Fluvial Geomorphology Assessment of the Mad River Watershed, Vermont

Prepared for

Friends of the Mad River
Waitsfield, VT

Public Swimming Hole (looking downstream)

Prepared by

Field Geology Services
Farmington, ME

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Field Geology Services
Fluvial Geomorphology

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EXECUTIVE SUMMARY

A Phase 2 Geomorphic Assessment of the Mad River Watershed was completed in Fall 2006 by Field Geology Services to determine stream channel response to human land uses and natural watershed conditions identified in the Phase 1 Assessment previously completed. The assessment was completed for the Friends of the Mad River following Vermont's Stream Geomorphic Assessment Handbook protocols. The Phase 1 Assessment covers 116 reaches along the mainstem of the Mad River and its tributaries. Twenty-one reaches, covering 23.4 miles of stream, were chosen for further analysis in the Phase 2 Assessment, representing a range of mainstem and tributary conditions within areas where municipalities are concerned with bank erosion and water quality issues. Two sites were chosen for a Phase 3 Assessment based on the Phase 2 results in order to select restoration strategies that will return the stream channel to equilibrium conditions at the selected sites and areas downstream.

The Mad River Watershed, like the rest of Vermont, is heavily influenced by its geological and glacial history. Bedrock constrictions, periodically encountered along the river, produce a backwatering, or ponding, effect upstream during large floods. The resulting decrease in flow velocities at these points result in the deposition of sediment, which, in turn, causes bank erosion as flow is diverted around the emerging gravel bars. Ample sediment is supplied from the steep tributary drainages where numerous mass failures of glacial sediments are found. While significant amounts of sediment are stored in the tributary drainages by woody debris jams, the sediment is periodically flushed out by large floods.

Another major control on the morphology of the Mad River is its human history. Widespread land clearance in the 19th Century and continuing through the early stages of the 20th Century destabilized the valley's hillsides and delivered excessive quantities of sediment, likely causing aggradation and a period of pronounced channel migration of the valley bottom. During the latter portion of the 20th Century, changing land use practices led to reforestation of the cleared slopes. The resulting decrease in sediment delivery to the river led to channel incision, or lowering of the stream's bed, most pronounced in Reaches M19 and M16 near Warren. Incision was also enhanced by channel straightening along portions of the Mad River, a practice conducted to increase flood flow velocities and reduce overbank flooding on agricultural fields and human settlements. Many of the stream reaches on the Mad River mainstem are currently undergoing widening, which reflects the natural evolutionary tendency of a stream after incision increases bank heights past an unstable threshold. Widening, in turn, reduces flood flow velocities and leads to the deposition of sediment in the river channel. Since sediment levels are probably still higher than prior to European settlement of the region, large unvegetated gravel bars are common along the Mad River as the rate of bar deposition exceeds the rate of revegetation. Gravel deposition is most pronounced at natural bedrock constrictions and hard bends in the channel as sediment transport capacity through artificially straightened channels is higher and sediment is not evenly distributed along the length of the channel.

The Mad River is still overwidened in many locations, as evidenced by high width:depth ratios, leading to increased water temperatures and reduced habitat complexity. The widening and habitat degradation is exacerbated by the lack of a mature riparian buffer and open channel canopy in many reaches. A number of restoration strategies are available, such as river corridor protection, riparian buffer restoration, and addition of wood to the river channel, that can lead to increased channel stability while improving ecosystem diversity.

A Phase 3 Assessment was conducted in the area of the Lareau Farm where active planform adjustments are occurring in response to earlier channel incision and bank widening. River corridor protection within this area will allow these adjustments to continue in an unconstrained manner. The resulting gravel deposition will improve aquatic habitat within the protected area while reducing sediment delivery downstream where excess sediment deposition could lead to severe bank erosion near developments in Irasville. The channel adjustments could be accelerated by increasing floodplain storage in the area by lowering portions of the floodplain abandoned during earlier channel incision. A second Phase 3 Assessment was conducted on a short section of Pine Brook where the riparian buffer is in poor condition and bank stability further jeopardized by cattle that have direct access to the stream. Corridor protection and riparian buffer planting within this area could lead to improved aquatic habitat, bank stability, and reduced sediment loading. Implementation of these and similar projects throughout the watershed holds the promise of mitigating erosion hazards, reducing sediment and nutrient loading, and improving aquatic habitat. However, landowner concerns will need to be satisfactorily addressed before river corridors can be protected, so natural fluvial processes can occur unconstrained and lead to the development of equilibrium conditions along the river channel.

1.0 PROJECT OVERVIEW

This report describes the results and recommendations of a fluvial geomorphology assessment of the Mad River Watershed completed by Field Geology Services for the Friends of the Mad River, a private, non-profit organization committed to protecting, improving and enhancing the ecological, recreational, and community values of the Mad River and its watershed. The assessment covered 23.4 miles of the Mad River and its tributaries, in the towns of Warren, Waitsfield and Moretown, VT.

The Phase 1 Assessment subdivided the Mad River and its major tributaries into 116 reaches. Twenty-one reaches were chosen for further analysis in a Phase 2 Assessment (Figure 1), including one reach, an unnamed tributary to Shepard Brook, that was not identified during the Phase 1 Assessment. Five of the 21 Phase 2 reaches were further segmented. The 21 reaches were selected from a list of reaches prioritized by the Friends of the Mad River based on factors of concern such as bank stability, riparian vegetation, bridge and culvert condition, stormwater inputs, impacts to infrastructure, landowner involvement and project feasibility. After completion of the Phase 2 Assessment, two sites were selected for further Phase 3 analysis to identify methods for restoring channel equilibrium and reducing erosion hazards, sediment loading, and habitat degradation.

Recognizing the value of fluvial geomorphology to improve bank stability and reduce sediment production, the State of Vermont has developed a three phase Stream Geomorphic Assessment Handbook to reveal the underlying causes for erosion and channel instability (Vermont Agency of Natural Resources, 2006). The current assessment of the Mad River Watershed employed the Phase 2 protocol outlined in the handbook; Phase 1 was completed previously, the results of which are reported here.

The goals of the Phase 2 Assessment are to achieve an understanding of existing stream morphology, ongoing stream channel adjustment processes, stage of channel evolution, and habitat condition in order to inform stream management decisions. By analyzing the watershed in its entirety, management decisions for individual reaches can be made with an understanding of their potential impacts on other surrounding reaches. Within this context, detailed Phase 3 studies within a specific project reach can identify restoration strategies that have the greatest potential to not only improve channel stability within the project reach but also move adjacent reaches towards stream equilibrium.

2.0 BACKGROUND INFORMATION

2.1 Geographic Setting

The Mad River Watershed drains 144 mi^2 in the towns of Duxbury, Fayston, Moretown, Waitsfield and Warren (Figure 1). The steep-walled basin includes historic villages, ski resorts, agricultural lands and 4000-foot high peaks. As a tributary to the Winooski River, the water from the Mad River Watershed eventually drains into Lake Champlain.

Historically, the region was heavily forested, but deforestation for grazing and agriculture in the 19th Century and continuing through the early stages of last century changed the face of the landscape. Today, following the decline of the family farm, much of the forest has returned. However, in the last few decades, the Mad River Watershed has been discovered by vacationers and second-home owners, transforming the valley into a desirable resort region. This new wave of development can be seen in the increase in new home and condominium construction, ski resort development, and commercial centers.

2.2 Geologic Setting

The Mad River Watershed lies in the heart of the Green Mountains. These mountains are composed of highly metamorphosed rock including phyllites, gneisses and schists with varying amounts of greenstones and amphibolites (Doll et al., 1961). This complex assemblage of rocks has a long history dating back to events that built the Grenville Mountains, an ancient mountain range, between 1.3 and 1.0 billion years ago. Much of the metamorphism seen today occurred during the formation of the ancestral Appalachian Mountains during the Taconic Orogeny in the Middle Ordovician about 460 million years ago (Doolan, 1996).

The Mad River Watershed, like the rest of Vermont, is heavily influenced by its glacial history, whose legacy can be seen in the sediments blanketing the valley. These sediments were deposited during the Wisconsin glaciation, which climaxed around 23,000 years ago (Stephen Wright, personal communication, 2006). At this time, Vermont, and the rest of New England, was covered by the Laurentide Ice Sheet, which advanced out of Hudson Bay and reached as far south as Long Island and Cape Cod and further east than New Foundland and the Coast of Maine (Van Diver, 1985). When this ice began to melt and retreat out of the Mad River Valley it left behind thick deposits of clay-rich sediments. These sediments were deposited in glacial lakes formed as ice blocked the mouth of the Mad River. The lakes extended far up the tributary drainages and valley side slopes. The location and extent of these glacial deposits and bedrock outcrops (formed hundreds of millions of years ago) are some of the major factors controlling the present landscape evolution and channel morphology in the Mad River Watershed.

2.3 Hydrology

The United States Geological Survey has operated a gauging station on the Mad River since 1928 at the downstream end of Reach M05 north of the village of Moretown. In that time, the largest flood occurred in 1938 with a magnitude of 18,400 cubic feet per second (cfs), with the next largest flood occurring in June of 1998 with a peak discharge of 14,500 cfs (Figure 2). An estimated discharge of 23,000 cfs occurred in November 1927 before the gage was installed. The morphological impact of the most recent large flood in 1998 can still be seen today. Human response (i.e., bank armoring and vegetation removal) to another large flood in 1973 continues to impact channel adjustment processes over 30 years later. A flood discharge in 1976 was even greater than the 1973 event, but did not cause as much immediate flooding and erosion problems. However, the flood control efforts completed shortly after the 1973 event may have enhanced the ability of floods, such as the 1976 event, to continue channel incision processes initiated by earlier human land uses as described further below. Such incision begins a channel evolutionary process that eventually results in hazardous erosion and flooding problems at the site and elsewhere along the stream system.

Using the 78 years of peak streamflow data, the recurrence interval of given magnitude flood events can be calculated. This is done using a software program called Peak FQ, which uses an USGS-endorsed algorithm to make its calculations of flood frequency. In the Vermont protocols, the expected dimensions of a river (i.e., channel width, depth, and cross sectional area) for a given watershed area are based on the bankfull discharge. The bankfull discharge, on an undisturbed alluvial river, is that flow which, when exceeded, will overtop its banks and cause inundation of the floodplain. The bankfull discharge is considered to be the channel forming discharge that creates and maintains the morphological features observed along the channel. In the eastern United States, the bankfull discharge is commonly associated with a recurrence interval of 1.5 years (Leopold et al., 1964). Based on the USGS gaging data, the bankfull discharge for the Mad River at the Moretown station is 4,931 cfs. The bankfull discharge is commonly referred to when working with streams and provides a means for comparing the Mad River to other watersheds.

3.0 METHODS

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. Topographic surveying and other fieldwork during Phase 2 of the assessment provides information on the existing morphology of the channel and how the channel is responding to the natural conditions and human land uses identified in Phase 1. Although the results of the Phase 1 assessment are reported on below, the data was collected during an earlier assessment.

