EFFECTS OF MAGNITUDE AND DURATION OF LARGE FLOODS ON CHANNEL MORPHOLOGY: A CASE STUDY OF NORTH FISH CREEK, BAYFIELD COUNTY, WISCONSIN, 2000–2005

by

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Abstract

Impacts of a flood on a stream are closely related to the magnitude and duration of the flood. Many applied applications in fluvial geomorphology are focused on the importance of the effective flow, commonly defined as stream discharge at the bankfull stage, as the driving force in channel form and biotic function. Reliance on bankfull stage may be insufficient when flow variability has changed or where extreme floods suddenly become more frequent. The present study examines how rare floods of catastrophic magnitude influenced channel morphology and eroded, transported, and deposited large volumes of sediment in North Fish Creek, Bayfield County, Wisconsin.

The present thesis presents results from monitoring changes in channel morphology and bluff erosion following installation of flow-deflecting vanes at three eroding bluff sites along North Fish Creek, Wisconsin, over the period 2000–05. Channel and bluff changes are described in the context of four floods that occurred from 2001-2005. Channel responses were measured following various floods that involved from 1-7 flood peaks. These floods illustrated a range of high magnitude, low frequency flows caused by differing rainfall and/or snowmelt conditions. Changes in channel morphology (based on changes in cross-section profiles) were quantified in terms of volume of sediment eroded or deposited along cross-channel survey transects representing point bar, stream bed, channel bar, and bluff margin locations.

Results show that a flood of moderate magnitude and long duration, e.g. here one of 30 days duration and 100 year flood recurrence interval and 39 days duration and 25-50 year flood recurrence interval, produce progressive deposition downstream from cross sections that experienced net erosion. On the other hand, more extreme, high magnitude floods, here represented by two floods that were respectively 2 and 7 days duration, and each associated with rainfall magnitudes that exceeded the 1,000 year expected rainfall frequency, produce different cross section to cross section morphologic changes depending on durations of flow and numbers of flood peaks. Here, an extremely flashy extreme flood mobilized large amounts of sediment, but a longer dura-

tion flood or a second flood peak was required to produce total net erosion at all cross sections over an extended reach.

If the present data are representative of long-term flood frequency behavior for North Fish Creek, for example, over a 1,000 year period, then in spite of the large magnitudes of erosion and sedimentation documented for recent extreme floods, summation of net sediment exchange implies that the smaller magnitude floods, transport more sediment in the long-term than do low frequency, high magnitude floods. This finding supports Wolman and Miller's (1960) conclusion that low magnitude, high frequency floods are more important than low frequency, high magnitude floods for the long term erosion and sedimentation from this small watershed in Northern Wisconsin. Nevertheless, present results also show the importance of extreme floods for exceeding stability thresholds of a channel system, such as incision of a previously long-term armored channel bed, and may lead to major lateral and vertical changes in the channel morphology.

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The support and understanding from my family and friends played the most important role in the whole process. I could not possibly list enough people here, but, thanks Mom for doing my laundry and Alane for cleaning my apartment.

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Introduction

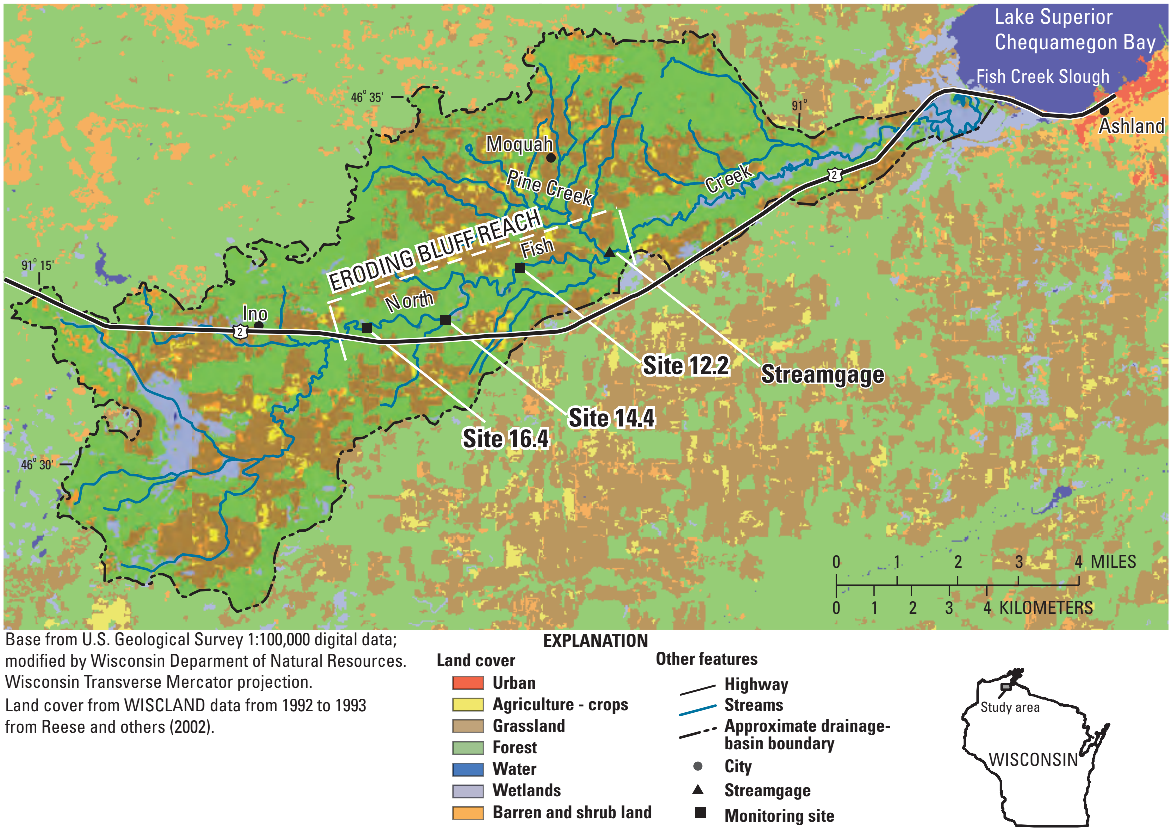
Many current applications in fluvial geomorphology are based on the importance of the effective flow, i.e. bankfull flow, as the driving force in channel form and biotic function. The importance of the bankfull flood is demonstrated by its essential position in many classification systems and natural-channel restoration designs and applications (Rosgen, 1996; Montgomery and Buffington, 1998). Wolman and Miller (1960) in their benchmark paper stated "The fact that the bankfull stage recurs on the average once every year or two years indicates that these features [channel shape and dimensions] of many alluvial rivers are controlled by these more frequent flows rather than by the rarer floods of catastrophic magnitude." This relationship has been shown to be true in many humid areas of the world and has led to many well designed and successful restoration projects. However, several projects that have utilized the approach of bankfull dimensions alone, without accounting for sediment loads or the effects of extreme events, in determining new channel dimensions for restoration projects have failed catastrophically (Juracek and Fitzpatrick, 2003). Reliance on bankfull stage may be insufficient in areas where the bankfull flow is not the dominant channel forming discharge or where alluvial processes have been strongly influenced by other factors related to relict glacial or geologic features or to human-induced processes such as urbanization or agriculture. The present study shows that the rare floods of catastrophic magnitude also influence channel form, move large volumes of sediment, and leave strong imprints on channel morphology.

Importance of Magnitude and Duration of Floods to Morphologic Changes

Extreme floods are known to accomplish large morphologic changes in a channel and move large volumes of sediment (Fitzpatrick and Knox, 2000; Magilligan and others, 1998; Schumm, 1977, 1973; Osterkamp and Costa, 1987). However, it has been commonly believed that in humid climate regions that the larger frequency floods of a smaller magnitude are responsible for the greatest amount of net transport sediment over long periods of time. In turn, prevailing opinion implies that the shape and form of the channel are predominantly related to the smaller magnitude floods of high (1-2 year) recurrence frequency (Wolman and Miller, 1960). In the example of stable point bar development, this is very logical; small amounts of sediment are progressively deposited, building up the channel and forcing progressive erosion of the cut bank. This approach does not account for the role of thresholds in forming channel shape. A large flood that exceeds a channel forming threshold has the ability to induce a large amount of morphologic change (Schumm, 1977). For example, a large flow exceeding the channel forming threshold forms features, such as meander cutoffs. This commonly occurs during an extreme flood where flow height exceeds the bank height at the cutoff and rapid erosion ensues as the channel develops a shorter, steeper new course. This changed course is commonly unstable until the channel adjusts to the new slope by altering erosion rates or other factors to reach a stable form.

In systems where streambanks do not have a typical mature alluvial floodplain, the processes may not follow these normal patterns. For example, in a river system where the channel is undercutting a high terrace, large floods may produce catastrophic erosion and major channel change as large volumes of sediment are injected into the channel. Once the terrace is undercut and exposed as a steep unstable bank even smaller subsequent flows may continue to inject anomalous high volumes of sediment. An example of such an environment is in the high relief area of North Fish Creek, Bayfield County, Wisconsin. Catastrophic erosion is likely to take place because the scale of the glacial bluffs is more than what the smaller scale stream can manage. When the flood pressures the banks, more erosion is possible with the larger sediment sources. The eroding bluff zone in North Fish Creek is in the sensitive transitional area of the stream longitudinal profile (fig. 1, Fitzpatrick and others, 1999). The area of the stream with the largest sediment sources (bluff area) is also the area that is the most sensitive to change and unstable. This setting and instability makes North Fish Creek an area that can be studied in term of large and small floods and how they affect the stability and channel of a stream because of the rapidly eroding and changing landscape.

The instability of the North Fish Creek system could be a result of its struggle to reach a dynamic equilibrium in an ever-changing post-glacial environment. The entire system is still adjusting isostatically to changes associated with intrusion of the region by the last continental glacier (Fitzpatrick, 1998; Fitzpatrick and others, 1999). Schumm (1975) suggests that as a river system approaches a state of dynamic equilibrium, is punctuated by episodes of more rapid erosion and deposition. Schumm argues that these episodes occur as fluvial systems shift from one steady state to another. After a river system reaches a steady state, it normally is not easily moved out of that state by outside factors. Even large floods may not cause drastic changes. On the other hand, when the stability threshold is exceeded, major fluvial adjustments in channel erosion, sedimentation, and river morphology may occur. Several recent large floods recorded at North Fish Creek in 2005 appear to have exceeded the stability threshold in the river system,



Base from U.S. Geological Survey 1:100,000 digital data; modified by Wisconsin Deparment of Natural Resources. Wisconsin Transverse Mercator projection.
Land cover from WISCLAND data from 1992 to 1993 from Reese and others (2002).

Figure 1. Location and land cover of North Fish Creek, Wisconsin and eroding bluff monitoring sites. Modified from Fitzpatrick and others, 2005.

and North Fish Creek may be in the process of adjusting toward a new steady state, similar to its morphology when first examined in 1994. A large flood damaged North Fish Creek in 1992 and the river may have still been adjusting to the post-flood changes (Fitzpatrick and Knox, 2000; Fitzpatrick, 1998)

Both flood magnitude and flood duration are important for understanding the impacts of floods on erosion, sedimentation and river morphology. A short duration flood with a high discharge will produce more damage than a small, less intense flood (Wolman and Miller, 1960; Nash, 1994). A flood of a very long duration can do more work in a channel transporting sediment than a flood of the same magnitude that does not last as long. When these two factors combine, they result in major erosion, sedimentation and morphologic change in the channel system. Conversely, if only magnitude or duration is maximized, a flood may result in relatively modest impacts on the river system.

Antecedent Conditions

Antecedent climatic conditions also strongly influence the size of floods and their effectiveness to impose erosion, sedimentation and morphologic change in a channel system. Snow pack significantly influences flood peaks. A heavy snow pack combined with rain leads to a much larger flood than snowmelt alone, as shown by the floods in this study.

If a flood is only one extreme peak in an otherwise flood free season, it may not be as damaging as one of similar magnitude but embedded in an array of other floods. Well-established vegetation cover on channel margins or stable bank slopes may prevent the erosion of stream banks during a single flood or lessen a flood's geomorphic effects. However, the occurrence of relatively small floods, very close to one another in time, may result in much more geomorphic change. The first flow could weaken the subtle defenses and render the channel system susceptible to damage by subsequent floods of even small size. This weakening includes removing streambank vegetation and increasing pore-pressure in the banks. An increase in the amount and rate of streambank erosion has been shown when vegetation is removed or altered (Abernethy and Rutherford, 2000; 2001; Gray and Sotir, 1996; Knighton, 1998).

This study measured floods with variable number of flood peaks and antecedent snow conditions. Results show these differences account for large variability in magnitudes of North Fish Creek responses to floods.

History of North Fish Creek Research

Erosion and sedimentation have been identified as problems related to floods in the tributaries to Lake Superior as early as 1955 (Red Clay Interagency Committee, 1957; 1960; 1964; 1967; 1971; 1972; 1977; Fitzpatrick and others, 1999; Fitzpatrick and others, 2005; Lentz and others, 2004; Inter-Fluve, Inc., 2003). Attention was directed to the issue of sediment pollution following a series of very large floods in the 1940s and 1950s combined with a failed flood control solution on Whittlesey Creek by the U. S. Army Corps of Engineers in 1946 (Fitzpatrick and others, in review).

The large flood in 1946 was over 9 inches of rain in a 24-hour period from a summer rain storm (Fitzpatrick and Knox, 2000). That flood, combined with other large flood in 1941 and an episode of more moderate, but large, floods in the 1950s, produced numerous channel avulsions and geomorphic change along the entire main stem of North Fish Creek (Fitzpatrick and Knox, 2000). These floods followed the land-use changes in the area by about 20 years and the large changes in North Fish Creek are likely the result of long-term climatic and land-use changes (Fitzpatrick and Knox, 2000). Two large floods (greater than the 100-year, 24-hour rainfall recurrence interval) also occurred in the North Fish Creek basin in 1960 and 1992, but they failed to produce such large responses in the channel morphology. The lack of response of large-scale channel change indicates a slow recovery from the disturbances of the land-use changes of the 1880s-1930s and the climate changes in the 1930s (Fitzpatrick and Knox, 2000).

Bank and bluff erosion have been identified as a major problem in tributaries to Lake Superior, negatively impacting in-stream, estuary, and lacustrine habitat (Fitzpatrick and others, 1999;

Fitzpatrick and others, 2005; Fitzpatrick and others, in review). Sedimentation problems were accelerated in North Fish Creek by changes in land use and storm runoff leading to habitat degradation from the silting in of fish habitat (Fitzpatrick and others, 1999). Similar changes in land use caused changes in the flood-flow characteristics leading to increased bank erosion in Whittlesey Creek (adjacent tributary to the north) (Lenz and others, 2004).

The high value of North Fish Creek as a recreational fishing area, and the observed siltation that was covering fish spawning gravels led to an early sediment load study (Rose and Graczyk, 1996). A streamflow gaging station was installed in 1990 and sediment loads were obtained for the 1990-91 water years. Building upon this study, sediment sources and historical geomorphic responses to changes in land cover and large floods were studied (Fitzpatrick and others, 2005; Fitzpatrick and Knox, 2000; Fitzpatrick, 1998). Fitzpatrick (1998) identified the bluffs as the major sediment source to North Fish Creek. Rates of bluff erosion were measured from historical aerial photographs. Bluff stratigraphy was identified and benchmarks were established to track long-term retreat at one bluff site (Fitzpatrick, 1998).

Recognition of the major sediment sources subsequently led to remedial efforts by the Wisconsin Department of Natural Resources and the University of Wisconsin-Madison Civil and Environmental Engineering Department to reduce erosion and stabilize the bluffs. The USGS was involved in research and monitoring techniques (Whitman, 2002; Fitzpatrick and others, 2005; Storrar, 2006). Over the course of these studies, three bluff sites were selected for testing flow-deflecting vanes and channel relocation. The bluffs were monitored by the USGS by repeat measurements of cross-sections, bluff retreat measurements, streamflow and local stage monitoring (Fitzpatrick and others, 2005). The monitoring study is ongoing and this report analyzes monitoring and hydrologic data collected as of the fall of 2005.

During the monitoring period, several large floods occurred. This provided an opportunity to use the detailed bluff monitoring data at three sites to examine some of the relationships between duration and magnitude of floods and the amount of erosion, sedimentation and morphologic changes that occur as a result of different types of floods.

Purpose and Scope

The purpose of this thesis is to describe changes in the bluff sites as a result of floods and offers hypotheses on causes for the observed changes as they relate to frequency, duration, and magnitude of floods. Results are applied to illustrate how floods effect erosion, sedimentation and channel morphology. These results are a product of monitoring changes in channel morphology and bluff erosion following installation of flow-deflecting vanes at three eroding bluff sites along North Fish Creek, Wisconsin. Channel and bluff changes are described in the context of four floods that occurred from 2001-2005. Changes in channel morphology (based on changes in cross-section profiles) were quantified in terms of volume of sediment removed or deposited from the point bar, stream bed, bars, and bluff. Occurrence of block failure from the top of the bluffs also was quantified.

Description of Study Area

North Fish Creek is located at the head of Chequamegon Bay, Lake Superior, approximately 1 mile west of Ashland, Wisconsin. The drainage area of North Fish Creek at its mouth is approximately 47 square miles (Fitzpatrick and others, 2005). The meandering reach along North Fish Creek with eroding bluffs extends from about river mile 10 to 18 (fig. 1) (river mile 0 is at the mouth of Fish Creek at Chequamegon Bay). The three monitored eroding bluff sites are at river miles 16.4, 14.4 and 12.2 (drainage areas of 19.8, 22.5 and 25.1 square miles, and reach water-surface slopes of 0.0048, 0.0059 and 0.0024, respectively). A streamflow gaging station (USGS station number 040263491) is located at river mile 10.5 (drainage area of 38.3 square miles). Immediately upstream of the gaging station, Pine Creek, a tributary, enters North Fish Creek (drainage area of 10.7 square miles) (Fitzpatrick, 1998). It is unknown what portion of flow Pine Creek contributes to North Fish Creek at the gaging station.

These bluffs are located in a steep reach of the stream that cuts through wave-planed topography underlain by lacustrine, fluvial, and glacial till sediment. A series of wave-planed and lacustrine surfaces formed during higher levels of Lake Superior following deglaciation (Clayton, 1984). Subsequent downcutting of the upper portion of North Fish Creek through post glacial shorelines during the Holocene has resulted in a steep-sided valley and series of terraces along the river. Accelerated deposition in the lower portions of North Fish Creek has also resulted in steep banks (Fitzpatrick and Knox, 2000). Channel slope in this reach averages 37 ft/mi or 0.7 percent (Fitzpatrick and others, 2005). Substrate in the eroding-bluff reach changes from boulder/cobble/sand in upstream areas to cobble/gravel/sand in downstream areas. Discontinuous units of sand, gravel, silt, and clay deposits associated with the Copper Falls Formation are present beneath the Miller Creek clay, and are exposed in many of the 100 feet and higher eroding bluffs (Fitzpatrick and others, 2005; Clayton, 1984). Soils developed in the Miller Creek clay have low infiltration rates (median of 0.1 in/h; Krug and others, 1992). The low infiltration rates result in high surface runoff rates. The main failure mechanism for the bluffs is undercutting of the steep valley walls, combined with groundwater seepage in the unconsolidated sands along the bluff face, further destabilizing the slopes (Fitzpatrick and others, 2005).

In 1992–93, land cover in the basin consisted of 58 percent forest, 31 percent pasture/grassland, 5 percent wetland, 3 percent cropland, and 3 percent barren (fig. 1; Reese and others, 2002). Historically, the basin was forested and clear cut from approximately the 1860-90s (Fitzpatrick and others, 1999). Following the decline of logging in the 1890s, the land returned to forest or remained in pasture or cropland. Agriculture peaked in the 1930s (fig. 2; Fitzpatrick and others, 1999).

Three bluffs on North Fish Creek are undergoing intensive monitoring for changes associated with installation of flow deflecting vanes and other erosion-control techniques (fig. 1; Whitman, 2002; Fitzpatrick and others, 2005; Storrar, 2006). The monitoring began when flow-deflecting vanes were installed at site 16.4 during summer 2000. Out of the 17 documented eroding bluffs, site 16.4 had the most previous data (channel cross-section and bluff surveys and profile of bluff stratigraphy; Fitzpatrick, 1998, Fitzpatrick and others, 2005). In 2001, vanes

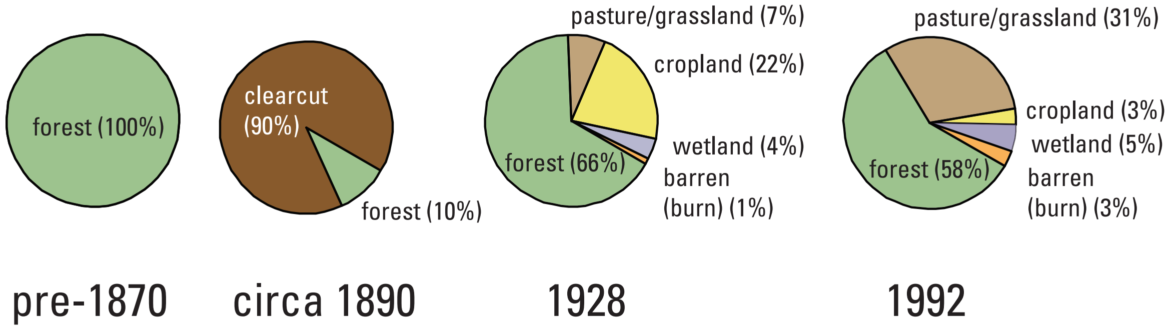


Figure 2. Land cover changes for the North Fish Creek Basin, pre-1870 to 1992. Modified from Fitzpatrick and others, 1999.

were installed at a second site at river mile 12.2. The eroding bluff at site 12.2 was similar in size to the eroding bluff at site 16.4; site 12.2 had an actively eroding toe and also was on public land. No previous data were available for site 12.2. In June of 2004, a third bluff was selected near river mile 14.4 in an area where the main channel migrated laterally into the bluff off of its armored bed and is cutting deeply into the bluff toe. Restoration activities at this site included digging a new channel approximately 10 feet into the point bar side of the floodplain, blocking off the old channel with boulders and anchored logs and flow deflecting vanes.

The detailed design and layout of the vanes for sites 12.2 and 16.4 are given in Whitman (2002). The detailed design and layout of site 14.4 and updated layout for sites 12.2 and 16.4 were completed by Storrar (2006). A summary of the design and layout follows here.

Vanes are vertical plates that protrude from a stream bed about one-third of the bankfull depth, are oriented at an angle to the local streamlines of stream flow. They are distributed in arrays (groups) along part of the channel. When the vanes are submerged, they induce a transverse force on the flow opposite in direction to their angle in the flow and cause a vortex from their top edge. The vortex causes erosion of the stream bed on the side to which they are turned and deposition of sediment carried by the flow on the other side (Whitman, 2002). Erosion of the stream bed by these vortexes moves the thalweg away from the outside of the bend (cut bank) and toward the point bar. Thus, placing arrays of vanes along the outside of a bend causes sedimentation at the toe of the cut bank, which prevents further undercutting and helps to stabilize the bank (Whitman, 2002; Fitzpatrick and others, 2005). The vanes were designed and installed according to the methods of Oddgard and Wang (1991 a,b) and Hoopes and others (1999). Dimensions and installation parameters (size, angle to flow, etc.) for all the sites can be found in Whitman (2002) and Storrar (2006).

Installation of the vanes at site 16.4 started in summer 2000 and was completed in summer 2001. Installation of the vanes at site 12.2 started in September and October 2001 and continued into summer 2003. Installation of engineering structures at site 14.4 began in June of 2004 and continued though the summer of 2005 and was significantly different than at the other two sites. The vanes were placed near the point bar, not the bluff like sites 12.2 and 16.4, and were designed to cut away at the point bar to assist in moving the channel towards the secondary channel away from the base of the bluff. A rock wing dam, anchored protective trees and rock barbs were installed on the cut bank upstream of the bluff face to alter the flow path more significantly. The point bar directly opposite the bluff was also artificially cut back and vegetation was removed within 15 feet of the stream. Horses were used in the channel bed to move large rocks that were obstructing the new flow path (fig. 3). The goal of these combined efforts was to direct the main flow into a newly created channel approximately 60 feet away from the bluff toe.

Figure 3. Photo of Dolly and Cher (horses) moving a large rock under the direction of Jacob Obletz at site 14.4. Photo taken on July 22, 2004 by Ted Koehler.

Methods

Channel cross-section and bluff surveys began before vane installation (site 16.4) or during vane installation (sites 12.2 and 14.4). The stream-flow gaging station at river mile 10.5 was reactivated in June 2000 to monitor streamflow during the study. Channel cross-section and bluff surveys were carried out two to three times a year after vane installation, depending on the timing of floods. Surveys done at the installation of each site and before and after each large flood were compared for each cross section at all three sites. Sediment volume estimates were calculated for the time periods between each large flood.

Channel Cross-Section Surveys

Eight permanent channel cross sections were established at site 16.4 in 2000, five cross sections were established at site 12.2 in 2002 by the USGS (Fitzpatrick and others, 2005). In 2004, ten cross sections were established at site 14.4 (fig. 4b). The most upstream and downstream cross sections extended slightly beyond the vane arrays at sites 16.4 and 12.2 (fig. 4a and c). At site 14.4, five cross sections were established along the main eroding bluff in the treatment area and four upstream to the boulder riffle (fig.4b). An additional cross section was added in the mouth of the tributary. The cross sections are perpendicular to the estimated bankfull channel and extend onto the flood plain on the point-bar side and up the eroding bluff to elevations above the bankfull stage. Steel reinforcing bars were driven into the ground at the endpoints of each cross-section (at the top of the bluff along the steep, eroding part of the bluff) as benchmarks. Multiple benchmarks are located on the point bar and bluff sides of the stream at all sites.

