SPATIAL AND TEMPORAL SENSITIVITY OF HYDROGEOMORPHIC RESPONSE AND RECOVERY TO DEFORESTATION, AGRICULTURE, AND FLOODS

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Abstract: Clear-cut logging followed by agricultural activity caused hydrologic and geomorphic changes in North Fish Creek, a Wisconsin tributary to Lake Superior. Hydrogeomorphic responses to changes in land use were sensitive to the location of reaches along the main stem and to the relative timing of large floods. Hydrologic and sediment-load modeling indicates that flood peaks were three times larger and sediment loads were five times larger during maximum agricultural activity in the 1920s and 1930s than prior to about 1890, when forest cover was dominant. Following logging, overbank sedimentation rates in the lower main stem increased four to six times above pre-settlement rates. Accelerated streambank and channel erosion in the upper main stem have been and continue to be primary sources of sediment to downstream reaches. Extreme floods in 1941 and 1946, followed by frequent moderate floods through 1954, caused extensive geomorphic changes along the entire main stem. Sedimentation rates in the lower main stem may have decreased in the last several decades as agricultural activity declined. However, geomorphic recovery is slow, as incised channels in the upper main stem function as efficient conveyors of watershed surface runoff and thereby continue to promote flooding and sedimentation problems downstream. [Key words: fluvial geomorphology, floods, erosion, sedimentation, deforestation, agriculture.]

INTRODUCTION

North Fish Creek, Wisconsin, served as a case study of the hydrogeomorphic responses of streams in the northern Great Lakes region to widespread clear-cut logging and deforestation following European settlement in the late 1800s. Most importantly, this study also examined geomorphic responses in the context of both land use impacts and the timing of large floods from approximately 1880 to 1995. Field studies were combined with hydrologic and sediment-load modeling to evaluate geomorphic responses in relation to stream position. Lastly, geomorphic recovery rates following decreases in agricultural activity during the recent decades were evaluated.

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Many studies have documented the hydrologic effects from deforestation (Hornbeck et al., 1970; Hetherington, 1987; Shiklomanov and Krestovsky, 1988). In the northern Great Lakes region, clear-cut logging has been shown to cause an increase in annual streamflow of 30 to 80 percent and a twofold increase in annual peak flow (Verry, 1986). If reforestation occurs, the annual streamflow and flood peaks normally return to pre-logging conditions in only a few years to several decades (Reinhart et al., 1963; Verry, 1986). However, in areas where natural vegetation is permanently altered to agricultural land, substantial long-term changes in flooding and sediment loads have occurred (Knox, 1977; Jacobson and Primm, 1997). The application of soil conservation practices in agricultural areas since the mid-1930s has resulted in potential decreases in flood peaks and volumes in southwestern Wisconsin streams (Potter, 1991).

Examples of geomorphic responses to land use impacts also are well documented. In southwestern Wisconsin, channel morphology and floodplain aggradation rates were altered in response to a three- to fivefold increase in flood magnitudes and increases in upland erosion caused by conversion of natural vegetation to agricultural land (Knox, 1977). Exact geomorphic responses varied spatially between tributary and main-stem channels, based on sediment-load characteristics. Better land management practices since the 1930s in southwestern Wisconsin have resulted in a reduction of overbank sedimentation rates in both tributaries and main stems (Trimble and Lund, 1982; Knox, 1987, 1999). In the Ozark Plateaus, Missouri, land-use-related disturbance after European settlement resulted in widespread stream aggradation (Jacobson and Primm, 1997). The Neuse River in the North Carolina Coastal Plain experienced a threefold increase in sediment yield and channel and floodplain aggradation following Colonial-era clearing (Phillips, 1991, 1993). In New South Wales, Australia, forest clearing following settlement caused changes in channel morphology, channel patterns, sediment sources, and sediment-transport dynamics in several large rivers (Brooks and Brierley, 1997; Fryirs and Brierley, 1999).

Changes in the intensity, magnitude, and frequency of precipitation also affect the frequency and magnitude of floods and sediment loads (Knox, 1983, 1984). Infrequent, large floods can trigger substantial geomorphic change, especially floods of medium to long duration (Erskine and Bell, 1982; Erskine, 1986; Baker and Costa, 1987; Costa and O'Connor, 1995). The long-term geomorphic impact of extreme events varies with climate (Wolman and Gerson, 1978). Such floods, although rare, can cause the formation of stream terraces and new floodplains and cause changes in channel morphology. Small, frequent floods also are important for rebuilding channel morphology after large floods (Wolman and Leopold, 1957). Large floods followed by more frequent moderate floods are particularly destructive to channel stability (Schumm and Lichty, 1963). Flashy streams with high gradients, abundant coarse bedload, low bank cohesion, and channel cross sections that promote deep, high-velocity flows appear to be particularly geomorphically responsive to large floods (Kochel, 1988). Depending on the spatial position of a stream within a network, its geomorphic response to changes in flood and sediment-load characteristics can be indicated by changes in floodplain aggradation and degradation