Phase 2 fieldwork consisted of walking the entire length of each reach while making detailed field sketches. Notes were taken on various morphologic and habitat parameters such as riffle-pool spacing, substrate embeddedness, composition and distribution of riparian and near-bank vegetation, and extent of the channel canopy. A detailed photo log was kept documenting features of interest throughout each reach (Appendix 1). After walking a significant portion of each reach, cross section locations were chosen based on their representativeness of bankfull indicators, entrenchment, channel pattern, and bank conditions observed throughout the entire reach or segment. If possible, the elevation of bankfull indicators relative to the water surface was measured in several locations throughout the reach in order to confirm the validity of the indicator at the site of the cross section. Cross sections were surveyed following the Handbook protocols using a metric tape measure and stadia rod (Vermont Agency of Natural

Resources, 2006). Pebble counts were conducted as outlined in the Handbook protocols at each cross section location.

Two cross sections, Reach M15 and M13, were completed with the use of a Sokkia Set 5 Total Station. This change in methodology introduced inconsistency in the methods used to collect cross section data. When comparing the cross sectional area for the various reaches, cross sections for Reaches M15 and M13 collected with the total station appear to have a larger cross sectional area. Those measured manually have underestimated cross sectional area, because sagging in the tape measure would lead to underestimated depth measurements. Keeping the tape measure completely taut across the stream channel is very difficult on wider channels, in windy conditions, and where non-cohesive bank materials effect the tension on the tape measure. The underestimation in depth will also lead to a slight increase in width:depth ratio. However, the variations in measurements gathered using the two surveying methods are not considered significant enough to effect the assessment results.

Since most reaches were only walked in their entirety while within the stream channel, some features found outside of the stream channel may have been overlooked. As a result, wetlands, stormwater inputs, and other features commonly located on the adjacent valley slope or floodplain could have been missed during the Phase 2 assessment, but frequent forays onto the floodplain were designed to limit the number of overlooked features.

The Phase 2 results were entered into a web-based data management system administered by Vermont's River Management Program (Vermont Agency of Natural Resources, 2006). The Phase 2 data was also used to update existing Phase 1 data where discrepancies were found. A number of channel features, including sites of bank erosion and armoring, channel straightening, debris jams, channel migration, and mass failures, were mapped along the assessed reaches of the Mad River and its tributaries and used to create GIS shapefiles with the Feature Indexing Tool extension for ArcView.

The Phase 1 and Phase 2 Assessment data can be viewed on the Vermont River Management Program Data Management System (DMS) website at: https://anrnode.anr.state.vt.us/ssl/sga/security/frmLogin.cfm?logout=true.

A Phase 3 Assessment was conducted on Reach M13 in the area of the Kinney Farm just upstream of the Flat Bread Pizza Company. Detailed surveys were conducted with a Sokkia Set 5.0 Total Station to characterize channel dimensions, gradient, and floodplain connectivity. The surveys also provided plan view and cross sectional data sufficient for creating scaled drawings of various restoration options. Phase 3 Assessment data is critical for analyzing the potential of various restoration strategies for achieving equilibrium within the project area and adjacent reaches. The preferred restoration option chosen from the Phase 3 Assessment in Reach M13 was further developed to assist the Friends of the Mad River in future implementation. While no detailed surveying was completed on a second Phase 3 Assessment site on Pine Brook

(Segment T5.02-B), a preferred restoration strategy was identified and also further to ease future implementation.

4.0 PHASE 1 ASSESSMENT

4.1 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. Break points between different reaches are made on the presence of one or more of the following conditions: natural grade control; change in valley slope; change in valley width; or confluence of a major tributary comprising more than 10 percent of the watershed upstream of the reach break. Grade controls are resistant features crossing the channel (e.g., waterfalls, dams) that tend to prevent the upstream or downstream transfer of channel instabilities. Human factors are generally ignored in the identification of reach breaks, but are analyzed as part of a Phase 2 assessment. One hundred sixteen reaches were identified in the Mad River Watershed using topographic maps and aerial photographs (Figure 1).

Reaches downstream of constrictions occupy more confined valleys where the river channel has a greater likelihood of flowing against glacial sediments or bedrock exposed along high valley walls. The potential for high rates of sediment production from glacial sediments or the likelihood of encountering natural grade controls (i.e., ledge crossing the channel) in these narrower valleys can affect channel morphology differently than reaches occupying wide valleys where the channel generally encounters floodplain sediments only. Flow expansion at the downstream ends of confined reaches can lead to greater channel response and adjustments in the less confined reaches downstream.

Reaches downstream of tributary confluences will generally have a different morphology 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. 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.

4.2 Natural Conditions

An analysis of valley confinement, valley slope, and other natural conditions help establish the reference channel condition that would be expected to develop in each reach in the absence of human influence. (Departures from this reference condition can later be identified during the Phase 2 Assessment to determine how the stream is responding to human land use and land management practices). The mainstem of the Mad River is characterized by an alternating pattern between confined and unconfined reaches, with bedrock outcrops and terrace deposits influencing the channel pattern. Given the valley confinements, the reference condition of the mainstem alternates between a C stream type in unconfined reaches and a B stream type in confined reaches. The lettered stream type designations are defined by Rosgen (1996) with C streams generally being more sinuous with access to a wide floodplain compared to the straighter and more confined B streams. Given the valley slopes, the reference bedform alternates between riffle-pool conditions, primarily in unconfined reaches, and plane bed in confined reaches. The bedform types are defined by Montgomery and Buffington (1997). This pattern of alternating confined and unconfined reaches is most dramatic between Warren and Waitsfield with Reach M19 unconfined, Reaches M18 and M17 confined in the Warren Gorge, Reaches M16 and M15 unconfined, Reach M14 confined by bedrock valley walls, and Reach M13 again unconfined.

4.3 Human Land Use and Constraints

Superimposed on the natural watershed characteristics that control channel morphology are numerous human land uses that can potentially alter the expected natural reference stream type. The Phase 1 Assessment assigns an impact rating (e.g., high, low, and not significant) for several human activities and morphological conditions that are possibly indicative of a channel response to human impacts. A higher impact score indicates a greater likelihood that the channel is responding to one or more human land uses in the watershed. While the impact rating scores are based on all of the human activities and morphological parameters, the following summary focuses only on those considered likely to have an influence on the morphology of the Mad River channel.

4.3a Watershed impacts

Extensive land clearance in a watershed can increase runoff and sediment delivery to the river channel. In the 19th Century most of the Mad River Watershed was cleared of its forest cover for agriculture (Figure 3), a condition that persists today along valley bottoms where agriculture and urbanization are important. Hillslopes in the watershed, however, are now largely tree covered. Consequently, the near-river corridor land cover–land use impact score is “high” for most of the mainstem reaches, while the watershed land cover–land use impact score is “low” (see DMS website).

Likely accompanying 19th Century and earlier land clearance in the watershed was the loss of wood from the river channel. Before European settlement of the region, thick forests were probably present throughout the Mad River Watershed with large trees falling into the stream channel and creating debris jams along tributaries and at least the margins of the Mad River. Much of this wood may have been purposefully removed from the channel to facilitate log drives and to reduce flooding. The recruitment of new wood in the channel was greatly reduced by the clearing of forests on the floodplain for agricultural purposes. While much of this activity originally occurred over 100 years ago, extensive debris removal also likely occurred after the 1973 flood and more locally after the 1998 event. The riparian buffer was removed along large lengths of the mainstem after the 1973 flood and replaced with riprap. The buffer has become reestablished in many localities in the subsequent 30+ years.

4.3b River corridor impacts

Land use in the river corridor, the area within six bankfull widths of the channel on low gradient alluvial rivers, can have a greater impact on channel morphology than land use in the larger watershed. (The bankfull width is taken as the width of the water surface when the river is about to overtop its banks and is often much wider than the low flow water surface observed most of the year). An unforested corridor exposes non-cohesive floodplain soils, increasing the potential for bank erosion and channel avulsions (i.e., a rapid shift in channel position caused when a new channel is carved through the floodplain during a large flood). The highest impacts within the corridor are seen in reaches M19, M18 and T11.01, which all have less than 10 percent forest cover (see DMS website).

4.3c In-channel impacts

Nine reaches in the Mad River Watershed are affected by impoundments. Of these, five reaches, M03, M15, M19, T1.02, and T7.1-S4.1.1.01, have a “high” flow regulation impact. These dams serve a variety of purposes and are in a range of conditions: one is a hydroelectric dam (M03), another is an old crib dam that is no longer operational (M19), and a third is used for snowmaking (M15). Dams have the potential to alter channel morphology by lowering flood peaks and storing sediment. Although dams are not present in each reach, their presence may engender upstream and downstream channel adjustments.

Other human activities in the river channel, such as channel straightening, can also have a significant impact on channel morphology. Thirteen reaches in the watershed scored a “high” impact for channel straightening, which has disrupted the natural planform and evolution of the channel: M05, M10, M10-S1.01, M11, M11-S4.01, M12, M15, M19, T4.01, T6.1-S1.01, T7.01, T9.01 and T9.03.

Bank armoring with large rocks (i.e., riprap) can prevent bank erosion where applied, but can also create channel instabilities that transfer the erosion to adjacent portions of the river bank. The total amount of riprap in any one reach is less than 30 percent of the reach length such that the bank armoring impact rating is “low” or “not significant” in all reaches. Bank armoring is more accurately mapped in the Phase 2 assessment such that localized impacts within a reach can be identified despite an overall “low” impact score for the entire reach.

Gravel mining and dredging are noted on nearly all of the mainstem reaches with a “high” impact rating assigned to M01, M04, M05, M06, M08, M09, M10, M11, M12, M13, M15, M18, and M19. Removing sediment from the river channel can alter the stream’s morphology and initiate channel incision by creating head cuts. Eventually the sediment load is increased through bank erosion as the incised channel begins to widen

(Schumm, 1977), generating more in-channel sediment. The impacts of gravel mining and dredging are largely historic as current management practices discourage in-channel gravel removal. However, channel adjustments related to past gravel mining and dredging may persist today.

4.3d Total impact score

Accounting for all of the human activities and morphological parameters for which an impact rating is assigned, reaches M15 and M19 have the highest impact scores (Score = 23) in the Mad River Watershed (see DMS website), reflecting the heavy land use in the corridors, extensive channel straightening, encroachments, gravel mining, and the presence of impoundments. Six other reaches scored an 18 or higher in total impacts: M05, M10, M11, M12, M13 and T4.01. In general, tributary reaches were less impacted than those along the mainstem. This is not surprising given the lower degree of development in the steep tributary valleys. The Warren Gorge (reaches M18 and M17) and other naturally confined reaches (such as M14) along the mainstem, also had lower impact scores than the alluvial reaches, given the natural resistance to channel modification offered by the bedrock valley walls and the difficult access for development.

5.0 PHASE 2 ASSESSMENT

The previously completed Phase 1 Assessment identifies human land uses and constraints that might result in morphological adjustments. The Phase 2 Assessment is designed to identify if and how the channel is responding (or has responded) to these human activities. The channel morphology in each reach is also a reflection of the region's geological setting and flood history. Phase 2 Assessments in the Mad River Watershed included ten mainstem reaches and eleven tributary reaches. Seven of the eleven tributary reaches are in the Clay Brook watershed, which drains the Sugarbush Ski Resort and enters the mainstem in Reach M16 just upstream of the Kingsbury Iron Bridge.

The Phase 2 results for the Mad River Watershed are discussed below, from upstream to downstream, beginning with the mainstem and then its tributaries. Ground photographs for each reach are presented in Appendix 1 with cross sectional information and substrate particle size analyses (i.e., pebble counts) in Appendix 2. The values cited for various morphological parameters (i.e., entrenchment ratios, width/depth ratios, sinuosity, habitat assessment, etc.) are recorded on the DMS website.

