Fluvial Geomorphology Assessment of the Northern Connecticut River, Vermont and New Hampshire

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EXECUTIVE SUMMARY

A fluvial geomorphic assessment of 137 km (85 miles) of the northern Connecticut River between Murphy Dam in Pittsburg, NH downstream to Gilman Dam between Gilman, NH and Lunenburg, VT has identified the major natural and human factors controlling channel morphology and causing bank erosion. A low gradient sinuous channel with pool-riffle or plane-bed bed morphology is typical of that portion of the river flowing across a wide floodplain in broad unconfined valleys. Straight higher gradient channels with plane-bed morphology characterize reaches within narrow valleys where the river frequently impinges on high banks of glacial outwash deposits found along the valley margin. Straight channel segments found in broad unconfined valleys are indicative of human interference, because a meandering channel planform would develop naturally where no valley confinement exists. Mid-channel bars and point bars are typically found downstream of the confined valley reaches where the valley begins to expand. The valley expansion results in a loss of stream power that decreases the capacity of the river to carry the sediment derived within the narrow valley segments upstream.

Three causes of erosion and channel instability were identified: 1) human channelization and straightening; 2) sediment inputs from tributary watersheds; and 3) sediment inputs from high eroding banks of glacial outwash deposits. The presence of former and existing dams on the mainstem and tributaries may also be an important cause of erosion downstream of the Upper Ammonoosuc River but further assessment will be needed to better understand their role. More than 30 percent of the river's length was straightened by humans prior to 1925. Most river banks along the straightened channels are now stable after undergoing an earlier period of erosion that left the straightened segments wider and deeper than their natural meandering counterparts. Continuing erosion occurs at the downstream and upstream ends of these straightened areas as the river encounters artificially sharp bends. This erosion will continue until the bends achieve a more natural open configuration where energy expenditure is spread out over a greater distance rather than focused at a single point where the erosion currently occurs. Bar formation resulting from sediment inputs from tributaries and high eroding banks diverts the river into adjacent river banks causing extensive erosion. Migration of the bars downstream means that the location of channel instabilities shifts through time and that attempts to armor the banks proves ineffective as the location of erosion changes.

A riparian buffer is absent along 20 percent of the river's length. While the absence of a buffer does not in itself cause erosion, banks are more susceptible to erosion where a riparian buffer is absent. Careful mapping of erosion in relation to the width of the riparian buffer indicates that establishing a riparian buffer of at least 7.6 m (25 feet) could improve bank stability significantly.

Impairments to bank stability and physical habitat resulting from this erosion would be best managed by directly addressing the cause of the erosion. Eliminating erosion at sharp bends at the ends of channelized segments could be achieved by

reintroducing the channel to its former meanders. However, channel incision since straightening of the channel has left the former channels more than 1.0 m (3.2 feet) higher than the current channel so this approach is not technically feasible. Reducing sediment inputs from tributaries and high eroding banks is technically feasible, but the necessary scale of the projects will make them impractical in most cases. Consequently, in the absence of an effective means for directly addressing the cause of erosion, the erosion must be managed where it occurs. Rather than hard armoring the banks with riprap that will serve only to transfer the problems downstream, the establishment of riparian buffers within acquired conservation easements will slow the erosion. Reducing the rate of erosion will minimize the physical habitat impairments resulting from fine sediment inputs into the river. Allowing the erosion to continue slowly will also accommodate some of the sediment being delivered from the tributaries or high eroding banks. By storing sediment in areas where easements have been established and human conflicts along the river removed, erosion problems resulting from excess sediment accumulation can be allowed to occur in these areas, thereby reducing sediment transport and improving stability downstream where human conflicts may still exist.

Several management options were considered for stabilizing erosion at the Colebrook Industrial Park caused by sediment inputs downstream of the Mohawk River in Colebrook, NH. The favored management option will combine the use of root wad deflectors to immediately reduce erosion and improve habitat with the establishment of a riparian buffer in an acquired conservation easement. As the bioengineered root wads decompose over a 10 to 20 year period, the riparian buffer will become sufficiently established to provide the necessary stability to slow erosion and improve habitat as an occasional tree falls into the river. Success with this approach will improve public willingness to consider more extensive management options that will directly address the cause of sediment impairments emanating from the Mohawk River. Further assessment will be needed before implementing any restoration projects on the Mohawk River. However, providing the river access to its alluvial fan may prove an effective means of increasing sediment storage within the tributary watershed, reducing sediment delivery to the Connecticut River, and improving physical habitat and channel stability impaired by excess sedimentation.

1.0 INTRODUCTION

This report describes the results and recommendations of a fluvial geomorphology assessment of the northern Connecticut River completed by Field Geology Services (Figure 1). The study area encompassed 137 km (85 miles) of the river from Murphy Dam in Pittsburg, NH downstream to Gilman Dam between Gilman, NH and Lunenburg, VT. The watershed area upstream of the Gilman Dam is 4,014 km^2 (1,550 mi^2). While the Murphy Dam, Canaan Dam, and other dams on tributary streams regulate flow, the Connecticut River in the study area is largely free flowing and unimpounded, unlike much of the river further south. Consequently, a number of fluvial hazards, principally erosion, occur in the area and remedies to address these problems are being sought by several communities adjoining the river.

The Connecticut River Joint Commissions has been working since 1989 to stem riverbank erosion on the Connecticut River. The Connecticut River Joint Commissions decided to undertake a fluvial geomorphology assessment of the northern Connecticut River in order to identify the underlying causes for erosion and develop more sustainable solutions that simultaneously reduce erosion, improve water quality, and restore aquatic habitat. Fluvial geomorphology is a science that attempts to understand how river channels adjust their shape (width and depth) and planform (sinuosity/“windiness”) through erosion and deposition to reach an equilibrium with natural conditions and human land use in the watershed. Since channels in equilibrium do not change their shape and planform over time, erosion and deposition levels can be greatly reduced and negative impacts on humans and aquatic habitat minimized.

Recognizing the value of fluvial geomorphology to reduce erosion hazards, the State of Vermont has developed a three phase Stream Geomorphic Assessment Handbook to reveal the underlying causes for erosion and other riverine hazards (Vermont Agency of Natural Resources, 2003; Appendix 1). The assessment of the northern Connecticut River employed the three phase handbook to accomplish five major goals discussed in turn below: 1) subdivide the river into distinct reaches; 2) characterize the existing channel morphology; 3) identify the natural conditions and human land uses causing erosion and channel instability; 4) develop strategies for erosion control that address the identified causes of erosion; and 5) design a project for bank stabilization at one high priority site that employs one or more of the developed erosion control strategies. Phase 1 of Vermont’s Stream Geomorphic Assessment Handbook utilizes topographic maps, aerial photographs, and archival records to characterize natural conditions and human land uses in the watershed (Appendix 1). Surveying and other fieldwork during Phase 2 of the assessment provides information on the existing morphology of the channel in each identified reach. Project designs are possible with the results of more detailed surveying during Phase 3. The Stream Geomorphic Assessment Handbook results are compiled in Appendix 2 and integrated into the report below. A number of channel features, including bank stability and composition, were mapped continuously along the 137 km (85 mile) long channel and entered into a GIS database in order to supplement results of the assessment handbook (Appendix 3). The results of the mapping are summarized in Table 1 and discussed further below. By comparing existing channel conditions with those that would be expected to develop in an undisturbed setting, the handbook can be used to better understand the natural and human causes for channel instability (Phase 1), identify the most unstable and degraded reaches in a river system (Phase 2), and choose restoration strategies that will bring rivers towards a natural equilibrium condition (Phase 3).

2.0 SUBDIVIDING REACHES

Since different portions of a river might respond differently to the same natural and human factors, the first assessment task is to subdivide the river into distinct reaches. Within a given reach, the river is assumed to respond similarly to changing watershed conditions while adjacent reaches may respond differently. Reaches that share similar traits are referred to as "like-reaches" and an understanding of channel response or effective restoration techniques gained in one reach may apply to other "like-reaches". Break points between different reaches are made on the presence of one or more conditions, including natural changes in valley slope, constrictions of valley width, expansions of valley width, and the confluence of a major tributary. Twenty such reaches of uneven length were identified on the northern Connecticut River using topographic maps with the reaches numbered consecutively from the downstream end of the river and designated M1, M2, etc. to indicate that the reaches are located on the mainstem of the river (Figure 1 and Table 2). Four of the reach breaks occur at valley constrictions, eight at expansions in the valley, and eight at the confluence of major tributaries (Table 2). No significant natural changes in valley slope occur along the length of the river. Of the 20 identified reaches, a Phase 2 assessment was completed on only ten (Table 2).

Reaches downstream of constrictions tend to occupy more confined valleys where the river channel has a greater likelihood of flowing against glacial sediments exposed along the high valley walls. The potential for high rates of sediment production in these locations can affect channel morphology differently than reaches occupying wide valleys where the channel encounters floodplain sediments only. Reaches 16, 17, 18, and 20 occupy narrower portions of the valley near the headwaters of the Connecticut River. Reaches 8-10 also occupy confined portions of the valley with much broader valley segments occurring upstream and downstream. Sediment production in Reaches 8-10, as will be discussed later, greatly influences channel stability in Reaches 6-7 downstream.

Reaches downstream of tributary confluences will generally have a morphology different than reaches immediately upstream of the confluence because of the introduction of sediment at the confluence. The morphological impacts of tributary confluences, as well as valley constrictions and expansions, are generally most noticeable at or near the reach break. Consequently, the locations of the reach breaks themselves are likely points of channel instability with active bar formation, bank erosion, and channel migration possible (Figure 1). For example, mid-channel bars typically form just downstream of points of valley expansion where the stream power to carry the sediment is lost with flow expansion (Figure 2a). Bars are also commonly observed downstream of tributaries because of the excess sediment added at the confluence (Figure 2b). Delineating the reach breaks and understanding the morphological conditions present in each reach are critical for identifying the natural and human conditions leading to erosion and channel instability.

3.0 EXISTING CHANNEL MORPHOLOGY

In the absence of human settlement, channel morphology (i.e., shape and planform) responds to natural conditions present in the watershed. Establishing the conditions present adjacent to the channel (e.g., soil type, valley confinement) and in the larger watershed (e.g., drainage area, forest cover) can help determine what channel morphologies would develop in the absence of human land use. Differences between the expected morphology under natural conditions and what morphology actually exists are generally an indication that human land use is altering channel morphology. The existing and expected morphological conditions within each reach on the northern Connecticut River were established by analyzing topographic maps and aerial photographs, surveying channel dimensions in the ten selected Phase 2 reaches, and mapping channel conditions continuously along the river’s length.

3.1 Slope and Sinuosity

Morphological parameters such as sinuosity, channel slope, and meander migration rates can be ascertained from current and historic topographic maps and aerial photographs. Large bar deposits can also be identified (see Appendix 1 for a description of bar types). Rivers flowing through broad valleys typically have lower slopes, higher natural channel sinuosities, and greater rates of channel migration than those in more confined valley segments. The northern Connecticut River is no exception with sinuosities greater than 2.0 in some unconfined reaches (e.g., Reach 6) and near 1.0 in confined reaches such as Reach 10 (Table 3; see Appendix 1 for a definition of sinuosity). Channel slopes in confined valleys (e.g., Reach 10) are nearly twice that found in adjacent less confined reaches such as Reach 11 (Table 3). Low sinuosity values in broad unconfined reaches, Reach 19 for example, suggest human alterations to the channel have occurred because a meandering planform would be expected under natural conditions.

To further detail the morphological differences between meandering and straight segments of unconfined reaches, cross sections were surveyed across both meandering and straight portions of the channel in five unconfined reaches (Table 4 and Figure 3). Generally, the bankfull width, depth, and area of the channel in straight segments is greater than in nearby meandering segments within the same reach (see Appendix 1 for a discussion of bankfull dimensions). The paired cross sections were part of a larger surveying effort to characterize the channel dimensions in the ten Phase 2 reaches (Appendix 4). The ten reaches surveyed are representative of all 20 reaches and therefore adequately characterize the morphological conditions present along the entire river. The results of the surveyed cross sections are described further in Section 4.0 – Causes for Erosion.

3.2 Channel Migration

Historical topographic maps and aerial photographs reveal that no significant channel migration has occurred on the northern Connecticut River since 1925 (Figure 4; see also current photographs in Appendix 3 and historic maps available on line at: http://docs.unh.edu/nhtopos/nhtopos.htm). Minor cutoffs of tight meanders have occurred but these were likely the result of human actions (see arrows on Figure 4). While channel migration in the recent past is most important in determining if the channel is currently unstable, a map from 1861 reveals significant channel migration occurred between 1861 and 1925. Some of this change is reflected in the growth of meanders (Figure 5a) and the development of new meanders along previously straight river segments (Figure 5b). The emergence of meanders along straighten segments reflects the natural tendency of rivers flowing across a broad valley floor to develop a meandering pattern.

The lack of channel migration since 1925 may be related to minor channel incision that has occurred within this same time frame. The current channel thalweg (i.e., deepest part of the channel) is consistently more than 1.1 m (3.6 feet) lower than the thalweg of abandoned channel segments along the same cross section (Figure 6). Similarly, two floodplain levels are present along much of the river with the lower, more recent, floodplain generally more than 1.1 m (3.6 feet) lower than the higher floodplain (Figure 6; see also Appendix 4 – Reach 3 Cross Section 2). While the higher floodplain is still inundated by floodwaters, it formed when the abandoned channels were still active. Where the river flows directly against this higher floodplain, which is the case along much of its length, the banks are slightly higher than would be present if no channel incision had occurred (see Appendix 3 – bank heights).

3.3 Bar Development

Mid-channel bars are commonly found just downstream of points of flow expansion (Figure 3a), tributary confluences (Figure 3b), and high eroding banks (Figure 7). Bar formation, however, does not generally persist far downstream from these points. Delta bars are frequently seen forming at the mouths of both large and small tributaries (Figure 8) with some of the sediment emanating from the tributaries moving further downstream to form mid-channel bars (Figure 3b). Unvegetated point bars are uncommon along the northern Connecticut River except in Reaches 6 and 7 where they occur on the inside of most meander bends (Figure 9). Reaches, or portions of reaches, that are far from tributary influences, flow expansions, or high eroding banks show very little evidence of bar formation, particularly Reaches 2-5 at the lower end of the river (Table 3).

3.4 Substrate Particle Size and Bed Form

Substrate particle size typically decreases in a downstream direction as the distance from the source area increases and channel slope decreases. The average of the three largest particles was determined at each cross section location surveyed in the ten

Phase 2 reaches (Figure 10). Grain size decreases downstream, as expected, along the upper 45 km (28 miles) of the northern Connecticut River but reverses itself when flowing through Reach 10 (Figure 10 and Table 3). Particle size rises for the next 9 km (6 miles) before beginning to decrease again in Reach 9. The increase in grain size through Reaches 9 and 10 is coincident with an increase in valley confinement that results in the river flowing more frequently against glacial outwash deposits along the valley margin. The outwash deposits provide a source of the coarse sediments that rejuvenates the system before the grain size begins to decrease as the valley once again becomes broad and unconfined downstream of Reach 8.

The increase in grain size in Reach 9 and 10 results in changes to the channel bed form (see Appendix 1 for a description of channel bed forms). Pool-riffle and dune-ripple morphologies, typical of meandering low gradient streams, occur in Reach 11-14 (Figure 11 and Appendix 3). Upon entering Reach 10, the bed form changes rapidly to plane bed in response to the increased sediment supply and channel gradient. A plane bed morphology continues downstream through the upper portion of Reach 9 before returning to a pool-riffle morphology as valley confinement is lost and sediment supply decreases. Dune-ripple morphology predominates the lower end of the river where a sand sized substrate is found while plane bed morphology occurs in Reaches 18-20 where the channel gradient is high, the valley confined, and sediment supply from tributaries and valley walls significant (Figures 10 and 11; Table 3).

3.5 Bank Stability

River bank stability and composition were mapped continuously along the length of the northern Connecticut River (Figures 12 and 13; Table 1). Bank erosion is a natural process along rivers in equilibrium as a channel migrates across its floodplain. Extensive erosion, however, can be an indication of channel instability associated with human activity. The natural level of background erosion will vary with the composition of the banks and levels of vegetation growing on the banks; typically, banks are more sensitive to erosion where sandier soils are present and vegetation is absent. Although no known level of erosion is associated with an equilibrium condition, erosion along 26 percent of the total length of the banks, as on the northern Connecticut River, is likely an indication of channel instability and active channel adjustment (Figure 12 and Table 1). Another 23 percent of the bank length is mapped as moderately eroding and can be considered sensitive to further instability. Taken together with the 17 percent of the bank that has been armored with large rock (i.e., riprapped), 66 percent of the river banks are either currently eroding, sensitive to erosion, or protected against further erosion. The human activities and natural conditions leading to this high rate of bank instability and sensitivity to erosion are discussed in Section 4.0 – Causes for Erosion.

The river channel is primarily composed of alluvial banks, or banks rarely higher than 10 feet (above the low flow water level), that are composed of floodplain soils with a sandy loam texture. High non-alluvial banks, sometimes over 100 feet high but more typically 10 to 30 feet high, occur along 12 percent of the total bank length (Table 1). These high banks are more prevalent where the valley is more confined and the river more frequently impinges against the non-alluvial glacial outwash deposits found along the valley side slopes (Figure 13 and Table 3). The river's greater interaction with the non-alluvial banks, resulting from the valley confinement, has a significant impact on the channel morphology. The confined reaches on the northern Connecticut River tend to have higher channel gradients, lower sinuosity, and a plane bed morphology while unconfined valley reaches are more likely to have a meandering pool-riffle channel with a lower slope. These largely natural differences in channel morphology between confined and unconfined reaches exert a strong influence on channel response to human land use in the watershed.

4.0 CAUSES OF EROSION AND CHANNEL INSTABILITY

A number of human activities in the channel, alongside the channel, and in the larger Connecticut River watershed appear to be contributing to erosion problems and channel instability. Natural factors are also present in the watershed that cause erosion and make the channel sensitive to human activities that might destabilize the channel. Six of the most important human and natural causes of erosion and channel instability are discussed below: 1) channelization; 2) land clearance and other human land use in tributary watersheds; 3) continuing adjustments to deglaciation; 4) agricultural practices in the riparian zone; 5) dams; and 6) reforestation of hillslopes cleared in the 18th and 19th Century.

4.1 Channelization

More than 30 percent of the northern Connecticut River was likely straightened by humans prior to 1925 (Figure 14). Fifteen of the 20 reaches show some evidence of channel straightening with 30 percent or more of the reach length straightened in eight reaches (Table 3). Evidence for this channelization includes the presence of straight channel segments longer than the wavelength of adjacent meandering sections (Figure 15; see Appendix 1 for definition of wavelength). Further bolstering the claim that straight segments are the result of human action is the presence of abandoned meandering channels adjacent to the straightened segments (Figure 15). In some instances these old meanders were occupied in 1861, indicating they were abandoned after European settlement of the region. All of the straightening occurred prior to 1925 with some predating 1861. Sinuosity has become reestablished along some straightened segments as evidenced by channel changes since the1861 map (Figure 5b).

The reasons for straightening are most likely related to log drives, railroad construction, and agricultural practices. Chapter 2805 of the NH RSA's was an act to incorporate the Upper Connecticut River and Lake Improvement Company in 1863. The corporation was given permission to "remove the boulders and rocks and all other obstructions from, and enlarge the channel of" the Connecticut River from 1st lake in Pittsburg to West Stewartstown in order to "facilitate rafting, driving, floating and securing lumber upon said river". The act was amended in 1867 to extend down river to Fifteen Mile Falls at the downstream end of the northern Connecticut River. Log drives on the Connecticut River may have begun as early as the 17th Century, became quite large after the 1860's, and had largely ended by 1920. In addition to the straightening that likely resulted from the log drives, railroad construction in the latter half of the 19th Century was also responsible for some channelization (Figure 16). Channelization for flood control purposes occurred on tributaries, such as on the Mohawk River in Colebrook (see Section 6.0 – Bank Stabilization Project Design below), but no clear evidence suggests this was the purpose of channelization on the mainstem.

The significant alteration of the channel's planform resulting from the straightening leads to channel instabilities that drive the river's response. Straightening increases a channel's slope, sometimes quite significantly. Channel slope is potentially doubled when a meandering channel with a sinuosity of 2.0 is straightened. Sinuosity values greater than 2.0 are observed in Reach 6 and four other reaches have sinuosities greater than, a still quite high, 1.5 (Table 3). Low sinuosity values in unconfined reaches are an indication of extensive straightening of what were likely originally high sinuosity channels (e.g., Reach 19). Although the gradient of the northern Connecticut River is quite low (Table 3), a doubling of slope, or even far less, can significantly increase the sediment transport capacity of the river. The greater stream power results in bed and bank erosion that together decrease channel slope and increase channel area (Figure 3; Table 4; Appendix 4). These responses tend to lessen the river's sediment transport capacity and bring the river back into equilibrium.

