Fluvial Geomorphology Study of the Turners Falls Pool on the Connecticut River Between Turners Falls, MA and Vernon, VT

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Table of Contents

List of Figures

List of Tables

List of Appendices

EXECUTIVE SUMMARY

A fluvial geomorphology study was conducted of the Turners Falls Pool on the Connecticut River between Vernon, VT and Turners Falls, MA to understand the causes of bank erosion and identify the most appropriate methods for bank stabilization on this section of river. Historical maps reveal that the channel position has remained largely unchanged through the Turners Falls Pool since the 18th century, but minor changes are observed by comparing historical aerial photographs extending back to 1939. Several mid-channel bars, many now submerged by the raising of the Turners Falls Dam in 1970, are visible on historic topographic maps from the late 19th century and on bathymetric maps compiled as part of this study. The bars preferentially develop and persist upstream of channel constrictions formed where natural high terraces approach close to the river and, in one case, at an old railroad grade that crosses the Moose Plain floodplain. Hydraulic modeling reveals that eddy formation is strongest at constrictions and tributary confluences. Due to these natural constrictions and eddies, as well as other natural and anthropogenic causes, erosion was occurring in the Turners Falls Pool prior to the opening of the Northfield Mountain Pumped Storage Project in 1972. However the location and extent of this erosion is unknown.

Four types of bank erosion are present in the Turners Falls Pool and occur together through time at any given location. Undercutting and notching at the base of the banks results in topples and slides as the stability of the upper bank is compromised. The slide and topple blocks are disassociated into flows and deliver loose sediment to the base of the bank. This loose sediment can be carried away from the bank by water currents generated by flood flows, boat waves, pool fluctuations, groundwater seeps, and overland flow. Where sediment is moved directly offshore, beaches can form that may promote the stabilization of the bank if the accumulated sediment is not removed or beach face inundated by flood flows. The monitoring of several cross sections since 1990 shows that bank recession rates are on the order of 1.0 ft/yr, but as much as 9.0 ft of erosion has occurred in a single year (i.e., Kendall Site). The average erosion rate of 1.0 ft/yr is corroborated by the measurement of bank recession adjacent to fixed bank points along sections of river armored with rock.

Bank erosion is currently caused by a complex interaction of multiple factors operating through time and space. As along all rivers, natural flood flows are a cause of erosion. Riverbanks in the Turners Falls Pool are particularly sensitive to natural flood flows due to the preponderance of noncohesive fine-grained soils. Natural stability is further compromised, because past channel incision through older terrace and floodplain surfaces confine more floodwaters to the channel rather than spreading out across broad floodplains.

Natural patterns of erosion have to some extent been altered by human use of the river and adjacent valley. The raising of the Turners Falls Dam in 1970 destabilized previously stable portions of the bank by increasing the pore pressure in bank sediments higher up the bank. An increase in pool fluctuations with the opening of the Northfield Mountain Pumped Storage Project in 1972 and an increase in boat waves accompanying

greater recreational use of the Turners Falls Pool could have played a role in the increase in erosion documented by mapping in 1978 and 1990. The lack of a riparian buffer in a few localities makes the banks more susceptible to erosion due to a lack of roots to bind the soil together and an increase in runoff over the bank that can cause gullying. An increase in overall bank stability between 1990 and 2001, as documented by erosion maps, may be related to the development of beaches observed throughout much of the Turners Falls Pool.

Comparisons of erosion maps from different years must account for variations in mapping season, mapping methods, and mapping personnel. Comparisons of two different erosion maps completed in 1990 reveal several discrepancies in the location and amount of erosion. The minor increases in erosion between 2001 and 2004 are less than the discrepancies between the 1990 maps. Consequently, policy decisions based on the erosion mapping data should be carefully reviewed, because apparent differences in erosion from year to year may simply be an artifact of the mapping process.

Currently 20 percent of the bank length has been protected with rock armor. As bank stabilization efforts proceed, new approaches should be considered, because the continued reliance on armoring at the base of the bank with rock, in both riprap and bioengineering projects, could lead to increased erosion elsewhere. While the development of beaches is an indication of increasing bank stability, erosion is likely to persist as natural flood flows rework beach deposits and inundate the beach face. However, promoting the development and preservation of beaches through the addition of large woody debris could improve bank stability by buttressing the banks against erosion and by further trapping fine sediment on the beaches.

Given the complexity of issues surrounding erosion in the Turners Falls Pool the results of this study should be considered preliminary in nature. Many areas of additional study are necessary including surveys of erosion using a systematic and explicit method for mapping the types of erosion present in order to eliminate artifacts in the mapping process. Experimentation with large woody debris placements on beach faces should also begin to determine their value in improving bank stability. Only with a thorough understanding of the character and causes of erosion can effective and sustainable bank stabilization efforts be implemented throughout the Turners Falls Pool.

1.0 INTRODUCTION

This report describes a fluvial geomorphology study completed by Field Geology Services in the Turners Falls Pool on the Connecticut River between Vernon, VT and Turners Falls, MA (Figures 1 and 2). The Turners Falls Pool is a 22-mile long impoundment extending from the Turners Falls Dam at the downstream end to the Vernon Dam upstream. The total watershed area upstream of the Turners Falls Dam and Vernon Dam is 7,138 mi^2 and 6,266 mi^2, respectively (US Army Corps, 1991). The Ashuelot River (420 mi^2 drainage area) and Millers River (375 mi^2 drainage area) are the only two tributaries of significant size entering the Connecticut River in the Turners Falls Pool (Figure 2). The fluvial geomorphology study had two principle objectives related to bank erosion and bank stabilization efforts in the Turners Falls Pool: 1) determine the success of previous bank stabilization efforts in stabilizing the riverbanks; and 2) identify the most appropriate techniques for bank stabilization given the current hydraulic conditions. Several additional questions related to the character, extent, rate, and timing of erosion were also necessarily addressed during the course of the study as were issues related to ongoing monitoring of the bank erosion and bioengineering efforts. The fluvial geomorphology investigation consisted of seven areas of study: 1) review of previous research and archival documents; 2) analysis of historical aerial photographs and topographic maps; 3) examination of discharge records, flood history, and water level fluctuations; 4) geomorphic characterization of the watershed; 5) bathymetric mapping and hydraulic modeling; 6) understanding the character of erosion; and 7) close inspection of previous bank stabilization efforts. The purpose and results of each area of study are described separately below and provide the basis for a discussion of the causes of erosion, the most appropriate measures for bank stabilization, and recommendations for future work.

2.0 PREVIOUS RESEARCH AND ARCHIVAL DOCUMENTS

In addition to studies and archival documents related to the erosion problems and history of the Turners Falls Pool, a great deal of published research is available on bank erosion along rivers and reservoirs, generally, that relates to the study objectives. The climate (U.S. Army Corps, 1991), geology (Bain, no date; Little, 2003), soils (Mott and Fuller, 1967), hydrology (U.S. Army Corps, 1979 and 1991), land use (NDT, 1991), and the history of dam construction and hydropower operations (U.S. Army Corps, 1991; Scott, 2005) in and around the Turners Falls Pool have been previously described. The reader is referred to these earlier works for a complete description, while only those specific conditions considered pertinent to this study are introduced as needed throughout the report.

While log drives on the Connecticut River were a significant annual event on the Connecticut River in the late 19th and early 20th centuries (Gove, 2003), the significance of log drives relative to current conditions is unknown, but is probably of minor importance compared to the history of dam construction. The first dam at Turners Falls was completed in 1798 as part of a canal and lock system for boat transportation (Deborah Noble, written communication, 2006). At least two floods washed out the dam, in 1824 (Pressey, 1910) and 1866 (Scott, 2005), with the log-crib dams being rebuilt each time. A concrete dam was completed by 1905, subsequently raised in 1913, and flashboards added in 1915 that raised the water level another 7.3 ft (Simons and Associates, Inc., 1998). The dam was rebuilt in 1970 and raised 5.9 ft as part of the construction of the Northfield Mountain Pumped Storage Project (Simons and Associates, Inc., 1998). With the opening of the Northfield Mountain Pumped Storage Project in 1972, the magnitude of pool fluctuations was increased. The Vernon Dam was built between 1907 and 1909 (Deborah Noble, written communication, 2006).

As a consequence of these modifications to the Connecticut River by dams, the Turners Falls Pool has hydraulic characteristics of both a free flowing river and reservoir, so the literature pertaining to the processes of bank erosion in both environments is pertinent. Bank erosion can be subdivided into five distinct types of movement with a continuum existing from the dislodging of single particles to the *en masse* movement of large sections of the bank (Table 1; Lawson, 1985). More than one type of erosion can occur at a single site with slides on the upper bank often giving way to flows on the lower bank. The dominant erosional mechanism at a given site and the overall susceptibility of the bank material to erosion is dependent on several factors including the cohesiveness and stratification of the sediment. Banks composed of noncohesive sediments and interlayered cohesive and noncohesive sediments are the most susceptible to erosion (Winterbottom and Gilvear, 2000). The erosion of noncohesive sediments such as sand and gravel tends to occur through shallow failure surfaces or movement of individual particles, whereas slumping becomes increasingly important with greater cohesiveness of the bank sediment (Thorne, 1991).

Bank erosion occurs when the sum of the gravitational shear stresses exceeds the resisting strength of the bank material (Easterbrook, 1993, p. 64). When a bank is at the threshold of failure, a slight increase in shear stress or a small decrease in shear strength can lead to bank erosion. The shear stress acting on a bank can be increased in several ways such as through the removal of the underlying support (i.e., undercutting), an increase in the surcharge (i.e., weight) on the bank slope accompanying precipitation or the addition of failed material from upslope, or the increase of lateral stresses that might accompany the formation of ice in cracks or pore spaces. Other factors leading to bank failure are further described by Easterbrook (1993, p. 65). Reductions in shear strength often result from increases in the water content of the bank material as this leads to the buildup of excess pore pressures. Undercutting is most severe in cohesive silt sediments with niches greater than 30 feet possible in extreme permafrost conditions, while undercutting greater than 10 feet in noncohesive sand and gravel is unlikely in similar settings (Lawson, 1985).

While composition is a very important factor determining the strength of the bank sediment, certain soil moisture conditions can further weaken the bank material and increase the likelihood of bank failure (Couper and Maddock, 2001). Quite commonly bank erosion will be greatest during the recession of high flows rather than during the high flow itself (Twidale, 1964; Thorne, 1982; Rinaldi et al., 2004). This occurs because the bank sediment becomes saturated with water during the high flow and then the confining pressure exerted on the bank by the river decreases as the river level recedes. Rapid water level fluctuations in reservoirs can cause similar discrepancies between the water surface and adjacent groundwater levels. The differences will be most pronounced in less permeable finer grained sediments as groundwater levels will more slowly equilibrate to the changing water surface (Lawson, 1985). Slope instability caused by the resulting seepage forces can be enhanced in stratified sediments as the presence of fine-grained impermeable layers will promote movement of water horizontally out of the bank along a single layer rather than along more vertically oriented flow lines. Conversely, the presence of highly permeable gravels near the base of the bank may prevent the development of a single failure surface along which bank material higher up the slope might slide.

Through the movement of material from the upper slope to the base of the bank, slides reduce the overall slope of the bank and, as a consequence, decrease the gravitationally driven shear stresses acting on the bank. If the rate of sediment accumulation at the base of the bank exceeds the river's capacity to transport the sediment downstream, the accumulated sediment will buttress the bank from fluvial attack and lead to greater bank stability (Thorne, 1991). In contrast, if the river's sediment transport capacity exceeds the amount of sediment accumulating at the base of the bank, the river will begin to scour the bed of the channel at the base of the bank. This scouring increases the bank height, increases the bank slope, and thus sustains the bank erosion. As the forces acting at the base of a bank in a particular location are diminished or eliminated, the overall slope of the bank will be slowly reduced through the movement of material from the upper slope to the base until a stable concave-up profile is reached (Brunsden and Kesel, 1973). Similarly, artificially armoring or buttressing the base of the bank against fluvial attack will ultimately lead to the stabilization of the upper slope if the base remains secure.

In reservoirs, waves tend to move sediment away from the bank in an offshore direction, which means sediment is moved perpendicularly away from the bank rather than downstream along the bank. Therefore, sediment accumulating at the base of an eroding bank can be slowly spread out over a greater distance to create a wide gently sloping beach face. If no beach face is present, waves impinge directly on the bluff (i.e., bank) face and all wave energy is dissipated on these sediments, a condition most conducive to erosion (Lawson, 1985). As a beach develops, a greater and greater proportion of wave energy is expended on the beach face with ultimately little, if any, wave attack at the base of the bluff or bank. The development of a beach, as long as it is not periodically removed by storms, longshore currents, or other processes, can, therefore, lead to the stabilization of eroding banks and the development of an equilibrium condition (Lawson, 1985). Bank equilibrium, or stability, will be sustained as long as the hydraulic regime remains unchanged (i.e., magnitude of flow velocities and water level fluctuations).

3.0 HISTORICAL AERIAL PHOTOGRAPHS AND MAPS

Historical maps of the Connecticut River Valley including at least portions of the area now within the Turners Falls Pool are presented in Appendix 1 with aerial photographs of the Turners Falls Pool since 1939 in Appendix 2. A map from 1650 is of historical interest, but is not of sufficient detail to discern changes in channel position on the Connecticut River. Portions of the Connecticut River in the Turners Falls Pool in Northfield, MA are depicted on maps of land sales in the 1730's, but the exact location shown is difficult to determine. More complete maps dating to the 18th Century of Montague (1750), Northfield (1792), and Hinsdale, NH (1753) show that the current channel position and configuration of the Connecticut River have remained largely unchanged for more than 200 years over the entire length of the Turners Falls Pool (Figure 3 and Appendix 1). More recent higher resolution maps from the 19th Century and aerial photographs of the 20th Century are consistent with this conclusion and show no significant changes in the location and planform of the river channel.

The lack of large scale changes does not imply that the river has not migrated even tens of feet in some locations; changes of this magnitude are simply not quantifiable given the scale and resolution of the maps and aerial photographs inspected. Reid (1990) describes minor changes in the meander shape and position along the western bank of the river across from Kidds Island. However, estimates of up to 400 feet of bank erosion between 1887 to 1944 have been questioned after consultations with the USGS raised concerns as to whether map measurements with an accuracy of 200 feet could be made given the methods and scale of ground surveys completed in 1887 (NDT, 1991).

Eastern Topographics, Inc. of Wolfeboro, NH has determined that sufficient information is known about the 1961 aerial photographs (e.g., height of airplane) to create a 10-foot topographic map of that time period. The 1961 aerial photographs could also be accurately overlayed with recent aerial photographs. This would enable a more reliable determination of small scale shifts (i.e., 10's of feet) in channel position and changes in bank height that may have resulted from the erosion of a low bench that previously existed along portions of the river (see Section 5.0 below). Distinguishing changes that occurred prior to the opening of the Northfield Mountain Pumped Storage Project from those that occurred after might be possible by resurveying portions of the detailed topographic plans of the river made prior to the opening of the project (WMECO, 1971). The original survey plans are still retained by Ainsworth and Associates, Inc. of Greenfield, MA and initial consultations with them indicate that determining changes in channel position since 1970 might be possible where the surveys can be tied to the same bounds (i.e., landmarks) used previously.

Additional minor changes and information gleaned from a careful visual inspection of the historical maps (Appendix 1) and aerial photographs (Appendix 2) are noted below:

1) Several changes in the presence and configuration of mid-channel bars in the river have occurred. The more significant changes are discussed from the upstream end of the Turners Falls Pool to downstream.

a) the unnamed bar downstream of the Vernon Dam and Stebbins Island have persisted in the same location since the earliest detailed map in 1753, although minor changes in the size and shape may have occurred.

b) Two bars are shown approximately 0.5 and 2.5 miles downstream of the Ashuelot River confluence on both the 1753 and 1802 maps of Hinsdale, NH. On maps from 1858 and 1895, only a single bar, situated between the two bars shown on the earlier maps, is present. This single bar is referred to as Davenports Island on the 1858 map. In 1917, a single bar is shown and located closer to the confluence of the Ashuelot River in the approximate position of the upstream bar seen on the maps of 1753 and 1802. This bar is named Doolittle Island on this map and is in the same location as the bar seen today. Consequently, this bar should be referred to as Doolittle Island and not Davenport Island as adopted by Simons and Associates, Inc. (1998). Given variations in scale and resolution of the maps, uncertainty remains as to whether Doolittle Island has disappeared and reappeared through time or if Doolittle Island and Davenport Island are the same feature. What is more certain is that two bars existed downstream of the confluence of the Ashuelot River until at least 1802, while only one has been present since 1858.

c) A bar appears immediately upstream of the railroad bridge in Northfield on a topographic map surveyed in 1887. The railroad bridge was constructed in 1847 (Deborah Noble Associates, written communication, 2006). The bar is not seen on the 1792 map of Northfield, which accurately depicts Kidds Island, nor is it present today. However, a shoal does appear to be present in this locality on the 1939 aerial photograph.

d) A bar is visible approximately 0.5 miles downstream of the current Route 10 Bridge on a topographic map surveyed in 1887. The bar is situated at the confluence of Millers Brook. The bar is not present on either the 1792 map or currently, although a shoal appears to exist on the 1939 aerial photograph.

e) Kidds Island has persisted in the same location since the first detailed map in 1792, although changes in shape and size have occurred.

f) Five bars that occupy much of the river's width are depicted just upstream of The Narrows (at the upstream entrance to Barton Cove) on an 1830 map of Gill. Only a single bar is seen on the topographic map surveyed in 1886 and 1887 at the upstream end of the multiple islands shown on the 1830 map. Today, a few very low marshy areas are observed in this area.

g) Barton Island in Barton Cove became an island only after the raising of the Turners Falls Dam in 1905 drowned an abandoned meander situated just downstream of the Lily Pond Barrier.

2) The scalloped embayment on the east bank immediately downstream of the Vernon Dam where active erosion of the high bank occurs today is present on the 1917 map, indicating that no significant change in the configuration of the bank has occurred in the past 90 years.

3) The 1917 map notes that the low meadow on the west bank just upstream of the Ashuelot River confluence was "entirely under water in the flood of 1869" (Appendix 1).

4) The west bank of the river just downstream of the railroad bridge between Vermont and New Hampshire, referred to as the Kendall Site, appears to have a convex shape on the 1939 aerial photograph but is concave on the 1961 aerial photograph as it is today, indicating that the ongoing erosion at the site began between 1939 and 1961.

5) Overall, the extent of riparian vegetation along the river channel has increased since the 1939 aerial photograph, but this trend is locally reversed.

6) The 1830 map of Gill denotes a falls just downstream of the confluence of the Millers River, which is the probable location of a dam and lock built around 1806 "to make slack water at the French King rapids" (Pressey, 1910, p. 165).

7) Turners Falls was 14 ft high at the time the first dam was completed in 1793 as indicated on a 1794 map of Greenfield.

4.0 EXAMINATION OF DISCHARGE RECORDS

Discharge records in the area of the Turners Falls Pool provide information on past floods and the impact of flood control structures upstream (Figure 4). Annual peak discharge data for the Connecticut River are available from stream gauges at Montague, Turners Falls Dam, and Vernon Dam. Millers River, Mill Brook, and the Ashuelot River are tributaries entering the Turners Falls Pool that have been gauged at various times. The gauged Deerfield River enters the Connecticut River downstream of the Turners Falls Pool, but upstream of the Montague gauge. All of the discharge data for the Connecticut River and its tributaries are available online at: http://waterdata.usgs.gov/nh/nwis/sw. The gauge record is longest for the Montague gauge, which begins in 1904 and continues until today. The Turners Falls gauge extends from 1915 to 1987. The Vernon Dam gauge is continuous from 1945 to 1973 with peak flow estimates for the large floods of November 1927, March 1936, and September 1938. Additional discharge data are maintained by hydropower companies operating facilities at Turners Falls Dam, Vernon Dam, and Northfield Mountain, but these data were not available for this study nor considered critical for the level of analysis discussed below.

The flood of March 1936 is the flood of record since gauging began with the floods of November 1927 and September 1938 also notable (Figure 4). Although several large events in Vernon during 1763, 1854, 1857, 1862, 1869, and 1870 as noted by Hemenway (1891) occurred before the gauge record, the 1936 flood is believed to be the largest flood on the Connecticut River since 1639, the earliest date of record (WMC, no date). Flood crests in Hartford, Connecticut have been recorded nearly continuously since the flood of March 1639 (Kinnison et al., 1938), providing an essentially complete record of flood crests over 350 years long. Not noted in the history of Vernon are large floods in 1896 (Bain, no date), 1866 (Scott, 2005), and February 1824 that washed out the South Hadley Dam, Turners Falls Dam, and the small dam built below the confluence of the Millers River (Pressey, 1910).

All flood discharges since gauging began at Montague in 1904 have been affected to some degree by flow regulation, because dams were already present on the Connecticut River. However, in response to the 1936 flood in particular, a more extensive system of flood control dams were built on several large tributaries in Vermont and New Hampshire. In conjunction with hydropower reservoirs on the mainstem, peak discharges on the mainstem have been noticeably reduced since completion of the last flood control structures in 1961 (Figure 4). The U.S. Army Corps (1991) provides a more extensive description of these flood control structures and their impact on the hydrology of the Turners Falls Pool.

The system of flood control reservoirs upstream has had a significant impact in controlling peak discharges. A 100-year modified flow at the Schell Bridge today is equivalent to a natural event with a recurrence interval of approximately 30 years (U.S. Army Corps, 1991). Since 1961, the average peak discharge at Montague has declined more than 14,000 ft^3/s, but the highest peak of 143,000 ft^3/s in May 1984 does rate as the fifth highest discharge on record. Only three years later in April 1987, the tenth highest discharge on record occurred; both large events in the 1980's, with estimated recurrence intervals of 10 to 15 years (U.S. Army Corps, 1991), took place after the opening of the Northfield Mountain Pumped Storage Project.

Although peak discharges have declined, the flood control reservoirs have tended to redistribute annual runoff from wetter to dryer months (U.S. Army Corps, 1991). Flows in the lower range of discharge at the Turners Falls gauge are greater since installment of the flood control structures, but this might also be partly the result of greater than normal runoff (U.S. Army Corps, 1991). An analysis of the Montague gauge through 2005 verifies that the trend of increased low flow discharges has continued since the U.S. Army Corps report was completed in 1991. While peak discharges have been reduced, the resulting greater flow volumes through dryer periods has resulted in river stages remaining higher for longer periods of time than would occur under unregulated or less regulated conditions.

Daily water level fluctuations in the Turners Falls Pool are larger and quicker since the opening of the Northfield Mountain Pumped Storage Project (U.S. Army Corps, 1991). Before the Turners Falls Dam was raised in 1970, Turners Falls Dam operated within an elevation of 176 ft and 179.6 ft (NDT, 1991). Fluctuations of this magnitude occurred 60 percent of the time but their effects, at that elevation, did not extend beyond the French King Gorge. When the Turners Falls Dam was raised 5.9 ft in 1970, the impoundment upstream of the Turners Falls Dam extended for the first time to Vernon Dam. The Northfield Mountain Pumped Storage Project is allowed to operate within a 9.0 ft range between an elevation of 176 ft and 185 ft, measured at the Turners Falls Dam, but water levels typically fluctuate only 2.5 to 3.5 feet daily near the tailrace with 5.0-foot fluctuations occasionally experienced (NDT, 1991; U.S. Army Corps, 1991). Weekly fluctuations of 6.0 feet can occur depending on the power operation of the

Turners Falls Dam, Northfield Mountain Pumped Storage Project, and upstream power projects (U.S. Army Corps, 1977). Fluctuations can also be caused by upstream flood control operations. Under typical operations, the river level reaches a low on Monday morning when the upper reservoir on Northfield Mountain is filled for a week of power generation. Although the upper reservoir is partially refilled each day, the river normally reaches a high on Friday before the upper reservoir is completely refilled during the weekend when a longer period of time is available for pumping.

Water level fluctuations are greatest at the Turner Falls dam and diminish upstream such that changes of only one foot or less are typically experienced at Vernon Dam. At flows greater than 20,000 ft^3/s the fluctuation of water levels due to operation of the pumped storage facility is also diminished, because of the natural backwatering that occurs behind the French King Gorge. Physical hydraulic modeling demonstrates that if the plant had been operating during the 1938 flood pool levels would have fluctuated less than 1.0 ft at the tailrace (Larsen, 1970). During normal operating conditions, however, large portions of the Turners Falls Pool that experienced minimal water level fluctuations prior to the opening of the Northfield Mountain Pumped Storage Project now experience daily water level fluctuations. These fluctuations are also occurring at a higher river stage due to both the raising of the dam level and higher low flow discharges (see discussion above).

5.0 GEOMORPHIC CHARACTERIZATION OF THE WATERSHED

5.1 Terrace and Floodplain Surfaces

While the width and orientation of the valley through which the Connecticut River flows is the result of ancient geological processes, the valley bottom is composed of a series of terraces stepping up from the river (Figure 5) with the highest and, therefore, oldest geomorphic surface formed since the last Ice Age (i.e., < 15,000 yrs). These terrace surfaces, and perhaps others, are seen throughout the Turners Falls Pool area, but in most instances not all of the terraces are found together along a single transect as at Moose Plain. The width of the valley is narrowest through the French King Gorge where the river encounters bedrock nearly continuously. Only 10 percent of the channel through the Turners Falls Pool encounters bedrock, however, with most of the channel flowing against glacial, lacustrine, or alluvial sediments underlying the various terraces. Both the surfaces and sediment beneath record a history of events that have shaped and continue to impact the channel's dimensions, characteristics, and susceptibility to erosion.

The geological history describing the formation of the terraces depicted in Figure 5 is summarized below, but is more thoroughly described in Little (2003). When glacial ice retreated from the Connecticut River Valley at the end of the last Ice Age great quantities of sediment were washed into the valley from the tributaries and from the glacial ice melting to the north, forming large deltas. One such delta in Rocky Hill, Connecticut dammed the width of the valley and created a long narrow lake, known as Lake Hitchcock, that extended as far north as West Burke, VT. The lake's water surface in the Turners Falls Pool area was likely more than 150 ft higher than the current level of the Connecticut River (Figure 5b). Tributaries built deltas at the lake's margins that are today the highest terraces in the valley and provide an excellent source of sand and gravel as evidenced by the gravel pits excavated below their surfaces (Figure 5a). The delta front sloped down to the lake bottom, which itself was over 75 feet above the current river level; the terrace on which the Town of Northfield rests is a remnant of the old lake bottom surface. Eventually the dam holding back Lake Hitchcock was broken and the Connecticut River was able to erode through the old lake sediments. The river's downcutting was stopped when hard bedrock was encountered as was the case at the Lily Pond Barrier (Figure 2), where a large waterfall previously existed and carved large plunge pools downstream, now deep areas within Barton Cove. Upstream, the river was graded to the top of this bedrock barrier and began eroding laterally into the old lake bottom sediments, creating a wide floodplain at the level of Second Moose Plain. Once the Lily Pond Barrier was bypassed through The Narrows (Figure 2), this higher floodplain level was abandoned when the river resumed downcutting. Once reaching a new graded level, the river eroded laterally to create its current floodplain, Moose Plain, in a process that continues until this day. Intermediate floodplain levels may have formed during this last period of downcutting, but more careful mapping of geomorphic surfaces (i.e., terraces) along the river would be necessary to confirm their existence and location.

The lowest floodplain levels have been overtopped by modern floods (Jahns, 1947), although less regularly today due to the effects of flood control structures upstream (Figure 4). The flood of 1936 spread across the floodplain with sufficient force to scour a new channel 20 ft deep across Moose Plain around Schell Bridge in part the result of floating debris that accumulated under the bridge (Figure 6; Jahns, 1947). Access to this channel was later blocked with the placement of riprap by government work projects. What appear to be similar avulsion channels (i.e., new channels into which the river can rapidly switch) are also seen immediately north of Munns Ferry, across Bennett Meadow near the Route 10 Bridge, and on Pine Meadow downstream of Kidds Island. Only the channel north of Munns Ferry was noted by Jahns (1947) to have formed in 1936, so the others may have resulted from earlier floods.

In addition to the broad, still active, floodplain surfaces (e.g., Moose Plain, Bennett Meadow, Pine Meadow) remnants (Figure 7a) of a low bench (Figure 7b) exist in many places at an elevation generally lower or equivalent to the floodplain level. The presence of rooted stumps that are now in the river or on gently sloping beaches at low flow demarcate the former position of the low bench (Figure 7c). The previous extent of these low benches is unknown. The low bench is still present in isolated areas where living trees, riprap, or rocky bank material have protected the bank from erosion. In East Deerfield along River Road, approximately 1.6 miles downstream of the Deerfield River confluence with the Connecticut River, a more continuous low bench is present below a higher bank that provides an analogue for what historically existed more extensively along long sections of the Connecticut River that now constitute the Turners Falls Pool (Figure 7d).

The low bench may have been very flat in places (Figure 7b), but where present today is generally gently sloping transverse to the river's flow (i.e., sloping away from the higher bank towards the river). The bench, although almost always lower than the more extensive floodplain surfaces, is found at varying elevations above the water surface. Both the slope and variable elevation suggest the bench has been formed, at least in part, by colluvial processes (i.e., mass movements of soil from the higher banks). Where flatter and closer to the water surface, floodplain processes are probably increasingly more important in the formation of the low bench.

The lowest surface level present in the Turners Falls Pool is a periodically exposed beach face that is completely submerged at higher flows (Figure 8a). The beach slopes gently towards the river with trains of ripples formed in the sand and silt that parallel the riverbanks. The width of the beach face is highly variable and in many places no beach is present at all with the river flowing against the riverbanks even at low flow. The exact location and width of the beach face is not well documented and is difficult to determine given the daily fluctuations in water level. However, beaches are a ubiquitous feature throughout much of the Turners Falls Pool. Remnant beach deposits are occasionally seen preserved at the base of the riverbanks (Figure 8b), particularly in protected areas within recesses and small gullies eroded into the bank. These beach deposits indicate that previous higher beach levels existed, but it is unknown how old these are, how quickly these higher beach levels formed, and for how long they were present.

5.2 Bank Heights

The channel's position relative to the various terraces determines the bank heights along the length of the river with higher banks encountered where the river flows against older terraces (Figures 5 and 9). At several locations, high banks are found on both sides of the river as can be seen on topographic maps (Appendix 1), thereby creating natural constrictions along the river relative to areas immediately upstream where low meadows (i.e., floodplain surfaces) are present. An artificial constriction was created when the railroad grade was built in 1847 across Moose Plain (Deborah Noble Associates, written communication, 2006). Artificial fill was added to keep the railroad and bridge at the same height as Second Moose Plain and an equivalent terrace of the same height on the east side of the river (Figures 5a and 10).

When encountering either natural or artificial constrictions, flows on the floodplain back up behind the constrictions before passing through the narrower areas. Ponded floodwaters upstream of the constriction at the railroad bridge appear to have at least once reached the height of the lowest terrace on the east bank, which is 14 ft above the level of Moose Plain but 20 ft below the level of the railroad grade and Second Moose Plain. Water overtopping this lowest terrace (a narrow minor terrace not described in Section 5.1) scoured a meander into the terrace surface before draining back to the river (Figure 11). Given that no constriction was present before the railroad was built in 1847, the meander has presumably formed since then. While the 1936 flood may have overtopped this high surface, the age of the trees growing in this old meander scar suggest an earlier flood may have been responsible for its formation (Figure 11). The railroad constriction may also have resulted in additional flooding at the upstream end of Moose Plain and contributed to the formation of the avulsion channel around Schell Bridge (Figure 6).

Another impact of the backwatering effect upstream of the constrictions is the loss of flow velocity and stream power. Many of the existing mid-channel bars (e.g., Kidds Island) as well as those no longer visible (e.g., upstream of the railroad bridge at Moose Plain) are located immediately upstream of constrictions where sediment would be deposited as a result of backwatering. Rather than shifting position through time, these bars, such as Kidds Island, appear long lived, since the backwatering occurs at the same location with each flood. Curiously, however, no bar has formed upstream of the French King Gorge, perhaps the most dramatic constriction in the Turners Falls Pool.