5.1 Reach M19

Location: Lincoln Brook confluence downstream to the Warren crib dam

Reach M19 is divided into two segments based on the influences of the Warren crib dam and a human-caused change in valley confinement. Segment M19-B is an overwidened channel (width:depth ratio = 37.3) flowing through a semi-confined valley.

This confinement has been altered by the encroachment of the road along the right bank of the channel. The segment is overwidened due to its history of incision and channel widening following reforestation and channel straightening in the past century. Channel incision following a period of reforestation, which reduces the sediment supply to the valley, has been documented elsewhere (Kondolf et al., 2002). Segment M19-B also shows evidence of historic channel straightening. The increased gradient resulting from straightening (by decreasing the channel length while maintaining the change in elevation) leads to greater stream power and channel incision (Knighton, 1998). As is described by Schumm's (1977) Channel Evolution Model, channel widening typically follows incision as the next stage in channel adjustment. M-19B is in the widening phase, or Phase III, of the Channel Evolution Model. Through incision, a greater proportion of flow is contained within the channel rather than spreading across a broad floodplain, leading to greater erosive power in the channel that destabilizes the overheightened banks. This erosive power is evidenced by leaning trees and freshly eroded banks in many areas (Figure 4). Much of Segment M19-B is armored to protect the road from the channel's propensity to erode its heightened banks. Consequently, widening is held in check in these areas, but is possibly transferring excess sediment and flow energy downstream. Reforestation and channel straightening have probably both played a role in the development of this segment's high width/depth ratio and very high incision ratio of 2.8.

The downstream section of M-19B is controlled by two bedrock ledge grade controls. The Route 100 Bridge crosses over this section of the segment, but its impact on the stream channel is somewhat reduced by the natural outcropping of bedrock in this area. This bedrock constricts the channel in one area, leading to deposition of a diagonal bar above the constriction. The other bar of interest in this reach occurs as a large delta, with an elevation at bankfull or above, at the mouth of Lincoln Brook. The source of this sediment is unknown as Lincoln Brook was not independently assessed. Large woody debris is limited to five pieces in the segment, a result of the narrow riparian buffer and historic channelization. The scarcity of wood in the channel, lack of unembedded cobbles and boulders, moderate deposition in pools, and significant historic channelization leads to a habitat stream condition score of 0.49 or fair condition.

Morphologically, segment M19-A is similar to its upstream counterpart M-19B with a high incision ratio of 2.0, low entrenchment ratio of 1.2 (i.e., flood flows do not access the floodplain), and high width:depth ratio of 28.6. Reach 19 is segmented partly due to a change in valley confinement, as M19-A occupies a wider valley. The primary reason for segmenting the reach, however, is presence of the Warren crib dam (Figure 5). The crib dam is an old wooden structure, approximately 15 feet high, with an upstream impoundment that is almost completely sedimented. The deposition behind the dam reaches a fair distance upstream and influences morphology (e.g., shallower pool depths) significantly enough to warrant segmentation of the reach with the lower portion of M19-A encompassing the area impacted by aggradation upstream of the dam.

Shallow pool depths, lack of available cover, channel straightening, and bank armoring result in a fair habitat stream condition based on the Rapid Habitat Assessment

(RHA condition rating = 0.53). Japanese knotweed (*Polygonum cuspidatum*) appears as the sub-dominant near bank vegetation type. This is problematic from both a ecological and bank stability standpoint. Japanese Knotweed's limited root mass provides little soil binding strength. Like segment M19-B, M19-A is presently in Stage III of its evolution, experiencing aggradation that is further enhanced by the presence of the Warren crib dam. The channel's tendency for widening is being combated through the extensive application of bank armoring.

Segments M19-A and M19-B are currently Rosgen (1996) F-type streams, meaning large floods are contained within the channel and only rarely access the floodplain. For Segment M19-A, with an abandoned floodplain present, this represents a departure from the expected C-type reference condition, because floodplain access was previously available in the low gradient, albeit relatively narrow, valley. The change in channel type is the result of channel incision and the greater confinement of flood flows due to the straightening and reforestation discussed above.

5.2 Reach M18

Location: Bedrock gorge downstream of the Warren crib dam

Reach M18 flows through a steep-walled bedrock gorge downstream of the Warren crib dam and through much of Warren Village. With abundant deep pools, a relatively intact riparian buffer, and unembedded boulders and cobbles, the reach rates as good habitat on the Rapid Habitat Assessment (RHA condition rating = 0.82). The low entrenchment ratio of 1.2 is due to the nearly vertical bedrock walls in the gorge, but the lack of floodplain access does not mean that the reach is actively incising as the Rapid Geomorphic Assessment score of 5 for the channel degradation component might suggest. In reality the likelihood of historic, current, or future channel adjustment due to the dam or other human land uses is very low given the natural grade controls, channel constrictions, and bedrock banks within the gorge.

5.3 Reach M17

Location: Bedrock gorge beginning at the Bradley Brook confluence and continuing downstream of Warren village

Reach M17 is very similar to Reach M18 in that it is an F-type stream flowing through a bedrock gorge. The reach exhibits good aquatic habitat (RHA condition rating = 0.80). The reach has experienced almost no historic alteration, has greater than 100 feet of riparian buffer on both banks along the entire reach, and only 50 feet of rip rap is present on the left bank at the mouth of Bradley Brook. Future channel adjustments are unlikely due to the erosion resistance of the bedrock gorge. However, increases in sediment load may result in the deposition of gravel bars upstream of narrow constrictions within the gorge.

5.4 Reach M16

Location: End of Warren Gorge downstream to the Kingsbury Iron Bridge

Reach M16 is the only reach along the mainstem other than Reach M19 that has experienced a stream type departure due to channel incision. The reference condition is a C-type stream, but currently an F-type stream is present after a period of historic incision (incision ratio = 2.1) that has led to an entrenchment ratio of 1.2 and loss of floodplain access. Like Reach M19, M16 is in Stage III of channel evolution and has been significantly altered by historic channel straightening and extensive bank armoring. The reach runs along Route100 with the road encroaching upon the channel’s left bank for much of its length and little to no riparian buffer or bank vegetative protection on the same bank. Japanese knotweed with little root mass is the sub-dominant near bank vegetation type. In contrast, the right bank has a relatively intact riparian buffer and little encroachment or development. The reach is within a naturally broad valley, but Route 100 has artificially constricted the valley width. The increased stream power resulting from this constriction may enhance scour along the riprap embankment where the river approaches the highway. The riprap is being undermined in places due to this enhanced stream power and additional remediation measures may be needed to reduce threats to Route 100.

Reach M16 displays sediment buildups at bedrock-controlled channel constrictions. These constrictions lead to backwatering during high flow events and the resulting reduction in flow velocity causes the sediment deposition (Figure 6). These enlarged gravel bars have been dredged in the past with one landowner recalling extensive removal in this reach following the 1998 flood. Sediment deposition in Reach M16 is also promoted by the drop in slope and flow expansion that occurs as the river leaves the confines of the bedrock gorge upstream (Reach M18 and M17). The slope decreases from 1.04 percent in Warren Gorge to 0.44 percent downstream (Appendix 2). Further deposition also occurs at the mouth of Clay Brook, but a significant delta bar has not been formed; the naturally straight bedrock-constrained reach in this area maintains a high rate of sediment transport sufficient to remove sediment emanating from Clay Brook. These naturally straight and constricted areas are controlling the location of sediment aggradation currently observed within the reach. Gravel bar formation is enhanced by large sources of sediment made available from land clearance over a century ago and still periodically transferred to the mainstem during large flood events as in 1998.

Excessive aggradation at the bedrock constrictions is enhanced by the straightening and channelization along sections of the reach (Figure 7). Sediment is transported through the channelized areas, which have an increased slope, armored banks, and lack of floodplain connectivity, and deposited above the channel constrictions where sediment transport capacity decreases rapidly during high flow events. Under natural conditions, sediment deposition would be more evenly distributed throughout the reach.

5.5 Reach M15

Location: Kingsbury Iron Bridge downstream past Sugarbush snowmaking pond to Fitzgibbons' property

Reach M15 is incised (incision ratio = 1.4), but the reach remains a C-type stream with an entrenchment ratio of 5.4. The width:depth ratio of 23.6 is only slightly higher than might be expected naturally. Consequently, Reach M15 is the only one of the primarily alluvial reaches along the mainstem to rate a "Good" score in the Rapid Geomorphic Assessment (RGA score = 0.68). Like much of the mainstem, M15 is not entirely alluvial. Areas of bedrock provide vertical and lateral controls on the stream channel. Large gravel bars are located behind these natural grade control and constrictions. Reach M15 is currently in Stage IV of channel evolution as evidenced by some widening and aggradation.

The reach has undergone alteration from its natural form as a result of channel straightening, bank armoring, a change in valley width due to encroachment of Rt. 100, and the creation of a snowmaking pond on the floodplain. Old meander scars present on the right bank (looking downstream and on the opposite bank from the snowmaking pond) provide some evidence of the former channel position prior to artificial straightening. In the area of the snowmaking pond, a channel-spanning concrete weir has been built. During the flood of 1998, the channel avulsed into the snowmaking pond and a small gully downstream was enlarged significantly as floodwaters exited the downstream end of the pond. After the flood, the accumulated gravel was removed from the pond. The river avulsed into the snowmaking pond a second time later in the same summer of 1998, highlighting the propensity of a channel to shift to an area of lower ground whether natural or, in this case, artificially created by the floodplain excavations and periodic removal of gravel. Rip rap was placed on the left bank of the Mad River at the upstream end of the pond and a series of rock vanes constructed in the channel to divert floodwaters towards the center of the channel, create sinuosity, and prevent a future avulsion. This project was one of six habitat enhancement projects constructed along the Mad River utilizing rock vanes related to permitting of the snowmaking pond.

In addition to the potential for future avulsions at the snowmaking pond, another area of concern is at the Punch Bowl, a popular swimming hole. Riprap just upstream on the right bank is preventing continuing erosion that may cutoff the meander and leave the Punch Bowl isolated from the main flow path. A house just downstream of the Punch Bowl was destroyed during the 1998 flood and has since been rebuilt. Riprap protecting the new home is enhancing a back eddying effect that is causing bank erosion at the downstream end of the potential neck cutoff, so additional efforts may be needed to stabilize the bank in order to preserve the Punch Bowl in its current condition.

Finally, the river impinges upon a bank of unconsolidated sediments over 15 feet high on the right bank near the confluence with Folsom Brook. This bank of stratified sand and cobbles is actively eroding and has already compromised the foundation of one building (Figure 8). While this is an area of concern, the conditions at this location are not representative of the reach as a whole.

Banks are moderately unstable throughout the reach with a dominant near bank vegetation type of Japanese knotweed. As a result of all of these factors, the Rapid Habitat Assessment resulted in a "Fair" rating (RHA condition rating = 0.57).

