

LAND USE IMPACTS ON FLUVIAL PROCESSES IN THE NEMADJI RIVER
WATERSHED

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ABSTRACT

The Nemadji River drains 1100 km² of eastern Minnesota and northwestern Wisconsin. Channel incision and mass wasting are natural responses to glacial rebound in this area and account for more than 95% of the annual sediment load. However, the clay and sand delivered by the Nemadji to Lake Superior has increased over the past 150 years. We researched land use history across the upper 520 km² of the Nemadji River Watershed, surveyed channel characteristics, identified relic channels and employed dendrochronology to date floodplains and terraces. Results indicate that two episodes of channel incision began propagating through the Nemadji River and its tributaries. One associated with timber harvesting in the mid 1800's and another associated a large fire in 1894. Streams impacted by incision had increased slope, reduced sinuosity, increased entrenchment, and reduced width depth ratios. Subsequent erosion from steep banks, mass wasting, and upstream incision provides sediment and space needed for the reconstruction of stable channels. The new channels are similar to the relic channels and unimpacted streams. Historical increases in water yield, particularly bankfull discharge, initiated the channel incision. This occurred with the onset of basin scale land use conversion in the 1850's. Forest fires in 1894 and 1918 and agricultural land use conversion during the early 1900's initiated additional episodes of channel incision.

Keywords: watershed management, land use, forest hydrology, fluvial processes, sedimentation, geomorphology

INTRODUCTION

The erosion and transport of suspended sediments from the 1100 km² Nemadji River Watershed of eastern Minnesota and northwestern Wisconsin have been largely attributed to fluvially driven processes (Andrews et al, 1978; Queen, et al, 1995; NRCS & USFS, 1998). More than 90% of the sediment load comes from erosion within the valley system (NRCS & USFS, 1998). The Nemadji River Watershed is naturally susceptible to slumping and channel incision. The average annual rainfall excess of 42% is among the highest in Minnesota, approaching those of the bedrock soil regions along the North Shore of Lake Superior. Though largely forested, sub-watersheds of the Nemadji River have some of the highest peak flow frequencies in the state, exceeding those of many watersheds within the agricultural Minnesota River Basin (NRCS & USFS, 1998). Per square mile, sediment loads of Nemadji tributaries are some of the highest in the state of Minnesota (Tornes, 1986).

