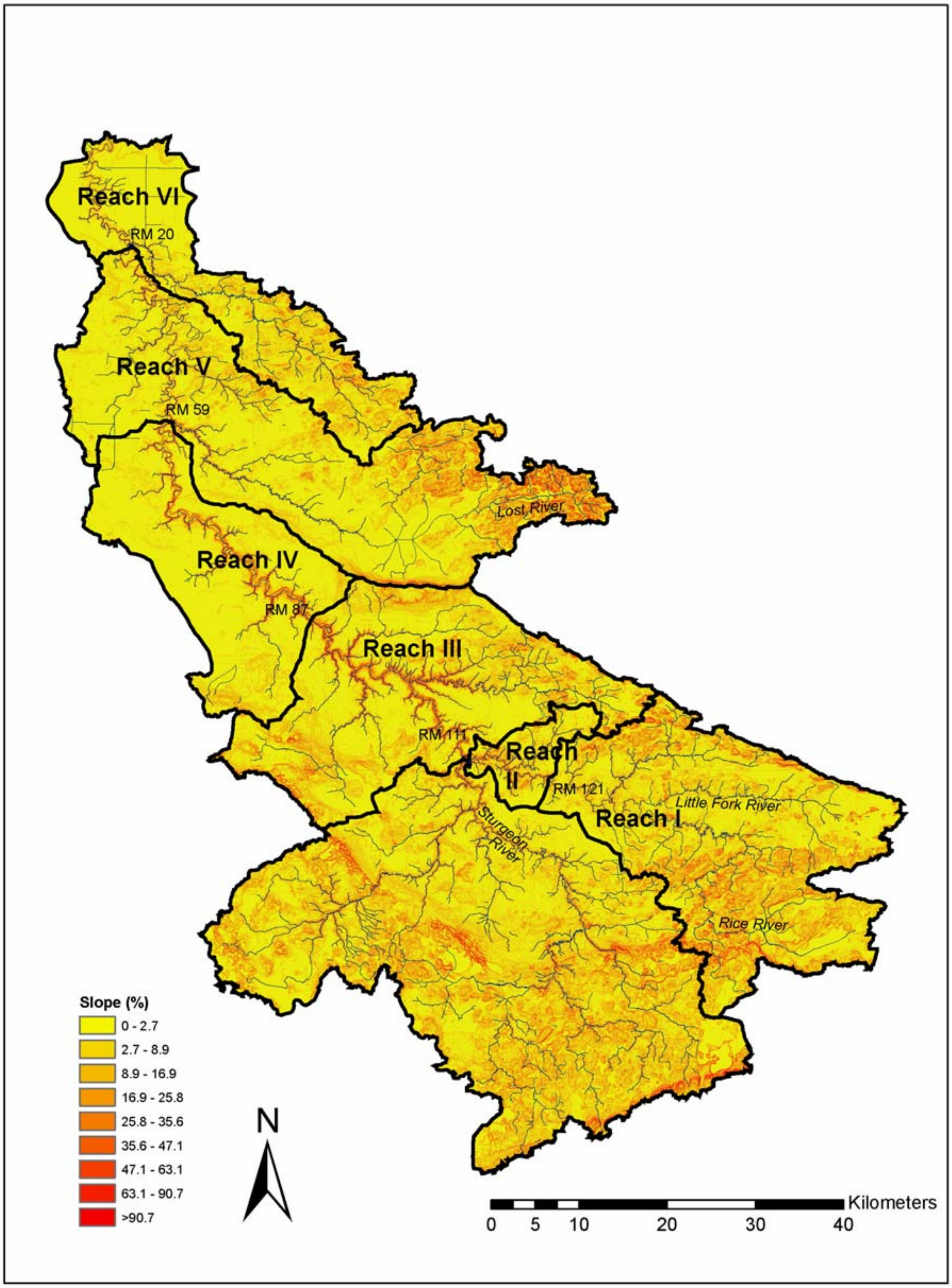

Figure 1.3: This map shows the same subdivisions as Figure 1.2, but overlain on a slope map rather than a DEM. Figures 1.4-1.9 show zoomed in portions of each subdivision, overlain on the same slope map, with the same shading (refer to this map for % slope designations).

Section I: Upper basin

This section contains the upper Little Fork River basin, upstream of Hannine Falls (RM 121). This region is not as entrenched as farther downstream, although it is still impaired for turbidity up through RM 142 (Anderson et al., 2006). Figure 1.4 shows the transition from section I to section II on a slope map. Above Hannine Falls, the river is not as entrenched and valley slopes are more gradual. The channel is thus more free to migrate without a net input of sediment to the system. In an entrenched system, erosion of high banks may not be balanced by deposition, leading to a net input of sediment to the system.

This study did not extend upstream of the Lindon Grove access (RM 124) on the mainstem. For the three miles in this study (RM 121 to RM 124), the sinuosity (valley/channel length) is 1.28, and the valley to channel width ratio was 2.5 with an average valley bottom width of 71 m and an average channel width of 28 m.

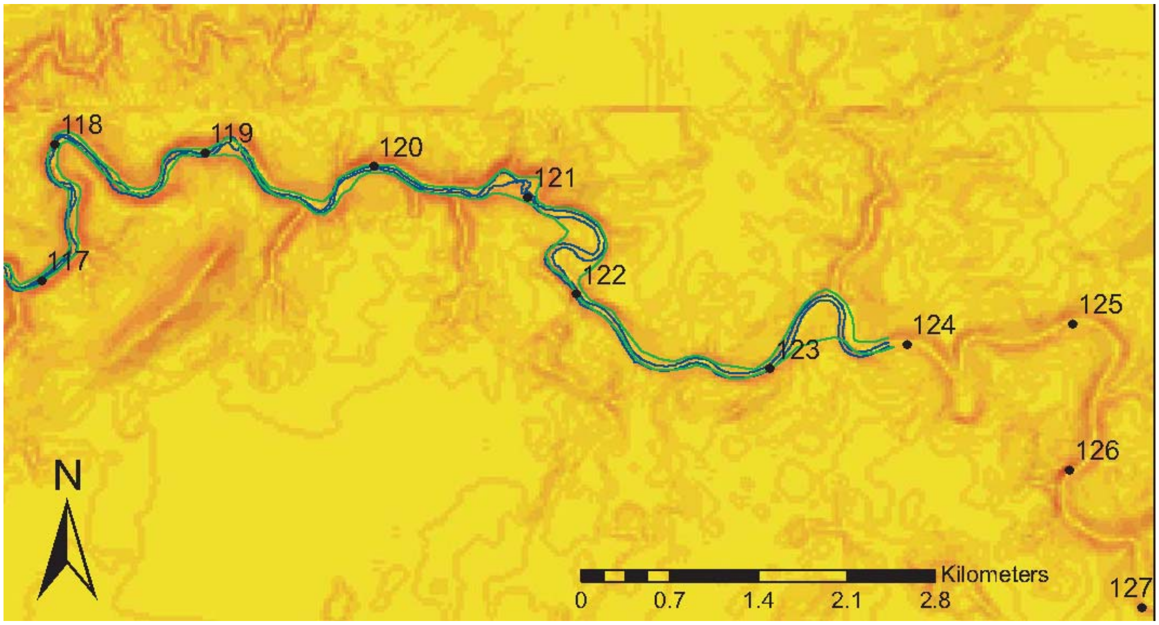

Figure 1.4: Hannine Falls (RM 121) represents the break between sections I (upper basin) and II. The entrenchment downstream of Hannine Falls is evident by the development of steep valley walls (shown in red on this slope map).

Section II: Hannine Falls to Sturgeon River confluence

Below Hannine Falls, the channel is entrenched, with steep valley walls. The channel and valley are tightly coupled, leading to a low overall sinuosity (1.18). The ratio of channel width to valley width ranged from 1 to 14 with an average of 5.4. The wide range in width ratios matches the observations of a valley alternating between wide and narrow. There is some room for the channel to migrate across the floodplain, but not much. Figure 1.5 shows that the channel is in contact with the valley wall <50% of the time between RM 111 and RM 115, but has greater contact with the valley wall upstream of RM 115. This is an indicator of how much sediment might be eroded due to normal channel migration – a channel meandering into the high valley wall can erode more sediment than one moving across the valley bottom.

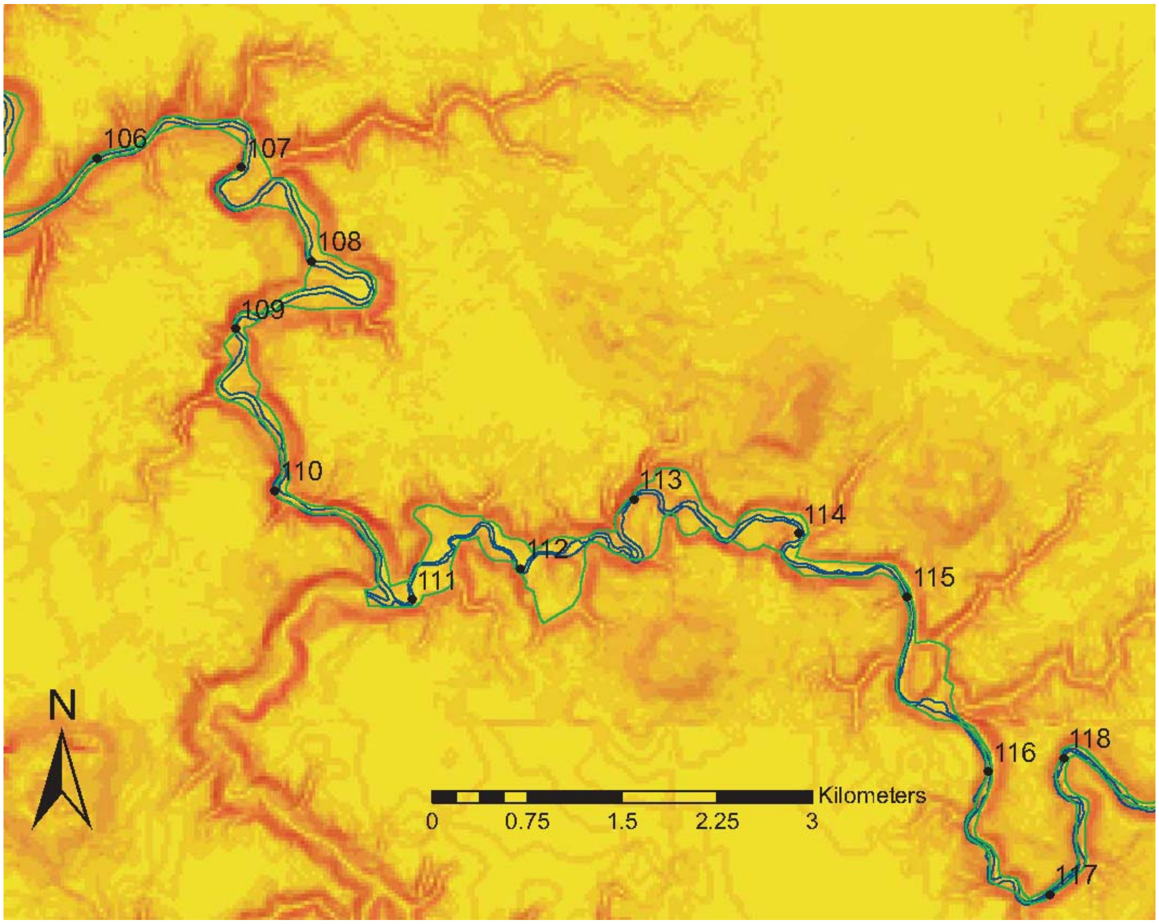

Figure 1.5: Little Fork River over Reach II (RM 121 to RM 111). RM 111 is the confluence with the Sturgeon River.

Section III: Sturgeon River confluence to RM 87

This reach represents the most entrenched and confined portion of the river (see Figure 1.6). Steep valley walls rise up right along the edge of the channel over most of this section. The addition of the Sturgeon River doubles the basin area. The average channel width increases by ~60% (average channel width of section II was 24 m; average channel width of this section is 38 m), and the average valley width increases ~40% (120 m in section II to 168 m here). The valley:channel width ratio remains low, with an average ratio of 4.6. The channel is often in contact with the valley walls, such that any channel migration cuts into the valley walls. Likewise, with little floodplain buffer, any incision on the mainstem through this reach will be tightly coupled with incision on tributary streams and gullies. This is very visible in Figure 1.6, which shows a high density of incised tributaries and gullies. Between RM 97 and 99, there are at least 5 tributaries on the north side and 11 gullies/ravines on the south side visible in the slope map alone. The tight coupling of channel and valley leads to a low overall sinuosity of 1.2.

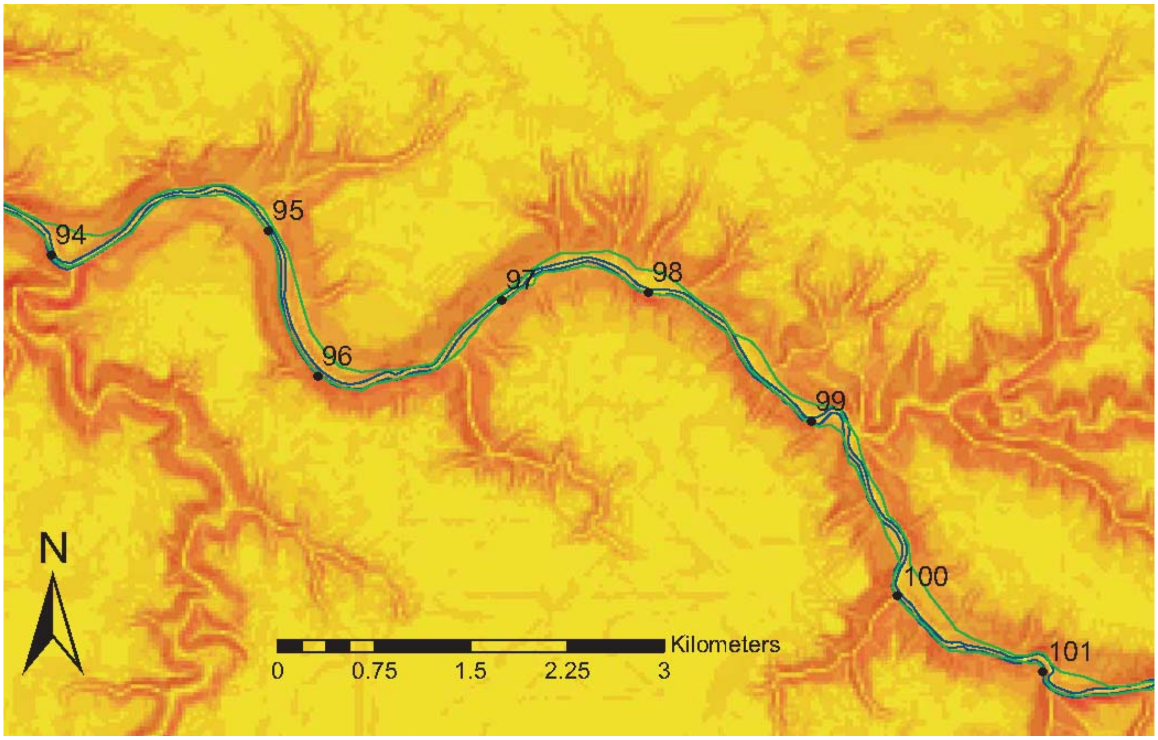

Figure 1.6: Section III on the mainstem Little Fork River. This is the most confined and entrenched portion of the river. Note the high density of gullies and incised tributaries visible on this 30-m slope map.

Section IV: RM 87 to RM 59

This section corresponds with a gradual opening up of the valley bottom from the tightly constrained conditions in section III (Figure 1.7). The valley width doubles from an average of 168 m in section III to 334 m in section IV, but the average channel width stays the same. This leads to an increase in the average valley:channel width ratio from 4.6 to 9.1. The channel is no longer as tightly coupled to the valley wall, thus incision on the mainstem will not propagate as quickly to tributaries and gullies, releasing less sediment overall. The channel sinuosity (channel:valley length ratio) is still low at 1.3, but it is a slight increase from section III.

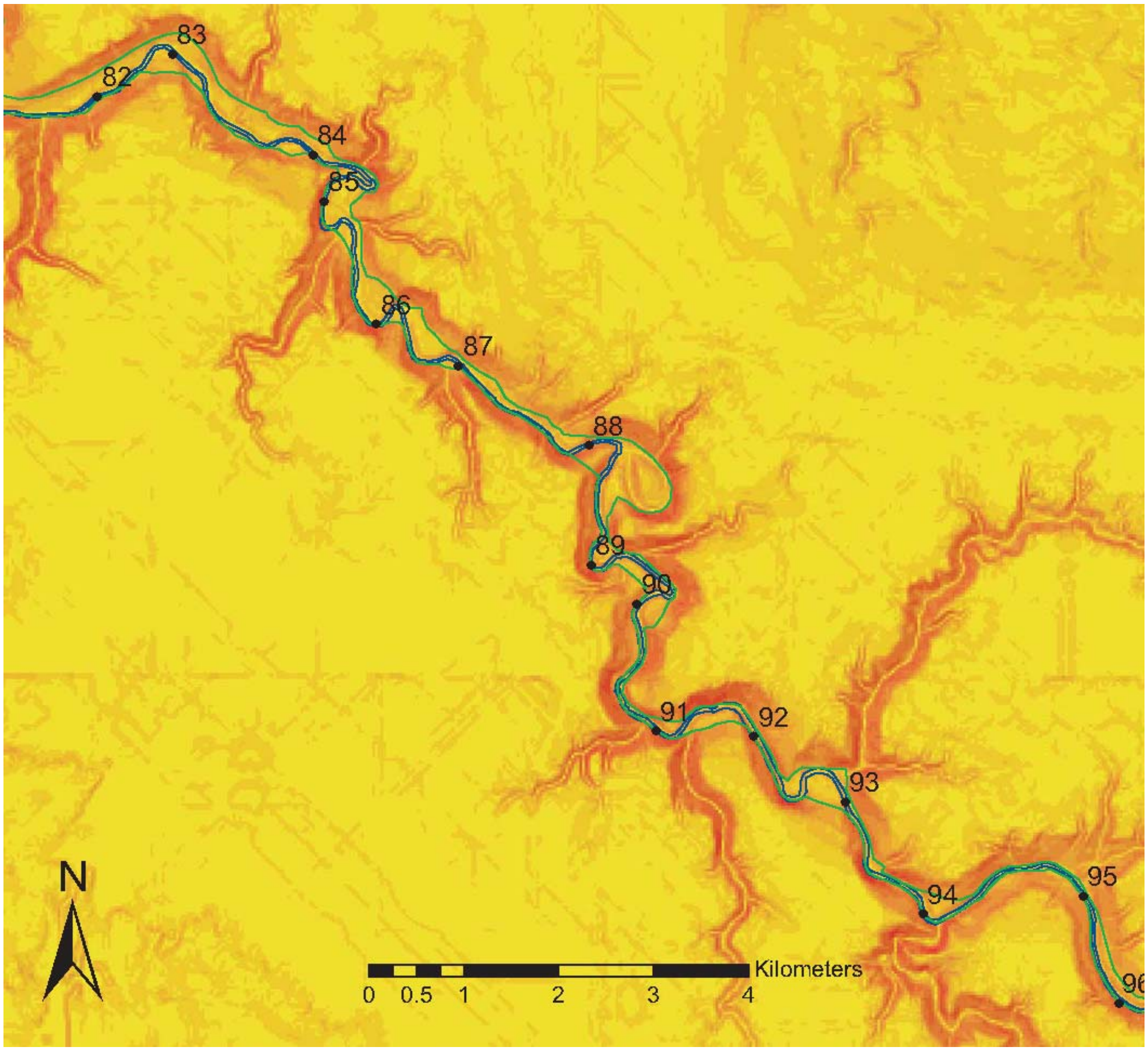

Figure 1.7: The break between section III and section IV is set at RM 87, although the transition is gradual as the valley width slowly increases. The oxbow at the Bois Forte site is visible at RM 88.

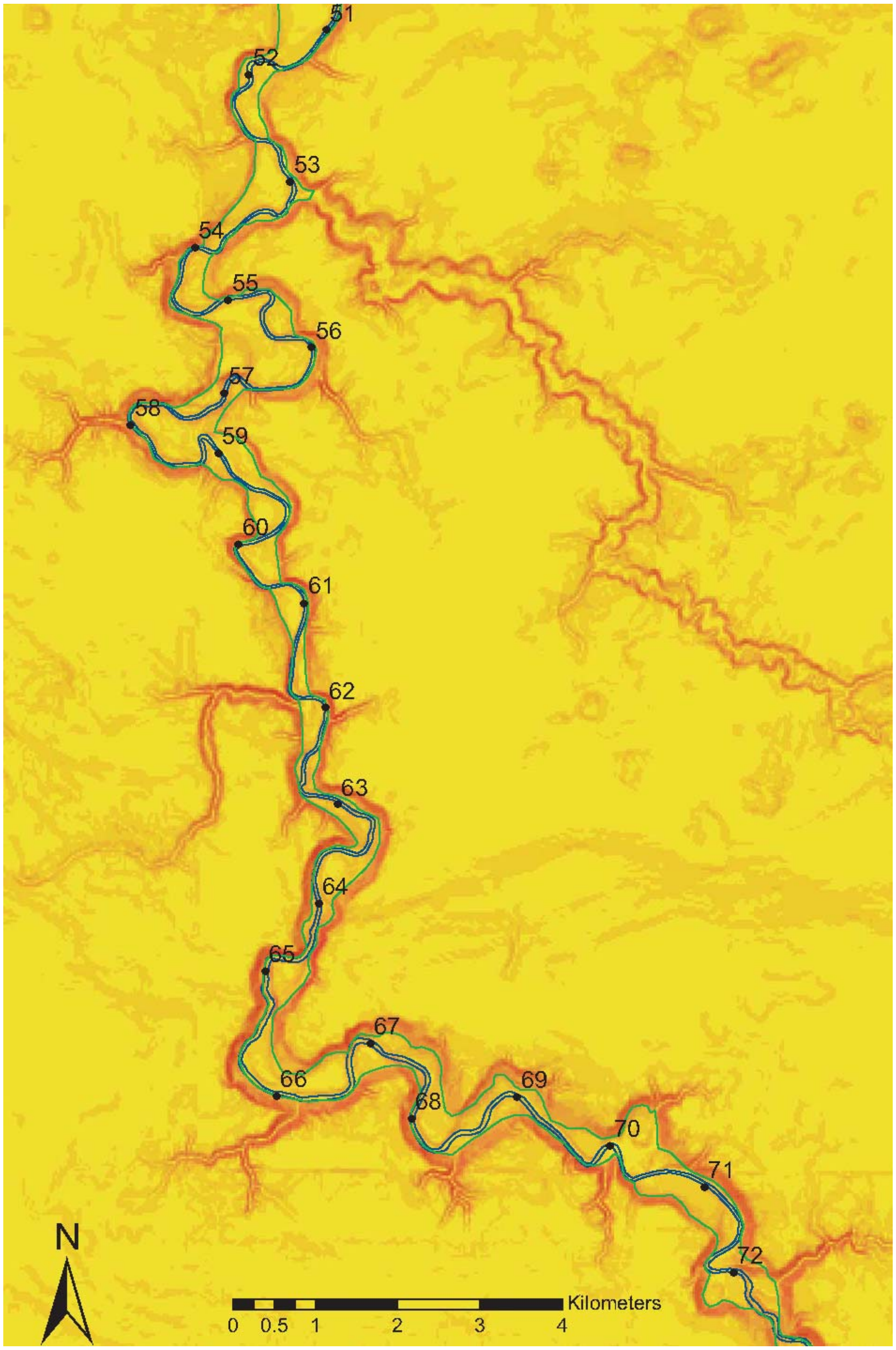

Figure 1.8: Transition from Section IV to Section V represents a gradual widening of the valley bottom starting around RM 59.

Section V: RM 59 to town of Littlefork (RM 20)

The gradual transition from section IV to section V corresponds to continued widening of the valley bottom. Figure 1.8 shows this transition. From section IV to section V, the average channel width increased only slightly (38 m to 41 m), but the average valley width almost doubled, from 334 m to 616 m. The valley:channel width ratio in this section ranged from 1.2 to 54.2 with an average of 16.6. This section is characterized by a sinuous meandering channel within a wide meander belt. Sinuosity averages 1.8. The valley walls as digitized include zones that are clearly fluvial (scroll bar topography visible from air, etc.), but which may be acting as terraces under the current hydrologic regime due to incision. It is likely the valley width is overestimated in those locations. This problem of separating out the current floodplain from the inactive valley bottom exists throughout the entire system, however, which is why the term "valley bottom" is being used instead of "floodplain".

Section VI: Town of Littlefork to Rainy River confluence

The downstream-most section of the Little Fork River (Figure 1.9) remains a separate section because this area is affected by backwater influences from the Rainy River. This area has the lowest slope of any section (0.00014), almost half that of section V, and the most evidence for deposition under the current hydrologic regime. This section had the vast majority of visible sandbars within the channel at low flow (see Figure 1.10). The valley width averaged 425 m, with an average channel width of 61 m. The valley:channel width ratio ranged from 1.4 to 18.4 with an average of 7.2. The valley is narrower and the channel wider than in section V.

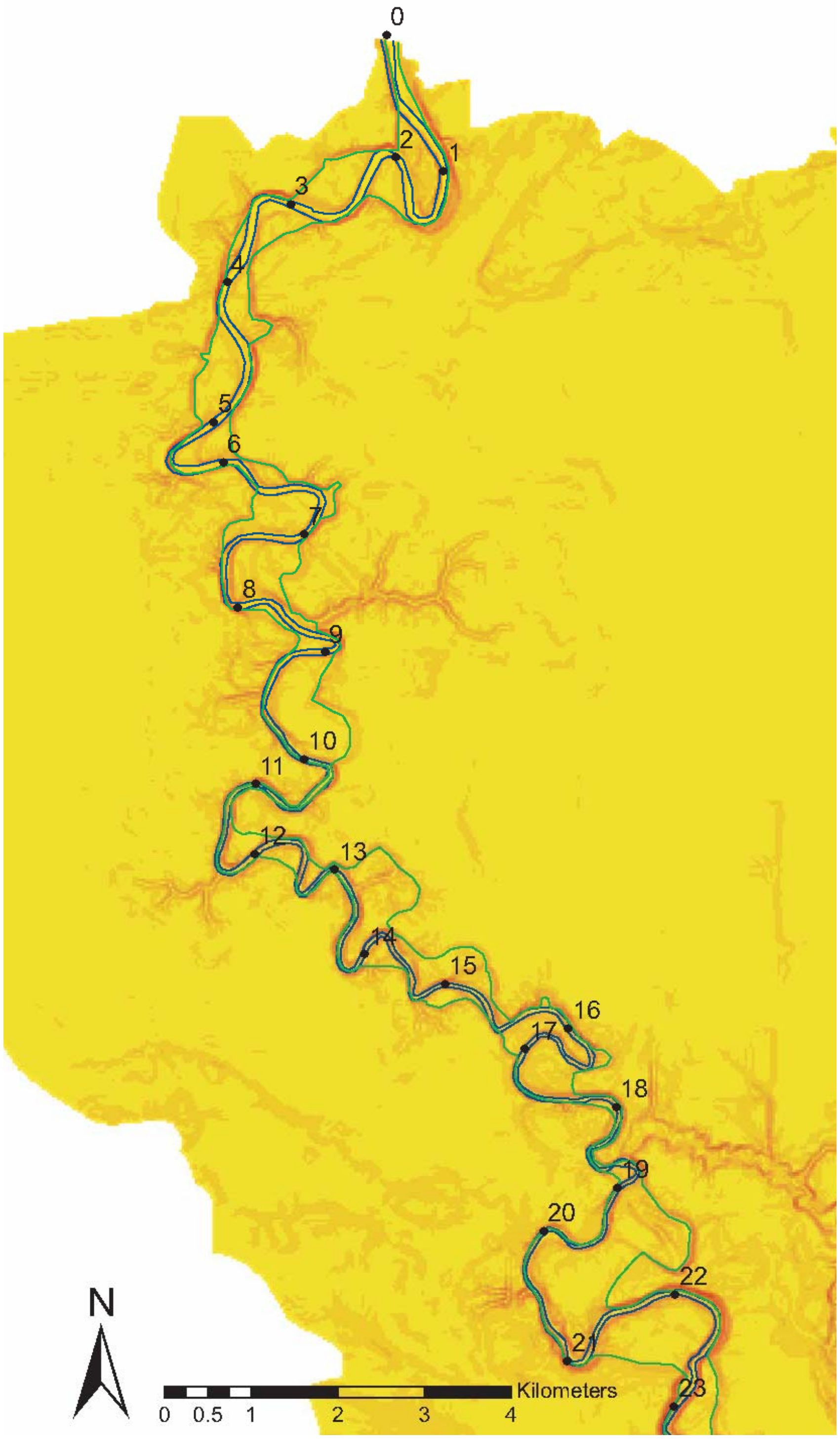

Figure 1.9: Section VI, from the town of Littlefork to the Rainy River confluence has the most evidence for floodplain and in-channel deposition of the entire system. The channel is wide although the valley bottom has narrowed some from section V.