Erosion persists today on the northern Connecticut River as adjustments to channelization continue. Straightened channels, in most instances, are wider than adjacent meandering channels (Figure 3; Table 4; Appendix 4). The channels also tend to have greater bankfull depths, reflecting the bed erosion that is at least partially responsible for the channel incision observed along the river (Figure 6; Appendix 4 – Reach 3 Cross Section 2). These overwidened channels have relatively stable banks because the resulting increase in channel area has brought the channel back into equilibrium (Figure 17). After widening, a river channel will begin to backfill with sediment and establish a new floodplain as part of an evolutionary process that returns the river to its original pre-channelization condition (see Appendix 1 for a discussion of channel evolution models). Such backfilling appears to have occurred in Reach 6 where human additions of hay bales and mud have accelerated the process, led to the creation of a lower floodplain, and created shallower bankfull depths (Table 4; Appendix 4). Other straightened segments on the northern Connecticut River appear to have progressed far enough through the widening phase that banks have become restabilized after an earlier period of erosion (Figure 17). Whether human activity could have led directly to the creation of overwidened channels without natural erosion is unknown. In some instances riprap was placed on the banks of the straightened channels to stop the erosion and bank widening. The older riprap in these areas shows signs of failing because the channel has not yet fully progressed through the widening phase (Figure 18). The constant pressure on the banks resulting from locking the channel into a nonequilibrium condition eventually leads to the undermining and erosion of the riprap.

Erosion often occurs at the downstream and upstream end of channelized reaches on the northern Connecticut River. The bends created as the channel either enters or exits straightened segments are repeatedly sharper than what were originally present (Figure 19a). Severe erosion is observed at many of these artificially "hard" bends as the river attempts to create a gentler meander so the turning, and energy expenditure along the channel, is spread out over a greater distance rather than focused at a single point (Figure 19). As a result, erosion extends downstream for some distance while banks immediately upstream of the sharp bend are generally stable. Riprap placed at these sharp bends to stop the erosion will fail over time because of the continuing pressure exerted on the banks at these bends (Figure 20).

4.2 Land Clearance and Human Land Use in Tributary Watersheds

Bank erosion along the bank directly opposite tributary confluences was observed at several locations. Delta bars formed by sediment entering the mainstem at the mouths of these tributaries reroute the river towards the opposite bank, leading to erosion (Figure 8). The watersheds of those tributaries creating the delta bars have a high percentage of land clearance within them while adjacent tributaries with little land clearance have no significant delta bars or erosion on the opposite bank (Figure 21). If the entry point of the tributary into the mainstem shifts position so does the location of the erosion. In Reach 7 across from Bog Brook just below the Maidstone Bridge, riprap placed on the bank across from the previous location of the confluence is holding up well because the mouth of the brook has shifted upstream slightly causing erosion in a new location and relieving pressure on the area where the riprap was placed.

Both small and large tributaries are responsible for erosion on the opposite banks. The effect of small tributaries on mainstem erosion problems is most noticeable in Reach 14 where the mainstem is still small enough to be impacted by the formation of a small delta bar. Further downstream, the delta bars created by small tributaries are generally not sufficient enough to destabilize the opposite bank. However, large tributaries, in almost all cases, do impact the mainstem along the entire northern Connecticut River. Sometimes the river bank across from a large tributary confluence is eroding while in other cases the unstable bank is protected by riprap. Additionally, sediment delivery from large tributaries moves further downstream to form mid-channel bars which create further erosion problems similar to those discussed in Section 4.3 – Continuing Adjustments to Deglaciation. While land clearance in these large watersheds is partly responsible for increased sedimentation at the confluence, other activities in the tributary channels, such as channelization for flood control purposes, also increase sediment delivery to the tributary mouths.

4.3 Continuing Adjustments to Deglaciation

Immediately after deglaciation of the Connecticut River Valley approximately 12,000 years ago, sediment left behind by the retreating ice sheet washed into the valley. The valley floor was more than 30 m (100 feet) higher in places at this time as evidenced by the remaining glacial outwash terraces seen along the valley margins today (Figure 22). Eventually, as the source of sediments washing into the valley was diminished or stabilized by reforestation of the surrounding hillslopes, the river began to cut down through these glacial outwash deposits and redistribute the sediment further downstream.

This process of erosion and redistribution of glacial outwash sediments continues today. In many places along the length of the river, especially in the confined reaches, the river channel flows against high nonalluvial banks composed of glacial outwash sediments (Figures 13 and Figure 23). Sediment derived from these high banks is moved downstream until a loss in stream power prevents further transport of the sediment. The most dramatic deposition typically occurs immediately downstream of the valley confinement created by the high banks because the flow is no longer confined and can spread out on the adjacent floodplain, resulting in a loss of stream power (Figures 2a and 7). Mid-channel bars that result from this deposition divert the river's flow into the adjacent banks, initiating erosion. Flow diversion and bank erosion around mid-channel bars results in a much wider and shallower channel than is present in the absence of bar formation (Figure 24). The length of bank affected by this type of erosion is roughly equal in length to the mid-channel bar itself. Bank erosion is not as severe immediately upstream or downstream of the bar and, therefore, the bank does not recede as dramatically, if at all. The resulting scalloped appearance of the bank line will remain even after the mid-channel bar causing the erosion migrates downstream and no longer diverts flow into that portion of the bank (Figure 25).

Deposition of point bars on the inside of meander bends tends to force flow to the outside bend where erosion, consequently, occurs (Figure 9). This relationship between point bar deposition and erosion of the opposite bank is observed along almost every meander bend in Reaches 6 and 7. Reaches 6 and 7 have some of the highest rates of bank erosion of all 20 reaches on the northern Connecticut River (Table 3). Sediment delivery from the high banks of glacial outwash sediments in Reaches 8-10 is the likely source for the sediment deposited on the bars. The loss of stream power associated with the dramatic downstream decrease in channel gradient and loss of valley confinement between Reaches 6 and 10 results in the bar deposition and drives the bank erosion (Table 3).

While the prevalence of bar deposition and erosion in Reach 6 and 7 may be the natural consequence of deglaciation thousands of years ago, human impacts may exacerbate the condition. Many of the high banks composed of glacial outwash are well forested and stable, keeping sediment delivery to the river at a minimum. However, channel straightening may have sometimes rerouted the channel directly against these high banks and inadvertently destabilized them (Figure 23). Consequently, human activity may have increased natural levels of erosion by increasing the amount of sediments derived from these high non-alluvial banks.

4.4 Agricultural Practices in the Riparian Zone

A riparian buffer of trees is absent along 20 percent of the northern Connecticut River, a figure that is even higher downstream of Canaan, VT where more intensive agriculture is found (Table 1; Appendix 2). While the absence of trees, in and of itself, does not cause increased bank erosion, the lack of roots to stabilize the soil does increase the sensitivity of the banks to erosion. Although erosion does occur in wooded areas, eroding banks are 67 percent more likely to be found where the riparian buffer is absent (Table 1). Besides just clearing fields to the edge of the river, certain agricultural practices, such as allowing cattle direct access to the river channel, can further destabilize the banks and promote erosion (Figure 26).

4.5 Dams

Existing and former dams are present on the northern Connecticut River as well as some tributaries, most notably the Upper Ammonoosuc River. Dams not only regulate water flow but they tend to completely stop sediment from passing downstream. Consequently, dams frequently create a sediment deficit downstream that results in erosion (Williams and Wolman, 1984). Existing dams on the mainstem, Murphy Dam, Canaan Dam, and Gilman Dam, are at the fringes of the study area (i.e., Murphy Dam and Gilman Dam) or in bedrock segments (e.g., Canaan Dam) such that they do not appear to exert a direct influence on bank erosion. They might, however, play a partial role in the channel incision that has occurred along the river downstream of the Canaan Dam (Figure 6; Appendix 4 – Reach 3 Cross Section 2).

Dams on the Upper Ammonoosuc River may be contributing more directly to mainstem erosion in Reach 5 downstream of the confluence. The lack of a delta bar at the mouth of the Upper Ammonoosuc, scouring at the edges of older vegetated mid-channel bars just downstream of the confluence, and continuous bank erosion along both banks are suggestive of a sediment deficit in Reach 5. The lack of sediment delivery to the mainstem from the Upper Ammonoosuc because of dams on the tributary may be responsible for this apparent sediment deficit. However, the current study did not include an assessment of the tributaries nor was it detailed enough to consider the role of the former Wyoming Dam in Reach 5 at Northumberland on the erosion problems. Further studies will need to be conducted on Reach 5 and the Upper Ammonoosuc River before the possible role of dams on bank erosion problems can be clarified.

4.6 Reforestation of Hillslopes

European settlement of northern New England in the 18th and 19th Century cleared nearly 80 percent of the forested land for farming and sheep herding. Exposure of the hillslopes, unlike any time since immediately after deglaciation, led to the mobilization of glacial sediments remaining on the hillslopes. The increased delivery of sediments to the valley bottoms led to a period of channel filling and rapid channel migration (Bierman et al., 1997; Brackenridge et al., 1988). As land use changed and northern New England became reforested throughout the 20th Century, sediment delivery from the surrounding hillslopes again decreased and rivers began to incise through the recently deposited sediment. The current assessment did not include a stratigraphic investigation of bank sediments to determine if post-European settlement deposits are present on the northern Connecticut River floodplain. However, the rapid rate of meander migration between 1861 and 1925 (Figure 5a) suggests sediment supply to the river was high during this period when land clearance was near a maximum. Given the documentation of similar processes elsewhere in northern New England, reforestation of the watershed over the past 100 years is a likely cause of channel incision along the northern Connecticut River. While channel migration is minimized with channel incision, bank stability is compromised as bank heights increase with the incision. The result of channel incision, therefore, is to increase the susceptibility of river banks to erosion by the other causes outlined above.

5.0 EROSION CONTROL STRATEGIES

Management of erosion problems must address, or at least recognize, the causes for erosion. By dealing with the root causes behind bank instability, erosion can be halted or minimized over the long term. Consequently, the most appropriate erosion control strategy for a particular area will depend on the underlying cause of erosion. Potential management strategies that could be used on the northern Connecticut River to address erosion resulting from the three primary causes for erosion identified during the assessment are discussed below: channelization; tributary land use; and adjustments to deglaciation. Potential management solutions for erosion problems associated with dams will need to be developed after further studies better clarify the relationship between dams and bank erosion problems.

The overall sensitivity to erosion can be decreased by encouraging the establishment of adequate riparian buffers. Erosion is more likely to occur where the riparian buffer is absent or less than 7.6 m (25 feet) wide (Figure 27). While erosion does occur in places where the riparian buffer is already quite wide, the establishment of buffers greater than 7.6 m (25 feet) should help to increase bank stability.

5.1 Managing Erosion Problems Associated with Channelization

Channelization has resulted in a period of bank erosion and channel widening that has largely ended. Consequently, banks are generally stable along the straight sections of the channel. However, some of the most severe erosion problems along the northern Connecticut River are located at unnaturally sharp bends at the upstream and downstream ends of straightened channel segments. Typically, the original channel prior to straightening had a much gentler bend (Figure 19a). Returning the channel to the original meander position would effectively spread out the river's energy expenditure over a greater distance and relieve the erosive pressures focused at the sharp bend. If opportunities arise to return the channel to its original position, the cause of erosion could be eliminated. Unfortunately, rerouting of a straightened channel is probably not feasible anywhere on the northern Connecticut River. The abandoned channels have in many cases been converted to agricultural fields, are surrounded by agricultural fields, or have homes built immediately adjacent to the former river banks. Landowners in these locations will likely resist such dramatic management strategies. Furthermore, returning a straightened channel segment to its original meander is also technically unfeasible in most cases. Channel incision accompanying straightening has left the current channel, along much of its length, more than 1.0 m (3.3 feet) above the abandoned meanders

(Figure 6). Large amounts of sediment would have to be added to the channel upstream and downstream of the straightened segments in order to build up the bed elevation to match that of the former meander bend. Such activities would have unknown consequences on aquatic habitat, potentially increase flooding on adjacent floodplains, and unlikely meet environmental permitting rules in Vermont or New Hampshire.

Without a feasible method for directly addressing the cause for erosion at these artificially sharp bends, the best management strategy is to try and slow the erosion. Decreasing the rate of erosion will help preserve the surrounding farmland and minimize impacts on aquatic habitat caused by excessive fines entering the river system. Completely stopping the erosion with riprap or other bank armoring techniques, however, will lock the channel instabilities in place and potentially transfer the erosion processes further downstream. Additionally, the continuing pressures exerted on the bank at the sharp bend will eventually cause the riprap to fail and allow the erosion to continue (Figure 20). The best approach, then, is to identify how far the erosion will extend until the bend has developed into a more natural meander where energy expenditure is more evenly distributed (Figure 19a). Recognizing that the river will be exerting unnaturally high erosive forces on the bend until reaching this more natural configuration, a riparian buffer could be established within this zone, if not already present, in order to slow the rate of erosion. While planting trees anywhere along the river where the riparian buffer is absent will decrease the potential for erosion, focusing buffer planting efforts along the artificially sharp bends would be particularly effective. Bioengineering techniques could be used along the banks to provide bank protection over the short term while the riparian plantings take hold.

5.2 Managing Erosion Problems Associated with Tributary Land Use

The formation of deltas bars at tributary mouths leads to erosion along the opposite bank of the northern Connecticut River. Decreasing the rate of deposition on the delta bar would in turn relieve the erosive forces on the opposite bank. Consequently, addressing the cause of erosion requires decreasing the amount of sediment emanating from the tributary. This could be achieved by either decreasing sediment production in the tributary watershed or by increasing sediment storage along the tributary channel. The best approach to take in any given tributary would require further assessment of that tributary. Recognizing that extensive land clearance in small watersheds is responsible for delta bar growth on some tributaries, efforts to revegetate these watersheds could prove effective in reducing erosion on the mainstem (Figure 21). Assuming landowner willingness exists, the revegetation of a small watershed would be feasible. Efforts to increase sediment storage along the tributary channel would probably prove a more effective technique of limiting delta bar growth in larger watersheds where extensive revegetation efforts would prove more difficult. As conflicts arise resulting from erosion on the mainstem caused by delta bar growth, conditions in the tributary should be analyzed to better understand the cause of erosion rather than simply trying to protect the eroding bank. Simply armoring the bank or implementing bioengineering techniques will only prove effective for a short time period if sediment delivery to the mouth of the tributary is not limited.

5.3 Managing Erosion Problems Associated with Adjustments to Deglaciation

Bar growth associated with sediment production from high non-alluvial banks or upstream tributary confluences results in numerous bank erosion problems along the northern Connecticut River. While much of the sediment production and bar growth driving the erosion is a continuing natural response to deglaciation, the rate of erosion can be increased by human activities. Simply protecting the eroding banks with riprap is often ineffective because the bars responsible for diverting the river's flow into the bank will migrate downstream over time. The location of the erosion will migrate with the bars, leaving the riprap in an area where the erosive forces are no longer present (Figure 25). Continuing to add riprap as a bar migrates downstream would help stop the newly emerging erosion but extended lengths of riprap will destabilize the river further downstream where no riprap is present and negatively impact aquatic habitat.

Directly addressing the cause for erosion would require stabilizing the sources that supply sediment to the bars. Approaches for stabilizing sediment sources from tributaries are discussed above in Section 5.2 - Managing Erosion Problems Associated with Tributary Land Use. Stabilizing high eroding banks is technically feasible but such engineering projects are often expensive and run a high risk of failure. Many high banks along the northern Connecticut River are well vegetated and stable so efforts to stabilize high eroding banks should focus on revegetating the bank slopes. A combination of bioengineering structures at the toe of the slope that deflect flow away from the bank and revegetation efforts higher on the slopes may help decrease sediment inputs. Given that some of these sediment sources are the natural result of deglaciation, stabilization efforts should be focused on those banks that were destabilized by human activities. Where destabilization resulted from humans rerouting the channel against the high bank, stabilizing the bank might be achieved by placing the channel back in its original position away from the bank. While such opportunities should be sought, they are often technically and politically difficult to implement as discussed above in Section 5.1 - Managing Erosion Problems Associated with Channelization.

The difficulties associated with stabilizing the sediment sources, whether from tributaries or high eroding banks, necessitates efforts to manage the sediment within the mainstem of the northern Connecticut River. Bank erosion is most troublesome to the public when it occurs adjacent to areas being used by humans (e.g., farm fields, homes, bridges, etc.). If conservation easements can be established where bar deposition is most pronounced, then the human conflicts can be removed and bar growth allowed to continue without significant public concern. By allowing bar growth to occur within established easements, sediments supplied from upstream sources will be stored in the bars and less sediment will move downstream. In this manner, bar growth can be limited in areas where human land use occurs adjacent to the river while allowed to continue within established easements. Bank erosion caused by the bar growth could be slowed by establishing riparian buffers on the banks within the acquired easements. Without a practical alternative for stabilizing the sediment sources, targeting the acquisition of conservation easements in areas close to the sediment sources will not only alleviate human conflicts within the easements but will decrease bar growth and associated bank erosion downstream where human conflicts may still exist.

6.0 BANK STABILIZATION PROJECT DESIGN

Implementing projects demonstrating the various strategies discussed above in Section 5.0 – Erosion Control Strategies will test their effectiveness and illustrate what can be done to manage similar erosion problems in other areas. As part of the assessment reported here, the Connecticut River Joint Commission's project advisory committee for this Northern Connecticut River Assessment decided to first address erosion associated with tributary inputs. Among the many sites where this problem exists, bank erosion at the Colebrook Industrial Park 500 m (1,640 feet) downstream of the Mohawk River confluence in Colebrook, NH was chosen (Figure 28). Not only is the erosion of concern to the landowners, but the site has a lot of public visibility given its popularity among local fishermen and proximity to the Colebrook business district. Demonstrating erosion control strategies that improve aquatic habitat in this area will prove beneficial for gaining public support for future projects elsewhere.

The site was carefully surveyed following Vermont's Phase 3 assessment protocols in order to better understand the erosion problem and develop several management options for consideration (Appendix 5). The amount of sediment supplied to the Connecticut River from the Mohawk River was likely increased in the 1960's when the lower 350 m (1,150 feet) of the Mohawk River on its alluvial fan was straightened for flood control purposes. With Vermont Highway 102 directly across the Connecticut River from the Mohawk River confluence, the opposite bank has been armored (i.e., riprapped) with large rock to prevent bank erosion from jeopardizing the highway (Figure 28). This has effectively transferred the sediment downstream to the Colebrook Industrial Park where the presence of large unvegetated point bars and mid-channel bars is forcing the river to erode the bank on which the industrial park is located (Figures 28 and 29). The development of the bars, or some other mechanism, caused a blockage at the upstream end of the existing side channel and forced flow into the current channel (Figure 28 and Appendix 5); the side channel is likely where the main channel used to flow at some time prior to 1925.

The upstream portion of the eroding bank at the Colebrook Industrial Park is a high bank composed of loose sand and gravel that is 2.0 m (6.6 feet) higher than the eroding floodplain silts downstream (Figure 30). Riprap is protecting a portion of the eroding floodplain deposits across from the mid-channel bar (Figures 28 and 30). The height and composition of the bank material is an important consideration in choosing the most effective management option for the site.

Six management options were considered for addressing bank erosion problems at the Colebrook Industrial Park: do nothing; plant a riparian buffer within a conservation easement; construct bioengineering structures along the bank; realign channel back into the current side channel; remove the existing riprap across from the mid-channel bar; and provide the Mohawk River access to its alluvial fan. A conceptual plan view design and list of pros and cons were developed for each option (Appendix 5). The realignment of the channel was ruled out as an option because of the great expense, likely permitting difficulties, and the possibility for unintended consequences to develop. While removing the riprap would allow the bank to recede and provide sediment storage that would help alleviate problems on eroding banks further downstream (Figure 28), this option was also dismissed because of the likelihood for public resistance, at least during initial management of the site.

The favored option for managing the site, at least immediately, is to combine the acquisition of a conservation easement with the installation of bioengineering structures. The bioengineering will provide immediate bank protection while improving fish cover habitat. Given the potential difficulty of securing structures to the high banks composed of sand and gravel at the upstream end of the site, bioengineering structures will initially be placed only along the lower floodplain surface between the riprap and high alluvial fan surface (Figure 30). The project will be extended later to the high banks if the initial structures succeed and public acceptance for bioengineering techniques increases.