5.6 Reach M14

Location: Short reach downstream of Fitzgibbons' property

Reach M14 is a short, straight, F-type stream in a semi-confined valley with extremely steep walls. The left corridor is bedrock, whereas the composition of the right bank is unknown because of dense vegetation. This reach is likely a bedrock gorge, as it shares many of the characteristics of Reaches M18 and M17. No floodplain is present, although high abandoned terraces are found along the valley walls, particularly in the lower section of the reach. These terraces range from 6.5 feet to approximately 14 feet above the current bankfull elevation. Similarly high terraces were seen in isolated places in Reach M15 (Figure 8). The lack of a modern floodplain leads to a low entrenchment ratio (1.1), although an emergent floodplain is present in the form of flat-topped alluvial benches along the channel's margins (Figure 9). These benches extended into the channel at least another 5.0 feet prior to the 1998 flood, indicating the power of large floods to alter channel morphology within confined reaches (Shayne Jaquith, personal communication, 2006). A similar bench was not observed in Reaches M18 and M17, which are more narrowly confined and where stream power may be too great for such benches to form. Reach M14 is apparently wide enough (bankfull width = 102 ft.; width:depth ratio = 36.2) to allow for the deposition of fines along its edges.

The reach has a relatively intact riparian buffer, a full bank canopy, and good bank stability. Despite these conditions in a forested reach with steep valley walls, only six pieces of large woody debris are presently in the channel and the reach has a low score for epifaunal substrate and available cover (Score = 5). Overall, the reach rated as "Good" on the Rapid Habitat Assessment (RHA condition rating = 0.75).

5.7 Reach M13

Location: Lareau Farm area downstream to Mill Brook confluence

Reach M13 is a moderately incised (incision ratio = 1.6) C-type stream with access to its broad floodplain during high flow events (entrenchment ratio = 3.7). Low to moderate flow events remain confined within the channel banks and, thus, may be contributing to channel instability within the reach and further downstream. The stream currently has a moderate width:depth ratio of 31.7, but the stream appears to be actively widening in this reach that is in Stage III of channel evolution. Bank erosion is widespread throughout the reach, in part due to the poor vegetated buffer (Figure 10). The dominant buffer width on the left bank is less than 5 feet and is only between 5 and

25 feet on the right bank. The active bank erosion is supplying excess sediment to the channel, filling some pools and supplying large gravel bars.

Reach M13 contains at least ten wide unvegetated point bars with flood chutes cutting across six of them. As is seen elsewhere in the watershed, these bars are concentrated upstream of bedrock constrictions and bedrock constrained bends in the channel. Gravel deposition is particularly dramatic just upstream of the confluence with Mill Brook where a channel constriction results when sediment from the tributary squeezes the mainstem's flow against bedrock on the opposite bank. Deposition upstream due to the backwatering effect behind the constriction diverts flow into one of the banks where dramatic erosion and meander development is observed (Figure 11). A large flood, perhaps the 1927 flood, may have been responsible for the development of a much longer meander upstream of Mill Brook along what was likely a previously straightened reach (Figure 12). This meander would have formed when the backwatering effect behind Mill Brook extended far upstream and caused the channel to "break out" of the main channel and carve the meander across the floodplain. As evidenced by the deposition and meander development behind Mill Brook, Reach M13 has a high potential for planform change given the broad flat valley and poor bank protection.

Reach M13 has experienced channel alteration in the form of channel straightening, bank armoring, and encroachment of Route 100, which represents an artificial valley wall in some stretches of the reach. Channel alteration has been greatest near the local public swimming hole where the channel has been straightened and armored on the left bank. Several rock vanes and boulder weirs were also constructed in the channel after the 1998 flood. The rock vanes were placed in the stream for habitat improvement as part of the permitting for the snowmaking pond for the Sugarbush ski resort. Despite these efforts over a short length of M13, the reach as a whole has only a "Fair" habitat condition (RHA condition rating = 0.48) due to channel straightening, lack of riparian buffer, and substantial bar deposition.

5.8 Reach M12

Location: Mill Brook confluence downstream through Irasville and Waitsfield to the High Bridge Brook confluence

Reach M12 is similar to Reach M13 in many ways. It is a moderately incised (incision ratio = 1.6) C-type stream with access to a broad floodplain only during large flood events (entrenchment ratio = 8.6). Like its upstream neighbor, Reach M12 is also undergoing channel widening in Stage III of channel evolution. Bank erosion and bar aggradation, particularly at bedrock constrictions, are the dominant processes active in the reach.

In the middle of the reach, through the village of Irasville, the river is confined between a bedrock knob in the bottom of the valley and the right bank valley wall. This constriction creates two sharp meanders in quick succession that cause a loss in the river's sediment transport capacity, resulting in the deposition of a series of large gravel bars. Downstream, in Waitsfield Village, an old dam has been partially breached and no longer acts as a grade control in the reach. The large gravel bars upstream are likely remnants of the sediments that accumulated in the impoundment upstream of the old dam. A large levee extending from the dam abutments is located on the left bank floodplain and protects several buildings from flooding, but by blocking floodplain access may exacerbate flooding and erosion problems elsewhere. The channel upstream of the dam has been straightened with remnants of the original meander still visible around the baseball field on the left bank (looking downstream). Although channel evolution has progressed to Stage III (i.e., widening phase) since the straightening, sediment transport capacity probably remains high and probably increases deposition in areas of decreased transport capacity downstream.

Six wide unvegetated point bars are found in Reach M12, but only one is cross-cut by flood chutes as opposed to the greater frequency of flood chutes in Reach M13. Consequently, the propensity for planform channel change is not considered as great as in Reach M13.

A massive clay slump 140 feet wide and up to 72 feet high is present on the right bank at the downstream end of Reach M12 (Figure 13; Springston et al., 2004). The slump appears to be very active with more than a dozen trees uprooted. The slump was triggered by erosion along the toe of a glacial deposit at the downstream end of a possibly straightened section of the channel. A significant quantity of sediment is added to the stream by the slump during high flow events, but no easy solution is available to immediately arrest this erosion.

Significant channel straightening, moderate deposition in pools, lack of favorable epifaunal substrate and available cover, and poor bank stability leads to a “Fair” habitat condition (RHA condition rating = 0.53). The riparian buffer width could be improved, particularly along the left bank, where a width of only 5 to 25 feet is the dominant buffer width category.

5.9 Reach M11

Location: High Bridge Brook confluence through agricultural lands below Waitsfield Village to Shepard Brook confluence

At 4.4 miles long, Reach M11 passes through a long stretch of agricultural land in the very broad valley north of Waitsfield Village. Reach M11 is an incised (incision ratio = 1.8) C-type stream with access to its floodplain only during high discharges (entrenchment ratio = 5.9). Reach M11 is one of the most altered reaches assessed on the mainstem. Seventy two percent of the reach has been straightened and may be responsible for the observed incision. This historically incised reach is currently undergoing widening and is in Stage III of channel evolution. Low bank stability is exacerbated by the prevalence of Japanese knotweed along the banks, the dominant near bank vegetation type. The riparian buffer width is narrow. Landowners suggest that much of the riparian buffer was removed after the 1973 flood and the banks stabilized with riprap. Bank armoring may explain the relatively low width:depth ratio (= 21.4) compared to other mainstem reaches. Landowners also suggest that trees that have grown since 1973 have weakened the bank armor in places and erosion has begun to work its way around the riprap. Bank erosion is also most notable where gravel bars have formed at bedrock constrictions or sharp bends in the channel. Deposition is focused in these areas because the increased transport capacity through the straightened and incised sections prevents sediment accumulation in those areas. Efforts to stabilize an eroding meander bend near the 1824 House with rock vanes and bioengineering techniques met with little success, because of the continuing erosive pressures created by deposition on the inside of the meander (Figure 14). This project was also part of the habitat improvement efforts related to the permitting of the Sugarbush snowmaking pond.

Sediment deposition in the reach, a lack of good epifaunal substrate and available cover, the high degree of channel alteration, poor bank stability, and low riparian buffer width combine to yield a “Fair” stream habitat condition (RHA condition rating = 0.45).

5.10 Reach M05

Location: S-curves downstream of Moretown Village

Located several miles downstream of the other assessed reaches, Reach M05 is also a moderately incised (incision ratio = 1.6) C-type stream. The valley is artificially narrowed for most of the reach by encroachment of Route 100B in the left bank corridor. Despite the encroachment, the stream maintains access to its floodplain during high flows with an entrenchment ratio of 3.0. Like Reach M11, much of this reach has been straightened (47 percent) with the subsequent incision continuing to confine small to moderate flow events to the channel.

Reach M05 flows through agricultural land with little or no riparian buffer, especially along the left bank. The condition of the riparian buffer in M05 is the worst of all of the assessed reaches. Japanese knotweed is the dominant near bank vegetation type, adding little stability to the already susceptible banks. These conditions offer little resistance to the active bank widening occurring as part of Stage III of channel evolution.

Bedrock is seen along the streambed in several locations, but nowhere were the outcrops observed to provide grade control by spanning the entire channel. While some sediment deposition occurs in the pools, enlarged bars, as commonly seen further upstream, are mostly absent in the reach. Instead, bar geometry is low and wide within the wide channel (width:depth ratio = 31.9). This is perhaps due to the relative scarcity of constrictions and bedrock constrained meanders and a significant reduction in bedload compared to the reaches upstream that are close to the significant sediment sources (e.g., high eroding banks and steep mountain tributaries).

The reach is in “Fair” habitat condition (RHA condition rating = 0.48) due to its high degree of channel alteration, lack of good epifaunal substrate and available cover, poor bank stability, and poor condition of the riparian buffer.

5.11 Mad River Tributaries

Eleven tributary reaches were chosen for Phase 2 Assessment including Clay Brook and three of its tributaries (Figure 1). Clay Brook drains the Sugarbush Resort area northwest of Warren Village where extensive development has occurred recently (Figure 15). The inclusion of the Clay Brook Watershed in the Phase 2 Assessment was motivated by the desire to determine the impacts, if any, this development is having on the morphology and habitat of Clay Brook and the Mad River. One reach of Pine Brook (Reach T5.02), a tributary that flows into Reach M11 north of Waitsfield Village, was included in the study because of concern that cattle have direct access to the stream. Furthermore, the lack of a riparian buffer in portions of this reach may be increasing bank instabilities (Figure 16). Finally, a tributary to High Bridge Brook and an unnamed tributary to Shepard Brook were added to the Phase 2 assessment to help address concerns related to perched culverts that may be impeding fish passage and destabilizing the adjacent roads (Figure 17).

Clay Brook and its tributaries occupy steep-walled confined valleys on the western slope of the Mad River Valley. These valleys are largely forested, but development is dense in some areas (Figure 15). The sections of stream most impacted by this development are: a) Reach T9.04 (5 culverts and an impoundment); b) Segment T9.03B (an artificially constructed channel through the Sugarbush Golf Club); and c) Segment T9.3-S1.01B (also flows through the Sugarbush Golf Club). The artificially constructed channel through the golf course was also completed as part of the mitigation for the Sugarbush snowmaking pond. The banks of the constructed channel have been stabilized with nearly continuous riprap that have prevented bank erosion, but have probably also increased sediment transport capacity downstream and prevented long-term channel migration processes critical for achieving and maintaining channel equilibrium.