From April 2000-June, 2004, monitoring was conducted by other USGS personnel. In July, 2004, beginning with the installation of the monitoring regime at site 14.4, the present author began conducting the periodic monitoring. Surveys were done with an electronic theodolite (Harrelson and others, 1994). Subsequent surveys were referenced to the same coordinate system by initially setting up the theodolite over a known base point and backsighting to a known

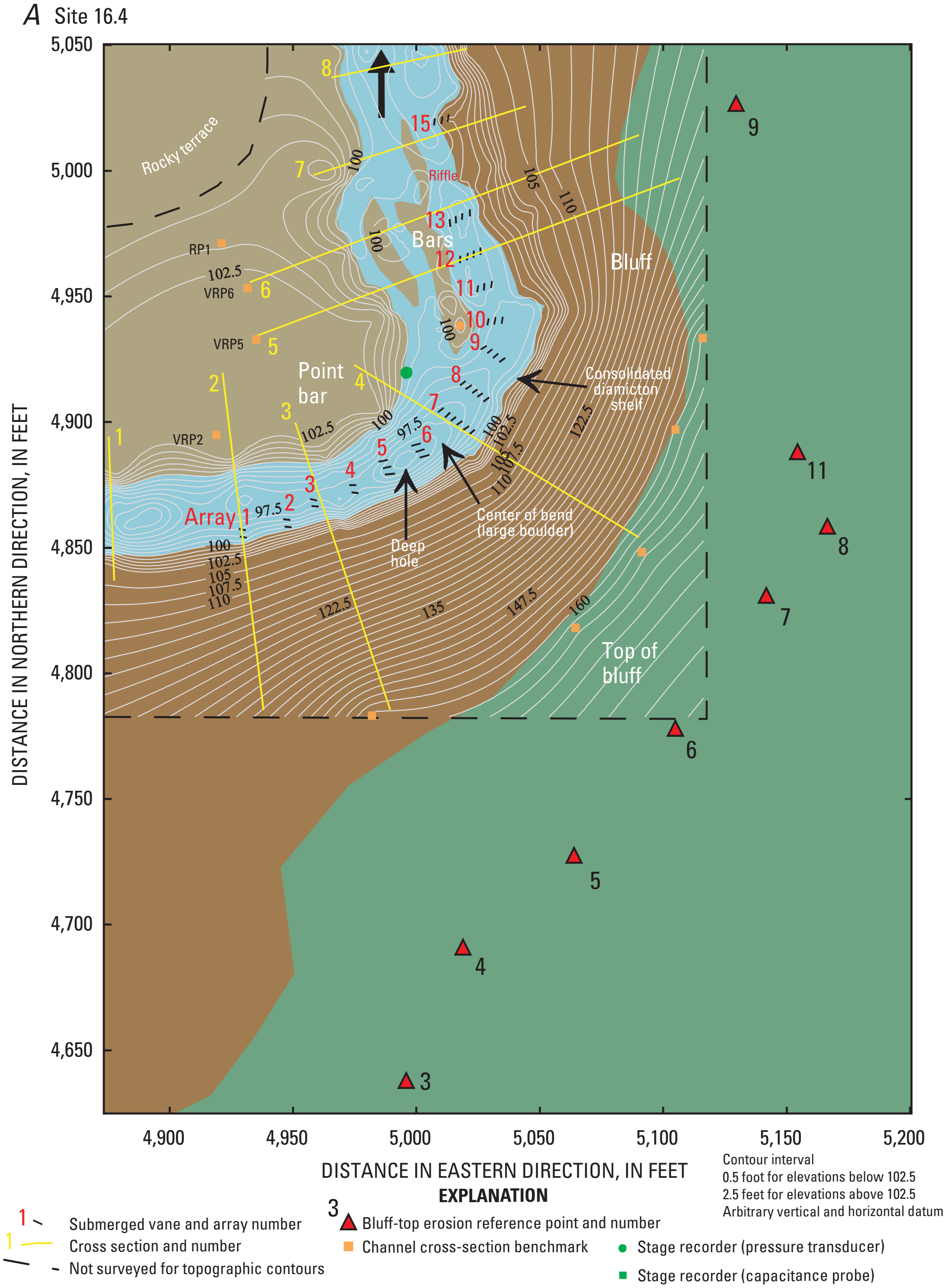
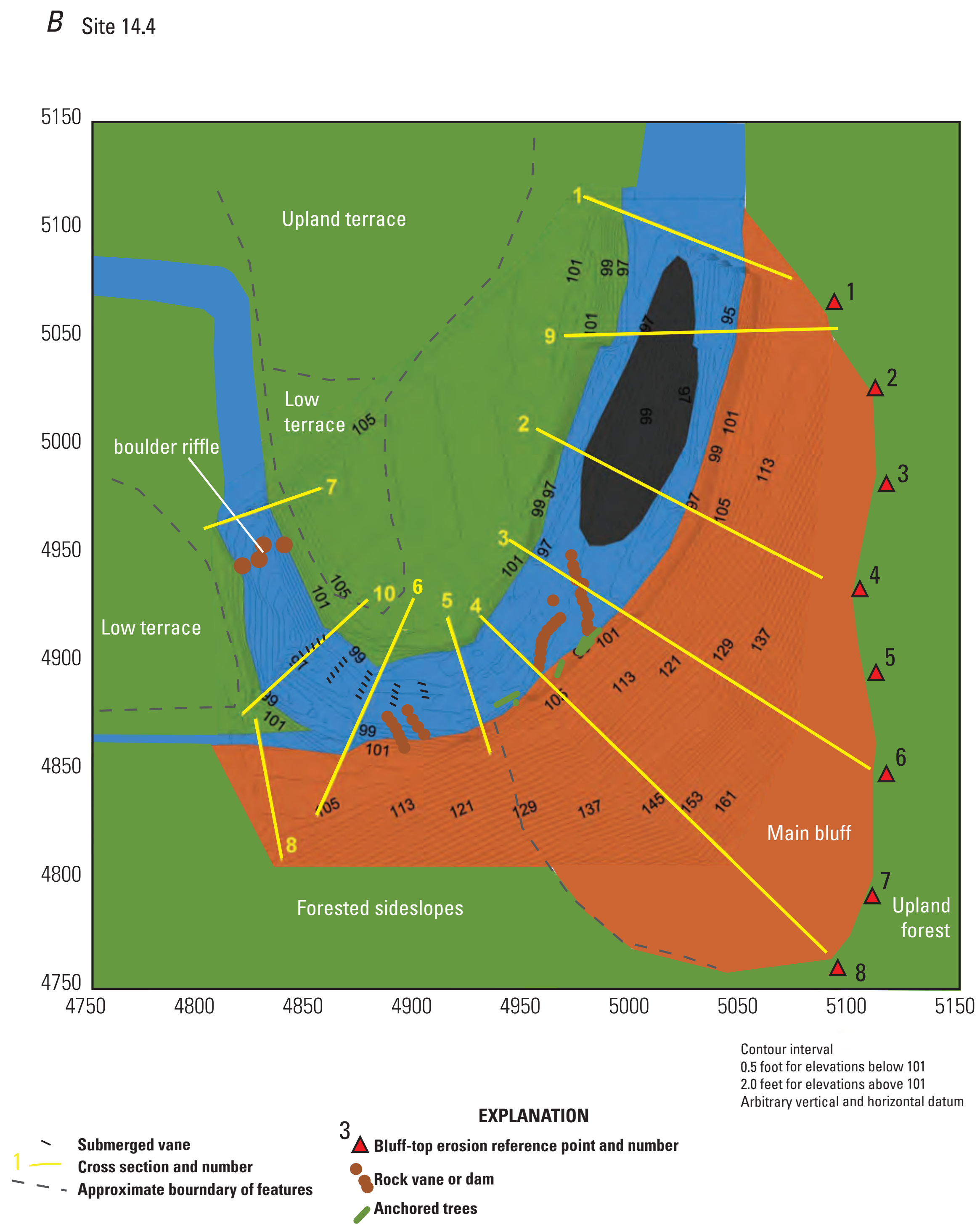


Figure 4. Layout of restoration and monitoring activities at A, site 16.4, B, site 14.4 and C, site 12.2 on North Fish Creek. (modified from Whitman, 2002 and Storrar, 2006)



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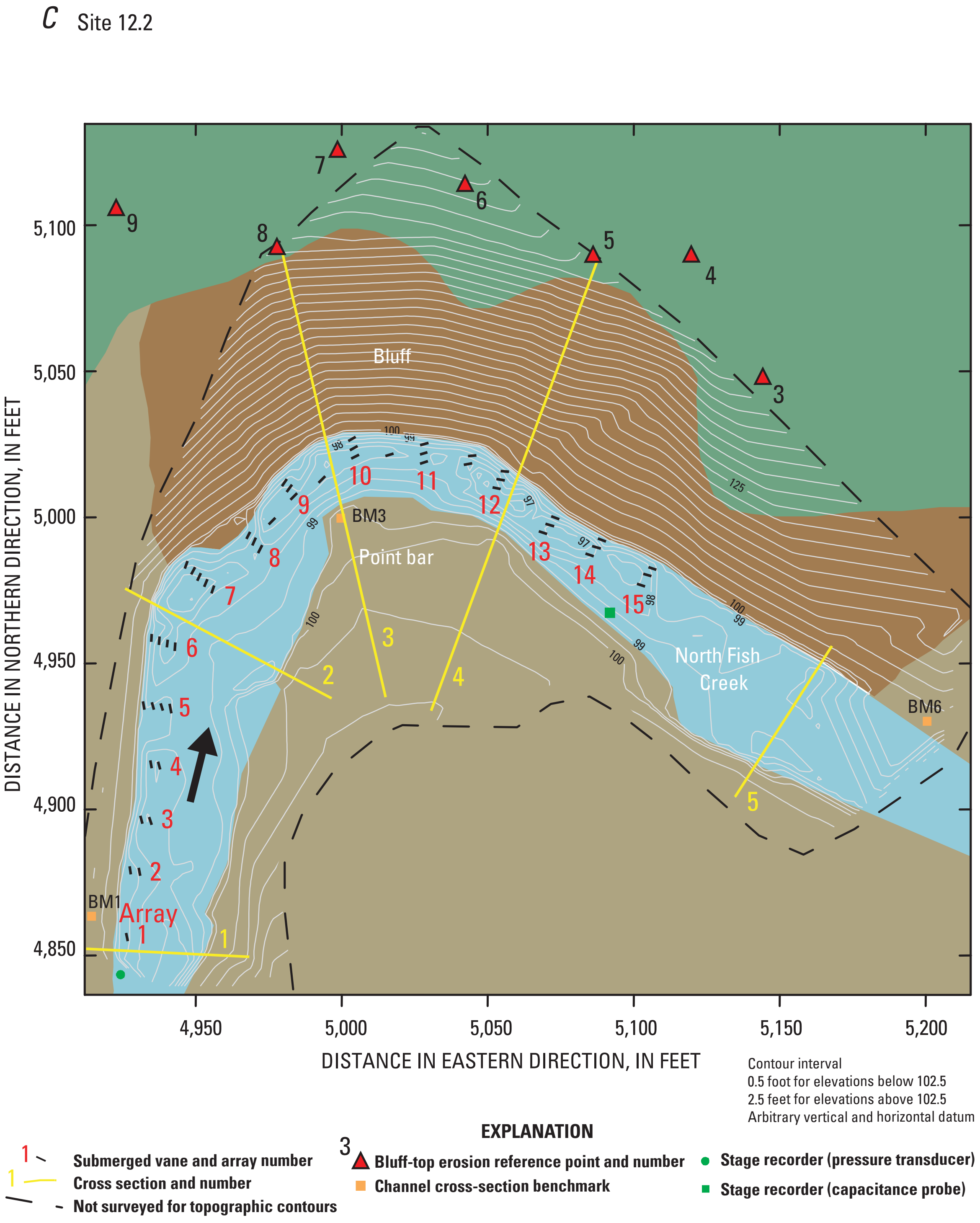


Figure 4. Layout of restoration and monitoring activities at A, site 16.4, B, site 14.4 and C, site 12.2 on North Fish Creek. (modified from Whitman, 2002 and Storrar, 2006)

benchmark. Each cross section was surveyed with 20 to 60 points, a number adequate to detect small changes in bank and channel elevations. Each site was surveyed in the spring and fall of each year, with additional surveys after large floods, like the August, 2005 survey.

Northing and easting coordinates were transformed into distances along a cross section by use of the following equation:

$$d_t = \sqrt{(x_e - x_s)^2 + (y_e - y_s)^2}$$

where d_t is the distance along a cross section from the cross-section endpoint, x_e is the easting coordinate of the cross-section endpoint, x_s is the easting coordinate of the survey point, y_e is the northing coordinate of the cross-section endpoint, and y_s is the northing coordinate of the survey point.

This transformation allowed subsequent surveys to be overlain for display of cross-section change and for calculation of sediment volumes and fluxes.

Sediment Volume Estimates

The volume of sediment lost and gained along the banks, bed, and bars from each site was estimated by quantifying the area differences in each cross-section profile after each survey. Each cross section was plotted on graphs with equal horizontal and vertical scales. The cross-sections were hand digitized with an equal area projection to avoid distortion, and area changes between the two surveys were calculated by use of a geographic information system. Areas were converted to volumes of sediment moved by multiplying the respective area of change by the representative left-bank, midchannel, and right-bank distances to the nearest upstream and downstream cross section. These lengths were estimated as the sum of half the distance to the next upstream cross section and half the distance to the next downstream cross section. The midchannel distance between the upstream and downstream cross sections is 344 ft at site 16.4, 596 ft at site 14.4 and 439 ft at site 12.2. The surveyed area that was below the bankfull elevation was used to estimate the volume of sediment loss of gain. The bankfull elevation was a visual estimate of the top of the point bar deposits and the same elevation was used for all transects at each site. The mass wasting part of the bluffs were not always surveyed due to safety concerns and were not included in the totals. Where possible, estimates of volume of changes in the upper mass-wasting part of the bluff were made. These estimates are shown in the tables separately. The total volumes for each site below the bankfull elevation were normalized by dividing by channel length measured. The sites could then be compared to determine the effects of both floods and restoration activities.

Bluff Erosion Monitoring

Eight reference points were established on the upland surface along the top of the eroding bluff at site 16.4 in 1994 to monitor mass wasting (slumping) from the top edge of the eroding bluff (Fitzpatrick, 1998; Fitzpatrick and others, 1999). The reference points were evenly spaced from the upstream to downstream margins above the actively eroding part of the bluff (fig. 4), where there was little or no vegetation. A perpendicular distance was measured from the benchmark reference point to the bluff edge (first occurrence of a slope break or edge in the upland surface), and the azimuth of the measurement line recorded so that subsequent measurements could be done along the same line. Reference points from 1994 were relocated in good condition in 2000 and were used as a basis for monitoring bluff erosion at site 16.4 (Fitzpatrick, 1998; Fitzpatrick and others, 2005). At site 12.2, nine reference points were established along the bluff top in 2002 in the same fashion as at site 16.4 (Fitzpatrick and others, 2005). At site 14.4, eleven reference points were established along the bluff top using the same methods in 2004.

Between survey differences in the measured perpendicular distances were used to determine when and where blocks of material were lost from the upper bluff. If blocks were lost, the distances are shorter. Distances also may become slightly longer over time because the number and width of tension cracks may increase and soil may creep outwards before a complete block failure occurs. Tension cracks, slumping, and soil creep are common processes along the top edge of the bluffs at all sites.

Streamflow and Stage Monitoring

Water stages (water-surface elevation) and flow have been monitored at USGS streamgage 040263491 at river mile 10.5 starting June 2000 and continuing to the present (2006) (Fitzpatrick and others, 2005). Historical stage data (1990–91 and 1994–97) also were available for this streamgage. Data were collected continuously at 15-minute intervals. North Fish Creek remains ice-free during winter months because of the close proximity of springs and high base flow (Fitzpatrick and others, 2005). Discharge (flow) measurements were made at a variety of stages throughout the year by use of standard USGS methods (Buchanan and Somers, 1984). Empirical relations between stage and flow were determined by the USGS (a rating curve), allowing flow to be directly determined from stage. These data were used to evaluate the impacts of flow magnitudes and their durations on the effectiveness of channel restoration activities.

Remote stage recorders with data loggers also were installed at sites 16.4 and 12.2 to monitor local changes in stage as part of the previous studies (Whitman, 2002; Fitzpatrick and others, 2005). At site 16.4, a submersible pressure transducer was installed just downstream from cross-section 4 on the point-bar side of the channel between vane arrays 7 and 8 in late March 2001 (fig. 4a). At site 12.2, two stage recorders were installed on April 4, 2002, at the upstream and downstream ends of the vanes reach (fig. 4c). Stage recorders were removed in 2003.

Proxy stage indicators, such as high water marks, were used to approximate maximum flood stage at sites where stage recording equipment was not available. Peak flood stages at individual sites were indirectly determined, if possible, from high water marks retained in the clay along the bluff faces, trash lines, and sand deposition (minimum level). At site 12.2, highly visible high water marks on the bluff face were left by each of the 2005 floods (fig. 5). The lines developed as flow passed along the outside bend of the channel along the base of the bluff. The bluff's clayey material has sufficient strength that is maintained the scour line after the flood. These lines were surveyed and the elevations were averaged to come up with a maximum flood stage. Additional proxy data included flood trash in trees on the point bar that was also surveyed.

Figure 5. Photo of scour line left by the July 2005 flood in the bluff at site 12.2. Eric Dantoin is surveying the line.

At site 16.4, no line was left etched in the bluff because this less cohesive bluff sediment failed more significantly. Similarly, no scour line was found along the bluff at site 14.4 because the local topography allows floods to spread out between the two channels, and the bluff toe is partially protected by trees and other vegetation. This bluff is also sandier and may not be able to preserve water marks as well as the clayey sediment at site 12.2. High water marks were also estimated from the uppermost extent of new sand deposits on the channel margin and from flood trash in trees on the channel margins.

Floods During the Monitoring Period

The North Fish Creek streamgage has been operated intermittently by the USGS over 16 years from 1990 to 2006. About 6 years of data were missing from two periods including, October 1991 to September 1994 and October 1997 to May 2000. During the 10-years of available streamflow data (1990–91, 1995–97, and 2000–05), 22 flows greater than 900 ft^3/s (stage of 10.0 ft considered to be bankfull flow (Fitzpatrick, 1998)) were recorded (fig. 6). Most of these flows occurred in the spring months; some were as little as few days apart. Differentiating the characteristics of multiple floods, closely spaced in time, was facilitated by having stage data collected at 15-minute intervals. Because of the flashiness of North Fish Creek, use of annual maximum time series or mean daily flow data were inadequate for assessing hydrologic conditions before, during, and after vane installation.

The floods of 2001 and 2002 were caused by rainfall that either combined with or shortly preceded snowmelt. The combined effects produced a record flood in 2001 and a relatively large flood in 2002. No other floods occurred in 2001 or 2002. Peak flows for North Fish Creek in spring 2003 were small compared to spring 2001 and 2002, with no flows near flood stage (fig. 6b). Flows of 1,000 and 800 ft^3/s happened in April of 2003 (the first from a fast snowmelt without rainfall and the second from a rainstorm), and two more rainfall-related flows of 1,300 to 1,000 ft^3/s happened in May of 2003. Five flows that reach bankfull stage (top of point bars and lateral accretion of sediment) in 2003 and 2004, but no overbank floods occurred. The year 2005 was the first instrumentally recorded year where the spring melt did not cause a bankfull or greater flood. However, 2005 was characterized by a total of 46 inches of precipitation recorded at the gage site. This rainfall is well above the annual regional average of 30 inches (Young and Skinner, 1974). The year 2005 was dominated by thunderstorm and large rainfalls. An overbank flow of 1,000 ft^3/s occurred on June 30, 2005, in response to 3.1 inches of rain. Two more thunderstorms in July and October produced record flood level flows.

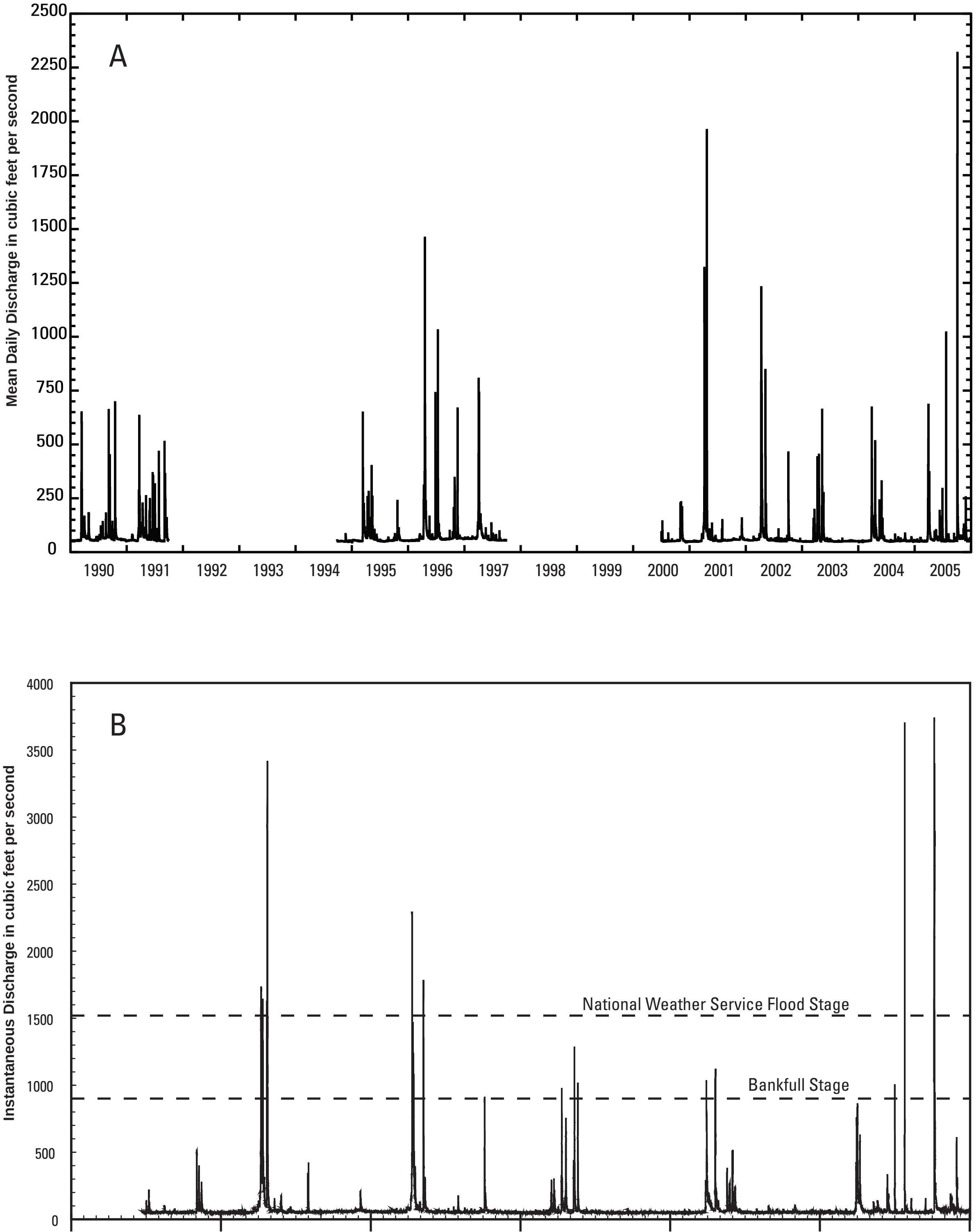


Figure 6. Hydrographs for the North Fish Creek streamgage at river mile 10.5 for the period from A, 1990-2005, mean daily values and B, 2000-2005, instantaneous values.

Streamflows larger than 1,520 ft^3/s (stage of 12.0 ft), which is larger than the geomorphically defined bankfull discharge of 900 ft^3/s, are considered floods by the National Weather Service. During the monitoring period on North Fish Creek, floods of this magnitude or greater occurred twice in 1991, four times in 1996 (one in April and three clustered closely at the end of June and beginning of July), four times in April 2001, twice in April/May 2002, and twice in late 2005 (fig. 6). These floods were caused by spring snowmelt, spring snowmelt combined with rainfall, and rainfall alone in the spring, summer, and fall. The typical duration for a moderate flood from a single summer rainstorm is only about two days, with stages rising and falling sharply in less than 12 hours. The spring snowmelt flood is normally of longer duration than summer rain floods, but also depends on the timing of adjacent rainstorms and climatic conditions at the time of the melt.

During the period that the bluffs were monitored, four large floods occurred that can be linked to specific channel morphologic changes. The characteristics, magnitude and duration of these floods are discussed below. It is important to note that the flood frequency statistics are in no way related to rainfall recurrence intervals. The two types of recurrence intervals cannot be compared because the same rainfall event will result in a different flood every time it occurs. Flood frequency is based on basin characteristics, like size, soil properties and land-use, which have a smaller scale spatial variation than a rainstorm. In this study, they are both used because there is no way to calculate the rainfall recurrence interval of a flood event that is strongly influenced by snowmelt and flood frequency curves cannot be reasonably extended beyond the instrumentation record for the area. The flood-frequency regression curves for North Fish Creek are based on regional flood statistics and cannot be reasonably extrapolated beyond 100 years.