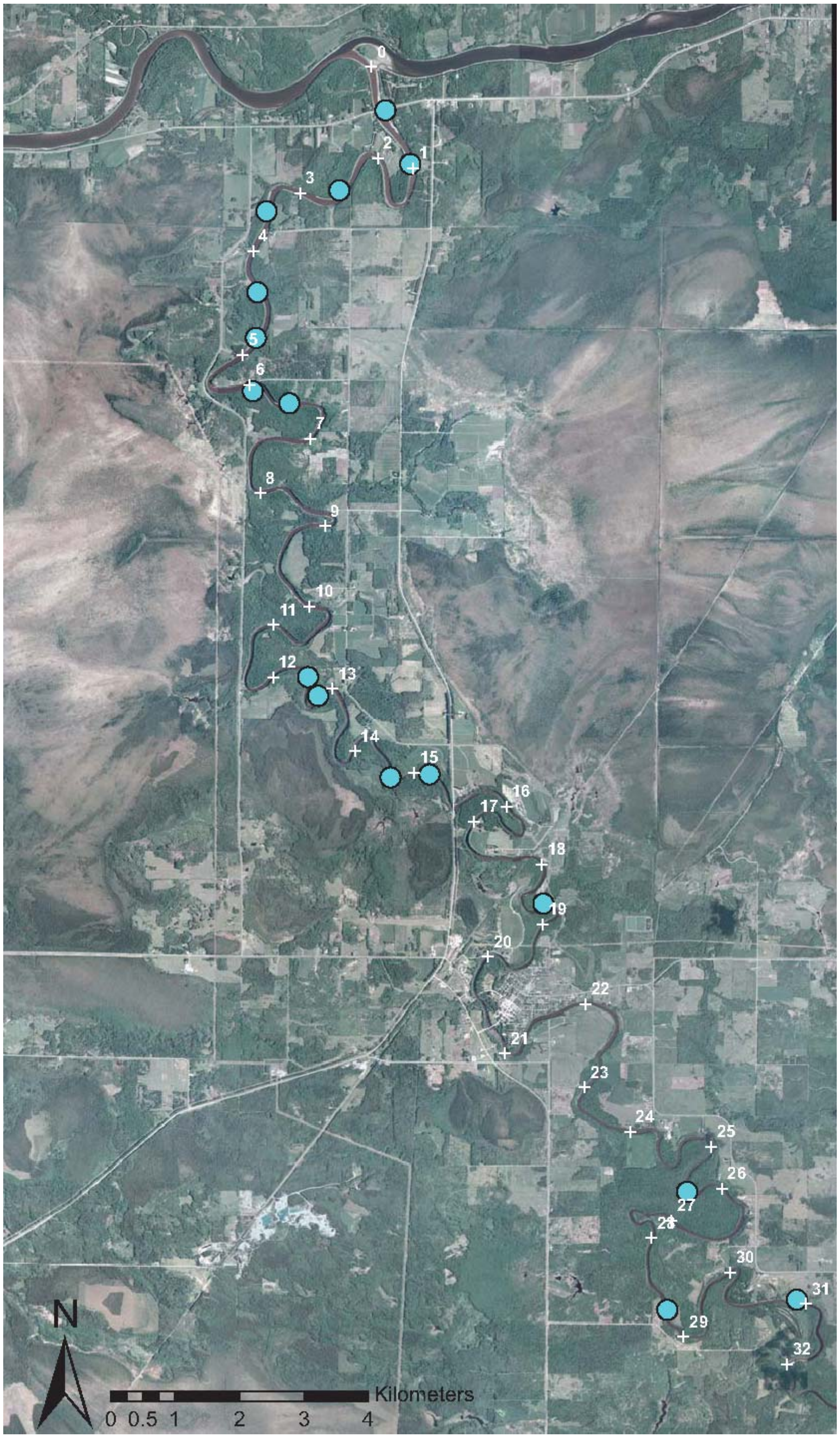

Figure 1.10: Visible sand bar locations on the mainstem Little Fork River. The marked bars (circles) represent sand bars that were visible during a flight on October 30, 2006, when the river was at low flow conditions. All but three of the mapped exposed sand bars were located in section VI.

Watershed Characteristics:

The Little Fork River watershed is 1843 mi^2 in area, heading along the north flank of the Iron Range then flowing through a relatively low-gradient area covered by glacial lake and till deposits and peat bogs. Glacially-derived sediments cover 62% of the total watershed area, and organic-rich deposits an additional 24% (see Table 1.3 and Figure 1.11).

Table 1.3: Drainage Area and Surficial Geology

Section	Upstream Area (mi^2)	Surficial Geology[1] (% total area)							
		Organic Deposits	Lake Agassiz	Rainy Lobe	Koochiching Lobe	Fluvial	Bedrock Uplands	Mines	Undiff.
I	298	28.3	0	35.3	30.5	0	5.9	0	0
II	331	28.1	0	31.8	34.7	0	5.4	0	0
III	1171	19.5	7.3	30.7	37.7	0	2.5	1.8	0.5
IV	1357	22.7	7.7	27.0	38.1	0.3	2.1	1.6	0.4
V	1707	23.6	6.4	21.4	38.1	0.7	8.1	1.3	0.4
VI	1843	24.0	6.0	19.5	36.7	0.8	11.4	1.2	0.3

[1] Surficial geology comes from geomorphology of Minnesota dataset (see Appendix A).

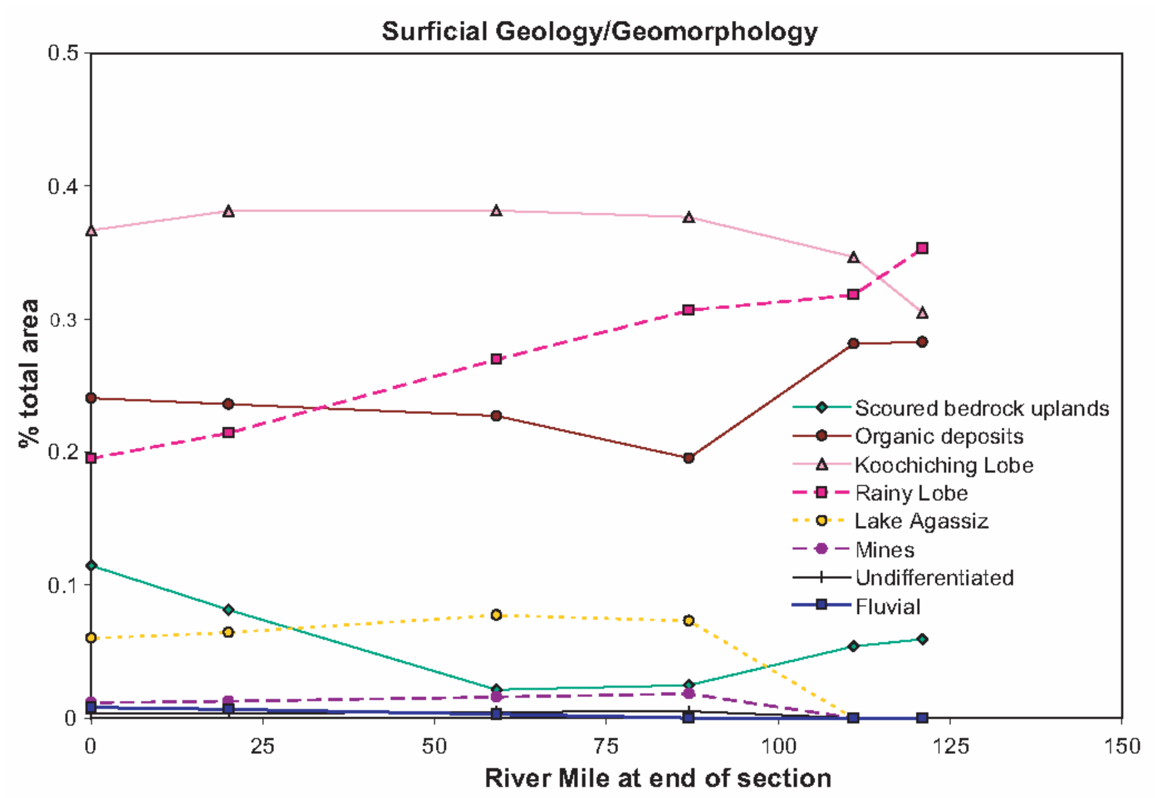

Figure 1.11: Surficial geology of drainage area contributing to each river section. Each section is plotted at the river mile on the downstream end, and the % area for each section represents the integrated total of the entire drainage area upstream.

The primary land cover is forest (58% total area); wetlands and open water occupy 29% of the area; grasslands, shrubs, and cultivated land 11%; and the remaining area is urban/industrial/farmsteads, gravel pits, open mines, and barren land (Table 1.4). The distribution of each land use/land cover differs little from the upper basin (contributing to section I) to the entire watershed of the Little Fork River (contributing to section VI).

Table 1.4: Land use/land cover

Section	Upstream Area (mi^2)	Land Use/Land Cover (% total area)					
		Forest[1]	Wetlands[2]	Open Water	Grasslands[3]	Urban/ Industrial/ Rural[4]	Bare[5]
I	298	49.7	28.4	3.2	18.0	0.5	0.2
II	331	50.2	28.1	3.0	18.0	3.8	0.4
III	1171	56.8	23.3	3.3	14.5	0.5	1.5
IV	1357	56.8	25.6	3.0	12.8	0.4	1.3
V	1707	58.0	25.5	3.3	11.9	0.4	1.0
VI	1843	57.7	25.9	3.1	12.0	0.4	1.0

Land use/land cover data come from the MN DNR and are derived from 1995-96 Landsat TM imagery.

[1] Includes mixedwood forest, regeneration/young forest, coniferous forest, and deciduous forest.

[2] Includes marsh, fen, and bog wetlands.

[3] Includes shrubby grassland, grassland, and cultivated land

[4] Includes farmsteads, rural residences, urban, and industrial

[5] Includes gravel pits, open mines, and bare rock

Most of the topographic relief in the Little Fork River watershed is found in the upper reaches of the Sturgeon River, the Rice River, and to a lesser degree, the Lost River (Nett Lake River above Nett Lake) watersheds (Figures 1.2, 1.3). The remaining relief is found adjacent to the Little Fork River and its primary tributaries. An erosion index (EI) was calculated to determine the erosion hot spots within the basin. The EI is a stream power-based measure of fluvial erosion potential, generally used to model bedrock erosion potential. Although EI was calculated for the entire watershed, the EI should only be used in areas of concentrated flow (channels, tributaries, and gullies) subject to fluvial erosion. The EI map in Figure 1.12 shows erosion hot spots in the high relief zones listed above and immediately adjacent to channels. Interestingly, even small gullies and tributaries, particularly in section III, show up as erosion hot spots despite their small drainage areas (Figure 1.13).

The EI values were sampled within a 1 km buffer zone surrounding the mainstem Little Fork River and then divided into river sections. This buffer zone is wide enough to cover the entire valley bottom and valley walls, thus sampling the EI along the mainstem and the valley walls. Although the inventory does include “hillslope” zones rather than strictly “fluvial” zones, the hillslope areas within this buffer zone do not fall into the highest EI bins. Within each section, EI values were binned into increments of 1000 EI values per bin. Data were normalized to account for differences in river length for each section. The resulting histograms are plotted in Figure 1.14. Clearly, section III has the highest overall distribution of EI values. This supports visual observations that high EI tributaries and gullies were the most closely spaced in this section. Section IV has the next highest values.

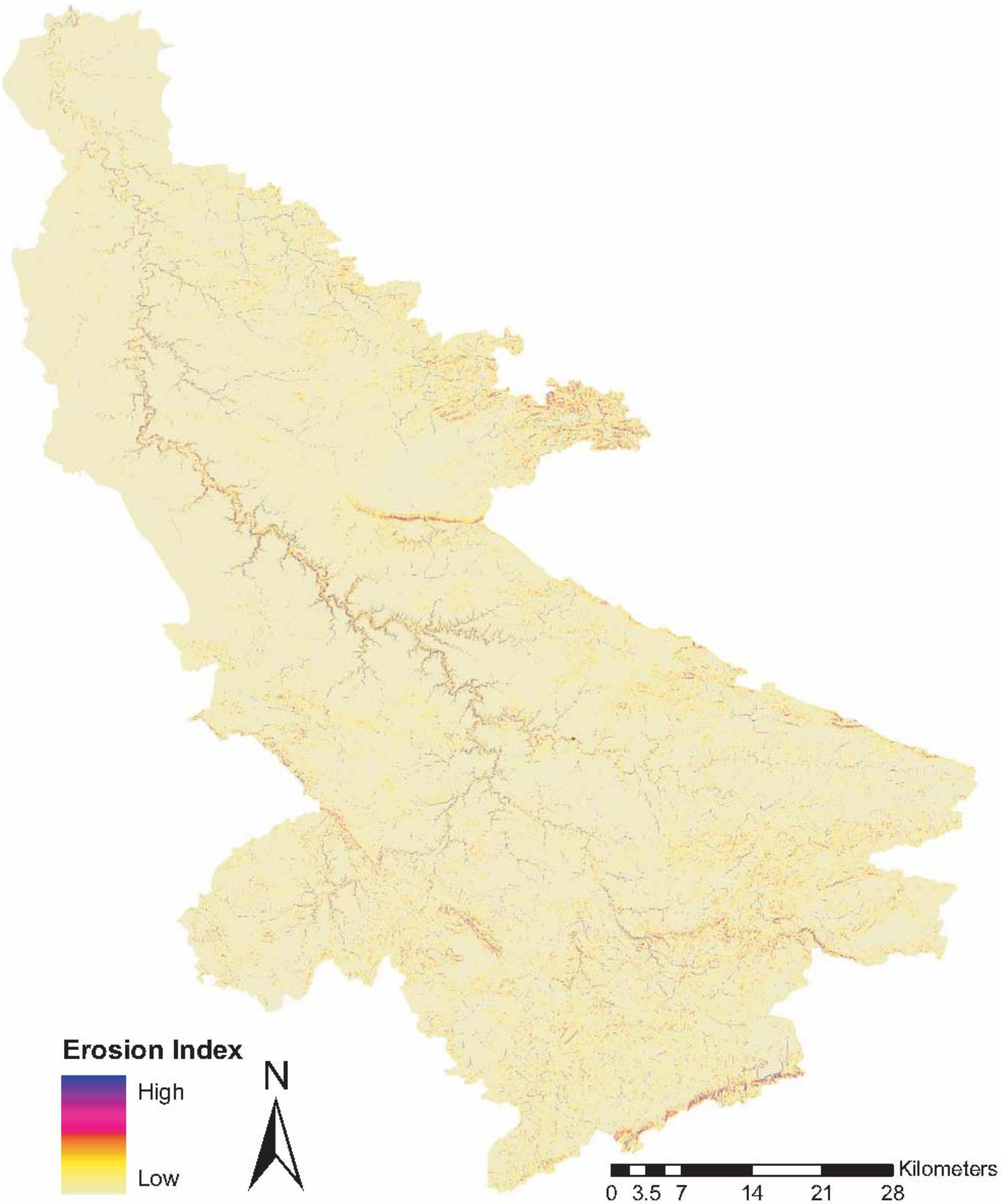

Figure 1.12: Erosion Index (EI) map for Little Fork River watershed. The highest values of EI are located in the uplands and in the middle 2/3 of the watershed, primarily along valley walls, tributaries, and gullies.

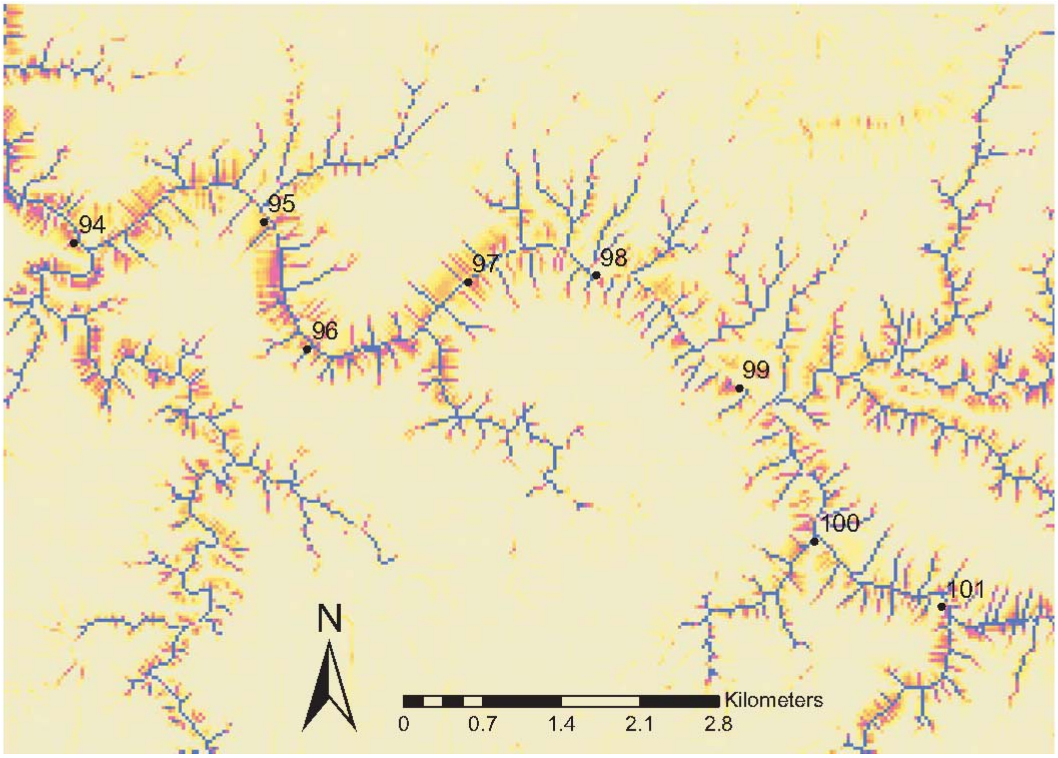

Figure 1.13: Close-up of Erosion Index map for part of Section III (same reach shown as a slope map in Figure 6). Tributaries, gullies, and parts of the mainstem show up with the highest values of the EI.

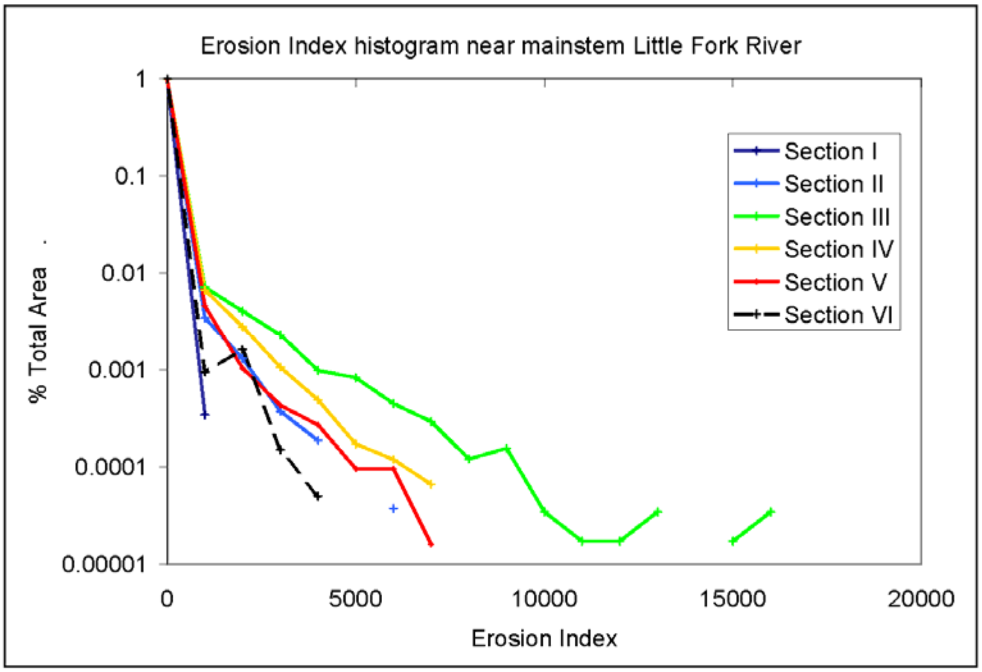

Figure 1.14: Histogram of EI values within 1km of the Little Fork mainstem channel. The EI values were binned at 1000 EI increments, and normalized to account for differences in area. Section III has the highest EI distribution.

The spatial analyses of erosion potential, high valley slopes, and confined channel all show that Section III is likely to have the greatest erosion potential, and much of the erosion may come from tributaries and gullies responding rapidly to channel incision or widening. Observations from the field indicate that this section of the channel is the most incised currently. During the week of November 13-17, 2007, surveys were taken from the lowest extensive surface adjacent to the channel to the water surface at the time of the survey. The water levels were low during this time period and did not fluctuate appreciably from day to day. The low elevation surfaces adjacent to the channel generally represent former floodplain surfaces, now acting as terraces, but new floodplain surfaces have not yet developed at any of the sites surveyed. In some places, small lower benches were developing: these locations are noted. Table 1.5 shows the location of surveys and the distance from the low terrace/old floodplain to the water surface. The greatest distance to the water surface elevation was found at RM 88, within Section III.

Table 1.5: Comparative heights of lowest extensive surface adjacent to channel.

Site Location	River Mile	Terrace[1] Height (m)	New surface height (m)
Samuelson Park	101	4.3	N/A
Bois Forte	88	6.8	3.9 (bench)
Dentaybow	56	3.8[2]	3.8 (slump)
Devereaux	36	5.8	4.5 (bench)
Lofgren Park	20	5.7	N/A

[1] Terrace refers to the lowest extensive surface adjacent to the channel. These surfaces are old floodplain surfaces. In most cases, new floodplain surfaces were difficult to distinguish, but new lower benches were forming in select areas.

[2] Surface measured at Dentaybow was the top of a large rotational slump block.

Conclusions:

The Little Fork River mainstem channel was subdivided into six sections, based on relationships between channel and valley topography; and observations made in the field, during a fly-over, and from aerial photography. This geomorphic framework can help guide future management and research efforts by focusing efforts on the most sensitive portions of the watershed. Based on this analysis, the section most likely to release sediment due to changes in mainstem channel base level or width was section III, which runs from the confluence with the Sturgeon River at RM 111 downstream to RM 87. Tight coupling between the channel and valley walls will lead to potentially more sediment eroded during channel widening and incision, and rapid propagation of channel incision to tributaries and gullies.

Chapter 2
Historical air photo analysis of landscape changes

Objectives:

Historic aerial photographs provide one of the best records of past land use and channel conditions. Coupled with gaging records, they may provide additional information on the status of the river and watershed historically. In the Little Fork River basin, aerial photographs from 1940-41 were compared with photographs from 1991 and 2003, land use derived from 1995-96 Landsat Thematic Mapper imagery, and a forest disturbance map from 2003. There were three main objectives: 1) Compare land use in the 1940s with current land use, 2) measure river migration rates at select reaches from 1940 to the present, and 3) track knickpoint migration or gullies developed during channel incision in select reaches.

Summary of Findings:

On five reaches along the Little Fork River, land use within a one kilometer buffer zone was compared between 1940-41 aerial photographs and 1995-96 land use maps. Reaches varied from 4-9 miles long, and included one for each geomorphic classification subdivision except section I (see Chapter 1 for geomorphic classifications). The reach in section V had the most dramatic changes in land use, shifting from predominately grasslands/pasture/fields to predominately forest cover. Other reaches varied from no significant change in cover (Sections II and IV) to a slight increase in forest cover (Section III) or a slight increase in grasslands (Section VI). A complimentary comparison looked at recently cleared area in the 1940s vs. area cleared between 1988 and 2003 within a 300-meter buffer zone for 24 kilometer-long reaches. Reaches in Section V showed the same dramatic decrease in the amount of cleared land. Reaches in Section IV showed an overall increase in clearing, and the other sections (II, III, and VI), showed little overall change in land use.

Analyses of mainstem channel features, including migration rates and bank characteristics as well as locations of gullies and knickpoints were hampered by aerial photograph resolution and difficulties georeferencing the 1940-41 photographs. Mainstem channel migration rates could not be measured because georeferencing errors exceeded migration distances. In addition, thick vegetation made tracking of individual gullies, ravines, and knickpoints challenging. To assess the overall distribution of slope and bank failures, a catalog was made of locations where meanders are actively migrating into steep valley walls. These are the areas with the greatest potential for erosion and slope failures. Bends were mapped in ArcMap, noting land use and presence or absence of visible slope or bank failures in 1940s and 2003 photographs. There was a positive correlation between visible slope failures and clearing in both 1940-41 and 2003 photos, likely due to a combination of greater visibility following land clearing and an increased risk for slope failures following forest removal (e.g. Sidle, 1992). In the 1940s air photos, ~ 53% of outer bends surveyed showed some signs of slope or bank failure, while in 2003, only 40% of the surveyed bends had visible failures. This mirrors the distribution of bends with full or partial clearing (56% in 1940s and 37% in 2003) which both increases the risk of slope failures and makes them much easier to see on aerial photographs.

Methods:

Historical air photos from 1940-41 of the mainstem Little Fork River below RM 116 were obtained from the University of Minnesota map library and scanned in at high-resolution by L. Engel. The photos were taken at a scale of 1:20,000. Five of those air photos, one for each geomorphic subdivision excluding Section I were georeferenced in ArcMap using primarily road intersections and buildings as control points. In remote areas, channel features like bars, bedrock knobs, rapids, or bank features were used as control points in addition to anthropogenic features. The images were georeferenced using a 2nd-order polynomial transform which allows for warping of the image rather than straight translation and rotation but which can achieve a better fit if enough control points are used. The RMS (root mean square) errors associated with each transform are shown in Table 2.1, along with the number of control points used and whether or not any control points included channel features. RMS values associated with georeferencing ranged from 1.1 – 2.7 meters. No additional efforts were made to orthorectify the images to account for distortion at the edges.

Table 2.1: 1940-41 Air photos used in analyses

1940 Air Photo #	Date	Section[1]	River Miles	RMS Error[2]	#Control Points	Channel features used?[3]
CIP-40-85	5-24-41	II	110-116	1.3 m	9	Yes - 2
CIO-9-66	10-12-40	III	96-101	1.1 m	8	No
CIO-6-187	9-28-40	IV	72-76	2.7 m	10	Yes - 3
CIO-7-115	9-29-40	V	34-43	1.8 m	9	Yes – 2
CIO-8-88	10-10-40	VI	6-12	1.5 m	10	No

[1] Section refers to the geomorphic classification in Task 1.

[2] Root Mean Square Error for a 2nd-order polynomial transform in ArcMap using these control points.

[3] Indicates whether channel features were used as control points for georeferencing, and how many control points were channel features.

Channel migration:

The five air photos from 1940-41 were compared with 2003 Farm Services Administration 1-m resolution digital color aerial photographs. The 2003 photos were obtained from the Department of Natural Resources (DNR) Data Deli website already orthorectified and georeferenced. A visual comparison was made of channel banks digitized in from the 2003 air photos and overlain on the georeferenced 1940s photos, and I determined that any channel migration over the 60 year period of record was minimal enough that it could not be determined from these paired photos. The Red River of the North, another northern, low-gradient channel with clay-rich cohesive banks, has migrated at a rate of 0.04-0.08 m/yr averaged over the past 6200 years (Brooks, 2003). A similar rate on the Little Fork River would have resulted in only 2 - 4 m of lateral migration in the last fifty years, which is within the uncertainty associated with georeferencing and photograph resolutions.

Marchner's presettlement vegetation maps also provide a record of the location of the mainstem Little Fork River. This map was made from ~1895 public land surveys and was obtained in digital format from the DNR Data Deli. Although it can be used to examine land cover in the late 1890s, it is less reliable for small positional changes in the mainstem channel due to relatively large positional off-sets. In the lower Little Fork

River watershed, the mainstem channel appears to be offset to the northwest by 50-100 meters. Although there are still places where channel migration is apparent despite the shift, quantitative measures are not advised. An example of the 1895 channel overlain by the 2003 banks as digitized by L. Engel can be seen in Figure 2.1.

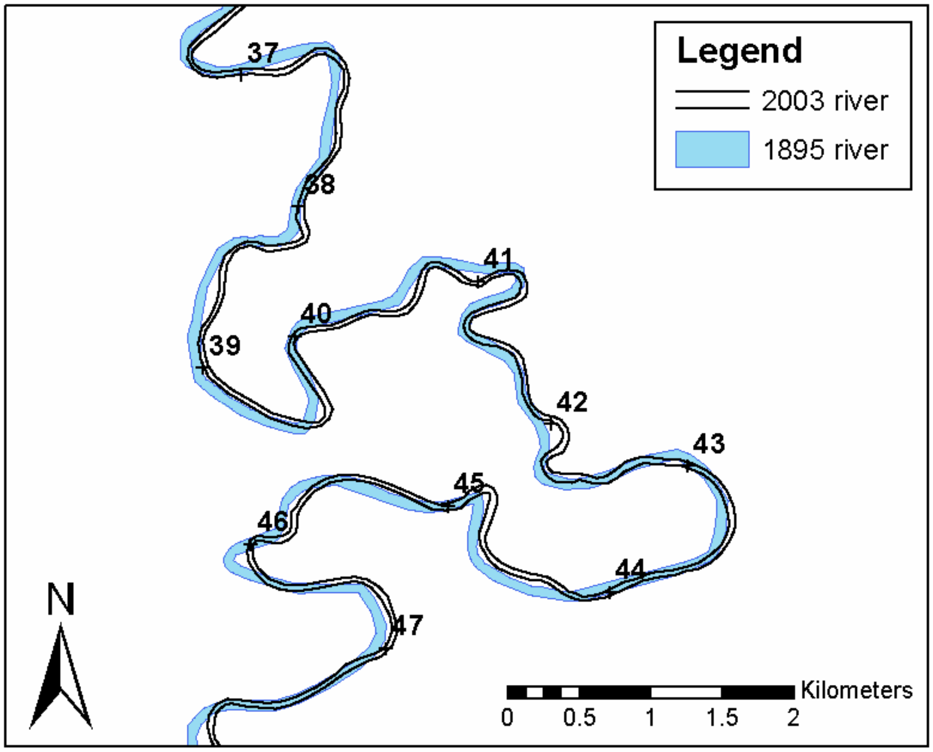

Figure 2.1: Channel banks in the 1895 presettlement map appear to be offset 50-100 meters to the southwest. However, some meander migration can still be seen (e.g. RM 42 and between RM 40 and 41).