Aside from stream crossings and channel manipulation at the golf course, direct alteration of the channel in the Clay Brook Watershed is minimal. Many problems are observed around stream crossings. Accumulation of sediment upstream of an undersized culvert on Rice Brook Segment T9.3-S2.01-B has necessitated periodic removal of debris from the opening of the culvert. The removed debris has been placed along the margins of the channel. Scour downstream of a box culvert under the Sugarbush Access Road on Rice Brook Segment T9.3-S2.01-A has led to a slight undermining at the base of the recently constructed culvert. Future events should be monitored to ensure the integrity of this structure is not further jeopardized. Aside from stream crossings and channel manipulations at the golf course, direct channel alterations are uncommon in the steeper portions of the Clay Brook Watershed. The lower portion of Reach T9.01, however, has been straightened and channelized where it enters the flatter less confined Mad River Valley. The flood of 1998 washed out a portion of the Sugarbush access road just upstream of Route 100 where Clay Brook exits the confined valley and enters the Mad River Valley. The road was subsequently repaired and the bank protected with large boulders. In response to the bank armoring, the channel has begun to incise and has undermined the riprap. Some of the boulders have slid down the destabilized bank, leaving portions of the bank unarmored.

Stormwater inputs related to development around Sugarbush may impact channel conditions. Four stormwater inputs were mapped in Reach T9.04, three in Segment T9.3-S1.0A adjacent to the golf course, and one each in segments T9.03B, T9.3-S2-01A and T9.3-S2-01B. More diffuse inputs are likely present, especially where roadside ditches influence drainage.

The most striking feature of the Clay Brook Watershed is the prevalence of mass failures (Figure 18). These mass failures are the result of several controlling factors. The extremely steep valley walls are composed of clay-rich glacial sediments blanketing the bedrock – a natural setting prone to mass failures. Springs and seeps percolating up through the clay-rich glacial sediments can lubricate fractures within the deposit and promote slumping and rotational failures. Deforestation in the 19th and 20th Century removed the stabilizing influence of trees on the hillslopes, leading to the extensive mass failures. In some areas, the forest's regrowth has been enough to stabilize these slopes. However, when the stream's flow impinges directly upon the toe of the slope, a mass failure is often triggered by destabilizing the steep slope above. Increased peak discharges associated with the development and snowmaking for the Sugarbush ski area could presumably increase the force of flow acting at the base of unstable slopes, but drawing a conclusive link between mass failures and recent human developments is not possible from the Phase 2 Assessment data. Mass failures occur throughout the watershed, not only near developments, and many of them were at least initially triggered by natural conditions and historical land clearance.

Clay Brook and its tributaries deliver a tremendous amount of sediment to the channel. An additional effect of the mass failures is the formation of debris jams. Many of the mass failures mapped in the study have a debris jam at their base (Figure 19). Within the Clay Brook Watershed, 45 mass failures are mapped and 20 debris jams are present, but not all debris jams are necessarily associated with a mass failure (see DMS website). Like Clay Brook and its tributaries, the other assessed tributaries, with similar geological settings and land use histories, also show a prevalence of mass failures and debris jams. Flood chutes cutting across point bars are common, especially where a floodplain has formed on the narrow valley bottoms. Flood chutes are more prevalent in the tributaries than along the mainstem due to the steeper slopes and greater frequency of debris jams. Sediment transported from upstream is stored behind the debris jams, which often span the channel.

Parts of Clay Brook appear to have been swept clean of accumulated debris and sediment during the 1998 flood (Figure 20). Large floods must periodically flush sediment and debris from the steep tributaries and deliver it to the Mad River mainstem. Unable to transport the spike in sediment load on the flatter valley floor, large gravel bars form, leading to channel avulsions and other damaging channel adjustments. Over a long period without large floods, debris and sediment can reaccumulate in the tributaries and prime the system for the next large event. Consequently, when two large events occur within a few years of each other, such as in 1973 and 1976 (Figure 2), the first event is likely to be more damaging, because the second event will be devoid of much of the debris and sediment. Extensive channelization and bank armoring after the 1973 event further minimized flood damages related to the 1976 event. However, the channelization has likely enhanced channel incision processes during subsequent large floods such as the 1976 event. This incision results in channel instabilities and bank erosion problems that may emerge over several decades as the channel adjusts to the initial channelization.

Considerable sediment was also removed by a large flood on the unnamed tributary to Shepard Brook. A number of small headcuts are now present along the channel, because the flood removed large woody debris and boulder steps that served as temporary grade controls and natural dams that prevented headcut migration and enabled sediment storage. The headcuts are migrating through the previously stored sediment, which is now easily transported through the steep and narrow tributary. Sediment supply to Shepard Brook will continue until large woody debris recruited into the channel reforms channel-spanning debris jams. Headcut migration may be contributing to the severity of perching observed at the downstream end of the culvert passing under North Fayston Road (Figure 17b). However, the size of the culvert is less than the bankfull width of the channel and the resulting deposition at the upstream end is causing a sediment deficit downstream that is primarily responsible for the bed scour at the culvert outlet.

Another culvert on a tributary to High Bridge Brook (Reach T6.1-S1.01) is creating backwatering because of the sharp bend in the stream channel at the culvert's entrance. This has caused deposition upstream (Figure 17a) and gullying around the culvert as large flows overtop the roadway. In addition, the footings of this concrete box culvert have settled, cracking the culvert and raising the floor of the culvert at the inlet. As a result, during low flows, water no longer flows through the culvert, but rather under it and through the cracks in the concrete. Three additional smaller constrictions are present on this tributary that have also caused aggradation upstream and scour downstream (see DMS data). The steep drainage as well as continuing channel evolution (currently Stage III) make this reach sensitive to change as exhibited by the dramatic response observed at the artificial constrictions along the channel. The reach is in "Good" habitat condition (RHA condition rating = 0.67) due to the presence of good epifaunal substrate, available cover, and variety of velocity/depth patterns.

Segment T5.02-B on Pine Brook was included in this assessment over concern with cattle grazing and crossing the stream. The channel was likely straightened in the past (Figure 16) and is now in Stage III of channel evolution, as evidenced by the channel incision (incision ratio = 1.3) and subsequent widening (width:depth ratio = 24.2). The lack of a riparian buffer and trampling of the bank by cattle leave the reach susceptible to continued widening; extensive sloughing of the low banks is observed (Figure 16). A cattle exclusion project with an alternate water supply as part of NRCS's Conservation Reserve Enhancement Program (CREP) is of interest to the Friends of the Mad River and is recommended based on the results of this study. Further consideration of riparian buffers and other techniques for restoring this reach are considered in Section 6.0 below. Segment T5.02-A is more naturally confined with a much healthier riparian buffer. The morphological differences between the two segments are the result of differences in valley confinement and slope, so T5.02-A should not be considered as a reference condition for guiding restoration of T5.02-B in the flatter and less confined valley.

The most common problems encountered on the tributaries are associated with road drainage and road crossings. Methods for addressing these and other problems are discussed in Section 6.0 below along with suggested reaches on the tributaries and the mainstem where these methods could be best implemented.

6.0 PRELIMINARY PROJECT IDENTIFICATION AND RECOMMENDATIONS

The objective of stream restoration is to return the stream channel to equilibrium and, by so doing, mitigate fluvial erosion hazards, reduce sediment and nutrient loading, and improve aquatic habitat. Several restoration techniques are discussed below that have the potential to meet these objectives if applied in the right situations. Example locations where each project type may be implemented in the Mad River Watershed are provided where appropriate. The use of riprap, rock vanes, and log deflectors, techniques widely used in the Mad River Watershed, are not discussed here as these approaches may inhibit the establishment of equilibrium conditions throughout the watershed. These techniques can provide critical bank protection and habitat improvements, but must be implemented parsimoniously in conjunction with other projects that reduce erosive pressures. Over time, the need for localized bank protection and habitat improvement will decrease as equilibrium is achieved through implementation of projects such as those discussed below. Recommended locations where each project type might be implemented are also provided.

6.1 River Corridor Protection

Villages in the Mad River Watershed, like the rest of Vermont, were built along streams where water was readily available for drinking, irrigation, transportation, and power. The benefits of life along the river outweighed the poorly understood risks associated with infrequent flood inundation and bank erosion. However, channel migration, incision, and widening, following a history of increased human land use and channel alterations, has led to increased risks. In Vermont, between 1995 and 1998, flood-related damages approached 60 million dollars (Vermont Agency of Natural Resources, 2006). Much of this damage is related to bank erosion rather than flood inundation. This has led to a movement by the Vermont River Management Program to undertake Fluvial Erosion Hazard (FEH) mapping and risk assessment.

Through protection of high-risk FEH corridors within a watershed, towns can seek to minimize flood-related damages while allowing the stream to move towards equilibrium. This passive approach to restoration, that protects portions of the floodplain within the river corridor (generally three bankfull widths on either side of the channel), has many potential benefits. The FEH corridors are designed to provide guidance to local municipalities dealing with bank erosion issues. The identified corridors can be used to set land use policies that discourage development or any other human activities that might prevent the river's ability to freely migrate and attenuate sediment and flow energy as equilibrium conditions are achieved.

As human activities are already present in most of the Mad River corridor, changes in land use may be required to prevent conflicts with natural channel evolution (i.e., widening, planform changes). Federal programs such as the Conservation Reserve Enhancement Program (CREP) are designed to lease land within the river corridor from landowners willing to allow river processes to continue unconstrained. River corridor protection efforts should be undertaken in previously straightened and incised reaches that are currently undergoing bank widening and planform changes. Protecting these areas, known as attenuation assets, from human constraints (e.g., riprap, berms, channelization) are essential for achieving equilibrium and reducing hazards and sediment loading at the site and in adjacent downstream reaches. In other areas where existing bank armoring or other management activities have prevented channel evolution from progressing along straightened reaches, more active restoration measures (as discussed below) can be employed to reenergize the channel evolutionary processes that will lead to equilibrium. Establishing protected river corridors must precede these efforts as channel evolution will cause bank widening and planform changes that will require unconstrained movement of the river.

Channel evolution within the protected corridor may result in increased floodplain connectivity and flow and sediment attenuation. This can reduce erosive forces in the channel further downstream where infrastructure may be adjacent to the channel and corridor protection less likely to be implemented. Ecologically, corridor protection zones can increase habitat diversity on the floodplain and in the channel through the establishment of wetlands, formation of overhanging banks, reestablishment of a riparian buffer, addition of woody debris in the channel, and erosion of side channels.

One negative impact of corridor protection is the potential for locally increased flood inundation risks as channel length increases with meander formation and roughness elements, such as large woody debris, are allowed to accumulate in the project reach. Therefore, corridor protection zones must be established where flood inundation will not pose risks to human developments or agricultural fields. On floodplains with heavy human land use, as is the case for much of the Mad River Valley, portions of the floodplain may need to be protected in order to provide space for flood attenuation within the corridor without placing investments outside the corridor at risk.

Areas prone to the formation and rapid growth of gravel bars, such as upstream of bedrock constrictions and downstream of straightened reaches, are particularly susceptible to erosion hazards. Establishing corridor protection zones in these high risk areas would be of the highest priority. Corridor protection along straightened reaches is also considered a high priority because of the potential to distribute sediment more evenly throughout the reach. This would increase bank erosion within the protected corridor as sediment is allowed to accumulate, but simultaneously alleviating erosive pressures downstream where human investments might be at risk.