April, 2001

The flood in April 2001 (fig. 7) was a record flood with an estimated recurrence interval of close to 100 years, based on flood-frequency regression equations for rural Wisconsin streams (Walker and Krug, 2003). On April 23, 2001, snowmelt combined with rainfall produced a peak

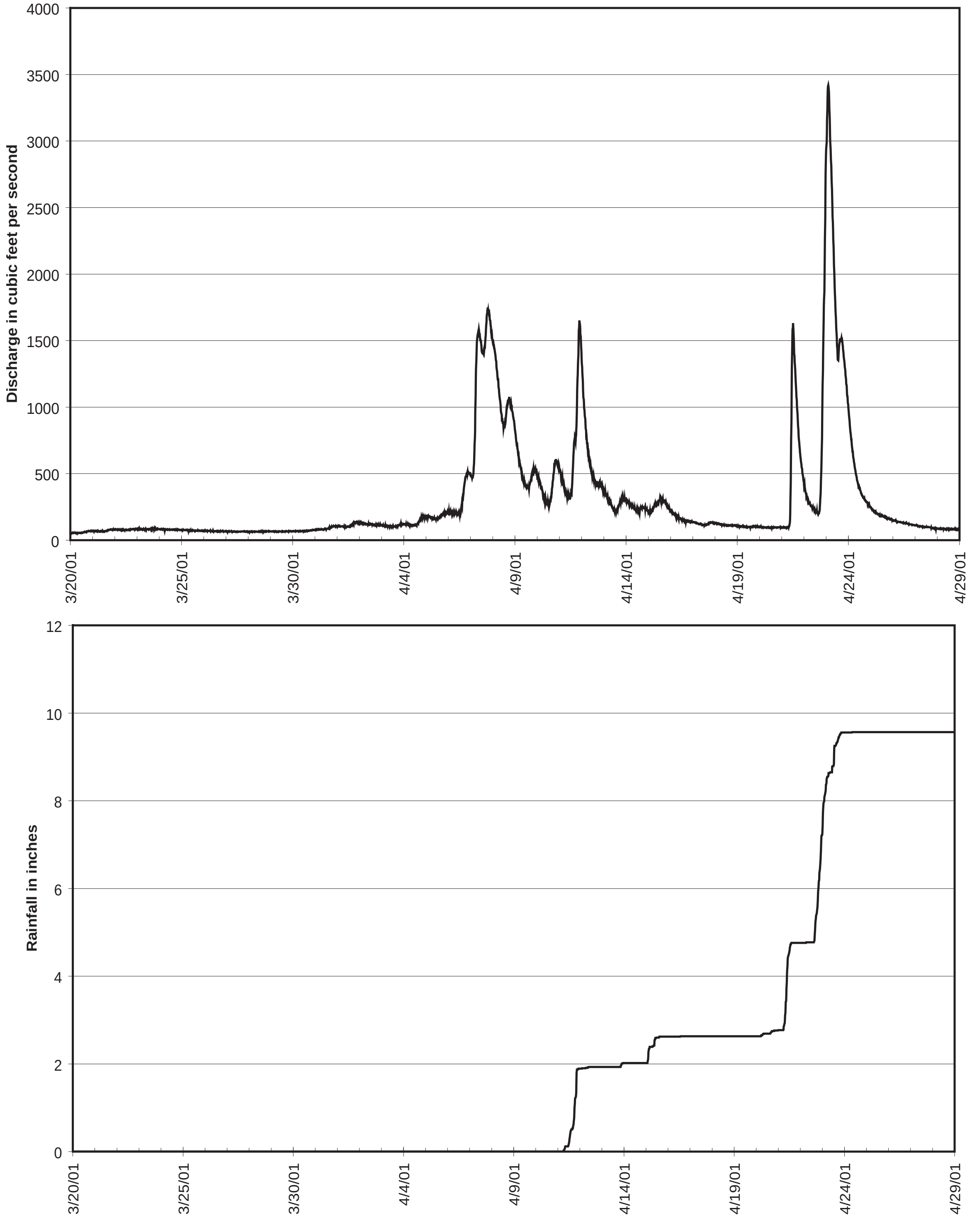


Figure 7. Hydrograph and rainfall for the North Fish Creek streamgage at river mile 10.5 for the April 2001 snowmelt and rain related flood event.

flow of 3,420 ft^3/s. This was the largest of four flood peaks during a period of generally high flows that lasted almost 20 days, from late March to late April. This flood was of very long duration punctuated by four large flood pulses (fig. 7).

The largest single rainfall, which influenced the last and largest flood peak was also a long duration flood. It rained 4.8 inches in 30 hours (fig. 7). That rain came on top of 4.7 inches that fell in the preceding 10 days. All of this, in combination with the spring snowmelt, led to a large flood of a very long duration.

April-May, 2002

The first flood on the hydrograph for 2002, reflects a combination of rainfall on snow (large peak) followed by snowmelt (smaller diurnal peaks) (fig. 8). The rain on snowmelt flood in early April, 2002 was followed by a larger rainstorm, very similar to the floods in 2001. On April 11, 2002, a small rainfall (0.37 inches) combined with the snowmelt to produce a peak flow of 2,290 ft^3/s (fig. 8). This flood had an estimated recurrence interval of 25–50 years (Walker and Krug, 2003). Two days later, additional rain on snow produced a second flow of about 1,500 ft^3/s. The rain continued sporadically for the next two weeks, ending with a single rainfall of about 3.4 inches on May 8th. This heavy rain produced a peak flow of 1,780 ft^3/s. Two days later, another inch of rain fell to produce a second peak flow of 1,350 ft^3/s.

These sets of floods seem to be representative of flooding that is characteristic of recent years. Long spring rainy periods with high intensity rainfall, generally from frontal systems, following or in association with snowmelt have been responsible for anomalous high frequencies of large floods. The floods are still flashy, rising quickly, but persist for longer durations than typical isolated convectional thunderstorm generated floods of other periods.

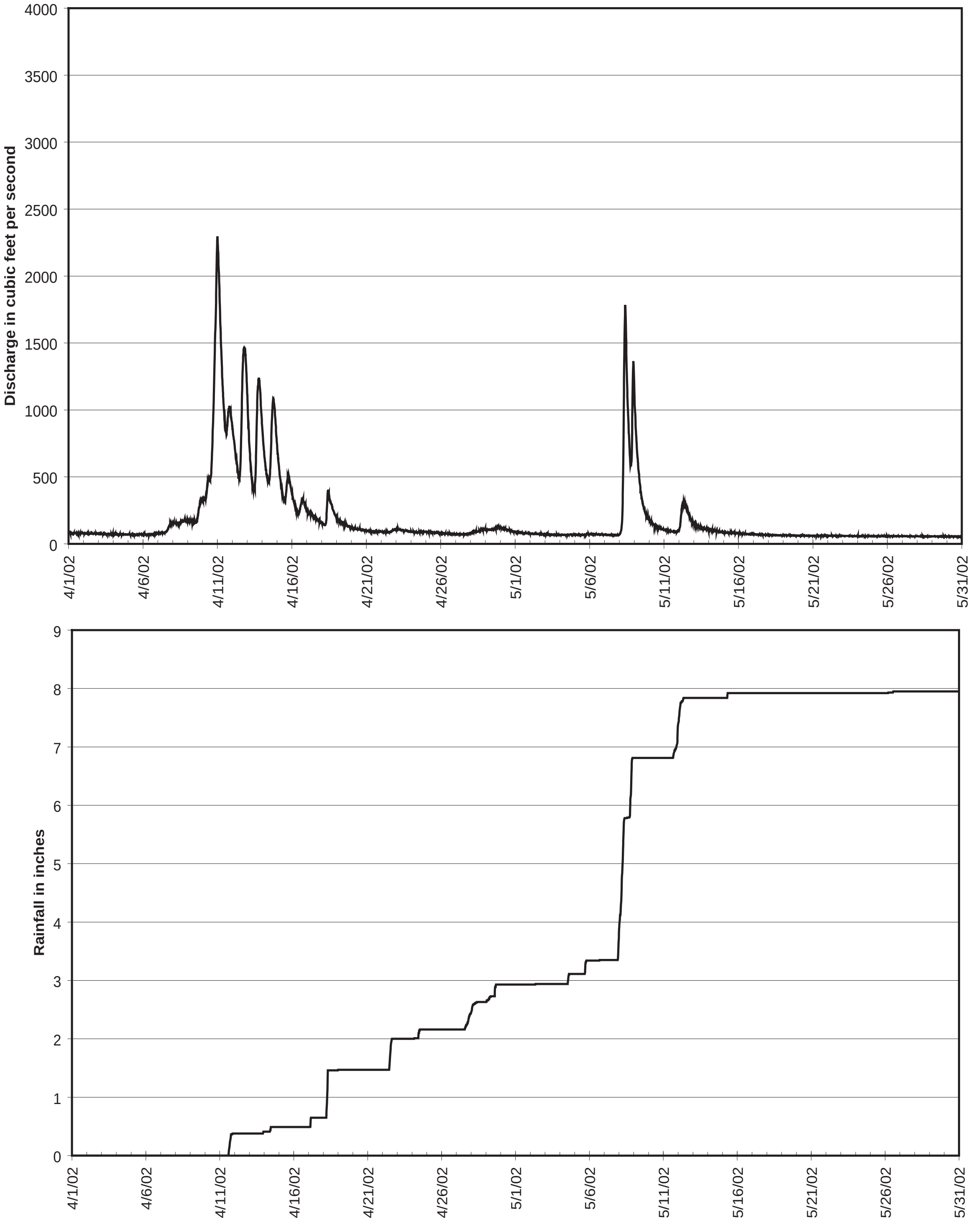


Figure 8. Hydrograph and rainfall for the North Fish Creek streamgage at river mile 10.5 for the April and May 2002 snowmelt and rainfall related flood event.

July, 2005

The flood that occurred in the early hours of July 24, 2005 was the largest on record to that date for the period of instrumentation. An isolated series of convection storms that were part of a thin, but intense squall line that caused a rainfall total of 5.87 inches in 5.5 hours (fig. 9). Furthermore, 5.7 inches of the total fell in just 2.5 hours, with a concentration of nearly 4 inches between 1:00 am to 2:00 am (fig. 10). Using extrapolated rainfall recurrence interval calculations from Hershfield (1961) and Huff and Angel (1992), this rainfall exceeded the expected 1,000 year rainstorm (table 1). The six-hour, two-hour, and 1-hour rainfall totals all exceeded their expected values for a 1,000 year recurrence interval. This clearly demonstrates that the peak flow of 3,700 ft^3/s, attained at 4:30 am, represents an extreme flood. The rainfall and related flood are noteworthy because they occurred over an extremely short duration of time. The flood peaked less than five hours after the rain started and runoff hydrograph returned to base flow conditions in three days. This is a momentary timeframe for such an extreme flood. This flood is distinguished by an extreme magnitude with a very low frequency and an extremely short duration.

Table 1. Estimates of the 1,000 year Rainfall event, as extrapolated from 100 year regression curves

[na, curves not available]

Duration	Dunne and Leopold (National Dataset)	Huff and others (Regional Dataset)
48-hour	na	8.307
24-hour	6.817	7.577
18-hour	na	7.120
6-hour	5.143	5.687
3-hour	na	4.853
1-hour	3.258	3.561
0.5-hour	2.622	2.802

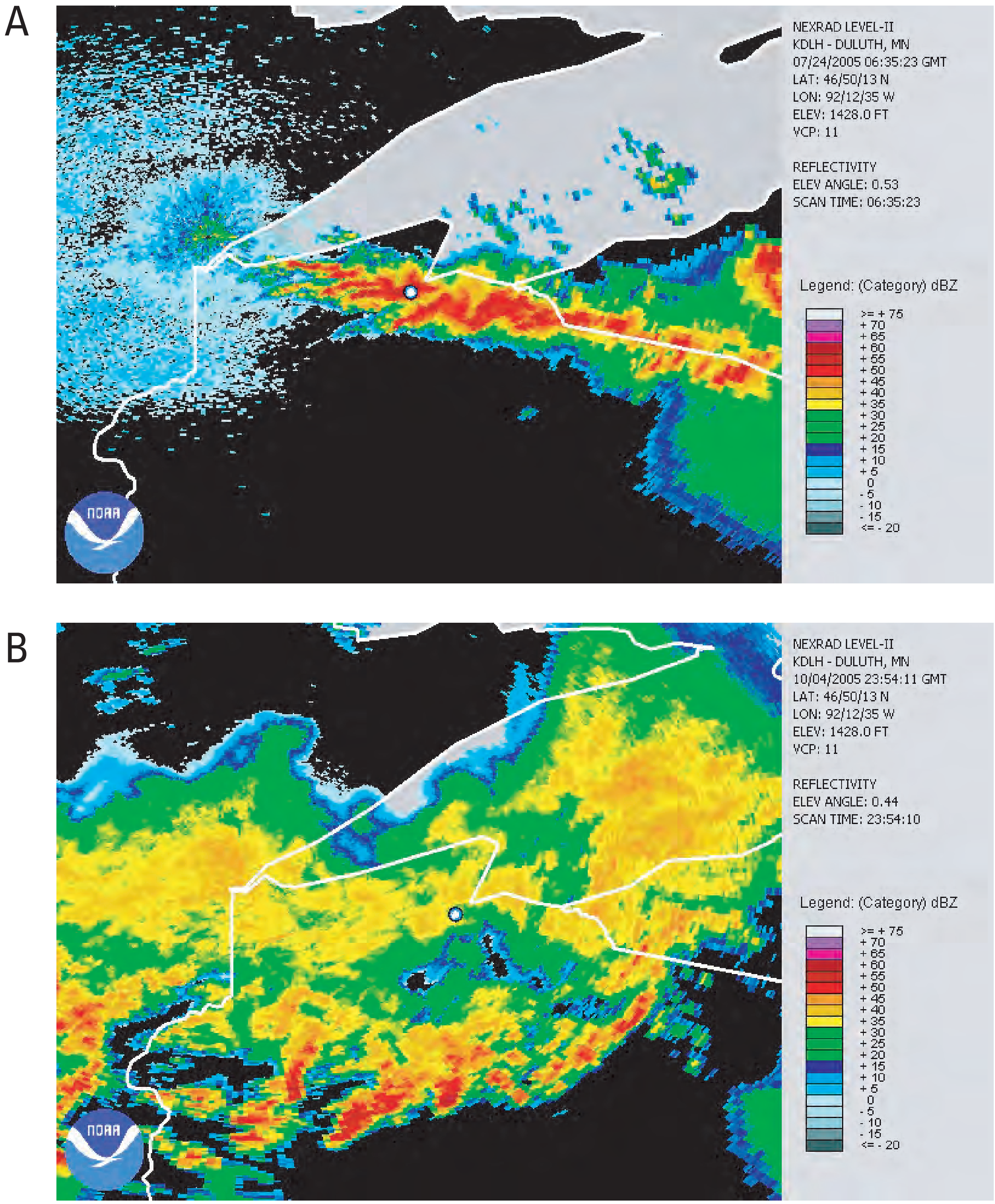


Figure 9. NEXRAD radar images from the Duluth, MN station KLDH for A, July 2005 storm and B, October 2005 storm (National Oceanic and Atmospheric Administration, 2006).

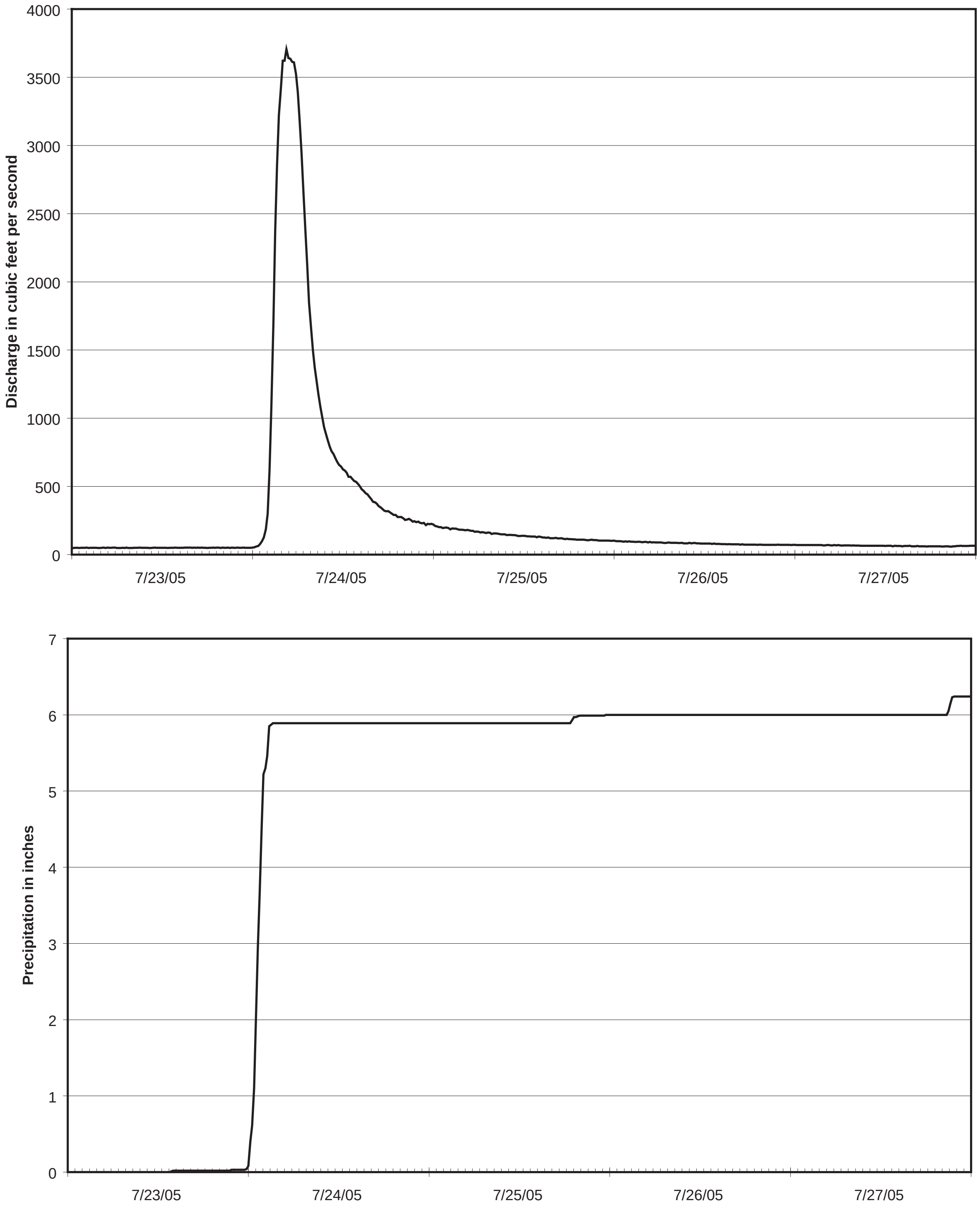


Figure 10. Hydrograph and rainfall for the North Fish Creek streamgage at river mile 10.5 for the July 2005 flood.

October, 2005

The flood that occurred on October 4-6, 2005 reached a slightly greater discharge than the July 2005 flood (3,700 ft^3/s). This flood was the result of a two part rain event from a larger-scale storm that totaled 11.5 inches in less than 38 hours (fig. 9 and 11). The first part of this rainstorm delivered 6 inches in 6 hours. After a 2 hour break, an additional 5.5 inches of rain fell in 17 hours. The double rains produced flood peaks of 3,740 ft^3/s and 3,400 ft^3/s, approximately 23 hours apart in the early morning hours of October 4th and 5th. Due to the heavy rain, the duration of the first peak flow was an hour. The recessional limb of the hydrograph returned to base flow conditions in a little over seven days. At that point, small rains occurred that caused modest stage fluctuations.

No matter how the rainfall rates are compared to the extrapolated regional intensity-duration curves of Hershfield (1961) and Huff and Angel (1992), the October rainfalls exceeded the 1,000 year rainfall recurrence intervals, similar to the July 2005 flood (table 1). The October floods are characterized by the same magnitude and magnitude flood as the July flood, but represent a longer duration geomorphic impact because of the close timing of the two flood peaks.

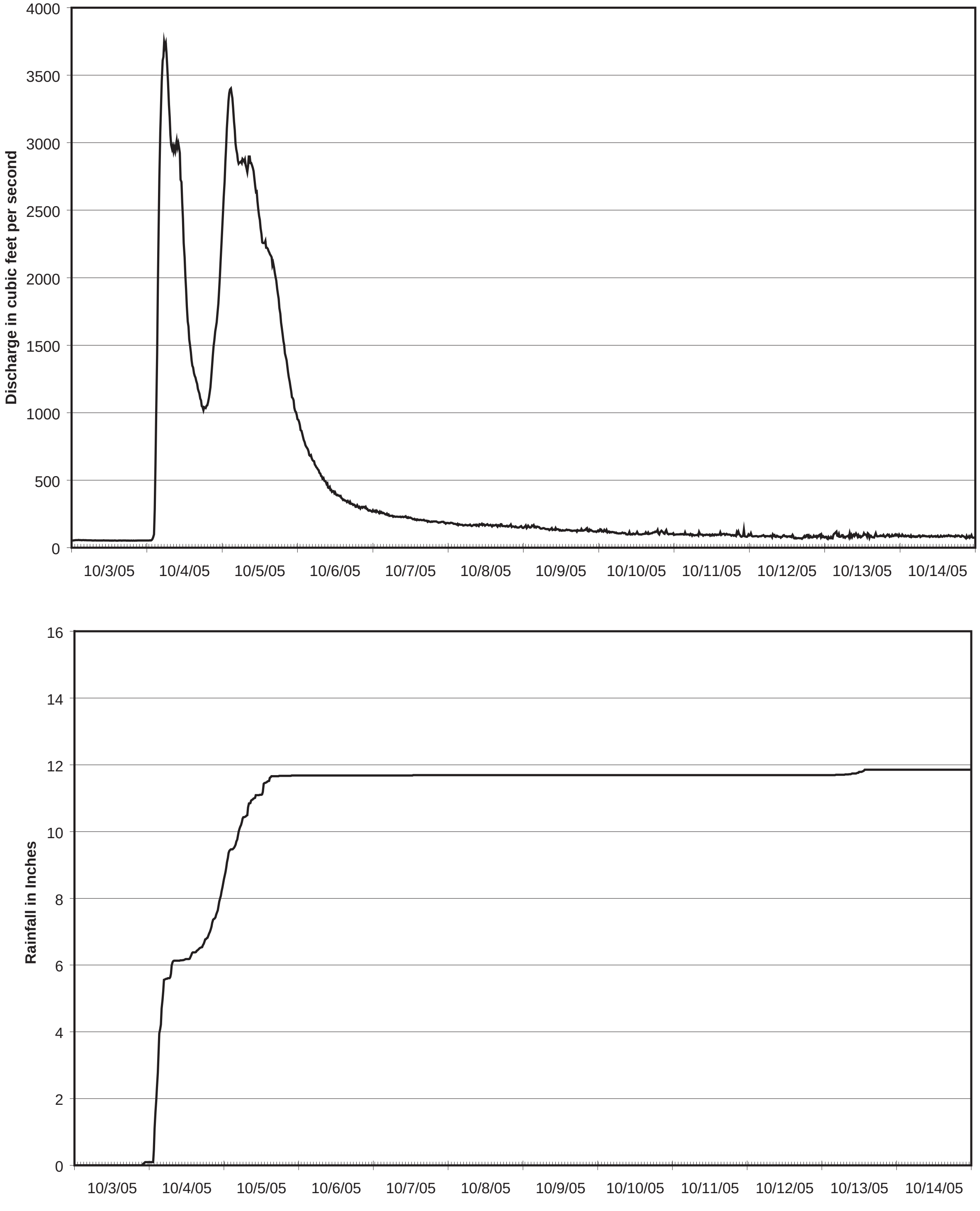


Figure 11. Hydrograph and rainfall for the North Fish Creek streamgage at river mile 10.5 for the October 2005 flood.

Changes in Channel Morphology and Sediment Movement

When a river is flooded there are expected geomorphic responses. Although all floods are represented by a rise of river stage, the magnitude and characteristics of geomorphic impacts vary significantly with flood characteristics. During restoration activities, North Fish Creek has been monitored very closely through several floods of varying character. Each of the three monitored sites responded differently to each flood based on local conditions, sediment supply, flood forces, the character of the flood and restoration activities. Channel morphology responses were documented through repeated cross-section surveys and estimated volumes of sediment gained or lost in association with each major flood.

Site 16.4

Site 16.4 is the most upstream location of the three bluff sites. Here, the bluff face rises an average of sixty feet above the base of the channel. The channel morphology was influenced by a large boulder in the upstream end of the reach (near cross-section 3) and a consolidated diamicton shelf that forms a riffle at the middle of the reach (cross-sections 4 and 5). These features influenced the channel bottom and restrict movement of the channel at higher flows. These controls contribute to flood energy being directed laterally into the bluff toe. The failure mechanism at this site is block failures (slides and slumps) that fall, due to gravity, from the top of the bluff when the toe and bluff face becomes sufficiently steepened through cumulative hydraulic removal of material from the bluff toe.

A series of photographs of the channel and bluff at site 16.4 show how the site changed over 10 years in response to floods and the presence of the vanes (fig. 12). Photographs at site 16.4 extend back 7 years before the vanes were installed because the site was part of the previous geomorphic assessment of North Fish Creek (Fitzpatrick, 1998; Fitzpatrick and others, 1999). The face of the bluff changed over time as blocks of the top and upper part of the bluff failed, and failed debris built up along the bottom half of the bluff during low-flow periods between large

November 1993

Photo by F. A. Fitzpatrick

June 1994

Photo by F. A. Fitzpatrick

November 1996

Photo by F. A. Fitzpatrick

May 1998

Photo by J. C. Knox

March 2000

Photo by F. A. Fitzpatrick

July 2001

Photo by F. A. Fitzpatrick

August 2002

Photo by M. W. Deibel

May 2004

Photo by F. A. Fitzpatrick

September 2004

May 2005

August 2005

November 2005

May 2005

August 2005

November 2005

Figure 12. Photographs of the bluff and channel at site 16.4, 1993–2005, North Fish Creek, Wis. Flow direction is from lower left to upper left. Bottom three photographs show the point bar from the top of the bluff, 2005.

floods (June 1994 as an example). During large floods, such as April of 1996, loose sediment was removed from the lower half and toe of the bluff, making the bluff face steeper (November 1996 as an example). The channel migrated toward the eroding bluff from 1993 to 2000 and formed a midchannel bar by 2000 (Fitzpatrick and others, 2005).

The result of the installation of the vanes along the bluff toe was that the toe was built up sufficiently to allow for the growth of vegetation and may, over a long time, have slowed the erosion of the bluff. The channel migrated away from the bluff toe and was eroding the point bar more and more with each successive survey. Similar to the photographs, the time series of cross sections also show channel migration toward the inside of the bend and point bar (left bank) after the April 2001 snowmelt/rainfall flood. The floods that occurred in 2005, which were much larger than what the vanes could withstand, removed the sediment that had been deposited over the length of the study and rebuilt the point bar (fig. 12).

The record of cross section surveys document channel geometry changes before and after each flood at site 16.4. The flood in October of 2005 moved the greatest volume of sediment out of the channel reach and the July 2005 flood moved the greatest volume of sediment into the channel reach. The results for the individual monitoring periods are described below.

The cross-sections were treated the same for the whole reach. The bluff length calculations only include distances between cross sections that were surveyed for that particular flood. See appendix A for more information on which bluff cross sections were surveyed for each flood.

2001 flood

The first channel survey was completed in April 2000, during the vane installation. The second survey was completed on April 27, 2001, just four days after the peak flow occurred. The stage had returned to nearly baseflow and was decreasing. The site is described in the field notes as having “sand deposits everywhere; on top of point bar all the way back to RP1 (H. Whitman).” The site was also described as having an undercut bluff with loose trees that were ready to fail and the bluff was still in the process of collapse with “rocks and gravel still coming down.”