Land Use/Land Cover:

To compare land use and land cover changes through time, the 1940s images were compared with a georeferenced land use/land cover dataset obtained from the Minnesota DNR. These data were derived from 1995-1996 Landsat Thematic Mapper images and included 15 categories of land use. The fifteen initial categories were combined into six more general categories (see Table 2.2) for comparison with 1940s land use.

Land use for the 1940s was divided into forest and grassland. Forested areas were hand-digitized on each of the five georeferenced photos. The area in forest cover was compared between 1940 and 1995-96 for a 1 km buffer zone around the Little Fork River on each georeferenced air photo. The area in grassland was taken as the total area within the buffer zone minus the area mapped as "open water" in 1995-96. This subtracted out the area of the Little Fork River itself. Only two photos (CIO-8-88 and CIO-6-187) had a sizeable area of wetlands in the buffer zone. In these photos, some or all of the area mapped in 1995-96 as wetlands was removed from the total area under comparison.

The area mapped as forest and grasslands in the 1940s photos was then compared to the forest and grasslands area in 1995-96. The forest area in 1995-96 contained all of the different forest classes listed on Table 2.2 as well as half of the area mapped as "shrubby grassland" which contained a mix of forest, grasslands, and shrubs. The grasslands area in 1995-96 was a combination of grasslands, cleared and cultivated lands, and the other half of the area mapped as shrubby grassland. All land uses categorized as "other" were not mapped in 1940-41, but they did not represent more than 1.2% of the total area in any of the photos.

Table 2.2: Land use categories for 1995-96 data

LUSAT #	Land Use Category[1]	General category[2]
1	Cultivated land	Grasslands
2	Deciduous forest	Forest
3	Open water	Open Water
4	Grassland	Grassland
5	Mixedwood forest	Forest
6	Wetlands: marsh and fens	Wetlands
7	Wetlands: bogs	Wetlands
8	Farmsteads and rural residences	Other
9	Coniferous forest	Forest
10	Other rural developmpents	Other
11	Shrubby grassland	Shrubby Grassland
12	Gravel pits and open mines	Other
13	Urban and industrial	Other
14	Regeneration/young forest	Forest
15	Bare rock	Other

[1] Land use category on the original data set from the Minnesota DNR.

[2] Lumped categories for comparison with the 1940s data.

In order to get a larger view of the watershed, a series of 1940-41 composite images produced by A. Streitz were georeferenced against the 2003 FSA images for the entire mainstem channel downstream of RM 115. The georeferencing on these composites is much poorer than on the five individual photos referenced above and include the errors associated with the initial compositing. None-the-less, they do allow a much more rapid assessment of near channel conditions in 1940-41 over a larger portion of the watershed. Using these georeferenced photos, I compared near-channel land use (within 300 m of the channel) in 1940-41 and 2003 in 24 kilometer-long reaches originally established by L. Engel. Cleared areas in the 1940's photos were digitized by hand and compared with cleared land including areas logged from 1988 – 2003 and areas cleared for other purposes (agriculture, dwellings, etc.) as mapped by L. Engel. Positional errors associated with georeferencing the composites were calculated for each reach, and areas with positional offset errors >5% of the buffer width were removed from the study.

Geomorphic Changes:

These same composite historical photos were used in conjunction with 2003 FSA photos and a contour map produced from 30-m DEMs to map out locations where the river appears to be actively meandering into steep valley walls. These bends were mapped in ArcMap, and annotated as to whether or not they had been recently cleared and whether or not slope failures, active gullies or ravines, or bank failures were visible. This allowed comparisons on whether recent clearing was associated with visible slope failures. This does not necessarily imply causation, especially considering that slope failures, scarps, gullies, ravines, bank slumping, and other features are much easier to see in areas that are cleared. It could provide a starting point for future field investigations or calculations of the potential sediment load from eroding bends.

In addition to the cataloging of bends, individual gullies and ravines were examined on the five georeferenced air photos from 1940 with 1991 and 2003 photos. In most cases, vegetation obscured gully tips or ravines in at least one set of photos, making measurements of growth through time impossible. A few select areas were visible throughout the entire time, and these were visually compared.

Results:

Land Use/Land Cover:

From 1940 to 1996, there was little change in overall land use within one kilometer of the mainstem channel in the five study reaches (Figure 2.2). Figures 2.3-2.7 show 1995-96 land use with the 1940-41 area in forest cover overlain on top of it. All figures have 2003 photos in the background. Details of the area in different land uses in the 1-km buffer zone around the Little Fork mainstem in each photo are given in Tables 2.3-2.7.

The most dramatic change in land use was in photo CIO-7-115 in section V. There was an increase in forest cover area and decrease in the area of grasslands (cleared lands). This is readily seen in the photo in Figure 2.6 and is primarily the result of forest regrowth in the south-central part of the photograph. Changes in land use in other photos were minor: Section III had a slight increase in forest cover, Section VI had a slight decrease in forest cover, and the other two sections had negligible changes, within mapping uncertainities.

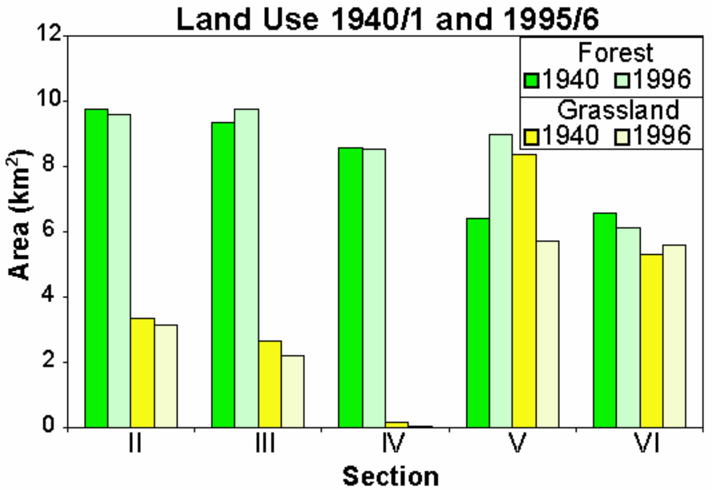

Figure 2.2: Land use in 1940 and 1996 for each of five photos covering area in sections II through sections VI. Land use was compared in a 1 km buffer zone around the mainstem channel.

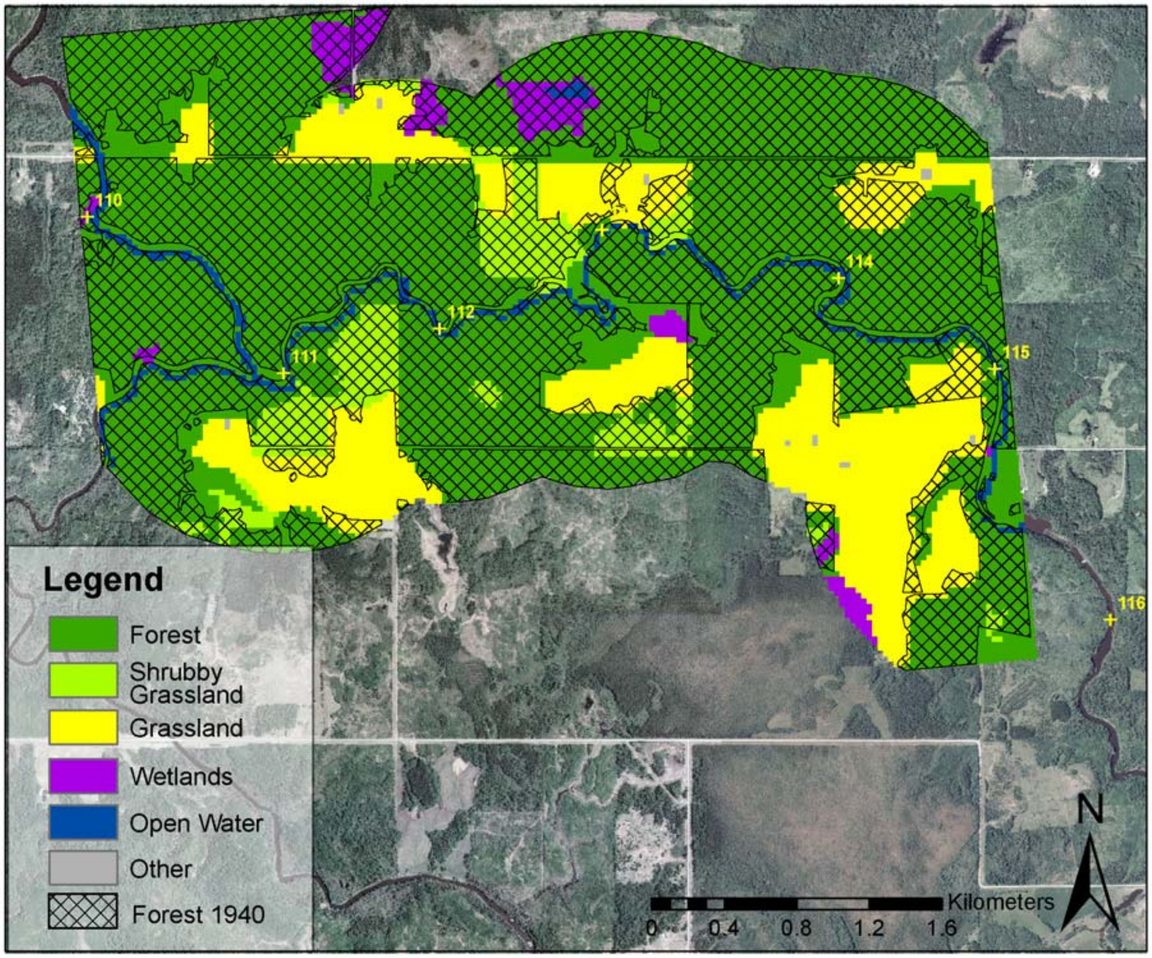

Figure 2.3: Land use in 1995-96 overlain by the forest cover in 1941 (patterned area). Land use was mapped in the area covered by the 1941 photo (CIO-40-85) and within a 1-km buffer of the mainstem Little Fork River.

Table 2.3: Area in each land use type in Figure 2.3.

CIO-40-85	1940 Area (km^2)	1996 Area (km^2)
Forest	9.77	9.59
Grassland	3.36	3.16
Wetlands		0.36
Other		0.017

[1] 1940 Grassland was calculated by subtracting the area in forest cover from the total area within a 1-km buffer minus the area covered by water.

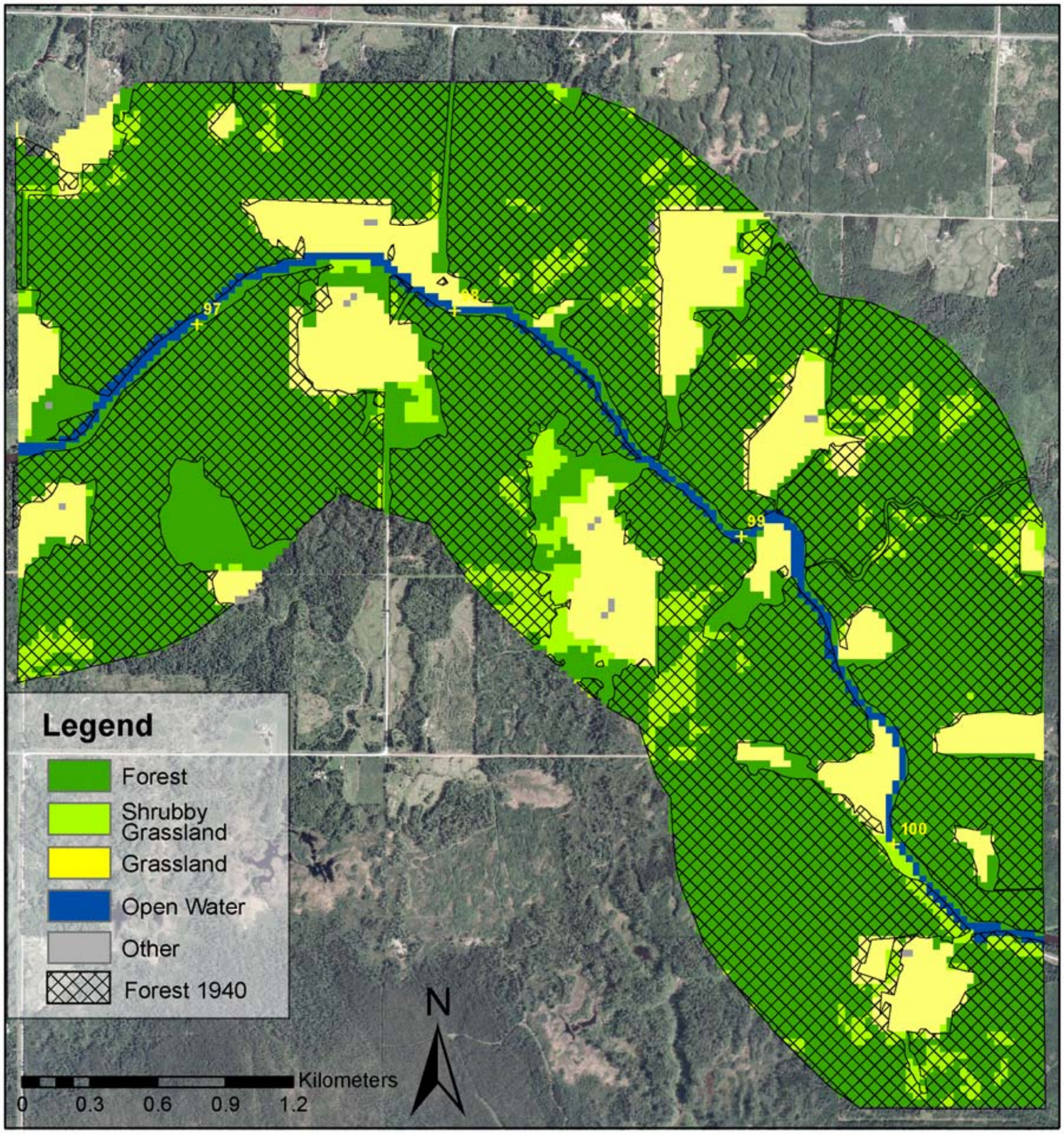

Figure 2.4: Land use in 1995-96 overlain by the forest cover in 1940 (patterned area). Land use was mapped in the area covered by the 1940 photo (CIO-9-66) and within a 1-km buffer of the mainstem Little Fork River.

Table 2.4: Area in each land use type in Figure 2.4.

CIO-9-66	1940 Area (km^2)	1996 Area (km^2)
Forest	9.36	9.77
Grassland	2.65	2.22
Wetlands		0
Other		0.017

[1] 1940 Grassland was calculated by subtracting the area in forest cover from the total area within a 1-km buffer minus the area covered by water.

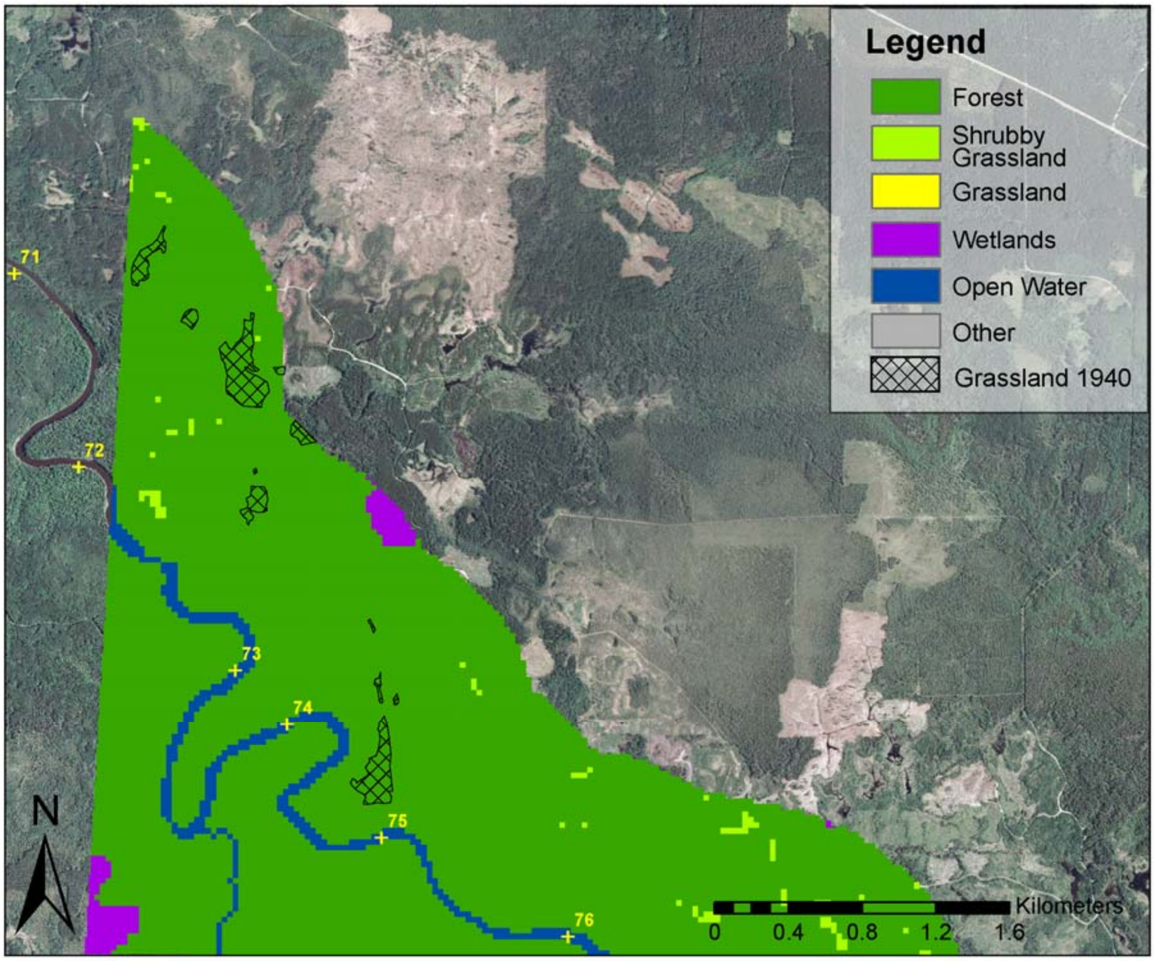

Figure 2.5: Land use in 1995-96 overlain by the grassland cover in 1940 (patterned area). Land use was mapped in the area covered by the 1940 photo (CIO-6-187) and within a 1-km buffer of the mainstem Little Fork River.

Table 2.5: Area in each land use type in Figure 2.5.

CIO-6-187	1940 Area (km^2)	1996 Area (km^2)
Forest	8.57	8.55
Grassland[1]	0.17	0.04
Wetlands[2]	0.063	0.14
Other		0

[1] 1940 Grassland was calculated by subtracting the area in forest cover from the total area within a 1-km buffer minus the area covered by water.

[2] One large bog was digitized on the 1940 photo (this area was not included in the total area from which the grasslands area was calculated).

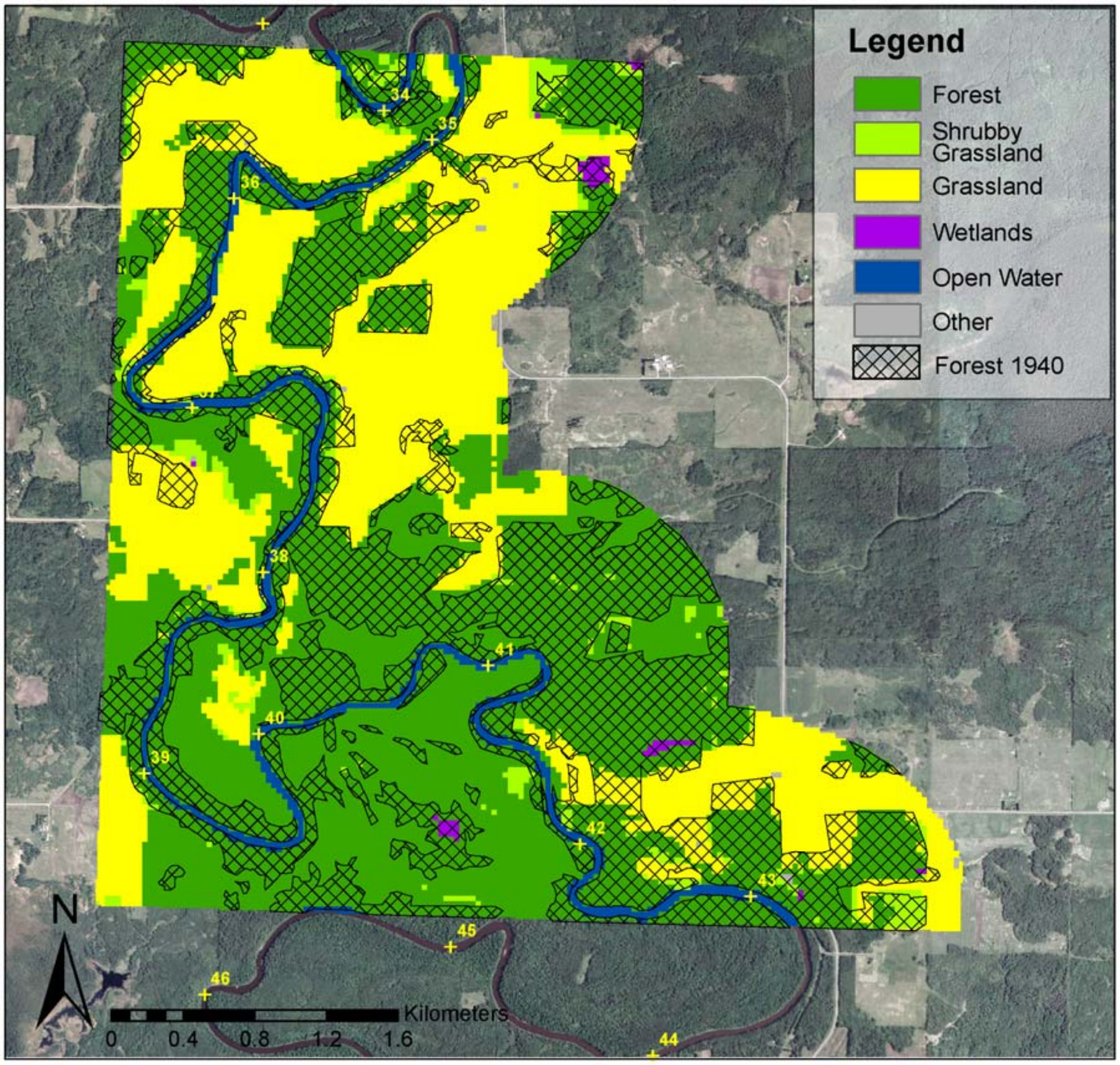

Figure 2.6: Land use in 1995-96 overlain by the forest cover in 1940 (patterned area). Land use was mapped in the area covered by the 1940 photo (CIO-7-115) and within a 1-km buffer of the mainstem Little Fork River.

Table 2.6: Area in each land use type in Figure 2.6.

CIO-7-115	1940 Area (km^2)	1996 Area (km^2)
Forest	6.43	9.00
Grassland[1]	8.38	5.74
Wetlands		0.059
Other		0.014

[1] 1940 Grassland was calculated by subtracting the area in forest cover from the total area within a 1-km buffer minus the area covered by water.

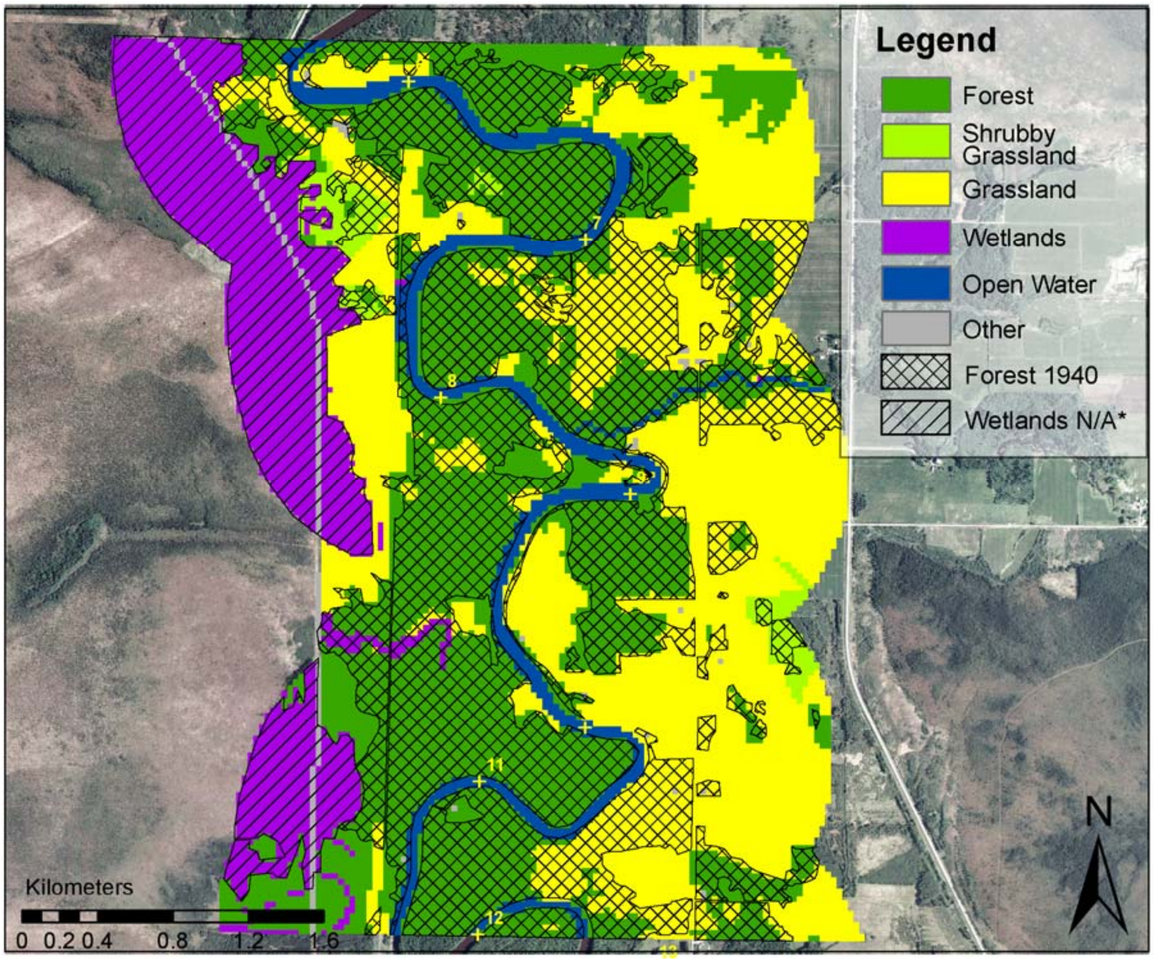

Figure 2.7: Land use in 1995-96 overlain by the forest cover in 1940 (patterned area). Land use was mapped in the area covered by the 1940 photo (CIO-8-88) and within a 1-km buffer of the mainstem Little Fork River. The large wetlands on the west side of the river were not included in the total area calculations.

Table 2.7: Area in each land use type in Figure 2.7.

CIO-8-88	1940 Area (km^2)	1996 Area (km^2)
Forest	6.60	6.14
Grassland	5.30	5.60
Wetlands[2]		2.01
Other		0.17

[1] 1940 Grassland was calculated by subtracting the area in forest cover from the total area within a 1-km buffer minus the area covered by water.

[2] The area in wetlands in 1996 was removed from the total area prior to calculating the grasslands area in the 1940 photo.

To gain a broader view of land use changes along the mainstem channel, I compared the amount of clearing within a 300-m buffer zone for 24 km-long reaches from RM 4 to RM 113. These were the same reaches analyzed by Engel for his study. Cleared areas from 1940-41 were compared with recently logged (1988-2003) and cleared areas in 2003 mapped by Engel (pers. comm., 2007). Several trends were evident between the time periods. Reaches in Section V, which showed substantial regrowth of forest cover in the previous study also showed a decrease in the amount of clearing in this study (negative values in Figure 2.8). Just upstream, in Section IV there was an overall increase in clearing. However, in Section IV, an average of only 20% of the land was cleared (13% in 2003 and 27% in 1940/41), while in the downstream Sections V and VI, an average of 42% of the land was cleared (38% in 2003 and 47% in 1940/41) (Figure 2.9). Thus the % change in those downstream sections represents a greater area overall.

