TRANSCANADA HYDRO NORTHEAST INC.

ILP Study 2 and Study 3
Riverbank Transect and Riverbank Erosion Studies

Final Study Report

In support of Federal Energy Regulatory Commission Relicensing of:

Wilder Hydroelectric Project (FERC Project No. 1892-026)
Bellows Falls Hydroelectric Project (FERC Project No. 1855-045)
Vernon Hydroelectric Project (FERC Project No. 1904-073)

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EXECUTIVE SUMMARY

The Riverbank Transect Study (ILP Study 2) and Riverbank Erosion Study (ILP Study 3) were conducted to characterize the types, rates, and processes of erosion on over 120 river miles of the Connecticut River from Newbury, Vermont and Haverhill, New Hampshire at the upper end of the Wilder impoundment to Vernon, Vermont and Hinsdale, New Hampshire downstream of Vernon dam. The resulting spatial and temporal understanding of erosion provides a context for analyzing the potential causes of erosion. Water level and flow fluctuations caused by the operations of the Wilder, Bellows Falls, and Vernon Hydroelectric Projects are considered within the context of naturally occurring flows and water level fluctuations.

This final study report incorporates additional data analysis and results related to effects of velocity and shear stress; additional data presentation in response to stakeholder comments on the initial study report filed August 1, 2016 and in FERC's November 29, 2016 Study Plan Determination; and adds clarifications as summarized in TransCanada's October 31, 2016 Response to Comments on the initial study report.

Bank erosion in the study area is a cyclic process that begins with the formation of notches and overhangs at the base of the bank. The resulting over-steepening at the bank's base destabilizes the upper bank generating planar slips, rotational slumps, topples, and flows that transfer bank material downslope. Material supplied from the erosion of the upper bank accumulates at the base of the bank and can ultimately lead to the stabilization of the bank unless the sediment and fallen trees are removed by river currents, wave action, groundwater seepage, or other forces. If the material is removed, the notching at the base of the bank can begin afresh and the cycle of erosion repeated. Similar erosion processes are documented in numerous peer-reviewed publications and are consistent with observations made throughout the study area and with previous observations made upstream of the study area in portions of the river unaffected by hydroelectric operations. The results from eight rounds of monitoring extending from November 2013 to September 2015 at 21 different sites demonstrate that the erosion cycle extends for more than two years even at the most actively eroding sites. Consequently, annual vegetation can overtake an eroding bank and give the appearance of stability even though the bank is actively eroding over time periods extending two years or more.

Nearly 40 percent of the riverbanks in the study area were mapped as unstable during bank stability mapping completed in 2014. The unstable banks are comprised of three categories used to characterize bank conditions on over 250 miles of mapped bank: eroding, vegetated eroding, and failing armor. Eroding banks consisted of those banks that had steep well exposed un-vegetated scarp surfaces along which bank material had slid down the slope. Vegetated eroding banks had erosion scarps obscured by vegetative growth, so were unlikely recognized as eroding banks in earlier mapping efforts but are considered as unstable as those banks mapped as eroding. The vegetated eroding banks may develop during the period in the cycle of erosion where eroded bank materials are accumulating at the base of the bank and temporarily buttressing the upper bank from further erosion. Consequently, the eroding and vegetated eroding banks are both part of the same erosion process. The failing armor category also represents banks that are as equally unstable as eroding banks but occur where previous bank armoring has failed either partially or completely due to ongoing erosion. The percentage of unstable bank largely holds steady in the impoundments and riverine sections alike such that no hydroelectric project is associated with greater rates of erosion than another despite differences in the magnitude of WSE variations between projects.

Several sources of information were used to understand long-term trends and rates of erosion including two years of monitoring, resurveys of previous land surveys, georeferencing of historical aerial photographs, and multiple erosion mapping efforts. Multiple repeat surveys of the riverbank at three locations in the study area demonstrate that long-term erosion rates (extending over periods of at least nine years and as many as 54 years) are highly variable in the study area ranging from nearly 10 ft/yr to 0.3 ft/yr. Two years of erosion monitoring at 21 sites (Study 2) documented bank recession at three sites with an erosion rate possibly as high as 3.9 ft/yr (but with only one recession event at each of the three sites a definitive rate cannot be established). The absence of any bank recession at 18 of 21 sites (with 12 of those 18 sites mapped as unstable) suggests erosion rates over much of the study area are more consistent with an erosion rate of 0.3 ft/yr.

Analysis of georeferenced aerial photographs from 1939/40, 1953/55, 1970/75, and 2010 corroborate rapid bank erosion rates along short lengths of the river but also demonstrate minimal to no change has occurred over most of the study area. The historical aerial photographs also suggest that in the limited areas where significant erosion has occurred the erosion rate in the Bellows Falls and Vernon impoundments has declined significantly (by nearly 50% in Bellows Falls impoundment and by nearly 100% in Vernon impoundment). A slight increase in erosion rates may have occurred along portions of upper Wilder impoundment.

Finally, comparisons of erosion mapping completed in 1958, 1978, and 2014 suggest that 75% of the riverbanks have been stable throughout the entire 56-year period spanning the first and last maps. Consistent with the findings from historical aerial photographs, the overall amount of erosion appears to have declined between 1958 and 2014 for the study area as a whole with the most dramatic declines in the Bellows Falls impoundment and to a lesser extent in the Vernon impoundment. Erosion in Wilder impoundment appears to have increased through the same time period, but the level of erosion has declined since 1978.

Erosion occurs when the driving forces of erosion exceed the resisting forces of the bank. Natural conditions are an important control on both with limited bank resistance associated with the loose unconsolidated bank material that predominates in the study area. Gravitational driving forces are increased along high banks where the river encounters old river and glacial terraces. Significant bank recession at the erosion monitoring sites occurred only through the winter and early spring months when the banks' resistance to erosion is reduced by freeze-thaw activities and increased pore-water pressures when spring flood levels recede. Erosive forces acting on the bank are also greatest during the passage of peak flows that generally occur in the early spring.

The notching at the base of the banks that initiates the cycle of erosion can result from a variety of potential factors such as flood flows, wave action, seepage forces generated by natural groundwater flows, or water level fluctuations. Material eroded from the upper bank accumulates at the base of the bank and if removed transverse to the bank by seepage forces or wave action can ultimately lead to the creation of a gently sloping beach face and stabilization of the bank.

Continuance of the erosion, however, ultimately depends on flood flows carrying accumulated material downriver so notching can once again occur at the base of the unprotected and more vertically oriented banks. Comparisons of velocity measurements taken during normal project operations with estimates of flood flow velocities determined through hydraulic modeling show sediment entrainment is unlikely in the impoundments and very limited in the riverine sections during normal project operations, while flood flows are capable of sediment transport throughout the study area. The magnitude of water surface fluctuations in the study area is less than 2.0 ft for 75% of the study area's length so hydraulic gradients between groundwater levels in the bank and the adjacent river level are likely small, whereas waves breaking against the bank at the same elevation as water level fluctuations may generate stronger erosive forces. Given the significant changes in the rate and amounts of erosion documented through historical aerial photography and multiple mapping efforts, respectively, normal project operations cannot adequately explain the observed patterns of erosion as a function of project operations. Project operations over the term of the current licenses have reduced daily fluctuations and overall drawdown extents in all three projects due in large part to increased inflows into Wilder from upstream hydroelectric projects, better coordinated operations, and crest control systems. Normal project operations over the past 10 years or more have remained stable and resulted in the narrowest range of impoundment fluctuations in the history of the projects. Attempting to identify a single cause for erosion fails to recognize that multiple processes operate collectively to effect change on the riverbanks through space and time. The role of flood flows in removing bank stabilizing material at the base of an eroding bank is a major factor and continually perpetuates erosion throughout the entire project area. Comparison between erosion and average channel shear stress levels suggest numerous other factors, such as bank height, control where erosion occurs during those flood events.

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List of Abbreviations

CRJC	Connecticut River Joint Commissions
CRWC	Connecticut River Watershed Council
CRREL	Cold Regions Research and Engineering Laboratory
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FWS	U.S. Department of Interior, Fish and Wildlife Service
GIS	Geographic Information System
ILP	Integrated Licensing Process
ISR	Initial Study Report
LiDAR	Light detection and ranging
NHDES	New Hampshire Department of Environmental Services
NHFGD	New Hampshire Fish and Game Department
NRCS	U.S. Natural Resources Conservation Service
PAD	Pre-Application Document
RSP	Revised Study Plan
SPD	Study Plan Determination
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
VANR	Vermont Agency of Natural Resources
WSE	Water surface elevation

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1.0 INTRODUCTION

The Riverbank Transect Study (ILP Study 2) and Riverbank Erosion Study (ILP Study 3) were conducted to identify current locations of erosion, monitor the rate of erosion at selected sites, characterize the character and severity of erosion, and identify potential causes underlying the erosion within TransCanada's Wilder, Bellows Falls, and Vernon project-affected areas.

This final study report incorporates additional data analysis and results related to effects of velocity and shear stress; additional data presentation in response to stakeholder comments on the initial study report filed August 1, 2016 and in FERC's November 29, 2016 Study Plan Determination; and adds clarifications as summarized in TransCanada's October 31, 2016 Response to Comments on the initial study report.

In their study requests, the Federal Energy Regulatory Commission (FERC), New Hampshire Department of Environmental Services (NHDES), New Hampshire Fish and Game Department (NHFGD), Vermont Agency of Natural Resources (VANR), the Connecticut River Watershed Council (CRWC), and others identified water level fluctuations and flow peaking related to Wilder, Bellows Falls, and Vernon project operations as a potential contributing factor to bank erosion and soil loss along the banks of the Connecticut River.

Although designated as separate studies in the August 2013 Revised Study Plan (RSP), results of these two studies are presented in this consolidated report, given the overlapping nature of study goals and objectives.

The RSP for Study2 was modified by FERC in its September 13, 2013, SPD with the following specific changes.

- Flow values that would trigger additional non-spring runoff high-flow event surveys are flows greater than 35,000 cubic feet per second (cfs) at Wilder, 44,000 cfs at Bellows Falls, and 49,000 cfs at Vernon.

- The study area includes an additional erosion monitoring site (for a total of 21 sites) at the Vernon dam east bank (Study 2 site # 02-VR-01). This site is currently the subject of ongoing biennial monitoring being conducted separately from relicensing studies.

The RSP for Study 3 was modified by FERC in its September 13, 2013, SPD with the following specific change.

- The study's analysis will include a correlation of visible indicators of erosion with project-caused water-level fluctuations at the 21 transect locations established in the Riverbank Transect Study (Study 2).

In addition to utilizing data collected as part of Historical Riverbank Position and Erosion Study (Study 1 [Field Geology Services and Normandeau Associates, 2016]), the Hydraulic Modeling Study (Study 4 [GEI, 2016]), and the Operations Modeling Study (Study 5, [Hatch, 2016]), data analyzed as part of Studies 2 and 3 came from information gathered from Light Detection and Ranging (LiDAR) data collected by TransCanada, topographic maps, aerial photographs, topographic surveying, and field mapping. The acquired data are compiled into appendices introduced in the following sections. Some of the findings herein are based on data presented in other studies, particularly Study 1, and as a consequence, are referenced here but not reproduced.

2.0 STUDY GOALS AND OBJECTIVES

The goal of the Riverbank Transect Study (Study 2) and Riverbank Erosion Study (Study 3) was to provide data relative to erosion in project-affected areas in order to consider in a reasoned way the potential effect and contribution of project operations on erosion. Documentation of the location, types, rates, and severity of erosion throughout the study area as well as characterizing the natural conditions (e.g., soil composition, valley confinement) and human influences (e.g., agricultural practices, bridges, project operations, etc.) potentially impacting that erosion provides an opportunity to quantify the spatial distribution of erosion relative to other factors and analyze the potential cause of erosion in the project-affected areas. FERC contends (in its March 1, 2013 Pre-Application Document (PAD) Deficiencies, Additional Information Requests, and Comments letter) that although erosion, in and of itself, is not necessarily an adverse effect, areas of excessive erosion that are a direct result of project operations or that may be having an adverse effect on another resource are of concern. Potential resources that may be affected are aquatic, terrestrial, cultural, recreation, and/or socioeconomic.

The primary objectives of these two studies were to:

- Monitor riverbank erosion at selected sites in the impoundments and project-affected riverine reaches below Wilder, Bellows Falls, and Vernon dams (Study 2);

- Determine the location of erosion in project-affected areas and compare these locations with previously compiled erosion maps (e.g., Simons et al., 1979);

- Characterize the processes of erosion (e.g., seepage, slumping, and slips);

- Ascertain the likely causes of erosion (e.g., high flows, groundwater seeps, eddies, and water-level fluctuations related to project operations); and

- Identify the effects of shoreline erosion on other resources (e.g., riparian areas and shoreline wetlands, rare plant and animal populations, water quality, and aquatic and terrestrial wildlife habitat).

The results of Study 1 (Historical Riverbank Position and Erosion Study [Field Geology Services and Normandeau Associates, 2016]) were also used to identify the character, rates, and causes of erosion. While Study 1 collected previous mapping data and created the GIS database to allow comparisons of the amount and locations of erosion through time, a thorough analysis of those results are provided herein. Although the erosion monitoring only occurred at 21 sites along 120 mi of river, the results can be used to better understand the rates of erosion elsewhere in the study area by comparing the mapped bank stability conditions completed as part of Study 3 with bank stability conditions throughout the study area (i.e., similarly mapped bank conditions may reflect similar erosion rates). Taken together, the three related erosion studies are intended to provide information on the association and effect of project operations on active erosion at various locations within, or affected by, the three projects.

3.0 STUDY AREA

The study area (Figure 3.1) included the shoreline of the Wilder, Bellows Falls, and Vernon impoundments, as well as the shoreline of the riverine reaches downstream of the Wilder and Bellows Falls dams, and to approximately 1.5 miles downstream of Vernon dam to the lower extent of Stebbins Island.

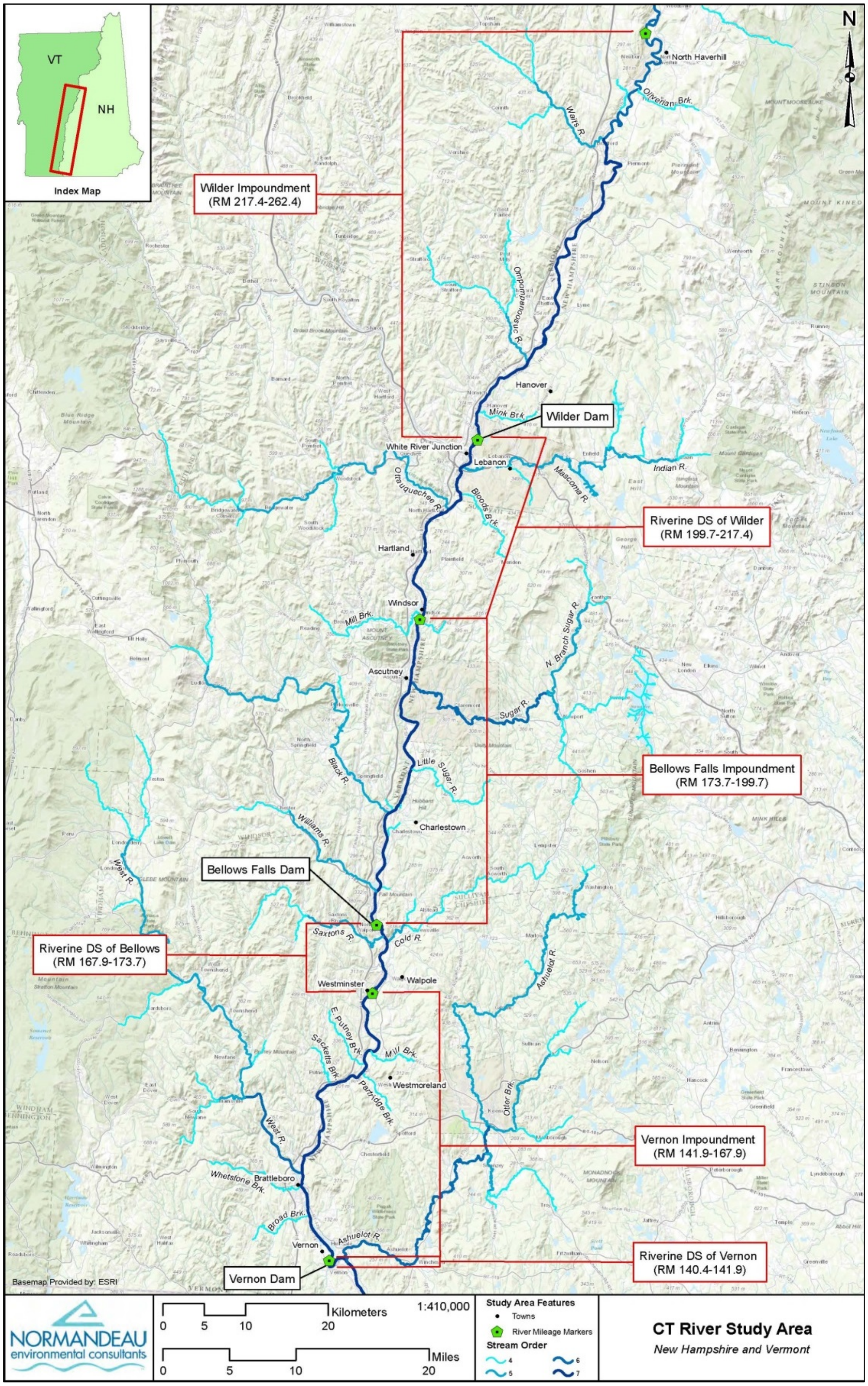


Figure 3.1. Study area.

4.0 METHODS

The following methods were employed to complete Studies 2 and 3:

- Review published literature on riverine and reservoir erosion and additional geological/hydrological studies completed within or near the study area;
- Characterize watershed conditions such as tributary influences, valley constrictions, and other natural factors that could potentially influence the distribution of erosion;
- Analyze historical aerial photographs compiled as part of Study 1;
- Select and establish 21 erosion monitoring sites that cover a range of soil types, stratigraphic conditions, vegetation densities, erosion types, bank slopes (and other morphological characteristics), water-level fluctuations, and peaking flow conditions;
- Conduct repeated surveys, take ground photographs, and collect water-level monitoring data at the erosion monitoring sites at least four times per year for 2 years;
- Conduct a bathymetric survey of the entire river channel adjacent to the 21 Study 2 monitoring sites to determine channel depth and morphology;
- Describe stratigraphic conditions at the 21 Study 2 erosion monitoring sites;
- Compile and refine (using LiDAR and field checking) surficial geological maps of the study area to characterize subsurface conditions and identify valley constrictions;
- Field mapping of bank conditions including severity and types of erosion;
- Conduct topographic surveying at select sites to characterize observed bank conditions (i.e., different types of erosion); and
- Analyze hydraulic modeling data to provide information on flow velocity, stage (water surface elevation or WSE), and shear stress impacting riverbanks in the study area.

The results and discussion (Section 5.0) is divided into subsections based on the methods outlined above. For simplicity and clarity, further information regarding the methods used for this study is integrated, as warranted, into Section 5.0.

5.0 RESULTS AND DISCUSSION

The data derived from each study method described in Section 4.0 and a discussion of the results is presented in the subsections below.

5.1 Literature Review

The literature review included studies related to the Connecticut River valley in or near the study area as well as studies related to bank erosion more broadly.

5.1.1 Connecticut River Valley Studies

The Pre-Application Documents (PADs) for the Wilder, Bellows Falls, and Vernon projects contain considerable information on the natural history and watershed characteristics of the Connecticut River valley as well as information on the history and operating parameters of the three hydro-electric projects. *Where the Great River Rises* produced by the Connecticut River Joint Commissions is also an excellent source of information on the watershed characteristics, natural history, and human history of the Connecticut River valley (Brown, 2009). The reader is referred to these documents for general information. A more specific discussion of previous Connecticut River valley studies pertinent to erosion issues is provided below.

A number of previous efforts have been undertaken to map erosion on the Connecticut River. TransCanada's predecessors operating the Wilder, Bellows Falls, and Vernon projects mapped erosion periodically throughout most of the study area from 1951 to 1991 with the original maps, reports, and ground photographs in TransCanada's archives (see Study 1 report [Field Geology and Normandeau, 2016]). Prior to mapping the location of erosion in 1951, ground photographs were also taken of several erosion sites between 1942 and 1948. The U.S. Army Corps of Engineers (USACE) mapped bank erosion on the Connecticut River in 1978 from Turners Falls Dam in Massachusetts to the upstream end of the Wilder impoundment (Simons et al, 1979). In addition to showing locations of erosion, the USACE study attempted to identify the causal mechanisms of erosion. High shear stress exerted on the banks and sediments built up at the base of banks during flood flows was considered the most significant cause of erosion with impoundment fluctuations, boat waves, and several other processes considered to be of secondary importance. Erosion was also mapped in the 1990's for the entire length of river in Vermont and New Hampshire (including the study area) by individual County Conservation Districts for the Connecticut River Joint Commissions in a multi-year effort (e.g., Kennedy, 1992). A more comprehensive erosion mapping effort of the study area was completed during the 2010 field season in advance of TransCanada's relicensing process for the Wilder, Bellows Falls, and Vernon projects (Kleinschmidt, 2011). The erosion mapping data from 1958 (the earliest complete mapping of the entire study area) and 1978 (also covering the entire study area) were digitized and provided as GIS shapefiles in the Study 1 report. Further details about these erosion mapping efforts are described in the comparison with erosion mapping conducted for these studies from 2014 (see Section 5.6.5b).

Additional erosion mapping along the Connecticut River has been completed outside of the study area. Erosion mapping in 1990 was completed by the USACE (in a follow-up to the 1978 effort) but extended only from the Turners Falls Dam north to the Massachusetts state line (USACE, 1991a). A second independent mapping effort was completed of the entire Turners Falls impoundment (upstream to the base of Vernon dam) in 1990 (NDT, 1991), providing a unique opportunity to determine the variation in results that arise when different individuals and different methods are used for mapping erosion (Field, 2007a). Since 2000, erosion mapping of the Turners Falls impoundment has occurred every three to five years with a thorough analysis of all pre-2007 erosion mapping completed by Field (2007a). The techniques and limitations of comparing erosion mapping from different years discussed by Field (2007) form the basis for comparing 2014 erosion mapping completed as part of this study with previous mapping efforts in the study area (see Section 5.6.5b).

Upstream of the study area, the Connecticut River Joint Commissions mapped erosion and other bank features along 85 miles of a largely free-flowing portion of the Connecticut River from Pittsburg, NH to Gilman, NH (Field, 2004). Discharges from Murphy Dam in Pittsburg, NH do not fluctuate on an hourly, sub-daily or daily basis. Operation of this storage reservoir augments low flows, curtails discharge, and impounds high natural inflows in such a way as to reduce flood peaks downstream of the dam. Along this 85-mile section of the river, 26 percent of the bank length was mapped as eroding, 23 percent was sensitive to future erosion, and 17 percent of the banks were armored. While some erosion on a free-flowing alluvial river is expected naturally as the channel migrates across its floodplain particularly in regions that experience high, annual flood flows in the spring, artificial channel straightening prior to 1925 was considered a primary cause of continuing erosion on the upper Connecticut River along with sediment inputs from tributaries and high banks of glacial outwash sediments forming sand/gravel bars that divert erosive flows into the adjacent banks. Human activities, including land clearance in tributary watersheds and rerouting the river against high banks along the valley edge, have likely exacerbated sediment inputs to the river.

In another study on the upper Connecticut River, bank erosion rates on a single meander bend near Stratford, New Hampshire just downstream of a recent meander cutoff accelerated from 10.8 ft/yr before the meander cutoff to 13.5 ft/yr after the cutoff (Black et al., 2010), demonstrating two important points. First, bank erosion can occur very rapidly on free-flowing sections of the Connecticut River and second, erosion rates can be significantly altered by localized changes in channel gradient associated with the shortening of the river at a meander cutoff. Similarly, the 1840 cutoff of the Mt. Tom meander on the Connecticut River in Hadley, Massachusetts caused significant increases in erosion rates in the Hadley-Hatfield Meadows for a decade or two until the knickpoint (i.e., increased slope) in the river's longitudinal profile resulting from the cutoff was attenuated by erosion (Jahns, 1947).

A number of other studies have been completed in the Connecticut River valley, including within the study area that are not explicitly focused on bank erosion but nonetheless are potentially informative for understanding the types, locations, and causes of erosion in the study area. Several studies have been completed on the influence of ice on bank erosion and river processes on the Connecticut River, in part due to the presence of the USACE Cold Regions Research and Engineering Laboratory (CRREL) in Lyme, New Hampshire. Ice jam flooding is common throughout New Hampshire with 11% of all recorded ice jams in the state occurring on the Connecticut River (USACE, 2000). Within the study area, the area near Windsor, Vermont has been a focus of research. Calkins et al. (1976) used low-altitude aerial photography and hydraulic modeling to study the formation and breakup of ice between Sumner Falls and Chase Island in the Wilder riverine reach where frequent ice jams have occurred in the past. While no single factor was attributed to the formation of ice jams, Calkins et al. (1976) found that ice jams were more likely to form during low discharges when the likelihood for grounding (i.e., ice hitting the river bottom) was higher. The processes of ice breakup were also investigated near the Cornish-Windsor covered bridge, a structure damaged multiple times by ice jams, in order to identify possible strategies for limiting impacts to the bridge (Ferrick et al., 1988). While these studies do not discuss the potential for ice jams to cause erosion, the report accompanying the erosion inventory for Sullivan and Cheshire Counties, New Hampshire and Windham and Windsor Counties, Vermont refers to ice backing up behind Bellows Falls dam in January 1996, causing severe erosion along 550 ft of bank and threatening river front homes and New Hampshire State Route 12. Other studies, not focused on the Connecticut River, have described how ice jams can cause erosion of river beds and banks (White et al., 2007; Tatinclaux, 1998)

Ice is also related to bank erosion processes through the freezing and thawing of soil moisture in bank sediments. Ice expands as it forms and when occurring on riverbanks can dislodge particles from the surface. Ice formation in soils is generally restricted to near-surface areas. The shallow nature of bank erosion along an unstable bank on the Connecticut River in Norwich, Vermont was consistent with freeze-thaw weakening of the soils where soil freezing penetrated only 2.5 ft below the ground surface (Ferrick et al., 2005). In addition to the actual displacement of soil particles by the growth of ice in bank soils, the increase in soil moisture concentrated near the bank surface as a result of freezing leads to an excess of soil moisture upon thawing and, in combination with the disrupted soil structure due to freeze-thaw cycling, can cause large mass failures in addition to surface erosion by rain impacts, river currents, and waves (Gatto, 1995). Since soils are sometimes weakest at the time of thawing compared to any other part of the year (when the excess soil moisture has drained and the interlocking of soil particles once again increases with compaction), freeze-thaw processes can cause more bank recession in cold regions than other processes (Gatto, 1995). Greater erosion rates in the winter on the shorelines of a North Dakota reservoir were attributed to the effects of freeze-thaw processes (Reid, 1993).

If the movement of ice can cause erosion, then the large log drives that occurred annually on the Connecticut River may have also impacted the riverbanks. While these log drives began in the 17th century, the biggest log drives occurred from the mid-19th century to the early 20th century (Gove, 2003). In addition to the direct forceful contact the logs may have had on the riverbanks, the legacy of the log drives remains today in the form of significant channel alterations that occurred along the river to ease the passage of logs. Artificial channel straightening occurred throughout New England, in large part due to log drives, with the resulting channel instabilities leading to accelerated bar growth and bank erosion that persists today on many rivers (Field, 2007b). More than 30% of the river channel was straightened on the upper Connecticut River prior to 1925 but these alterations are still considered a major cause of bank erosion as the river continues to slowly reestablish its former sinuosity (Field, 2004).

Flooding exerts a strong control on the timing and distribution of bank erosion. Significant floodplain scour and deposition occurred during the 1936 and 1938 floods on the Connecticut River but severe bank erosion of up to 150 ft was limited to two meander bends in Massachusetts because of the stabilizing influence of vegetation elsewhere (Jahns, 1947). The 1936 and 1938 floods were able to inundate terraces more than 30 ft above the normal river level and were likely the largest floods on the Massachusetts portion of the river in several hundred years (Jahns, 1947). The earliest written record of a flood along the Connecticut River is from 1635 which washed away and buried corn crops (Thomson et al., 1964). River stage information for significant floods is available back to 1639 from Hartford, Connecticut (Jahns, 1947), 1801 from Springfield, Massachusetts (Thomson et al., 1964), and 1854 from Holyoke, Massachusetts (Thomson et al., 1964). In response to the 1936, 1938, and other 20th century floods, the Connecticut River Flood Control Compact was signed into law by President Eisenhower in 1953 to assure adequate storage for flood waters on the Connecticut River and its tributaries for the protection of life and property from floods (Web citation 1). The USACE National Inventory of Dams lists 990 dams in the Connecticut River watershed of which 75 (most on tributaries) are primarily run as flood control facilities (Web citation 2). When combined with state lists, the total number of dams in the watershed exceeds 2,700 (Web citation 3). Other dams, such as the hydroelectric facilities on the Connecticut River, may also play a secondary role in controlling floods. Dams on the Connecticut River in Vermont and New Hampshire impound 54 percent of the river's length (Web citation 3).

The geology of the Connecticut River valley is discussed in the PADs and has broad implications regarding river processes and bank erosion. The valley itself owes its existence to the tectonic boundary that runs its length. Through most of the study area, the floodplain is relatively narrow due to the mountainous valley margins (and glaciogenic terraces) such that meander migration is constrained. While bedrock outcrops are uncommon along the riverbanks (see Section 5.6), valley constrictions created by bedrock that narrow the valley can cause backwatering during floods, deposition of sand/gravel bars, and the development of high amplitude meanders – all of which potentially relate to patterns of bank erosion (see Section 5.2.2). The Connecticut River is unlike most other large rivers in the United States given the numerous bedrock thresholds with broad low gradient valleys upstream (Jahns, 1947) such that generalizations made from studies of other large rivers (see Section 5.1.2) may not necessarily apply to the Connecticut River.

The glacial history of the valley more directly relates to bank erosion as much of the river flows against sediments of glaciogenic origin. Some of the earliest research in the Connecticut River valley focused on establishing a varve chronology from Glacial Lake Hitchcock sediments (Antevs, 1931), a proglacial lake that occupied the Connecticut River valley in the study area when the river valley was blocked behind a natural dam made by a large delta of sand and gravel in the present town of Rocky Hill, Connecticut (Web citation 4) for more than 3,500 years beginning approximately 15,000 years ago as the ice cap retreated north (Web citation 5). Sandy deltas built out into the valley at the mouths of tributaries with the tops of these deltaic sediments serving as indicators of the surface elevation of the lake (Web citation 6). While Glacial Hitchcock sediments might be expected along the river given that the lake extended across the valley (Web citation 5), non-glacial lakes at lower elevations persisted after the draining of Lake Hitchcock (Ridge and Larsen, 1990), so the presence of varved clays or sandy deltaic sediments in the study area cannot be immediately attributed to Glacial Lake Hitchcock. In addition, fluvial sediments, inset into the lake and delta terraces, were deposited as the river became fully established from northern New Hampshire to Long Island Sound. However, in regard to bank erosion studies, the age and origin of the deposits along the river are perhaps less important than the texture and stratigraphy of those sediments. Surficial geology maps are presented in Section 5.5 and provide information on the distribution of clay and other deposits underlaying the terrace surfaces with which they are associated.

5.1.2 Erosion Studies

Bank erosion can be subdivided into five distinct types of movement along a continuum from the dislodging of single particles to the *en masse* movement of large sections of the bank (Table 5.1.2-1; Lawson, 1985). More than one type of erosion can occur at a single site with slides on the upper bank often giving way to sediment 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 height, cohesiveness, and stratification of the sediment. Banks composed of non-cohesive sediments and interlayered cohesive and non-cohesive sediments are the most susceptible to erosion (Winterbottom and Gilvear, 2000). The erosion of non-cohesive sediments such as sand and gravel tends to occur through shallow failure surfaces (i.e., planar slips) or movement of individual particles, whereas rotational slumps (see Table 5.1.2-1) are increasingly likely with greater cohesiveness of the bank sediment (Thorne, 1991).

Table 5.1.2-1. Typical types of slope movements on eroding banks.

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 sediment flows
Sediment 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

Bank erosion occurs when the sum of the forces driving erosion exceeds the resisting strength of the bank material (Easterbrook, 1993, p. 64; Parker et al., 2008). 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 removal of the underlying support (e.g., overhanging banks), an increase in the surcharge (i.e., weight) on the bank slope accompanying precipitation or the addition of failed material from upslope, or an increase of lateral stresses that can accompany the formation of ice in cracks or water added to pore spaces. A saturated soil can be double the weight of a dry soil (Thorne, 1991). Bank strength is dependent on bank material properties (such as grain size and cohesion), vegetation (type and amount), and other bank characteristics such as form roughness (i.e., topographic surface irregularities) that effects the magnitude of shear stress acting on the bank (Konsoer et al., 2016).

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). During floods when the river stage is high on the bank, water moves into the bank and then flows back out of the bank after the river level recedes (Hagerty, 1991a). In the case of a rapid drawdown in impoundment or river level, the internal pore-water pressures of the bank sediments continue to reflect the original water level for some time after drawdown, increasing the hydrostatic pressure on the bank face (Lane and Griffiths, 2000). Bank instability results from the increasing pore-water pressures that cause a loss in the cohesion that holds soil particles together (Rinaldi et al., 2004). Bank erosion quite commonly will be greatest during the recession of high water flows rather than during the high flow event itself (Twidale, 1964; Thorne, 1982; Rinaldi et al., 2004), because the pore pressure of the saturated bank sediments exceeds the confining pressure exerted on the bank once the flow level drops (Fox and Wilson, 2010). The development of only minor pore-water pressures is sufficient to trigger mass failures in fine-grained, weakly cohesive soils (e.g., silt and sand) that are not even at a completely saturated condition (Rinaldi et al., 2004). However, bank failure can occur during the rise of floodwaters where loose coarse sediment is present at the base of the bank due to the loss of sediment cohesion despite the confining pressure of the high flow (Nardi et al., 2012). The hydrostatic pressure differences (between the bank sediments and free air surface above the lowered river stage) and consequently bank instability, will persist the longest in less permeable finer grained sediments as groundwater levels in the bank sediments will more slowly equilibrate to the changing impoundment (or river) level (Lawson, 1985). Water surface elevation fluctuations due to hydropower operations can also lead to positive pore-water pressures in the bank but such fluctuations typically operate over a much smaller portion of the total bank height and for shorter durations of time than results from natural flood flows.

In addition to the bank instability created when pore water pressures exceed the confining pressure of the river (or, more accurately, the confining pressure of air against the bank after the river level has receded), bank instability also results from the water seeping out of the bank as the groundwater drains back into the river. Seepage erosion is defined as the entrainment of soil, sediment, or rock by water flowing through and exfiltrating from a porous medium (on a riverbank, hillslope, or sand bar) (Dunne, 1990; Alvarez and Schmeeckle, 2013). Similar to the changes in pore-water pressures described above, water level fluctuations can also create seepage forces, particularly in finer grained sediments, because of the hydraulic gradient that results between the higher groundwater surface in the bank sediments and the lowered river stage. Not surprisingly, greater rates of seepage lead to greater levels of erosion (Fox et al., 2007). Bank erosion caused by seepage can occur in areas and at times that would not be expected by tractive force erosion generated by the river's flow such as on the inside of meander bends or long after the passage of a flood crest (Hagerty et al., 1995). Seepage erosion can be enhanced where agricultural activities concentrate flow on flat terrace surfaces (Crosta and di Prisco, 1999). Erosion on steep sand bars in the Grand Canyon downstream of the Glen Canyon Dam has been attributed to seepage created by fluctuating water levels (Budhu and Gobin, 1995). A study of landslides in Windsor County, Vermont within the Connecticut River watershed that occurred following a period of heavy rain and melting of a thick snowpack in 1984 showed that some slope failures resulted from increased pore-water pressures in the soil and high seepage pressures associated with the drawdown of impoundment levels on tributaries in response to the flooding (Baskerville and Ohlmacher, 1988).

Slope instability caused by the resulting seepage forces can be enhanced in stratified sediments as the presence of fine-grained impermeable layers promotes movement of water horizontally out of the bank along a single layer rather than along more vertically oriented flow lines (Fox et al., 2007). 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. Small variations in the texture (e.g., amount of clay) of different sedimentary layers, a typical condition in alluvial floodplain soils, can give rise to significant differences in the vertical conductivity of water through the soil and thus lead to lateral seepage flow that increases bank instability (Haggerty, 1991b; Fox et al., 2007; Fox and Wilson, 2010). Erosion of permeable sands above impermeable varved clays has been observed after flood recession in the Connecticut River valley (Jahns, 1947) and in tributary watersheds after periods of heavy rain (Baskerville and Ohlmacher, 1988). While lateral seepage flow typically causes erosion of a permeable layer above a water-restricting horizon (e.g., impermeable clay), erosion can sometimes occur underneath the primary seepage layer (Fox et al., 2007).

The removal of sediment from the bank face that typically occurs when seepage is focused along a single layer can create an overhanging bank (Fox and Wilson, 2010) and eventual collapse of the upper bank above (Hagerty, 1991b). Overhanging banks are most severe in cohesive silt sediments with niches greater than 30 ft possible in extreme permafrost conditions, while overhangs greater than 10 ft in non-cohesive sand and gravel are unlikely in similar settings (Lawson, 1985). However, only a small seepage-induced overhang is needed to greatly reduce the stability of the bank above (Fox and Wilson, 2010). Furthermore, a basal overhang is not necessary for bank failure to occur as changes in pore-water pressures and the associated loss of soil strength are sufficient to create instability without seepage (see above; Rinaldi et al., 2004).

A number of terms have been used in the literature to describe seepage, seepage erosion, and related processes such as piping, sapping, and tunnel scour. Unfortunately, in many cases, different terms have been used to describe the same process and the same term used by various researchers to describe different processes, thus creating confusion in the literature. In particular, piping has been used to describe erosion by: 1) flowing water that entrains particles seeping through and out of a porous medium, and 2) the application of a shear stress to the margins of a macropore (i.e., large open space) that may have formed independently of flowing water (e.g., desiccation cracks [Dunne, 1990]). Although these two processes are not mutually exclusive with one potentially promoting the other, the term “piping” has been further confused by its use as a physical characteristic of a soil (i.e., a conduit in the soil) without reference to its formation by seepage or other erosion process. In an attempt to clarify this confusion, Dunne (1990) recommended that the term “seepage erosion” be applied to the first concept above and “tunnel scour” applied to the second concept above. While Dunne’s (1990) suggestions do not seem to have resolved the confusion during the subsequent 25 years, this study will utilize these terms and will refrain from using the term “piping” so no confusion results as to which of the above processes or soil conditions is being considered by using that term. The term “piping” has been used by landowners and stakeholders in previous study requests and comments to refer to what is termed “seepage erosion” in this report, but “tunnel scour” was also observed in at least two locations (Springfield and Fairlee, Vermont) in the study area (see Section 5.6.1). Another related term is “sapping” which more broadly refers to any erosion caused by undermining, so refers to both seepage erosion and tunnel scour (Dunne, 1990) and can also result from undercutting by river flow (Green et al., 1999).

Regardless of the cause, as material eroded from the upper slope slides, topples, sediment flows, or falls to the base of the bank, the overall slope of the bank is reduced and as a consequence, the gravitationally driven shear stresses acting on the bank decrease. In contrast, bank failure occurs when erosion at the toe of the bank increases the height and angle of the bank to the point that gravitational forces exceed the shear strength of the bank material (Simon et al., 2000; Darby et al., 2007). 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 erosive forces and the bank will remain stable (Thorne, 1991; Simon et al., 2000). Vegetation can take root in the material accumulating at the base of the bank and prevent its removal (Hagerty, 1991a), but generally the disaggregated material accumulating at the bank toe is much less resistant to erosion and the material can be easily removed (Thorne and Abt, 1993). For bank erosion to continue, the accumulated material at the base of the bank must be removed by river transport (Hagerty, 1991b), waves (Hagerty, 1991a), or other processes such as seepage flow (Fox et al., 2007). Such a pattern of bank failure, sediment accumulation at the base, subsequent removal by high river flows, and renewed erosion has been observed along the Connecticut River (Jahns, 1947; Field, 2007a). Removal of sediment from the base of the bank has been observed to occur by frequent small to moderate flood flows during the winter months (Green et al., 1999; Simon et al., 2000) as occurred at several Connecticut River monitoring sites (see Section 5.4). If 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). Erosion on sand bars in the Grand Canyon stops once an equilibrium slope is established regardless of the magnitude and frequency of subsequent water level fluctuations (Alvarez and Schmeeckle, 2012).

In impoundments, wind and boat waves have been identified as a cause of erosion (Gatto and Doe, 1987; Porter, 1993). Over time, waves tend to move sediment away from the bank in an offshore direction, which means that sediment is moved transverse to the bank rather than downstream along the bank as is typical of normal river flow. 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 which is 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 (flood flows), 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 (i.e., magnitude of flow velocities and water level fluctuations) remains essentially unchanged.

Gently sloping beaches formed from eroded sediment transported transverse to the bank (ultimately leading to bank stability) may be similar in appearance to but are genetically distinct from other types of benches that can form on regulated rivers. Where river stage is maintained at a higher level than under unregulated conditions, gently sloping benches typically form below the maintained stage as the bank above that stage erodes at a higher rate than the portion of the bank below that stage regardless of whether the upper bank is eroding at a higher, the same, or a slower rate than before the flow regulation (Hagerty et al., 1995). The slower rate of erosion below the maintained stage may be due to reduced stage fluctuations during floods, reduced flow velocities on the lower bank, and/or reduced seepage from the permanently inundated portion of the bank.

5.2 Watershed Characterization

The project PADs detail many of the general watershed characteristics such as watershed area, physiography of the basin, elevations, and gradients, so the reader is referred to those documents for further details. Provided below is a more detailed description of other watershed conditions that directly impact the river and potentially influence channel morphology and the distribution of bank erosion.

5.2.1 Tributary Influences

Tributaries entering a larger river often have an impact on the morphology, position, and bank stability of the receiving waterbody with multiple examples of this seen throughout the study area. At least 150 tributaries enter the Connecticut River within the study area ranging in watershed size from less than one square mile to several hundred square miles. Many tributaries have deltas building out into the Connecticut River at their mouths (Figure 5.2.1-1). The impact on the Connecticut River can be quite dramatic at the confluence of large tributaries. The Williams River delta building out into the Connecticut River valley in Rockingham, Vermont for thousands of years forced the river up against the opposite valley wall at the apex of a meander that as a whole delimits the outer edge of the delta (Figure 5.2.1-2). By building out across the whole valley, the Williams River delta backwaters the Connecticut River upstream creating low meadows that now extend for 4.4 mi upstream; the channel upstream also has a higher sinuosity than adjacent areas.

Other tributaries show similar, if less dramatic and extensive, impacts, including the Ompompanoosuc River in Norwich, Vermont, and the Mascoma River and Blood’s Brook in Lebanon, New Hampshire. The White River and other large tributaries are not included on this list because they enter the river where the valley is narrow and no floodplain is present onto which a delta can build out. A topographic survey was completed at Blood's Brook to document how the channel morphology has been altered by the boulder delta building out into the river (Figure 5.2.1-3). The river is much narrower where the delta has constricted the channel. Water flows much more swiftly through the constricted areas created by tributaries building out into the channel and often leads to erosion along the opposite bank. Where erosion is not present, the bank as at Blood's Brook, has been armored to prevent erosion.

Figure 5.2.1-1. Delta building out from a small tributary into Vernon impoundment.

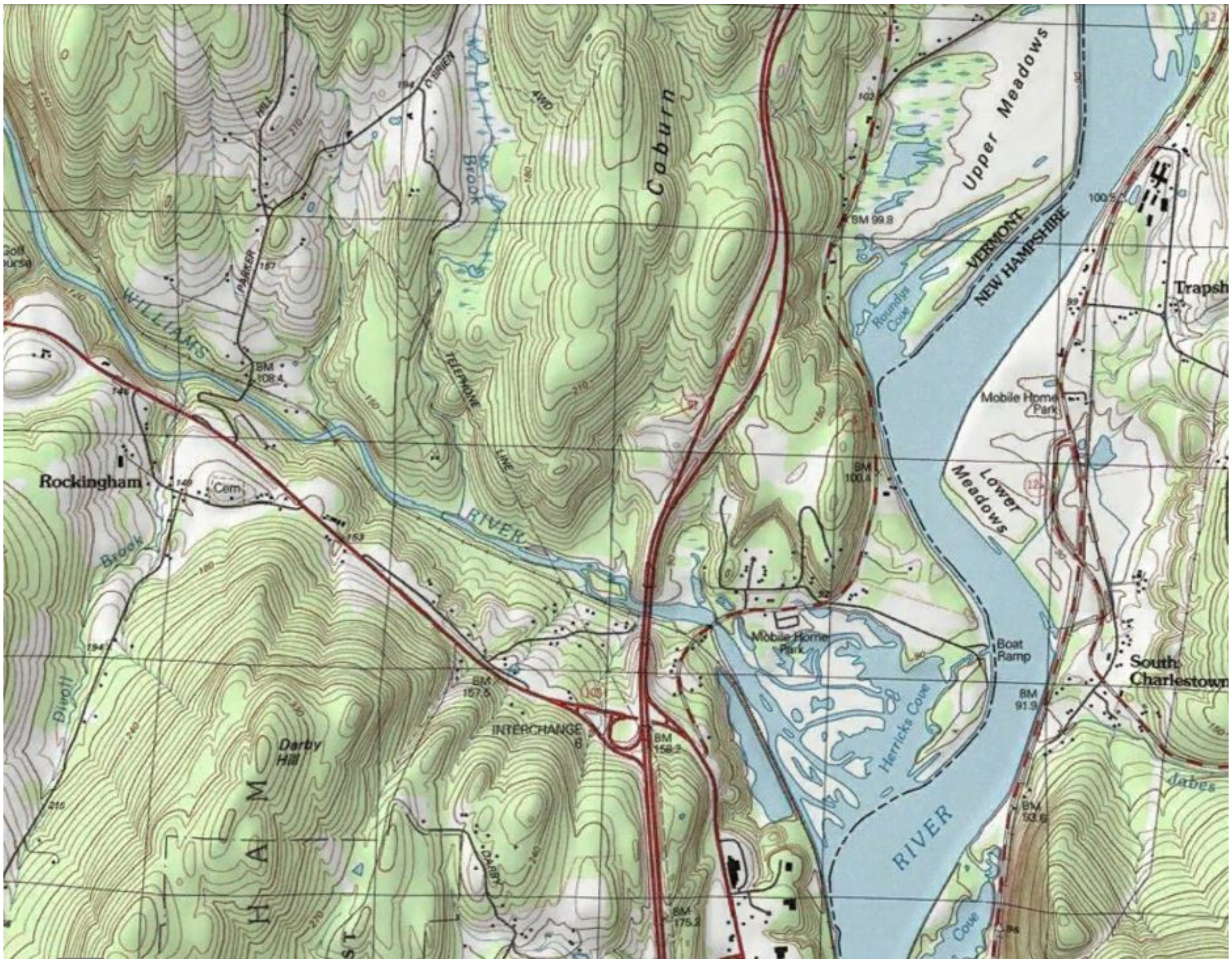


Figure 5.2.1-2. Williams River delta in Rockingham, Vermont forces river to opposite valley wall and backwaters upstream to form low meadows.

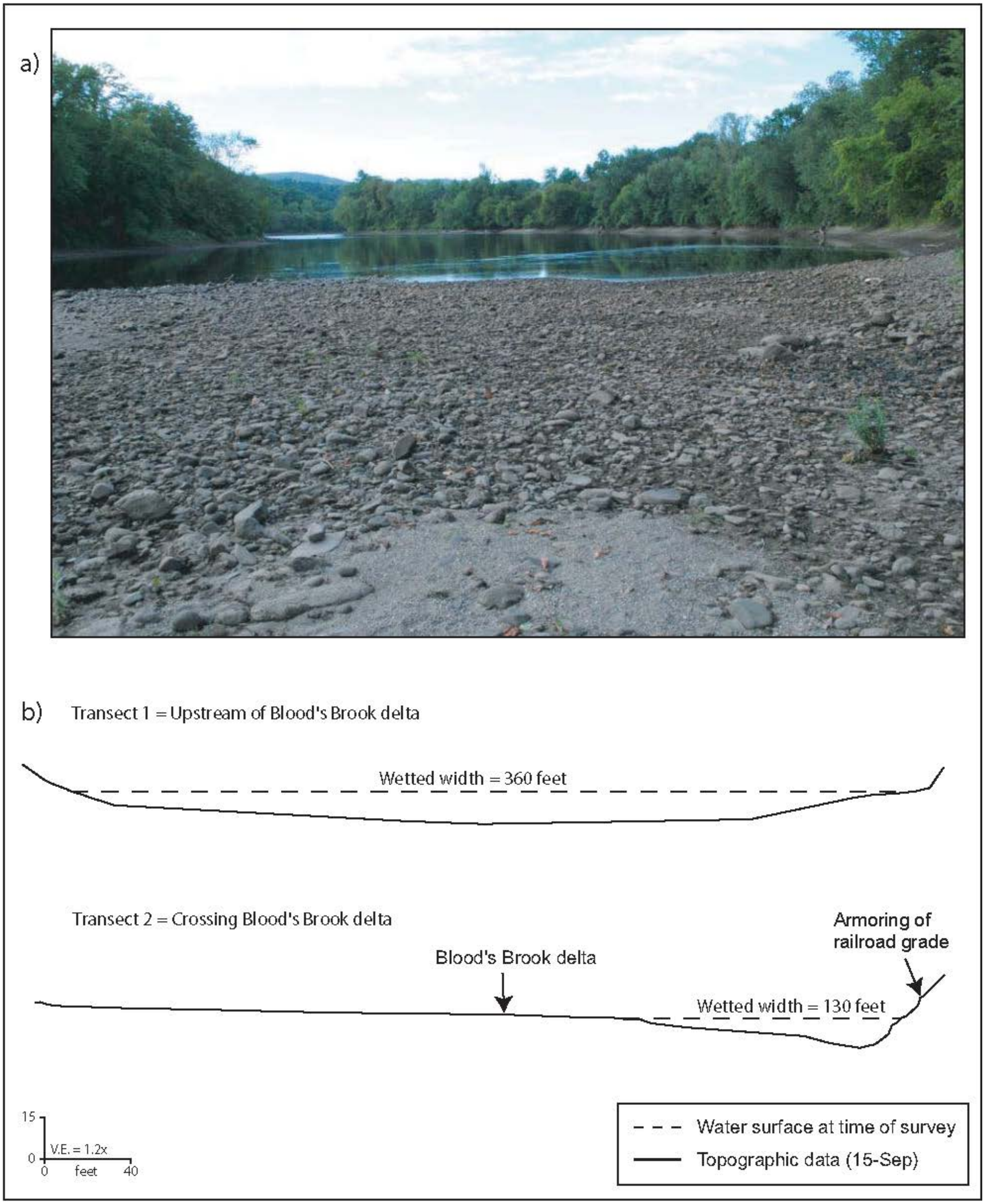


Figure 5.2.1-3. Blood’s Brook has a) formed a large boulder delta that has b) narrowed the channel compared to upstream (and downstream, not shown).

5.2.2 Valley Constrictions

At several locations in the study area, the river is constrained by mountainous valley side slopes or by the high banks of stream or glacial terraces, thereby creating natural constrictions along the river relative to areas immediately upstream where a wide floodplain is present (Figure 5.2.2-1). At least 36 significant constrictions were identified in the study area by carefully inspecting topographic maps and a GIS point shapefile (Appendix C, filed separately in ArcGIS [zipfile] format) created to show their locations. Flood flows encountering a constriction like these will back up on the wider floodplain upstream before passing through the narrower constricted valley. Deposition often results upstream of the constriction in response to the backwatering and associated reductions in flow velocities. The deposition, in turn, results in flow deflection into the riverbanks and consequent bank erosion. These processes ultimately lead to the growth of the high amplitude meanders that are evident at many valley constrictions in the study area (Figure 5.2.2-1). Although developed over long periods of time (i.e., decades or centuries), the presence of these meanders is evidence that the constrictions are capable of altering the passage of flood flows down the valley, so are likely to govern the distribution of depositional features and bank erosion near the constrictions.

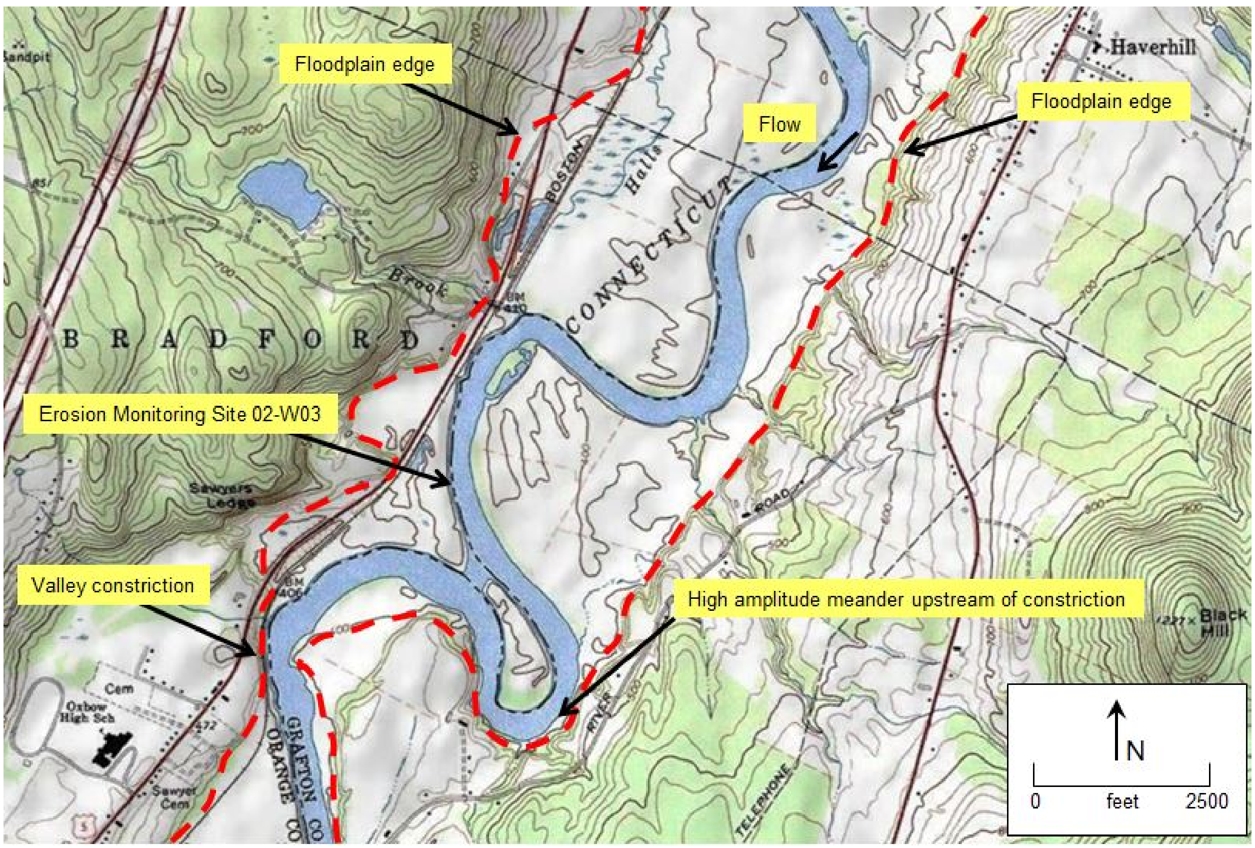


Figure 5.2.2-1. Valley constrictions are often associated with upstream deposition, meander formation, and bank erosion.

5.2.3 Other Watershed Factors

Human activities in the watershed and in the channel have also impacted channel conditions and the distribution of bank erosion. On the upper Connecticut River upstream of the study area, evidence drawn from maps and field studies suggests more than 30% of the river channel was artificially straightened and is considered a primary cause for erosion today (Field, 2004) even though much of that straightening was due in large part to large log drives that occurred throughout the late 19th and early 20th centuries (Gove, 2003); and railroad construction in the latter half of the 19th century. The evidence for straightening is ubiquitous on rivers and streams throughout New England (Field, 2007a). Straightening is more difficult to confirm within the study area due to the river's large size, the presence of impoundments which may obscure evidence of straightening, and extensive valley confinement (where the channel could be naturally straight). In the upper Wilder impoundment where the floodplain is at its widest, some straightening can be observed on topographic maps (Figure 5.2.3-1). At least one of three features should be present to verify channel straightening: 1) a straight reach longer than the wavelength of nearby meanders; 2) a channel position that "hugs" the edge of the valley; and 3) the presence of the original meandering channel in some form on the adjacent floodplain. Figure 5.2.3-1 shows possible evidence for all three features and also shows how railroad construction cut off the apex of a meander, a type of partial straightening (or channel shortening) seen at multiple locations in the study area. The shortening of the channel resulting from straightening increases the channel slope and flow velocity which in turn, often results in bank erosion as the channel adjusts in response to the alteration of its natural form.

The channel adjustments following straightening ultimately lead to the reformation of meanders along artificially straightened channels (Field, 2007b). Evidence for this is also seen in upper Wilder impoundment on the Haverhill/Piermont, New Hampshire town line where a small unnamed tributary built out sediment into a straightened reach of channel to form a symmetrical meander (Figure 5.2.3-2). Although the meander formed prior to 1935 (as seen on an historic topographic map), topographic surveying of the area as part of this study confirms a low area along the bank where the delta built out into the channel several decades ago (see data presented in Section 5.7). Very rapid meander formation, and as a result rapid bank erosion, can occur where considerable sediment enters the channel at tributary confluences. This is enhanced where the tributary passes through easily erodible clay deposits, producing high sediment loads. At the mouth of Clark Brook near North Haverhill, New Hampshire, after flowing for over 2.5 miles through clay deposits, well stratified bank sediments on the Connecticut River show evidence for the rapid growth of a point bar that has now developed into a low floodplain surface (5.2.3-3). Slowly deposited bank sediments are often homogenized through disturbance by animals (e.g., burrowing) and plant growth (e.g., roots), so the preservation of point bar features in the bank is an indication of rapid bar growth.