5.3 Soil Composition and Stratigraphy of Bank Sediments

Not only is the bank height controlled by the terrace or floodplain level along which the river flows, the character of the soil and sediments exposed along the banks also varies depending on which surface is intersected by the river. The two dominant soil types associated with abandoned (e.g., Second Moose Plain) and active floodplains (e.g., Moose Plain) in the Turners Falls Pool area is the Hadley very fine sandy loam and the Suncook loamy sand (Mott and Fuller, 1967). The stratigraphy of sediments underneath these floodplain surfaces is characterized by poorly consolidated alternating fine sand and silt layers (Figure 12).

The Agawam fine sandy loam is the dominant soil type associated with the older and higher terraces, but several other soil types also occur (Mott and Fuller, 1967). The stratigraphy underlying each terrace depends largely on the depositional environment in which the terrace surface formed (e.g., deltaic, lacustrine). In most instances the uppermost sediments exposed in these high banks are well stratified sands with the underlying sediments at river level varying between well sorted sand, cobbly to gravelly sand, or varved lacustrine clays (Figure 13). Given the close proximity in which the varied depositional environments were found, the type of sediment exposed at the base of the high banks along the river can vary over short distances. Bedrock ledge is also intermittently seen at the base of the banks and buried in the sediment above.

5.4 Tributary Inputs

Tributaries of different size periodically enter the Connecticut River along the length of the Turners Falls Pool. Sand bars are developed just downstream of the Ashuelot River confluence, the tributary with the largest watershed area. Unlike the bars formed behind valley constrictions, the position of bars downstream of the Ashuelot River varied earlier in the map record and may reflect the episodic nature of sediment inputs from the tributary (Appendix 1). However, very few changes have occurred since 1917, the oldest map postdating the installation of the Vernon Dam and raising of the Turners Falls Dam in the early 1900’s. While smaller tributaries have not formed bars in the river, they have in places created deltas or alluvial fans, creating low areas easily overtopped during floods on the Connecticut River (e.g., southern end of Pauchaug Meadow). The mouths of smaller tributaries are also associated with beaches of fine silt and clay that are built higher and wider than beach faces elsewhere (Figure 14).

All of the larger tributaries are graded to the current river level with no headcuts present (i.e., migrating steps or waterfalls). Occasionally, headcuts are seen along small gullies eroded into high banks along the river with the adjacent gully walls showing signs of active slope failure (Figure 15). While the gullies have formed as a result of surface runoff over the bank or groundwater springs in the banks, the headcuts and the resulting rejuvenated gully incision is likely the result of bank erosion along the Connecticut River causing a shortening and, therefore, steepening of the gully. Longer more gently sloping tributaries are not as affected by the bank erosion, so headcuts are not formed and active incision is not seen. Active incision of the Connecticut River is not considered to be occurring as headcuts and incision of tributaries would be more widespread.

The larger tributaries are incised below higher terrace levels, indicating that the tributaries have previously adjusted to earlier incision of the Connecticut River following the draining of Lake Hitchcock and erosion around the Lily Pond Barrier (see Section 5.1). Where the tributaries cross these higher surfaces, they are found in deep steep-walled ravines dissected below the terrace surface, the result of an earlier period of headcutting and incision that occurred thousands of years ago. The well forested stable steep side slopes of the ravines are evidence that the incision is no longer active, in contrast to the unstable slopes of the few smaller gullies that are actively incising (Figure 15).

6.0 BATHYMETRIC MAPPING AND HYDRAULIC MODELING

Bathymetric surveying of the Turners Falls Pool was conducted by Hydroterra Environmental Services, LLC of Dover, NH. The results of the bathymetric surveys are provided in Appendix 3 with the methodology used and data points collected further described in the hydraulic modeling report (Appendix 4). The bathymetric survey was primarily utilized for the hydraulic modeling, but visual inspection of the data reveals certain trends in the vicinity of constrictions. Channel bed elevations are lowest (i.e., water depths greatest) at and just downstream of constrictions such as Schell Bridge and the railroad bridge downstream (Figure 16), as the scour potential is greatest at these locations. Immediately upstream of the railroad bridge, bed elevations are significantly higher in the center of the channel compared to adjacent areas, suggesting that the mid-channel bar visible on the topographic map surveyed in 1887 (Appendix 1) still persists, although now submerged after the periodic raising of the Turners Falls Dam throughout the 20th century. Mid-channel bars, also submerged, continue to persist in backwater areas behind other constrictions where the bars are visible on earlier maps (Appendices 1, 3, and 4). The deepest point recorded during the bathymetric mapping was over 100 ft, located downstream of the Millers River at the end of the French King Gorge. The water is approximately 65 ft deep upstream of the Route 10 Bridge where both the bridge and a bedrock outcrop just upstream combine to create a significant constriction. Further analysis of the bathymetric data is warranted to better understand variations in channel bottom elevations both longitudinally and transverse to the river, but was beyond the scope of this study. Cross sections from the data were generated for the hydraulic modeling (Appendix 4) and could be useful in such an analysis.

Two-dimensional numerical hydraulic modeling of the Turners Falls Pool was conducted utilizing the bathymetric data. Topographic maps provided data for those areas above the water surface in order to incorporate the banks and portions of the adjacent floodplains in the model. The methods and results of the modeling were completed by Woodlot Alternatives, Inc. of Topsham, ME (Appendix 4). The hydraulic modeling predicts water surface elevations, flow direction, flow velocity, and shear velocity along the river for 4 different flow recurrence interval events: 1.05 yr, 2 yr, 10 yr, and 100 yr. The discharge for any given model run were held steady throughout the model run and did not consider short term changes that might result from operations of the Northfield Mountain Pumped Storage Project. The resolution of the model, in order to cover the entire length of the pool, was not sufficient to address how flow is disrupted by individual obstructions such as bridge piers.

The hydraulic modeling results were compared with the location of bank erosion mapped in 2004 (NEE, 2005). (The bank erosion mapping is further described in Section 7.2). In an unregulated river, erosion is most likely to occur where high flow velocities and shear stresses approach closest to the bank (Easterbrook, 1993). While erosion does occur where high flow velocities and shear stresses approach near the bank (Figure 17), significant amounts of erosion also occur where flow velocities near the bank are low (Figure 18 and Appendix 4). Bedrock outcrops are generally found if no erosion is present where high flow velocities approach the bank. Areas of intense erosion occur where eddies are well developed such as the Route 10 Bridge (Figure 18), as the eddy currents impinge directly on banks composed of floodplain sediments (Figure 12). The western bank in this area has already been stabilized using bioengineering techniques (Figure 18; see Section 8.3). Further comparisons of the hydraulic modeling and future erosion mapping might reveal relationships between the intensity of flow along the banks and the type and rate of erosion. Past erosion mapping has showed only the location, but not the type and rate, of erosion occurring in the Turners Falls Pool (see Section 7.0).

7.0 UNDERSTANDING THE CHARACTER OF EROSION

Erosion occurs naturally on all rivers. A river can maintain an equilibrium condition, where the dimensions of the river remain unchanged, while migrating across its floodplain as long as erosion of one bank is balanced by an equal amount of deposition on an opposite bank. Erosion also results as rivers adjust to natural changes in the watershed such as occurred along the Connecticut River long before European settlement after the last Ice Age (see Section 5.1). Erosion in the Turners Falls Pool is reported to have accelerated after the raising of the Turners Falls Dam and opening of the Northfield Mountain Pumped Storage Project in November 1972 (U.S. Army Corps, 1977), suggesting human use of the river may also be contributing to bank instability. Numerous studies have been conducted since 1977 to understand the causes of erosion and to identify the most appropriate approaches for bank stabilization (U.S. Army Corps, 1977, 1979, and 1991; NDT, 1991; Simons and Associates, Inc., 1998). This study is a continuation of those efforts, but an adequate discussion of the causes and management of erosion depends on an understanding of the types, distribution, rates, and temporal sequence of erosion in the Turners Falls Pool. Data on the character of erosion was drawn from previous studies and collected during multiple field visits in 2006 and 2007. Observations were made over a range of discharges between 42,000 ft^3/s and less than 10,000 ft^3/s.

7.1 Types of Erosion

Four of the erosion types described by Lawson (1985) (Table 1) are widely observed in the Turners Falls Pool: falls, topples, slides, and flows (Table 2). Lateral spreads may also occur, but are not widespread or distinct enough from flows or slides in the Turners Falls Pool to be considered separately here.

7.1a Falls

While falls might typically be considered to involve masses of sediment free falling through the air to the base of the bank, the removal of individual particles by water currents are also categorized as falls in this report as these particles are first dislodged then rolled or carried in suspension away from the bank. Erosion by tractive forces described by the U.S. Army Corps (1979) and NDT (1991) are equivalent to the water driven falls described here. Water currents strong enough to erode and transport sediment in the Turners Falls Pool are generated by at least five different mechanisms: waves, pool fluctuations, normal river flow (including floods), overland flow, and groundwater seeps. Currents acting at the base of the bank over prolonged, although not necessarily continuous, periods of time can create the notches and undercuts seen throughout the Turners Falls Pool (Figure 19). Banks can be undercut as much as 3.5 ft as observed in Barton Cove while the height remains less than 0.5 ft high (Figure 19a and Table 2). In other areas the height of the undercut can be more than 6.0 ft with roots from underlying trees exposed and left hanging down from the intact soil mass above (Figure 19b). The taller undercuts probably begin as narrow cuts that increase in height as material from the “ceiling” falls to the ground in a process more characteristic of falls. Taller undercuts are probably further enhanced by water currents acting at multiple levels along the bank due to varying river stages. Deeper narrower undercuts are more likely to persist in finer grained more competent soils while sandier less competent soils give rise to taller shallower undercuts.

A less common means of erosion through the movement of individual soil particles is by overland flow and groundwater seeps that result from the migration of headcuts away from the bank to form short, usually steep, gullies (Figure 20). Active gully incision on lower floodplain surfaces, although uncommon, is seen where no riparian buffer is present, allowing concentrated overland flow spilling over the bank to scour the fine-grained bank material (Figure 20a). Minor, sometimes severe, gullying has occurred shortly after the construction of bank stabilization projects if vegetation on the bank has been removed (see Section 8.0). Gullies are more common on high banks but the steep side slopes are generally well forested and stable (Figure 20b), although exceptions are infrequently observed (Figure 15). The largest gullies are up to 600 ft long and are found incised into higher terrace surfaces (Figure 20b). Gullies on high banks are most likely the result of groundwater springs emanating from the banks. While the springs are still present today, the gullies have stabilized as they have achieved an equilibrium slope consistent with the discharge from the spring. Consequently, larger springs typically lead to the formation of longer gully systems.

Although difficult to observe, removal of individual particles by river currents below the water surface is likely an important agent of erosion in the Turners Falls Pool. Material accumulating at the base of the slope can, thus, be removed by such currents, especially where the river's flow impinges directly on the bank.

7.1b Topples

Topples occur when vertical tension cracks (Figure 21a) forming at the top edge of the bank widen to the point where the top portion of cohesive masses of soil rotate forward about a pivot point near the base of the soil mass. Topples are typically enhanced when soil attached to a root mass of a severely undercut tree leans over and collapses over the bank (Figure 21b). Individual soil blocks involved in topples when no trees are incorporated are generally rectangular in shape with less than 2.0 ft of width between the tension crack and bank face and a length of up to 6.0 ft parallel to the bank. Once the support of the soil mass has been removed, new vertical tension cracks might form parallel to the bank and the process is able to repeat itself.

Topple blocks are typically more circular in shape if a tree is attached, reflecting the shape of the root system supporting the tree. Larger trees can produce topple blocks over 8.0 ft in diameter and over 3.0 ft thick. After the soil mass is removed, a semicircular embayment in the bank line is created (Table 2) that can be confused with smaller rotational slumps (see Section 7.1c). The pivoting motion away from the bank leaves trees leaning towards the river if they do not fall completely down. After a tree falls over the bank with its top end in the water, the root mass with soil attached leaves a large mound at the base of the bank such that a profile of the bank displays a ridge of soil and root mass between the river and the remainder of the bank (Table 2).

7.1c Slides

Both shallow planar slips (Figure 22a) and deep-seated rotational slumps (Figure 22b) occur in the Turners Falls Pool with transitional forms present. These types of mass movements give rise to what have been described as sloughing banks by others (e.g., U.S. Army Corps 1979 and 1991). Planar slips can be over 200 ft in length as tension cracks develop on the upper slope or at the top of banks, creating a failure surface along which the slide occurs. A series of slips along the bank can result in hundreds of feet of nearly continuously eroding bank. The exposed failure surface, or scarp, is steep and planar. Where the slip mass does not slide all the way down the slope, a narrow bench develops part way down the bank, the top surface of which sometimes has trees remaining in growth position (Figure 23 and Table 2). The presence of well-wooded continuous narrow benches on the slopes of many high banks suggests these banks once experienced active slipping that has since stabilized. High banks that exhibit these benches are now generally stable, but active scarps up to 10 ft high and over 200 ft long are present along the forested high bank just downstream of Dry Brook (Figure 24). Multiple scarps are seen stepping down from near the top of the bank with multiple slips exposed along a nearly 1.0 mile reach. The slips were first observed as vertical tension cracks near the top of the bank approximately 15 years ago and have since experienced sliding along the failure surfaces (Tim Storrow, personal communication, 2007). The active slipping in this location may represent an analogue for more extensive slides that were occurring in the past along these high banks. The active long continuous slipping as seen downstream of Dry Brook was not observed elsewhere on high banks along the river, but not all of the high banks in the Turners Falls Pool were carefully inspected by walking through the woods along the bank slope.

Where the slip block is completely removed, the bank is left bare as the failure surface, potentially more than 40 ft high on high banks, is completely exposed. In plan view, the failure surfaces can be arcuate in shape on high banks as the center of the slip plane extends higher up the bank slope (Figure 22a and Table 2). Slips beginning at the top of the bank, as on most lower banks, have top edges that are much straighter in plan view. In profile, slip surfaces are steep and planar with narrow benches formed, as discussed above, where the failed mass does not reach the base of the bank (Table 2).

Rotational slumps are typically less than 30 ft wide with head scarps that are arcuate in plan view and, therefore, are similar in shape to topples caused by the collapse of undermined trees (Figure 22b and Table 2). One distinguishing feature is that trees within a slump block will generally be leaning back towards the bank as the result of block rotation (Table 2). In profile the failure surface is more concave than planar slips. Benches formed partially down the slope represent the top of the failed slump block and will typically be wider and slope back towards the bank in contrast to planar slips (Table 2). Slumps are less prevalent in the Turners Falls Pool than slips as a result of the preponderance of less cohesive sandy soils that favor shallower failure surfaces.

7.1d Flows

Flows generally occur in association with other mass failures (Figure 25). Long flows are unable to develop given the relatively short length of even the highest bank slopes, although some might continue below the water surface where the bank drops off steeply. Flows form at the base of planar slips and rotational slumps if the moving mass becomes disaggregated and liquefied with sufficient soil moisture. Dry grain flows can occur for sometime after an event if the material remains loose, especially on the oversteepened base of the slide masses (Tables 2). The characteristics of a flow transition from the intact slide mass above to a slope of colluvial deposits below. While individual flows are narrow (< 30 ft wide), a series of adjacent flows lead to the development of a colluvial apron potentially several hundred feet wide (Figure 23).

Colluvial aprons are well formed at the base of some high eroding banks, but also occur on lower banks (Figure 23). The colluvial deposits are typically restricted to the lower half of the bank where gentler slopes develop as the angle of repose is established in the loose sediments. The grade of the colluvial slopes is slightly concave upward, but not as dramatically as the failure surfaces of rotational slumps (Table 2).

Soil creep, an extremely slow flow process (i.e., inches per year or less), is occurring on well forested higher banks as evidenced by tree trunks curved downslope near their base (Table 2). Creep is occurring on steep high banks protected by a lower bench at the base of the slope. High banks not buttressed by a bench drop straight to the river and are more likely to show signs of more rapid mass movements (e.g., topples, slides).

7.2 Distribution of Erosion

The distribution of erosion in the Turners Falls Pool can be analyzed through both space and time. Erosion maps of the Turners Falls Pool have been created several times in the past 30 years (Table 3). In some cases the erosion has been differentiated into categories of different severity, but not by the types of erosion present (Table 2). For the analysis conducted here the distribution of erosion sites is considered only relative to areas of stability rather than attempting to analyze differences in the location of more or less severe erosion. The reasons for this are further described below.

7.2a Spatial distribution of erosion

Although the location of erosion has been mapped several times in the last 30 years (see Section 7.2b), only the most recent mapping in 2004 (Appendix 5; NEE, 2005) is used in the analysis of spatial distributions described below. The 2004 mapping by and large accurately reflects conditions seen during visual inspections of the banks made in 2006 and 2007 as part of this project. New areas of erosion that have developed since 2004 were evident on the eastern downstream end of Doolittle Island. In many locations trees leaning far over the bank obscure erosion occurring behind the vegetation. Some erosion in these areas was not mapped, although such erosion was likely occurring in 2004, particularly along the high bank downstream of Dry Brook (Figure 24). Despite these discrepancies, the analysis of the spatial distributions of erosion throughout the pool is considered valid.

Twenty one percent of the banks in the Turners Falls Pool were rated as severely or moderately eroding in 2004 with an additional 20 percent of the banks protected with rock armor or other stabilization techniques (NEE, 2005). No information was collected on the types of bank erosion present. The distribution of this erosion relative to differences in bank composition, bank height, vegetative cover, and channel position (i.e., inside or outside of bend) was determined by an analysis of GIS data of these various parameters (Appendix 5). Bank composition and bank height along the riverbanks in the Turners Falls Pool has to date been mapped in only a limited fashion (NEE, 2005). The bank material at the river’s edge is delineated as bedrock, silt or sand, gravel or cobble, or cohesive soil (i.e., greater clay content) (Appendix 5). Bank armoring (i.e., riprap) is also mapped, but the soil type protected by the armor is not differentiated. Vegetative cover on the banks was rated as heavy (>80 percent), moderate (30-80 percent), and sparse (5-30 percent). Bank heights are classified as high (> 8 ft), medium (4-8 ft), and low (< 4 ft). The position of the riverbanks within meander bends was mapped by Simons and Associates, Inc. (1998) and their classification is adopted here for consistency.

Despite the potential limitations in the erosion data, an overlay of bank erosion sites and bank composition reveals that nearly 96 percent of the erosion is associated with silt or sand soils, which outcrop along 62 percent of the stream's length (Table 3). This results in an erosion ratio greater than 1.0 and indicates erosion is more likely to occur on banks of this composition compared to others (Table 3). Conversely, only 2 percent of the erosion occurs along gravel or cobble banks (7 percent of the total stream length), resulting in an erosion ratio of 0.31. Therefore, gravel or cobble banks, typically associated with older terraces, are less likely to be eroding than elsewhere along the river. Nearly all of the mapped erosion (94 percent) is congruent with the location of high banks (> 8ft), which occur along 59 percent of the total bank length. This indicates a strong tendency for erosion to be identified within the high bank category. However, multiple terrace and floodplain surfaces are associated with banks greater than 8 ft high, so no conclusion can be reached regarding the association of erosion with particular geomorphic surfaces. Field studies during this project suggest that less erosion occurs along the higher terrace surfaces where cobbles and bedrock are more likely to be encountered at the base of the banks, but more careful mapping of bank composition and bank heights is needed to corroborate this preliminary conclusion.

Heavy vegetative cover appears to reduce the likelihood of erosion (erosion ratio = 0.24), but the lack of vegetative cover was used as an indicator for the presence of erosion (NEE, 2005), so the data were collected in such a manner that erosion occurring in vegetated areas would not be mapped. Field observations during this study revealed unmapped erosion in well forested areas (Figure 24) and masked by thick vegetative cover. Although erosion is generally believed to be less likely on vegetated banks (Thornes, 1990), accurate comparisons between vegetative cover and vegetation in the Turners Falls Pool are not possible with the given data. A comparison of the areas mapped as eroding relative to positions within meander bends show that 14 percent of erosion occurs along the outside bends of meanders, 28 percent on the inside of meanders, and 56 percent along straight reaches (Table 3). Relative to the total stream length of these features, erosion is more likely to be encountered on the inside bends of meanders (erosion ratio = 1.7). Additionally, 21 percent of the erosion along the river is associated with erosion along both banks simultaneously, often including both the inside and outside bend of a meander (Appendix 5).

The distribution of erosion relative to its proximity to the project's tailrace was analyzed by determining the degree of erosion on both banks in 2000-foot segments of river moving away from the tailrace in both directions (Figure 26). Since much of the area around the tailrace and Barton Cove has been armored with rock to protect against erosion, the results for erosion alone are skewed, so a complimentary analysis was conducted combining both areas of erosion and riprap (Figure 26). Although variable, more erosion or riprap is present in the tailrace area compared to most other sections of the Turners Falls Pool. The variability in the amount of erosion between adjacent 2000-foot sections of river (i.e., the peaks and valleys in Figure 26) is likely controlled by the position of higher terrace surfaces, which appear to be associated with more stable banks. Even with the fluctuations, the amount of erosion generally decreases with increasing distance upstream of the tailrace. The trend would be more striking if areas along the high bank downstream of Dry Brook were incorporated as eroding, but the results of the 2004 mapping were left unaltered for this analysis. A noticeable exception to the trend of decreasing erosion away from the tailrace is the area around the Route 10 Bridge where the percentage of erosion is equivalent to the tailrace area. This suggests soil type may also exert an important control on the distribution of erosion, but its effect on this analysis cannot be determined without more careful mapping of bank composition and bank height along the river. Additionally, the eddies that form immediately upstream of the Route 10 Bridge, where bridge abutments and bedrock constrict the channel, may enhance erosion (see Section 6.0). Trends in the percentage of erosion moving downstream of the tailrace are more difficult to identify, because very little erosion occurs in the French King Gorge and for a short distance downstream where bedrock is exposed nearly continuously along the banks. The margins of Barton Cove are nearly completely armored with rock, further skewing an attempt to identify trends in the percentage of erosion downstream of the tailrace.

To provide a method for visually identifying and confirming the location of eroding banks in the future, a photographic log of the riverbanks was made with the location and orientation of each photograph recorded (Appendix 6). Rephotographing the riverbanks periodically from the same locations will provide a means of identifying new erosion sites or, conversely, areas that are stabilizing. The initial photographic log (Appendix 6) could also be compared with continuous digital image logs taken during 2001 and 2004 (NEE, 2005).

7.2b Temporal distribution of erosion

Changes in the location and amount of erosion through time were studied by comparing erosion maps of the Turners Falls Pool from 1978, 1990, 2001, and 2004 (Appendix 5). Mapping was conducted twice in 1990 by both NDT (1991) and the U.S. Army Corps (1991). Erosion mapping was completed in 1998 as well by Simons and Associates, Inc. (1998), but the comparable GIS shapefiles were not located in digital or paper files kept by the Northfield Mountain Pumped Storage Project or Simons and Associates, Inc. Although erosion mapping did not occur prior to the opening of the Northfield Mountain Pumped Storage Project, historical ground photographs (Figure 27), aerial photographs (see Section 3.0), and written reports (Jahns, 1947) demonstrate that erosion was occurring in the Turners Falls Pool prior to 1972. As described in Section 3.0, detailed photogrammetry may permit an accurate overlay of current aerial photographs with the 1961 aerial photographs. In conjunction with topographic mapping completed in 1970, the location of erosion prior to 1970 might be discernable. Currently, however, changes in the distribution of erosion can only be studied between 1978 and 2004.

The techniques used for mapping and the types of features mapped have varied through time as has the season in which the mapping occurred (Table 4). Although similar criteria are used between different mapping efforts, subdivisions within those criteria sometimes vary (e.g., different bank height categories used). Given the reliance on using the percentage of vegetative cover present as a means of identifying erosion sites, the amount of erosion identified will likely be more in the Spring (i.e., May-early June) or Fall (i.e., November) compared to the Summer (i.e., late June-September) when vegetative growth is at a maximum. Furthermore, no distinction is made in the mapping between annual herbaceous growth and perennial trees and shrubs even though the density and depth of roots exert a strong control on bank stability (Thornes, 1990). The U.S. Army Corps (1979 and 1991) used the same methods to identify erosion sites in September 1978 and June 1990, but the season of mapping was different. Similarly, the mapping in June 2001 and November 2004 were based on the same techniques but conducted at a different time of year. The greatest discrepancy in mapping methods used is between 1990 and 2001. The 1990 map by the U.S Army Corps (1991) was used in the analysis of temporal distributions described below rather than maps by NDT (1991) to maintain greater consistency in mapping techniques. The analysis of temporal distributions of erosion is largely restricted to the area downstream of the Massachusetts state line, because the U.S. Army Corps (1991) mapping did not extend further north. Mapping of bank stability also excluded data for islands in the river as this data was not collected every year.

South of the Massachusetts state line, the data reveal an 18 percent increase in the amount of mapped erosion between 1978 and 1990, a 6 percent decline between 1990 and 2001, and a 3 percent decline between 2001 and 2004 (Figure 28a and Appendix 7). If the portion of the Turners Falls Pool north of the state line is included, a 2 percent increase in the mapped erosion occurred between 2001 and 2004 (Appendix 5), indicating that the overall increase in mapped erosion is the result of the 13 percent increase north of the state line (Figure 28b). While new areas of mapped erosion did emerge south of the state line, a greater length of bank south of the state line switched from the eroding category in 2001 to stable in 2004. Rock armoring and bioengineering projects (see Section 8.0) account for one third of the change from eroding in 2001 to stable in 2004 (Appendix 5). The other areas either stabilized naturally or changed as an artifact of the mapping process (e.g., due to differences in the season mapping was completed). The levels of mapped erosion in 2004 (20 percent of the total length of riverbanks), although lower than the high in 1990 (29 percent of bank length), were still greater than 1978 (11 percent of bank length). Despite increases in the total amount of mapped erosion, 4 percent of the areas mapped as eroding in 1978 were mapped as stable in 1990, partly due to the placement of rock armor on the banks (Figure 28a and Appendix 7). The erosion mapping suggests that specific points on the bank can change from eroding to stable or vice versa regardless of whether the total amount of mapped erosion increases or decreases from year to year (Appendix 5 and Appendix 7). Consequently, using changes in the overall totals of mapped erosion to understand how the patterns of erosion in the Turners Falls Pool are evolving is not justified at this time. Where those changes are occurring must be taken into account before ascribing potential causal mechanisms for variations in the amount of mapped erosion from year to year.

Mapping in 1990 was conducted twice, providing an opportunity to determine how differences in mapping methods alter the results acquired (Table 4). The approach used by the U.S Army Corps (1979) was designed to be simple as the mapping in 1978 covered 141 miles from the Turners Falls Dam to the upper end of the Wilder Pond between Wells River, Vermont and Haverhill, New Hampshire. The severity of erosion is not noted by the U.S. Army Corps (1991), but NDT (1991) categorizes mapped erosion sites as low to moderate, moderate, moderate to severe, and severe. Comparisons of the two 1990 mapping efforts downstream of the Massachusetts state line reveal numerous discrepancies in the amount and location of erosion (Appendix 7). NDT (1991) maps show 32 percent of the riverbanks are eroding in all erosion categories compared to 29 percent in the U.S. Army Corps (1991) mapping for a total difference of 3 percent. If the low to moderate category is removed from NDT (1991) mapping, erosion is found along only 23 percent of the banks. While these differences do not seem significant, the actual location of the erosion varies significantly. Ten percent of the riverbank length categorized as eroding by the U.S. Army Corps (1991) is mapped as stable by NDT (1991), which means that more than one third of the erosion mapped by the U.S. Army Corps (1991) was not recognized as even low to moderate erosion by NDT (1991). Conversely, more than 40 percent of the areas mapped by NDT (1991) as eroding do not appear on the U.S. Army Corps (1991) map of erosion sites (i.e., 13 percent of the riverbank length compared to the total 32 percent of bank length mapped as eroding). Combined, the two maps would appear to show that 42 percent of the riverbank length is eroding, whereas, in actuality, only 19 percent of the total bank length is shown as eroding in both reports and is, therefore, probably a more reliable estimate for the amount of erosion that was occurring at the time (Appendix 7).

The discrepancies seen in the location of mapped erosion between the U.S. Army Corps (1991) and NDT (1991) reports are significant. The difference in percentage of total riverbank length mapped as eroding in the two 1990 efforts (3 percent), while seemingly small, is three times greater than the increase in the total mapped erosion observed between the 2001 and 2004 mapping (1 percent). Given that the actual location of the erosion varies even more significantly from year to year, reliable conclusions cannot be formulated about actual changes occurring on the ground. A significant amount of the apparent changes between map years may merely be an artifact of differences in mapping techniques, personnel, and season of mapping.

Future efforts for monitoring erosion in the Turners Falls Pool must utilize a consistent well documented technique for identifying erosion sites that is conducted in the early Spring or late Fall when bank exposures are least obscured by vegetation. Such a technique should be based on the types of erosion observed and stage of erosion present (see Section 7.4) not proxies for erosion or erosion susceptibility such as the amount of vegetation, percentage of exposed soil, bank height and slope, or soil type. The written and visual descriptions of erosion types presented in Tables 1 and 2 and described in

Section 7.1 could provide the basis for such an approach. Furthermore, advanced remote sensing techniques such as LIDAR (i.e., Light Detection and Ranging) might provide detailed topography of the riverbanks, which can be used to monitor bank retreat over time if the LIDAR mapping is periodically repeated. While this approach may eliminate problems previously experienced with the ground monitoring by giving precise measurements of the location and rate of bank erosion, field mapping should also continue in the future, because of the important information that could be provided regarding the types of bank erosion present.

7.3 Rates of Erosion

While methods may be available to accurately assessing bank erosion rates in the future along the entire Turners Falls Pool, determining past bank erosion rates is more difficult. Two sources of data are available for establishing bank erosion rates: a) repeated cross sections and b) continued bank recession adjacent to riprap of known age.

7.3a Repeated cross sections

Twelve monumented full river cross sections were established in 1990 at various points in the Turners Falls Pool and have been resurveyed almost every year since, with 2005 the latest year for which data was available (Appendix 8). Nine additional cross sections have been monitored for shorter durations. Multiple surveys were conducted on all of the cross sections during certain years. Drafted cross sections provided in CAD format were converted to data points in Excel in order to more carefully determine the amounts of change from year to year at each cross section (Table 5). Only 14 cross sections were used in the analysis with two cross sections around the Route 10 Bridge (Cross Sections 5d-e) excluded as three others that were analyzed are in the immediate vicinity and are of longer duration. Four cross sections in Barton Cove (Appendix 8) were not included in this study of bank erosion as rock armor protects the banks at these cross sections, although future analysis may reveal aggradation of the channel bed.

One cross section shows an apparent accretion of 6.0 ft during a four month period in 1995 at the top of a high bank (Cross Section 8b), indicating problems with data collection potentially related to the loss of control points due to bank erosion. The establishment of new control points appears not to have matched the previous survey data accurately. The initial analysis of the data described below was focused on identifying the total change and the greatest change in a single time period, so further study might reveal apparent accretion on other cross sections as well. As no record exists for which cross sections control points were lost, the data for all cross sections must be considered suspect, but an analysis was conducted anyway, assuming the problem is not extensive.[1]

[1] FirstLight has independently reviewed the 21 cross sections and checked the over 400 individual data sets and determined that a small percentage of them are suspect and should not be used for analysis. Therefore, it appears the problem is not extensive and it is unlikely the results of the analysis will change. FirstLight is working to resolve the matter.