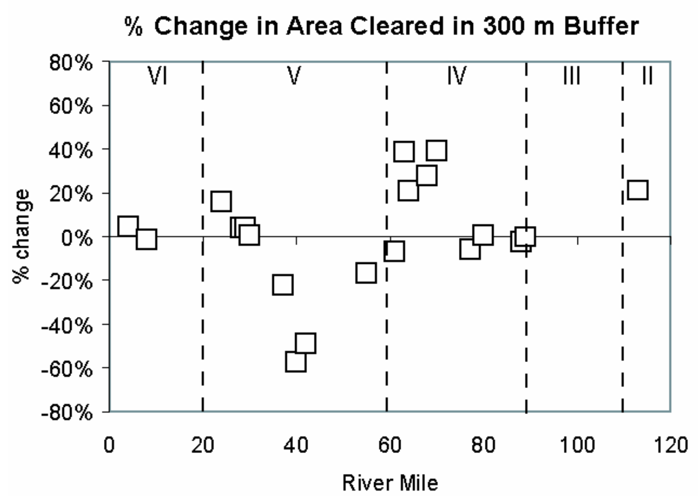

Figure 2.8: Change in the area cleared within a 300-m buffer zone around the mainstem Little Fork River. A positive % change indicates more clearing, and a negative % change indicates more forest cover.

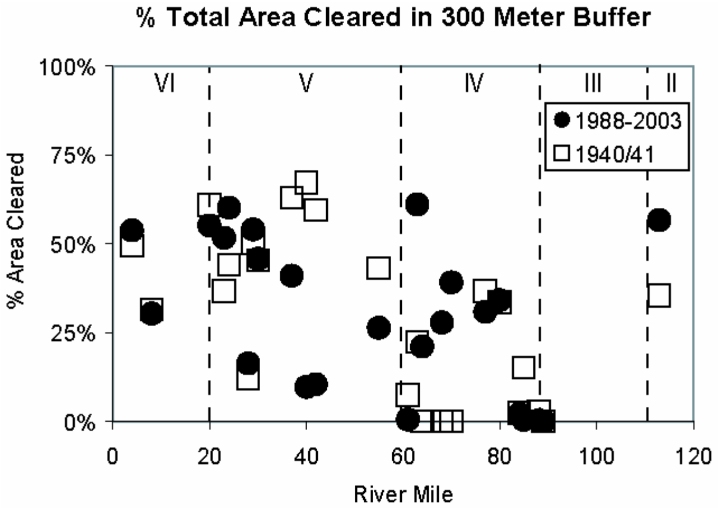

Figure 2.9: Area cleared within kilometer-long reaches in a 300-m buffer zone around the mainstem Little Fork River. The % area cleared includes areas logged and cleared for other purposes as a % of the total area within the reach.

Geomorphic Changes:

Geomorphic changes were visually compared immediately adjacent to the channel along the five study reaches in Figures 2.3 – 2.7. Features including landslide scars, exposed gullies, and bank slumps were tracked from 1940 through 2003 on air photos. These observations were limited by the resolution of the photographs and by vegetation cover, which can be quite thick. Very few areas remained clear of forest cover in both 1940 and 2003, allowing for a direct comparison. In Figure 2.10, at RM 37, landslide scars visible in 1940 are still visible in 1991, but they appear to be less sharp and are covered with vegetation by 2003. Figure 2.11 reveals the slopes along the outside of the meander bend at RM 39, including one location where the steep valley walls were cleared. Forests regenerated on the slopes by 1991, while the uplands remained in grasslands. Slumps are visible on the steep slopes in 1940, but due to vegetation cover, they cannot be seen in 1991 or 2003 for comparison. The opposite is true in Figure 2.12 at RM 73: The steep valley wall on the outside of a meander bend was forested in 1940, but cleared by 2003. Once again, slumps are visible in the cleared 2003 photo, but comparisons through time cannot be made due to tree cover in 1940.

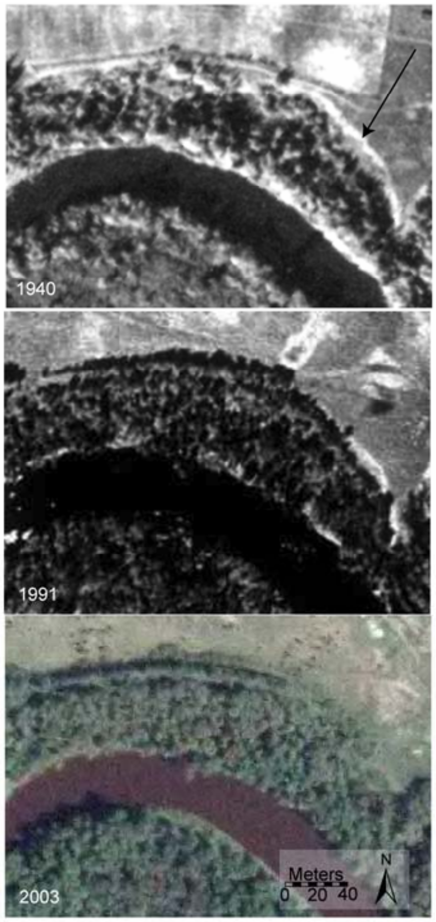

Figure 2.10: Landslide scarps at RM37 are visible in 1940 photo as white lines. This scarp is still visible on the east side of the photo in 1991, but is no longer visible in 2003.

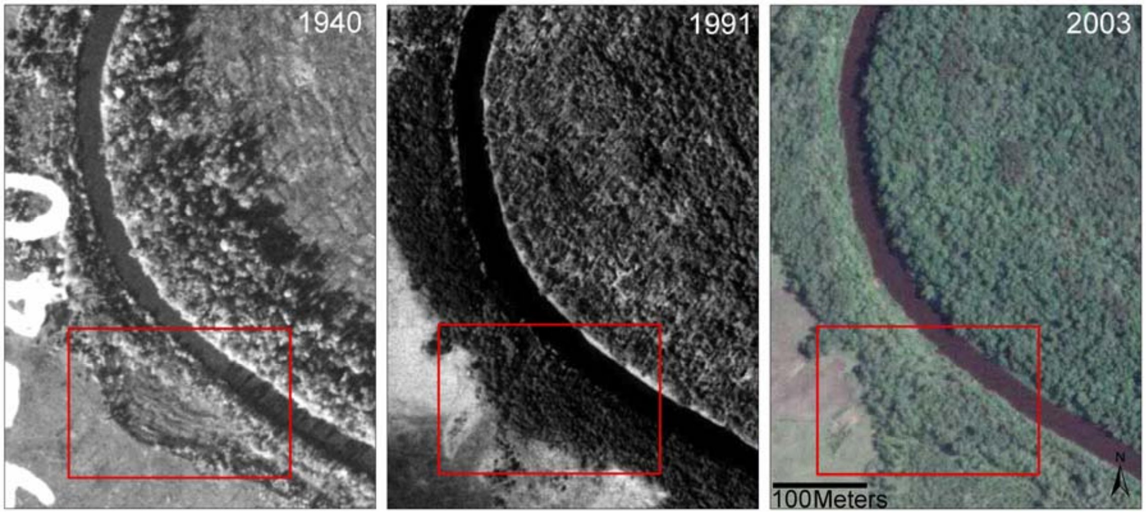

Figure 2.11: At RM39, steep valley walls with slump features visible in 1940 due to lack of forest cover have regrown by 1991. Other features along the right bank which may be deposits of sediment or debris are no longer visible in the 1991 and 2003 photos.

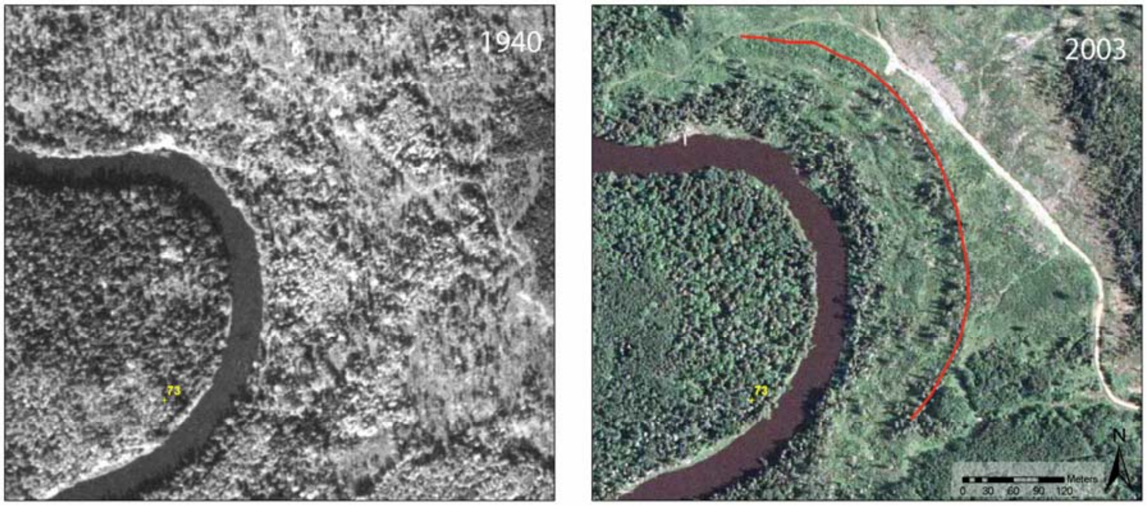

Figure 2.12: Steep slope on outer bank of meander bend at RM 73. In 1940, the entire area was still forested. By 2003, these trees have been removed, and multiple slumps are visible. The red line marks the slope break at the top of the meander bend. Slumps are visible below the slope break as irregular lines.

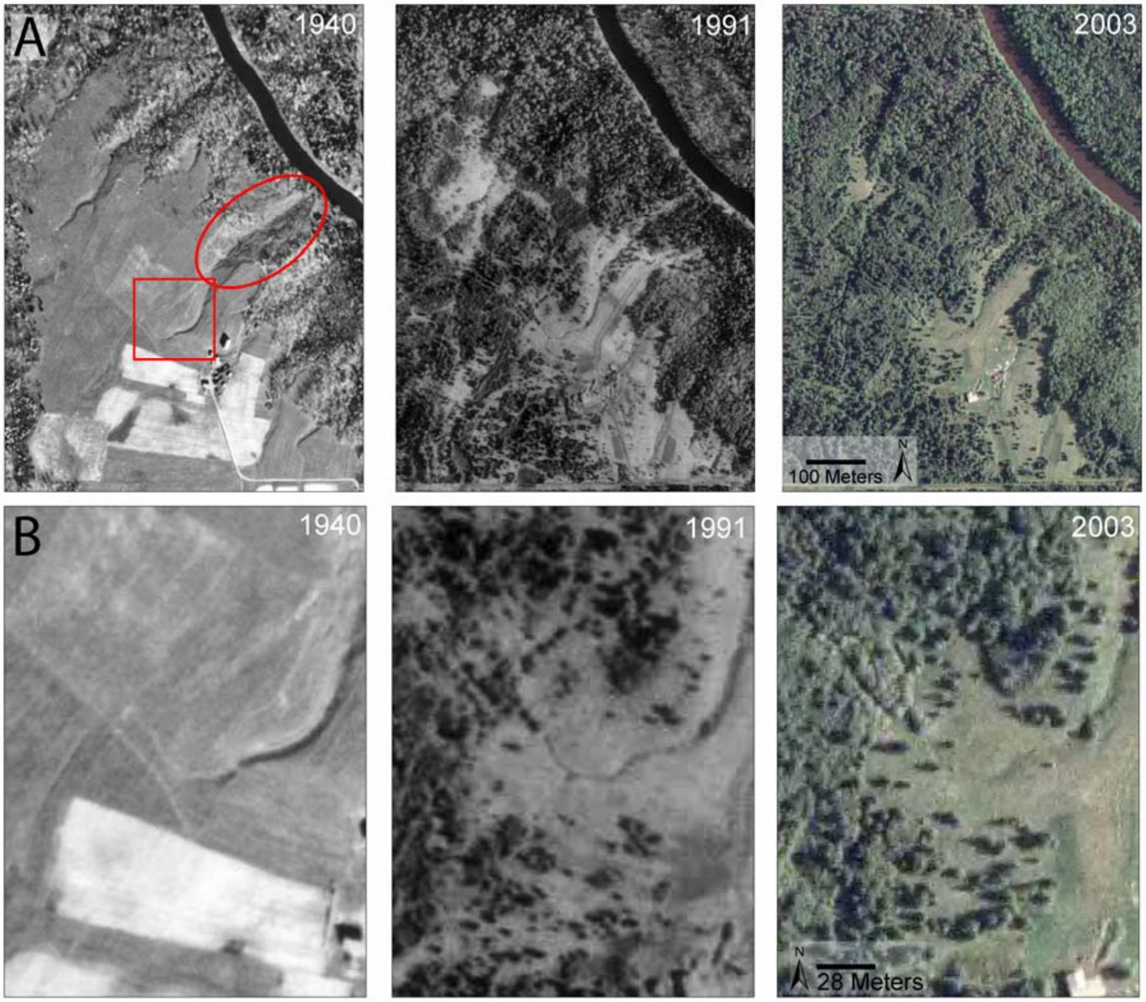

Figure 2.13: (A) A cleared field in the uplands near RM99 shows the heads of at least six ravines. One of those ravines was logged prior to 1940 (circled in red). (B) The head of this drainage remains visible through 2003, with no measurable growth or extension. A substantial area of cleared land in 1940 was reforested by 1991.

Tracking knickpoint migration was equally difficult. Figure 2.13 shows a series of minor tributaries/ravines cutting from the uplands down steep valley walls to the mainstem channel at RM 99. The heads of these tributaries are exposed in an open agricultural field in 1940. These tributaries did not extend headward by any measurable amount from 1940 to 2003. By 1991, the agricultural fields appear to be abandoned, and the forest is regenerating in this area. Slumps are visible in one of the tributary valleys in 1940, where steep slopes were cleared all the way to the channel.

Although these comparisons are useful, they are limited in scope due to the sparse number of visible slope failures, bank failures, gullies, or ravines visible in these photographs. To gain a broader perspective on slope and bank failures throughout the basin, I examined the parts of the landscape most susceptible to slope or bank failures: locations where meander bends abut steep, valley walls. In these areas, undercutting at the toe of the slope by the migrating river can trigger slope failures up to the top of the slope (see Figure 2.14). I cataloged outer bends throughout the mainstem from RM 115 to the mouth of the channel. A contour map produced from a 30-m DEM was used to determine if the channel was flowing against a high, steep valley wall.

Figure 2.14: The outer edge of a meander bend has slumps reaching up to the top of the slope break.

The catalog (Appendix B) was annotated as to whether or not the bend was cleared and whether or not signs of slope or bank failures were present (as delineated above). Sharp scarps or ravine/gully features were also noted. A simple comparison of whether any clearing was present or absent and any failures were visible or not shows a significant bias towards either forested with no visible failures or cleared with visible failures (Figure 2.15). This is either related to the visibility gained by removing the forest cover (i.e. the failures were there irrespective of the land cover, but only become visible when forest cover is removed), or it indicates a greater propensity for slope failures when the forest cover is removed. Slope failures do increase in steep terrain when forest cover is removed due to a loss of vegetative root reinforcement (Sidle 1992). Forest clearing can also lead to slope failures at lower slopes (Brardinoni et al. 2002) which would increase the number of slope failures overall.

Overall, slope or bank failures were visible on 53% of all outer bends migrating into steep valley walls in the 1940s. In 2003, that number had dropped to 40% of the bends. This did not include bends where steep slopes were set back from the river, which are prevalent in the lowlands of Sections V and VI. It also does not include bends migrating into low valley walls or floodplain deposits. The number of visible failures mirrors the distribution of bends with full or partial clearing (56% in 1940s and 37% in 2003) which both increases the risk of slope failures and makes them much easier to see on aerial photographs.

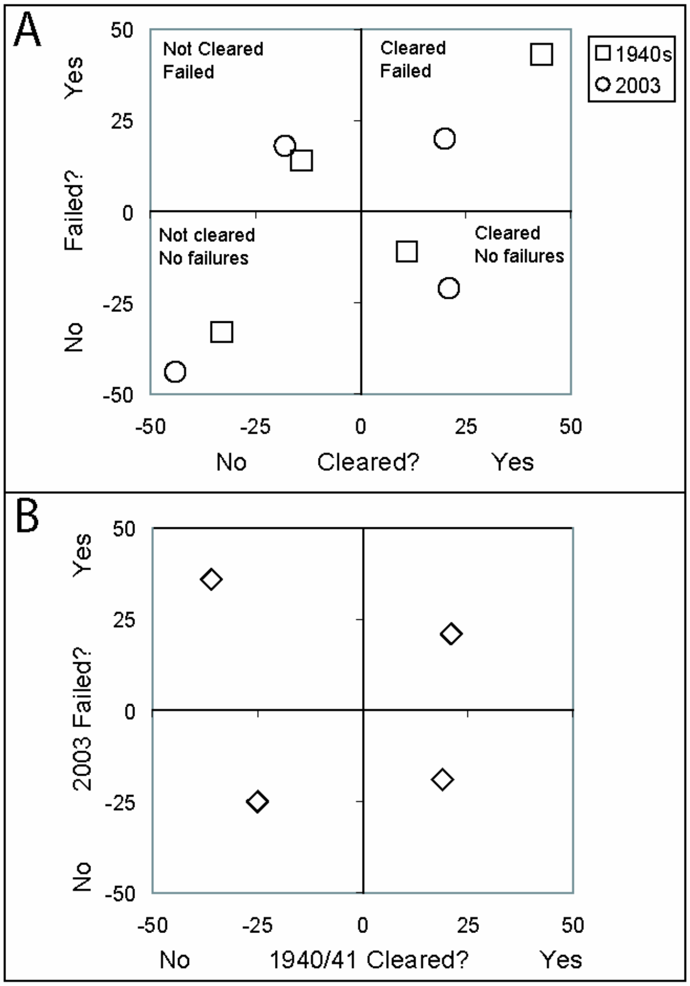

Figure 2.15: Matrices showing number of outer bends with and without forest clearing and with and without visible slope or bank failures. A) Bend conditions in 1940/41 and 2003 are plotted, showing a significant correlation between land clearing and visible failures. B) Land clearing in 1940 was compared with visible failures in 2003 with no significant correlations.

Conclusions:

There were no overall trends in land use in the reaches examined for this study. However, there was a significant increase in forest cover in section V reaches, both in the 1-km buffer focused study and the 300-m buffer study. This part of the basin has an upland landscape (paleofloodplain/lacustrine deposits) more suitable for agriculture than in the upper two-thirds of the basin. Some of the clearing may have been for agriculture which was less prevalent in 2003. Meanwhile, Section IV had a slight decrease in forest cover in 2003 in the 300-m buffer zone. In the 1940s photos, most of the cleared lands were found in the lowlands of sections V and VI. In 2003, cleared lands appear to be spread more evenly throughout the lower half of the basin (below ~RM 80), leading to the measured increase in clearing in section IV and decrease in clearing in Section V.

Slope failures are prevalent on many of the outer meander bends, where meanders are abutting steep valley walls. These areas are the most susceptible to slope failures and undercutting at the toe of the slope can trigger slope failures up to the top of the valley slope, releasing large amounts of sediment into the channel. In 1940, approximately 53% of mapped bends migrating into steep valley walls had visible slope or bank failures. In 2003, approximately 40% of these bends contained visible failures. The number of bends with full or partial clearing also decreased during this time period from 56% of bends in 1940s to 37% in 2003. Even if the land use in the buffer zones overall did not change appreciably over the 50+ years of study, clearing on these highly sensitive parts of the landscape did decrease.

Chapter 3
Floodplains

Objectives:

Investigations of the current active floodplain can yield information on whether or not there has been recent aggradation or degradation. The objectives of this chapter were to A) examine the current active floodplain for signs of aggradation through in-field observations and soil probing and B) if applicable, use tree cores to date new floodplain surfaces. Recognizing the entrenched nature of the Little Fork River, efforts initially were focused on the uppermost part of the basin, above Hannine Falls, and the lowermost part of the basin near the confluence as these areas were the most likely to have floodplain surfaces still hydraulically connected to the mainstem channel.

Summary of Findings:

The Little Fork River is still hydraulically connected to its floodplain upstream of Hannine Falls and downstream near the confluence with the Rainy River. In between these two areas, we visited eight different sites and found no evidence for post-settlement alluvium or recent floodplain deposition at six of those eight sites. However, two sites had evidence for recent aggradation on surfaces 3 – 4 m above the water surface and well above bankfull elevations. At Fielder Landing (RM 43) and the Sturgeon River confluence (RM 110), there was ~ 1 m of sand deposited on top of a buried sandy clay horizon. Buried tree stumps were found at both sites. At Fielder Landing, live trees ~30-50 years old were found 3 meters above the water surface, buried in at least 1 meter of sand. More work needs to be done to better understand the spatial extent of these large, sandy deposits and how the timing of their deposition relates to the timing of incision. Specific work might include comparing tree ages to gaging records to look for floods on record that may have caused the depositional event. In addition, further field studies on the river should include observations of whether or not fresh sediment is being deposited on different surfaces to help map out locations within the basin that are hydraulically connected to the channel and are still receiving sediment during flood events.

Methods:

Observations from field work in November 2006 indicated that the Little Fork River is entrenched throughout much of its length downstream of Hannine Falls, leaving very few areas where the channel and the floodplain were still hydraulically connected at reasonable flood flows. Observations from Samuleson Park (RM 101), Bois Forte access (RM 89), Dentaybow canoe launch (RM 56), Devereaux canoe launch (RM 36), and Lofgren Park (RM 20) showed no sign of recent aggradation, no buried tree crowns, and no obvious post-settlement alluvium deposits. The channel did appear to still have an active floodplain near the confluence with the Rainy River as observed from the Hwy. 11 bridge (RM 0) and above Hannine Falls as observed from Lindon Grove canoe access (RM 124). Figure 3.1 shows site locations.

To expand our area of study, a survey between RM 124 and RM 40 was done in ArcMap to look for areas with a high potential for maintaining active floodplain surfaces (Figure 3.2). This was done by comparing a contour map created from a 30-m DEM with 1-m resolution air photos from 2003. Locations with low, flat surfaces adjacent to the mainstem channel were mapped. In Itasca and St. Louis counties, a FEMA 100-year floodplain map was used as an additional guide. Upstream of RM 76, potential active floodplain sites were located primarily around the confluence with the Sturgeon River at RM 111, with only isolated patches elsewhere. Downstream of RM 76, there were likely floodplain areas on the inside of most meander bends, but it was not clear from remote mapping if they were low enough to still be hydraulically connected to the mainstem channel.

The reconnaissance mapping in ArcMap allowed us to target potential sites. From May 8 -11, 2007, B. Hansen visited the Lindon Grove access site (RM 124), the floodplain near the Rainy confluence (RM 0), and three additional sites: near the Sturgeon confluence covering RM 110-114, above Deadman's Rapids at RM 69, and Fielder Landing at RM 43. On all sites, soil probing was done to look for buried soils, and observations were made regarding buried root crowns or signs of recent floodplain deposits.

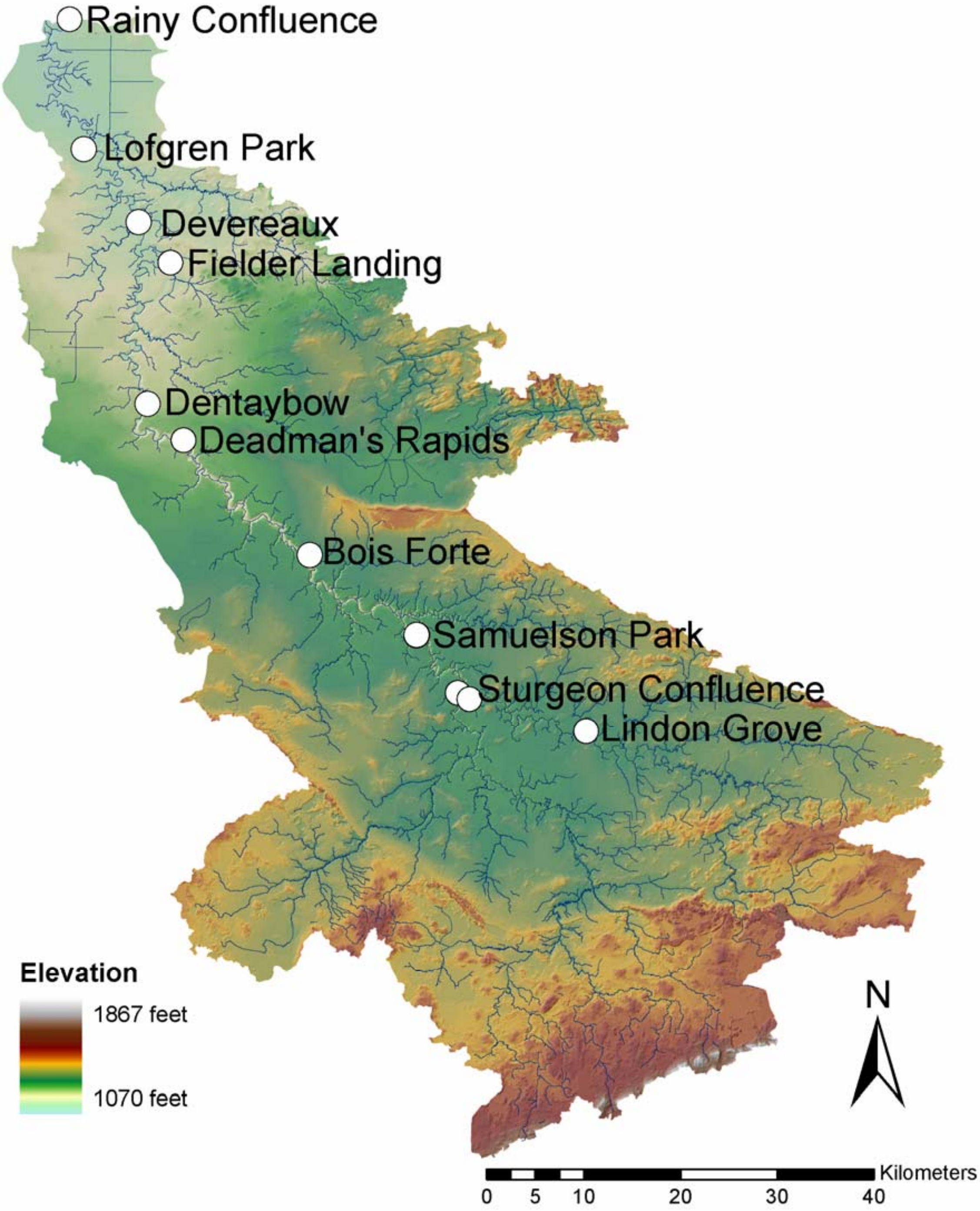

Figure 3.1: Site locations.

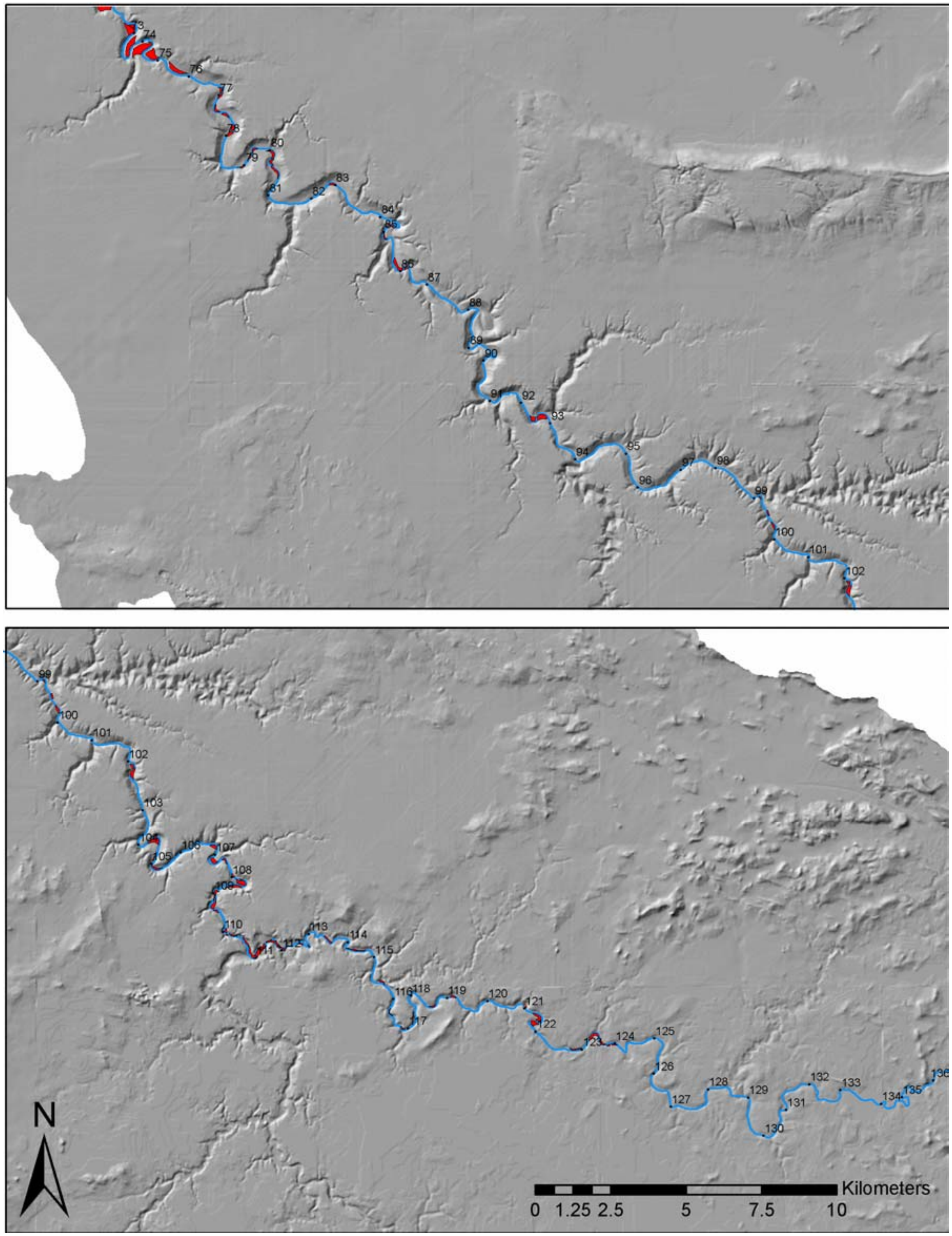

Figure 3.2: Map of potential floodplain locations, based on elevation and proximity to channel. The red areas show sites with low surfaces adjacent to the channel. Most of the potential floodplain sites were located near the Sturgeon River confluence or downstream of RM 76.