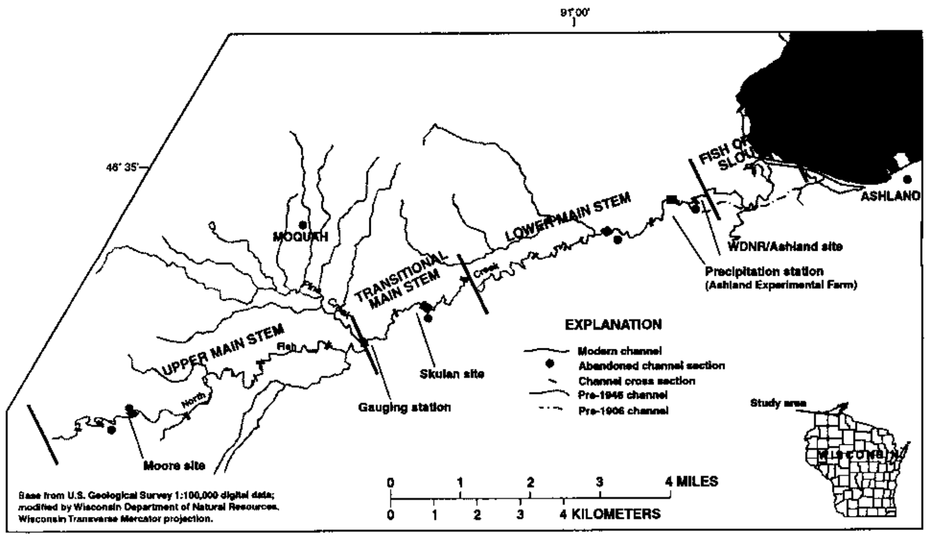

Fig. 1. Location of North Fish Creek.

rates, and changes in channel morphology, channel pattern, and gradient (Schumm, 1968; Schumm and Brakenridge, 1987; Kochel, 1988).

STUDY AREA

The 122 km^2 drainage basin of North Fish Creek (Fig. 1) is located in the northern hardwood forest region (Curtis, 1959). The average annual precipitation is 810 mm and average annual runoff is 360 mm (Gebert, 1986). The drainage network of North Fish Creek is geologically young and developed quickly following deglaciation of the region about 10,000 years ago (Clayton, 1984). The creek is not altered by dams or channelization. On the basis of 1992 satellite data, 60 percent of the basin is forest, 31 percent is grassland or pasture, and less than 3 percent is used for forage crops. The remaining 6 percent consists of wetland, barren land, and shrubland (Wisconsin Department of Natural Resources, 1998). Extensive areas of the uplands have surficial deposits of lacustrine clays that have been locally mixed with other proglacial and ice-contact sediments. The clayey lacustrine sediments have very low infiltration rates of 0.25 cm per hour (Clayton, 1984; Krug et al., 1992). The low infiltration rates produce high runoff rates. The upper main stem of North Fish Creek is incised through extensive proglacial fluvial sand and gravel deposits. These deposits are noncohesive, and are easily eroded under the modern hydrologic regime.

Land Use History

Extensive logging and burning of old-growth forests in the North Fish Creek basin occurred from approximately 1882 to 1889; more than 47 million board feet of logs

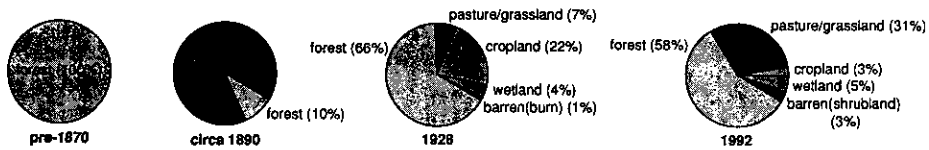

Fig. 2. Land use history in the North Fish Creek basin ca. 1890 (historical accounts, newspaper articles); 1928 (Wisconsin Department of Agriculture and Wisconsin Geologic and Natural History Survey, 1928); and 1992 (Wisconsin Department of Natural Resources, 1998).

were floated down North Fish Creek (D. Pratt, Wisconsin Department of Natural Resources, pers. comm., 1996). After a decline in logging, agricultural activity peaked in the late 1920s to early 1930s (Wisconsin Department of Agriculture and Wisconsin Geological and Natural History Survey, 1928) (Fig. 2). Following peak agricultural activity, the amount of forested land has remained nearly constant, but much of the cropland has been converted to pasture or grassland (Fig. 2).

Flood History

The flood history of North Fish Creek was reconstructed from long-term precipitation records collected near Ashland, Wisconsin, near the mouth of North Fish Creek (Fig. 1) and from articles in local newspapers. Floods from spring snowmelt dominate the annual maximum series, but the largest floods recorded in newspapers resulted from intense summer storms. The temporal distribution of precipitation events greater than 94 mm was examined for the period 1900 to 1997 (Fig. 3). The 10-year, 24-hour rainfall for the Ashland area is approximately 94 mm (Hershfield, 1961). The temporal distribution of large storms has been episodic. Only three large storms occurred between 1910 and 1940, followed by exceptionally large storms in 1941 and 1946. Seven large storms occurred between 1950 and 1954. The largest rainfall on record in 1946 was greater than 230 mm. For comparison, the 100-year, 24-hour rainfall for the area is 114 mm (Hershfield, 1961).

METHODOLOGY

The geomorphic responses of North Fish Creek were reconstructed from field and laboratory analyses of exposures and cores from floodplain and channel deposits. Hydrologic and sediment-load modeling were employed to supplement field data. Government Land Office (GLO) survey notes from 1855 also were used to compare modern and pre-settlement channel-width and streambed-sediment conditions at locations where section lines intersected the channel of North Fish Creek. Other historical documents, such as aerial photographs, bridge construction records, and newspaper articles, were used to support field, laboratory, and modeling data. Additional descriptions of the methodology used in this study can be found in Fitzpatrick (1998).