The cross section locations were initially chosen to reflect a range of conditions in the Turners Falls Pool (NDT, 1991), so, not surprisingly, the total amount of change is highly variable with an average recession rate of less than 1.0 ft/yr for all cross sections (Table 5). The most recession at the top of the bank through the period of record is 23 ft at Cross Section 3 for an average annual recession rate of 1.5 ft/yr. This cross section is located at the Kendall Site downstream of the railroad bridge between Vermont and New Hampshire where pool fluctuations are minimal as the site is several miles upstream of the Northfield Mountain Pumped Storage Project tailrace. Historical aerial photographs indicate erosion at this site began prior to 1961 (see Section 3.0). The greatest one year change of 9.5 ft also occurred at Cross Section 3 between 1995 and 1996. The most significant one-year change also occurred between 1995 and 1996 at one other cross section (Cross Section 6b). The peak discharge at the Montague gauge during this time period was the second highest from 1990-2005 (Figure 4). The year with the highest peak discharge since 1990 at the Montague gauge was 1998, a year in which the greatest one-year change in bank position did not occur at any of the cross sections. A careful analysis of rainfall in the area preceding these flood events would be needed to determine if variations in soil moisture can explain the variations in response to these larger flood events. The most significant period of bank recession for several cross sections occurred in the early 1990's with average rates of recession ranging between 1.7 and 4.5 ft/yr during this short time period (Table 5). No high flood discharges were recorded during this period (Figure 4). At one cross section just upstream of the Narrows (Cross Section 9), the low left bank (looking downstream) has accreted 22 ft at an average rate of 1.5 ft/yr, perhaps reflecting a backwatering effect behind the Narrows and the Turners Falls Dam.

7.3b Bank recession adjacent to riprap

In many locations in the Turners Falls Pool, the riverbank has been protected from erosion with large rock (i.e., riprap). The bank protection is not continuous, so the bank has continued to recede adjacent to the static bank positions protected by riprap (Figure 29a). At one location in Barton Cove recession has occurred within the riprapped area where the rock protection has failed (Figure 29b). Assuming the receding banks were originally flush with the riprap when first installed, the average bank recession rate can be calculated if the date of riprap installment and total amount of bank recession is known. The location and age of various bank protection efforts were mapped and tabulated by NDT (1991). Surveys of the bank line from areas of riprap to adjacent sections without protection were conducted at either the base of the bank or top of the bank depending on access, visibility, and water levels (Appendix 9). Data were compiled for seven sites where the age of the bank protection was known and measurable bank recession was observed. Measurements of the total recession were not taken immediately adjacent to the terminus of the riprap as bank recession is sometimes greater just upstream or downstream of the riprap due to hydraulic effects caused by the bank armor itself (Appendix 9). Since other locations showed minimal bank recession around riprap, the results of these surveys are indicative of conditions at the survey locations only and cannot be generally applied to the Turners Falls Pool as a whole. However, the results do provide a general understanding of recession rates in the area.

The maximum amount of bank recession is 41 ft at Site 4 (picnic ground across from Munns Ferry Road) where the riprap was installed in 1977 for an average recession rate of 1.4 ft/yr (Table 6 and Appendix 9). Recession of only 9 ft is observed at Site 1 (Wickey Site). This is at a bioengineering project installed in 1998, so the average recession rate is still 0.8 ft/yr, higher than at other locations with more total recession (e.g., Site 6). The overall average recession rate for all seven sites is 0.9 ft/yr with a maximum rate of 1.7 ft/yr at Site 5 (L'etoile Farm) and a minimum of 0.4 ft/yr at Site 2 (Route 10 Bridge)(Table 6 and Appendix 9). Site 6 is the only location where the riprap appears to wrap around the bank (Appendix 9). This may indicate that additional riprap was added after the bank began to recede. If so, the results at Site 6 would represent a minimum rate of recession. The range of calculated recession rates is in general accordance with those measured from the full river cross sections and suggests, at some locations at least, the average recession rates measured have held steady since the 1970's. Bank recession at Site 3 (Munns Ferry Road) and Site 4 directly across the river reveals that erosion has apparently occurred on both banks simultaneously for an extended period of time. Comparisons of bank recession rates longitudinally (i.e., progressing downstream) were not made given the relatively few sites available for such an analysis.

7.4 Temporal Sequence of Erosion

The four erosion types observed in the Turners Falls Pool (see Section 7.1a) rarely occur in isolation, but rather work in concert to remove bank material from the upper and lower slope. Visual observations of bank conditions at various places in the Turners Falls Pool permits the development of an idealized model that describes a sequence of events occurring through time at a single point (Figure 30). The model described below should not be construed to occur everywhere in the exact steps detailed. Some types of erosion might be more dominant in some areas, enabling bank recession to progress without portions of this idealized sequence occurring. However, erosion likely proceeds as the model describes in most localities with only minor differences. The sequence of erosion is similar to that briefly described by Gatto (1982).

A stable bank can become destabilized by the individual removal of particles, leading to the creation of a notch or undercut at the base of the bank (Figure 30a). As the notch grows taller and steeper by advancing further into the bank or the undercut deeper and higher through falls, the driving gravitational forces will eventually exceed the bank's resisting forces. As a result, further erosion will occur higher on the bank slope by either topples or slides (Figure 30b). The mass of sediment moved downslope temporarily buttresses the bank from further failure. However, flows soon develop at the base of the slide (or topple) mass either during the initial failure or by notching and undercutting into the loose material (Figure 30c). These flows are generated by the additional gravitational stress acting on the steeper base of the slide mass, creating thin sheets of colluvial material that move further down the bank face. In many instances, flows might not occur but the slide (or topple) mass will be disassociated into individual particles and carried away from the bank by water currents. As all of the material that has accumulated at the base of the bank is carried away, a steep bare bank face remains

(Figure 30d). The near-vertical bare slope, a condition typically associated with an eroding bank, arises only at the end of a longer sequence of erosional processes (Figure 30a-c). Continued recession of the bank is dependent on the development of new notches or undercuts that can begin the process afresh.

The presence of large trees on the bank can slow the progress of the erosion sequence. Trees that topple down from the top of the bank can produce a ridge of roots and soil between the bank and water surface (Table 2). Over time water currents working on this ridge will remove the soil particles between the roots and leave a bare skeleton of roots that alone are less effective at protecting the bank. Eventually, the tree itself will float downstream during a highwater event when the tree has lost its anchoring to the bank; currents can then once again attack the base of the bank. However, this process can take several years as evidenced by numerous trees in the Turners Falls Pool that have decomposed while still attached to the base of the bank (Figure 31). During this extended process the tree branches, roots, and adhering soil will provide bank protection and delay progression of the erosion sequence.

Sediment delivered to the base of the bank by the erosion sequence described above can be transported away from the bank by a variety of water currents. River currents will tend to transport material downstream while currents generated by waves and pool fluctuations will tend to move material directly away from (i.e., transverse to) the bank. Currents acting transverse to the bank promote the development of beaches as the transported sediment accumulates in quieter water areas. The buildup of a beach over time will lead to bank stability, because the energy of the waves and seepage forces created by water fluctuations will be expended on the beach face rather than at the base of the bank. When water levels do not reach the base of the bank, the steep bare upper bank may continue to erode until the overall bank slope is reduced by recession of the upper bank and sediment accumulation at the base of the slope, creating a more stable bank profile capable of revegetating. The presence of a beach face is, therefore, an indication that the bank is approaching a stable equilibrium condition. However, if river currents still periodically remove sediment at the base of the bank or remove the accumulating beach sediment entirely, then notching and undercutting at the base of the bank can be rejuvenated and the bank will once again be prone to further erosion.

Understanding the sequence of erosion that occurs on the riverbanks in the Turners Falls Pool reveals that a steep bare bank might actually be closer to a stable condition than a heavily vegetated bank with mature trees with an undercut base. The presence of undercuts on an otherwise stable and well forested bank is an indication that future failure might be imminent with slides or topples eventually developing. Therefore, the presence of vegetation on the bank is not necessarily an indicator of bank stability, even though vegetation can exert an important stabilizing influence on the banks.

The amount of bank vegetation should not be used as a variable in identifying the presence or absence of bank erosion. Many of the moderately eroding areas mapped by NEE (2005) appear to be differentiated from severe erosion by the presence of herbaceous and shrub vegetation, although in some cases the vegetation is growing on active planar slips (Figure 32). The vegetation might remain undisturbed if the slip remains intact while sliding or can become established if the position of the slip mass remains unchanged for a season or two. However, continued erosion of these areas is likely and will eventually lead to a steep bare face, more likely to be categorized as severe erosion, as the sequence of erosion progresses. Consequently, without further distinction available, moderately eroding sites should be considered sites of severe erosion, although some localities mapped as moderately eroding might be beginning to stabilize.

8.0 BANK STABILIZATION EFFORTS

Rock armoring and other bank stabilization efforts have been undertaken in many locations throughout the Turners Falls Pool, particularly in Barton Cove and near the Northfield Mountain Pumped Storage Project tailrace (Figure 33). While some riprap was present before construction of the Northfield Mountain Pumped Storage Project, only those efforts conducted since that time are discussed here in terms of the approach used, success over time, and potential impacts both at the site and elsewhere in the Turners Falls Pool. Three principal stabilization techniques have been applied: a) helicopter logging with hydroseeding, b) rock armoring, and c) bioengineering.

8.1 Helicopter Logging With Hydroseeding

By 1975, after the raising of the Turners Falls Pool and opening of the Northfield Mountain Pumped Storage Project, a number of trees had toppled into the river as a result of erosion around their root masses (U.S. Army Corps, 1981, p. H-25-3). In response, other trees believed susceptible to falling into the river were logged and removed by helicopter (Figure 34a) along more than 20 miles of riverbank. The year of this logging was given as 1976 by NDT (1991) and 1977 by U.S. Army Corps (1981). The total length logged represents nearly one half of the total riverbank length in the Turners Falls Pool. Whether this entire logged length was actively eroding is unknown, but some areas of tree removal appear to show signs of active slip failures at the time of logging (Figure 34b). Nine miles of the logged area was hydroseeded in order to encourage the growth of grasses to stabilize the banks. Riprap was placed along 1.6 miles of bank where logging and hydroseeding proved immediately ineffective. Steep banks that were logged and hydroseeded showed signs of erosion by overbank drainage (i.e., overland flow), sloughing (i.e., sliding), and undercutting when inspected in 1980, but gentler slopes appeared more stable (U.S. Army Corps, 1981).

Evidence for the helicopter logging remains today in the form of stumps along the lower beach face at low water or completely submerged at higher flows (Figure 7c). The current position of the stumps with roots exposed indicates that the low bench on which many of the logged trees were growing (Figure 7b) has been removed by erosion. A beach that is lower, wider, and perhaps in places flatter than the preexisting bench has developed as the bank has receded. Given that trees falling into the river can slow the erosion process (Figure 31; see Section 7.4), the removal of trees by helicopter logging may have accelerated bank erosion. The original bank profile and low bench are still preserved in some locations where trees were not removed (Figure 7a).

8.2 Rock Armoring

Extensive rock armoring was placed on the riverbanks from 1969 through at least 1986 (NDT, 1991) with most of Barton Cove riprapped with stone generated during construction of the Northfield Mountain Pumped Storage Project. In most locations the riprap has held well with only negligible failure compared to the total length of bank protected with armor (Figure 29b). At the picnic area across from Munns Ferry erosion has broken through portions of the bank protection (Figure 35). More frequently, minor notching is seen above the top of the riprap due to currents acting on the bank at higher flows, leading to some erosion of the bank without significant topple or slide failures (Figure 36). Excess scour and more rapid bank recession have occurred at the ends of riprapped sections (Appendix 9) where outflanking and minor damage to the riprap is seen (Figure 29a). However, in most areas the riprap has successfully held the bank position and vegetation has grown between the rocks and on the bank above (Figure 36).

In addition to rock armoring, a 2000-foot section of the east bank downstream of the Route 10 Bridge in Northfield was protected using three experimental techniques installed by the U.S. Army Corps in 1980: concrete block mattress, auto tire wall, and auto tire mattress (Figure 37). A rock berm was placed at the toe of the auto tire wall and mattress below the normal low water line (U.S. Army Corps, 1981). Portions of the auto tire wall and mattress are now buried in silt and trees are growing out of the center of the tires (Figure 37b-c). Except for the occasional missing concrete block (Figure 37a), the experimental project has performed well with the upper bank since stabilized with vegetation.

The long-term integrity of riprap and other hard armoring techniques in the Turners Falls Pool has been aided by the reduction in peak flows since the early 1960's (Figure 4). More severe flooding, as has not been experienced for several decades, may place shear stresses on the bank armoring that cross a stability threshold and precipitate failures not seen to date. Much of the bank armor installed since the raising of the Turners Falls Dam in the early 1970's has been placed higher on the bank, potentially leaving portions of the bank toe unprotected. Large flows might scour the bank toe, undermine the riprap, and cause its collapse. Additional problems might also arise along armored reaches in the future when trees growing through the riprap mature, die, and topple into the river, ripping rock from the protective armor and exposing the fine-grained bank material underneath to scour.

8.3 Bioengineering

With the development of the Connecticut River Riverbank Management Master Plan (NDT, 1991), bioengineering was adapted as the preferred approach to bank stabilization in the Turners Falls Pool. Eleven bioengineering projects have been completed since 1996 (Figure 33) with several more scheduled for construction in the next few years. Although minor differences exist in the bioengineering techniques used between sites, the same general approach has been used to construct each project (FRCOG, 1999 and no date). The base of the bank is armored with rock set on geotextile fabric with coconut fiber coir logs placed above the rock and anchored to the bank with Duckbill anchors (Figure 38). The bank above, typically steep and near vertical before project construction, is shaped to reduce the bank slope. The slope is then covered with erosion control fabric before trees, shrubs, and herbaceous vegetation is planted with a row of fast-rooting willow cuttings placed just above the coir logs.

While the projects remain largely intact, a number of maintenance issues have arisen that have necessitated repairs. At several sites, the coir logs have been removed by water currents (Figure 39a) or pushed out by mass movements higher on the bank (Figure 39b). Once removed, notching of the bank just above the rock armor has ensued and can lead to planar slip failures on the upper slope (Figure 39c). Since existing bank vegetation is removed during the bank shaping, the projects are particularly prone to gullying by overland flow generated during heavy rains before new vegetation is rooted on the slope (Figure 39d). This gullying, along with strong river currents at the base of the bank, can unravel the erosion control fabric and rip up metal staples used to anchor the fabric to the bank. Numerous rusted metal staples are found lying loose on the ground at several sites.

The purpose of the bank shaping is to mimic a bank slope that will arise naturally over time when the bank toe is stabilized and erosion of the upper slope continues until reaching its angle of repose. With bank shaping, the top of the bank is set back several feet with vegetation, often including mature trees, and top soil removed. Given that the underlying floodplain sand may have fewer nutrients than the topsoil, the revegetation of the bank might be slowed. This may partially explain why the oldest bioengineering projects are still dominated by herbaceous rather than woody vegetation (Figure 40). If only the bank toe is armored and the remainder of the bank left untouched during future bioengineering efforts, erosion of the upper bank will only continue until the angle of repose is reached. Therefore, by leaving the upper bank untouched, mature trees can remain at the top of the bank with their eventual collapse over the bank potentially slowing the erosion of the upper slope. During the several years, or even decades, that would be required for the bank to reach the position created by bank shaping, the remaining trees could provide shade, add nutrients to the soil, and preserve travel corridors for animals along the riparian buffer that are potentially disrupted with bank shaping.

Variations to the general bioengineering design approach have been attempted with mixed success. Bank shaping was not conducted at the Flagg Site and rock armor was placed at the lower end of the beach face exposed at low water rather than at the toe of the bank. Several logs with root wads attached were placed on the beach face behind the rock armor and marsh vegetation planted in the same area. While many of the logs washed away, the bank appears to be revegetating on its own, although this might be compromising bank swallow nesting areas that were present on the unvegetated bank face (Figure 41a). A similar low beach or bench was constructed at the Durkee Point Site

(Figure 41b). The presence of the bench appears to be limiting notching at the base of the banks as seen at other sites, but creation of the bench required moving the top edge of the bank back even further than would have occurred with normal bank shaping. The creation of a narrow bench at the Country Road Site was intended to act as a floodplain bench to reduce shear stress on the upper bank during highwater events (Figure 41c). However, the bench was constructed with a slight slope back towards the bank, producing a low swale that trapped and concentrated runoff from the upper bank and further exacerbated gullying on the newly shaped bank face. Another variation to the typical construction technique at the Country Road Site was the placement of coir logs below the water surface away from the bank face in order to trap sediment and build up a beach face to buttress the bank (Figure 41d). The success of this effort is unknown at this point, because the project was installed less than one year ago.

Although the bioengineering efforts and earlier rock armoring have largely arrested erosion in the treated areas, continued widespread placement of rock at the toe of the banks, already totaling 20 percent of the river length (or 13 percent excluding Barton Cove), could lead to systemic erosion problems elsewhere in the Turners Falls Pool. Rivers achieve an equilibrium condition when erosion and deposition are equally distributed along the length of the channel. Consequently, preventing erosion in one area through bank armoring can accelerate erosion of the channel bed or adjacent banks. Bed scour can undermine riprap, resulting in its collapse and continued erosion of the banks (Figure 42). Such impacts may be harder to identify and are less likely to occur in larger rivers with heavily regulated flows, such as the Turners Fall Pool, where flood flow velocities and shear stresses are markedly less than under natural conditions. To date, excess scour is limited to areas immediately adjacent to armored banks (Appendix 9). However, if the extent of bank armoring continues to increase, a threshold level might be reached, at which point erosion to unprotected areas might be more widespread and cause additional bed scour that might compromise the bank protection efforts themselves.

9.0 DISCUSSION

The results of the fluvial geomorphology study described above provide the information necessary to evaluate the causes of erosion, identify alternative approaches to bank stabilization, and make recommendations for future work related to erosion problems in the Turners Falls Pool.

9.1 Causes of Erosion

A discussion of the causes of erosion is essential before identifying appropriate measures for stabilizing the riverbanks, because successful stabilization efforts must address the causal forces behind the erosion and be consistent with processes active in the Turners Falls Pool. Erosion occurs when the driving forces exceed the resisting forces of the bank material, so any condition that reduces the resisting force or increases the driving force might initiate erosion when the bank is at the threshold of stability. Several natural conditions can lead to bank erosion including strong flows at the base of the bank that increase gravitational forces by oversteepening the bank face and increased soil moisture from rainfall events that reduce bank resistance through higher pore pressures.

The character of sediments in the Turners Falls Pool produces banks with low resisting forces. Fine-grained and unconsolidated floodplain sediments are particularly prone to erosion. Interbeds of permeable sand and less permeable silt (Figure 12) further reduce the resisting force of floodplain sediments by creating planar surfaces of groundwater movement along which mass movements (i.e., slides) can occur. The incision of the Connecticut River into older lake and floodplain sediments (Figure 5; see Section 5.1) naturally enhances the driving forces exerted on the riverbanks. With the limited areal extent of active floodplain in the Turners Fall Pool, flood flows are largely confined to the channel and the stream power produced by the floods is expended on the channel bed and banks rather than spread out over a broad floodplain. Not surprisingly, the large floods of 1936 and 1938 were able to create large fresh areas of erosion (Jahns, 1947). Natural conditions in the Turners Falls Pool, by both reducing the resisting forces and increasing the driving forces, create a situation where the riverbanks are near the threshold of erosion. Minor natural or anthropogenic changes in the Turners Falls Pool, therefore, have the potential to cause significant changes in the extent and severity of bank erosion.

The U.S. Army Corps (1979 and 1991) posited several potential causes for bank erosion in the Turners Falls Pool including natural flood flows, seepage forces, pool fluctuations, boat waves, and stage variations. Additionally, Reid (1990) suggested that bank erosion resulted from channel incision caused by sediment-starved flow downstream of Vernon Dam. These potential causes plus a combination of factors are analyzed below and their likelihood of being effective agents of erosion considered in terms of whether the expected conditions to arise from those causes is consistent with observations made in the Turners Falls Pool (Table 7). While ice is certainly an important erosive agent (Gatto, 1984), it is considered here as increasing the effectiveness of erosion caused by other factors, so is not considered as a separate cause below. Agriculture and other land use practices along the river increase overland flow to the river that can cause gullying of the riverbanks (Figure 20a), but this is not extensively observed in the Turners Falls Pool nor discussed separately here. Land use practices along the river might more significantly increase the susceptibility of the banks to erosion by other processes where trees along the river are removed, leading to a loss of roots that help hold together otherwise noncohesive sediments. Extensive land clearance along the river, following European settlement, has likely increased the susceptibility of the banks to erosion. Various land use practices, including direct modifications to the river channel, have been shown to cause extensive erosion elsewhere on the Connecticut River (Field, 2004). Although direct modifications to the stream channel are only localized in the Turners Falls Pool, bridge crossings are present at some of the most severely eroding sites (e.g., Route 10 Bridge, abandoned railroad bridge at the Kendall Site).

9.1a Channel incision downstream of Vernon Dam

Channel incision is a common response downstream of dams, since the trapping of sediment behind the dam creates sediment starved waters, or "hungry water", downstream (Williams and Wolman, 1984; Kondolf, 1997; Brandt, 2000). Bank erosion typically results from incision as the gravitational driving forces increase with the increasing bank heights (Schumm, 2005). While the presence of erosion on both banks simultaneously (Table 3) is consistent with the idea that channel incision resulting from "hungry water" is occurring downstream of Vernon Dam, several other conditions suggest incision is not a major cause of erosion throughout the Turners Falls Pool. Erosion would be expected to be most severe closer to the dam, although, in actuality, the erosion is concentrated in an area between the Northfield Mountain tailrace and the Route 10 Bridge (Figure 26). As a channel bed is lowered through channel incision, tributaries entering the river also incise in order to remain graded with the main river. Such active incision is seen only on minor gullies in the Turners Falls Pool and is not as widespread as would accompany ongoing incision of the Connecticut River. Larger tributaries are incised into older lake and floodplain terraces, but the fact that these are graded to the current river level and have wide beaches formed at their mouths (Figure 14) indicate the incision was in response to much earlier bed level changes on the Connecticut River (see Section 5.1). If incision was occurring in response to the opening of Vernon Dam around 1909, banks along the river would be increasing in height. However, this is not consistent with the presence of a low bench that existed in many areas prior to the opening of the Northfield Mountain Pumped Storage Project (Figure 7a-c). Insufficient time has transpired for such a low bench to have formed and mature trees to grow on its surface if a period of incision since the opening of Vernon Dam preceded its formation.

Although "hungry water" downstream of Vernon Dam does not adequately explain the patterns of erosion throughout the Turners Falls Pool, the possibility that Vernon Dam is causing some erosion, particularly immediately downstream of the dam, cannot be discounted. Severe areas of erosion are present on the banks and sand bars immediately downstream of the dam (Figure 23). Sediment generated from this erosion and that delivered by the Ashuelot River, the tributary with the largest watershed area entering the Turners Falls Pool, might offset that stored behind Vernon Dam and, as a result, limit the downstream extent of erosion possibly attributable to the effects of Vernon Dam.

9.1b Natural flood flows

Shear stresses exerted on the bank by high velocity flood flows can result in erosion and these forces created by flooding were rated by the U.S Army Corps (1979 and 1991) as the most effective agents of erosion in the Turners Falls Pool. Jahns (1947) documented new areas of erosion related to the effects of the 1936 and 1938 floods. While care must be taken in interpreting the results of the erosion mapping (see Section 7.2b), the timing of the two largest floods since the opening of the Northfield Mountain Pumped Storage Project (1984 and 1987) falls within the period when the percentage of mapped erosion increased most significantly (i.e., 1978-1990; see Appendix 7). The large percentage increase is probably greater than can be explained by variations in mapping technique or season of mapping, suggesting that the large floods played some role in the increase of mapped erosion from 1978-1990. The congruence of some erosion sites with areas where hydraulic modeling predict high shear stress and flow velocities near the riverbanks is further evidence that natural flood flows play a causal role in the distribution of erosion in the Turners Falls Pool (Figure 17; Appendix 4 and 5). Natural and artificial constrictions along the river channel can enhance eddying and create strong river currents that impinge directly on the riverbanks. Hydraulic modeling shows eddies developing upstream of the Route 10 Bridge and just downstream of a bedrock outcrop on the western bank that constricts the channel (Figure 18); this is an area of rapid bank recession (Table 6 and Appendix 8). The western bank is already stabilized with bioengineering (i.e., Crooker Road Site) and the eastern bank proposed for future stabilization (NEE, 2005).

The reported increase in erosion since the opening of the Northfield Mountain Pumped Storage Project (U.S. Army Corps, 1977), at a time when flood flow velocities have decreased due to the raising of the Turners Falls Dam and implementation of flood control projects upstream, suggests other factors may also be causing erosion in the Turners Falls Pool. Other observations inconsistent with natural flood flows being the sole cause of erosion is the higher incidence of erosion on the inside bends of meanders compared to outside bends (Table 3). Typically, flow velocities and erosion on unregulated rivers are greatest on the outside bends of meanders (U.S. Army Corps, 1979; Easterbrook, 1993). Furthermore, a comparison of mapped erosion sites (Appendix 5) with the hydraulic modeling (Appendix 4) reveal extensive areas of erosion where shear stresses and flood flow velocities are relatively low (Figure 18).

9.1c Seepage forces

As mentioned in Section 2.0, bank erosion is sometimes greatest during the recession of high flows (Twidale, 1964; Thorne, 1982; Rinaldi et al., 2004) as water seeps out of the saturated banks. Seepage also occurs from groundwater movements, perhaps enhanced locally in some areas from the irrigation of adjacent farmlands. Springs and seeps were observed repeatedly along banks exposed below higher terraces in contrast to NDT (1991) that reported encountering very few seeps. Along high banks, planar slides often have seeps present at their base. Seeps can promote erosion by lubricating failure surfaces, and therefore, decrease the resisting force of the bank material. Seeps can also remove individual grains of silt or sand as they flow out of the bank, potentially creating undercuts at the base of the banks, and, as a consequence, increase the driving forces causing erosion. Gullies that have eroded back from high banks are likely the result of runoff from springs with a small trickle of water seen along the bottom of the gully (Figure 20b). The gully length is proportional to the groundwater discharge from the springs with gully walls becoming stabilized once the slope of the gully floor is able to convey the spring water without further incision (i.e., shorter steeper gully equals less discharge).

The preponderance of bank erosion of floodplain sediments, where natural groundwater seeps are uncommon, indicate natural seepage forces are not a primary cause of erosion in the Turners Falls Pool. However, human management of river levels has potentially created additional seepage forces that have enhanced erosion where natural groundwater seeps are absent.

9.1d Pool fluctuations

Daily pool fluctuations of 2.5 ft or more occur throughout much of the year in the Turners Falls Pool with weekly pool fluctuations of up to 6.0 ft possible (NDT, 1991; U.S. Army Corps, 1991). Given the potential similarities between pool fluctuations in the Turner Falls Pool with fluctuating water levels in tidal environments, the literature related to the development of tidal creeks was briefly reviewed, but no research was identified that directly addressed the question of bank erosion. Bank heights on tidal channels tend to be low and bank composition very clay rich in contrast to the high sandy banks that predominate in the Turners Falls Pool. Consequently, the literature related to bank erosion in reservoirs is considered more germane to the discussion of erosion in the Turners Falls Pool and is described further below.

Slope failures following rapid and repetitive drawdowns of water level are frequently observed in reservoirs (Lawson, 1985). Rapid drops in water level adjacent to banks comprised of low permeable sediments, or low permeable interbeds when stratified, creates instabilities, because pore pressures in the bank sediment do not rapidly equilibrate with the changing water level, generating seepage forces moving out of the bank (Lawson, 1985). Floodplain sediments throughout the Turners Falls Pool are comprised of interbedded fine sands and less permeable silt layers (Figure 12) with some of the higher terrace sediments containing even less permeable clay (Figure 13b). Terrace sediments comprised of coarser gravels (Figure 13a) may be less susceptible to seepage forces created by pool fluctuations, but may be sites of natural groundwater flow. Seepage is observed across beach faces after drawdowns in the Turners Falls Pool, although such seepage is difficult to distinguish from groundwater flow when emanating from the base of the riverbanks. The creation of small drainage channels across the beach faces demonstrates the ability of the minor flows generated by seepage to transport individual fine-grained particles away from the bank (Figure 43).

Although the removal of individual particles by seepage could enhance the development of undercuts at the base of the bank, erosion at specific sites is difficult to attribute directly to pool fluctuations. Undercuts are only the initial stage of the erosion sequence (Figure 30) with more noticeable slides and topples resulting later in the sequence, potentially at times not corresponding with the most significant pool fluctuations. Several aspects of the erosion in the Turners Falls Pool, however, are consistent with the possibility that erosion is enhanced by pool fluctuations (Table 7). Erosion density generally decreases away from the Northfield Mountain Pumped Storage Project tailrace as the magnitude of pool fluctuations decrease (Figure 26). However, definitively ascribing the erosion to pool fluctuations will require normalizing erosion density data to specific terrace and floodplain surfaces. The presence of erosion on both banks of the river simultaneously (Table 3) is consistent with erosion by pool fluctuations, as drawdowns of the water surface would impact both margins of the river equally. Similarly, pool fluctuations would affect both the inside and outside bends of meanders and, therefore, provides a plausible explanation for a pattern of erosion inconsistent with natural flood flows.

While pool fluctuations may influence the distribution of erosion in portions of the Turners Falls Pool, the presence of erosion where pool fluctuations are minimal, such as near Vernon Dam (Figure 23), indicate other factors are also controlling the location of erosion in the Turners Falls Pool. Flow releases at the Vernon Dam used for power generation mimic pool fluctuations near the dam as the river stage rapidly varies with the episodic discharges.

9.1e Boat waves

Wind generated waves are probably of limited importance in bank erosion in the Turners Falls Pool given the limited fetch along the narrow water course, but boat waves may impact bank stability. Boat and wind waves have been considered an important cause of erosion on the Connecticut River (U.S. Army Corps, 1979) and other localities (Gatto, 1982; Reid, 1984; Lawson, 1985). Boat waves are most effective when breaking at the base of the bank and are capable of moving material away from the bank, creating notches and undercuts that initiate the erosion sequence (Figure 30). Boat waves have the potential to exert greater stress directly on the banks compared to pool fluctuations. However, seepage forces similar to those formed by pool fluctuations would not result from wave processes alone. Similar to pool fluctuations, boat waves can impact both banks simultaneously regardless of bend position and, therefore, are consistent with erosion occurring on both bank simultaneously and on the inside bends of meanders. Although distinguishing the relative importance of boat waves and pool fluctuations in creating these distributions would be difficult without further study, the U.S. Army Corps (1979) rated pool fluctuations as the more effective process on the Connecticut River between Turners Falls, MA and Wells River, VT.

9.1f Stage variations

The Turners Falls Dam was raised 5.9 ft in 1970 as part of the construction of the Northfield Mountain Pumped Storage Project. This rise in the dam elevation resulted in a rise in river stage extending to Vernon Dam, although the magnitude of the rise diminished upstream with a predicted rise of only 2.2 ft at the Northfield Mountain Pumped Storage Project tailrace and 0.8 ft at Schell Bridge during a 1.05-yr recurrence interval flow (46, 545 ft^3/s) (Woodlot Alternatives, written communication, 2007). As water levels in a reservoir rise, the groundwater table in the bank sediments gradually rises and adjusts to the water level in the impoundment (Lawson, 1985, p. 39). As the once relatively dry sediment becomes saturated, the pore pressures increase and the resisting forces of the bank material decrease. Together with the added weight of the water in the bank sediment (causing an increase in the driving forces), the reduced strength of the bank material creates an unstable situation that leads to bank failure

(Brunsden and Kesel, 1973; Lawson, 1985). Bank strength can be further reduced if vegetation is killed when inundated by the rising water. Thus, erosion can be further enhanced by the loss of soil strengthening root systems and the ability of roots and vegetative cover to dissipate the energy of water currents impinging on the banks. Helicopter logging in the Turners Falls Pool (see Section 8.1) after trees were inundated by the rise in river level probably accelerated bank erosion as vegetative cover and root strength were probably lost quicker than if the trees were left untouched, especially those above the new pool level.

