Analysis of Erosion in the Vicinity of the Route 10 Bridge Spanning the Connecticut River

by

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Executive Summary

The Route 10 Bridge spans the Connecticut River in the town of Northfield, MA (see Figures 1 and 2). This reach of the Connecticut River is impounded by the Turners Falls Dam located approximately 11 miles downstream of the Route 10 Bridge. The Turners Falls Impoundment extends approximately 20 miles upstream of the Turners Falls Dam to the base of the Vernon Dam in New Hampshire (see Figure 1). A dam has existed near the present Turners Falls Dam since 1798. The elevation of the Turners Falls Dam was raised in 1972 by approximately 6 feet, to create additional storage for the Northfield Mountain Pumped Storage Project.

The Connecticut River at the Route 10 Bridge has experienced riverbank erosion and was listed among the 20 eroding sites in the Erosion Control Plan[1] (Simons & Associates, 1999). Erosion at this location is evident in a comparison of aerial photos from their earliest availability (1929) to the present. Aerial photographs taken as early as 1929 (see Appendix A) show that erosion has been occurring at this location for decades prior to raising the dam height and associated impoundment elevation and prior to the construction and operation of the Northfield pumped-storage project.

At the Route 10 Bridge, significant changes in hydraulic conditions occur due to a combination of narrowing of the channel width as the flow passes between a rock outcrop on the west bank and rock bridge abutment from the old Bennett Meadow Bridge (located several hundred feet upstream of the Route 10 Bridge). As the river flows downstream, it bends to the left as it flows by a rock outcropping that juts out into the current. Narrowing of the river accelerates the velocity of flow. Also in the same reach of river, the river bed rapidly drops into a deep hole and then just as rapidly returns again to its typical depth. These significant and rapid changes in physical channel characteristics that govern the flow through this reach cause eddies to form adjacent to both river banks. The channel geometry and resulting flow patterns cause additional turbulence and acceleration/deceleration of the velocity in the water flowing through this reach (see Figure 9). These unique hydraulic conditions in this reach are the primary cause for erosion in the vicinity of the Route 10 Bridge.

In addition to the hydraulic conditions causing erosion at the Route 10 Bridge, boat waves have been observed causing erosion, specifically on the east bank between the old Bennett Meadow Bridge abutment and the Route 10 Bridge. Fluctuation of the Turners Falls Impoundment level that occur slowly over periods of hours due to hydropower operations do not have any impact forces against the riverbank and do not cause erosive

[1] The Erosion Control Plan was developed in compliance with Federal Energy Regulatory Commission (FERC) license terms and conditions dealing with erosion. It included a full river reconnaissance that delineated the 20 top erosion sites to be considered for stabilization, many of which have been stabilized after implementation of the plan through 2012.

forces approaching the magnitude of those experienced by natural hydrodynamic forces (high river flow and the unique combination of river hydraulics resulting in eddies and turbulence) or those caused by boat waves (which cause direct impact forces and rapid changes in water level that occur over a period of seconds). Hours of videotape are available showing the effect of slow water level fluctuations with no observable erosion, but significant erosion occurring when boat waves impact the riverbank (for detailed discussion of the various causes of erosion, photographs, and an evaluation of the causes of erosion see "Hydraulic and Geomorphic Analysis of Erosion in the Turners Falls Impoundment of the Connecticut River," 2012, Simons & Associates).

The most significant erosion in the Turners Falls Impoundment is located at the far upstream end of the impoundment, just below Vernon Dam. At this location, strong eddying occurs due to the hydraulic conditions caused by the Vernon Dam overflow spillway causing significant erosion within the Turners Falls Impoundment that has nothing to do with the hydropower operations associated with Northfield Mountain. Similar hydraulic conditions occur at the Route 10 Bridge. Thus, the combination of unique hydraulic conditions resulting in eddying and turbulence that affect the riverbanks at the Route 10 Bridge, the existence of the most significant eroded area within the Turners Falls Impoundment (immediately downstream of Vernon Dam) which also is caused by unique hydraulic characteristics resulting in eddies and turbulence, both of which are independent of hydropower operations at Turners Falls Dam and Northfield Mountain; confirm that these operations are not responsible for erosion that has occurred and continues to occur in the vicinity of the Route 10 Bridge.

1. Introduction

The Connecticut River flows out of Quebec in a southerly direction from the Connecticut Lakes in Northern New Hampshire, forming the border between New Hampshire and Vermont, through western Massachusetts and central Connecticut into Long Island Sound. Figure 1 shows the path of the Connecticut River as it flows through New England. On its journey through New England, the river is impounded by 15 dams, a number of which are equipped with hydropower generation facilities. A few of the dams create impoundments that are large enough to seasonally re-regulate[2] river flows. The majority of hydropower dams are low-head facilities, which form narrow impoundments that generally experience low water velocities at low flow and higher velocities with near full riverine conditions at high flows.

One of these impoundments is formed by the Turners Falls Dam in Massachusetts. Figure 2 shows the Turners Falls Impoundment and the location of the Route 10 Bridge approximately 11 miles upstream of the Turners Falls Dam.

[2] Dams with sufficient storage capacity to store water during the high flow season and release water during periods of low flow thereby re-regulating flow include Murphy, Moore, and Comerford Dams.

Figure 1. Connecticut River (modified, after "The Connecticut River Watershed – Conserving the Heart of New England," The Trust for Public Land, 2006)

The Connecticut River through the Turners Falls Impoundment is several hundred feet wide, typically ranging from as narrow as about 250 feet wide to over 1,000 feet wide. The magnitude of these river widths (averaging over 500 feet wide) limits the number and location of bridges crossing the river due to the significant expense involved in building and maintaining bridges of this length. At the present time there are three[3] bridges for vehicular traffic across the Turners Falls Pool (including one at the Turners Falls dam). One of these major bridges is the Route 10 Bridge, at a location where the river is relatively narrow and in the vicinity of a previous bridge (Bennett Meadow Bridge). Figure 3 shows the Connecticut River in the vicinity of the Route 10 Bridge. Note the location of the Bennett Meadow Bridge, which was removed decades ago. This previous bridge was located in a narrower location of the river where a rock outcrop juts out into the river on the west bank (left side of the river in Figure 3) and a rock abutment remains on the opposite bank. The existence of the previous bridge and established roads leading to the bridge, dictate that the Route 10 Bridge was placed in the vicinity of the previous bridge along with the features and characteristics that affect the flow at that location including the rock outcrop, rock abutment and other factors that affect river hydraulics at this location.

[3] The three vehicular bridges in downstream to upstream order include Montague A Street (the bridge that crosses at the Turners Falls Dam, the French King Bridge, and the Route 10 Bridge. A railroad bridge crosses the river a few miles upstream and another inactive bridge (Schell Bridge) is located farther upstream.

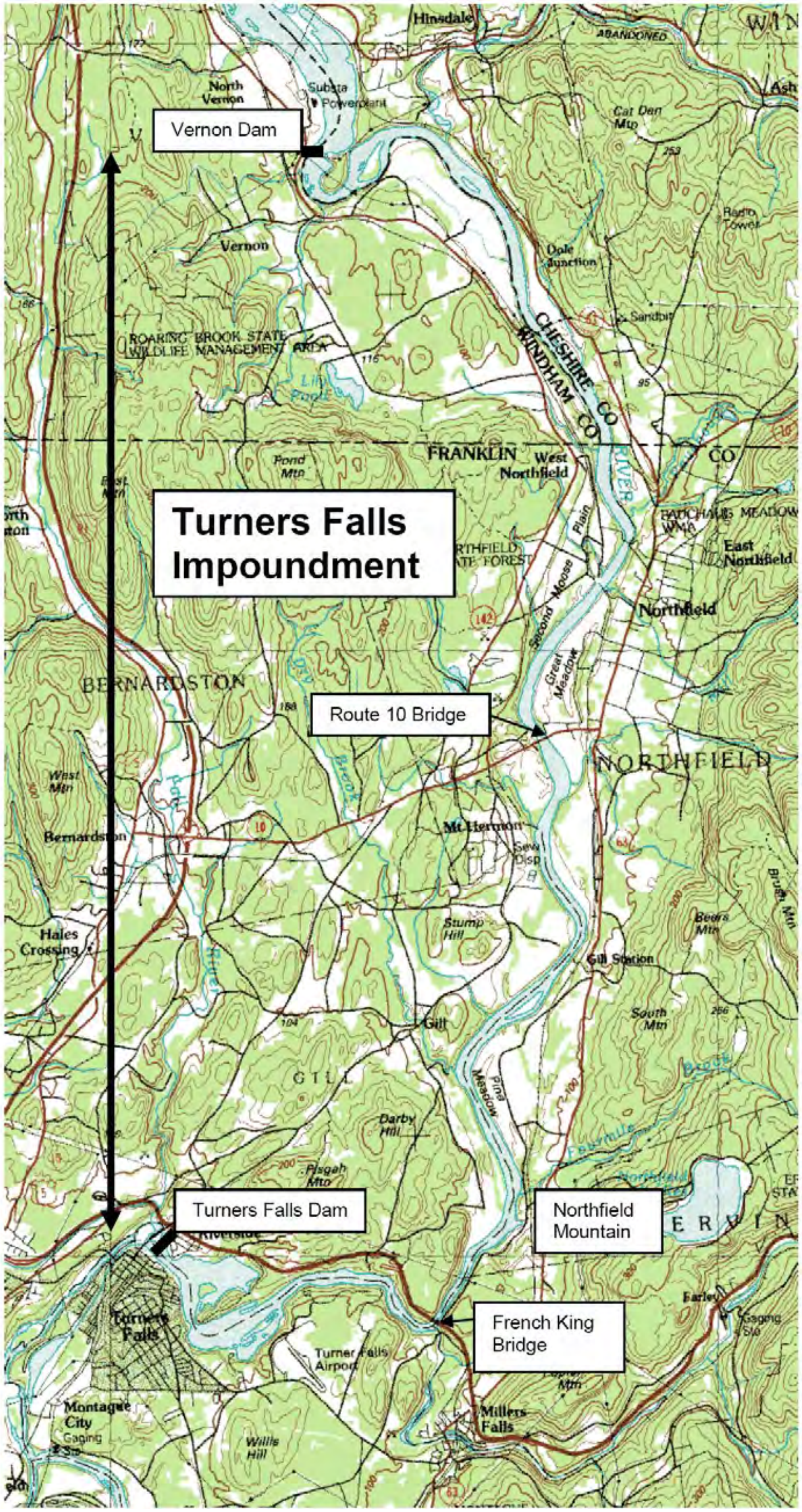


Figure 2. Turners Falls Impoundment, Route 10 Bridge

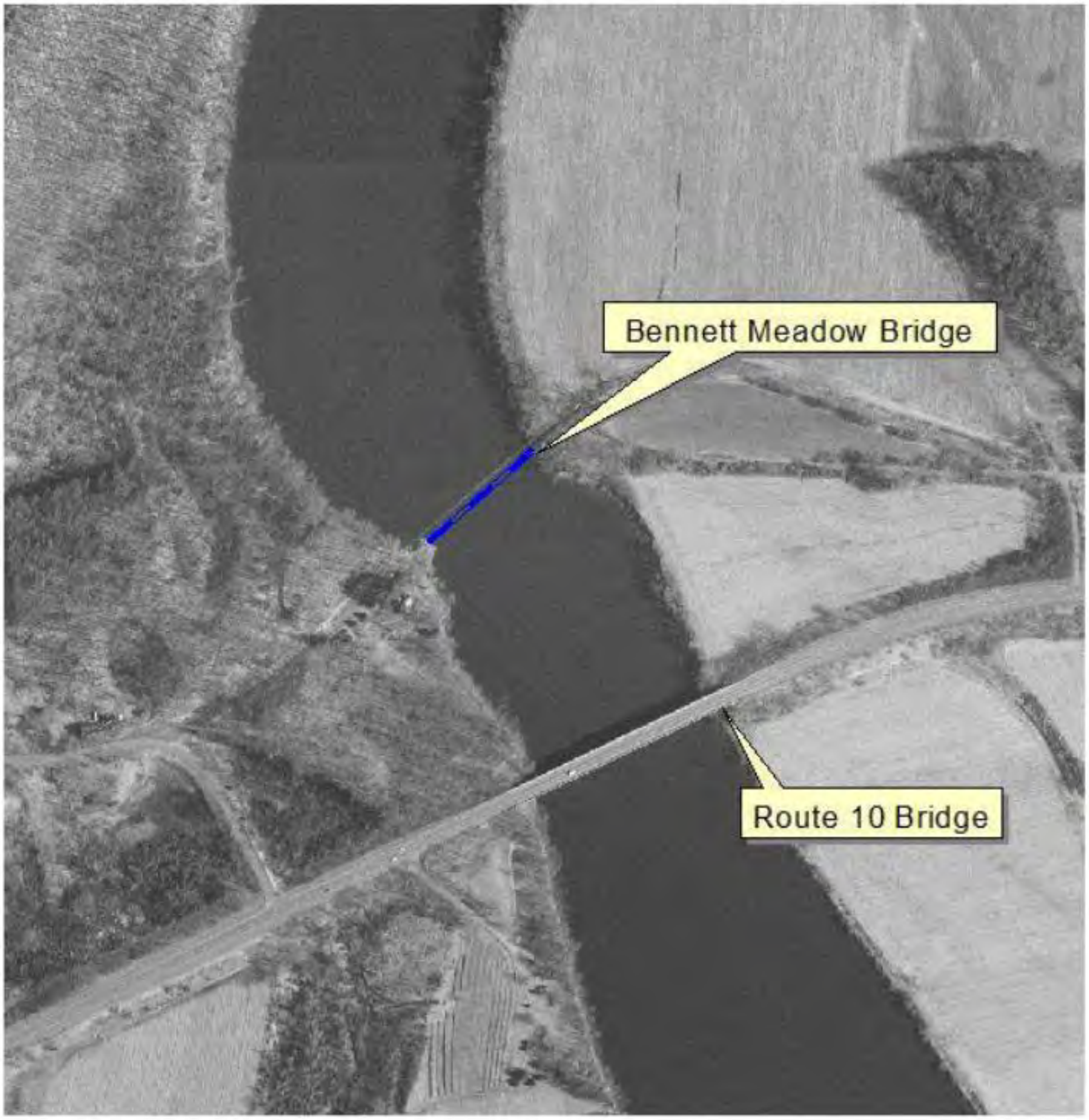


Figure 3. Connecticut River near Route 10 Bridge

Erosion has been occurring in the vicinity of the Route 10 Bridge for decades. To address the question of whether hydroelectric operations are responsible for this erosion, it is necessary to understand the actual causes of erosion at this location and the hydraulic forces acting on the riverbanks. This requires the collection and use of various types of data, including: channel geometry, hydraulics (depths, velocities, flow patterns), and bank material. Based on these data, hydraulic and erosion analyses coupled with geomorphic analysis provide insight into the causes of erosion at this location.