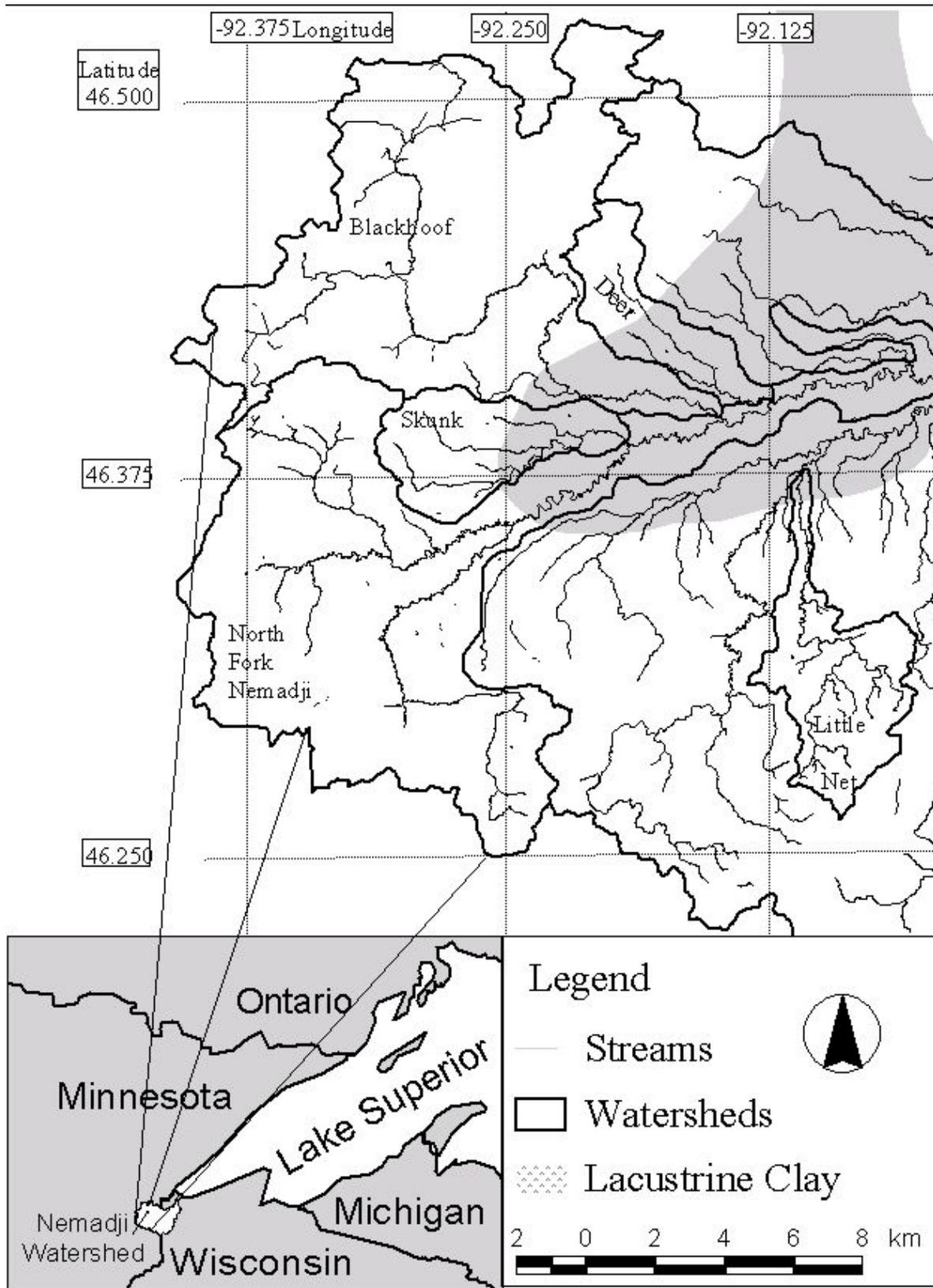
Forest harvesting and landuse conversion in this region significantly increase water yield and hydrograph peaks (Bosch and Hewlett, 1982; Verry, et al, 1983; Verry, 1986). Sediment cores from the St. Louis River delta in Lake Superior indicate that alluvial sediment deposition in the region has increased beyond historical levels (Kingston et al, 1987). Have land use practices inadvertently exacerbated the rates of fluvial processes within the Nemadji Watershed?

The North Fork of the Nemadji River and three tributaries, Deer Creek, Skunk Creek, and Blackhoof River are the study sites for this project, shown in Figure 1. These streams were chosen because they are located, to varying degrees, within the lacustrine clay area which is prone to mass wasting. The headwaters of each stream drain glacially deposited sands and gravel. The streams then incise into the Superior Lobe till, known locally as red clay. After cutting through this till, each stream encounters the cohesive, lacustrine clay deposits of glacial Lake Nemadji (Riedel, 2000).

Geology

More than 12,000 years ago, much of the Nemadji Watershed was submerged beneath Glacial Lakes Duluth and Nemadji. These lakes created vast lakebeds by depositing tens of meters of lacustrine clay across the Nemadji watershed. After these lakes drained, subsequent advances of the Superior Lobe buried these clays with 15 to 130m of glacial tills (Basig, 1993). The last glacial period ended with the final retreat of the Superior Lobe. With the removal of the immense masses of glacial ice and lakes depressing the land in this region, the earth began to rebound. The present rate of glacial rebound in this region has been estimated to be from one-half to one meter per century (Schumm, 1977). This rising of the land has caused the local base level for streams to fall from 330 m above sea level, the historical elevation of glacial Lake Duluth, to the present day 183 m average elevation of Lake Superior (Olcott et al, 1978). To maintain their connection with base level, the Nemadji River and its tributaries have followed by incising into the vast glacial till and lacustrine clay deposits. This has created a steep and unstable valley system. An abundance of seeps and springs fed by high potentiometric heads further destabilize the valley walls (Andrews et al, 1978). Mass wasting and erosion within the Nemadji Watershed are natural responses to this complex geologic setting.

Figure 1: Map of the Nemadji Watershed and study sub-watersheds.