Results:

Field observations were made on the most extensive surfaces adjacent to the channel. In some cases, a new bench was being constructed or slumps along the channel were forming a new surface immediately adjacent to the channel. The elevations of both types of surfaces were noted with respect to the current water level at the time of field work (November 13 – 17, 2006, and May 8 – 11, 2007). During both times, the river level was fairly low. In November 2006, the discharge at Littlefork (USGS gage 05131500) was between 400 and 500 cfs. In May 2007, discharge varied between 700 and 900 cfs. This is a difference of < 0.3 m in stage, thus, comparisons of height "above the water level" for different sites are reasonable between time periods. Table 3.1 lists the heights of surfaces adjacent to the channel in terms of elevation above water level.

Table 3.1: Comparative heights of lowest extensive surface adjacent to channel.

Site Location	**River Mile**	**Terrace/Floodplain Height[1] (m)**	**Floodplain accessible?**	**New surface? Height?[2] (m)**
Lindon Grove	124	<2	Yes	
Sturgeon confluence	110	2.5-3	No	
Sturgeon confluence	110.5	3-3.5	Yes? up to 1m of sand; tree crowns buried	
Sturgeon confluence	112	Bankfull bench ~ 1m		Yes, planar slumps becoming new bench
Samuelson Park	101	4.3	No	N/A
Bois Forte	88	6.8	No	3.9 (bench)
Deadman's Rapids	69	4.5-5.5	No	
Dentaybow	56	3.8	No	3.8 (slump)
Fielder Landing	43	4	Yes? ~1m of sand; buried root crowns	
Devereaux	36	5.8	No	4.5 (bench)
Lofgren Park	20	5.7	No	N/A
Rainy confluence	0		Yes	

[1] Height of the lowest extensive surface adjacent to the channel with respect to the water level.

[2] If old surface was a terrace and a new bankfull bench was being constructed, the height of that new surface above the water level.

The floodplains both above Hannine Falls and near the confluence with the Rainy are still accessible under the current flow regime. At Lindon Grove (RM 124), the river is in a backwater zone from Hannine Falls downstream. The floodplain is low with respect to the river, and bulrushes were seen growing along the edges of the channel suggesting a shallow bench below water (Figure 3.3). At the confluence with the Rainy, the floodplain was clearly inundated in 1991 aerial photographs (Figure 3.4). This area experiences backwater effects during floods on the Rainy River.

Figure 3.1: Upstream of Hannine Falls, near RM 124. Bulrushes growing on the edges of the channel indicate a shallow, submerged bench rather than the steep, near vertical channel side slopes seen further downstream. The floodplain is accessible in this area.

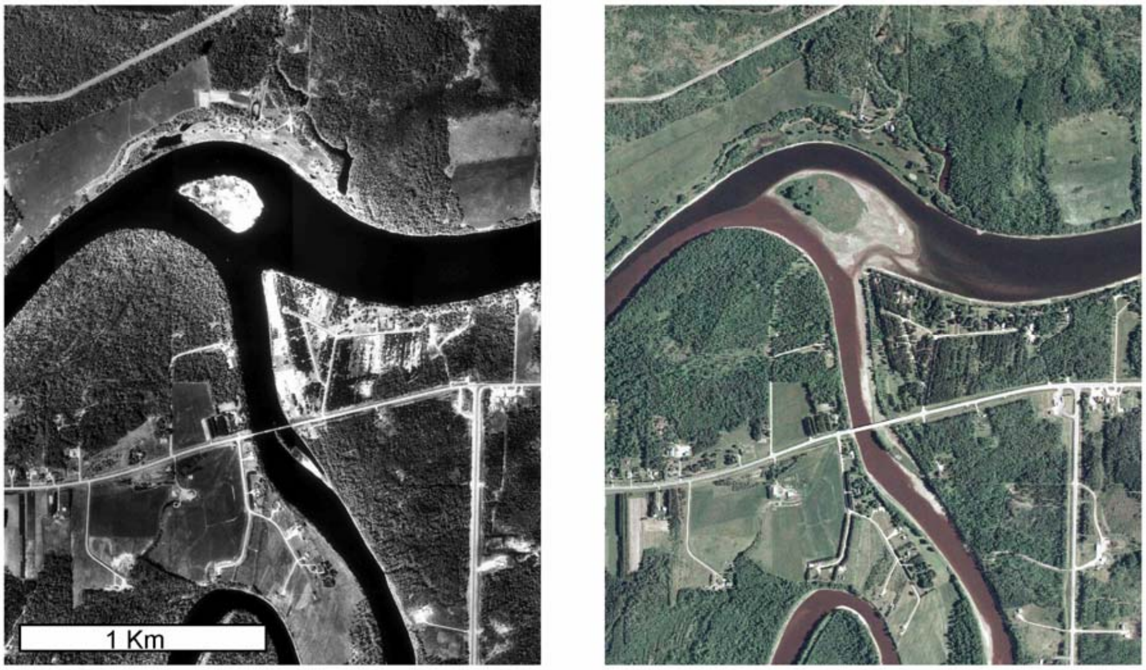

Figure 3.4: Mouth of the Little Fork River at the Rainy River confluence. In 2003 (right), water levels are low, exposing the Little Fork delta and part of the floodplain on the right bank side of the river. At the time photos were taken in 1991, the delta and floodplain were both inundated.

Between Lindon Grove and the mouth of the river, most of the sites we visited showed no signs of buried soils, buried root crowns, fresh sediment, or other signs of aggradation. The channel appears to be detached from its historic floodplain, only accessing it during large flood events or during back-up from ice jams.

Two sites did lead to some intriguing observations. At Fielder landing (RM 43) on the right-bank side there was about 1 m of sand deposited on top of a buried sand-clay horizon on a terrace. The terrace was 4 m above current water levels, and 2.5 – 3 m above the estimated bankfull level. Numerous dead stumps were being exposed by bank erosion (Figures 3.5 and 3.6). Live trees had root crowns buried under 0.3 – 1 m of sand (Figure 3.7). These trees were not cored, but ages were estimated at 30 – 50 years. This indicates that the aggradation occurred well after the initial wave of land clearing in the basin. A nearby tributary showed severe downcutting and bank erosion with no evidence of an active floodplain (Figure 3.8).

Figure 3.5: Buried stumps at Fielder Landing (RM 43).

Figure 3.6: Close-up of a buried stump at Fielder Landing (RM 43).

Figure 3.7: Trees with buried root crowns at Fielder Landing (RM 43). The tree on the far right was excavated, and the root crown was not found in the top 1 m.

Figure 3.8: Tributary to the mainstem Little Fork River just downstream of Fielder Landing (RM 43). The tributary shows signs of incision, with no evidence of a current active floodplain.

At the Sturgeon River confluence, a number of observations were made between RM 110 and 112. At RM 110.5, ~0.5 km upstream from the 114 bridge, another terrace had buried tree root crowns in dead trees (Figure 3.9). It, too, had 1 m of sand overlying a clay-rich unit. This terrace was estimated at 2 – 2.5 m above the current bankfull level. Slightly downstream, at RM 110, a terrace 1.5 – 2 m above current bankfull had no buried soils in the top 1.3 m. The site with the buried trees was downstream from the confluence with the Sturgeon River, and the site without tree burial was upstream of the confluence.

Figure 3.9: Tree crown buried under ~ 1 m of sand at RM 110, just downstream of the Sturgeon River confluence.

Conclusions:

Why some sites have significant aggradation well above bankfull while others show no signs of aggradation is still an open question. With only two sites showing significant aggradation, we do not feel we have enough data to draw firm conclusions yet. One hypothesis is that the sites with aggradation are low enough in elevation that the channel can access them currently or could access them in the last ~50 years. The sites we cored were fairly high above the water surface (4.3 – 6.8 m). Other sites we visited, like Devereaux and Deadman's Rapids, were 4.5 – 5.8 m above the water surface. Contrast that with the two aggrading sites which were ~3 – 4 m above the water surface. In addition, the two aggrading sites were ~1 m lower in elevation when the sand was first deposited. At three other sites, new bankfull benches appeared to be developing at similar elevations to the aggrading reaches (3.8 – 4.5 m).

Another hypothesis is that aggradation is patchy and related to local flow complexities generated by features like tributary confluences, rapids or waterfalls, or the dynamics related to ice damming during spring thaw events. The situation near the Sturgeon River confluence suggests that local complexities may play a role. Just downstream of the confluence, there is evidence for tree burial by up to 1 m on a surface ~2 – 2.5 m above the estimated bankfull level. A lower elevation surface nearby (~1.5 – 2 m above bankfull) showed no signs of tree burial. In this area, a bankfull bench had formed ~ 1 m above the water surface on top of old planar slump blocks, and the channel appeared to be in better shape than sites further downstream. More work is needed to better understand both the pattern and timing of local aggradation episodes on the Little Fork River floodplain.

Chapter 4
Post-settlement alluvium

Objectives:

The current hypothesis based on the weight of evidence from the Anderson et al. (2006) study is that historical logging at the turn of the century is responsible for destabilizing the Little Fork mainstem, releasing excess suspended sediment. It is quite common for initial land clearing activities to release a wave of sediment into the river system. This type of sedimentation is so widespread that it is known as post-settlement alluvium (PSA), and it has been studied fairly extensively in the humid East (e.g. Costa 1975, Meade 1982, Jacobson and Coleman 1986, Phillips 1991, Phillips 1993) and in the Driftless regions of the upper Midwest (e.g. Magilligan 1985, Knox 1987, Orbock Miller 1993, Beach 1994, Lecce 1997, Faulkner 1998).

The primary objective of chapter 4 was to determine the depth and extent of PSA in the Little Fork River watershed. The presence of PSA would indicate that a wave of sediment did occur from historical land use changes, and the volume of PSA deposited would give an indication of the severity of the problem. In addition, PSA stored in floodplain sediments can provide a rich source of sediment in the future, and thus it is worth assessing the volume of PSA in floodplain storage as a potential future source of suspended sediment.

To estimate the depth of PSA, soil cores were collected at three sites along the length of the Little Fork River, at river mile (RM) 20, 89, and 101. These soil cores were collected on the lowest extensive surface adjacent to the channel. The cores were analyzed to look for buried soil horizons as well as the presence of cumulic horizons which would indicate on-going fluvial aggradation. In addition, observations were made at all three coring sites as well as two additional sites along the channel for the presence of any active aggradation on these low surfaces.

Summary of Findings:

Our findings indicate that little or no PSA exists on the lowest extensive surface adjacent to the channel at three sites along the length of the impaired section of the Little Fork River. Several reasons for this may exist. First of all, due to current entrenchment of the Little Fork River, there may not actually be active floodplain surfaces upstream of the town of Littlefork (RM 20) and below the Lindon Grove canoe launch (RM 124). Although we cored the lowest extensive surfaces adjacent to the channel, these surfaces may no longer represent the active floodplain, inundated every 1.5 – 2 years. In some cases, the channel banks adjacent to our coring locations did have lower benches in them, but these were not yet fully developed surfaces, nor were they accessible. None of the cores showed cumulic A horizons which would be another indication of an actively aggrading surface. Our conclusions from these findings are that if a wave of PSA was released, it was preceded by channel incision, thus limiting access to the original floodplain. Since the floodplain was no longer accessible, little or no deposition of PSA occurred. The fate of any PSA sediment is not known, but it does not appear to be stored in the Little Fork River basin, upstream of the town of Littlefork. Thus, it is unlikely that PSA along the mainstem channel is a current source of turbidity, nor will it be an important source in the future.

Methods:

Our assessment of PSA is based on soil cores collected from three locations within the Little Fork River watershed. Cores were collected from Samuelson Park (RM 101), the Bois Forte Reservation site at RM 89, and Lofgren Park in the town of Littlefork at RM20 (Figure 4.1). We chose coring sites primarily for their accessibility, making efforts to get samples from the lowest extensive surface adjacent to the mainstem channel. In some cases, there were small “benches” developing at a lower elevation, but these surfaces were not accessible, continuous, nor extensive (generally less than a few meters in width). In some cases, they were defined more by a break in slope than a horizontal surface. Sometimes, these lower “surfaces” were clearly the top of slump blocks sliding into the channel. It other cases, they were convex-upward surfaces leading from the surface where cores were collected down several meters to a steep drop-off to the water surface. These lower surfaces may represent bankfull benches developing under the current hydrologic regime. Coring locations at each site are shown in Figures 4.2, 4.3, and 4.4.

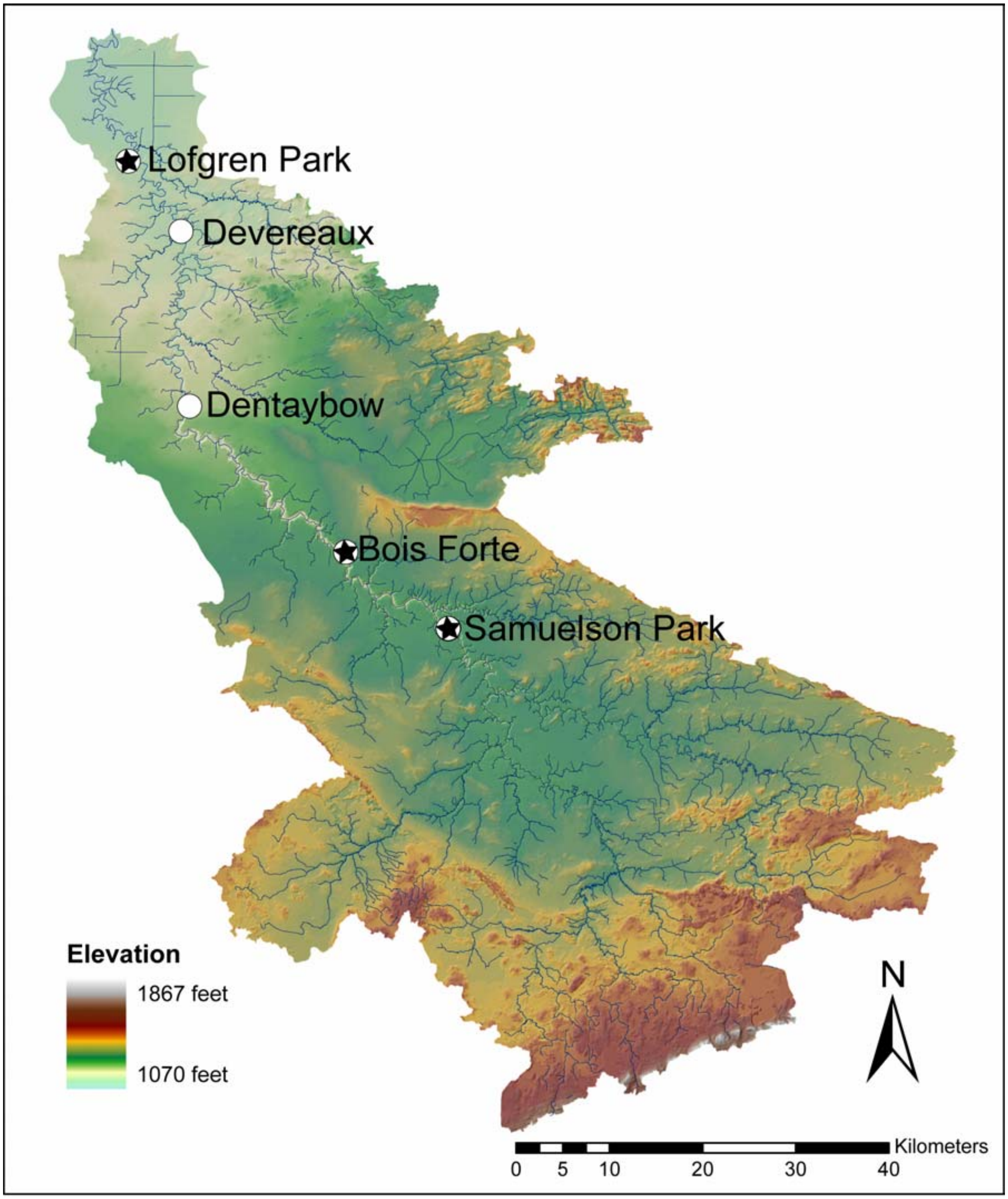

Figure 4.1: Locations of coring sites (stars) and additional sites where observations were made regarding the presence of on-going fluvial aggradation.

At Samuelson Park, we collected five cores, including a transect of four cores starting at the edge of the channel bank and extending back 100 m inland over ridge and swale topography (Figure 4.2). The surface was clearly an active floodplain at a relatively recent point in the river's history, given the topography and fluvial features. A fifth core was collected off the transect, adjacent to the edge of the channel bank.

Figure 4.2: Location of cores collected from Samuelson Park, RM 101, TR Section.

At the Bois Forte site, we collected two cores, one adjacent to the top of the channel bank, and one 46 m further inland on the same topographic surface (Figure 4.3). At Lofgren Park, we collected two cores (Figure 4.4). The first was collected adjacent to the edge of the channel bank (3-4 m from edge). The second was collected 150 m inland on the next terrace up in elevation. This last core was only two meters long. Most cores were > 4 m deep.

Two-inch diameter soil cores were collected with an MPCA Geoprobe (Figure 4.5), wrapped, and brought back to the lab for analyses. All cores were split in half lengthwise using a rotary saw and wire. One of the splits was used for soil and stratigraphic descriptions. The other half of the splits were saved for any future analyses.

In addition to core collection, observations were made at all sites as well as two additional sites: Devereaux canoe launch (RM 36) and Dentaybow canoe launch (RM 56). At all five of these sites, we looked for evidence of recent aggradation including exposed sediments, sparse vegetation, or buried tree crowns. At the time of our surveys (Nov. 13 – 17th, 2006), these sites varied from 3.8 to 6.8 m above the water surface.

Figure 4.3: Location of sediment cores collected from Bois Forte site (RM 88).

Figure 4.4: Location of sediment cores collected from Lofgren Park in the town of Littlefork (RM 20). LF-1 was 3-4 m from the slope break at the channel edge. LF-2 was on the next terrace up in elevation.

Results:

In Samuelson Park, we collected 4 soil cores (SAM-1 through SAM-4) in a transect moving from the channel across an old floodplain surface, with prominent scroll bar topography. A map showing locations of soil cores is shown in Figure 4.2, and descriptions of the cores are given in Appendix C. We collected an additional fifth core (SAM-5) near the channel in a second location, adjacent to a current bedrock knickpoint. In 4 of the 5 cores, I saw no evidence for any buried soils. In the SAM-5 core, there was a distinct buried soil, overlain by 11 cm of clay, with a new A-horizon developed in the upper 6 cm of the clay. Both the SAM-5 and the SAM-1 site were located in similar positions, near the edge of the channel, but the SAM-5 site was located 104 cm lower in elevation than the SAM-1 site, and thus may have received more deposition from slightly lower flood stages. It is possible this represents PSA deposition. Although the material on top of the buried horizon was dissimilar from many PSA deposits in other parts of the state like the Driftless area (generally lighter in color, sandy, and containing distinct depositional features (e.g. Knox 1987, Beach 1994, Faulkner 1998)), the Little Fork River has a very different geologic setting than the Driftless area, and PSA deposits may be quite different in character.

At the Bois Forte site, we collected two cores, one right next to the channel (BF-1) and the second (BF-2) located 46 m further inland (see Figure 4.3). Both cores were at similar elevations (~ 6.8 m above current river level). At both sites, buried soils were present, but they were overlain not by a fine clay-rich overbank deposit, but instead by a coarser sandy unit. At BF-1, a thin loamy A-horizon was developed in 9 cm of loam with coarse sand and gravel. At BF-2, an A-horizon was developed in 8 cm of sandy loam on top of a silty clay loam A-horizon. One potential source for this sandy horizon may by historic activities at the site: We were drilling fairly close to a road in a small picnic/campground area. Both the road and some significant land disturbance in the area are visible in 1940s aerial photographs. I do not believe these represent PSA deposits.

At the Lofgren Park site in the town of Littlefork, we collected two soil cores: LF-1 was taken directly adjacent to the channel, and LF-2 was located on the next highest terrace (Figure 4.4). The LF-1 core was quite deep (8.5 m), extending back to Glacial Lake Agassiz lacustrine clays (encountered at 7.1 m). The LF-2 core was shallow (2.4 m) to determine the composition of the upper alluvial terrace. Neither site had a buried soil present, nor was there any evidence for PSA deposition.

To summarize, of all the sites where we collected soil cores, only three cores had any buried soils. At the Bois Forte site, overlying material was coarse and sandy and was more likely derived from direct anthropogenic land disturbance rather than overbank deposition of excess alluvium. At Samuelson Park, although the overlying material was fine-grained (clay loam to clay), it had a distinct A horizon developed in it, and lacked any features of more standard cumulic PSA deposits. It is more likely that the overlying deposit simply represents standard fine-grained pre-settlement floodplain or backwater sedimentation.

Additional information can be gleaned from these cores. Active floodplain deposits close to the channel often show cumulic A horizons. These horizons contain both pedogenic and sedimentologic characteristics showing soil development occurring at the same time as episodic deposition (for example: many layers of organics mixed in with sandy or silty layers). Although the subsurface deposits show this kind of depositional system (layers of sand from event deposits intermixed with more clay-rich deposits), soils developed at the surface were more well-developed and did not show evidence for on-going deposition during soil development. This may be further evidence that the floodplain surfaces we were coring are no longer connected hydraulically to the river channel at 1.5-2 year flows and are only inundated during large, less frequent events.

The surfaces we chose to core were the lowest extensive surfaces adjacent to the mainstem channel. In some cases, lower benches were forming, although these had not yet developed into continuous, extensive surfaces, and they were not accessible to the Geoprobe. A photo taken at the Bois Forte site shows one of these low benches (Figure 4.5). It is possible that these surfaces contain PSA deposits. Even if they do, their small width (generally < 2-3 meters wide) and local extent only would lead to a relatively small volume of PSA deposited along the mainstem channel.

Figure 4.5: Left bank of Little Fork River at Bois Forte site. We cored the upper surface on the right-bank side of the channel. This was 2.9 meters above the low bench seen here on the opposite bank. The coring location was on the outside of a meander bend, and the low bench was narrower on the right-bank side.

Conclusions:

The low surfaces we sampled adjacent to the mainstem Little Fork River channel no longer appear to be connected to the mainstem channel at flows as low as the 1.5 – 2 year flood, and are thus no longer "active floodplain" surfaces. Anecdotal evidence and observations of flood debris in trees and bushes, indicates that these surfaces are not far above the elevation of these semiannual flood events, or they experience flooding during ice jams in the spring. They were probably active floodplain surfaces until recently, and incision of the mainstem has stranded them above the active channel. This incision may have occurred during the early years of forest clearing or even earlier given the degree of soil development on these near-channel surfaces. The lack of PSA deposits on these surfaces indicates that either incision preceded PSA deposition, or that PSA in the Little Fork was minimal compared to other systems. Either way, PSA is not a concern as a future supply of suspended sediment to the Little Fork River.

It has been shown in other fluvial systems in the Upper Midwest that valley width and the degree of entrenchment play an important role in the deposition or transport of PSA materials (Faulkner, 1998). Channels that are deeply incised have less PSA deposited in them, as the channel is able to transport flood discharges of greater magnitude without spilling out onto adjacent floodplain surfaces. Likewise, channels with narrow valley bottoms tend to have a lower volume of PSA deposited in them because there is less room to accommodate deposition. In addition, wide valley bottoms are correlated with larger drainage areas and thus a larger source for sediment. In the Little Fork River, the channel is entrenched, so higher flows can be accommodated before the channel accesses the floodplain. Most of the valley bottom surfaces that may have been in the active floodplain in the past appear to now be stranded above the elevation of the 1.5 – 2 year flood. In some reaches of the river, the valley bottom, even including these surfaces, is quite narrow (see chapter 1) leaving little room for floodplain deposition. Given our observations, the incision and entrenchment of the channel likely occurred during or prior to any wave of PSA released from land clearing, leading to a narrow valley and entrenched channel that was unable to accommodate any widespread deposition of PSA.

Chapter 5

Mid-channel island at confluence

Objectives:

An increase in sediment loading historically on the Little Fork River may be evident through growth in the delta at the confluence with the Rainy River. Historic air photos were used to assess island changes from the 1940s to the present. To look back further in time, tree borings were used to determine ages of trees along the edges of the island. A systematic decrease in tree age towards the banks could give a measure of the rate of island growth.

Summary of findings:

The mid-channel island at the confluence with the Rainy River has been fairly stable over at least the last 60 years. Air photos from 1940 through 2003 show no significant growth in the island and little change in island boundaries. An effort to date trees to look at longer term island history found a distinct gradient in tree age from east to west. This gradient in ages is not related to island growth, but may be related to greater risk of ice damage on the east side than on the relatively protected western edge. Soil cores show a soil developed into alluvial sands and gravels overlying glacial clay tills or lacustrine deposits at a depth of 24" – 34". An unusual horizon composed primarily of wood debris was found on the northern side of the island. Future dating could determine the age of that deposit, now covered in alluvial sand and gravels.

Methods:

There were two parts to this study. The first involved a comparison of historic aerial photographs to look at potential island growth (or erosion) over the past 63 years, from 1940 through 2003. A photo of the island from 1940 was scanned in at high resolution. The photo was georeferenced in two stages. The first pass at georeferencing used only anthoropogenic features like roads or buildings with a second-order polynomial fit. Unfortunately, there were not enough georeferencing points to get a good fit. A second pass compared the banks along the Rainy River in both 1940 and 2003, since both photos were taken at similar flow stages. Then the photo was georeferenced with a first-order polynomial fit.

To compare the photos, the raised portion of the island (with "permanent" vegetation) was digitized in all three years. In 1940 it was not as easy to see the slope break on the eastern side, so both the apparent slope break and the edge of grasses were digitized in. In 1991, flow stage was high enough that only this raised portion of the island was visible. Photos from each year and a comparison of the island are shown in Figures 5.1 and 5.2.

On May 8, 2007, B. Hansen visited the mid-channel island to determine tree ages along the western half of the island and study the island stratigraphy more. He was able to core five trees on the western end of the island using an increment borer to obtain ages for the trees. He also collected soil samples using a soil probe or shallow pit to determine the stratigraphy on the island. The focus was on a transect from the water's edge to the upper surface and replicate upland samples. A map detailing locations of trees cored and soil samples collected is in Figure 5.3.

Results:

The island has an elevated core surface on the western half of the island. Although most of the flow from the Little Fork River flows to the west of this raised island, a smaller channel drains around the eastern edge of the island. There is a noticeable delta building in that location. The size of the delta cannot be readily compared between years because different flow stages cover different portions of it. Photos in 1940 and 2003 were taken at a relatively low flow, exposing the low eastern half of the island and the delta. In 1991, flows were higher, and everything was submerged except for the elevated central core of the island (outlined in yellow on Figure 5.1).

Island growth from 1940 – 2003 was not noticeable (Figure 5.2). There were some changes in the island geometry, but the overall area of the upper surface did not change appreciably. The surface has been fairly stable since at least 1940.