2. Riverbank Change Over Time

To understand hydraulic forces and geomorphic processes in the vicinity of the Route 10 Bridge, changes to the river that have occurred over time is needed. Several aerial photographs have been taken of the Connecticut River over the time period from 1929 to 1990 (see Appendix A). These photographs were inspected to evaluate riverbank alignment and changes that have occurred over this period of time.

1929 – The 1929 photograph shows the old alignment of the Bennett Meadow Bridge as it crossed the river in basically a perpendicular direction from a rock point on the west bank (right descending bank – in the direction of flow). This bridge alignment took advantage of the rock point extending out into the river making this location as narrow as possible (to minimize the span and cost of the bridge). The bridge abutment on the east bank (left descending bank) was constructed on the bank itself and did not extend significantly out into the river channel. As the river flows downstream, it bends significantly to the left. Once the river passed the rocky point on the west bank, the bank developed a curved shape back in a westward direction as the river width expanded indicating that some erosion along the west bank was likely occurring beyond the normal width expansion from the narrow section where the bridge was located. On the east bank there is a small but abrupt change in the bank alignment that appears to indicate some local erosion is occurring. The east bank also exhibits some mild curvature indicative of a more general pattern of erosion as well.

1939 – The river shows similar riverbank alignment and characteristics compared to the 1929 photograph. The area of localized but abrupt change in bank alignment on the east bank noted in 1929 has eroded more, and the curved area indicating more general erosion appears somewhat more pronounced.

1952 – Again, the riverbank alignment appears similar to the previous photographs. There appears to be increased curvature of the riverbanks in the landward direction on both banks downstream of the bridge indicating ongoing erosion. There were several fallen trees on the east bank downstream of the bridge.

1980 – This photograph shows that the old Bennett Meadow Bridge had been removed and the new Route 10 Bridge had been built (finished in 1969). The new bridge is located about 800 feet downstream of the old bridge. This photograph shows fewer trees along the east bank with a short distance showing no trees. There is more pronounced curvature indicating ongoing erosion of both banks in the same area where erosion had been occurring in the previous photographs (downstream of the old bridge location).

1990 – The 1990 photograph shows three fallen trees on the east bank of the river and a wider band of no trees along this bank. There is again even more pronounced curvature in the landward direction, particularly on the east bank compared to 1980. This again indicates ongoing erosion. The area of landward curvature expanded farther downstream on the west bank.

The series of aerial photographs show that erosion was occurring progressively during the entire period from 1929 to 1990 on both riverbanks focused primarily in the area downstream of the old Bennett Meadow Bridge. Erosion is evident during the entire sequence of aerial photographs from 1929 through 1990 and erosion was progressing prior to raising the Turners Falls Dam in 1972 and before the construction and operation of the Northfield Mountain Pumped Storage Project. No erosion is noted in the immediate vicinity of the newer Route 10 Bridge due to the erosion protection (rip-rap) placed starting at the toe of the bank and extending up the bank under the bridge. In addition, the eastern riverbank downstream of the new bridge had also been stabilized for a distance of about 2000 feet downstream of the new bridge by the United States Army Corps of Engineers (USACE) in a program of experimental erosion protection measures. This area of experimental bank protection was constructed in the 1970s (for the most part, it has performed well and remains in good condition – with only a few small areas of disrepair).

3. Riverbank Characteristics near the Route 10 Bridge

3.1 Riverbank Characteristics at the Route 10 Bridge

To further understand the geomorphic processes in the vicinity of the Route 10 Bridge, the riverbanks were characterized by Simons & Associates in 2008. At approximately 100-foot increments, photographs of the riverbanks were taken to document the material types and vegetation along the riverbanks. Figure 4 shows a visual summary of this riverbank characterization. At the Route 10 Bridge itself (segment 2W and 4E), both riverbanks have been rip-rapped with boulder-sized material. The rip-rap extends in the vertical dimensions from below the water surface presumably near the toe of the slope and essentially all the way up the bank to the concrete abutment. The rip-rap also extends horizontally from about 50 feet upstream and 50 feet downstream of the bridge.

3.2 Riverbank Characteristics on West Riverbank

Downstream of the bridge (Segment 1W) on the right descending bank (west side of the river), the riverbank has a relatively flat lower slope and a moderate to steep to near vertical areas of upper river bank. The banks in this area consist primarily of relatively fine sand. There is considerable woody debris deposited on the lower banks. The upper banks are vegetated with areas of trees and some shrubs and herbaceous vegetation. While generally moderately well vegetated, there are small patches of sparse vegetation and other areas that are more heavily vegetated.

Upstream of the bridge (Segment 3W) on the right descending bank has been protected against erosion for several hundred feet. The toe of the slope has been covered with cobble-sized rip-rap. On top of the rip-rap, coir logs can be seen in some areas. The upper slope has been cut back to a moderate slope and is heavily vegetated with shrubs, trees, and herbaceous vegetation. Upstream of this area the rip-rap toe continues (and transitions to a rock outcrop) but above the rock is grass lawn area associated with the home that exists quite far up the bank. Going farther upstream the natural rock outcrop continues to the hook-shaped rock point (4W). Some trees and shrubs grow on top of the soil found above the rock outcrop area. Upstream of the rock outcrop (on the right descending bank) the lower bank consists of small rocks to sand (5W). The upper banks are moderately steep and are vegetated with trees, shrubs and herbaceous vegetation. This transitions into a lower bank consisting of sand on a flat slope with the upper bank continuing as moderately steep, vegetated with trees, shrubs and herbaceous vegetation (6W).

3.3 Riverbank Characteristics on the East Riverbank

On the left descending bank (east side of the river) downstream of the Route 10 Bridge, the USACE constructed experimental bank protection. The first segment consists of small concrete blocks glued on fabric placed on the lower bank (3E). The upper bank is vegetated with trees, shrubs and herbaceous vegetation. The next two segments consist of used automobile tires banded together on the lower riverbank slope with a vegetated upper bank (trees, shrubs, and herbaceous vegetation). In one of the segments, the tires are stacked and stepped back to create a moderate slope (2E). For the most downstream segment, the tires are laid on a moderate slope on their sides with tires touching at their circumference so their circular shape is visible (1E). Upstream of the bridge, the lower bank consists of sand and is relatively flat-sloped (5E). The upper riverbank is generally steep with some areas of moderate to vertical slopes. There is some vegetation but fairly limited. This segment is actively eroding and extends several hundred feet. The next segment has a rip-rapped toe, where the old Bennett Meadow Bridge used to be (6E). The upper river bank consists of silt and sand and lies on a moderate slope. It is vegetated with trees and some shrubs and herbaceous vegetation. Beyond the old segment of rip-rap, the lower riverbank consists of sand lying on a relatively flat slope (7E). The upper riverbanks continue (moderate sandy slope) with vegetation consisting of trees, shrubs and herbaceous vegetation.

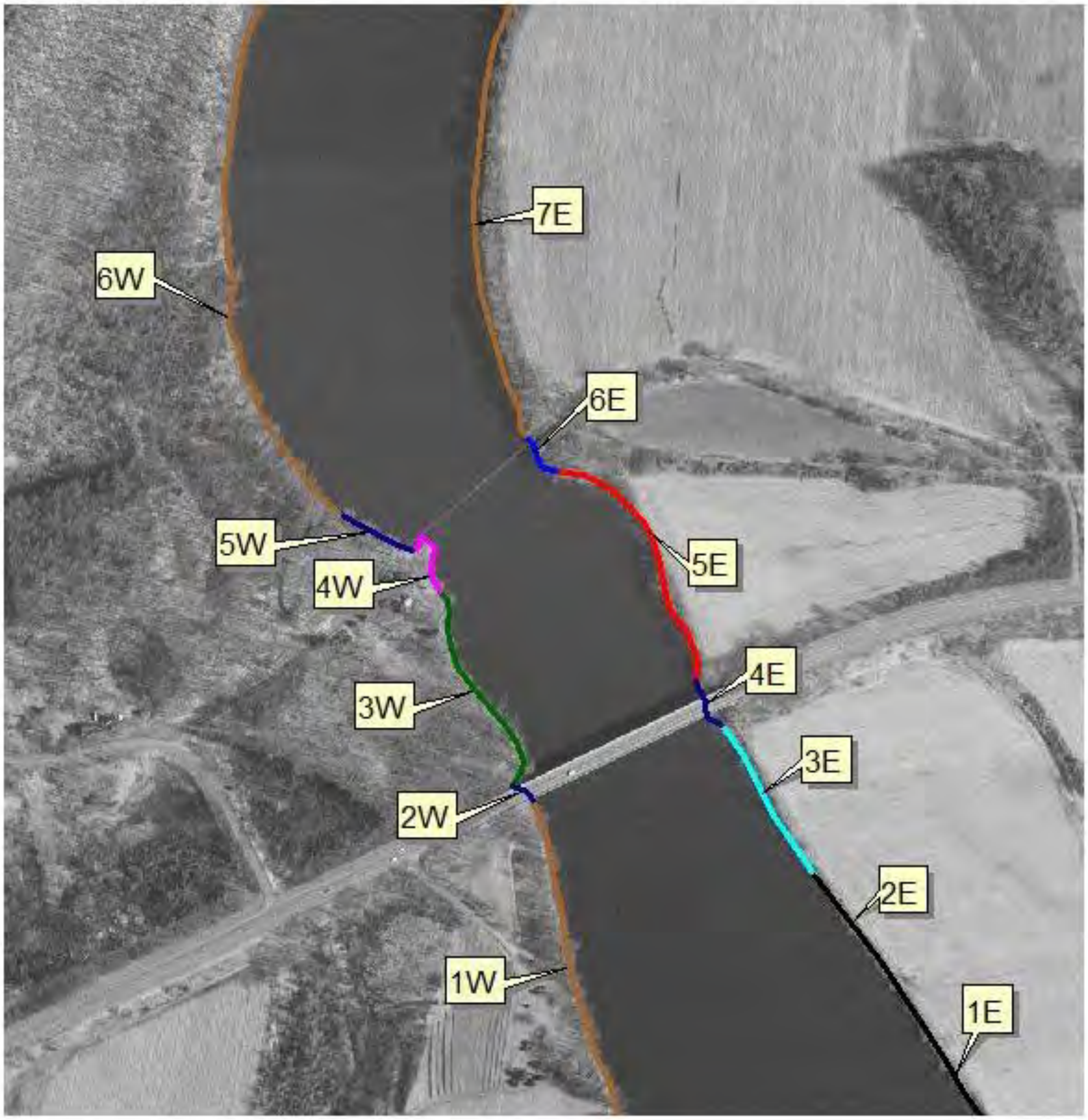


Figure 4. Riverbank Characteristics near Route 10 Bridge

4. Data

4.1 Channel Geometry Data

A bathymetric survey of the entire Turners Falls Impoundment was conducted by Hydroterra Environmental Services between July 30 and August 5, 2006. The bathymetric data were linked with available topographic data (USGS 10 m Digital Elevation Model [DEM] and the 1:5000 Massachusetts Digital Terrain Model [DTM]) to create a full set of channel geometry in the form of cross-sections that include the river bed, river banks and flood plain. The datum used for the combined data is the North American Vertical Datum 1988 (NAVD1988). These data were used to develop two hydraulic models including a one-dimensional model (HEC-RAS) and a two-dimensional model (River2D). Hydraulic modeling was conducted by Woodlot Alternatives ("Connecticut River Hydraulic Analysis Vernon Dam to Turners Falls Dam," 2007). Figure 5 presents a segment of the cross-sections for the HEC-RAS model and inundation at the 100-year flood level (indicated in blue) in the vicinity of the Route 10 Bridge, noting that the bridge is 56,986.3 feet or approximately 11 miles upstream of the Turners Falls Dam.