The bioengineering structures will decompose over a period of 10 to 30 years but this will allow time for a riparian buffer to become established within a conservation easement. The vegetation in the easement will slow erosion over the long term. By not completely stopping the erosion, as riprapping the bank with large rock would do, sediment transfer downstream will be minimized, thereby increasing downstream stability. The vegetation will also improve habitat by shading the stream and providing cover habitat as trees are undercut by erosion and fall into the stream.

Neither the acquisition of a conservation easement nor the installation of bioengineering structures directly address the impairments to channel stability caused by the sediments emerging from the Mohawk River. While providing the Mohawk River access to its alluvial fan is not a practical short-term solution for alleviating bank erosion at the Colebrook Industrial Park, decreasing sediment production or increasing sediment storage within the Mohawk River watershed would directly address the causes for erosion and channel instability on the Connecticut River mainstem. Under natural conditions, excess sediment produced in the Mohawk River watershed would be deposited on its alluvial fan as the river began to bifurcate into multiple channels. With deposition on the alluvial fan, sediment delivery, bar growth, and bank erosion on the Connecticut River would be minimal. Heavy land use in the watershed since European settlement of the region has increased sediment production in the watershed, although reforestation over the past 100 years has reversed this trend. With channelization of the lower Mohawk River in the 1960’s, the excess sediment from the watershed was more easily transported directly into the Connecticut River which would exacerbate instabilities caused by bar growth and bank erosion. Reestablishing a more natural condition of bifurcating channels on the Mohawk River alluvial fan would increase deposition on the fan and decrease sediment delivery to the mainstem. The practicality of increasing alluvial fan access or implementing other management strategies in the Mohawk River watershed that directly address the question of sediment delivery to the mainstem will require further assessment. In the interim, successful attempts at slowing erosion and improving habitat at the Colebrook Industrial Park through bioengineering and riparian buffer establishment will increase public acceptance for future management efforts on the Mohawk River.

7.0 CONCLUSIONS

A fluvial geomorphic assessment of the northern Connecticut River has revealed that 66 percent of the river's banks are either eroding, have been protected from erosion, or are susceptible to further erosion (Table 1). This bank erosion and attempts to stabilize the banks with riprap has caused a number of impairments to river stability and physical aquatic habitat. A number of factors, with excess sediment being a primary cause, are responsible for these impairments. Channel straightening, that occurred along 30 percent of the river's length prior to 1925 (Figure 14 and Table 3), has left the channels wider and deeper than natural meandering segments of the channel. Erosion is prevalent at the upstream and downstream ends of these straightened areas where the river's energy is focused at sharp bends. Sediment inputs at tributary confluences and high eroding banks of glacial outwash deposits leads to the deposition of delta bars, mid-channel bars, and point bars that deflect flow into adjacent river banks. This flow deflection results in bank erosion. While sediment inputs and bar deposition are naturally occurring phenomenon, human land use in tributary watersheds and human activities on the mainstem (e.g., channel straightening) has accelerated the delivery of sediment to the river and caused extensive erosion. Attempts to stabilize the banks with hard armoring techniques (i.e., riprap) merely transfer the sediment downstream, promulgating the impairment further, rather than directly addressing the source of the problem. Erosion caused by dams on the mainstem and on tributaries is still poorly understood and will require further study downstream of the Upper Ammonoosuc River where this factor appears most significant. Impairments resulting from erosion due to these various causes are worsened by the lack of a riparian buffer along 20 percent of the river's length. The banks' susceptibility to erosion is highest where no riparian buffer is present (Figure 27). Bank stability generally increases as buffer width increases with buffer widths greater than 7.6 m (25 feet) needed to lower a bank's susceptibility to erosion below the average condition.

Management strategies to deal with the identified impairments must address the cause of the problem if long term improvements in bank stability and aquatic habitat are to be realized. Reducing erosion at the upstream and downstream ends of channelized reaches could be achieved by realigning the river channel back into its former meanders but technical and political concerns make such an approach unfeasible in most, if not all, situations. Channel incision resulting from the straightening, dams, and reforestation of the watershed has left the current channel over 1.0 m (3.2 feet) above abandoned segments which means reoccupying these former flow paths is not possible. Managing impairments associated with sediment inputs from tributaries or high eroding banks requires stabilizing the sediment sources or increasing sediment storage along the tributary. While such approaches are more feasible than managing channelization problems, the necessary scale of the projects on very high banks or large tributaries will preclude their implementation in most cases.

In the absence of practical approaches to directly address the causes of impaired channel stability and physical habitat, the problems must be managed where they occur. The best approach would be to acquire conservation easements in order to reduce human conflicts and allow space for sediment storage. Although erosion will continue if sediment is allowed to accumulate, the establishment of a riparian buffer within the acquired easement will slow the progress of erosion. More importantly, the reduction in sediment moving further downstream will improve channel stability and physical habitat elsewhere where human conflicts may be more significant and habitat conditions more sensitive. Attempting to completely stop the erosion with hard armoring (i.e., riprap) techniques will merely transfer instabilities further downstream. While establishing riparian buffers anywhere along the river will increase bank stability, establishing buffers in high priority areas (i.e., ends of channelized reaches or areas of bar formation) will improve channel stability and physical habitat beyond the immediate area where the buffer is planted. Implementing demonstration projects that illustrate these management strategies, such as at the Colebrook Industrial Park, will serve to educate the public concerning the benefits resulting from these techniques and, over the long term, will make implementation of more ambitious projects that directly address the causes of instabilities more acceptable and practical.

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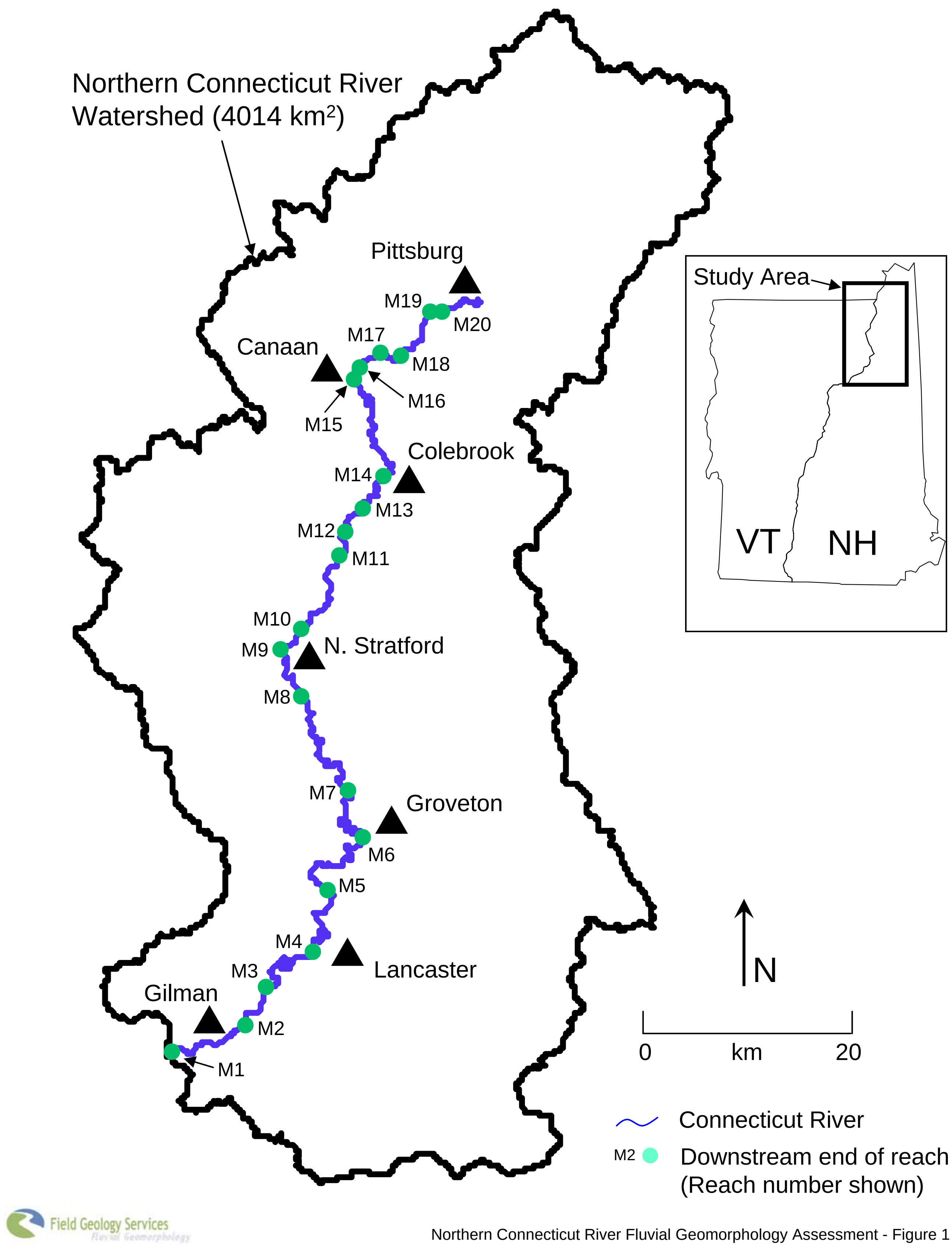
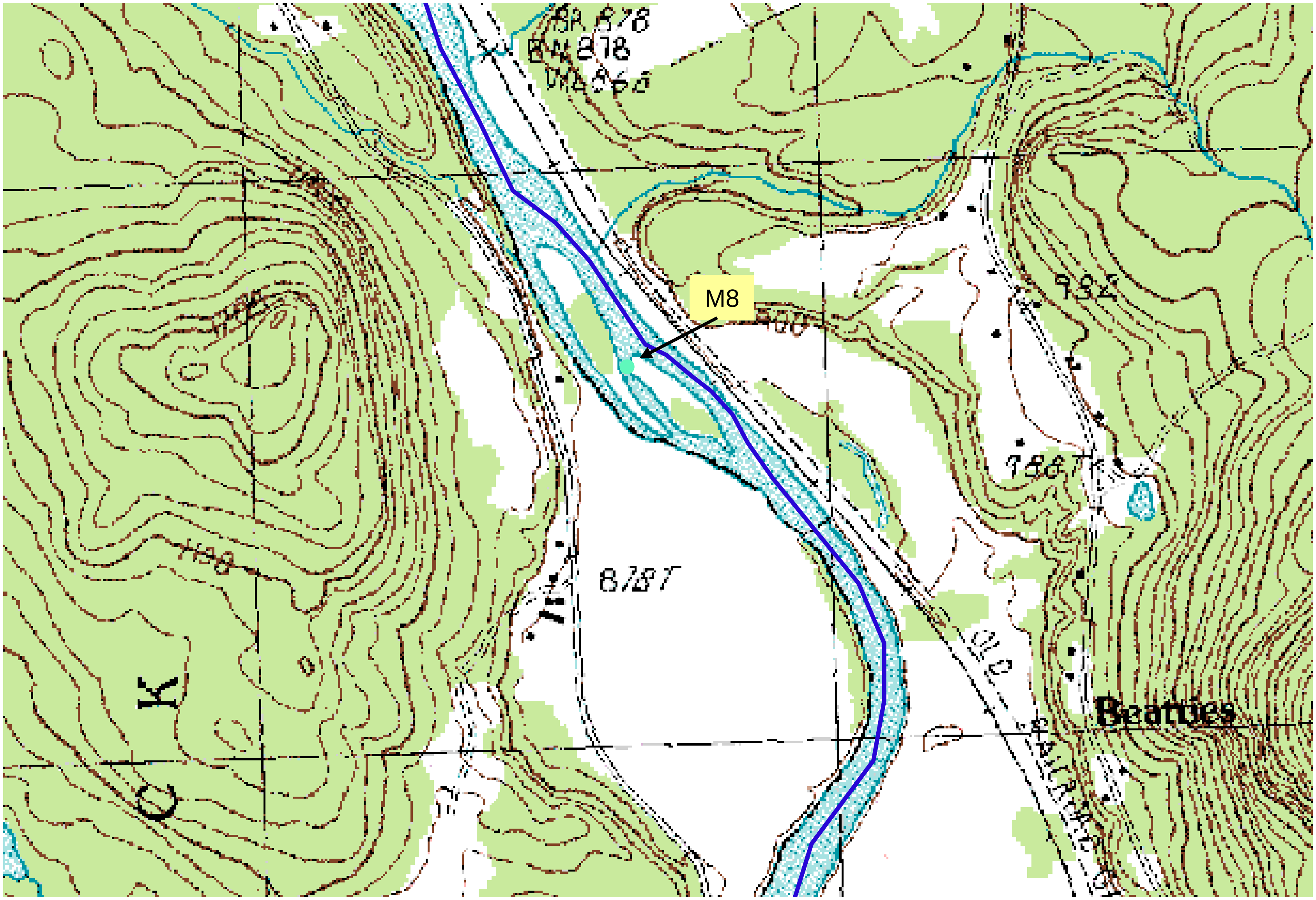
Brakenridge, G.B., Thomas, P.A., Conkey, L.E., Schiferle, J.C., 1988, Fluvial sedimentation in response to postglacial uplift and environmental change, Missisquoi River, Vermont: Quaternary Research, v. 30, p. 190-203.

Williams, G.P., and Wolman, M.G., 1984, Downstream effects of dams on alluvial rivers: U.S. Geological Survey Professional Paper 1286, 83 p.

Location of Study Area With Reach Breaks



Bar Deposition - Expansion of Valley Width



Note: Reach break (M8) at gravel bars formed coincident with valley expansion

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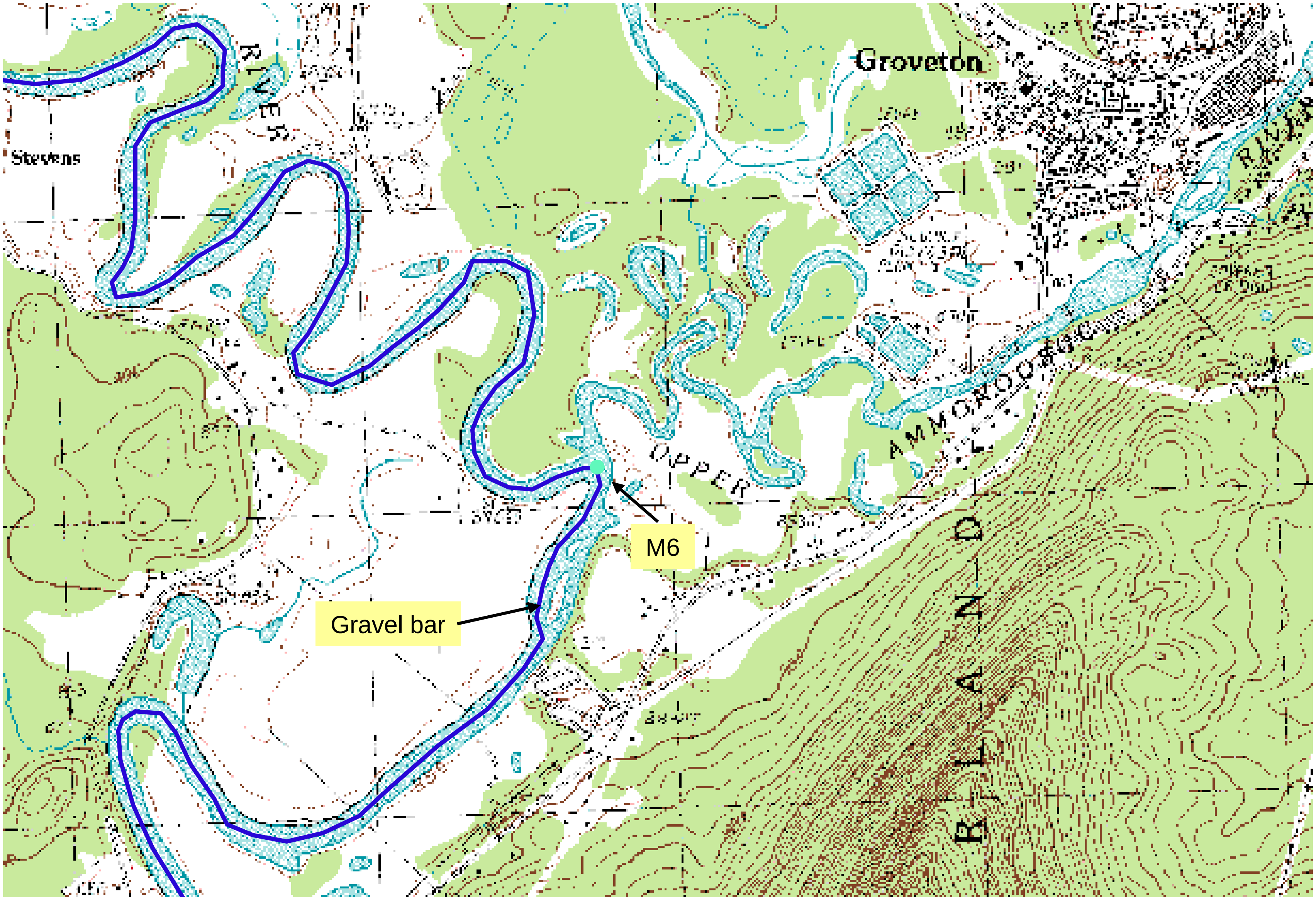
Bar Deposition – Downstream of Confluence



Note gravel bar formed just below reach break (M6) at confluence with the Upper Ammonoosuc River

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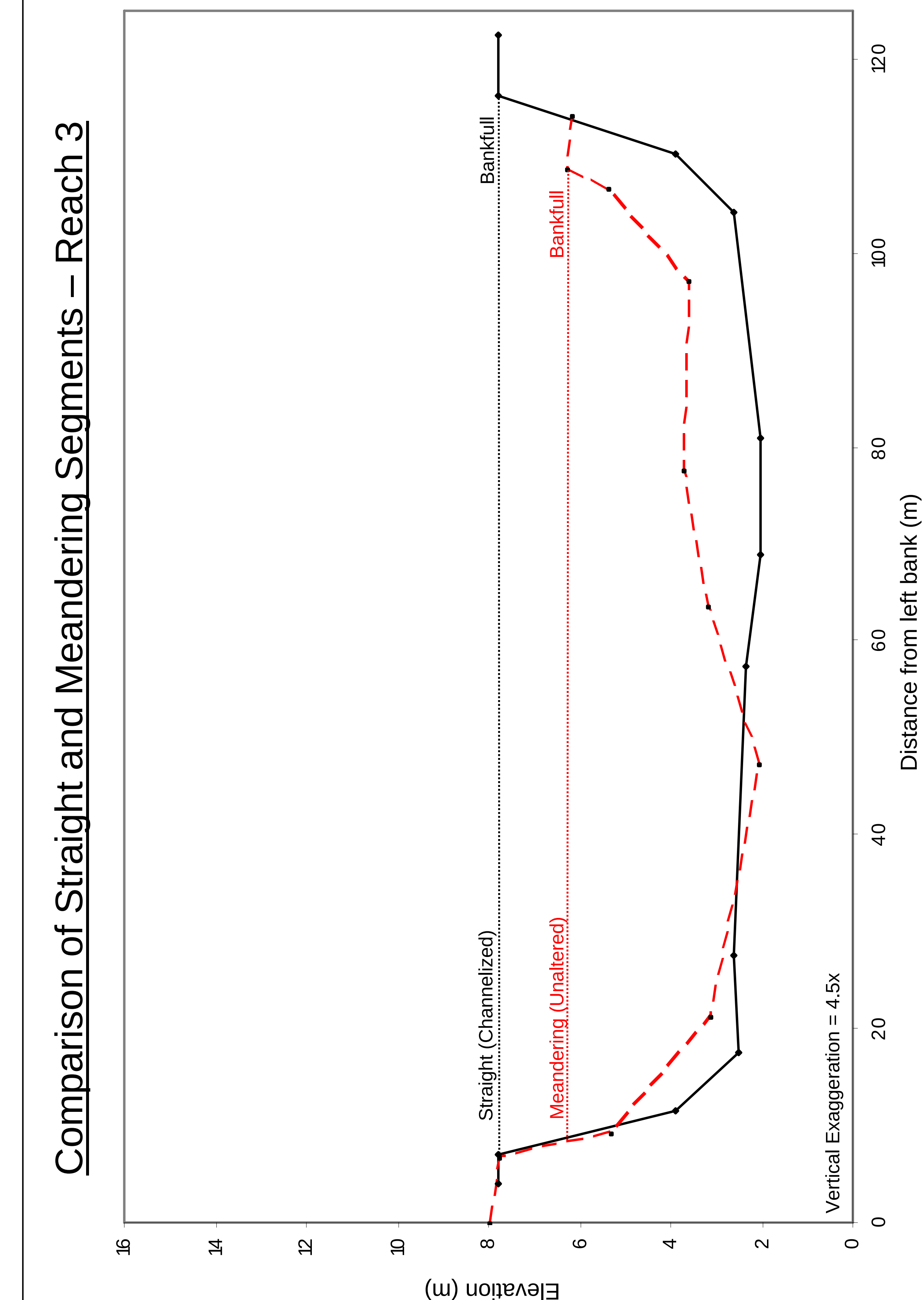