Flood control projects upstream have redistributed runoff from wetter to dryer months, resulting in greater flows in the lower range of discharge (U.S. Army Corps, 1991). Consequently, river stage remains higher during low flow periods compared to natural conditions and the river will be flowing directly against the bank for longer periods of time than if the river stage was lower and flowing across a beach face. Flood control upstream, therefore, may be increasing the length of time river currents, boat waves and pool fluctuations can act on the base of the bank to effect erosion.

9.1g Combination of factors

Attempting to discern which of the causal mechanisms for erosion is the most important would fail to recognize that these various processes operate collectively to effect change on the riverbanks through time and space. The rise in river stage accompanying the raising of the Turners Falls Dam in 1970 along with helicopter logging of the inundated areas destabilized riverbanks that were already naturally prone to erosion. Erosion might have quickly ensued as river currents, boat waves, and pool fluctuations began to act on the destabilized portion of the riverbank that until then was largely beyond the reach of the currents and forces generated by these processes. Reports of accelerated erosion shortly after the opening of the Northfield Mountain Pumped Storage Project (U.S. Army Corps, 1977) are consistent with this idealized sequence of events. Assuming the erosion data accurately reflect changes on the ground, a large increase in mapped erosion from 1979 to 1990 suggests that the spatial extent of erosion continued to expand for several years. The sequence of erosion, from bank undercutting to the removal of sediment by flows, that create steep bare banks from previously well forested rounded banks may take several years to complete in some areas (Figure 30). Such expansion of eroded areas might have been aided by large floods in 1984 and 1987.

More widespread stabilization of the banks appears to have begun after 1990 as the total amount of mapped erosion declined through 2001, although some areas had already stabilized between 1979 and 1990 (Appendix 7). Not only do boat waves and pool fluctuations play a role in the creation of undercuts that begin the erosion sequence, but they also create beaches that extend out from the base of the banks as sediment is transported towards the center of the river. In a reservoir or impoundment without strong river or longshore currents, fluctuating water levels and waves can attack the base of the banks until a beach is built out wide enough such that water level fluctuations and wave runup are contained within the beach face (Lawson, 1985). Before reaching that equilibrium width, boat waves will be most effective in terms of bank erosion when pool levels are high and impinging directly on the base of the bank. At low pool levels, waves will break on the beach face (Figure 44) and are unable to undercut the bank or remove sediment delivered to the base of the bank by erosion of the upper slope. As the beach face continues to widen and currents are less able to transport material away from the base of the bank, the entire bank begins to stabilize through a process described by Brunsden and Kesel (1973) (see Section 2.0). Consequently, if boat waves and pool fluctuations were the only causes of erosion in the Turners Falls Pool, erosion would continue for a certain length of time following the raising of the Turners Falls Dam before the banks, protected by the growing beach faces, would stabilize.

However, the Turners Falls Pool is not a true reservoir and changes in river stage accompanying flood flows are greater than the height of the gently sloping beaches. If the beaches are entirely inundated by high water, boat waves, pool fluctuations, and river currents are able to attack the banks despite the presence of the beaches that serve as a protective barrier at lower flows. Therefore, bank erosion can continue regardless of beach width. Beaches in the Turners Falls Pool extend out for a short distance before dropping off steeply to a deeper portion of the channel. At high flows, the greatest shear stresses are generally exerted in the deepest parts of the channel. Strong currents could scour the base of the beach and, potentially, remove the entire beach. The presence of higher beach deposits preserved at the base of the bank, particularly in protected areas, suggest prior beaches have been removed by scour (Figure 8b). Where beaches are removed, river currents, boat waves, and pool fluctuations can once again attack the base of the bank, create notches or undercuts, and rejuvenate the erosion sequence (Figure 30). As a result of natural flood flows, boat waves and pool fluctuations remain effective agents of change; without natural flow variations, the banks would have a greater opportunity to stabilize as the beach faces reached an equilibrium width.

9.2 Alternative Approaches to Bank Stabilization

Recognizing that the creation and preservation of beaches is a prerequisite for bank stability, a better understanding of beach formation is needed, so future bioengineering efforts in the Turners Falls Pool can incorporate techniques that promote their development. Beaches appear most pronounced near the confluences of small tributaries where sediment supply to build the beaches is high (Figure 14). Remnant beach deposits are found in crevices in the bank and at the mouths of small gullies where they are protected from strong currents (Figure 45). Some deposition also occurs downstream of logs lying directly on the beach face (Figure 46a), further indicating the tendency for sediment to be deposited and preserved where sediment supply is high or currents are reduced. Large concentrations of wood accumulate on the beaches in some areas, but are often too loosely arranged or lying directly on beach face to effectively trap sediment (Figure 46b). The wood found on beaches is largely derived directly from trees falling off of the adjacent banks. While some trees on the beaches remain in place for a considerable length of time (Figure 31), most of the wood is probably transient in nature with few logs recruited from upstream to replace those that are floated downstream.

Bioengineering projects that place dense accumulations of wood on beach faces could potentially capture additional wood floating from upstream, accumulate sediment by baffling currents, and protect the bank from further erosion. Large logs at the base of the bank could prevent erosion, even if high water inundates the beach face, as the energy of boat waves and river currents would be expended on the wood and not the bank sediments. A mass of logs at the base of the bank, if anchored properly, could also buttress the bank from mass failures higher on the slope generated by seepage forces, perhaps performing better than coir logs and rock armor that can be pushed out by the upslope forces (Figure 39b). If the beach is undercut by strong currents deeper in the channel, the wood placements could be constructed so they could collapse to the base of the scoured bank and prevent notching and undercutting of the bank itself. The mass of wood remaining at the base of the bank would also enhance redeposition of fine sediment and the rapid reformation of the beach.

Wood placed further out on the beach could help to trap sediment and build up the beach face. Sediment accumulations on previous stabilization efforts (Figure 37c) and remnants of former beaches (Figure 8b) indicate that considerable fine sediment is in transport during high flows in the Turners Falls Pool. Different arrangements of wood could be experimented with to determine the best log orientations and densities to most efficiently trap sediment. Logs arranged as deflectors that are angled slightly upstream could turn river currents away from the bank when high flows pass over the logs, potentially providing more immediate bank protection before sediment accumulates between the logs.

If sediment is successfully trapped by the wood placements, the raised beach faces could eventually become vegetated, which, in turn, could trap more sediment and build up a low bench that buttresses the bank from future erosion. Such a bench would be similar to the low bench that existed along much of the Turners Falls Pool prior to the raising of the Turners Falls Dam in 1970 (Figure 7). The bench created by the woody debris placements would form at a slightly higher elevation than the former bench in accordance with the higher river stage resulting from the raising of the dam. The long term evolution of the channel and banks may eventually lead to the creation of such a bench, but the woody debris placements would speed up its development. As the original wood placed on the bank decomposes, the development of the vegetated bench would sustain the bank protection beyond the residence time of the originally placed logs.

Dense concentrations of large woody debris would be necessary for the proposed efforts to be successful. Loosely arranged accumulations do not effectively trap sediment (Figure 46b). Even without sediment accumulation, wood placed at the base of the bank could improve bank stability by buttressing the upper bank and baffling currents operating at the bank toe. Wood would need to be anchored in place as the low concentrations of wood moving from upstream mean that the natural recruitment of wood will be limited. Dense accumulations of wood along the banks of the river may have been typical 400 years ago, prior to European settlement, when the entire watershed was heavily wooded and flood flows were loaded with wood floating downstream. The woody debris placements would, therefore, mimic natural processes and be consistent with the restoration of native ecosystems.

The costs and technical feasibility of such efforts are unknown. Engineering designs with recommended approaches for anchoring logs and cost estimates should be made for selected areas to ascertain the effectiveness of woody debris placements compared to existing bioengineering projects. Experimental efforts may reveal that long-term maintenance costs are much reduced as woody debris placements are potentially a sustainable approach to bank protection. Woody debris placements are consistent with ongoing river processes and address the causes of erosion rather than previous efforts that rely on rock armor to protect against the causal forces of erosion. An over reliance on rock armor leaves such bank stabilization efforts prone to large floods and may eventually create additional instabilities that threaten the stabilization efforts themselves (Figure 42). Initial woody debris placements should be undertaken where beaches are currently well developed before attempts are made in more challenging areas where currents are too strong to sustain beach development without the presence of woody debris.

9.3 Recommendations for Future Work

Several areas of future work outlined below could, to the extent necessary and practicable, provide for: a) an improved understanding of the causes of erosion; b) more accurate monitoring of erosion; and c) more successful bank stabilization efforts. Recommendations of future work in one area (e.g., monitoring of erosion) may also be valuable for other areas of research (e.g., understanding the causes of erosion).

9.3a Understanding the causes of erosion

The following recommendations are suggested to better understand and document the causes of erosion in the Turners Falls Pool:

1. A more thorough comparison should be made with other river reaches, including erosion and bank composition mapping, to see if the amount of erosion and characteristics of the erosion (e.g., bank undercutting) are similar where the magnitude of pool fluctuations are less. Potential areas of study are downstream of the Turners Falls Dam and the Wilder Pool near Hanover, NH where erosion rates are also reportedly high (U.S. Army Corps, 1979).

2. U.S. Army Corps (1979) contains maps of erosion sites between Turners Falls, MA and Wells River, VT. A more thorough analysis of this map data should be made to determine if erosion is most severe in the Turners Falls Pool or whether the percentage of eroding banks is consistent with other areas. Remapping of the entire area covered by the U.S. Army Corps (1979) could be used to determine if the noted trends are still valid today.

3. A careful inspection of high banks throughout the Turners Falls Pool is necessary to confirm whether the long continuous slips observed downstream of Dry Brook (Figure 24) are present elsewhere or whether this condition is restricted to an area near the Northfield Mountain Pumped Storage Project tailrace.

4. A more thorough understanding of beach formation and the processes that lead to bank stabilization is needed. A remote sensing technique should be used to map the location and width of beaches in the Turners Falls Pool. LIDAR could be an effective method of doing this if the flight occurs during low pool levels. Otherwise, another technique may be needed that can reliably map features at a shallow depth beneath the water surface. A study of higher remnant beach sediments should also be undertaken (e.g., sedimentological study, dating of sediments) to understand how beach sediments accumulate and how quickly such beaches can form.

5. Further analyze the mapped erosion data (Appendices 5 and 7) to see how the location of new areas of erosion and areas that have stabilized correspond to the width of beaches, the position of floodplain or terrace surfaces, and distance from the tailrace.

6. Further analyze the hydraulic modeling results (Appendix 4) for the entire length of the Turners Falls Pool to determine to what degree mapped erosion sites (Appendix 5) correspond to areas where high shear stresses and flow velocities impinge directly on the bank. The initial analysis performed here shows the value of such an analysis (see Section 6.0), but did not encompass the entire pool.

7. Determine if narrow beaches correspond to the areas of highest shear stress as predicted by the hydraulic model (Appendix 4). This analysis is dependent on the mapping of beach widths suggested in Recommendation 4 above.

8. A more thorough study of boat waves is merited to better document how many boats use the Turners Falls Pool, how fast they travel, the type and size of waves they produce, and their impact on shoreline erosion.

9.3b Monitoring of erosion

1. Monitor changes in the position of the top of the bank by periodically completing surveys. These efforts will more accurately identify areas of erosion than current erosion mapping techniques and avoid artifacts in the erosion monitoring process introduced by different people completing the mapping, using different techniques, and mapping in different seasons. Repeated surveys will have the added benefit of providing accurate measures of the rates of erosion over a large area.

2. The mapping of erosion sites as conducted during previous full river reconnaissance efforts (NEE, 2005) should be modified to include the types of erosion present (e.g., undercut banks, topples, slides, slumps, flows), other features indicative of erosion (e.g., tension cracks, exposed roots, leaning trees), and the stage of erosion present (Figure 30). LIDAR surveys, if practicable, might be a more reliable means for determining where

bank recession is occurring, so the full river reconnaissance should be used to identify the types of erosion occurring and areas where future bank recession is possible (e.g., undercut banks). Table 2 could provide the basis for the development of a standardized checklist for identifying and recording the types of erosion present. Monitoring using this approach will reveal how the types of erosion are changing over time at a particular locality and whether an area is progressing through the sequence of erosion (e.g., undercutting leading to slides). Some aspects of the previous approaches should also be maintained to enable comparisons with erosion data from earlier efforts (Appendix 5).

3. The mapped erosion data (Appendix 5) should be compared with the location and dates of rock armoring and bioengineering projects (Table 6 and Appendix 9) to ascertain to what degree the emergence of stable banks in different map years is the result of human stabilization efforts.

4. The position of various terrace and floodplain surfaces with respect to the river channel is unclear. The mapping of riverbank features to date has classified banks by height but the height categories used (e.g., 4-8 ft) can encompass multiple surfaces of different age and composition. A one time mapping effort of the terrace and floodplain surfaces adjacent to the river is required to better understand the height and composition of the riverbanks at various points along the river. The mapping should be accompanied with a stratigraphic study to better understand how the composition of the banks varies laterally and vertically and to determine the age of sediments where datable material is found. This information will be critical for understanding and anticipating the types and rates of erosion present at various points, for determining the susceptibility of the banks to erosion, and for selecting the most appropriate techniques for bank stabilization.

5. Erosion mapping should occur immediately after the next large event exceeding 120,000 ft^3/s in order to more accurately determine the effect of large floods on the pattern, severity, and extent of erosion.

6. Monitor selected erosion sites monthly with photographs and partial cross sections for a period of 2 to 5 years to determine the season of greatest erosion and relate erosion to spring thaw, times of greatest pool fluctuations, and other variables.

7. Erosion mapping completed by Simons and Associates, Inc. (1998) was not located during this project but a renewed effort should be undertaken to find this data, so changes between 1990 and 2001 can be better understood.

8. Recommendations by Simons and Associates, Inc. (1998) for future monitoring should be reviewed and those still considered relevant should be implemented.

9. An attempt should be made to overlay the 1961 aerial photographs with a current flight and to create a topographic map from the 1961 flight. The feasibility of this effort has been confirmed by Eastern Topographics, Inc. This effort will identify the previous extent of the low bench (Figure 7a-b) and identify areas of the most significant bank recession in the past 45 years.

10. Portions of the 1971 ground surveys by Ainsworth and Associates, Inc. of Greenfield, MA should be resurveyed to identify changes in bank position since the opening of the Northfield Mountain Pumped Storage Project.

11. The photo log of the banks completed for this study (Appendix 6) should be repeated with each full river reconnaissance and comparisons made with previous years to identify changes visible along the banks. Digital image logs taken in 2001 and 2004 (NEE, 2005) should also be incorporated into this analysis where the bank position can be confirmed relative to the photo log.

12. A more thorough analysis of the monitored full river cross sections (Appendix 8) is warranted, but was not completed here, because of the effort required to reduce the data into a format capable of being analyzed. Such an analysis will reveal the role of flood discharges in bank recession and more clearly identify those cross sections where data are suspect because of lost control points. Additionally, further analysis could reveal changes in the bank profile that might indicate the bank is beginning to stabilize. Any such changes could then be compared to the presence or absence of a beach in the vicinity. Finally, additional cross sections could be monitored in the future to establish a large enough data set to see if the rate of erosion varies with distance from the tailrace. This might not be needed if LIDAR surveys of the Turners Falls Pool are periodically completed.

13. Future surveys of the full river cross sections should extend to the top of the bank and include a portion of the floodplain. The start and end points of each survey should remain the same each year to ease comparisons of the data.

14. Wood movements on beaches and off the banks should be monitored by tagging logs on the beach and trees susceptible to falling off the bank. This effort will provide a better understanding of how long logs persist in one location and determine if logs drifting down from upstream are recruited on beaches further downstream.

15. Reid (1990) shows portions of a bathymetric survey done in 1913, but the original data were not found during archival searches during this project. An additional effort should be made to locate these maps as they will provide an opportunity for comparisons with the results of bathymetric mapping completed for this study (Appendix 3) and reveal how the river bottom topography has changed through time

16. Monitoring of the bioengineering projects should include areas upstream and downstream of the site utilizing the same monitoring techniques currently used at the sites. Cross sections should be spaced closely enough to determine where continued recession adjacent to the site is accelerated by localized hydraulic effects created by rock armor placed at the toe of the bank. More detailed photo logs than acquired for the entire Turners Falls Pool (Appendix 6) should be completed at and adjacent to bioengineering sites to determine if bank undercutting and notching above the rock toe is leading to more extensive planar slip failures further up the slope. The detailed photo logs will also be

able to document if the bioengineering projects are increasing bank instabilities along adjacent sections of the riverbank.

9.3c Bank stabilization efforts

1. Current bioengineering strategies should be modified to eliminate bank shaping wherever possible, so the existing riparian vegetation is not removed.

2. The creation of narrow floodplain benches during the construction of bioengineering projects should be avoided given the potential to concentrate overland flow and increase gullying (Figure 39d). The reduction of flow velocities hoped for by creating the narrow benches are likely negligible given the width of the river in the Turners Falls Pool, so they provide little benefit.

3. Biodegradable or photodegradable stakes should be used instead of steel staples to hold erosion control fabric in place.

4. The use of coconut fiber coir logs should be limited to higher on the bank and the rock toe should extend higher to limit the notching and undercutting that has occurred above the rock armor on earlier projects.

5. Debris jams should be placed at the downstream and upstream ends of bioengineering projects using stone toes to ease the transition to unprotected areas and limit the increased scour occurring at the ends of armored reaches.

6. Future bioengineering efforts should experiment with woody debris installments to buttress the bank, trap fine sediment, and create a low bench similar to what existed prior to the raising of the Turners Falls Dam (Figure 7b). Multiple designs should be tested and monitored (e.g., deflectors, crib walls, engineered debris jams) to identify the most effective techniques for implementation elsewhere.

7. The hydraulic modeling results should be used to identify low velocity areas near the banks where sediment might be most likely to accumulate to aid in the formation of beaches.

8. The results of the bathymetric and hydraulic modeling studies should also be consulted during the planning phases of bioengineering projects to identify potential issues that might be encountered related to deep water and high velocity flows near the bank. Work in high velocity areas should be avoided or stronger toe protection used.

10.0 CONCLUSIONS

Erosion is a naturally occurring phenomenon that is present even on rivers in equilibrium where erosion is offset by an equal amount of deposition in adjacent areas. Erosion also results from channel adjustments to changing watershed conditions that might arise from natural variations in climate, vegetation, and sediment inputs.

Consequently, distinguishing between natural and anthropogenic causes of erosion is difficult, especially when such factors are operating simultaneously.

Bank erosion in the Turners Falls Pool has most recently been mapped along 21 percent of the riverbanks (NEE, 2005). Erosion in most areas progresses through a predictable sequence of steps involving four different types of erosion. Undercutting and notching of the banks results in topples and slides as the stability of the upper bank is compromised. The slide and topple blocks are disassociated into flows at different rates in different locations and deliver loose sediment to the base of the bank. This loose sediment can be carried away from the bank by water currents generated by flood flows, boat waves, pool fluctuations, groundwater seeps, and overland flow. Where sediment is moved directly offshore, beaches can form that may promote the stabilization of the bank if the accumulated sediment is not removed or beach face frequently inundated by flood flows.

Bank erosion is the result of a complex interaction of multiple factors operating through time and space. Most of the riverbank sediments in the Turners Falls Pool are naturally susceptible to erosion given their noncohesiveness and fine-grained texture. Natural stability is further compromised by the results of past channel incision through older terrace and floodplain surfaces, leading to greater flow energy expended on the banks rather than across broad floodplains. The raising of the Turners Falls Dam in 1970 and subsequent helicopter logging of the inundated trees resulted in bank instabilities that potentially led to the increased erosion noted by the U.S. Army Corps (1977). An increase in pool fluctuations with the opening of the Northfield Mountain Pumped Storage Project in 1972 and an increase in boat waves accompanying greater recreational use of the Turners Falls Pool at approximately the same time could have sustained the increased erosion through 1990 when the percentage of mapped erosion reached a high of 32 percent of the bank length south of the state line. Since that time, the bases of the banks have been protected in some localities by the development of beaches and may explain why the amount of mapped erosion since 1990 has decreased south of the state line (Appendix 7). Erosion, however, is likely to persist as flood flows rework beach deposits and inundate the beach face, enabling boat waves, pool fluctuations, and natural river currents to remain active at the base of the banks. Relatively minor changes in the total amounts of erosion between 2001 and 2004, despite more significant changes in the actual location of such erosion, might suggest that a steady-state level of erosion is being approached for the current hydraulic conditions. However, a greater time difference between mapping efforts and more reliable mapping techniques are needed to confirm this supposition.

Bank stabilization, to date, has relied on armoring the toe of the bank with rock riprap, including the base of most bioengineering projects. Currently 20 percent of the bank length in the Turners Falls Pool is protected with riprap (or 13 percent excluding the heavily armored Barton Cove). Rather than addressing the causes of erosion, these projects are designed to resist the forces of erosion. To date, most projects have faced relatively minor maintenance issues, but flood control projects in the upper watershed, to date, have helped prevent significant flood flows from testing the stability of the rock armor. If the total amount of rock armor continues to increase, river erosion could eventually be aggravated on the channel bed or elsewhere on the banks as potential areas for river response are reduced and concentrated in the remaining unprotected areas.

Given the complexity of issues surrounding erosion in the Turners Falls Pool the results of this study are considered preliminary. Several questions regarding the reliability of the earlier erosion mapping remain. The minor increases in erosion between 2001 and 2004 are not verifiable given the potential errors introduced by the mapping process. Consequently, basing policy decisions for managing the erosion on the results of this mapping are not warranted. Many areas of additional study are needed to better understand the distribution, rates, and causes of erosion and to identify the most appropriate measures for bank stabilization. The highest priority recommendations for future work are: 1) study patterns of erosion in other reaches of the Connecticut River for comparative purposes; 2) map the distribution of terrace and floodplain surfaces relative to the position of the river channel throughout the Turners Falls Pool; 3) initiate LIDAR surveys of the channel banks in order to more accurately monitor erosion in the future; 4) develop a systematic and explicit method for mapping erosion in order to eliminate artifacts in the mapping process, so the full value of the collected data is realized; 5) map the distribution of beaches throughout the Turners Falls Pool and study the processes that lead to their formation and preservation; and 6) experiment with the addition of large woody debris on the beach faces as a means of bank stabilization. The results of these additional efforts will provide an improved understanding of erosion problems and lead to the development of more effective bank stabilization efforts that will address the causes of erosion and, therefore, potentially improve conditions throughout the Turners Falls Pool rather than lead to additional instabilities that could negatively impact the bank stabilization efforts themselves.

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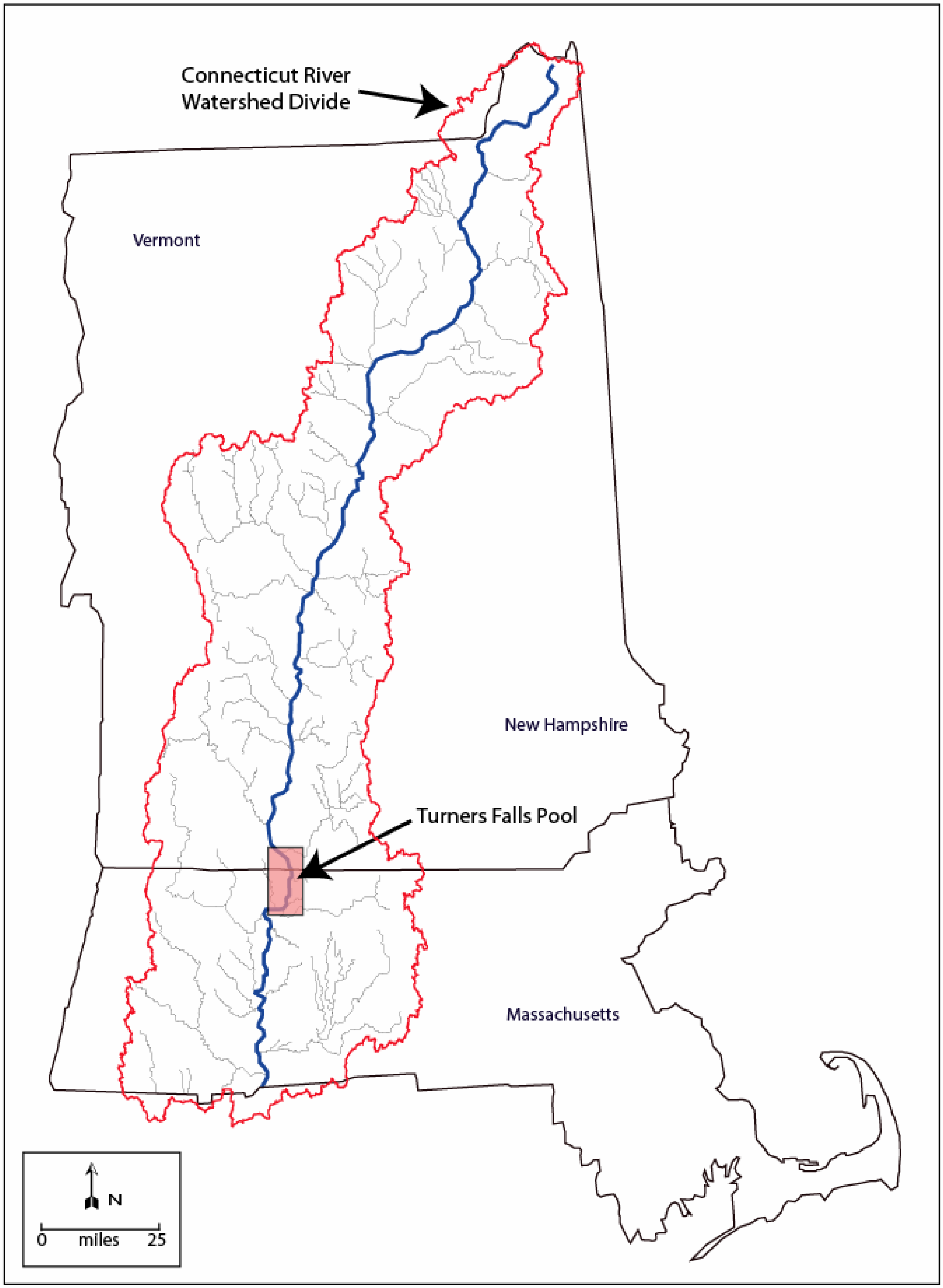

Figure 1: Map of the Connecticut River Watershed highlighting the position of the Turners Falls Pool. The portion of the watershed in Connecticut is not shown.

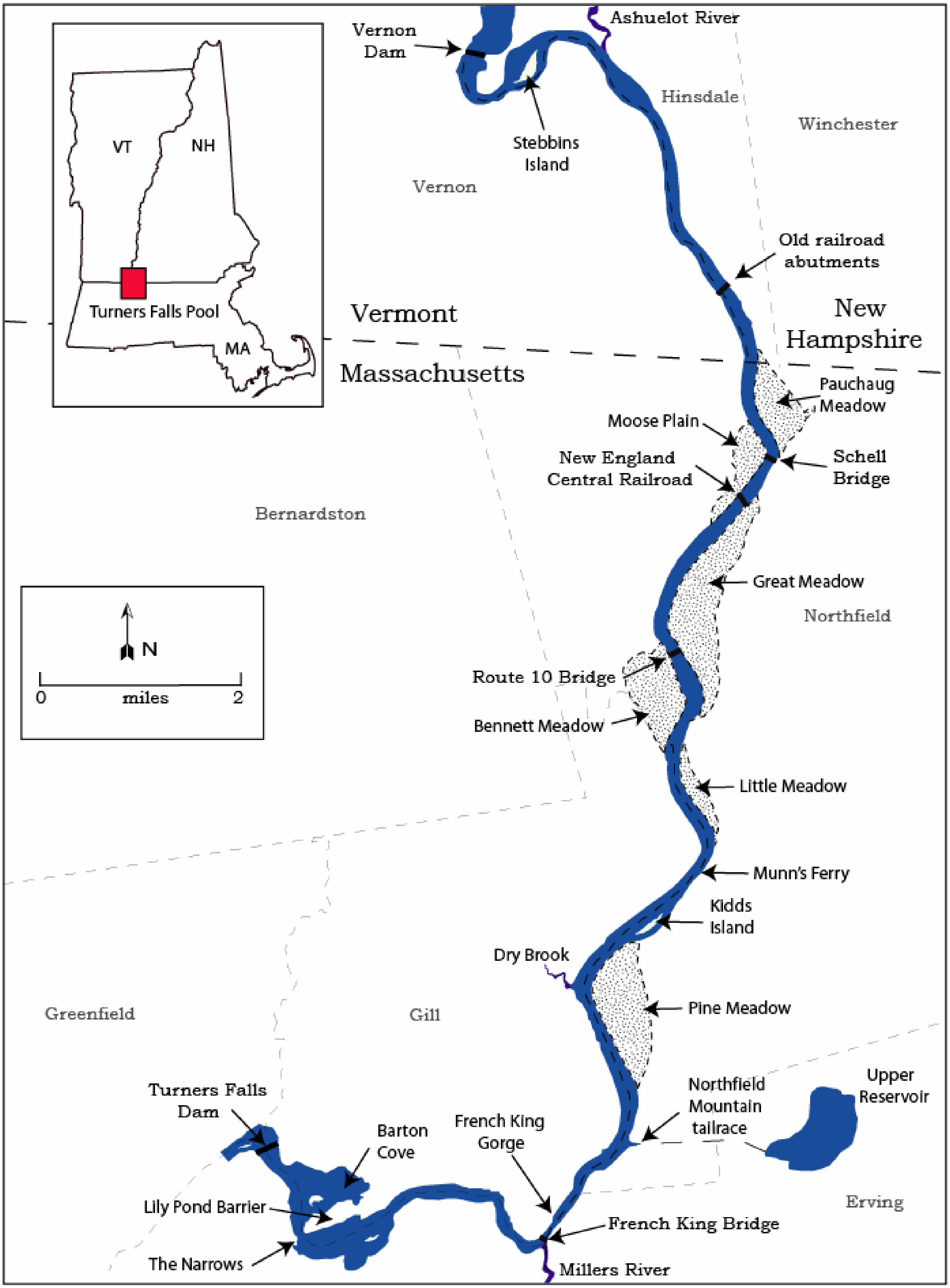

Figure 2: Map of the Turners Falls Pool showing town boundaries and major natural and human landmarks mentioned in text. The gray shaded areas are low meadows along the river that largely represent the extent of the active floodplain.