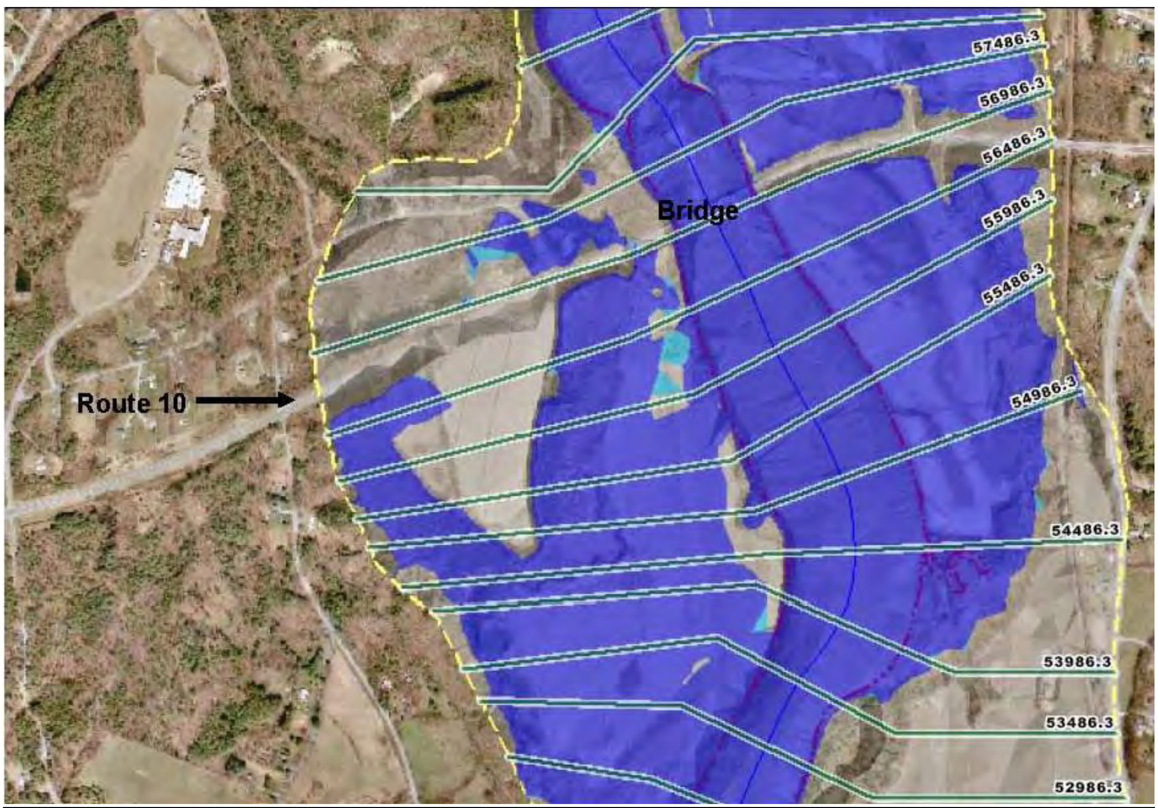


Figure 5. Cross-sections upstream of Turners Falls Dam near the Route 10 Bridge (after, Woodlot 2007)

In addition to 2006 bathymetry and channel geometry data developed for hydraulic modeling, several cross-sections (see Figure 6) have been surveyed in the Route 10 Bridge area (cross-sections 5A, 5B, 5D, 5E, and 5C). These cross-sections are part of the set of monumented cross-sections that are surveyed routinely by a surveyor contracted by FirstLight to monitor changes in riverbank geometry. The survey of these cross-sections began in 1990 and was repeated in 1992, 1993, 1995 – 2000 (twice each year), and 2001 – 2008 (annually). Cross-section 5A is located about 1200 feet upstream of the bridge and extends in a perpendicular direction across the river. Cross-sections 5B, 5D, and 5E start on the east bank about 500 feet upstream of the bridge. These are partial cross-sections that fan out to provide a range of locations out into the river. Cross-section 5C is located about 850 feet downstream of the bridge and extends perpendicularly across the river.

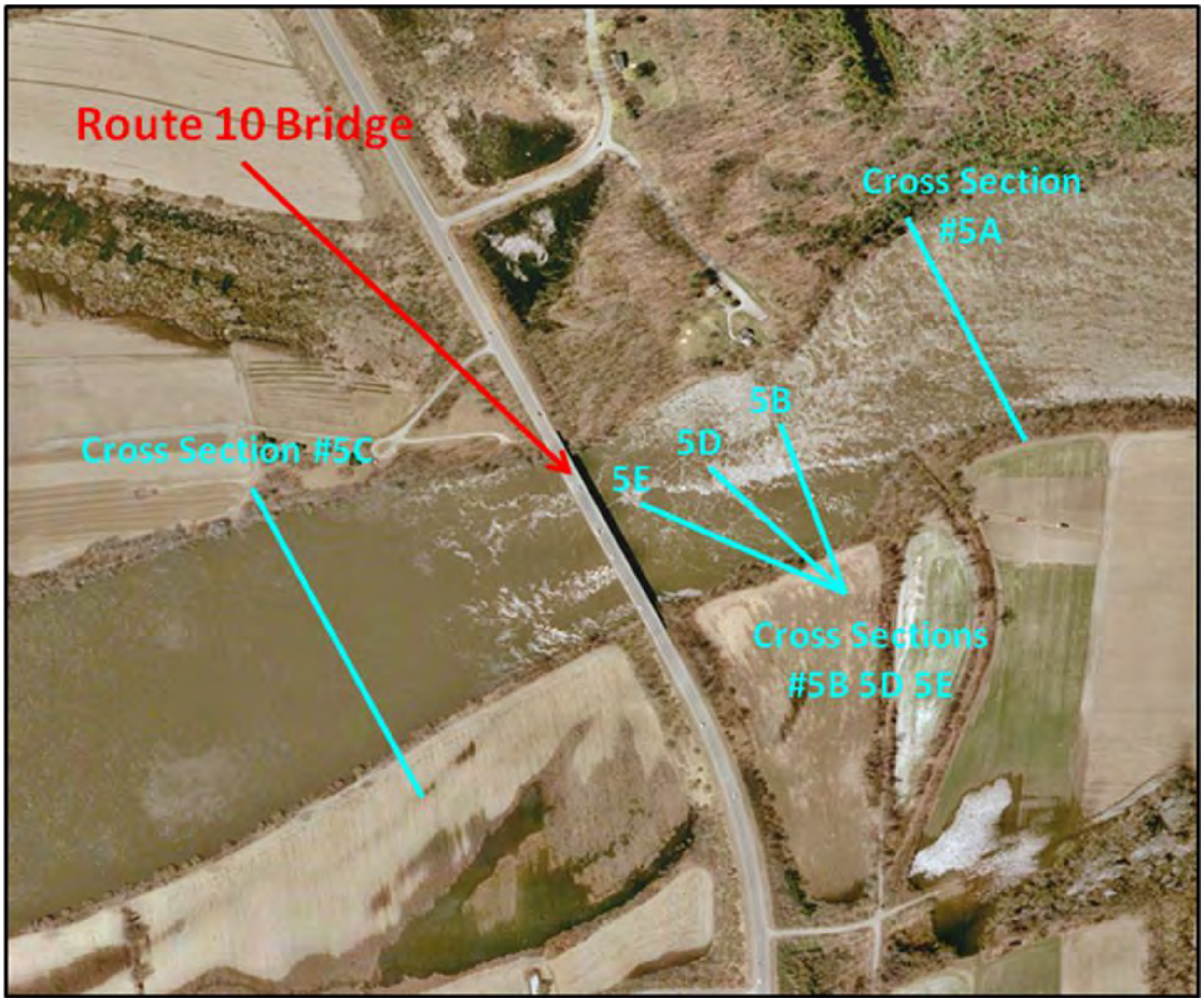


Figure 6. Cross Section Locations near Route 10 Bridge (after North by Northeast, 2004)

A comparison of cross-section graphs through the 1990s (1990-1997) shows changes in cross-sections at the surveyed locations (see Appendix A "Long Term Riverbank Plan for the Turners Falls Pool of the Connecticut River," Simons & Associates, 1998). At 5A, the data show very little change in the cross-section below the typical impoundment level. Near to above the typical water level, there appeared to be some fluctuation in bank line that appears to vary with some aggradation and some degradation. At cross-section 5B on the east bank, there appears to be some bank erosion of the near vertical upper bank of something on the order of about 10 feet horizontally. 5C shows relatively small changes for between all but one of the surveys. Likewise, 5D shows no significant changes. 5E shows a couple of feet of change on the west bank.

Some comparisons of the surveyed cross-section data (routine monitoring sections) with the bathymetric survey combined with topographic data (for hydraulic modeling) were made as shown in Appendix B. Cross-section 5A appears to be close to the location of cross-section 58486 in the HEC-RAS hydraulic model. From a general perspective, the overall width, depth, and shape of the two cross-sections are quite similar. Cross-section 5C appears to lie between HEC-RAS cross-sections 55986 and 56486. The graph of all three cross-sections plotted together shows that cross-section 5C lies essentially between the two HEC-RAS cross-sections in terms of overall width, depth, and cross-sectional shape. Thus, the surveyed cross-sections suggest that the channel geometry used in modeling reasonably represents the geometry of the Connecticut River in this reach.

4.2 Hydraulic Data

Some hydraulic data were collected in the vicinity of the Route 10 Bridge. This data collection effort focused on near-bank velocity since the near-bank velocities immediately affect the potential for erosion and transport of sediment. Data collection occurred on several occasions in the 1990s as well as in 2008. The hydraulic data collected in the vicinity of the Route 10 Bridge are found in Appendix C.

Some of the highest velocities near the banks of the Connecticut River in the Turners Falls Impoundment are found adjacent to the rock outcrop on the west bank of the river upstream of the bridge. For example, a velocity of 3.47 feet per second was measured at the water surface about 1 foot from the west bank on July 26, 2008 (when the mean daily flow at Walpole was 40,900 cfs and at Montague was 54,000 cfs based on data from the United States Geological Survey [USGS]). Flows at this level are significantly greater than needed for maximum power generation capacity at Turners Falls and Northfield Mountain but are below the normal peak flows that are typically experienced on an annual basis (approximately 64,000 cfs at Walpole and 91,000 cfs at Montague). Velocities measured off this rocky point are frequently 5 to 10 times greater, if not even more; compared to most near-bank velocity data in the Turners Falls Impoundment. The high near-bank velocity vector oriented strongly across the river plays a role in the formation of a large eddy in this reach. Velocities along the rest of the riverbanks in this reach are considerably lower, typically a few hundredths to a few tenths of a foot per second in the near-bank region. This is partially due to woody debris that disrupts the velocity near the banks along other segments of the river. Where there is no woody debris, velocities tend to be higher (as indicated by data collected adjacent to the banks with the USACE bank protection as well as other areas that are similarly protected).

Velocity data were collected in the vicinity of the Route 10 Bridge at flows ranging from about 2,800 cfs to 70,000 cfs at the North Walpole USGS gage (upstream of Vernon Dam) with corresponding flows ranging from 3,900 cfs to 86,000 cfs at the Montague USGS gage. The drainage areas at the North Walpole and Montague USGS gages are 5,493 and 7,860 square miles, respectively. While the velocity data cover a relatively wide range from quite low to approaching or exceeding the average annual peak flow, no velocity data were collected in the higher flow ranges significantly greater than the average annual peak or higher. The data indicate that as flow increases there is a general increase in near-bank velocities; with reason to believe that at higher flows, velocities would continue to increase.

4.3 Bank Material

Samples of bank material were collected on the Connecticut River in the vicinity of the Route 10 Bridge (see Figure 7 for location of samples).

FIGURE 7. Sediment Sample locations

These sediment samples were analyzed by Simons & Associates using standard dry sieving techniques with a mechanical shaker and standard mesh sieves. The particle size distribution curves are found in Appendix D. Table 1 summarizes the data for the particle size distribution curves for samples collected in the vicinity of the Route 10 Bridge. The sediment diameter (in mm) for which X percent of the sample is finer (i.e., 16, 50 and 84), as well as an indication of the minimum and maximum size of sediment in the sample; are provided in the table. In other words, D_{16} is the sediment diameter for which 16 percent of the sample is finer (by weight).

Table 1. Bank Material (mm)

Sample Number	Sample Description	D_{min}	D_{16}	D_{50}	D_{84}	D_{max}
1	D/S Bridge LDB (lower bank mtl on top of USACE concrete)	<0.0625	0.081	0.15	0.21	<0.5
2	U/S Bridge LDB (lower bank)	<0.0625	0.07	0.12	0.21	<0.5
3	D/S Bridge RDB (beach)	<0.0625	0.11	0.18	0.22	<0.5
4	D/S Bridge RDB (upper bank – Bennett Meadow)	<0.0625	<0.0625	0.19	0.43	<1.0
5	U/S Bridge LDB (beach)	<0.0625	0.08	0.16	0.23	<2.0
6	D/S Bridge RDB (beach – Bennett Meadow)	<0.0625	<0.0625	0.08	0.13	<0.5

Note: U/S – upstream, D/S – downstream, LDB – left descending bank, RDB – Right descending bank.

The average of the D50 (median sediment diameter) in Table 1 is 0.15 mm. A sediment diameter of 0.15 mm is classified as fine sand. The particles range from silt to coarse sand.

5. Flow Characteristics

Flow characteristics result from a combination of unique geomorphic and hydraulic conditions in the vicinity of the Route 10 Bridge:

- In approaching the Route 10 Bridge, the channel width narrows significantly pinched by the rock outcrop that juts out into the river on the west bank and the rock abutment from the old Bennett Meadow Bridge on the east bank.
- The river channel bends sharply to the left (looking in the downstream direction) as the river must pass by the rock outcrop on the west bank.
- The narrowing of the river and bending to the left accelerates the flow and causes turbulence.

- At the same time, the channel bed drops rapidly; reaching a maximum depth of about 54 feet about 500 feet upstream of the Route 10 Bridge (see Figure 8)
- Just as rapidly as the river deepens, it then shallows to a depth of about 16 feet as the river bends slightly back to the right.
- A large eddy forms along the east bank of the river between the old Bennett Meadow bridge abutment and the Route 10 Bridge abutment.
- The Route 10 Bridge Piers cause some obstruction to the flow and cause additional turbulence.