Note: Other comparisons of straight and meandering segments are found in Table 4 and Appendix 4

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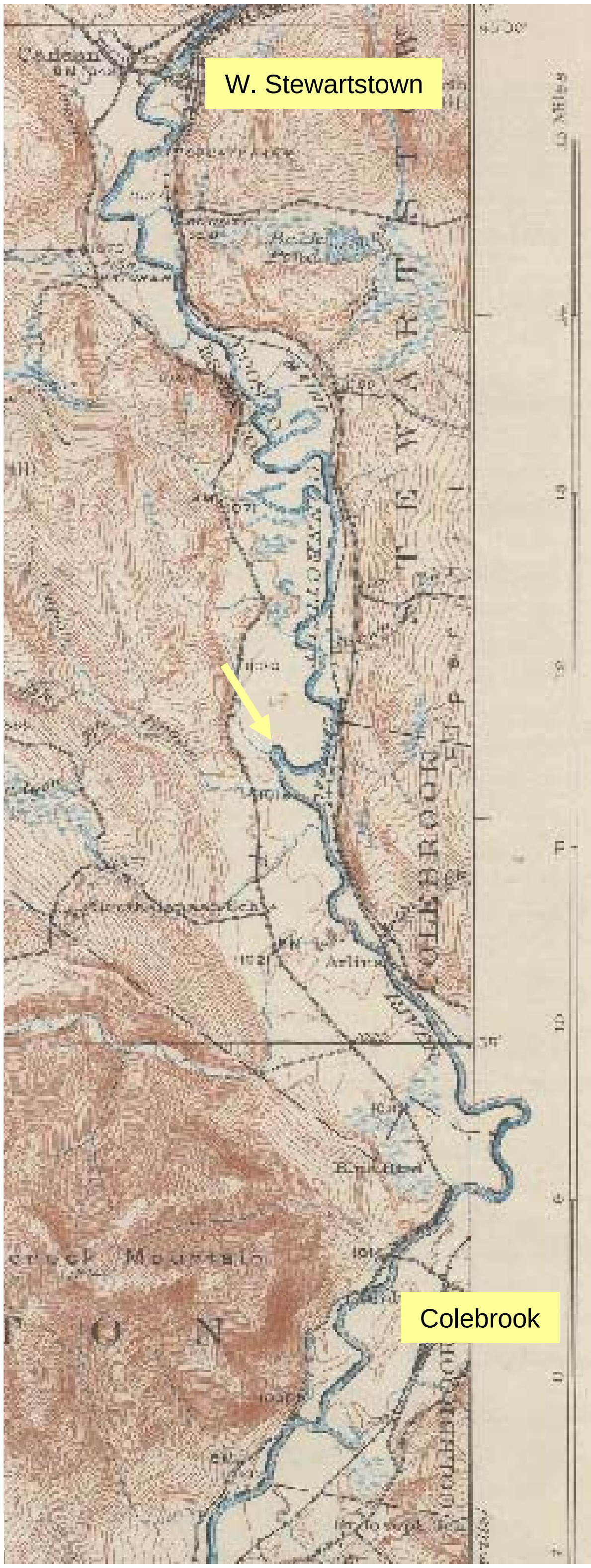
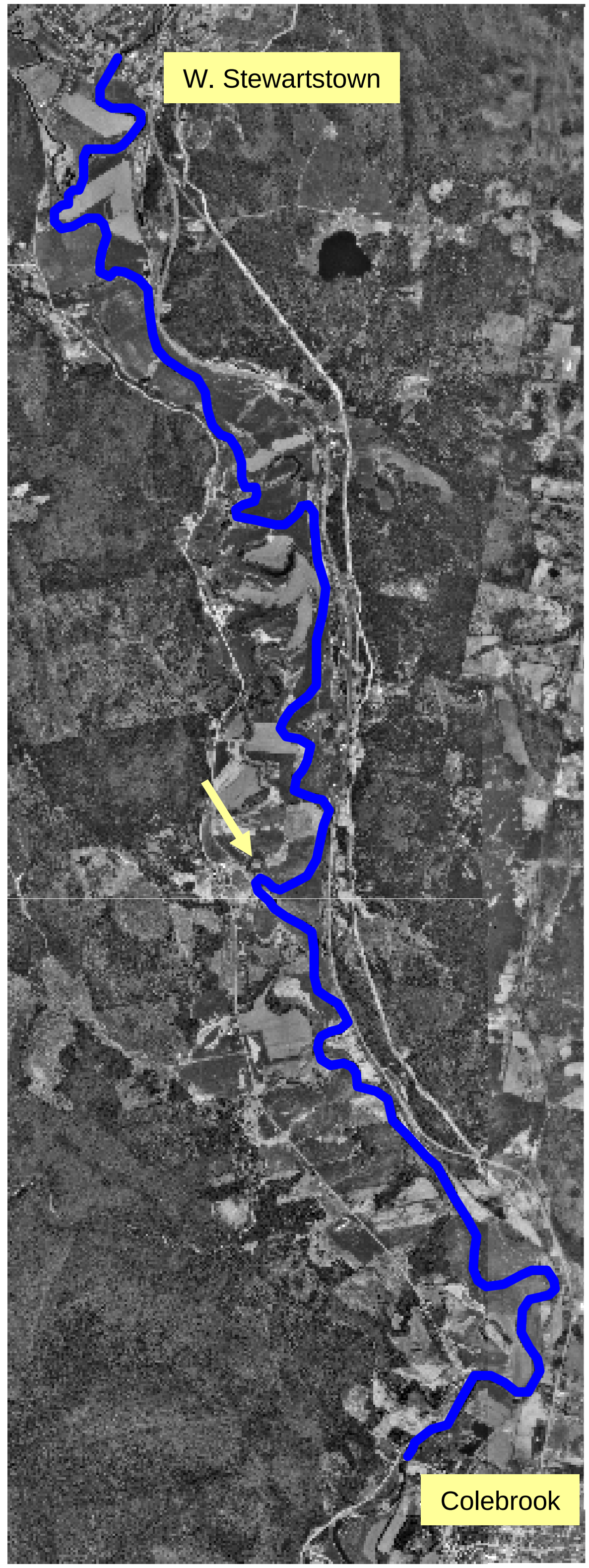
Northern Connecticut River Fluvial Geomorphology Assessment – Figure 3

Channel Position in 1925 and 1998



1925



1998

Note: Markings described in text

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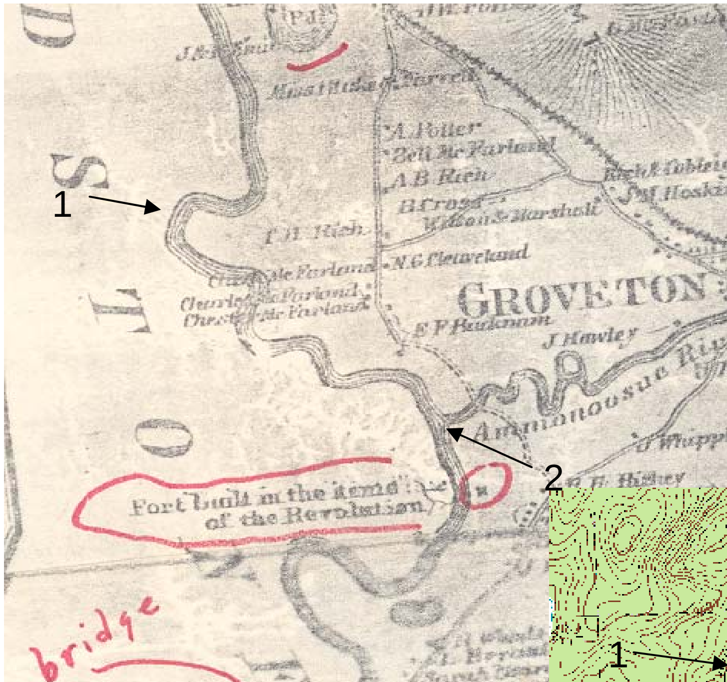
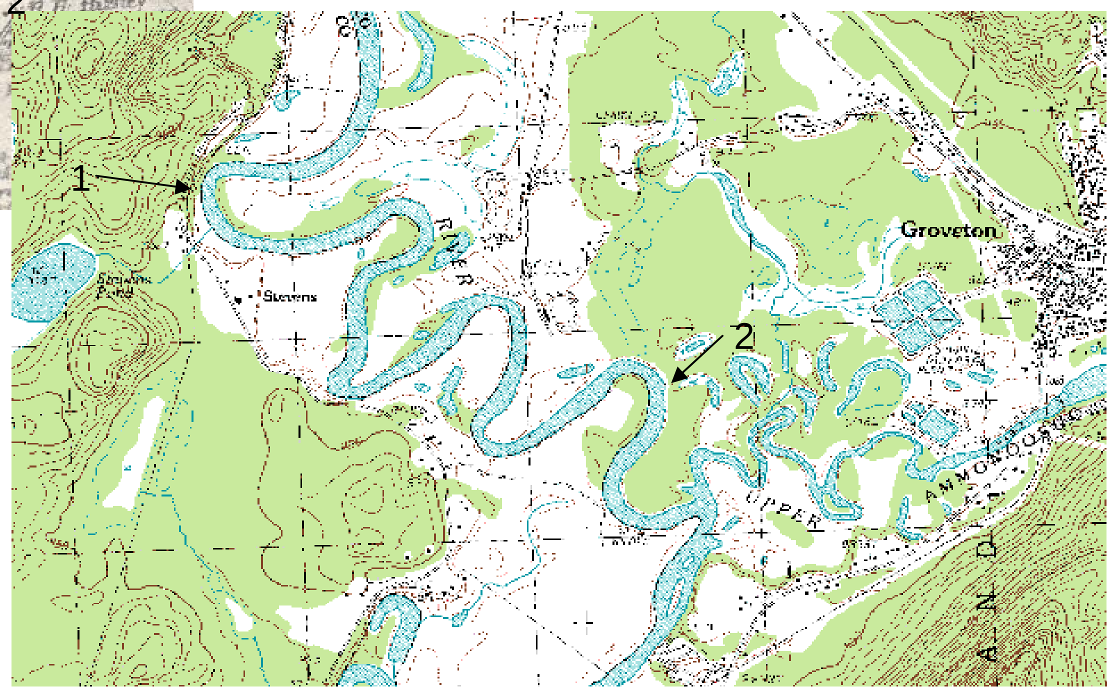
Meander Growth Between 1861-1925

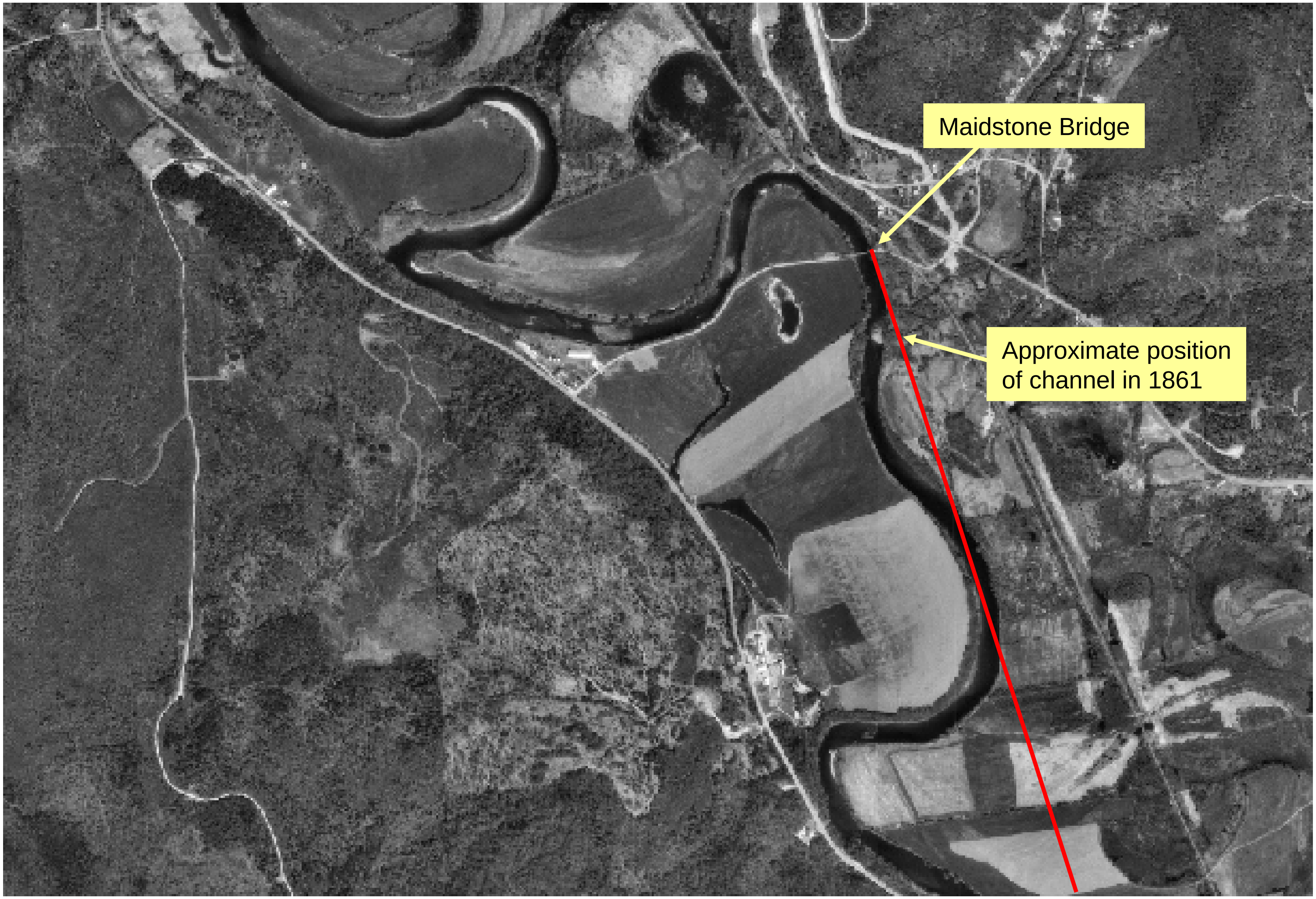


1861



1988 (Note: No changes occurred after 1925)

Sinuosity Developing in Previously Straightened Reach



Note: In Reach 7 at Maidstone Bridge

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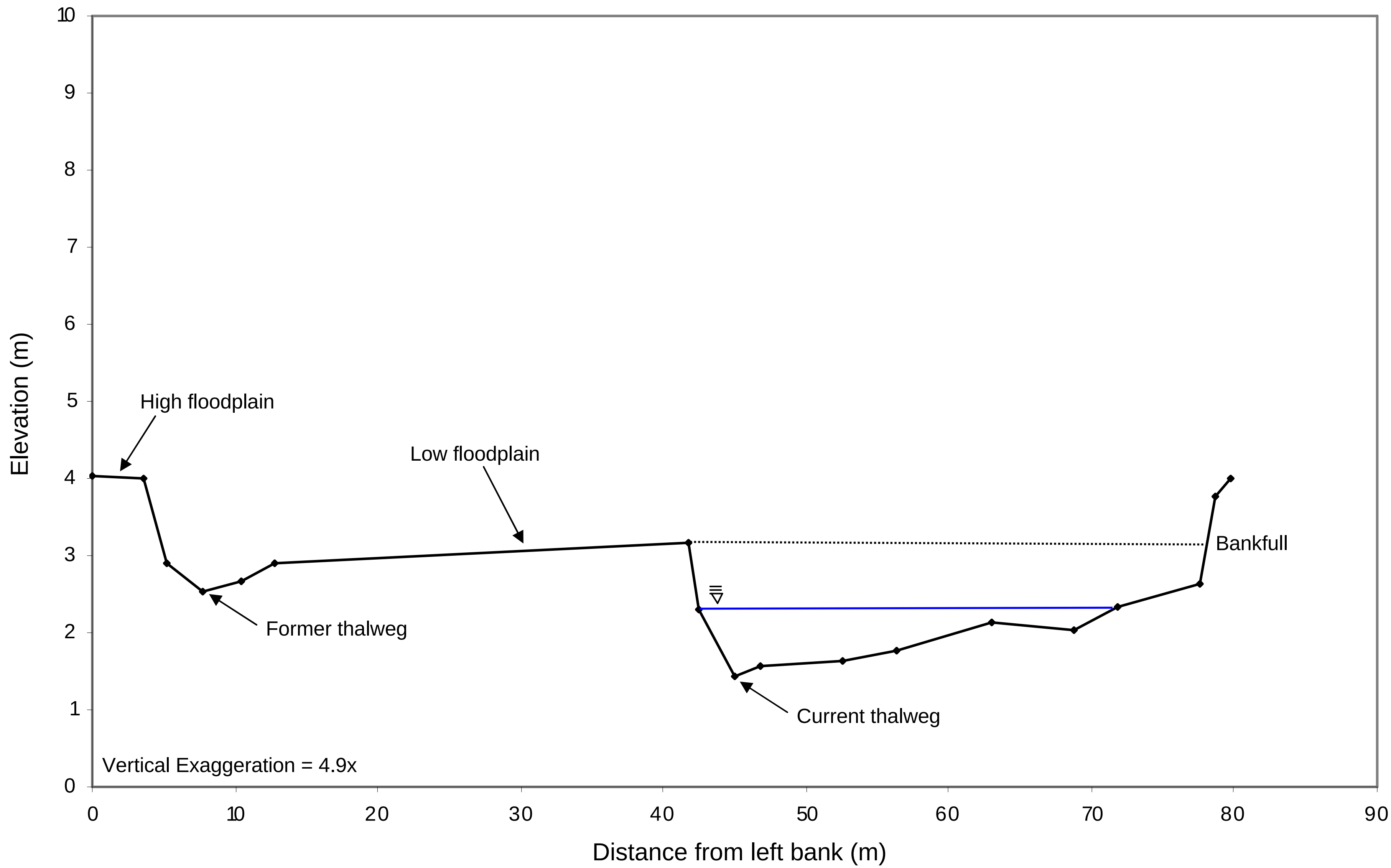
Channel Cross Section Showing Evidence of Channel Incision – Reach 14