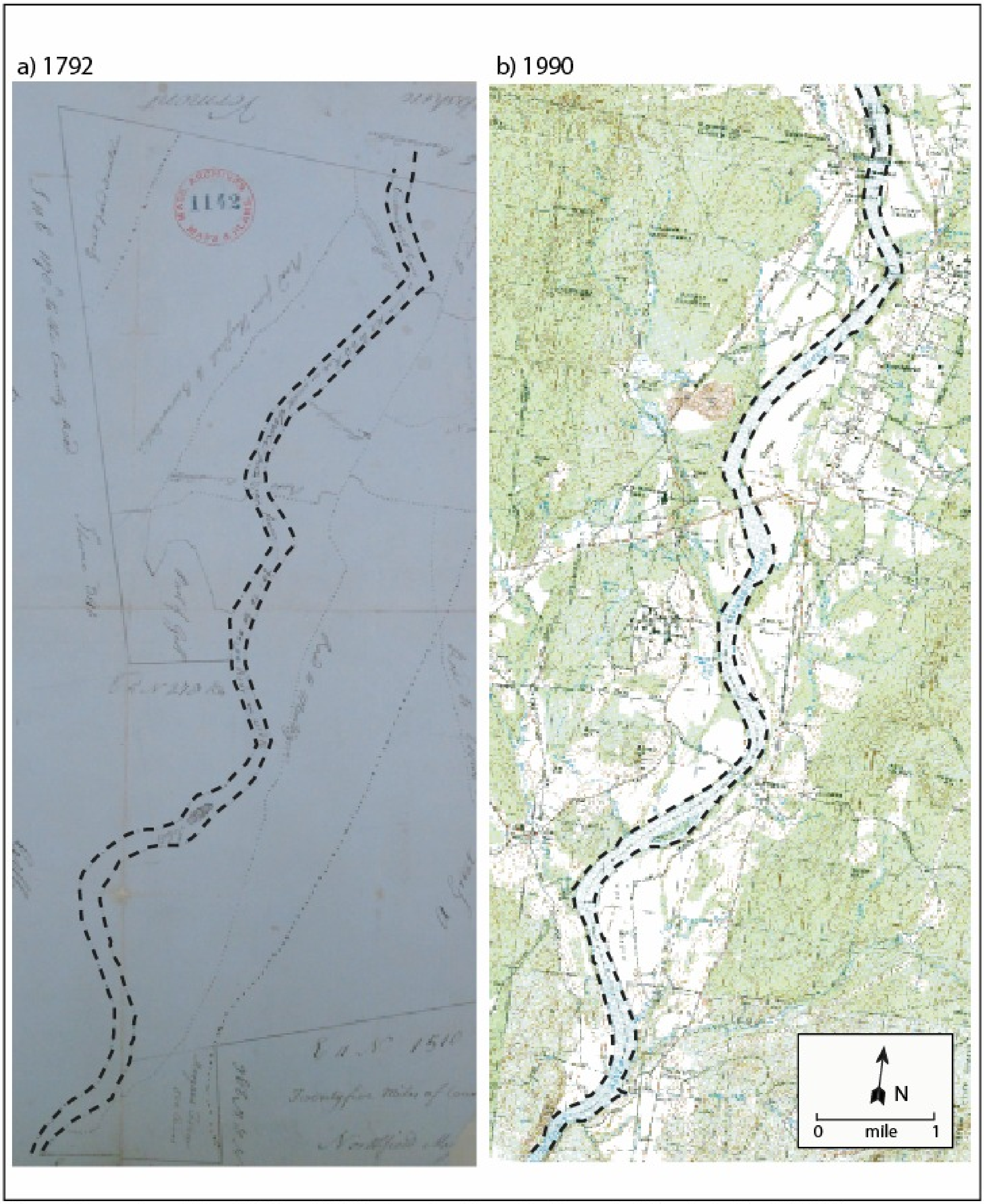

Figure 3: Comparisons of the a) 1792 and b) 1990 channel position of the Connecticut River in the Northfield, MA area.

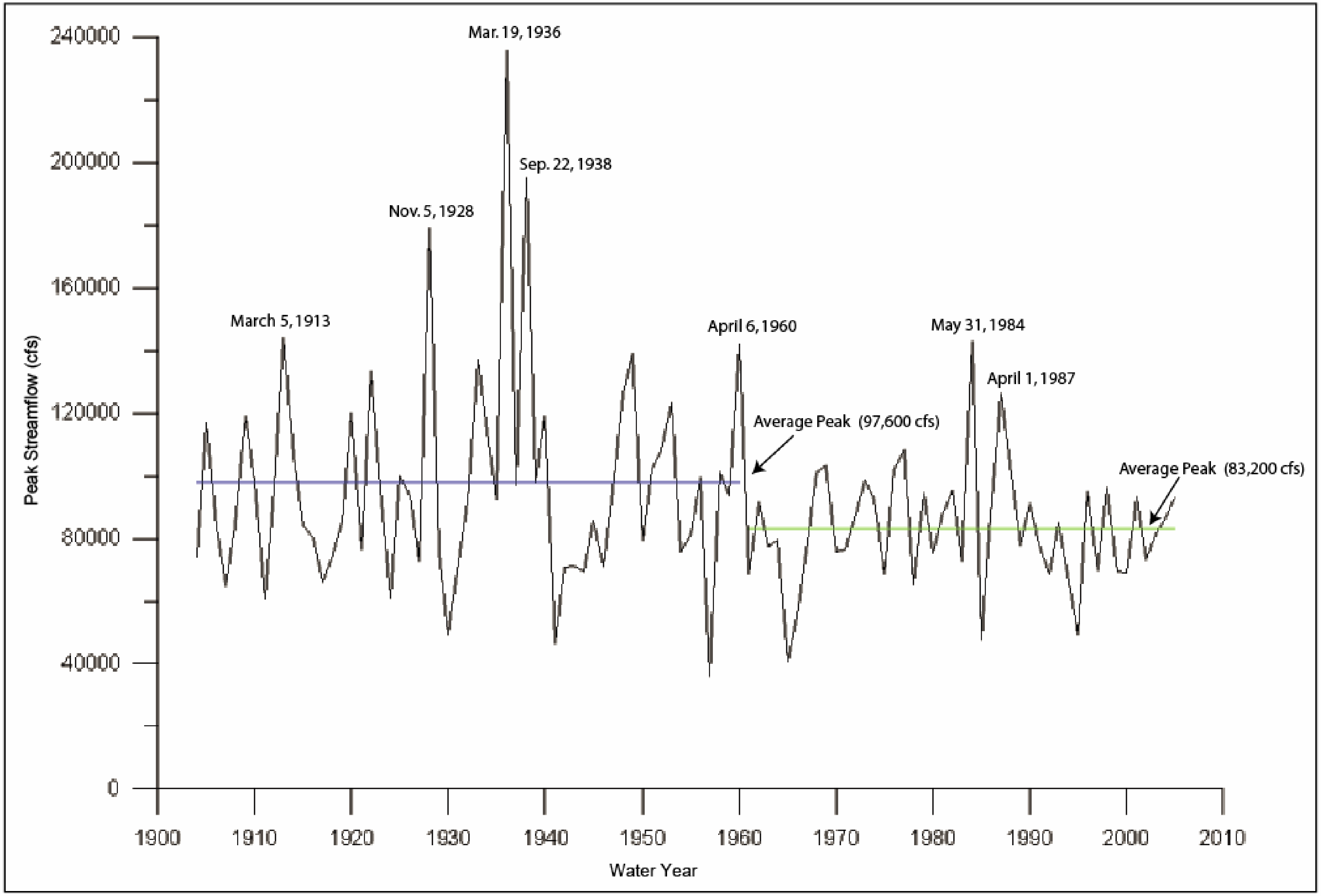

Figure 4: Annual peak discharges on the Connecticut River at Montague, MA showing the decline in average peak discharges after completion of flood control projects in the upper watershed in 1961.

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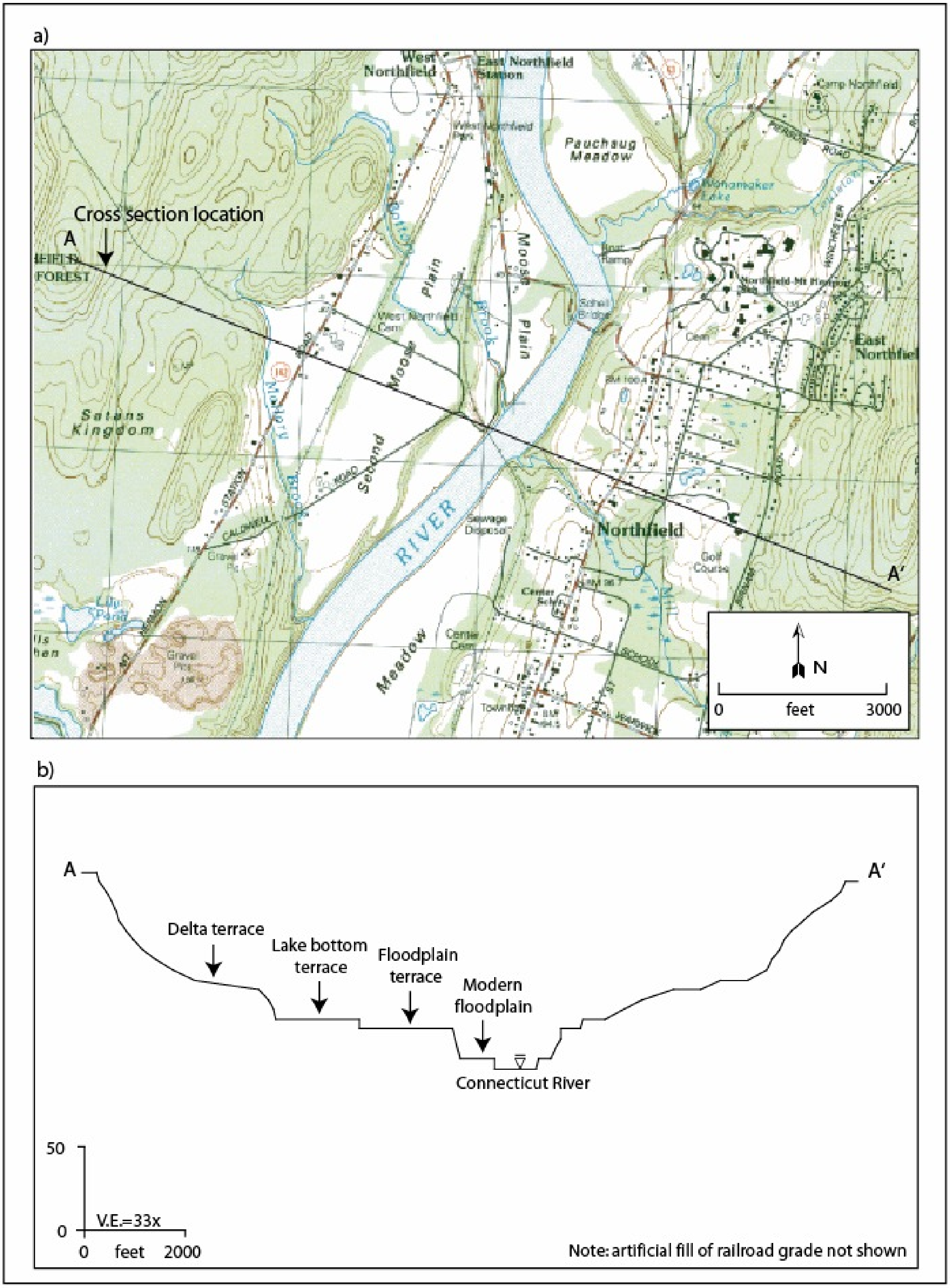

Figure 5: a) Topographic map and b) topographic cross section of terrace and floodplain surfaces in the Moose Plain area.

Figure 6: Abandoned avulsion channel formed across Moose Plain during the 1936 flood.

Figure 7: a) Remnant of low bench protected by tree that was once more continuous in the Turners Falls Pool, b) historical photograph of the bench, c) tree stumps at the edge of water once growing on bench, and d) a similar bench located approximately 1.6 miles downstream of the Deerfield River.

a)

b)

Figure 8: a) Active beach face and b) remnants of a higher beach.

Figure 9: Higher bank developed where the river intersects older terrace surface.

Figure 10: Hill created by artificial fill placed across Moose Plain during railroad construction in 1847.

Figure 11: Meander scar preserved on terrace surface 14 ft higher than Moose Plain upstream of the railroad grade shown in Figure 10.

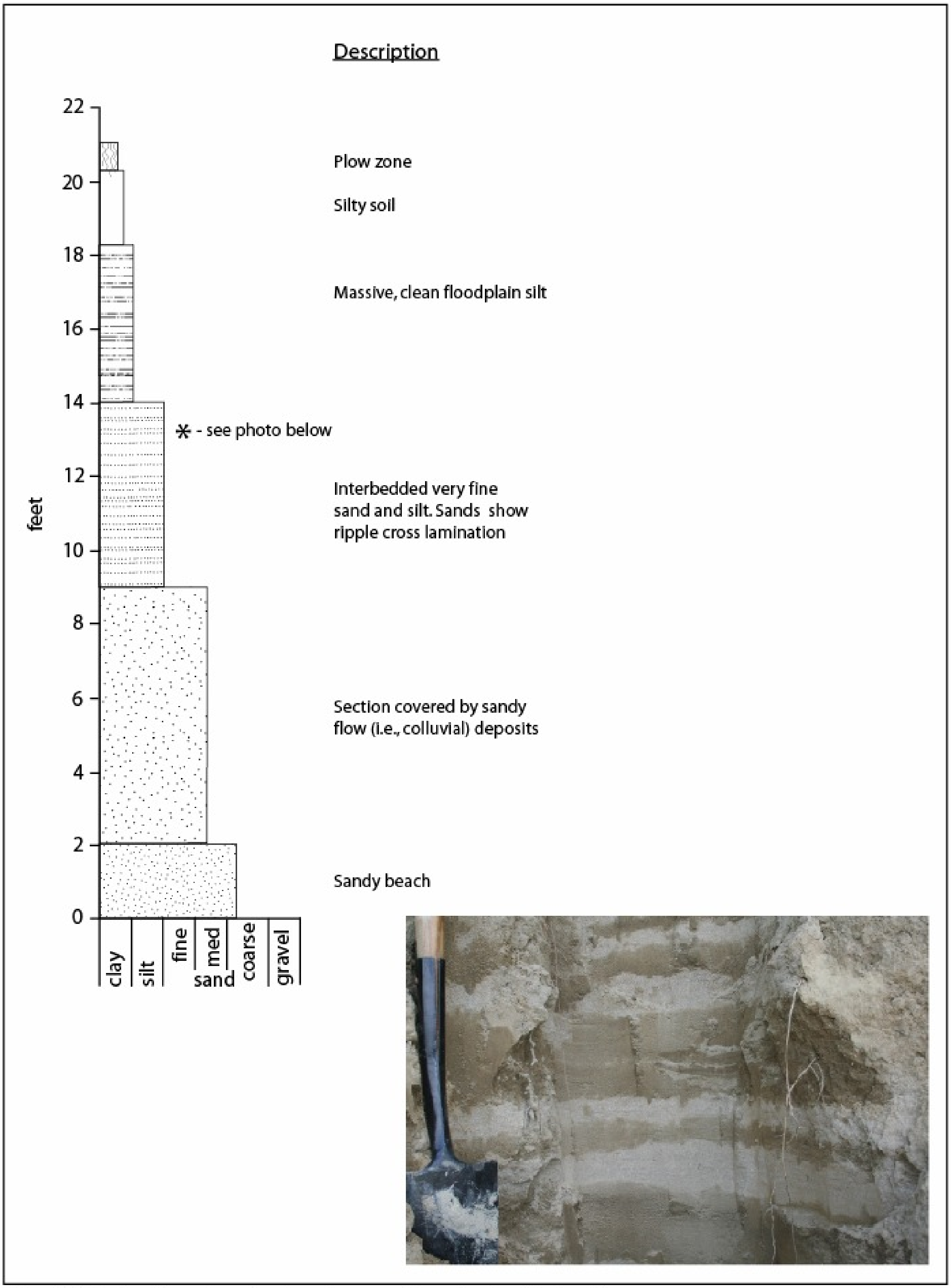

Figure 12 : Stratigrphic section of sediments exposed beneath a floodplain surface.

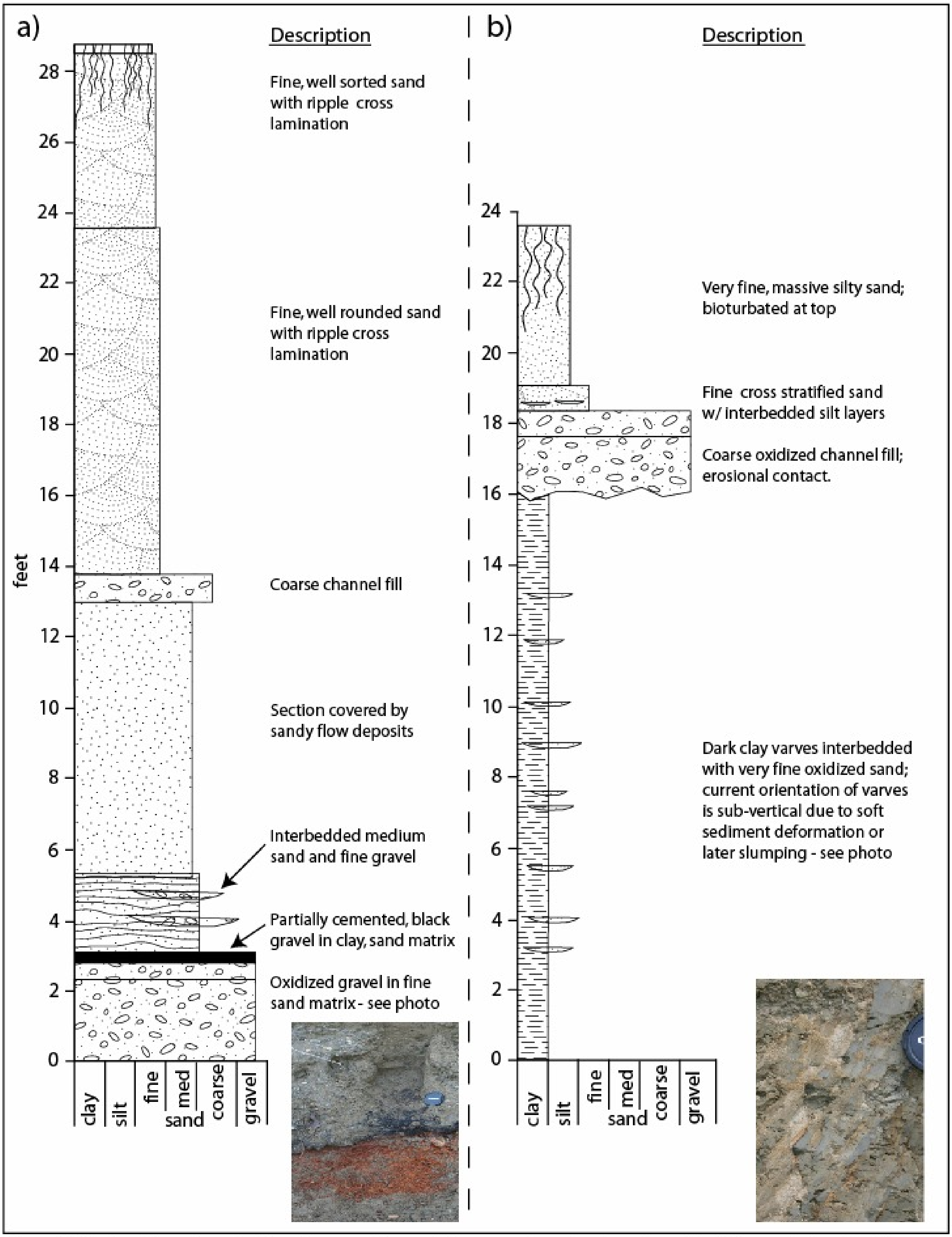

Figure 13: Stratigrphic section of sediments exposed beneath terrace surfaces showing a) gravel and b) varved clay at the base.

Figure 14: Wide beach face developed at the mouth of Bennett Brook.

Figure 15: Active headcut on a small gully incised into a high bank downstream of Dry Brook. Note top of headcut is delineated by dashed yellow line.

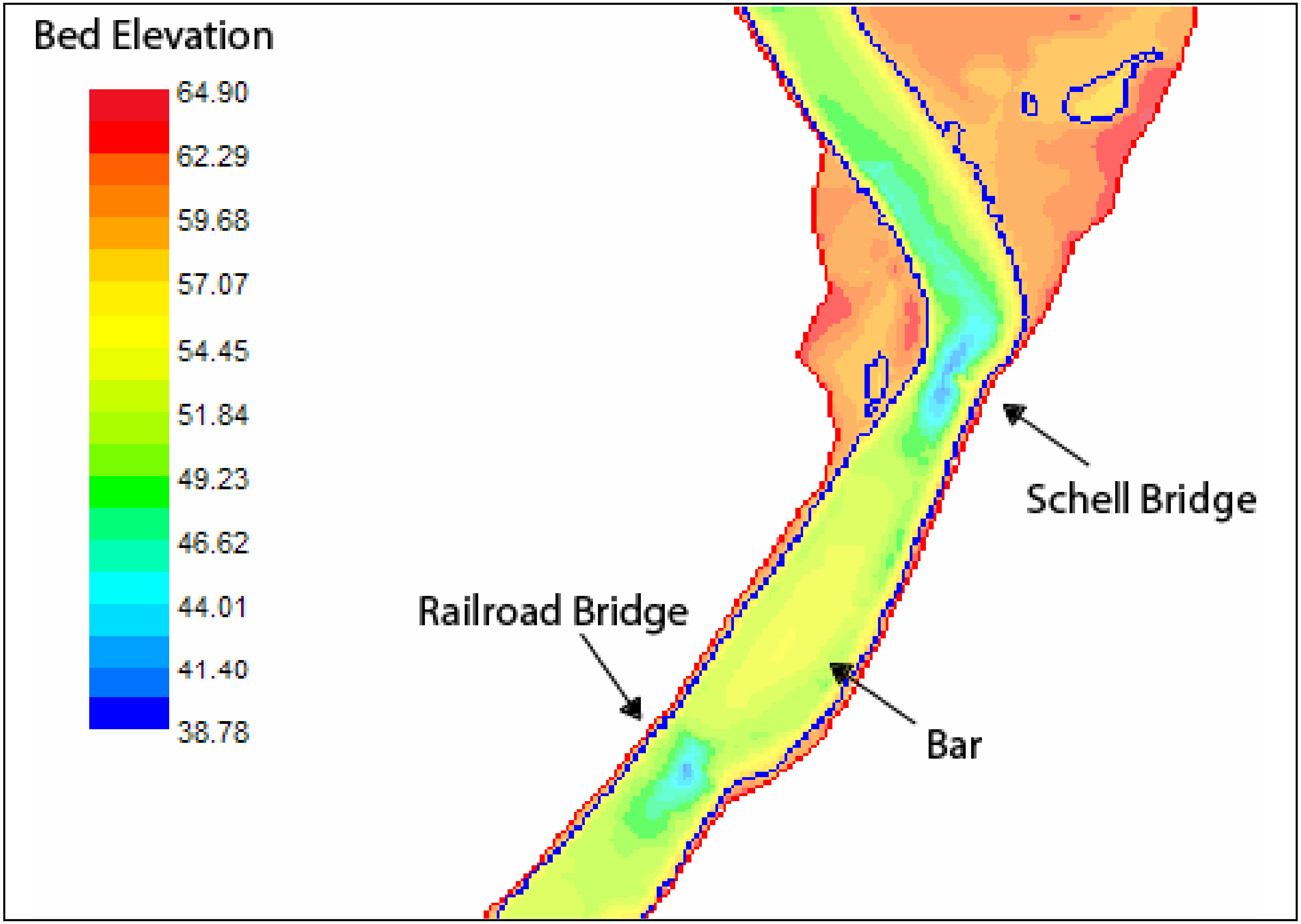

Figure 16: Bathymetric map of area near railroad bridge in Northfield, MA showing mid-channel bar formed upstream of railroad bridge. Also note deep areas at constrictions by bridges. Bed elevation in meters above sea level.

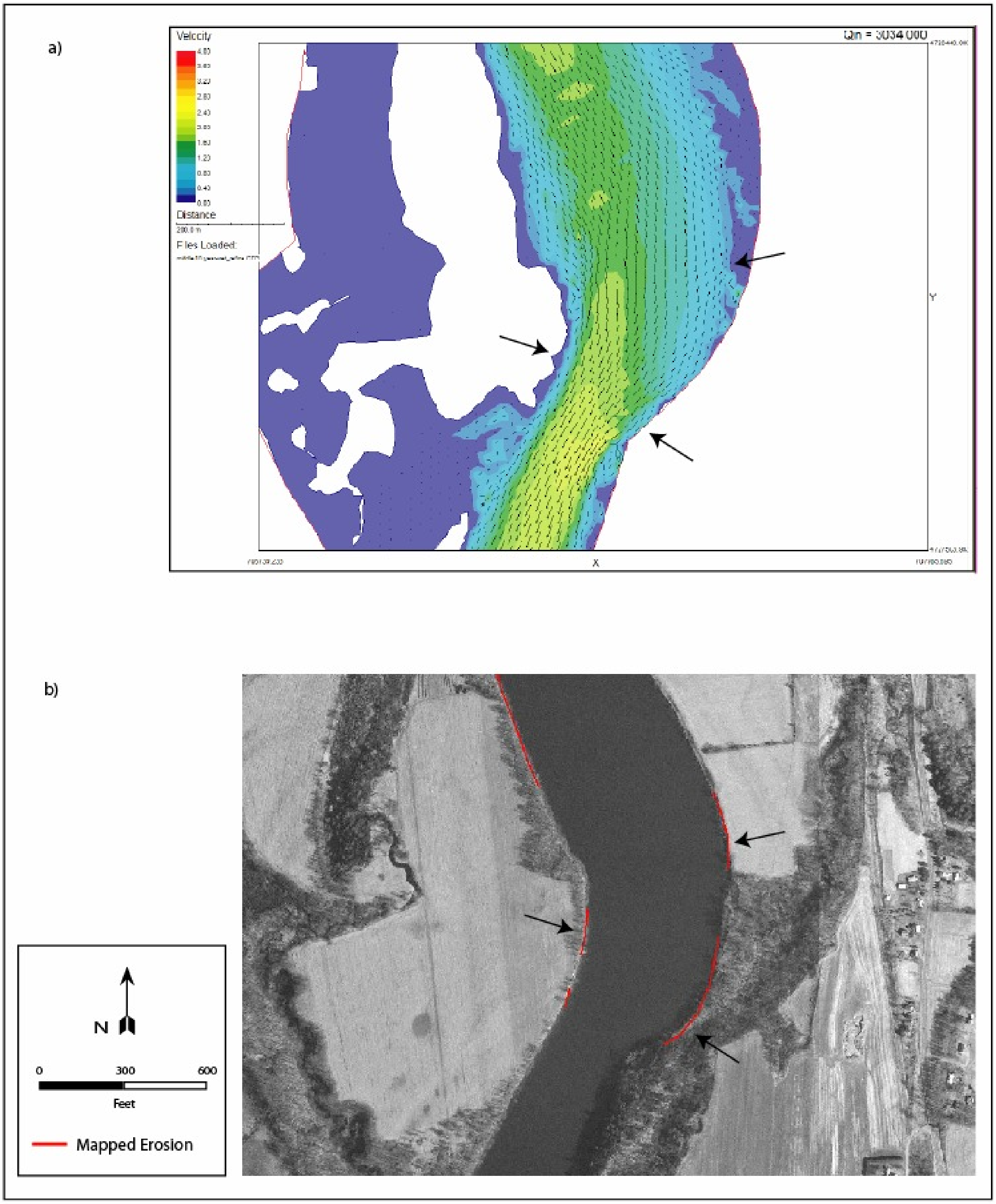

Figure 17: Comparison of a) areas of high velocity predicted by the hydraulic model for a 10-year recurrence interval event (yellow colors) with b) mapped erosion sites. Arrows in both images at same location demonstrating some erosion occurs where high velocity flows are present while some is in low velocity areas (blue colors).

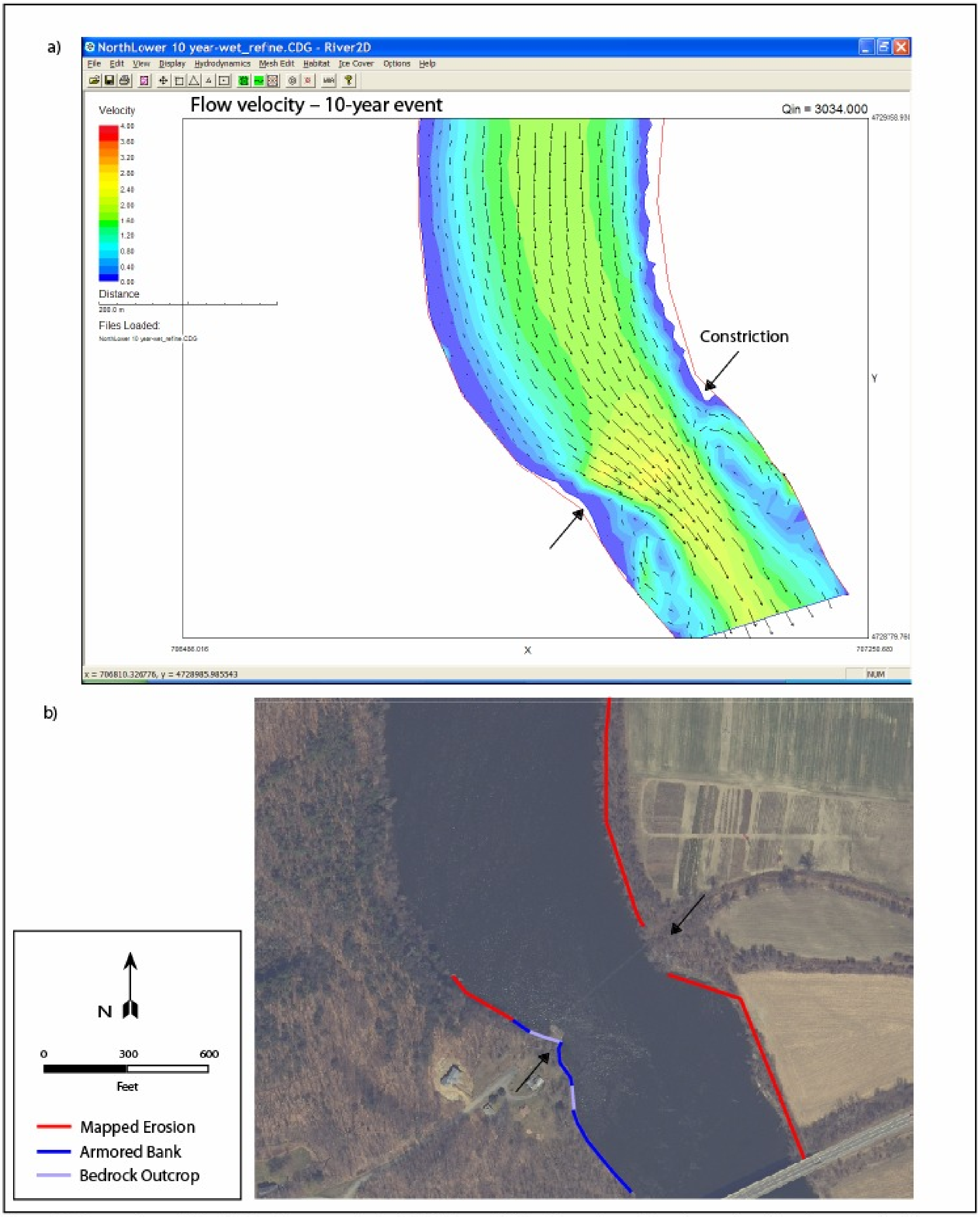

Figure 18: Comparison of a) eddy locations near Route 10 Bridge and b) bank erosion and bank armoring sites. Arrows on both maps are at same location. Note that location of erosion and bank armoring is largely congruent with eddy formation.

a)


b)


Figure 19: Undercut bank with a) narrow notch at base of bank and b) cavity extending higher up the bank.

a)

b)

Figure 20: Gully formed by a) overland flow and b) groundwater seeps. Note berm in a) built to prevent additional overland flow from enlargening gully.

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Figure 21: a) Vertical tension cracks lead to b) a topple blocks with tree attached and c) mounds of soil and roots at the base of the bank.

a)

b)

Figure 22: a) Planar slip and b) rotational slump.

Figure 23: High eroding bank downstream of Vernon Dam showing trees still growing on bench at top of a slip block. Note colluvial apron formed from flow deposits below bench

Figure 24: Long continuous planar slips on high bank downstream of Dry Brook.

Figure 25: Flow formed at the base of a planar slip. Note colluvial deposits on lower slope are composed of individual flows such as visible on the surface.