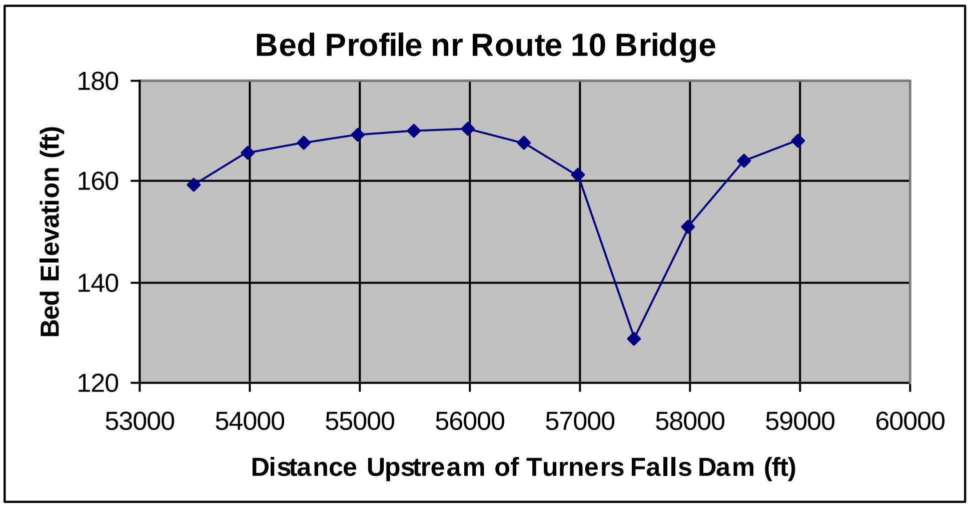


Figure 8. Riverbed Profile near Route 10 Bridge (from cross-section data in Woodlot, 2007)

While there are several deep areas along the Turners Falls Pool, it should be noted that the deep area just upstream of the Route 10 Bridge is the deepest area over a distance from the confluence of Millers River into the Connecticut River to the Vernon Dam, a distance of approximately 16 miles.

As can be seen in Figure 9, a recent aerial photograph (MASSGIS, photo date April 2001) shows turbulence at the water surface in the reach of river upstream and through the Route 10 Bridge due to the bend, constriction and narrowing through the rock outcrop and old bridge abutment, acceleration of flow, extreme and rapid depth changes, separation zone and eddy, and the bridge piers. Once the flow has gone through these intense hydraulic changes, note that downstream of the Route 10 Bridge, the flow becomes much more tranquil as indicated by the much calmer water surface.

Figure 9. Flow characteristics in the vicinity of the Route 10 Bridge

There are few reaches of the river that experience such a concentration of factors including significant direction change, significant narrowing and expansion, rapid depth changes, construction of bridges, as well as a wide range of bank material (from rock and concrete from river bank protection measures, rock outcropping to sand).

6. Hydraulic Analysis

Hydraulic analysis based on the two hydraulic models developed by Woodlot (2007) was conducted by Simons & Associates using both models. Woodlot utilized the HEC-RAS model to develop boundary conditions for segments of the RIVER-2D model (The Turners Falls Impoundment had to be broken into several segments to allow the two-dimensional model to run with sufficient detail over this 20 mile reach of river). These hydraulic models compute water surface elevations, depths and velocities of flow over a range of flows. This allows simulation of hydraulic conditions at higher flows than data that were collected for calibration of these models (see Woodlot, 2007 for discussion of the calibration process and other details of these models).

The two-dimensional model (RIVER-2D) computes hydraulic variables including velocity laterally across the channel and output of such models typically includes velocity vectors showing the direction and magnitude of the velocity. Such a model can simulate the formation of eddies, where flow swirls in a circular pattern counter to the river's main direction of flow – an observation of flow conditions found in the vicinity of the Route 10 Bridge. Figure 10 is an example of the simulation of eddy formation shown in the model output, in this case where Millers River discharges into the Turners Falls Impoundment. The arrows show the velocity vectors which indicate the direction and magnitude of velocity (by the length of the arrow). The magnitude of the velocity is also shown by the color, where lower velocities are blue and higher velocities are indicated by yellow, orange and red.

As noted above, an eddy is a circular pattern of flow that separates or breaks away from the main direction of flow and flows towards the riverbank, then upstream along the bank, before completing a circular pattern returning again to a downstream direction farther away from the bank. Eddies typically form when there is an obstruction in the flow pattern or a relatively abrupt change in the bank alignment such that the main current continues in its ongoing path and cannot immediately follow the obstruction or change in bank alignment.

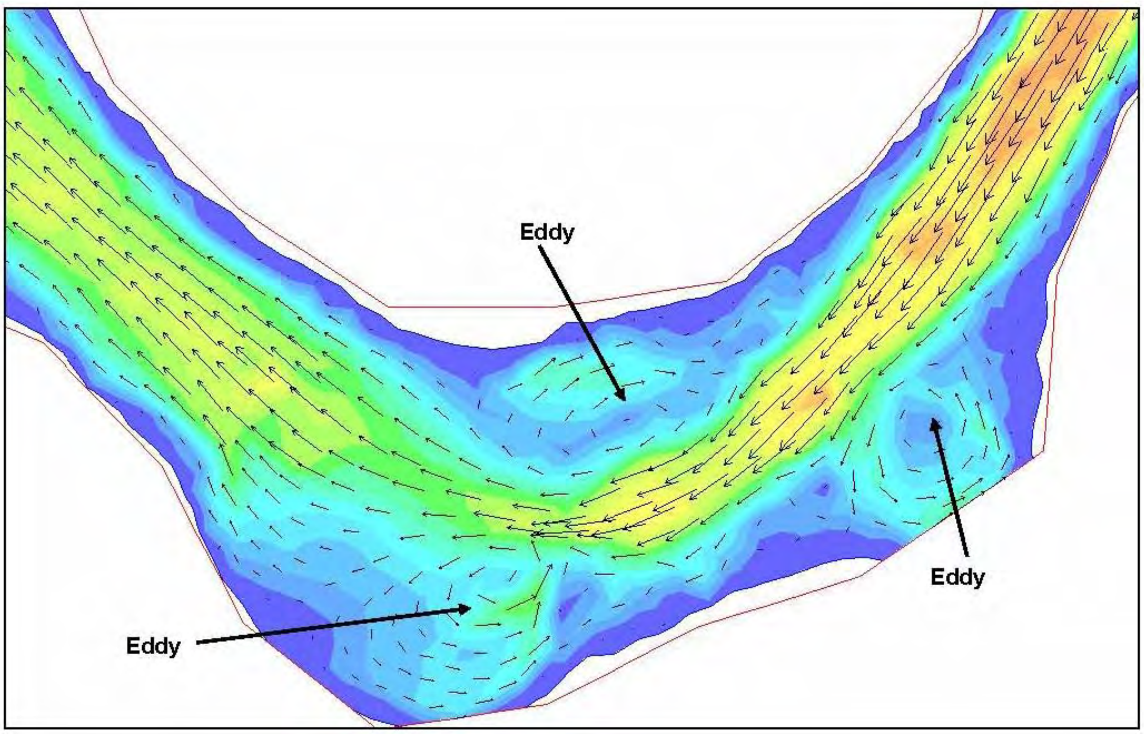


Figure 10. Eddy formation near confluence with Millers River (based on model results from Woodlot, 2007)

A range of flood flows were simulated in the two-dimensional hydraulic model as presented in Table 2. The average flow between North Walpole and Montague was used as input to the model.

Table 2. Flows used in Hydraulic Models

Flow Gage	**Flow (cfs)**			
Return Period (years)	1.05	2	10	100
North Walpole USGS Gage	39,460	64,060	84,730	100,600
Montague City USGS Gage	53,630	86,450	129,400	183,500
Average	46,545	75,255	107,065	142,050

Figure 11 is an example of the velocity vectors computed by this model showing the formation of eddies in the vicinity of the Route 10 Bridge for the 100-year flow. The eddies are shown by the black velocity vectors showing a circular pattern near both riverbanks just downstream of the rocky point and between the old Bennett Meadow Bridge and the Route 10 Bridge. Appendix E presents the results of the River-2D model in this reach of interest for the 1.05 to 10-year events. The magnitudes of the velocities are shown by the length of the black velocity vectors and also by the colors. The blue color represents low velocities while the red color represents high velocities (ranging from 0-3 feet per second). Note on Figure 11 the small white area outlined in red representing the rock outcrop. The model shows that the rock outcrop accelerates the flow (as noted by the red shading and the longer arrows). Note the formation of eddies (circulatory pattern of velocity vectors) just downstream of the rock outcrop adjacent to both banks of the river. Acceleration of flow and the formation of eddies on one or both banks occurs for other flows (see Appendix E) and is consistent with flow patterns observed in this part of the river.

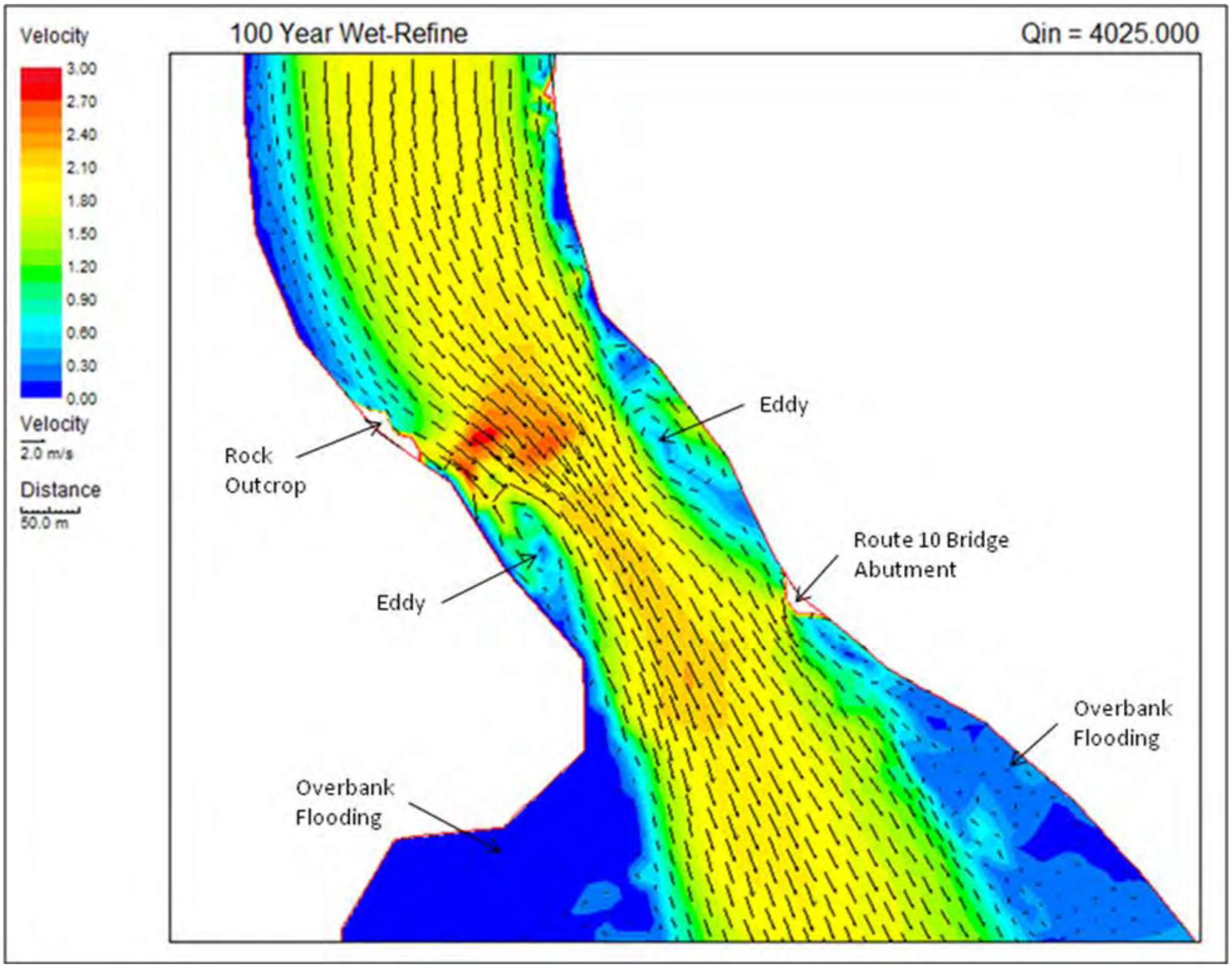


Figure 11. River-2D Results, 100-Year Flow

7. Analysis of Riverbank Erosion

The segments of riverbank that have been stabilized or are founded upon rock outcroppings are currently stable and no significant erosion is evident. The artificially stabilized areas are all in generally good condition and are meeting their intended function of preventing significant erosion and movement of the riverbanks.

On the right descending bank (west) downstream of the bridge, the lower and upper riverbanks consist primarily of fine sand. Sand can erode and be transported at relatively low velocities. A relationship has been developed between the shear stress caused by the flow and the size of sediment that can be moved. The shear stress that just begins to erode and transport a particular sediment size is called the critical shear stress. This is determined by the Shield's criteria.

$$\tau_c = \tau_*(\gamma_s - \gamma)d_s$$

Where τ_c is the critical shear stress, τ_* is the dimensionless Shield's parameter (typically set at 0.047 based on flume data), γ_s is the specific weight of sediment, γ is the specific weight of water and d_s is the sediment size.

The shear stress generated by flowing water can be calculated as follows:

$$\tau = (1/8)\rho f V^2$$

Where τ is the shear stress, ρ is the density of water (γ/g), f is the Darcy-Weisbach friction factor, and V is the velocity of flow.