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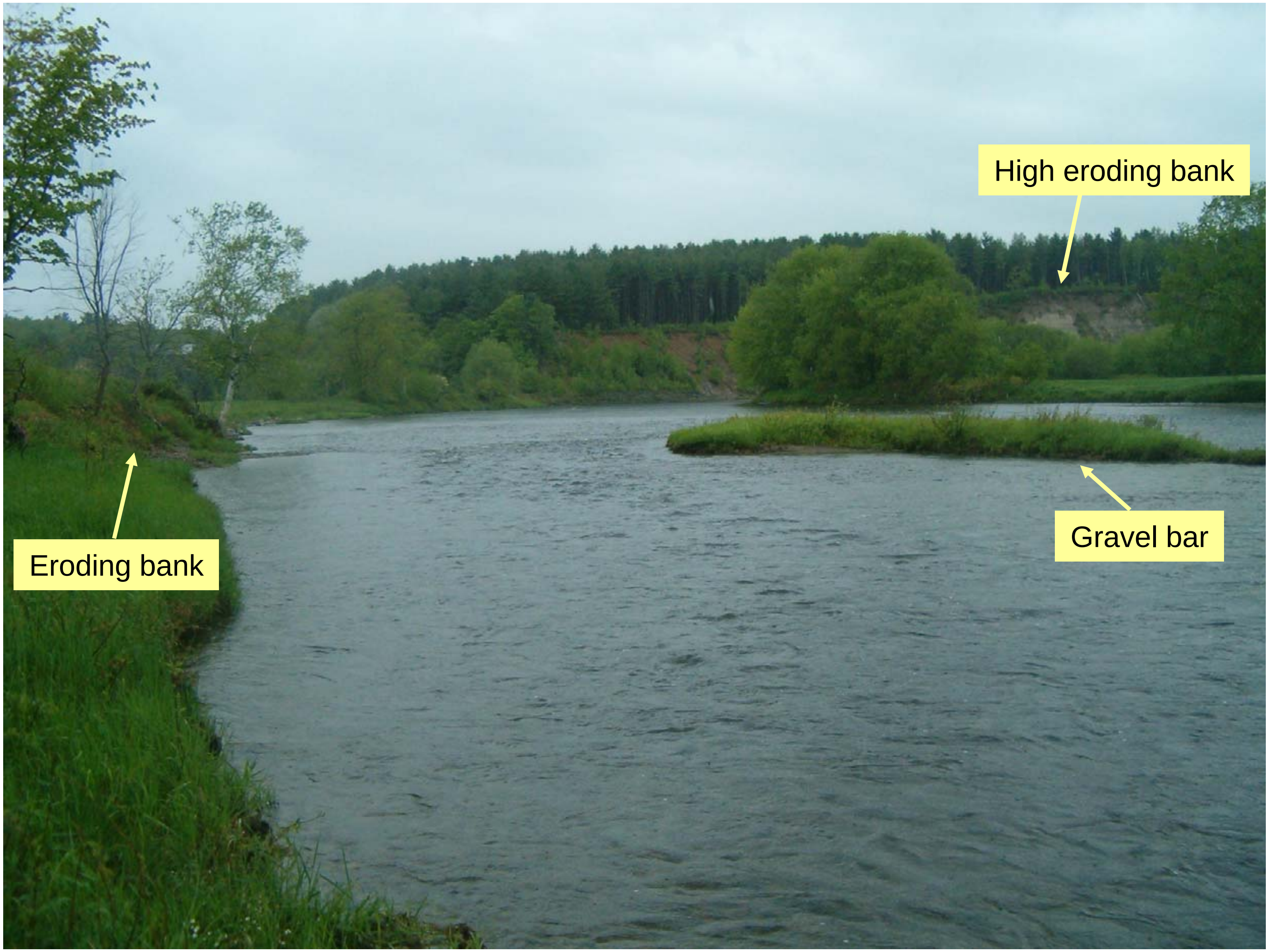
Northern Connecticut River Fluvial Geomorphology Assessment – Figure 6

Bar Formation Downstream of High Eroding Bank in Reach 8



Note: Erosion in foreground caused by flow deflection around gravel bar supplied by erosion of high bank in background

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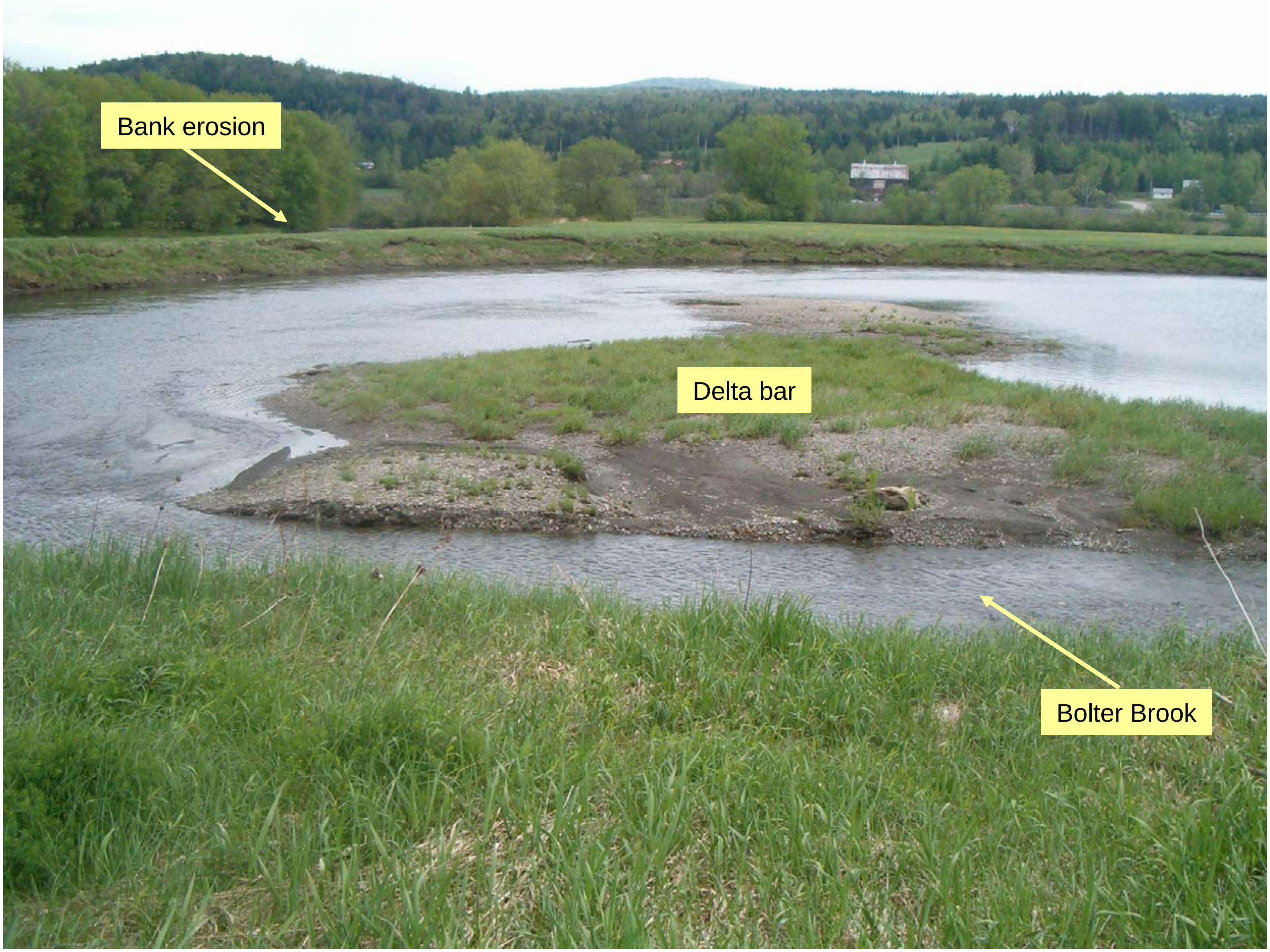
Growing Delta Bar on Bolter Brook Causing Erosion of Opposite Bank



Note: In Reach 14

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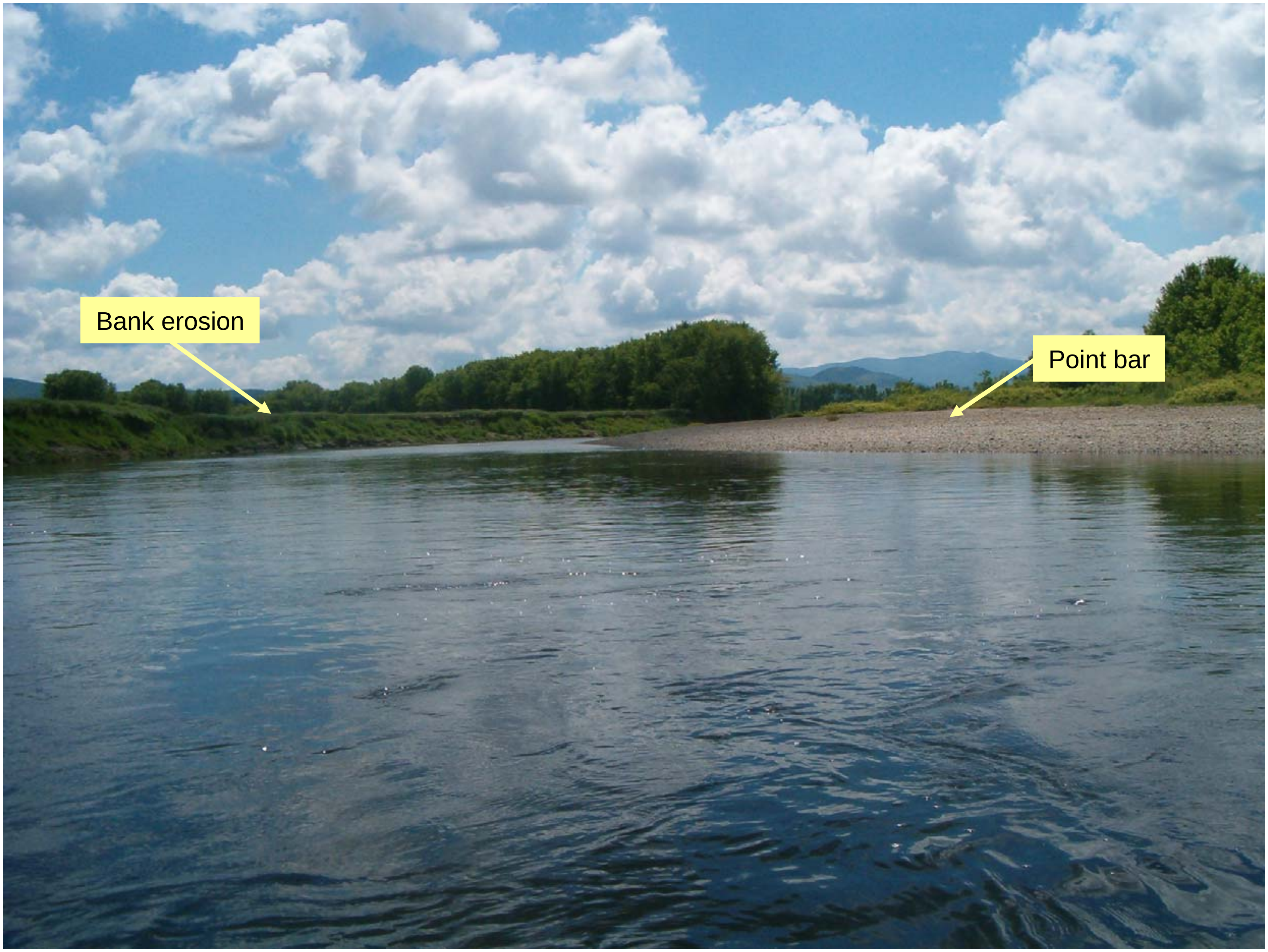
Point Bar Formation Causing Erosion of Opposite Bank – Reach 7



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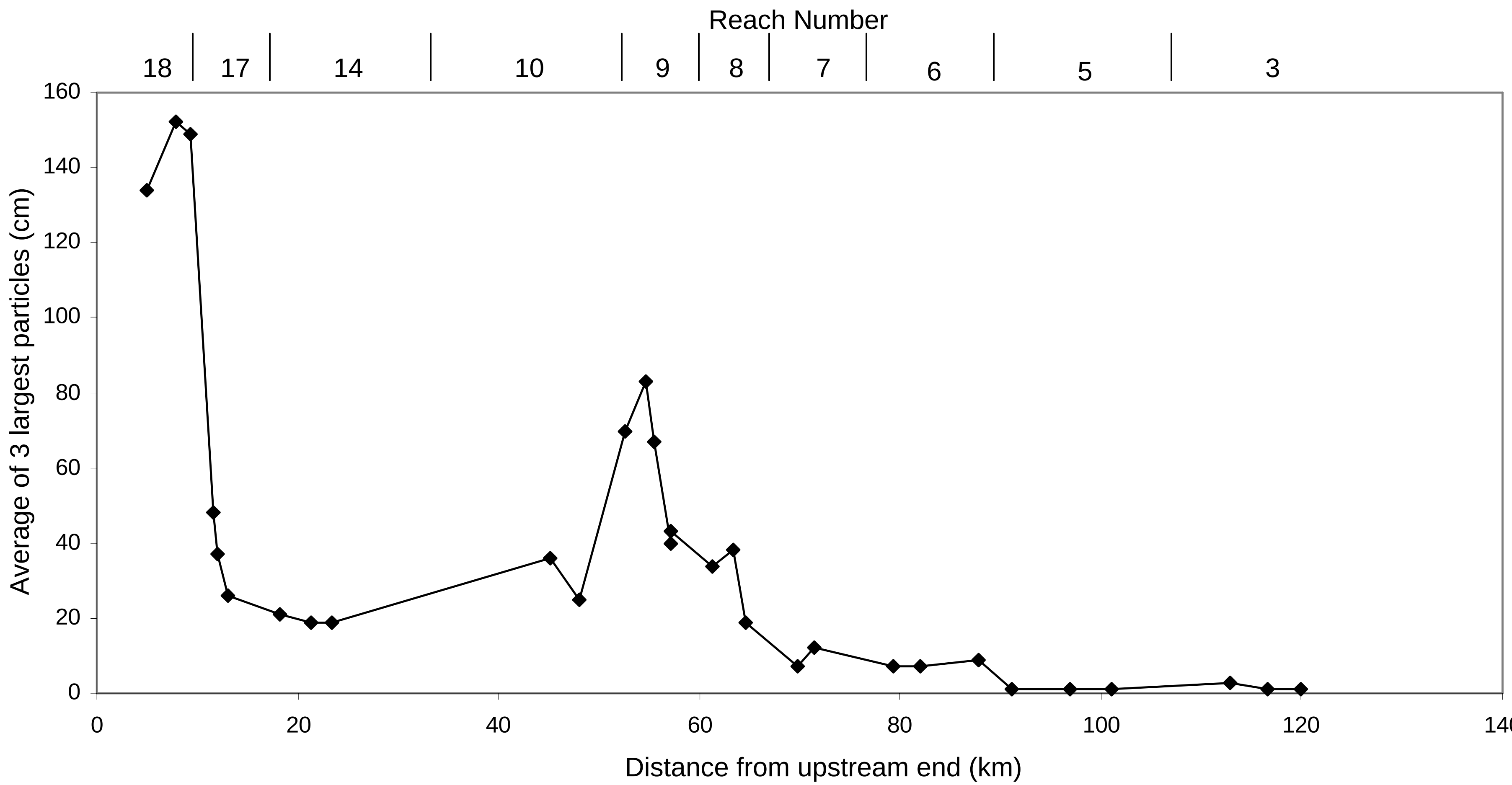
Northern Connecticut River Fluvial Geomorphology Assessment – Figure 9

Downstream Changes in Particle Size



Note: Data on average size of 3 largest particles is available only for those reaches studied during the Phase 2 assessment

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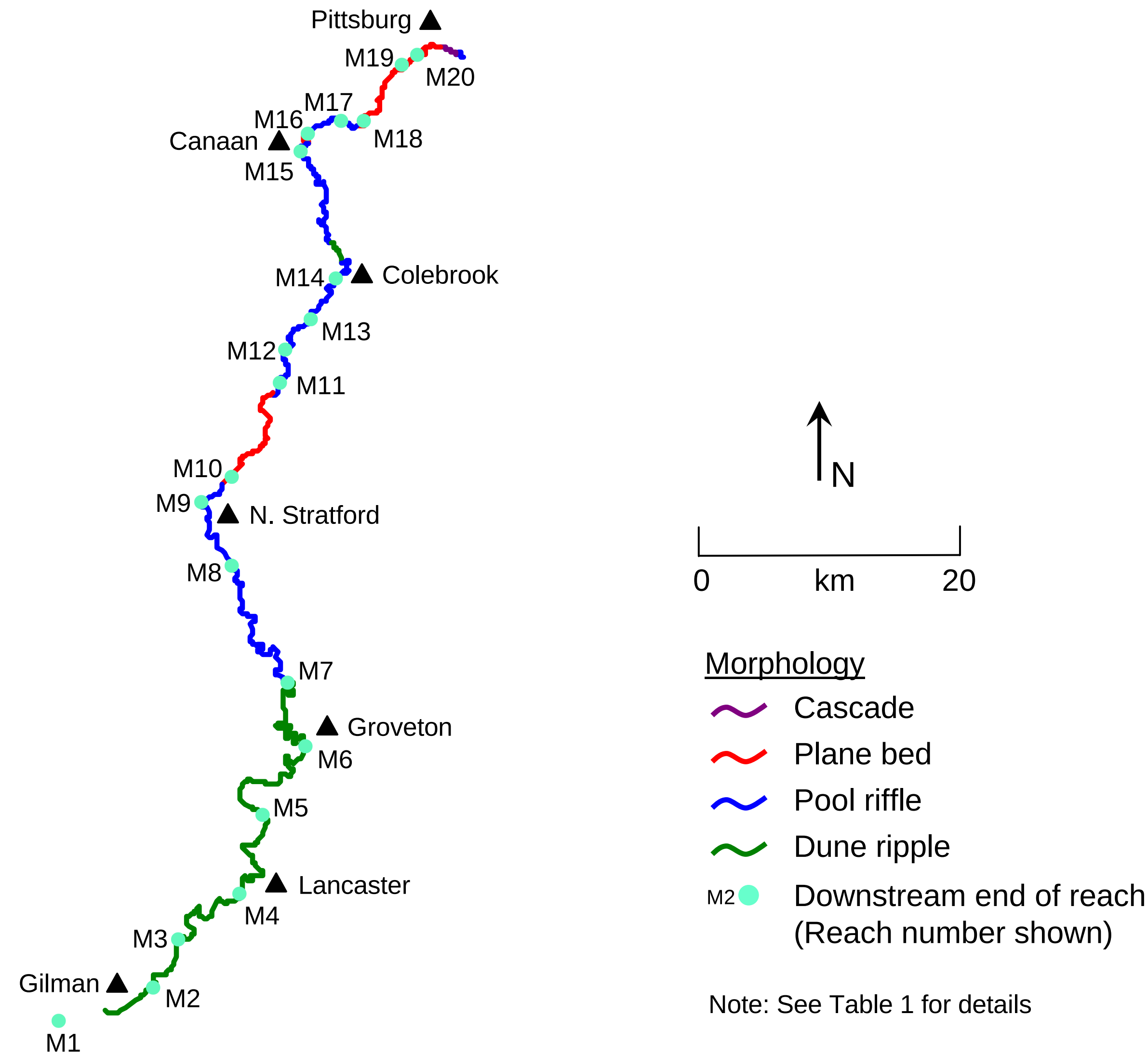
Northern Connecticut River Fluvial Geomorphology Assessment – Figure 10

Distribution of Channel Bed Morphology



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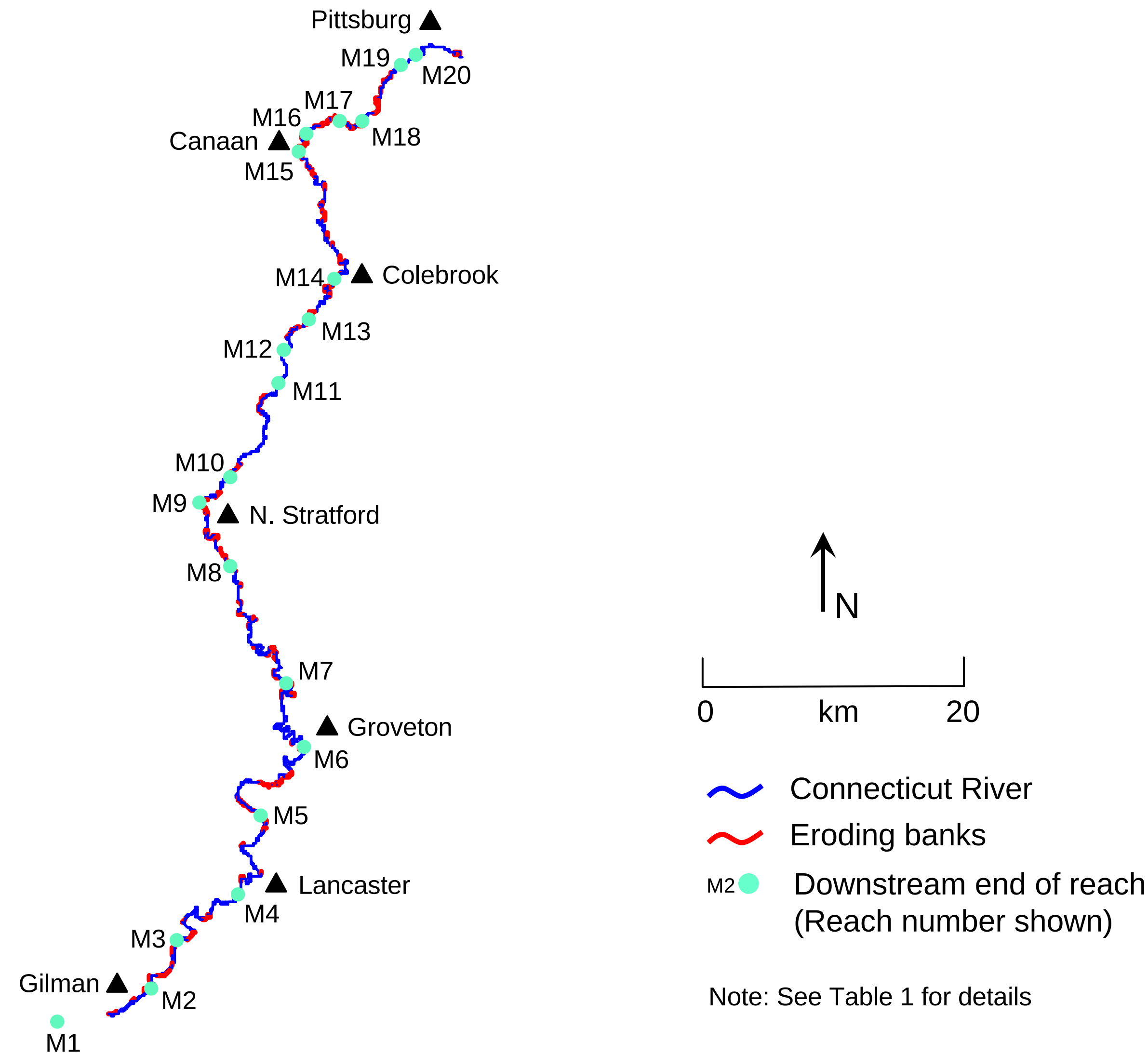
Distribution of Bank Erosion