The vanes were damaged, but still managed to erode the midchannel islands slightly and some were buried in the bluff collapse (one purpose of the vanes is to trap sediment after a bluff section collapses).

Also during the record 2001 flood, a large block failure occurred from the top of the bluff near cross-section 5 (fig. 12, large tree). The block remained at the toe of the bluff and was not washed away during the flood or by any subsequent floods through September 2003. Boulders also fell from the upper half of the bluff and hit some of the vanes, bending them out of alignment. The damaged vanes were replaced in summer 2001 (Whitman, 2002; Fitzpatrick and others, 2005).

Water levels at site 16.4 increased about 4 ft above normal stage during the April 2001 flood. After the flood, trash lines from the flood were observed in trees about 5 ft above normal stage. The stage reached an elevation of about 3.4 ft above the top of the vanes (Whitman, 2002). After the April 2001 flood, the bluff toe appeared to extend into the channel more than before the flood, and mass-wasted material from the top part of the bluff accumulated along the bluff toe and was trapped in the vanes. The channel had migrated toward the point-bar side, concurrent with erosion of the midchannel bar (Whitman, 2002).

The change in sediment volume for the 2001 flood totaled a net loss of 10.6 cubic feet of sediment per downstream foot of bankfull channel distance (table 2). The bluff at cross-sections 7 and 8 (where it could be measured) showed a gain of 8.6 cubic feet of sediment per downstream foot of bluff measured. This gain in the channel is due to the collapse of the top of the bluff down into the channel and bank area, where it could be measured, during and after the flood. Bluff losses from the bluff face were not adequately quantified. A large volume of sediment was lost in the main section of the bluff face (between cross-sections 4 and 5) and if it were measured, would probably show a net loss for the entire bluff volume for the flood.

The left bank and channel lost almost twice as much sediment as the right bank and bars. This is expected because the vanes were placed to favor erosion of the point bar (left bank) and cause deposition at the bluff toe (right bank and bluff). Locally, cross-sections 1 and 6 gained

Table 2. Summary of net sediment volume change for all cross sections at site 16.4, North Fish Creek.

	Sediment volume in cubic feet							
Event Description	Left bank	Channel	Bar	Right bank	Volume in bankfull channel	Volume In bluff[1]	Cubic feet of change per downstream foot of bankfull channel distance	Cubic feet of change per downstream foot of measured bluff distance
2001 flood	-1,139	-1,173	-728	-601	-3,641	435	-10.6	8.6
2002 flood	-965	-1,270	-896	-1,107	-4,239	6,406	-12.3	52.0
July 2005 flood	1,649	1,688	1,255	1,199	5,790	2,007	16.8	5.8
October 2005 flood	-141	2,730	893	-10,345	-6,863	-44,402	-20.0	-129.1

[1] Bluff area immediately above the bankfull channel

sediment, while all the remaining sections lost sediment (see table A1 for detailed cross section information). It is important to note the shifts in the channel in addition to the net changes. For example, in the right bank of cross-section 2 there is a net loss of 8 cubic feet of sediment. This does not show that within the right bank there was over 200 cubic feet of sediment was eroded from the area near the channel and deposited at the bluff toe. The net was just close to zero making it seem like very little sediment was moved, when in fact, the opposite is true. This type of phenomena is present at all three sites in the flood volume calculations for every flood and can lead to misleading data. Appendix A helps clarify by showing the amount eroded, deposited and net change for each area of each transect for each flood.

These data show that the vanes functioned well for a 100- year recurrence interval flood, but the bluff remained unstable after the flood; mass wasting continued. The flood still caused major sediment losses within the reach, but the sediment also shifted in the channel and along the banks, with mixed gains and losses between the cross sections.

2002 flood

The sediment volume data for the 2002 flood is calculated using the change between surveys completed in August, 2001 and May, 2002, after the water had returned to base flow. The results from this flood are very similar to the 2001 flood. The channel, bars and banks lost sediment equivalent to 12.3 cubic feet of sediment per downstream bankfull channel foot. However, the bluff, where measured, gained 52.0 cubic feet of sediment per downstream linear foot (table 2). This pattern shows that the vanes helped to build out the bluff toe during the flood, thereby protecting the bank.

Along cross-sections 3 and 5, significant changes in the channel were not recorded in the net volume calculations. In both areas, the channel sediment was locally eroded and deposited across the channel bed during the floods or was eroded and deposited sequentially over the course of the floods. In cross-section 4, sediment was eroded out of the channel near the bluff toe.

The amount of change for the 2001 and 2002 floods are similar to each other in the channel, but greater changes in sediment volume were recorded along the bluff for 2002 than in 2001. In fact, more sediment was transported by the series of smaller floods in the spring of 2002 than the large single flood and melt event in the spring of 2001. The smaller magnitudes of changes evident in the bluff measurements are most likely due to measurement inadequacies. The measured amount of change in the bluff retreat is within the error of the method. The changes in the channel form may be due to a set of floods with a longer total duration acting on the channel instead of the single, flashy flood of 2001 with sustained lower melt flows.

July 2005 flood

The July 2005 flood was extremely flashy with the flood peak moving very quickly through the system and causing very different changes in the channel at site 16.4 than resulted from the previous two large floods in 2001 and 2002. Storrar (2006) observed that the toe of the bluff that had been stabilizing and becoming vegetated was completely removed (fig. 12). However, in July 2005 the vanes were either damaged or removed, and the few that remained were ineffective because of the new channel cutting behind the vanes and not across the vanes. A large sand and cobble deposit at the apex of the bend was pinching the river and pushing the high velocities against the bluff (Storrar, 2006). Overall the monitored reach gained sediment, even with the loss of the bluff toe and some of the vanes. Subsequently, the UW-CEE crews removed the remaining vanes and altered the material on the newly created sand and gravel point bar (fig. 12). The vanes were not repaired or replaced before the October 2005 flood, because it occurred before work could be completed.

During the July 2005 flood, an average of 16.8 cubic feet of material was deposited for every downstream foot of channel monitored (table 2). This includes the net balance of material that was removed from the bluff toe and filled the channel and sediment that extended the point bar towards the bluff. In cross-sections 1-4 the channel bed filled with one to three feet of sediment. Cross-sections 5-6 showed the channel shifting toward the bluff and downcutting along the bluff face to levels below the original 2000 survey (fig. B1). The overall gain occurred in all of the areas of the reach (right and left banks, channels and bars). However, cross-sections 1, 5, and 8 showed small net erosion, but these changes were offset by larger amounts of deposition at the other cross-sections, specifically in the point bar measurements. Large amounts of sand and coarse material was deposited along the point bar side of the channel and on the point bar. The texture of these deposits is more coarse than the sand and clays that are in the bluff. Even though the bluff contributes some boulders to the channel, it is mainly finer sands, implying that the source material for the fresh deposits is likely upstream and not the local bluff.

Along the bluff face, 5.8 cubic feet per downstream foot of bluff measured of material was gained. This is most likely due to bluff mass wasting at the upstream and downstream ends of the bluff (cross-sections 2, 5, and 6). The bluff also lost sediment along the bluff toe in cross-sections 3 and 4. The bluff face at cross-section 4 could not be measured due to the steepness of the face and safety concerns.

Channel erosion and deposition within cross sections were significant for this flood (table A4). The channel at cross-section 5 had an estimated gain of 1,660 cubic feet of sediment along the point bar side of the channel that was negated by a loss of 1,990 cubic feet of sediment from the bluff side of the channel in the net measurements. These shifts are important because they highlight displacement of sediment within the channel between cross-sections as well as within cross sections. Large amounts of sediment were eroded in the channel, approximately 4,300 cubic feet across the length of the reach. On the other hand, over 6,000 cubic feet of sediment were deposited in the channel bed, with over 70% of that in cross-sections 4 and 5.

The resultant sediment gain from the largest flood on record is somewhat unexpected. There were no vanes present at the end of the flood to assist in trapping sediment and the extent of their effectiveness during the flood in unknown. Sediment was mostly deposited along the point bar and instream bars with smaller amounts of erosion near the steepest part of the bluff. The total volume of sediment deposited is larger than for either of the other two floods previously discussed.

October 2005 flood

The geomorphic changes that resulted from the October 2005 flood at site 16.4 were catastrophic. The two peak flows were slightly higher and lower, respectively, than the July 2005 flood, but yielded tremendously different impacts on the channel. The base of the bluff at the apex of the bend was not protected by vanes, bluff toe, or by vegetation. The basal erosion of the bluff produced a 30 foot high, vertical wall near the center of the bluff, between cross-sections 4 and 5. According to survey data, the bluff toe cut 30 feet at cross-section 4 (fig. 13 and B1). Soon after the flood, slumps of sediment began to accumulate at the base of the bluff and reform a toe. The sediment came from mass wasting of the upper bluff and from sandy deltas where seepage was occurring along the base of the bluff. A large block failure, which had fallen as a result of the 2001 flood and remained in place for the 2002 and July 2005 floods, was swept away by the October flood and much of the sediment was deposited in the channel downstream about 30 feet. As the series of photos show, this block had a live tree in it and was supporting a large portion of the bluff toe; the rootwad of the tree was buried in the channel (fig. 12).

At the upstream end of the reach at site 16.4, a new bank/bluff slump failed in response to erosion of the bluff toe in an area that was vegetated (fig. 14). This bluff section was previously stable, but now may destabilize as the vegetation was removed at the toe of the bluff. At the upstream end of the reach, considerable amounts of gravel and cobble sediments formed the channel, point bar and instream bars, as opposed to sand-sized sediment that was present in July. The fines may have been washed out of the deposits, leaving behind the larger materials, or the area could have been completely eroded and the gravels deposited from upstream. The middle ground is probably likely, with some gravel inputs from upstream and many of the fines washed away by the sustained high flood waters.

The changes in cross section area for this flood were the largest recorded at this site. A net loss of 20 cubic feet per downstream foot of bankfull channel was recorded and a loss of 130 cubic feet per downstream foot of bluff was observed. Bluff changes for this flood are probably

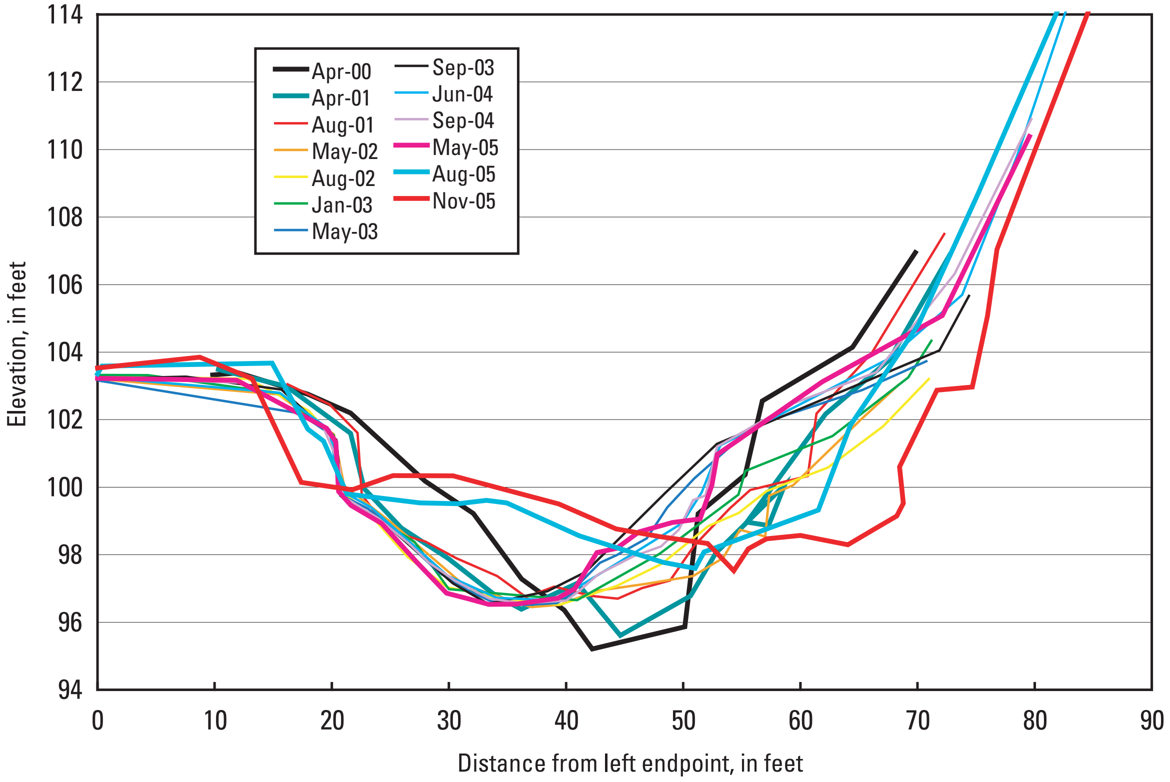


Figure 13. Cross-section 4 showing the changes at site 16.4, North Fish Creek, Wis.

the most accurate of those documented for all the floods because a larger portion of the bluff face was able to be surveyed. Similar to previous floods, channel bed and channel bars gained material. But, both left and right banks lost considerable amounts of sediment and overwhelmed the net measurements. The right bank lost over 10,000 cubic feet of sediment along the bluff toe throughout the reach. Similarly, the bluff lost large volumes throughout the reach, totaling over 44,000 cubic feet of sediment (table 2). In fact, the only place that the bluff gained sediment was in cross-section 2 as a result of the upstream slump that was not washed away (fig. 14).

Figure 14. Photographs of site 16.4: the vertical bluff face between cross-sections 4 and 5 and upstream slump between cross-sections 2 and 3 after the October 2005 flood. See figure 4a for cross section locations. Photographs by C. Storrar, November, 2005.

Site 14.4

Site 14.4 has a longer and taller bluff and has more factors influencing its morphology along the reach than the other two bluff sites. The channel stabilization, which began in 2004, included efforts to shift the main channel at the head of the study reach into an abandoned channel that is farther from the bluff (fig. 4b). One possible reason for the channel moving towards the bluff was the fact that it laterally eroded beyond its armored boulder lag that previously prevented downcutting and now prevented lateral migration away from the bluff base. The channel had moved along an armored bed of cobbles and boulders that overlay sandy glacio-fluvial deposits that are easily incised. Similar situations have been observed by the author in the nearby Marengo River along reaches with eroding bluffs. Before the recent large floods and significant alterations, the channel next to the bluff was only about one foot lower than the secondary channel along cross-section 2 (fig. 15). After the floods, the incised channel follows a lower path and has abandoned the higher secondary channel. Consequently, the recent new channel is cutting more deeply in the bluff and destabilizing the bluff. By moving the channel away from the bluff, back to its older channel, the bluff is expected to stabilize.

Also influencing the morphology at site 14.4 is the presence of a large tributary (1.7 square mile drainage area) that enters North Fish Creek at cross-section 6. The tributary also has a large bluff just upstream of the confluence and is also a large sediment contributor to the reach. Cross-section 8 monitors the tributary and there is a photo point that highlights the significant changes that the tributary has experienced (fig. 16).

Restoration began at site 14.4 in 2004, thus only the two floods in 2005 were monitored (Storrar, 2006). During the large floods in 2005, the bluff remained largely stable, with large failures occurring only at the downstream end (cross-sections 1 and 9, fig. 4b and 17). A large amount of sediment was moved in the channel as a result of both the floods and restoration practices.

The analysis for this site is complicated by the tributary inputs in the middle of the reach (fig. 4b). Cross-section 8 documents changes within the tributary and is evaluated separately from the rest of the cross-sections. Cross-section 6 is perpendicular to the main channel, but then extends up the mouth of the tributary. The right bank calculations for cross-section 6 are not included in the totals and are listed separately in table 3. Cross-section 7 is located above a boulder riffle, at the upstream margin of the study reach. Left bank morphology changes for cross-section 7 reflect the collapse and erosion of a terrace on the point bar (across from the bluff) and are also listed separately in table 3. The bluff distance includes cross-sections 9 and 2-5 for all the surveys. Cross-sections 9 and 10 were established in September, 2004 and morphologic changes are calculated forward from that date.

2005 Spring Snowmelt

The morphologic changes to site 14.4 began before the first survey was completed. The changes in volume and channel position measured between July, 2004 and May, 2005 are primarily due to the engineered alterations to physically move the channel away from the bluff (fig.

May. 2005

August, 2005

November, 2005

Figure 15. Photo series looking up the reach at site 14.4 from downstream of cross-section 1, North Fish Creek, Wis.

July, 2004

August, 2005

note: trees that were across in the upper photo are moved to the right side of the frame

November, 2005

Figure 16. Photo series looking up the mouth of the tributary that enters site 14.4.

Figure 17. August 23, 2005 photo of failure at downstream end of bluff at site 14.4.

4b, table A6). The jet pump used by the engineering crews did a significant amount of work on eroding the point bar across from the bluff.

The only flood that occurred during the period of surveys was the 2005 spring snowmelt. This snowmelt flood in 2005 was not accompanied by rainfall and resulted in a peak flow of only 840 ft^3/s (below bankfull at the gage) on March 31, 2005. North Fish Creek was above low flow for almost a month and was characterized by diurnal flood peaks that are indicative of a snowmelt.

Cross section losses due to this small flood represent combined effects of engineering activities and the flood. They involve a net loss of 10.3 cubic feet per downstream bankfull channel foot and a loss of 6.3 cubic feet per downstream bluff foot. The losses were mainly in the channel, and on the left bank and bar where engineering activities were focused. Gains were measured on the right bank where material was artificially transported to protect the base of the bluff and divert flow. The anchored logs at the base of the bluff near cross-section 4 trapped sediment from

Table 3. Summary of net sediment change for all cross sections at site 14.4, North Fish Creek.

	Sediment volume in cubic feet							Cross sectional area			
Description	**Left bank**	**Channel**	**Bar**	**Pool**	**Right bank**	**Volume in bankfull channel**	**Volume in bluff**[1]	**Terrace (LB, US; T7)**	**Tributary (T6)**	**Cubic feet of change per downstream foot of bankfull channel distance**	**Cubic feet of change per downstream foot of measured bluff distance**
Installation to pre 2005 flood	-639	-5,366	-979	677	164	-6,144	-2,316	-924	-128	-10.3	-6.3
July 2005 flood	540	3,139	3,612	147	-846	6,592	-9,848	-103	4,538	11.1	-26.9
October 2005 flood	-2,239	-5,688	994	-1,100	-703	-8,736	2,282	-836	-1,487	-14.7	6.2

[1] Bluff area immediately above the bankfull channel

Table 4. Changes in cross sectional area in the Tributary at site 14.4, cross-section 8.

Description	Left bank	Channel	Right bank
Start of study to pre 2005 flood	-4.2	1.5	15.6
July 2005 flood	-0.5	10.0	46.5
October 2005 flood	-2.9	1.8	-20.7

the bluff over the course of the monitored period and minimized erosion in that area. A large portion of the changes for this time period included shifts in the channel and banks due to the human and horse removal of rock and gravels in some areas and moving them to other areas. For details of the channel relocation, please see Storrar's full report (2006).

Changes in the tributary area include a gain in cross-sectional area at cross-section 8 (13 square feet) and a loss in cross-section 6 (128 cubic feet) (tables 3 and 4). Volumes were not calculated for the tributary because there is only one cross-section that is perpendicular to the channel.

July 2005 flood

Channel cross section volume changes between May 2005 and August 2005 mainly represent responses to the July 2005 flood, because the time in between was used by the UW-CEE crew to repair damages caused by the flood. Estimates were made by the survey crew (who was also part of the engineering team) about the approximate extent of the flood changes versus the engineering changes. The estimated changes due only to the flood were used in the volume calculations along cross-sections 5 and 6 (fig. 18).

Similar to site 16.4 in the July 2005 flood, site 14.4 gained a significant amount of sediment. The reach, on average, gained 11.1 cubic feet of sediment per downstream bankfull channel foot. The bluff lost 26.9 cubic feet of sediment per downstream foot of bluff (table 3). The majority of that loss came from a failure at the downstream end of the reach that removed approximately 15 feet of material along cross-section 1 and caused the loss of the endpoint of that cross-section (it was replaced, extending the cross section into the woods). The bluff experienced net losses of sediment at each of the measured cross sections, except for cross-section 4, where collapse from above slumping had accumulated near the bluff base. The cobble bar that separates the old and new channels gained approximately one to two feet of gravel and cobble, totaling about 3,600 cubic feet of sediment. The channel gained almost that much due to sedimentation in the pool in the bend upstream of the bluff (cross-section 10), across from the vanes, and in the channel

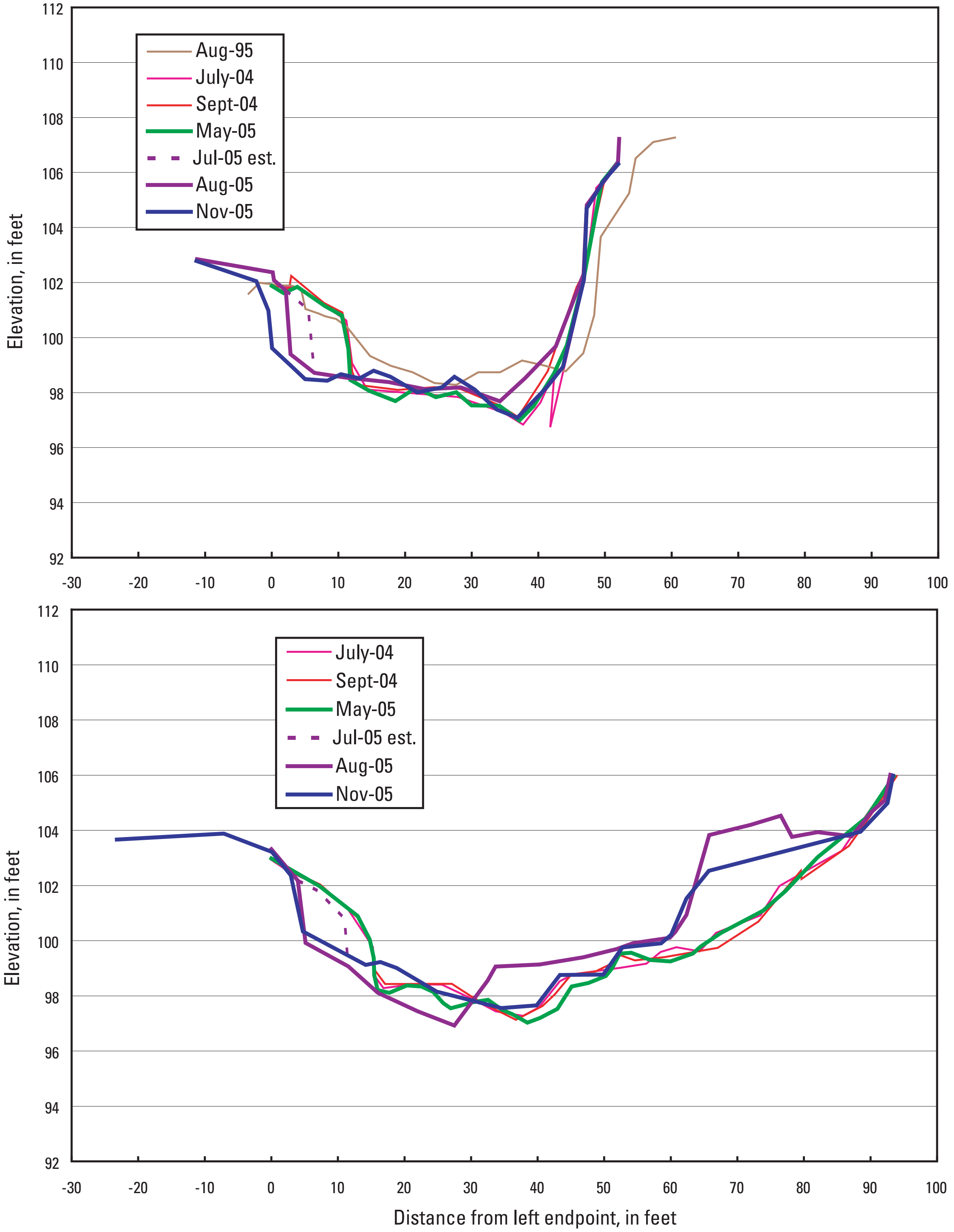


Figure 18. Cross-sections 5 (top) and 6 (bottom) showing the changes at site 14.4, North Fish Creek, Wis. August 1995 survey for cross-section 5 from Fiztpatrick (1998) unpublished data.

point bar area across from the base of the bluff (table 3). At the time of the August 2005 survey, the pool along the base of the bluff was filled with boulders and soft sand from the original rock stairs that were strengthened, raised and lengthened to downstream of cross-section 2. The remainder of the pool was shallow, stagnant water over recently deposited soft clay derived from the upper bluff collapse.

The tributary also gained a very large amount of sediment from its upstream and adjacent bluff. The channel filled with sand and gravel as a result of the flood. Episodes of downcutting and refilling followed the July 2005 flood. Finally, a series of gravel layers remain as a lag deposit from former sandy gravel. A hole dug a few feet from the channel showed no gravel, indicating that the initial deposits at the site were mainly sand and the subsequent gravel bed is due to episodic downcutting and filling and influx of sediment from upstream. Figure 16 shows photographs of the tributary and the deposits found. Cross-section 8 showed a gain of 56 square feet in cross-sectional area for the net change due to the flood. The amount of sediment gained and lost over the course of the flood is unknown, but from the photos, it is possible to see that the amount of sediment moved by the flood was significantly more than what was measured as a net gain.

Also measured was a small collapse (107 cubic feet) of the upstream left terrace by cross-section 7 (fig. 4b). The point bar eroded significantly also, but all of the vanes were lost or damaged in the course of the flood. They were found bent in place or scattered downstream throughout the reach and beyond (Storrar, 2006). The UW-CEE crew removed the damaged vanes and had time to reinstall five vanes before the October 2005 flood.

October 2005 flood

The changes measured for the October 2005 flood also include artificial removal of point bar sediments completed by UW-CEE. The majority of the changes made by the crew were along cross-sections 5 and 6. By the end of the October 2005 flood, only one vane, of the five that were recently installed, remained intact. It is unknown if any changes in the point bar were a result of the vanes, because they were gone and the channel had been altered by the time of the survey.