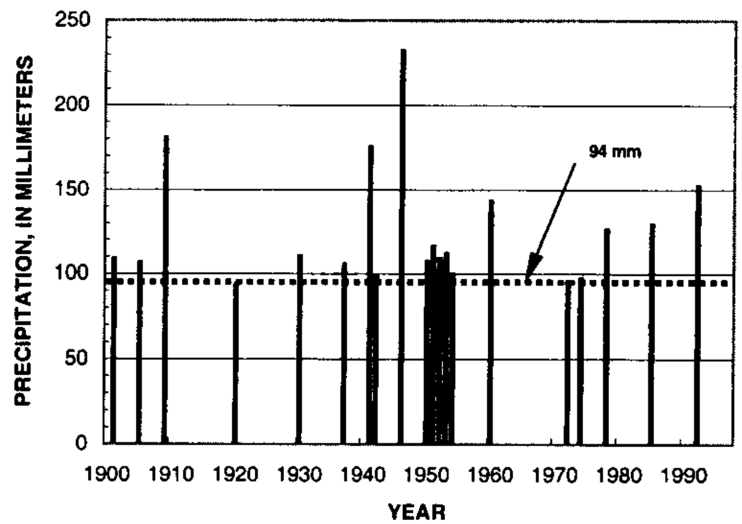

Fig. 3. Rainfalls greater than 94 millimeters, Ashland Experimental Farm, Wisconsin, 1900 to 1997. Data from the State Climatologist's Office, Madison, Wisconsin.

Field and Laboratory Methods

Relative degree of soil development, radiocarbon dating, and floodplain stratigraphy were used to determine pre- and post-settlement rates of erosion and sedimentation. Cores were collected and exposures examined in 1994 and 1995 along the main stem and near the mouth of North Fish Creek. Sediment samples were analyzed for particle size and organic carbon content at the University of Wisconsin–Madison. Wood and organic material were collected for radiocarbon-age determinations of floodplain deposits and abandoned channels. Calendar-calibrated age ranges were calculated from conventional radiocarbon ages using the Stuiver and Reimer (1993) calibration procedure. The calendar-calibrated ages are given as a range that included a possible statistical error of 2 standard deviations (95% probability).

The cross-section geometry, elevation, gradient, sediment characteristics, and age for each of five abandoned channels along the main stem were used to estimate former bankfull flows and erosion and sedimentation rates. Bankfull flows in the modern and abandoned channels were estimated by use of a one-dimensional, steady-state, step-backwater hydraulic model HEC2 (U.S. Army Corps of Engineers, 1991). Full-channel-capacity flows (flows extending to the level of the relict pre-settlement floodplain surface) also were estimated for contemporary incised channels using HEC-2.

Hydrologic and Sediment-Load Modeling

Flood peaks for various historical land use conditions in the North Fish Creek basin were estimated with the HEC-1 rainfall/runoff model (U.S. Army Corps of

Table 1. General Description of Methods Used in the North Fish Creek HEC-1 Model

Parameter	Description
Time step	15-minute
Precipitation	Hourly precipitation data from Ashland Experimental Farm for historical storm on September 3, 1991
Base flow	Observed flow data
Runoff	SCS Curve numbers
SCS unit hydrographs	Based on time-lag calculations of time of concentration and travel times for sheet flow, shallow concentrated flow, and channel flow (U.S. Department of Agriculture, 1986)
Channel routing	Muskingum-Cunge method
Calibration	15-minute streamflow data from gauging station near Moquah, Wisconsin

Engineers, 1990) (Table 1). Flood peaks were modeled for a historical storm expected to occur on average every two years (Hershfield, 1961). The drainage basin above the U.S. Geological Survey (USGS) gauging station near Moquah, Wisconsin, was divided into 10 subbasins, based on location of major tributaries, land use, and soils (Fitzpatrick, 1998).

The modeled floods were integrated with empirical sediment-transport relations derived from streamflow and sediment data collected at a gauging station on North Fish Creek (Rose and Graczyk, 1996; Fitzpatrick, 1998) (Fig. 1). Total sediment discharge at the gauging station was determined by use of the modified Einstein procedure (Colby and Hembree, 1955). Sediment-transport curves were constructed by use of USGS procedures (Glysson, 1987). Equations defining the curves were determined by regression analysis (least squares) of 15-minute stream flow and total-sediment discharge (Table 2). The hydrologic/sediment-load model was calibrated with historical streamflow data from the gauging station. Three types of basin land use conditions were modeled: complete forest representing pre-settlement conditions, peak agriculture in the mid-1920s to mid-1930s, and lowintensity agriculture (modern conditions based on 1992 satellite imagery).

RESULTS

The geomorphic responses to changes in flooding and sediment loads are described in terms of three reaches along the main stem of North Fish Creek (Fig. 1; Table 1).

Post-Settlement Changes in Channel Planform and Morphology

Almost all channel avulsions identified on aerial photographs from 1938, 1954, and 1990 occurred between 1938 and 1954 (Fig. 1). The extreme flood in 1946 fol-

Table 2. Empirical Sediment-Transport Equations for North Fish Creek Near Moquah, Wisconsin[a]

Sediment-transport equations
If $Q_w \leq 67$, $Q_S = 1.22857$
If $67 < Q_w < 181.5$, $Q_s = 1E-9 * Q_w$ ^4.9342
If $Q_w \geq 181.5$, $Q_s = 0.0116 * Q_w$ ^1.8065

[a]Q_w is discharge, in cubic feet per second; Q_S is sediment load, in tons per day.

Table 3. Selected Characteristics of Three Reaches along the Main Stem of North Fish Creek

Characteristic	Upper main stem	Transitional main stem	Lower main stem
1995 channel substrate	Cobble/boulder, minor sand	Transition from mainly cobble/boulder to sand	Sand
1995 bank stability	Unstable	Unstable	Stable
1995 gradient, m/m	.003–.011	.006–.0012	.0004–.0012
1995 full-channel area, m^2	23–28	25–44	17–18
Pre-1946 full-channel area, m^2	11–14	14–24	12
1995 full-channel discharge, m^3/s	25	55	15
Pre-1946 full-channel discharge, m^3/s	10	20–25	5–10

lowed by frequent, moderate floods in the early 1950s presumably caused these avulsions. Most of the avulsions occurred in the upper main stem. A major change in the outlet of North Fish Creek occurred prior to 1906 (based on plat maps).