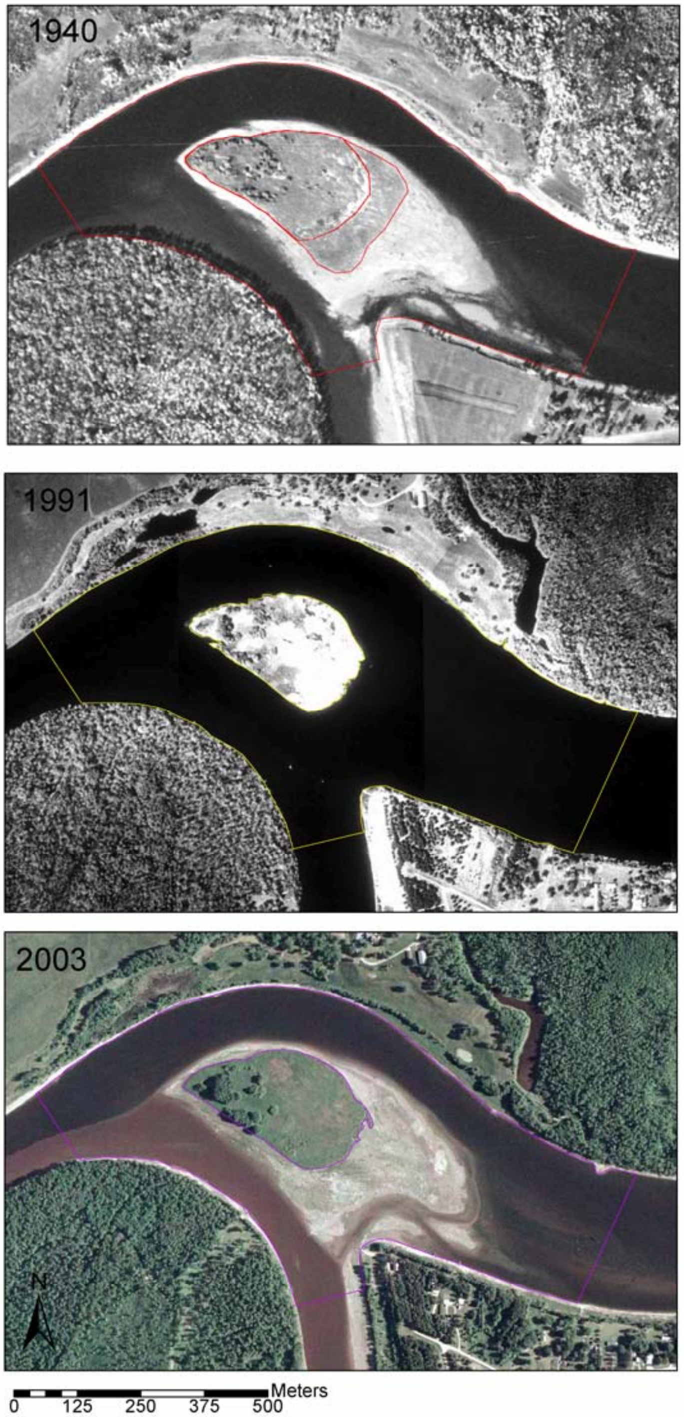

Figure 5.1: Mid-channel island at the Little Fork – Rainy River confluence in 1940, 1991, and 2003. The raised core of the island was digitized each year (outlined in red, yellow, and purple). Most of the Little Fork River discharge flows to the west, but some flows to the east, where a delta is being built out into the Rainy River.

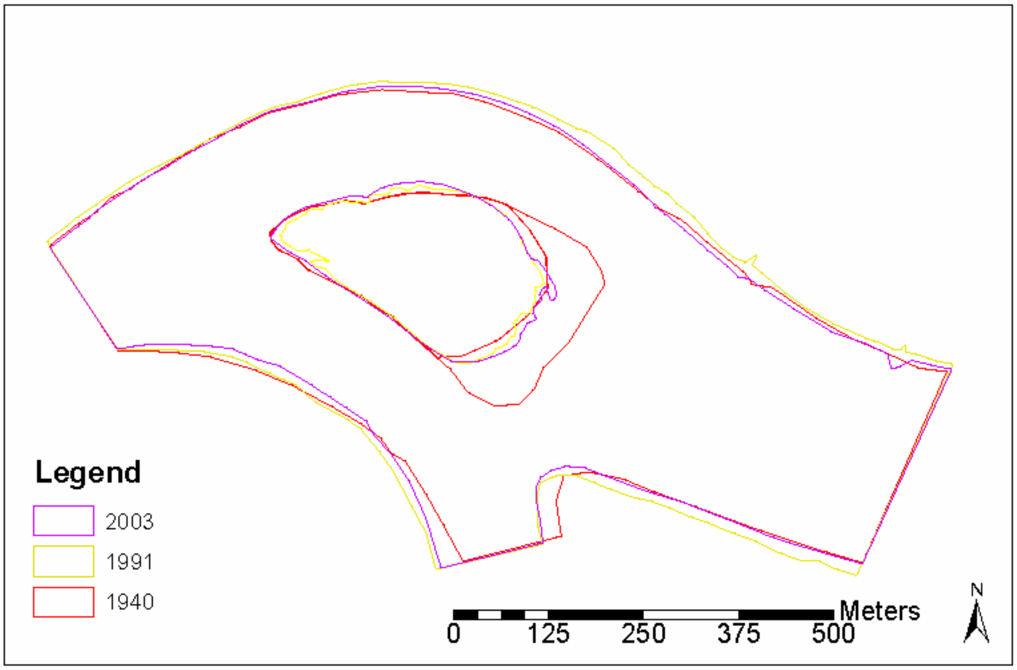

Figure 5.2: Traces showing the location of the mid-channel island in 1940, 1991, and 2003. In 1940, it was difficult to determine the slope break, so both the estimated slope break and the edge of the vegetation were digitized in.

To investigate the island's history further back in time, tree borings and soil cores were taken. Figure 5.3 shows a location map with the approximate location of trees that were dated and soil cores that were collected. Five trees were cored and dated, with ages running between 25 years on the east to 75+ years on the west. This does not represent growth of the island from west to east over that 50-year time period though, as there was evidence of older tree stumps mixed in with the younger trees to the east. The mechanism for this age distribution is not clear, but one hypothesis is that it relates to the effects of ice damage on trees. Most of the trees were found in clumps (see Figure 5.4) which offers a form of protection to the innermost trees against damage from ice rafts during high flows. The trees on the eastern half of the island are more exposed than those on the western half, and thus have a harder time surviving, especially if isolated. The age gradation may be the result of periodic destruction of trees to the east and subsequent regrowth.

Figure 5.3: Location map of island showing trees that were cored (labels are offset from the actual trees cored) and locations of soil cores/pits (B1-B5).

Figure 5.4: Trees on the island tend to grow in clumps, which may help protect them from ice damage during high flows.

Figure 5.5: Rise on the south side of the island. The pole sticking up marks the location of a soil pit (B2).

Soil cores were collected from five locations on the island including a transect on the Little Fork River side from the sand bar adjacent to the river up to the elevated core of the island (see Figure 5.5). On the sand bar (B1), the entire column was sand and gravel. On the rise (B2), the upland (B3) and a replicate sample 200 feet to the east (B4), there was an organic soil developing on top of sand and gravel overlying a clay till unit (at 24-34”). On the Rainy River side of the island, a core produced sand and gravel on top of 16” of wood residue. This wood lay on top of another sand and gravel unit on top of the clay till. Five different holes were dug covering a distance of around 200 feet, and all five had the wood layer present. On top of the island, the wood was deeper down. Without any dating, it is unclear when the wood was deposited and then covered with a fresh sand and gravel deposit without being washed away. The wood could represent an old log jam that has decayed in place.

Conclusions:

The mid-channel island at the confluence with the Rainy River has been stable over at least the last 60 years. Air photos from 1940 through 2003 show no significant growth in the island and little change in island boundaries. Trees show a distinct gradient in age from east to west that is not related to island growth, but may be related to greater risk of ice damage on the east side than on the relatively protected western edge. Soil cores showed alluvial sands and gravels overlying glacial clay tills or lacustrine deposits at a depth of 24” – 34”. An unusual horizon composed primarily of wood debris was found on the northern side of the island. Future dating could determine the age of that deposit, now covered in alluvial sand and gravels.

Chapter 6
Basin hydrology and bankfull flow

Objectives:

The goal of this analysis was to use U. S. Geological Survey gage data coupled with MPCA cross-sectional surveys to determine the current location of bankfull depth in the lower Little Fork River. This involved doing a peak flow analysis on six different reaches and calculating the flood discharge for a 1.5-year to 2-year flood event ($Q_{1.5} - Q_2$) at fourteen locations within the watershed. Bankfull depths were estimated in the field at access points and compared with relict floodplain/terrace heights. Finally, the effective discharge at the USGS gage in Littlefork was calculated based on suspended load transport data from the 1970s and compared with field observations of bankfull depth and calculations of $Q_{1.5}$ from Anderson et al. (2006).

Summary:

Peak flow analyses conducted on six gaging stations were used to adapt regional USGS curves to the Little Fork River basin. A new empirical equation was used to calculate Q_2 discharge on 14 sites in the Little Fork River basin. There is a strong relationship between Q_2 and drainage area which potentially could be used to extend the analysis throughout the basin.

Effective discharge as measured at the Littlefork gaging station was determined to be ~7250 cfs, within the range of measured $Q_{1.5}$ flows of 6900 cfs (Anderson et al., 2006) and 7330 cfs (this study). This indicates that floods of low-magnitude but high-frequency are responsible for moving the majority of the sediment over the long term. This flow likely corresponds to the discharge currently building new bankfull bench surfaces below the level of near-channel terraces. For most of the middle Little Fork River, the topographically extensive near-channel surfaces are relict floodplains, now terraces that lie above the area accessed by a 50-year flood.

Background:

The bankfull discharge is the flow that fills a channel to the tops of its banks (thus the term "bankfull"). According to an analysis by Leopold et al. (1964), bankfull discharge corresponds to a flow with a recurrence interval of ~ 1.5 to 2 years ($Q_{1.5} - Q_2$). Williams (1978) did a frequency analysis on the recurrence interval of bankfull discharge in 28 streams and found that although the peak in the distribution is at $Q_{1.5}$ (Figure 5.1), in most channels the $Q_{1.5}$ discharge does not correspond to a bankfull flow, and the distribution of bankfull flows includes flows from ~Q_1 to Q_{50}.

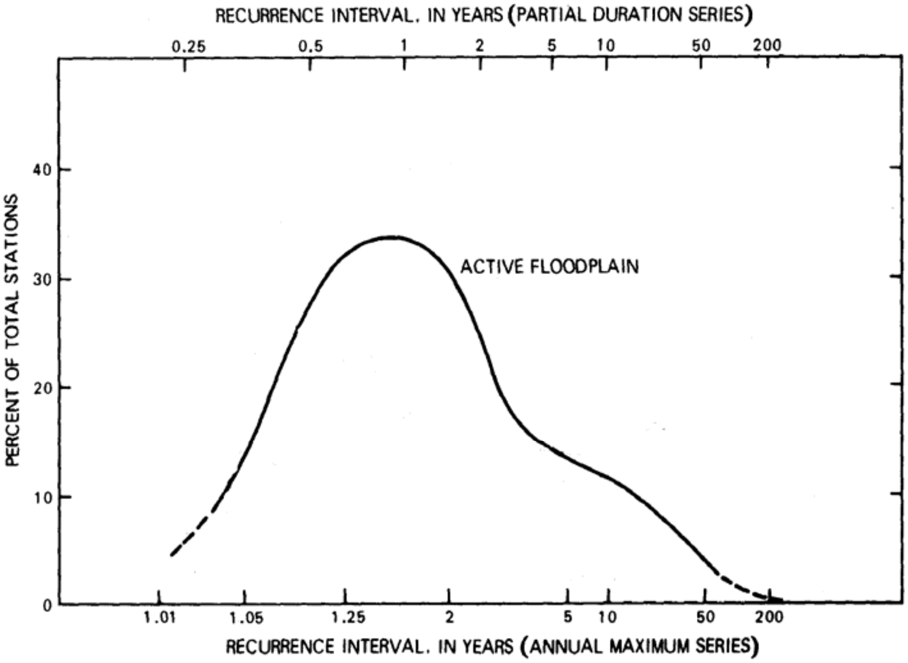

Figure 5.1: Frequency distribution of the recurrence intervals for bankfull flows (from Williams (1978)).

The link between the channel-filling discharge (Q_{bf}) and the channel-forming discharge (effective discharge) (Q_{ef}) originated with the theory by Wolman and Miller (1960) that it is low-magnitude, high-frequency events that are responsible for modifying the shape of a channel, because these flows mobilize the most sediment over the long term (Figure 5.2). Thus the Q_{bf} that occurs every ~1.5 years is also the flow responsible for creating and modifying the shape of a self-formed alluvial channel. Measurements of sediment transport in the field found that, indeed, the Q_{ef} correlates well with the Q_{bf} (i.e. Andrews, 1980). Later studies have shown that the effective discharge can have a recurrence interval of anywhere from a week to several decades (Nash, 1994).

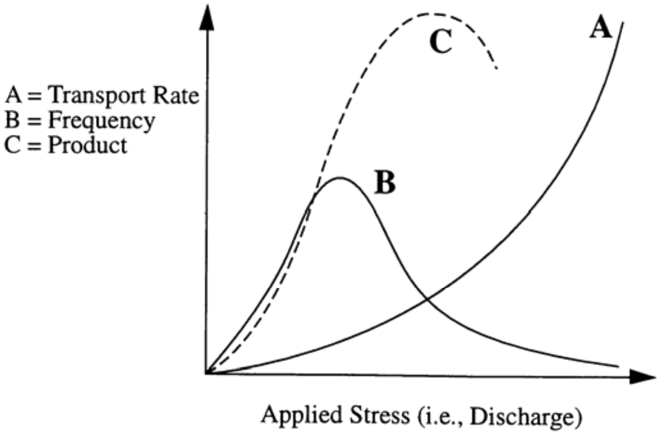

Figure 5.2: Effective discharge is the flow that moves the maximum sediment load over time which is the product of the transport rate for a given flow (A) and the frequency at which that flow occurs (B), which is shown by curve C. The Q_{ef} is theorized to be a low-magnitude, high-frequency flood events (peak in curve C). From Wolman and Miller (1960).

In systems with altered hydrology, the term "bankfull" can be misleading and complicated. If a system has recently entrenched, then the $Q_{1.5}$ may be well below the current banks. In these cases, the term "bankfull" can either be used to refer to the classic $Q_{1.5}$ flood event or to the discharge at which the river reaches the top of the banks and spills into the floodplain. In both cases, the implication that the bankfull discharge is also moving the most sediment, and is thus the effective discharge, needs to be addressed. For this study of the entrenched Little Fork River, we have tried to separate measures of the $Q_{1.5}$ or Q_2 flood event from observations in the field of where the banks are located and where new "bankfull" benches are being constructed. The implication here is that bankfull benches mark the location of the current bankfull discharge which may or may not be the same as a classic $Q_{1.5}$ flood event. The effective discharge was calculated from suspended load records to compare with different flood discharges determined from gaging records to determine if Q_{bf} is equivalent to Q_{ef} under current conditions in the Little Fork River.

Methods:

Records from six gaging stations within the basin were used to determine discharge for different flood events, including $Q_{1.5}$ and Q_2 events. These gaging stations included two on the mainstem Little Fork River at Cook and at Littlefork, and four on tributaries including the Sturgeon River, Dark River, Nett Lake River, and Wood Duck Creek. Table 5.1 lists gaging station records used for these analyses. Standard procedures from Bulletin 17B (USGS, 1982) were followed to compute flood frequency curves for each station.

Table 5.1: USGS Gaging stations used for peak flow calculations

Station	Station ID	Drainage Area (mi^2)	Years of Record
Little Fork River at Cook	05129650	61.5	17
Little Fork River at Littlefork	05131500	1680	85
Sturgeon River at Chisholm	05130500	180	63
Dark River at Chisholm	05131000	50.6	33
Nett Lake River near Nett Lake	05131455	128	9
Wood Duck Creek near Nett Lake	05131448	31.8	9

Two-year event flows (Q_2) were calculated on fourteen reaches along the Little Fork River (see Table 5.2). Calculations involved a two-step process. Regional curves developed by the U. S. Geological Survey (Lorenz et al., 1997) were initially used to calculate the discharge for a two-year flow event. Regional flood frequency curves in northern Minnesota depend upon drainage area (*DA*), storage in the watershed (*ST*), % of the watershed in lakes (*L*), and generalized mean annual runoff (*RO*). For the 2-year flood event, the regional curve is

$$Q_2 = 5.6 \times DA^{0.82} \times (ST+1)^{-0.136} \times (L+1)^{-0.4} \times RO^{0.859}$$

using the units listed in Table 5.2. The results for the 2-year flood event were compared with calculations from peak flow analyses, and a correction to the leading coefficient was made to more closely align the regional curve results with the gaging records within the basin. The resulting curve used for this study is

$$Q_2 = 9 \times DA^{0.82} \times \left(ST + 1\right)^{-0.136} \times \left(L + 1\right)^{-0.4} \times RO^{0.859}$$

This curve was applied to fourteen reaches in the Little Fork River basin, including seven sites on the mainstem and seven tributaries (See Table 5.2). The standard error for the regional curve from Lorenz et al. (1997) was 38%. Figure 5.3 shows the relationship between drainage area and Q_2 for these fourteen sites.

Table 5.2: Q_2 on select reaches in Little Fork (LF) River Drainage Basin

Reach	**Drainage Area (mi^2)**	**Storage (% of basin area)**	**Lakes (% of basin area)**	**Annual runoff (in)**	**Q_2 (cfs)**
LF Beaver to Rainy	1680	40%	2%	7.7	8919
LF Cross to Beaver	1633	40%	2.11%	7.7	8589
LF Ester to Cross	1585	40%	2.27%	7.7	8214
LF Nett to Ester	1357	38%	1.85%	7.7	7694
LF Nett Rapids	1021	34%	2.35%	8	5989
LF Sturgeon to Nett Lake	330	40%	1.8%	8	2494
LF Cook	61	40%	2%	8.9	666
Sturgeon River	573	32%	3.14%	8	3454
Dark River	283	30%	4.81%	8	1706
Nett River	215	49%	5.18%	8	1245
Rice River	128	36%	3.73%	8	943
Beaver River	105	43%	0%	8	1461
Willow River	75	33%	0%	8	1146
Sturgeon River	180	32%	4.1%	8	1230

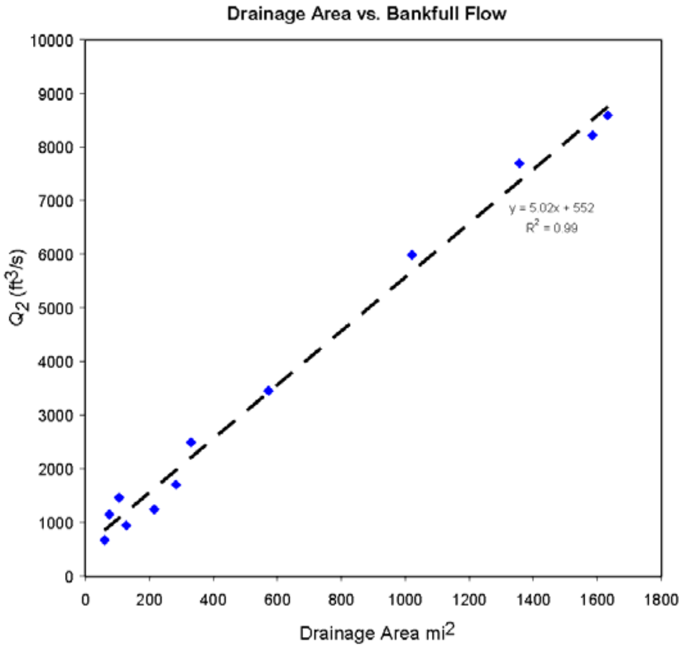

Figure 5.3: Relationship between drainage area and Q_2 in the Little Fork River basin.

Potential bankfull elevations were determined in the field visually using clues from vegetation, fresh deposition, or topographic benches or low surfaces (see Figure 5.4). These correspond to the elevation reached by the current channel-modifying flow. Elevations of terraces adjacent to the channel were also surveyed or estimated in the field. Terrace heights (D_{terr}) were compared with two times the bankfull depth (D_{bf}) as a proxy for measuring an entrenchment ratio. The classic entrenchment ratio is a measure of the channel width at $2*D_{bf}$ vs. the channel width at D_{bf} (Rosgen, 1994). Here, we compare $2*D_{bf}$ with D_{terr} (see Table 5.3 and Figure 5.5). The elevation of $1.8*D_{bf}$ is the approximate depth of a Q_{50} flood event based on streams in the eastern United States (Leopold et al., 1964), so $2*D_{bf}$ represents a depth greater than the Q_{50} flood depth.

Figure 5.4: Bankfull bench near RM 88.

Table 5.3: Terrace heights vs. estimated bankfull depths above the bed surface.

River Mile	D_{terr} (m)	D_{bf} (m)	$2 * D_{bf}$
124	2.0	1.0	2.0
111	3.1	1.2	2.4
101	5.0	1.4	2.9
88	7.7	1.9	3.8
69	6.6	2.1	4.2
56	5.0	2.3	4.7
43	5.3	2.5	5.1
36	7.2	2.8	5.5
20	7.3	3.3	6.5

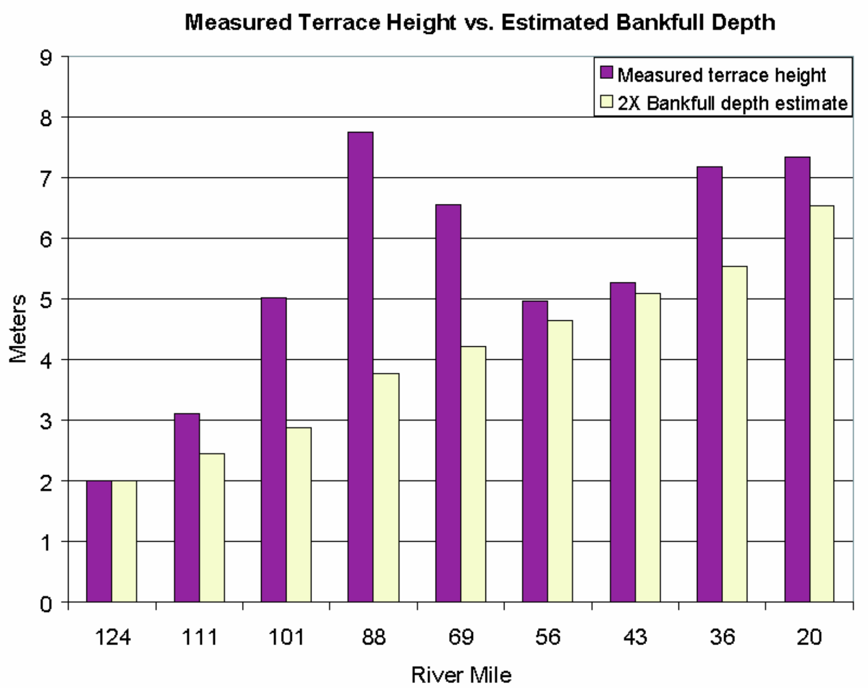

Figure 5.5: Relationship between measured terrace heights and estimated bankfull heights. Bankfull heights were estimated visually based on developing benches, recent deposits on surfaces, and vegetation changes. Plotted here are 2* D_{bf} vs. D_{terr}.

To determine the Q_{ef}, suspended sediment samples collected at the Littlefork gage in the 1970s were analyzed to find the discharge at which maximum suspended sediment transport occurred over time. Because there are no good bankfull indicators near the gaging station, this could provide some confirmation as to whether the $Q_{1.5}$ as determined from gage data is a reasonable proxy for the Q_{ef} at this site. A frequency distribution was created from the 433 samples to determine the discharge at which the maximum sediment transport occurred (Figure 5.6). This was compared to the $Q_{1.5}$ reported by Anderson et al. (2006) and the value calculated here by standard flood frequency analysis of the Littlefork gage data.

Results

The results from peak flow flood frequency analyses for each of six gaging stations in Table 5.1 are given in Table 5.4, including the $Q_{1.5}$ and Q_2 and the length of record. The actual discharge – frequency plots are in Appendix D. These peak flows were used to help calibrate the regional curves from Lorenz et al. (1997) which were then applied to fourteen reaches or tributaries in the Little Fork River basin. Table 5.2 lists the Q_2 calculated at each of these reaches. There is a very good correlation between drainage area and Q_2 discharge as seen in Figure 5.3.

Table 5.4: Results of peak flow analyses at six gaging stations

Station	$Q_{1.5}$ (cfs)	Q_2 (cfs)	Years of Record
Little Fork River at Cook	450	550	17
Little Fork River at Littlefork	7330	8990	85
Sturgeon River at Chisholm	810	1010	63
Dark River at Chisholm	260	320	33
Nett Lake River near Nett Lake	500	610	9
Wood Duck Creek near Nett Lake	130	190	9

For most of the Little Fork River, any large, wide, flat surfaces near the channel are relict floodplain surfaces, now acting as terraces (See chapter 3). The main exceptions to this are in the far upper and lower reaches of the river where floodplains are still accessible. In between, the channel is entrenched. We made observations in the field on terrace heights as well as the heights of any bankfull benches currently forming. A comparison was made between these visual bankfull features and the heights of the terraces to assess how accessible the terraces are to larger floods (~50-year return interval). Floods with a recurrence interval of 50 years have depths that average 1.8 * D_{bf} for streams in the eastern United States (Leopold et al., 1964). In all cases but the far upper reaches of the basin, the terrace height exceeds 2 * D_{bf}. This is an indirect measure of entrenchment, which is the degree of vertical confinement of the channel (Kellerhals et al., 1972), and indicates that most terraces are likely only accessed by floods with a recurrence interval > 50 years.

The effective discharge (Q_{ef}) responsible for current modifications to the channel form may or may not coincide with the bankfull depth as determined from these bankfull bench observations or from the $Q_{1.5}$ flood event. A frequency distribution of suspended load samples from the 1970s indicates that the peak in sediment transport over the long term is at $Q_{ef} = 7250$ cfs (Figure 5.6). This is quite similar to $Q_{1.5}$ as determined from gaging records here ($Q_{1.5} = 7330$ cfs) and from Anderson et al. (2006) ($Q_{1.5} = 6900$ cfs). Thus, the Q_{ef} does coincide with the $Q_{1.5}$ at the Littlefork gage.

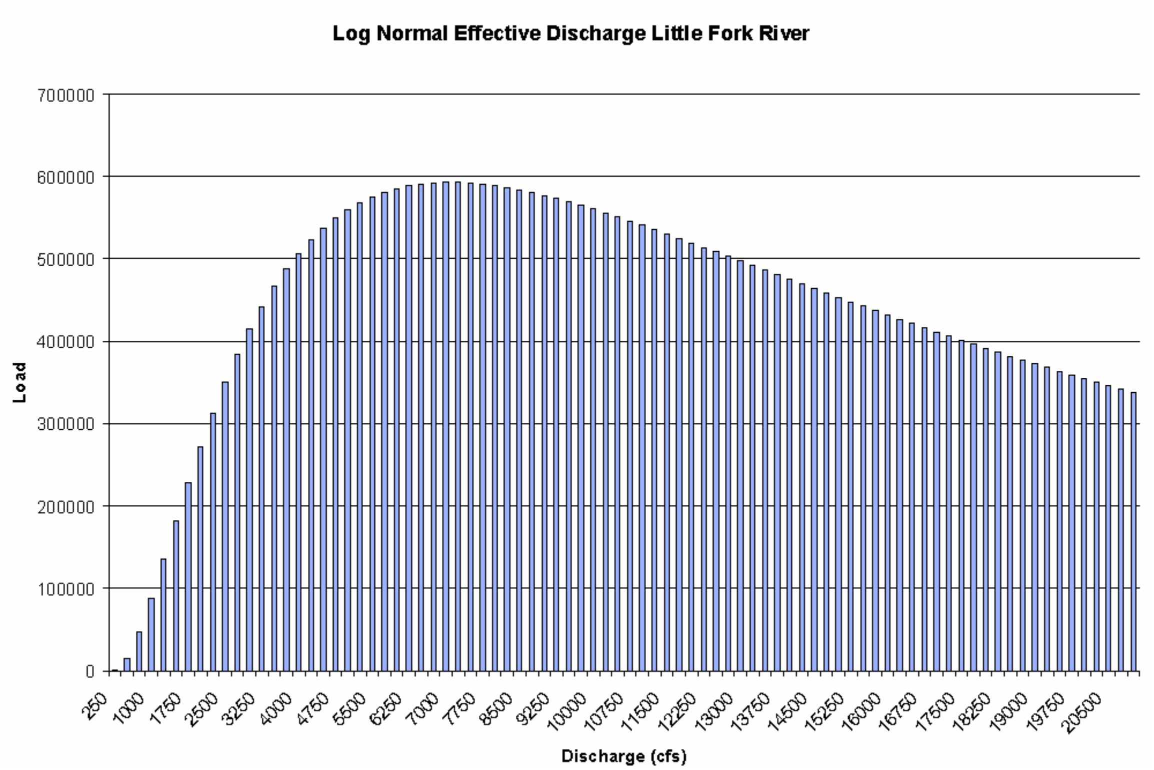

Figure 5.6: Frequency distribution for effective long term sediment load at different discharge intervals. Data were derived from a series of suspended load samples collected at the Littlefork gage in the 1970s.

Conclusions

Peak flow analyses on six gaging stations were used to adapt regional curves to conditions in the Little Fork River basin. Using the adapted curve, Q_2 discharge was calculated throughout the mainstem Little Fork River and seven tributary basins. There is a strong relationship between Q_2 and drainage area which could be used to extend the analysis even further throughout the basin.

Effective discharge does correspond to a $Q_{1.5}$ flow of approximately 6900-7330 cfs at the Littlefork gaging station. This indicates that floods of low-magnitude but high-frequency are responsible for moving the majority of the sediment over the long term. This likely corresponds to Q_{bf} as relates to the newly constructing bankfull bench surfaces. For most of the middle Little Fork River, the topographically extensive near-channel surfaces are relict floodplains, now terraces that lie above the area accessed by a 50-year flood. New bankfull benches are being constructed at the new topographic level below the terrace heights. Until these bankfull benches develop into extensive floodplain surfaces, the mainstem Little Fork River will remain entrenched.