Land Use

Prior to initial timber harvesting in the mid 1800's, the Nemadji Watershed was dominated by vast stands of White Pine (*Pinus strobus*) and Red Pine (*Pinus resinosa*) (Koch, et al, 1977). This made it a prime target for forest harvesting. To facilitate the transport of logs, loggers removed woody debris from the channel, straightened tortuous meanders and constructed temporary dams to raise water levels (Rector, 1951). This destabilized the Nemadji River and it's tributaries. The natural rates of mass wasting, channel erosion and sediment transport have increased beyond historical levels (Riedel, et al, in Review).

METHODS

Land Use

We obtained current land use data from 1992 series NAPP aerial photographs. Historical land uses were determined from public land survey data and aerial photographs from 1937. We obtained presettlement land use information from the original vegetation maps of Marschner (1974). We used dendrochronology to establish the ages of the oldest trees on floodplain and terrace features at numerous sites in the Nemadji Watershed. We also utilized dendrochronology data that have been previously reported by Verry (2000).

Channel Metrics

We identified a minimum of four study reaches along each stream. Straight reaches at least 20 times bankfull width were chosen as locations for these sites. We chose the locations of the sampling reaches to acquire stream data under various land uses, stratigraphic units, and watershed sizes. At least one reach for each stream was installed in forested land use conditions. Reaches were installed on Skunk Creek, Deer Creek, and the Blackhoof River just upstream of their confluences with the Nemadji River. Additional reaches were installed along the main stem of each stream. Sampling reaches along the Nemadji River were installed upstream of confluences and along the main stem. We identified bankfull stage as the floodplain elevation along each reach. We surveyed three cross sections in each reach according to the methods of Harrelson, et al (1994). For each cross section, we measured and computed the bankfull metrics of width, cross sectional area, thalweg depth, flood prone width, water surface length, valley length, slope, average depth, and sinuosity. We measured sinuosity and valley slope at numerous additional points along the study streams using 1:40,000 scale aerial photographs and USGS 7.5 minute series quadrangle maps. We computed bankfull slope at these points as the quotient of valley slope and sinuosity.

RESULTS

Land use

Current land uses for the study watersheds are summarized in Table 2. Before the arrival of European settlers, the region was dominated by coniferous forests with large expanses of wetlands and bogs in the flat uplands of the watershed. The first commercial timber harvest occurred in the 1850's, immediately following the original land and timber surveys. Widespread harvesting continued across the Nemadji Watershed for the remainder of the 1800's. The harvested timber was floated down the Nemadji River to Lake Superior. The log drives were facilitated by river cleaning and the use of splash dams (Rector, 1951).

In the 1890's, a severe drought plagued the region. This combined with the vast amounts of residual harvesting slash that had accumulated across the watershed to fuel the massive Hinckley fire. On September 1, 1894, this fire burned hundreds of thousands of hectares of forest across east central Minnesota.

TABLE 2: Current Land Use Composition (in percent) for Study Watersheds

	Coniferous Forest	Deciduous Forest	Wetland	Agricultural or Open	Watershed Size (km ²)
Blackhoof	13	31	31	35	147
Deer	15	42	16	27	21
Nemadji	14	34	28	24	328
Skunk	15	39	19	27	26

Rail transportation replaced log driving by 1904. Continued harvesting produced more fuel in the basin. Numerous small fires were sparked by steam locomotives used to haul timber including the last significant forest fire in the region, the Moose Lake Fire in 1918. This fire burned more than half of the Nemadji Basin as it consumed forests as far north as Duluth, MN. Large-scale agricultural land use conversion occurred in two phases during the 1930's and the 1950's. More recently, agriculture within the region has been in decline and forest regeneration has reduced agricultural land use from its peak of nearly 50% in the 1950's to the present day average of approximately 30%.

The historical changes of land use across the Nemadji have left a legacy in the riparian forests. As previously reported by Verry (2000), "Tree ages were used to date when the channels changed. They were in old channels, on existing floodplains, and abandoned flood plains on the first terrace to date channel down-cutting and a progressive loss of stream sinuosity. The tree dates group into periods associated with landscape changes: original stream cleaning (late 1840's), original logging (1870 – 1905), the catastrophic Hinckley Fire (1918)...and agriculture development from two periods: the late 1920's to the early 1930's and the mid 1950's following the Korean War."

The oldest terrace is occupied by trees dating to the mid 1800's. The current floodplain on the North Fork of the Nemadji is occupied by trees from the turn of the century. Advancing up the tributaries, these trees grade into younger trees occupying younger terraces and flood plains. The trees on the floodplains of the tributaries in this study date primarily to the 1930's while the older trees on the terraces became established after the fire in 1918.