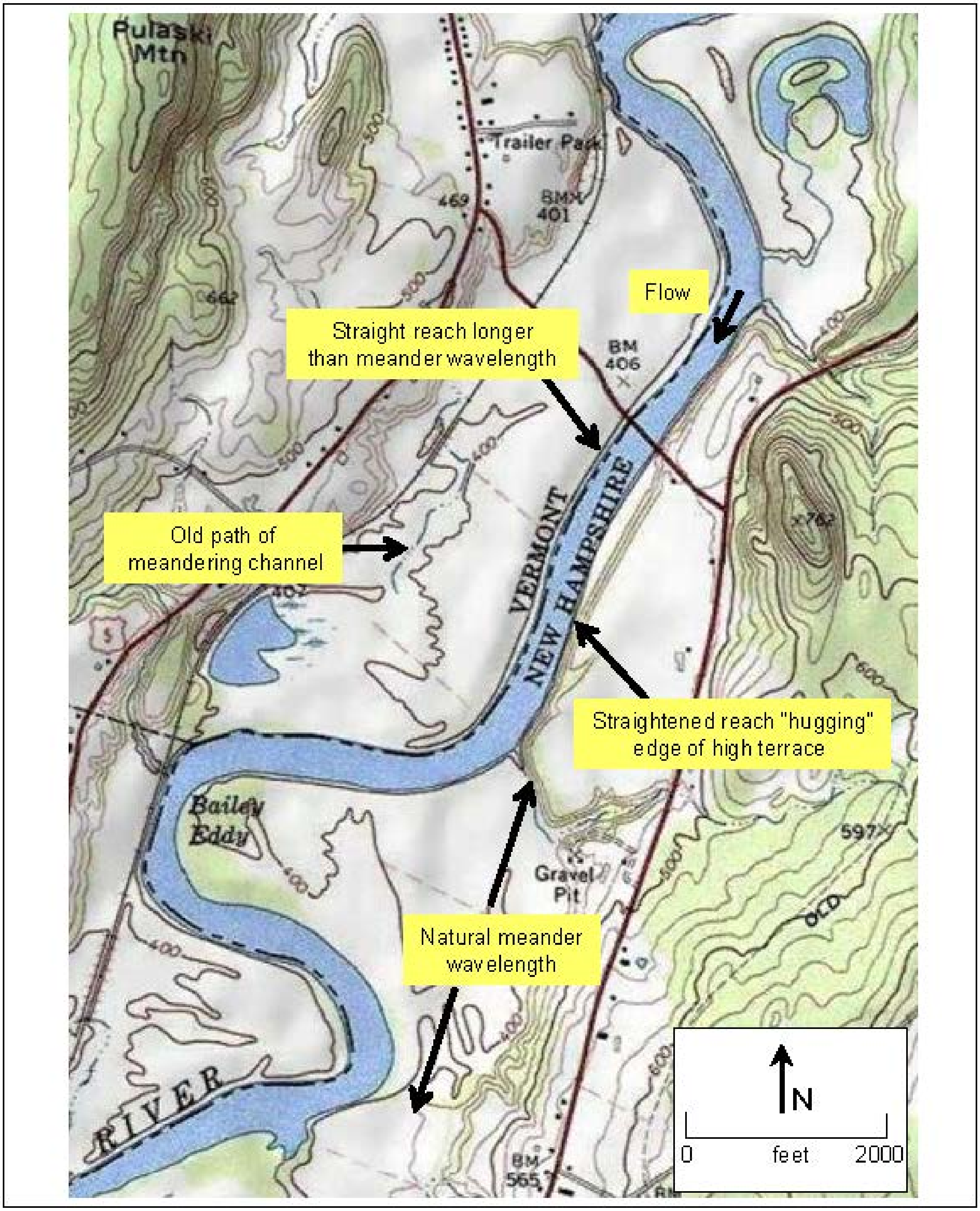


Figure 5.2.3-1. Evidence for channel straightening near Newbury, VT.

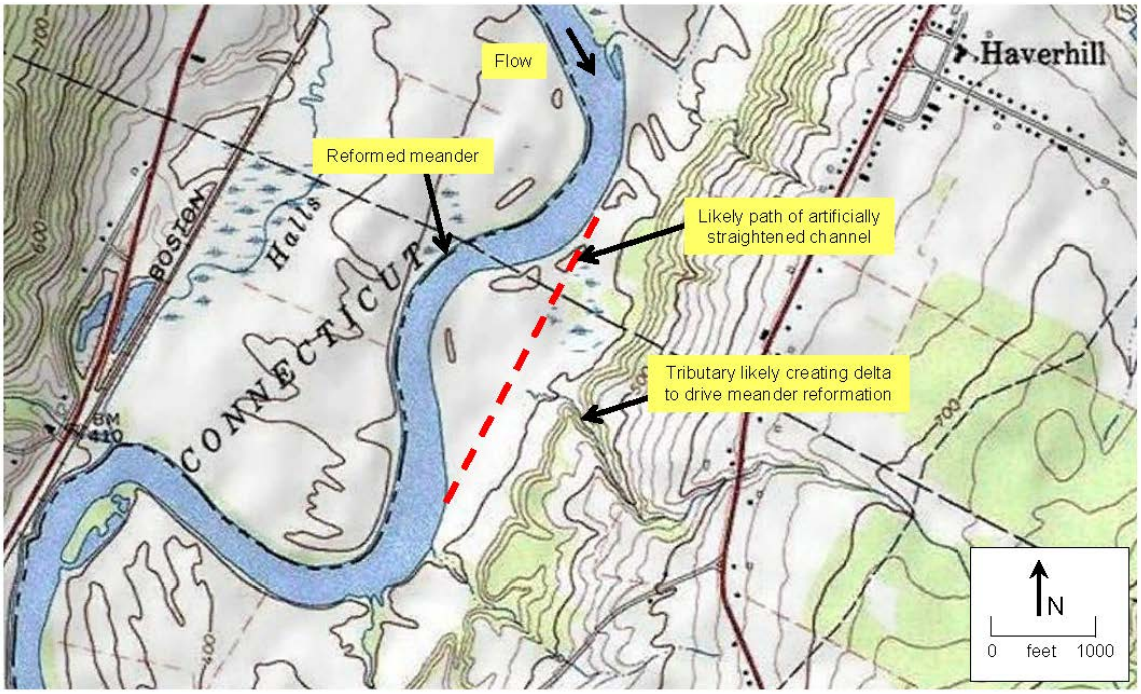


Figure 5.2.3-2. Meander reformed on straightened reach at Piermont/Haverhill, NH town line where tributary enters Connecticut River valley.

Figure 5.2.3-3. Bank sediments preserving rapidly deposited point bar near North Haverhill, NH.

5.3 Analysis of Historical Aerial Photography

Data from and an initial analysis of historical aerial photography was provided in the Study 1 report (Field Geology and Normandeau, 2016). The Study 1 report also described the methods by which historical aerial photographs were georeferenced and overlaid on the 2010 digital orthophotographs. The 2010 digital orthophotographs used for this analysis are unrelated to, and should not be confused with, erosion mapping completed in the same year (Kleinschmidt, 2011). Georeferencing a single set of historical aerial photographs for comparison with recent orthophotographs is imperfect but further complications arise when attempting to compare multiple sets of georeferenced aerial photographs. The initial analysis in the Study 1 report focused on 11 locations where the river channel had changed significantly enough that the changes could be considered real and were not merely apparent changes resulting from errors in the georeferencing process. The trend observed at these locations through time led to a preliminary conclusion that the rate of change along the river in the study area had decreased through time except for in the upper Wilder impoundment where the rate of change appeared to increase. Analysis of the georeferenced aerial photographs as part of this report is presented below for the entire study area and not merely at the 11 locations previously analyzed.

The analysis was completed by measuring the amount of change between each available photo year every 0.5 mile along the river beginning at each dam and moving upstream to the next dam where a new tally of 0.5-mile measurements was begun. Consequently, Bellows Falls impoundment and the Wilder riverine reach were combined together in a continuous count of mileage as were the Vernon impoundment and Bellows Falls riverine reach. Wilder impoundment was completed on its own and the reach below Vernon dam was not included in the analysis given its short (1.5 mi) length. At each 0.5-mile interval, a determination needed to be made as to whether the position of the banklines for each photo set was accurate or if their position was in error due to inherent difficulties in the georeferencing process. An assessment of accuracy was made by determining if the implied changes from the georeferencing process were consistent with evidence observed on the aerial photographs. For example, if the comparison of bank lines suggest 50 ft of bank accretion occurred (i.e., bar deposition) on one bank and a similar amount of erosion on the opposite bank between the 1970's and 2010 but tall mature trees are present in the area of supposed deposition and no fallen trees are seen along the forested supposedly eroding bank then the georeferenced banklines were considered in error. If the georeferencing was thought to be suspect, consideration was given to whether shifting the bank lines to reflect no change made greater sense of the data. For example, if the 1950's and 2010 data set were in the same position and the 1970's bankline had appeared to move 50 ft but visual evidence suggested otherwise, then an assumption was made that no change had occurred between the 1950s and 2010. Each 0.5-mile segment was carefully investigated in a similar manner but not in isolation as considering the layout of the banklines over approximately 2 miles was more effective at discriminating true channel movements from artifacts in the georeferencing process.

The results of the historical photo analysis are presented in Figure 5.3-1a, b, and c and display the rates of change derived by dividing the total change in a given time interval by the length of time between the photo sets (with 1940 used as the date for the 1939/40 series, 1954 used for the 1953/55 series, and 1973 used for the 1970/75 photos since the actual year of the photo at any given site was not known and the use of an interim year was considered the best means of limiting the potential error that might result from that uncertainty). The graphs in Figure 5.3-1a, b and c layer the latest time interval on top such that only that color appears when other time intervals show the same rate of change in a given area. This is particularly true for the extensive lengths of river that show no measurable change during multiple time intervals and the lines fall on the graph's x-axis. However, a zero rate of change determined from the analysis of historical aerial photographs should not imply that no change has occurred. Given the original low resolution of the historical aerial photographs and potential errors in the georeferencing process, bank position changes of up to 50 ft may have occurred in some areas that are not captured in this analysis. Additionally, to reiterate, the measurements of change were taken at 0.5-mile intervals so some shorter areas of significant change may not be captured in this analysis. Despite these limitations, the analysis does provide some insights into where and when significant changes in channel position have occurred within the study area.

Upstream of Wilder dam, considerable change occurred between the 1939/40 and 1953/55 sets of aerial photographs. Changes observed on the historical aerial photographs are most dramatic in the lower Wilder impoundment between the 1939/40 and 1953/55 photographs. Although displayed as a rate of change in Figure 5.3-1a, these changes are the result of inundation caused by the raising of Wilder Dam in 1950, likely happened in less than a year, and are not the result of erosion. Actual erosion seems likely around mile 32 above the dam on the right bank (as shown on Figure 5.3-1a) as matching deposition is present on the left bank, whereas at other locations the changes occur on both banks simultaneously, a trend consistent with the inundation up and perhaps over the banks. The actual change due to the raising of the dam in 1950 likely occurred in less than one year but expressing the change as a rate over the whole time period enables more meaningful comparisons with the rest of the data set. The rapid spatial changes expressed by spikes on the graphs in Figure 5.3-1 with large changes at one 0.5-mile point and no change at an adjacent 0.5-mile point may reflect changes in bank height (as a steep vertical bank would reflect little change in position in response to the raising of the dam) and bank composition or armoring (as a resistant bank would be less likely to recede even if the erosive forces are the same over a mile long reach of river). After the 1953/55 series very little change is documented through the historical aerial photograph analysis and what change is observed is almost exclusively restricted to the upper half of the Wilder impoundment. The lack of change in the lower impoundment is likely due to the extensive bank armoring in that area (see Section 5.6).

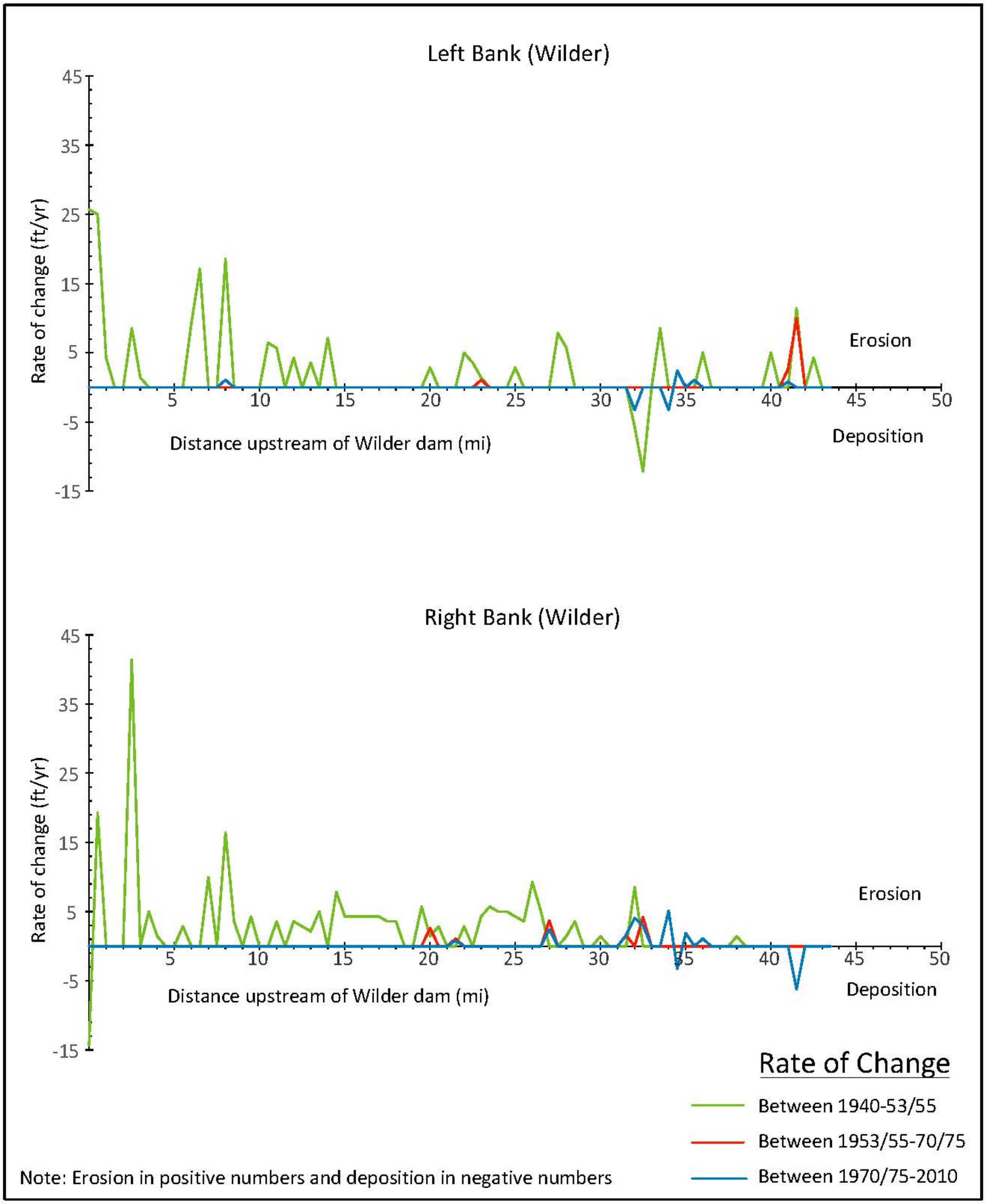


Figure 5.3-1a. Rates of change in riverbank position through time upstream of Wilder dam.

The channel through the Bellows Falls impoundment appears to have experienced far more bank erosion and deposition than Wilder (and Vernon) impoundments through time (Figure 5.3-1b). Ground evidence such as sand bars in the channel, scroll bars on the low floodplain (i.e., subtle ridge and swale topography formed by meander migration), and the most significant bank retreat at any of the 21 monitoring sites throughout the study area (see Section 5.4) all corroborate the finding that significant changes have occurred. Spatially, the rate of erosion in the lower Bellows Falls impoundment in general, has been higher through time than in the upper impoundment or Wilder riverine reach. This may be due to the backwatering effects upstream of the Williams River confluence that could enhance erosion in the lower impoundment (as described in Section 5.2.1). Temporally, the rate of erosion appears to have declined through time as expressed in Figure 5.3-1b by the shorter peaks of the 1970s-2010 time interval nested inside the taller peaks of the 1950s-1970s time interval. Very few aerial photographs from the 1939/40 series were available downstream of Wilder dam so were not included in those analyses below Wilder dam. The rate of erosion has declined by 50% or more since the 1970s at many locations. As described in Section 5.4, one Study 2 erosion monitoring site (Site 02-B07) along the left bank (looking downstream) in the lower Bellows Falls impoundment experienced more than 7 ft of bank recession over a two year period. Based on the approximately 3 ft/yr erosion rate derived from the historical photo analysis at many sites in the lower impoundment for the 1970s-2010 time interval, additional bank recession at that monitoring site seems possible every few years.

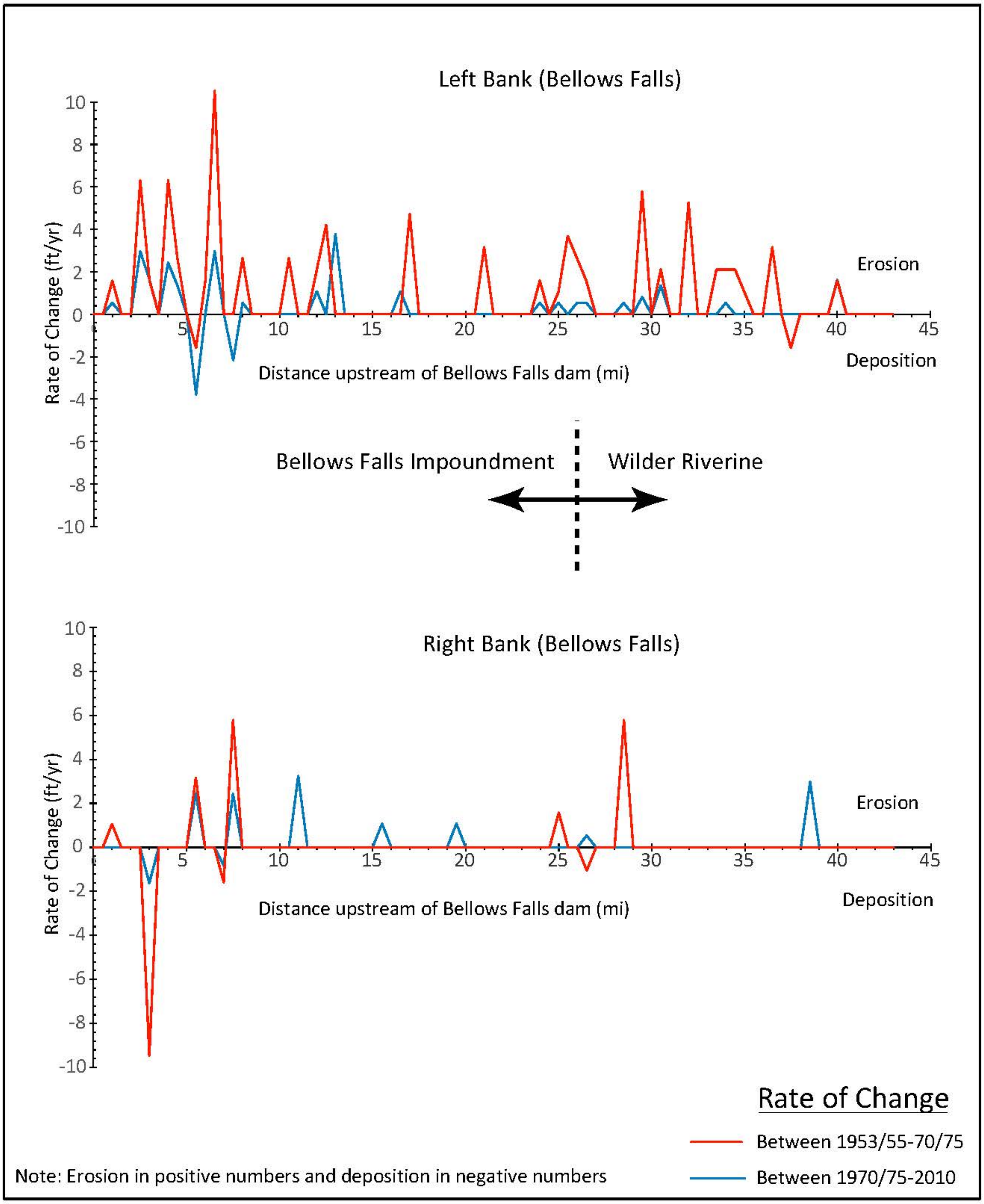


Figure 5.3-1b. Rates of change in riverbank position through time upstream of Bellows Falls dam.

In contrast to the significant changes in the Bellows Falls impoundment and Wilder riverine reach, the Vernon impoundment and Bellows Falls riverine reach show relatively little change in bank positions since the 1950/55 aerial photographs (Figure 5.3-1c). Although more locations in the lower Vernon impoundment show change, the rate of change appears higher in the upper impoundment, perhaps because of the extensive slackwater (i.e., low velocity current) areas in the lower impoundment. Very little change is documented in the Bellows Falls riverine reach. As with the Bellows Falls impoundment, the rate of change in Vernon impoundment appears to have decreased through time. In fact, most of the change observed occurred during the 1950s-1970s interval, with what little erosion did occur in the 1970s-2010 interval occurring mostly in the lower impoundment.

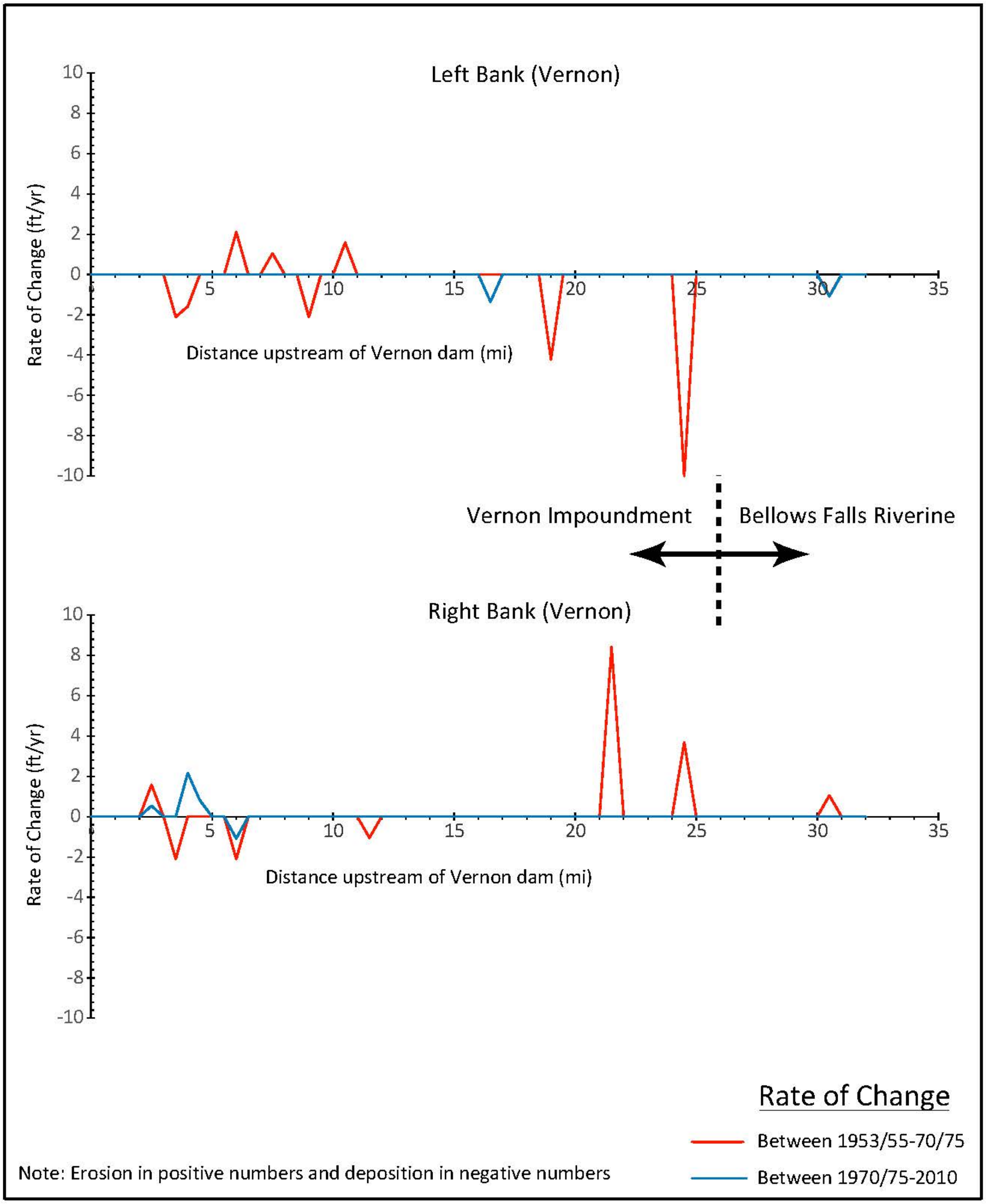


Figure 5.3-1c. Rates of change in riverbank position through time upstream of Vernon dam.

5.4 Erosion Monitoring

Erosion monitoring as part of Study 2 was conducted at 21 sites (10 associated with Wilder, 6 with Bellows Falls, and 5 with Vernon) (Figure 5.4-1, Plates 1-6). For each site, the monitoring included repeated surveys along a single transect of the selected bank, repeat photography of the bank from multiple locations, and water level monitoring at 15-minute intervals. The cross section surveys and repeat ground photography were completed eight times in total: November 2013, May 2014, July 2014, September 2014, November 2014, May 2015, July 2015, and September 2015. Erosion monitoring was conducted to determine the character, rate, and timing of erosion in the study area (as part of Study 2) in order to assess whether bank erosion may be related to high river flows, project-related water level fluctuations, or other factors (as part of Study 3). To better characterize and contextualize the conditions at each of the 21 Study 2 sites, the monitoring also included a detailed description of the bank sediments and a one-time survey of the entire river channel cross section and bank opposite each study site (i.e., full river cross sections). The results and discussion of the erosion monitoring consist of descriptions regarding: 1) selection of the monitoring sites, 2) repeat monitoring, 3) water level monitoring, 4) full river cross sections, and 5) bank sediments.

The results of the erosion monitoring described below have been compiled into individual data packets for each of the 21 monitoring sites (Appendix A). Each packet is organized with a site map on an aerial photograph on the first page to provide context of the surroundings (e.g., on the outside of a meander bend) and to show the location of the surveyed transect, water level monitoring, and various monumented control points. Control points were established at backsight locations (BS), where the electronic total station survey instrument was set up (ST), and where water level loggers were deployed (GAGE). The second page shows the transect plots of the eight monitoring surveys overlain on each other with annotations that highlight the changes observed during the two-year monitoring period. A more detailed narrative of observed changes is provided in a table on the subsequent page. Next, the final survey is used to show where various water levels (including the median WSE fluctuations) and discharges fall on the transect. Following the page showing where various river flow levels fall on the monitored transects, plots of the water level monitoring data for 2014 and 2015 are shown along with the median water level fluctuation established from Study 4 (GEI, 2016) hydraulic modeling and Study 5 (Hatch, 2016) operations modeling (see Section 5.6.5a). Periods of drawdown at the dams that may be initiated when high river flows are anticipated are also shown on the graphs but no such drawdowns occurred during the 2014 monitoring period and only once in 2015. Following the water level plots, a detailed stratigraphic description of the site is provided and then a drafted full river cross section with notable features highlighted. Lastly, each packet contains a table detailing the location (GPS coordinates), orientation (compass azimuth), and subject of each ground photo taken at a given site before presenting the ground photographs themselves from each monitoring round at each photo point.

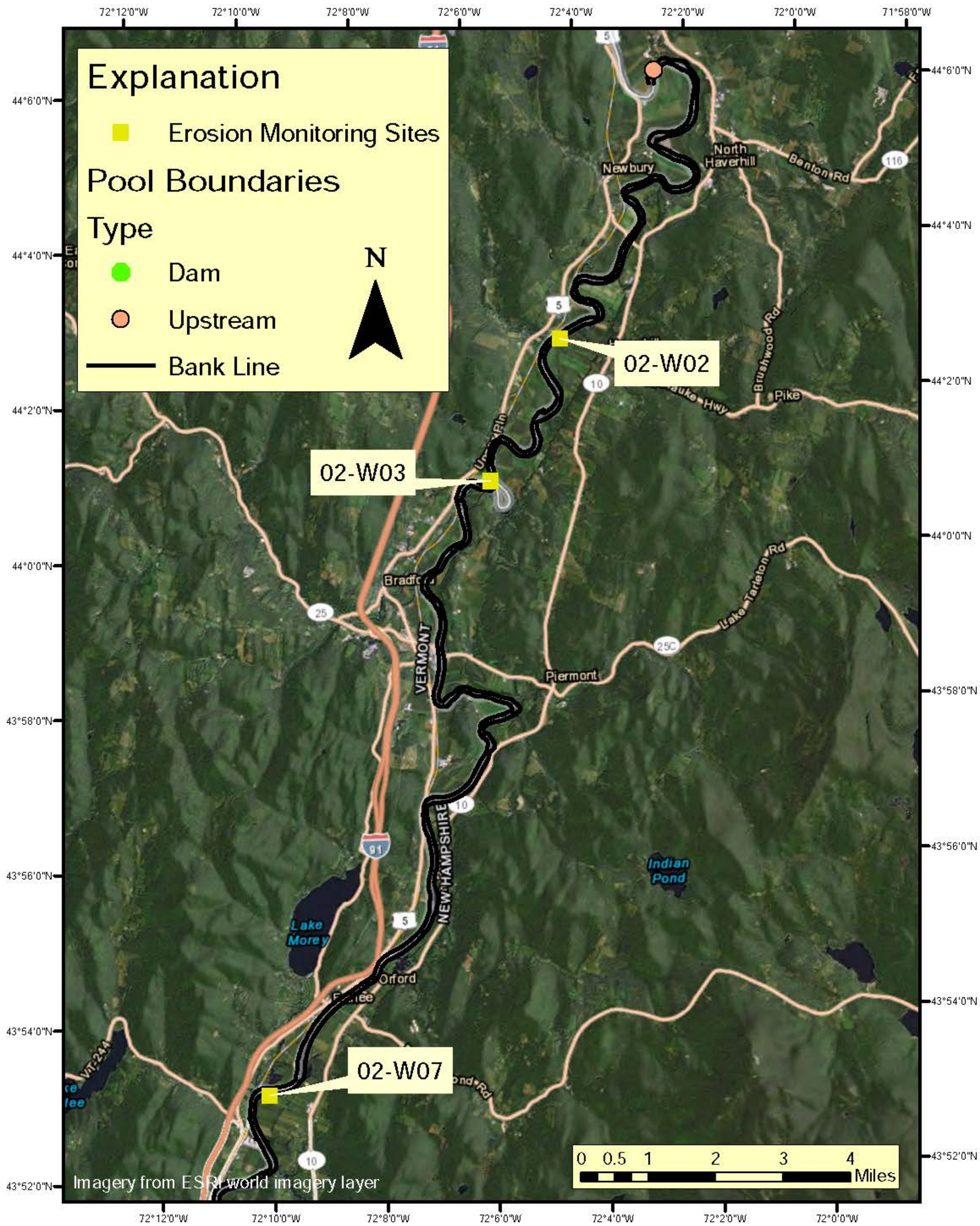


Figure 5.4-1. Plate 1: Erosion monitoring sites in the upper Wilder impoundment.

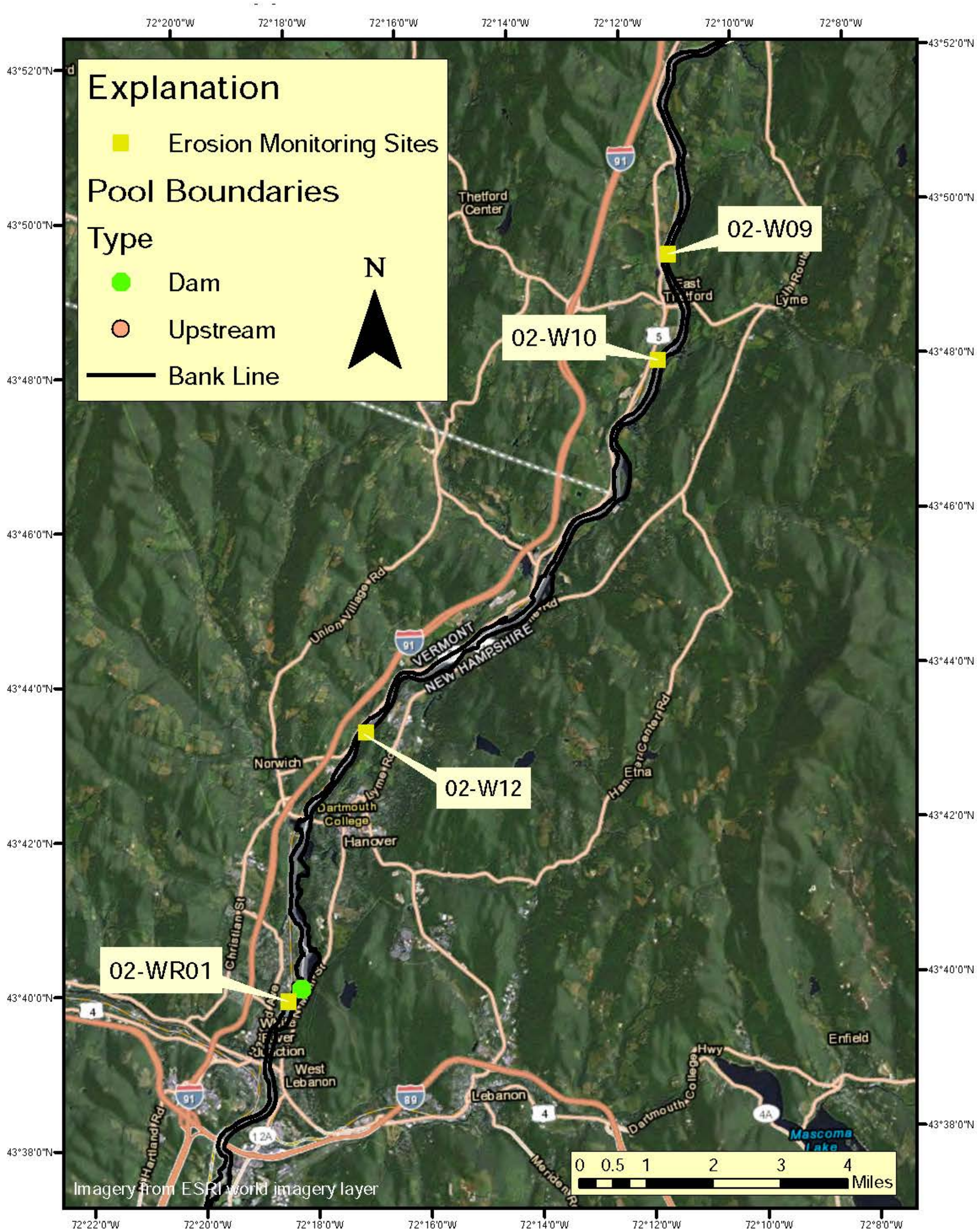


Figure 5.4-1. Plate 2: Erosion monitoring sites in the lower Wilder impoundment.

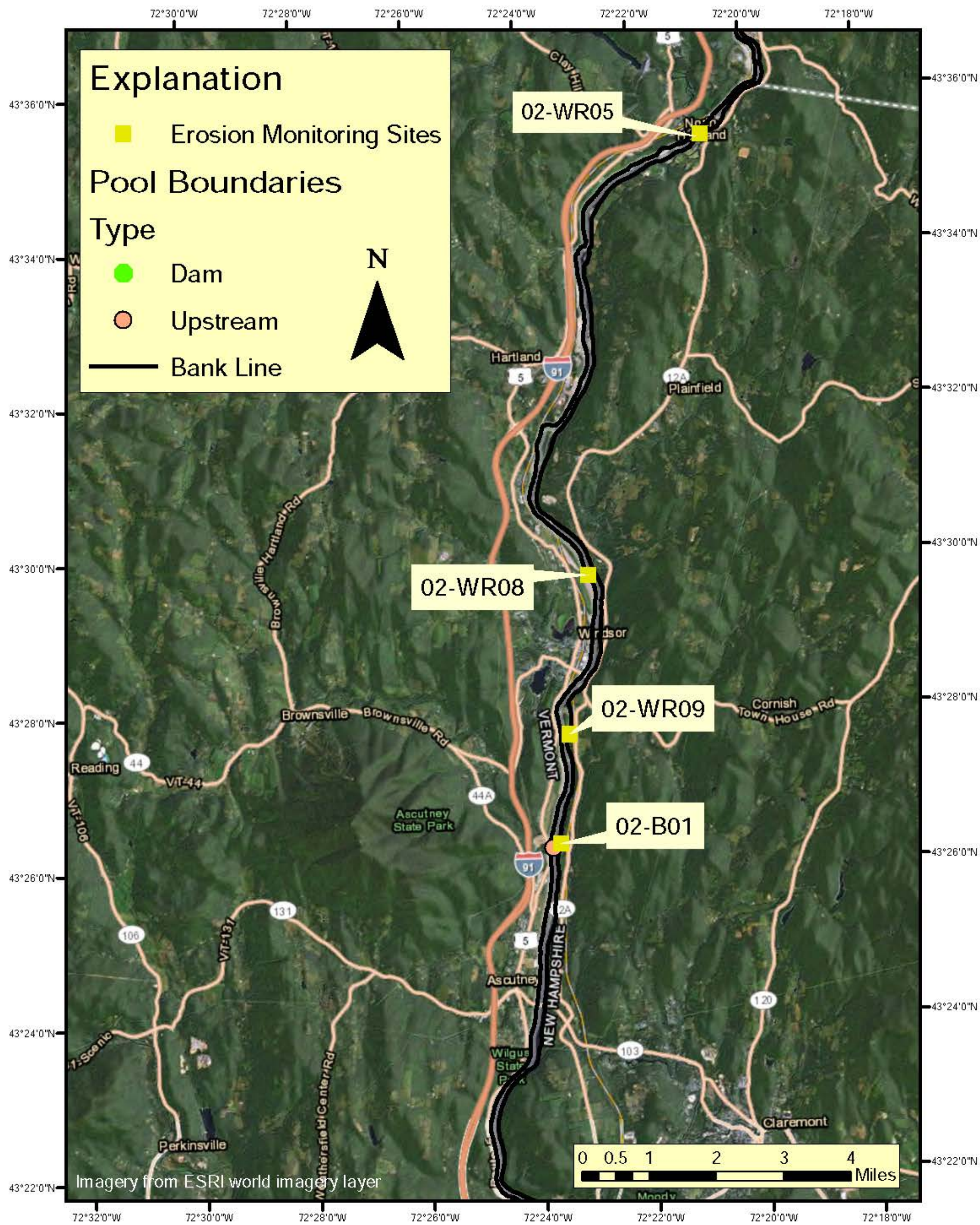


Figure 5.4-1. Plate 3: Erosion monitoring sites in the Wilder riverine section and upper Bellows Falls impoundment.

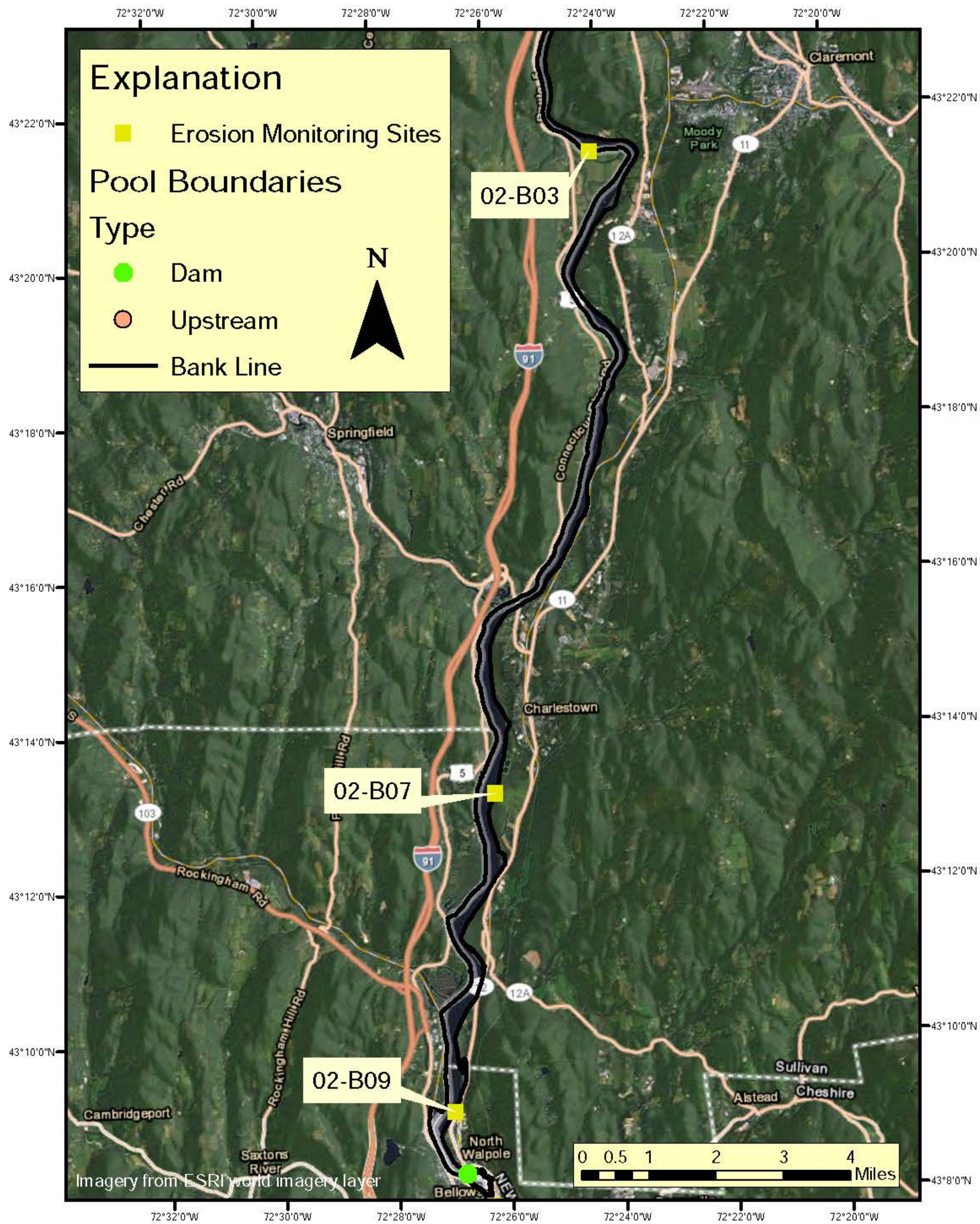


Figure 5.4-1. Plate 4: Erosion monitoring sites in the lower Bellows Falls impoundment.

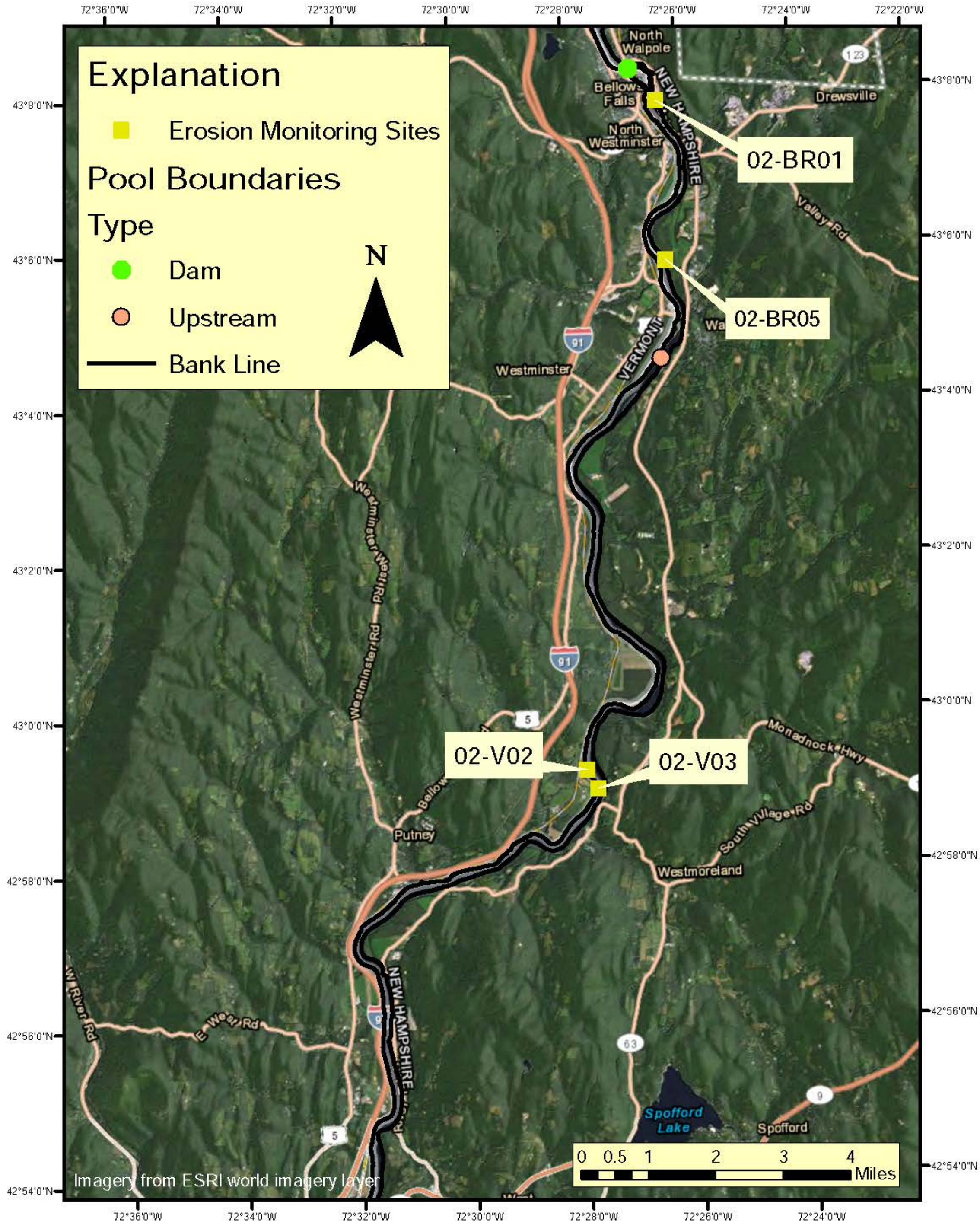


Figure 5.4-1. Plate 5: Erosion monitoring sites in the Bellows Falls riverine section and upper Vernon impoundment.

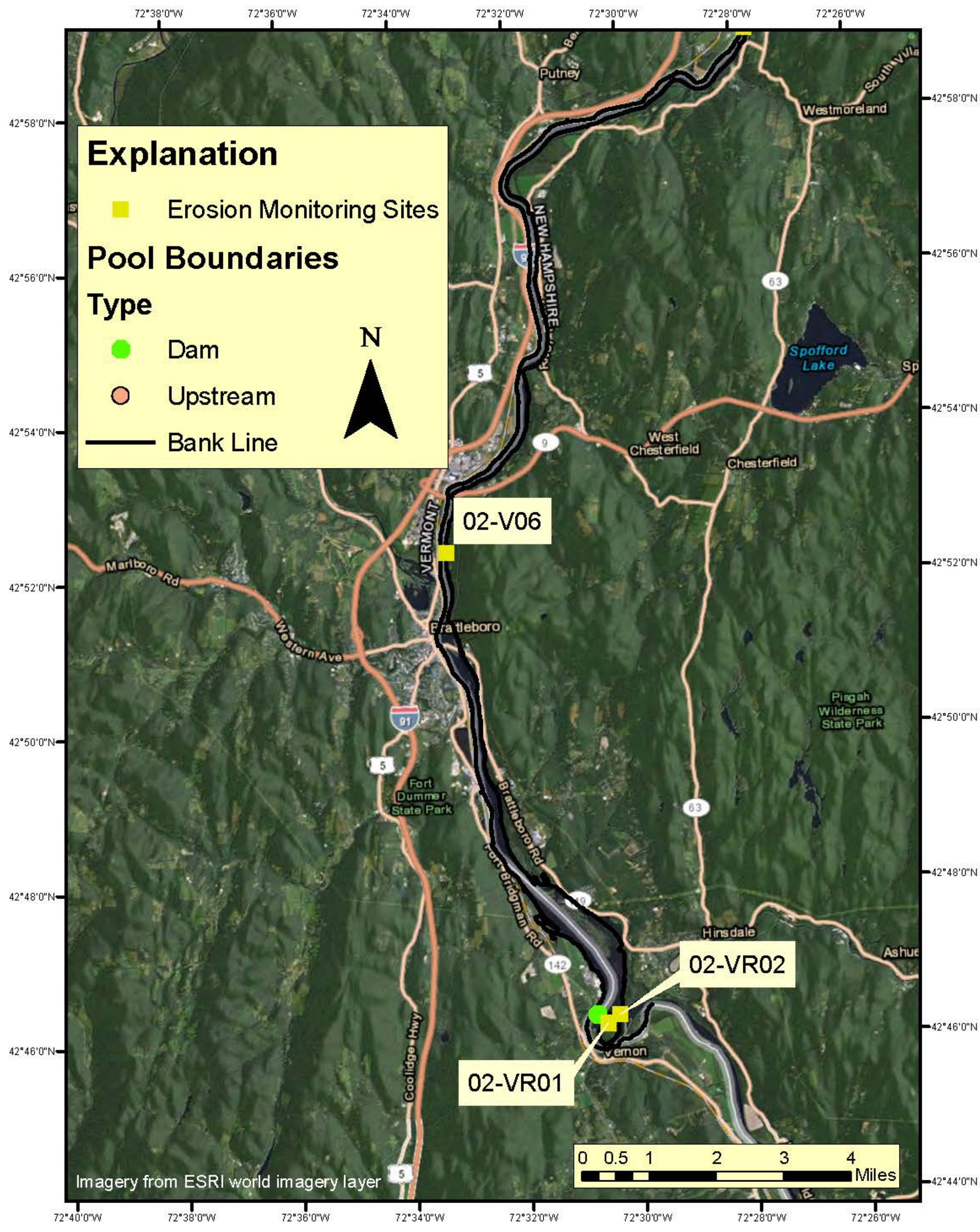


Figure 5.4-1. Plate 6: Erosion monitoring sites in the lower Vernon impoundment and Vernon riverine section.

5.4.1 Selection of Monitoring Sites

A catalogue of 46 possible erosion monitoring sites was developed based on an initial analysis of aerial photographs, topographic maps, previous erosion studies, and field reconnaissance. For each site, information was tabulated on an Excel spreadsheet regarding location, land owners, bank stability, bank composition, position along the river channel (i.e., inside or outside of meander bends), proximity to tributaries, and other information relevant to the bank stability at the site. After visiting all of the 46 selected sites in the field, the list was narrowed down to 20 sites. Several factors were used in the final site selection including ease of access and ensuring the sites were spread throughout the study area and covered a characteristic range of various soil types, bank heights, bank stability, channel positions, and other factors. Consultation with the erosion working group (consisting of governmental agencies, landowners, and other stakeholders) in the fall of 2013 was used to finalize the list of erosion monitoring sites with only minor changes made in the position of the initially selected sites based on stakeholder knowledge of site conditions and history. A 21st site (at the high eroding bank immediately downstream of Vernon Dam) was added at the request of FERC in its SPD. The final selection of sites included six sites in the Wilder impoundment, four in the Wilder riverine reach, four in the Bellows Falls impoundment, two in the Bellows Falls riverine reach, three in the Vernon impoundment, and two in the Vernon riverine reach.

The name, location, physical characteristics, and other information about the 21 erosion monitoring sites are presented in Appendix A in Excel format. Each site has a unique site identifier such as 02-W12 indicating that the monitoring site is part of TransCanada's Study 2 (02), in the Wilder impoundment (W), and is the 12th site from the upstream end in the impoundment of the initial 46 sites under consideration for monitoring (12). Riverine sites have the letter "R" added to the project letter such as 02-BR05 indicating the site is in the Bellows Falls riverine reach and is the 5th site downstream of Bellows Falls dam that was initially under consideration. Consequently, the numbering of the 21 sites is not sequential as most of the initial 46 sites were removed from consideration but the initial site numbers were not changed after final selection of the 21 monitoring sites.

To ease the interpretation of the tabular information, several graphs are provided that show the distribution of sites relative to various features and physical characteristics (Figure 5.4.1-1). The rate of erosion at a given site is potentially influenced by a number of factors shown on the graphs such as river position, bank composition, vegetation, and bank height. As described above, an effort was made in the final site selection to represent a range of various conditions that might control erosion. Therefore, not all of the selected sites were located where the riverbank was unstable; six sites were stable and 15 unstable (see below).

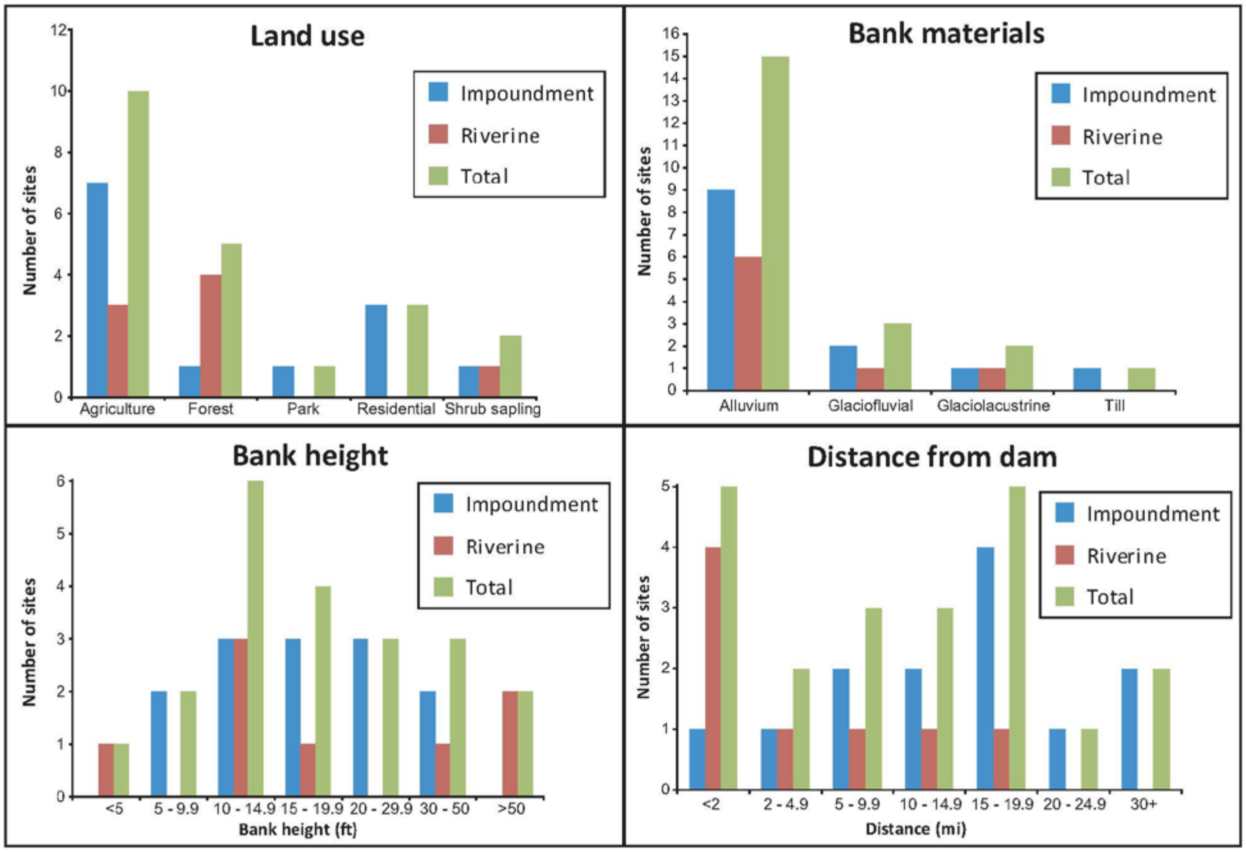


Figure 5.4.1-1. Distribution of monitoring sites.

5.4.2 Repeat Monitoring

Monitoring at the 21 erosion monitoring sites was initiated in November 2013 and repeated seven additional times until September 2015 with the specific months and years of the intervening monitoring rounds listed above and in the erosion monitoring packets in Appendix A. While a stipulation in the FERC SPD required additional monitoring rounds in the event of high water of over 35,000 cubic feet per second (cfs) at Wilder, 44,000 cfs at Bellows Falls, and 49,000 cfs at Vernon, the one time this did occur between April 16-18, 2014 the regularly scheduled monitoring in May 2014 was the earliest such monitoring could have occurred due to continuous high water until that time. No monitoring rounds were conducted in the winter and early spring given ice and high flow conditions between November and May.

The topographic survey of a single bank transect (i.e., cross section) at each site was completed with a Sokkia Set 5 electronic total station. The initial surveys were referenced to a local project datum with at least three, but generally more, control points established at each site so subsequent surveys were tied to the same vertical and planar coordinates. The established control points were transformed to NH State Plane Coordinates and North American Vertical Datum 1988 (NAVD 88) using a Real Time Kinematic (RTK) GPS unit that took readings from at least three control points at each site. However, the results of the RTK survey were not adequate for two sites. Dense vegetation at Pine Park (02-W12) prevented reliable readings so LiDAR was used to establish the vertical elevation at the site. Immediately downstream of Vernon dam (02-VR01) readings were also poor due to the distance from the chosen base station, so the coordinates and elevation were established by surveying to nearby control points established by earlier surveys. The full river cross sections were intended to be surveyed during the initial monitoring round, but the cold weather in November 2013 and need to setup water level loggers in May 2014, delayed the full river cross section surveys until subsequent monitoring rounds in 2014.

The monitoring surveys of a single bank were completed during each of the eight monitoring rounds. Each transect extended from a point at least 50 feet upland from the top of bank to a wadeable depth into the water at the base of the bank with data collected at a sufficient density to accurately describe the slope geometry. The transect endpoint in the water varied with each monitoring round depending on the elevation of the water surface which controlled how far out into the river the survey could be extended. Beginning with the third monitoring round in July 2014, the electronic total station was setup at the top of the bank directly on the surveyed transect line itself to ensure the surveyed points were precisely on the survey line; this minimized the potential error created by surveying a point slightly off the line during one monitoring round and potentially off the line in the other direction during a subsequent survey (minor potential errors created in this manner did not materially alter the results of the first two monitoring rounds but the new approach was adopted in an effort to minimize potential error as much as possible). To further reduce potential error, pin flags were placed at each surveyed point so that the exact same points could be resurveyed in subsequent rounds if no change occurred on the bank slope as slight variations in survey points even along the same line (especially on uneven banks with rough topography) can lead to the appearance of minor changes on drafted cross sections even when no changes have actually occurred. Despite efforts to limit error, some minor variations in the transects of less than a foot resulted even though no actual changes had occurred as confirmed by ground photographs and field observations. In such cases where the overlays of surveyed transects show apparent change but visual observations confirmed no such change actually occurred on the ground, notes are included on the drafted transects in Appendix A site packets to indicate that the apparent change is an artifact of the survey process (e.g., at Site 02-W12).

In places where the bank was overhanging, a survey point was measured at both the base of the overhang and top of the overhang. A stiff foldable ruler was then used to measure the maximum depth of the overhang and its height above the base of the overhang. During drafting of the cross sections, the survey data were amended to incorporate the measurements of the overhang. Using this approach, the overhangs are essentially represented as triangles, so do not provide details on the overhangs' true shapes but do accurately represent their maximum depth, height, and bank position.

At least four ground photographs were taken, when possible, from the same position and orientation during each monitoring round using a Ricoh G700SE camera that records the GPS coordinates, azimuth, date and time, and other information about each photograph. In some instances, differences in photo position were necessitated by high water or changes in bank conditions. The matched ground photographs are presented at the end of the monitoring packets in Appendix A.

To monitor water surface elevations at each monitoring site, Hobo water level loggers (i.e., pressure transducers) were placed in slotted PVC well pipes fastened to rebar stakes and then driven into the bed of the channel, sometimes with the help of a sledge hammer, to remain secure. The position of each logger was tied to control points at the site using the electronic total station and their positions were also marked during the RTK survey. An attempt was made to install water level loggers as early in the spring as possible but also at low water so they could be set as deep in the channel as possible. As a result, loggers were deployed in June 2014 but given persistent high water in 2015 the deployment of loggers was delayed until July 2015. Despite efforts to install loggers as deep as possible, some loggers were exposed above the water surface during extreme low flow periods leaving short gaps in the records. Loggers were removed in November of each year to prevent ice or other damage through the winter. Flow records at the dams provided information on water levels during the winter months and confirmed that no significant high river flows occurred during the two-year monitoring period other than the previously mentioned April 2014 high flow event, so the data collected during the summer and fall is considered representative of water level fluctuations through the study period.

Once installed, the water level loggers recorded water pressure and temperature at 15-minute intervals. The pressure and temperature readings were later converted to water depths using software provided with the loggers. Six additional atmospheric loggers deployed by Normandeau throughout the study area for other studies in 2014 were used to document changes in barometric pressure that are needed to make the necessary adjustments to convert the water depths recorded at the erosion monitoring sites to actual WSEs. The closest atmospheric logger to a particular monitoring site was used to make the adjustment. In 2015, barometric pressure readings from regional airports and weather centers were used to make the conversions.