Recommended Locations:

Several undeveloped areas in the Mad River Watershed are good candidates for river corridor protection. This passive restoration practice is recommended wherever landowner approval can be secured. Possible enticements for landowners include federal programs such as CREP that provide funds for lands that are taken out of production along the river. Many landowners on the mainstem are concerned with rapid bank widening and channel avulsions that can cause the loss of large sections of land in a single flood event. Landowners might be convinced to relinquish a corridor along the river if land outside the corridor were protected from bank erosion and channel migration.

Ideally, corridors should be established that are six times the bankfull width of the channel, so the river has ample space for the lateral migration necessary to reestablish an equilibrium meandering planform. Straightened and channelized reaches within the Mad River Valley (see DMS website) have the greatest potential for planform change, and, therefore, are areas that would benefit the most from corridor protection. One section in Reach M13, the Lareau Farm, has already changed dramatically from its channelized planform and was one of the two sites chosen for a detailed Phase 3 assessment, because corridor protection will allow planform changes to continue unimpeded while reducing sediment loads and erosive pressures further downstream (see Section 7.0 below). The careful analysis of this section of Reach M13 during the Phase 3 assessment provides a detailed understanding of how a protected river corridor might evolve over time and lead to reductions in flood hazards and improvements of aquatic habitat. Using this reach as a template or reference conditions might prove useful for educating landowners elsewhere on the Mad River mainstem of the benefits of river corridor protection.

6.2 Riparian Buffer Planting

A healthy riparian buffer is essential to long-term sustainability of equilibrium conditions and healthy aquatic habitat. Trees with their roots growing in the soil along an eroding bank help bind the soil together but do not harden the bank like riprap, so erosion continues at a reduced rate. Consequently, if a riparian buffer occurs along the entire river, erosion can be evenly distributed along its length and excessive erosion not focused at any one site or excessive sediment produced by the concentrated erosion in one area. Some erosion of river banks is critical for maintaining overhanging bank cover and for recruiting wood into the river as the banks are slowly undercut and trees fall into the channel. Wood in the river channel is not only critical for habitat diversity but also adds hydraulic roughness that reduces flood flow velocities. Reduced flow velocities, in turn, helps the channel maintain a connection to its floodplain and increases sediment retention. The time required for the full habitat and morphological benefits of riparian buffers to be realized is several decades from the initial planting as significant amounts of time are required for the trees to mature. Consequently, other restoration actions are often needed where a more immediate return to equilibrium conditions is sought. However, over the long term, the reduced rates of erosion associated with healthy riparian buffers would result in less sediment delivery to downstream areas prone to the rapid growth of gravel bars and extreme bank erosion (e.g., upstream of constrictions). Given the eventual advantages created by planting buffers and the minimal effort and expertise required to do so, planting buffers along river banks and their adjacent floodplains should be considered a high priority in the Mad River Watershed wherever such buffers are missing (see DMS website).

Beyond the immediate river banks, the growth of trees on the floodplain would increase the resistance of floodplain soils to erosion. Floodwaters flowing over bare soils on the floodplain have the power to scour new channels and create additional sources of sediment and nutrient inputs over and beyond what is derived from bank erosion alone. In rare cases, the floodplain scour might cause an avulsion, whereby the channel's position might rapidly shift out of the current channel and into a new position. The establishment of a riparian buffer would tend to baffle floodplain flows, reduce their velocity, and encourage the deposition of fine sediment rather than erosion of floodplain soils. Consequently, riparian buffer plantings would enhance floodplain deposition and reduce fine sediment delivery downstream.

Continued, albeit slower, bank erosion where a riparian buffer has become established will result in mature trees being undermined. This will provide a source of wood to the channel, an essential component of good fish habitat. Riparian buffer plantings also provide increased shading through the development of a channel canopy, which will lower water temperatures. This is particularly important on the Mad River where high water temperatures may be limiting trout populations. Other important habitat benefits of an established riparian buffer include development of overhanging bank cover and improved water quality by buffering contaminants introduced by overland flow across the floodplain.

The establishment of a riparian buffer should be encouraged along the entire length of the river, not only where bank erosion is currently active. Planting trees in areas that are relatively stable will allow trees a chance to mature and be better able to resist strong flows if the location of erosive forces shifts over time. Buffer plantings occurring where erosion is currently active should be of sufficient width, so there is ample time for the trees to mature before continued bank failure undermines all of them. Trees that do not have time to develop a large root mass will not slow the rate of erosion. Planting of large or fast rooting trees and shrubs on the bank slope and top edge of the bank may help slow the rate of erosion more immediately by baffling flows and providing surface protection while other trees with larger, but more slowly growing root masses, are planted further back from the slope and have more time to mature. Where banks are vertical, portions of the upper bank could be reshaped so a gentler bank slope results, on which shrubs and other vegetation could be more easily planted.

Recommended Locations:

Riparian buffer planting would ideally be undertaken throughout the watershed, but several reaches stand out as particularly good candidates for riparian planting. Reaches M05 and M11 are the two reaches in greatest need of improved riparian zones. Both reaches have very low buffer widths, low degree of bank protection, low bank stability, and lack of available cover (see DMS website). Also, both reaches are very accessible and are located in agricultural areas where infrastructure is limited. Further upstream, the left bank of reach M12 may be a good candidate for riparian planting adjacent to the ball fields and at the downstream end of the reach below the Waitsfield covered bridge. Reach M13 is a very active reach with many flood chutes and a high likelihood of planform change, but this reach may still benefit from riparian planting in the areas of the Easy Street Café, Lareau Farm, and in the area downstream of the public swimming hole that was the focus of mitigation work for the Sugarbush snowmaking pond. The left bank of Reach M16 is also a good candidate for riparian planting. The reach's position in the upper portion of the watershed makes its benefits for trapping sediment and nutrients even greater. On the tributaries, Pine Brook Segment T5.02B may benefit from riparian planting done in conjunction with a cattle exclusion project which will prevent trampling of the plantings (see Section 7.0 below).

6.3 Arresting Headcuts and Gullies

Most of the reaches assessed in the Mad River Watershed are in Stages III or IV of channel evolution and are no longer actively incising, so arresting the advancement of headcuts and gullies is not of primary concern in the watershed, particularly the mainstem. However, two tributary reaches could benefit from such efforts. The first site is the unnamed tributary to Shepard Brook included in the Phase 2 Assessment. The stream appears to have several active headcuts that could further destabilize the stream's bed and banks as the headcuts advance upstream (Figure 21). Continued incision could deliver a significant quantity of sediment into Shepard Brook and potentially cause the collapse of a culvert passing under North Fayston Road. Some headcuts expose glacial clays at their base, indicating the ongoing rejuvenation of the tributary is significant. The cause of the current headcutting appears related to a large flood that may have removed large woody debris jams from the stream channel that were storing sediment behind them. The removal of the jams has initiated headcuts through the stored sediment.

The addition of large woody debris to the stream by felling trees on the steep side slopes of the tributary valley would trap sediment, encourage aggradation, arrest the active advancement of headcuts, and more rapidly return the stream to an equilibrium condition. Other options include the construction of check dams or other artificial grade controls that would also store sediment behind them, but access to the stream bottom is difficult and the cost of such approaches is likely prohibitive.

The second site of concern is gullying along Floodwoods Road, a dirt road, that crosses Pine Brook at Segment T5.02-B and continues up the steep valley side slopes. Drainage ditches run along both sides of the steep road. The runoff is directed away from the road and down the steep valley slopes in three localities (Figure 22), causing active incision of the glacial deposits. Continued upstream migration of the headcuts found at the upstream ends of the current gullies could potentially cause the road to washout in the future. Furthermore, the downcutting of the gullies is delivering sediment to the floodplain of Pine Brook during significant runoff events. A large alluvial fan is forming in the same locality where riparian buffer plantings have been recommended to prevent continued widening of Pine Brook Segment T5.02-B (see Sections 5.11 and 6.2 above as well as 7.0 below). Success of the riparian planting efforts may depend on curtailing the amount of sediment deposited on the floodplain from continued incision of the gully.

Potential solutions to the gullying include diverting water away from the road in several more locations in order to distribute runoff more diffusely, so runoff at no one location is substantial enough to initiate and sustain incision. Funneling runoff off of the steep roadside ditches would require careful engineering and may be cost prohibitive for such a small road. Another option is to enlarge the drainage ditches along the road, armor them with large rocks, and eliminate all diversions of water away from the road. Sediment will still be delivered to the floodplain at the base of the road and the ditches would need to be constantly maintained to prevent them from becoming clogged or having breaks in the armor develop. These and other possible options should be discussed with town officials to consider the difficulties in protecting this road while limiting the downstream delivery of sediment to Pine Brook.

6.4 Addition of Wood in the Channel

Large woody debris plays an important role in shaping the morphology and physical habitat of streams. Large woody debris redirects local flow patterns, creates backwater areas, scours pools, and forms gravel bars with well sorted particles (Manga and Kirchner, 2000). Yet, in the 19th Century and into modern times large woody debris was removed from stream channels to reduce flooding, improve navigation, and remove obstructions to fish passage (Wohl, 2000). In New England, the removal of wood from streams was also frequently done to facilitate log drives.

More recently, wood has been purposefully added to stream channels either as individual logs or in the form of engineered debris jams. Wood in the channel increases flow resistance, which decreases flow velocities and leads to an increase in sediment storage (Wohl, 2000). Large gravel bars form upstream of debris jams (Figure 23) with the resulting increase in bed elevation leading to a reconnection of the channel to its floodplain in incised reaches. Once flood flows are able to accesses the floodplain, the flow spreads out, decreases its velocity, and deposits fine sediment, thus allowing sediment storage to once again occur on the floodplain. Within the stream channel, the addition of woody debris decreases the shear stress applied to the streambed , thereby reducing the erosive forces (Manga and Kirchner, 2000).

Large woody debris also increases habitat diversity by carving scour pools, providing cover, creating sites for the deposition of sediment and organic material, and enhancing substrate diversity (Wohl, 2000). This is important for the Mad River where the majority of reaches scored poorly on the Rapid Habitat Assessment for epifaunal substrate and available cover. Single logs in the Mad River were observed to have small pools scoured around them where flow was locally plunged downward on the stream bed by the obstructing log (Figure 24). Another habitat benefit is the potential increased connection of the channel to its floodplain, which can lead to the creation of secondary channels, wetlands and vernal pools. Thus, the habitat diversity of the floodplain can also be increased with the addition of wood in the channel.

The sediment storage and habitat benefits to be gained by the addition of woody debris jams would have to be carefully weighed against increased flooding that might accompany such a restoration scheme. The addition of wood in the channel will increase the roughness in the channel and reduce flood flow velocities. Consequently, for the same flood discharge, the water surface elevation will increase such that a discharge that previously would have reached the top of the riverbanks might spill out onto the floodplain with the addition of wood in the channel. While the addition of small amounts of wood would have only a negligible effect on flood elevations elsewhere, careful hydraulic modeling would be necessary to alleviate landowner concerns associated with increased flooding for more robust restoration schemes. In addition, the debris jams would also need to be carefully engineered to ensure that they will remain intact and stationary, so a large mass of logs does not break free and create hazards at bridges or other human infrastructure downstream.