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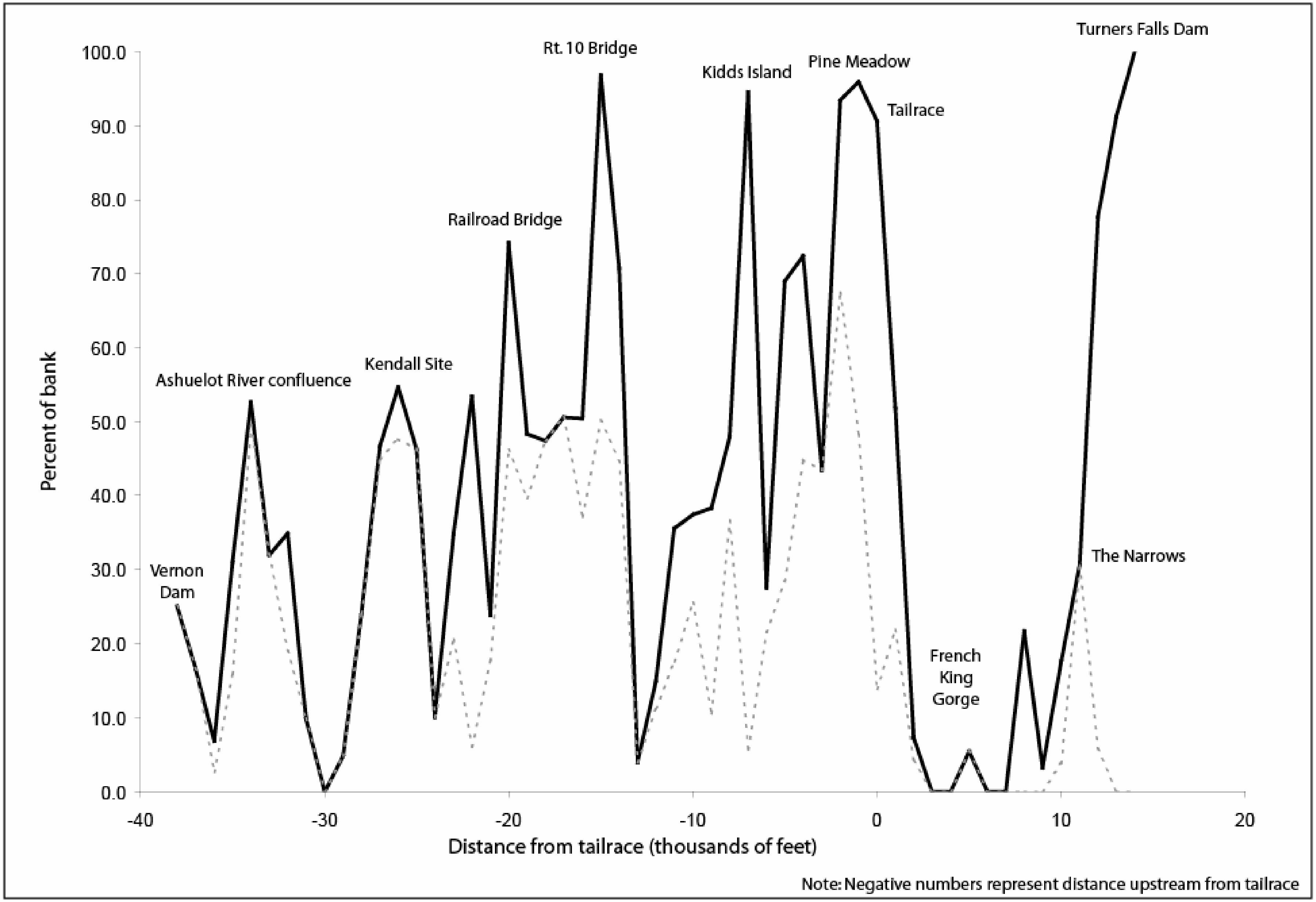

Figure 26: Density of bank erosion (dashed line) and bank erosion with rock armoring (solid line) as a function of distance from the Northfield Mountain Pumped Storage Project tailrace. Percentage calculated by comparing total length of eroding and armored banks within each two thousand foot length of river (4000 ft of bank) upstream or downstream of the tailrace.

Figure 27: Eroding banks near the Narrows at a time of a log drive in the late 1800's or early 1900's before the opening of the Northfield Mountain Pumped Storage project. Modified from Northeast Utilities (1991, p. 133).

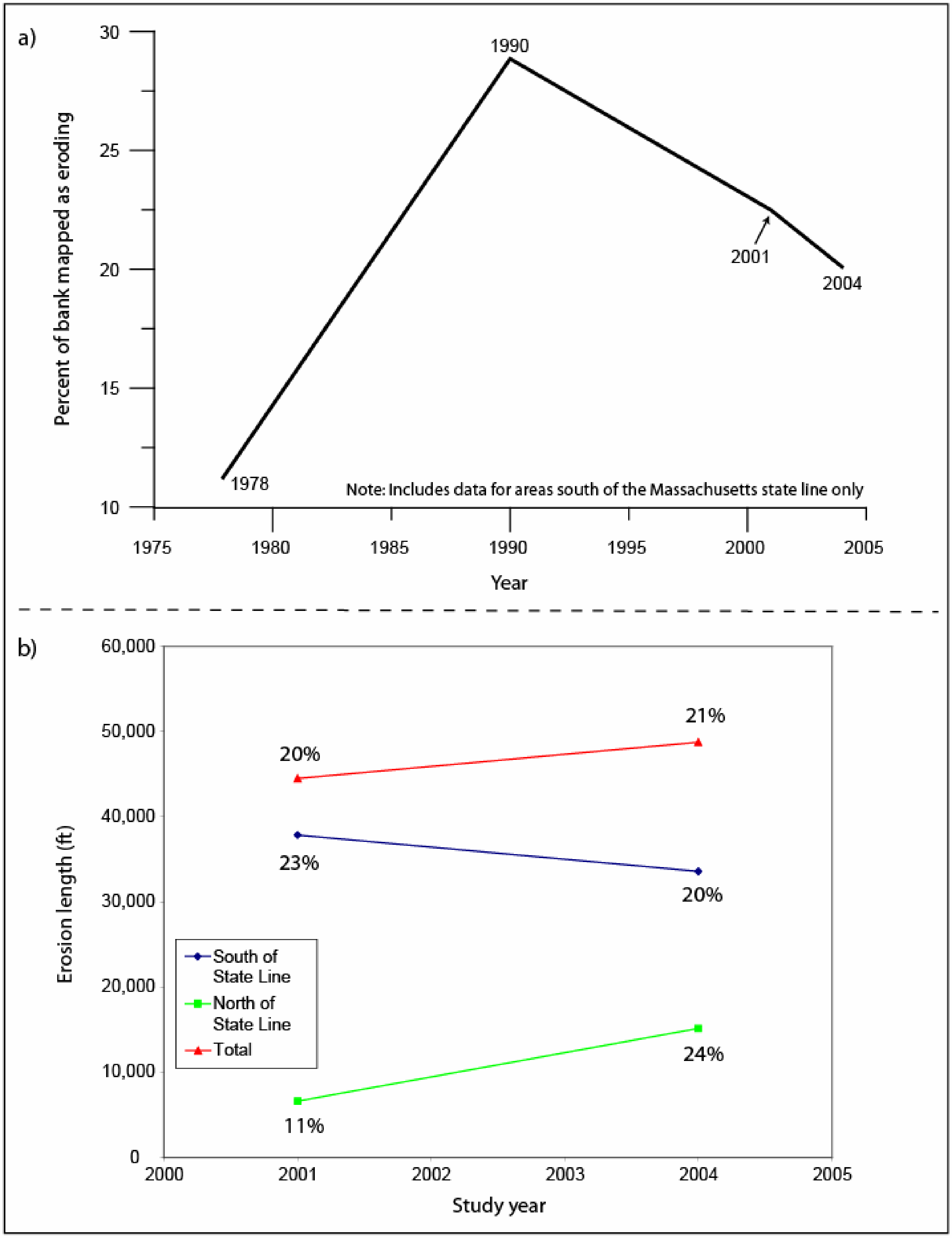

Figure 28: a) Changes in the percentage of banks mapped as eroding south of the state line in various years and b) changes in total mapped erosion between 2001 and 2004 and changes north and south of the state line.

a)

b)

Figure 29: a) Bank recession continuing beyond riprap and b) failed section of riprap in Barton Cove (dashed line indicates former position of riprap).

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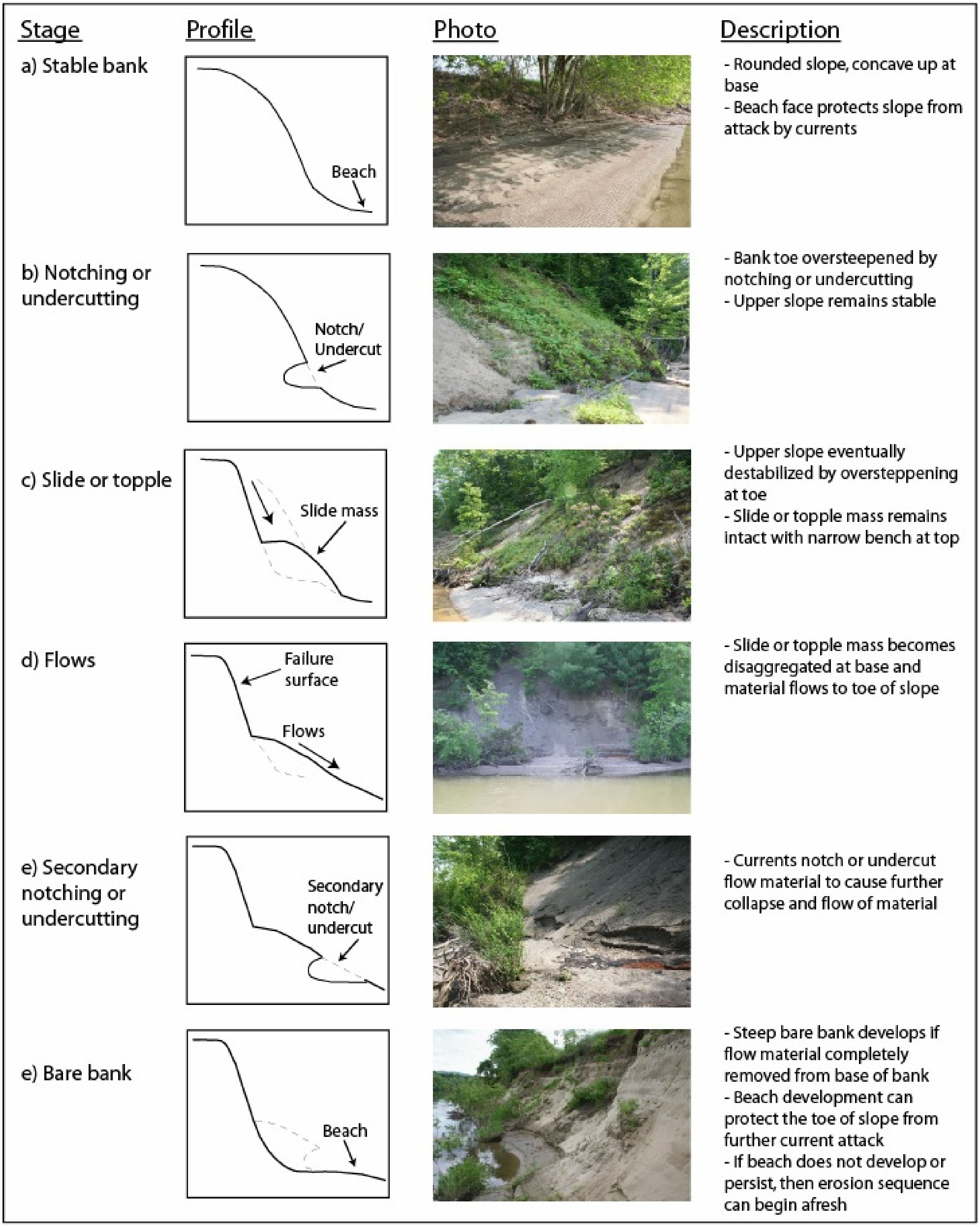


Figure 30: Model illustrating idealized sequence of erosion. Different stages of erosion can be occurring adjacent to each other along a long continuously eroding bank.

Figure 31: Decaying tree still attached to the bank and providing bank protection.

Figure 32: Active planar slip with vegetation growing on the surface.

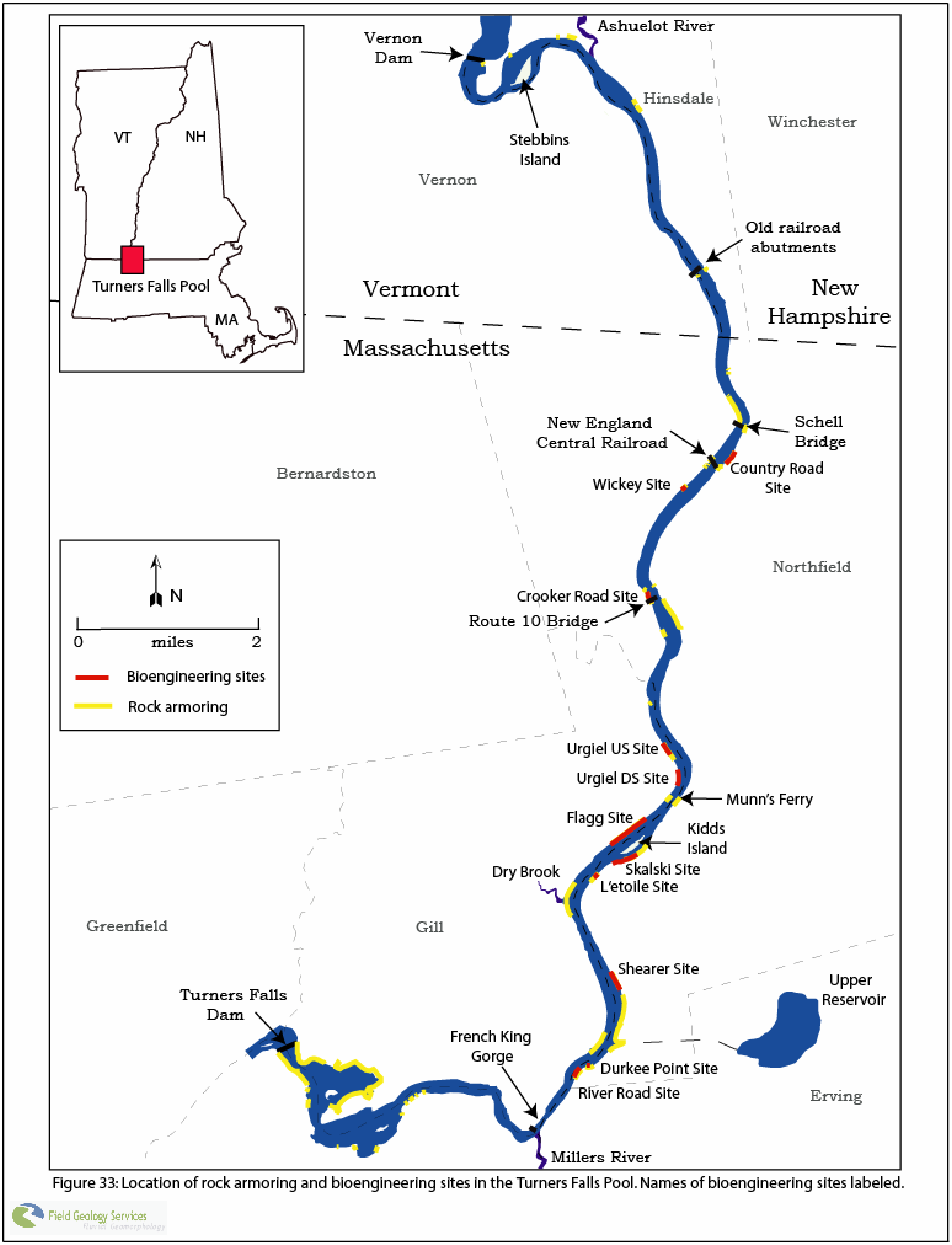


Figure 33: Location of rock armoring and bioengineering sites in the Turners Falls Pool. Names of bioengineering sites labeled.

a)

b)

Figure 34: a) Log being removed by helicopter and b) erosion in area of helicopter logging.

Figure 35: Failing rock armor at Munn's Ferry picnic area.

Figure 36: Notching above rock armoring with resulting minor erosion across from the Northfield Mountain Pumped Storage Project tailrace.

a)

b)

c)

Figure 37: Experimental bank protection efforts using a) concrete mattress, b) tire wall, and c) tire mattress downstream of Route 10 Bridge.

Figure 38: Bioengineering project (Skalski Site) with rock toe and coir log above.

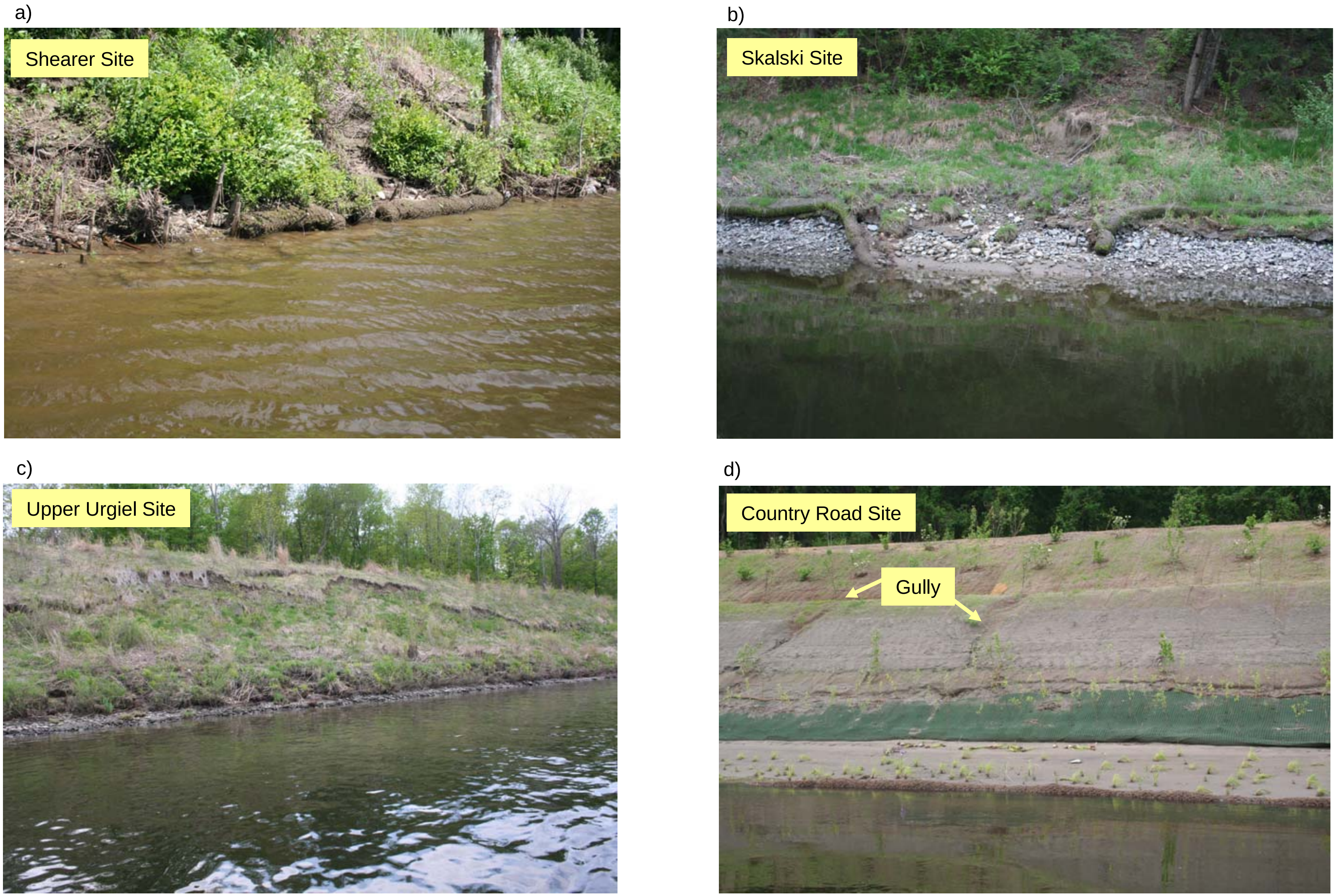


Figure 39: a) Coir logs removed by water currents, b) coir logs detached from bank by mass movements on upper slope, c) planar slips on upper slope resulting from removal of coir logs and notching at the base of the slope, and d) gullying on the slope of a recently shaped bank.

Figure 40: Crooker Road Site with growth of herbaceous vegetation but limited tree growth.

Figure 41: a) Vegetating bank face protected by beach despite logs removed from beach, b) low bench created during construction, c) floodplain bench created during construction, and d) coir logs placed under the water surface to encourage beach development.

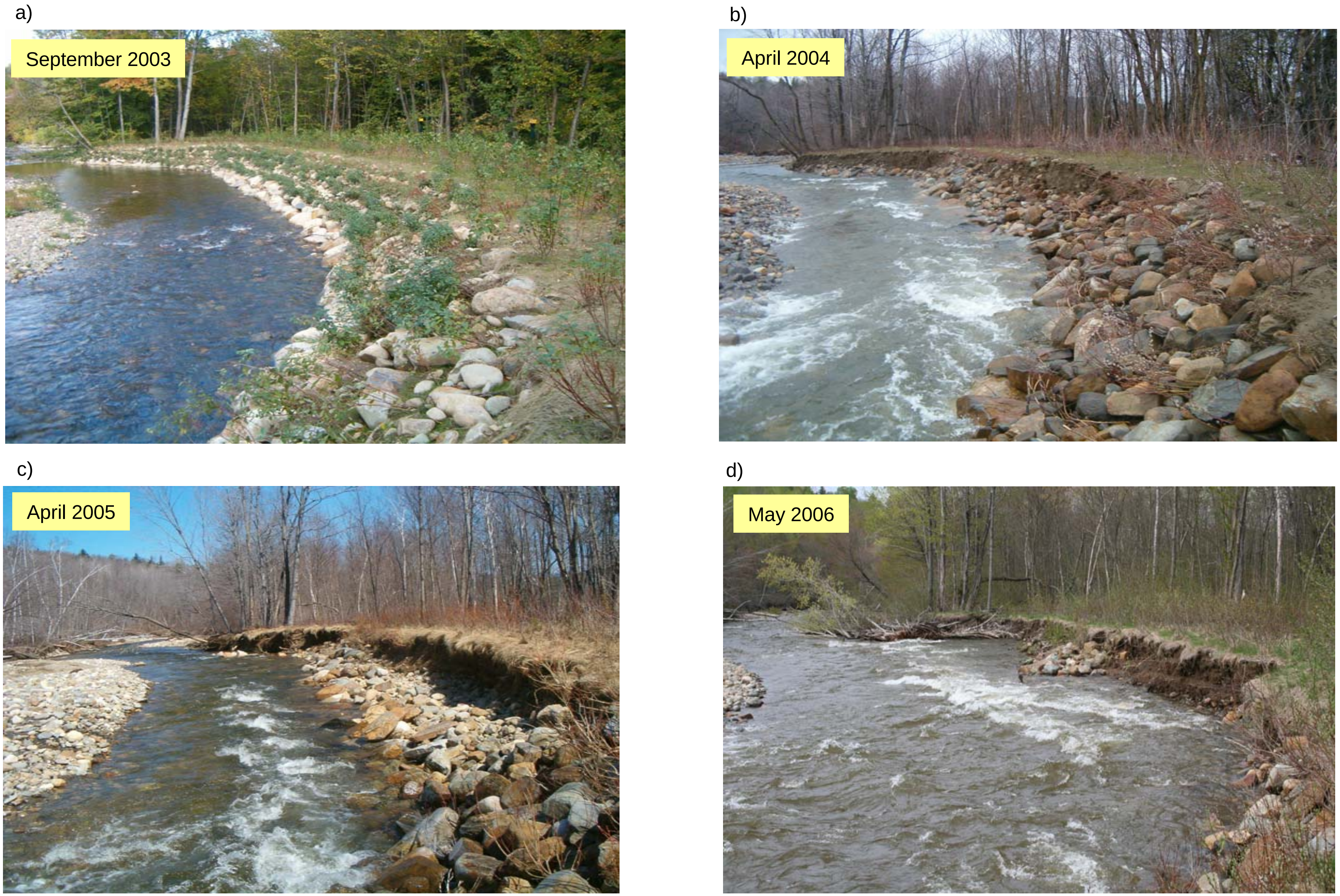


Figure 42: Time sequenced photographs showing collapse of bank armoring and continued erosion due to undermining on the South Branch of the Sandy River, ME.

Figure 43: Seepage channels forming across a beach face.

Figure 44: Boat waves breaking on a beach face.

a)

b)

Figure 45: Beach deposits accumulating in a) a crevice in the bank and b) at the mouth of a small gully.

a)

b)

Figure 46: a) Sediment accumulation downstream of a tree lying on a beach and b) wood accumulation on a beach.

Erosion Type	Description
Falls	- Material mass detached from a steep slope and descends through the air to the base of slope - For the purposes of this study, also includes erosion resulting from transport of individual particles by water
Topples	- Large blocks of the slope undergo a forward rotation about a pivot point due to the force of gravity - Large trees undermined at the base enhance formation
Slides	- Sediments move downslope under the force of gravity along one or several discrete surfaces - Two forms occur: planar slips and rotational slumps - Slumps rotate down and out along a surface that is concave upward - Slips move along shallow planar surface without rotary motion
Lateral spreads	- Transitional form between slides and flows
Flows	- Sediment/water mixtures that are continuously deforming without distinct slip surfaces - Two forms occur depending on rate of movement: slow creep and rapid grain flows

Table 1: Typical types of slope movements on eroding banks.

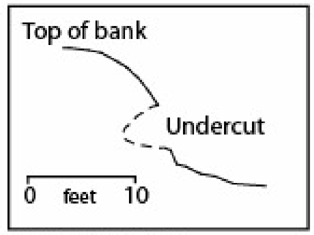
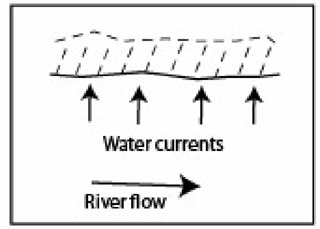
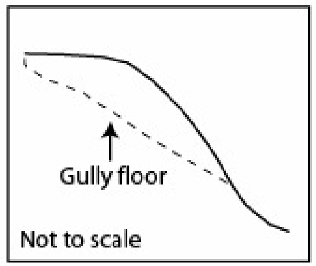
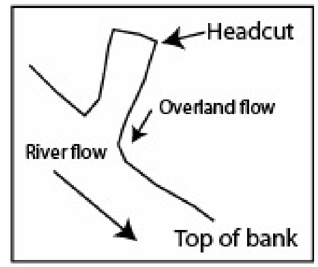
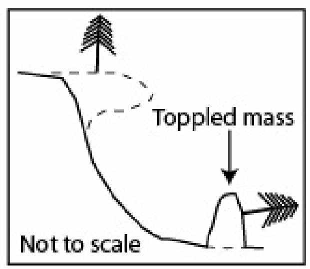
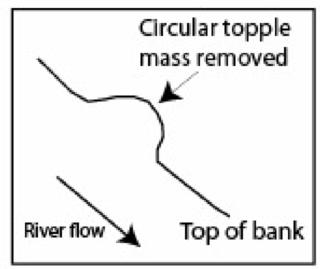
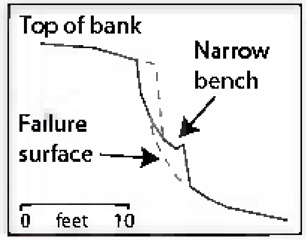
Erosion type	Photo	Profile	Planview	Description
Falls - Undercuts		 Across from tailrace		- Undercutting - Notching and oversteepening at the toe of the slope
- Gullies				- Gullies formed by overland flow and groundwater seeps
Topples				- Vertical tension cracks at the top of slope - Trees lean away from bank - Toppled mass creates mound of soil at base of bank

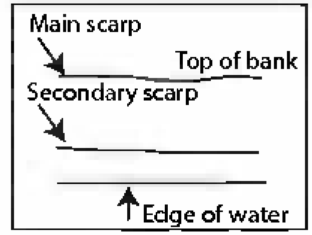
Table 2: Types of erosion occurring in the Turners Falls Pool and their characteristics.

Erosion type | **Photo** | **Profile** | **Planview** | **Description**

Slides
- Planar slip

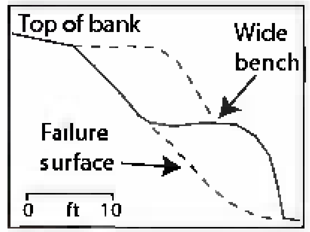


Across from tailrace (Split River)

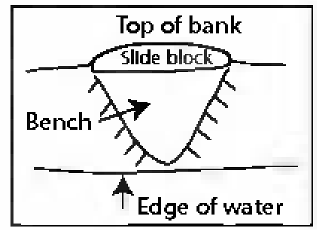


- Vertical tension cracks at top of slope
- Top surface of slide mass has flatter slope than rest of bank (narrow bench)
- Trees lean in towards bank
- Trees can remain in growth position despite sliding

- Rotational slump

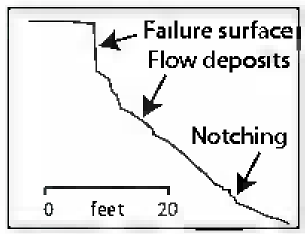


Munns Ferry

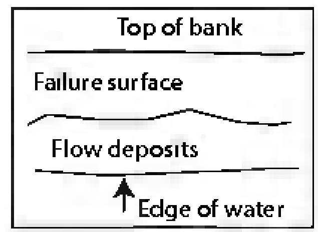


- Vertical tension cracks at top of slope
- Deeper seated than slips
- Trees lean in towards bank
- Arcuate failure surfaces

Flows
- Grain flows

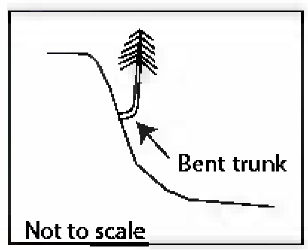


Downstream RR Bridge in VT (Kendall)



- Colluvial deposits created by flows accumulate at base of slope to form concave up surfaces

Creep



Not applicable

- Tree trunks bent downslope at base

Table 2 (continued).

Feature	Erosion length (ft)	Feature length (ft)	Erosion (%)*	Total erosion in pool (ft)	Total erosion within feature (%)**	Total bank length (ft)	Feature length (%)[$]	Erosion ratio[#]
Bank Composition								
- Silt /sand	46,774	143,709	33	48,936	96	230,171	62	1.5
- Gravel /cobble	1,087	16,473	7	48,936	2	230,171	7	0.3
- Cohesive (clay/silt)	0	403	0	48,936	0	230,171	0	0.0
- Rock outcrop	317	24,293	1	48,936	1	230,171	11	0.1
- Armored	758	45,293	2	48,936	2	230,171	20	0.1
Bank Height								
- High (>8 ft)	45,955	136,313	34	48,936	94	230,237	59	1.6
- Medium (4-8 ft)	2,858	59,454	5	48,936	6	230,237	26	0.2
- Low (<4 ft)	123	21,702	1	48,936	0	230,237	9	0.0
Vegetative Cover								
- Heavy (>80%)	6,659	123,312	5	48,937	14	219,331	56	0.2
- Moderate (30-80%)	23,351	74,011	32	48,937	48	219,331	34	1.4
- Sparse (5-30%)	17,881	20,626	87	48,937	37	219,331	9	3.9
- None	1,046	1,382	76	48,937	2	219,331	1	3.4
Bend Geometry[&]								
- Outside of bend	6,783	59,237	11	48,936	14	229,963	26	0.5
- Inside of bend	13,661	38,064	36	48,936	28	229,963	17	1.7
- Straight section	27,275	113,393	24	48,936	56	229,963	49	1.1
- Cove	1,217	19,269	6	48,936	2	229,963	8	0.3

* = percent of feature length mapped as eroding
** = percent of total mapped erosion occurring within that feature
[$] = percent of total stream length represented by feature
[#] = erosion ratio is the ratio of percent of total erosion within a given feature divided by percent of total bank length represented by that feature; an erosion ratio greater than one indicates erosion preferentially occurs within that feature
[&] = 4.5% of total stream length is mapped as eroding on both banks simultaneously

Note: Minor variations in stream length result from data processing while the larger difference for vegetative cover is because vegetation was not mapped in Barton Cove

Table 3: Distribution of erosion relative to other mapped features.