Magnitudes of post-settlement changes in channel morphology were dependent on the location of the channel along the main stem. Comparisons of 1995 and 1855 channel widths indicated that the steep-gradient upper main-stem channel narrowed up to 42 percent (Table 4). In contrast, the gentle-gradient lower main-stem channel widened by as much as 30 percent. Channel area in the upper and transitional main stems doubled (Table 3). In the lower main stem, channel area increased by 1.5 times. Channel substrate did not change following European settlement (based on comparison of 1855 GLO notes and 1995 channel surveys). No evidence was found for changes in channel gradient (based on comparison of modern and abandoned channel gradients).

Discharge magnitudes estimated with HEC-2 for full-channel capacities indicate that modern full-channel discharges are about twice as large as pre-1946 full-channel discharges at the same sites in the upper and transitional main stems (Fig. 4;

Table 4. Comparisons of North Fish Creek Channel Width in 1855 and 1995[a]

Reach	River kilometer above mouth	1855 channel width (m)	1995 channel width (m)	Change in channel width 1855 to 1995 (m)	Percent change in channel width 1855 to 1995
Upper main stem	26.5	6	5	–1	–17
	24.8	8	8	0	0
	22.8	10	10	0	0
	19.6	12	7	–5	–42
	19.1	12	9	–3	–25
	17.1	8	9	1	13
Transitional main stem	14.6	14	11	–3	–21
	12.4	13	10	–3	–23
	12.1	12	13	1	8
Lower main stem	9.1	12	12	0	0
	6.6	10	13	3	30
	5.1	14	14	0	0
	4.2	12	15	3	25

[a]1995 channel width measured from water's edge during low-flow conditions to match most probable width measured in the 1855 Government Land Office Survey notes, which were also done during low-flow conditions.

Table 3). In the lower main stem, there was no difference observed between full-channel capacities for the modern channel and a pre-1906 abandoned channel (Fig. 4).

Post-Settlement Degradation and Aggradation Rates

Comparisons of the modern and abandoned channel morphologies and their differences in relative elevations indicate that changes in runoff after forest clearance and agricultural settlement caused channel incision of 1 to 3.5 m in the upper and transitional main stem and approximately 1 m of channel aggradation in the lower main stem.

A valley cross section from the upper main stem of North Fish Creek (Fig. 5) illustrates how the modern channel is incised compared to a pre-1946 channel. The valley cross section shows the absence of a modern floodplain, typical for rapidly downcutting streams. The incised modern channel is very efficient at transporting water and sediment downstream. Presence of at least five terraces indicates that the upper main stem has been subject to many episodes of incision over the last 10,000 years.

Field evidence indicates that floodplain deposition rates were high along the transitional main stem after European settlement (Fig. 6). Approximately 0.5 to 2 m

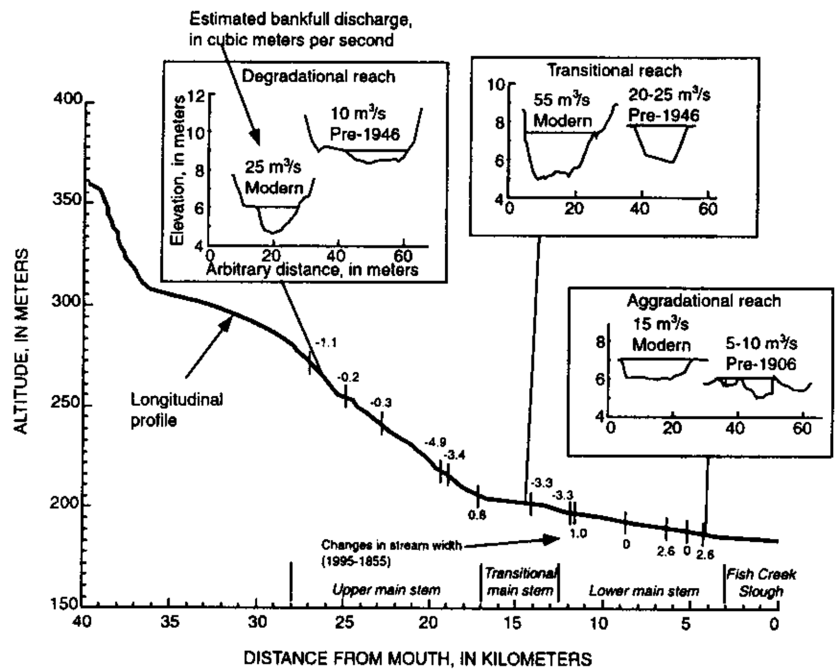

Fig. 4. Longitudinal profile of North Fish Creek with bankfull discharges and changes in channel width, 1855 to 1990. Stream-width changes calculated from 1855 Government Land Office surveys and from cross-section surveys done as part of this study in 1995. Bankfull discharges estimated from HEC-2 modeling results (Fitzpatrick, 1998).

of post-settlement alluvium covers the pre-settlement floodplain surface. Post-settlement floodplain sedimentation rates were approximately 10 to 20 times greater than pre-settlement sedimentation rates, based on radiocarbon ages of buried wood (Table 5). After this aggradational episode, channel incision became the dominant geomorphic process in the transitional reach. The channel bed has eroded approximately 1 m since 1946, as indicated by the elevation difference between beds of the modern channel and a channel abandoned during the 1946 flood. The combination of historical channel incision and overbank floodplain sedimentation results in an extremely entrenched channel. This channel, similar to the upper main stem channel, is highly efficient for transporting sediment and water downstream.