Note: See Table 1 for details

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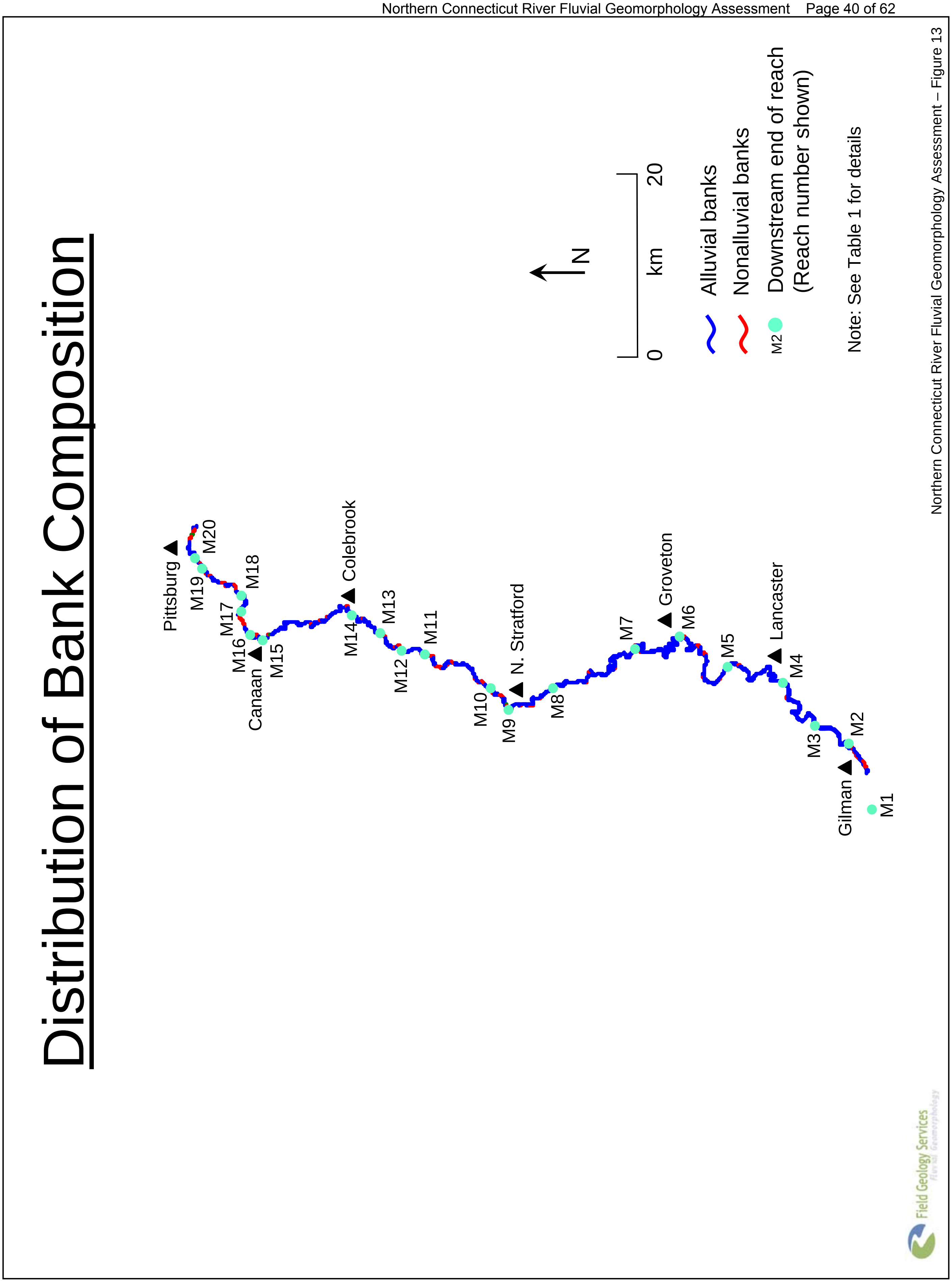
Northern Connecticut River Fluvial Geomorphology Assessment – Figure 12


Distribution of Bank Composition
Pittsburg
M20
M19
M18
M17
M16
Canaan
M15
Colebrook
M14
M13
M12
M11
N. Stratford
M10
M9
M8
M7
Groveton
M6
M5
Lancaster
M4
M3
M2
Gilman
M1
N
0
km
20
Alluvial banks
Nonalluvial banks
M2
Downstream end of reach
(Reach number shown)
Note: See Table 1 for details
Northern Connecticut River Fluvial Geomorphology Assessment – Figure 13
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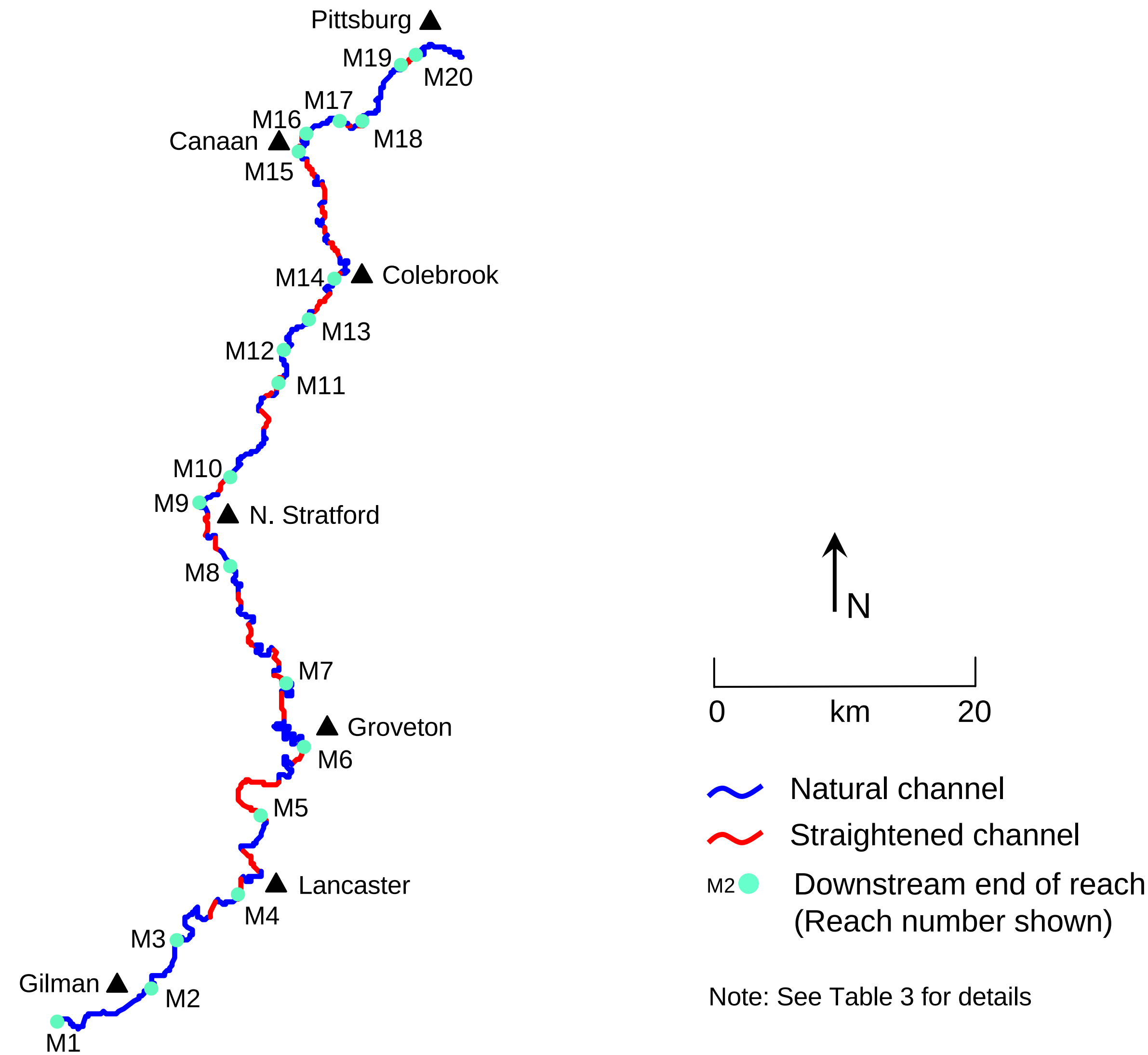
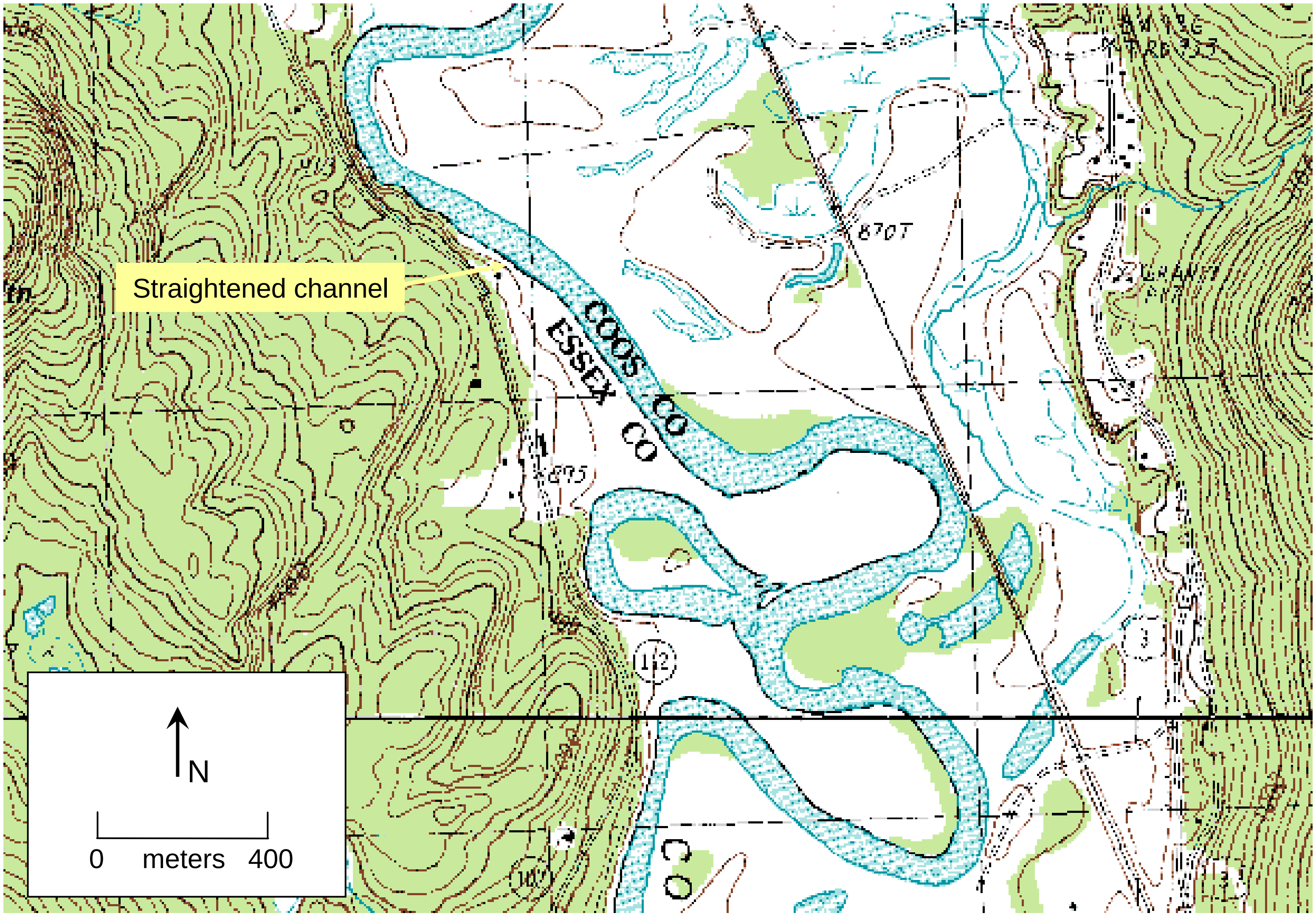
Location of Straightened Channel Segments



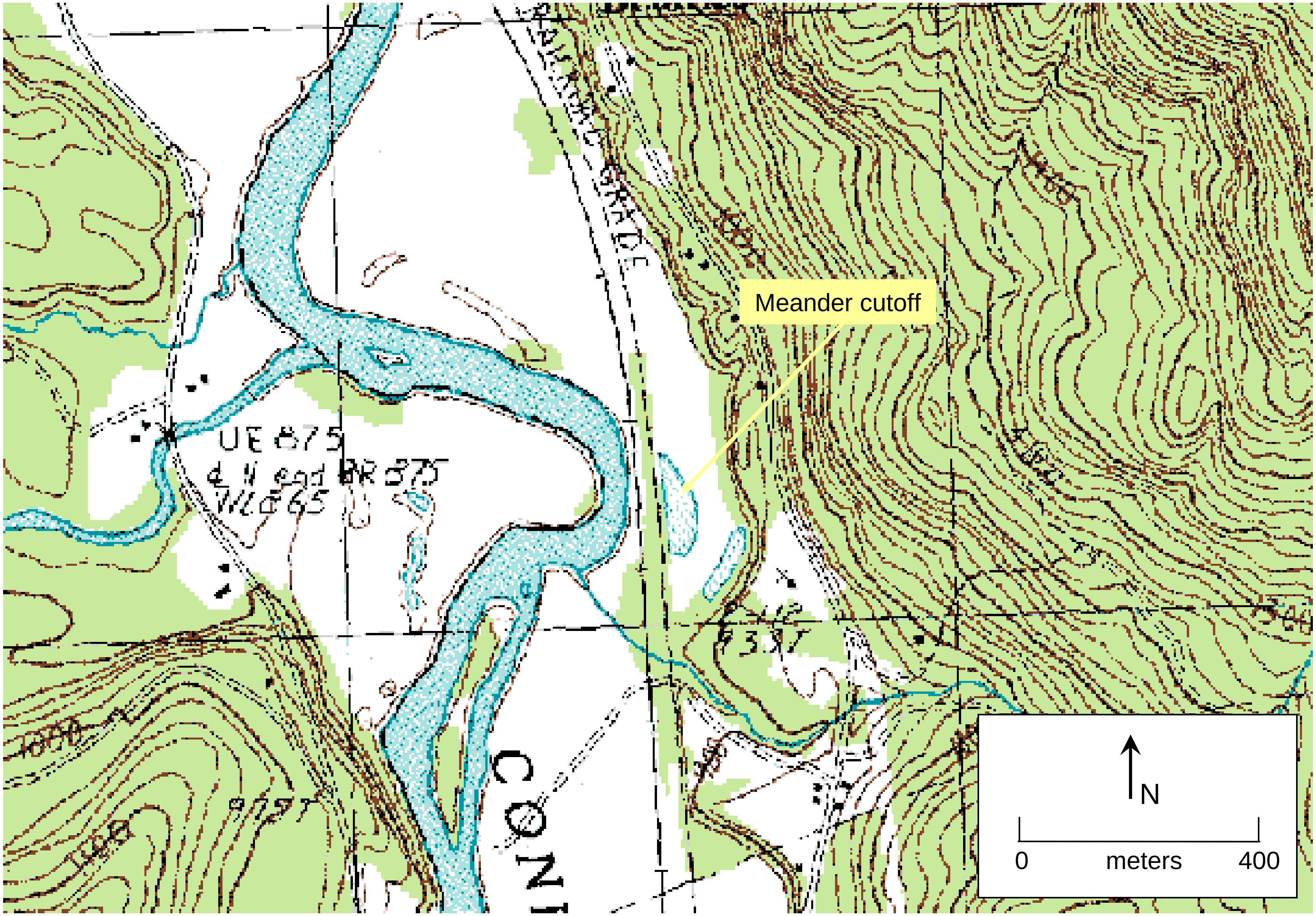
Field Geology Services Fluvial Geomorphology

Evidence for Channel Straightening – Reach 7



Note that straightened portion of channel is longer than wavelength of adjacent meander

Meander Cutoff by Railroad Construction – Reach 7



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Northern Connecticut River Fluvial Geomorphology Assessment – Figure 16

Stable Banks Along Straightened Channel – Reach 7

Old Riprap Failing Along Straightened Channel

Note: In Reach 14

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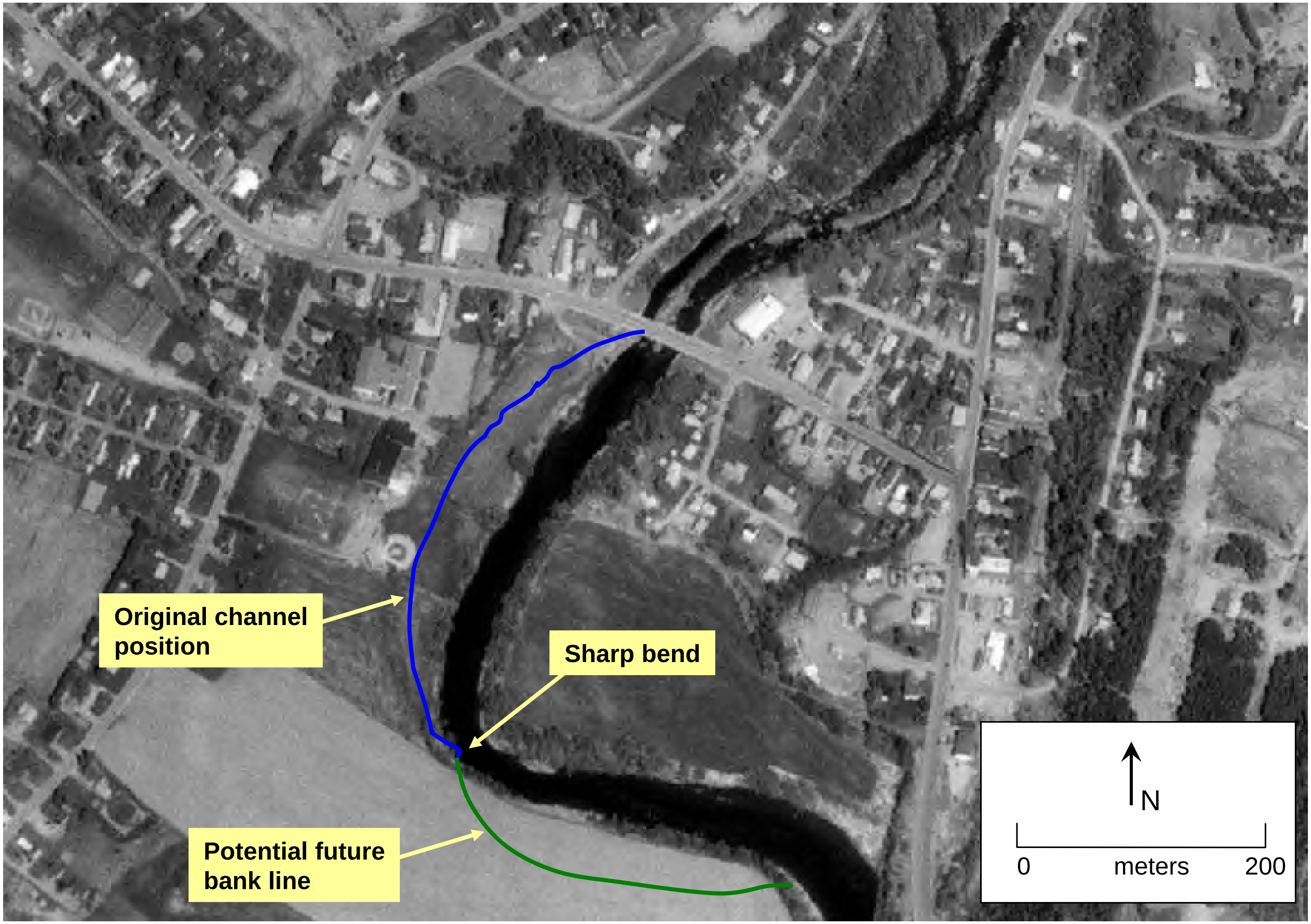
Sharp Bend at End of Straightened Channel – Reach 15