Recommended Locations:

While the addition of wood to the channel will slowly occur naturally with the reestablishment of a riparian buffer, the addition of isolated logs and engineered woody debris jams in the channel could provide more immediate and beneficial impacts at several places in the Mad River Watershed. Since large woody debris increases sediment storage, the addition of wood to headwater tributaries is a high priority as this would prevent considerable sediment from reaching the Mad River mainstem where excess sediment delivery is a significant contributor to bank erosion and habitat degradation. As discussed above in Section 6.3, the addition of woody debris to the unnamed tributary of Shepard Brook would help arrest headcut migration and channel incision in addition to the advantages of sediment storage. If wood should be added on the mainstem, the ideal location is upstream of areas where bar formation is causing channel instabilities and bank erosion problems, but corridor protection within the areas of channel instability would be a higher priority. Reaches with poor habitat diversity and in an incised condition may also be well suited for wood additions. Segment M19-B, the most upstream segment assessed on the mainstem, is an ideal section for engineered debris jams as are portions of Reach M16. Reach M14 would benefit from the improved habitat diversity, but access could be difficult. The straightened section of Reach M12 above the old Waitsfield Dam site may technically be a good location, but the potential for increased flooding near the village might make this option socially unfeasible. Reaches M11 and M05, with poor habitat diversity, would benefit from the addition of woody debris but their position lower in the watershed would mean fewer downstream benefits would be realized from sediment storage within these reaches. The addition of woody debris on the tributaries would also be an effective technique for increasing sediment storage and improving aquatic habitat.

6.5 Culvert Replacement

Bridges and culverts are important pieces of infrastructure, allowing roads to cross over stream channels. However, these structures can result in channel adjustments that, in the end, can jeopardize road stability or impede fish passage. Several culverts in the Mad River Watershed, as discussed below, are impacting channel stability and should be considered for replacement.

Undersized culverts can create problems in the stream because they cannot effectively transmit high flows and the sediment they convey. Backwatering upstream of a culvert can lead to deposition, gully formation at the downstream face of the road surface if overtopped, and, in severe cases, a bypassing of the culvert if the road is washed out. Nearly all of the culverts observed in the Phase II Assessment were undersized with diameters less than the bankfull width of the stream. However, not all of these showed signs of significant backwatering. The culvert displaying the worst affects of backwatering was found on Segment T9.3-S1.01-B, an unnamed tributary to Clay Brook at the Sugarbush Golf Club. A large gravel bar has aggraded in the pool above the culvert, which at 2.0 feet in diameter is significantly undersized to convey the stream's flow (bankfull width = 13 feet). The backwatering has caused water to flow out of the channel banks and over the top of the culvert, cutting a gully through the golf course sod and exposing the culvert underneath (Figure 25). Another culvert on a tributary to High Bridge Brook (Reach T6.1-S1.01) is creating backwatering because of its sharp angle to the stream channel. This has caused deposition upstream and gullying around the culvert that is compromising the road (Figure 17a). The footings of this concrete box culvert have settled, cracking the culvert and raising the floor of the culvert at the inlet. As a result, during low flows, water no longer flows through the culvert, but rather under it and through the cracks in the concrete.

Undersized culverts can also block fish passage when the bed of the channel at the downstream end of the culvert is lowered by scour. The culvert is said to be perched in these instances and is caused as sediment-free waters exit the culvert outlet and scour the channel bed. This is more likely to occur when the culvert is undersized, as flow velocities and sediment transport are more significantly altered. On Clay Brook Reach T9.04, which drains the Sugarbush ski resort, all five culverts are perched. In some areas, boulders have been placed at the culvert outlet to armor the bed and slow this scour. In other instances, culverts are originally installed in a perched condition with further scour occurring after installation. The downstream most culvert in Reach T9.04, passing under Inferno Road, is perched 9.8 feet above the water surface and displays all of these conditions (Figure 26). In addition to blocking fish passage, this culvert is compromising the culvert and road due to undermining of the culvert footings by scour. Another badly perched culvert (approximately 5.0 feet above the water surface) crosses under North Fayston Road on an unnamed tributary to Shepard Brook discussed earlier in regards to headcut migration and incision (see Section 6.6 and Figure 17b).

Rectifying problems associated with undersized culverts may require replacement of the culverts with larger structures that more closely match the bankfull width of the channel. The bankfull data collected as part of the Phase 2 Assessment may prove useful for determining the appropriate culvert width for a given stream reach (see DMS website and Appendix 2). The installation of floodplain culverts is important for proper conveyance within the channel itself. Floodplain culverts are at the level of the floodplain, and, therefore, are placed above the bankfull stage in order to pass flow under road or rail grades crossing the floodplain. With floodplain culverts, water flowing across the floodplain can continue through the culverts without being squeezed into the culvert on the main channel, reducing localized upstream deposition and downstream scour. Installation of floodplain culverts is feasible for stream reaches that have experienced only limited incision and have maintain floodplain access. Culvert replacement or installation of floodplain culverts, where feasible, should be coordinated with scheduled maintenance with the most severely impacted culverts, discussed above, given priority.

7.0 PHASE 3 ASSESSMENT

The most active channel adjustments in the Mad River Watershed are currently focused near areas of rapid sediment inputs (e.g., tributary confluences, high eroding banks) or decreased sediment transport capacity (e.g., upstream of bedrock constrictions, undersized culverts, artificially hard bends in the river). Along many other portions of the river, lateral channel adjustments have not occurred due to channel armoring or straightening. Consequently, channel adjustments are magnified at the points of decreased transport capacity or increased sediment delivery. Long-term channel stability along the entire river is difficult to achieve given the sharp contrast that exists between areas of increased transport capacity (e.g., straightened and armored segments) and decreased capacity (e.g., upstream of constrictions). Ideally, within alluvial reaches of the river, differences in sediment transport capacity from one area to the next are minimized. When such equilibrium conditions are achieved, sediment deposition and erosion are equally distributed along the river's length and the rates of bank recession and channel migration are diminished.

A Phase 3 Assessment was undertaken on an actively adjusting portion of the Mad River at the downstream end of Reach M13 (Figure 27) to detail typical channel adjustment processes occurring along the Mad River and to conceptualize restoration projects that can promote channel stability and equilibrium. The favored restoration options were developed further, so the Friends of the Mad River have sufficient information to gain landowner and funding agency support for implementation. Also, the potential for riparian buffer restoration and cattle exclusion on Pine Brook (Segment T5.02-B) was considered and initial plans developed to assist the Friends of the Mad River in securing funding and landowner support for implementation.

7.1 Restoration of the Lareau Farm area (Reach M13)

The Phase 3 Assessment on Reach M13 of the Mad River mainstem occurred at the downstream end of an artificially straightened portion of the reach (Figure 27). The project area may also have been previously straightened, but the presence of bedrock outcrops may have resulted in decreases in sediment transport capacity sufficient enough to initiate bank widening and the ongoing channel adjustments. The assessed portion of M13 is characteristic of channel adjustments occurring in other areas of decreased transport capacity and, thus, provides a template for what areas of sediment and flow attenuation might look like as straightened and incised reaches elsewhere on the river naturally evolve, or are purposefully restored, to an equilibrium condition.

Reach M13 of the Mad River, including the Phase 3 Assessment project site (Figure 28), has an incision ratio of 1.6 (Figure 29 and see DMS website). Consequently, a lower floodplain and large unvegetated gravel bars are inset within the abandoned floodplain as the river's planform continues to adjust (Figure 28). A large meander was carved into the floodplain on the left bank (i.e., Lareau Farm) during the 1998 flood and continues to serve as an active side channel during even small discharge events (Figures 28 and 30). This meander is located in an area of flow expansion immediately downstream of a bedrock knob protruding into the channel from the left bank. After the 1998 flood, bioengineering was used to stabilize the banks of the newly formed meander, but most of the hand-installed log deflectors have since been removed by continuing erosion (Figure 31).

The sinuous planform of the river within the assessed area contrasts with the straightened channel in the upstream portion of Reach M13 (Figure 27). The current sinuous planform in the project area may have developed from a previously straightened channel after a period of bank widening and subsequent gravel bar deposition (Figure 32). The excess sediment delivered from the still straightened portion of M13 upstream is likely accelerating the adjustments within the assessed area. Sediment deposition and planform changes are continuing the bank widening, creating side channels (Figures 30, 31, and 33), and setting the stage for channel avulsions as a minor headcut at the upstream end of one side channel migrates towards the main channel (Figure 28). Attempts to stop the bank widening with log vanes (Figure 31) and riprap (Figure 34) have met with little success, since erosive pressures on the bank persist as the channel continues to adjust within the project area.

Restoration within the assessed portion of Reach M13 must satisfy three primary objectives: 1) mitigate erosion and flood hazards; 2) reduce sediment and nutrient loading; and 3) improve aquatic and riparian habitat. The five restoration alternatives described below are judged on their ability to meet these objectives in order to identify the best and most practical restoration option to implement. Ultimately, combinations of these approaches may prove the most effective way to manage the site.

7.1a Option 1: River corridor protection

If no actions are taken at the site, bank widening and planform adjustments will continue until the channel dimension, pattern, and profile remain largely unchanged through time. However, even as the channel approaches an equilibrium condition, bank erosion and channel migration rates are likely to remain higher than under natural conditions given the excess sediment delivered from the straightened and incised reach upstream. Only minor amounts of riprap, portions of which have already been undermined (Figure 34), currently constrain lateral channel migration. Consequently, the project site can and should continue to accommodate and attenuate the excess sediment delivered from upstream. Storage of sediment within the project area will reduce sediment loading and assist, not hinder, the establishment of equilibrium conditions downstream.

Continued channel widening and gravel bar deposition will ultimately lead to expansion of the currently active floodplain inset into the previously abandoned floodplain surface (Figure 28). The large unvegetated gravel bars present at the site today are slowly becoming colonized with vegetation (Figure 32). While the pervasiveness of Japanese knotweed (*Polygonum cuspidatum*) is probably delaying the emergence of other plants, once woody shrubs and trees do become established on the bars, fine sediment and debris should be more readily trapped. The vertical accretion of fines on the bar surface will initiate the development of a new floodplain. In addition to storing fine sediments and nutrients, the creation of a floodplain will enable floodwaters to spread out, attenuating stream power at the site and decreasing potential erosion and flood hazards downstream.

Aquatic habitat conditions are rated as fair at the site (RHA condition rating = 0.48) with limited cover, a narrow or absent riparian corridor (Figure 32 and see DMS website), large unvegetated gravel bars (Figure 32), and overwidened channels (width:depth ratio = 31.7). The reach also suffers from less than adequate cover, fine sediment inputs, and elevated water temperatures in the summer. As channel evolution progresses and a new floodplain emerges, habitat conditions should improve but in time spans measured over decades rather than years. The trend with natural evolution of the site will be towards improved habitat complexity associated with the development of channel sinuosity. As a result, more complex flow depths and velocity patterns, better particle size sorting, and lower embeddedness ratios should emerge.

The current and evolving condition at the project site represents an important asset for the overall restoration of equilibrium conditions on the Mad River. Efforts should be made to conserve the river corridor in this area, so lateral migration of the channel can continue unconstrained. Achieving this goal may require public education and landowner outreach that explain how the dynamic nature of the river at the project site is important for reducing sediment loading, and, in turn, flood and erosion hazards downstream.