The combination of these two equations can be used to calculate the velocity required to move a certain size of sediment or conversely, the size of sediment that can be moved for a given velocity.

Most of the riverbanks in the vicinity of the Route 10 Bridge have been protected against erosion. Most of this erosion protection appears to be in good condition and is functioning properly. As a result, the stability analysis focuses on the segment of riverbank that is currently experiencing significant erosion (segment 5E).

Fortunately, for much of the time, the near-bank velocities are very low and do not cause significant erosion. The two-dimensional model shows velocities of approximately 1 fps near the east bank where significant erosion is occurring for the 1 and 2-year flows and approximately 1.5 fps for the 10-year flow (see Appendix E). Near bank velocities are also approximately 1.5 fps for the 100-year flow (see Figure 6). The critical velocity when erosion would begin, based on the sizes of sediment found in the eroding area, is about 0.3 to 0.45 fps (for a range of reasonable critical shear parameters). Thus, the near bank velocities significantly exceed critical shear for the sizes of sediment found in this area thereby resulting in erosion at these higher flows. Because velocities (at high flow conditions) on the east riverbank between the Route 10 Bridge and old Bennett Meadow Bridge (Segment 5E) exceed the critical shear stress, sediment erosion and transport occurs.

For other unprotected riverbanks (segments 1W, 5W, 6W, and 7E) near-shore velocities for the 100-year flood range from about 0.5 to 1.0 fps (based on RIVER-2D). Based on the modeling results, it appears that near-shore river velocities generally meet or exceed critical velocities (those causing erosion) for the 2-year event and higher flows. These velocities are mitigated, however, by the existing vegetation and moderate riverbank slopes. As a result, riverbank stability for these other segments is generally better. There is a narrow slide that exists at the downstream end of segment 6W. Overall, for these other segments, riverbanks are sufficiently stable that no erosion protection has been considered necessary.

On the left descending bank (east) the segment between the rip-rap toe of the old bridge and the rip-rap toe of the new bridge (segment 5E) is experiencing active erosion. This is the location of the eddy where velocities and turbulence are increased and vegetation is relatively sparse; offering little protection from current or wave action. This is the primary area of concern regarding riverbank stability and ongoing future erosion in this reach of the river. Without stabilization measures, erosion will likely continue until enough material has fallen from the upper bank to form an adequate beach at the toe of the slope ultimately resulting in a sufficiently flat upper bank to form along with a beach so that vegetation can naturally colonize the area eventually forming a more stable riverbank.

8. Causes of Erosion

Erosion occurs whenever the forces that cause motion of sediment exceed the forces that resist motion. The forces that work on sediment particles or masses of particles include shear stress caused by flowing water, the forces due to wave impact and associated rapid changes in water level that occur virtually instantaneously or at most over seconds of time, gravity, and hydrostatic forces of fluctuating water levels that occur over hours, seepage, and other similar and related forces.

The riverbanks in the vicinity of the Route 10 Bridge experience all the general causes of erosion in the Turners Falls Impoundment. In addition to these general factors, the riverbanks in this segment of the river also experience the additional effect of eddies. Eddies are a recognized cause of riverbank erosion. In a study entitled "Scales of Bank Roughness and Their Relationship to Bank Erosion Processes," (by Erik Hankin and Karen Prestegaard, 2008); the authors state, *"bank protrusions can generate macroturbulent eddies along banks . . . and that these eddies can generate significant bank erosion."* In "Streambank Protection Guidelines," (1983) by the U.S. Army Engineer Waterways Experiment Station, eddies are described and they state, *"The eddy can cause severe erosion if the bank is not properly protected."*

Perhaps the area of most significant erosion along the Turners Falls Impoundment is located just downstream of the Vernon Dam on the left descending bank (east). Simons & Associates visited the site and conducted an evaluation of erosion at this location for New England Power in 1996. In this evaluation we stated, *"As water flows downstream of the dam along the left side (looking downstream) it forms a large eddy which circulates to the left in a counter clockwise direction into and around the eroded area."* This large eddy has caused what is the most significant erosion of any part of the Turners Falls Impoundment. Figure 12 shows a water level view at relatively low flow and Figure 13 is an aerial view of the erosion caused by the eddy as high flows are discharged from the Vernon Dam spillway. As can be seen in Figure 13, a white-water jet is being discharged over the spillway at high velocity that induces a strong eddy and associated turbulence.

Figure 12. Riverbank Erosion downstream of Vernon Dam

Appendix F presents additional photographs of this very significant eddy-induced erosion taken from boat and ground. Based on the aerial photo (April 2001 in the Massachusetts GIS), the toe of the eroded slope is about several hundred feet back from a straight line along the bank from the left abutment of the Vernon Dam (looking downstream) to the point on the bank downstream of the eddy-induced erosion where the power-line tower is located. The horizontal distance along this eroded slope from the toe to the top is about 150 feet. This eroded bank is about 90 feet high. This segment of eroded riverbank is larger than any other eroded bank in the Turners Falls Impoundment. These photos clearly show the erosive effect of such a large-scale eddy on the riverbanks in the Turners Falls Impoundment and confirm that significant erosion is occurring independent of Turners Falls and Northfield Mountain operations since this erosion is located far away from the effect of these projects where backwater and fluctuations due to these projects are not significant.

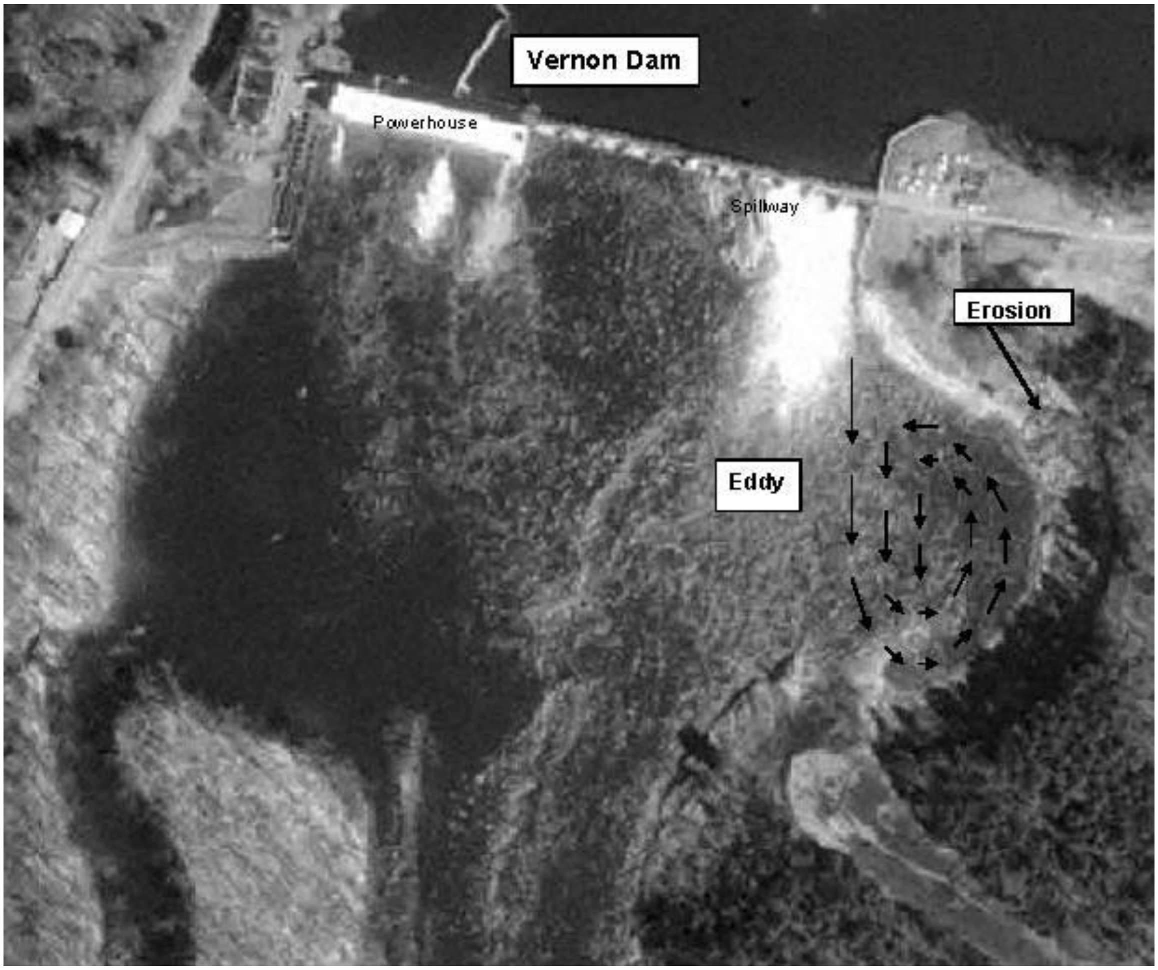


Figure 13. Eddy-induced erosion downstream of Vernon Dam

Field ("Fluvial Geomorphology Study of the Turners Falls Pool on the Connecticut River Between Turners Falls, MA and Vernon, VT," 2007 discusses the erosive effect of eddies specifically on the Connecticut River at the Route 10 Bridge, *"Areas of intense erosion occur where eddies are well developed such as the Route 10 Bridge . . . as the eddy currents impinge directly on banks composed of floodplain sediments."* The existence of large-scale eddies that circulate and intensify velocities against the riverbank at this location are a primary cause of erosion. The fact that very significant eddy-induced erosion is occurring in another segment of the Turners Falls Pool and the existence of eddies at the Route 10 Bridge suggests that these hydraulic conditions resulting in eddies are the primary and dominant cause of erosion at this location.

In observing the riverbanks at the Route 10 Bridge, we have seen boat waves cause erosion in Segment 5E). Waves impacted the toe of the slope and undercut small areas causing small blocks of sediment to collapse and fall and create other unstable blocks ready to fail (see Appendix G, images 138, 142, and 143 from Segment 5E). Thus; boat waves, in addition to eddies at this location, play a role in creating instability in this segment of river. The adverse effect of boat waves or wakes is acknowledged by the Connecticut River Joint Commissions supported by Rivers and Trails Conservation Assistance Program of the National Park Service through the Connecticut River Valley Partnership Program in a guide entitled, "River Dynamics and Erosion." This document states,

> *Waves or wakes washing away soil at the base of the bank will undercut it, particularly if it is unvegetated, allowing the unsupported bank material above to collapse into the stream.*

The effect of waves on erosion is documented in the scientific literature, an example of which is found in "Experimental measurements of river-bank erosion caused by boat-generated waves on the Gordon river, Tasmania," 1993, Gerald C. Nanson, Axel Von Krusenstierna, Edward A. Bryant and Martin R. Renilson. They state,

> *Erosion of natural river banks by boat-generated waves is an increasingly serious problem on the navigable reaches of many rivers.*

The particular segment currently experiencing erosion (east bank between the Route 10 Bridge and the old Bennett Meadow Bridge) is also affected, to some smaller degree, by the fact that riverbanks upstream and downstream of this segment as well as across the river either consist of rip-rap bank protection or rock outcrop. While advocating for rivers and associated habitat, the previously referenced document ("River Dynamics and Erosion") is a guide to develop adequate understanding of the river and whether it might be appropriate to attempt a riverbank stabilization project. In this document they state the following:

> *A major difficulty in addressing erosion is that some solutions can have unintended effects. For example, if the river is prevented from overtopping its banks in a floodplain, this water will move to downstream floodplains where it may cause increased erosion and flooding. A bank stabilization project in one location may worsen erosion on someone else's property downstream, since bank erosion is a natural way in which a stream dissipates energy. In some circumstances, it is better to leave the situation alone rather than interfere with the complex dynamics of the stream. Interrupting stream channel movement is costly, and may be futile in the long run.*

The concept that stabilizing a riverbank in one area can cause problems in another was echoed by the Vermont Agency of Natural Resources (2007) when discussing stabilization or restoration projects by "*'fixing,' and often re-fixing, the location of the channel,* but in reality end up "*perpetuating the conflicts at the restoration site or exacerbating the conflicts somewhere downstream."*

Because of the eddies near the Route 10 Bridge, and all of the adjacent riverbanks have been stabilized and precluded from any lateral adjustment, the riverbank between the old

Bennett Meadow Bridge and the Route 10 Bridge along the east side of the river whose banks consists of fine sand on steep to near vertical slopes without sufficient vegetation is subject to ongoing erosion.

9. Conclusions

Riverbank erosion in the vicinity of the Route 10 Bridge is primarily the result of a combination of unique flow characteristics that cause eddying and turbulence that is further exacerbated by boat waves and the hardening of riverbanks upstream, downstream and across the river from the eroding segment as supported by the following points:

- Based on evaluation of aerial photographs from 1929 through 1990, riverbank erosion has been occurring throughout this period of time in the vicinity of the Route 10 Bridge – long before 1972 when the Turners Falls dam was raised and Northfield Mountain was constructed and began operation.
- Unique hydraulic conditions including a significant bend, channel narrowing constricted by a rock outcrop and an abutment from the old Bennett Meadow Bridge accelerating the flow velocity, a rapid change in depth from shallow to deep back to shallow; all combine to cause eddies and turbulence upstream of the Route 10 Bridge.
- Velocities frequently exceed the critical shear required to erode and transport sediment sizes found in the riverbanks.
- Boat waves have been observed causing erosion in this particular segment of the river.
- All areas of the river in the vicinity of the Route 10 Bridge have been protected against erosion focusing any potential for the river to adjust in just one segment, the east bank upstream of the Route 10 Bridge and downstream of the old Bennett Meadow Bridge abutment.
- Hydraulic conditions that induce eddies and turbulence immediately downstream of Vernon Dam due to operation of high flow sluice gates have also caused very significant erosion in the Turners Falls Impoundment. This location is far upstream of the Turners Falls Dam where backwater effects are minimal to non-existent and far upstream from the Northfield Mountain tailrace so water level fluctuations from the operation of this facility are minimal to non-existent. Erosion just below Vernon Dam indicates significant erosion caused by eddies and turbulence exists independent of Turners Falls and Northfield operations.