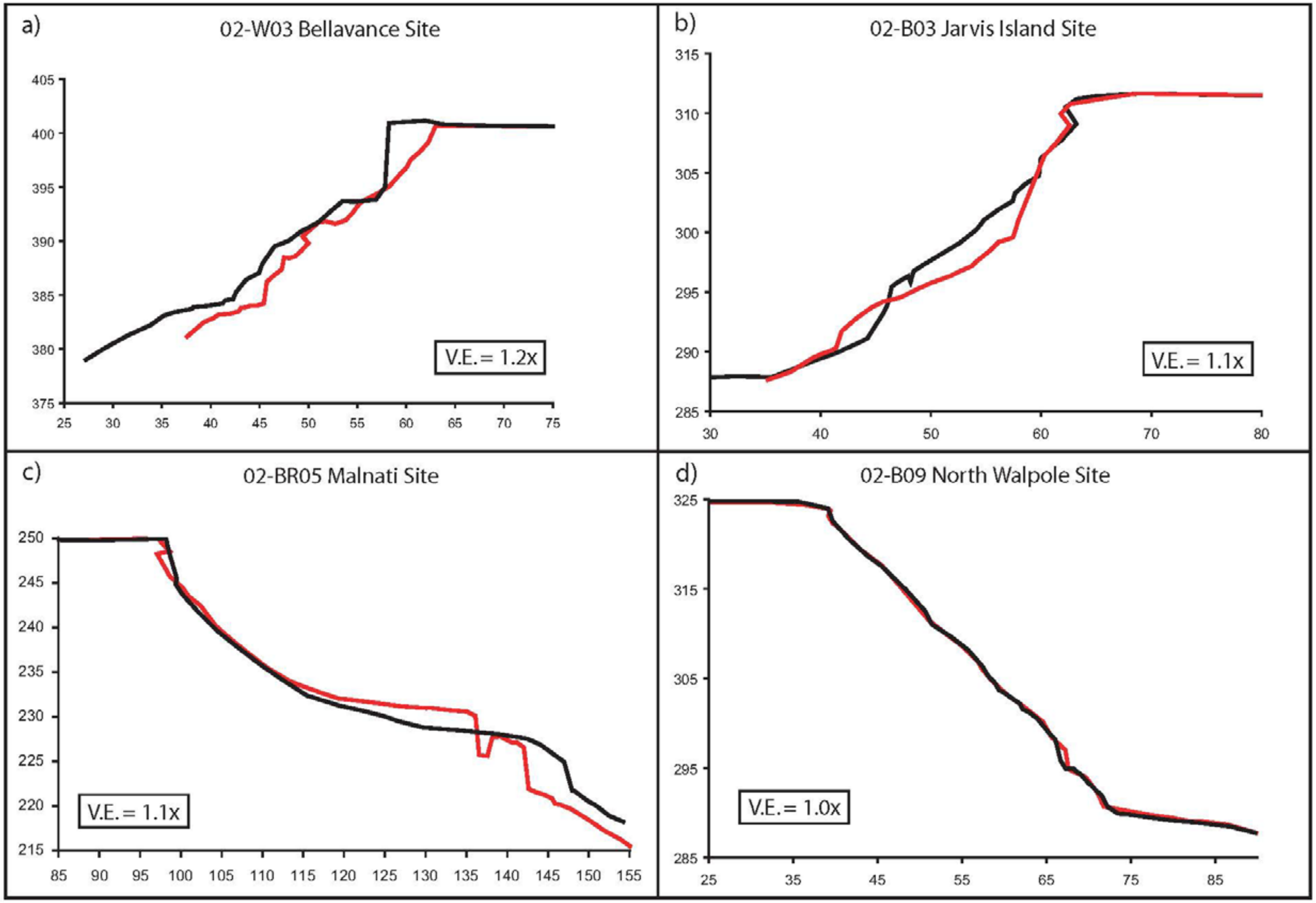
Various problems arose with the water level loggers at a small subset of monitoring sites during the two-year study period. Data at three sites was compromised, at least partially, during 2014. At 02-VR01 (just below Vernon) the logger was removed by unknown individuals and a second logger was deployed upon discovering the missing logger. A second logger was also deployed at 02-WR01 (below Wilder) when the first logger was removed and later found nearby damaged and unusable on the riverbed. As a result, Vernon operations data was used for this site (Appendix A). At 02-WR09 (Hartwell Site) the logger was installed in clay and was pushed three feet out of the ground by natural upwelling forces. Upon discovery the logger was redeployed in a slightly different position without further incident. Problems with data collection occurred with six loggers in 2015. The logger at 02-VR01 was placed across the river in 2015 to be less susceptible to removal but, despite those efforts, was likely inadvertently removed by the Vermont State Police during a search for a missing body in the area. The logger was removed in the fall so was not redeployed, but its proximity to the dam allowed information from the project operations records to be used instead (Appendix A). The five other sites for which water level logging data were not successfully retrieved in 2015 were 02-W12 (Pine Park Site), 02-WR09 (Hartwell Site), 02-B03 (Jarvis Site), 02-V06 (LaCroix Site), and 02-VR02 (Stebbins Island Site). At each of these sites when a data download was attempted an “invalid pressure data” was reported apparently due to equipment malfunction. This was in variance to the RSP, data was not downloaded during each monitoring round because the water level loggers were set at as low an elevation as possible making retrieval impractical at higher water levels. Furthermore, early data downloads in 2014 created data gaps during retrieval, so for these reasons a decision was made to retrieve data only in November when the loggers were removed. Given the reasonable corroboration of operations model data over the five modeled annual hydrologies (Study 5 [Hatch, 2016]) with the WSE data retrieved at other selected sites (see below), a reasonable estimate of conditions at these sites could be made.

Stratigraphic descriptions of the bank sediments were completed at each monitoring site and are included in the monitoring packets (Appendix A). An attempt was made, with the use of a shovel, to create as near as practicably possible a clean vertical bank exposure free of vegetation, sloughed soil, and sediment covering the bank exposure such that the individual soil horizons and sedimentary layers were exposed and depth could be accurately and easily measured down from the top of the bank. In many instances, however, better exposures were located some distance (e.g., tens of feet) from the transect line so stratigraphic descriptions were undertaken at these locations as long as the geomorphic surface and stratigraphy below were the same as at the monitoring transect. Also, a continuous vertical exposure could not be created at all locations, especially on high banks, so exposures were stepped down the bank and care taken to ensure total depth was accurately determined by adding depths from different sections of exposure down the bank. Given the amount of eroded material accumulating at the mid and lower bank at some sites, portions of the stratigraphic column in some cases were designated as a covered interval with a presumption made regarding the likely texture present beneath the cover material.

The depth below the surface of each visibly distinct (albeit sometimes subtle) contact between stratigraphic layers (also referred to as stratigraphic units) was recorded with the use of a tape measure. The thickness of each unit was then determined by the difference in depth between the upper and lower contact of that unit. A description of the characteristics of each unit was undertaken including information on the texture (following USDA soil texture classes), color (determined using a Munsell color chart), sedimentological features (e.g., cross bedding), other soil properties (e.g., structure, roots), and the nature of the basal contact (e.g., sharp, gradational). Distinct soil horizons near the top of the bank were treated as separate units even if technically the result of soil forming processes (e.g., weathering, organic matter accumulation) rather than a different depositional layer. The stratigraphic layers were drafted to scale with layers having a coarser texture extended further to the right such that variations in texture are readily visible (Appendix A). Other characteristics are shown within each unit. The number of each unit (numbered sequentially from the top) is labeled to align with a narrative description of each unit provided below the stratigraphic columns. A sample photograph is also provided for most sites.

Several general findings gleaned from the results of the erosion monitoring are discussed below but readers interested in the details of change at a particular site or sites are encouraged to look at the relevant monitoring packet(s) in Appendix A. Quantitative measurements of change were made at the top and toe of bank. The bank slope between the top and toe was subdivided into an upper, middle, and lower bank area (generally one third the bank height for each on uniformly sloping banks but morphological/slope variations were also considered) and changes within each bank area were noted if present (i.e., bank loss or bank gain). However, quantitative measurements of change on the bank slope were not made given difficulties in determining where on the bank such measurements should be made or how best to measure differences from one monitoring period to the next as bank angles changed with slope movement. Furthermore, changes occurred along the bank slope in many instances without any net loss or gain of bank material (e.g., partial translation of material downslope). As a result, a notation of change was made and is more telling than a potentially misleading measurement suggesting that no change occurred.

Four general conditions were observed along the transects during the two-year monitoring period: 1) bank recession at the top of the bank, 2) changes on the bank slope, 3) loss or accumulation of bank material at the bank toe slope (y = some change, n = no change, add = material added to that portion of the bank), and 4) no change (Figure 5.4.2-1 and Figures 5.4.2-2a and 5.4.2-2b). Note that two or more of the above conditions reflecting bank change could occur along a single transect (even during a single interval between monitoring periods) and that change may have occurred during only one monitoring interval with no other change observed during the rest of the monitoring period (Table 5.4.2-1).



Notes: Black = November 2013 survey, red = September 2015 survey. Axes measured in feet; V.E.=vertical exaggeration.

Figure 5.4.2-1. The types of conditions observed on the monitoring transects included a) top of bank recession, b) bank slope changes, c) bank toe accumulation or loss, and d) no change.

Table 5.4.2-1. Changes in bank stability at the 21 monitoring sites, 2013 – 2015.

Site	Bank Stability[a]	Position[b]	11/2013 to 05/2014	05/2014 to 07/2014	07/2014 to 09/2014	09/2014 to 11/2014	11/2014 to 05/2015	05/2015 to 07/2015	07/2015 to 09/2015	Total Study Period
02-W02	Stable	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	n	n	n	n	n	n	n	n
		Mid-bank	n	n	n	y	y	y	y	y
		Lower bank	n	n	n	n	n	n	n	n
		Toe of bank	0	0	0	0	0	0	0	0
02-W03	Eroding	Top of bank	4.5	0	0	0	0	0	0	4.5
		Upper bank	y	n	n	n	n	n	n	y
		Mid-bank	add	n	y	y	y	y	y	y
		Lower bank	add	y	add	y	y	y	y	y
		Toe of bank	-1.5	0	0	0	1.4	1.7	2.9	3.2
02-W07	Eroding	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	y	n	n	y	y	n	y	y
		Mid-bank	y	y	y	y	y	y	y	y
		Lower bank	add	y	y	add	y	y	y	y
		Toe of bank	-2.4	2.4	2.2	-0.4	-1.4	0.3	1.2	1.8
02-W09	Eroding	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	n	n	n	n	y	n	y	y
		Mid-bank	y	y	y	n	y	n	y	y
		Lower bank	y	y	y	y	y	n	y	y
		Toe of bank	-2.7	1.7	0.5	0.4	0.3	0	1.4	1.8
02-W10	Eroding	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	n	n	n	n	y	y	n	y
		Mid-bank	n	n	n	n	n	n	n	n
		Lower bank	n	n	y	y	y	y	n	y
		Toe of bank	0	0	1.2	0	0	-1.2	0	0
02-W12	Failing armor	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	n	n	n	n	n	n	n	n
		Mid-bank	n	n	n	n	n	n	n	n
		Lower bank	n	n	n	n	n	n	n	n
		Toe of bank	0	0	0	0	0	0	0	0

Site	Bank Stability[a]	Position[b]	11/2013 to 05/2014	05/2014 to 07/2014	07/2014 to 09/2014	09/2014 to 11/2014	11/2014 to 05/2015	05/2015 to 07/2015	07/2015 to 09/2015	Total Study Period
02-WR01	Eroding	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	n	n	n	n	n	n	n	n
		Mid-bank	y	n	n	n	y	n	n	y
		Lower bank	y	n	n	n	y	n	n	y
		Toe of bank	0	0	0	0	0	0	0	0
02-WR05	Stable	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	n	n	n	n	n	n	n	n
		Mid-bank	n	n	n	n	n	n	n	n
		Lower bank	n	n	n	n	n	n	n	n
		Toe of bank	0	0	0	0	0	0	0	0
02-WR08	Stable	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	n	n	n	n	n	n	n	n
		Mid-bank	n	add	n	n	add	n	add	add
		Lower bank	n	n	n	n	n	n	n	n
		Toe of bank	0	0	0	0	0	0	0	0
02-WR09	Eroding	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	y	n	n	n	y	n	n	y
		Mid-bank	n	n	y	n	y	y	y	y
		Lower bank	y	y	y	n	y	y	y	y
		Toe of bank	0	0	0	0	0	0	0	0
02-B01	Eroding	Top of bank	0	0	0	0	4.5	0	0	4.5
		Upper bank	y	y	n	n	y	n	n	y
		Mid-bank	y	n	n	n	add	n	n	add
		Lower bank	add	n	n	n	add	n	n	add
		Toe of bank	-2	0	0	0	0	0	0	-2
02-B03	Eroding	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	n	n	n	n	n	n	n	n
		Mid-bank	y	n	n	n	y	n	n	y
		Lower bank	add	y	y	y	y	n	y	y
		Toe of bank	-4	0	0	0	1.5	0	0.8	-1.7

Site	Bank Stability[a]	Position[b]	11/2013 to 05/2014	05/2014 to 07/2014	07/2014 to 09/2014	09/2014 to 11/2014	11/2014 to 05/2015	05/2015 to 07/2015	07/2015 to 09/2015	Total Study Period
02-B07	Eroding	Top of bank	7.5	0	0	0	0	0	0	7.5
		Upper bank	y	y	y	n	n	n	n	y
		Mid-bank	y	y	y	n	y	y	y	y
		Lower bank	add	y	y	n	y	y	y	y
		Toe of bank	-4.9	0	0	0	0	0	0.1	-4.8
02-B09	Healed erosion	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	n	n	n	n	n	n	n	n
		Mid-bank	n	n	n	n	n	n	n	n
		Lower bank	n	n	n	n	n	n	n	n
		Toe of bank	0	0	0	0	0	0	0	0
02-BR01	Armored	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	n	n	n	n	n	n	n	n
		Mid-bank	n	n	n	n	n	n	n	n
		Lower bank	n	n	n	n	n	n	n	n
		Toe of bank	0	0	0	0	0	0	0	0
02-BR05	Vegetated eroding	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	n	n	n	y	n	n	y	y
		Mid-bank	add	y	n	n	y	y	n	y
		Lower bank	y	y	y	n	y	y	y	y
		Toe of bank	1	-2.1	1.5	0	2.1	-2	2	2.9
02-V02	Eroding	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	y	y	n	n	y	n	y	y
		Mid-bank	y	n	n	n	add	n	n	y
		Lower bank	add	y	y	y	y	add	add	add
		Toe of bank	-1.5	0.7	0.8	0	0	-0.8	-0.2	-1
02-V03	Eroding	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	y	n	n	n	n	n	n	y
		Mid-bank	y	n	n	n	y	y	n	y
		Lower bank	y	n	y	y	y	y	y	y
		Toe of bank	1.2	0	0.8	0	0.8	0	1.3	4

Site	Bank Stability[a]	Position[b]	11/2013 to 05/2014	05/2014 to 07/2014	07/2014 to 09/2014	09/2014 to 11/2014	11/2014 to 05/2015	05/2015 to 07/2015	07/2015 to 09/2015	Total Study Period
02-V06	Vegetated eroding	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	n	n	n	n	n	n	n	n
		Mid-bank	n	n	n	n	n	n	n	n
		Lower bank	n	n	n	y	y	y	n	y
		Toe of bank	0	0	0	0.3	-0.4	1.1	0	1
02-VR01	Eroding	Top of bank	N/A	0	0	0	0	0	0	0
		Upper bank	N/A	n	n	n	y	y	y	y
		Mid-bank	N/A	n	n	n	n	n	n	n
		Lower bank	N/A	n	y	n	y	y	n	y
		Toe of bank	N/A	0	0	0	0	0	0	0
02-VR02	Stable	Top of bank	0	0	0	0	0	0	0	0
		Upper bank	n	n	n	n	y	n	y	y
		Mid-bank	n	n	n	n	y	n	n	y
		Lower bank	add	y	n	n	y	y	y	y
		Toe of bank	0	0	0	0	0	0	0	0

a. As mapped during 2014 bank stability mapping (see Section 5.6).

b. Values for “Top of bank” represent the amount of recession at the top of bank in feet. Notes regarding changes in bank slope for the Upper, Mid and Lower bank include: n = no change; y = some change; and add = material added to that portion of bank. Values for the “Toe of bank” represent the amount removed or added in feet with negative values representing material added to the base of the bank causing it to build out.

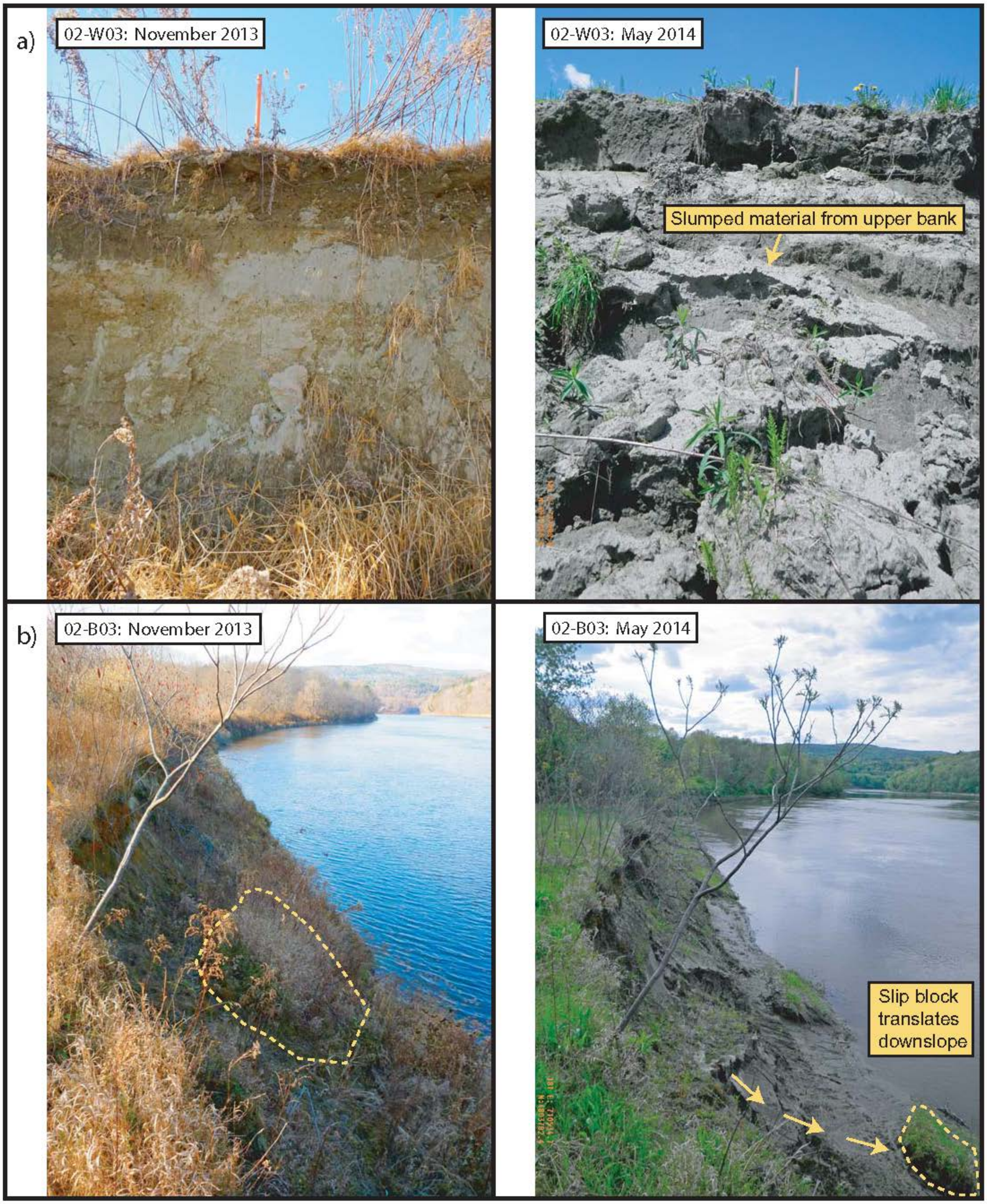


Figure 5.4.2-2a. The types of conditions observed on the repeated ground photographs included a) top of bank recession, and b) bank slope changes.

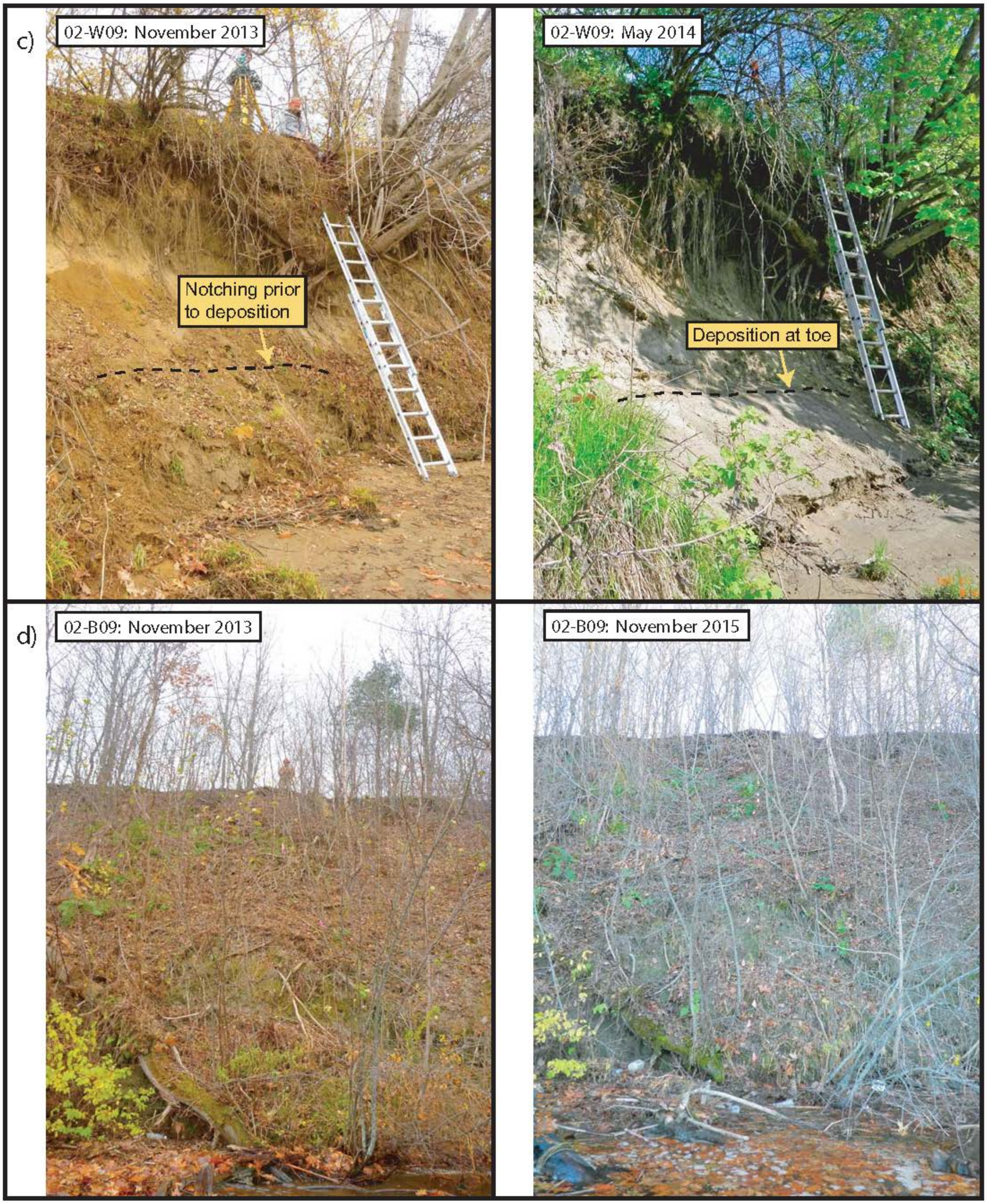


Figure 5.4.2-2b. The types of conditions observed on the repeated ground photographs included a) top of bank recession, and b) bank slope changes.

Only three of the sites experienced measurable recession at the top of the bank (02-W03 [Bellavance Site], 02-B01 [Lipfert Site], and 02-B07 [Charlestown Site]) even though 15 of the 21 monitoring sites were mapped as eroding or another unstable category (i.e., vegetated eroding or failing armor) during the bank stability mapping completed in 2014 (see Section 5.6). Bank recession at these three sites occurred between November and May (presumably during the spring freshet) with recession occurring only once at each site (documented in May 2014 at Sites 02-W03 and 02-B07 and in May 2015 at Site 02-B01). The maximum bank recession was 7.5 ft at Site 02-B07 in Charlestown, NH. Local conditions exist at all three sites that could explain why upper bank recession occurred. The Bellavance Site (02-W03) is immediately upstream of a meander cutoff that occurred in the 1950s (Figure 5.2.2-1) and the active erosion is consistent with accelerated erosion following cutoffs elsewhere on the Connecticut River (Black et al., 2010; Jahns, 1947). At 02-B01 (Lipfert Site), the high bank is composed of loose, easily erodible sand and is situated across from a large sand bar that, based on the location of the deeper channel, directs flow into the monitored bank (Figure 5.4.2-3). Finally, 02-B07 (Charlestown Site) is a low bank on a floodplain with numerous, very large scroll bars that indicate significant erosion, deposition, and channel migration has occurred for decades if not centuries prior to construction of the Bellow Falls Project, , given their presence across the entire wide floodplain (Figure 5.4.2-4).

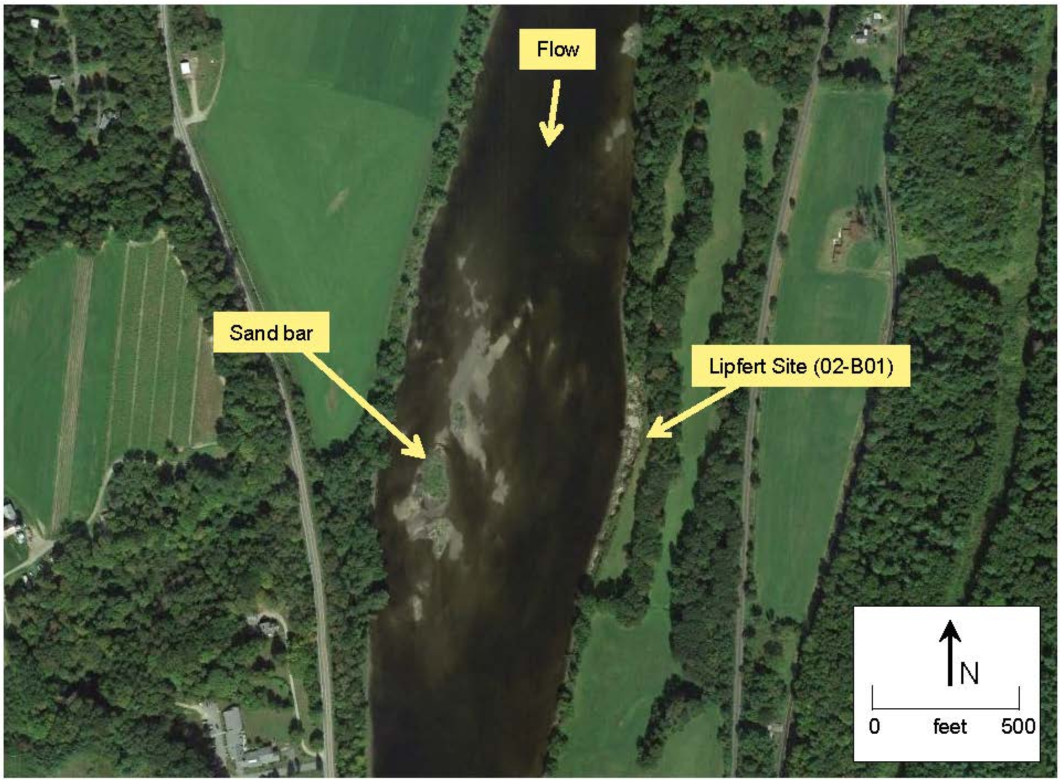


Figure 5.4.2-3. Large sand bar is situated across from 02-B01 (Lipfert site).

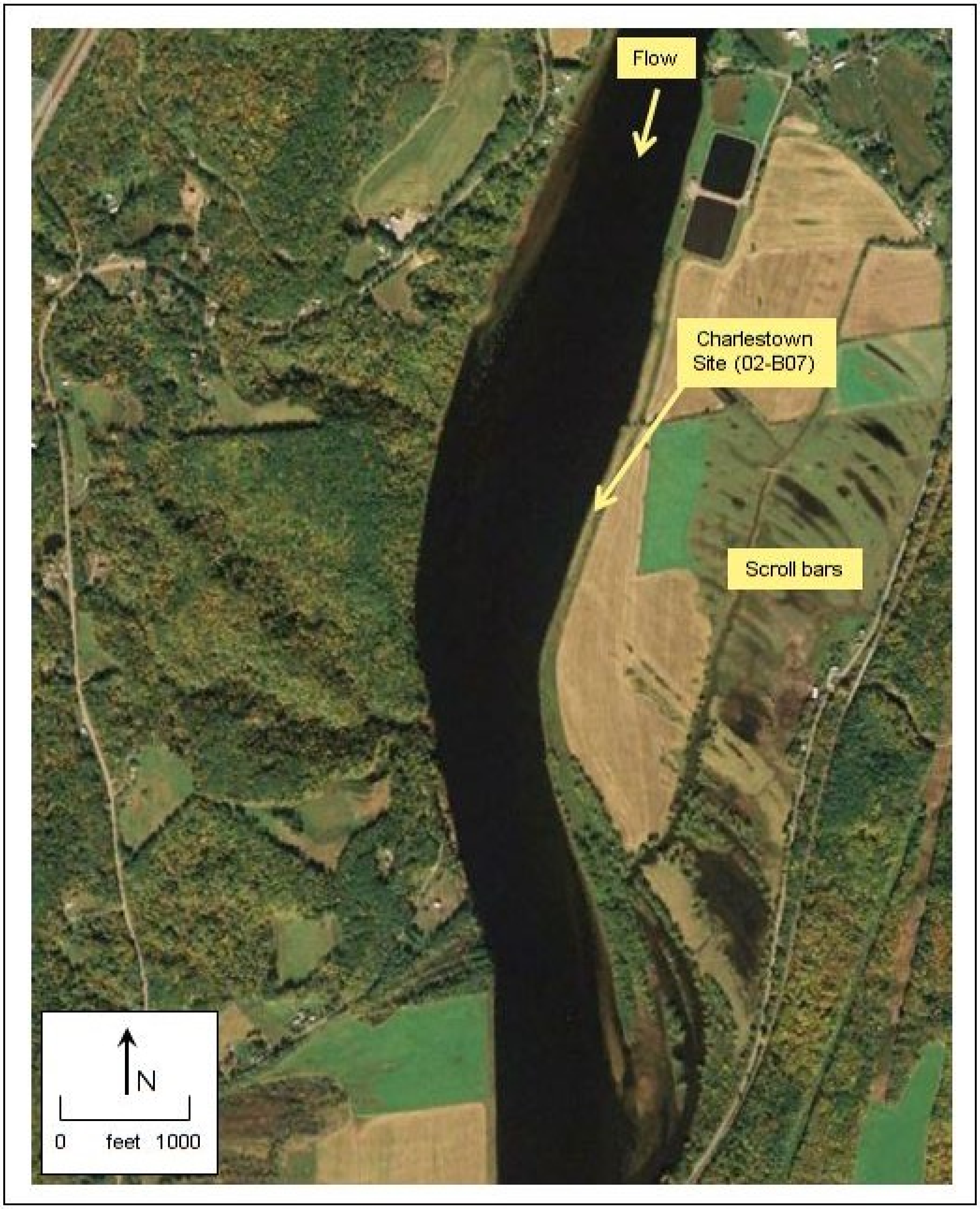


Figure 5.4.2-4. Scroll bars on floodplain at 02-B07 (Charlestown Site) are indicative of decades, if not centuries, of channel migration.

The fact that these three sites experienced recession only once during two years of monitoring and that 12 additional monitoring sites mapped as unstable did not experience any bank recession at all may seem incongruous but actually indicates that bank recession, even in the most unstable areas monitored, does not occur annually but rather occurs episodically, at time scales extending more than two years. The lack of recession at the top of the bank at the surveyed transect (only a single point along the bank) does not imply that other nearby portions of the bank are not receding (Figure 5.4.2-5). This indicates that bank erosion not only occurs episodically in time, but also varies spatially with long lengths of bank unlikely to recede at the same time but rather shorter sections recede over time that taken together over a period of years leads to the entire bank receding. Better refinement of the spatial distribution of erosion along a single section of eroding bank was beyond the scope of this study.

Figure 5.4.2-5. Bank collapse and recession in 2015 occurred near 02-W09 (Mudge Site) despite no recession at the transect itself.

Although not all of the 15 monitored banks mapped as unstable experienced top of bank recession, all but one did experience some change below the top of the bank (Table 5.4.2-1). Material translates downslope from the upper bank as a single unit (Figure 5.4.2-1b) and as smaller blocks or disaggregated sediment (see Appendix A). Changes observed at the toe of bank included: 1) the building out of the bank toe as sediment eroded from upslope accumulates at the base (reflected as a negative number in Table 5.4.2-1) and the removal of such accumulated sediment or native bank material to form a notch or overhang (Appendix A). Sediment accumulation at the base of the bank is not always the result from downslope movement of bank material but can also result from river deposition (Figure 5.4.2-1c). Notching at the base of the bank predominately occurred into material accumulated at the base of the bank (Figure 5.4.2-1c) but notching of native bank material is also possible as was the case at 02-W10 (Vaughn Site) and 02-BR01 (Walpole Beach Site; Appendix A).

Normal project operations result in daily or sub-daily fluctuating water levels that occur within a relatively narrow and consistent band each day. While there are variations within the band, as a whole, the narrow band is consistent from day to day under non-flood conditions. At 8 of the 21 monitoring sites, as would be expected, this consistent band of daily water surface elevations aligns with the location of notching at the base of the bank (Figure 5.4.2-6 and Appendix A: 02-W03, 02-W07, 02-W09, 02-W10, 02-W12, 02-B03, 02-B09, 02-BR01). At 2 of the 8 sites (02-W10 and 02-BR01) where the bank stratigraphy is exposed at the base of the bank, the notch has formed at a contact between a coarser sedimentary layer above and a finer layer below. Seepage is typically enhanced along such contacts between permeable layers above and less permeable layers below. Even where the elevation at which the WSE fluctuations occur changes with discharge, the seepage will remain most prevalent at the stratified soil contact. While such contacts may exist at the base of the other 6 monitoring sites where notching aligns with the band of daily water levels, the layers were covered by eroded sediment from upslope and were not directly observed.

In determining whether project-related WSE fluctuations are a cause for erosion (see Section 5.6.5), the elevation range on the bank where those WSE fluctuations most often occur is as important as the magnitude of the fluctuation itself. Under no-spill conditions project operations range from minimum flow discharge to full generating capacity but periods in the range of full generating capacity typically corresponds with periods of equal levels of inflow. Since dam WSE can differ at a single discharge flow, the most common impoundment elevation for the generated minimum flow (700 cfs at Wilder dam) was determined by querying three years (2013-2015) of hourly discharge data. For example, the most common impoundment elevation at Wilder dam during this three year period for a 700 cfs discharge was 383.6 ft. This generated minimum flow of 700 cfs at a WSE of 383.6 at Wilder dam was then used in the Hydraulic Model (Study 4 [GEI, 2016]) to determine the low flow WSE on the bank at the monitoring site (i.e., the bottom of the gray bar in Figure 5.4.2-6 and Appendix A) above which the median WSE fluctuation band or range is believed to most often occur at each of the 21 erosion monitoring sites. The WSE fluctuation ranges at each monitoring site were derived from the operations model (Study 5 [Hatch 2016]) 50th percentile exceedance level for no-spill conditions.

At some impoundment sites close to project dams such as 02-W12 (Pine Park), higher project discharges under spill conditions require operating at a lower elevation at the dam to reduce upstream flood elevations. This operation correspondingly results in lower WSE's at the monitored transects near the dams during high flow events. High water operations (exceeding normal operations in terms of flow and/or WSE) can occur as part of river flow management when TransCanada may periodically initiate "River Profile Reservoir Operations" by lowering WSE to specific elevations in anticipation of inflows greater than maximum generating capacity at each project. This is done pursuant to high water procedures developed under Article 32 of the existing project licenses and stipulated in Coordination Agreements with the US Army Corps of Engineers which operates flood control dams on several tributaries to the Connecticut River. These high water operations are initiated in order to maintain upstream water elevations within a range that protects specific railroad grade embankments along the river and to reduce the potential for river flows to spill outside of the normal operating ranges. These conditions and operating protocols are not considered normal project operations as they are instituted before and during all spill events; they typically occur often for sustained periods of time, each spring during the freshet.

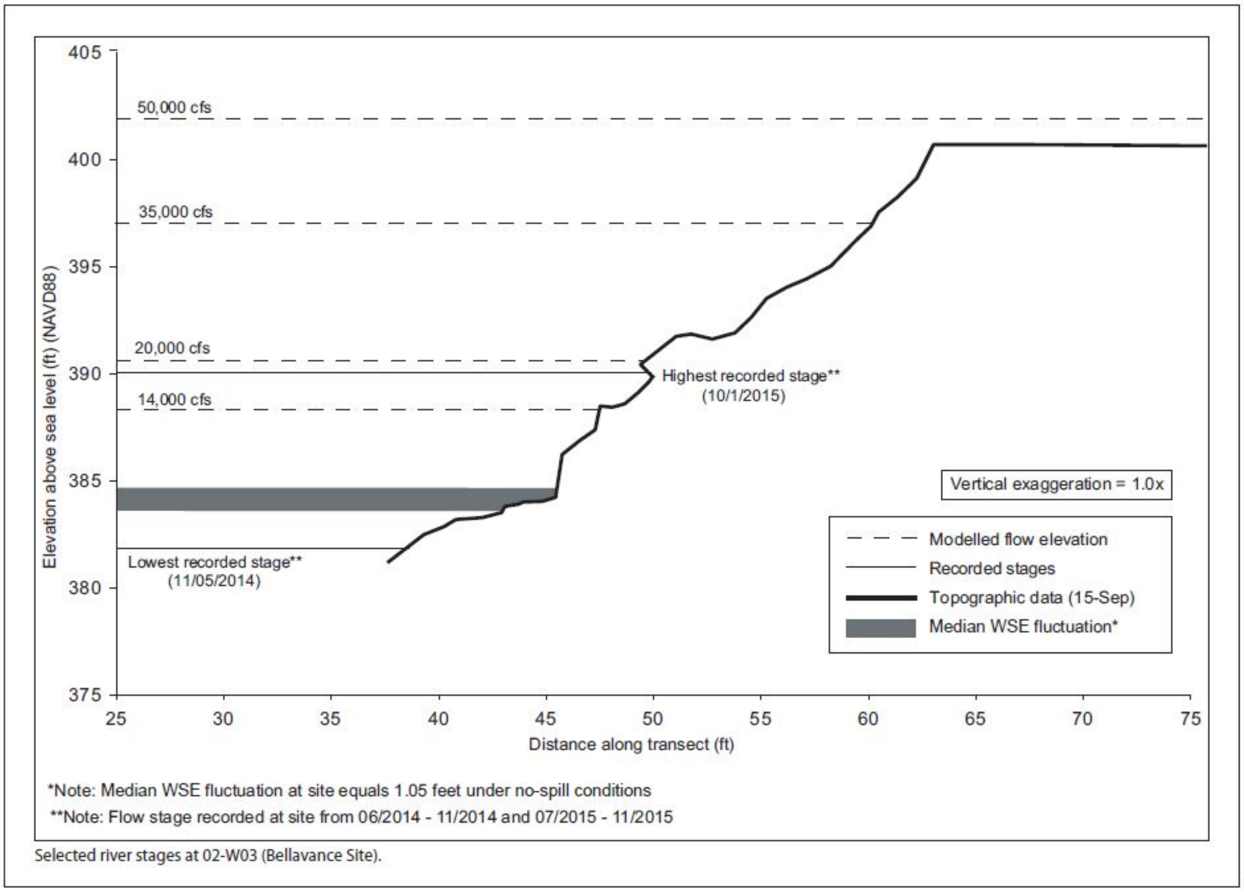


Figure 5.4.2-6. Position on bank of normal operating range aligns with location of notching at 02-W03 (Bellavance Site).

No change of any kind was recorded at four of the 21 sites (Table 5.4.2-1) during the two-year monitoring period with bank stability for those sites mapped as stable or, in one case, unstable (i.e., failing armor) during bank stability mapping (see Section 5.6). WSE fluctuations at these sites were similar to those at sites where notching and other changes at the bank toe were aligned with the elevation range of normal project operations. The lack of change at an unstable site further indicates that a site can show the physical characteristics of erosion but not experience such erosion over time periods exceeding two years. In addition to the four sites without any change, an additional six sites had no change at either the top or base of the bank during the two years of monitoring. Of these, three sites were mapped as eroding and three as stable, indicating again that an eroding bank may not experience changes in bank position for periods of two years or more. In contrast, banks that are stable may experience some minor changes on the bank slope without changes in bank position.

The water level logger data for the monitoring sites typically show the daily band of WSE's associated with normal (non-spill) project operations superimposed upon longer-scale WSE variations associated with variations in flow caused by rainfall events and other factors (Figure 5.4.2-7 and Appendix A). Higher river flows caused by such events can result in significant increases in WSE independent of project operations at the dam. While a site-by-site analysis of WSE fluctuations is not provided here, the results of the water level monitoring were used to calibrate the hydraulic model developed as part of Study 4 (GEI, 2016) and were used to confirm the Study 5 (Hatch, 2016) operations model results regarding the magnitude of normal WSE fluctuations associated with normal project operations. The WSE variation associated with the 50% exceedance probability reported by the operations model during no-spill conditions was considered to most closely match the typical fluctuation observed in the water level logger data, so that median value is shown on the transects as a gray shaded zone to indicate where on the bank WSE fluctuations under no-spill conditions operate on the bank. The graphs of the water level logger data from the erosion monitoring sites (Appendix A) show that river stage closely adheres to the shaded area at least during the seasonal sampling period. This median value was also used to establish WSE fluctuations throughout the study area in order to assess whether erosion is concentrated in areas of greatest water level variation (see Section 5.6.5b).

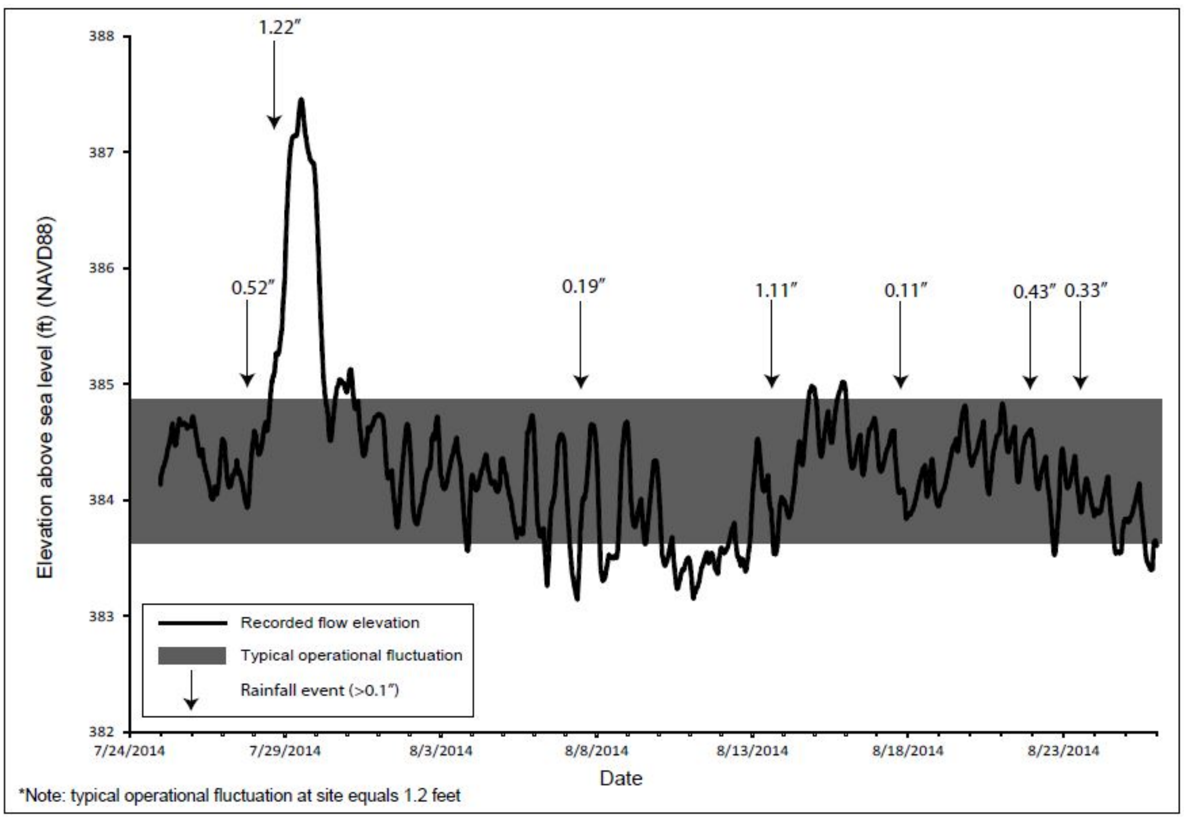


Figure 5.4.2-7. Sample graph created from water level logger data.

5.5 Surficial Geological Maps

Surficial geological maps for most of the study area have been published by the New Hampshire Geological Survey (Web citation 7) and Vermont Geological Survey (Web citation 8) on 7.5' USGS topographic quadrangles and show the distribution of geomorphic surfaces (i.e., landforms created by different processes and at different times). In most cases, the landforms are depositional in nature such that the surface is genetically related to the underlying sediment with a lake bottom terrace, for example, likely underlain by clay and other fine sediments deposited on the lake bottom. As part of this study, the surficial geological maps were compiled, simplified, and uniformity brought to the numerous maps created in two different states by different workers using different protocols and map legends. Supplemental information was gathered to cover portions of the study area not covered by published maps. The supplemental data and published maps were used to create simplified surficial geological maps with LiDAR data serving as a base layer in order to show the topographic characteristics of the various mapped surfaces (Appendix B). The maps were used to provide information on the height of banks, subsurface material, and the location of valley constrictions (i.e., where the floodplain surface narrows downstream). The information on bank heights and bank composition is discussed further in Section 5.6.5 and was used to assess whether bank erosion is preferentially associated with certain geomorphic surfaces.

The surficial geology of the Connecticut River valley consists of a series of terraces stepping up from the river (Figure 5.5-1) with the highest and, therefore, oldest geomorphic surface formed since the last Ice Age (i.e., < 15,000 years ago). The river channel's position relative to the various geomorphic surfaces determines the bank heights and bank composition along the length of the river with higher banks encountered where the river flows against older and higher terraces. These terrace and floodplain surfaces, among others, are seen throughout the study area, but not all of the surfaces are found together along a single cross-valley transect. The greatest number, extent, and complexity of surfaces occur where the valley is wide. Much of the Connecticut River valley in the study area is quite narrow such as between Putney and Brattleboro, Vermont, but several wider sections exist where a complex assortment of geomorphic surfaces are present. The widest portion of the valley in the study area is in the upper Wilder impoundment upstream of Orford, New Hampshire with other wide, but much shorter, portions of the valley present in the Bellows Falls impoundment upstream of the Williams River and in the Vernon impoundment between the Cold River confluence and East Putney, Vermont.

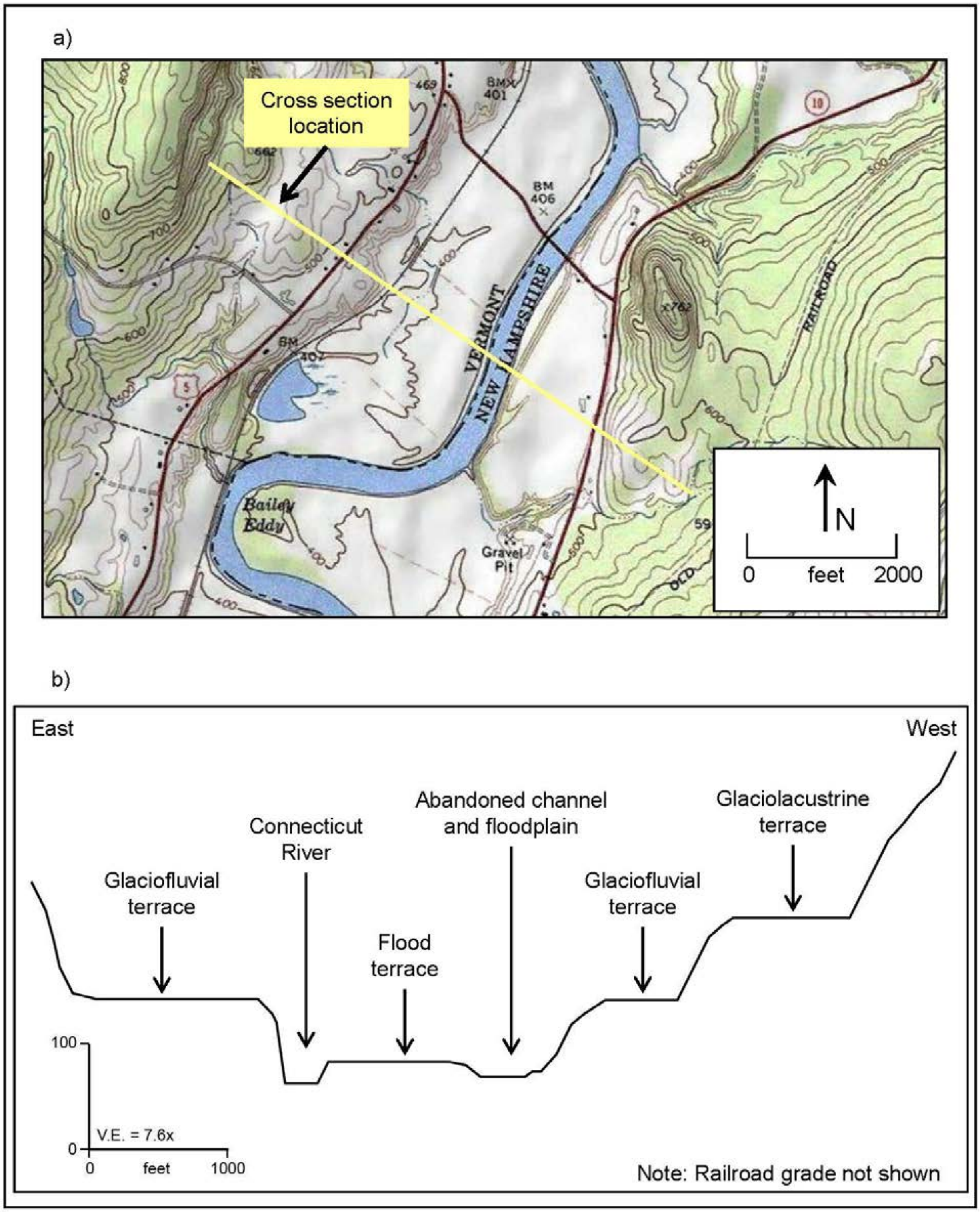


Figure 5.5-1. a) Topographic map and b) topographic cross section across the Connecticut River Valley in the upper Wilder impoundment showing various floodplain and terrace surfaces and their height.

5.6 Field Mapping of Bank Conditions

The Study 1 report presented maps of erosion data from 1958 and 1978. To compare those earlier maps of bank erosion with current conditions, bank stability was mapped in 2014 as part of Study 3. A number of other bank characteristics were also mapped in 2014 to provide context to the bank stability mapping, including erosion types, bank heights, bank composition, depositional features, presence of riparian vegetation, and large wood. Depositional features included marking all tributaries that had a delta building out into the river. Information on the position of these various features were recorded as GIS point files (for wood locations) and GIS line files that followed the left and right banklines of the river. LiDAR data collected by TransCanada as part of the relicensing studies and the surficial geology maps (Appendix B) were used to extract information on bank heights and bank composition with the GIS line files showing the extent of banks of various heights and composition. The results of this extraction process were later confirmed or revised as needed through field verification. A GIS line file was created for the presence or absence of riparian vegetation by hand-digitizing the locations of riparian vegetation as viewed on 2010 digital orthophotographs available through NH Granit (Web citation 8). The remaining features were mapped in the field using a hand-held Yuma Trimble tablet computer with an embedded GPS unit, ArcPad software, and digital USGS topographic maps and 2010 orthophotographs as base maps. During the mapping, GIS line files were preloaded into the tablet computer with dropdown menus created for each feature’s subcategories such that, for example, the upstream end of an eroding bank could be marked on the bank stability line file and assigned to the “Eroding” category. The endpoint of the erosion was not explicitly marked but was implied when the upstream end of a new bank stability category, such as “stable”, was recorded. Later post-processing converted the points into line segments connecting the beginning and (implied) end point of each bank feature mapped. The various categories/subdivisions within each mapped feature are listed in Table 5.6-1. Given that multiple bank features were being mapped simultaneously, multiple shapefiles each consisting of multiple categories were under consideration at the same time, so a slow mapping pace was maintained to ensure accurate mapping.

Mapping of the entire study area, consisting of over 250 miles of bank and islands, was completed over a two-month period in the fall of 2014 while slowly progressing down the impounded portions of the study area in a motorboat equipped with a large sun umbrella to eliminate glare on the tablet computer screen. The riverine reaches were covered in canoe and in some locations such as Sumner Falls, on foot. While the mapping would have ideally occurred in leaf-off conditions, the total mileage to be mapped precluded the entire study area being covered during the short window of time between the leaves falling and the onset of winter temperatures and shortened daylight. For this reason, among others, frequent stops or backtracking were made in the boat during the mapping to more closely examine bank conditions, especially those obscured by vegetation.

The mapping did not begin until an extensive reconnaissance of the study area was completed to better understand the types and processes of erosion occurring in order to identify the bank feature categories to be used and to establish a workable mapping procedure that could be maintained throughout a study area having highly variable bank and channel conditions. The subsequent mapping of bank stability and other features then provided a context for analyzing the distribution of erosion, both spatially and temporally. With this in mind, the following discussion regarding bank erosion is organized into the following subsections: a) types of erosion, b) processes of erosion, c) bank stability categories, d) mapping results, and e) analysis of erosion through space and time.

Table 5.6-1. Categories of mapped bank features.

Bank Feature	**Subcategories**	**GIS File Type**	**Explanation**
Stability	Stable Healed erosion Armored Failing armor Vegetated eroding Eroding	Line	First 3 on list are stable banks and last 3 are unstable
Erosion type	Notching/overhangs Tunnel scour Topples Planar slips Rotational slumps Sediment Flows Soil creep None	Line	Both a dominant and as many as 2 additional secondary erosion types mapped
Bank texture	Bedrock Boulder Cobble Gravel Sand/Loam Glacial clay	Line	Based on observations at base of bank
Surficial geology	See Appendix B	Line	Subcategories based on the geomorphic surfaces listed in Appendix B legend that intersect the bank line
Depositional features	Point bar Side bar Delta bar Mid-channel bar Island Diagonal bar Sand spit	Line	Position of bars and islands digitized with line segments
Large wood	Bank derived Recruited	Point	Recruited wood represents wood that has floated to location from upstream

5.6.1 Types of Erosion

Four of the erosion types described by Lawson (1985) (Table 5.1.2-1) were widely observed in the study area: falls, topples, slides, and sediment flows but were further subdivided for greater detail in the mapping process (Tables 5.6-1 and 5.6.1-1). Lateral spreads may also occur, but are not widespread or distinct enough from sediment flows or slides to be considered separately. As many as 3 erosion types were recorded at any location during the mapping process: the dominant type and as many as two secondary erosion types. While all of the erosion types could theoretically be present at any given site, three erosion types were actually mapped along only 0.7% of the bank length (and two erosion types were mapped along an additional 22.9%).

5.6.1a 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. Water currents strong enough to erode and transport sediment in the study area are potentially generated by at least five different mechanisms: waves, water level fluctuations, overland flow, groundwater seeps, and tractive forces (e.g., shear stress) generated by river flow (particularly during higher discharges). Currents or river flow, by whichever mechanism, acting at the base of the bank over prolonged (although not necessarily continuous) periods of time can create the notches and overhangs seen at the base of 37% of the river's banks (see Section 5.6.4). Overhangs can extended over 5 ft into native bank soils and, while not overhanging, the back, nearly vertical face of notches can be as much as 5 ft high when formed in accumulated material at the base of the bank (e.g., 02-W09 in Appendix A). While the height of overhangs is generally less than 1.5 ft at the base of the bank, they are sometimes almost 5 ft high or higher where the roots from trees higher on the bank maintain an intact soil mass on the "roof" of the overhang (Figure 5.6.1-1). The taller overhangs probably begin as lower features that increase in height as individual particles from the "roof" fall to the ground in a process more closely resembling a true fall. Eventually the "roof" of an overhang may completely collapse to create what appears as a narrow gully formed from overland flow but is actually the result of riverine or groundwater processes (Figure 5.4.2-5). Deeper narrower overhangs are more likely to persist in finer grained soils while sandier less competent (i.e., less firm and more erodible) soils are expected to give rise to taller shallower features. During the bank features mapping (see Section 5.6.4) only notches and overhangs observed at the base of the bank were recorded, but in some areas notches and/or overhangs are present higher on the bank face (Figure 5.6.1-1).

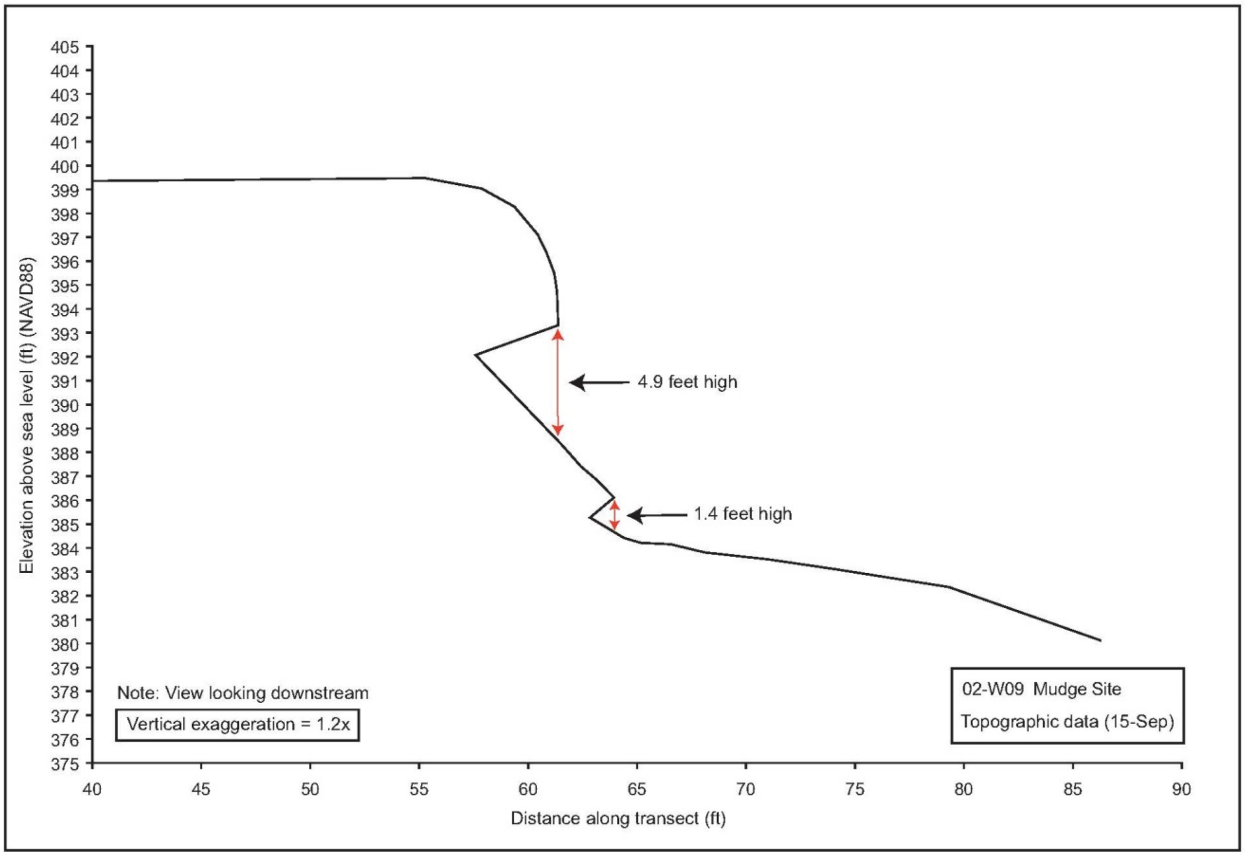


Figure 5.6.1-1. The height of overhangs is generally less than 1.5 ft but can reach nearly 5 ft (or more).