Summary

The Little Fork River is entrenched along much of its length, downstream from Hannine Falls to the town of Littlefork. Immediately below Hannine Falls at RM 121, the channel and valley are tightly coupled, with almost no active floodplain area (Figure 7.1a). Near the Sturgeon River confluence at RM 111, the valley widens, and the river is more free to meander throughout its valley (Figure 7.1b). Shortly after the confluence with the Sturgeon, the channel becomes even more entrenched, and for the next 20 river miles, it passes through the most sensitive part of the landscape in terms of potential net sediment loss to the channel. The valley and channel are tightly coupled, with high valley walls (Figure 7.1c). Any incision or migration of the channel can rapidly translate into incision in closely-space tributaries, gullies, and ravines. Below RM 87, the valley widens, and the channel begins meandering across the valley again (Figure 7.1d). However, even in this alluvial valley, near-channel surfaces appear to be detached from the current hydraulic regime, and no longer flood on an annual to biannual basis. The channel is still entrenched, although to a lesser degree. This pattern continues to the mouth of the Little Fork. The lower 20 miles of the channel do show signs of an active floodplain. This part of the river is affected by backwater from the Rainy River during flood events.

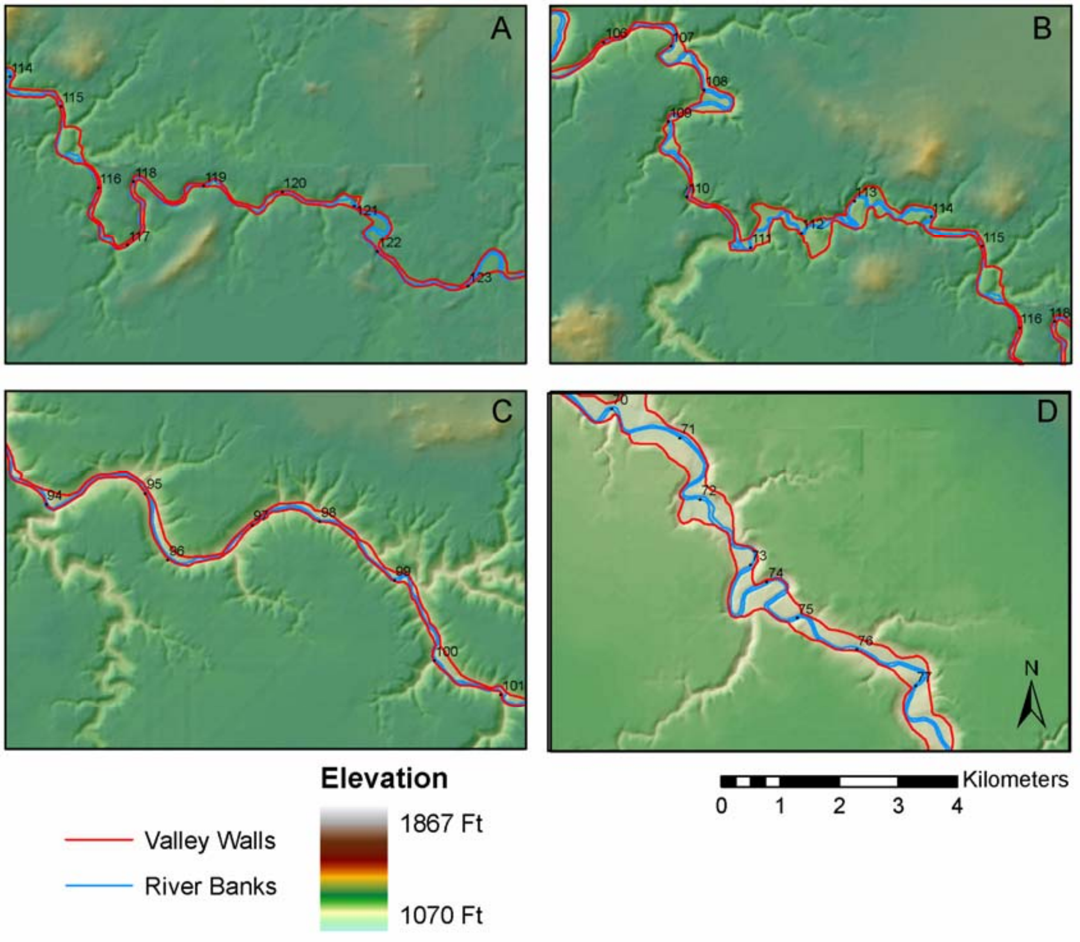

Figure 7.1: Illustration of different geomorphic regimes along the Little Fork River.

Evidence for incision of the Little Fork River into its former floodplain includes many near-channel surfaces with clear floodplain features like scroll bars or ridge and swale topography now positioned several meters above new bankfull benches. Benches are being constructed at lower elevations, although they are not very extensive yet. A comparison of the bankfull bench height and the paleofloodplain heights show that most of the paleofloodplain surfaces are between 0 and 4 meters above $2*Q_{bf}$ elevation. This is likely an estimate of the minimum amount of incision that has occurred since the floodplain surfaces were still frequently being flooded. However, the timing on this incision is not known, because we have no dating on when terrace surfaces were still active floodplains. Areas with the highest amounts of incision were in Sections III and IV. This incision seems to have propagated up small tributaries and ravines. Some of them show up to ~1 meter of incision at their mouths (Appendix E). Incision estimates on tributaries may provide a better measure of "recent" incision on the mainstem.

The timing of river incision, the degree of incision, and the cause for incision may be complex. River incision is most likely related to A) post-glacial rebound, B) climate change, or C) historical land clearing. Since the retreat of Glacial Lake Agassiz around 9-10 ka BP, differential uplift has caused the lower reaches of the channel to uplift as much as 16 meters more than the headwaters. On the mainstem channel, this is an uplift differential of ~8 m from the confluence with the Sturgeon River to the mouth of the Little Fork River. Most of this uplift occurred early in the Holocene. If the river was meandering during uplift, this could create floodplain surfaces now stranded as terraces at decreasing height with respect to the bed elevation near the channel.

The post-glacial rebound uplift could have been compounded by changes in hydrology both from climate change and from land use changes. The mid-Holocene dry period would have decreased flows, which should not lead to incision. Work by Anderson et al. (2006) showed that recent trends in precipitation appear to be decoupled from changes in peak flows, which seems to indicate that any recent climate change is not affecting current discharge patterns. Thus, changes in hydrology which may have led to additional incision are more likely due to land use changes than climate change.

Basin-wide land clearing started in the 1890s and continued until the last large-scale old-growth logging in 1937, although logging continues through the present. Forest clearing has been shown to increase peak discharge during snowmelt events in small watersheds by 30-80%, with the effects lasting for 10-15 years following logging (Verry, 1986). This peak flow increase would likely be dampened in a large watershed like the Little Fork River. Analyses by Anderson et al. (2006) did find a trend towards decreasing $Q_{1.5}$ flows in the latter half of the decade, decoupled from climatic fluctuations which is used to infer that peak flows did increase during the original phase of logging, and were on the decline in the latter half of the decade as forests regenerated. However, our analyses of historical land use on several reaches of the channel found little change in forest cover vs. cleared areas from the 1940s to 2003, with the exception of Section V. We did not investigate forest cover outside of the near-channel corridor. If land clearing did affect a change in $Q_{1.5}$ discharge, then either most of the basin had already recovered by the time the 1940s photos were taken, or most of the land clearing responsible for the change in basin hydrology was located away from the mainstem channel. A basin-wide analysis of 1995-96 land use shows that only 16% of the basin is in grasslands, urban, rural, or bare lands. This is actually much less than the % cleared area measured for most of the near-channel buffer zones we analyzed.

An increase in peak flows could lead to incision followed by widening as the channel adjusts to the new conditions. Our observations indicate that bankfull benches are being constructed along much of the middle portion of the Little Fork River, between 1 and 6 m below terrace surfaces. It is possible for these surfaces to have formed in the past 60 years, but we currently have no direct evidence for this. The surfaces lacked woody vegetation on them that might be used to date the surface. The lack of trees could be a sign of recent formation, or simply a sign that the slopes are too steep for trees to grow.

The timing of incision vs. sedimentation in the middle Little Fork River is complicated. We did an investigation to look for post-settlement alluvium at several sites in the basin, and found no evidence for a large-scale sediment flushing event that deposited sediment on the paleofloodplain/terrace surfaces studied. We found no evidence for growth in the mid-channel island at the mouth of the Rainy River over the past 75 years. Later field observations did uncover two sites with tree burial and significant deposition. In one case, trees <50 years old were still growing through a deposit of ~1 m of sand. Thus, some significant deposition has occurred on surfaces above the level of bankfull benches in the last 50 years.

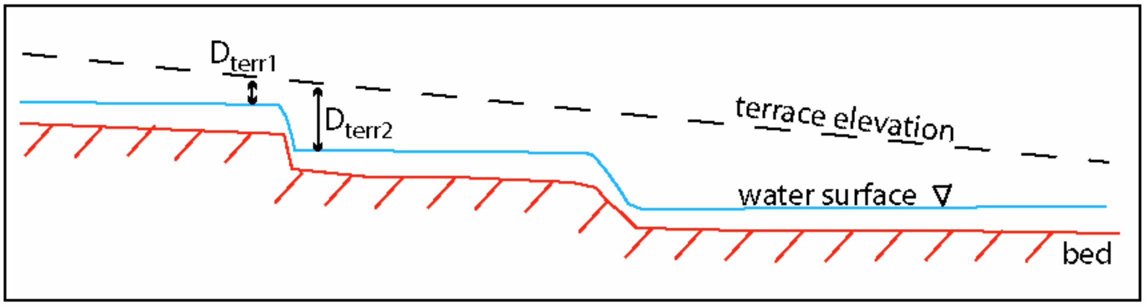

Figure 7.2: Schematic showing how local amounts of incision may relate to location above or below a bedrock knickpoint.

The complexities of local hotspots of deposition may be related to the stair-step pattern of the mainstem Little Fork River. Although the river banks are primarily composed of fine-grained sands, silts, and clays, the bed of the channel encounters bedrock at numerous points along the channel, resulting in waterfalls and rapids. Most of the gradient of the channel is taken up by these knickpoints, and between them the water surface slope is quite low. This could lead to a situation where the channel alternates between areas with high incision downstream of the knickpoint and low-gradient backwater zones upstream of a knickpoint (see Figure 7.2). More careful mapping needs to be done to look specifically at bank and terrace heights with respect to local bedrock knickpoints and grade control.

Our overall conclusion based on the data presented here is that incision has occurred in the middle portion of the Little Fork, peaking in Section III, but the timing and cause cannot be determined from these data alone. In the lower half of the basin, differential post-glacial rebound could account for all of the incision. In the upper basin, it is likely a combination of post-glacial rebound, changes in hydrology, and the unique set-up of bedrock knickpoints that can lead to greater depths of incision locally. Obvious signs of land clearing-induced sedimentation are not present in the Little Fork River, and our reach study of historical land use shows few changes in overall forest cover vs. cleared lands over the past 60 years. Thus, it is difficult to ascribe all of the incision and sediment loading to historical land use changes on the mainstem.

Future study could be undertaken to pinpoint the timing of the incision through geochemical analyses on terrace surfaces and stratigraphy. A more thorough investigation of the role of tributaries, ravines, and gullies could be undertaken to get a better handle on the magnitude of recent incision on these features. This might help determine how much of the incision is recent vs. Holocene-aged. In addition, the potential sediment load from incision on tributaries can be calculated and compared with the potential sediment load from mainstem incision or widening, which could help management agencies better target BMPs.

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Appendix A: Spatial datasets used for analyses in Chaper 1

These datasets were obtained from the Minnesota Department of Natural Resources (DNR) Data Deli (http://deli.dnr.state.mn.us). Datasets are listed with their name, scale, and metadata product ID #. Detailed information on data sources can be obtained on-line at the DNR website. Additional datasets were derived from these primary sources.

DNR 100k Hydrography, ID #39000337

Farm Services Administration (FSA) Color Orthophotos 2003-2004, 1-meter resolution, ID# 39000378

Geomorphology of Minnesota, 1:100K scale, ID #28000006

Landsat-based Land Use/Land Cover, Derived from 30-meter resolution 1995-1996 Landsat Thematic Mapper imagery, ID# 25000012

Minnesota Digital Elevation Model – Tiled 30 meter resolution, ID# 39000282

Minnesota Hydrologic Unit – Sheds (polygons), ID# 39000341

Appendix B: Inventory of steep, outer bends

Places where the mainstem river abuts steep, valley walls have the potential to trigger slope failures including slumping, sliding, and mass wasting of steep banks. Because the river is eroding into the high valley wall instead of into a floodplain surface, the volume of sediment eroded will likely be greater than the volume deposited on the inside of the meander bend, leading to a net increase in the volume of sediment in the mainste.

I mapped out areas where the outside of a meander bend is eroding into a valley wall. Land use in that zone was noted in 1940-41 and 2003 from aerial photographs, and any visible signs of slope failure were noted. These signs included scars visible at the top of slumps or slides (sometimes visible as stripes perpendicular to the slope), cones at the base of the slope, base earth visible on steep slope, and sharp features in gullies indicating recent activation. In general, once forest cover returns, it is difficult to see any slope failures. Thus, it is impossible to say whether the mass movements have stopped or simply been covered up. An inventory of each steep, outer bank is listed in Appendix A with annotations regarding land use and visible slope failures. Not all of the bends that were forested in both years with no visible scars were inventoried, especially if the slopes were short or gradual.

Notes on table: +/- indicates upstream (+) or downstream (-) of the river mile listed. If any clearing or failures were present on the slope, it's marked as 'Y'. The outer bends listed here are mapped on a GIS layer which will be included with the final report.

River Mile	Cleared 1940s?	Cleared 2003?	Failures 1940s?	Failures 2003?	Notes
114-	N	N	N	N	
113	Y	Y	Y	N	Upstream 1/2 cleared ('40) with scars visible
110	Y	Y	Y	Y	Small patch upstream of apex clear in both years
109+	N	Y	N	Y	Head scarp visible in 2003
109	N	Y	N	Y	Small barren patch in 2003
108+	N	Y	N	N	Some clearing mid-slope; no visible failures
107	Y	Y	Y	N	Slump in middle in 1940; Not clear in 2003
106	N	N	N	Y	Lower bank slumping in 2003
105+	Y	N	Y	N	Before bend
105	Y	Y	N	N	Slope sparsely forested in 2003; uplands cleared in 2003
105-	Y	Y	N	N	Partially cleared/shrubby in both years; No visible slumping
104	Y	Y	N	N	Partially cleared in 1940; Uplands cleared in 2003
104-	N	N	N	Y	Debris cone visible from tributary in 2003; Road had been rerouted closer to channel
103	Y	Y	Y	Y	Cleared to water's edge in 1940 – numerous active gullies; Upper end reforested by 2003
100	N	Y	N	Y	Landslide emanating from road in 2003
99+	Y	N	Y	N	Bank slumping in 1940 – upstream of bend
99	Y	Y	Y	Y	Cleared scarps and gullies in 1940; Partial clearing in 2003 – gully heads still visible
98+	Y	Y	Y	N	Gully on right bank appears active near channel in

					1940; forested in 2003
98	Y	Y	Y	Y	Inner bend; gullies visible in 1940, forested in 2003; bank failures near water
98	Y	Y	Y	Y	Outer bend; Large-scale slumping visible in 1940 and 2003; Slope is not overly steep here
96+	Y	Y	Y	Y	Left bank: Cleared in uplands – gullies extending up into uplands; forest cover greater in 2003
96+	Y	N	Y	N	Right bank: Cleared in 1940; gully extension and bank failures
94-	Y	N	Y	Y	Sparsely forested in 1940 – gullies visible; Cleared in uplands in 2003 – landslide scars and deposits visible
93-	N	Y	N	Y	Sparsely forested in 1940; Landslide scars and cleared patches in 2003
92	Y	N	Y	N	Gullies extending up into partially cleared uplands; Uplands (including gully tips) cleared prior to 2003, but were shrub-covered by 2003
92-	Y	Y	Y	Y	Landslide scars visible in 1940 and 2003 on downstream end of bend
91	N	N	N	N	Forested; tributary just downstream of bend has bar at confluence in both 1940 and 2003
91-	N	N	N	N	Forested
90	N	N	N	N	Forested
89	Y	Y	Y	Y	Cleared on upper half of bend, but scars visible on lower part of slope, downstream end of bend
88	N	N	N	Y	Possible slumping in 2003; Uplands cleared prior to both 1940 and 2003
87-	N	N	N	N	Forested; Uplands cleared prior to 2003
86	Y	N	Y	N	Right bank: Cleared in 1940, slumps visible; forested in 2003
86	N	N	N	Y	Left Bank: Scars visible in 2003 at steepest point at apex of bend; Forested in 1940 and 2003
85+	N	N	Y	Y	Right bank: Slides on downstream end of bend on lower slope.
85	Y	N	Y	Y	Left bank: Cleared prior to 1940, landslide scars visible. Scars still visible in 2003.
85-	Y	N	Y	Y	Cleared prior to 1940; landslide scars visible. In 2003, scars visible at base of slope
81	N	Y	N	Y	Sparsely forested in 1940; Cleared over much of slope in 2003; scars visible and growth of deposit at base of slope
80	Y	N	Y	N	Cleared in 1940; slump scars visible; banks are clear; gullies on downstream end
79-	N	N	N	Y	Forested; Clear banks downstream of bend apex.
79-	N	N	N	N	Forested; Steep valley walls
77	Y	Y	Y	Y	Retreating scarp – not adjacent to channel; Scarp and slope surrounding it are cleared in both 1940 and prior to 2003
75-	N	Y	N	N	Cleared prior to 2003; Few barren spots; no obvious slumps or scars
74	Y	Y	N	Y	Cleared in 1940; Uplands cleared prior to 2003; Banks open in 2003 downstream of bend apex
74-	N	N	N	N	Forested; steep
73	Y	Y	Y	Y	Partially cleared in 1940; Cleared in 2003 with visible scars; Some bank slumping downstream of

					bend apex; Scarp at top of slope.
72	N	N	N	Y	Forested; Scars on bank at bend apex. Note: oxbow at RM 72
71	Y	N	Y	N	Partial clearing in 1940; Slumps visible on banks, esp. on downstream end of bend; Some gullies visible near top of slope; Forested in 2003.
67	N	N	Y	Y	Steep slope; Scars on banks downstream of bend apex
67-	N	N	N	N	Forested
66	N	N	N	N	Forested on slope; Cleared in uplands in 2003 – tips of ravines visible
66-	Y	Y	N	N	Cleared prior to 1940; clear in 2003; barren patches, but not visible slumps or slides
65-	Y	N	Y	Y	Cleared prior to 1940 – visibility poor. Banks clear in 2003 downstream of bend apex.
63	Y	N	Y	N	Cleared in 1940; Steep slopes set back from river; Slumps on banks at water's edge.
62	Y	N	Y	N	Partially cleared in 1940 with some bank failures; Forested in 2003; Steep slopes set back from river.
61	N	N	Y	Y	Forested in 1940 and 2003; Banks open in 1940, banks open on downstream end in 2003.
60	Y	N	Y	Y	Cleared in 1940; Cleared prior to 2003 – mostly regrown; Slumps visible in both years.
58	N	Y	N	Y	Sparse forest in 1940; Cleared prior to 2003 - shrubby. Slump scars visible in 2003.
54	Y	Y	N	N	In 1940, scarp at top of slope visible on upstream end of bend; In 2003, barren ground but no slope failures visible.
51-	N	N	Y	N	Banks clear in 1940 downstream of bend apex.
50+	Y	N	Y	N	Right bank: Slumping in 1940.
50+	N	N	N	N	Left bank: Forested on slope; Cleared on uplands; No visible failures in 1940 or 2003.
50-	Y	N	Y	Y	Cleared in 1940; Scarp set back from channel, failing banks, slumps visible; Forested in 2003, but possible slumps downstream of bend apex.
49	Y	N	Y	Y	Steep cliff along outer bend; In 1940, downstream end of bend is cleared and shows scars on banks; In 2003, slope remains tree-free.
48	Y	Y	Y	N	In 1940, scarps and large slump scars visible at the top of the slope; In places, can see gully growth emanating form slumps; Gullies look healed in 2003.
46	N	N	Y	Y	In both 1940 and 2003, banks clear with scars downstream of bend apex.
					Note: Many bends have cliffs set back from channel here – these are not mapped.
45+	N	N	N	N	Forested on slope; Cleared to top of slope in 1940.
44	N	Y	N	N	In 2003, cleared only at far downstream end.
43	Y	N	N	N	Not very steep; In 1940, cleared on upper end, no visible failures; In 2003, some clearing up at top of slope – striped, but no visible scars.
42	Y	N	Y	N	Cleared to water's edge in 1940 – scarp visible at top of slope; Bank failures close to water's edge;

					Forested in 2003.
41+	Y	N	Y	N	Failing banks visible in 1940.
41	Y	N	Y	N	Partially cleared in 1940; failing banks and slumps visible.
39	Y	N	Y	N	Cleared in 1940; Scarp at top of slope very visible; slumps along slope
38+	Y	N	Y	N	Cleared in 1940 with visible slumps.
37+	N	N	Y	N	Forested in 1940, but cleared on uplands; Scarp visible in 1940 along upper edge of slope
37-	N	N	N	N	Steep but forested; cleared to edge of scarp
36-	N	N	Y	N	Scars on banks, downstream end of bend
34+	N	N	Y	Y	Scars on lower banks just downstream of bend apex.
33+	N	N	N	Y	Scars on banks downstream of bend apex.
32	N	N	Y	N	Cleared to top of slope in 1940 – scarps visible at top of slope break
31	Y	Y	Y	Y	Downstream end of bend has scalloped scars on bank in 1940 – scars visible, but not as sharp in 2003.
30	Y	Y	N	N	Cleared in 2003 – barren spots visible, but no clear failures
29	Y	N	N	N	Scarp visible in 1940 at top of slope
28-	N	N	Y	N	Deposits in channel on downstream end of bend, visible in 1940
27-	N	Y	N	N	Partial clearing in 2003; No visible failures; In 1940, cleared on uplands and gullies visible in uplands
25	Y	Y	Y	N	½ cleared in 1940 with slumping, partially cleared in 2003
24	Y	Y	Y	N	Partial clearing in both 1940 and 2003; bank scars near water's edge downstream of bend apex in 1940.
23	N	N	Y	Y	Scars on banks downstream of bend apex; Ravines and gullies visible, esp. in 1940.
22	Y	Y	N	N	Partial clearing; in town of Littlefork
19-	Y	Y	Y	Y	In 1940; scars on banks downstream of bend apex; in 2003, slump scars visible mid-slope throughout bend.
17+	Y	N	N	N	Cleared on top of slope in 1940 – scarp visible at top of slope, but smooth, not sharp
14+	Y	N	Y	N	Bank scars in 1940 near water's edge
14	Y	N	N	N	Scarp visible in 1940 at slope break – set back from water's edge. No visible failures.
13	Y	N	Y	N	Bank scars downstream of bend apex in 1940.
13-	Y	N	N	N	Slope partially cleared in 1940, mostly forested.
11	N	N	N	N	Forested in 1940 and 2003
9-	N/A	N	N/A	N	Forested on slope in 2003; Cleared on uplands in 1940 – hard to see slope due to poor photo quality
8	N	N	N	N	
7	Y	Y	Y	Y	Scalloped features visible in both 1940 and 2003 close to top of slope (short slope)
6-	Y	N	N	N	Small amount of clearing in 1940; No visible falures
5-	N	N	N	N	1940 – uplands cleared, not slope

3+	N/A	N	N/A	Y	Photo cut off in 1940; Forested in 2003, but gullies/ravines with debris cones
3-	N	Y	N	N	Clearing on upstream end of bend, no visible failures.

Appendix C: Soil core descriptions

Little Fork River soil core descriptions. Soil cores were collected at Samuelson Park (11/13/06), the Bois Forte reservation (11/14/06) and Lofgren Park (11/14/06).

Note: Recovery for each core section is listed above as X cm out of 116 cm (core length), but depths below were listed assuming each push was 122 cm (48 inches). The last 6 cm were located in the plug at the end of each core and were unrecoverable.

Samuelson Park (11/13/06)
5 cores collected as a transect (SAM1, SAM2, SAM3, SAM4) starting at the river and working out, and one additional core near the current bedrock knickpoint (SAM5).

SAM1:
5 sections (0-4', 4'-8', 8'-12', 12'-16', 16'-20')
Section 1 Recovery: 96 cm out of 116 cm (83%)
Section 2 Recovery: 101 cm out of 116 cm (87%)
Section 3 Recovery: 88 cm out of 116 cm (76%)
Section 4 Recovery: 77 cm out of 116 cm (66%)
Section 5 Recovery: 75 cm out of 116 cm (65%)

Depth (cm)	Description
0-10	A hz; dark gray; granular structure; Loam to SiCL; gradual transition to AB
10-20	AB hz; CL; some blocky structure; medium gray
20-45	C hz; CL
45-96	2C hz; sand to SC; alternating lenses of sand in a SC matrix; sand is fine to medium; occasional mottles of organics mixed in; light brown; alluvium
96-122	No Recovery
122-223	Same as above; alternating SC and fine-medium sand; occ. organics; charcoal mixed in; light brown; alluvium
223-244	No Recovery
244-332	Same as above; alternating SC with fine sand lenses; SC is softer here (moisture content is higher); alluvium
332-366	No Recovery
366-411	Same as above; light gray SC with sand lenses; SC is soft; alluvium
411-428	SC with sand lenses; clay is stiffer; mottled gray and rust color
428-443	Dark gray clay; stiffer than above; some pieces of charcoal present
443-488	No Recovery
488-495	Same as above, but brown; fine SC; soft
495-539	Gray SC, soft at top; some mottling, perhaps along root casts?; grading into sandier SC at base (523-539 cm); at 538 cm, hit root/chunk of wood – lighter in color
539-562	3C hz; coarse sand & gravel (gravel up to 4 cm in diameter); dark gray; big chunk of wood in sand and gravel (wood collected from 54-61 cm)
562-563	4C hz; light gray lacustrine clays

SAM2:
4 sections (0-4’, 4’-8’, 8’-12’, 12’-16’)
Section 1 Recovery: 101 cm out of 116 cm (87%)
Section 2 Recovery: 107.5 cm out of 116 cm (93%)
Section 3 Recovery: 68 cm out of 116 cm (59%)
Section 4 Recovery: 116 cm out of 116 cm (100%)

SAM 2:

Depth (cm)	Description
0-17	A hz; SiCL; roots throughout; fine blocky structure; dark brown, not black
17-37	B hz ?; SiCL; strong blocky structure; med brown
37-45	C hz; Clay (stiff); blocky structure; criss-crossed by charcoal (old roots?); same color
45-48	SC lens; light brown
48-64	C hz; stiff clay; strong columnar structure
64-66	Organics
66-101	2C hz; fine SC; distinct sand lenses and 80cm, 88.5cm, 92 cm; breaks into columnar blocks with clay coats on faces; rootlets present (alluvium); lt brown
101-122	No recovery
122-152	2C hz (same); fine SCl some columns with clay coats; sand lenses not prominent (alluvium); lt brown
152-229.5	Alternating fine-med SC and sand lenses; Alluvium; lots of sand lenses, usually < 1 cm; Some sand lenses have clay present; lt brown
229.5-244	No recovery
244-260	Same as above; fine – SC with sand lenses; lt. brown
260-272	SC; more sandy than above, perhaps due to greater concentration of sand lenses; Alluvium; lt brown
272-291	SC transitioning to C; mottled brown and grey; Alluvium
291-312	S and SC; clay lenses in sand; grey with some mottling at top – not a sharp transition; Alluvium
312-366	No recovery
366-442	Same as above; SC to C mixed with fine sand lenses; lt brown at top to grey at base; Alluvium
442-449	3C hz; Coarse sand and gravel; dark gray
449-482	4C hz; Layered light gray clay; Lacustrine deposits (Likely Glacial Lake Agassiz seds)
End Core	

SAM3:
4 sections (0-4’, 4’-8’, 8’-12’, 12’-16’)
Section 1 Recovery: 84 cm out of 116 cm (72%)
Section 2 Recovery: 112 cm out of 116 cm (97%)
Section 3 Recovery: 71 cm out of 116 cm (61%)
Section 4 Recovery: 116 cm out of 116 cm (100%)

Depth (cm)	Description
0-2	O hz; Root mat; SiC
2-6	A hz; SiC
6-19	A2 hz; SiC, heavier on clay; small blocky structure
19-38	C hz; mottled clay – mostly gray with black mixed into layers; strong, blocky structure – large blocks; roots present; clay
38-84	Clay; gray mottled with roots; thin sand lens at 76cm and 83 cm; structure blocky to platy; charcoal at 80 cm
84-122	No Recovery
122-175	Same as above; Clay, gray mottled with rust; strong blocky structure, sometimes with coats; There is some fine sand mixed in with clay (thus, clay to sandy clay in texture)
175-222	SC; fine sand in mostly clay; mottled gray and rust; occasional sand lenses (still SC in lenses); blocky structure with clay coats
222-234	SC; mostly gray with some rust mottling; softer than above; no structure
234-244	No Recovery
244-260	SiC; lt brown; slightly platy structure
260-305	SC; gray; no structure
305-315	2C hz; Sand and Gravel; core ended on large piece of gravel (4 cm diameter); Gray
315-366	No Recovery
366-402	3C hz; Clay; gray; almost no sand – isolated small pebbles
402-414	4C hz; Coarse sand and gravel; gray; old channel deposit
414-431	5C hz; Clay; gray; with isolated small pebbles (2-4 mm)
431-446	6C hz; Sand and gravel;
446-478	7C hz; SC; gray
478-482	Same as above, SC; color changing to brown – may have oxidized since being collected

SAM4:
Four sections (0-4’, 4’-8’, 8’-12’, 12’-16’)
Section 1 Recovery: 88 cm out of 116 cm (76%)
Section 2 Recovery: 93 cm out of 116 cm (80%)
Section 3 Recovery: 111 cm out of 116 cm (96%)
Section 4 Recovery: 88 cm out of 116 cm (76%)

SAM4:

Depth (cm)	Description
0-3	O hz; SiCL; root mat; black
3-11	A hz; SiCL-SiL; small blocky structure
11-18	C hz; SiC; color changing to gray brown
18-28	C Hz; CL; lt gray/brown
28-88	2C Hz; SC; some peds with sand coats on faces; rounded edges; light brown; roots
88-122	No Recovery
122-132	Cont. SC; light brown; large peds with sand coats
132-215	Same SC; light brown; softer than above (not as stiff); peds occ. but not as prevalent; very distinct sand horizons scattered throughout – thin (2-5 mm), esp. prevalent near base of core (76-93 cm)
215-244	No Recovery
244-271.5	Same as above; soft SC to C; light brown; occ. sand coats – not many
271.5-272	Small organic layer – black with charcoal – either flood deposit or buried soil
272-274	Medium sand; black to light brown
274-296	Soft, fine SC to C; 1-2 sand lenses (1-2mm)
296-322	Coarse Sand; Reddish brown; occ. clay lenses
322-325	Clay lens
325-335	Coarse Sand; Reddish Brown
335-355	Mixed coarse SC with Sand lenses; charcoal around 347 cm
355-366	No Recovery
366-389	Fine SC; same lt brown color; some organics mottled in? and swirled – some of this may be slough from the sides of the hole
389-392	Clay; brownish gray
392-406	Medium SC; grayish-brown
406-445	Clay; gray; sand lens from 413-416 cm (fine SC lens); charcoal roots mixed in
445-446	Wood
446-454	Coarse sand; gray
End of Core	

SAM5:

Three sections (0-4’, 4’-8’, 8’-12’)
Section 1 Recovery: 111 cm out of 116 cm (96%)
Section 2 Recovery: 116 cm out of 116 cm (100%)
Section 3 Recovery: 103 cm out of 116 cm (89%)

SAM5:

Depth (cm)	Description
0-6	A hz; Loam to CL; leaf litter on top; black; granular structure; fairly abrupt lower boundary
6-11	C hz; dark gray; massive; clay; abrupt lower boundary
11-40	2A hz; Loam – Sandy Loam; gravel present; couple sand lenses; looks like a cumulative soil in channel deposits; buried soil; dark brown; charcoal at base
40-75	2BC hz; strong blocky structure; small peds; clay loam (CL); some areas with greater concentrations of v. fine sand
75-111	2C hz; Clay; medium brownish gray; breaks into blocks with clay coats; alluvium
111-122	No Recovery
122-238	Same as above; no longer breaks into blocks; massive clay; medium brownish gray
238-244	No Recovery
244-281	Same as above; clay; medium brownish gray
281-301	Clay; softer; many sand lenses present; sand is fine, layered; med. Brownish gray
301-343	Medium gray Clay with light tan sand layers; sand layers are thicker now (1-4 cm), and one is oxidized; organic layers with wood present at 319 cm and 324-326 cm (collected)
343-347	Dark gray Sand and Gravel

Lofgren Park: 2 cores were collected at Lofgren Park in Littlefork. The first was on the floodplain terrace near the channel (LF1). The second was the upper section of a high terrace, near the playing fields (LF2).