The October 2005 flood produced a very similar pattern of cutting and filling at site 14.4 as it did at site 16.4. Overall, the reach lost a large amount of sediment, a net loss of 14.7 cubic feet per downstream foot of bankfull channel length (table 3). The loss was focused on the channel, point bar and pool along the bluff toe. The bar area experienced a large shifts in material at cross-sections 9 and 2, resulting in a net gain for the bar area, but it was the result of a shift in material towards the inside of the point bar, indicating a strong current flowing in the channel along the bluff toe. The loss of material in the pool along the bluff toe area is also related to channel scour along the bluff base. The only large gain in material is in the channel bed along the right bank side of cross-section 10 in the pool area of the bend, just upstream of the tributary mouth. This deposition is likely from the tributary and pool areas silting in.

On the whole, the bluff gained 6.2 cubic feet of sediment per downstream foot of bluff length. The gain occurred in cross-section 4, but was offset by large losses and shifts in cross-sections 2 and 3. Cross-section 9 gained material in the bluff as a result of the previous failure (along cross-section 1 during the July 2005 flood) extending collapsing farther upstream. As the bluff slumped, it diverted the flow at the downstream end of the bluff and caused bank scour on the point bar side, downstream of cross-section 1.

The upstream terrace at cross-section 7 also slumped with a loss of about 830 cubic feet of material. The tributary recorded similar losses in cross-section 6 (table 3), and cross-section 8 experienced a loss of 21.7 square feet of cross-sectional area. The tributary channel reworked and removed much of the remnant sand and gravel from the July 2005 flood and began to form a more confined, sinuous channel in the lower reach of the tributary (fig. 16).

The October 2005 flood damaged many of the rock structures and vanes, but the cabled logs remained in place at the upstream end of the bluff. The logs were undercut by the flood, but remained in place and retained their ability to capture sediment from the bluff. The logs are the likely reason that losses were not observed in the bluff area along cross-section 4 (fig. 19).

Figure 19. July, 2004 photo of rock dam and cabled logs at base of bluff at site 14.4.

Site 12.2

The photo points at this site are not as encompassing or consistent as the vantage points at site 16.4 or 14.4. The photos from photo point 1 show the upstream part of the bluff and bed (fig. 20). The photos from photo point 2 show the bed and point bar looking down from the top of the bluff (not available for all years) (fig. 20 and 4c). The eroding bluff face was virtually vertical to slightly convex from 2001 to 2005, with minimal or no vegetation. Rills were common in the face of the bluff and the toe of the bluff was eroded. The bluff was steepened and partially failed as a result of the 2005 floods.

The bluff at site 12.2 sits on a much sharper curve than the other two sites, which affects the flow into the bluff and away from the bluff. The face of the bluff must deflect all of the flood flow, unlike site 16.4 where the flow expands through a floodplain and vegetated section of the bluff before coming to the exposed portion of the bluff and at site 14.4 where the flow is mediated by flow from the tributary and a vegetated bank on the outside of the apex of the curve. For this reason, the vanes were installed farther upstream than at site 16.4 and may have been slightly less effective at deflecting flow over the higher, well vegetated point bar. The vanes successfully

July 2001

Photo by H. E. Schwar

April 2002

Photo by B. N. Lenz

March 2003

Photo by B. N. Lenz

May 2004

Photo by F. A. Fitzpatrick

September 2004

May 2005

August 2005

November 2005

May 2005

August 2005

November 2005

Figure 20. Channel and bluff at site 12.2, North Fish Creek, Wis,. Flow is generally from left to right in the upper photos, taken from instream, upstream of the bluff, near cross-section 1. Flow is from top to bottom in the lower photos taken of the point bar from the top of the bluff.

cut the point bar back and down several feet over the first part of the study, but the 2005 floods show that it was not enough to alter the flow around the sharp bend at the bluff site.

The vanes were installed at site 12.2 in the summer and fall of 2001, after the 2001 flood. Changes in sediment volume were calculated for the 2002 flood, the intervening three years with no floods, and the 2005 floods. There are relatively few cross-sections at this site, so extrapolations are more difficult. The length of bluff used for analysis extends through cross-sections 2-4. There are no bars, pools, or other channel features at this site. Additionally, the channel has been directed away from the bluff along the downstream section of the reach and cross-section 5 is no longer perpendicular to flow. It remains close to perpendicular and is likely perpendicular at flood stages. It is not known when the channel shifted out of cross-section alignment, but it was sometime before the July 2005 flood.

The top of the bluff face has remained largely intact at site 12.2, with only one block failure recorded as a result of the October 2005 flood. Based on subjective observations only, the bluff at site 12.2 has significantly higher clay content than the other two bluff sites, whose basal units are dominated by sand and upper units that are clay rich. The higher amount of clay in the bluff face may make the site more resistant to erosion, thus less likely to accumulate a protective toe composed of easily collapsed material. The high cohesiveness of clay allows the site to hold a steeper bluff face without collapsing.

2002 flood

The surveys conducted in August 2001 and in May 2002, just after a sequence of floods, were used in calculating the changes in cross section morphologies associated with the 2002 floods. The April and May 2002 floods caused erosion along the channel upstream at cross-section 1, deposition along the channel bed at cross-section 2, erosion of the bluff toe at cross-section 4, and deposition along the channel at cross-section 5. These changes resulted in a net loss of 6.3 cubic feet of sediment per downstream foot of bankfull channel distance. The bluff also lost an average of 2.8 cubic feet of sediment per downstream foot of bluff length (table 5).

Table 5. Summary of net sediment volume change for all cross sections at site 12.2, North Fish Creek.

	Sediment volume in cubic feet						
Description	Left bank	Channel	Right bank	Volume in bankfull channel	Volume in bluff[1]	Cubic feet of change per downstream foot of bankfull channel distance	Cubic feet of change per downstream foot of measured bluff distance
2002 flood	-720	-2,171	117	-2,774	-617	-6.3	-2.8
three years in between	-144	225	-6	76	-2,549	0.2	-11.7
July 2005 flood	1,419	2,537	6,532	10,489	-476	23.9	-2.2
October 2005 flood	-1,364	-2,211	-1,995	-5,571	322	-12.7	1.5

[1] Bluff area immediately above the bankfull channel

The majority of the cross section changes were due to sediment shifting within the reach. The net values do not tell the whole story of the flood. The upstream cross-section, 1, lost 1,750 cubic feet of sediment, but the next cross-section, 2, gained 1,220 cubic feet of sediment. The measurements from cross-section 3 yield a net change of 0 cubic feet; although sediment was eroded along the bluff toe and deposited along the channel and right bank. Cross-sections 4 and 5 show a similar pairing with cross-section 4 loosing 4,835 cubic feet and cross-section 5 gaining 2,595 cubic feet of sediment. This shows how the sediment has a tendency to be redistributed with cutting and filling in the channel. Net change can easily be deceiving.

The 2002 floods behaved similarly at sites 16.4 and 12.2. Both sites experienced a net loss of sediment, and involved extensive cutting and filling of channel margins. The flood moved about half as much sediment out of the channel at site 12.2 as it did at site 16.4. This may be due to the different way that water can move through the bend at site 12.2 or difference in slopes of the two local reaches.

Period of no large floods 2002-2005

The intervening three years of record between large flood occurrences show very interesting changes in the volume moved at site 12.2. The relatively small floods during this period include six that are over the bankfull flow level but are not large floods. These small floods were the result of small rains or snowmelt. The volume of sediment changed in the reach as a result of these six floods is a net gain of 0.2 cubic feet of sediment per downstream foot of bankfull channel (table 5). The sediment in the channel and banks, involved significant erosion and deposition but very little net change (table A10). The only large change occurred in the bluff along cross-section 4 with a loss of 2,549 cubic feet of sediment. The bluff toe was progressively cut back over the course of the surveys, but not by any single flood (fig. 21). The absence of large floods at site 12.2 also explains the absence of large volumes of sediment moving into and out of the study reach. The bluff area showed a loss, but the bankfull channel area that was affected by these floods did not change significantly during these three years.

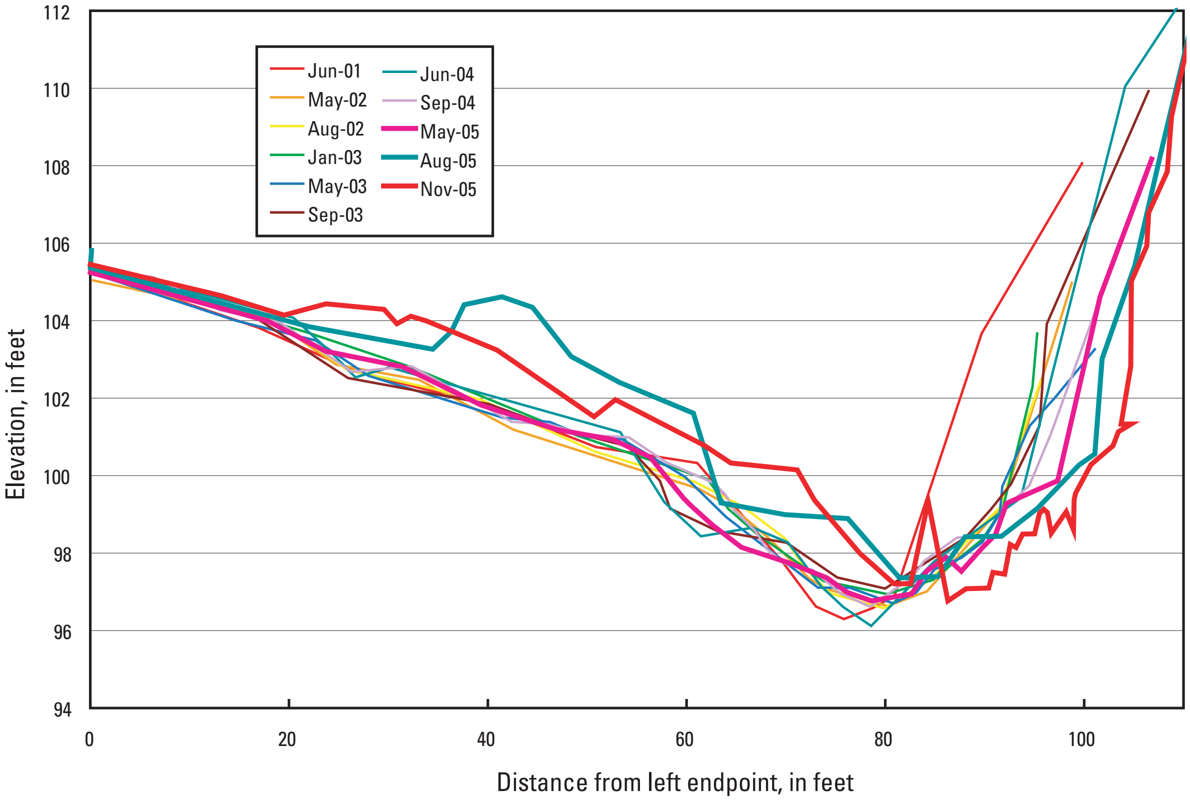


Figure 21. Cross-section 4 showing the changes at site 12.2, North Fish Creek, Wis.

July 2005 flood

The July 2005 flood at site 12.2, as at the other sites, also resulted in large volumes of sediment being deposited in the study reach. On average, 23.9 cubic feet of sediment was deposited per downstream foot of bankfull channel monitored. Large amounts of sand were deposited in the channel along the whole reach and along the point bar at cross-section 4 (table A11). The left bank of cross-section 2 also had a large sand deposit along the top of the bank, in the flat area just upstream of the bluff face. This was also just downstream of the possible eddy flow (discussed below) and could have been the result of that altered flow.

The bluff changed very little, in relation to net volume changes. The average loss was only 2.2 cubic feet per downstream foot of bluff length, as the bluff did not change very significantly due to the flood and where it failed was missed by survey lines (between cross-sections and very steep inaccessible areas). The bluff did not erode or undercut; in fact, the flood left a high water carved line in the clay of the bluff that was firm and definite enough to survey (fig. 5). The average elevation of this line was 10.7 feet above the average channel bottom elevation at the time of the survey (August, 2005). Flood trash in the trees about 40 feet from the channel on the point bar coincides with that flood stage as the peak elevation of the flood waters above the channel bottom. Below the flood debris, several inches to several feet of sand covered the point bar up to 100 feet away from the channel, extending to a terrace. On the upstream, outside of the reach, there was evidence for a similar flood stage from trash in the trees, coarse sand on top of the bank and large woody debris moved on the bank.

An anomaly was observed in the flood debris that was on the top of the left bank between cross-sections 1 and 2 and at the base of the bluff downstream of cross-section 2. Large amounts of flood debris were pressed up against the bases of trees, but the debris was on the *downstream* side of the trees (fig. 22). Typically, debris would be pressed against the upstream side of the trees, indicating the direction of flow and the way the debris was flowing. This location of the flood debris shows very complex flow dynamics as the flood waters entered the bend. A large eddy may be controlling the flow at this site and needs to be understood in order to help explain the characteristics at this site under high flow conditions. The depositional nature of this high flow may be impacting the debris, but these features were not witnessed as a result of the October 2005 flood, perhaps due to the double-peaked flow and erosional nature of the flood washing away any flood debris that may have been left behind.

October 2005 flood

The same pattern of loss of sediment was measured at site 12.2 as for sites 14.4 and 16.4 for the impacts of the October 2005 flood. The flood caused a net loss of 12.7 cubic feet of sediment per downstream foot of bankfull channel length in the reach (table 5). The point bar sediments showed evidence of reworking into the channel and evidence that a new coarser point bar had formed and extended farther out in to the channel, toward the bluff (fig. 20). The bluff area showed a slight gain, on average, of 1.5 cubic feet of sediment per downstream foot of

Figure 22. Photo showing unusual placement of flood debris at site 12.2 following the July 2005 flood. Flow is from right to left. The field book is for scale and the total station in the background is setup over the left endpoint of cross-section 1.

bluff length. The net change does not show the shift between the 1,907 cubic feet of sediment deposited at cross-section 3 and erosion of 1,585 cubic feet of sediment at cross-section 4 that was nearly negated in the calculations of net change. The shift comes from a bluff collapse at the downstream end of the bluff that was also recorded as a loss of several feet of erosion from the bluff pins above. Tension cracks were also observed on the top of the bluff above the failure, indicating that more material is likely to collapse soon.

A new flood scour line was observed on the bluff face after the October 2005 flood. The average elevation of the line indicated an average flow depth of 8.7 feet above the average channel bottom along the bluff. This indicates a local flow depth that was over two feet lower than the July 2005 flood, when taking channel bed scour into account. No other indicators of flood height were found and the flood trash was washed out of the trees, either by floodwaters or the heavy rains.

The result of the October 2005 flood is a large amount of erosion and reworking of sediment at site 12.2. Large amounts of erosion were recorded in the channel and the bank areas. The failure of the bluff is the first large failure since the start of monitoring and may be what is required to start the process of stabilizing the bluff toe and the site in a similar manner to the way that site 16.4 was stabilized previous to the 2005 floods.

Discussion and Implications

Each of the three bluff sites on North Fish Creek responded differently to each of the monitored floods, based on local conditions, sediment supply, flood forces and characteristics, and channel restoration activities. Channel morphology responses were documented through repeated cross-section surveys from which estimated volumes of sediment gained or lost in association with each major flood were determined. Changes in channel morphology have been linked to the magnitude and duration of floods. This link is commonly expressed as the "effective discharge" of the channel (Wolman and Miller, 1960; Nash, 1994 and references within). The data presented in this report show that large magnitude floods produce major impacts on channel forming processes in North Fish Creek, although their normally expected rare recurrence frequency implies lesser long-term geomorphic importance than high frequency, low magnitude floods. Data related to the rates of bluff recession are not discussed here because available measurements are inadequate to represent sediment eroded by each flood.

Table 6 summarizes flood characteristics and volumes of sediment affected by each flood on North Fish Creek. The 2002 snowmelt and rain flood produced a net sediment loss within the channel margins at both available study sites. Net upstream erosion and net downstream deposition are reasonable for a flood of long duration, 39 days. The long duration allows sediment to accumulate in reaches of slightly lower slope as the flood slowly diminishes (fig. 8). Cross section surveys undertaken following the 2001 and 2002 floods of long duration show similar, moderate amounts of net erosion may be common for upstream, steep sloped reaches when large floods of long duration occur on North Fish Creek.

In contrast, the July 2005 flood showed the opposite effect of the long duration floods in 2001 and 2002. Erosion increased from upstream to downstream and then decreased farther downstream. The large amounts of deposition during this flood are likely due to its short duration and possibly the presence of channel/bluff stabilization work for part of the flood (much of it was destroyed sometime during the flood). The extremely high intensity rainfall was able to

Table 6. Summary table of hydrologic events and the volume of sediment recorded at each site

[nm, not measured; na, not applicable]

	April 23, 2001	April 11-May 12, 2002	July 24, 2005	October 4-5, 2005
Type of event	Rain on Snowmelt	Snowmelt and Rain	Rain	Rain
Duration of event (stage above baseflow of ~50 cubic feet per second)	30 days	39 days	2 days	7 days
Peak discharge in cubic feet per second	3420	2290	3700	3740
Duration of peak discharge in hours	1:00	0:45	less than 15 min	0:45-1:15
Total rainfall in inches	4.78	7.84	5.87	11.56
Duration of rainfall	30 hours	almost daily for 30 days	5.5 hours	37.75 hours
Maximum 15 minute rainfall in inches	0.26	0.18	0.97	0.64
Number of flood peaks (exceeds NWS flood stage)	4	2	1	2
Number of above bankfull flows (not including flood peaks)	0	5	0	0
Flood recurrence interval of largest peak (Walker and Krug, 2003)	100 years	25-50 years	over 100 years	over 100 years
Rainfall recurrence interval (Dunne and Leopold, 1964)	na	na	over 1,000 years	over 1,000 years
Rainfall recurrence interval (Huff and others, 1998)	na	na	over 1,000 years	100 to +1,000 years*
Total volume of sediment eroded in the bankfull channel in cubic feet (normalized by downstream channel length)				
Site 16.4	8,380 (24.4)	5,960 (17.3)	5,640 (16.4)	13,950 (40.6)
Site 14.4	nm	nm	7,810 (13.1)	18,160 (30.5)
Site 12.2	nm	9,150 (20.8)	5,020 (11.4)	9,560 (21.8)
Total volume of sediment deposited in the bankfull channel in cubic feet (normalized by downstream channel length)				
Site 16.4	4,740 (13.8)	1,720 (5.0)	11,430 (33.2)	7,080 (20.6)
Site 14.4	nm	nm	14,400 (24.1)	9,430 (15.8)
Site 12.2	nm	6,380 (14.5)	15,790 (36.0)	3,990 (9.1)
Total volume of sediment changed in the bankfull channel in cubic feet (normalized by downstream channel length)				
Site 16.4	13,120 (38.1)	7,680 (22.3)	17,070 (49.6)	21,030 (61.1)
Site 14.4	nm	nm	22,210 (37.2)	27,590 (46.3)
Site 12.2	nm	15,530 (35.4)	20,810 (47.4)	13,550 (30.9)
Net volume change in the bankfull channel in cubic feet (normalized by downstream channel length)				
Site 16.4	-3,640 (-10.6)	-4,240 (-12.3)	5,790 (16.8)	-6,870 (-20.0)
Site 14.4	nm	nm	6,590 (11.1)	-8,730 (-14.7)
Site 12.2	nm	-2,770 (-6.3)	10,770 (23.9)	-5,570 (-12.7)
Net Volume of sediment moved in cubic feet per downstream foot of measured bluff length				
Site 16.4	8.6	52.0	5.8	-129.1
Site 14.4	nm	nm	-26.9	6.2
Site 12.2	nm	-2.8	-2.2	1.5

* Depending on which rainfall event is measured (each downpour or aggregate storm)

flush sediment out of side tributary gullies and into the channel, but the flow was not sustained long enough to carry the sediment out of the study reaches. The violent flow left unusual traces and large sand and gravel deposits, as shown by the debris in figure 22 and by the large accretion of sand at each site (appendices). Although this flood was of very short duration, the flood was sufficiently large to destabilize the bluff sites and damage the vegetation. This destabilization made the sites more vulnerable to future floods. Damage to the vegetation was due to burial in sand and gravel; over three feet were recorded over established point-bar vegetation at site 12.2, sediment removal also occurred with erosion of the bluff toe at site 16.4.

Sources of sediment for the large deposits at site 16.4 and 12.2 that occurred with the July 2005 flood are likely to be from upstream reaches for two reasons. One, the grain size of the deposits does not match the adjacent bluff. Second, the volume of deposited sediment exceeds the estimated quantity eroded from adjacent bluff sites. Even though the bluff losses probably are underestimated, the gains are still exceed the relatively minor bluff erosion. At site 14.4, the bluff was a principal source of sediment deposited in the channel because large clay blocks derived from the bluff mostly remained in place after the flood.

A little over two months later, in October 2005, a second rare, large flood occurred on North Fish Creek. Although the two large floods of 2005 have almost identical peak flows (3,700 and 3,740 cubic feet per second, respectively), channel responses were quite different. During the October flood, erosion decreased in magnitude downstream. Deposition increased downstream (from 16.4 to 14.4) and decreased farther downstream (from 14.4 to 12.2). These patterns could be due to flood characteristics or to local channel gradient variation (site 12.2 is half as steep as the other two sites through the study reaches). Overall the flood caused net erosion at all three sites in higher amounts than what was recorded for the moderate long duration floods in 2001 and 2002.

The large losses and gains in the channel for the October 2005 flood are probably due to two factors. One, the flood had two peaks, and persisted 3.5 times longer than the July 2005 flood, giving the water time to entrain the sediment and move it through and out of the reach before the flood receded. Two, the bluffs were almost entirely unprotected from the flood because vegetation was damaged and flow deflection vanes were subsequently destroyed by flooding. The only remaining post flood vegetation at site 16.4 was a tree in the remnant block failure, which also was eroded in the flood waters, did not attenuate the flow, and involved 30 feet of bluff face retreat. Here, the loss of over 53,000 cubic feet of sediment from the bluff at site 16.4 indicates that bluffs can be a major source of sediment to the North Fish Creek system (table A5). The other two study sites also experienced net sediment losses during the October 2005 flood. Here too, bluffs served as significant sediment sources, and some of the bluff sediment was deposited on the channel bed and along the point bars.

These data from the floods on North Fish Creek show that a flood of moderate magnitude and long duration (2001 and 2002) commonly produced a net erosive effect on the channel that is moderated by increasing deposition at downstream sites perhaps due to decreasing slope downstream throughout the eroding bluff reach. On the other hand, the channel response to more extreme, high magnitude floods vary with their duration and number of flood peaks. An extremely flashy flood mobilizes large amounts of sediment, but a long duration extreme flood or multiple flood peaks are required to produce net sediment losses to given stream reaches.

Placement of present data collected over five years into the context of the overall frequency of floods North Fish Creek over a 1,000 year period under assumed conditions of uniform climate and land cover provides a basin for estimating the long-term geomorphic significance of recent extreme floods. Although recurrence intervals for rainfall and floods are not equivalent, especially for high-frequency events, the recurrence intervals tend to converge for more extreme rainfalls and floods. The rainfalls that produced the 2005 floods are estimated to have a 100-year recurrence probability (Huff and Angel, 1992). Estimates of the amount of sediment transported by the average flood magnitudes for respective flood recurrence intervals support the idea that the more frequent, smaller floods are more important than less frequent, extreme floods when accounting for long-term net fluxes of sediment (table 7). These calculations in table 7 do not include the bluff volumes lost, which would likely alter the data significantly. The high magnitude, low frequency floods destabilize and damage the bluffs, while bluffs tend to stabilize after slumping during periods characterized by high-frequency, low magnitude floods.

The typical cycle of channel system recovery from a flood of any size has been documented by Wolman and Gerson (1978). The response of North Fish Creek to an array of large historical floods in the 1940s and 1950s included large channel avulsions (Fitzpatrick and Knox, 2000). These 1940s and 1950s channels possibly hat not yet fully recovered from early land-use disturbances, and this might explain several channel avulsions that occurred then. Alternatively, the 1940s flood involved a dam break, and an unknown very large flood peak that may have significantly exceeded the flood peaks of 2005. The large floods of 2005 did not result in channel avulsions. Within the smaller time scale of 2005, the first flood destabilized the channel and bluffs and the vegetation and bluff toes were unable to recover by October, setting the stage for large amounts of erosion. Wolman and Gerson emphasize the importance of the role of vegetation in the recovery of a stream channel to a pre-disturbance state (1978). In a humid region, like North Fish Creek, recovery begins within weeks as grasses recover, but the total recovery may take from 10-15 years.

The inability of North Fish Creek to rapidly recover its pre-flood morphology is due in a large part to the threshold nature of the bluffs. Bluff erosion is episodic and only occurs when a threshold slope is reached when the channel erodes the bank toe. The recovery of North Fish

Table 7. Sediment volume estimates over 1,000 years for different recurrence intervals of floods.

Recurrence interval in years	Number of floods	Total volume of sediment eroded and deposited per bankfull channel foot in cubic feet	Net change in sediment volume per downstream bankfull channel foot in cubic feet	Source of data
1,000	1	45	0.73 or ±16.5[A]	Average over all three sites and both 2005 floods
100	10	381	106	Site 16.4, 2001 flood
2	500	10,150	100	Site 12.2, intermediate data

[A] 0.73 is the net sediment change and 16.5 is the average of the absolute values of the net sediment eroded or lost in each flood.

Creek, following large floods, is related to the rate of bluff toe formation and its vegetation cover. Toe formation is dependent upon the amount of sediment that is supplied to the bluff toe from the bluff above and the inability of floods to remove the bluff toe, when the base of the bluff is sufficiently steepened and the channel narrowed to the point where high flow velocities are concentrated along the base of the bluff, bluff erosion typically is accelerated. In turn, this inhibits the formation of a bluff toe and limits the recovery of vegetation. Vegetation on the toe helps trap sediment and produces a positive feedback that favors further sediment deposition. These types of positive feedbacks shorten the recovery time (Wolman and Gerson, 1978).

Summary and Conclusions

Each of the four flood periods monitored from 2001-2005 left a distinct erosion and deposition signature in North Fish Creek that was universal to all three monitoring sites (table 6). The floods of 2001 and 2002 were of long duration, 30 and 39 days respectively, and resulted from a combination of snowmelt and rain. Each had multiple peaks. The four flood peaks in 2001 occurred in combination with rain on melting snow and during subsequent rains. These long duration floods produced only moderate erosion and sedimentation at monitored cross sections.