A less common means of erosion through the movement of individual soil particles is by tunnel scour (see Section 5.1.2) whereby continuous cylindrical voids are created through the soil. Eventual collapse of the voids can give rise to nearly circular depressions or “sink holes” that may not initially be connected to the river but over time can lead to the river through a gully that forms if that portion of the bank between the river and “sink hole” also eventually collapses (Figure 5.6.1-2). The growth of very large circular depressions (e.g., > 20 ft in diameter) at the surface can be quite rapid (e.g., days) but likely result from a much longer unseen period of subterranean erosion. While the formation of deep overhangs may be related to the formation of these circular depressions, overland flow draining through vertical voids and causing tunnel scour is likely also important. Consequently, such features albeit similar in appearance to collapsed overhangs (see Figure 5.4.2-5), are treated as a separate, although minor, erosion type herein. Given the difficulty in distinguishing between true tunnel scour features and those created by the collapse of overhangs, tunnel scour was identified with confidence at only two locations throughout the study area (e.g., Fairlee and Springfield, VT) but may have occurred elsewhere where gullies, that may have originated as “sink holes”, are present. True gullies formed by overland flow headcutting back from the bank were not mapped in the study area but gullies formed by the collapse of overhangs or subterranean voids may enlarge over time by overland flow.

Figure 5.6.1-2. Tunnel scour can form circular depressions that transform over time into gullies as the material between the river and depression collapse. Photo from Fairlee, VT – in left foreground is portion of circular depression initially formed in 2014.

5.6.1b Topples

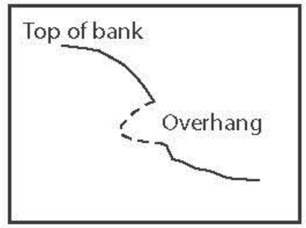
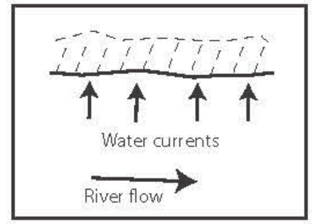
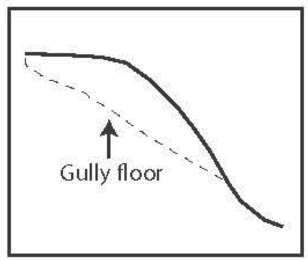
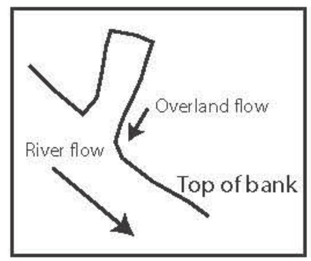
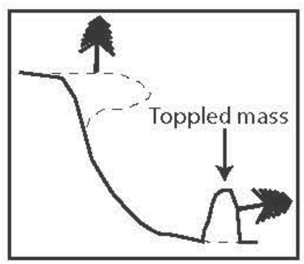
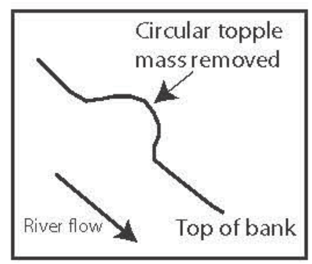
Topples occur when vertical tension cracks that form parallel to the top edge of the bank widen to a point where the top portion of cohesive masses of soil rotate forward about a pivot point near the base of the soil mass. Topples are typically enhanced when soil attached to a root mass of a severely undercut tree leans over and collapses over the bank. Individual soil blocks involved in topples when no trees are involved 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 allowing the process 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 5.6.1-1) that can be confused with smaller rotational slumps (see Section 5.6.1c). Semicircular embayments can also result when a tree resists erosion and persists on the bank while the bank recedes on either side of the tree. When an overhanging tree does ultimately fall through the toppling process, the pivoting motion away from the bank leaves trees leaning towards the river if they do not become completely detached from the bank. After a tree falls over the bank with its top end potentially in the water, the root mass with soil attached creates 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 5.6.1-1).

5.6.1c Slides

Both shallow planar slips and deep-seated rotational slumps were observed to occur in the study area with transitional forms present. These types of mass movements give rise to what have been described as sloughing banks by others (e.g., Simon et al., 1979). 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 parallel to the bank (e.g., 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 (Table 5.6.1-1).

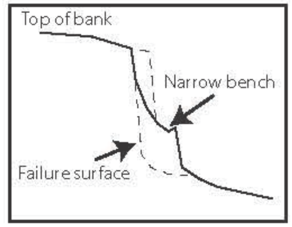
Table 5.6.1-1. Types of erosion occurring in the study area and their characteristics (adapted from Field, 2007a).

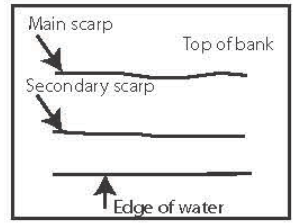
Erosion type	Photo	Profile	Planview	Description
Falls - Notches/ Overhangs				- Notching and overhangs create oversteepened toe of slope
- Tunnel scour/ Gullies				- Tunnel scour creates circular collapse structures ("sink holes") - Collapse structures elongated and connected to river through later gullying by overland flow
Topples				- Vertical tension cracks at the top of slope - Trees lean away from bank - Toppled mass creates mound of soil at base of bank

Erosion type	Photo	Profile	Planview	Description

Slides

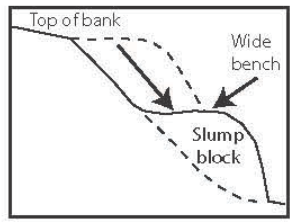
- Planar slip

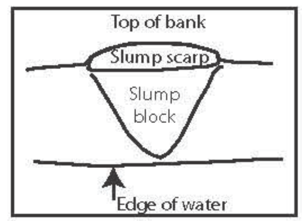




- Vertical tension cracks at top of slope
- Top surface of slide mass has flatter slope than rest of bank (narrow bench)
- Trees lean in towards bank
- Trees can remain in growth position despite sliding

- Rotational slump

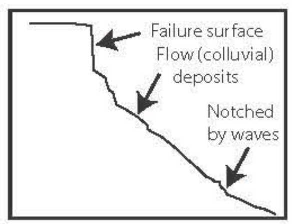


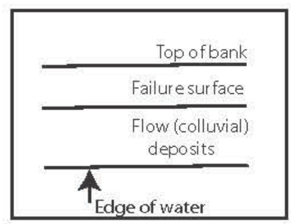


- Vertical tension cracks at top of slope
- Deeper seated than slips
- Trees lean in towards bank
- Arcuate failure surfaces

Flows

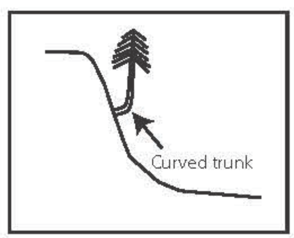
- Colluvial apron





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

- Soil creep



Not applicable

- Tree trunks bent downslope at base

In some instances the only evidence of erosion on the bank is the exposure of a bare scarp only a foot tall at the top of the bank indicating a large portion of the bank has slipped down slightly while remaining largely intact. For this reason, banks that appeared stable were carefully inspected during the mapping to look for these often barely visible scarps that are sometimes present on well vegetated banks (Figure 5.6.1-3). Elsewhere, in contrast, multiple slide blocks were sometimes seen stepping down from the top of a high bank with several narrow relatively flat benches separating well exposed high bare scarps. The benches will often retain the vegetation (grass or trees) that was growing at the top edge of the bank before the slip block slid down the bank. Aside from notching and overhangs, planar slips were the most prevalent type of erosion observed in the study area (see Section 5.6.4).

Figure 5.6.1-3. Sometimes barely visible scarps are the only evidence of active erosion on well vegetated banks.

Where the slip block is completely removed, the bank is left bare as the scarp along which the block moved, potentially more than 70 ft high on high banks, is completely exposed. Viewing a planar slip from the river, the failure surfaces can be arcuate in shape on high banks as the center of the scarp often extends higher up the bank slope (see photo in Table 5.6.1-1). On lower banks, the entire slip will extend to the top of the bank such that the top edge of the scarp is much straighter and less arcuate in shape. In profile, slip surfaces are steep and planar with narrow benches formed, as discussed above, where the slip block does not reach the base of the bank (Table 5.6.1-1).

Rotational slumps were uncommonly observed in the study area and were typically less than 50 ft wide with the top edge of the scarp arcuate in shape. One distinguishing feature of slumps is that trees within a slump block will generally be leaning back towards the bank as the result of block rotation (Table 5.6.1-1). In profile the failure surface is more concave than for planar slips. Benches formed partially down the slope represent the top of the failed slump block, are typically wider, and slope back towards the bank in contrast to planar slips. Slumps were far less prevalent in the study area compared to slips as a result of the preponderance of less cohesive sandy soils that favor shallower failure surfaces.

5.6.1d Sediment Flows

Sediment flows generally occur in association with the other erosion types described above. Long areas of sediment flows in the study area 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. Sediment 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 sediment flows, although believed to be less important than saturated sediment flows, can occur for some time after an event if the material remains loose, especially on the over-steepened base of the slide masses (Table 5.6.1-1). The characteristics of a sediment flow transition from the intact slide mass or disaggregated topple blocks above to a slope of colluvial deposits below. While individual sediment flows observed were narrow (< 30 ft wide), a series of adjacent sediment flows lead to the development of a colluvial apron potentially several hundred feet wide (Figure 5.6.1-4).

Figure 5.6.1-4. Wide colluvial apron at base of bank formed by series of adjacent sediment flows.

Colluvial aprons in the study area were observed to be well formed at the base of some high eroding banks, but also were observed to occur on lower banks. The colluvial deposits were typically restricted to the lower half of the bank and form gentler slopes as the angle of repose is established in the loose sediments. The grade of the colluvial slopes was slightly concave upward, but not as dramatically as the failure surfaces of rotational slumps (Table 5.6.1-1).

Soil creep, an extremely slow flow process (i.e., inches per year or less), was observed to occur in the study area and is characterized by tree trunks curved downslope near their base. In the study area, creep was mapped in only a few small areas where the curves in tree trunks were evident, but may also be present elsewhere. Less than 1% of the riverbanks in the study area were mapped as exhibiting creep (see Section 5.6.4).

5.6.2 Processes of Erosion

The four erosion types observed in the study area rarely occur in isolation, but rather work in concert to remove bank material from the upper and lower slope. The results of the erosion monitoring and visual observations of bank conditions throughout the study area clearly reflect a “cycle of erosion” model that describes a sequence of events occurring through time at a single point (Figure 5.6.2-1). 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 cycle of erosion is similar to that briefly described by Gatto (1982).

A stable bank can become destabilized by the removal of material at the base that ultimately leads to the creation of a notch or overhang (Figure 5.6.2-1a). As the notch grows taller and steeper by advancing further into the bank or the overhang becomes deeper and higher through falls from the "roof" of the overhang, the driving gravitational forces will eventually exceed the bank's resisting forces. As a result, further erosion will eventually occur higher on the bank slope by either topples or slides (Figure 5.6.2-1b). The mass of sediment moved downslope temporarily buttresses the bank from further failure and the bank will stabilize with no further erosion if this accumulated material is not removed from the base of the bank. Sediment flows develop at the base of slide (or topple) masses that have moved only partially down the slope (Figure 5.6.2-1c), resulting from the additional gravitational stress acting on the steeper base of the slide mass. These sediment flows create thin sheets of colluvial material that move further down the bank face. In many instances, sediment flows might not occur but the slide (or topple) mass will become disassociated into individual particles and carried away from the bank by water currents. If the material that has accumulated at the base of the bank is carried away by currents in the river, a steep bare bank face is all that remains (Figure 5.6.2-1d-f). 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 5.6.2-1a-c). Continued recession of the bank is dependent on the development of new notches or overhangs that can begin the "cycle of erosion" afresh.

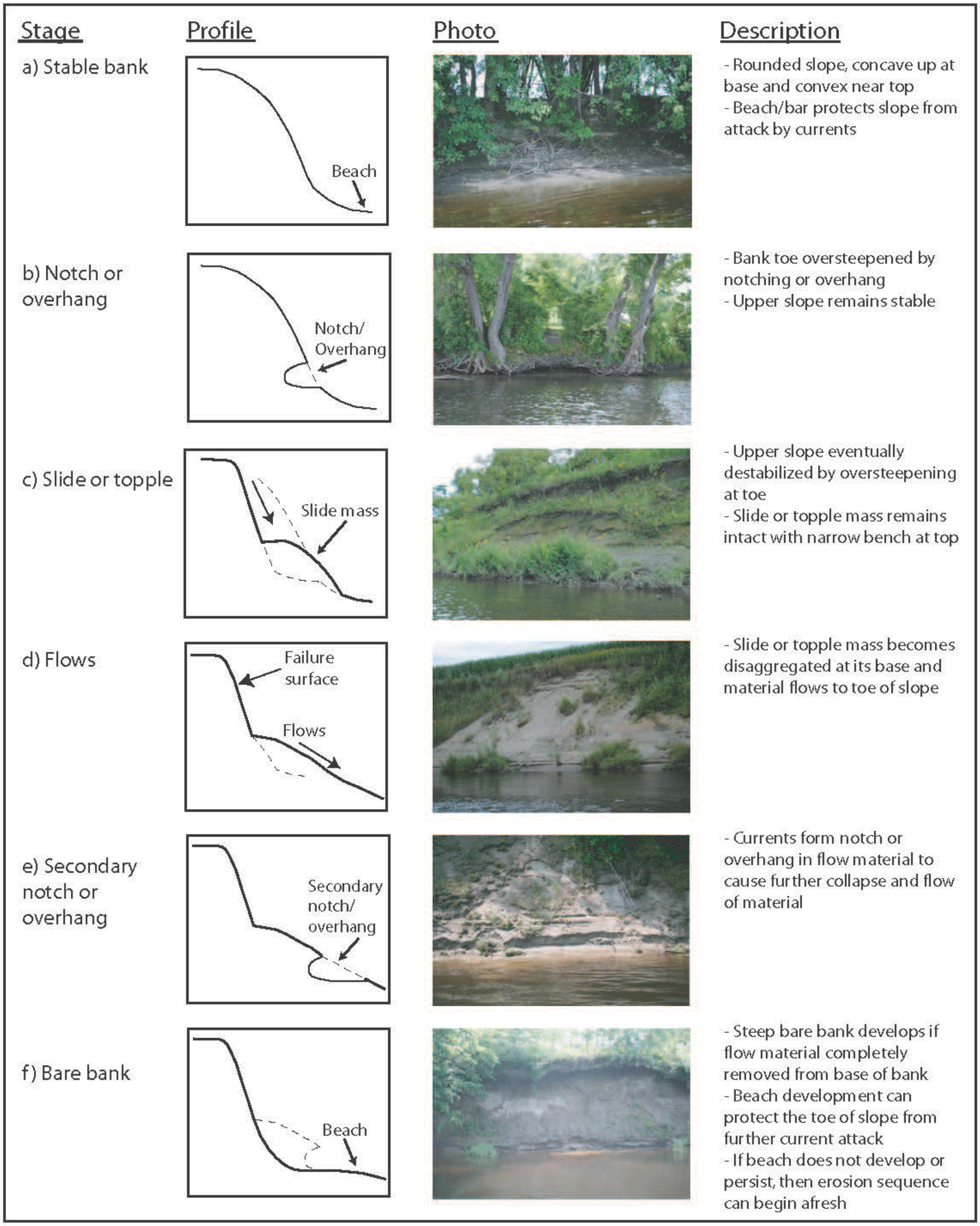


Figure 5.6.2-1. Model idealizing steps in the cycle of erosion. Different stages of erosion can be occurring adjacent to each other along a long, continuously eroding bank (adapted from Field, 2007a).

The presence of large trees on the bank can slow the progress of the erosion cycle. Trees that slide, fall, or topple down from the top of the bank can produce a ridge of roots and soil between the bank and water surface (Table 5.6.1-1). Over time water currents working on this ridge will remove the soil particles between the roots and leave a bare skeleton of roots that are less effective at protecting the bank. Eventually, the tree itself will float downstream during a high water event when the tree has lost its anchoring to the bank; water currents can then once again attack the base of the bank. However, this process can take several years as corroborated by the monitoring data (see Section 5.4) and evidenced by numerous trees in the study area that have decomposed while still attached to the base of the bank (Figure 5.6.2-2). During this extended process the tree branches, roots, and adhering soil provide bank protection and delay progression of the erosion cycle.

Figure 5.6.2-2. Trees that have fallen to the base of the bank may remain for several years and buttress the bank from further erosion.

Sediment delivered to the base of the bank by the erosion cycle can be transported away from the bank by a variety of water currents. River currents tend to transport material downstream while currents generated by waves and seepage forces tend to move material directly away from (i.e., transverse to) the bank. Currents acting transverse to the bank promote the development of gently sloping beaches as the transported sediment accumulates in quieter water areas. The buildup of a beach over time further promotes the bank stability resulting from the initial accumulation of material at the base of the bank from upslope slides, topples, and sediment flows, because the energy of the waves and seepage forces created by water level fluctuations that could otherwise form notches and overhangs in the accumulated materials is instead 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, although protected from the formation of new notches and overhangs, may continue to experience slides, sediment flows, and topples until a more stable bank profile capable of revegetating is established. The presence of a wide 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 at the base of the bank can be reinitiated and the bank will once again become prone to further erosion through the cycle of erosion.

The cycle of erosion suggests that a steep bare bank could, under certain conditions, actually be closer to a stable condition than a heavily vegetated bank with mature trees and a high and deep overhang at the base. The presence of overhangs on an otherwise stable and well-forested bank is an indication that future failure is possible 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. However, while the possibility exists that some well-forested banks may be more prone to erosion than a steep bare bank, the presence of a steep bare bank, in general, is likely an indication that the cycle of erosion is frequently rejuvenated in that area and erosion is progressing at a more rapid rate than a well-forested bank with overhangs at the base. Again, continuance of the erosion cycle depends on the removal of sediment accumulating at the base of the bank and the lack of beach development as the forces necessary to initiate erosion would otherwise be expended across the beach face.

The amount of bank vegetation cannot be used as a reliable indicator in identifying the presence or absence of bank erosion. Many of the banks in the study area have extensive herbaceous and shrub vegetation growing but also show evidence of active planar slips (Figure 5.6.2-3). Vegetation on actively eroding banks can result in at least two ways. First, vegetation might remain undisturbed as a slip block slides down from the top of the bank intact with vegetation remaining. Second, vegetation can become established if the position of a slip block remains unchanged for a season or two while the base of the bank is buttressed by trees or material accumulated from upslope erosion. However, continued progression of the erosion cycle will eventually lead to continued downslope movement and ultimate removal of the (vegetated) slip block. Consequently, vegetation alone cannot be used as an indicator of bank stability, especially where other evidence of erosion exists.

Figure 5.6.2-3. Active erosion can occur despite the presence of bank vegetation. Dashed yellow line outlines top of planar slip scarp.

5.6.3 Bank Stability Categories

In addition to identifying the types of erosion (see Section 5.6.1) the field mapping of bank conditions also included the mapping of bank stability. After extensive reconnaissance of the study area and viewing the range of varying bank conditions present, six bank stability categories (Figure 5.6.3-1) were established for mapping purposes: stable, armored, eroding, vegetated eroding, failing armor, and healed erosion. Three of the stability categories reflect bank instability (i.e., eroding, vegetated eroding, and failing armor) with the differences between them and reasons for mapping them separately detailed further in the subsections below. The stability categories are distinct from the types of erosion described in Section 5.6.1, although an eroding bank will exhibit one or more of the erosion types and, in fact, the presence of one or more erosion types is generally an indication of bank instability.

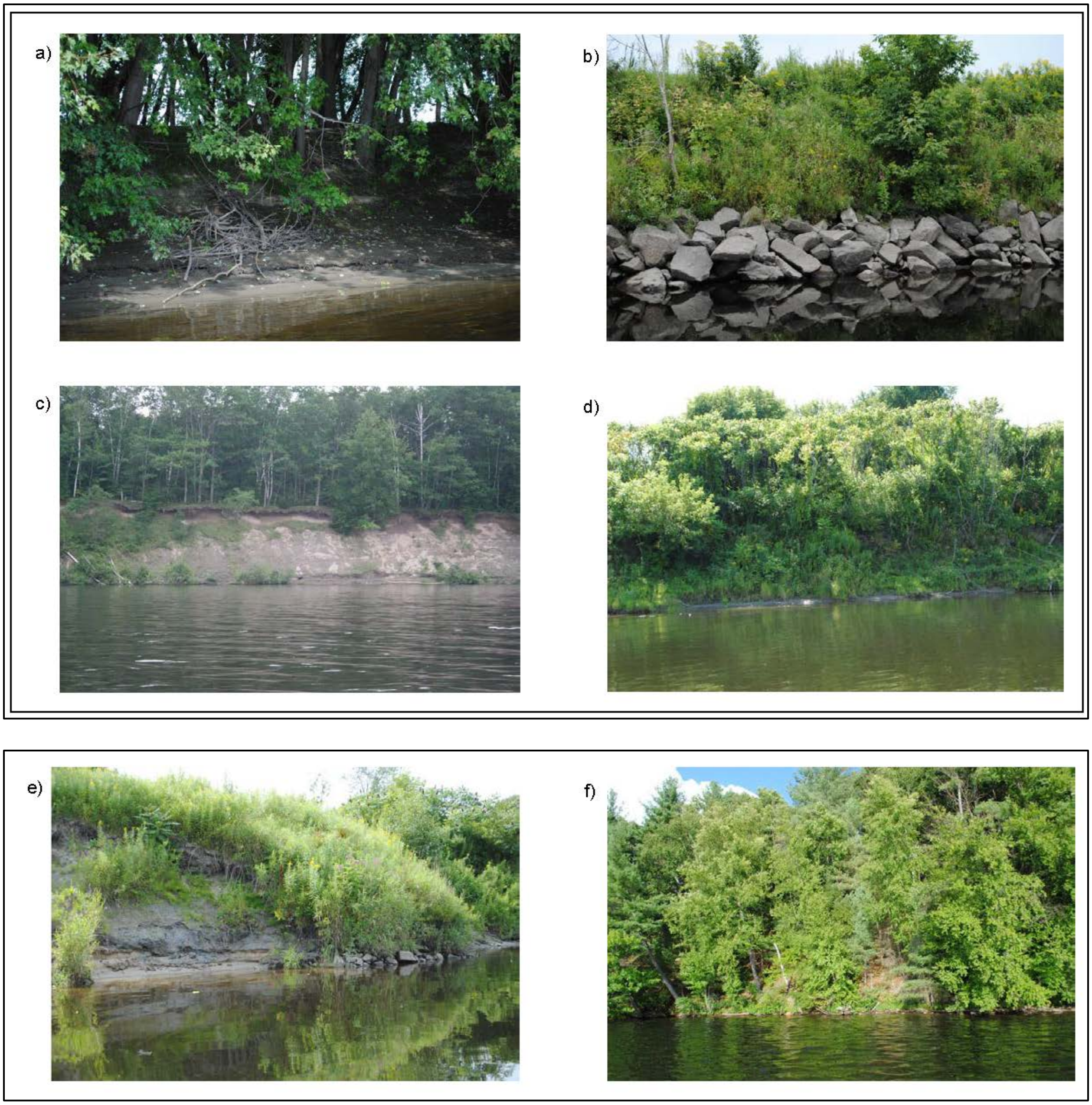


Figure 5.6.3-1. Photos of the six erosion categories: a) stable, b) armored, c) eroding, d) vegetated eroding, e) failing armor, and f) healed erosion.

5.6.3a Stable

Those banks mapped as stable are generally well forested and have a rounded bank profile without sharp breaks in slope from top edge to bank toe (Figure 5.6.3-1a). The upper bank may have a convex-up profile whereas the upper portions of unstable banks will typically have a concave-up profile. The bank surfaces are generally smooth as no large masses of failed bank are on the slope to create a rough surface texture. The base of stable banks is typically fronted by a gently sloping bar or beach face that buttresses the bank from future failure and protects the bank from strong water currents generated by river flow, waves, and seepage flow. Trees, when present on a stable bank, are generally growing straight while multiple trees leaning over due to notching or an overhang underneath suggest that the bank has experienced topples and thus, even in the absence of more pronounced erosion types, indicates that the bank is not stable. In these cases, such a bank was categorized in one of the unstable categories.

While stable banks exhibit none of the erosion types on the upper bank, banks with notching or low overhangs at the base of the bank were mapped as stable as long as no other erosion types or failure surfaces were present higher on the bank face. Previous efforts at mapping erosion in the study area (see Section 5.6.5b) and mapping in the Turners Falls impoundment just downstream of the study area (Field, 2007a) have not considered banks exhibiting only notching as erosion, so to do so as part of this study would artificially bias the results towards a greater percentage of erosion than has previously been documented or accepted in earlier FERC rulings. The cycle of erosion represents a continuum between a stable bank and an eroding bank. A minor notch at the base of the bank does not result in the rest of the bank sliding, falling, or toppling downslope. As a notch/overhang increases in size, the gravitational driving forces destabilizing the bank continue to increase until eventually the bank begins to erode. The notch/overhang is related to the destabilization of a stable bank but should not in itself be considered an eroding bank unless accompanied with other evidence of instability.

5.6.3b Armored

Large portions of the riverbanks in the study area have been armored against erosion generally with large rock (Figure 5.6.3-1b), but also trees and old tires have been used along a few short reaches. Generally the armoring is present only at the toe of the bank, but on low banks the armor sometimes covers the full height of the bank. Where the armoring remains intact and the bank stable, the characteristics of the bank are much like described above for stable banks – well vegetated, smooth surface, and no erosion types visible. Uncertainty occasionally arose in some locations as to whether the bank had been armored or if natural cobble was exposed at the base of the bank, but the armoring could usually be distinguished by the angularity of rocks and proximity to active or former agricultural fields, roads, railroads, or other human activity.

5.6.3c Eroding

Eroding banks typically have bare slopes largely devoid of vegetation (Figure 5.6.3-1c), but may support a moderate amount of annual vegetation or even mature trees when such trees have slid down the bank as part of a planar slip block or rotational slump. In addition, especially on higher banks, only a portion of the lower bank may be eroding while the upper portion of the bank remains well forested and stable. Mature trees that have been involved in the mass movement of bank material will typically be leaning in one or multiple directions depending on the type of erosion involved (e.g., with slides trees lean towards bank, with falls the trees lean away from bank, and if mass has disassociated into topples then trees may lean in multiple directions).

Whether vegetated or not, the key indicator for categorizing a bank as eroding is the presence of one or more of the erosion types other than notching. Planar slips are the most common type of erosion observed (other than notching) and expose a bare scarp where the bank material has slid downslope. Planar slips give rise to a stepped bank profile with the top of the slide block forming the flatter narrow step and the scarp forming the steep riser. In some instances, multiple steps may be present as an initially thick slide block weakens and itself becomes subject to the development of thinner planar slips that move further downslope outboard from the initial slide block. More typically, the initial slide block becomes disaggregated, at least initially, into large topple blocks and ultimately further downslope (and over time) into grain flows consisting of individual particles of sand (or other particle sizes). Consequently, a typical bank profile on an eroding bank consists of one or more steps on the upper bank giving way to a rough uneven surface of topple blocks in the mid-bank area and ultimately to a smoother apron of colluvium at the base of the bank deposited by grain flows originating from upslope. However, a single flood could potentially remove all eroded material from the bank slope and result in a steep, slightly concave-up bank face completely devoid of vegetation or eroded material.

Bank composition plays a key factor in the character and appearance of an eroding bank. With very sandy soils, the bank material more readily disassociates into individual grains such that sediment flows predominate and the bank face is smoother from top to bottom. Large slide blocks are more likely to remain intact in more competent loamy and silty bank sediments and retain a more complex bank profile with steps on the upper bank, rough surface of topples in the mid bank area, and a smoother colluvial apron at the base. Clay bank sediments are the most likely location of deep-seated rotational slumps that result in a deeply embayed arcuate bank line, where as a straighter bank line is more likely with other bank textures. In all cases, regardless of bank composition and resulting bank profile, an eroding bank has some portion, generally a large portion, of the bank surface that is bare and devoid of vegetation due to movement of bank material by one or more of the erosion types. Ultimately, the designation of a bank as eroding was based on the presence of one or more of the erosion types (other than notching) that create a bare bank scarp but is not based merely on the presence of the bare bank.

5.6.3d Vegetated Eroding

The major difference between those banks mapped as eroding and those mapped as vegetated eroding is that the banks mapped as vegetated eroding are well vegetated, generally with annual growth, that obscures the bare scarps indicating that planar slip blocks have moved downslope (Figure 5.6.3-1d). Vegetation growth can occur on the step at the top of the slip block, the rough surface of topple blocks in the mid-bank area, and the smoother colluvial slope at the base of the bank. Sometimes this varying surface topography on the bank face can be seen through the vegetation growth indicating bank instability. Upon careful inspection, the bare scarp face on vegetated eroding banks can also be seen through the vegetative growth and provides stronger evidence that the bank is actively eroding. In fact, the presence of significant annual vegetation on any bank was a cue during the mapping process to look more carefully for bare scarps, no matter how short, to confirm erosion was occurring.

Vegetated eroding banks are considered to be as unstable and possibly eroding just as quickly as those banks mapped as eroding. The vegetated eroding banks may represent areas where eroding banks are temporarily buttressed by trees or eroded material that has accumulated at the base of the bank, thus allowing annual growth to flourish on the upper bank. Therefore, the vegetated eroding banks may form at certain stages in the cycle of erosion described in Section 5.4 but can quickly transform back to what would be mapped as an eroding bank when material accumulated at the base of the bank is removed. Similarly, a bank mapped as eroding may become a vegetated eroding bank if material at the base of the bank temporarily stalls the cycle of erosion. The erosion monitoring results indicate that the cycle of erosion can occur over periods greater than two years (see Section 5.4), providing sufficient time for annual vegetation growth to become established even on actively eroding banks. Discussions with riverfront landowners corroborate that banks mapped as vegetated eroding were receding over time and not becoming stable over the long term.

Despite similarities between eroding and vegetated eroding banks, the two bank conditions were categorized separately because vegetated eroding banks were not likely mapped as eroding in earlier mapping efforts (see Study 1 report). In order to more accurately compare erosion mapped in 2014 with previous years, the two erosion categories were established with only the eroding category used in comparisons with previous erosion mapping efforts. However, to reiterate, vegetated eroding banks should be considered as equally unstable as those mapped as eroding and the only difference between them may be that they represent different stages in the cycle of erosion.

5.6.3e Failing Armor

Previously placed bank armoring has failed to arrest erosion at many locations throughout the study area (Figure 5.6.3-1e). At some locations only a portion of the armor has failed and only short lengths of erosion are found between otherwise stable areas where the armor remains intact. Where armor failure is extensive, the bank has all the characteristics of an eroding bank or vegetated eroding bank with only short remnants of the once continuous armor remaining. Occasionally large armor stones are visible below the water surface still in a line several feet from the current bank toe, indicating how far the bank has receded since armor failure. At least three locations in the Wilder impoundment have had armor completely removed: in Newbury, Vermont between 37.04 and 36.62 miles upstream of Wilder dam, at the Haverhill/Piermont, New Hampshire town line between 34.63 and 34.16 miles upstream of Wilder dam (where a lone small island now in the middle of the river is all that remains of an armored bank that has since receded over 300 ft), and in Fairlee, Vermont between 19.82 and 19.64 miles upstream of Wilder dam (where a tree revetment rather than rock armor was used – without success). The previous armoring at these locations would have likely gone unrecognized without personal communications between study staff and landowners involved in the earlier armoring efforts. The extent of failing armor at a site can vary along a continuum from fully intact armor to completely removed armor with the presence of one or more erosion types becoming more distinct and appearing over greater lengths of bank as the degree of armor failure increases.

5.6.3f Healed Erosion

Approximately 4% of the riverbanks were mapped as healed erosion representing areas that are well forested and stable but retain some evidence of past movement (Figure 5.6.3-1f; see Section 5.6.4). Former rotational slumps are perhaps easiest to identify because of the large step at the top of the slump block and deep arcuate embayment in the bank line delineating the top of the former scarp face. Straight mature trees growing on the slump block and the steeper scarp face provide evidence of the long term stability of these formerly eroding banks. However, healed erosion can also occur where sediment flows or other erosion types were once active and the presence of a stable, persistent mass of accumulated material at the base of the bank or beach has interrupted or halted the cyclical nature of erosion (Figure 5.6.3-2). Areas mapped as healed erosion are considered to be as stable as those areas mapped as stable, but an erosion type other than notching was assigned to indicate the type of erosion that had occurred when previously active. Therefore, healed erosion is an indication of past, but not current, bank instability much like a currently unstable bank may have previously been stable at some point in the past (see Section 5.6.5b).

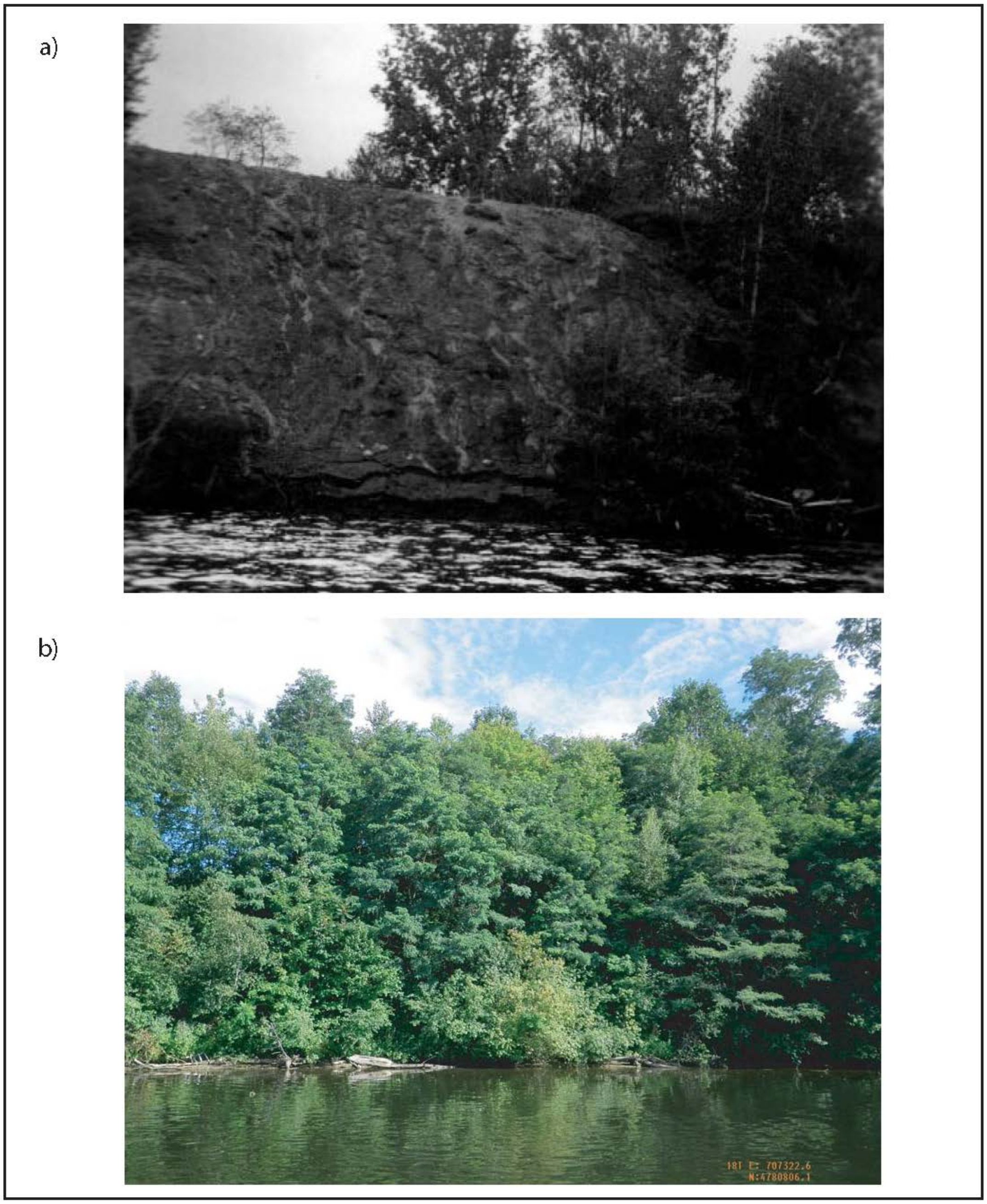


Figure 5.6.3-2. Bank near 02-B09 shown in a) historic photo from 1964, and b) modern photo from 2015. Previously eroding bank dominated by sediment flows is now stable.

5.6.4 Mapping Results

The results of the bank features mapping are presented in Appendix C (filed separately) as GIS shapefiles. Within GIS, the bank conditions at any location can be shown and compared with other bank features such as bank stability and bank height (Figure 5.6.4-1). Considering bank stability for the study area as a whole, 11% of the banks were mapped as eroding, 22% as vegetated eroding, and 6% as failing armor, resulting in a total 39% of bank length that can be considered unstable (Figure 5.6.4-2). In contrast, 61% of the banks are either stable (42%), armored (15%), or no longer eroding (i.e., healed erosion) (4%). For comparison, mapping along 85 miles of the upper Connecticut River outside of the study area found that 49% of the banks were unstable (Field, 2004). Both the mapping of the upper Connecticut River and within the study area in 2014 had a similarly defined "eroding" category. The "moderately eroding" category in the upper Connecticut River study represented eroding banks with vegetation like the "vegetated eroding" category of Study 3 with the name change merely representing an acknowledgement that banks in the previously-named "moderately eroding" category may have been just as susceptible to erosion as the "eroding" banks despite the presence of vegetation. Banks with failing armor were simply mapped as "eroding" in the upper Connecticut River study such that a combination of the "eroding" and "moderately eroding" category of the upper Connecticut River study represents unstable banks as does the combination of the "eroding", "vegetated eroding", and "failing armor" categories of the Study 3 mapping. As with Study 3, banks along the upper Connecticut River exhibiting notching and overhangs but no other signs of erosion were categorized as stable banks. Given the above, a comparison of these two mapping efforts is considered valid.

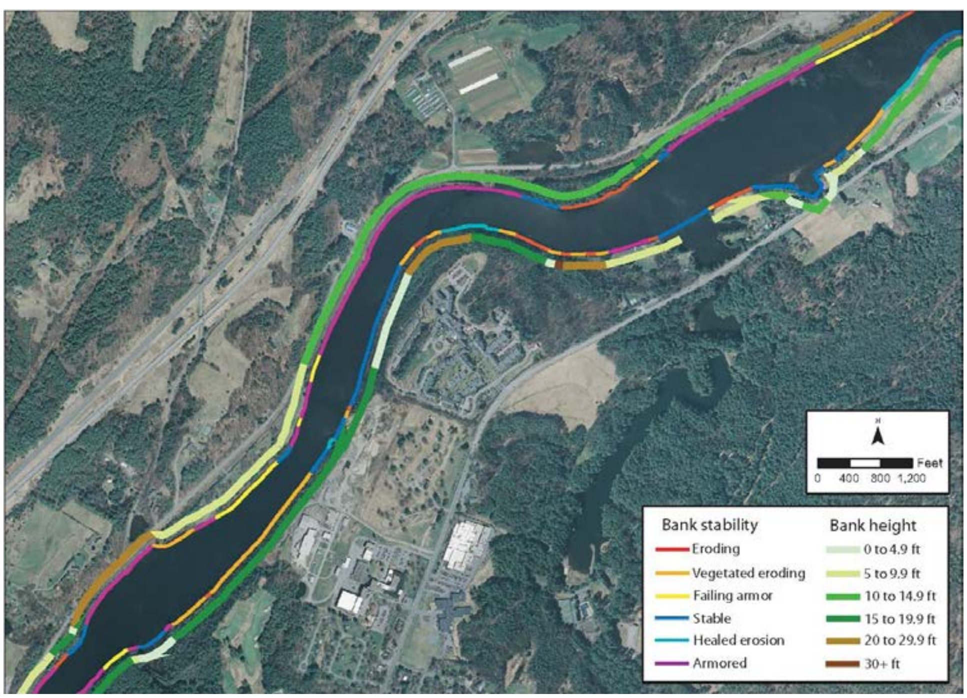


Figure 5.6.4-1. Map of a short portion of the study area (in lower Wilder impoundment) comparing bank stability and bank height.

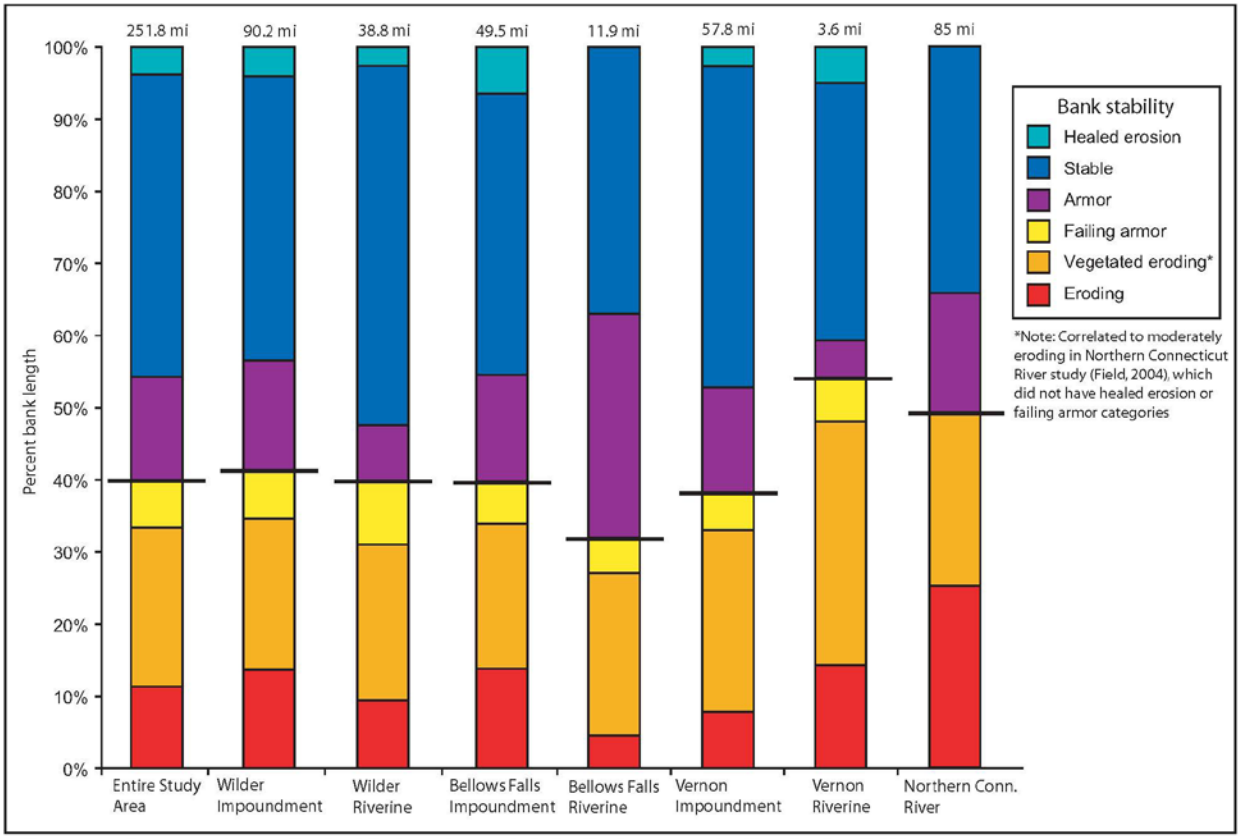


Figure 5.6.4-2. Percentage of mapped bank stability by study reach. The three unstable categories are illustrated below the bold line across each bar in the plot. The right hand bar shows the upper Connecticut River for comparison from Field (2004).

In Study 3 no erosion type was mapped along 38% of riverbank length with notching observed at the base of the remaining 21% of the stable and armored banks (Figure 5.6.4-3). A total of 37% of the banks were observed with notching at the base, so actually slightly more notching was observed along stable and armored banks (21%) than on unstable banks (16%). Notching may have initially triggered instability on the eroding, vegetated eroding, and failing armor banks even where notching was not mapped, but is no longer evident due to the presence of other erosion types that have obscured evidence of notching. Among the erosion types mapped solely along the unstable banks, planar slips were the dominant erosion type observed (36%) compared to topples (8%), rotational slumps (3%), grain or sediment flows (2%), and other erosion types. However, other erosion types might be present where planar slips are found but only the dominant erosion type was mapped.

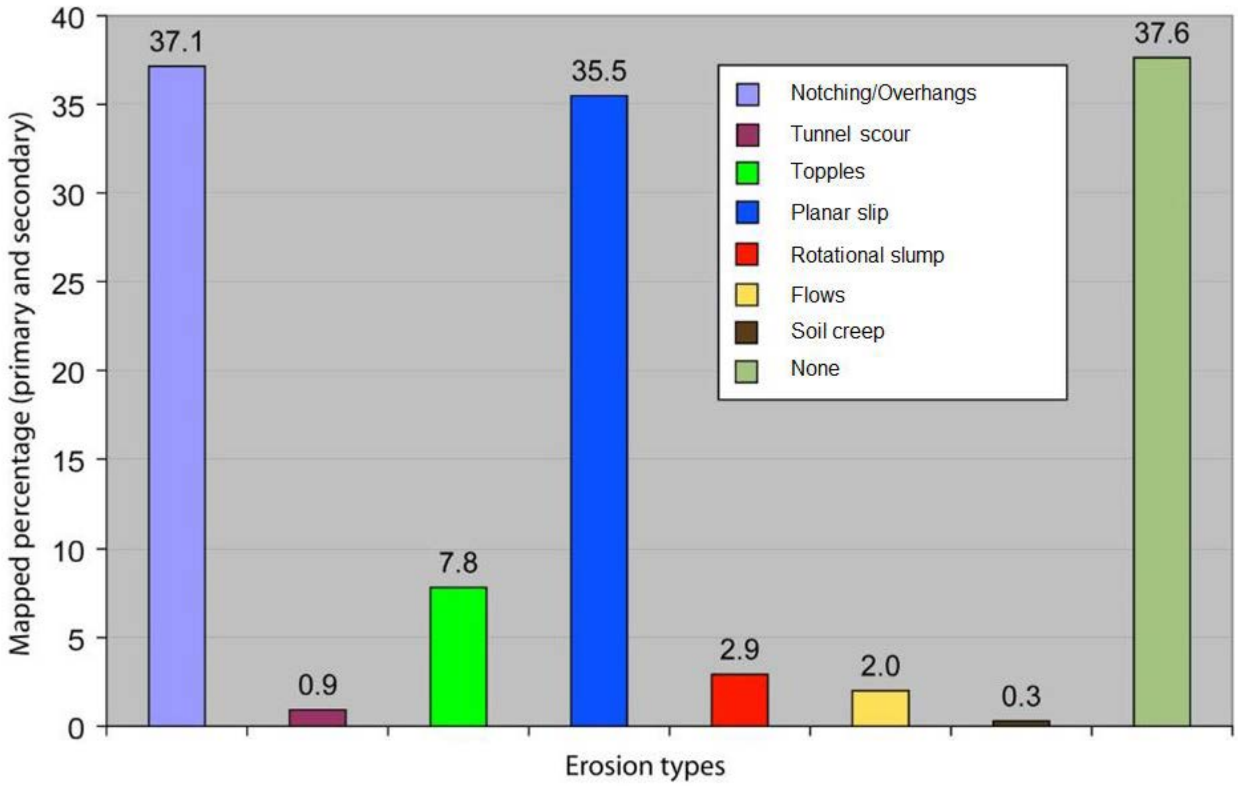


Figure 5.6.4-3. Percentage of different erosion types in the study area as a whole. Two or more erosion types can occur at the same location so totals exceed 100%.

5.6.5 Analysis of Erosion through Space and Time

The results of the bank features mapping permits a more detailed examination of how erosion varies or has varied through space and time as described separately below. The ensuing discussion also includes a focus on the rates of erosion through time. The analysis of spatial variations in erosion is focused only on the results of the 2014 mapping completed as part of this study and combines three bank stability categories together as part of the discussion: eroding, vegetated eroding, and failing armor. These three categories collectively are referred to as unstable banks and all three must be considered equally prone to erosion so are included together when discussing the distribution of unstable banks. However, when discussing the temporal distribution of erosion based on comparisons with earlier erosion mapping efforts, only the "eroding" bank stability category is considered as earlier mapping efforts were not likely to have reported as eroding banks those with the characteristics of the vegetated eroding and failing armor categories as described in Section 5.6.3.

5.6.5a Spatial Variations in Erosion

At the broadest level, the percentage of unstable bank in the study area largely holds steady at around 40% regardless of the project (Figure 5.6.4-2). The only exceptions are: 1) Bellows Falls riverine where the percentage of unstable bank is less and the amount of armoring much greater than elsewhere (e.g., in the Bellows Falls tailrace and the channel immediately downstream of the dam adjacent to the railroad and NH Route 12); and 2) Vernon riverine where the level of erosion is much higher but the analyzed reach is only 1.5 mi long so cannot be reliably compared with the other much longer sections of the study area. The levels of armoring in the three impoundments are also largely the same at approximately 11%. A considerable amount of armoring is associated with protecting the railroad grade that runs along much of the river in the study area. The Boston-Maine railroad secured an indenture for armoring and stabilizing banks along the railroad prior to the raising of the WSE associated with the development of the Wilder Project in 1950.

A more detailed analysis of unstable banks relative to other features was completed to determine if erosion is preferentially occurring where certain conditions exist (Table 5.6.5-1). Bank instability was compared with bank height (and geomorphic surface), position on meander bends, presence of riparian vegetation, distance from nearest dam in the study area, and magnitude of water surface fluctuations associated with project operations. The analyses were completed through GIS to establish an erosion ratio (e.g., an instability ratio given the combination of the three bank stability categories in the analysis) that represents the percentage of unstable banks in the study area (or portion thereof) that were present within a specified feature (e.g., outside bend of a meander) divided by the percentage of bank length occupied by that feature. For example, if 20% of all the unstable banks in the study area occurred where the bank heights were between 5 and 10 ft high, and banks 5 to 10 ft high represent 10% of the total bank length then the erosion ratio would be 2.0 (i.e., 20/10 = 2.0). An erosion ratio of 2.0 in practice is actually quite a high value (compare with actual results in Table 5.6.5-1) and would indicate a very strong tendency for unstable banks to occur where banks were 5 to 10 ft high based on the example above. Any erosion ratio above 1.0 indicates that unstable banks preferentially occur within the given feature while erosion ratios less than 1.0 indicate unstable banks are less likely to occur within the feature. The erosion ratio is derived from data that has been collected using standard geomorphological methods (i.e., GIS-based mapping). The erosion ratio was initially developed by Field Geology Services, LLC to identify potential causes of erosion in the Turners Falls impoundment (Field, 2007a). The Field (2007a) report was accepted by FERC with no substantive stakeholder comments regarding the erosion ratio, so the approach should be considered valid and accepted for the study area given the proximity and similarity in setting to the Turners Falls impoundment.

When considering bank height, the erosion ratio (E.R.) is greatest where the riverbanks are 15 to 30 ft high (E.R.=1.2). Unstable banks appear to preferentially occur along these bank heights because they are generally associated with flood terraces (Figure 5.6.5-1) that are composed of sandier, more erodible soils. The height of the banks is also sufficient to create gravitational forces that lead to bank instability with such height-dependent gravitational forces. In contrast, reduced gravitational driving forces might best explain why erosion ratios decline steadily with decreasing bank heights in the three bank height categories less than 8 ft (Figure 5.6.5-1). An erosion ratio of 0.3 where bank heights are less than 1 ft indicates that unstable banks are highly unlikely to occur in these areas, generally associated with slackwater conditions found in the lower Vernon impoundment.

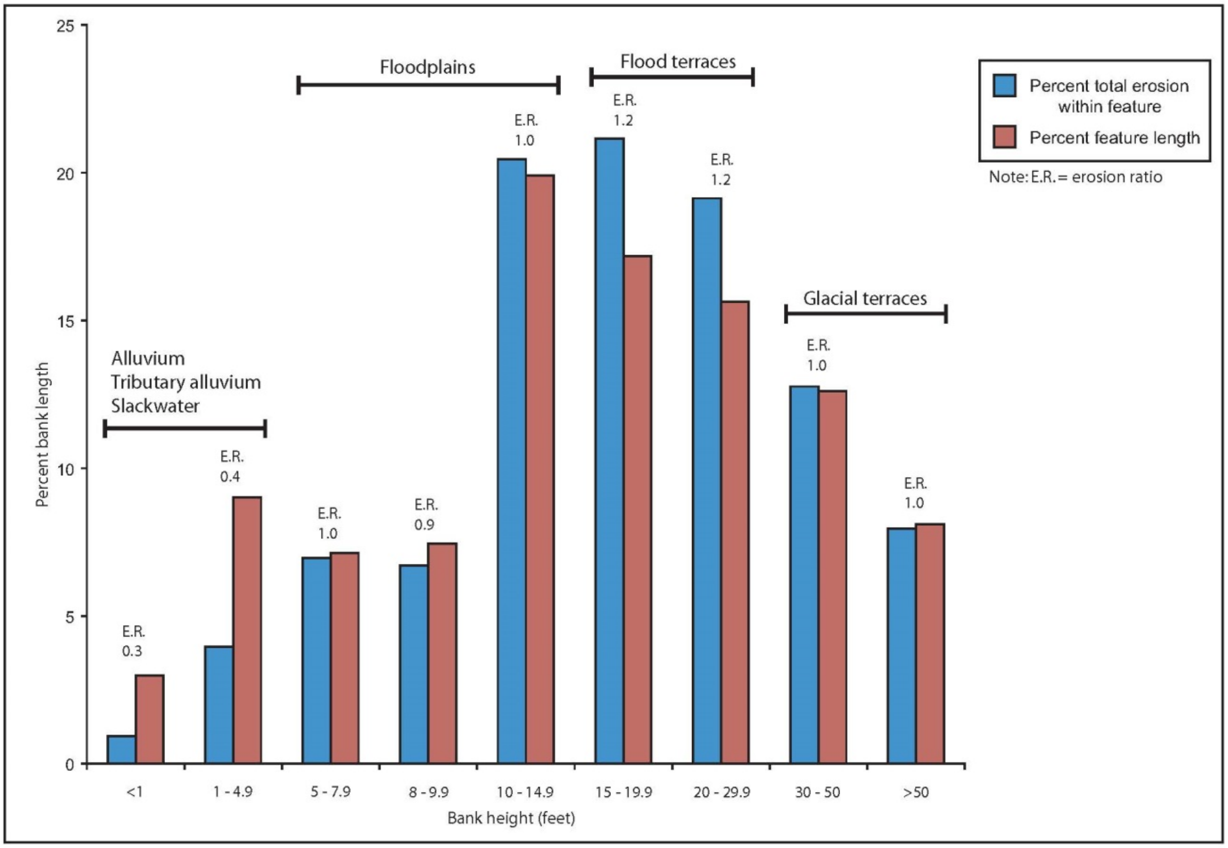


Figure 5.6.5-1. Erosion rates associated with bank heights and geomorphic surfaces.

On unaltered meandering alluvial rivers, erosion preferentially occurs on the outside bends of meanders and deposition on the inside portion of the bend (Easterbrook, 1993, p. 121). In addition to meander bends, an analysis of unstable banks relative to bend geometry on the Connecticut River must also consider straight reaches, whether natural or artificially straightened. No pronounced trend between unstable banks and bend geometry is evident on the Connecticut River (Figure 5.6.5-2a and Table 5.6.5-1). An erosion ratio of 1.0 on the inside bends of meanders and 0.9 on the outside bends of meanders is counter to what might be expected on an unaltered alluvial river. The most likely explanation for this counterintuitive finding is the presence of bank armoring placed to prevent erosion. Intact bank armoring in the study area (i.e., armored stability category but not failing armor) is almost twice as likely to be found on the outside bends of meanders and straight segments compared the inside of bends as demonstrated by an armor ratio (defined the same as erosion ratio but instead considering armoring rather than erosion) of 1.1 on outside bends and straight segments and only 0.6 on the inside bends (based on calculations from Appendix C data).

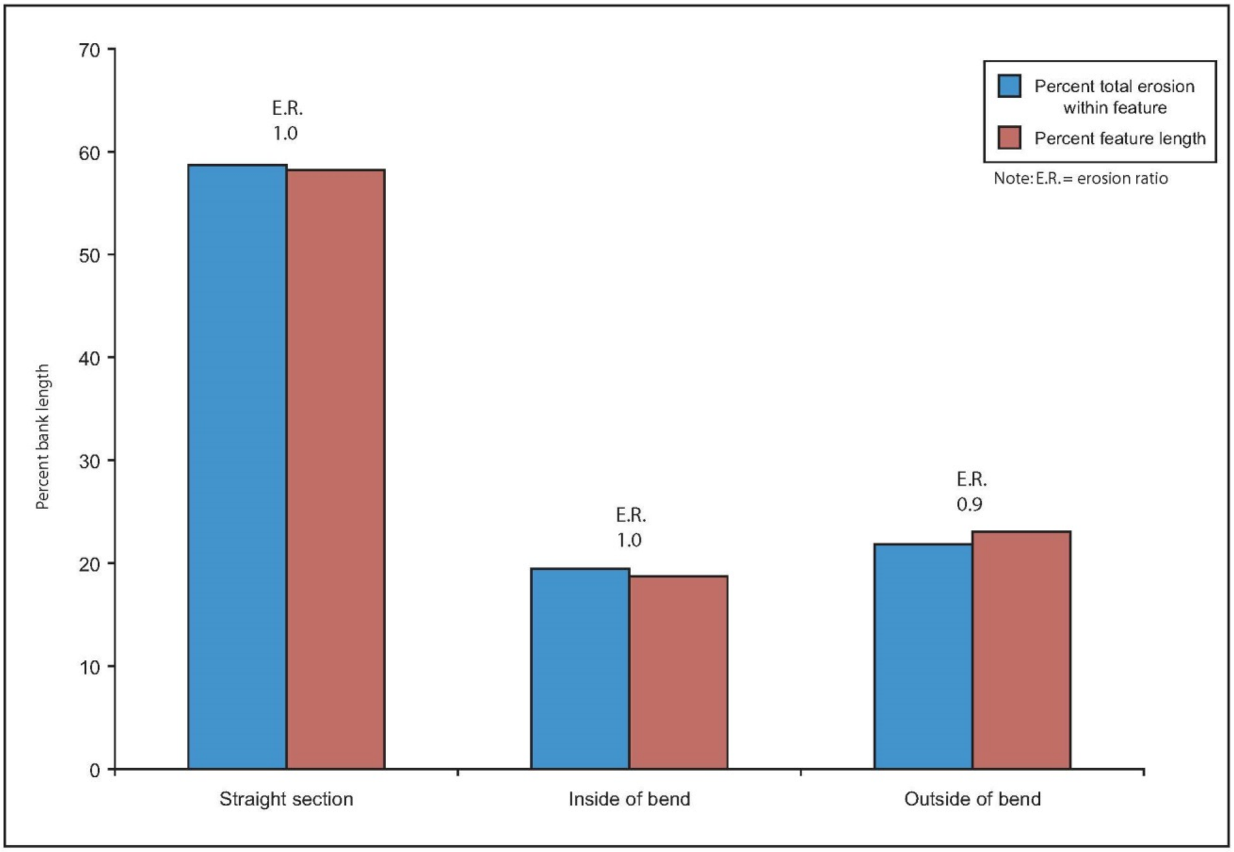


Figure 5.6.5-2a. Erosion ratios associated with bend geometry.