In the lower main stem, approximately 1 to 2 m of post-settlement aggradation has occurred. Figure 7 presents a valley transect from this reach, showing the typical distribution, particle size, and thickness of post- and pre-settlement overbank deposits. Post-settlement overbank deposits consist of fine or medium sand, whereas pre-settlement deposits were generally dominated by silt- or clay-rich sediment high in organic matter. Near the lower end of this reach, North Fish Creek branches into multiple channels, causing widespread distribution of sandy sediment throughout the floodplain. For example, near a pre-1906 channel 300 m south of the main channel, approximately 0.5 m of sediment has been deposited from a nearby distributary channel of North Fish Creek (Fig. 7).

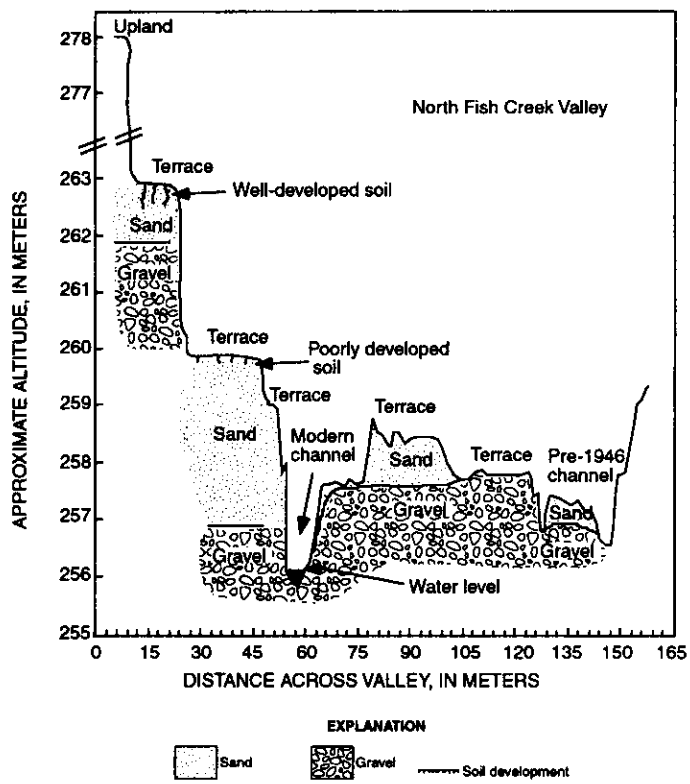

Fig. 5. Valley cross section of North Fish Creek from the upper main stem at the Moore site.

Table 5. Sedimentation Rates for Various Time Periods and Radiocarbon Data from the Skulan Site in the Transitional Reach

Site and reach	Depth (cm)	Radiocarbon age of wood sample	Estimated age	Time period used for calculating sedimentation rate	Sedimentation rate (cm/yr)
Terrace 1	208–211	280 ± 80 ^{14}C yr B.P. (1450–1700, 1720–1820, 1855–1860, 1920–1950 A.D.)	1870 A.D.	1870–1995 A.D.	1.66
	255–265	420 ± 60 ^{14}C yr B.P. (1525 ± 115 A.D.)	1525 A.D.	1525–1870 A.D.	0.14
Terrace 2	1.11	–[a]	1870 A.D.	1870–1995 A.D.	0.89
	260–270	3255 ± 55 ^{14}C yr B.P. (1670 ± 20 B.C.)	1670 B.C.	1670 B.C.–1870 A.D.	0.04

[a]No radiocarbon age, depth and estimated age based on presence of pre-settlement soil.

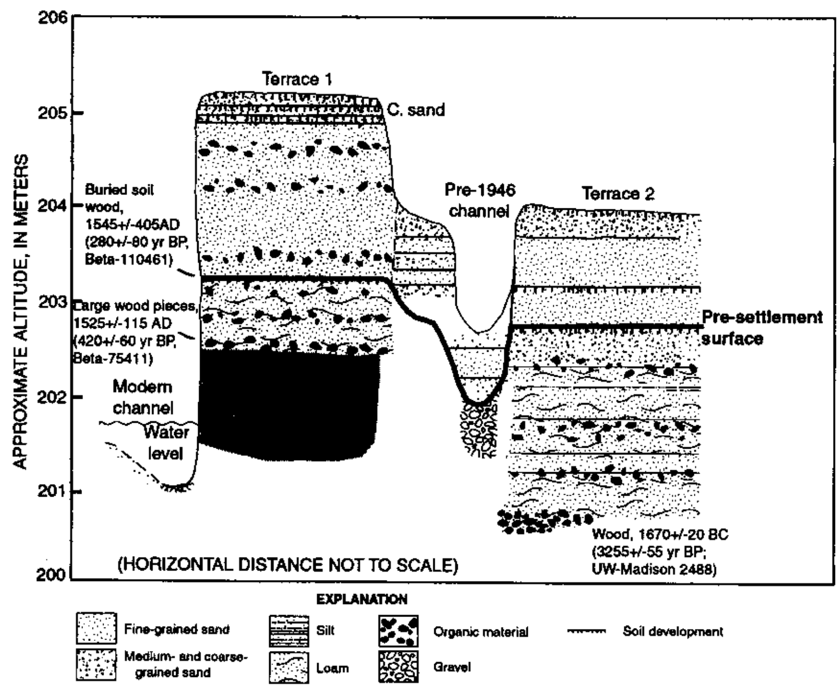

Fig. 6. Partial valley cross section of North Fish Creek from the transitional main stem at the Skulan site. Calendar-calibrated radiocarbon ages calculated from conventional radiocarbon ages using the Stuvier and Reimer (1993) calibration procedure.