LF1:
Seven sections (0-4', 4'-8', 8'-12', 12'-16', 16'-20', 20'-24', 24'-28')
Section 1 Recovery: 104 cm out of 116 cm (90%)
Section 2 Recovery: 93 cm out of 116 cm (80%)
Section 3 Recovery: 78 cm out of 116 cm (67%)
Section 4 Recovery: 98 cm out of 116 cm (84%)
Section 5 Recovery: 112 cm out of 116 cm (97%)
Section 6 Recovery: 116 cm out of 116 cm (100%)
Section 7 Recovery: 116 cm out of 116 cm (100%)

LF1:

Depth (cm)	Description
0-13	A hz; dark brown; Loam; gradual boundary to AB
13-19	AB hz; Loam; v. fine sand; medium brown
19-104	C hz; mostly fine sand with some clay for cohesion (not much); light brown; thin layers, particularly visible at top (19-32 cm); alluvium
104-122	No Recovery
122-215	cont.; light brown sand w/some slightly cohesive layers; mostly just fine sand; layered in places – more massive elsewhere; wood at 146 cm; alluvium
215-244	No Recovery
244-322	mixed fine sand layers (0.5-10 cm thick) with soft clay layers (up to 8 cm thick); well layered here
322-366	No Recovery
366-374	Same as above; fine sand, light brown
374-429	Fine SC to Clay; mostly gray brown; layered; few black lenses; few sand lenses
429-464	Mixed layers of fine sand and clay; brownish gray; some sand layers are oxidized and rust-colored
464-488	No Recovery
488-506	Fine SC; brown; massive; soft
506-530	Mottled brownish gray and rust; mostly sand with few layers of clay mixed in (~2 cm thick)
530-600	Gray; mostly sand with some clay layers mixed in – all gray; charcoal scattered, esp. at 575-577 cm
600-610	No Recovery
610-711	Gray, medium sand; organics near base; large collection of wood at 686-892cm; scattered wood at 705-707 cm; some charcoal
711-726	Stiff, dark gray clay with isolated pebbles; lacustrine, probably with dropstones
726-732	No Recovery
732-848	Same as above; dark gray clay with isolated pebbles; lacustrine

LF2: Two sections (0-4’, 4’-8’)
Section 1 Recovery: 77 cm out of 116 cm (66%)
Section 2 Recovery: 92 cm out of 116 cm (79%)

LF2:

Depth (cm)	Description
0-4	A hz; grass on top
4-11	C hz; gravelly SL – gravel up to 1.5 cm
11-13	2C hz; SCL
13-29	SCL, lighter brown
29-30	Sand lens
30-92	Alternating sand with clay lenses (31-60 fine sand, clay increasing with depth; 60-66 fine sand; 66-76 clay-rich sand, no structure evident; 87-92 SC blocky structure; Alluvium
92-122	No Recovery
122-130	Sand with clay lens at 129-130cm
130-152	Medium sand with gastropods
152-163	Slightly clay-rich sand (SC); clay is concentrated in lenses
163-200	Medium sand; clay lens from 185-186; Concentration of gastropos from 194-196
End of Core	

Bois Forte Site:
We collected two cores from the BF site. BF1 is located close to the river's edge, and BF2 is farther inland.

BF1:
Four sections (0-4', 4'-8', 8'-12', 12'-16')
Section 1 Recovery: 90 cm out of 116 cm (78%)
Section 2 Recovery: 105 cm out of 116 cm (91%)
Section 3 Recovery: 113cm out of 116 cm (97%)
Section 4 Recovery: 82 cm out of 116 cm (71%)

BF1:

Depth (cm)	Description
0-3	A hz; Loam; roots present; Sand is coarse
3-9	Loam mixed with coarse sand and gravel – may be from road? (near turn around)
9-26	2A hz; dark gray to black; Loam to CL; granular structure
26-60	2B hz; dark gray; CL; fine blocky structure
60-90	2C hz; v. fine SCL; charcoal at 80 cm; light-med brown
90-122	No Recovery
122-164	Same as above; v. fine SCL; few sand lenses; lt-med brown
164-227	CL with some fine sand lenses near base; less sand in matrix; darker brown, primarily due to less sand)
227-244	No Recovery
244-248	Dark brown clay (slough?)
248-250	Sand and gravel (slough?)
250-305	New unit; soft C-CL; light brown to gray, becoming more gray with depth
305-357	Gray brown with mottles; soft C-CL; some oxidized root cases and mottles; gravel piece at 92-93 cm
357-366	No Recovery
366-378	Slough? 0-7 brown CL, soft; 7-12 SCL mixed with coarse sand
378-396	C-CL; light brownish gray; some mottling; soft; chuck of gravel at base
396-448	Gray, becoming darker gray with depth; very soft, very sticky C to SC with v. fine sand

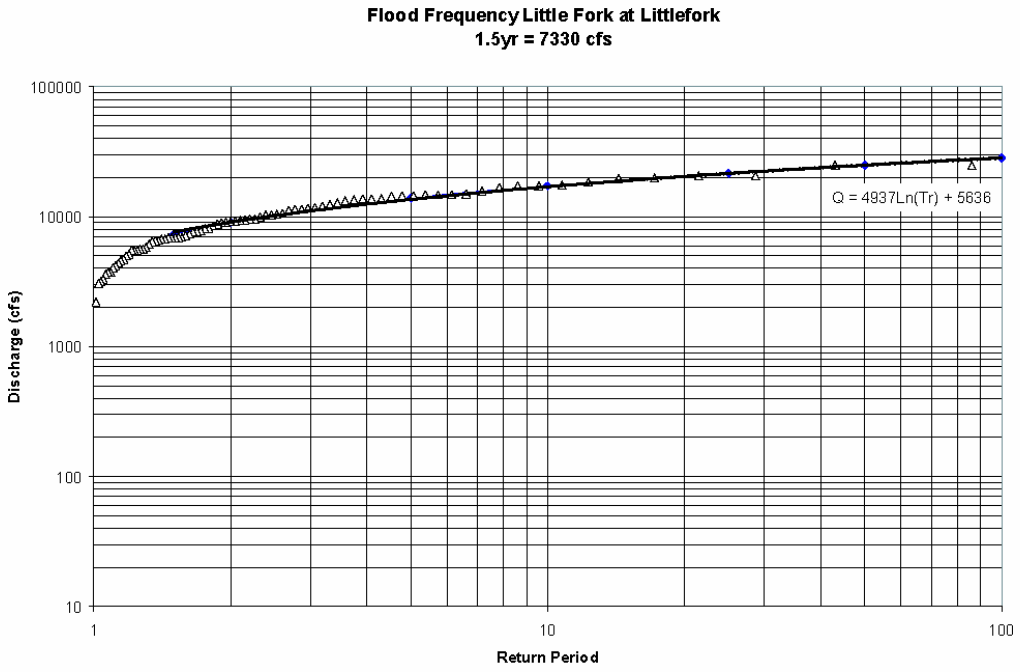
BF2:
Four Sections:
Section 1 Recovery: 107 cm out of 116 cm (92%)
Section 2 Recovery: 86 cm out of 116 cm (74%)
Section 3 Recovery: 85 cm out of 116 cm (73%)
Section 4 Recovery: 72 cm out of 116 cm (62%)

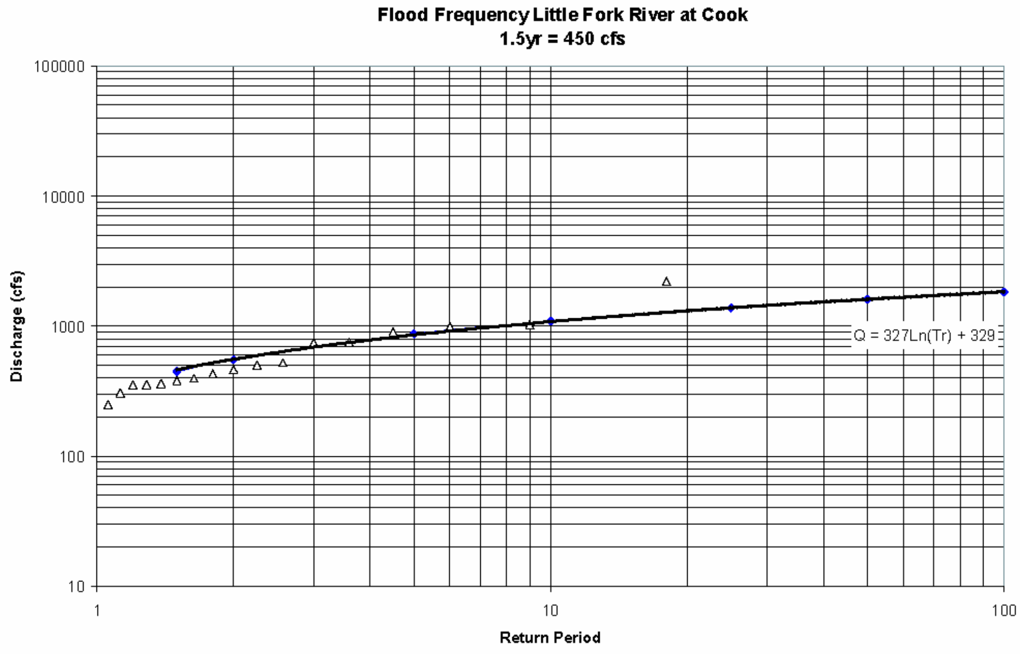
BF2:

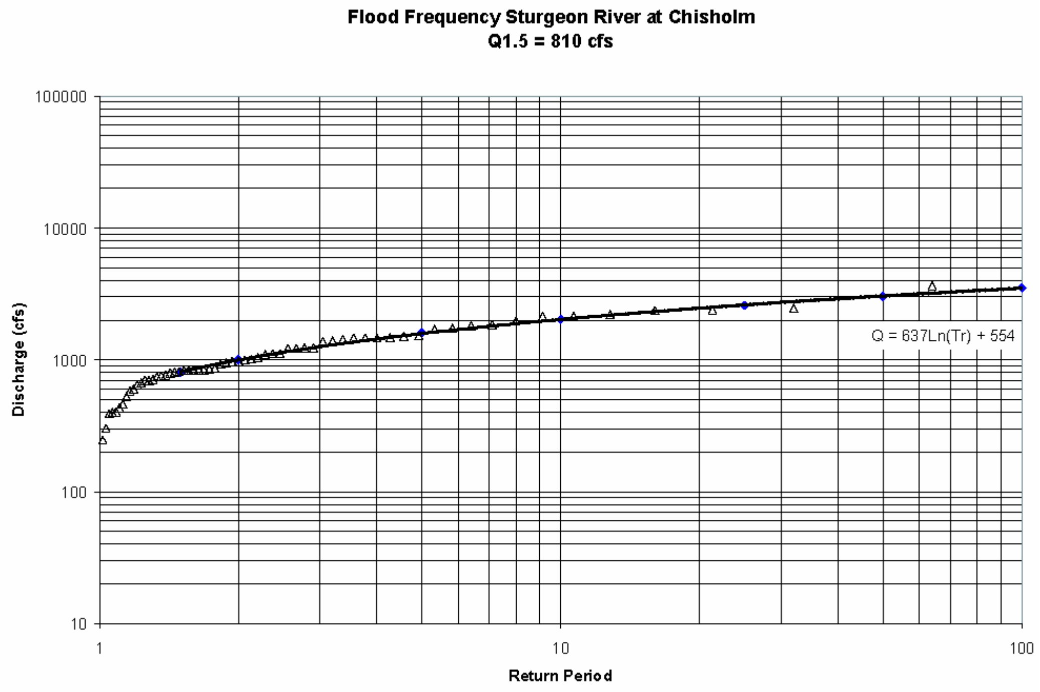
Depth (cm)	Description
0-2	O hz; organic leaf litter; black
2-10	A hz; SL; black-dark brown
10-27	2A Hz; SiCL to CL; dark brown; strong granular structures
27-50	2AB hz; CL; granular structure; color changing to medium brown – gradual boundary with 2A Hz above
50-107	2C Hz; CL; massive at base, some blocks at top; medium brownish gray; few layers of organics (dark brown material); few sand lenses (~2-3 – not distinct)
107-122	No Recovery
122-208	Same as above; lt brownish gray; CL; v. fine sand present in few layer (layers of v. fine SCL rather than layers of sand, <1cm thick); one 3-4 cm layer of dark brown coarse sand
208-244	No Recovery
244-294	Same as above; lt brownish gray; Clay; few sand lenses, but not distinct (SCL lenses); massive; 261-261.5 dark brown coarse sand layer
294-320	Clay with more SC lenses; gray to lt brownish gray mottled; soft
320-329	Medium gray Clay; soft; massive
329-366	No Recovery
366-396	Mixed brown and gray clay; v. soft; v. sticky
396-438	Gray clay; v. soft; v. sticky; there may be silts or v. fine sand mixed in – can't really feel it, but can see texture

Appendix D: Flood frequency analysis

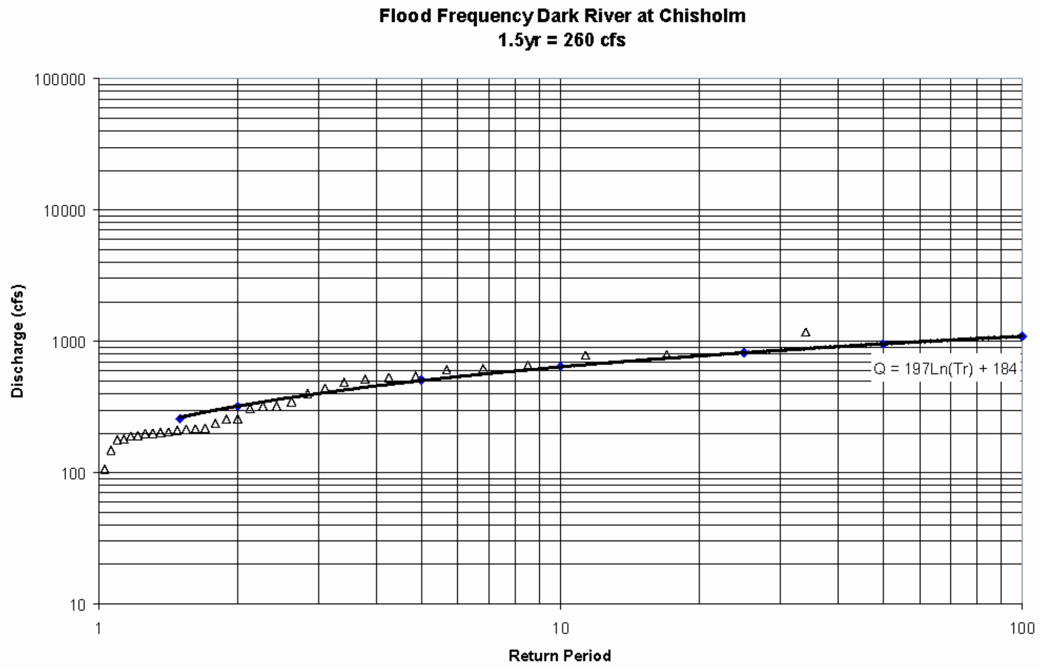
Peak flow analyses for six gaged basins in the Little Fork River watershed. The log-linear regression listed for each basin is a best fit for the derived data set using the analysis techniques of Bulletin 17B (USGS, 1982).



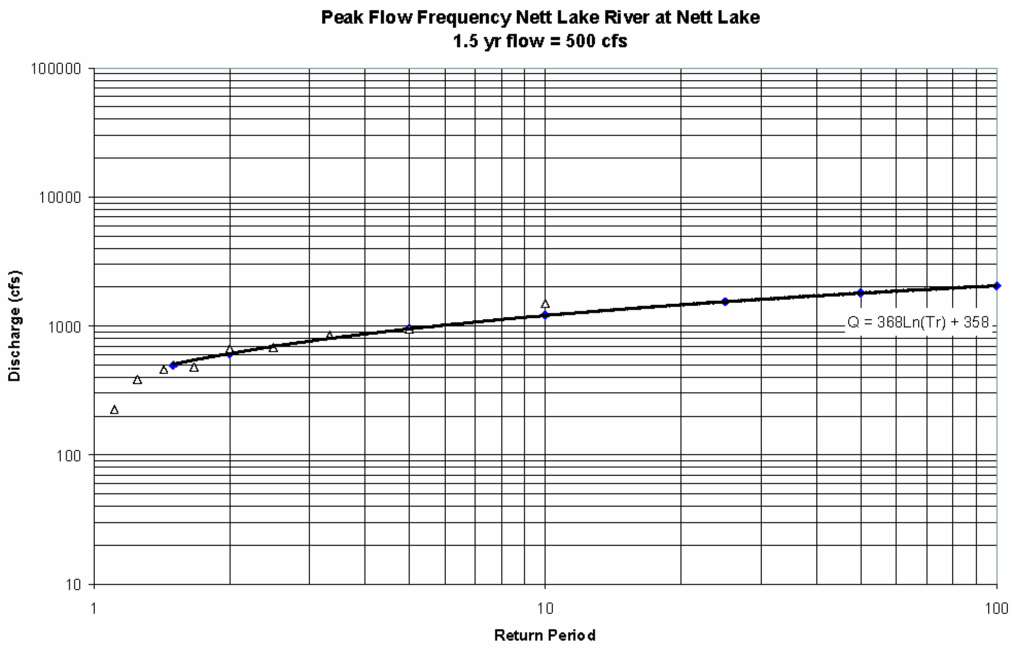


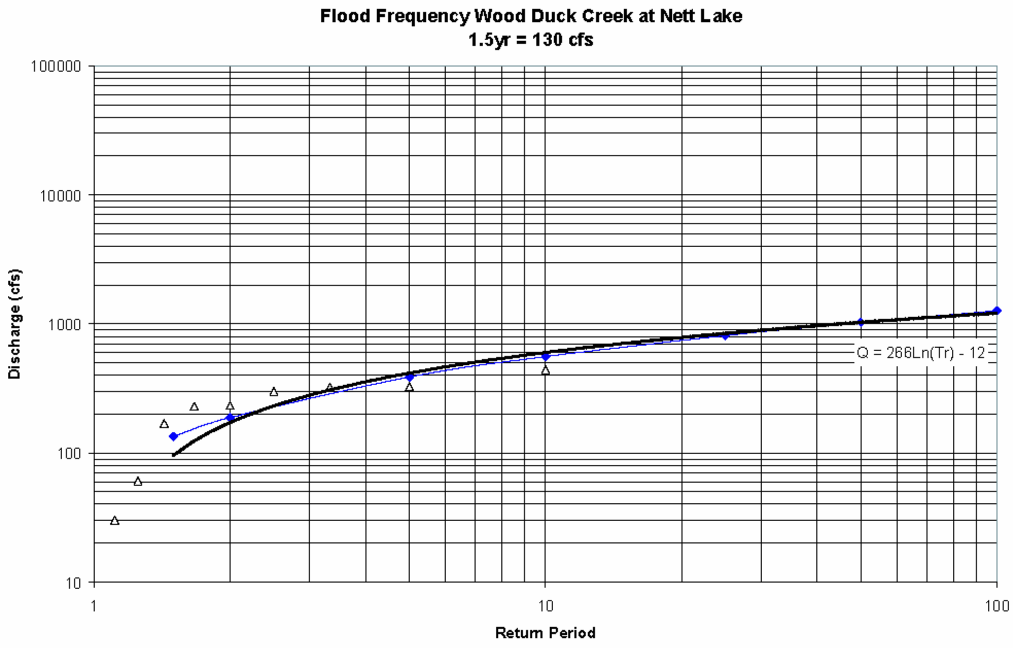


Flood Frequency Sturgeon River at Chisholm
Q1.5 = 810 cfs



Flood Frequency Dark River at Chisholm
1.5yr = 260 cfs


Peak Flow Frequency Nett Lake River at Nett Lake
1.5 yr flow = 500 cfs
100000
10000
1000
100
10
Discharge (cfs)
1
10
100
Return Period
Q = 368Ln(Tr) + 358


Flood Frequency Wood Duck Creek at Nett Lake
1.5yr = 130 cfs
100000
10000
1000
100
10
Discharge (cfs)
1
10
100
Return Period
Q = 266Ln(Tr) - 12

Appendix E: Overview of field work at Nandrasy Residence

Overview of site:

On November 15, 2006, Jesse Anderson (MPCA), Karen Gran (U of MN), Brad Hansen (U of MN), and Kelly O'Hara (MPCA) visited the Nandrasy property, located in western St. Louis County, T63N R21W, Section 19. In 2001, much of the property was logged, and the owners were concerned about the effects of logging on a tributary running through their property. Some specific concerns included the tributary becoming "trashed" with logging debris and downstream siltation near the confluence with the Little Fork River. We walked much of the tributary streambed and some surrounding hillslopes, including the area where the loggers had created a crossing over the tributary. We made observations instream and in the uplands and took a series of photos. This memo summarizes those observations.

The Nandrasy property runs from County Road 962 west to the Little Fork River. The tributary of concern drains from gently rolling, low-gradient uplands down to the mainstem Little Fork River, entering just downstream of River Mile 103. The elevation change is substantial, from just over 1290 feet in the uplands to 1207 feet in the channel. Most of this elevation change occurs within 1000 feet of a channel. Hillslopes measured off of a standard USGS 1:24K topographic map indicate average slopes of 10-12% within 600 feet (200 meters) of the tributary.

These steep slopes were logged in 2001 (see Photo 1). Near the lower end of the tributary, an opening in the tree cover marked a former crossing for logging equipment. We observed numerous snags left on the ground and in the tributary itself (Photo 2). Further downstream, there was even more slash in the channel (Photo 3). In this reach, the tributary was rectangular in shape and incised ~2-3 feet. The incision has started propagating up smaller tributaries as knickpoints. We observed two steps in one of these smaller channels, extending approximately 20 feet from the mainstem tributary. Below the crossing, many large conifers were left standing along the tributary riparian zone (visible in background in Photo 2).

At the confluence with the Little Fork, there was evidence of both incision and recent deposition of fines. At the confluence, a fresh bar composed of fine-grained sediment was visible, about fifteen feet long and twelve feet wide at the mouth of the tributary. We estimated the deposit to be 2 feet thick (approximately 150-200 ft^3 of fine sediment). On the first meander bend, a large cedar tree was undercut and poised to fall into the channel. Photo 4 shows both the deposit on the far left and the undercut cedar tree on the right. Photo 5 shows a close-up of the cedar tree. These observations indicate the stream has fluctuated between deposition and incision over the relatively recent past. Several banks of fine-grained material had slumped into the channel, a further sign of recent channel instability. Photo 2 shows a slumped bank in the channel crossing zone, and Photo 5 has a slump on the far left.

Another interesting feature of the lowermost tributary was its highly sinuous nature. After 3-4 large, looping meander bends, the sinuosity decreases upstream (see Photo 6 of upstream reach). The depth of the channel was approximately 5-6 feet in the highly sinuous lower reach, decreasing to 3-4 feet as the sinuosity changes upstream, although the width did not appear to vary greatly.

In the far upper reaches of the tributary, near the road, we made a few more observations. The tributary was clearly incised on the downstream side of County Road 962, and there appeared to be a knickpoint that had almost reached the road. On the east side of the road, the channel was not incised.

Potential future work:

This site could make a nice case study site for logging in the uplands near the channel. The Nandrasy property is within one of the most sensitive zones of the channel: the Little Fork River is tightly coupled to its valley with very little floodplain in which to meander. Changes in base elevation on the Little Fork in this area should propagate rapidly into the uplands. Slopes are fairly steep in tributaries adjacent to the channel, increasing the likelihood that landscape disturbance may release excess sediment to the channel.

The site could be monitored through repeat channel surveys on the tributary, to look for incision, deposition, channel widening, and/or other signs of channel adjustment. Suspended load sampling either by grab sample in conjunction with other survey efforts in the basin or through use of a continuous sampler during floods would help give an indication of the volume of sediment that could be shed by the uplands into the stream channel in this sensitive part of the landscape. Sediment fences could be established along the channel banks to see if much sediment is being shed overland from hillslopes in select areas, or if the sediment is coming primarily from tributary channel adjustments.

The survey efforts would benefit from A) pre-logging photos if they are available and B) complimentary surveys and samples collected on an unlogged basin with similar topographic features.

If there is interest in pursuing this further, I would recommend getting baseline surveys in this summer and monitoring for several years. This is a fairly low-cost research effort that could be established now with repeat surveys and photos taking only a few days each year. If funds were located in the future to set up a suspended sediment sampler, a more detailed analysis could be carried out then.

Photo 1: Tributary running through Nandrasy property. Hillslopes were logged in 2001.

Photo 2: Tributary at the logger's crossing zone. Note downed trees in the channel and a large slumped bank on the left side.

Photo 3: Slash in tributary channel.

Photo 4: Confluence with Little Fork River (looking upstream). On the left is the fresh deposit of mud and silts. In the middle is a cedar tree that is significantly undercut (close-up in Photo 3).

Photo 5: Cedar tree undercut by recent erosion. Erosion extends back several feet. On the far left is a slump deposit comprised of fine-grained materials.

Photo 6: Meandering tributary upstream of confluence. Downstream of this photo, meander sinuosity increases greatly, with tight, looping meanders. Incision is greater in the downstream reach than in this reach.