Similarly, floods during 2002 were a result of the spring snowmelt, closely followed by multiple rains that produced seven, above bankfull flows, two of which were above the National Weather Service defined flood stage. This series of floods produced slightly more net erosion at site 16.4 than the larger flood in 2001. This result suggests that a long duration of high flows comprised of multiple floods removes more sediment, even when the peaks are smaller than a shorter duration higher magnitude flood. Moderate channel erosion was also recorded at site 12.2, but comparisons cannot be made between the two floods.

The July 2005 flood produced large volumes of net sediment deposition at all three study reaches (table 6). This flood was a very short (two days), single flood peak. This single-peak flow of 3,700 cubic feet per second did not last longer than one measurement interval at the streamflow-gaging station (15-min). One explanation for the large net sedimentation at all three reaches is that the flood was large enough to erode and mobilize substantial volumes of sediment but the high flows did not last long enough to transport material downstream during waning stages associated with low sediment concentrations. The flood deposited large volumes of coarse material on point bars at all three sites (fig. 12, 15, 20 photos).

The October 2005 flood was responsible for net erosion of large volumes of sediment from all three sites (table 6). The flood involved a long duration of seven days and had a double peak, resulting from two distinct rainfalls, spaced approximately twelve hours apart. The flood peaks were each associated with over 5.75 inches of rain. Each flood peak was approximately the same magnitude (3,740 and 3,400 cubic feet per second, respectively) and both flowed at nearly peak flow for an hour. This October flood had the magnitude and duration to both entrain sediment and transport it downstream, which caused a considerable amount of net bluff and net channel erosion at all three sites (table 6).

Results of the present study show the major geomorphic importance of high magnitude, low frequency floods to influence mobility and storage of fluvial sediments. Here, much of the channel morphologic change and channel migration resulted from large floods, with minimal changes during bankfull flows. Two large floods in 2005 produced greater sediment exchanges than any other monitored flood. Nevertheless, more sediment was removed at site 16.4 during an array of small floods in 2002 than during larger floods recorded in 2001. This result shows that timing arrays of floods are also very important for influencing the amount of work that can be done by a given flow.

Extrapolating these data over a 1,000 year period will not likely provide a reliable estimate of actual change in the eroding bluffs because the monitoring period is extremely short and the whole North Fish Creek stream system is only about 9,000 years old (Clayton, 1984). However, present results show that over a short term, large magnitude floods are very significant drivers of channel morphologic change and sediment loads into and out of unstable reaches. On the other hand, over the long term, low magnitude, high frequency floods still dominate sediment transport (table 7). Present data support Wolman and Miller's sediment transport curve which implies that the dominant effective discharge is the modal flow or flows of moderate magnitude and high recurrence frequency (1960). Present data confirm that flows in the modal range are the most dominant for explaining long-term sediment transport. Reliance on the modal flow for explaining sediment transport may be insufficient when flow variability is altered and extreme floods suddenly become more frequent. Present results also show the importance of extreme floods for exceeding stability thresholds of a channel system. These extremes can lead to major lateral and vertical changes in the channel morphology.

The frequency of observed high-magnitude floods in the upper Midwest may increase under conditions of global warming (Knox, 2000; Knox, 1993). More frequent recurrences of these extreme and large floods would increase their importance as a mechanism for movement and storage of sediment. An increased frequency of large floods also would increase the incidence of changes in channel morphology, in spite of all of the restoration efforts that are being carried out in the area. Over the course of this study, flow-deflecting vanes were shown to stabilize bluff toes and allow vegetation to grow and further stabilize the bluffs (Fitzpatrick and others, 2005; Storrar, 2006). The vanes survived a 100-year flood but were destroyed by larger floods in 2005. Restoration projects are rarely designed to withstand flows larger than 100-year recurrence probability (usually less or recurrence intervals are not even considered), but since flood recurrence frequencies change with climate change, these changes should be anticipated when protecting the stream and designing rehabilitation projects.

In summary, this thesis presents the results from 6 years of stream channel cross section surveys associated with engineered stabilization projects. Such surveys, involving a series of frequent floods of highly different magnitudes are very rare, as such intense monitoring is expensive and difficult to justify with limited resources. Present data were collected as part of a series of engineering studies conducted by the University of Wisconsin – Civil and Environmental Engineering Department and the U. S. Geological Survey. The demonstration nature of the restoration projects provided the funding for intense, long term monitoring. This level of monitoring is rarely, if ever, conducted for commercial stream restoration projects (even though they constitute the vast majority of projects). Data of this caliber should be collected and used in every application to further the science of stream rehabilitation and assist in adaptive management of our resources. Much can be learned about floods and restoration activities by continuing this level of intense channel monitoring.

References Cited

Abernethy, B and I. D. Rutherford, 2000, The effect of riparian tree roots on the mass-stability of riverbanks, Earth Surface Processes and Landforms, v.25, p. 921-937.

Abernethy, B and I. D. Rutherford, 2001, The distribution and strength of riparian tree roots in relation to riverbank reinforcement, Hydrological Processes, v. 15, p. 63-79.

Buchanan, T. J., and W.P. Somers, 1984, Discharge measurements at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A8, 65 p.

Clayton, Lee, 1984, Pleistocene geology of the Superior Region, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 46, 40 p.

Fitzpatrick, F.A., 1998, Geomorphic and hydrologic responses to vegetation, climate, and base level changes, North Fish Creek, Wisconsin: Madison, Wis., University of Wisconsin-Madison, Ph.D. dissertation, 275 p.

Fitzpatrick, F.A., Knox, J.C., and H.E. Whitman, 1999, Effects of historical land-cover changes on flooding and sedimentation, North Fish Creek, Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 99-4083, 12 p.

Fitzpatrick, F.A., and J.C. Knox, 2000, Spatial and temporal sensitivity of hydrogeomorphic response and recovery to deforestation, agriculture, and floods: Physical Geography, v. 21, no. 2, p. 89-108.

Fitzpatrick, F.A., Peppler, M. C., Schwar, H. E., Hoopes, J. A., and M. W. Diebel, 2005, Monitoring Channel Morphology and Bluff Erosion at Two Installations of Flow-Deflecting Vanes, North Fish Creek, Wisconsin, 2000-03: U.S. Geological Survey Scientific Investigations Report 2004-5272, 34 p.

Fitzpatrick, F. A., Peppler, M. C., Saad, D. A. and B. N. Lenz, in review, Geomorphic, Flood, and Ground-Water-Flow Characteristics of Bayfield Peninsula Streams, Wisconsin, and Implications for Brook Trout Rehabilitation, U.S. Geological Survey Scientific Investigations Report.

Gray, D. H. and R. B. Sotir, 1996, Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control. John Wiley and Sons: New York, 378 p.

Harrelson, C.C., Rawlins, C.L., and J.P. Potyondy, 1994, Stream channel reference sites: an illustrated guide to field technique: U.S. Department of Agriculture, Forest Service, General Technical Report RM-245, 31 p.

Hershfield, D. M., 1961, Rainfall Frequency Atlas of the United States, U. S. Weather Bureau Technical Paper 40.

Hoopes, J.A., Boomstra, B.R., Burmeister, E.M., Dussaillant, A., Horton, C.L., Hrzic, M.A., Lee, C., Roerish, E.D., and M.T. Schwar, 1999, Channel realignment and bank protection in Pheasant Branch Creek, Middleton, WI: Civil and Environmental Engineering Department, University of Wisconsin – Madison, Unpublished Sediment Engineering Class Project Report, 15 p.

Huff, F. A. and Angel, J.R., 1992, Rainfall Frequency Atlas of the Midwest, Bulletin 71, Midwestern Climate Center Research Report 92-03, 140 p.

Inter-Fluve, Inc. and Brian Graber, 2003, Bayfield Peninsula stream assessment, final report: fluvial geomorphology, hydrology, and management recommendations: Lake Mills, Wisconsin, Inter-Fluve, Inc., variable pagination.

Juraeck, K.E., and F.A. Fitzpatrick. 2003. Limitations and implications of stream classification, Journal of the American Water Resources Association, v. 39:3. p. 659-670.

Knighton, D., 1998, Fluvial Forms and Processes: A New Perspective: Oxford University Press, New York, 383 p.

Krug, W.R., Conger, D.H., and W.A. Gebert, 1992, Flood-frequency characteristics of Wisconsin streams: U.S. Geological Survey Water-Resources Investigations Report 91-4128, 185 p.

Knox, J.C., 2000, Sensitivity of modern and Holocene floods to climate change, Quaternary Science Reviews, v. 19, p. 439–457.

Knox, J.C., 1993, Large increases in flood magnitude in response to modest changes in climate, Nature, 361, p. 430-432.

Lenz, B.N., Saad, D.A., and F.A. Fitzpatrick, 2003, Simulation of ground-water flow and rainfall runoff with emphasis on the effects of land cover, Whittlesey Creek, Bayfield County, Wisconsin, 1999-2001: U.S. Geological Survey Water-Resources Investigations Report 03-4130, 47 p.

Leopold, L.B., Wolman, M.G., and J.P. Miller, 1964, Fluvial processes in geomorphology: San Francisco, W.H. Freeman and Company, 522 p.

Magilligan, F. J., Phillips, J. D., James, L. A, and Gomez, B., 1998, Geomorphic and Sedimentological Controls on the Effectiveness of an Extreme Flood, Journal of Geology, v. 106, p. 87-95.

Montgomery, D. R. and J. M. Buffington, 1998, Channel Processes, Classification, and Response, in River Ecology and Management: Lessons from the Pacific Costal Ecoregion, eds. R. J. Naiman and R. E. Bilby. Springer-Verlag: New York, New York, p. 13-42.

Nash, D. B., 1994, Effective sediment-transporting discharge from magnitude-frequency analysis, Journal of Geology, v. 102, p. 79–95.

National Oceanic and Atmospheric Administration, 2006, Level II Next Generation Weather Radar (NEXRAD) Doppler radar data from the National Environmental Satellite, Data, and Information Service (NESDIS) in the National Climatic Data Center, accessed June 1, 2006, http://www.ncdc.noaa.gov/oa/radar/radardata.html

Odgaard, A.J., and Wang, Y., 1991a, Sediment management with submerged vanes, volume I, theory: Journal of Hydrologic Engineering, American Society of Civil Engineers, v. 117, no. 3, p. 267-283.

Odgaard, A.J. and Wang, Y., 1991b, Sediment management with submerged vanes, volume II, applications: Journal of Hydrologic Engineering, American Society of Civil Engineers, v. 117, no. 3, p. 284-302.

Osterkamp, W. R. and Costa, J. C., 1987, Changes accompanying an extraordinary flood on a sand-bed stream, in Catastrophic Flooding, eds. L. Mayer and L. Nash. Allen & Unwin: Boston, p. 201-224

Reese, H.M., Lillesand, T., Nagel, D.E., Stewart, J.S., Goldmann, R.A., Simmons, T.E., Chipman, J.W., and P.A. Tessar, 2002, Statewide land cover derived from multiseasonal Landstat TM data—A retrospective of the WISCLAND project: Remote Sensing of the Environment, v. 82, p. 224-237.

Red Clay Interagency Committee, 1957, Whittlesey watershed: a report: Madison, Wis., Soil Conservation Board, 32 p.

Red Clay Interagency Committee, 1960, Whittlesey watershed: a progress report: Madison, Wis., Soil Conservation Board, 20 p.

Red Clay Interagency Committee, 1964, Second progress report: Madison, Wis., Soil Conservation Board, 40 p.

Red Clay Interagency Committee, 1967, Erosion and sedimentation control on the red clay soils of northwestern Wisconsin: Madison, Wis., Soil Conservation Board, 23 p.

Red Clay Inter-Agency Committee, 1971, Preliminary report: erosion and sedimentation control, Lake Superior Basin, Wisconsin: Madison. Wis., Soil Conservation Board, variable pagination.

Red Clay Inter-agency Committee, 1972, Erosion and sedimentation in the Lake Superior Basin: Madison, Wis., Wisconsin Department of Natural Resources, 81 p.

Red Clay Interagency Committee, 1977, 1976 Evaluation of RCIC works project: Madison, Wis., Soil Conservation Board, 56 p.

Rose, W.J., and D.J. Graczyk, 1996, Sediment transport, particle size, and loads in North Fish Creek in Bayfield County, Wisconsin, water years 1990–91: U.S. Geological Survey Water-Resources Investigations Report 95-4222, 18 p.

Rosgen, D., 1996, Applied River Morphology, Pagosa Springs, Colorado, Wildland Hydrology, variable pagination.

Schumm, S.A., 1977, The Fluvial System: New York, John Wiley and Sons, Inc., 338 p.

Schumm, S. A., 1975, Episodic Erosion: a Modification of the Geomorphic Cycle in: Theories of Landform Development, Melhorn, W. N. and R. C. Flemal, eds. State University of New York: New York, p. 69-85.

Storrar, C., 2006, Field and Laboratory Investigation of Submerged Vane Effects on Channel Morphology: Madison, Wis., University of Wisconsin–Madison, Independent Study Report for Master of Science Degree, 168 p.

Walker, J.F., and W.R. Krug, 2003, Flood-frequency characteristics of Wisconsin streams: Water-Resources Investigations Report 03-4250, 37 p., 2 pl.

Whitman [Schwar], H.E., 2002, Demonstration of the effect of submerged vanes on bluff erosion and channel characteristics at North Fish Creek, Wisconsin: Madison, Wis., University of Wisconsin–Madison, Independent Study Report for Master of Science Degree, 198 p.

Wolman, M. G. and R. Gerson, 1978, Relative Scales of Time and Effectiveness of Climate in Watershed Geomorphology, Earth Surface Processes, v. 3, p. 189-208.

Wolman M. G. and J. P. Miller, 1960, Magnitude and Frequency of Forces in Geomorphic Processes, Journal of Geology, v. 68, p. 54-74.

Young, H.L., and E.L. Skinner, 1974, Water resources of Wisconsin-Lake Superior Basin: U.S. Geological Survey Hydrologic Investigations Atlas HA-524, 3 sheets, scale 1:1,000,000.

Appendix A

Tables of changes in sediment volume by cross-section for each site

Table A1. Volume of localized erosion (-) or deposition (+) in each cross section at Site 16.4 from April, 2000 to May, 2001, illustrating changes due to the 2001 flood

[na, not applicable; ns, not surveyed]

	Left bank (point bar)			Channel bed			Bar			Right bank[A] (bluff toe)				Bluff[B]		
Transect	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Total**	**Gained**	**Lost**	**Net**
1	431	-30	401	1,260	-17	1,243	na	na	na	0	0	0	1,644	na	na	na
2	0	0	0	32	-232	-201	na	na	na	209	-216	-8	-208	ns	ns	ns
3	0	0	0	125	-608	-483	na	na	na	128	0	128	-354	ns	ns	ns
4	0	-825	-825	476	-1,599	-1,122	na	na	na	0	-1,178	-1,178	-3,125	ns	ns	ns
5	405	-300	105	0	-799	-799	0	-799	-799	8	0	8	-1,484	ns	ns	ns
6	18	-115	-97	567	-73	494	57	-10	47	757	-77	680	1,123	ns	ns	ns
7	0	-469	-469	0	-173	-173	24	0	24	0	-358	-358	-977	244	0	244
8	0	-253	-253	112	-244	-132	na	na	na	126	0	126	-260	192	0	192
Total	854	-1,994	-1,139	2,573	-3,746	-1,173	82	-809	-728	1,228	-1,830	-601	-3,641	435	0	435

[A] Transects 1 and 8 are upstream and downstream of the bluff, respectively and 2-7 are the bluff toe area

[B] Bluff area immediately above the bankfulll channel

Table A2. Volume of localized erosion (-) or deposition (+) in each cross section at Site 16.4 from May, 2001 to August, 2001, illustrating changes due to the time between floods

[na, not applicable; ns, not surveyed]

	Left bank (point bar)			Channel bed			Bar			Right bank[A] (bluff toe)				Bluff[B]		
Transect	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Total**	**Gained**	**Lost**	**Net**
1	199	-1	199	0	-1,488	-1,488	na	na	na	0	0	0	-1,289	ns	ns	ns
2	75	0	75	84	-49	35	na	na	na	0	0	0	110	ns	ns	ns
3	70	0	70	165	-355	-190	na	na	na	0	0	0	-119	ns	ns	ns
4	56	-28	28	1,091	-13	1,078	na	na	na	743	-94	649	1,756	ns	ns	ns
5	0	-419	-419	259	-517	-258	365	0	365	388	-7	382	69	ns	ns	ns
6	11	-37	-26	141	-275	-135	1	-67	-67	145	-5	140	-88	ns	ns	ns
7	51	-27	23	119	-198	-79	206	-22	184	71	-11	60	187	0	-446	-446
8	277	0	277	233	-24	208	na	na	na	115	-2	113	599	ns	ns	ns
Total	740	-512	228	2,092	-2,920	-828	572	-90	482	1,462	-118	1,344	1,225	0	-446	-446

[A] Transects 1 and 8 are upstream and downstream of the bluff, respectively and 2-7 are the bluff toe area

[B] Bluff area immediately above the bankfulll channel

Table A3. Volume of localized erosion (-) or deposition (+) in each cross section at Site 16.4 from August, 2001 to May 2002, illustrating changes due to the 2002 flood

[na, not applicable; ns, not surveyed]

	Left bank (point bar)			Channel bed			Bar			Right bank[A] (bluff toe)				Bluff[B]		
Transect	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Total**	**Gained**	**Lost**	**Net**
1	0	-277	-277	46	-233	-188	na	na	na	99	-21	79	-386	ns	ns	ns
2	0	0	0	19	-195	-176	na	na	na	61	-27	33	-143	ns	ns	ns
3	10	-41	-31	192	-119	73	na	na	na	0	0	0	41	ns	ns	ns
4	0	-204	-204	70	-895	-825	na	na	na	8	-1,445	-1,437	-2,465	ns	ns	ns
5	0	0	0	243	-191	52	0	-387	-387	0	0	0	-335	3,698	0	3,698
6	60	-11	49	295	-83	212	45	0	45	298	-134	164	469	1,051	0	1,051
7	85	-39	46	88	-291	-203	0	-553	-553	96	0	96	-613	1,657	0	1,657
8	0	-548	-548	4	-219	-215	na	na	na	1	-44	-43	-807	ns	ns	ns
Total	155	-1,120	-965	956	-2,227	-1,270	45	-941	-896	564	-1,671	-1,107	-4,239	6,406	0	6,406

[A] Transects 1 and 8 are upstream and downstream of the bluff, respectively and 2-7 are the bluff toe area

[B] Bluff area immediately above the bankfulll channel

Table A4. Volume of localized erosion (-) or deposition (+) in each cross section at Site 16.4 from May, 2002 to August 2005, illustrating changes due to the July 2005 flood

[na, not applicable; ns, not surveyed]

	Left bank (point bar)			Channel bed			Bar			Right bank[A] (bluff toe)				Bluff[B]		
Transect	Gained	Lost	Net	Gained	Lost	Net	Gained	Lost	Net	Gained	Lost	Net	Total	Gained	Lost	Net
1	141	0	141	175	-360	-185	na	na	na	0	0	0	-44	ns	ns	ns
2	0	-272	-271	1,019	-66	953	na	na	na	1,446	-10	1,436	2,118	1,446	0	1,446
3	0	0	0	316	-184	132	na	na	na	335	0	335	467	0	-1,133	-1,133
4	312	-49	263	2,703	-12	2,691	na	na	na	0	-601	-601	2,352	ns	ns	ns
5	178	-9	169	1,666	-1,992	-326	0	-137	-137	0	0	0	-294	672	0	672
6	7	-103	-96	0	-1,070	-1,070	1,392	0	1,392	0	0	0	226	1,022	0	1,022
7	1,541	0	1,541	68	-454	-386	0	0	0	1	-13	-11	1,144	ns	ns	ns
8	9	-107	-98	72	-192	-120	na	na	na	46	-7	39	-179	ns	ns	ns
Total	2,188	-539	1,649	6,019	-4,331	1,688	1,392	-137	1,255	1,829	-630	1,199	5,790	3,140	-1,133	2,007

[A] Transects 1 and 8 are upstream and downstream of the bluff, respectively and 2-7 are the bluff toe area

[B] Bluff area immediately above the bankfulll channel

Table A5. Volume of localized erosion (-) or deposition (+) in each cross section at Site 16.4 from August 2005 to November 2005, illustrating changes due to the October 2005 flood

[na, not applicable; ns, not surveyed]

	Left bank (point bar)			Channel bed			Bar			Right bank[A] (bluff toe)				Bluff[B]		
Transect	Gained	Lost	Net	Gained	Lost	Net	Gained	Lost	Net	Gained	Lost	Net	Total	Gained	Lost	Net
1	329	-93	237	1,105	-315	790	na	na	na	165	0	165	1,191	ns	ns	ns
2	150	0	150	181	-677	-495	na	na	na	55	-59	-4	-350	8,819	-617	8,202
3	0	-736	-736	283	-349	-65	na	na	na	0	-340	-340	-1,141	480	-3,576	-3,096
4	24	-327	-303	1,118	-283	835	na	na	na	0	-1,271	-1,271	-740	1	-5,883	-5,882
5	276	-47	229	938	-38	900	0	0	0	0	-5,411	-5,411	-4,282	0	-39,806	-39,806
6	17	-22	-5	257	-111	145	855	0	855	0	-1,389	-1,389	-393	0	-3,276	-3,276
7	58	-290	-232	111	-14	97	117	-80	38	0	-1,222	-1,222	-1,320	0	-139	-139
8	520	0	520	525	0	525	na	na	na	0	-872	-872	172	0	-405	-405
Total	1,374	-1,515	-141	4,518	-1,788	2,730	973	-80	893	220	-10,565	-10,345	-6,863	9,300	-53,702	-44,402

[A] Transects 1 and 8 are upstream and downstream of the bluff, respectively and 2-7 are the bluff toe area

[B] Bluff area immediately above the bankfulll channel

Table A6. Volume of localized erosion (-) or deposition (+) in each cross section at Site 14.4 from July 2004, to May 2005, illustrating changes monitored before the floods

[na, not applicable; ns, not surveyed]

	Left bank (point bar)			Channel bed			Bar			Pool (old channel)			Right bank[A] (bluff toe)			
Transect	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Total**
1	33	-29	5	420	-1,042	298	na	na	na	na	na	na	0	-618	-618	-315
9	21	-91	-70	23	-138	-116	630	-1,909	-1,279	1	-61	-60	0	0	0	-1,524
2	0	0	0	0	-4,712	-4,712	299	0	299	745	-8	737	0	0	0	-3,676
3	402[C]	-881[C]	-478[C]	728	-816	-88	na	na	na	na	na	na	0	0	0	-566
4	19	-1	17	193	-527	-334	na	na	na	na	na	na	0	0	0	-316
5	1	-32	-31	169	-82	87	na	na	na	na	na	na	385	0	385	441
6	28	-4	24	36	-432	-395	na	na	na	na	na	na	na	na	na	-371
10	0	-107	-107	232	-375	-143	na	na	na	na	na	na	443	-157	287	37
7	na	na	na	90	-52	37	na	na	na	na	na	na	110	0	110	148
Total	505	-1,145	-639	1,891	-8,176	-5,366	930	-1,909	-979	746	-69	677	938	-775	164	-6,144

	Bluff[B]			Terrace (LB, US)			Tributary		
Transect	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**
1	0	0	0	na	na	na	na	na	na
9	665	-1,648	-983	na	na	na	na	na	na
2	0	-6	-6	na	na	na	na	na	na
3	3,832	0	3,832	na	na	na	na	na	na
4	141	-5,170	-5,029	na	na	na	na	na	na
5	0	-130	-130	na	na	na	na	na	na
6	na	na	na	na	na	na	241	-180	61
10	na	na	na	na	na	na	na	na	na
7	na	na	na	0	-924	-924	na	na	na
Total	4,638	-6,954	-2,316	0	-924	-924	241	-180	61

[A] Transects 5-7 and 10 are upstream of the bluff and 1-4 and 9 are the bluff toe area

[B] Bluff area immediately above the bankfulll channel

[C] Human induced change

Table A7. Volume of localized erosion (-) or deposition (+) in each cross section at Site 14.4 from May, 2005 to August, 2005, illustrating changes due to the July 2005 flood

[na, not applicable; ns, not surveyed]

	Left bank (point bar)			Channel bed			Bar			Pool (old channel)			Right bank[A] (bluff toe)			
Transect	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Total**
1	1,718	-12	1,705	833	-1,071	-238	na	na	na	na	na	na	0	-2,187	-2,187	-720
9	28	-69	-42	165	-16	149	964	-9	954	75	-1	73	0	-924	-924	211
2	69	-28	41	0	-694	-694	2,658	0	2,658	96	-22	74	0	0	0	2,078
3	69	-564	-495	1,643	0	1,643	na	na	na	na	na	na	0	0	0	1,148
4	0	-323	-323	1,287	-202	1,085	na	na	na	na	na	na	0	0	0	762
5	0	-247	-247	523	0	523	na	na	na	na	na	na	1,922	0	1,922	2,197
6	0	-236	-236	1,334	-473	860	na	na	na	na	na	na	na	na	na	624
10	136	0	136	480	-482	-2	na	na	na	na	na	na	185	-52	133	267
7	na	na	na	8	-195	-187	na	na	na	na	na	na	210	0	210	23
Total	2,020	-1,480	540	6,273	-3,134	3,139	3,621	-9	3,612	171	-24	147	2,317	-3,163	-846	6,592

	Bluff[B]			Terrace (LB, US)			Tributary		
Transect	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**
1	0	-1,028	-1,028	na	na	na	na	na	na
9	68	-3,793	-3,725	na	na	na	na	na	na
2	89	-1,649	-1,560	na	na	na	na	na	na
3	0	-7,307	-7,307	na	na	na	na	na	na
4	5,482	-1,711	3,771	na	na	na	na	na	na
5	na	na	na	na	na	na	na	na	na
6	na	na	na	na	na	na	4,586	-49	4,538
10	na	na	na	na	na	na	na	na	na
7	na	na	na	264	-367	-103	na	na	na
Total	5,639	-15,487	-9,848	264	-367	-103	4,586	-49	4,538