Sediment cores collected near the confluence of North and South Fish creeks in Fish Creek Slough (Fig. 1), indicate that approximately 1.8 m of post-settlement alluvium, mainly fine sand, accumulated on the floodplain at a location 20 m from the modern channel (Fig. 8). Government Land Office Survey field notes and maps for this location indicate that the modern channel at the confluence is in the same location as it was in 1855. Radiocarbon ages of wood samples from buried soils below the pre-settlement soil indicate that the post-settlement sedimentation rate of 1.4 cm/yr at this site is five times greater than the average rate of 0.28 cm/yr during the 500 years before European settlement. Data on particle size indicate an increase in the sand content of post-settlement floodplain deposits compared to silt- and clay-rich pre-settlement deposits. Percentages of organic carbon increase near the modern floodplain surface in this core and at other sites along the lower main stem, indicating a reduction in overbank deposition along this reach.

Post-Settlement Changes in Flood Peaks and Sediment Loads

HEC-1 modeling results at the streamflow gauging station on North Fish Creek indicate that under peak agricultural land use in the basin (about 1928), flood peaks for a two-year storm were about 3 times greater than under pre-settlement forest cover (Fig. 9A). Flood peaks of this recurrence interval for 1992 land use in the

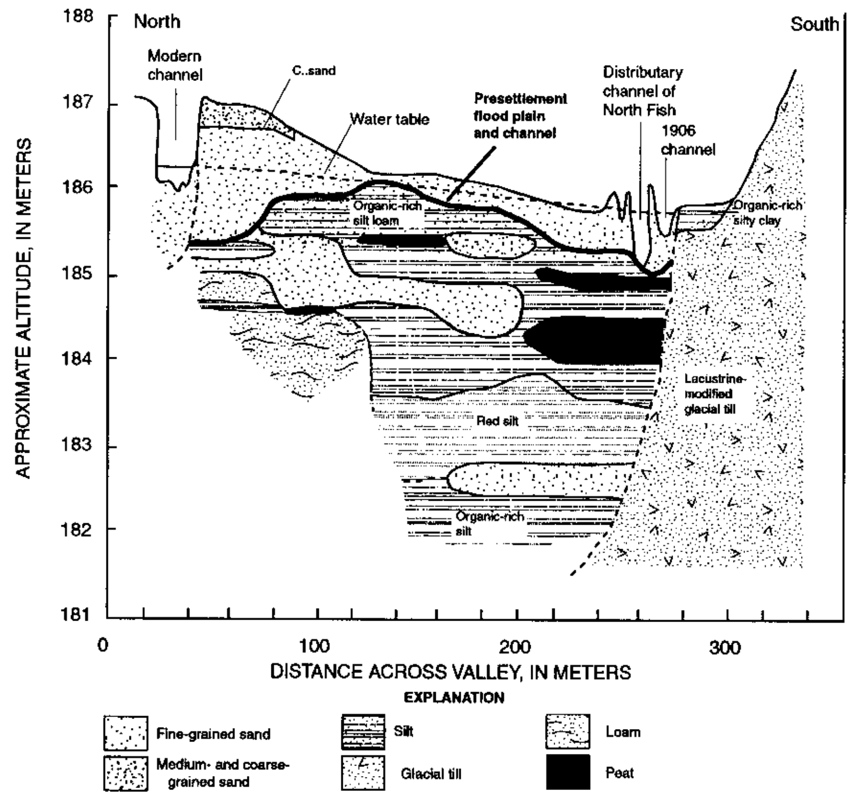

Fig. 7. Partial valley cross section of North Fish Creek from the lower main stem at the WDNR/Ashland site.

basin are about twice as large as during pre-settlement conditions. In turn, sediment-load modeling indicates that sediment loads for a two-year storm under peak agricultural land use were about 2.5 times greater than under modern land use conditions, and may have been 5 times greater than under pre-settlement forest cover (Fig. 9B).

DISCUSSION

Channel Adjustments from Deforestation and Influence of Stream Position

Deforestation and subsequent agricultural activity associated with European settlement in the North Fish Creek basin resulted in a threefold increase in flood peaks and a fivefold increase in sediment loads, even though during peak agricultural activity in the 1920s and 1930s, more than half of the basin was reforested. These increases in flood peaks and sediment loads are comparable to those observed in previous studies of southwestern Wisconsin and North Carolina Coastal Plain streams (Knox, 1977; Phillips, 1993). It is possible that because of the highly impermeable clayey upland deposits in the North Fish Creek basin, less intensive agricul-

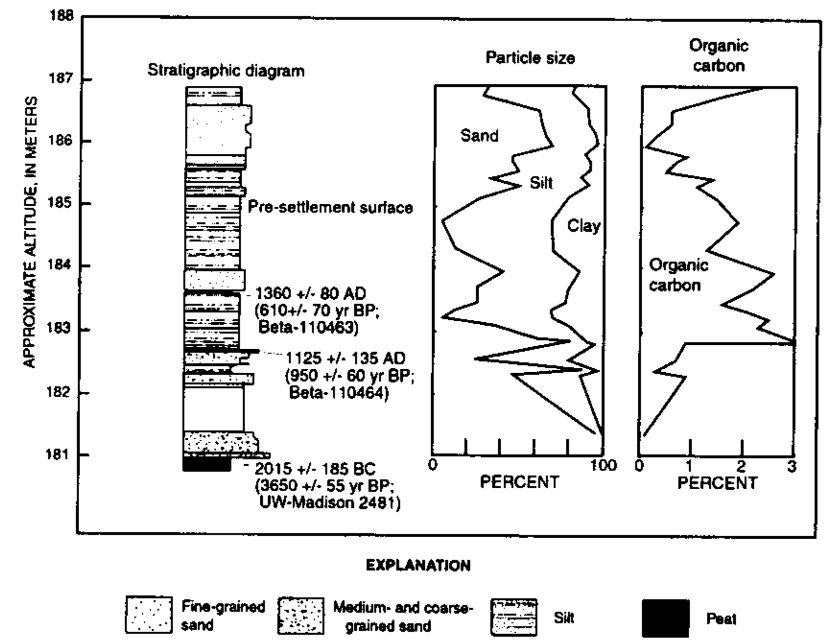

Fig. 8. Stratigraphic description, particle size, and organic carbon percentages for a core collected at the confluence of North and South Fish creeks in Fish Creek Slough.