Bank and riparian vegetation is considered to have a stabilizing influence on riverbanks given that roots tend to bind soil particles together and increase bank resistance to erosion (Micheli and Kirchner, 2002). The presence or absence of riparian vegetation was mapped from the 2010 digital aerial photographs and hand digitized as a shapefile in GIS (Appendix C) and then compared with the location of unstable banks (Table 5.6.5-1). The erosion ratio of 0.9 for the absence of riparian vegetation and 1.1 for banks where riparian vegetation is present indicates that erosion is actually slightly more likely to be found where riparian vegetation is present (Figure 5.6.5-2b). This erosion ratio is calculated for riparian vegetation which in many locations represents trees growing on the edge of the floodplain or higher terrace surfaces and not, in most cases, vegetation growing on the bank slope itself such that the riparian vegetation is not creating a stabilizing influence on the bank since the stabilizing roots are found well above the base of the bank where the erosive forces, by whatever mechanism, are likely to be strongest. The fact that the erosion ratios are so close to 1.0 indicates that riparian vegetation has little influence on the distribution of erosion in the study area.

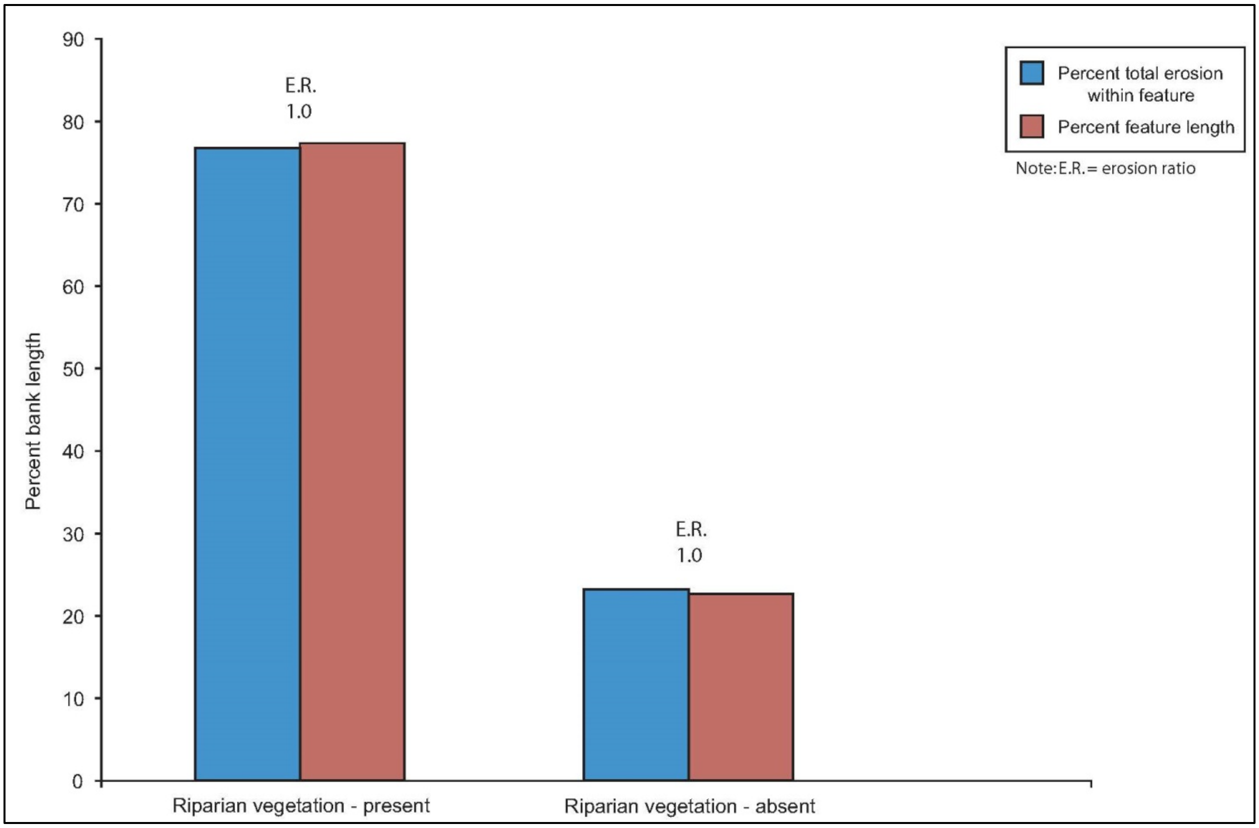


Figure 5.6.5-2b. Erosion ratios associated with riparian vegetation.

The possible impact that the distance from the three dams has on bank erosion was analyzed by subdividing the river into one-mile segments and calculating the total amount of erosion along both banks in each segment. Since each segment represents the same percentage of the total bank length, an erosion ratio did not need to be calculated as the graphed result would appear the same as the graphs presented in Figures 5.6.5-3a - c that show the percentage of the banks that are eroding in each mile-long segment upstream and downstream of the three dams.

The upper and middle portions of Wilder impoundment show considerably more erosion than the lower impoundment (Figure 5.6.5-3a). The greater erosion could be related to the wider floodplain and more riverine character of the upper impoundment, but the significant armoring along the banks of the lower impoundment are a more likely explanation for this discrepancy (Appendix C). The extensive armoring for the most part was completed as a preventative measure in the early 1950's shortly before and after raising of the Wilder dam and was not necessarily placed where banks were actively eroding. The development of Wilder dam raised the water level above the previous dam at Olcott Falls and the result of that increase largely affected the lower portion of the impoundment where the extensive preventative armoring occurred. No strong pattern in the amount of erosion relative to distance downstream of Wilder dam is apparent in Figure 5.6.5-3a, although the percentage of erosion does appear highest in the first mile downstream of Wilder dam and in the downstream most mile at the lower end of the Wilder riverine reach. The dramatic drops in erosion rates in certain mile-long segments in the middle portion of the Wilder riverine reach (e.g., mile 5 and 11 below the dam) are most likely associated with sections where significant bedrock is found along the banks.

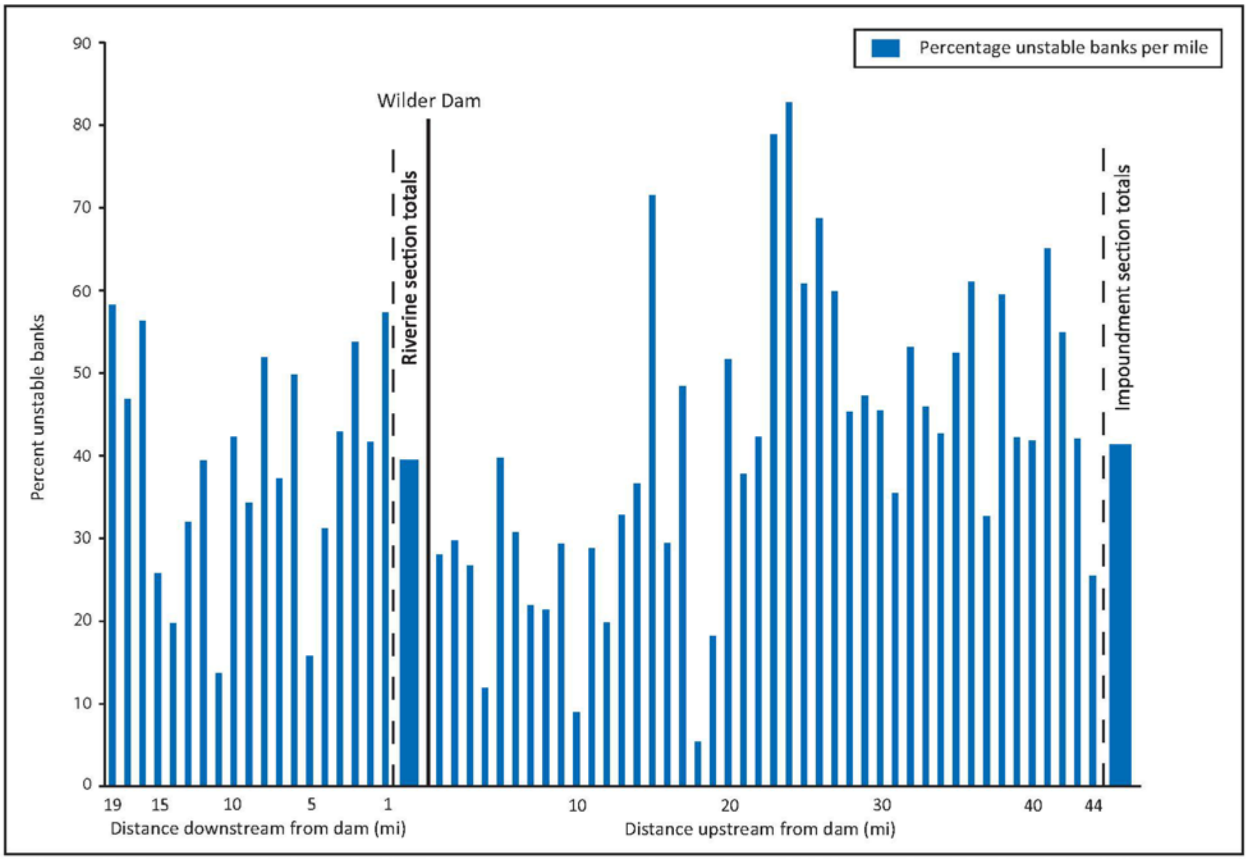


Figure 5.6.5-3a. Variation in amounts of erosion with distance from Wilder dam.

Upstream of Bellows Falls dam erosion rates are greatest in the mid to upper impoundment, perhaps a reflection of the higher percentage of lower banks and slackwater areas in the lower impoundment (Figure 5.6.5-3b). The level of erosion in the Bellows riverine reach tends to increase with increasing distance downstream of Bellows Falls dam, with the absence of erosion in the first mile downstream of the dam the result of bedrock banks.

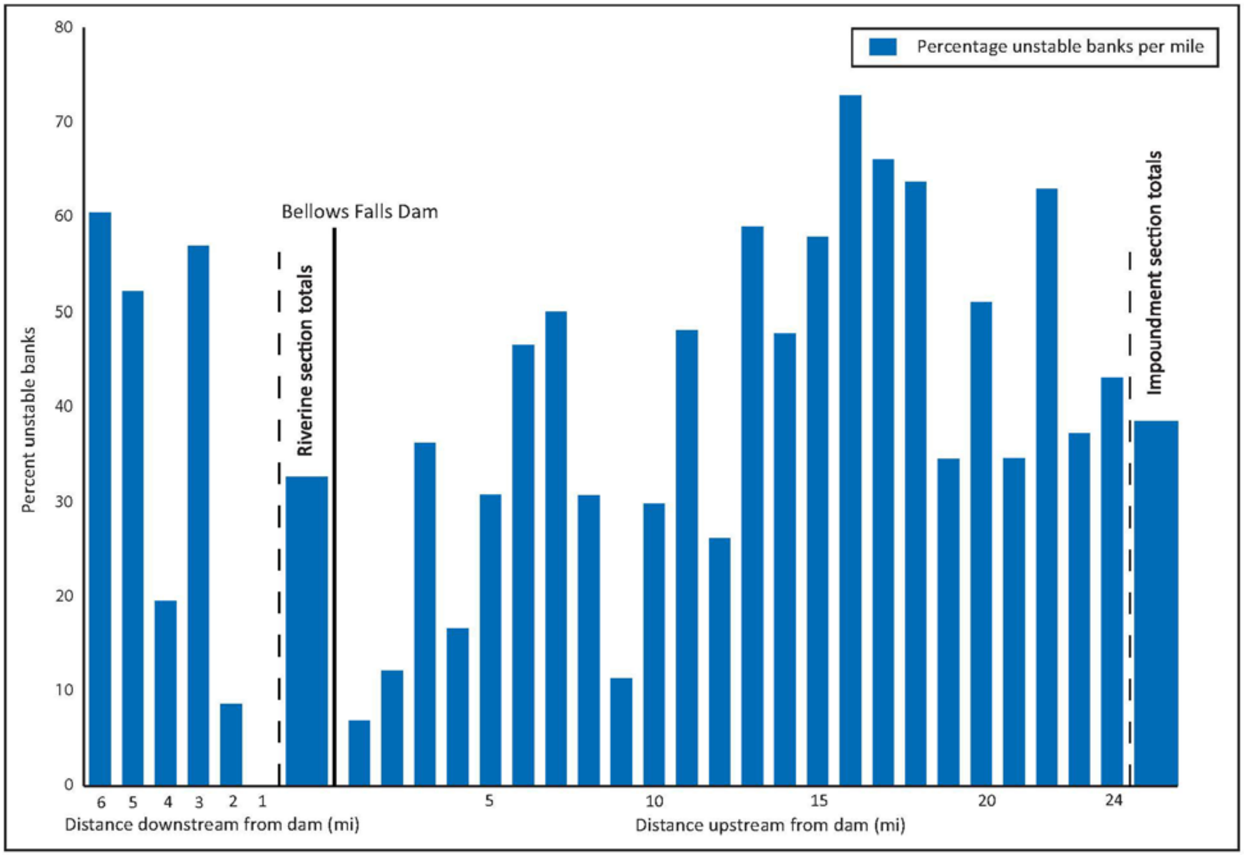


Figure 5.6.5-3b. Variation in amounts of erosion with distance from Bellows Falls dam.

As with the Bellows Falls impoundment, the low levels of erosion in the lower Vernon impoundment compared to the mid and upper impoundment is likely associated with the prevalence of low banks and slackwater areas in this area (Figure 5.6.5-3c). Although only a small portion of the study area is downstream of Vernon dam, the erosion rates are much higher than observed immediately downstream of Bellows Falls dam where bedrock predominates, and more similar to erosion rates below Wilder dam. No true riverine reach is present downstream of Vernon dam as the Turners Falls impoundment extends upstream to the base of Vernon dam.

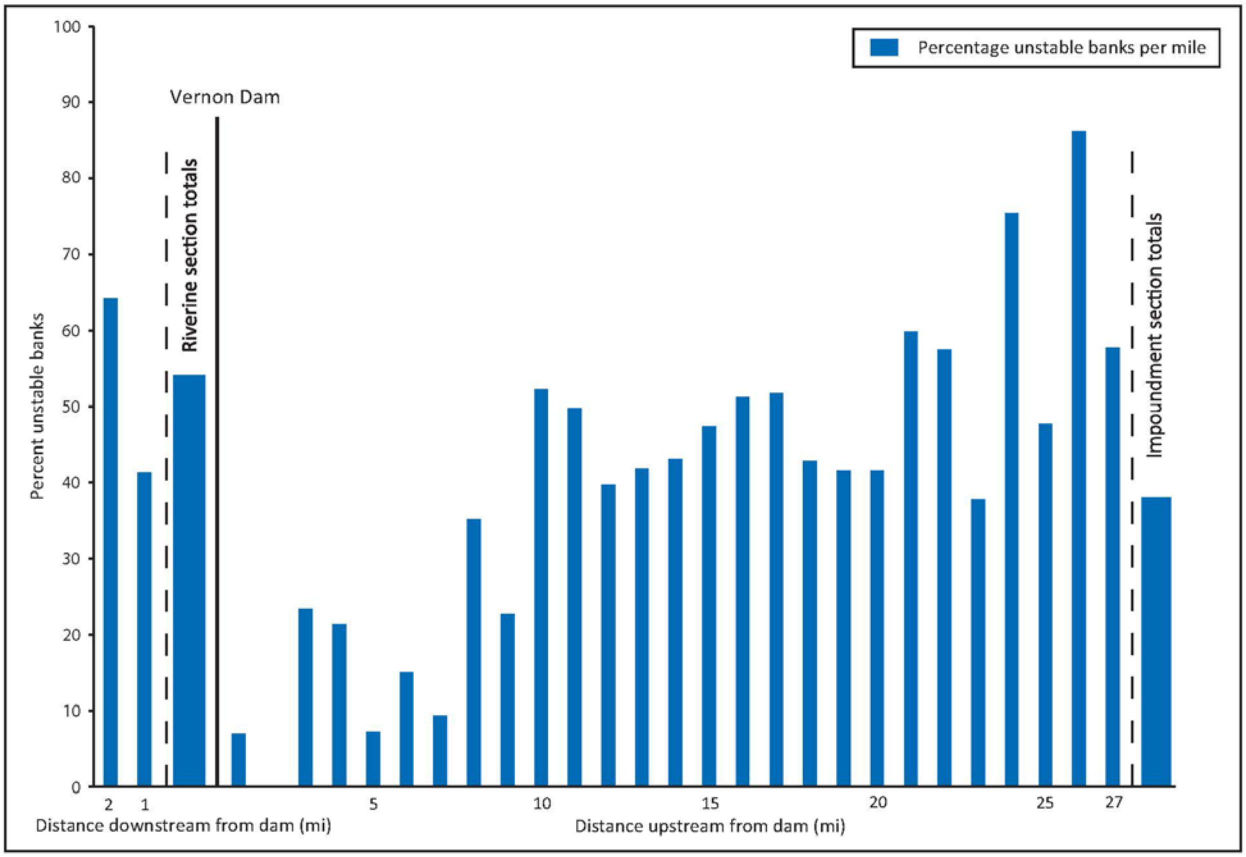


Figure 5.6.5-3c. Variation in amounts of erosion with distance from Vernon dam.

The levels of erosion relative to the distance from the dams do not appear related to the magnitude of the WSE fluctuations (see below on how this was calculated) due to normal project operations (Figures 5.6.5-3d-f). The magnitude of WSE fluctuations remains relatively constant throughout most of the length of the impoundments while the levels of erosion sometimes vary significantly from one mile to the next. Although the magnitude of WSE fluctuations varies more dramatically within the riverine sections downstream of the dams, the locations of large WSE fluctuations do not align with the areas where the levels of erosion are highest as would be expected if WSE fluctuations exert a strong influence on erosion. In the riverine reaches, WSE fluctuations are influenced by discharge from the dams, simultaneous inflow from tributaries, river channel constrictions, and channel morphology.

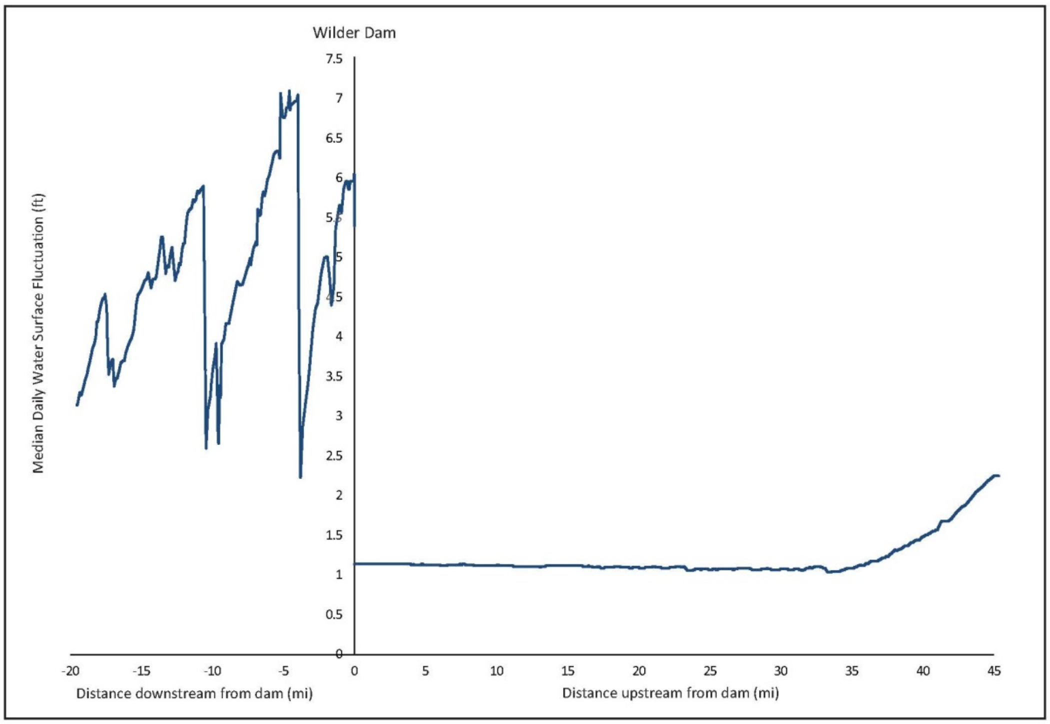


Figure 5.6.5-3d. Variation in median water surface elevation with distance from Wilder dam.

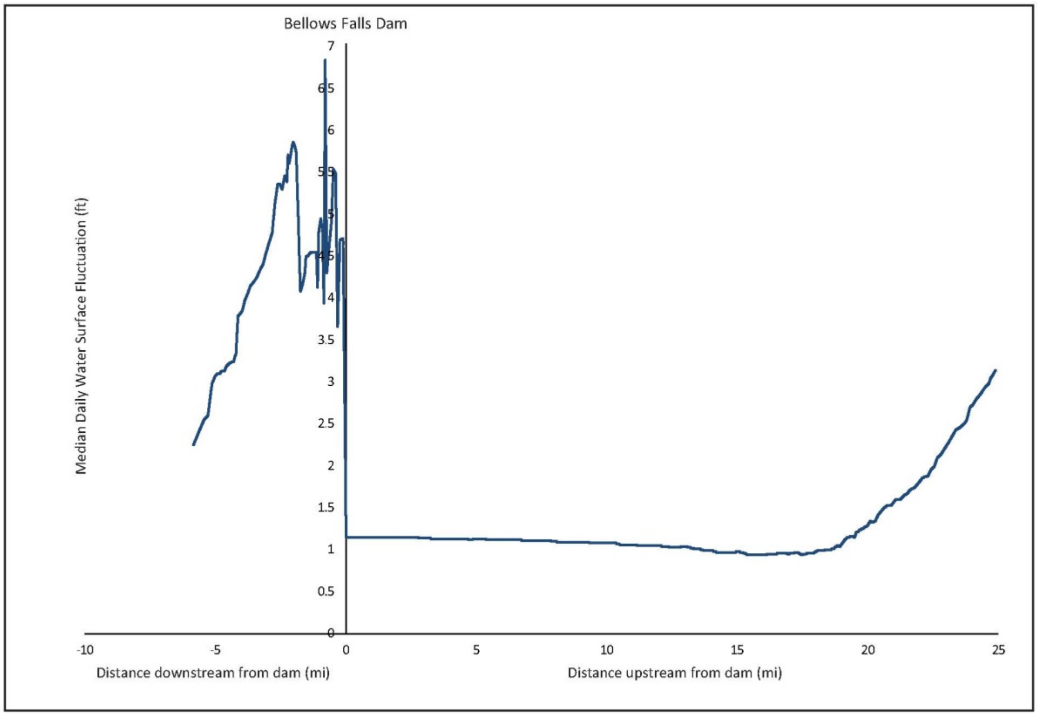


Figure 5.6.5-3e. Variation in median water surface elevation with distance from Bellows Falls dam.

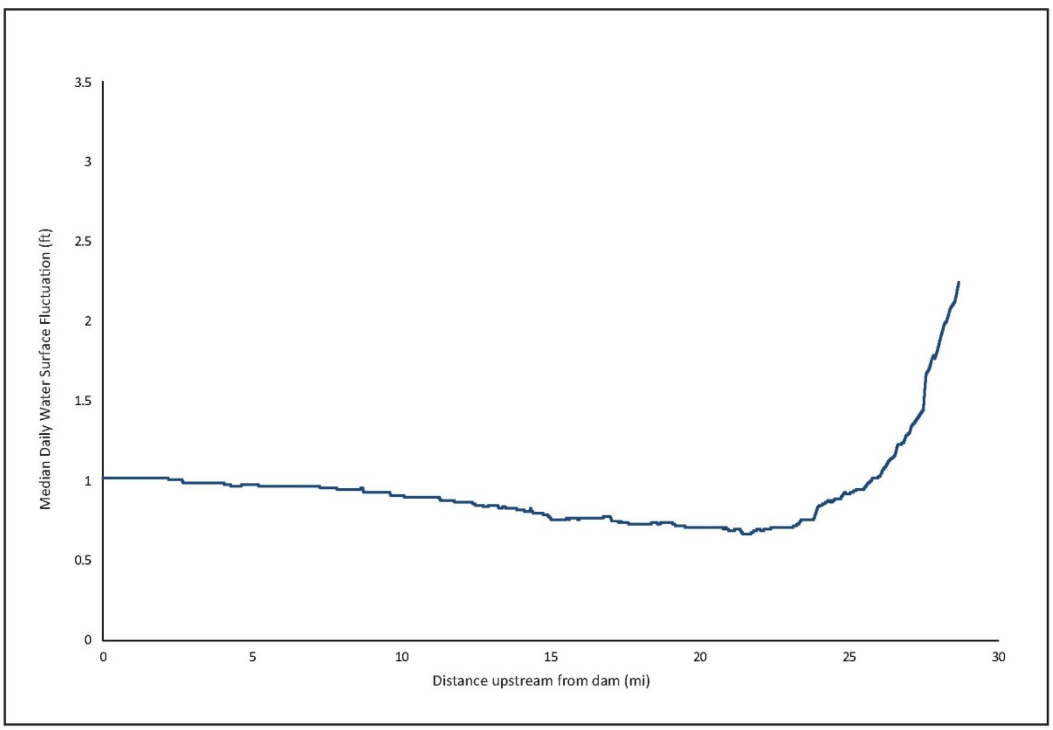


Figure 5.6.5-3f. Variation in median water surface elevation with distance from Vernon dam.

To determine if the magnitude of WSE fluctuations due to normal project operations is related to the location of erosion, Study 4 (GEI, 2016) hydraulic modeling data combined with Study 5 (Hatch, 2016) operations modeling data were used to establish the median WSE fluctuation (i.e., 50% exceedance interval) under no-spill conditions for each of the 1,087 hydraulic model cross sections in the study area (see Section 5.7). The median values were assigned to points along the bank stability shapefile that enabled the creation of a matching shapefile showing the magnitude of WSE fluctuations anywhere in the study area, that were then grouped in 0.5-foot increments for analysis (Appendix C). The median WSE fluctuation was used as these values most closely matched WSE changes recorded by water level loggers at the Study 2 erosion monitoring sites. Furthermore, the median value represents the WSE fluctuation range that occurs most frequently and, therefore, would be most likely to affect erosion if WSE fluctuations have a destabilizing influence on the banks. Comparing erosion to the median WSE fluctuations enabled calculation of erosion ratios to determine if erosion preferentially occurs where WSE fluctuations due to normal project operations are greatest (Figures 5.6.5-4a - f and Table 5.6.5-1).

Table 5.6.5-1. Distribution of erosion relative to other mapped features.

Feature	Erosion Length (ft)[a]	Feature Length (ft)[b]	Erosion (%)[c]	Total Erosion in Analysis Area (ft)	Percent of Total Erosion within Feature (%)[d]	Total Analysis Area Bank Length (ft)	Feature Length (%)[e]	Erosion Ratio[f]
Bank Height								
< 1 ft	4,860	38,922	12.5	523,817	0.9	1,299,893	3.0	0.3
1-4.9 ft	20,759	117,235	17.7	523,817	4.0	1,299,893	9.0	0.4
5-7.9 ft	36,447	92,653	39.3	523,817	7.0	1,299,893	7.1	1.0
8-9.9 ft	35,127	96,868	36.3	523,817	6.7	1,299,893	7.5	0.9
10-14.9 ft	107,108	258,725	41.4	523,817	20.4	1,299,893	19.9	1.0
15-19.9 ft	110,761	223,219	49.6	523,817	21.1	1,299,893	17.2	1.2
20-29.9 ft	100,205	203,083	49.3	523,817	19.1	1,299,893	15.6	1.2
30-50 ft	66,866	163,845	40.8	523,817	12.8	1,299,893	12.6	1.0
> 50 ft	41,685	105,343	39.6	523,817	8.0	1,299,893	8.1	1.0
Bend Geometry								
Outside of bend	115,690	306,772	37.7	529,706	21.8	1,329,574	23.1	0.9
Inside of bend	103,113	248,744	41.5	529,706	19.5	1,329,574	18.7	1.0
Straight section	310,903	774,058	40.2	529,706	58.7	1,329,574	58.2	1.0
Riparian Vegetation								
Present	406,717	1,028,382	39.5	529,706	76.8	1,329,623	77.3	1.0
Absent	122,989	301,241	40.8	529,706	23.2	1,329,623	22.7	1.0
Median Water Surface Elevation Fluctuation								
Entire study area								
0.50-0.99 ft	124,308	291,317	42.7	519,486	23.9	1,309,865	22.2	1.1
1.00-1.49 ft	238,835	639,321	37.4	519,486	46.0	1,309,865	48.8	0.9
1.50-1.99 ft	34,310	65,018	52.8	519,486	6.6	1,309,865	5.0	1.3
2.00-2.49 ft	17,458	38,570	45.3	519,486	3.4	1,309,865	2.9	1.1
2.50-2.99 ft	8,298	18,831	44.1	519,486	1.6	1,309,865	1.4	1.1
3.00-3.49 ft	17,476	31,159	56.1	519,486	3.4	1,309,865	2.4	1.4
3.50-3.99 ft	13,252	35,462	37.4	519,486	2.6	1,309,865	2.7	0.9
4.00-4.49 ft	14,214	39,949	35.6	519,486	2.7	1,309,865	3.0	0.9
4.50-4.99 ft	19,083	65,088	29.3	519,486	3.7	1,309,865	5.0	0.7
5.00-5.49 ft	8,396	26,252	32.0	519,486	1.6	1,309,865	2.0	0.8
5.50-5.99 ft	18,294	36,035	50.8	519,486	3.5	1,309,865	2.8	1.3
6.00-6.49 ft	1,418	9,211	15.4	519,486	0.3	1,309,865	0.7	0.4

Feature	Erosion Length (ft)[a]	Feature Length (ft)[b]	Erosion (%)[c]	Total Erosion in Analysis Area (ft)	Percent of Total Erosion within Feature (%)[d]	Total Analysis Area Bank Length (ft)	Feature Length (%)[e]	Erosion Ratio[f]
6.50-6.99 ft	3,735	11,930	31.3	519,486	0.7	1,309,865	0.9	0.8
7.00-7.49 ft	409	1,723	23.7	519,486	0.1	1,309,865	0.1	0.6
Wilder impoundment								
1.00-1.49 ft	170,954	421,454	40.6	196,910	86.8	475,277	88.7	1.0
1.50-1.99 ft	19,718	36,199	54.5	196,910	10.0	475,277	7.6	1.3
2.00-2.49 ft	6,238	17,624	35.4	196,910	3.2	475,277	3.7	0.9
Wilder riverine								
2.00-2.49 ft	360	895	40.2	69,424	0.5	182,771	0.5	1.1
2.50-2.99 ft	2,015	4,527	44.5	69,424	2.9	182,771	2.5	1.2
3.00-3.49 ft	5,596	11,735	47.7	69,424	8.1	182,771	6.4	1.3
3.50-3.99 ft	9,363	24,607	38.1	69,424	13.5	182,771	13.5	1.0
4.00-4.49 ft	8,722	18,771	46.5	69,424	12.6	182,771	10.3	1.2
4.50-4.99 ft	16,353	48,275	33.9	69,424	23.6	182,771	26.4	0.9
5.00-5.49 ft	5,479	19,650	27.9	69,424	7.9	182,771	10.8	0.7
5.50-5.99 ft	15,975	31,747	50.3	69,424	23.0	182,771	17.4	1.3
6.00-6.49 ft	1,418	9,032	15.7	69,424	2.0	182,771	4.9	0.4
6.50-6.99 ft	3,735	11,809	31.6	69,424	5.4	182,771	6.5	0.8
7.00-7.49 ft	409	1,723	23.7	69,424	0.6	182,771	0.9	0.6
Bellows Falls impoundment								
0.50-0.99 ft	29,193	49,493	59.0	116,398	25.1	287,917	17.2	1.5
1.00-1.49 ft	54,207	167,390	32.4	116,398	46.6	287,917	58.1	0.8
1.50-1.99 ft	10,053	20,414	49.2	116,398	8.6	287,917	7.1	1.2
2.00-2.49 ft	5,140	12,106	42.5	116,398	4.4	287,917	4.2	1.1
2.50-2.99 ft	4,144	10,242	40.5	116,398	3.6	287,917	3.6	1.0
3.00-3.49 ft	7,265	9,759	74.4	116,398	6.2	287,917	3.4	1.8
3.50-3.99 ft	1,953	6,723	29.0	116,398	1.7	287,917	2.3	0.7
4.00-4.49 ft	3,714	7,922	46.9	116,398	3.2	287,917	2.8	1.2
4.50-4.99 ft	730	3,868	18.9	116,398	0.6	287,917	1.3	0.5
Bellows Falls riverine								
1.00-1.49 ft	2,615	3,830	68.3	27,263	9.6	70,657	5.4	1.8
1.50-1.99 ft	3,907	7,898	49.5	27,263	14.3	70,657	11.2	1.3
2.00-2.49 ft	3,792	6,056	62.6	27,263	13.9	70,657	8.6	1.6
2.50-2.99 ft	3,103	6,701	46.3	27,263	11.4	70,657	9.5	1.2
3.00-3.49 ft	3,269	6,870	47.6	27,263	12.0	70,657	9.7	1.2

Feature	Erosion Length (ft)[a]	Feature Length (ft)[b]	Erosion (%)[c]	Total Erosion in Analysis Area (ft)	Percent of Total Erosion within Feature (%)[d]	Total Analysis Area Bank Length (ft)	Feature Length (%)[e]	Erosion Ratio[f]
3.50-3.99 ft	1,804	8,327	21.7	27,263	6.6	70,657	11.8	0.6
4.00-4.49 ft	2,215	13,418	16.5	27,263	8.1	70,657	19.0	0.4
4.50-4.99 ft	2,790	9,801	28.5	27,263	10.2	70,657	13.9	0.7
5.00-5.49 ft	2,705	5,484	49.3	27,263	9.9	70,657	7.8	1.3
5.50-5.99 ft	1,061	2,043	52.0	27,263	3.9	70,657	2.9	1.3
6.00-6.49 ft	0	147	0.0	27,263	0.0	70,657	0.2	0.0
6.50-6.99 ft	0	52	0.0	27,263	0.0	70,657	0.1	0.0
Vernon impoundment								
0.50-0.99 ft	95,115	241,824	39.3	109,491	86.9	292,968	82.5	1.1
1.00-1.49 ft	13,674	50,442	27.1	109,491	12.5	292,968	17.2	0.7
1.50-1.99 ft	702	702	100.0	109,491	0.6	292,968	0.2	2.7

a. Erosion is taken as all unstable banks collectively: eroding, vegetated eroding, and failing armor.
b. Variations in stream length between features analyzed result from variations in areas processed.
c. Percent of feature length mapped as unstable.
d. Percent of total mapped unstable occurring within that feature.
e. Percent of total stream length represented by feature.
f. Erosion ratio is the ratio of percent of total unstable within a given feature divided by percent of total bank length represented by that feature; an erosion ratio greater than one indicates unstable banks preferentially occur within that feature.

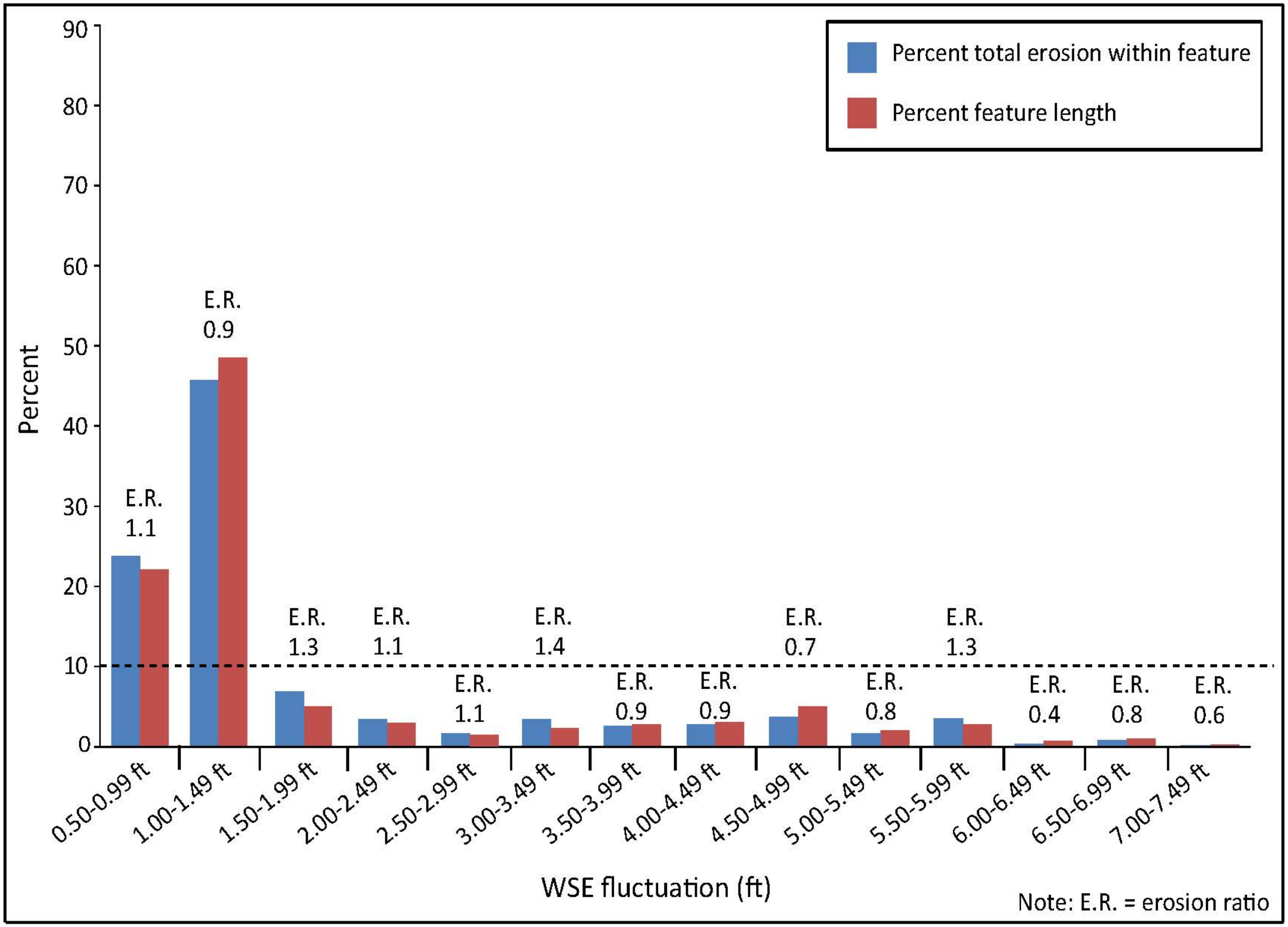


Figure 5.6.5-4a. Erosion ratios associated with WSE fluctuations under normal project operations for the whole study area.

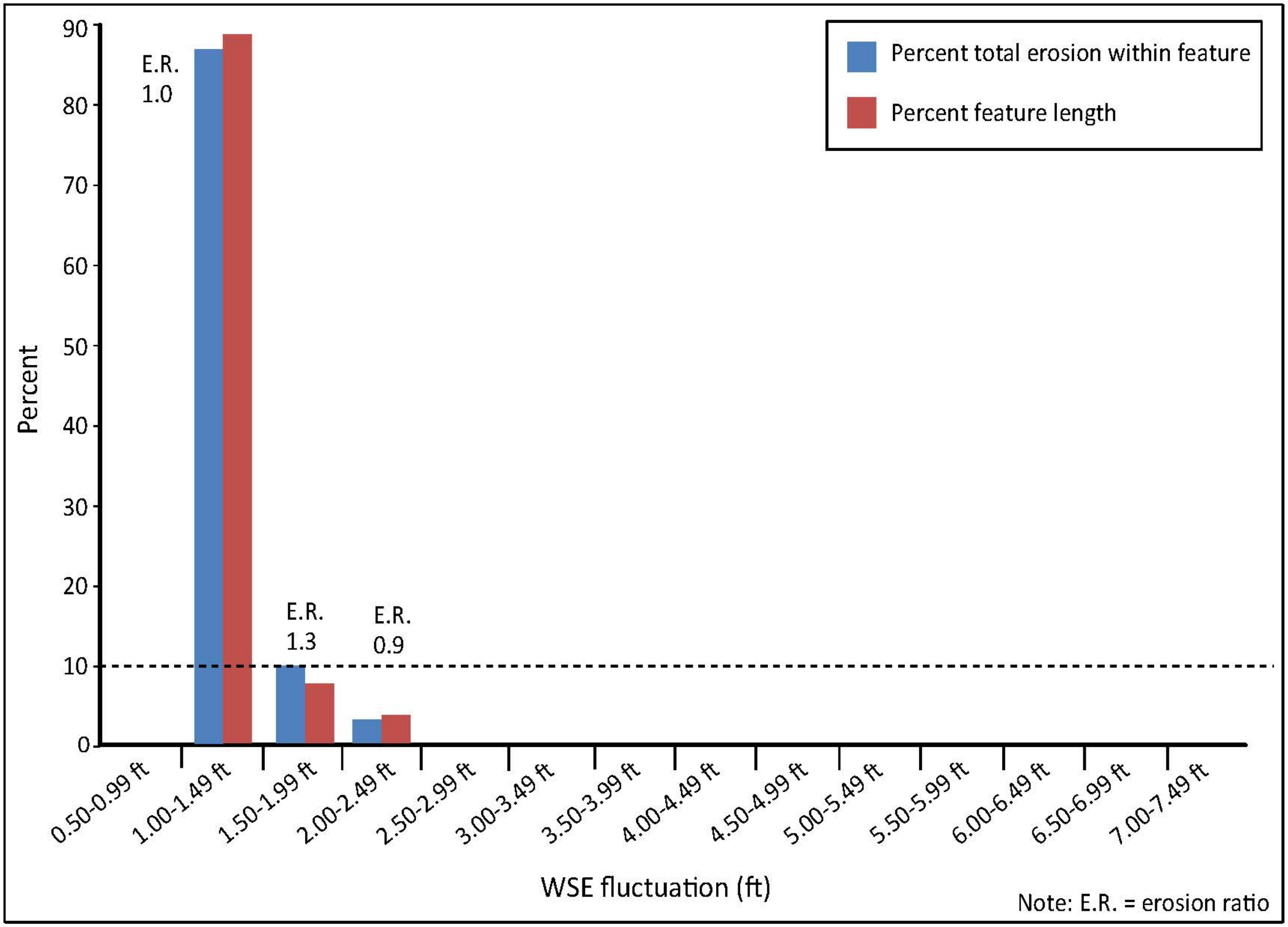


Figure 5.6.5-4b. Erosion ratios associated with WSE fluctuations under normal project operations in the Wilder impoundment.

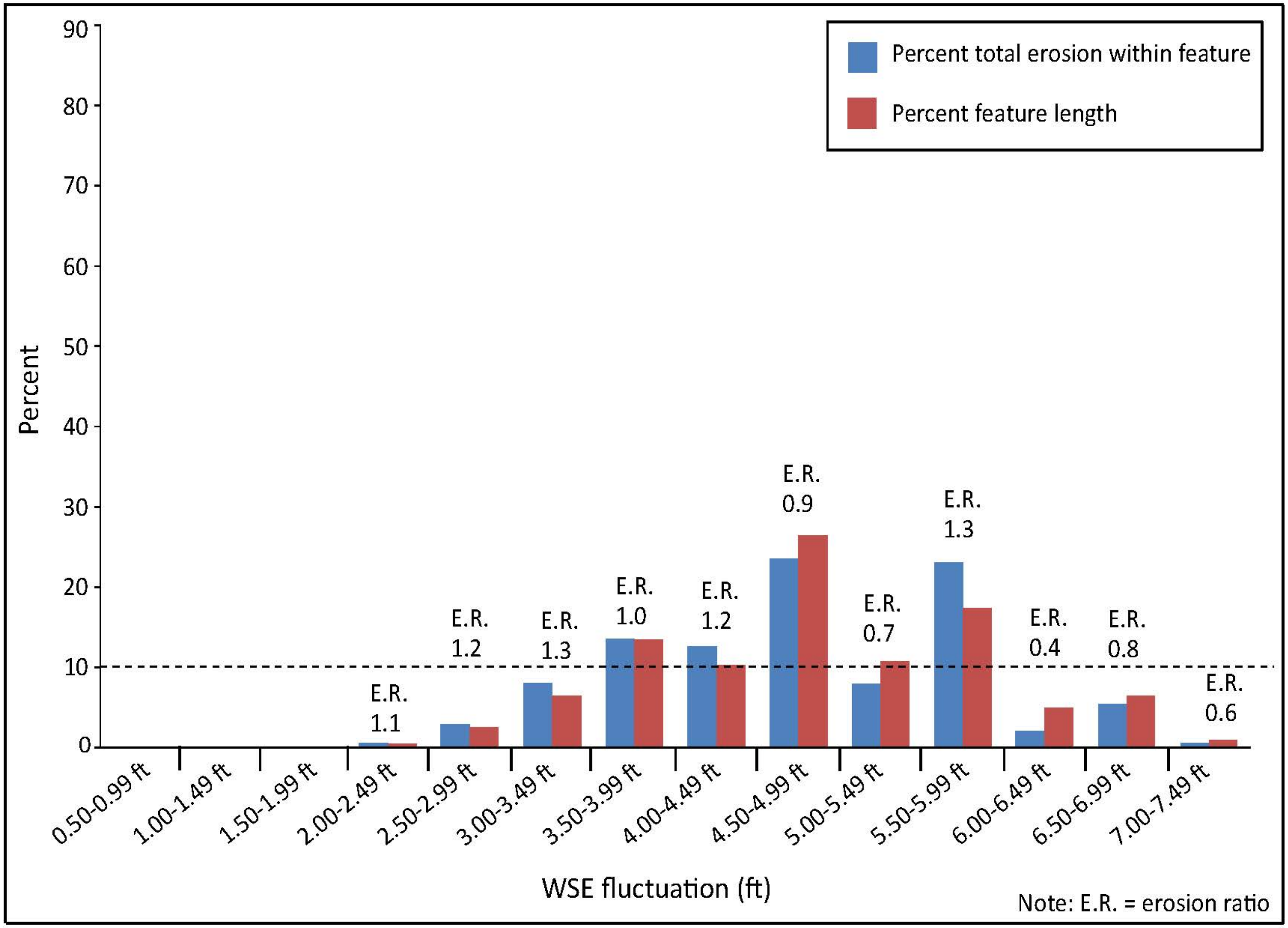


Figure 5.6.5-4c. Erosion ratios associated with WSE fluctuations under normal project operations in the Wilder riverine reach.

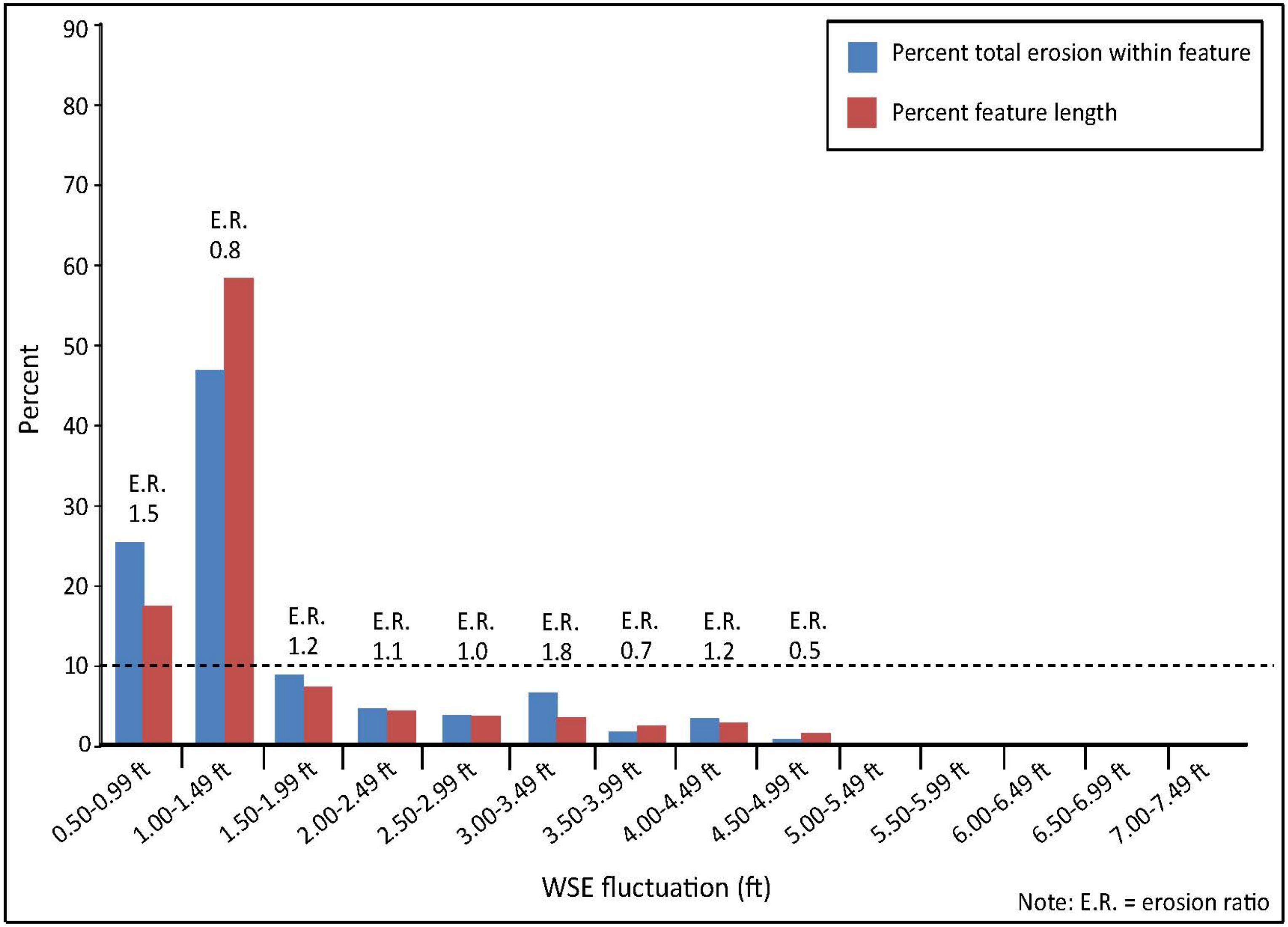


Figure 5.6.5-4d. Erosion ratios associated with WSE fluctuations under normal project operations in the Bellows Falls impoundment.

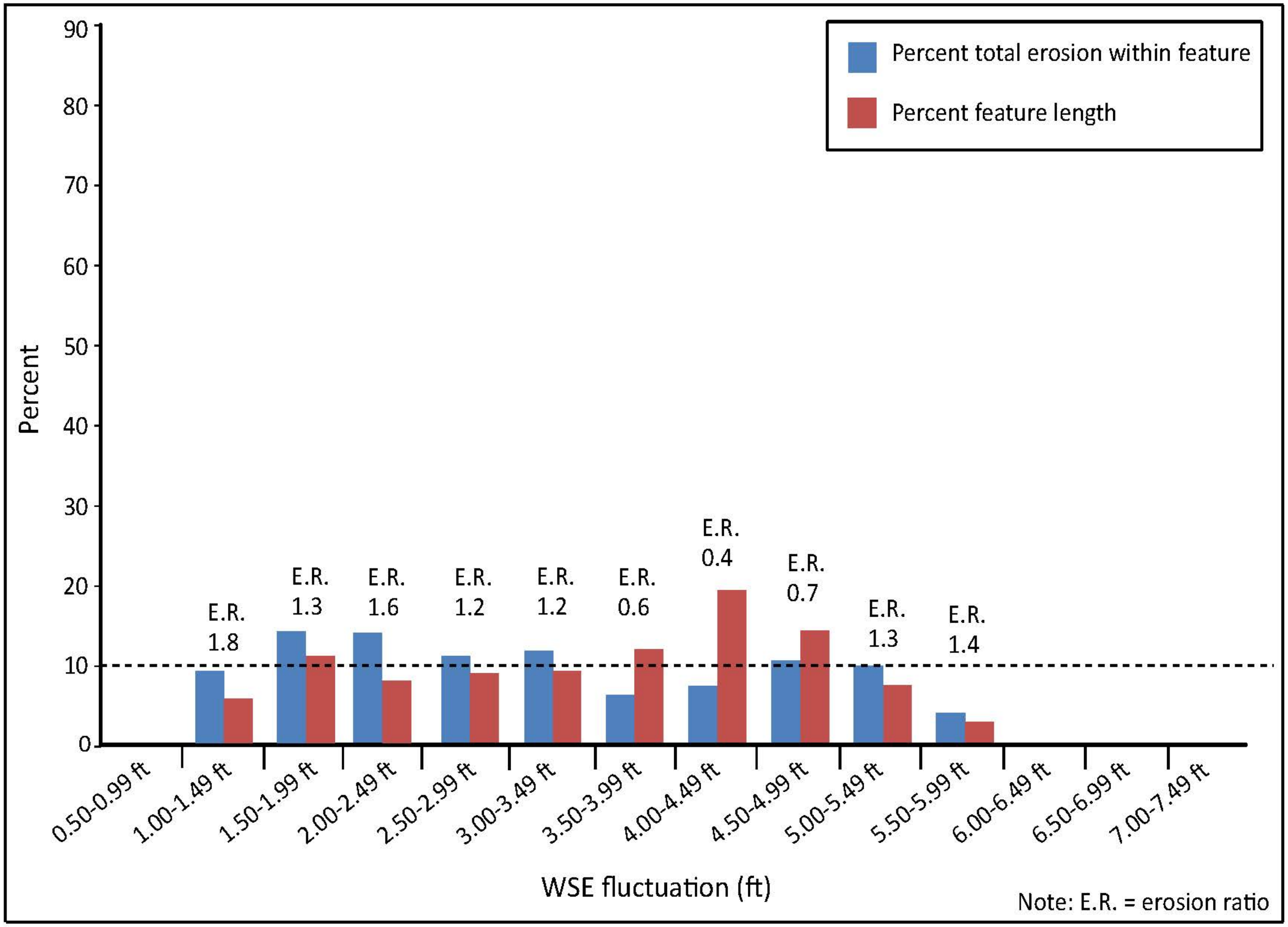


Figure 5.6.5-4e. Erosion ratios associated with WSE fluctuations under normal project operations in the Bellows Falls riverine reach.

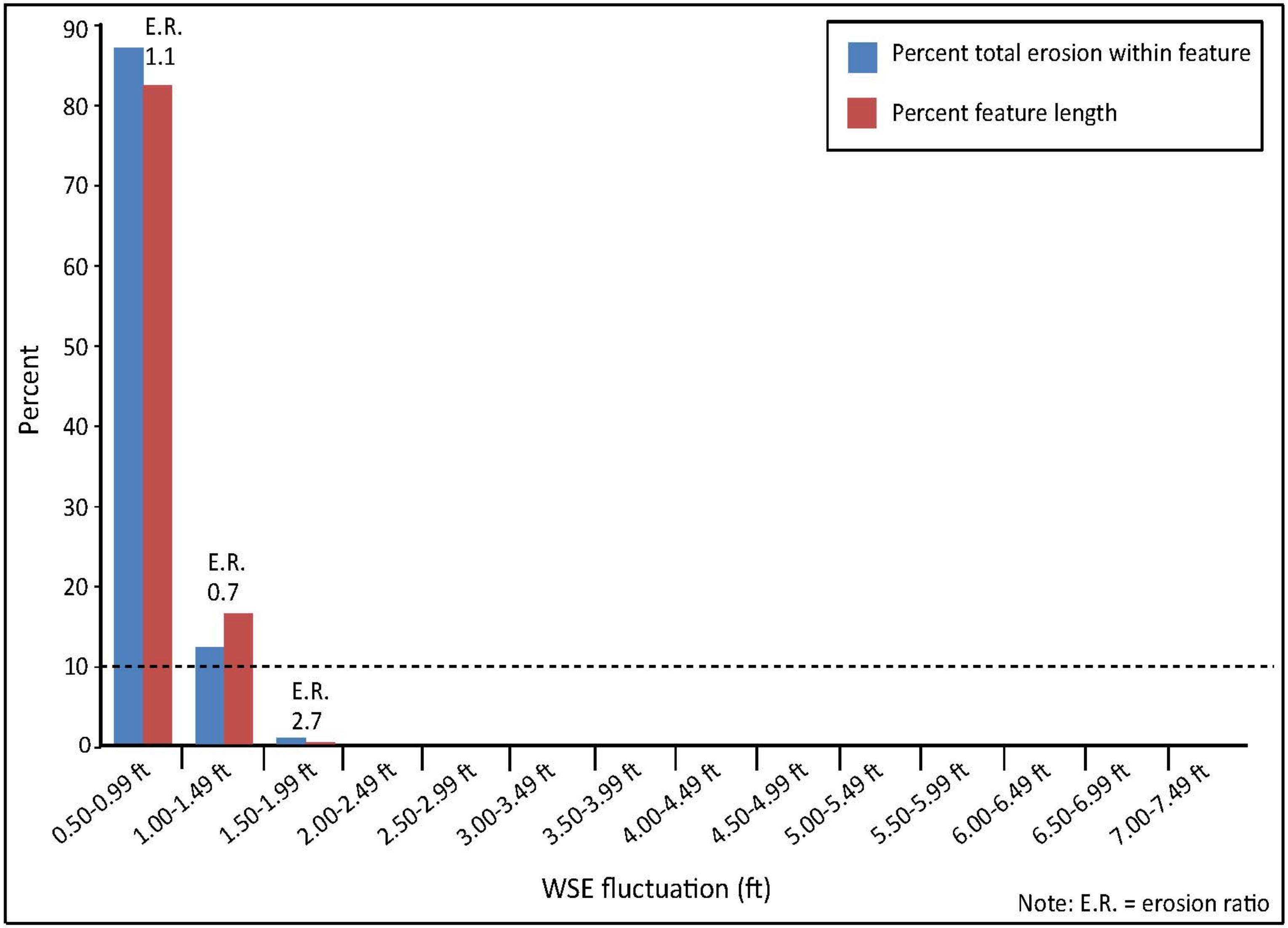


Figure 5.6.5-4f. Erosion ratios associated with WSE fluctuations under normal project operations in the Vernon impoundment.

Drawing conclusions from the comparison between erosion and WSE fluctuations is complicated by the limited range of these fluctuations. Nearly half of the total bank length in the study area has a median WSE fluctuation range of 1.0-1.5 ft under normal project operations and no other 0.5-foot fluctuation range greater than 1.5 ft occurring along more than 10 percent of the total bank length. When considering the individual impoundments separately, 89% of the Wilder impoundment has a median WSE fluctuation between 1.0-1.5 ft, 58% of the Bellows Falls impoundment has a median WSE fluctuation between 1.0-1.5 ft, and 83% of the Vernon impoundment has a median WSE fluctuation between 0.5-1.0 ft.

The Wilder and Bellows Falls riverine sections experience greater variability but 37% of the bank length in Wilder riverine is still restricted to only two 0.5-foot interval WSE fluctuation ranges (between 4.50 ft to 5.49 ft) and 33% of the Bellows Falls riverine bank length is also restricted to two 0.5-foot increments (between 4.00 ft and 4.99 ft). The Vernon riverine reach, given its short length, was not included in the analysis. While significant erosion ratios are calculated for some 0.5-foot WSE fluctuation intervals, the total bank length of these intervals represents a small percentage of the total bank length analyzed (Figures 5.6.5-4a - f and Table 5.6.5-1). For example, an erosion ratio of 2.7 is associated with WSE fluctuations of 1.5-2.0 ft in the Vernon impoundment but this fluctuation range occurs along only 702 ft or 0.3% of the bank length. With such short bank lengths, high erosion ratios might result from a small amount of erosion that could be the result of numerous factors other than WSE fluctuations, including local factors such as flow alteration around islands or bars, tributary confluences, or valley constrictions.