[A] Transects 5-7 and 10 are upstream of the bluff and 1-4 and 9 are the bluff toe area

[B] Bluff area immediately above the bankfulll channel

Table A8. Volume of localized erosion (-) or deposition (+) in each cross section at Site 14.4 from August, 2005 to November, 2005, illustrating changes due to the October 2005 flood

[na, not applicable; ns, not surveyed]

	Left bank (point bar)			Channel bed			Bar			Pool (old channel)			Right bank[A] (bluff toe)			
Transect	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Total**
1	125	-867	-742	67	-1,936	-1,868	na	na	na	na	na	na	0	-491	-491	-3,102
9	58	-17	41	0	-1,643	-1,643	-1	1,509	1,508	2	-407	-405	0	0	0	-499
2	0	0	0	0	-2,320	-2,320	1,004	-1,519	-515	36	-730	-694	0	0	0	-3,530
3	8	-575	-567	206	-2,406	-2,200	na	na	na	na	na	na	0	0	0	-2,766
4	0	-263	-263	515	-1,617	-1,102	na	na	na	na	na	na	0	0	0	-1,366
5	0	-359	-359	204	-991	-787	na	na	na	na	na	na	15	-10	5	-1,141
6	8	-263	-254	816	-978	-162	na	na	na	na	na	na	na	na	na	-416
10	0	-94	-94	4,744	-156	4,588	na	na	na	na	na	na	75	-105	-30	4,464
7	na	na	na	36	-230	-194	na	na	na	na	na	na	0	-187	-187	-381
Total	199	-2,438	-2,239	6,588	-12,276	-5,688	1,003	-10	994	37	-1,137	-1,100	90	-793	-703	-8,736

	Bluff[B]			Terrace (LB, US)			Tributary		
Transect	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**
1	3	-63	-60	na	na	na	na	na	na
9	715	-485	231	na	na	na	na	na	na
2	280	-1,201	-921	na	na	na	na	na	na
3	1,812	-5,197	-3,385	na	na	na	na	na	na
4	11,496	-5,079	6,417	na	na	na	na	na	na
5	na	na	na	na	na	na	na	na	na
6	na	na	na	na	na	na	88	-1,574	-1,487
10	na	na	na	na	na	na	na	na	na
7	na	na	na	31	-868	-836	na	na	na
Total	14,306	-12,025	2,282	31	-868	-836	88	-1,574	-1,487

[A] Transects 5-7 and 10 are upstream of the bluff and 1-4 and 9 are the bluff toe area

[B] Bluff area immediately above the bankfulll channel

Table A9. Volume of localized erosion (-) or deposition (+) in each cross section at Site 12.2 from August, 2001 to May, 2002, illustrating changes due to the 2002 flood

[na, not applicable; ns, not surveyed]

	Left bank[A] (bluff toe)			Channel bed			Right bank (point bar)				Bluff[B]		
Transect	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Total**	**Gained**	**Lost**	**Net**
1	0	-837	-837	37	-734	-697	16	-234	-219	-1,753	na	na	na
2	0	-5	-5	2,273	-1,172	1,100	141	-17	123	1,219	na	na	na
3	0	-235	-235	564	-384	180	88	-33	55	0	ns	ns	ns
4	0	0	0	388	-4,852	-4,465	268	-639	-371	-4,836	0	-617	-617
5	357	0	357	1,712	-1	1,710	533	-4	529	2,596	na	na	na
Total	357	-1,078	-720	4,973	-7,144	-2,171	1,045	-928	117	-2,774	0	-617	-617

[A] Transects 1-2 and 5 are upstream and downstream of the bluff, respectively, and 3 and 4 are the bluff toe area

[B] Bluff area immediately above the bankfulll channel

Table A10. Volume of localized erosion (-) or deposition (+) in each cross section at Site 12.2 from May, 2002 to May, 2005, illustrating changes due to the period of bankfull floods

[na, not applicable; ns, not surveyed]

	Left bank[A] (bluff toe)			Channel bed			Right bank (point bar)				Bluff[B]		
Transect	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Total**	**Gained**	**Lost**	**Net**
1	22	-281	-259	110	-435	-325	418	0	418	-166	na	na	na
2	0	0	0	653	-852	-199	13	-144	-132	-331	na	na	na
3	0	0	0	1,963	-962	1,001	124	0	124	1,126	ns	ns	ns
4	0	0	0	275	-1	273	722	-435	286	560	0	-2,549	-2,549
5	116	0	116	71	-597	-526	0	-703	-703	-1,112	na	na	na
Total	138	-281	-144	3,071	-2,846	225	1,276	-1,282	-6	76	0	-2,549	-2,549

[A] Transects 1-2 and 5 are upstream and downstream of the bluff, respectively, and 3 and 4 are the bluff toe area

[B] Bluff area immediately above the bankfulll channel

Table A11. Volume of localized erosion (-) or deposition (+) in each cross section at Site 12.2 from May, 2005 to August, 2005, illustrating changes due to the July 2005 flood

[na, not applicable; ns, not surveyed]

	Left bank[A] (bluff toe)			Channel bed			Right bank (point bar)				Bluff[B]		
Transect	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Total**	**Gained**	**Lost**	**Net**
1	8	-17	-10	2,185	0	2,185	939	0	939	3,114	na	na	na
2	1,617	0	1,617	1,443	-1,493	-50	592	-3	589	2,157	na	na	na
3	0	-232	-232	420	-754	-334	604	0	604	38	ns	ns	ns
4	0	0	0	2,109	-1,314	796	4,709	0	4,709	5,505	0	-476	-476
5	43	0	43	839	-898	-59	277	-309	-32	-48	na	na	na
Total	1,669	-249	1,419	6,997	-4,459	2,537	7,121	-312	6,809	10,766	0	-476	-476

[A] Transects 1-2 and 5 are upstream and downstream of the bluff, respectively, and 3 and 4 are the bluff toe area

[B] Bluff area immediately above the bankfulll channel

Table A12. Volume of localized erosion (-) or deposition (+) in each cross section at Site 12.2 from August, 2005 to November, 2005, illustrating changes due to the October 2005 flood

[na, not applicable; ns, not surveyed]

	Left bank[A] (bluff toe)			Channel bed			Right bank (point bar)				Bluff[B]		
Transect	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Gained**	**Lost**	**Net**	**Total**	**Gained**	**Lost**	**Net**
1	22	-23	-1	256	-2,054	-1,798	90	-104	-15	-1,814	na	na	na
2	8	-416	-409	931	-450	482	376	-34	343	416	na	na	na
3	0	-913	-913	499	-63	436	2	-213	-211	-688	2,986	-1,079	1,907
4	0	0	0	254	-1,302	-1,048	788	-2,413	-1,625	-2,674	10	-1,596	-1,585
5	0	-42	-42	502	-785	-283	259	-746	-487	-812	na	na	na
Total	30	-1,394	-1,364	2,443	-4,654	-2,211	1,514	-3,510	-1,995	-5,571	2,996	-2,674	322

[A] Transects 1-2 and 5 are upstream and downstream of the bluff, respectively, and 3 and 4 are the bluff toe area

[B] Bluff area immediately above the bankfulll channel

Appendix B

Figures of cross section data

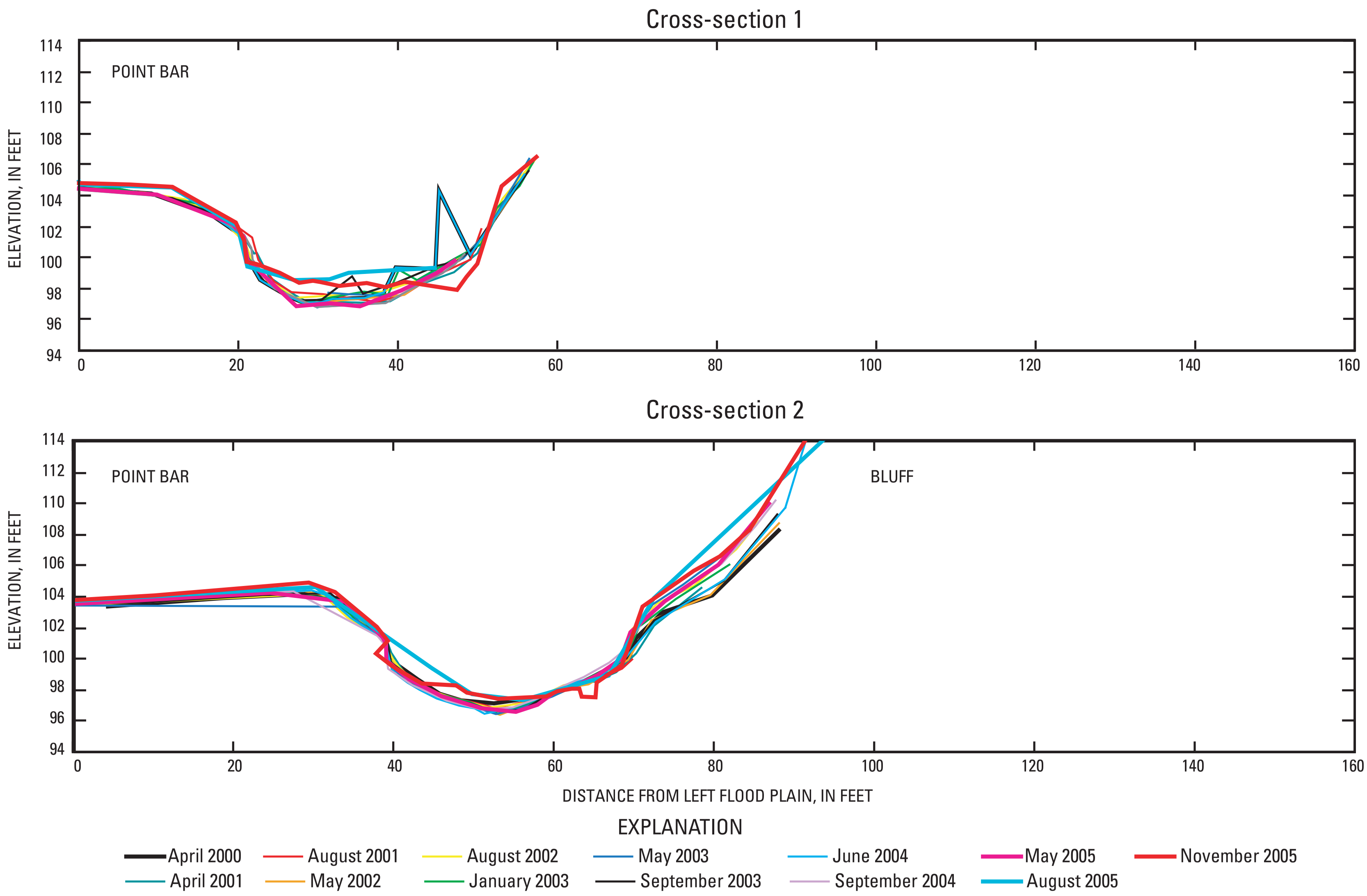
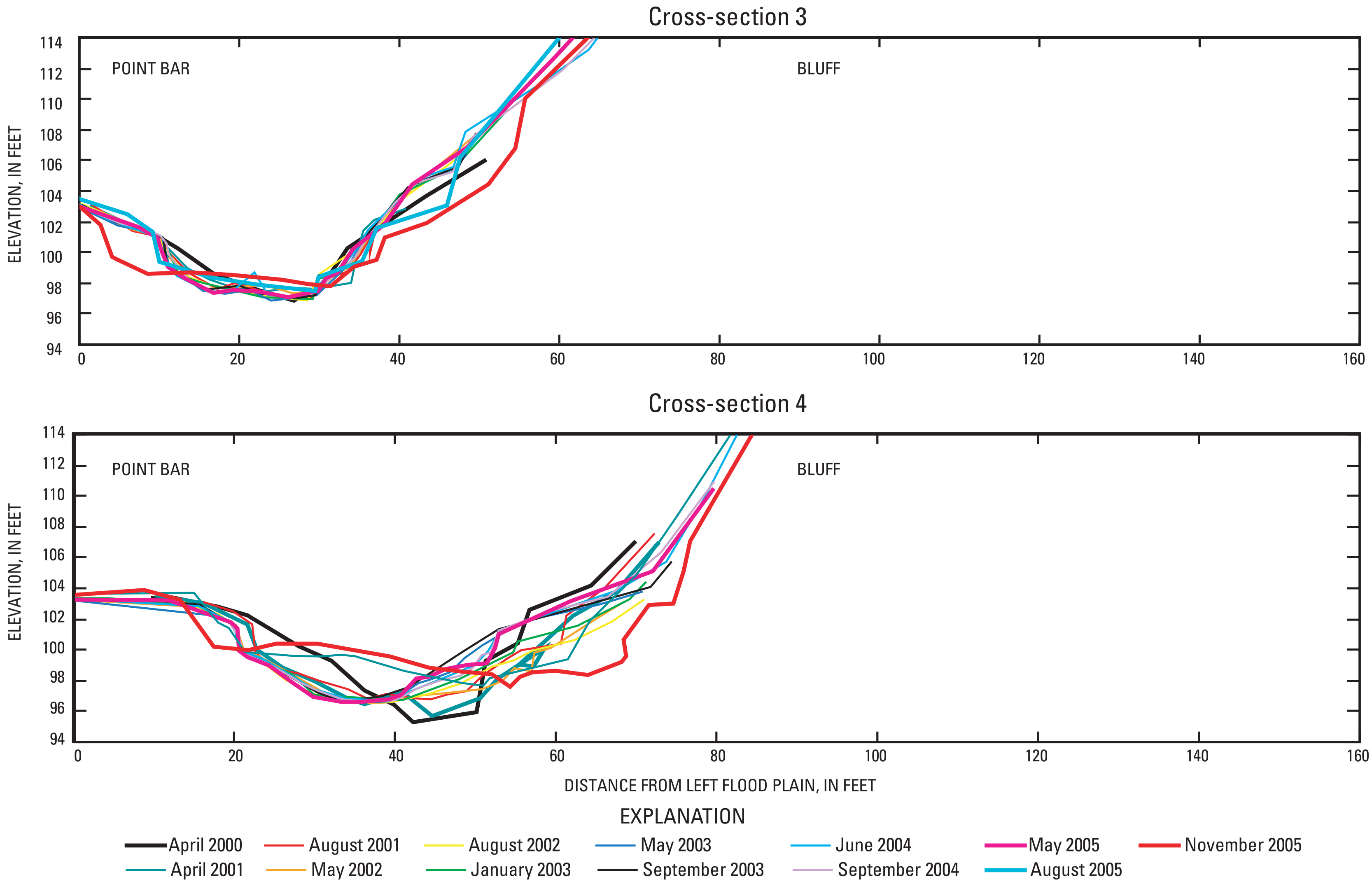


Figure B1. Cross section data for site 16.4, for North Fish Creek, Wis.



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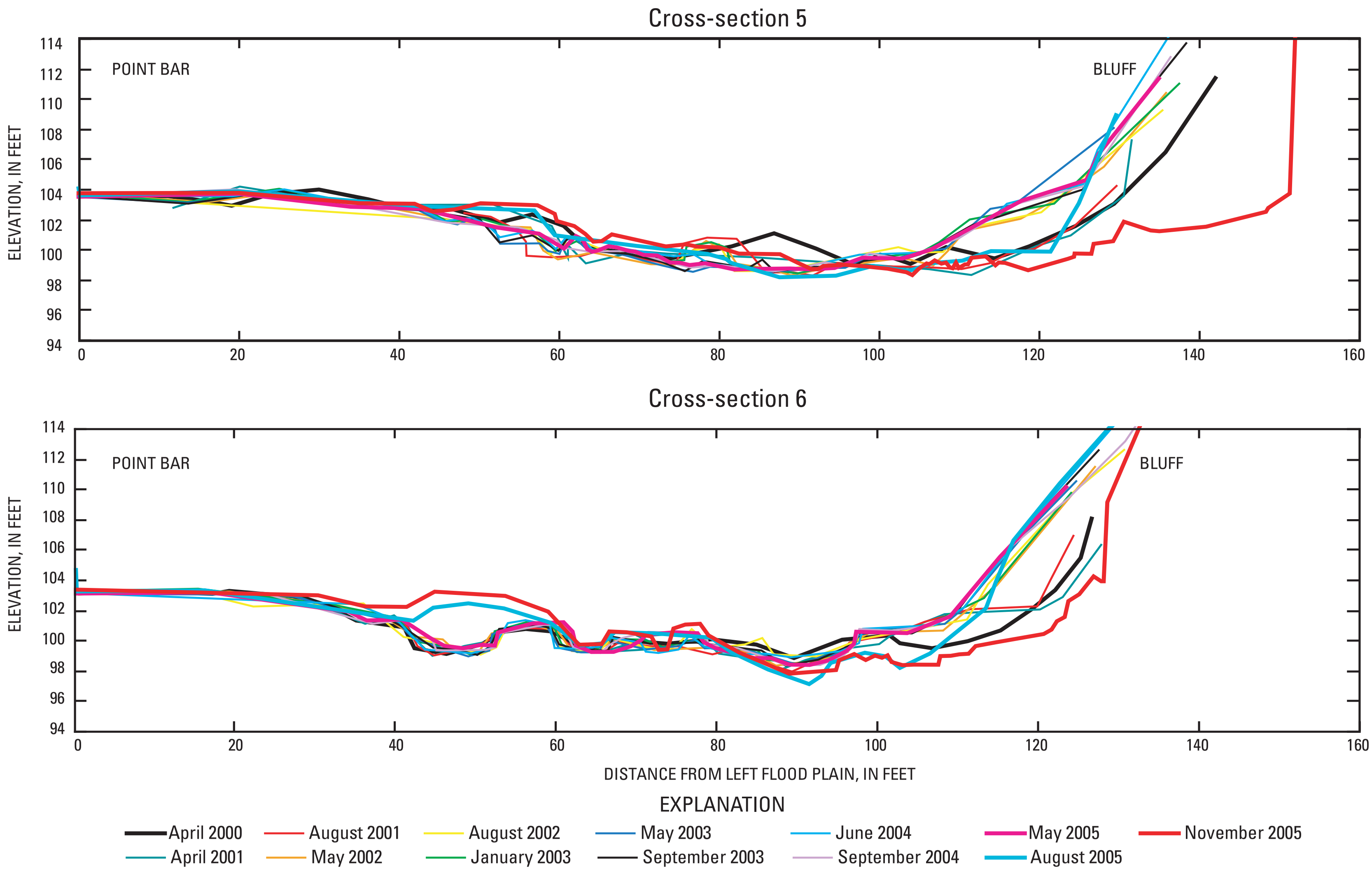

Figure B1. Cross section data for site 16.4, for North Fish Creek, Wis.

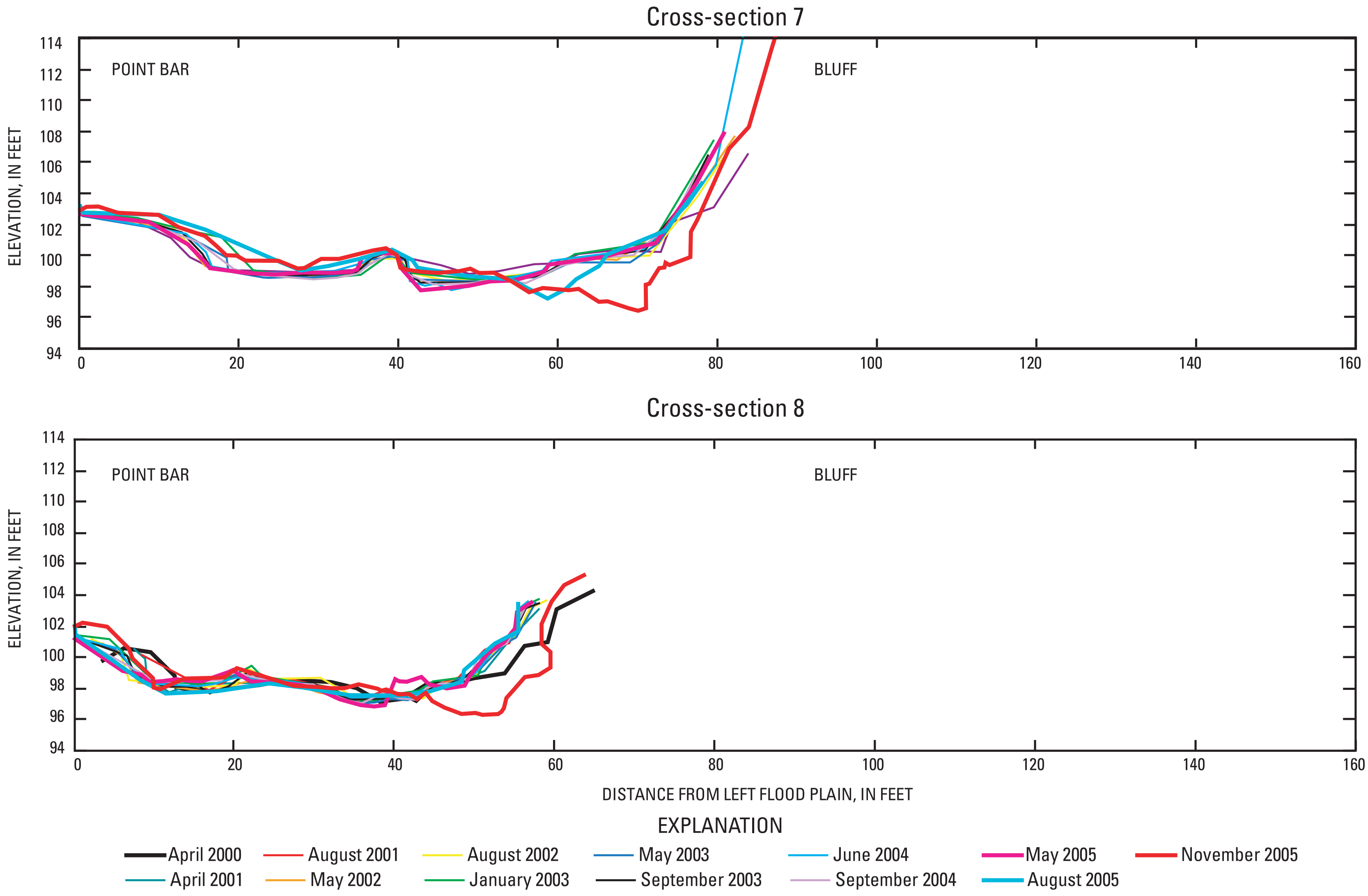

Figure B1. Cross section data for site 16.4, for North Fish Creek, Wis.

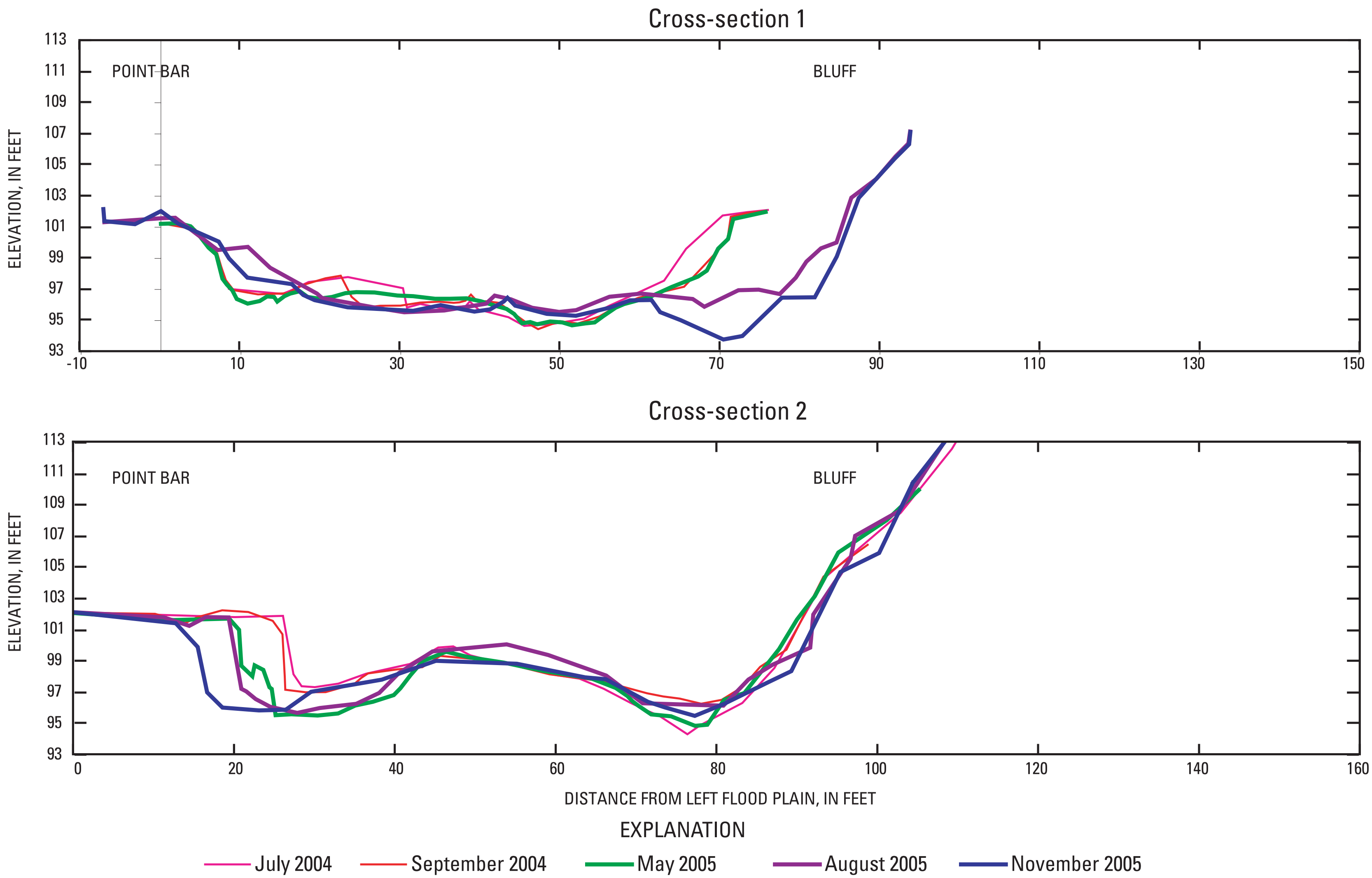

Figure B2. Cross section data for site 14.4, for North Fish Creek, Wis.