tural practices in the North Fish Creek basin have resulted in runoff rates and flood peaks typical for more intensive agriculture on more permeable soils elsewhere, such as those found in southwestern Wisconsin.

The results from this study re-emphasize the importance of considering stream position in the prediction of geomorphic responses to increases in runoff, flood peaks, and sediment loads. Major differences and similarities exist between the types of geomorphic responses in North Fish Creek and southwestern Wisconsin streams. Unlike southwestern Wisconsin streams, upland erosion in North Fish Creek is negligible because of the general lack of cropland and exposed soil. Instead, sediment-starved accelerated runoff from pastures and abandoned fields easily erodes both horizontally and vertically through coarse proglacial fluvial deposits in the upper main stem. As a result, long-term natural degradation rates are accelerated. Modern incised channels in the upper main stem contain larger flows than their pre-settlement counterparts, which, in turn, have caused a reduction in overbank sedimentation during floods. Unlike North Fish Creek, overbank sedimentation rates on southwestern Wisconsin headwater streams increased in the late 19th century, but by the 1920s large-capacity tributary channels developed and caused a reduction in overbank sedimentation rates (Knox, 1987). Similar to North Fish Creek, overbank sedimentation rates in southwestern Wisconsin main stems rose during the late 19th century and continued to increase to a maximum in the 1930s (Knox, 1987). Consequently, the downstream spatial patterns of floodplain

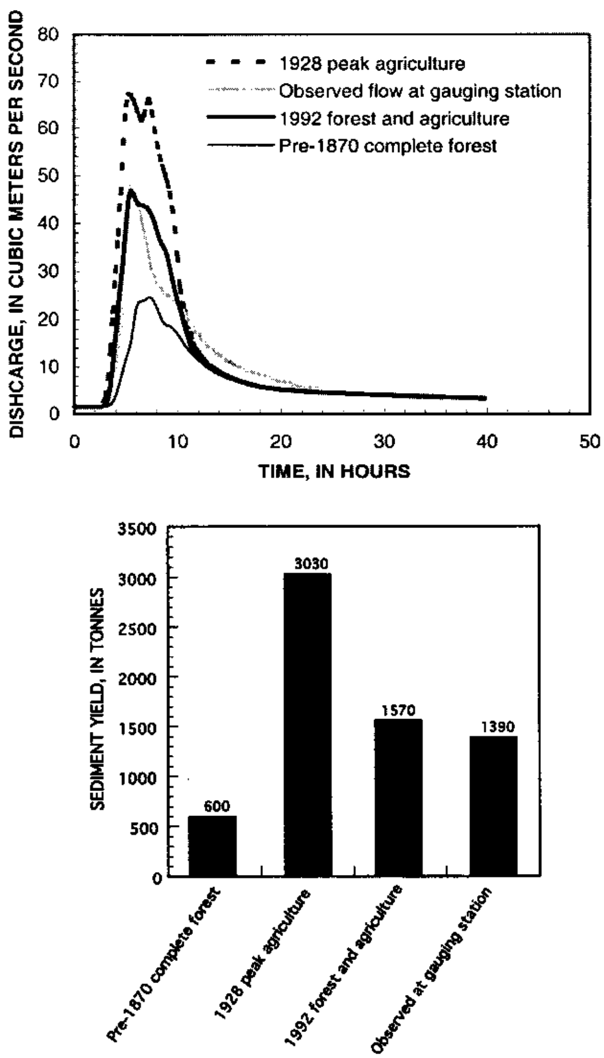

Fig. 9. Modeled (A) storm hydrographs and (B) sediment yields for North Fish Creek near Moquah, Wisconsin, for a historical storm on September 3, 1991, under three land-cover conditions. Precipitation data from the State Climatologist's Office, Madison, Wisconsin. Streamflow data from U.S. Geological Survey gauging station on North Fish Creek near Moquah, Wisconsin, Station ID 040263591. Sediment-load data from Rose and Graczyk (1996) and Fitzpatrick (1998).

and valley-floor sedimentation in North Fish Creek and southwestern Wisconsin watersheds are similar in this respect.

Temporal fluctuations between aggradation and degradation appear to have been a long-term characteristic of the transitional reach between the upper and lower main-stem reaches of North Fish Creek. The gradient lessens considerably in the transitional reach, and both aggradation and degradation have occurred before and after European settlement. Aggradation apparently was dominant between about 1670 B.C. and 1870 A.D., based on a radiocarbon age from wood in a soil buried approximately 1.5 m below the pre-1946 channel bed (Table 5). From about the 1890s to the mid-1940s, aggradational conditions continued in the transitional main stem because upstream sediment loads were at a maximum in response to clear-cut logging and intensive agricultural activity. Later, as forest regeneration occurred and the amount of cropland decreased, flood peaks and associated streambank and channel erosion and sediment loads in the upper main stem decreased. These changes in land use are apparently responsible for a shift in the transitional reach from primarily aggradational to degradational. Geomorphic conditions in the transitional main stem appear to be particularly sensitive to upstream changes in runoff and sediment loads. The sensitivity of this reach is largely dependent on the position of a substantial break in slope at the upstream end of the reach (Fig. 4). Possible future changes in floods and sediment loads are of concern because gravel beds in this reach provide important spawning habitat for several Lake Superior fish species.