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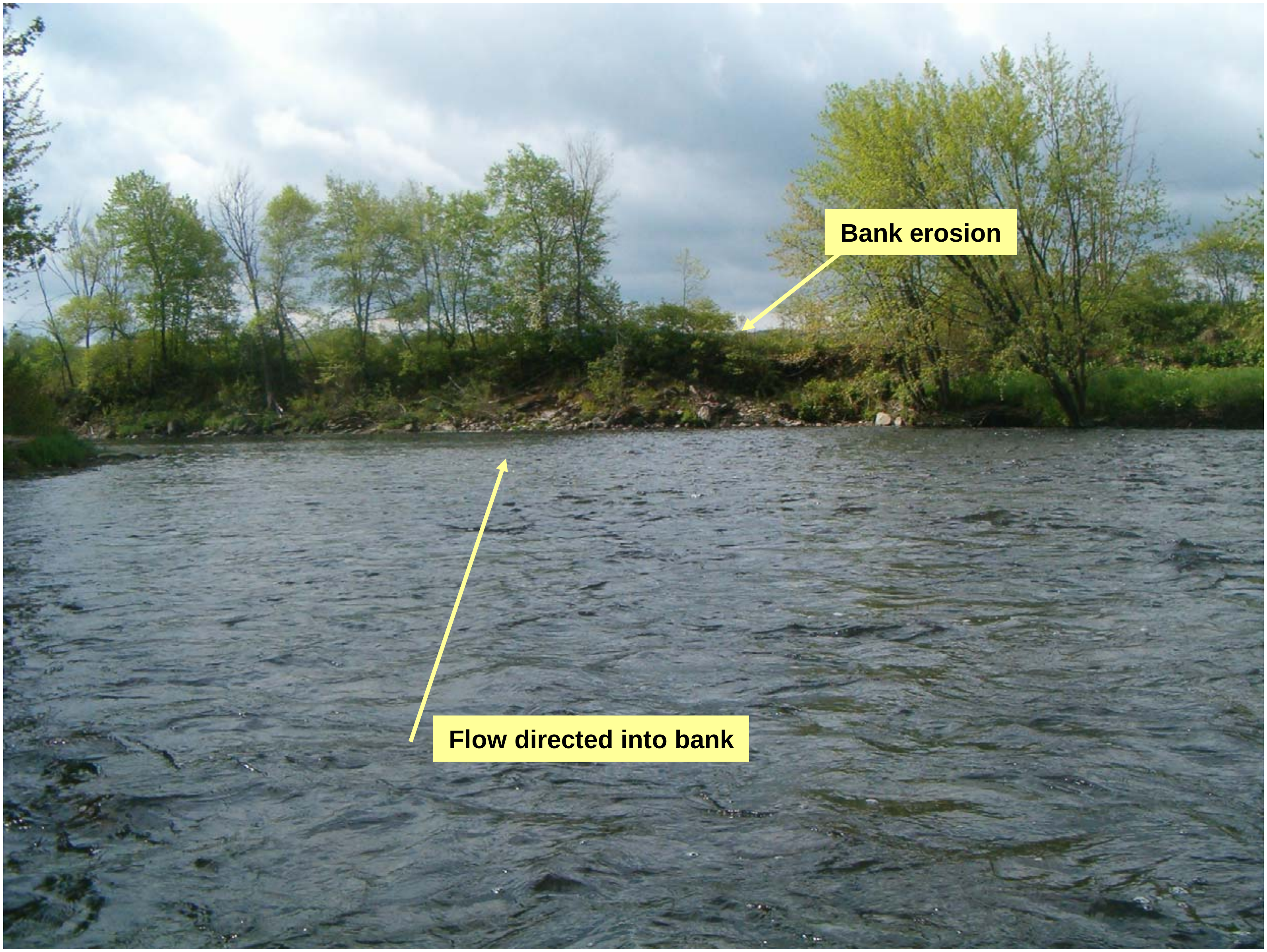
Northern Connecticut River Fluvial Geomorphology Assessment – Figure 19a

Bank Erosion at Artificially Sharp Bend – Reach 15



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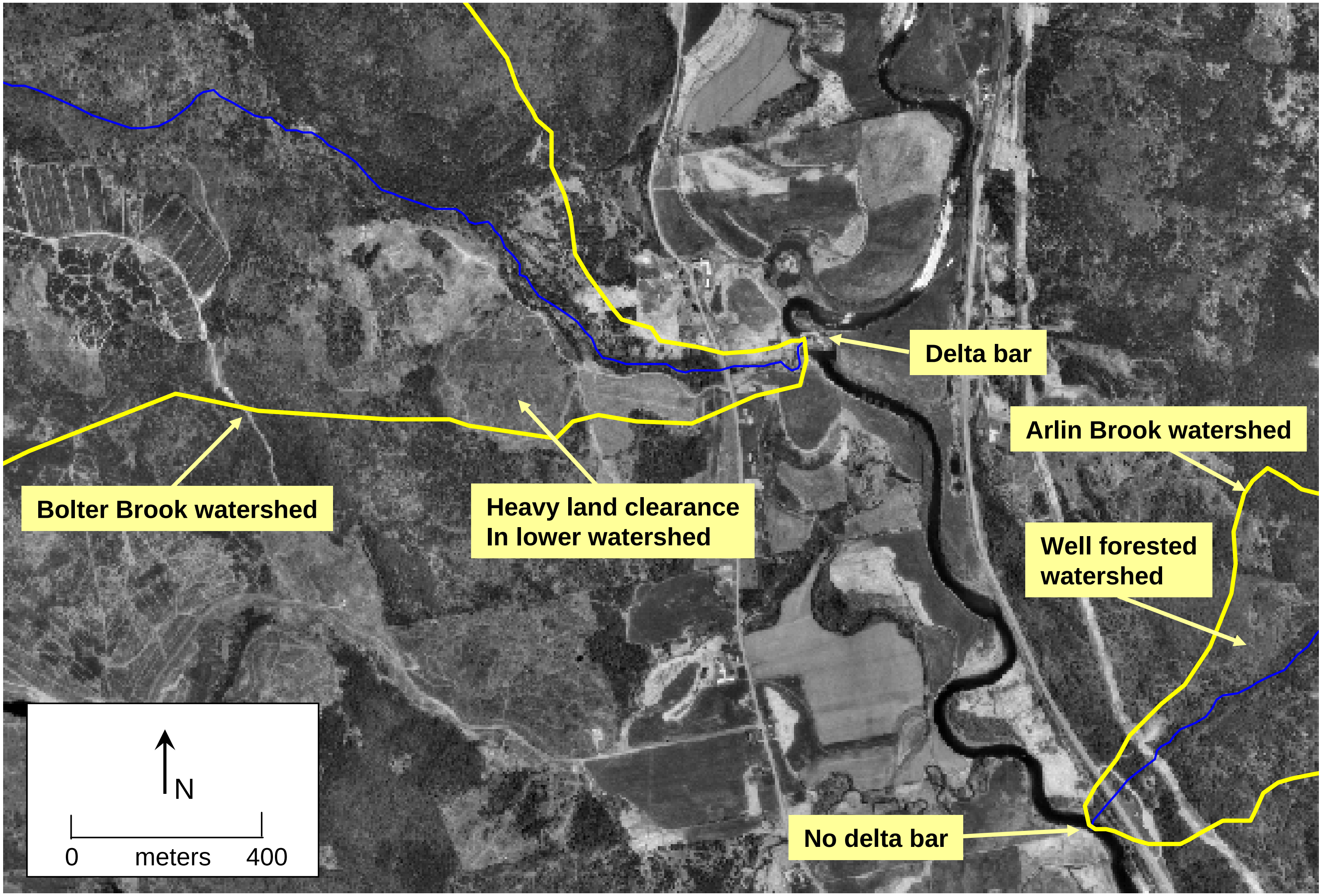
Northern Connecticut River Fluvial Geomorphology Assessment – Figure 19b

Old Riprap Failing at Artificially Sharp Bend – Reach 14

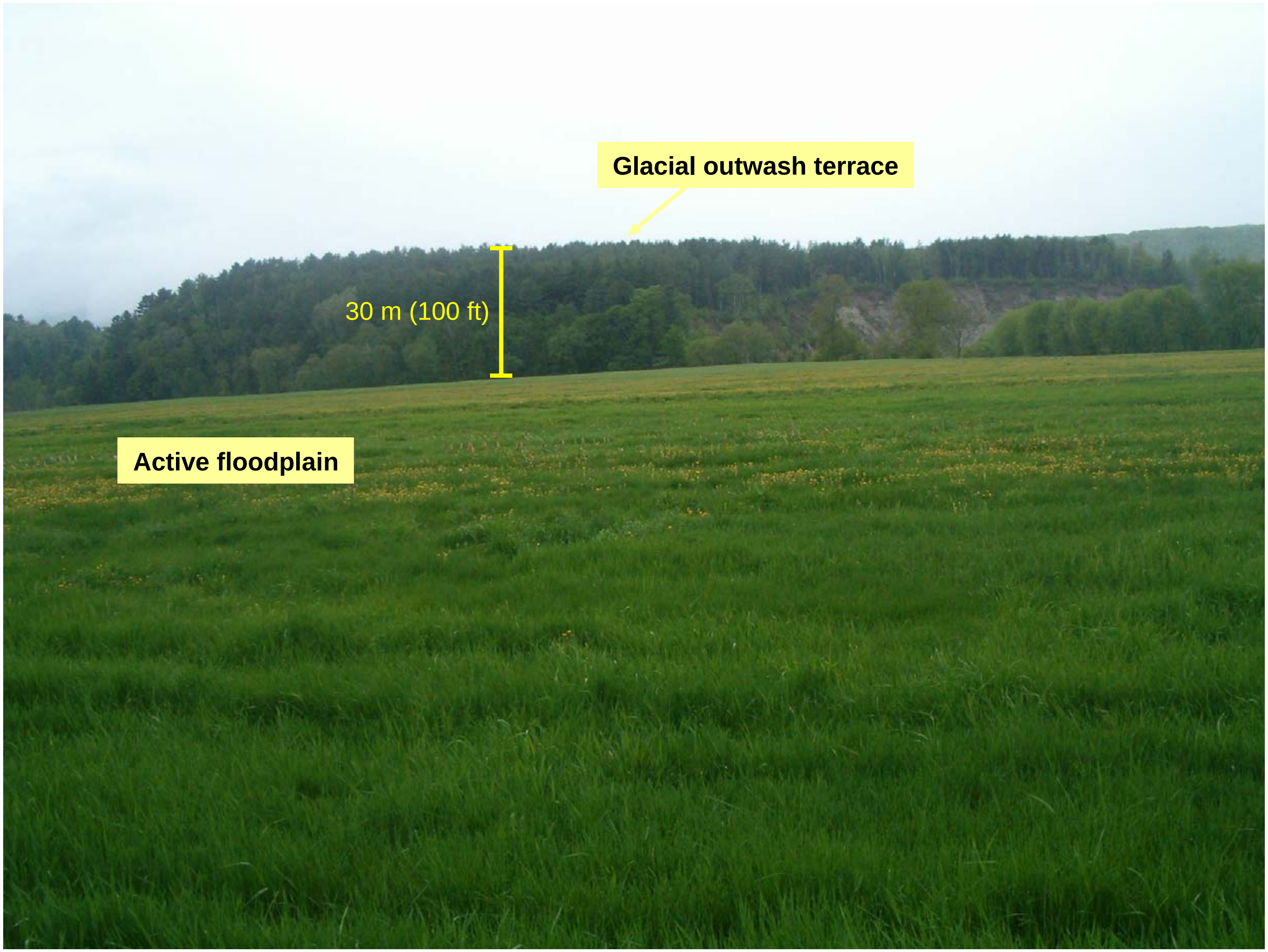
Note: Bank has receded more than 6.0 m (20 feet) in places since construction of riprap

Delta Bar Formation in Watershed with Heavy Land Clearance



Note: Ground photograph of delta bar at mouth of Bolter Brook is shown in Figure 8

Glacial Outwash Terrace Along Valley Margin – Reach 8



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High Eroding Bank of Glacial Outwash Deposits – Reach 8

Note: Near Brunswick Springs, VT

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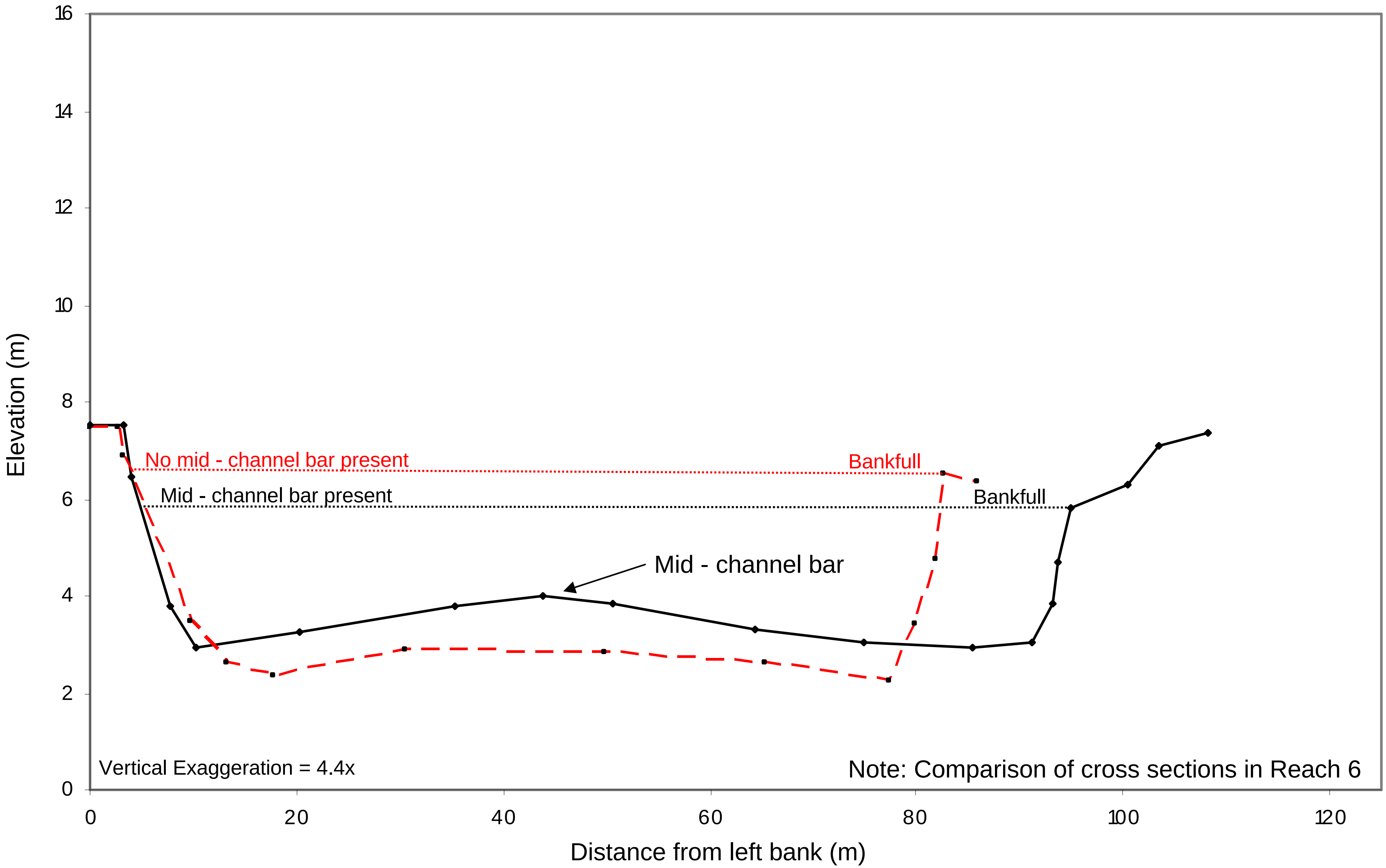
Bank Widening Resulting from Formation of Mid-channel Bars



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Scalloped Bank Line Due to Erosion by Flow Diverted Around Mid - Channel Bar

Note: Mid - channel bar migrated downstream after riprap was placed on bank to stop erosion (Reach 8)

Agricultural Practices Decreasing Bank Stability – Reach 13

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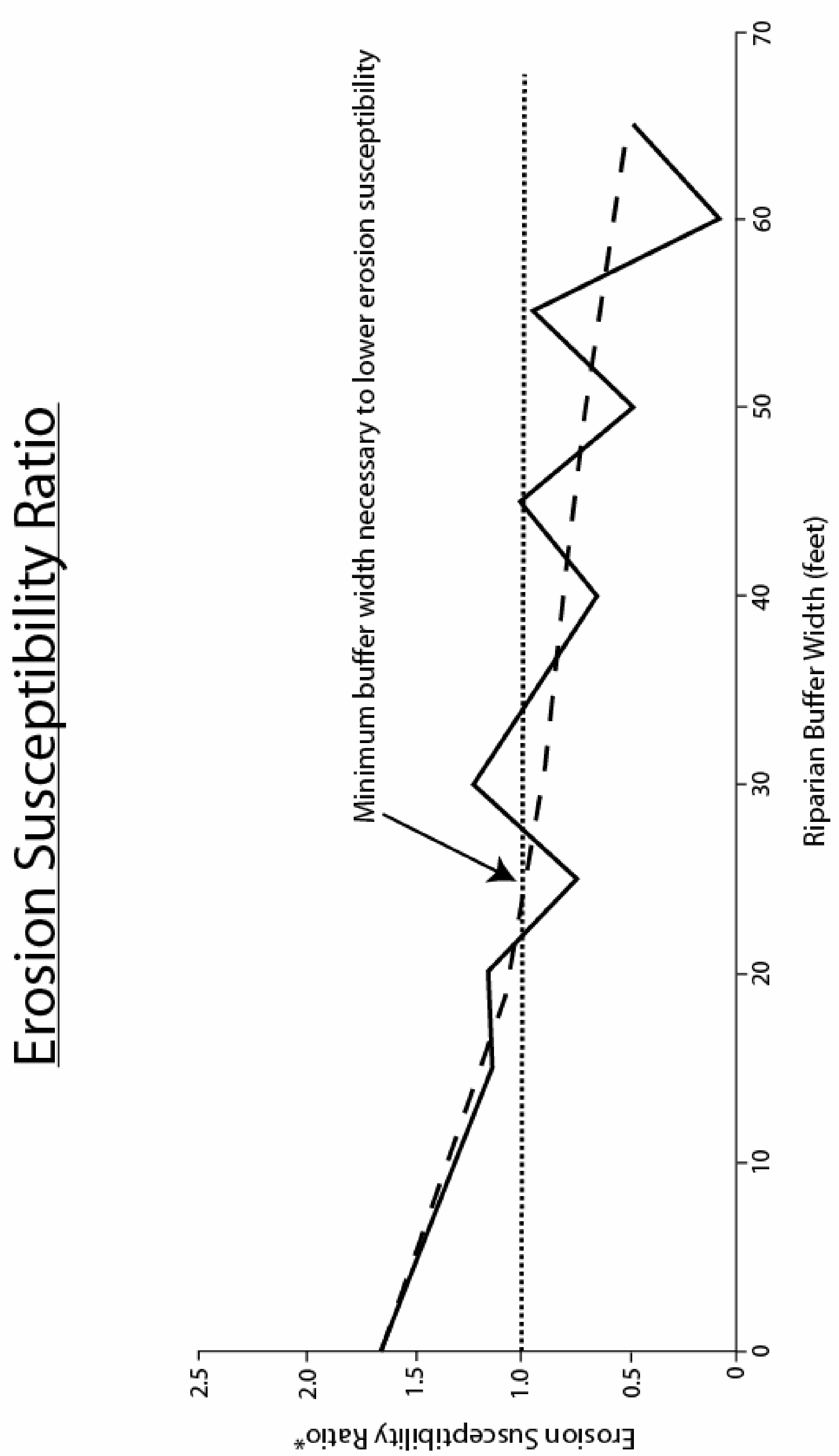
Northern Connecticut River Fluvial Geomorphology Assessment – Figure 26