Channel Evolution

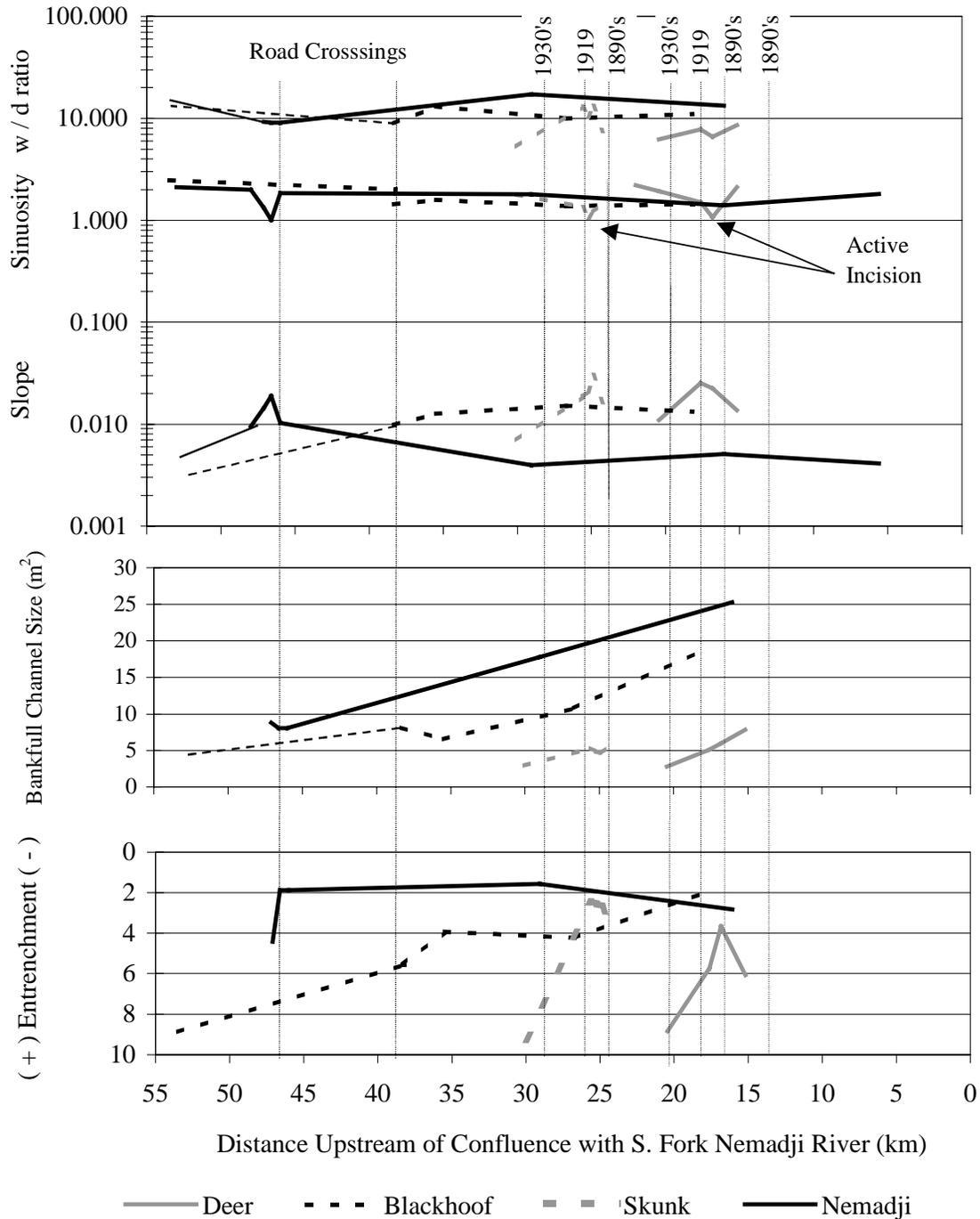
The channel metrics of slope, sinuosity and width depth ratio along each of the study streams are shown in Figure 2. The dates of the floodplain and terraces, inferred from the oldest trees on these features, are noted in this figure as well as the locations of active channel incision. Deer and Skunk creeks show a distinct reduction in sinuosity, slope increases, and drops in width depth ratios where they are actively incising, just upstream of their confluence with the Nemadji River. Similar, but less dramatic changes are evident on the Blackhoof River. The floodplains upstream of the active incision on these streams date to 1919 while those further upstream, in the headwaters, date to the 1930's. Immediately downstream of the actively incising reaches the streams join the Nemadji River. Here, the trees on the floodplains date to the turn of the century while those on the first terrace date to the late 1840's.