Aggradational conditions were present in the lower main stem of North Fish Creek prior to European settlement (Figs. 7 and 8) because of the long-term increase in base level from differential isostatic rebound of the Lake Superior basin (Larsen, 1985). After European settlement, elevated sediment loads originating from the upper and transitional main stem caused a 4- to 6-fold increase in overbank sedimentation rates in the lower main stem (Fig. 9). This increase is considerably less than the 15- to 250-fold increase in overbank sedimentation rates observed in southwestern Wisconsin streams (Knox, 1987). Post-settlement floodplain deposits are also much coarser than their pre-settlement counterparts, indicating that modern overbank flows in the lower main stem have the capacity to carry larger particle sizes than pre-settlement overbank flows.

The channel morphology of North Fish Creek also was altered by changes in flood peaks and sediment loads, similar to the Bega River in New South Wales. In response to increases in sand bedload resulting from land use impacts, the Bega River widened up to 340 percent (Brooks and Brierley, 1997). However, channel widening in the aggradational lower main stem of North Fish Creek was less severe than the Bega River by an order of magnitude.

Importance of Timing of Large Flood Events

The effects of deforestation and agricultural activity on geomorphic conditions in North Fish Creek were especially noticeable after large floods. The large floods in 1941 and 1946, followed by an episode of frequent moderate floods in the early 1950s, produced substantial geomorphic change along the entire main stem of North Fish Creek. In the upper and transitional main stems, several meanders were abandoned and incision occurred (Fig. 1). The cross-sectional area of the pre-1946 abandoned channels in the upper and transitional main stems (Fig. 4; Table 3) are significantly smaller than the modern channels even though the entire basin was clear cut by 1900 and agricultural activity was flourishing. During peak agricultural activity, no major floods occurred and drought conditions were present in the mid-

1930s. Thus, major geomorphic change in North Fish Creek occurred during and following large floods that post-dated deforestation and agricultural activity by about 20 years.

Many previous studies have focused on only one major cause for geomorphic response, with changes in channel morphology attributed to either human impacts (changes in land use in many cases) or climatically induced large floods. For example, geomorphic responses of New South Wales streams have been attributed to either human impacts (Brooks and Brierley, 1997) or climate-related extreme floods (Erskine, 1986). In contrast, this study examined both land use history and the occurrence of climatically induced large floods. Historical changes in the channel morphology of North Fish Creek were driven mainly by land use impacts; however, effects from land use impacts were intensified by the occurrence of two large floods followed by more frequent moderate floods. The results from this study support the findings from land use impact studies such as Brooks and Brierley (1997), but also support the findings of flood-related studies, such as Wolman and Leopold (1957). Land use, flood, and climate histories need to be examined in concert to truly understand the complex causes for changes in channel morphology.

Geomorphic Recovery Following Decreases in Agricultural Activity

Hydrologic and sediment-load modeling indicated that runoff and sediment loads should have decreased following peak agricultural activity. However, there was insufficient field evidence to substantiate whether decreases in degradation rates in the upper and transitional main stem occurred following decreases in agricultural activity; however, increases in the organic content of floodplain alluvium of the topmost strata for sites along the lower main stem and in Fish Creek Slough (Fig. 8) indicate that overbank sedimentation rates have decreased since the 1940s or 1950s. Floods from two large rainfalls (greater than the 100-year, 24-hour rainfall of 132 mm) occurred in 1960 and 1992; however, neither approached the magnitudes of the 1941 and 1946 floods (Fig. 3). Furthermore, none have produced the geomorphic response associated with the 1941 and 1946 floods. Nevertheless, the larger full-channel capacities of the modern entrenched channels continue to promote streambank erosion and channel instability in the upper and transitional main stems.

CONCLUSIONS

Northern Wisconsin streams such as North Fish Creek are typically used as baseline reference sites because they are presumed to represent nearly natural conditions. Although accelerated sedimentation rates in North Fish Creek are less than in other more agriculturally dominated basins elsewhere, the results from this study indicate a strong human influence on the stream's geomorphology and hydrology. Modern temporal and spatial characteristics of runoff and sediment transport strongly reflect land use history and its effect on geomorphic response. Deforestation and past agricultural land use continue to accelerate erosion and sedimentation in the Fish Creek watershed even though the majority of the North Fish Creek basin is forested and the remaining agricultural land mainly consists of pasture or abandoned pasture. Persistence occurs because changes in runoff caused by early disturbances produced larger flows, which erode in the headwaters and transition reaches and cause continued aggradation along the lower main stem. Geomorphic recovery also was slowed by the occurrence of the largest recorded flood in 1946, followed by five floods caused by 10-year 24-hour rainfalls from 1950 to 1954. Nevertheless, both field evidence and modeling results indicate a slow recovery toward more natural rates of erosion and sedimentation has been occurring over the past several decades.

The results of this research have illustrated the complexity of how river systems respond to environmental change. The results further indicate that it is not possible to predict a geomorphic response simply by assessing changes in runoff and sediment loads. To understand response and recovery of North Fish Creek to historical land use change, other factors, including the historical sequence of flood events and their relative magnitudes, the downstream spatial variability in sensitivity of channel morphology to erosion and sedimentation, and physiographic diversity in the watershed, need to be assessed. Short-term climatic anomalies have the potential to greatly impact hydrologic and geomorphic processes and should be examined in the context of long-term climatic variability for proper interpretation of geomorphic response and recovery to changing land use.

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