Because of these factors that cause erosion and the fact that similar factors cause erosion in another segment of the Turners Falls Impoundment that is unrelated to hydroelectric operations at Turners Falls and Northfield Mountain, these operations are not responsible for erosion at the Route 10 Bridge – consistent with previous consensus.

10. References

Connecticut River Joint Commissions, Rivers and Trails Conservation Assistance Program of the National Park Service through Connecticut River Valley Partnership, "River Dynamics and Erosion."

Field Geology Services, 2007, "Fluvial Geomorphology Study of the Turners Falls Pool on the Connecticut River Between Turners Falls, MA and Vernon, VT."

Hankin, Erik and Karen Prestegaard, 2008, "Scales of Bank Roughness and Their Relationship to Bank Erosion Processes."

Nanson, Gerald C., Axel Von Krusenstierna, Edward A. Bryant and Martin R. Renilson, 1993, Experimental measurements of river-bank erosion caused by boat-generated waves on the Gordon River, Tasmania."

Simons & Associates, 1998, "Erosion Control Plan"

Simons & Associates, 2012, "Hydraulic and Geomorphic Analysis of Erosion in the Turners Falls Impoundment of the Connecticut River."

Simons & Associates, 1998, "Long Term Riverbank Plan for the Turners Falls Pool of the Connecticut River."

U.S. Army Corps of Engineers Waterways Experiment Station, 1983, "Streambank Protection Guidelines."

Vermont Agency of Natural Resources, 2007, "River Corridor Planning Guide to Identify and Develop River Corridor Protection and Restoration Projects."

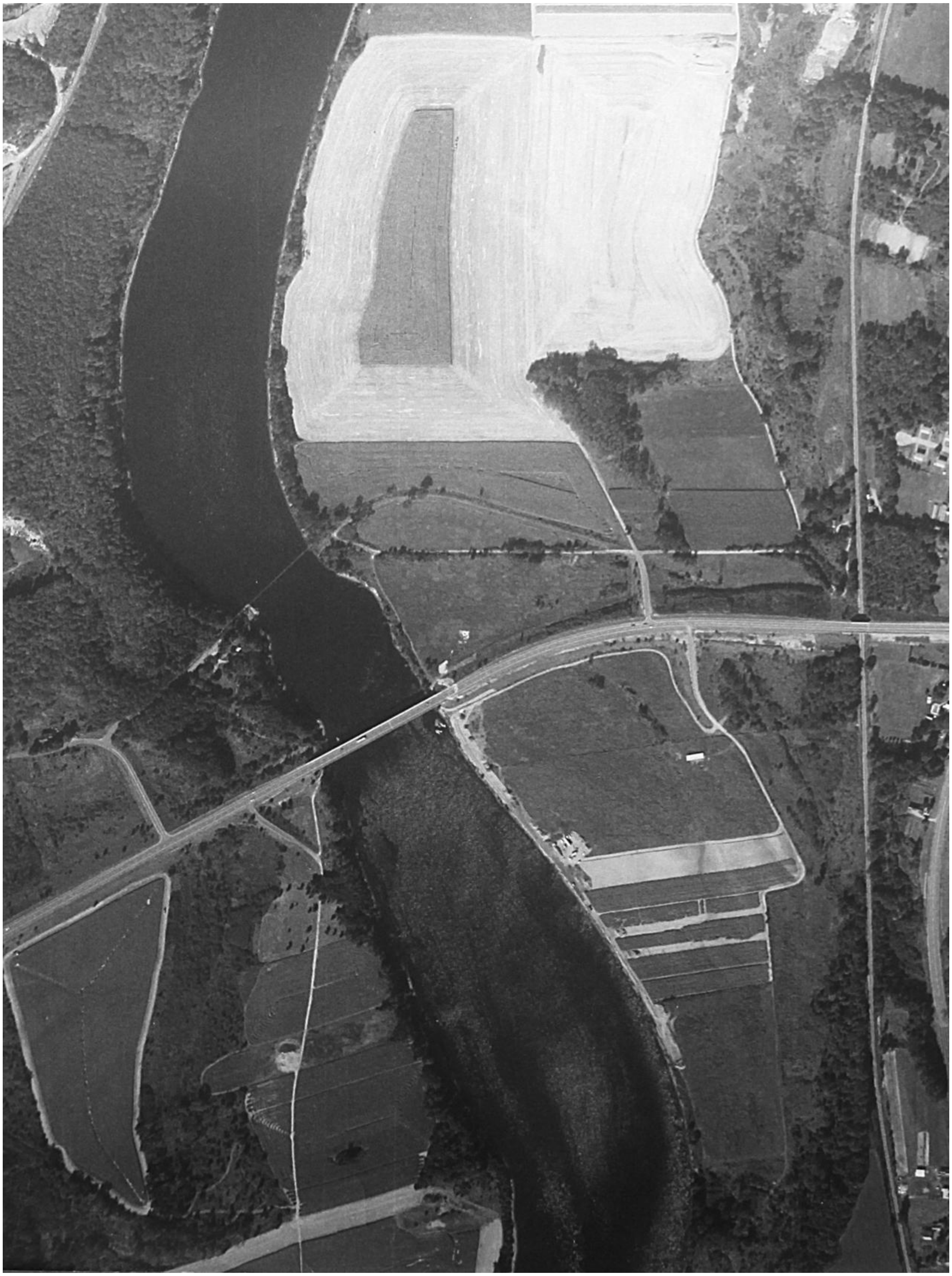
Woodlot Alternatives, 2007, "Connecticut River Hydraulic Analysis Vernon Dam to Turners Falls Dam."

Appendix A: Aerial Photos

Connecticut River, Bennett Meadow Bridge – 1929

Connecticut River, Bennett Meadow Bridge - 1939

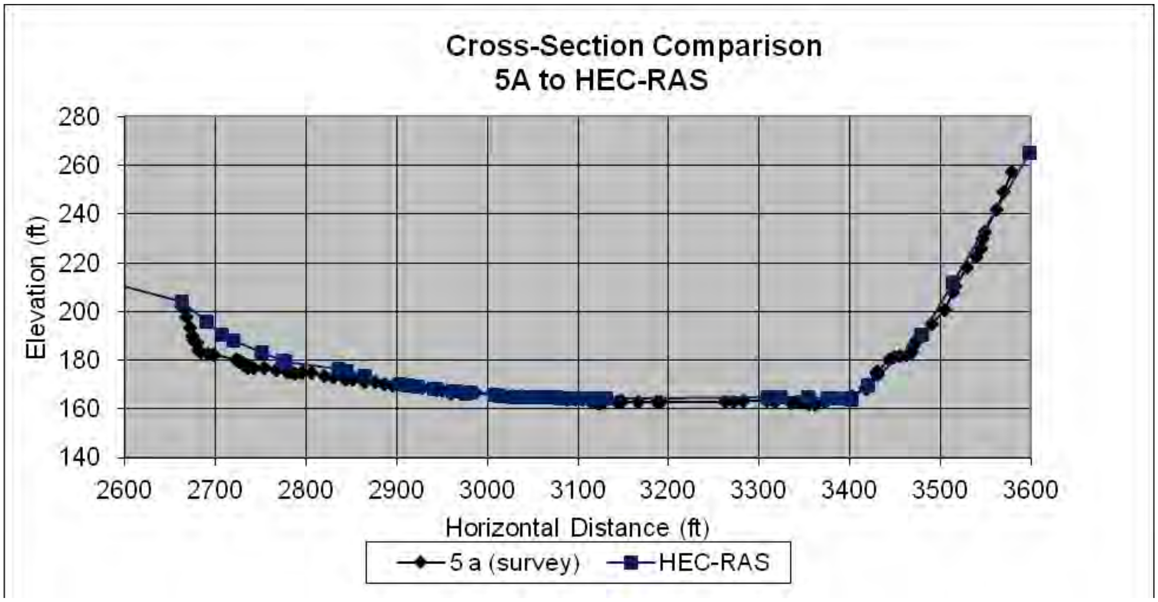
Connecticut River, Bennett Meadow Bridge – 1952