The cross sectional area and entrenchment ratios of the streams are also plotted in Figure 2. The entrenchment ratio is the width of the flood prone area (valley width at twice the maximum depth above the channel bottom) divided by the bankfull width. Hence, a low entrenchment ratio indicates a deeply incised valley. Perturbations in the cross sectional area and entrenchment ratios for Deer and Skunk Creeks and the Blackhoof River coincide with the shifts in the ages of the floodplain and terrace trees. The decrease in channel size is associated with increased entrenchment (decreased entrenchment ratio). Notably, the decrease in the size of the Deer Creek channel along the incising study reach is not statistically different from the upstream and downstream reaches while the change in the entrenchment ratio is significant.

DISCUSSION AND CONCLUSIONS

The longitudinal patterns of stream morphology and channel metrics of Deer and Skunk creeks, and to a lesser extent the Blackhoof River, indicate that these streams were perturbed by water yield increases resulting from basin scale land use changes at the turn of the century and during the 1930's. The channel evolution scenario begins at the most downstream location on each stream and progresses upstream, through three general stages. Abandoned floodplains and relic channels near the mouths of each stream indicate that their morphology before incision was similar to that of the minimally impacted reaches in the headwaters. When large-scale land use conversion increased water yield, head cuts were initiated in the Nemadji River and these propagated up the tributaries. The streams incised into the valley bottoms, accelerating bank erosion and mass wasting. This created room for the construction of the new, stable flood plains at a lower elevation.

FIGURE 2: Shifts in channel metrics along each study stream. 1890's dates represent the current flood plains of the Nemadji River and Deer and Skunk Creeks and the Blackhoof River at their confluence with the Nemadji. The affiliated terraces at these locations date to the late 1840's. 1919 dates are the oldest floodplain trees in the area of active incision. 1930's dates represent trees on flood plains in the upland portions of the tributary watersheds.



The next stage is located upstream where the Blackhoof River, Deer Creek, and Skunk Creek are actively incising; turning their floodplains into terraces and leaving relic channels behind. Unlike the downstream reaches, these reaches have yet to create a stable morphology, defined as experiencing no net aggradation or degradation. It is here that the perturbations in slope, sinuosity, width depth ratio, channel size, and entrenchment serve as indicators of fluvial response to basin-scale land use change. The streams are creating room for new flood plains via bank and valley erosion. Progressing into the headwaters of each stream, the channels transition to a stable morphology and show no evidence of basin scale destabilization subsequent to the agricultural land use conversion of the 1930's. Localized areas of channel instability exist (i.e. bank erosion) in the headwaters. These are caused by riparian land use impacts rather than basin scale land use conversion.

Fitzpatrick (1999), using sediment core analyses and modeling, reported a similar pattern of fluvial response to basin scale land use change in the Fish Creek basin of North Central Wisconsin. Fitzpatrick found that fluvial adjustments were associated with increased water yields stemming from forest harvesting efforts of the mid to late 1800's, agricultural land use conversion in the 1920's and 1930's and large floods in 1941 and 1946.

The scenario presented represents an upstream migration of a head cut through a drainage network. Simon and Hupp (1986), in their model of stream evolution, identified a series of fluvial stages that streams go through in response to basin scale land use disturbance. It is consistent with the evolutionary trends found in this study. The stream classification system of Rosgen (1996) identifies a similar pattern of evolution however, it is based upon reach level impacts rather than the basin scale perturbations addressed by Simon and Hupp and the current study.

It is clear that the evolution of the channels continues today. On Deer and Skunk Creek, it appears that the propagation of the incision episodes will be halted when the head cuts reach reinforced road crossings. However, the wing-walls and box culvert arresting one of the head cuts in Deer Creek at Highway 23 are failing. The active region of incision on the Blackhoof River has nearly cut to the perimeter of the lacustrine clay deposits. The rate of the head cut migration will likely increase as it propagates into the weakly consolidated glacial till and beach sand interface. Dendrochronological evidence indicates that the Nemadji is actively evolving however; the spatial extent of this study was insufficient to address this scale of fluvial evolution.

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