To prevent interpreting results potentially skewed by including short lengths of bank, the analysis of erosion ratios was limited to only those 0.5-foot increments that occur along 10% or more of the bank length (as highlighted by the bars extending above the bold horizontal line at 10% in Figures 5.6.5-4a - f). For the entire study area, only two 0.5-foot fluctuation ranges fall above 10% (0 to 0.5 ft and 0.5-1.0 ft) with the data suggesting a slight preference for erosion to occur where WSE fluctuations are less than 0.5 ft. If all the 0.5-foot increments above 1.0 ft are combined so that the combined total exceeds 10% of the bank length, the erosion ratio for the combined 1.0-7.5-foot fluctuation range is 1.0 (30% of erosion in 29% of the bank length, Table 5.6.5-1), indicating that greater magnitudes of WSE fluctuation are not associated with greater levels of erosion.

No distinct pattern emerges even if each impoundment or riverine area is analyzed independently. The Wilder and Vernon impoundments do not lend themselves to analysis as virtually all of the bank length is subject to WSE fluctuations within only one or two 0.5-foot fluctuation intervals (see Figures 5.6.5-4a and 5.6.5-4f, respectively). Bellows Falls impoundment has slightly more variability with the data showing erosion preferentially occurring where the magnitude of WSE fluctuations is lowest. This trend holds even when the higher magnitude ranges that total less than 10% are combined into a single interval because the combined erosion ratio is only 1.1 (28% of erosion in 25% of the bank length, Table 5.6.5-1).

In the Wilder riverine reach, the highest erosion ratio for the 0.5-foot intervals consisting of more than 10% of the bank length is associated with the WSE fluctuation of the greatest magnitude. However, WSE fluctuations of lower magnitude are also associated with erosion ratios above 1.0 while intermediate WSE fluctuation magnitudes have erosion ratios of less than 1.0 such that no distinct pattern in the data is present. For those 0.5-foot WSE fluctuation ranges representing greater than 10% of the bank length, erosion ratios greater than 1.0 are associated with lower magnitude WSE fluctuations in the Bellows Falls riverine reach while higher magnitude fluctuations have values considerably less than 1.0. A value greater than 1.0 would emerge from a combined 5.0-6.0-foot category, so the data do not necessarily suggest that erosion preferentially occurs where WSE fluctuations are lowest but, as with the Wilder riverine reach, suggest no distinct relationship emerges when comparing erosion with project-related WSE fluctuations.

As the erosion ratio approach for identifying potential causes of erosion has not been widely used, the erosion data was also analyzed using multiple logistic regression, a widely used and accepted statistical method (Appendix E). In general, the statistical analysis corroborates the results of the erosion ratio analysis. The statistical analysis confirms that the best predictor of bank instability is bank height with banks between 15-30 ft high the most likely to be unstable and banks less than 5 ft more likely to be stable.

Despite being the strongest predictor, bank height explains only 3.5 percent of the deviance, so represents only a weak relationship. Relationships between bank stability and other predictors are even weaker with the magnitude of WSE fluctuations explaining only 1.1 percent of the deviance using a Generalized Linear Model (GLM) and only 0.2 percent in a Generalized Additive Model (GAM) framework (see Tables 1 and 2 in Appendix E). The statistical analysis, therefore, shows that WSE fluctuations are not a significant cause of bank instability. As suggested by the erosion ratio analysis, the statistical analysis also shows no strong relationship between erosion and the outside bends of meanders or erosion and the absence of riparian vegetation.

In addition to corroborating the results of the erosion ratio analysis, the statistical analysis was also used to determine if erosion preferentially occurs where the channel average shear stress derived from the Study 4 (GEI, 2016) hydraulic modeling is highest. The shear stress values were determined for each model cross section (node) and then interpolated for every foot between nodes. Shear stress is the force acting on the bed and banks of a channel responsible for transporting sediment. Near bank shear stress, therefore, is critical in the erosion process as sediment accumulating at the base of the bank from upslope must be transported away if the cycle of erosion is to continue. While shear stress is simply generated by faster moving water flowing past the lower velocity water near the bank face, the effects of bank vegetation (Lopez and Garcia, 1998), secondary flow circulation (Kean et al., 2009), bend geometry (Ursic et al., 2012), and other factors complicate efforts to quantify shear stress levels in near bank areas, can lead to widely varying shear stress levels over short lengths of bank, and helps to explain why bank stability in the study area varies dramatically over short distances. Further complicating the relationship between erosion and shear stress is the difficulty in establishing the critical shear stress necessary to initiate transport of the sediment at the base of the bank. While decades of research have focused on the shear stress needed to move particles of different size, the relationships developed tend to perform poorly given the added complications of grain shape, sorting, sediment cohesion, and other parameters that affect the critical shear stress at a particular site. Numerical models have been developed to predict the location and amount of erosion by combining methods for estimating near bank shear stress and critical shear stress, but such models require significant site specific information (Nardi, et al., 2008), rendering the models unreliable when applied to other settings with different bank characteristics and flow patterns.

Given the complications of quantifying near bank shear stress and the critical shear stress needed to mobilize sediment along the banks, channel average shear stress was used to compare shear stress relative to erosion in the study area. The use of the average channel shear stress does not adequately capture all of the factors controlling the dynamic near bank flow conditions, but does embody general morphological and hydraulic characteristics of the channel and valley that exert some influence on near bank shear stress such as channel gradient, channel confinement, and backwatering upstream of valley constrictions. Collection of the detailed topographic and particle size data along 250 mi of riverbank needed for usable values for near bank shear stress and critical shear stress was beyond the scope of this study.

Shear stress values were established for two different flow conditions, a “high operational” flow condition (Case 1) and a higher flow condition beyond station generating capacity (Case 2). For the Case 1 condition, shear stress values were calculated for river flows at the upper end of the normal operating ranges (i.e., flows near the maximum station generating capacity) as that flow would be expected to have the highest shear stresses associated with normal project operations. Shear stresses were also calculated for Case 2 which is defined as the flood flow approximating the 10-year recurrence interval event. The statistical analysis shows a weak relationship between Case 1 flow shear stress values and locations of erosion, but shows a stronger relationship than all of the other investigated parameters except for bank height with 3.3% of deviance explained.

For the Case 1 shear stress condition, erosion ratios are slightly higher for higher shear stresses (Table 5 in Appendix E). A similar trend is not present for the Case 2 flow condition as the higher erosion ratios are concentrated in the lower and middle ranges of shear stress values (Table 6 in Appendix E), suggesting that shear stresses at higher river flows are sufficient to entrain sediment in almost all locations. Therefore, other factors, such as bank height, exert a stronger control on the distribution of erosion and explain why erosion does not occur at all locations at higher river flows.

The explanation of deviance is slightly improved when multiple factors are considered, but the best combination of four factors – a model considering bank height, maximum operating shear stress, armoring, and bend geometry – explains only 7.4% of deviance. Models considering all factors never improve the explanation of deviance above 8.2% (Figure 11 in Appendix E). To underscore the weakness of the relationships between erosion and the various factors, consider that approximately 40 percent of the banks are unstable in the study area such that a 40 percent chance exists that a randomly chosen point along the banks of the river will be unstable. If information about bank height is provided, the likelihood of correctly identifying whether a randomly chosen spot along the bank is unstable would increase to 43.5% rather than 40% without the bank height information and with all factors unstable banks could be correctly identified 48.2% of the time. The results of the statistical data underscore that the distribution of erosion is the combination of multiple factors not all of which (e.g., some local in nature) could be considered in a study covering nearly 250 mi of river bank.

The analyses presented here were done without accounting for armored banks that represent nearly 15% of the entire study area. Erosion ratios could presumably be recalculated with the length of armored banks completely removed from the total bank length under consideration or, alternatively, the length of armored banks could be added to the areas of bank instability assuming that erosion would result if the armor were not present (although such an assumption may not be valid as discussed above). Because of the uncertainties associated with removing or adding armor to the analyses, a decision was made to not make armor-related adjustments to bank length when conducting the analyses presented in Table 5.6.5-1; completing multiple iterations of similar analyses based on assumptions regarding armoring was also beyond the scope of this study.

A number of other similar analyses comparing erosion with potential causal factors are possible with the GIS data provided in Appendix C such as determining if erosion preferentially occurs upstream of valley constrictions, adjacent to tributary confluences, or near sites of bank armoring. However, a complete and exhaustive analysis of all possible relationships was beyond the scope of this study.

5.6.5b Temporal Variations in Erosion

Changes in the location of erosion through time were studied by comparing erosion maps of the study area from 1958, 1979, and 2014 (Appendix D). Data of and comparisons between the 1958 and 1979 mapping were presented and discussed in Study 1 report. The analysis was restricted to the three impoundments only as the 1958 mapping did not include the riverine reaches of the river. The 2014 data were discussed in Section 5.6.3 and presented in Appendix C. Only the erosion category from the 2014 bank stability mapping was used in the comparisons under the assumption that earlier mapping efforts would not have considered the vegetated eroding category or failing armor category as eroding. None of the photographs or descriptions accompanying the earlier mapping efforts suggest the areas mapped as eroding consisted of notching or overhangs alone, which is consistent with the mapping completed in 2014.

Erosion maps completed by Kleinschmidt (2011) were not used in this study as field reconnaissance efforts for this study in 2013 identified several locations where bank erosion was occurring, and clearly had been occurring for several years (e.g., rotten fallen trees clinging to bank), but were not mapped as eroding in the 2010 survey. Erosion maps completed in the 1990s by county conservation districts for CRJC were also not used as these maps were made over several years and by different workers, so the likelihood exists for significant variations in the amount of erosion mapped despite consistency in the mapping protocol. In the Turners Falls impoundment downstream of the study area, mapping was conducted twice in 1990 by NDT (1991) and USACE (1991a) revealing that wide discrepancies in the amounts and locations of erosion. All three of the above mentioned surveys by others illustrate how data can be misrepresented at the time of collection when different individuals are completing the mapping (Field, 2007a). The three mapping efforts used for comparison in this study (1958, 1979, and 2014) were used to establish areas that have over several decades: 1) been eroding, 2) destabilized, 3) stabilized, or 4) remained stable. The three data sets are not sufficiently refined to establish if some areas, for example, might have destabilized and re-stabilized in a period of 25 to 30 years such that the given area would be represented in the comparisons presented below as having remained stable through time. Actual occurrences of the foregoing example and similar circumstances have occurred locally throughout the study area (especially where recent armor has been placed and sometimes removed) but likely represent less than 1% of the study area's length.

The basic mapping technique of transferring visual observations of where erosion is occurring on the banks onto maps or aerial photographs was used in 1955, 1978, and 2014 despite changing technologies (i.e., paper vs. digital). What is uncertain for the 1955 and 1978 mapping efforts is the visual cues used to identify a site as eroding. While some sites may seem unmistakably eroding, different workers separated by several decades may have made different decisions as to what was eroding where the evidence for erosion may have been more subtle or less clear. Neither of the earlier studies provides much detail or description of how eroding banks were different or distinguished from stable banks, essentially letting the word erosion speak for itself. An effort has been made in Section 5.6.3 to describe how the identification of an eroding bank is based on the presence of certain observable characteristics, most prominently the occurrence of one or more erosion types other than notching. Also worth noting is that notching alone would unlikely have been considered as eroding in 1955 or 1978 either. An effort was made in the 2014 mapping to not consider vegetation as an indicator of bank stability as may have been done to some unknown degree in 1955 and 1978; this is a primary reason for establishing the vegetated eroding category (see Section 5.6.3d) as these are areas of erosion but were unlikely to have been mapped as such in 1955 or 1978. Variations in the season of mapping, especially when vegetation may be used as an indicator of stability, could also skew the results. A slow pace of mapping in 2014 allowed for careful inspection of the banks so subtle cues for bank erosion (e.g., slip scarps) could be identified through vegetation overgrowing the bank (and, if found, were categorized as vegetated eroding).

For the study area as a whole, the total amount of erosion appears to have changed very little through time with only a 4% spread from 11% in 2014 to 15% in 1978 (Figure 5.6.5-5 and Table 5.6.5-2).

Table 5.6.5-2. Percentage of bank erosion in 1958, 1978, and 2014.

Study Reach	Time period	Bank length (miles)	Stable (miles)	%	Eroding (miles)	%
Entire Study Area	1958	218.4	190.3	87.1	28.2	12.9
Wilder Impoundment	1958	93.3	88.5	94.8	4.8	5.2
Bellows Falls Impoundment	1958	52.6	37.9	71.9	14.8	28.1
Vernon Impoundment	1958	59.9	53.2	88.8	6.7	11.2
Entire Study Area	1978	218.4	186.3	85.3	32.1	14.7
Wilder Impoundment	1978	93.3	76.1	81.6	17.2	18.4
Bellows Falls Impoundment	1978	52.6	48.8	92.8	3.8	7.2
Vernon Impoundment	1978	60.0	50.2	83.8	9.7	16.2
Entire Study Area	2014	251.8	223.3	88.7	28.5	11.3
Wilder Impoundment	2014	90.2	77.9	86.3	12.4	13.7
Bellows Falls Impoundment	2014	49.5	42.6	86.1	6.9	13.9
Vernon Impoundment	2014	57.8	53.2	92.1	4.6	7.9

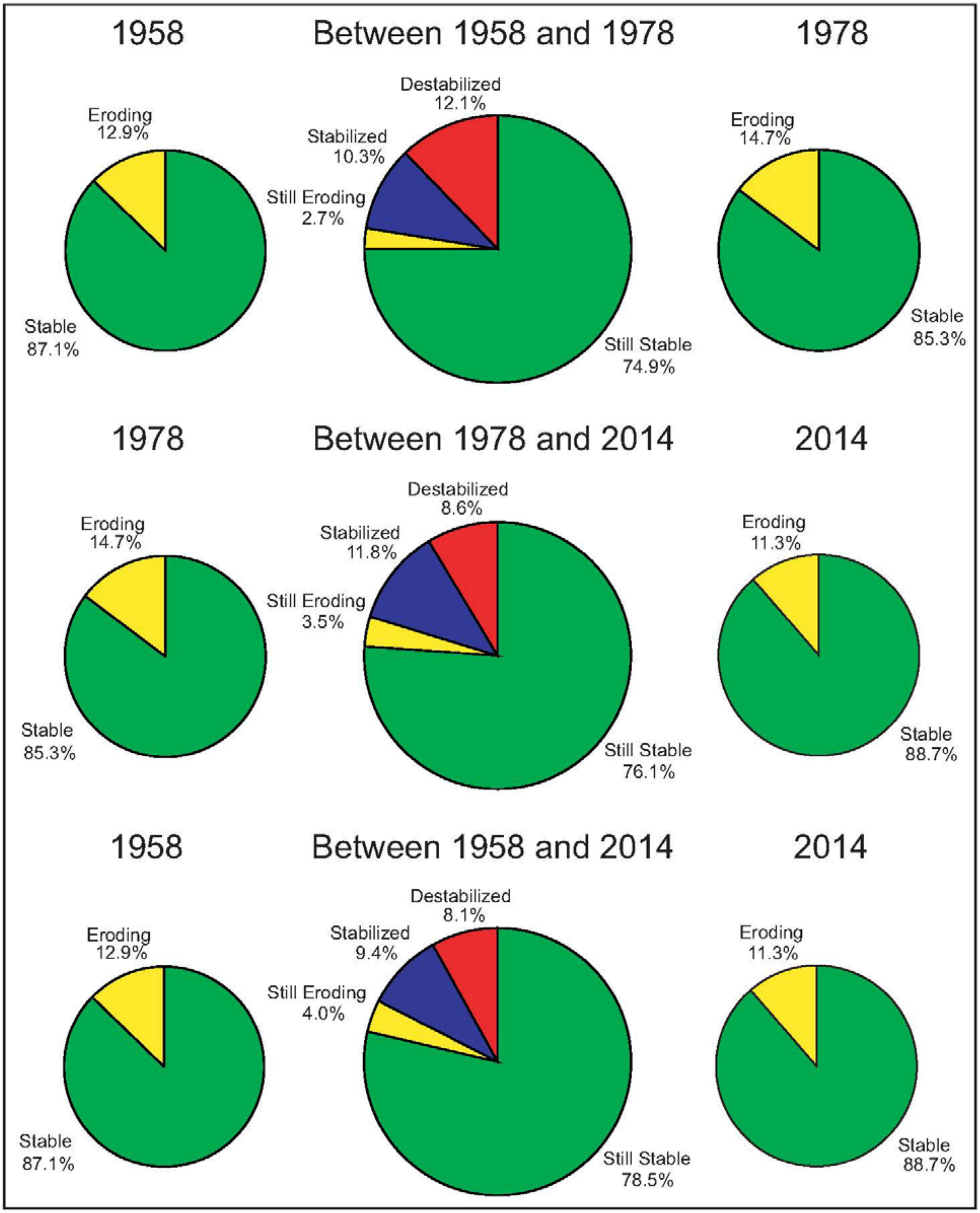


Figure 5.6.5-5. Percentage of bank erosion in 1958, 1978, and 2014 for the whole study area.

Given a low confidence level in comparing mapping efforts over different years, the conservative conclusion to draw from the data is that the level of erosion has stayed essentially constant through time. However, levels of erosion do show variation through time when analyzing each impoundment and riverine reach on its own. In the Wilder impoundment, erosion apparently increased between 1958 and 1978 over 10% before decreasing again slightly between 1978 and 2014 (Figure 5.6.5-5 and Table 5.6.5-2). Bellows Falls impoundment, in contrast, appears to have had an over 20% decrease in the amount of erosion between 1958 and 1978 before increasing back to approximately half of the 1958 levels. Erosion levels in the Vernon impoundment first increased slightly between 1958 and 1978 before declining to below 1958 levels between 1978 and 2014. Trends over time in the Wilder and Bellows Falls riverine reaches are also variable with trends in the first time interval reversed in the second time interval (Figure 5.6.5-5, Table 5.6.5-2).

Using changes in the overall totals of mapped erosion does not elucidate where specific changes are occurring. With respect to erosion, riverbanks can change (or not change) through time in four basic ways: 1) the bank was stable and continued to be stable; 2) the bank was stable and then began to erode; 3) the bank was eroding and continued to erode; and 4) the bank was eroding and then became stabilized. Appendix D contains maps displaying the locations of where these changes (or lack of changes) appear to have occurred along with pie charts showing the relative percentage of each possible condition through the overall time period from 1958 to 2014. Table 5.6.5-3 provides data for the interim time steps as well. While the study area as a whole shows the length of bank that stabilized is roughly the same as that which destabilized, the Bellows Falls impoundment shows significantly more bank stabilized (20%) compared to destabilized (5%). This trend is consistent with evidence from historical aerial photographs that suggest a decline in erosion rates through time in the impoundment. Vernon impoundment shows a similar but less dramatic tendency toward stabilization with only the Wilder impoundment showing more destabilized bank compared to stabilized. Visual inspections of the Wilder impoundment maps in Appendix D show that most of this new erosion was located in the upper impoundment (i.e., 30 miles or more upstream of Wilder dam) largely unaffected by WSE or station discharge changes at Wilder dam as compared to WSE changes due to inflow from upstream. While some trends identified in the temporal analysis of erosion mapping are likely real, especially where corroborated with other independent evidence, a significant amount of the apparent changes between map years may be merely an artifact of differences in mapping techniques, personnel, and season of mapping, so a detailed parsing of the data is discouraged as that may lead to erroneous conclusions.

Table 5.6.5-3. Bank stability conditions through time.

Study Reach	Time period	Bank Length (miles)	Still Stable (miles)	%	Still Eroding (miles)	%	Stabilized (miles)	%	Destabilized (miles)	%
Entire Study Area	1958 to 2014	210.2	164.9	78.5	8.3	4.0	19.8	9.4	17.1	8.1
	1958 to 1978	217.4	162.9	74.9	5.8	2.7	22.4	10.3	26.3	12.1
	1978 to 2014	210.0	159.8	76.1	7.4	3.5	24.8	11.8	18.0	8.6
Wilder Impoundment	1958 to 2014	90.3	74.8	82.9	1.8	2.0	3.0	3.4	10.6	11.8
	1958 to 1978	93.5	72.7	77.8	1.2	1.3	3.6	3.8	15.9	17.1
	1978 to 2014	90.2	65.3	72.4	4.7	5.2	12.5	13.9	7.6	8.4
Wilder Riverine	1958 to 2014	5.5	3.6	65.5	0.1	2.1	0.8	14.8	1.0	17.5
	1958 to 1978	5.5	4.3	78.1	0.0	0.0	0.9	17.0	0.3	4.9
	1978 to 2014	5.5	4.3	77.9	0.2	3.3	0.1	1.6	1.0	17.1
Bellows Falls Impoundment	1958 to 2014	49.8	32.6	65.5	4.8	9.6	10.0	20.1	2.4	4.8
	1958 to 1978	51.1	34.0	66.4	1.4	2.8	13.4	26.2	2.4	4.6
	1978 to 2014	49.5	40.0	80.8	1.2	2.4	2.6	5.3	5.7	11.5
Bellows Falls Riverine	1958 to 2014	7.0	5.7	80.2	0.1	1.7	0.8	11.8	0.4	6.3
	1958 to 1978	8.0	6.5	80.5	0.6	7.1	0.4	4.8	0.6	7.7
	1978 to 2014	7.1	5.4	76.4	0.1	1.2	1.1	15.6	0.5	6.8
Vernon Impoundment	1958 to 2014	57.8	48.2	83.4	1.6	2.7	5.1	8.9	2.9	5.0
	1958 to 1978	60.3	46.5	77.1	2.6	4.3	4.1	6.8	7.1	11.8
	1978 to 2014	57.7	44.8	77.5	1.3	2.2	8.4	14.6	3.3	5.7

5.6.5c Rates of Erosion

Several independent sources of information provide an indication for the rates of erosion and deposition for certain widely spaced locations in the study area, but determining rates of erosion for the entire study area with a high level of confidence is not possible. Remote sensing and field evidence provides an indication that rapid change can occur along the river. Portions of the channel in the upper Wilder impoundment appear to have been artificially straightened, most likely in the latter half of the 19th century, and near the Haverhill-Piermont, New Hampshire town line a meander had reformed along a straightened reach by 1930 that implies over 1,200 ft of erosion may have occurred in less than a century (i.e., a possible erosion rate of more than 12 ft/yr) and prior to the raising of Wilder dam in 1950 (see Section 5.2). Well preserved scroll bars on the low floodplain near Charlestown, New Hampshire are also suggestive of very rapid rates of channel migration (and associated erosion and deposition) over a long time period (Figure 5.4.2-4) and is consistent with 7 ft of bank recession documented at the Charlestown monitoring site (Site 02-B07) over a two-year period (see Section 5.4) implying a short-term erosion rate of as much as 3.5 ft/yr at this location. Examination of the digital elevation layer developed by the sub-meter accurate LiDAR dataset suggests that channel migration has occurred historically throughout large portions of the floodplain. Shaded relief maps created from this data show numerous scroll bars (appearing as arcuate or curved ridges) and abandoned channels across the entire floodplain, indicating that channel migration and associated bank erosion has occurred along the river for decades if not centuries (Figures 5.6.5-6 and 5.6.5-7).

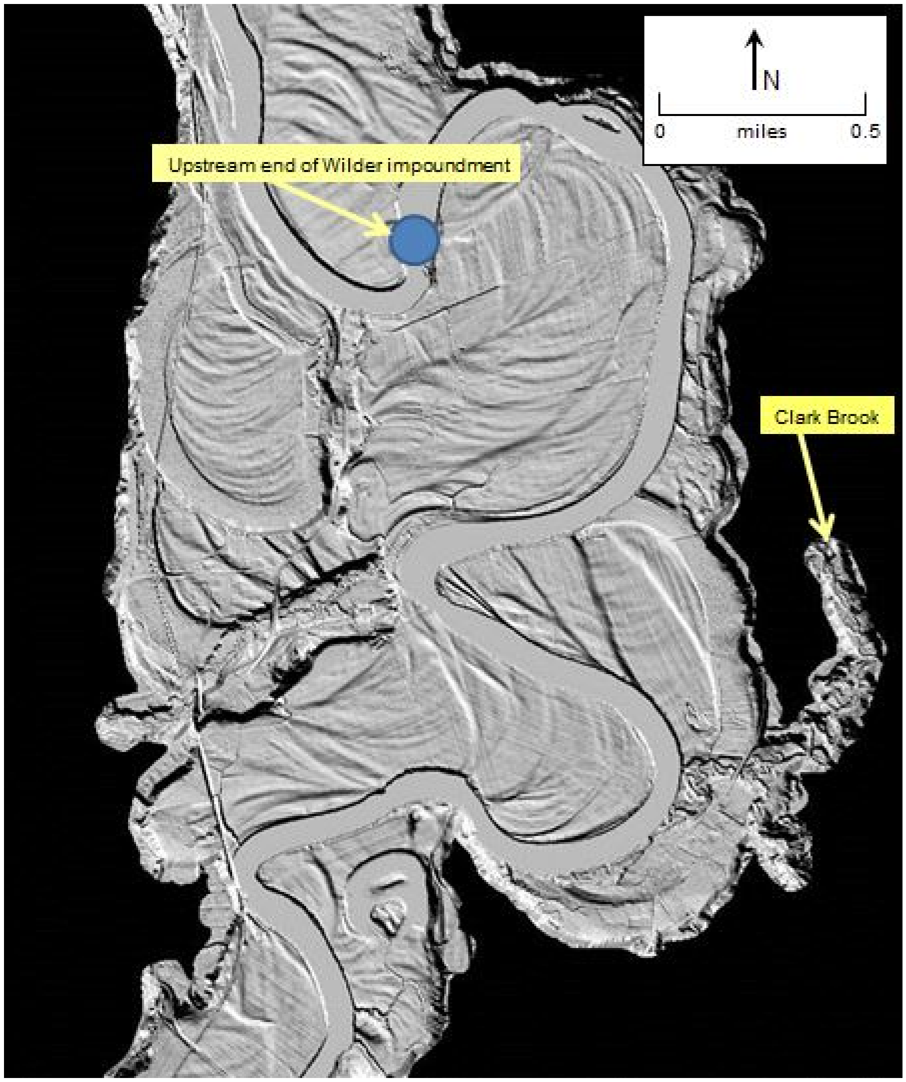


Figure 5.6.5-6. Hillshade relief map of upper Wilder impoundment generated from LiDAR data showing evidence of historical channel migration on floodplain.

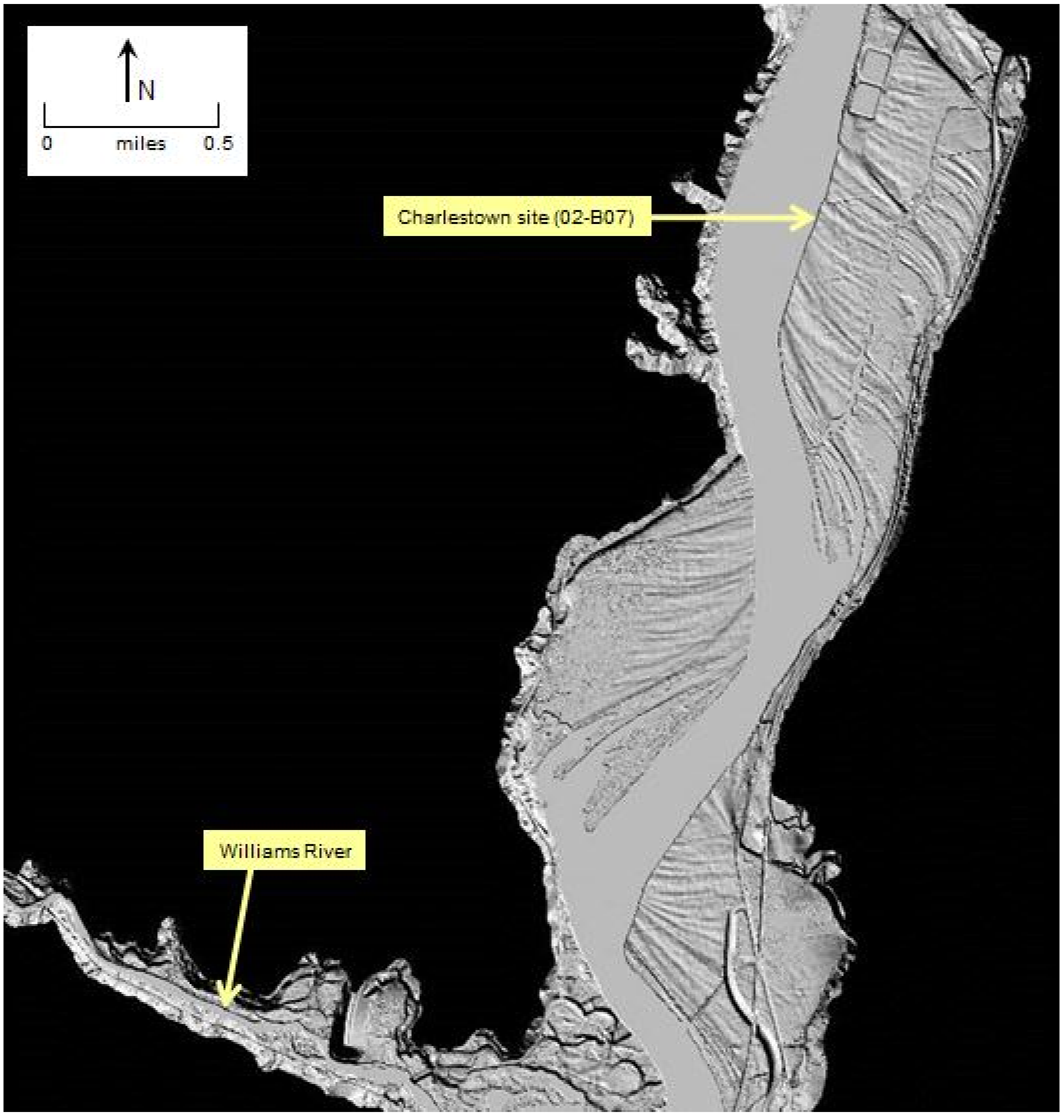


Figure 5.6.5-7. Hillshade relief map of a portion of Bellows Falls impoundment generated from LiDAR data showing evidence of historical channel migration on floodplain. (Compare with Figure 5.4.2-4.)

As discussed above previous armoring placed on the banks of the river have been almost completely removed in at least three locations (see Section 5.6.3e). At the site described in Fairlee, Vermont the river had eroded through a tree revetment by the time of a 2014 site visit and had nearly reached the back end of a 40-foot strip of riparian vegetation planted when the revetment was installed in 2002, indicating bank erosion has occurred at a rate of over 3 ft/yr. A detailed analysis of changes on historical aerial photographs was presented for 11 sites as part of the Study 1 report. Erosion rates of more than 5 ft/yr were identified at seven of the 11 sites during at least one of the time intervals between photo years. Through landowner contacts identified through a study area wide landowner outreach effort, two previous surveys of the riverbank in the Wilder impoundment were identified and these banks were resurveyed in 2015 to identify changes since the earlier surveys.

In addition, the monitoring site 02-VR01, a high eroding bank immediately downstream of Vernon dam on the left bank, has been extensively surveyed every two years along the entire bank including submerged portions since 1991 as part of long term monitoring conducted by TransCanada independent of this study. Twenty-five years of monitoring on a 73-ft high bank immediately downstream of Vernon dam on the left bank (of Vernon Neck so-called) documents an average erosion rate of approximately 2.6 ft per year. Based on aerial photographic evidence indicating the top of bank in 1952, 1966, and 1975 and survey monitoring from 1991 until present, it is apparent that rates of erosion have varied over the 61-year period (Figure 5.6.5-8). The greatest rate of top-of-bank retreat corresponds with the period between 1975 and 1991. It was at the start of this time frame that the Northfield Mountain Pumped Storage Project commenced operation which included increasing the Turners Falls dam WSE by 5.4 ft. This change in turn, resulted in an increase of WSE at the base of Vernon dam and the Vernon Neck east bank, causing a consistently higher WSE-bank interface.

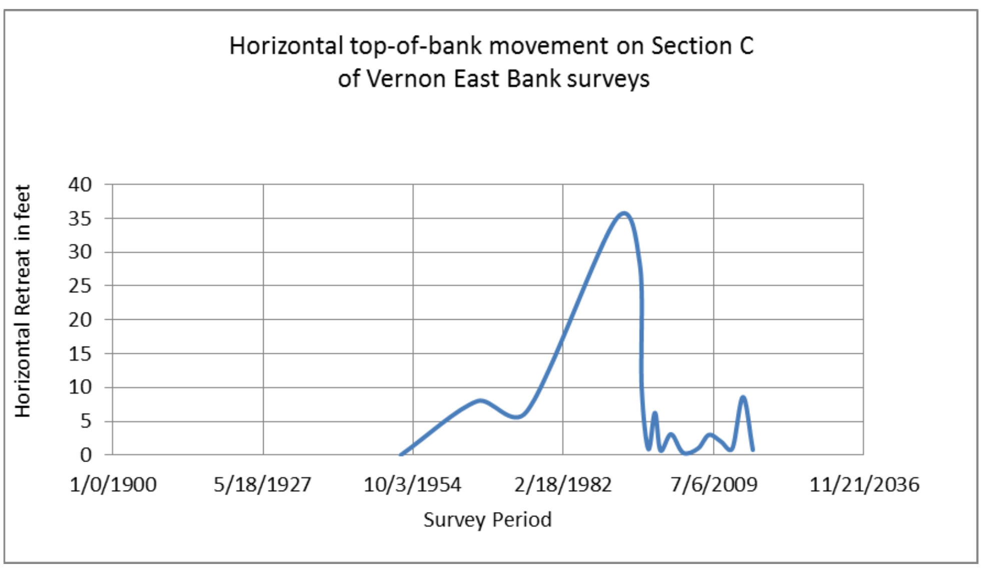


Figure 5.6.5-8. Vernon East Bank historical top-of-bank movement.

High water events, combined with the higher WSE acting on the high bank, appear largely responsible for the increased rate of erosion. In 1986, as part of the Vernon Project's spillway crest control and gate modifications, bedrock was removed below the tainter gates on the left bank to re-direct flow into the center river channel and reduce the whirlpool effect in the pool below the Vernon Neck east bank. This action may be in part supportive of the development of the beach at the base of the steep bank. Monitoring of the east bank included hydrographic monitoring of the submerged pool below and confirmed the gradual development of a submerged bench and beach at the base. Since 2006, despite annual high flow events with the exception of Tropical Storm Irene in 2011 causing a slight increase in slope failure immediately following that event, biennial surveys indicate little change in the top-of-bank and erosion has remained uniform and slight along the entire length of the bank. The toe-of-slope also shows little change along the entire length of the base of the bank and only minor and normal settling, a common phenomenon in open sloped areas composed primarily of sandy soils.

For the Wilder impoundment sites, the upstream most location is near the Haverhill-Piermont, New Hampshire town line (and just upstream of the reformed meander discussed in Section 5.2.3) with the original survey from 1975 showing the east bank of the Connecticut River extending 384 ft further west than in the 2015 survey, suggesting bank recession has occurred at a rate of 9.6 ft/yr in the past 40 years (Figure 5.6.5-9).

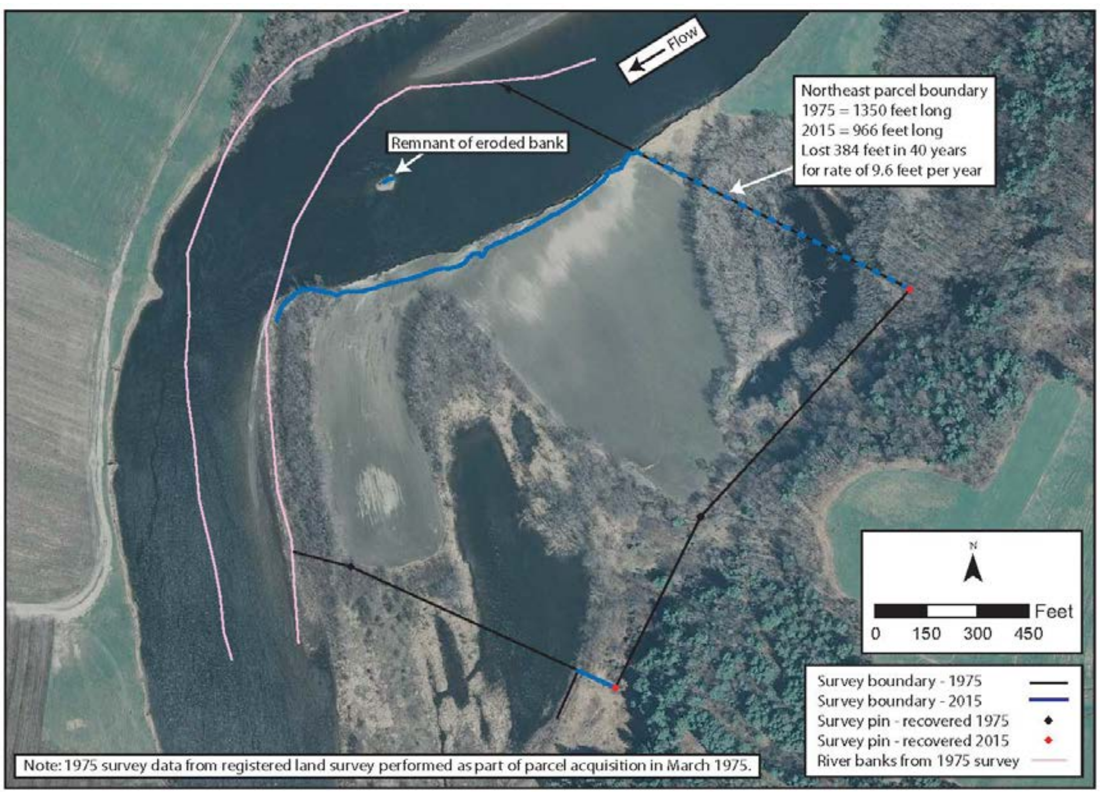


Figure 5.6.5-9. Comparison of 1975 and 2015 surveys of the Lewis property on the Haverhill/Piermont town line.

This is less than the 11 ft/yr established by comparing historical aerial photographs of the same area and presented in the Study 1 report but, along with erosion rates of 12 ft/yr implied by long-term meander development, corroborate rapid channel migration rates in this area. Two previous property surveys from 1961 and 1989 were also conducted in the area surrounding the Mudge monitoring site (Site 02-W09). Along one survey transect, 24 ft of erosion occurred between 1961 and 1989 documenting an erosion rate of 0.9 ft/yr. A resurvey of the same line in 2015 indicates an additional 8 ft of erosion has occurred since 1989, suggesting the erosion rate has decreased to less than 0.3 ft/yr. An erosion rate of less than 1.0 ft/yr is consistent with the lack of any recorded bank recession at Site 02-W09 over the two-year monitoring period, although more than a foot of bank recession did occur nearby (Figure 5.4.2-5).

The examples provided above represent isolated examples for rapid rates of bank erosion in the study area. On the whole, however, erosion rates must be considered far less than the isolated examples suggest. Comparisons of erosion mapping data suggest that nearly 80% of the riverbanks remained stable between 1958 and 2014, suggesting very little, if any, bank retreat has occurred along the vast majority of the study area. Furthermore, an analysis of historical aerial photographs demonstrates little demonstrable bank recession has occurred over the past 60 years or longer for most of the study area (see Section 5.3). Finally, the occurrence of bank recession at only three of 21 monitoring sites over the two-year monitoring period even when 15 of those sites were mapped as unstable (i.e., eroding, vegetated eroding, or failing armor) suggests bank recession rates for most of the study area are far less than 1.0 ft/yr (Table 5.4.2-1).

5.7 Topographic Surveying at Selected Sites

Topographic surveying was conducted at several locations other than the Study 2 monitoring sites in order to further characterize bank conditions and erosion rates. The surveys were used to document: 1) morphological adjustments to the Connecticut River channel occurring at tributary confluences (e.g., Blood's Brook survey), 2) evolution of bank morphology due to tunnel scour erosion (e.g., Hodge Site in Fairlee, Vermont and Governors Farm Site in Springfield, Vermont), 3) rates of bank erosion by comparing river position with earlier surveys (e.g., Mudge survey in Lyme, New Hampshire and Lewis survey in Piermont, New Hampshire), 4) bank line position along receding bank for possible future monitoring (e.g., Charlestown, New Hampshire monitoring site), 5) channel morphology in confined reach (e.g., near Wilgus State Park in Springfield, Vermont), 6) changes in bank elevations where meander has reformed since being straightened (e.g., site near Haverhill-Piermont, New Hampshire town line), and 7) morphology of a rotational slump (e.g., survey in Piermont, New Hampshire). The survey data are presented in Appendix F with the results for the surveys already integrated, where relevant, into the discussions presented in various sections above.

5.8 Bathymetric Survey of Impoundments and Riverine Sections

Bathymetric mapping was completed for the entire study area as part of Study 7 (Normandeau, 2015). The depth of water in near-bank areas can have a profound impact on erosion issues in two ways. First, the height of the bank ultimately includes both the portion of the bank below the waterline and the bank above. Consequently, the gravitational forces operating on a bank with deep water present will be greater than a bank with shallow water, assuming the heights of the banks above water are similar. Second, where deep water is present, a greater portion of the bank will be impacted by flowing water and the shear stresses acting at the base of the bank will be greater, increasing the likelihood that sediment accumulating at the base of the bank will be removed and the upper portion of the bank destabilized as a result. While a comparison between the location of erosion in the study area relative to water depths along the bank may be instructive, such a comparison was not possible for the entire study area as accurate measurements of water depth in all near-bank areas was of lesser quality than the rest of the channel given the difficulty of approaching the bank in boats used in the mapping, especially in shallow areas. However, the bathymetric mapping does improve the understanding of erosion at selected localities, as exemplified below, and underscores the importance of bank height in the distribution of erosion in the study area.

The above-water-level bank height exerts some control on the distribution of erosion (see Section 5.6.5a), a relationship that would likely be strengthened if the full bank height (including the portion below the water level) were considered. Near the Lipfert Site (02-B01), the bathymetry shows shallow water where sand/gravel bars are present and multiple narrow and deeper threads of the channel along both banks as flow is diverted around the bars, leading to the unstable banks where the deeper water threads are present (Figure 5.8-1). A discontinuous narrow thread of deeper water appears to be present right along the bank at the Lipfert Site, with material eroding from the slope potentially filling in portions of that deeper channel thread. As the material is removed, a continuous deeper thread may be rejuvenated with greater erosive force focused on the base of the bank, furthering the erosion. The deepest water at the Lewis Property in the upper Wilder impoundment is focused on the outside of a meander bend (Figure 5.8-2) where the highest documented erosion rates in the study area occur (see Section 5.6.5b) and the submerged sand bar is well defined by the shallower water on the opposite bank. The narrowest thread of deeper flow is located at the Lewis Site and the next meander bend downstream where erosion on the western bank is also continuous. As the deep-water thread becomes wider and erosive forces less concentrated, erosion is also present but is less continuous with stable banks continuing into the upstream end of the outer bends of meanders. The bathymetric mapping, therefore, documents how local flow patterns in the river, particularly around sand/gravel bars (Figure 5.8-1) and meander bends (Figure 5.8-2), exert a control on the distribution of erosion in the study area.

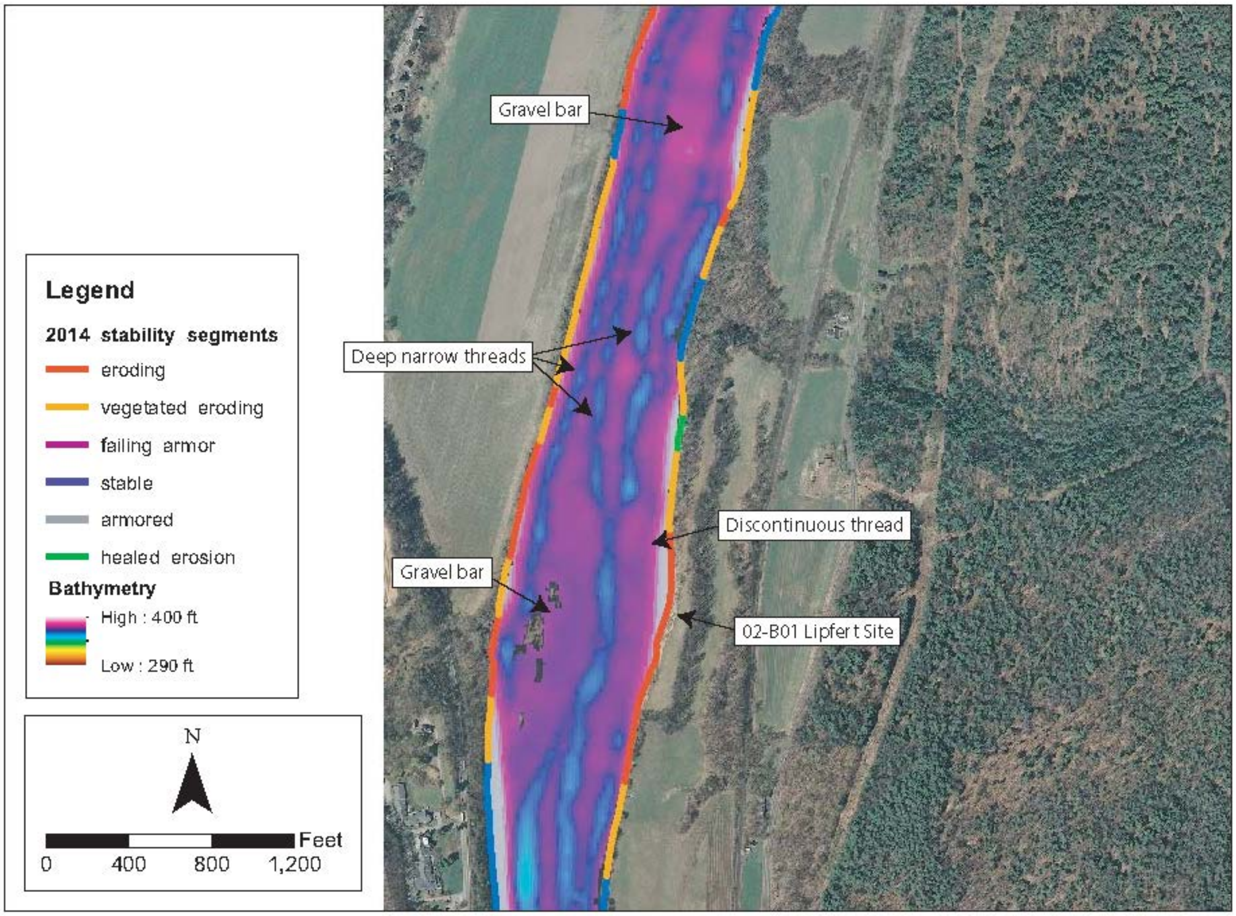


Figure 5.8-1. Bathymetric data showing deeper channels within the river diverted around gravel bars and toward unstable banks, Lipfert Site, upper Bellows Falls impoundment.

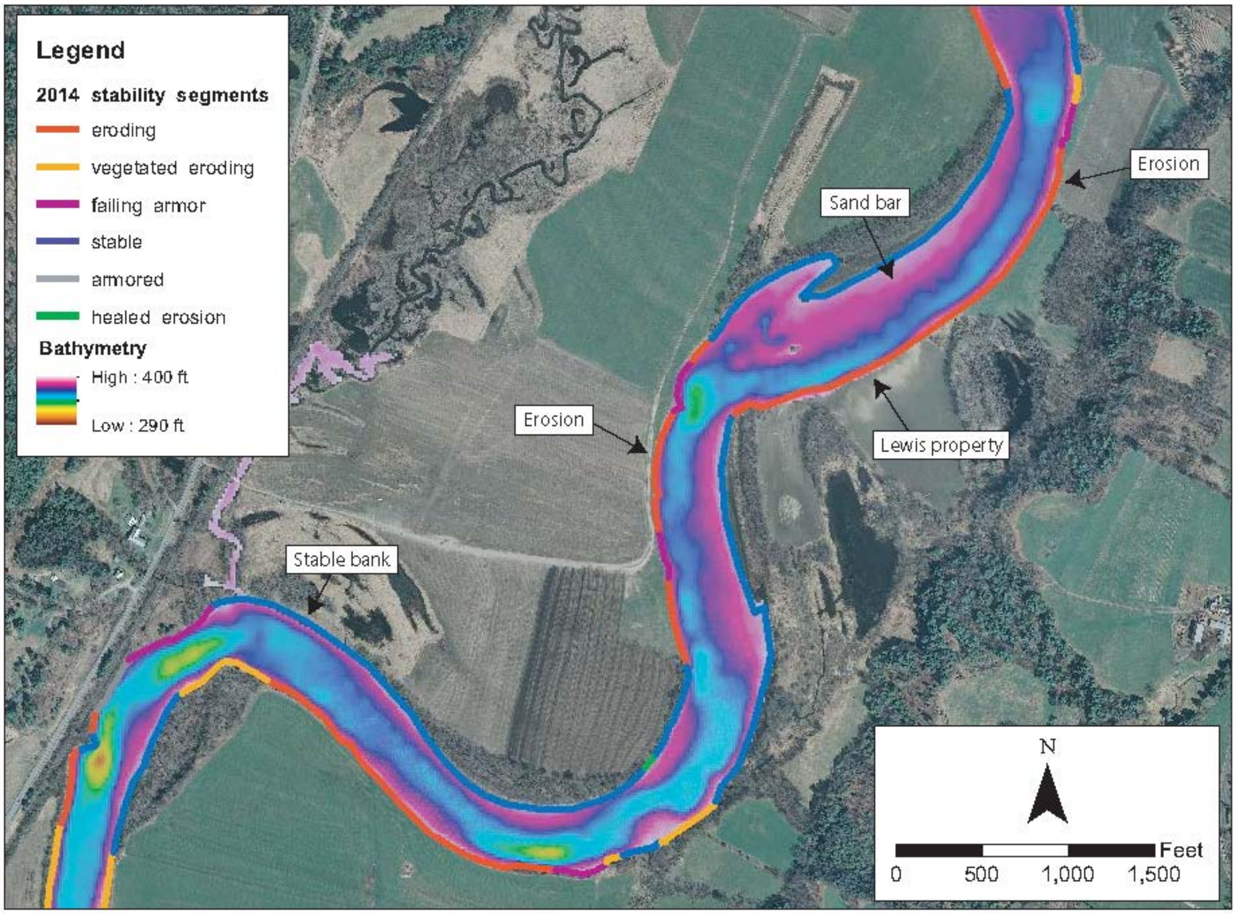


Figure 5.8-2. Bathymetric data showing channel thalweg along outside of meander bends and adjacent to unstable banks, Lewis Property, upper Wilder impoundment.

5.9 Hydraulic and Operations Modeling

Hydraulic modeling was completed for the entire study area and presented in the Study 4 report (GEI, 2016). The hydraulic modeling data were used in both Study 2 and Study 3. For Study 2, the hydraulic modeling data were used to establish the WSEs for river flows of varying magnitude at each of the 21 monitoring sites (Appendix A). Of particular interest was the impoundment level elevation at each monitoring site under normal project operating (non-high water, non-spill) conditions so a base elevation could be established around which water levels are most likely to fluctuate in response to project-related operations. The actual magnitude of the fluctuations was determined based on the operations model (Study 5 [Hatch, 2016]) that provided the exceedance probability of WSE fluctuations of various magnitudes for each of the Study 4 econodes (i.e., cross sections). The median (i.e., 50th percentile exceedance probability) was used for Study 2 and 3 investigations as this magnitude of fluctuation most closely matched the water surface data collected by water level loggers in Study 2. For each of the monitoring sites, this median WSE fluctuation was added to the base WSE at the site (i.e., low level under no-spill conditions) to display where on each of the monitored transects the WSE fluctuation resulting from project operations occurred on the bank and to see if this elevation aligned with certain physical bank features observed on the bank or any changes documented through two years of monitoring. These results were then compared with the locations of bank erosion to establish whether erosion preferentially occurs where the magnitude of WSE fluctuations are the greatest (see Section 5.6.5a). The actual results stemming from the use of the modeling data are discussed and presented in the relevant sections above so are not repeated here.

High water operations (exceeding normal operations in terms of flow and/or WSE) can occur as part of river flow management when TransCanada may periodically initiate “River Profile Reservoir Operations” by lowering WSE to specific elevations in anticipation of inflows greater than maximum generating capacity at each project. This is done pursuant to high water procedures developed under Article 32 of the existing project licenses and stipulated in Coordination Agreements with the US Army Corps of Engineers which operates flood control dams on several tributaries to the Connecticut River. These high water operations are initiated in order to maintain upstream water elevations within a range that protects specific railroad grade embankments along the river and to reduce the potential for river flows to spill outside of the normal operating ranges. These conditions and operating protocols are not considered normal project operations as they are instituted before and during all spill events; they typically occur often for sustained periods of time, each spring during the freshet.

During high water or flood conditions a corresponding changing slope in lower portions of the impoundments results from reduction of WSE at the dam as river flows increase at the upper extent of the impoundment. This reduction rate is managed and restricted to a rate of drawdown of less than 0.3 ft/hr and typically 0.1 – 0.2 ft/hr. As a result of lowering WSE at the dams, a convexity in the longitudinal profile develops in the impoundments, most pronounced at the lower end (Figure 5.8-1), that could potentially engender a channel response as a stable river profile typically has a concave-up profile in contrast to the observed convexity. The convexity appears in the hydraulic modeling data, because the model shows a “snapshot” in time. In actuality, such a convexity is constantly changing; increasing as upstream inflows continue to rise and then shifting toward concavity as inflows decrease. As inflows decrease, WSE at the dams are then adjusted upward which moderates the degree of concavity. The rate of drawdown is not matched by the rate of WSE increases.

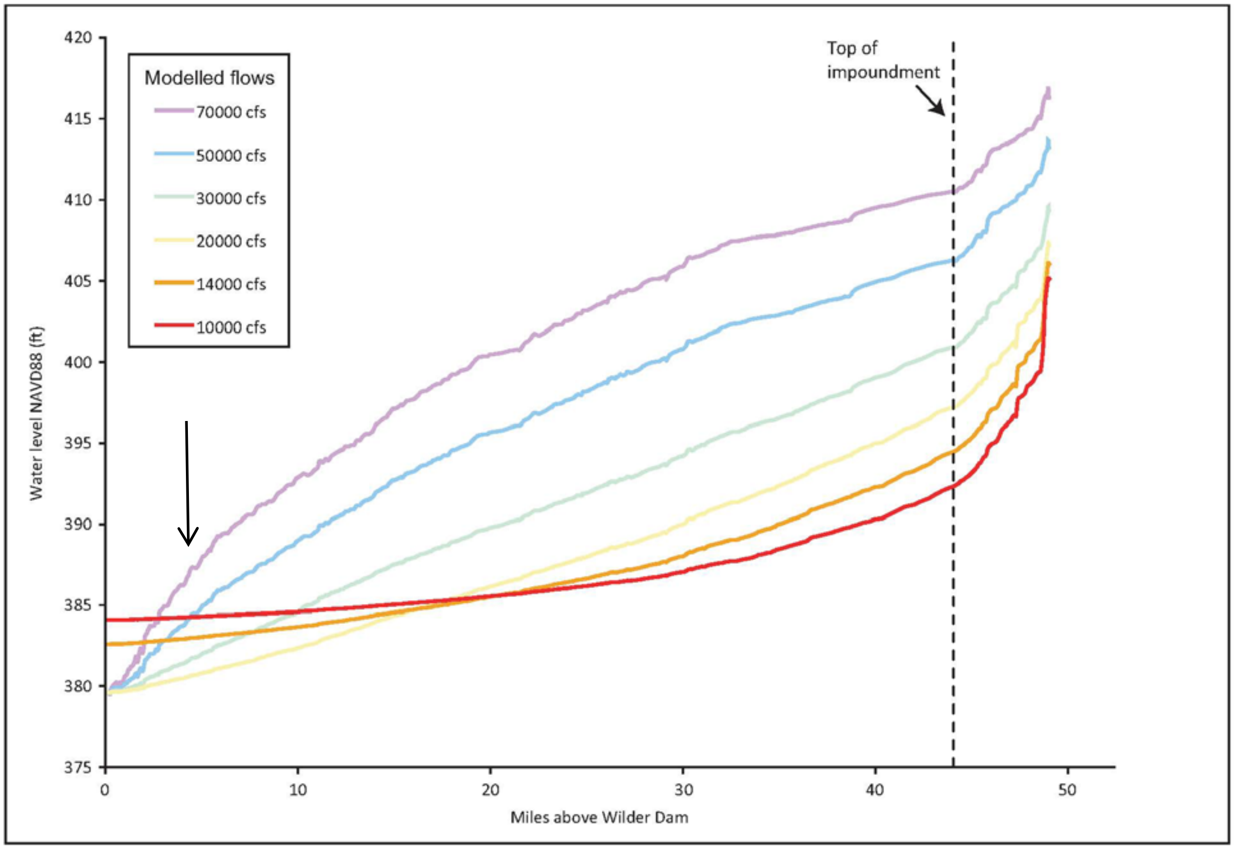


Figure 5.8-1. Convexity develops in longitudinal profile of the Wilder impoundment when the dam WSE is lowered for high inflows. The convexity is most pronounced, as indicated by the arrow on the left side of the figure, during high flows at the lower end of the impoundment.

The Study 4 (GEI, 2016) hydraulic model was used to determine if the convex profile, could lead to bank instability by comparing flow velocities at various discharges and dam elevations at the 13 erosion monitoring sites in the impoundments (Table 5.8-1). Velocity increases indicated by the hydraulic model are the result of increases in river flow while some of the changes are associated with prescribed project-related changes in WSE at the dams that increase the water surface gradient. For example, at Wilder dam, under high flow profile operations, lowering of the WSE from an elevation of 384.6 ft begins when the inflow at the upper extent of the project exceeds 10,000 cfs As a result of increase in discharge (velocity) and to some extent the reduction in WSE at the dam, the velocity calculated at 02-W12 (Pine Park site) increases 78 percent from 0.9 ft/s to 1.6 ft/s, the largest such increase in Wilder impoundment (Table 5.8-1). In general, the greatest velocity increase associated with an increased gradient occurs at sites closest to the dams. To estimate how much of the flow increase might be associated with increasing the hydraulic gradient due to reduction in WSE at the dam as opposed to increasing flows, the hydraulic model was also used to compare flow velocities at different WSE at the dam under similar flow conditions although such scenarios do not occur with the actual operation of the projects. The velocity increase at 02-B07 (Charlestown Site) of 23 percent in the Bellows Falls impoundment at a discharge exceeding 11,000 cfs represents the largest increase that would occur from WSE lowering if the flow was held constant (Table 5.8-1). This increase is far less than the 321 percent increase at the site when the discharge varies with the lowering, suggesting that the increase in gradient associated with WSE lowering at the dams exerts only a small control on the velocity increases resulting from the lowering of WSE at the dams at times of high flow. Project-related changes, therefore, are unlikely a cause of bank instability associated with the convexity that develops in the profile when the WSE at the dams is lowered at high discharges, especially given the short-lived nature of the unstable water surface profile and the limited number of such drawdowns (e.g., only one such drawdown occurred during the two years of seasonal water level logger data collection at the erosion monitoring sites).

Table 5.8-1. Velocities at various discharges and dam elevations at the 13 erosion impoundment monitoring sites.