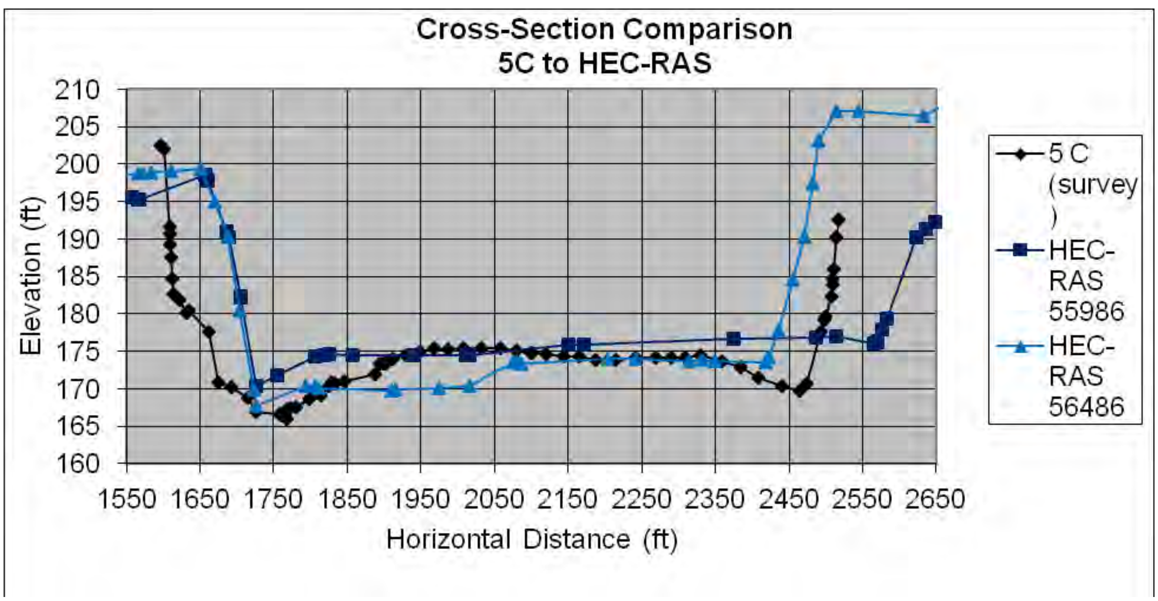


Connecticut River, Route 10 Bridge – 1980

Connecticut River, Route 10 Bridge – 1990

Appendix B: Cross-Section Data Comparison

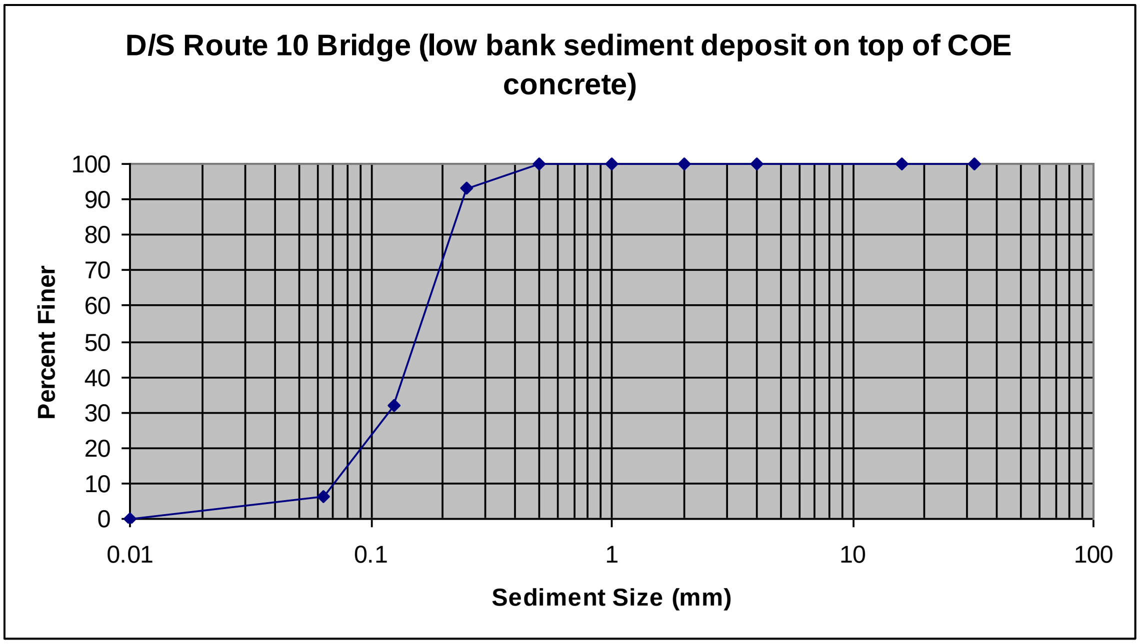


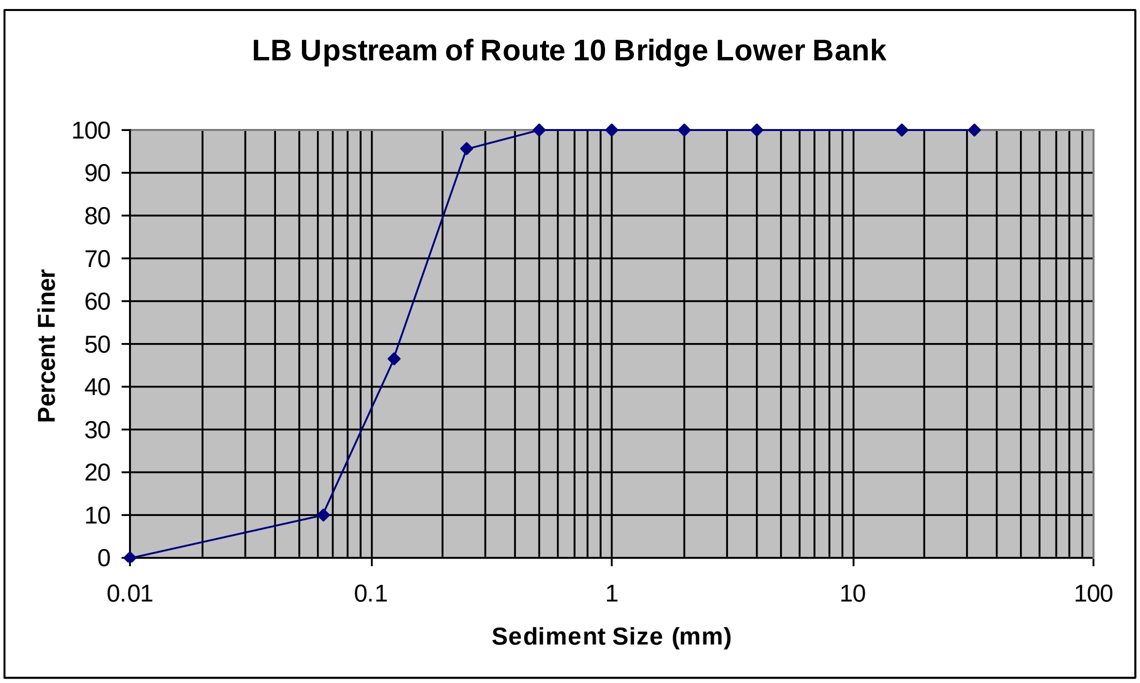


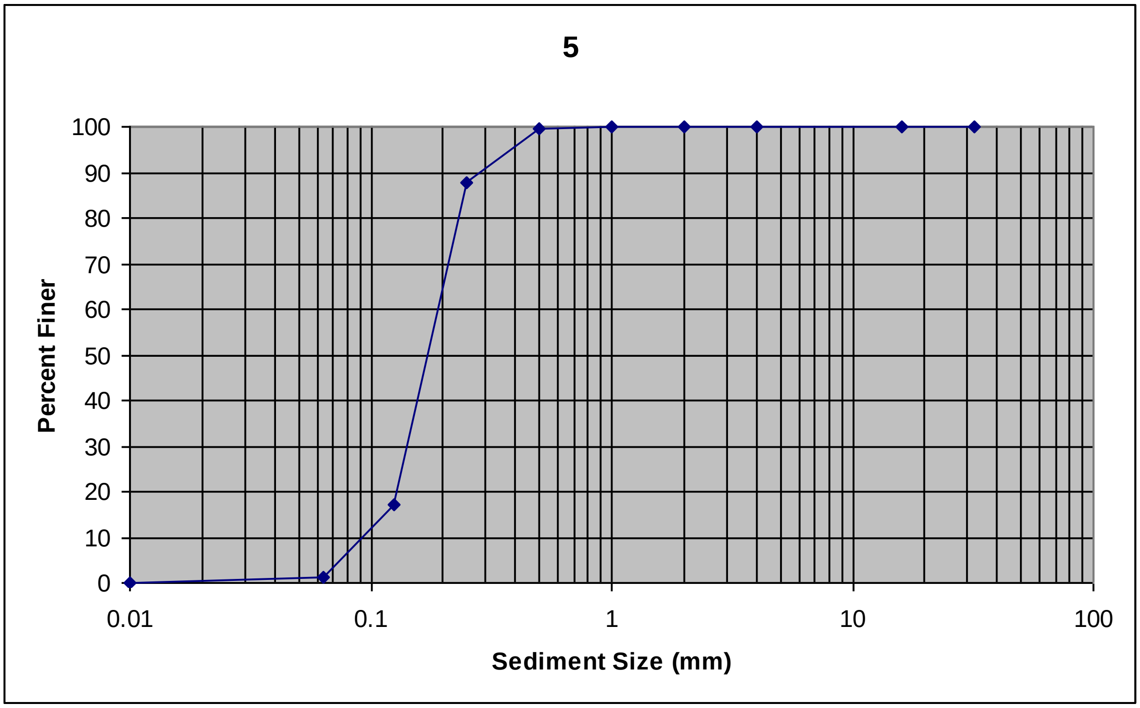
Appendix C: Hydraulic Data

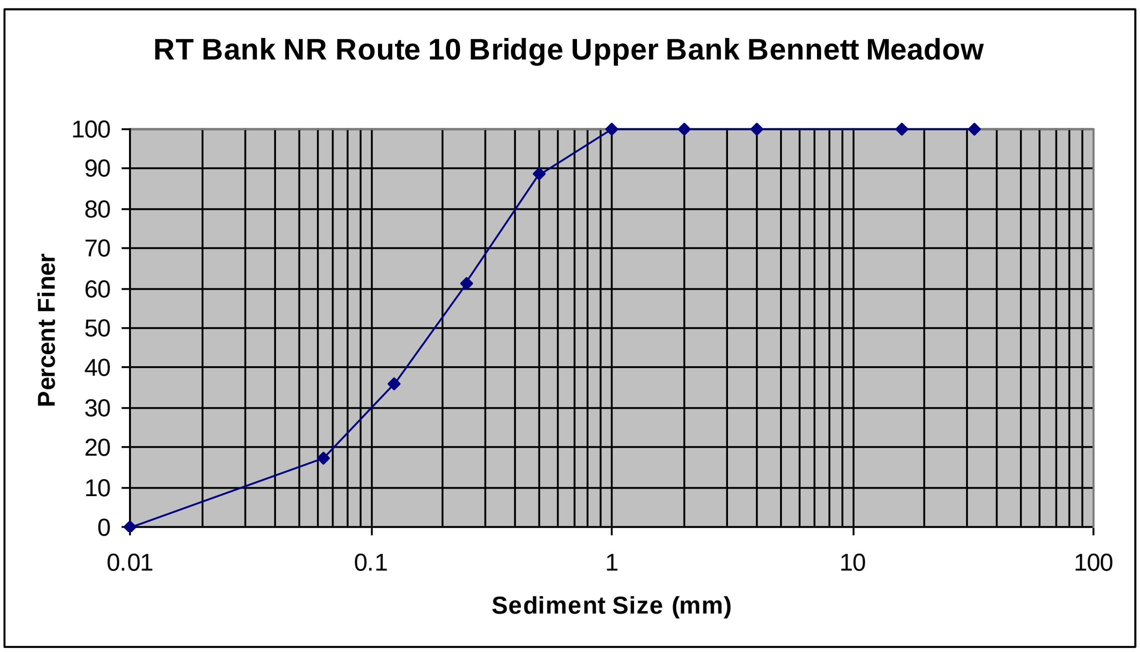
Date	Time	Location	Depth	V Surface	V.2	V.6	V.8	Mean
5/8/1997	17:10	5C-LB	2		0.4	0.24	0.15	0.2575
5/9/1997	9:52	5A-RB	1.3		-0.15	-0.14	-0.17	-0.15
5/9/1997	10:15	5B-RB	2		-0.05	-0.05	-0.2	-0.0875
5/9/1997	11:21	5B-LB	1			0.34		0.34
5/9/1997	11:41	5A-LB	1.2		-0.02	-0.02		-0.02
9/23/1997	13:30	5-LB	3.2			0.2		0.2
9/23/1997	13:42	5-RB	0.5			-0.03		-0.03
9/23/1997	14:00	5B-RB U/S CROOKER	3			-0.09		-0.09
9/23/1997	14:15	5B-LB ACROSS FROM CROOKER	0.5			-0.05		-0.05
9/23/1997	14:25	5A-RB	0.5			-0.04		-0.04
9/23/1997	14:35	5A-LB	1.3			-0.03		-0.03
1/10/1998	14:45	5A EAST BANK	1.5			0.01		0.01
1/11/1998		5B W. BANK						
1/11/1998		5C W. BANK						
1/11/1998	9:55	5B U/S CROOKER	1.3			-0.4		-0.4
1/11/1998	10:15	5C BENNETT MEADOW		0.01				0.01
1/11/1998	11:20	5C EAST BANK COE		-0.33				-0.26
4/4/1998	10:35	5C BENNETT MEADOW		-0.18				-0.114
4/4/1998	11:10	5B OLD BR. ABUTMENT	1			2.25		2.25
4/5/1998	10:20	5C BENNETT MEADOW		0.08				0.064
6/20/2008	12:30	RDB - Rocky point	2.8		1.4	1.1	1.32	
6/20/2008	15:50	LDB u/s Rte 10 br	0.4					0.1
7/26/2008	17:25	RDB - Rocky point	2	3.47	2.68	1.98	1.82	
9/30/2008	12:37	XS 5C RDB	1					0.15
9/30/2008	12:37	XS 5C RDB ~25 ft off-shore	3.2	0.57	0.54	0.47	0.44	
9/30/2008	12:37	XS 5C LDB	1.3					0.21
9/30/2008	12:37	XS 5C LDB ~25 ft off-shore	>4 (surf, 1 ft, 2ft, 3ft, 4 ft)	0.52	0.44	0.52	0.43	0.48
9/30/2008	12:55	XS 5B LDB	0.8					0.01
9/30/2008	12:55	XS 5B LDB ~25 ft off-shore	3.8	-0.15	-0.17	-0.15	-0.15	
9/30/2008	12:55	XS 5B RDB	0.3					0
9/30/2008	12:55	XS 5B RDB ~25 ft off-shore	4.2	-0.03	-0.01	0.01	-0.01	
9/30/2008	13:36	XS 5A RDB	0.5					-0.05
9/30/2008	13:36	XS 5A RDB ~25 ft off-shore	3	0.01	-0.06	-0.01	-0.03	
9/30/2008	13:45	XS 5A LDB	0.3					-0.04
9/30/2008	13:45	XS 5A LDB ~25 ft off-shore	2	0	0.01	0.03	0.04	

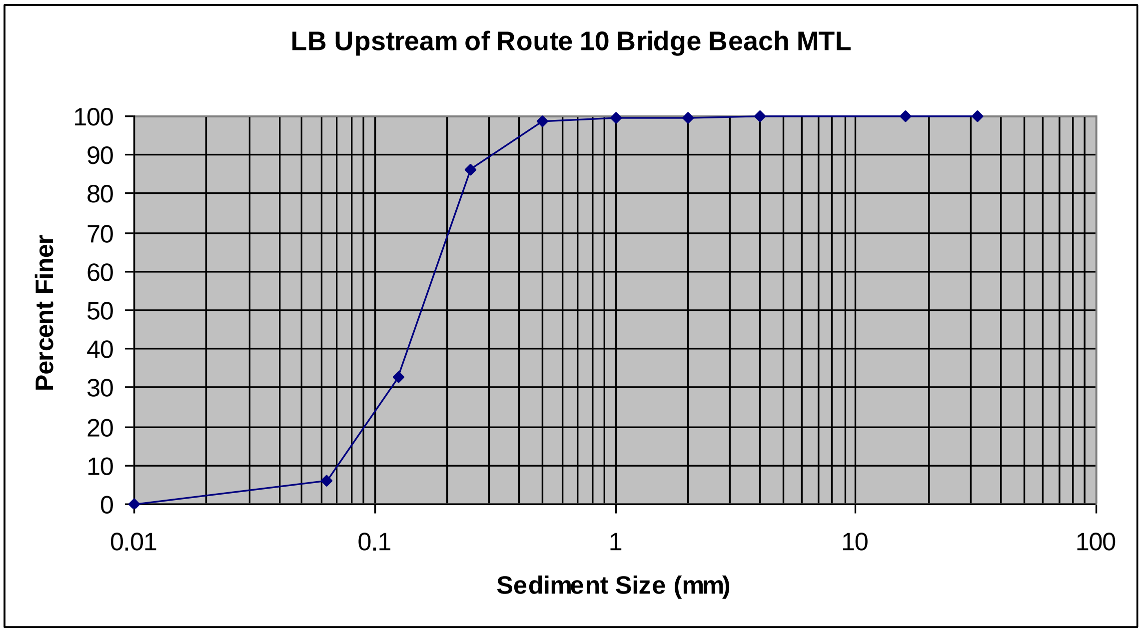
Appendix D: Sediment Data (Particle Size Distribution Curves)