* Erosion suceptibility ratio is the percentage of the total erosion occurring within a given buffer width divided by the percentage of the total length that buffer width encompasses

Note: Erosion suceptibility ratio of greater than 1.0 for a given buffer width indicates that erosion is more likely to occur along a buffer of that width

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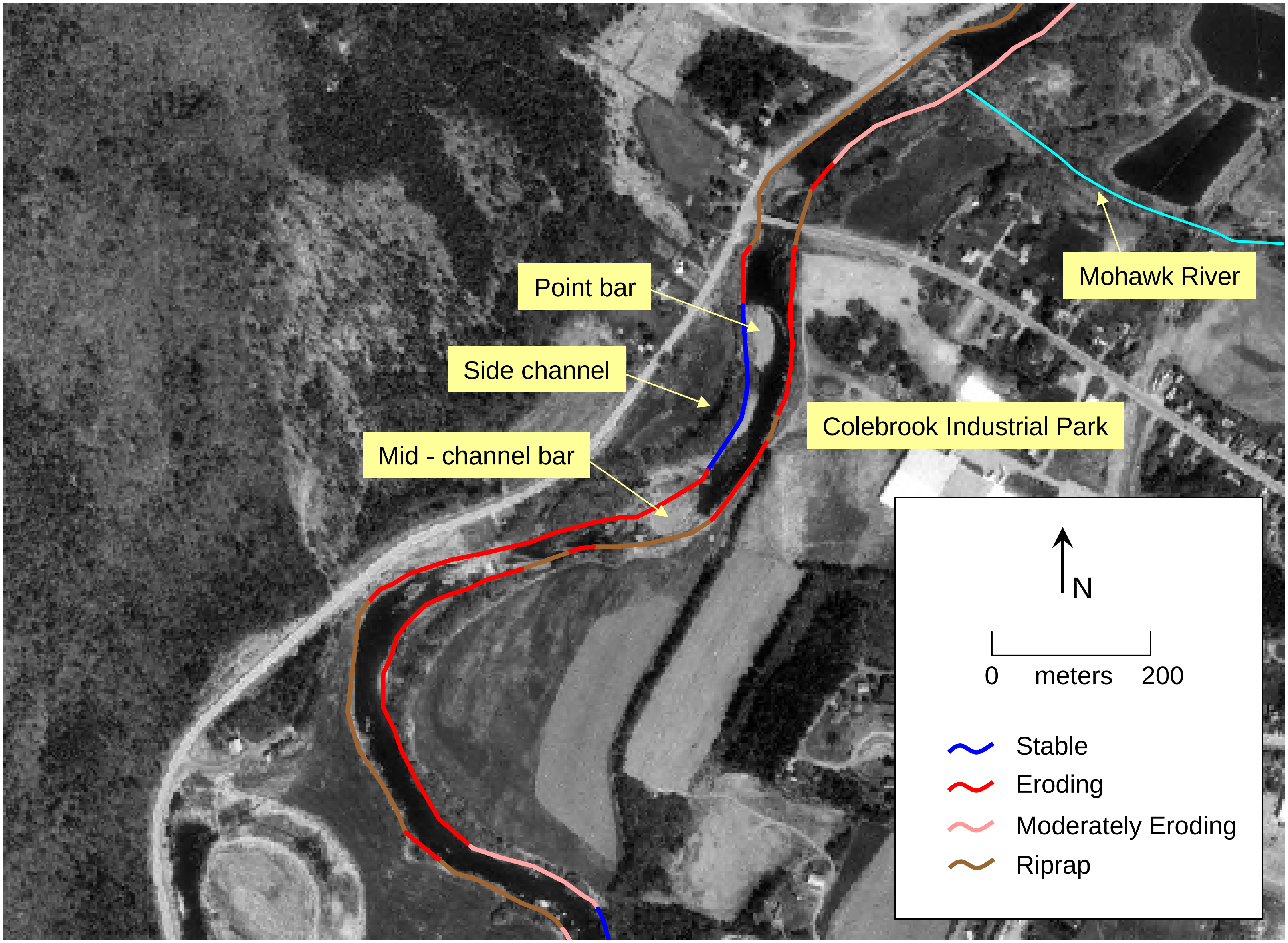
Northern Connecticut River Fluvial Geomorphology Assessment – Figure 27

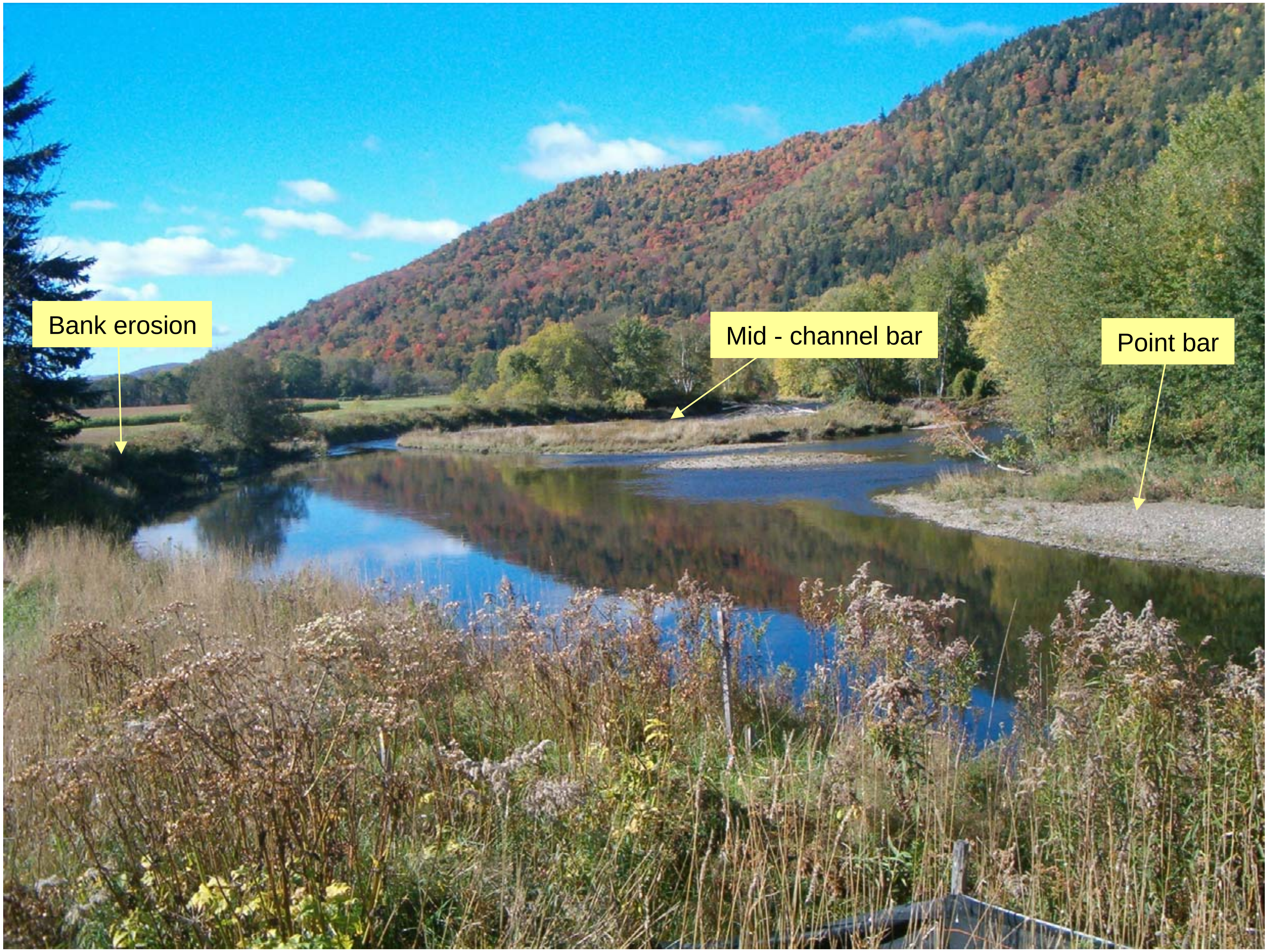
Location of Colebrook Industrial Park Site – Reach 13



Field Geology Services

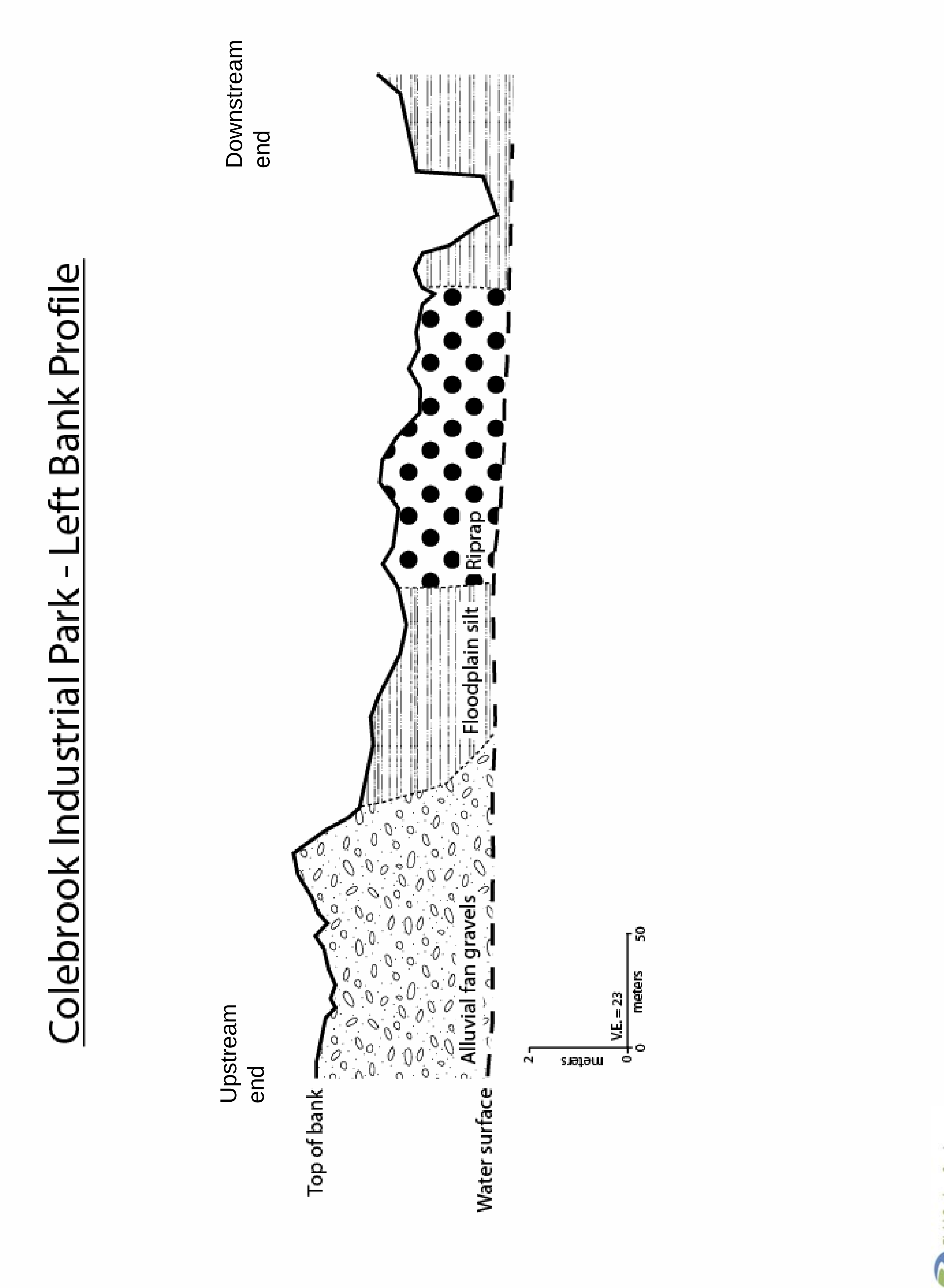
Northern Connecticut River Fluvial Geomorphology Assessment – Figure 28

Bar Formation Causing Bank Erosion – Reach 13



Field Geology Services
Fluvial Geomorphology

Northern Connecticut River Fluvial Geomorphology Assessment – Figure 29



Northern Connecticut River Fluvial Geomorphology Assessment – Figure 30

Mapping of Channel Features - Summary Statistics

Feature/Characteristic	Left Bank (NH) Length (km)	Left Bank (NH) % Length	Right Bank (VT) Length (km)	Right Bank (VT) % Length	Channel/Totals Length (km)	Channel/Totals % Length	# of Features
Length of channel					131.66	100.0	
Length of channel banks	132.66	100.0	133.08		265.74	100.0	
Bank Height							
0-5 feet	15.22	11.5	18.21	13.7	33.43	12.6	
5-10 feet	93.69	70.6	86.91	65.3	180.60	68.0	
10-30 feet	21.90	16.5	25.61	19.2	47.51	17.9	
30+ feet	1.86	1.4	2.36	1.8	4.22	1.6	
Bank Composition							
Alluvial	116.89	88.1	115.39	86.7	232.28	87.4	
Non-alluvial	15.43	11.6	17.00	12.8	32.43	12.2	
Bedrock	0.35	0.3	0.70	0.5	1.05	0.4	
Bank Stability							
Eroding	34.28	25.8	34.31	25.8	68.59	25.8	
Erosion where no riparian buffer	12.54	36.6*	9.89	28.8*	22.43	32.7*	
Moderately eroding	31.86	24.0	28.10	21.1	59.96	22.6	
Riprap	7.72	5.8	7.46	5.6	15.18	5.7	
Old riprap	13.85	10.4	16.52	12.4	30.37	11.4	
Stable	43.26	32.6	44.99	33.8	88.25	33.2	
Windrowed	1.68	1.3	1.71	1.3	3.39	1.3	
Riparian Buffer Width							
0 m	31.58	23.8	20.39	15.3	51.97	19.6	
1-5 m	10.79	8.1	14.71	11.1	25.50	9.6	
6-10 m	15.48	11.7	22.71	17.1	38.19	14.4	
11-15 m	9.14	6.9	12.34	9.3	21.48	8.1	
16-20 m	6.31	4.8	10.29	7.7	16.60	6.2	
21-25 m	9.50	7.2	3.88	2.9	13.38	5.0	
26-30 m	5.78	4.4	7.13	5.4	12.91	4.9	
31-35	4.85	3.7	1.11	0.8	5.96	2.2	
>35 m	39.25	29.6	40.55	30.5	79.80	30.0	
Depositional Features							
Mid-channel bars	3.40	2.6	2.72	2.0	6.12	4.6	
Vegetated mid-channel bars	1.77	1.3	2.17	1.6	3.94	3.0	
Point bars	5.43	4.1	4.94	3.7	10.37	7.9	
Mud bars	1.27	1.0	2.54	1.9	3.81	2.9	
Delta bars	0.46	0.3	0.48	0.4	0.94	0.7	
Channel Morphology							
Cascade					1.60	1.2	
Step-pool					0.00	0.0	
Plane-bed					20.87	15.9	
Pool-riffle					55.21	41.9	
Dune-ripple					54.01	41.0	
Substrate Particle Size							
Bedrock					0.44	0.3	
Boulder					3.85	2.9	
Cobble					35.93	27.3	
Gravel					22.94	17.4	
Sand					68.51	52.0	
Point Features							
Dams							3
Breached dams							2
Bridges							16
Bridge abutments							15
Natural waterfalls							3
Woody debris jams							124
Isolated wood							166

* Represents percentage of total length of erosion not total length of banks

Reach Break Locations

Reach #	Downstream Point	Upstream Point	Cause of Reach Break	Phase 2 Assessment Completed?
M1	Moore Reservoir	South Lunenburg - RR Bridge	Moore Reservoir	no
M2	South Lunenburg - RR Bridge	S. Lancaster - covered bridge	Constriction	no
M3	S. Lancaster - covered bridge	Israel River	Expansion	yes
M4	Israel River	Lancaster-Northumberland town line	Israel River	no
M5	Lancaster-Northumberland town line	Upper Ammonoosuc River	Constriction	yes
M6	Upper Ammonoosuc River	2 miles below Maidstone Bridge	U. Ammonoosuc	yes
M7	2 miles below Maidstone Bridge	1 mile upstream of Paul Stream	Expansion	yes
M8	1 mile upstream of Paul Stream	Nulhegan River	Expansion	yes
M9	Nulhegan River	2 miles upstream of North Stratford	Nulhegan River	yes
M10	2 miles upstream of North Stratford	Beaver Brook in Columbia, NH	Expansion	yes
M11	Beaver Brook in Columbia, NH	Columbia Bridge	Constriction	no
M12	Columbia Bridge	1 mile below Columbia Village	Expansion	no
M13	1 mile below Columbia Village	Mohawk River	Constriction	no
M14	Mohawk River	Leach Creek	Mohawk River	yes
M15	Leach Creek	Canaan Dam	Leach Creek	no
M16	Canaan Dam	Halls Stream	Expansion	no
M17	Halls Stream	2 miles upstream of Beecher Falls	Halls Stream	yes
M18	2 miles upstream of Beecher Falls	Indian Stream	Expansion	yes
M19	Indian Stream	1 mile upstream of Indian Stream	Indian Stream	no
M20	1 mile upstream of Indian Stream	Lake Francis	Expansion	no

Northern Connecticut River Fluvial Geomorphology Assessment - Table 2

Morphological Parameters of Reaches

Reach #	Valley Confinement	Channel Gradient	Sinuosity	Amount of Bar Development	Amount of Channel Migration	% Channelized	% Bank Erosion
M1	Narrowly confined	0.000693	1.04	Low	None	0	7
M2	Very broad	0.000491	1.19	Not significant	None	0	7
M3	Very broad	0.00011	1.57	Low	None	31	37
M4	Very broad	0.000105	1.54	Not significant	None	49	35
M5	Very broad	0.000083	1.44	Low	None	63	43
M6	Very broad	0.000178	2.26	High	High	19	41
M7	Very broad	0.00034	1.52	High	Not significant	27	32
M8	Narrow	0.000615	1.21	High	None	34	24
M9	Semi confined	0.003059	1.21	High	Not significant	16	13
M10	Semi confined	0.002093	1.11	Low	None	16	19
M11	Very broad	0.000442	1.19	Low	Not significant	12	41
M12	Semi confined	0.000233	1.03	Low	None	0	26
M13	Very broad	0.000147	1.29	Low	None	18	29
M14	Very broad	0.000427	1.36	Low	Low	30	24
M15	Broad	0.002755	1.45	High	None	56	9
M16	Semi confined	0.004947	1.04	Low	None	0	5
M17	Narrow	0.001008	1.32	Low	None	49	11
M18	Narrowly confined	0.003549	1.04	Low	Low	0	1
M19	Broad	0.003961	1.18	Low	None	77	0
M20	Narrowly confined	0.007343	1.17	High	None	9	1

Northern Connecticut River Fluvial Geomorphology Assessment - Table 3

Comparison of Channel Dimensions Between Channelized and Unchannelized Reach Segments

Bankfull Dimension	Unchannelized	Channelized	% Difference*
Reach 17			
Width (m)	33.2	34.1	+2.7
Maximum Depth (m)	1.0	1.7	+70.0
Mean Depth (m)	0.9	1.4	+55.6
Area (m^2)	30.0	46.0	+53.0
Reach 14			
Width (m)	36.2	46.0	+27.1
Maximum Depth (m)	1.8	2.1	+16.7
Mean Depth (m)	1.4	1.7	+21.4
Area (m^2)	45.0	73.0	+62.2
Reach 7			
Width (m)	82.2	83.3	+1.3
Maximum Depth (m)	3.3	5.3	+60.6
Mean Depth (m)	2.2	4.6	+109.1
Area (m^2)	215.0	397.0	+84.7
Reach 6			
Width (m)	77.8	83.4	+7.2
Maximum Depth (m)	4.4	2.8	-57.1
Mean Depth (m)	3.8	2.3	-65.2
Area (m^2)	286.0	218.0	-31.2
Reach 3			
Width (m)	100.0	108.6	+8.6
Maximum Depth (m)	4.5	5.9	+31.1
Mean Depth (m)	3.0	5.4	+80.0
Area (m^2)	347.0	577.0	+66.3

* with respect to change from unchannelized to channelized condition

Northern Connecticut River Fluvial Geomorphology Assessment - Table 4