	Elevation (ft)(NAVD88)		384.6	381.6		384.6	381.6		384.6	381.6	
	Flow (cfs)		10,000	10,000		16,000	16,000		10,000	16,000	
Wilder	**Site**	**Model Node**	**Velocity Total (ft/s)**		**Difference (%)**	**Velocity Total (ft/s)**		**Difference (%)**	**Velocity Total (ft/s)**		**Difference (%)**
	02-W02	1166	1.9	2.1	8	2.5	2.6	5	1.9	2.6	39
	02-W03	1143	1.1	1.3	18	1.4	1.6	9	1.1	1.6	36
	02-W07	1040	1.0	1.2	22	1.5	1.7	16	1.0	1.7	69
	02-W09	999	1.2	1.3	14	1.8	2.0	11	1.2	2.0	71
	02-W10	985	1.0	1.1	14	1.5	1.7	13	1.0	1.7	74
	02-W12	919	0.9	1.0	13	1.5	1.6	12	0.9	1.6	78
	Elevation (ft)(NAVD88)		**291.2**	**289.2**		**291.2**	**289.2**		**291.2**	**289.2**	
	Flow(cfs)		**11,000**	**11,000**		**50,000**	**50,000**		**11,000**	**50,000**	
Bellows Falls	**Site**	**Model Node**	**Velocity Total (ft/s)**		**Difference (%)**	**Velocity Total (ft/s)**		**Difference (%)**	**Velocity Total (ft/s)**		**Difference (%)**
	02-B01	686	2.6	2.8	8	3.9	3.9	1	2.6	3.9	51
	02-B03	632	2.0	2.3	19	4.3	4.4	2	2.0	4.4	121
	02-B07	552	0.7	0.9	23	2.7	3.0	11	0.7	3.0	321
	02-B09	523	0.6	0.7	12	2.6	2.9	13	0.6	2.9	400
	Elevation (ft)(NAVD88)		**219.6**	**217.6**		**219.6**	**217.6**		**219.6**	**217.6**	
	Flow (cfs)		**17,000**	**17,000**		**45,000**	**45,000**		**17,000**	**45,000**	
Vernon	**Site**	**Model Node**	**Velocity Total (ft/s)**		**Difference (%)**	**Velocity Total (ft/s)**		**Difference (%)**	**Velocity Total (ft/s)**		**Difference (%)**
	02-V02	377	1.9	2.1	13	3.4	3.5	3	1.9	3.5	83
	02-V03	373	1.6	1.7	8	3.2	3.3	2	1.6	3.3	108
	02-V06	194	1.6	1.7	7	3.8	4.0	5	1.6	4.0	157

6.0 ASSESSMENT OF PROJECT EFFECTS

Trying to distinguish specific effects of normal project operations among the panoply of potential factors (both primary and secondary) affecting bank erosion in any given location is not possible. Bank erosion in the study area, where it occurs, is likely the result of multiple causal factors that, in one manner or another, enable the cycle of erosion (described in Section 5.6.2 and illustrated in Figure 5.6.2-1) to proceed. Not all causal mechanisms need be present at any given site to effect erosion, but where they are present they all work in concert to increase bank instability.

Bank erosion results when and where the driving forces promoting bank instability exceed the bank's resistance to erosion. As discussed in Section 5.1.2, commonly occurring natural conditions can lead to bank erosion including: 1) strong river flows that can remove material at the base of the bank and increase gravitational forces by over-steepening the bank face; and 2) increased soil moisture from rainfall events or flood inundation that reduce bank resistance through a loss in soil cohesion and strength. When a bank is at the threshold of stability, any changes along the bank that reduce the resisting force or increase the driving force could initiate erosion. Within the study area, the resisting and driving forces determining bank stability may vary dramatically over short distances giving rise in places to short reaches of stable bank alternating with short lengths of unstable bank. For the 60 percent of the bank length mapped as stable, armored, or healed erosion, the resisting forces of the bank to erosion currently exceed the driving forces acting on the bank.

The character of sediments in the study area creates banks with limited resistance to erosion. The bank sediments at the monitoring sites, representative of the study area as a whole, are nearly ubiquitously comprised of fine-grained and unconsolidated floodplain or glaciogenic sediments that are particularly prone to erosion (see Appendix A stratigraphic columns). Frequently observed inter-beds of permeable sand and less permeable silt can further reduce the resisting force of floodplain sediments by creating horizontal surfaces along which groundwater can preferentially move, potentially increasing seepage forces acting on the bank. The downcutting of the Connecticut River over thousands of years into geologically older lake and river terraces (Figure 5.5-1 and Appendix B) creates high banks in many places that naturally enhance the gravitational driving forces exerted on the riverbanks. The influence of bank height and composition on erosion is highlighted by the tendency for erosion to preferentially occur on higher banks composed of loose unconsolidated sediments (Figure 5.6.5-1).

With the limited geographic extent of active floodplain in many portions of the study area, small to moderate flood flows are largely confined to the channel and the stream power produced by the floods (an additional driving force) is expended on the channel bed and banks rather than being spread out over a broader floodplain. Large floods have created long lengths of fresh erosion on the Connecticut River in the past where the resisting force provided by bank vegetation was absent (Jahns, 1947). Taken together, natural conditions in the study area, by both reducing the resisting forces and enhancing the driving forces of erosion, create a situation where the riverbanks are likely near the threshold of erosion. Multiple causal mechanisms that either increase erosive driving forces or decrease bank resistance are likely acting to effect erosion on the riverbanks in the study area that are naturally sensitive to erosion.

Tractive force erosion during floods was rated the most important cause of erosion during an earlier investigation of erosion in the study area (Simons et al., 1979). Flood flows are particularly effective in sustaining erosion, including on the Connecticut River (Jahns, 1947; Field, 2007a), because they carry downriver material accumulating at the base of the bank that might otherwise promote bank stability (Hagerty, 1991b). The three monitoring sites where bank recession was documented are associated with local conditions where tractive forces are increased at the monitored bank (see Section 5.4.2).

Tractive force erosion has been observed to occur during small to moderate floods during the winter months (Green et al., 1999; Simon et al., 2000) and is consistent with wintertime bank recession at the three monitoring sites that recorded such change (Appendix A). Two of the three sites receded during the winter of 2013-14 when the largest flows (April 2014) occurred during the two-year monitoring period. Wintertime recession is also at a time when freeze-thaw processes, a known erosion mechanism (Gatto, 1995), would be most effective. Both freeze-thaw processes and flood flows could be working in concert to enhance erosion in the winter months. The erosion might also occur shortly after passage of the flood peak due to seepage forces or changes in pore-water pressures in the bank.

A 1,000-foot section of River Road in Lyme, NH in the Wilder impoundment was damaged due to bank failure that occurred during the weekend of April 30 – May 1, 2011. High flows persisted for 2.5 days prior to this bank failure as recorded upstream at a gauge on the Connecticut River in Wells River, VT (Figure 6.0-1). Although a July 2016 bank collapse farther south along Route 10 in Hanover, NH demonstrates that bank recession does not always occur in the winter or spring months (John Mudge, email communication, July 15, 2016 to the Connecticut River Joint Commissions Upper Valley Subcommittee), the erosion monitoring data appear to demonstrate that significant bank recession is more likely to occur in the winter or during the spring freshet.

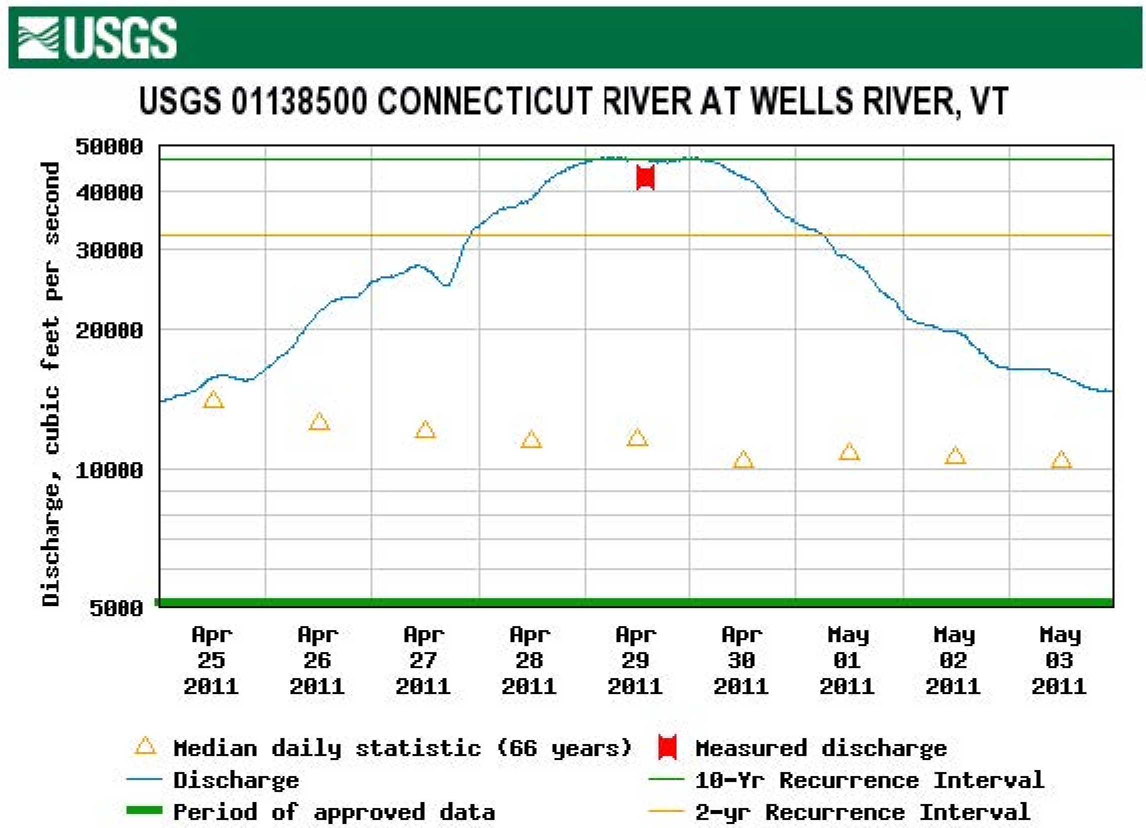


Figure 6.0-1. USGS gage data upstream of Wilder impoundment, April 25 – May3, 2015.

6.1 Flow Velocities and Erosion

To determine the conditions under which transport of sediment accumulating at the base of the bank can occur, comparisons were made between flow velocities generated at various flow levels and the minimum threshold velocity necessary to transport (or entrain) sediment in the project areas. Flow velocities were measured at three impoundment erosion monitoring sites and three riverine erosion monitoring sites with an acoustic Doppler current profiler (ADCP) that measures flow velocities using the Doppler effect of sound waves scattered back from particles within the water column. The measured ADCP velocities show good agreement or are slightly higher than the calculated average velocities from the hydraulic model (Study 4 [GEI, 2016]) except for the Hartford Site (02-WR01) where the modeled velocities are higher than the ADCP measurements (Tables 6.1-1 and 6.1-2). The threshold velocity needed to entrain sediment (i.e., initially mobilize sediment from a stationary state) at a given location depends on a variety of parameters such as grain size (i.e., soil texture), cohesion between the sediment grains, turbulence and turbidity of the water, and vegetative cover. The predominant soil textures in the study area consist of fine sandy loam and fine silty loams (Web citation 10). NRCS' (2007) publication on thresholds for small channel design recommends a maximum permissible velocity of 1.5 feet per second (ft/s) for fine sand in clear water without any detritus but 2.5 ft/s in water carrying colloidal silts as higher velocities are needed to transport silt and clay, because of their cohesiveness, than fine sand. For sandy loam, NRCS (2007) recommends a maximum permissible velocity of 1.75 ft/s for clear water and 2.5 ft/s for water carrying colloidal silts as water already concentrated with sediment is less likely to entrain additional sediment. Finally, for silty loam, NRCS (2007) recommended a maximum permissible velocity of 2.0 ft/s for clear water and 3.0 ft/s for water carrying colloidal silts. Because these values are design parameters, they contain a factor of safety, so actual transport might be expected to occur at velocities even higher than specified. For example, USACE (1991b) used an allowable mean velocity for non-scouring flood control channels of 2.0 ft/s for fine sand compared to the 1.5 ft/s specified in NRCS (2007). Considering these values, the character of sediment in the study area, and vegetative growth on the banks, a conservative minimum threshold for sediment entrainment along the Connecticut River is considered to be 2.0 ft/s while a reasonable range for sediment entrainment is estimated at 2.0 to 3.0 ft/s based on values provided in NRCS (2007) and USACE (1991b).

Table 6.1-1. Flow velocities measured at corresponding impoundment erosion monitoring sites.

Parameter	Units	Study 2-3 Site ID and Name		
		02-W03	02-W09	02-B07
		Bellavance	Mudge	Charlestown
Study area		Wilder Impoundment	Wilder Impoundment	Bellows Falls Impoundment
Town		Bradford, VT	Lyme, NH	Charlestown, NH
Latitude		44.014852	43.822787	43.220017
Longitude		-72.09461	-72.187887	-72.437683
Streamflow Velocity Measurements in the field				
Date		August 6, 2015		
Measured velocity (mean)	ft/s	0.6	0.7	0.7
River flow at measured velocity	cfs	2,690	4,990	8,560
Max. station discharge	cfs	11,700[a]	11,700[a]	11,400
Percent of total generation		23%	43%	75%
Additional contribution from spill		0%	0%	0%
Modeled Streamflow Velocities				
Velocity at measured flow[b]	ft/s	0.3–0.4	0.7	0.4–0.6
Velocity at minimum flow	ft/s	0.1	0.1	0.1
Velocity at maximum generating flow[b]	ft/s	0.7–0.9	1.3–1.4	0.6–0.7
Minimum flow needed for threshold velocity[c]	cfs	100,000	17,000	28,000
Modeled velocity at 30,000 cfs	ft/s	1.7	3.3	2.3

Parameter	Units	Study 2-3 Site ID and Name		
		02-W03	02-W09	02-B07
		Bellavance	Mudge	Charlestown
Modeled velocity at 60,000 cfs	ft/s	1.8	5.0	3.4
Modeled velocity at 100,000 cfs	ft/s	2.0	6.6	4.2
Threshold velocity for erosion[c]	ft/s	2.0–3.0		

a. The maximum Wilder station discharge with all three units operating is approximately 11,700 cfs, although 98% of the time discharge is between 10,700 cfs and 700 cfs.

b. Ranges indicate variations due to the range of normal operations WSEs at the downstream dam.

c. Threshold velocity data from NRCS (2007) and USACE (1991b). Reasonable range is 2.0–3.0 ft/s.

Velocities were measured in August 2015 at three impoundment monitoring sites (Bellavance, Mudge, and Charlestown sites) when river flows were at 23 percent, 43 percent, and 75 percent, respectively, of the applicable projects' maximum station discharge. Velocities were also modeled for the projects' minimum flow and maximum station discharge, and for flood flows (30,000, 60,000, and 100,000 cfs) as part of the Study 4 analysis (Table 6.1-1). Both the measured and modeled velocities at the impoundment sites were well below the 2.0 ft/s minimum threshold velocity for sediment entrainment under normal project operations, indicating that the sediment accumulating at the base of the riverbanks is unlikely removed by normal project operations. All flood flows exceed the threshold velocity at the Mudge and Charlestown sites and can, therefore, remove material from the base of the bank, but only the largest modeled flow reaches the threshold velocity at the Bellavance site. Bank recession occurred at the Bellavance site during the two year monitoring period in which no flows of 100,000 cfs occurred indicating that local factors are at play (e.g., recent nearby meander cutoff) to enhance sediment transport beyond what is expected based on the modeled average flow velocities.

Flow velocities were also measured at erosion monitoring sites in the riverine reaches downstream of the projects (Hartford, Malnati, and Stebbins Island sites) and at the North Walpole USGS gage (no. 01154500) in May 2015. Flows in the Wilder and Bellows Falls riverine reaches consisted of project discharges plus natural inflow at that time and since no major tributaries enter the Vernon riverine reach, Vernon flows consisted of station flows only. (Table 6.1-2). Velocities were also modeled for each project's minimum flow and maximum station discharge, and for flood flows (30,000, 60,000, and 100,000 cfs) as part of Study 4 (Table 6.1-2). The minimum threshold entrainment velocity is not reached at the Hartford site and is just reached at the North Walpole gage under the range of normal project operating discharges but is exceeded at the Malnati and Stebbins Island sites at higher flows within the normal project operating ranges, suggesting some sediment movement could occur at some locations in the riverine reaches under normal project operations.

Table 6.1-2. Flow velocities measured at corresponding riverine erosion monitoring sites and the North Walpole USGS gage.

Parameter	**Units**	**Study 2-3 Site ID and Name**			
		02-WR01	**NA**	**02-BR05**	**02-VR02**
		Hartford	**USGS Gage N. Walpole**	**Malnati**	**Stebbins Island**
Project Area		Wilder Riverine	Bellows Falls Riverine	Bellows Falls Riverine	Vernon Riverine
Town		Hartford, VT	Walpole, NH	Walpole, NH	Hinsdale, NH
Latitude		43.6638	43.125964	43.095957	42.770815
Longitude		-72.30636	-72.4 37676	-72.438574	-72.504831
Streamflow Velocity Measurements in the field					
Date		May 9, 2015	May 13, 2015		May 14, 2015
Measured velocity (mean)	ft/s	1.3	2.0	2.6	2.3[a]
River flow at measured velocity	cfs	11,540	11,970	12,040	11,848[a]
Max. station discharge	cfs	11,700[b]	11,400	11,400	15,500[c]
Percentage of total generation		99%	100%	100%	76%[a]
Additional contribution from spill		0%	5%	6%	0%
Modeled Streamflow Velocities					
Velocity at measured flow[c]	ft/s	1.9	1.9	2.5–2.6	1.9–2.1
Velocity at minimum flow[c]	ft/s	0.3	0.5	0.5–0.6	0.4–0.7
Velocity at maximum generating flow[d]	ft/s	1.9	1.8	2.4–2.5	1.8-2.2
Minimum flow needed for threshold velocity[d]	cfs	13,000	13,000	8,000	11,000–14,000
Modeled velocity at 30,000 cfs	ft/s	3.1	3.5	4.0	2.7
Modeled velocity at 60,000 cfs	ft/s	4.3	4.8	5.2	3.1
Modeled velocity at 100,000 cfs	ft/s	5.4	6.0	6.1	3.4
Threshold velocity for erosion[e]	ft/s	2.0–3.0			

a. Velocity and flow were measured in the left (New Hampshire side) channel at 8,290 cfs, while Vernon total discharge was 11,848 cfs. Modeled values are based on whole river flows including both left and right (Vermont side) channels.

b. The maximum Wilder station discharge with all three units operating is approximately 11,700 cfs, although 98% of the time discharge is between 10,700 cfs and 700 cfs.

c. The maximum Vernon station discharge with all ten units operating under ideal or optimum conditions is considered to be about 17,100 cfs. However, actual operating data suggests that total station discharge is rarely, if ever, greater than 15,500 cfs, and 98 percent of the time discharge is between 14,500 cfs and 15,300 cfs.

d. Ranges indicate variations due to the range of normal operations WSEs at the downstream dam.

e. Threshold velocity data from NRCS (2007) and USACE (1991b). Reasonable range is 2.0–3.0 ft/s.

The Malnati site is located in the Bellows Falls riverine reach and receives inflow from Bellows Falls as well as from the Saxtons and Cold rivers, both large tributaries (fifth order streams). The threshold entrainment velocity of 2.0 ft/s is reached at 8,000 cfs at the site, a flow that occurs most often during the spring freshet and fall rain events. Based on flow exceedance curves the occurrence of 8,000 cfs flows from Bellows Falls and excluding tributary flows is 95 percent in April and 14 percent overall from July through September (average = 43 percent on an annual basis), so sediment entrainment at times other than the spring freshet would be uncommon. Furthermore and as noted above, an overall reasonable range for sediment entrainment is estimated at 2.0 to 3.0 ft/s. The flow at the Malnati site required for sediment entrainment based on a 3.0 ft/s entrainment velocity rather than the more conservative 2.0 ft/s used in this analysis is approximately 17,000 cfs, well above the maximum station discharge of 11,400 cfs. Therefore, project operational discharges are only a minor contributor to sediment entrainment, while moderate spill conditions that occur throughout the year and high flows typically in the spring of the year are likely the major contributors.

At the Stebbins Island site, flow at the time of field measurement was 76 percent of the maximum station discharge. FirstLight had purposely lowered WSE at Turners Falls dam below the typical operating range to accommodate these flow measurements, thus the velocity measurements can be considered worst case as the typically higher water level in the Turners Falls impoundment would reduce velocity. Flows in the Vernon riverine reach required to reach the threshold entrainment velocity are influenced by WSEs at the downstream Turners Falls dam and range from 11,000 to 14,000 cfs within Turners Falls normal operating range (Table 6.1-2), and between 12,000 and 13,000 cfs at the Turners Falls dam median WSE of 181.3 ft (NGVD29). Flows within the range of 11,000 to 14,000 cfs occur primarily during the spring freshet and fall rain events. Based on flow exceedance curves the occurrence of these flows are 85 and 91 percent respectively, in April, but only 7 and 12 percent respectively, overall from July through September (average = 26 and 36 percent respectively, on an annual basis).

Measured and modeled velocities are difficult to compare at the Stebbins Island site where total river flow is split around the island, because the modeled velocities represent an average velocity across both channels. As noted above, the overall reasonable range for sediment entrainment is estimated at 2.0 to 3.0 ft/s. The flow required for sediment entrainment based on a 3.0 ft/s entrainment velocity rather than the more conservative 2.0 ft/s used in this analysis, and based on full river flow is nearly 60,000 cfs (Table 6.1-2), well above the maximum station discharge.

To establish if any pattern is present between flow velocities and observed changes at the 21 erosion monitoring sites only modeled flow velocities were available as ADCP velocity measurements were made at only six of the monitoring sites. Flows at the upper end of the normal operating range at the 21 monitoring sites generally fall below the minimum entrainment threshold of 2 ft/s and in all cases are below 3 ft/s (Figure 6.1-1). In contrast, velocities for the modeled flood flows exceed the minimum entrainment threshold at all but the Bellavance Site (02-W03). The degree of change at the monitoring sites does not appear to be related to flow velocities as some of the sites with the highest flow velocities experienced no or little change during the two year monitoring period as illustrated by the numerous sites in the lower right corner of Figure 6.1-1. Similarly, some of the sites with the lowest flow velocities experienced the greatest amount of change during the two years of monitoring as at the Bellavance Site. The comparison between flow velocity and documented change at the monitoring sites shows no strong relationship and indicates that other factors, such as bank composition and vegetation, may also exert some control on the location of bank changes.

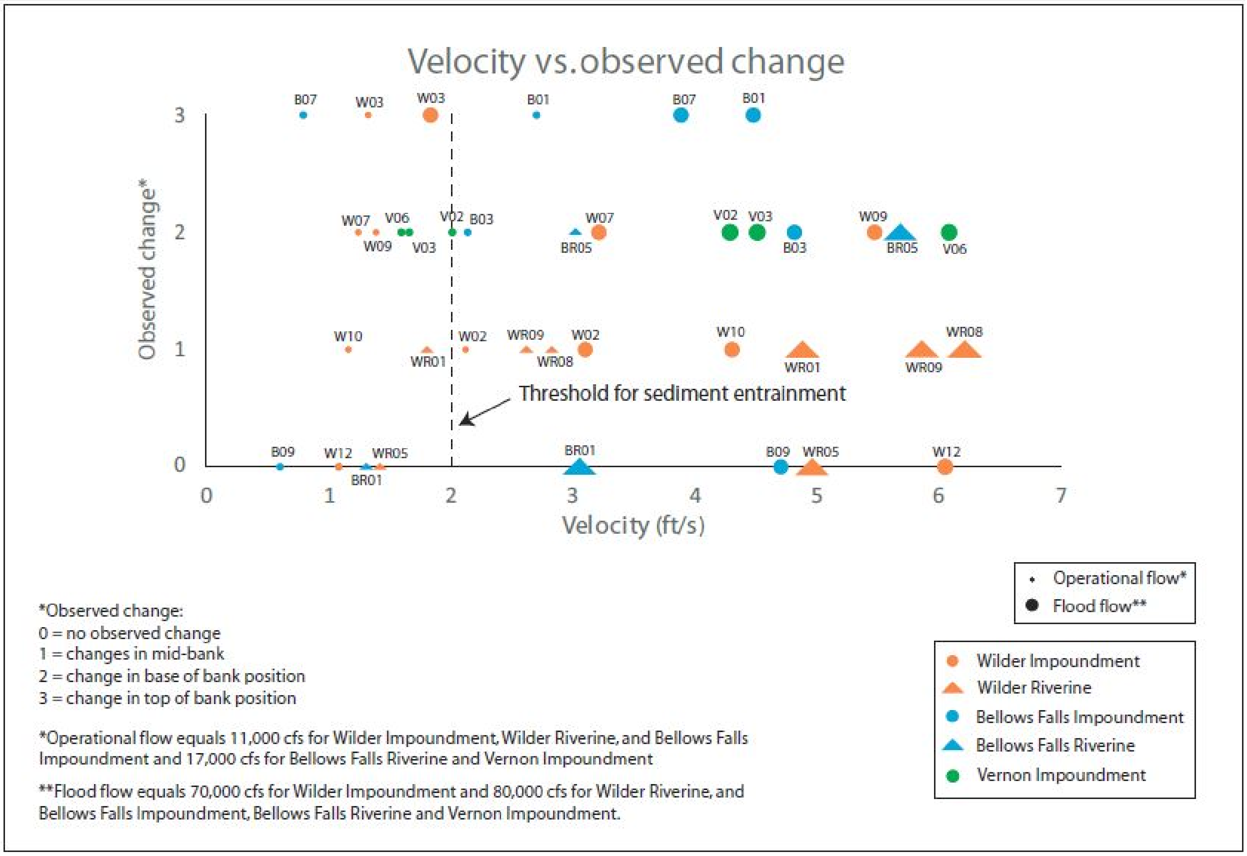


Figure 6.1-1. Comparison of modeled flow velocities with observed changes at the Study 2 erosion monitoring sites.

While multiple factors affect sediment entrainment thresholds, the velocity data suggest that removal of the material accumulating at the base of the banks along the shore of the impoundments is attributable to high flow events outside of normal project operations. Along the riverine reaches, removal of material at the base of the banks is almost exclusively attributable to high flow events but may occur at some sites for short durations during higher generating flows depending on local bank composition and particle size. Flow velocities at or above the threshold entrainment value do not necessarily mean that erosion is continuously occurring at a given site. Preferential removal of the most easily moved particles (i.e., fine sand) will lead to armoring at the base of the bank by coarser particles that are not entrained, and over time, will reduce erosion of finer particles at a given flow velocity. Furthermore, removal of any material accumulating at the base of the riverbanks from upslope erosion caused by the processes described in Figure 5.6.2-1 must occur before further erosion of the bank itself can continue.

6.2 Erosion Rates

A decline in erosion rates in the Bellows Falls and Vernon impoundments during the 1970's-2010 time period compared with the 1950's-1970's time period is suggested by an analysis of historical aerial photographs (5.3-1b-c), while a slight increase in erosion rates is apparent in the upper Wilder impoundment data. Repeated ground photographs presented in Study 1 demonstrate a number of locations throughout the study area that were eroding have stabilized over time. A comparison of erosion maps from 1958, 1978, and 2014 provides a more comprehensive assessment of how the amount of erosion has changed through time (Table 5.6.5-2). Changes of less than 10% between the various years of erosion mapping should be considered within the margin of error given the discrepancies in mapping that should be expected from year to year. Within this context, the 21% decline in the amount of erosion from 1958 to 1978 in Bellows Falls impoundment and the 13% increase in Wilder impoundment during the same time period likely represent actual trends whereas the 8% decrease in erosion in Vernon impoundment between 1978 and 2014 is less certain, although the analysis of historical aerial photographs do corroborate a decline in erosion in Vernon impoundment (Figure 5.3-1c). Declines in the rate of erosion in Bellows Falls impoundment and Vernon impoundment while rates are increasing in upper Wilder impoundment may be associated with the construction of numerous flood control projects in the late 1950's and early 1960's in tributary watersheds (Web citation 1) that have reduced flood peaks and erosive forces most significantly downstream of Wilder dam.

The apparent trends in erosion rates may also be associated with the year when the three project dams were last raised: Wilder in 1950, Bellows Falls in 1929, and Vernon in 1909. When the water surface in an impoundment is increased when a dam is raised, the previously dry bank sediments inundated by the rising water 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). The higher water surface itself helps ameliorate this impact as the weight of the water against the bank adds support to the bank, but, as the cited literature suggests, may not be enough to maintain bank stability. Absent changes other than a permanent rise in WSE, however, the banks will eventually re-stabilize when an equilibrium condition is reached with the new impoundment level. The decline in erosion rates in the Bellows Falls and Vernon impoundments may indicate that equilibrium conditions are becoming reestablished after a period of instability initiated by the earlier raising of Vernon dam and Bellows Falls dam. The apparently increasing rate of erosion in the upper Wilder impoundment (Figure 5.3-1a) is more likely related to upstream inflows than Wilder project operations. The upper Wilder impoundment is affected much more by inflows that likely have a greater impact on erosion rates in the upper Wilder impoundment than do Wilder operations at the dam. In fact, Wilder operations currently serve to reduce some of those effects when inflows exceed its station capacity by storing some of the incoming flows.

6.3 Historic Trends in Project Operations

WSE fluctuations associated with the hydro project study area can be categorized as: 1) normal operation of the station generation and impoundment storage under non-spill conditions; 2) operation of the station, spillway and impoundment storage and 3) non-project related influences such as inflows from upstream and tributary sources. An analysis of historic project operation, reflecting both 1) and 2) above was performed using historic impoundment WSE data collected and recorded at the dam. A 20-year history of daily WSE readings (midnight, end-of day) spanning years 1975 through 1995 was available in digital format (original data was recorded on daily log sheets) for examination. Digital records were not available until sometime in 2001 for the projects and therefore, for comparison purposes, similar midnight WSE readings were examined for 2002 through 2016 at each project. There were noticeable differences between earlier years of operations and present-day operations, where generally the overall impoundment fluctuation range decreased and variation within the range itself decreased. Figures 6.3-1 to 6.3-3 reflect these distinct shifts using WSE exceedances over three, 10-year periods. Figure 6.3-4 also shows multiple annual exceedance curves for individual years at Vernon dam.

As Figure 6.3-1 for Wilder shows, there is a distinct shift in the fluctuation range of the impoundment from a wider range in the earlier years of the current license to a narrower range associated with the past 10 years. There are specific reasons for why this has happened. The introduction of minimum flows at the upstream Fifteen Mile Falls Project in April 2002, where there were none prior, provided an increased and constant inflow into the Wilder project that exceeded the minimum flow at Wilder dam. The most obvious benefit in terms of WSE and impoundment storage operation would be over low energy demand, two or three-day weekends when prior to the upstream minimum flows, generation might have largely been curtailed at the upstream plants, resulting in use of Wilder impoundment storage to provide the Wilder minimum flow. Another major factor was automation of the remaining staffed Connecticut River plants: Comerford (Moore-McIndoes), Wilder, Bellows Falls and Vernon) and consolidation of controls for all of the plants into a single control center and SCADA system to operate them. Historically, plants were operated in coordination but in four separate operating rooms using four different sets of operators and operating tools. Automation and control consolidation brought a much better coordinated and optimized system for dispatching and managing the plants but water utilization as well. The projects consistently responded to daily peaks in demand for energy and price signals throughout this entire period and that was not factor in this observed trend. Also consistent throughout the history of project operation was the “river profile” operation associated with responding to higher than station capacity inflows. Water availability through winter snowpack, spring runoff and precipitation into the drainage area probably did contribute to minor differences year to year but by using the 10-year periods for analysis, these differences would be absorbed and accounted for.

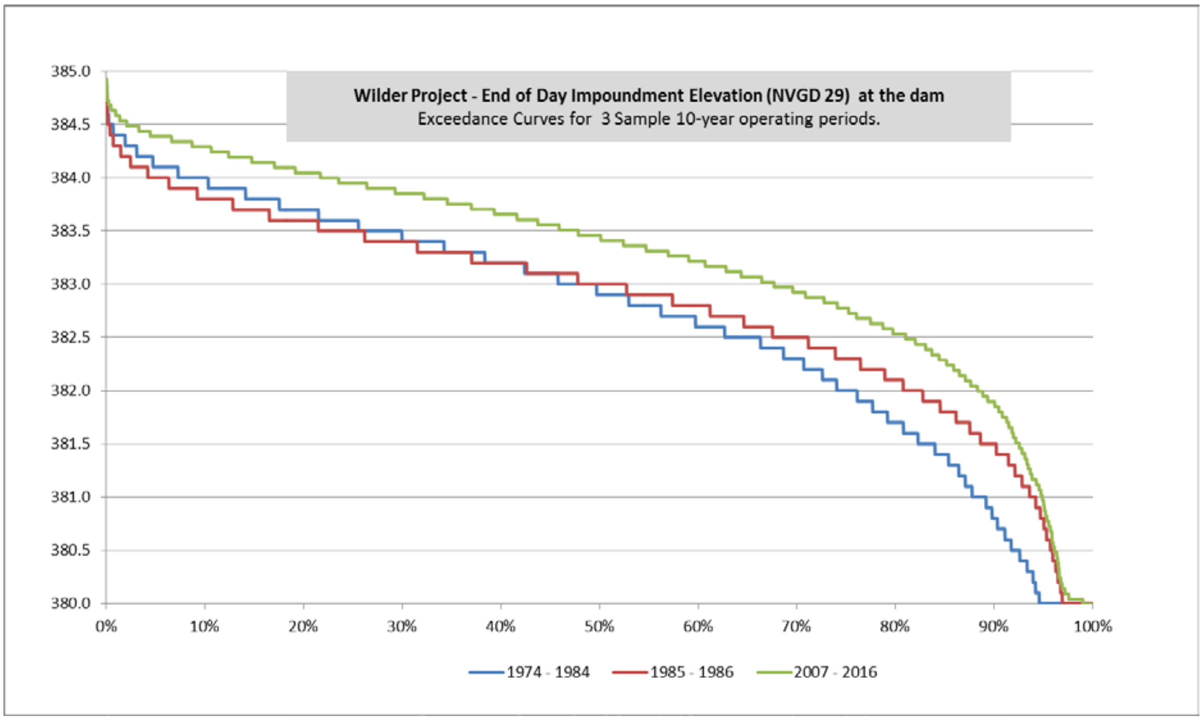


Figure 6.3-1. Comparison of Wilder dam WSE over the current license term.

Figure 6.3-2 for Bellows Falls shows a slightly different but similarly trend toward narrowing of the normal impoundment operating or daily WSE fluctuation range. The most recent 10-year curve is notably a flatter than prior years. This is likely to be a result of mainly the automation and consolidated, improved coordinated hydro system that largely completed for the Connecticut River hydro projects in 1998.

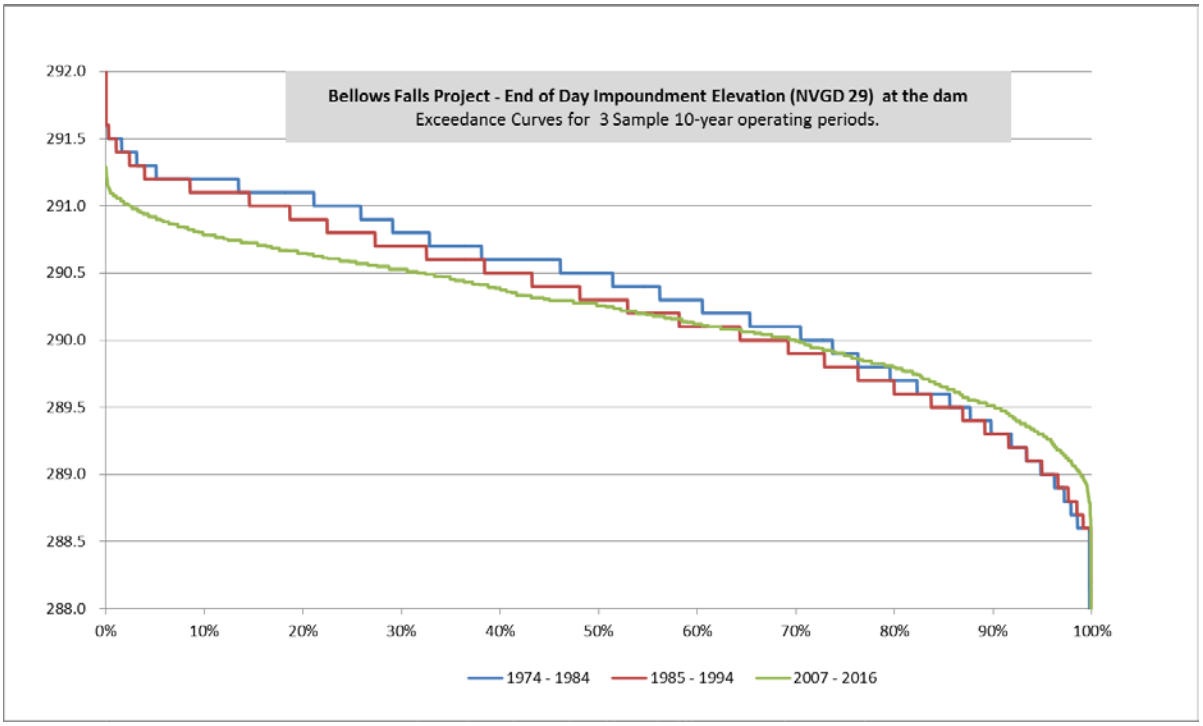


Figure 6.3-2. Comparison of Bellows Falls dam WSE over the current license term.

Figures 6.3-3 and 6.3-4 for Vernon show the most significant change in project operations over the course of the current license. Station generation dispatch, similar to Wilder and Bellows Falls, remained the same – responding to energy demand and price signals and values, during periods covering both pre-deregulation and post-deregulation of the wholesale generation market. In addition, the re-powering of Vernon by replacing Units 5-8 with more efficient turbine-generator units with slightly higher discharge capacity also does not appear to be a significant factor in the observed changes in impoundment operation and WSE fluctuation range. The major reasons for the shift over the term of the present license were the significant civil changes to the dam's spillway crest control that were completed sometime in 1986 and the automation and consolidated central control center completed in 1998. Prior to completing the crest control project, the Vernon spillway was largely an ogee dam crest with eight feet of pin-type flashboards across the entire length of the spillway. Water elevations had to rise to a significant height above the board to cause them to fail as low as the crest (Elevation 212 ft m.s.l. NGVD29) and then the WSE of the impoundment would have to drop to control elevation based on board failure to rebuild the boards and restore the impoundment level. The crest control improvements at Vernon brought significant tainter gate capacity, hydraulic and stanchion flashboards and eliminated the re-occurring pin-flashboard failure operation. High flows can be passed through the project while managing WSE by this much improved tainter gate crest control. As mentioned above, significant improvement in water management and coordination between Vernon and upstream projects brought about by station automation and consolidation of operating staff and controls into a single control center accounted for a significant reduction in the normal impoundment operating or daily WSE fluctuation range.

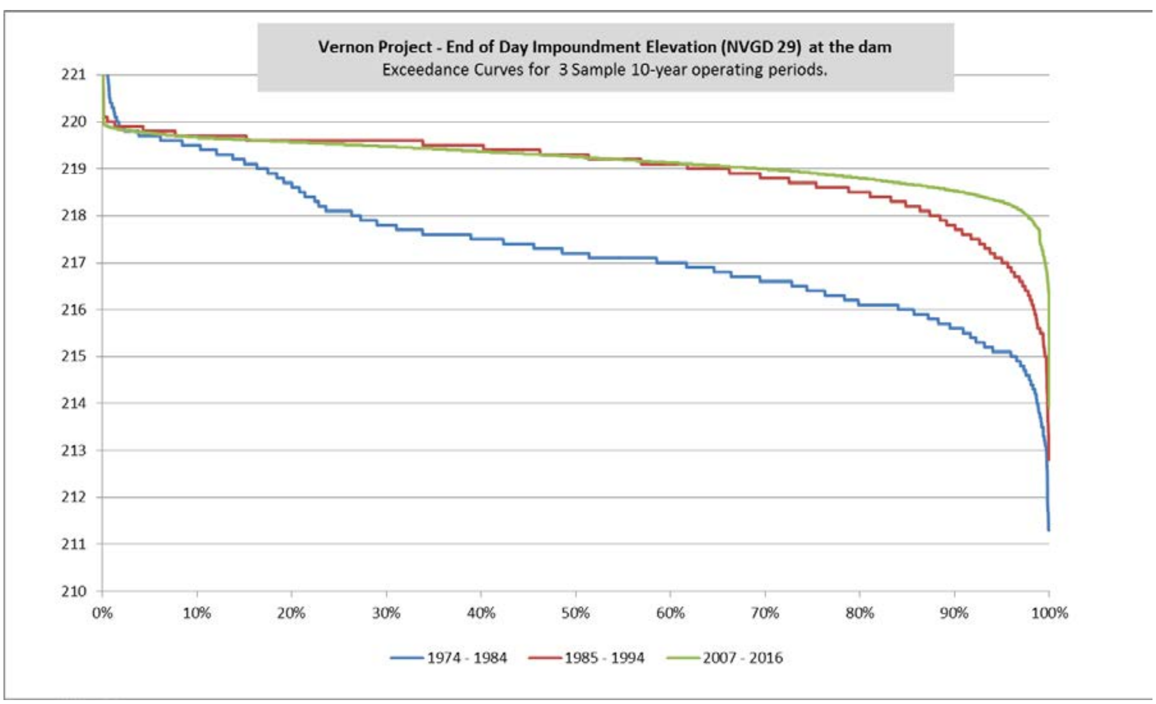


Figure 6.3-3. Comparison of Vernon dam WSE over the current license term.

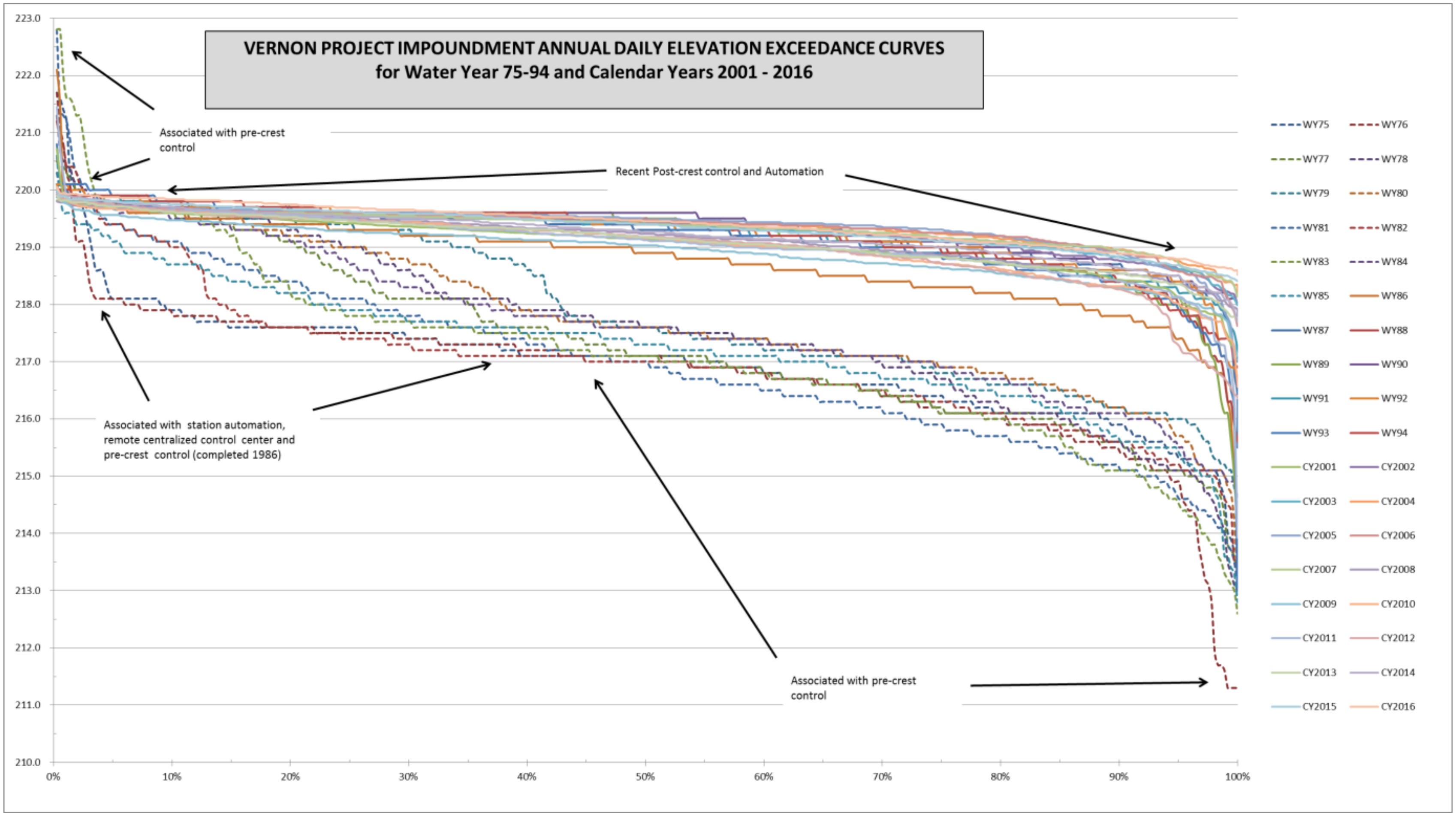


Figure 6.3-4. Vernon dam daily elevation exceedance curves over the current license term.

6.4 Notching and Erosion

WSEs related to normal project operations under no-spill conditions are consistent with notching and overhangs observed at the bases of 8 of the 21 monitored banks at some point during the two-year monitoring period (Appendix A). The 8 sites showing notching at the base of the bank are: 02-W03 (Bellavance site), 02-W07 (Tullando site), 02-W09 (Mudge site), 02-W10 (Vaughn site), 02-W12 (Pine Park site), 02-B03 (Jarvis site), 02-B09 (North Walpole site), and 02-BR01 (Walpole Beach site).

Erosion can result from seepage forces generated by WSE fluctuations (Budhu and Gobin, 1995) with overhangs developing when seepage is focused along a single layer (Fox and Wilson, 2010). However, the rate of seepage, and the resulting rate of erosion (Fox et al., 2007), depends on the hydraulic gradient between the groundwater levels in the bank and the WSE of the river. With median project operations WSE fluctuations of less than 2.0 ft for more than 75% of the entire study area's length (and over 80% in the three impoundments) (Table 5.6.5-1), the hydraulic gradients between the groundwater levels in the bank and the river WSE are likely small and, therefore, would not result in strong seepage forces. Direct measurements of seepage forces emanating from the banks was beyond the scope of the study, but the magnitude of the seepage force is directly related to the hydraulic gradient between the groundwater level in the bank and the adjacent river level (Midgley et al., 2013; Fox et al., 2010), so lower seepage forces would be associated with smaller WSE fluctuations. In addition, project-related WSE fluctuations are of short duration, so the distance that water seeps into the bank is much less than for high flow conditions that generally persist for a longer duration than project-related fluctuations. While even small WSE fluctuations could still contribute to bank instability, the texture and stratigraphy of bank sediments are also important controls on the hydraulic gradient and associated seepage forces (Fox et al., 2010) such that the stability of two adjacent banks with slight differences in bank composition could be very different despite experiencing identical WSE fluctuations, thereby complicating efforts in discerning whether bank instability is the result of project-induced WSE fluctuations.

Normal project operational WSE fluctuations do not appear to exert a strong control on the distribution of erosion as greater levels of bank instability do not occur where the magnitudes of WSE fluctuation are the greatest (Figure 5.6.5-4) and the resulting seepage forces would be highest. In fact, the percentage of unstable banks largely holds steady at around 40% regardless of the riverine or impoundment section under consideration (except for the short Vernon riverine section) (Figure 5.6.4-2). Additionally, significant changes in the rate (Figure 5.3-1) and levels of erosion (Appendix D) have occurred through time despite little change in Wilder, Bellows Falls, and Vernon project operations over the same time period.

Notching and overhangs can also develop due to natural groundwater seepage, river flow (Green et al., 1999), and wave action (Gatto and Doe, 1987). While seepage forces generated by normal project operations may be insufficient to generate erosion, the WSE under no-spill conditions is relatively constant such that wave action would regularly occur along the same portion of the bank and the notching observed may be more the result of wave action than WSE fluctuations. Wind generated waves are probably of limited importance in the study area given the limited fetch along the narrow water course, but boat waves could cause bank instability. Boat and wind waves have been considered an important cause of erosion in the study area (Simons et al., 1979) and other localities (Gatto, 1982; Lawson, 1985; Porter, 1993). 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 overhangs that initiate the cycle of erosion. Boat waves have the potential to exert a greater erosive force directly on the banks compared to WSE fluctuations.

In the absence of strong river currents, WSE fluctuations and waves would tend to move sediment transverse to the bank out towards the center of the waterbody, developing a low gradient beach face. Eventually, the beach may become wide and high enough for WSE fluctuations and wave run-up to be completely confined to the beach face with erosive forces no longer acting on the base of the bank (Lawson, 1985). At this stage, material eroded from the upper bank can no longer be carried away from the base of the bank by seepage forces and wave action such that the entire bank begins to stabilize through a process described by Brunsden and Kesel (1973). Where such fluctuations are contained on the beach (at 9 of the 21 sites, Appendix A) erosion is unlikely to be due to normal project-related WSE fluctuations. If boat waves and WSE fluctuations were the only erosive forces acting in the study area, erosion would continue for only a certain length of time following a significant change in impoundment level or project operations before the banks, protected by the growing beach faces, would stabilize.

6.5 Effects of Erosion on Other Resources

One of the Study 3 objectives was to identify the potential effects of bank erosion on other resources (e.g., riparian areas and shoreline wetlands, rare plant and animal populations, water quality, and aquatic life, and terrestrial wildlife habitat). For purposes of the following discussions, “stable” banks include those mapped in Study 3 as stable, armored, or healed erosion; and “unstable” banks include those mapped as eroding, vegetating eroding, or failing armor.

As discussed throughout this study report, erosion within the study area is a cyclical process that can include up to four of the erosion types described by Lawson (1985): falls, topples, slides, and sediment flows, although generally only one or two were present at any one location. The results of the erosion monitoring and visual observations of bank conditions throughout the study area clearly reflect a “cycle of erosion” that is comprised of a sequence of events occurring through time at a single point. Potential impacts to other resources therefore can be affected by one of these events in isolation or as a result of the erosion cycle over time. As stated previously, the impact of normal operations associated with the three projects, be it the normal fluctuation of impoundment levels or discharge levels often dwarfed by episodic high flows, is minimally associated with any of the sequential events and the erosion cycle itself. Flow velocities and shear stresses during normal project operations have been shown to be inadequate, within the impoundment sections and at nearly all locations within the riverine sections, to mobilize sediment accumulating at the base of the banks and are by themselves unable to sustain the cycle of erosion.

A quantitative analysis of the effects of shoreline erosion on each resource is beyond the scope of this study. However, a detailed qualitative discussion of the potential effects of ongoing erosion within the project areas on riparian areas and shoreline wetlands, rare plant and animal populations, water quality, aquatic habitat, and terrestrial habitat is provided below.

6.5.1 Cultural and Historic Resources

Cultural and historic resources were investigated as part of Study 33. Phase IA archaeological reconnaissance surveys (Hubbard et al., 2013a; 2013b) were conducted within the Area of Potential Effect (APE) of the Wilder and Bellows Falls projects in 2011 and evidence of erosion was notably associated with the recent extreme high water from Tropical Storm Irene. Sites within the APE of the Vernon project, originally surveyed under Phase 1A in 2008 were revisited in 2014 (Cherau and O'Donnchadha, 2008; Cherau and Duffin, 2014). The Phase IA surveys consisted of archival research and field investigations designed to collect information about and inventory previously recorded archaeological sites within the Project fee-owned lands and identify additional areas of archaeological sensitivity where previously documented, but unrecorded sites are likely to exist. On the Vermont side of the Connecticut River, archaeological consultants identified 34 archaeologically sensitive areas (18 in the Wilder Project, 10 in the Bellows Falls Project, and 6 in the Vernon Project), on the New Hampshire side, 33 archaeologically sensitive areas were identified (17 in the Wilder Project, 11 in the Bellows Falls Project, and 5 in the Vernon Project).

Phase IB surveys (Elquist and Cherau, 2015; Elquist and Cherau, 2016a) were conducted to locate and identify any potentially significant archaeological sites in areas of erosion within the Projects' Area of Potential Effect (APE), defined to include all land within the FERC project boundaries owned in fee simple by TransCanada and 10 meters (33 feet) of land inland from the top of the bank in areas along the Connecticut River and affected portions of tributaries where TransCanada holds flowage rights. Phase IB surveys were conducted for all erosion areas on TransCanada fee-owned lands and on private property parcels where landowner access permissions were granted. Test pits were dug at 33 of 67 locations deemed by the consultant as experiencing erosion. TransCanada was unable to obtain landowner permission to access the remaining 34 sites and the presence of significant resources cannot be determined. Seven tested sites were recommended for more in-depth Phase 2 archaeological evaluations (Elquist and Cherau, 2016b; 2016c) to determine eligibility for listing in the National Register of Historic Places. These investigations were conducted in 2016, including at one site in the Wilder project and at six sites in the Vernon project; no sites in the Bellows Falls project were identified as potentially significant.

Six of the seven Phase 2 sites (18 percent of all tested sites) were recommended for listing in the National Register and periodic monitoring, and to the extent necessary, management measures to protect them will be identified and implemented. The specific steps recommended to avoid, minimize, or mitigate any impacts will be forthcoming in the Project-specific Historic Properties Management Plans.

6.5.2 FERC Project Recreation Facilities

Study 30 – Recreation Facility Inventory and, Use and Needs Assessment (Louis Berger Group and Normandeau, 2016a) conducted onsite assessments and user surveys at 67 public access sites within the project area, including sites owned by TransCanada and other entities. The study did not identify erosion as one of the significant factors affecting recreation area quality or use. Seven sites were linked to either observed erosion in limited areas or user comments that mentioned erosion as a concern. TransCanada manages impacts from erosion, scour, and sedimentation at FERC Project recreation facilities through as-needed maintenance such as dredging of boat launches where sedimentation occurs and repair or re-construction of boat launches where the base of the boat ramps are impacted by high water velocity or ice scour removing the base at deeper portions of the ramp. The forthcoming Recreation Management Plan (to be filed with the license applications) will provide more details on maintenance or repair of recreation areas associated with erosion, scour, and sedimentation.

6.5.3 Riparian Resources

Excessive erosion in the riparian zone can result in the loss of riparian agricultural land; impede access to the river such as at recreational access points; expose previously buried archaeological or cultural/historic resources; and affect riparian vegetation and habitats for terrestrial species. The term “riparian habitat” refers to the vegetated zone connected to, or immediately adjacent to, the shoreline or bank of a river. The riparian zone can include floodplain, wetland (forested, scrub-shrub, or emergent), upland forest, or grassland. The riparian zone serves as the primary interface between riverine and upland habitats, influencing both the primary productivity and food resources within the river, and the vegetation, wildlife, and function of the terrestrial habitats. In areas of erosion, damage can be seen in the loss of established or mature trees from the riverbanks. Degradation can also result from invasive species colonization on newly exposed substrates.

Despite these adverse effects, erosion in riparian habitats can also be beneficial in sustaining natural riverine and riparian processes, and providing important ecosystem services (Piegay et al., 2005). In a study evaluating the impacts of bank stabilization efforts on riparian ecosystems (Florsheim et al., 2008), bank erosion was shown to be important for sediment transfer, river evolution, and ecosystem sustainability, as well as for overall riparian diversity since erosion supports riparian vegetation succession and maintains habitats in a more dynamic state which supports early successional aquatic and riparian species. That study demonstrated that bank stabilization efforts and bank infrastructure create static banks that limit riparian ecological function and reduce availability of habitat.

Wetlands

Wetlands were mapped as part of Study 27 (Normandeau, 2016a). Palustrine wetlands (wetlands dominated by trees, shrubs, or emergent herbaceous vegetation) along the mainstem banks that were mapped for erosion (referred to here as “shoreline wetlands”) were more likely to occur along stable banks than along unstable banks. This is particularly pronounced in impoundments where 88 percent of shoreline wetlands were identified along stable banks while 70 percent of identified shoreline wetlands were located along stable banks in the riverine sections (Table 6.4-1). The majority of shoreline wetlands were also located within impoundments (87 percent) rather than in the riverine sections.

Emergent herbaceous wetlands mapped for erosion were even more strongly associated with stable banks (98 percent, Table 6.4.3-1). Other wetland cover types were also more likely to be found along banks mapped as stable (84 percent of scrub-shrub wetlands, 72 percent of forested wetlands) than along unstable banks (Table 6.4.3-1). In many locations, shoreline wetlands spanned areas mapped as having both stable and unstable banks as well as different subcategories of each (Figure 6.4.3-2). Among wetlands found along unstable banks, 70 percent of those banks were mapped as vegetated-eroding (Figure 6.4.3-3), 27 percent were mapped as eroding, and 3 percent were mapped as failing armor.

Table 6.4.3-1. Shoreline frontage (ft) of wetland cover types relative to erosion in riverine and impoundment reaches.

Wetland Cover Type	Riverine Reaches (ft)			Impoundments (ft)		
	Unstable	Stable	Percent Stable (%)	Unstable	Stable	Percent Stable (%)
Emergent	197	479	71	1,440	81,071	98
Forested	1,537	2,661	63	14,490	43,495	75
Forested/ Emergent	0	0	n/a	340	0	0
Forested/ Scrub-shrub	0	0	n/a	2,416	2,162	47
Scrub-shrub	0	0	n/a	359	12,280	97
Scrub-shrub/ Emergent	0	997	100	343	1,639	83
Total	**1,733**	**4,136**	**70**	**19,387**	**140,647**	**88**

There are two potential mechanisms that could account for the apparent association of wetlands with stable banks: erosion may scour underlying substrate from wetlands, which can dislodge existing wetland vegetation or prevent it from establishing; or wetlands may help to stabilize the bank by retaining sediment in their root systems and dampening energy from river currents. The first mechanism appears evident in that emergent herbaceous wetlands are more closely associated with stable sites, as herbaceous vegetation generally has a shallower root structure than woody vegetation, and is more vulnerable to scouring during erosion events.

However, the latter mechanism is also a likely factor in the overall association of wetlands with stable banks in both impoundments and riverine reaches. It should be noted that wetlands located at backwaters associated with tributary mouths can be subject to episodic deposition from the tributary itself (e.g., Figure 6.4-3) that main channel flows can affect and appear as mainstem erosion, but is in fact a channel constriction response due to high mainstem flows.

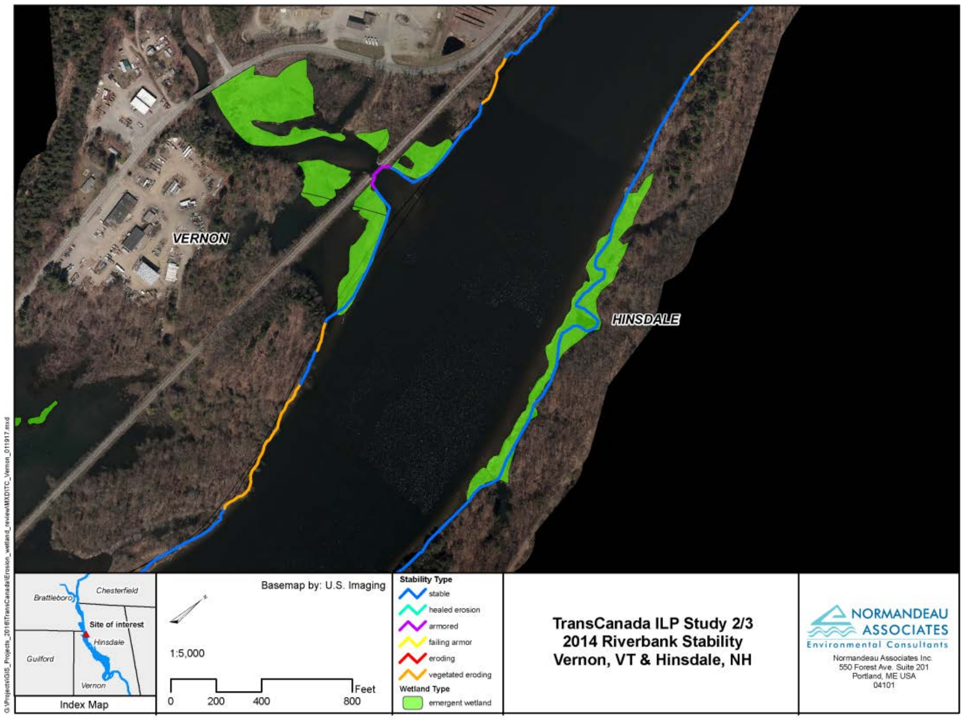


Figure 6.4.3-1. Example of emergent wetland associated with stable bank (Hinsdale NH side).