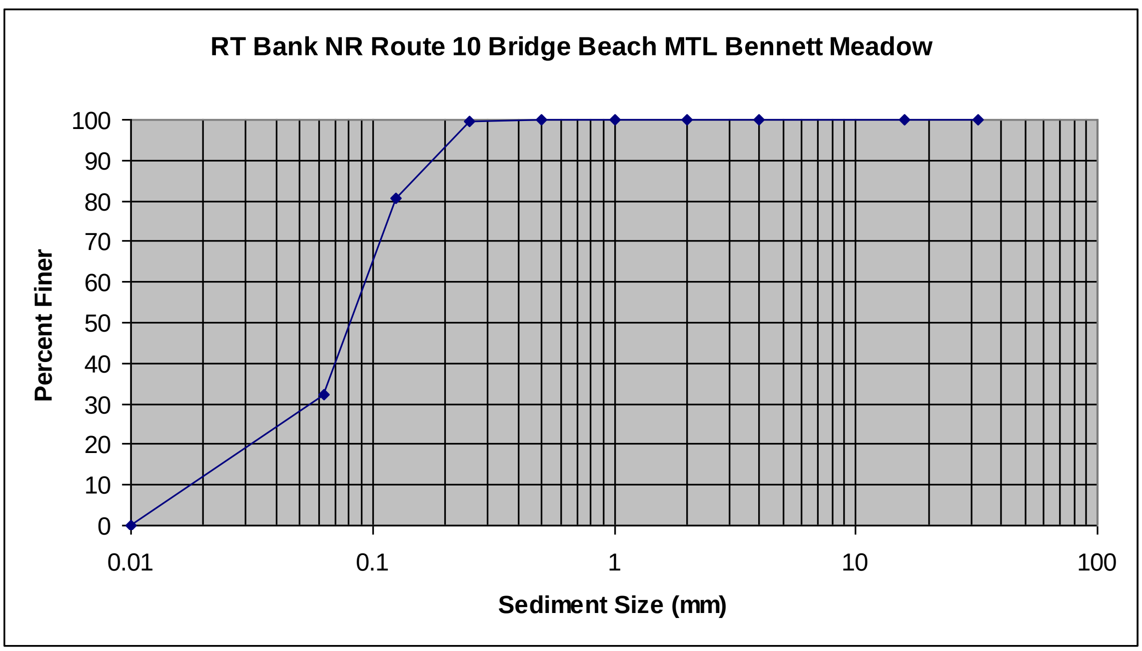





5
100
90
80
70
60
50
40
30
20
10
0
Percent Finer
0.01
0.1
1
10
100
Sediment Size (mm)

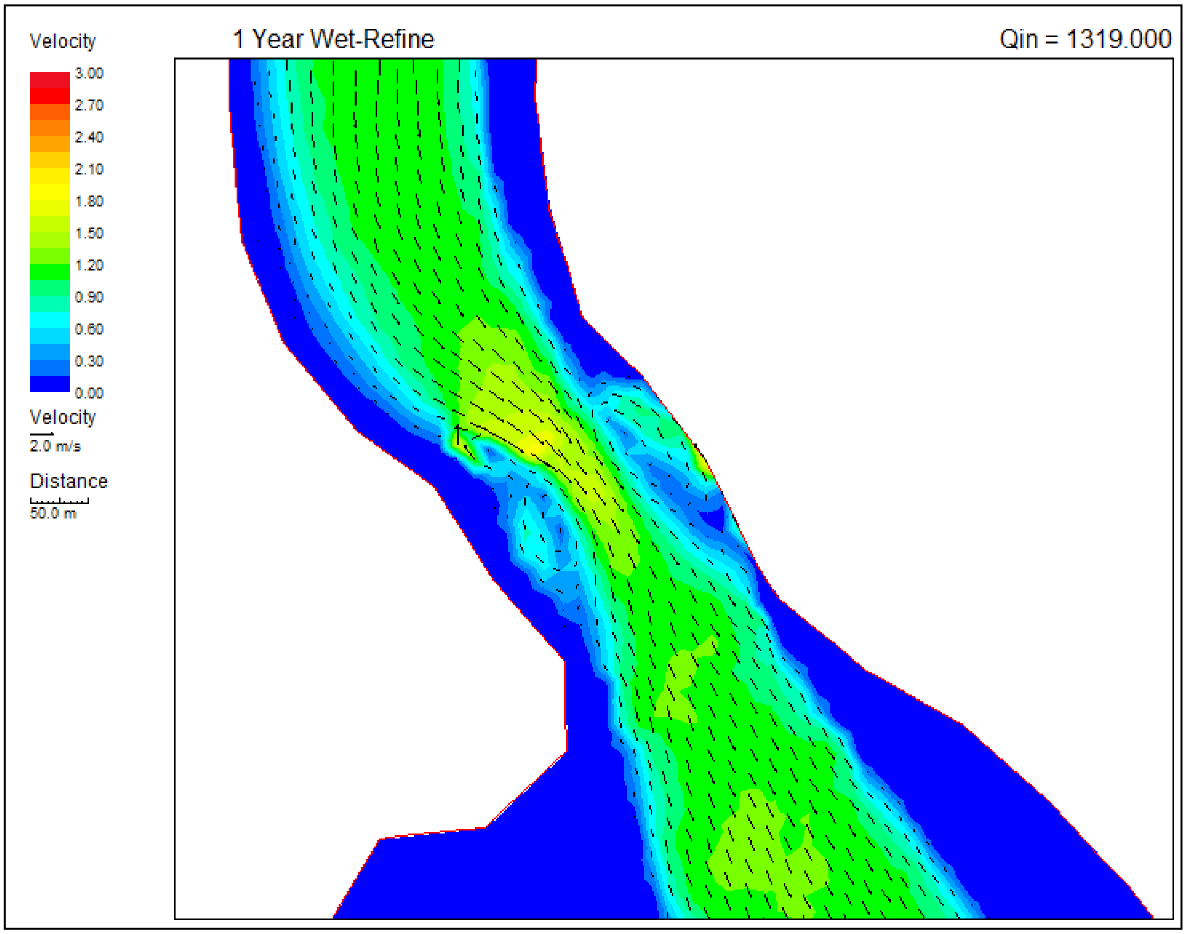

RT Bank NR Route 10 Bridge Upper Bank Bennett Meadow
100
90
80
70
60
50
40
30
20
10
0
Percent Finer
0.01
0.1
1
10
100
Sediment Size (mm)


LB Upstream of Route 10 Bridge Beach MTL
Percent Finer
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
100
Sediment Size (mm)

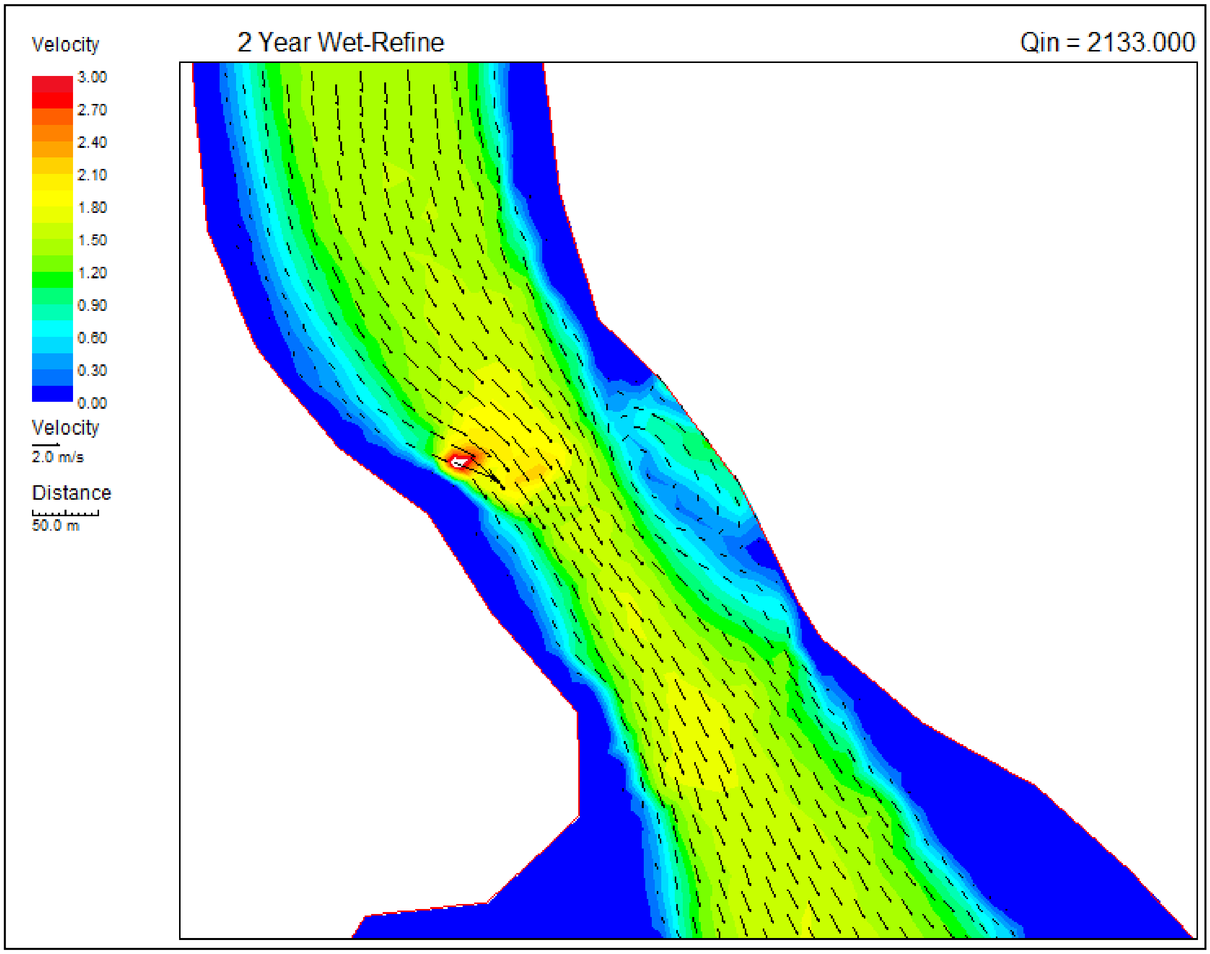

RT Bank NR Route 10 Bridge Beach MTL Bennett Meadow
Percent Finer
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
100
Sediment Size (mm)

Appendix E: River-2D Output

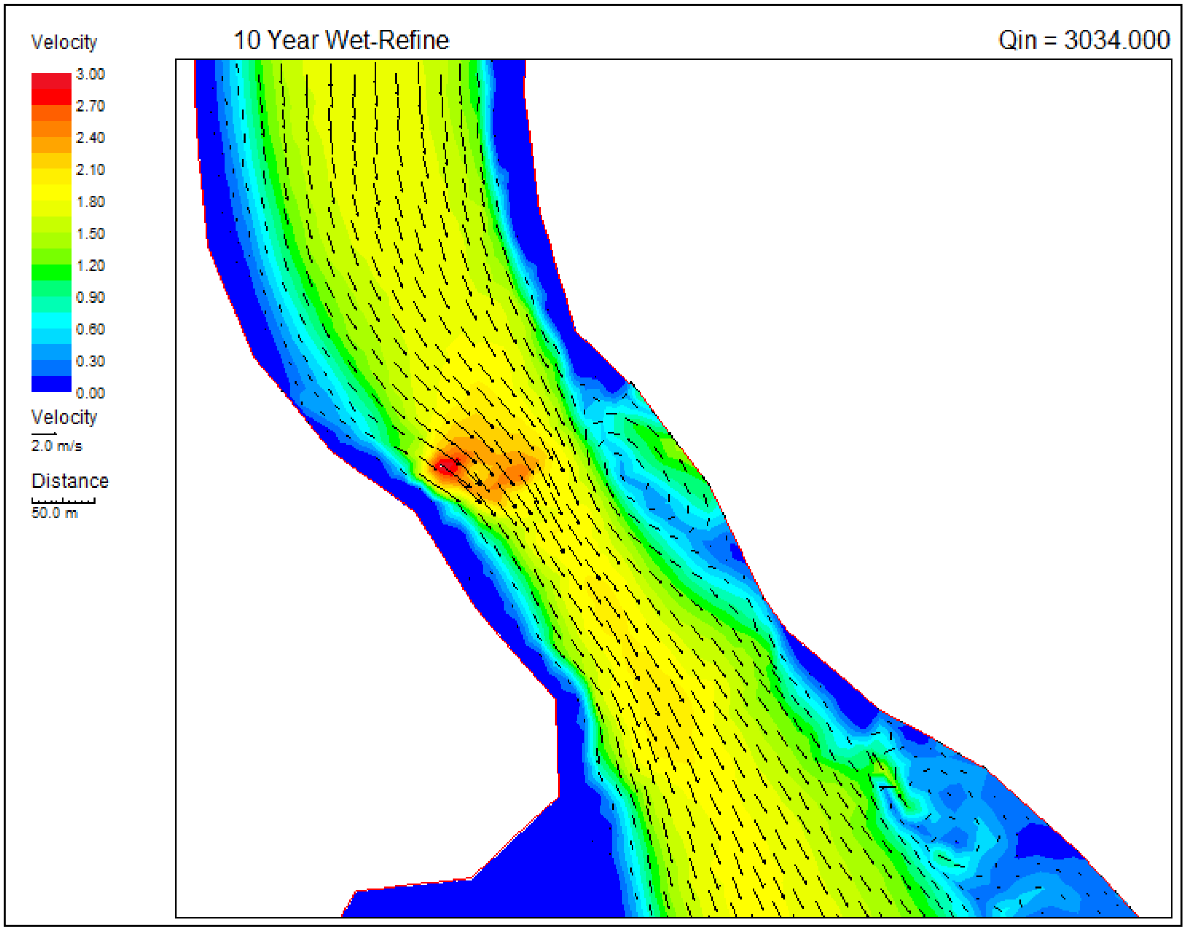
1-Year Flow Results



2_Year Flow Results



10-Year Flow Results



Appendix F: Eddy Induced Erosion below Vernon Dam

Note: Discharge from gates on left side of dam (looking downstream – right side of photo) has created a large eddy that has eroded into the hillside just downstream of the left abutment. The eddy has carved out a circular area consistent with the circulation pattern of the eddy.

Photos of hillslope eroded by eddy just downstream of Vernon Dam – 1996

Photos of hillslope eroded by eddy just downstream of Vernon Dam – 2008

Appendix G: Riverbank Erosion – Segment 5E

Undercut bank (jpeg.138)

Erosion at toe of bank (jpeg.142)

Erosion at toe of bank (jpeg.143)