Year of mapping	Reference	Month of mapping	Features mapped	Feature subdivisions
1978	U.S. Army Corps (1979)	September	- Bank height	Low (<15 ft) or high (>15 ft)
			- Erosion type	Sloughing, mass wasting, or undercutting
			- Bank location	Inner bend, outer bend, or straight
			- Soil type	Noncohesive or stratified
			- Vegetation	Vegetated or barren
1990	U.S. Army Corps (1991)	June	Same as 1978	Same as 1978
1990	NDT (1991)	Feb.-August	- Percent soil exposure	<10, 10-25, 25-50, 50-75, or >75 percent
			- Level of movement within vegetated areas	<10, 10-25, 25-50, 50-75, or >75 percent
			- Severity of erosion	none to low, low to moderate, moderate, moderate to severe, or severe
2001	NEE (2005)	July	- Bank height	Low (< 4 ft), medium (4-8 ft), or high (>8 ft)
			- Bank slope	Flat (< 40%), moderate (40-80%), or steep (>80%)
			- Bank material	Silt or sand, gravel or cobble, cohesive (silt/clay), rock outcrop, or armored bank
			- Areas of erosion	Moderate or severe
2004	NEE (2005)	November		Same as 2001

Note: Data for mapping completed by Simons and Associates, Inc. (1998) was not available for this study

Table 4: Variation in mapping techniques and season of mapping during past erosion mapping efforts.

Cross Section	Total change on east bank (ft)	Rate of change (ft/yr)	Total change on west bank (ft)	Rate (ft/yr)	Greatest change between surveys (ft)	Bank	Year(s)	Rate (ft/yr)
1	-2	-0.1	0	0				
2	-4	-0.3	0	0				
3	-6	-0.4	-23	-1.5	-9.5	WB	95-96	-9.5
4	2	Error	-3	-0.2				
5a	0	0	0	0				
5b	-17	-1.1	0	0	-6	EB	90-93	-2
5c	-1	-0.1	-3	-0.2	-5	WB	90-93	-1.7
6a	-3	-0.3	-8	-0.6	-2	WB	92-93	-2
6b	0	0	-9	-0.6	-3	WB	95-96	-3
7	-13	-0.9	0	0	-13	EB	90-95	-2.6
8a	0*	0	-10	-0.7	-9	WB	90-92	-4.5
8b	0	0	0	0	6[$]	EB	6/95-10/95	Error
9	22[#]	1.5	0	0				
10	0	0	-2**	-0.5				

Notes:
- Negative numbers represent apparent bank recession; positive numbers represent apparent bank aggradation
- Two cross sections did not start until after 1990 (6a - 1992 and 10 - 1991)
- See Appendix 8 for cross section locations
- WB = west bank and EB = east bank

* = LB position was not mapped prior to bank treatment

[$] = LB appears to aggrade 6ft in a 4 month period in 1995; this is due to survey errors stemming from bank erosion at the L'Etoile Site and loss of control points; survey errors also resulting in apparent bank accretion at Cross Section 4

[#] = LB has aggraded 22 ft and gained 3 ft of elevation, showing the effects of impoundment

** = Total change represents change before Urgiel Site project installation in 2001, there has been no change since

Table 5: Total bank recession at full river cross sections.

Site	Site location	Recession (ft)	Year of installation	Age (yrs)	Recession rate (ft/yr)
1	Wickey Site	8.8	1996	11	0.80
2	DS of Rt 10 Bridge	10.3	1980	27	0.38
3	Munn's Ferry Road	21.8	1976	31	0.70
4	Munn's Ferry Campground	41.3	1977	30	1.38
5	L'etoile Farm*	34	1987	20	1.7
6	Split River Farm	17.7	1977	30	0.59
7	Barton Cove	20.5	1969	38	0.54

Note: See Appendix 9 for site locations
* = Recession occurring adjacent to concrete irrigation pad not riprap

Table 6: Total bank recession adjacent to areas of bank armoring

Cause of Erosion	**Observations consistent with cause**	**Observations not consistent with cause**
Channel incision downstream of Vernon Dam	- Erosion on both banks simultaneously and on inside of meanders - Some erosion occurring immediately downstream of dam	- Erosion not concentrated closest to dam - Widespread tributary incision not occurring - Previous presence of well forested low bench
Natural flood flows	- Erosion in pool prior to 1970 - New areas of erosion identified immediately after floods - Erosion where eddy currents most strongly developed	- Considerable erosion on inside of meander bends - Increase in erosion since 1970 at a time when flood magnitudes had decreased - Considerable erosion where flood flow velocities low
Seepage forces	- Occurrence of slides where seeps are present - Occurrence of seeps in gullies	- Most of erosion occurs where seeps are not present
Pool fluctuations	- Erosion on both banks simultaneously and on inside of meanders - Concentration of erosion in proximity to tailrace - Documented in other localities (Lawson, 1985) - Seepage from banks and across beach faces common	- Considerable erosion where pool fluctuations are minimal - Erosion often coincident with flood flows - Rising water levels impart limited shear stress directly on banks
Boat waves	- Erosion on both banks simultaneously and on inside of meanders - Documented in other localities (Lawson, 1985)	- Considerable erosion where boat waves are minimal - Not considered important in earlier studies (U.S. Army Corps, 1979)
Stage variations	- Increase in pore pressures in bank sediments - Higher river stages during low flow times as a result of flood control efforts upstream	- Considerable erosion where stage variations minimal

Table 7: Potential causes of erosion with observations consistent and inconsistent with that cause.

APPENDIX 1

Historical Maps

(see attached CD)

APPENDIX 2

Historical Aerial Photographs

(see attached DVDs)

APPENDIX 3

Bathymetric Data

(see attached CD)

APPENDIX 4

Hydraulic Modeling Report

(see attached CD)

APPENDIX 5

Erosion Mapping Data and Related GIS Shapefiles

(see attached CD)

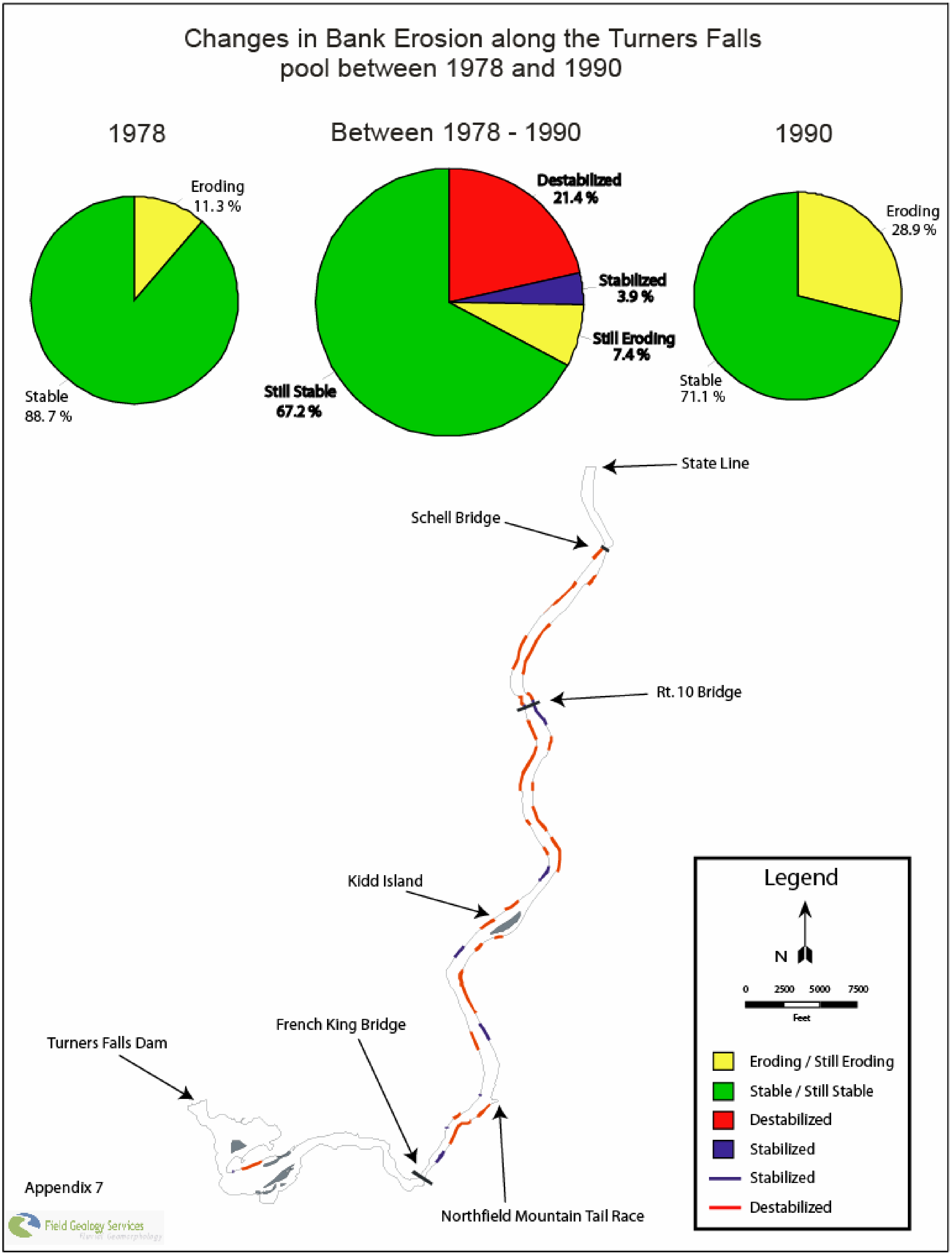
APPENDIX 6

Digital Photolog of Banks in the Turners Falls Pool

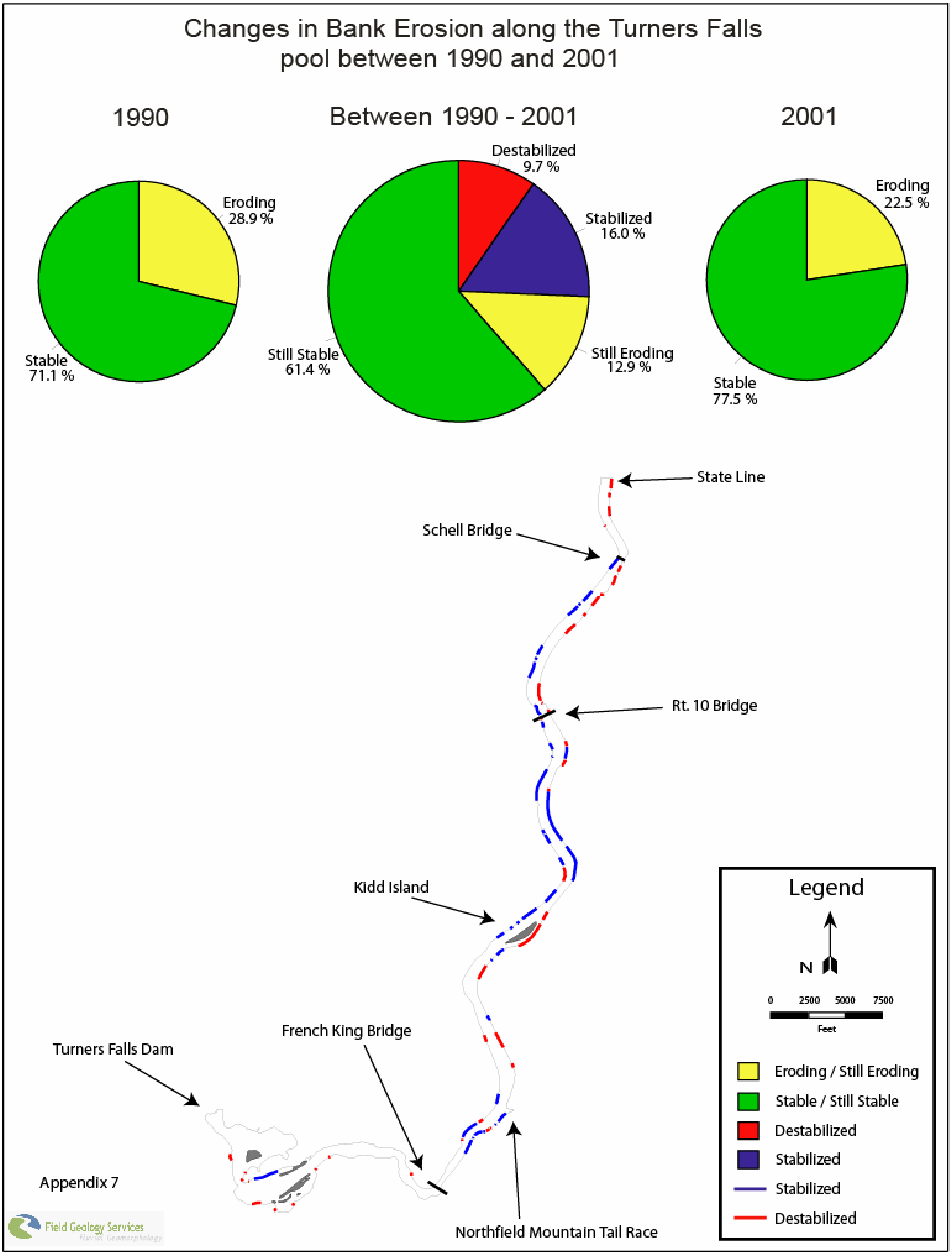
(see attached DVD)

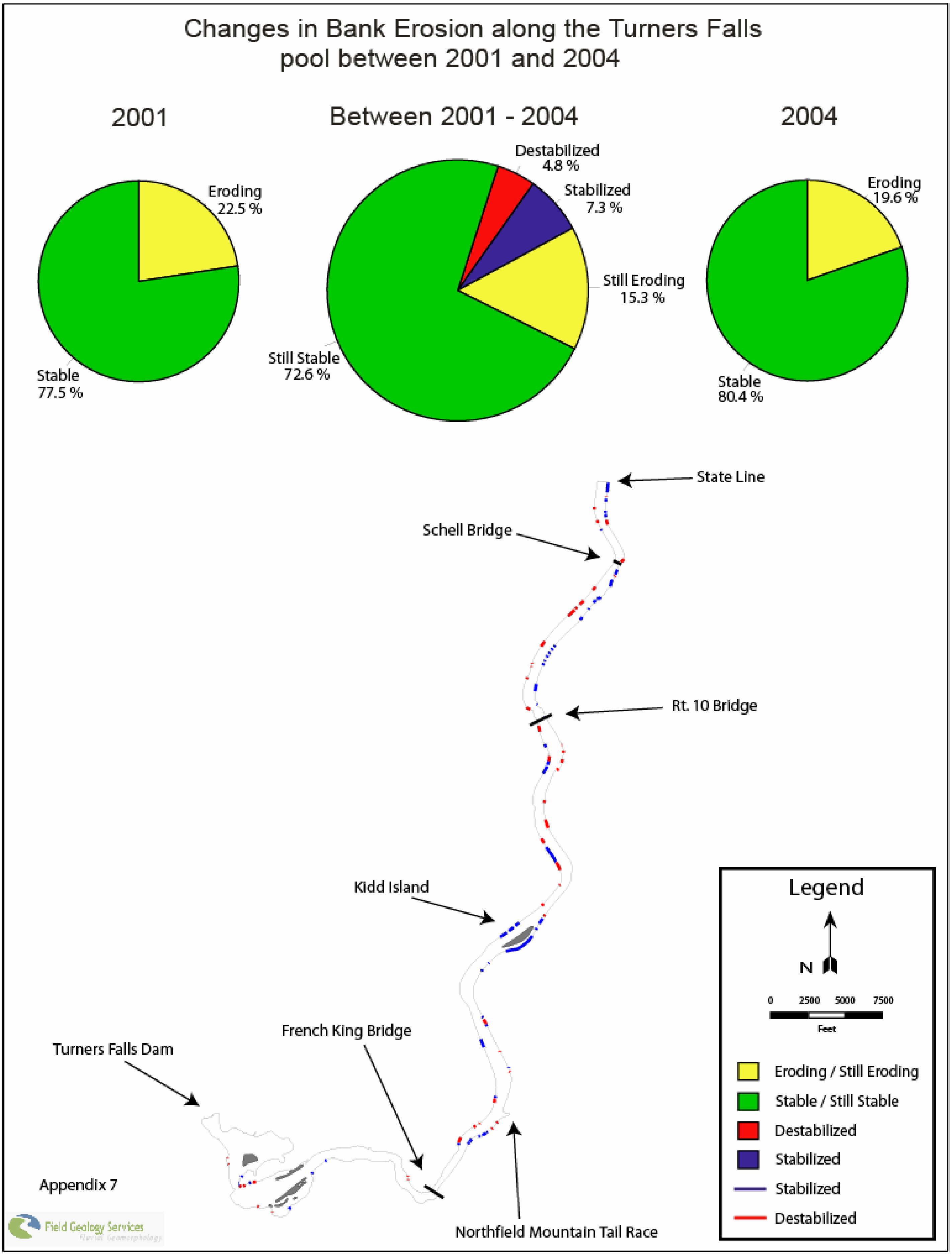
APPENDIX 7

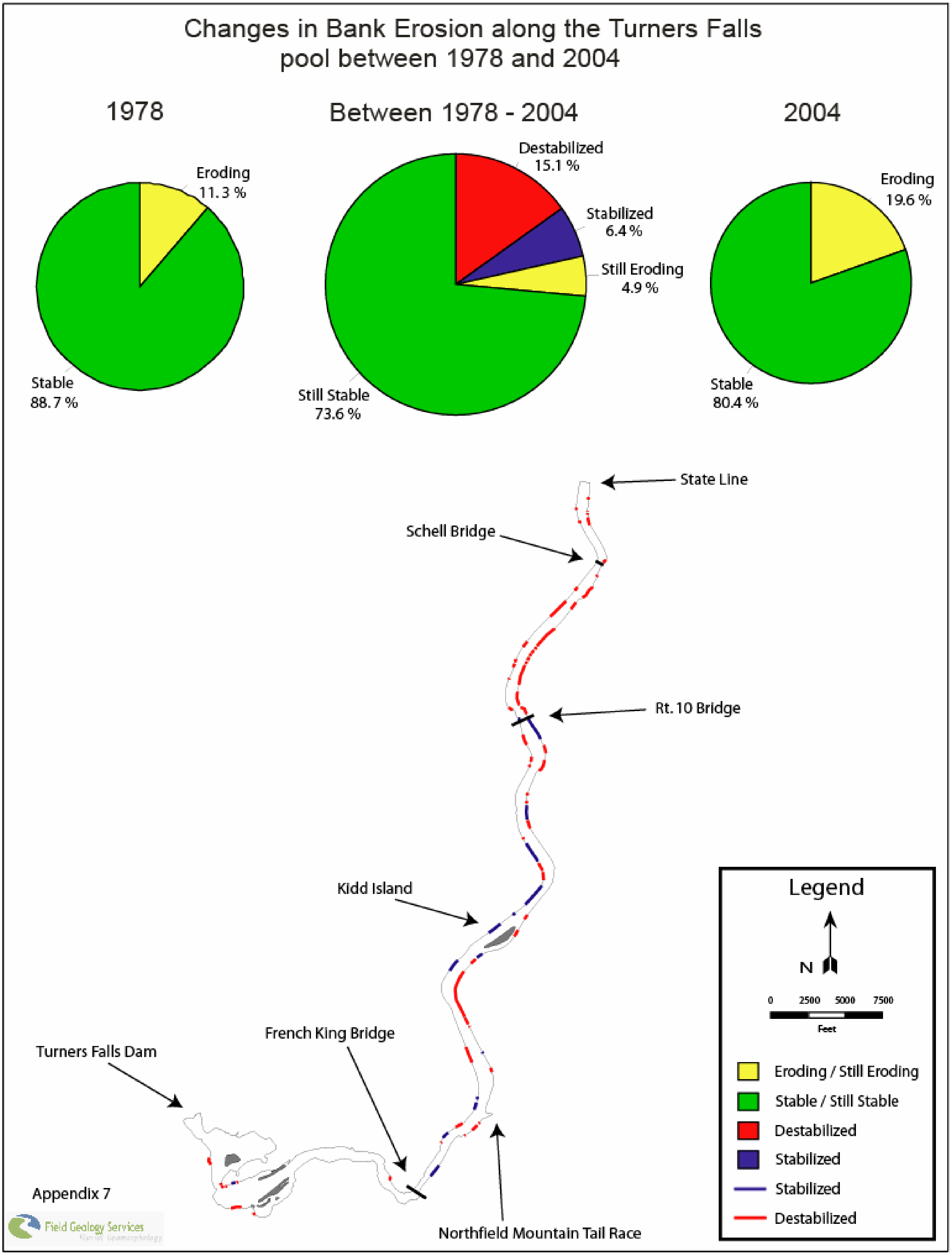
Graphs and Maps Showing Variations in Percentage of Erosion Between Different Mapping Efforts



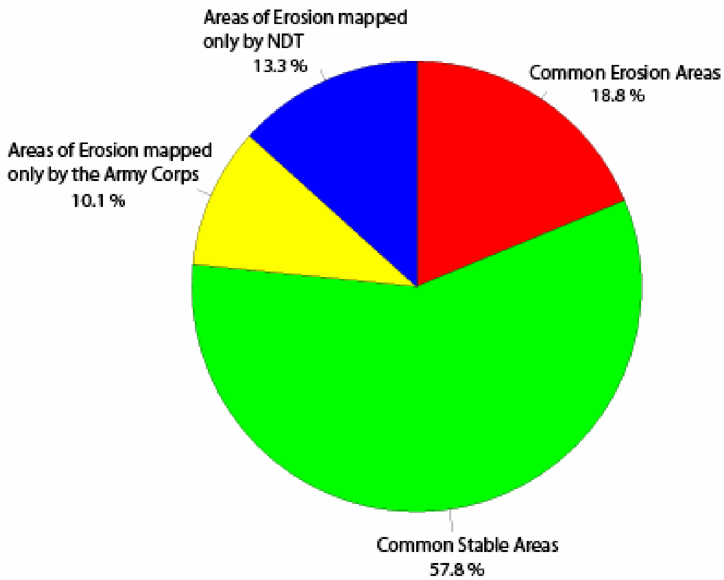
Changes in Bank Erosion along the Turners Falls pool between 1978 and 1990
1978
Eroding 11.3 %
Stable 88. 7 %
Between 1978 - 1990
Destabilized 21.4 %
Stabilized 3.9 %
Still Eroding 7.4 %
Still Stable 67.2 %
1990
Eroding 28.9 %
Stable 71.1 %
State Line
Schell Bridge
Rt. 10 Bridge
Kidd Island
French King Bridge
Turners Falls Dam
Northfield Mountain Tail Race
Legend
N
0 2500 5000 7500
Feet
Eroding / Still Eroding
Stable / Still Stable
Destabilized
Stabilized
Stabilized
Destabilized
Appendix 7
Field Geology Services
Fluvial Geomorphology

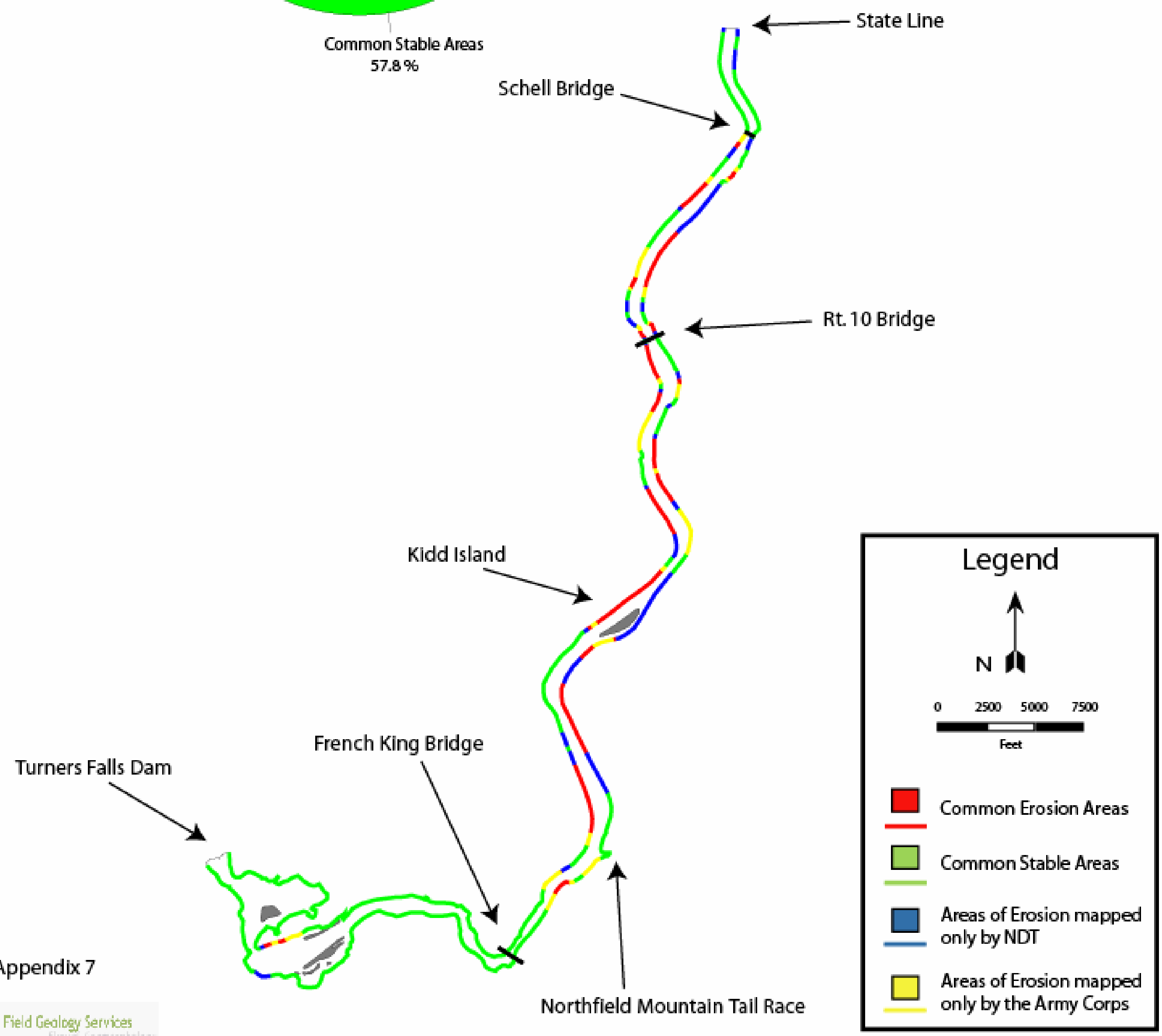

Changes in Bank Erosion along the Turners Falls pool between 1990 and 2001
1990
Eroding 28.9 %
Stable 71.1 %
Between 1990 - 2001
Destabilized 9.7 %
Stabilized 16.0 %
Still Eroding 12.9 %
Still Stable 61.4 %
2001
Eroding 22.5 %
Stable 77.5 %
State Line
Schell Bridge
Rt. 10 Bridge
Kidd Island
French King Bridge
Turners Falls Dam
Northfield Mountain Tail Race
Appendix 7
Field Geology Services
Legend
N
0 2500 5000 7500
Feet
Eroding / Still Eroding
Stable / Still Stable
Destabilized
Stabilized
Stabilized
Destabilized


Changes in Bank Erosion along the Turners Falls pool between 2001 and 2004
2001
Eroding 22.5 %
Stable 77.5 %
Between 2001 - 2004
Destabilized 4.8 %
Stabilized 7.3 %
Still Eroding 15.3 %
Still Stable 72.6 %
2004
Eroding 19.6 %
Stable 80.4 %
State Line
Schell Bridge
Rt. 10 Bridge
Kidd Island
French King Bridge
Turners Falls Dam
Northfield Mountain Tail Race
Appendix 7
Legend
N
0 2500 5000 7500
Feet
Eroding / Still Eroding
Stable / Still Stable
Destabilized
Stabilized
Stabilized
Destabilized


Changes in Bank Erosion along the Turners Falls pool between 1978 and 2004
1978
Eroding 11.3 %
Stable 88.7 %
Between 1978 - 2004
Destabilized 15.1 %
Stabilized 6.4 %
Still Eroding 4.9 %
Still Stable 73.6 %
2004
Eroding 19.6 %
Stable 80.4 %
State Line
Schell Bridge
Rt. 10 Bridge
Kidd Island
French King Bridge
Turners Falls Dam
Northfield Mountain Tail Race
Legend
N
0
2500
5000
7500
Feet
Eroding / Still Eroding
Stable / Still Stable
Destabilized
Stabilized
Stabilized
Destabilized
Appendix 7
Field Geology Services