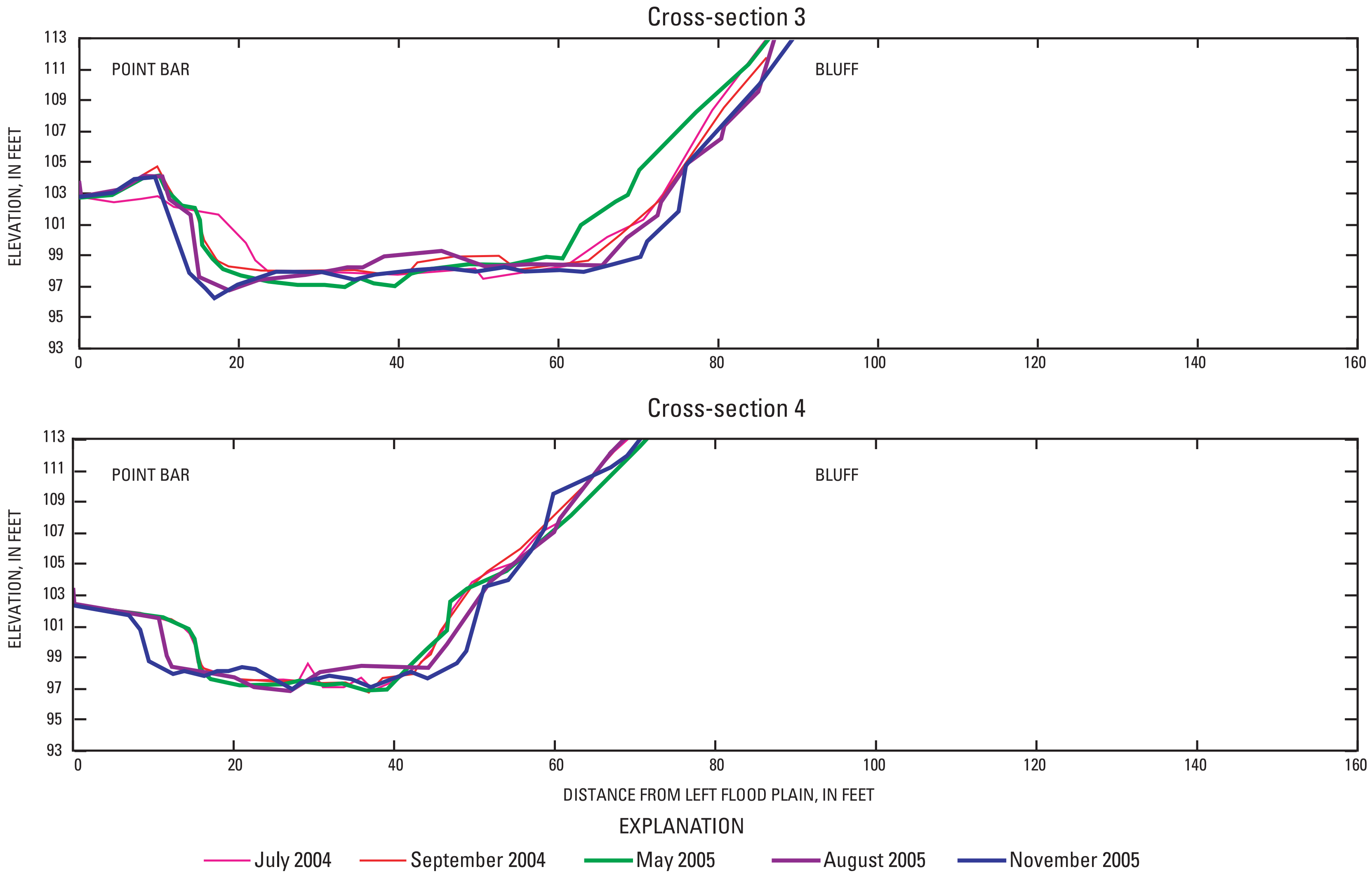

Figure B2. Cross section data for site 14.4, for North Fish Creek, Wis.

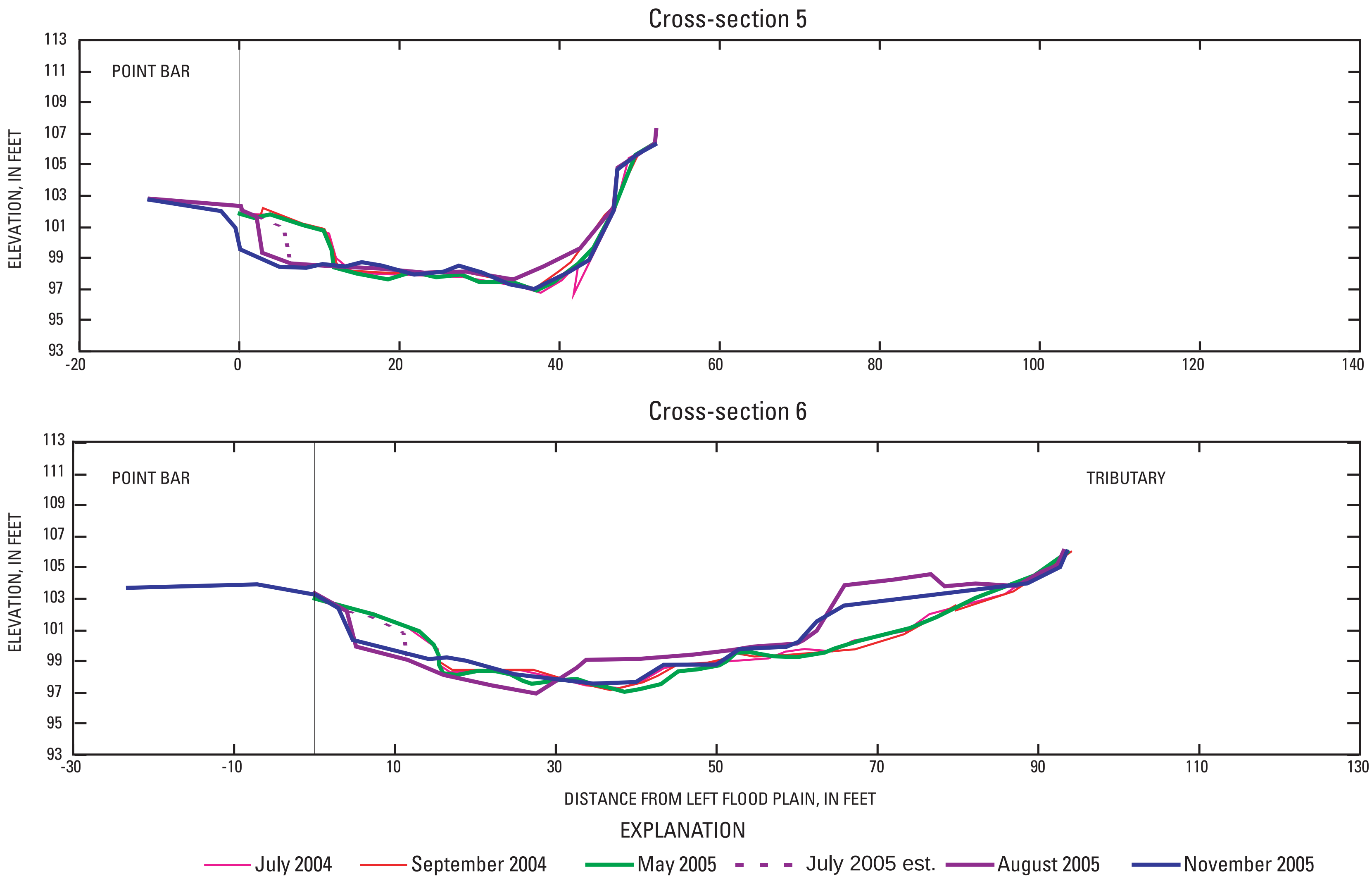

Figure B2. Cross section data for site 14.4, for North Fish Creek, Wis.

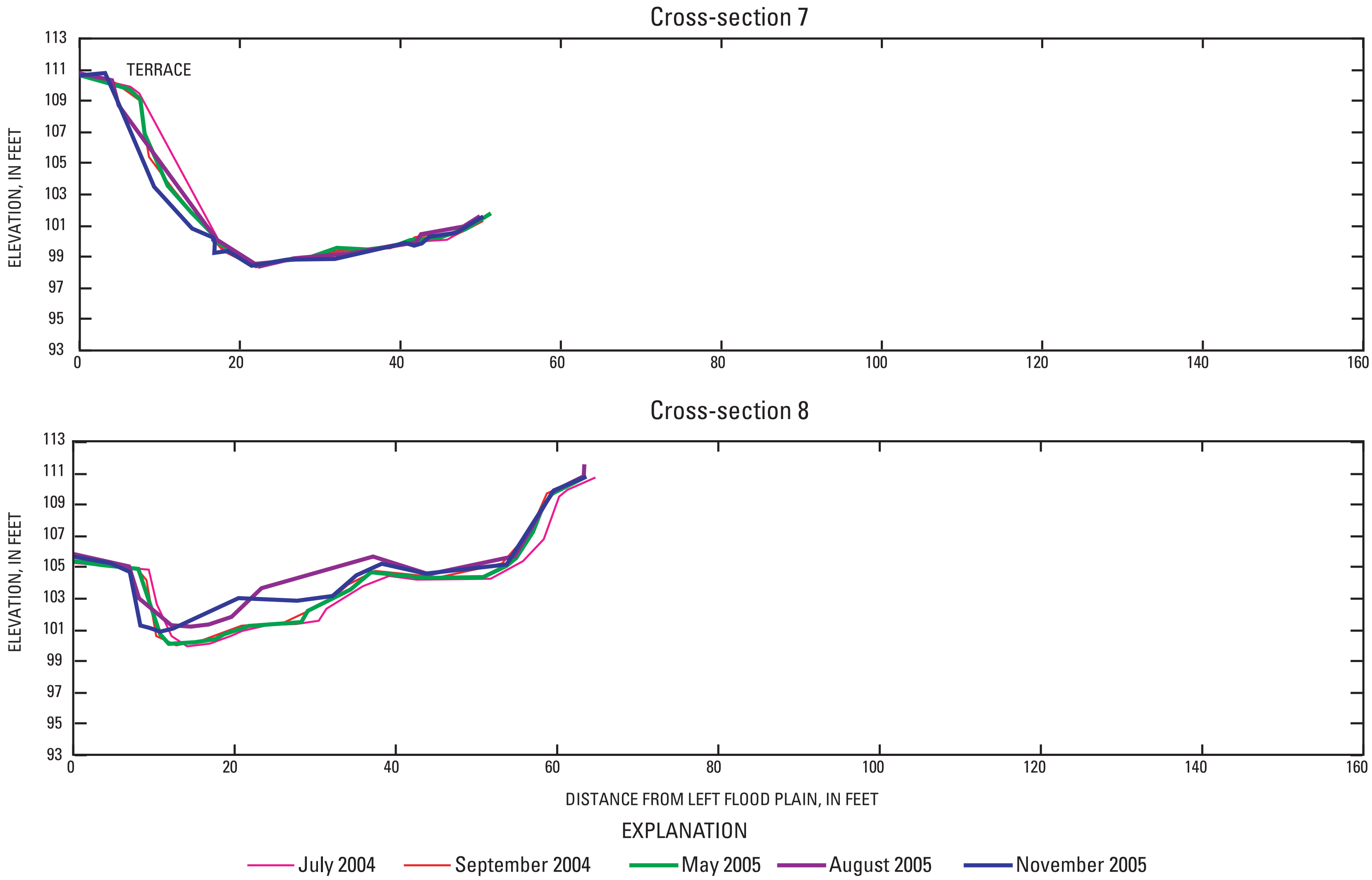

Figure B2. Cross section data for site 14.4, for North Fish Creek, Wis.

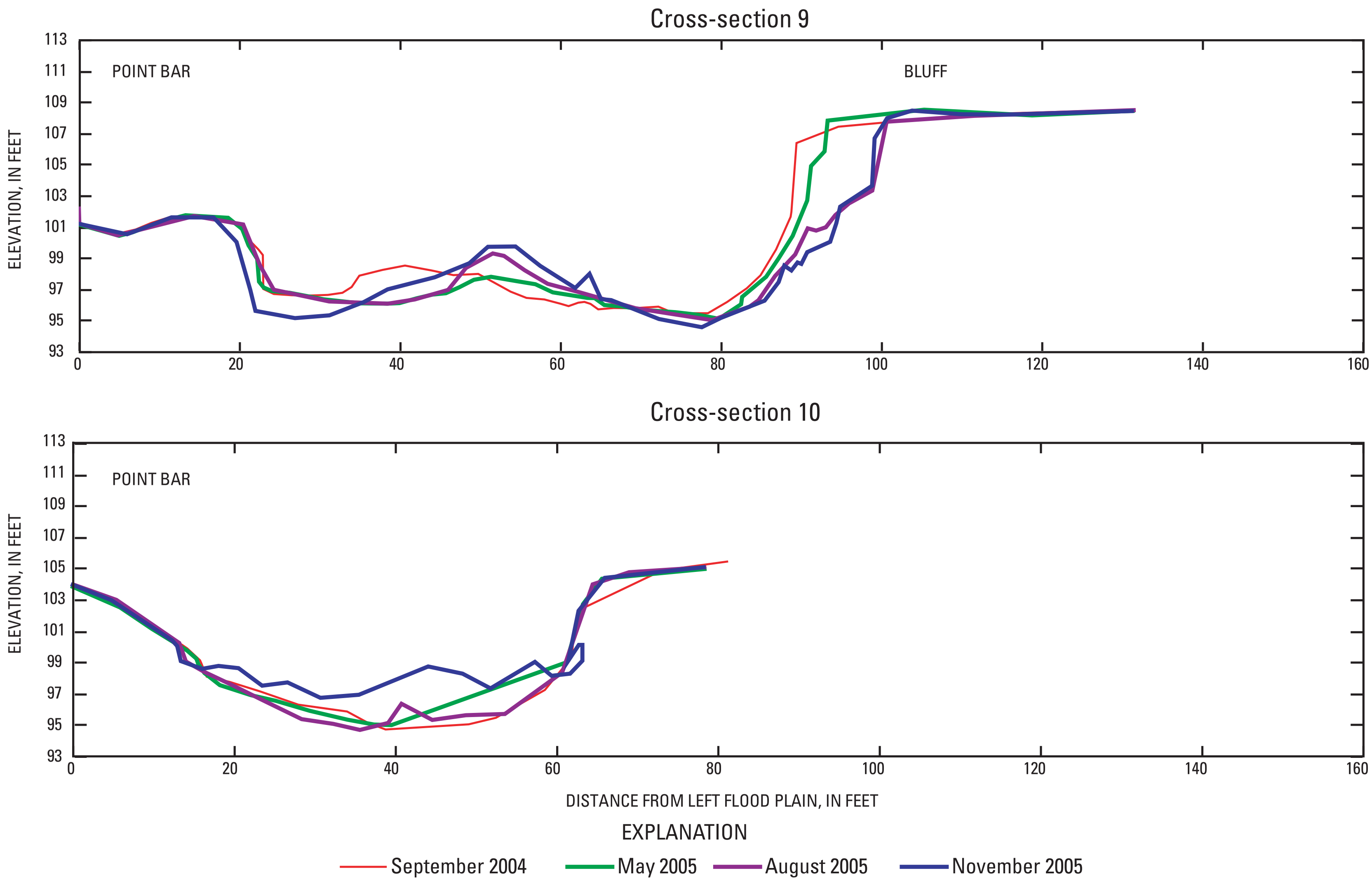

Figure B2. Cross section data for site 14.4, for North Fish Creek, Wis.

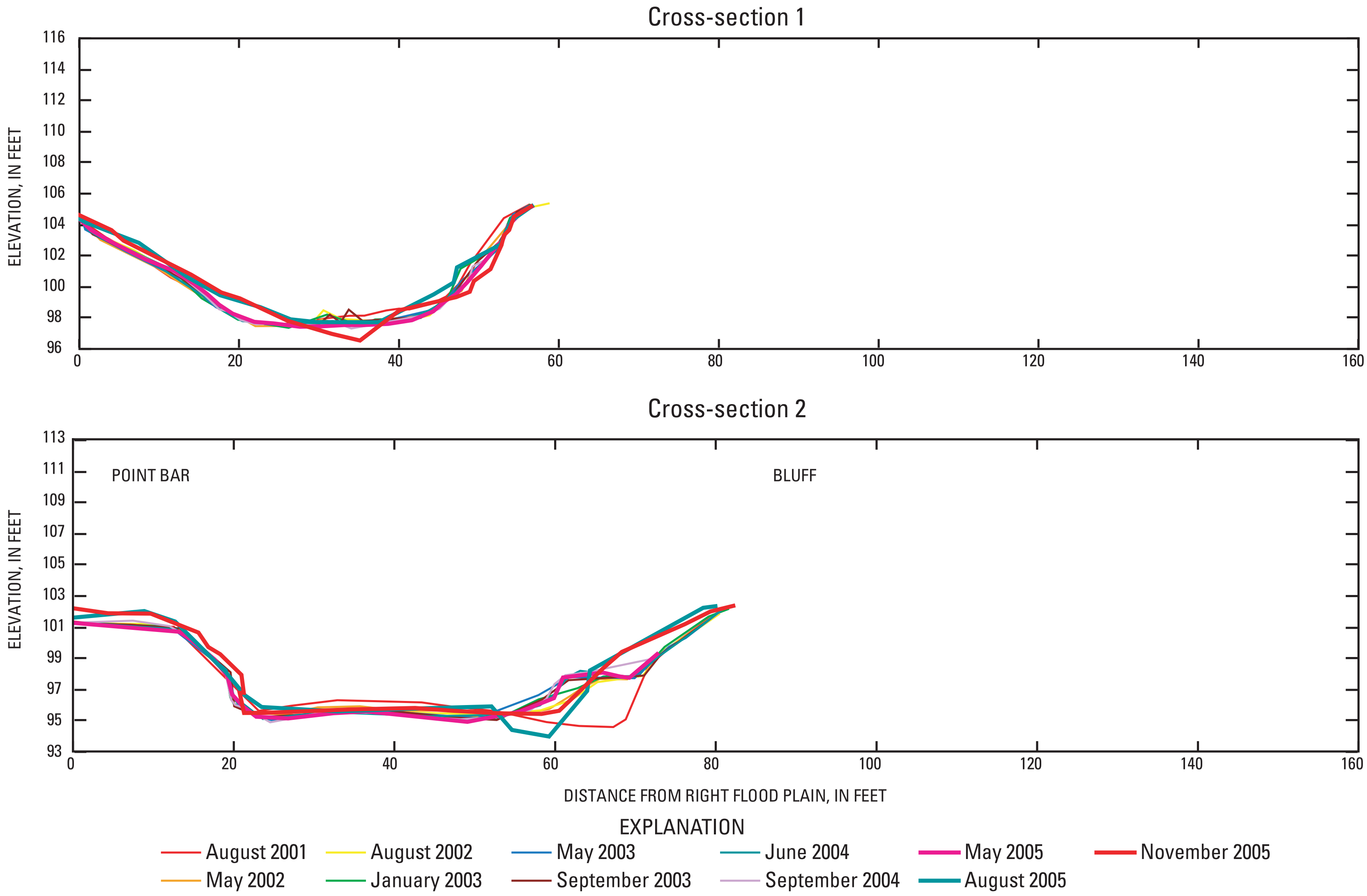

Figure B3. Cross section data for site 12.2, for North Fish Creek, Wis.

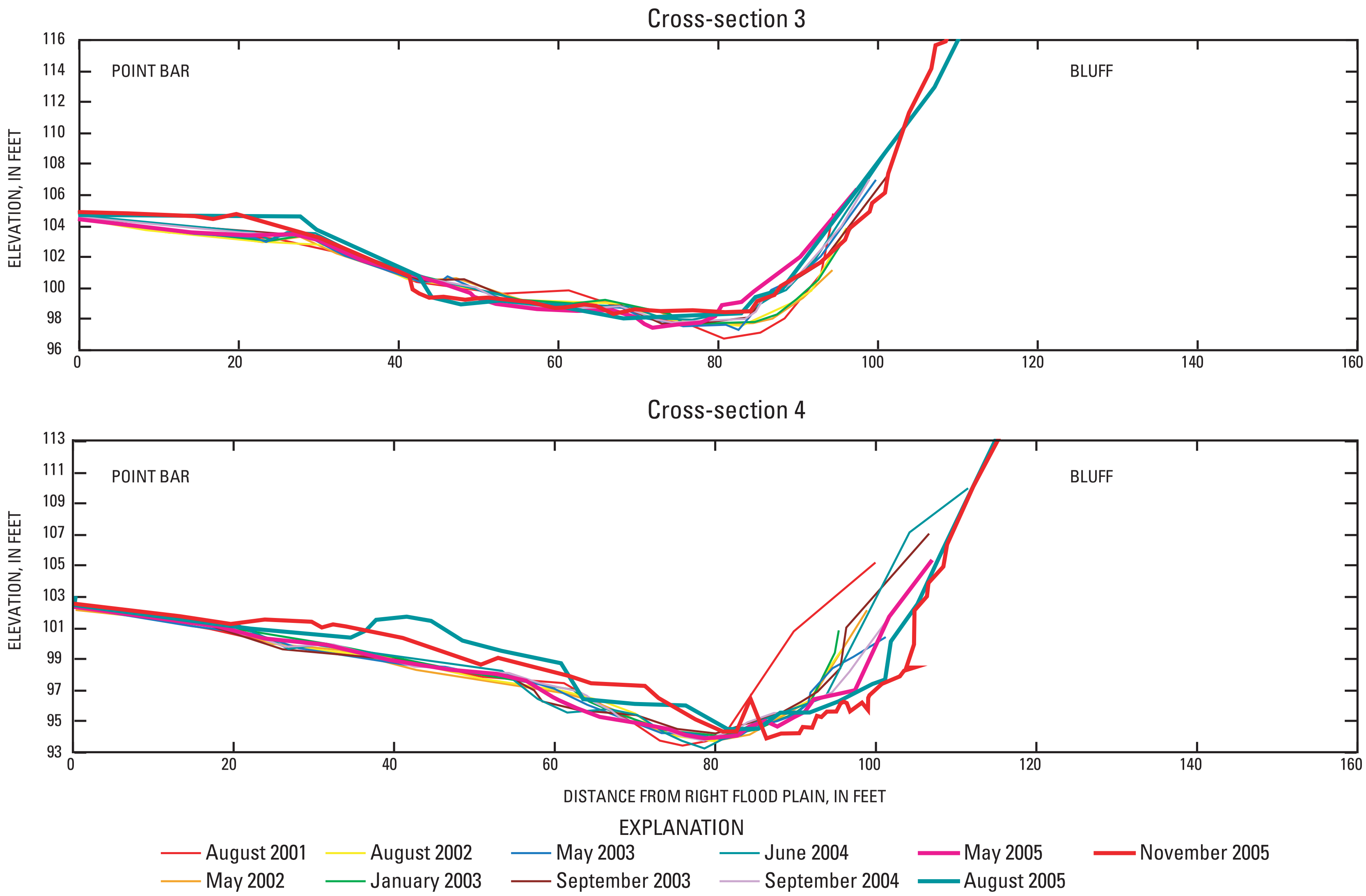

Figure B3. Cross section data for site 12.2, for North Fish Creek, Wis.

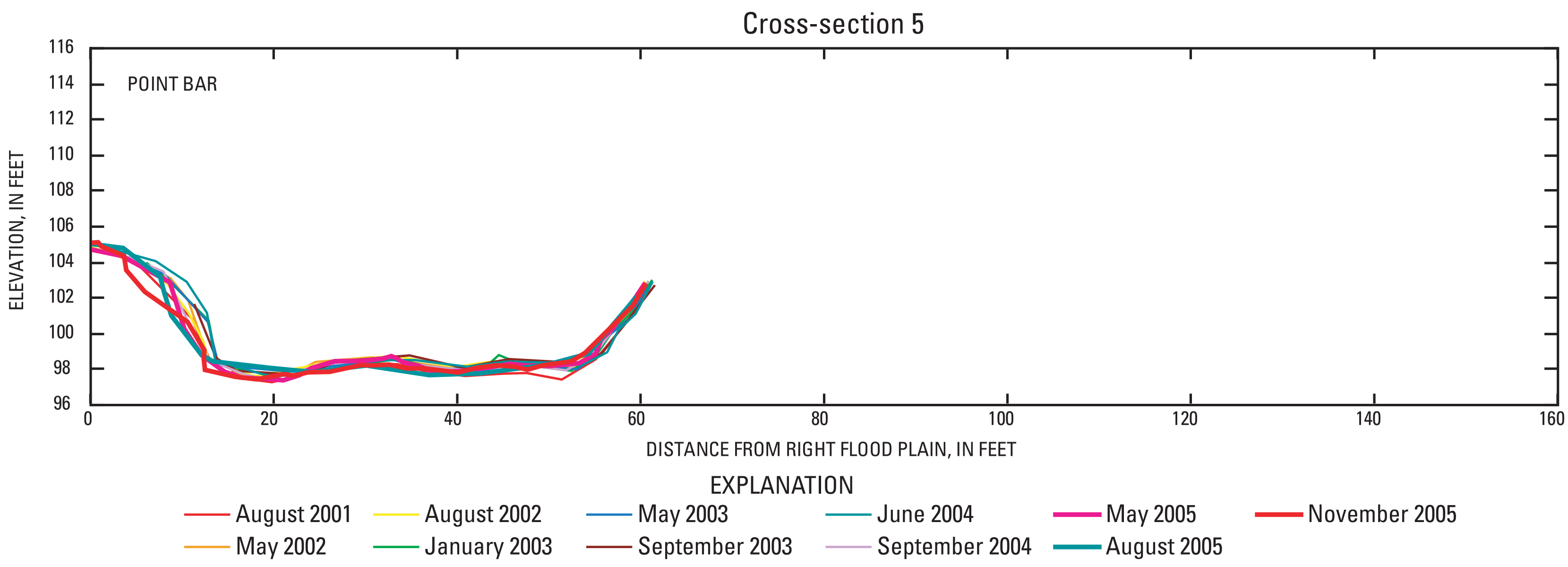

Figure B3. Cross section data for site 12.2, for North Fish Creek, Wis.