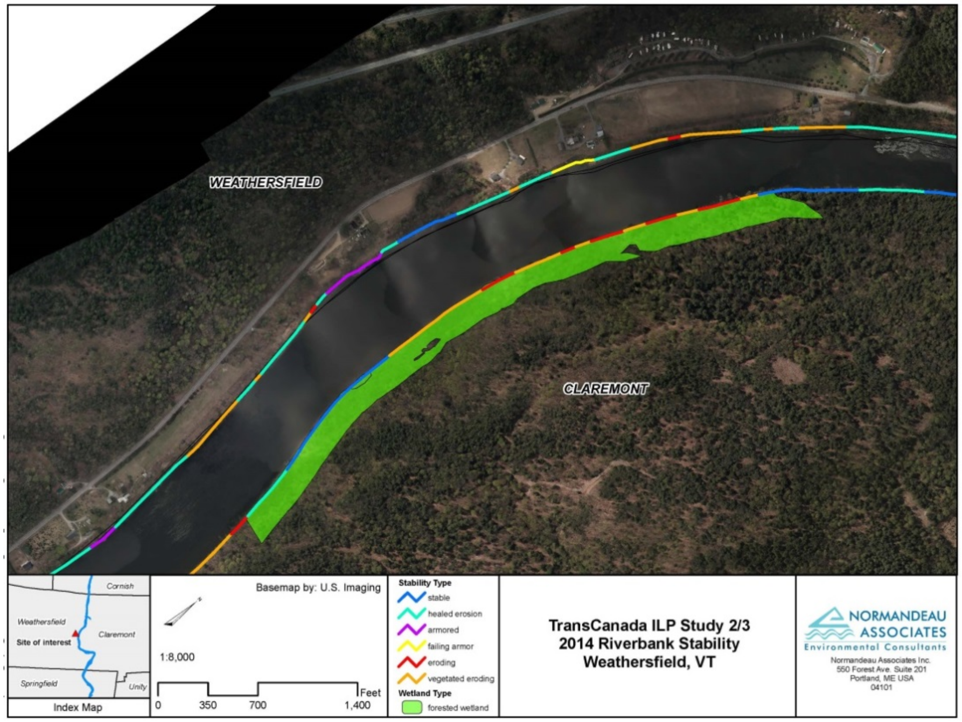


Figure 6.4.3-2. Example of forested wetland associated with both stable and unstable bank.

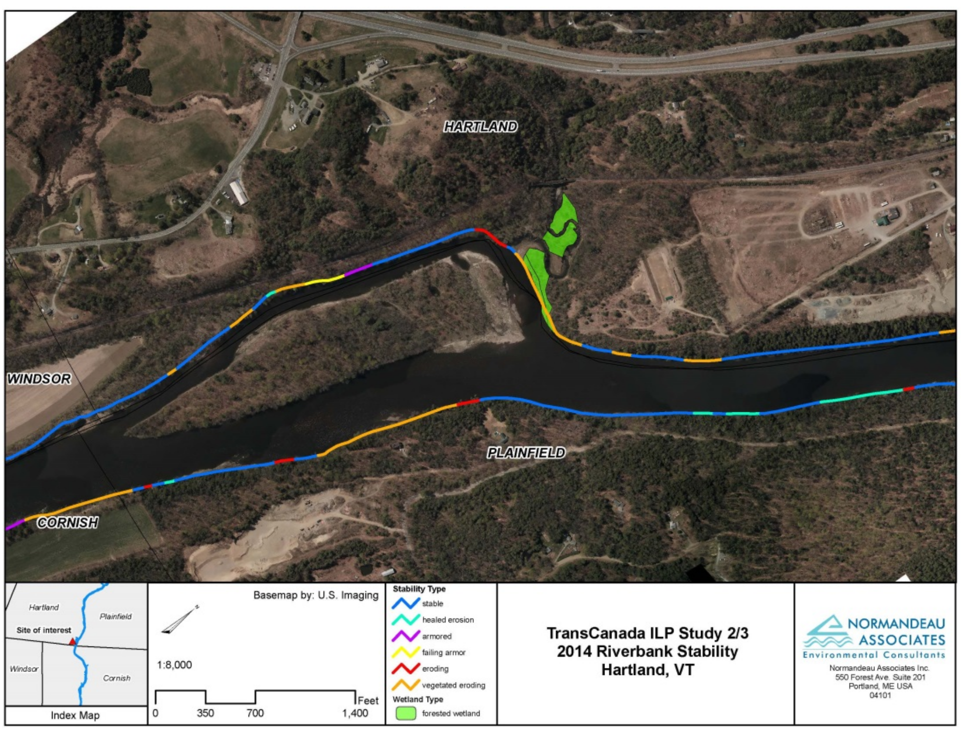


Figure 6.4.3-3. Example of forested wetland associated with unstable bank.

Rare Plant Populations

Jesup's Milk Vetch

Jesup's milk vetch (*Astragalus robbinsii var. jesupii*) is a federally endangered plant that occurs naturally at only three known sites in the world (and at one transplant site) which are located along the Connecticut River downstream of Wilder dam. It inhabits dam rock crevices within calcareous ledge along the upper reaches of the scour zone of the river. It is flood-tolerant, which allows it to out-compete many other species (FWS, 2010).

Three of the four Connecticut River sites with Jesup's milk vetch occurrences were identified in the erosion mapping as having stable riverbanks, mostly due to the presence of exposed ledge. The fourth site was mapped as vegetated eroding. All plants identified during the 2012 field study (Normandeau, 2013a) occurred above the observed high water mark vegetated line and were well above the elevation of normal project operations. The lowest elevations at which Jesup's milk vetch plants grew at any of the four sites were equated to discharges of 29,000 cfs or more, much higher than the maximum operational flow (approximately 11,700 cfs) from the Wilder Project. In addition, given this species preference for ledge areas, it is unlikely that erosion would have negative impacts. It is more likely that scour from high flows has a positive effect in the establishment or maintenance of Jesup's milk vetch plants by reducing competing species.

Northeastern Bulrush

Northeastern bulrush (*Scirpus ancistrochaetus*) is a federally listed endangered perennial species in the sedge family. Habitat requirements can range from inundated pond margins to emergent wetlands with a subsurface water table. The common characteristics of northeastern bulrush habitat in the northern part of its range are an open canopy and an intermittently variable water table. It is hypothesized that receding water caused by seasonal variation or the removal of an impoundment (beaver dam or structure) exposes bare substrate that the northeastern bulrush requires for flowering and germination. Without intermittently exposed substrate, the bulrush appears to be outcompeted by other species adapted to more consistent water levels. Long-term changes in hydrology, such as prolonged inundation or drought, have also been shown to adversely affect the species (FWS, 2008, 1993; Royte and Lortie, 2000).

Field surveys conducted in 2014 in Study 29 (Normandeau, 2016b) did not find the species and the four study sites identified in the field as having potentially suitable habitat were all located behind beaver dams at elevations higher than normal project operations would inundate. Therefore, erosion along the mainstem of the Connecticut River would not impact these habitats or the species.

Other Rare Plant Species

Other rare plant populations were found within the project area during a comprehensive 2012 survey of state-listed rare, threatened, and endangered (RTE) plant species (Normandeau, 2013b) at approximately twice the frequency at stable bank sites compared with observations at unstable bank sites. Of the 96 rare plant populations (Element Occurrences, or EOs) occurring along the mapped banks of the Connecticut River, 65 populations (57 percent) were found entirely in areas in which banks were mapped as stable; 23 populations (24 percent) were found entirely in areas in which banks were mapped as unstable; and 17 (18 percent) were found in areas in which banks were mapped as both stable and unstable.

Thirty-two state or federally listed species and natural communities were identified within the terrestrial study area during the 2012 survey and of those, 14 species (44 percent) were found in shoreline areas. Of these, only one species was found exclusively at unstable sites; five others were found at both locations mapped as stable and locations mapped as unstable; and four species were found only at locations mapped as stable. An additional four species were found only in areas away from mapped riverbanks, either adjacent to backwaters (1 species) or on islands (3 species) in the middle of the river. These areas were not mapped for erosion so direct comparison of population locations to bank stability cannot be made; however, most backwaters in the study area appear to be located in generally stable locations while sections of many islands appear to be potentially prone to erosion and deposition.

The four species found only where banks were mapped as stable were northern arrowhead (*Sagittaria cuneata*), Canada shore quillwort (*Isoetes riparia*), wild chives (*Allium schoenoprasum*), and tradescant aster (*Symphyotrichum tradescantii*). Populations of these species are unlikely to be adversely affected by eroding banks, as there is no overlap between unstable banks and their known populations. Only one species, black-seeded clearweed (*Pilea fontana*), was found to occur exclusively in unstable areas. This species is an annual often associated with disturbance conditions, and likely is capable of rapidly recolonizing suitable habitat after an erosive event. It may specialize in taking advantage of the early successional conditions present at eroded sites.

Five species were found both in areas of stable and unstable substrates and as a result they are unlikely to be erosion specialist species (which would be preferentially found at unstable sites), and may be vulnerable to negative effects as a result of erosion. Two of these species, obedient plant (*Physostegia virginiana*) and balsam groundsel (*Packera paupercula*), were widespread at stable sites, with eight and six populations, respectively, found at stable sites. Long-leaved pondweed (*Potamogeton nodosus*) is primarily aquatic and was also found frequently at stable sites. Even if populations of these species along eroding banks are ephemeral, the species' overall populations within the study area would likely not be significantly threatened by erosion as there are source populations within the study area that could allow for recolonization. The remaining two species found along both stable and unstable banks, common silverweed (*Argentina anserina*) and incurved umbrella sedge (*Cyperus squarrosus*), were only found at one stable site each compared to two and one unstable sites, respectively. These low numbers of populations make it difficult to draw conclusions about the relationship between species' occurrence and riverbank stability, and therefore the effect of erosion on the population.

Rare Animal Populations

Cobblestone Tiger Beetle

The cobblestone tiger beetle (*Cicindela marginipennis*) is listed as threatened in both New Hampshire and Vermont. It has an extremely restricted habitat and is found on cobble and gravel beaches with sparse vegetation on medium and large rivers (Leonard and Bell, 1998). This habitat is often found on river edges and the upstream side of riverine islands where the river deposits small to medium-sized cobble in times of high flow and ice scouring removes encroaching vegetation from the cobbled shore (NHFGD, 2015).

In Study 26 (Normandeau, 2016c) beetle larval habitat was hypothesized to occur primarily within the highest 25 percent elevation of the habitat range based on observations of burrows fitting the description of the common shore tiger beetle at three study sites. Anecdotally, those burrows occurred at the transition between the lower cobble bed and the sandy substrate found above the observed, estimated high water mark where the ratio of interstitial sand to cobble generally increases with elevation.

In the 2014 field surveys conducted for Study 26, cobblestone tiger beetles were observed within the identified study transects at seven of the 14 study sites. Individuals were also incidentally observed outside of the study transects at one additional site. Of the 14 study sites, only five were mapped for erosion (two sites were outside of project influence in tributaries and seven were on unmapped islands). All five riverbank study sites mapped for erosion were categorized as stable banks and contained exposed beaches below the riverbank elevation that was mapped. Of those riverbank sites, two had cobblestone tiger beetle observations (one with prior record of occurrence and one being a new record), two sites did not have observations, and one site had a possible occurrence but with low certainty. Of the seven island study sites that were not mapped for erosion, five had cobblestone tiger beetle observations (all with prior records), one site did not, and one site had a possible occurrence with low certainty. Figure 6.4.3-4 illustrates island habitat where the species was observed.

While erosion (and related scour) is clearly a vital process in maintaining the open, coarse substrates required by cobblestone tiger beetle, the results of erosion mapping do not indicate a strong relationship between bank erosion and cobblestone tiger beetle habitat. This is partially a result of the low association between bank erosion and in-river gravel bars. However, most of the cobblestone tiger beetle habitat occurs on islands which were not mapped for erosion.

Figure 6.4.3-4. Example of island habitat with cobblestone tiger beetle observations.

Fowler's Toad

Fowler's toad (*Anaxyrus fowleri*) is listed in Vermont as endangered, and is considered a Species of Greatest Conservation Need (SGCN) in New Hampshire. It requires early successional habitats that provide suitable breeding, estivation, and hibernation habitat. For breeding, pools with sparse to no vegetation and relatively stable hydrology during the breeding season are required. For estivation and hibernation sandy or gravelly bare or sparsely vegetated soils which toads can burrow into are required. Early successional habitats along riverbanks, shorelines, and floodplains that are maintained by hydraulic regimes, (e.g., flooding, scour and/or wave action) that deposit sand and gravel, clean away vegetation, and create and support backwater pools potentially provide suitable habitat for this species (VT WAP Team, Normandeau, 2016d).

Study 28 (Normandeau, 2016d) found that this combination of conditions in close proximity to each other appears to be inherently rare on the Connecticut River. In general, persistent, shallow pools tend to be concentrated in and around large wetland features associated with bays and old oxbows (e.g., Herricks Cove). However, the most extensive areas of bare, sandy soils in the project area are associated directly with the banks of the river, and some of the islands. Locations with both potential breeding pools and bare soils appear to be most abundant in the Wilder riverine section and the Bellows Falls impoundment where potential breeding pools form on sand bars and behind scour deposits along the river's edge or on islands, as well as at some riverbank-associated wetlands, while islands, sandbars, and some other riverbank features provide some areas of bare soils.

The species was documented at only one of 10 study sites identified in the field as having suitable habitat in the 2014 surveys conducted for Study 28. That site is on an island that was not included in erosion mapping. Other potential breeding habitat for this species seems to be concentrated on islands and along the shorelines of the river. According to VANR, regular removal of vegetation, new deposits of sand and gravel, and creation of small pools may be necessary to maintain breeding habitat (VT WAP Team, 2015). Periodic scouring and erosion during high flow events would contribute to creating and maintaining that habitat and potentially supporting the species.

Dragonflies and Damselflies

Dragonflies and damselflies (odonates) are most frequently observed as adults but they spend most of their life cycle as aquatic larvae. The larval stage can last for a year or more, after which time larvae crawl from the water and metamorphose to adults. Appropriate habitat for the eight odonate species considered SGCN in Vermont and/or New Hampshire that occur within the project area typically consists of fine aquatic substrates for larvae (mud, sand, or silt) with nearby steep, sparsely vegetated banks for eclosion (the process of leaving the larval exoskeleton to assume the adult flying form), along with adjacent riparian vegetation and forested habitats for resting and forage during the adult stage (NHFGD, 2015; VT WAP Team, 2015).

In the 2015 odonate surveys conducted for Study 25 (Normandeau, 2016e) 28 species of odonates were found on transect surveys at all 11 study sites including six SGCN species observed at 10 of the 11 study sites. One site was located on an island not mapped for erosion. Another three sites were located in riverine reaches with two (67 percent) being classified as unstable banks. Of the seven impoundment sites, two (29 percent) were mapped as stable banks, three (43 percent) were mapped as mostly stable but each contained a small area of unstable bank at the upstream or downstream end of the site, and two sites (29 percent) were mapped as unstable banks.

Collectively the four sites with unstable banks (two in impoundments and two in riverine sections) had the majority (73 percent) of SGCN species and a slight majority (50.5 percent) of all species observations. A further comparison of bank stability was made between two impoundment sites with similar numbers of all species, all individuals, SGCN species, and SGCN individuals. The two sites were different with one, Site 25-07 (Figure 6.4.3-5), located at a mostly stable bank and another, Site 25-09 (Figure 6.4.3-6), located at an unstable (sub category "eroding") site.

Given the above results, it is unlikely that erosion has adverse effects on odonates and may provide positive benefits by periodically creating or maintaining desirable habitat conditions. Eroded banks may also provide odonates with additional cover during eclosure, in the form of exposed roots and coarse woody debris along the bank.

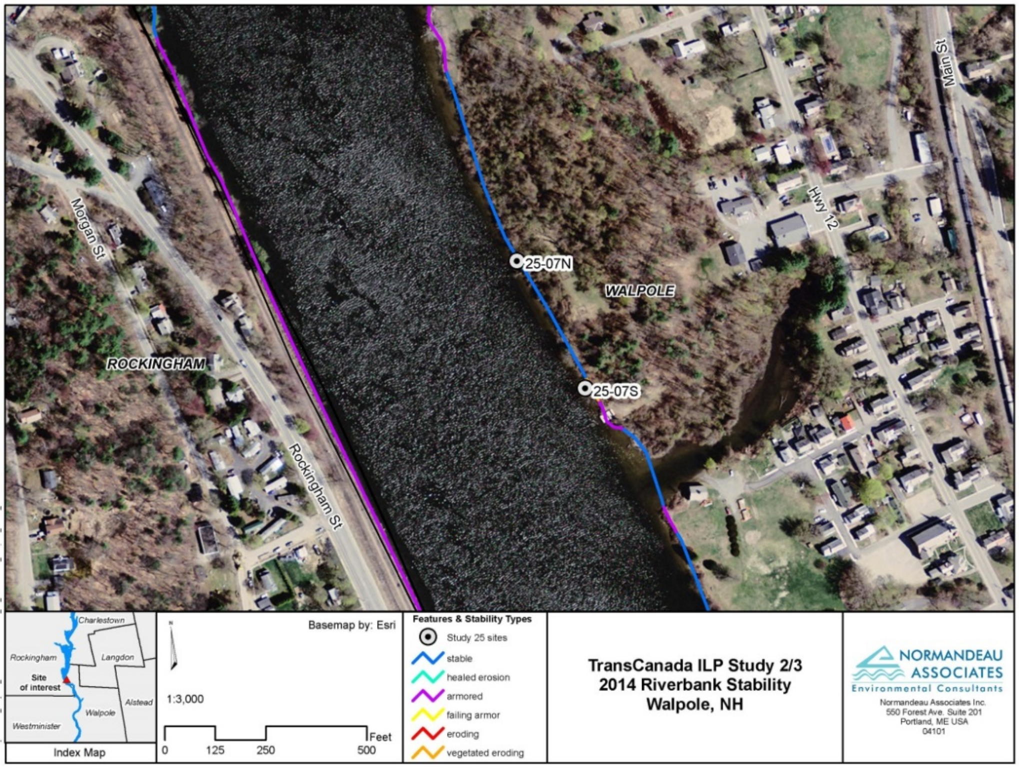


Figure 6.4.3-5. Example of Odonate site mapped with stable banks.

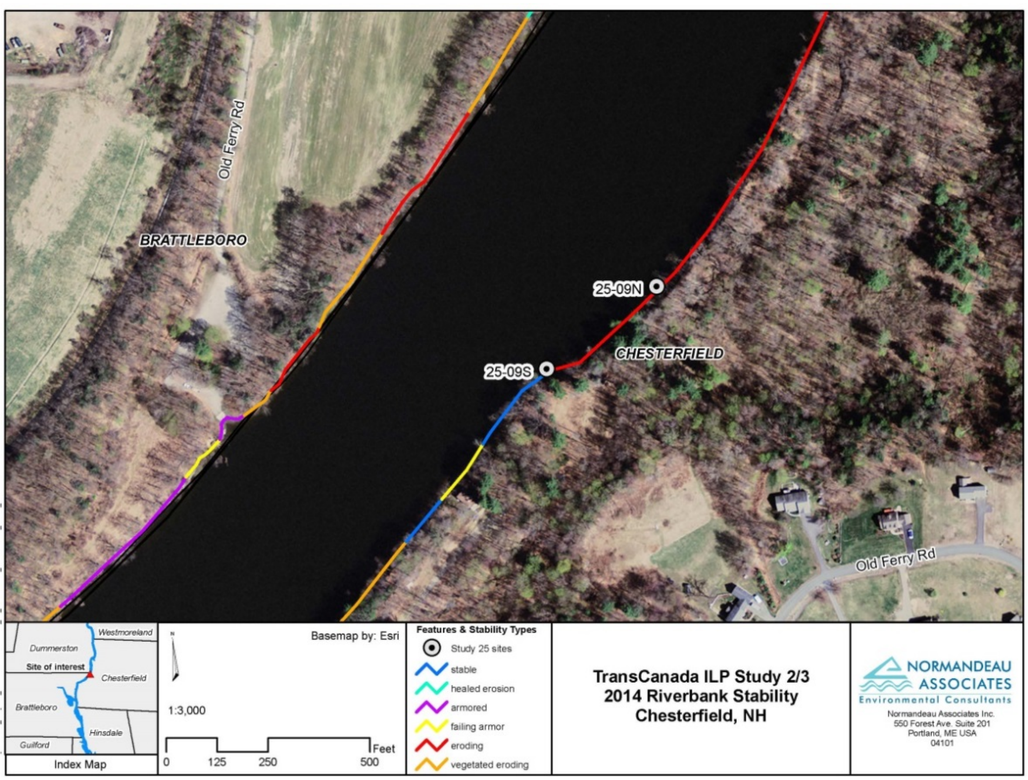


Figure 6.4.3-6. Example of Odonate site mapped with unstable banks.

Terrestrial Wildlife Habitat

Study 27 (Normandeau, 2016a) incidentally observed 87 wildlife species or their signs, including numerous species of birds, small mammals (beaver, mink, muskrat, opossum), large mammals (white-tailed deer), as well as frogs, toads, and turtles. Primary wildlife resources associated with riparian habitats include early spring plant growth in lowland riparian habitats which provide food sources for migrating birds, black bear, white-tailed deer, and otter, among other species. In addition, bank swallows and belted kingfishers dig nesting sites in sandy riparian areas adjacent to rivers (Sperduto and Kimball, 2011).

Although bank erosion has generally been treated as a negative process in river systems, it is an ecologically important natural process (Florsheim et al., 2008) creating and maintaining bank habitat. Eroded banks provide habitat for nesting birds, and undercut banks are an important habitat component for a wide variety of wildlife. During field studies, ducks such as common mergansers were observed using undercut banks as cover for adults and dependent young. Wood turtles use undercut banks for hibernation (NHFGD, 2015) and are considered SGCN in both New Hampshire (NHFGD, 2015) and Vermont (VT WAP Team, 2015). River otter habitat use is strongly tied to available cover along riverbanks, and undercut banks have been identified as one such source of cover by several studies (Gallant et al., 2009; Waller, 1992).

Bank Swallows and Belted Kingfishers

Bank swallows (*Riparia riparia*) require banks with large expanses of exposed substrate for nesting (Figure 6.4.3-7). These expanses are created by eroding banks, and attempts to stabilize banks have eradicated bank swallow colonies along the Connecticut River (Silver and Griffin, 2009). Incidental observations of five bank swallow colonies within the study area during 2014 terrestrial habitat mapping were located exclusively along banks that were mapped as unstable. Bank swallow is listed as a SGCN in New Hampshire and modifications to banks for erosion control is identified as a high priority threat (NHFGD, 2015). Erosion within the study area may be having a positive effect on bank swallow colonies by creating and maintaining suitable habitat, similar to that observed by Silver and Griffin (2009). Belted Kingfishers (*Megaceryle alcyon*) also rely on eroded banks for nesting; however, their solitary nesting behavior and low density distribution appear to make them less sensitive to loss of individual nest sites (Silver and Griffin, 2009).

Figure 6.4.3-7. Bank swallow holes established in an eroded riverbank at the Lipfert Site (02-B01, see Appendix A).

Bald Eagles

The bald eagle is listed as endangered in Vermont and threatened in New Hampshire, and is a federally protected species. Bald eagles breed and overwinter in the vicinity of the Connecticut River in the terrestrial study area. Eagles generally nest in mature softwoods with easy access to fishing and limited disturbance. For nesting and roosting, bald eagles require mature softwood stands with easy access to riverine food resources. Availability of food resources during winter is also a critical component of roosting habitat, and open, unfrozen water provides eagles with the ability to fish and hunt waterfowl.

As part of Study 27 (Normandeau, 2016a), aerial photo interpretation followed by field verification identified 14 softwood stands that appear to offer suitable winter roosting conditions including two stands previously identified. Ten of these identified habitats were located along the mainstem riverbank and were mapped for erosion. Three were located along stable banks, five were located along mostly stable banks with small areas of instability, and two were located along banks that were mapped as mostly unstable. Floodplain forests and terrestrial forests within the project area are generally higher in elevation than the zone of normal project operations and, therefore, above the influence of normal project-related water level fluctuations and potential project-related erosion, but could be impacted by high flow events that scour and undercut banks. Singular roost trees located immediately adjacent to the river could be susceptible to downing as a result of bank slumps or topples. However, winter roosting habitat is plentiful and therefore is unlikely to be significantly affected by potential erosion. Bald eagles are highly mobile using multiple roosts in the course of a winter (Beuhler, 2000), and the use of a particular stand is likely, in part, a function of the amount and location of winter open water on the river.

6.5.4 Aquatic Resources

In the river itself, erosion is a source of fine-grained material (sand, silt) in the water column that has the potential to reduce water clarity and contribute sediment that increases embeddedness of more coarse-grained substrates, which upon deposition, can reduce dissolved oxygen or physically smother certain aquatic species or lifestages and reduce habitat availability for aquatic species that require coarser-grained substrates. Fine-grained material in the river also comes from sources other than local mainstem riverbank erosion including: direct runoff from surrounding land, discharges from stormwater conveyance systems, bedload, and suspended materials in mainstem and tributary inflows entering the project area. Both fine- and coarse-grained materials are also introduced from tributaries discharging into the project area. Study 8 (Stantec and Normandeau, 2016) found that coarse-grained material (gravel, cobble) can also be transported within the mainstem under high flows. It is important to note that the sources and relative contributions of suspended materials in the mainstem Connecticut River were not quantified in the erosion studies or in any other relicensing studies.

Sediment transported by the river consists of both bedload and suspended load. Bedload typically consists of coarser sediment (i.e., sand, gravel, and coarser material) that moves along the bed of the channel. Suspended load is largely comprised of silt and clay that is held in suspension by the turbulence of the flow throughout the entire water column. While bedload is commonly considered to comprise only 10 percent of the total load of a river (Pratt-Sitaula et al., 2007), the bedload exerts the strongest control on river morphology as the formation of bars can divert flow into the banks and cause channel migration that alters the dimensions and position of the river channel. The velocity needed to maintain suspended sediment in transport is far less than needed to initially entrain the sediment. Consequently, suspended sediment tends to move great distances during high flows, complicating the possibility of linking deposits of fine suspended sediment with its source area. Significant accumulations of fine sediment deposits are generally more a reflection of flow conditions than an indicator of a nearby fine sediment source. For example, the accumulation of fine sediment within the slackwater areas immediately upstream of Vernon dam are more a consequence of the low flow velocities there and not the presence of nearby eroding banks. Where a large input of fine sediment occurs rapidly due to bank erosion or at a tributary confluence, fine sediment may accumulate in the short term, but large pulses of fine sediment deposits will be redistributed relatively rapidly farther downstream by subsequent high flows unless the sediment is deposited locally in areas of persistently low flow velocity.

Periodic bedload disturbance and sediment transport is essential to many aquatic species, and helps to maintain habitat and species diversity. Flows high enough to mobilize fine sediments can benefit benthic invertebrates and fish that rely on coarse-grained substrate for spawning by flushing out those fine sediments that may have become embedded in the coarser substrate. Conversely, high-intensity flood flows that mobilize the coarser substrates can ultimately reduce refuge opportunities for mobile species and alter the substrate enough to potentially eliminate those habitats (Pitlick and Wilcock, 2001).

Water Quality

The velocity analysis in Section 6.1 indicates that river flow velocities are typically too low to entrain sediments from the riverbanks during normal project operational flows. This is consistent with the low turbidity of generally less than 2 nephelometric turbidity units (NTU) measured during Study 6 in 2015 (Louis Berger Group and Normandeau, 2016b) which found that the Wilder, Bellows Falls, and Vernon projects had negligible to no effect on turbidity, with recorded values remaining generally very low and generally within state water quality standards. The few recorded spikes in turbidity were found to occur in response to high flows resulting from heavy rain events. Nevertheless, even during high-flow events, water quality parameters such as dissolved oxygen were not observed to be impacted by higher turbidity.

Turbidity is commonly thought of as measuring water clarity, which people think of as cloudy water due to inorganic grains (clay/silt) but this is not always the case. Turbidity is a measure of the amount of light scattered by particles. The particle could be algae, debris, sediment, or tannins. It is possible to have unclear water that has little suspended sediment.[1]

The continuous and vertical profile turbidity data collected in Study 6 at all mainstem monitoring stations indicate that turbidity on very rare occasions exceeded the New Hampshire surface water quality standard of 10 NTU beyond

[1] There is generally a strong positive relationship between turbidity measurements (in NTU) and total suspended sediment (TSS) concentration in the water column. Holliday et al., (2003) determined correlations between NTU and TSS of 1:1 for the silt and clay fractions, but a smaller ratio (1:2) for clay and bulk-soil samples. Using these ratios, 2 NTU of turbidity would correspond to 1 - 2 mg/L TSS.

upstream receiving waters and that under low-flow conditions turbidity in the project area did not exceed the Vermont surface water quality standard. The New Hampshire turbidity standard was exceeded on one occasion in June 2015, in the Wilder forebay; this exceedance was attributed to sampling through a debris field (e.g., floating leaves, organic matter). In addition, periodic turbidity spikes occurred at the continuous monitoring stations but most notably within each Project tailrace. These spikes were also attributed to debris drifting in front of the turbidity sensor.

Study 14/15 (Normandeau, 2016f) included measurements of turbidity at nearshore spawning sites. Turbidity was generally low (<10 NTU) for nearly 95 percent of all measurements. One site located at a tributary confluence at the upper end of the Wilder impoundment measured 99.1 NTU on one occasion, but the average of all site measurements over the course of the study was 8.9 NTU. Studies 16 and 21 (Normandeau, 2016g, 2016h) collected water quality data at sea lamprey spawning sites and American Shad egg collection sites, respectively. Turbidity across all lamprey sites with suitable habitat ranged from 0 to 36 NTU in Study 16 with 99 percent of all readings less than 10 NTU. The single nest site with the highest measured turbidity was located near the mouth of Partridge Brook, and the average of all site turbidity readings over the course of the study was 3.9 NTU. Turbidity measured in Study 21 was limited to a single measurement at each trawl location, and ranged from 0.2 to 37.9 NTU across all measurements. Of valid measurements, 81 percent were less than 10 NTU, 16 percent were between 10 – 20 NTU, and remaining 3 percent (4 measurements) were between 36.6 and 37.9 NTU, all of them on a single night when river flows were well above normal project operational levels.

Water quality sampling for the spawning studies often occurred during periods of high flows with heavy runoff from tributaries which are likely the cause of high turbidity. But in general, the near shore turbidity measurements were low, did not differ from the Study 6 mid-channel continuous monitoring results, and did not indicate specific locations with excessive suspended sediment (as measured by turbidity) that might have adverse impacts on fish spawning.

Based on the turbidity results from Studies 6, 14/15, and 16, erosion would not result in, or significantly impact, water quality negatively in the river beyond short-lived and localized episodic high flow events.

Aquatic Habitat and Substrate

Substrate composition has a significant influence on the suitability of habitat for fish spawning, feeding, and rearing (especially benthic fish); mussel colonization; invertebrate productivity; and vegetation establishment. Aquatic habitat mapping conducted in Study 7 (Normandeau, 2015) found that fines (sand, silt, and mud/clay) dominate the substrate in each project impoundment (72-84 percent of substrate). Gravel/cobble substrate is the only other substrate type in abundance in the impoundments (12-21 percent). Boulder, riprap, bedrock ledge, and woody debris comprise 1-3 percent of substrate in each impoundment. As expected, the proportion of larger, rocky substrate types is greater in the riverine reaches than in the impoundments. Combined together, gravel, cobble, and boulder make up 65-76 percent of the dominant substrate along Study 7 transects in the three riverine reaches and fines range from 21-33 percent of substrate. The heads of islands in the riverine reaches often have significant gravel/cobble bars present as well.

Fish Spawning

Most of the 14 fish species assessed in Studies 14/15 and 16 (Normandeau, 2016f, 2016g) have specific substrate or other habitat requirements for successful spawning, however many of these fish spawn in locations that are not directly influenced by the stability of riverbanks, such as backwater habitats. For example, Yellow Perch, Northern Pike, and Chain Pickerel require zero or near zero velocities for egg deposition and incubation, and consequently these fish target backwater habitats or other locations that are highly protected from high, bank scouring flows. Such areas also tend to have well developed riparian vegetation which also reduces the incidence of bank erosion. In addition, all three species prefer to deposit eggs onto emergent or suspended vegetation (Scott and Crossman, 1998; Farrell et al., 1996; McCarraher and Thomas, 1972), which maintains the eggs above the substrate where settled fines could otherwise smother the eggs and reduce hatching success.

Although data was lacking, it is likely that Golden Shiner also target such protected habitats for spawning, as do the backwater spawning species such as Black Crappie, Bluegill, Pumpkinseed, and Largemouth Bass. These Centrarchid species also exhibit active nest cleaning behaviors, where they sweep away fine sediments from selected nest locations prior to egg deposition and, if necessary, to maintain a silt-free nest environment during egg incubation. Although heavy and rapid deposition of fines into an active nest could result in nest abandonment and egg mortality, such heavy deposition of fines is unlikely to occur in backwater habitats, unless associated with a silt-bearing tributary which would not be directly influenced by project operations.

The riverine spawning species including Smallmouth Bass, Fallfish, White Sucker, Walleye, Spottail Shiner, and Sea Lamprey could be more directly influenced by sedimentation due to locally eroding banks or due to high suspended sediment loads from other sources. Similar to the Centrarchid species, Smallmouth Bass are capable of actively cleaning nest areas of fine sediments (Figure 6.4.4-1), however heavy and rapid silt deposition could lead to nest abandonment. Some nests monitored during Study 14/15 did appear to be abandoned with subsequent filling of nest sites with fine sediments (Normandeau, 2016f), however it could not be ascertained if high sediment loads, high water velocities (due to spill events), angler catches, or other factors were responsible for the empty nests.

Figure 6.4.4-1. Smallmouth Bass nest with attending adult. Note large woody debris and fines.

Unlike the bass and sunfish species, Fallfish, White Sucker, Walleye, Spottail Shiner, and Sea Lamprey deposit eggs on or within the substrate but do not exhibit any parental care, such as nest cleaning. Fallfish and lamprey construct nests that have hydraulic characteristics that serve to protect eggs from sedimentation, however high sediment loads could infiltrate the nests and result in high mortality of incubating eggs. Eggs of suckers, Walleyes, and Spottail Shiners are deposited directly on the substrate and would be susceptible to sedimentation, although suckers and Walleyes (and lampreys) typically spawn in locations having gravel and cobble substrates swept by rapid water velocities (Appelgate, 1950; Wigley, 1959; Bozek et al., 2011; Curry and Spacie, 1984; McMahon et al., 1984; Twomey et al., 1984; Scott and Crossman, 1998), which are more likely to be scoured by high flows than smothered by deposited sediments. Detailed information on Spottail Shiner spawning habitats and locations within the project area are insufficient to assess the likelihood of erosion-related effects on spawning success.

Comparison of over 1,080 actual resident species spawning locations with bank stability classifications was non-informative because bank erosion was not mapped where most resident fish spawning observations were made (i.e., within tributaries or across tributary mouths, in backwaters, or along riverine islands). Direct comparative data is available for only eight nests that were located along mainstem banks adjacent to riverine islands: four Smallmouth Bass nests along stable banks, and four along unstable banks (one bass nest along a vegetated eroding bank, one

Fallfish nest along an eroding bank, and two Fallfish nests along banks with failing armor). No sucker or walleye spawning observations were made within riverine riffles where banks were mapped for erosion. Despite a lack of directly comparable data, assessment of habitat characteristics at unmapped spawning sites versus adjacent sites mapped as unstable banks may be informative.

Comparison of nearshore bathymetry at unstable banks in the impoundments with known spawning locations of Smallmouth Bass clearly shows that bass utilize low-slope habitats for spawning. The slopes to nests were measured from the bank to each nest and the mean distance of the nests from the banks was used to generate equivalent distances from unstable banks to calculate those bank slopes. For example, eight Smallmouth Bass nests constructed along the margin of Jarvis Island in the Bellows Falls impoundment showed an average slope of 13 percent, whereas a comparable number of slope measurements estimated from the same mean distance from the mainstem banks mapped as unstable showed a mean slope of 27 percent (Figure 6.4.4-2, Figure 6.4.4-3). When comparative slope measurements from three tributary delta study sites were added, similar results were produced (11 percent slope for bass nests, 33 percent for eroding banks (Figure 6.4-10).

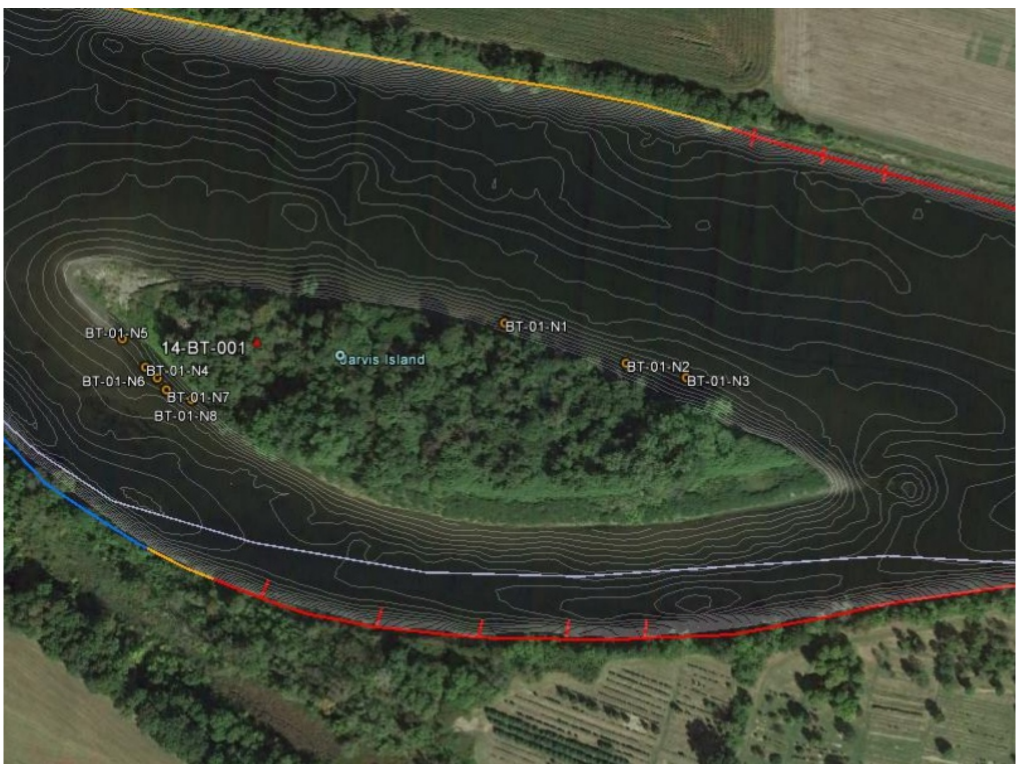


Figure 6.4.4-2. Map of Jarvis Island study site (site 14-BT-001) showing location of 8 Smallmouth Bass nests and 8 comparative slope transects at eroding banks (red perpendicular lines). Note the length of erosion slope transects is equal to the average distance of bass nests from the bank.

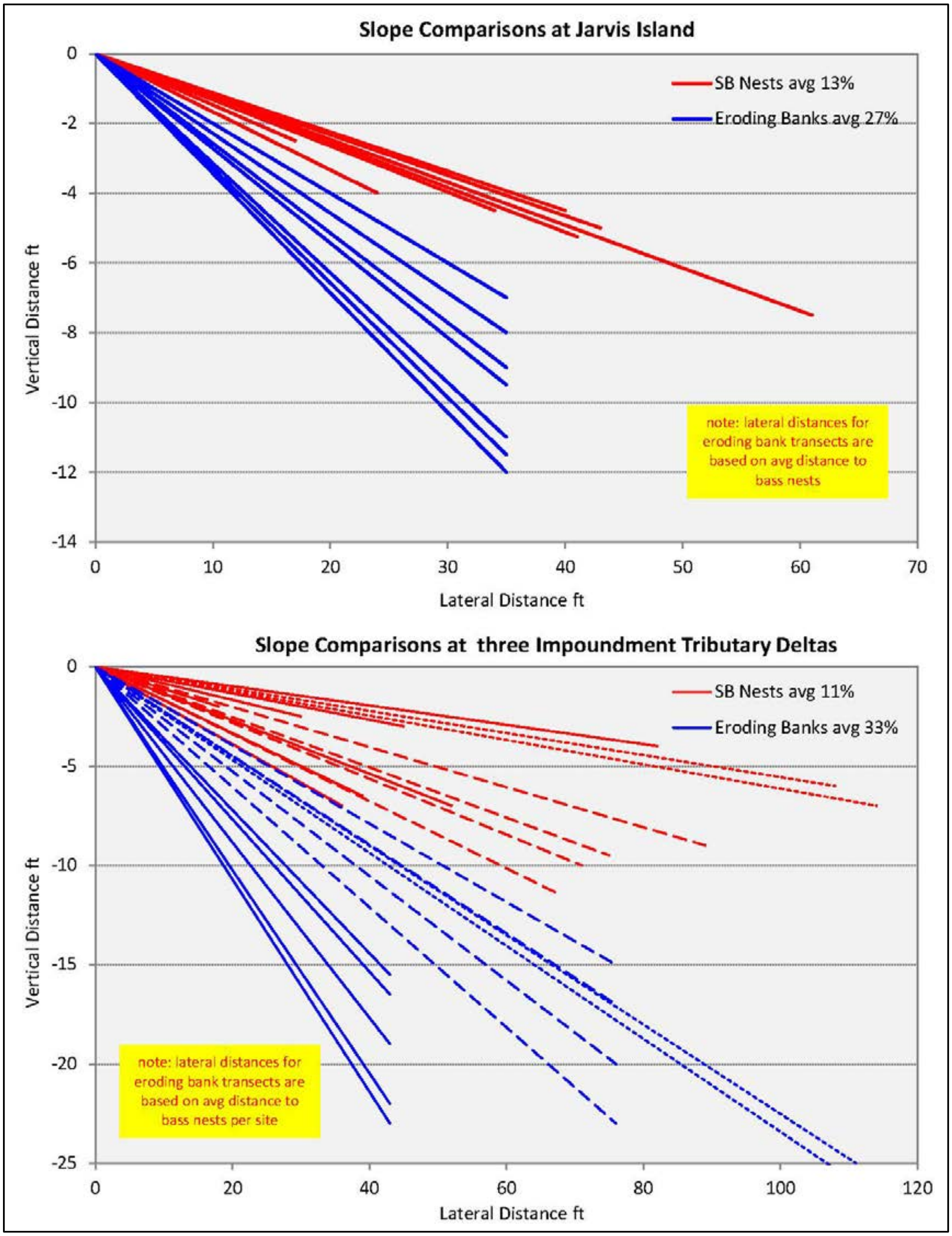


Figure 6.4.4-3. Channel slopes at Smallmouth Bass (SB) nests and at nearby eroding banks at Jarvis Island (top graph) and at three tributary deltas (bottom graph). Note that the lateral distance of eroding bank slopes were equal to the mean distance of bass nests per study site. Line types represent different study sites.

Sea lamprey nests were sometimes observed in Study 16 (Normandeau, 2016g in areas with unstable banks, but lamprey nests in the impoundments were typically located far from the margins (mean distance to bank = 131 ft) where direct impacts from sloughing or eroding banks is unlikely. Lamprey nests were also typically found in low slope gravel/cobble shoal areas (Figure 6.4.4-4). Nest caps were placed at sites where spawning was observed; however, during high flows the cap mesh was able to trap suspended fine sediments and buried the nest at one site. The capping effort was later suspended due to this result as well as to a lack of ammocoetes collected at two other sites.

Figure 6.4.4-4. Sea Lamprey nest site in the project-affected reach of Partridge Brook.

Comparison of slopes at seven lamprey nests with slopes at nearby eroding banks (also extending far from shore) at four impoundment study sites again showed that lampreys typically did not spawn at sites proximal to eroding banks, which possessed steeper slopes with deeper water (Figure 6.4.4-5).

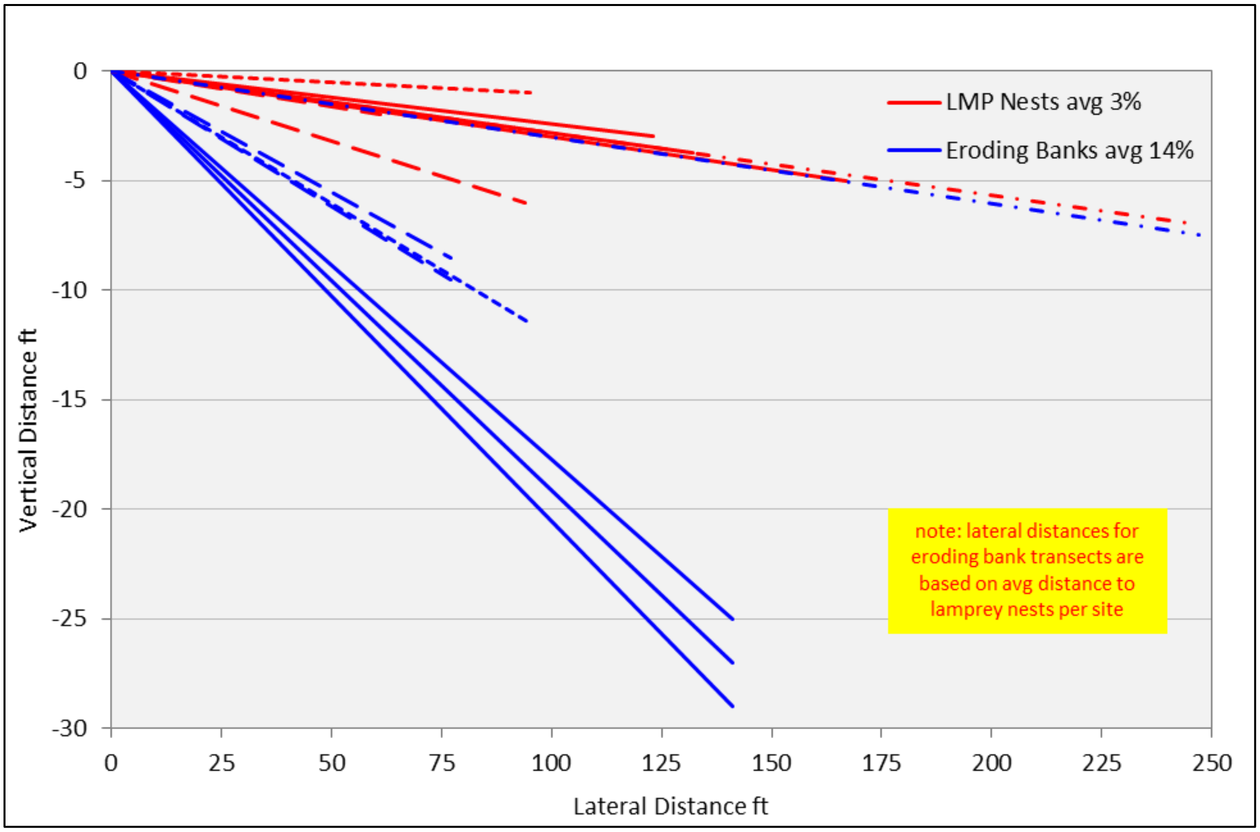


Figure 6.4.4-5. Comparison of slopes at Sea Lamprey (LMP) nest sites and at nearby eroding banks at four impoundment study sites. Note that the lateral distance of eroding bank slopes were equal to the mean distance of lamprey nests per study site. Line types represent different study sites.

As discussed in Section 5.8, the gravitational forces operating on a bank with deep water present will be greater than a bank with shallow water, assuming the heights of the banks above water are similar. Where deep water is present, a greater portion of the bank will be impacted by flowing water and the shear stresses acting at the base of the bank will be greater, increasing the likelihood that sediment accumulating at the base of the bank will be removed and the upper portion of the bank destabilized as a result. The slope data at spawning sites illustrate that areas with observed spawning are not likely to occur in the deeper (steeper), narrower channels with higher flows, which do not tend to create or maintain spawning habitat. A possible exception to this could be in cases where large woody debris is recruited into a deeper, steeper margin habitat, which could produce suitable spawning habitat in an area of erosion or sedimentation.

Freshwater Mussels

Although freshwater mussels are adapted (behaviorally and morphologically) to inhabiting flowing waters that transport sediment both as bedload and suspended load, studies have suggested that mussels either prefer or naturally congregate in areas where riverbanks, streambed, or hydraulic forces are more stable (Strayer, 1999; Strayer, 2008; Allen and Vaughn, 2008). Acute erosion and sedimentation, which may be associated with high flow events, alterations to riverbanks or uplands, and aspects of channel geomorphology, have been shown to degrade mussel habitat, kill or displace mussels or their host fish, and thereby influence the diversity, distribution and abundance of mussels across a range of spatial scales within a river or watershed (Brim Box and Mossa, 1999; Arbuckle and Downing, 2002; Strayer, 2008). These effects would be most pronounced in river systems that, due to a combination of natural and anthropogenic influences, experience relatively frequent and high levels of hydraulic instability, erosion, and sedimentation. Mussels are typically more tolerant of short-term events, such as deposition associated with a single storm event, due to their ability to anchor themselves in the substrate, move horizontally or laterally in response to stimuli, and "clam up" when stressors (such as high turbidity) are present (Strayer, 2008).

Freshwater mussel surveys were conducted in 2011 and 2013 for Study 24 (Biodrawversity and Louis Berger, 2014). The federally endangered dwarf wedgemussel (DWM, *Alasmidonta heterodon*) were found at 31 locations (69 total individuals) and nearly all were found in water depths of 6-20 feet and in a variety of substrate types, often with some combination of clay, silt, sand, and gravel. Some were found in pockets of these fine substrates in areas dominated by cobble, boulder, or bedrock. Most DWM were found in areas with light to moderate flow velocities. They tended to be associated with two other uncommon mussel species classified as SGCN in New Hampshire: creeper (*Strophitus undulatus*), and alewife floater (*Anodonta implicate*) also a SGCN species in Vermont. This discussion is limited to these three sensitive species.

Creeper were found at 22 locations and nearly all (54 total individuals) were found in water depths between 3–15 feet in a variety of substrate types, often with some combination of clay, silt, sand, and gravel. Some were found in pockets of these fine substrates in areas dominated by cobble, boulder, or bedrock. All were found in areas with light to moderate flow velocities. Alewife floater were found at 26 locations (460 total individuals) in water depths between 3–20 feet in a variety of substrate types, often with some combination of clay, silt, sand, gravel, and small cobble. Most were found in a broad range of flow velocities, including in strong flows downstream from the Bellows Falls and Vernon dams.

The locations surveyed in 2011 and 2013 at which these three species were found were compared to erosion mapping (Table 6.4.4-1). Erosion mapping was available at 27 DWM sites and the other four sites were not mapped (two were in tributaries and two were associated with mid-channel islands). Thirteen of the 22 sites with creeper were mapped for erosion and the remaining nine sites were in tributaries or located mid-channel. Twelve of the 26 sites with alewife floater were mapped for erosion and the remaining 14 were in tributaries or located mid-channel.

Table 6.4.4-1. Comparison of mussel observations with bank stability.

Species	Number of Mapped Sites	Percent of Mapped Sites (%)	Number of Individuals at Mapped Sites	Percent of Individuals at Mapped Sites (%)
Dwarf Wedgemussel				
Unstable	12	44	29	48
Stable	11	41	27	45
Mixed	4	15	4	7
Creeper				
Unstable	6	46	6	15
Stable	7	54	33	85
Mixed	0	0	0	0
Alewife Floater				
Unstable	4	33	48	19
Stable	5	42	123	50
Mixed	3	25	77	31

Slightly more DWM sites were found in areas where banks were classified as unstable (44 percent) than near banks classified as stable (41 percent) with the number of individuals following a similar trend. Banks classified as “mixed” in Table 6.4-2 were in areas where the bank was mapped as partially stable and partially unstable. Conversely, both creeper and alewife floater were found more frequently in areas where banks were classified as stable with greater numbers of individuals at those sites than at unstable sites.

While these data might suggest some correlation, it is important to note that study sites were not selected on a randomized basis and surveys purposely avoided areas with highly unstable banks because, based on surveyor experience, mussels are less likely to be found near those types of banks. Given that these three species were found in areas of both stable and unstable banks, that they are somewhat mobile, and that sedimentation inputs include those not related to bank erosion, it is unlikely that eroding or otherwise unstable banks alone would have an adverse effect on these species.

6.5.5 Summary of Erosion Effects on Other Resources

The results of this erosion study in combination with the results of other resource studies, and the qualitative assessments described above when taken together do not show compelling evidence that excessive erosion has a significant adverse impact on those resources. While there may be localized real or potential impacts at specific sites) there is no indication that other natural resources in general are significantly impacted at the scale of the entire the project area. As an example, the Vernon riverine reach (Figure 6.4.5-1) is very biologically productive and diverse. Freshwater mussels, dragonflies, toads, and numerous spawning sites for resident fish, Sea Lamprey, and American Shad are all present in association with

55% of banks mapped as unstable in that reach (see Figure 5.6.5-3c, Section 5.6.5a).

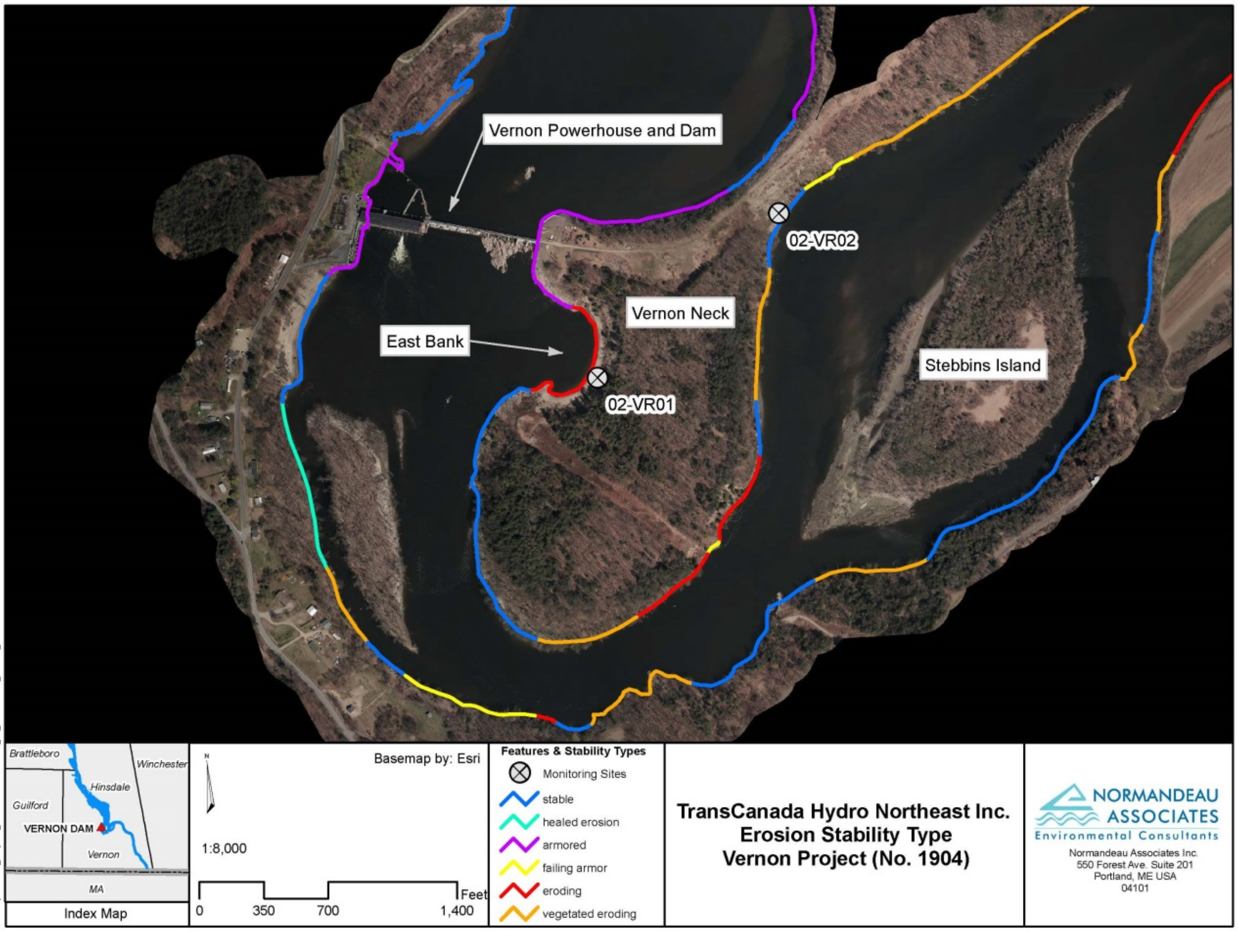


Figure 6.4.5-1. Bank stability in the Vernon riverine reach.

6.6 Study Conclusions

The focus of the Study 2 and Study 3 erosion studies was to identify broad patterns of erosion along more than 250 miles of riverbank and these studies were not intended to detail or understand the numerous local characteristics potentially controlling erosion at specific locations. Over the entire study area, multiple corroborating sources of information indicate that the rates and amounts of erosion have decreased in the Bellows Falls and Vernon impoundments while slightly increasing in the upper portion of the Wilder impoundment where WSE's and flows are largely a function of upstream and tributary inflow rather than operations at the Wilder dam. Although the specific reasons for these trends are unclear, normal project operations cannot be considered an adequate explanation. Consistent with the findings from historical aerial photographs, the overall amount of erosion appears to have declined between 1958 and 2014 for the study area as a whole with the most dramatic declines in the Bellows Falls impoundment and to a lesser extent in the Vernon impoundment. Erosion in Wilder impoundment appears to have increased through the same time period, but the level of erosion has declined since 1978, under the existing licensed operations.

Currently, the levels of erosion hold nearly constant through the different portions of the study area despite variations in project-related WSE fluctuations, further suggesting that normal project operations do not exert a strong control on the broad patterns of erosion in the study area. Furthermore, the approximately 40% of bank instability mapped through the study area is similar to more free-flowing portions of the Connecticut River (Field, 2004), which suggests that normal project operations may not be a direct cause of excessive erosion, although such operations could contribute to erosion by creating seepage forces associated with daily fluctuations.

In summary, erosion within the study area is ultimately the result of multiple causal mechanisms working in concert to sustain the cycle of erosion. Where that erosion occurs and how quickly the cycle of erosion progresses may have more to do with variations in natural bank characteristics throughout the study area rather than the causal forces acting on the banks. Bank heights and the geomorphic surfaces and bank compositions with which they are associated exert the strongest control on where erosion occurs in the study area (Figure 5.6.5-1). Flood discharges have an effect during all stages in the cycle of erosion while other processes are capable of contributing to only certain stages in the cycle. However, flood flows play a distinct role in the continuation of the erosion cycle. Flood flows are primarily responsible for the removal of sediment from the base of the bank that accumulates from the slides, flows, and topples resulting from the notches and overhangs forming at the base of the bank. Tractive forces generated by flood flows are the only mechanism capable of removing the sediment from the base of the bank that otherwise would lead to bank stabilization if not removed. While other processes such as waves or seepage forces created by project-related WSE fluctuations may exert some control on the cycle of erosion by potentially contributing to the destabilization of the banks, they cannot be considered as resulting in excessive erosion that negatively impacts other resources since ultimately the continuation of erosion depends on flood flows that sustain the cycle of erosion.

Given the significant changes in the rate and amounts of erosion documented through historical aerial photography and multiple mapping efforts, respectively, normal project operations that have trended toward reduction of daily fluctuation and the overall fluctuation range in several decades associated with the current licenses, cannot adequately explain the observed patterns of erosion. Attempting to identify a single cause for erosion fails to recognize that multiple processes operate collectively to effect change on the riverbanks through space and time.

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APPENDICES FILED SEPARATELY AS SPECIFIED BELOW:

APPENDIX A: Erosion monitoring data (A-1 through A-3 in zipfile format)

APPENDIX B: Surficial geological maps (with Appendices D, E in pdf format)

APPENDIX C: Supporting Geodata of Bank conditions mapping (in zipfile, kmz format) and Arc (zipfile) format

APPENDIX D: Comparison of erosion maps from 1955, 1979, and 2014 (with Appendices B, E in pdf format)

APPENDIX E: Memo on multiple regression analysis (with Appendices B, D in pdf format)

APPENDIX F: Topographic Surveying Data (in zipfile of Excel files)