Comparison of Mapped Erosion between 1990 NDT and Army Corps Surveys



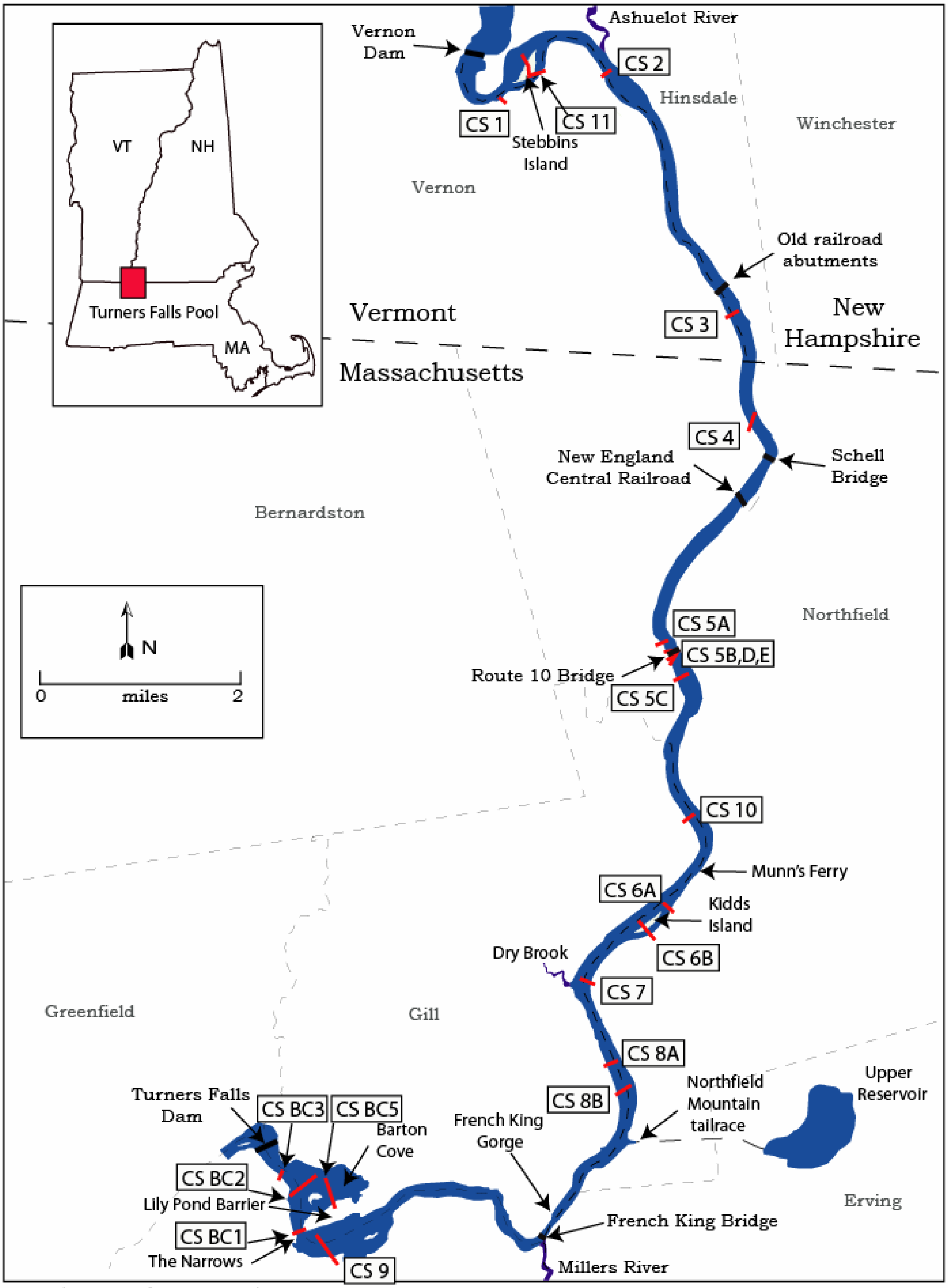


Appendix 7

APPENDIX 8

Full River Cross Sections

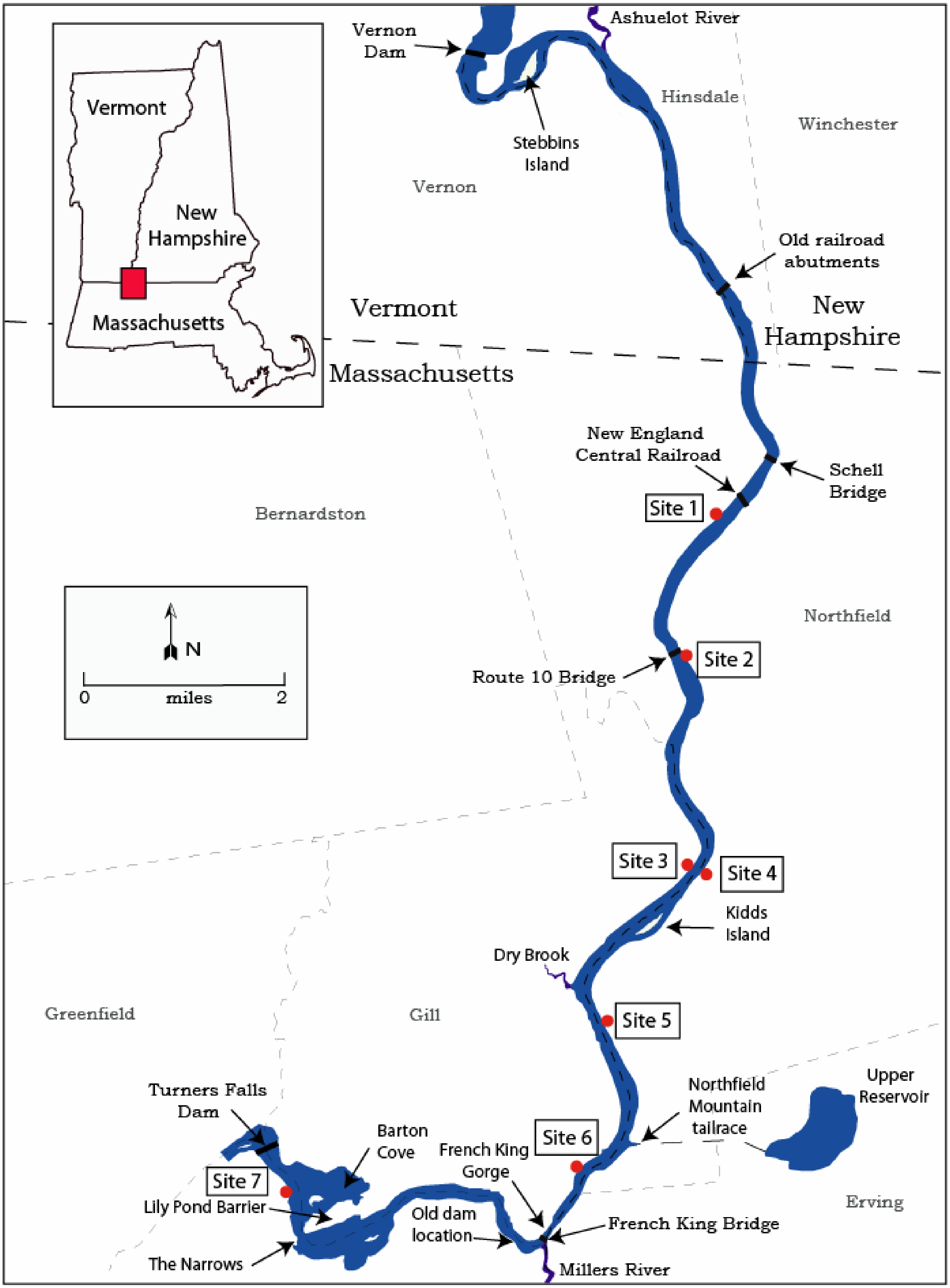
(see map below and attached CD)



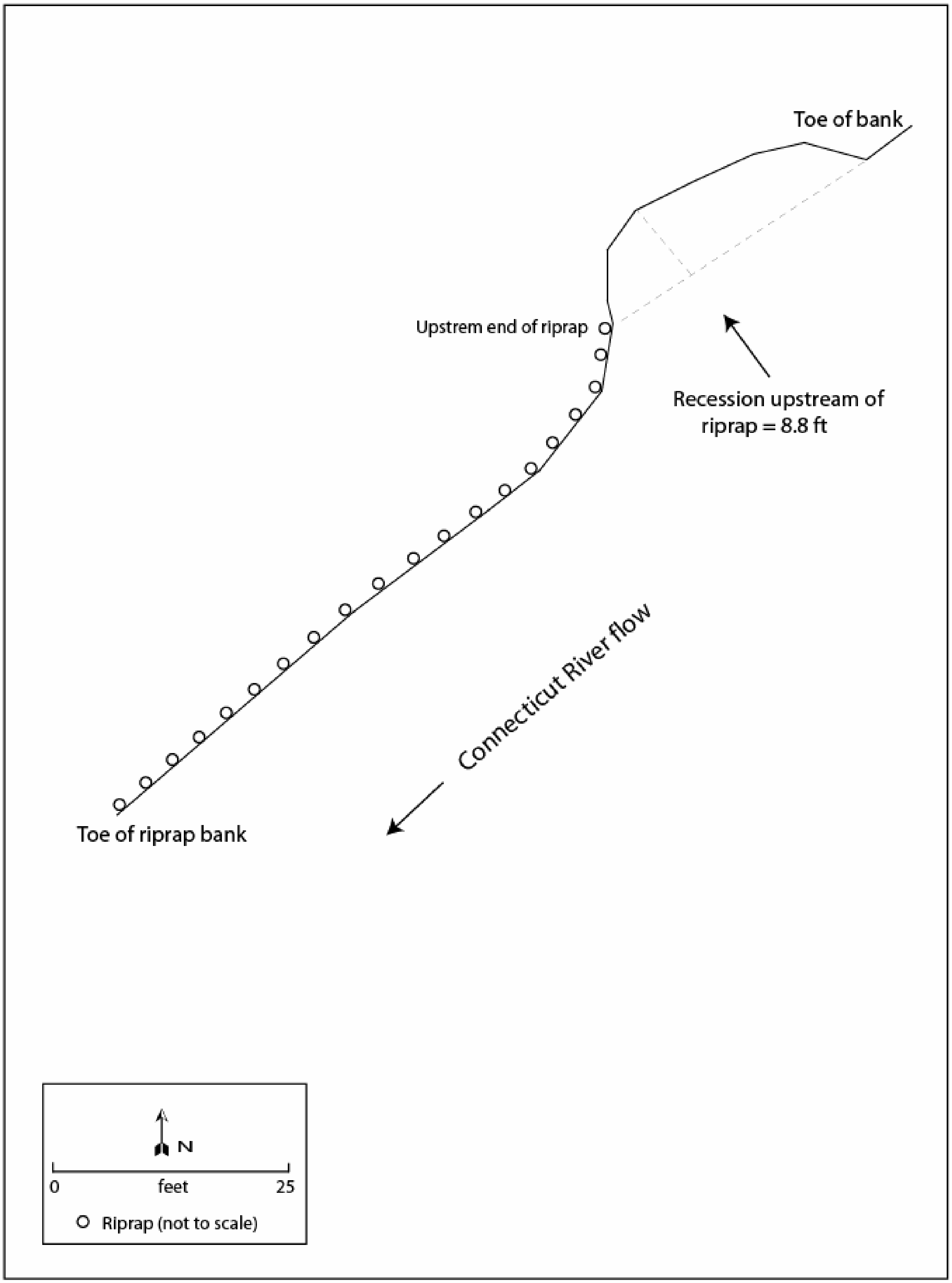
Appendix 8: Map of cross section locations.

APPENDIX 9

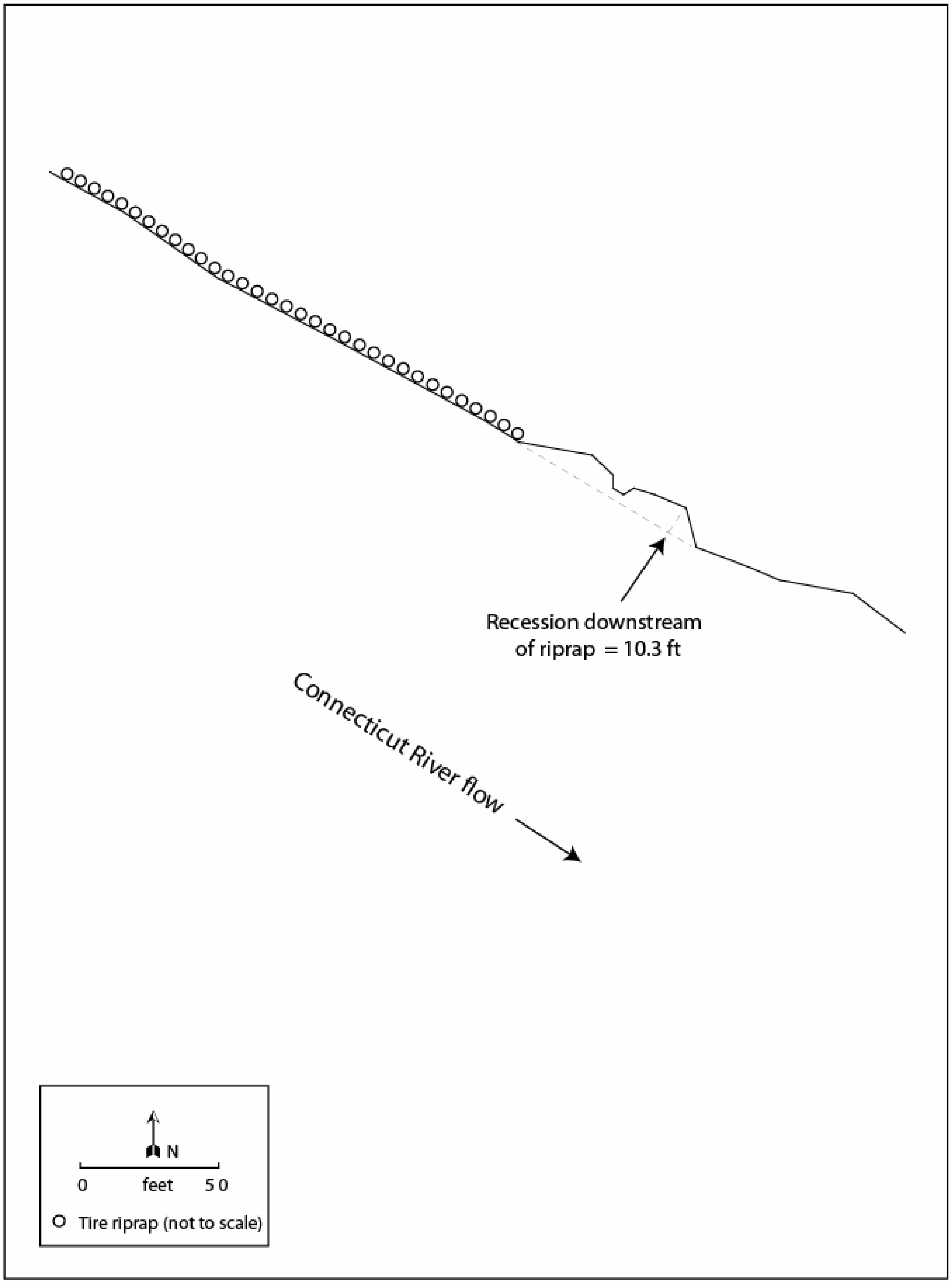
Surveys of Bank Recession Adjacent to Riprap



Appendix 9: Bank recession rate site map.

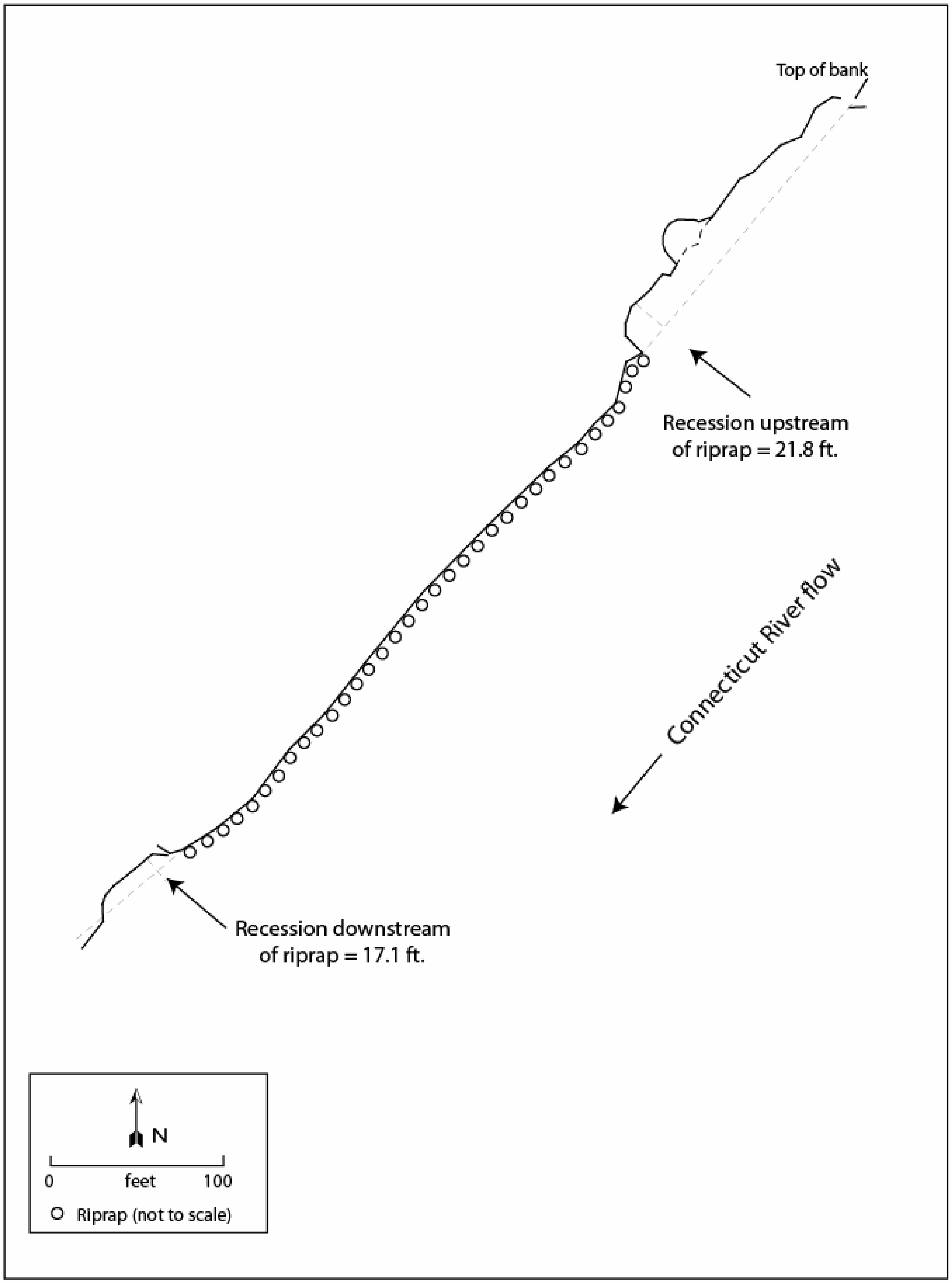


Appendix 9: Site 1 (Wickey Site)

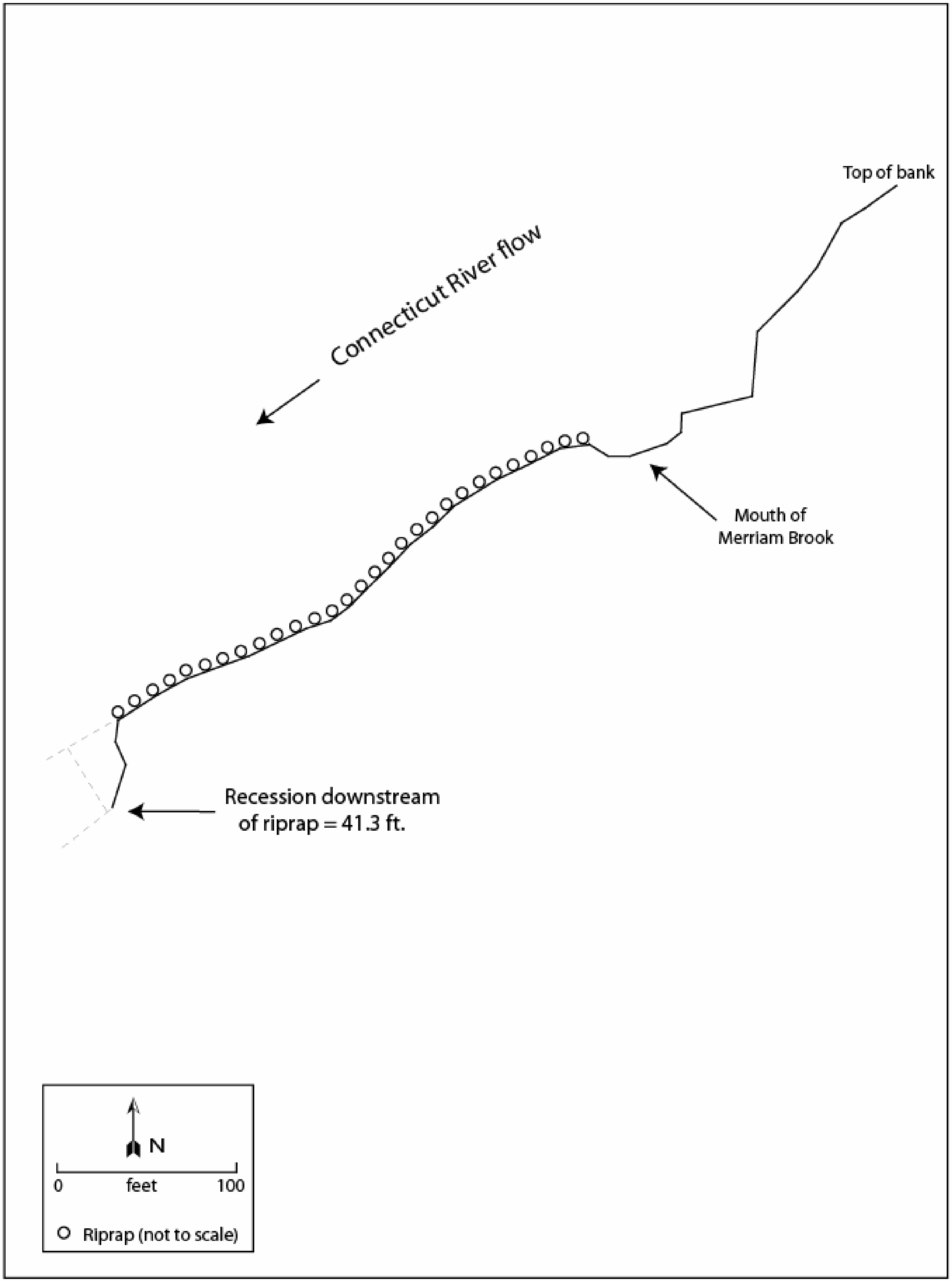


Appendix 9: Site 2 (DS of Rt 10 Bridge)

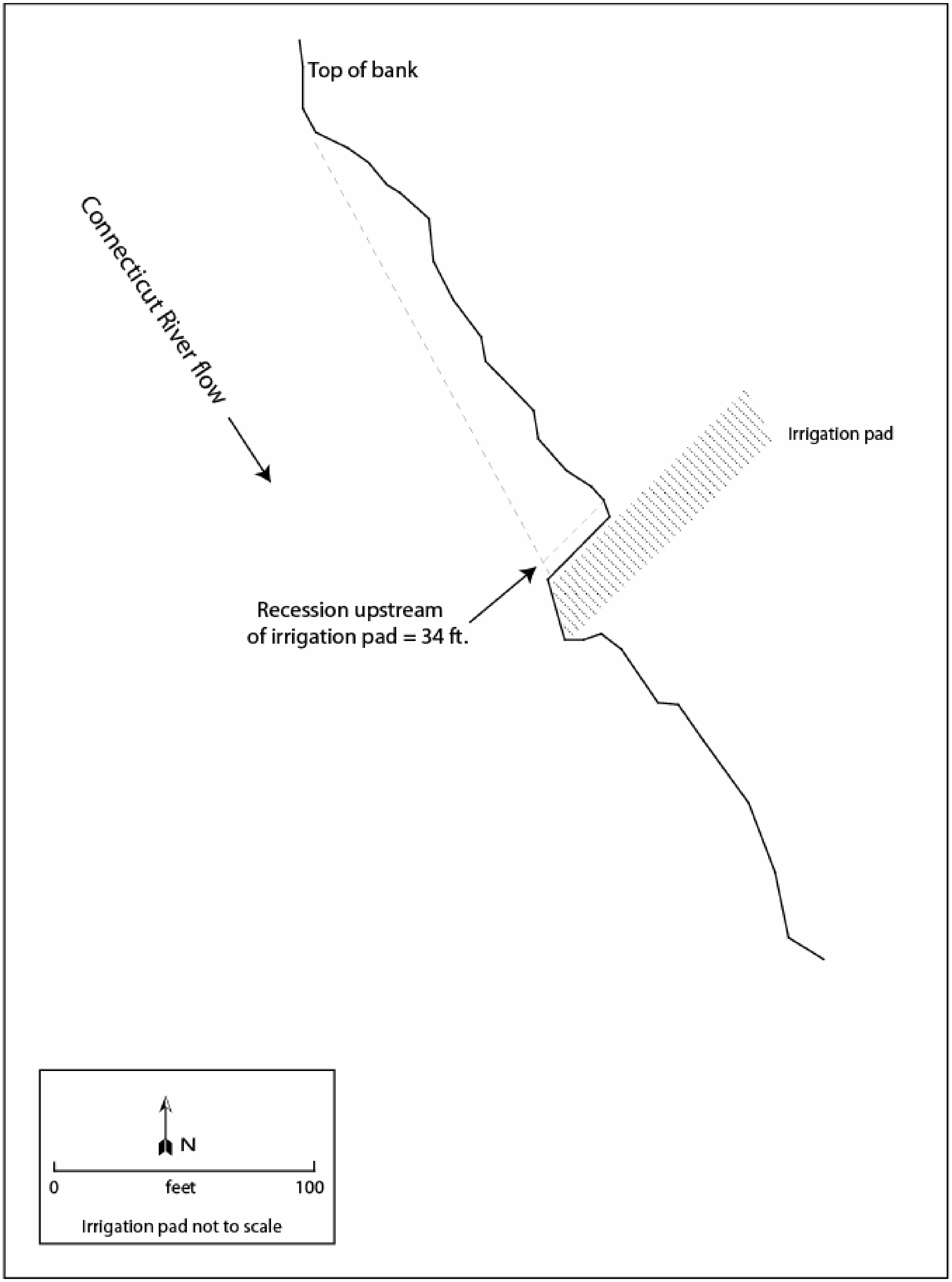
Field Geology Services
Fluvial Geomorphology



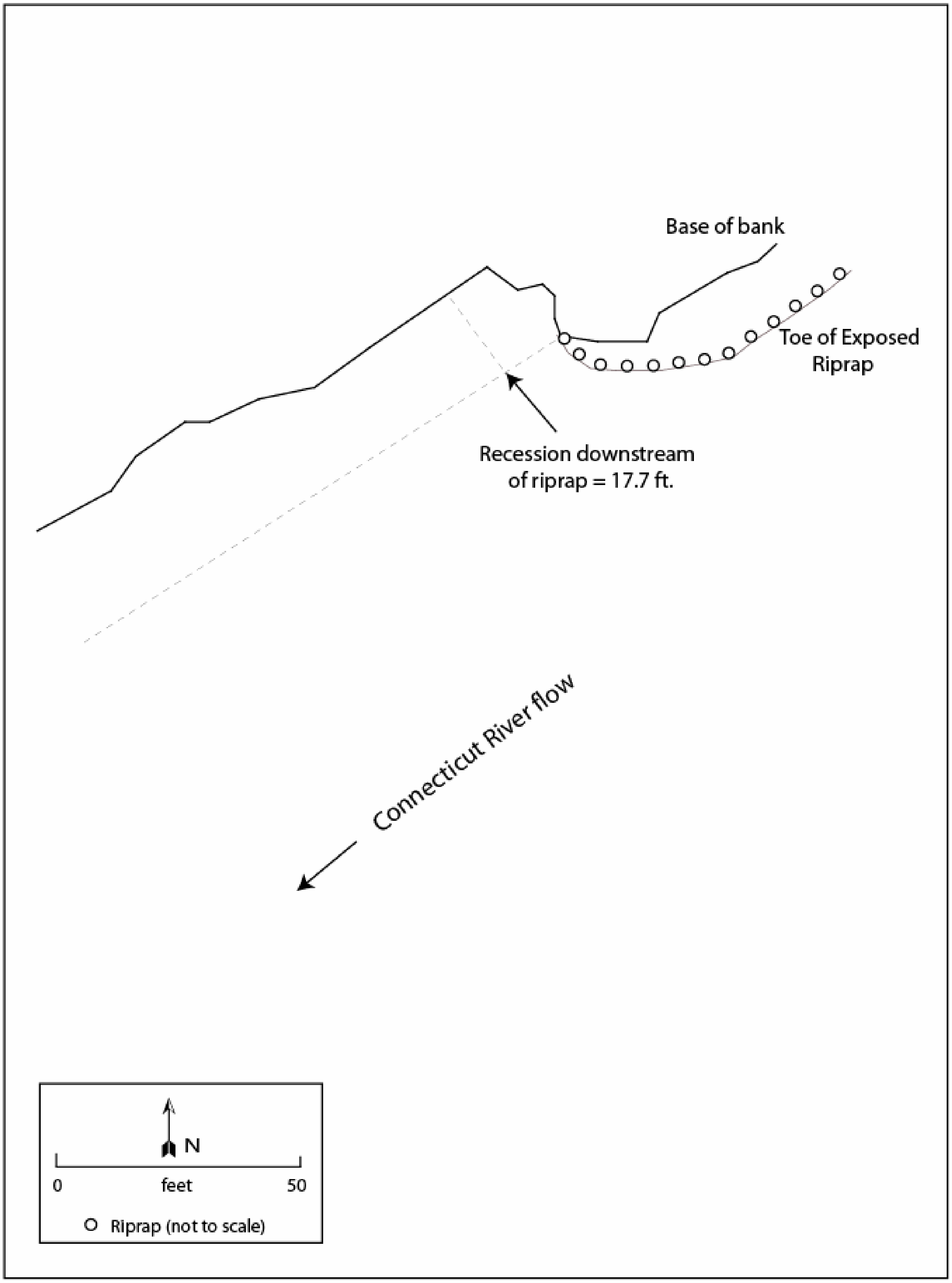
Appendix 9: Site 3 (Munn's Ferry Road)



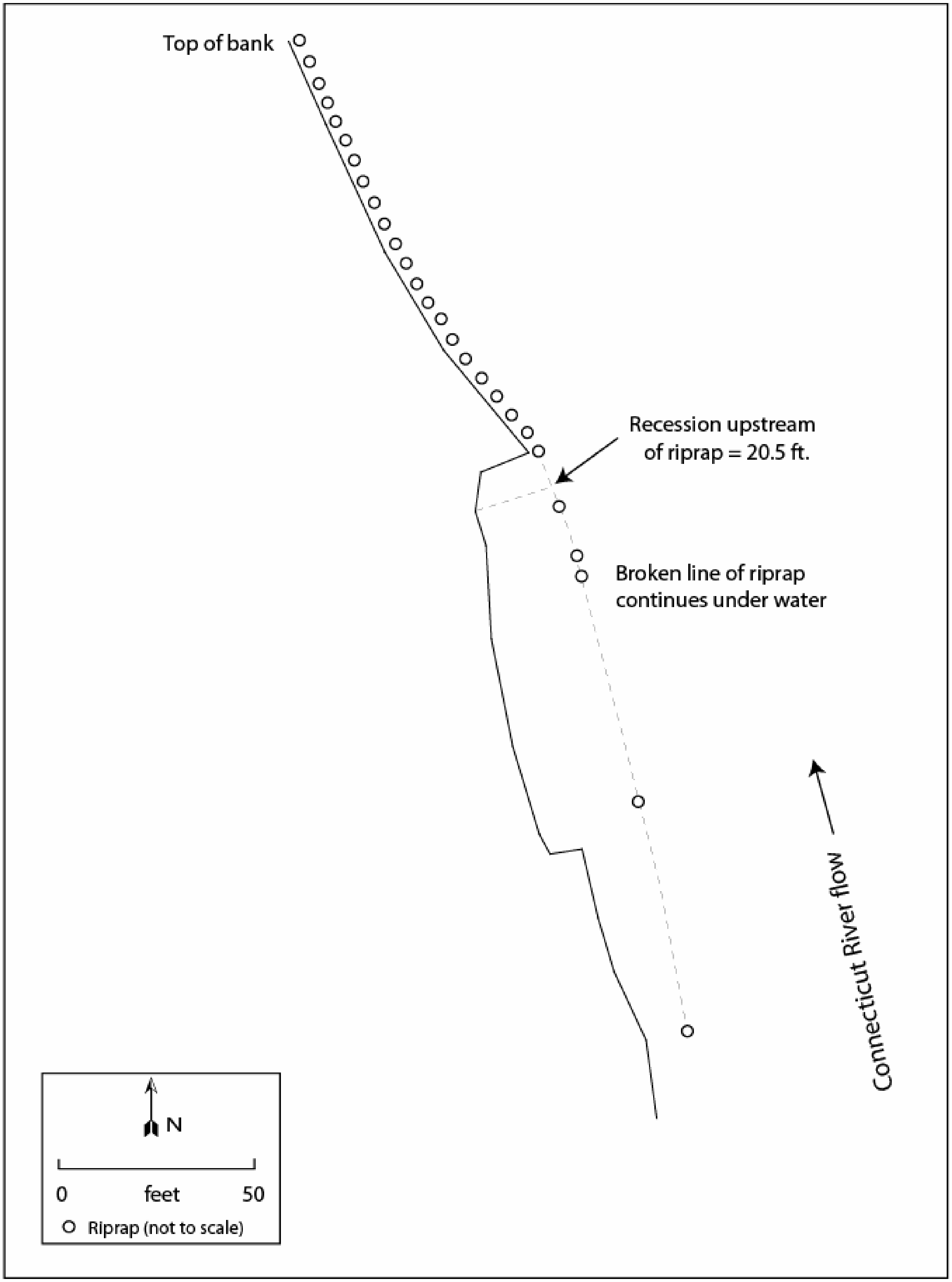
Appendix 9: Site 4 (Munn's Ferry Picnic Area)



Appendix 9: Site 5 (L'etoile)



Appendix 9: Site 6 (Split River)



Appendix 9: Site 7 (Barton Cove)