7.1b Option 2: Riparian buffer plantings

Riparian buffer plantings as a form of river restoration are generally proscribed for areas where low boundary resistance may lead to accelerated bank erosion within a reach that is already at or near equilibrium conditions. Within the project area on Reach M13, riparian buffer plantings may not succeed because of the ongoing channel adjustments (Figure 35). Additionally, the current absence of a riparian buffer over most of the site (Figure 32) is not, in the near term, a severe limitation to the development of channel equilibrium. Ultimately, though, as the channel achieves an equilibrium dimension, pattern, and profile, a well wooded buffer will be important for providing some boundary resistance and slowing the rate of channel migration. Currently, however, riparian plantings immediately along the banks of the channel are likely to be undermined by erosion before reaching maturity. Plantings placed tens of feet from the river would have a greater chance of reaching maturity and, at that time, would offer some resistance to erosion if the river were to continue migrating towards the planted area.

A riparian buffer is essential for the long-term development of equilibrium conditions. Plantings on the bank and floodplain provide resistance to flow and, therefore, attenuate stream power. The added roughness resulting from mature trees falling into the river after being undermined by erosion will encourage deposition, raise the bed elevation of the river, and assist in the reconnection of the incised channel to its floodplain, further reducing stream power and sediment loading downstream.

Establishment of a riparian buffer within a reach where the corridor is largely devoid of tress, as at the project site in Reach M13 (Figure 32), would also improve riparian ecosystem diversity and aquatic habitat. Mature trees provide shade that reduces summer water temperatures. As large trees are recruited into the river channel over time, cover habitat improves as does flow complexity. The planting of large trees may increase survival in areas that might be potentially undermined before younger saplings have a chance to reach maturity.

While the habitat and morphological improvements associated with a mature riparian buffer are unmistakably important, establishing a buffer where the river is experiencing dynamic planform changes may require considerable effort, time (i.e., decades), and expense (e.g., use of large trees, repeated plantings) with uncertain results. More immediate improvements may result from efforts that actively discourage the growth of Japanese knotweed on the large gravel bars. In the absence of Japanese knotweed, the natural colonization of the bars by woody shrubs and trees will accelerate the development and growth of the active floodplain.

7.1c Option 3: Increasing sediment attenuation

The project site is actively undergoing planform changes associated with channel aggradation. The largely unconstrained lateral movement of the river at this location is providing the accommodation space necessary to store and attenuate sediment. At least three side channels currently receive flow at varying flood stages depending on their height above the active channel bottom (Figures 28 and 33). With increasing discharge, flow becomes distributed into multiple flow paths, resulting in the attenuation of flow energy and deposition of sediment. The last side channel to receive flow under current conditions is located on the left bank (looking downstream) and is well defined at the downstream end (Figure 33). The channel terminates at a low headcut at the upstream end and receives flow through a gentle swale when the banks of the main channel are overtopped (Figure 28). Sediment and flow attenuation within the project site could be increased by lowering the height of the bank at this location and allowing flow to access the side channel at lower flow stages. Greater stream power could initiate headward migration of the knickpoint (Figure 28) and lead to the capture of the main channel (Figure 36). Extension and enlargement of the side channel could be accelerated by: 1) removing trees and other roughness elements in the swale to encourage headward erosion of the side channel or 2) excavating a channel that connects the headcut and the main flow path (Figure 36). Depending on the scale of project to be undertaken, further sediment attenuation could occur by connecting other side channels and flood chutes across gravel bars to the main flow path (Figure 36). With flow more evenly distributed between flow paths at even low discharges, sediment and flow attenuation within the project area would be maximized.

If nothing was done at the site, natural evolution of the channel may ultimately result in the partial capture of the main flow path by various side channels. Implementation of this restoration option, therefore, would not hinder but rather accelerate the development of an equilibrium condition and: 1) reduce flood and erosion hazards downstream, 2) increase sediment and nutrient storage within the project site, and 3) improve aquatic habitat conditions.

7.1d Option 4: Increasing floodplain storage

The relatively high incision ratio of 1.6 in Reach M13 means that the former floodplain extending across most of the valley floor (Figure 28) is inundated during only larger flood events, not on a nearly annual basis as likely occurred prior to incision. As a result, floodwaters are now confined to a narrower area with the excess flow energy transferred downstream. By lowering portions of the former floodplain to a level even with the emerging active floodplain, additional flood relief and flow energy attenuation can be realized at lower discharges (Figure 37). Since the lowered area would still be higher than the active channel, only fine sediment would be deposited and stored within this zone. However, additional coarse sediment would be deposited within the channel as a result of this restoration option, because the sediment transport capacity of the river would be reduced with the attenuation of flow over a larger area. The resulting rise in bed elevation would encourage further planform changes and promote the development of the emerging active floodplain. These conditions will slowly emerge with the natural evolution of the channel, so the creation of additional floodplain access would accelerate the development of equilibrium conditions at the site and lead to more immediate flood relief and sediment load reductions downstream. Aquatic habitat should also improve at the project site as described in *Option 1* above.

A possible location for lowering the former floodplain is on the right bank where the Town of Waitsfield recently acquired the land (Figure 37). To reduce the threat of a possible avulsion (i.e., rapid shift of the Mad River) towards Route 100, woody debris, tree plantings, and other roughness elements should be placed on the lowered floodplain surface to prevent a new channel from forming if a large flood were to inundate the site shortly after project completion. These concerns could be avoided by lowering the floodplain on the left bank (looking downstream) on the Lareau farm property as no infrastructure would be threatened by the increased frequency of flooding (Figure 37).

7.1e Option 5: Addition of woody debris in the channel

Very little wood is currently found in the channel at the project site or on the large gravel bars. However, where isolated pieces of wood are found (Figure 24), the disruption in flow that they cause results in the scouring of small pocket pools (Figure 38). The depths of the pools, while modest, are greater than elsewhere in this aggrading reach where steep riffles, gravel bars, and multiple flow paths predominate (Figure 28). The addition of even isolated pieces of wood in the project area should result in almost immediate improvements in aquatic habitat as flow complexity and pool formation are enhanced (Figure 39). With the addition of more wood recruited naturally from a maturing riparian buffer, greater hydraulic roughness will induce deposition of gravel and sustain the width and planform changes that are producing an equilibrium channel form over time. The more immediate introduction of large amounts of wood as part of a restoration project might accelerate the emergence of equilibrium and, therefore, increase sediment and nutrient storage at the site while reducing flood and erosion hazards downstream. However, anchoring of the wood may become necessary if the amount added could locally increase flood and erosion hazards if the logs were dislodged in a large flood and floated downstream.

7.1f Preferred Options

Of the five restoration options described above, the preferred option is river corridor protection combined with riparian buffer plantings. This option need not be limited to the project site, but would ideally extend upstream to encompass the artificially straightened section (Figure 27). Areas within the identified river corridor (Figure 39) would be protected from future development and other human activities that would constrain the river's natural evolution and migration. Although the section upstream of the project site is straightened (Figure 27), the river will over time begin to widen and develop a meandering planform as wood and debris is allowed to naturally accumulate in the channel and deflect water into the banks. With the corridor protected, this process could occur with limited constraints.

The total area of the river corridor upstream of the Route 100 Bridge in Reach M13 is 51 acres, which is owned by nine separate landowners (Figure 39). Approximately 20,000 trees spaced 6.0 ft apart are needed to plant all of the currently unforested areas within the corridor. Several native tree and shrub species that are tolerant to frequent overbank flows would be best suited for these areas that will experience increasingly more frequent flooding as the channel evolves to an equilibrium condition: Silver maple (*Acer saccharinum*), Cottonwood (*Populus deltoides*), Slippery elm (*Ulmus rubra*), Boxelder (*Acer negundo*), Black willow (*Salix nigra*), and Sycamore (*Platanus occidentalis*).

If a more rapid return to equilibrium conditions is desired, the preferred active restoration option is to increase floodplain storage by artificially lowering the abandoned floodplain to the new active floodplain, or bankfull, level. Floodplain lowering could occur at two locations within the project site (Figures 37 and 39). The first site encompasses 2.7 acres (117, 600 ft^2) of the right bank on land owned by the Town of Waitsfield. The land would need to be lowered 7.5 feet in this area to reach the bankfull stage (Figure 33), requiring a total removal of 882,000 ft^3 (32,700 cubic yards) of soil. A typical large dump truck has a 10 cubic yard capacity, so over 3,000 truck loads of material would need to be taken from the site. The lowered area should be planted with trees to increase the roughness of the new floodplain surface and reduce the possibility of scour and avulsion. Approximately 3,200 trees spaced 6.0 ft apart would be needed for the 2.7 acre area. Given that the lowering of the floodplain on the right bank would increase the risk of channel avulsion towards Route 100, implementation of this option would require detailed hydraulic analysis to more accurately assess the potential risk. Lowering 1.9 acres of the floodplain on the left bank would pose no increased threat to infrastructure (Figure 39), so would probably not require hydraulic analysis. The current surface is lower than the proposed area of lowering on the right bank, so considerably less soil removal is needed. The surface is currently 4.4 feet above bankfull, so 364,000 ft^3 (13,500 cubic yards) or 1,350 truck loads of soil need to be removed. The lowered surface should be planted with 2,300 trees spaced 6.0 ft apart to reduce the threat of scour and avulsion across the new surface.

7.2 Restoration of Pine Brook (Segment T5.02-B)

Segment T5.02-B on Pine Brook has a limited riparian buffer and cattle have access to the stream along a 2,500-foot section of the segment, 850 ft is downstream of the Floodwoods Road bridge crossing and 1,650 ft upstream. The banks in this section are unstable and the channel overwidened (width:depth ratio = 24.2) (Figure 16). Restoring the riparian buffer and excluding cattle from the corridor along this 2,500-foot section of the segment should improve bank stability and aquatic habitat. The area of the corridor within this portion of the segment is 11.4 acres (Figure 41). Planting the corridor of this 2,500-foot section of stream, where no riparian buffer currently exists, would require approximately 4,900 trees spaced 6.0 ft apart. An alternate water source can be created for cattle to assist the landowner in creating the buffer zone and entering the corridor into the Natural Resource Conservation Service's Conservation Reserve Enhancement Program (CREP).

Although the segment is actively widening and in Phase III of channel evolution, substantive losses of floodplain soils are not expected given the localized cause (i.e., cattle trampling) of the bank erosion. Consequently, CREP guidelines (NRCS, 2004) for recommended buffer widths of stable channels can be used, which will not require, nor do they preclude, protection and planting of the entire corridor as described above. Given the low slope of the floodplain and the presence of Hydrologic Soil Group "C" soils, the recommended width of the grass filter strip outside of the forested buffer is 30 ft. The recommended forested buffer width along the river is 35 ft given that the adjacent lands are used for pasture and hay. Accounting for both sides of the stream (70 ft), only 2.0 acres of the 4.0 acres total within this zone is currently unforested. Planting this unforested portion of the buffer would require approximately 2,500 trees spaced 6.0 ft apart.

8.0 CONCLUSIONS

A fluvial geomorphic assessment of the Mad River Watershed identified the major geological and human conditions that control river processes and morphology. The Mad River Watershed is largely controlled by its natural geologic conditions, with bedrock outcrops creating channel constrictions, confining meander geometries and providing grade controls. The steep topography of the drainage basin and the clay-rich glacial deposits blanketing the bedrock also provide important controls on stream morphology by contributing large amounts of sediments to the mainstem through mass failures. Sediment delivery to the mainstem is episodic as a significant amount of sediment is stored in the tributary drainages by woody debris jams that are periodically dislodged by large floods.

The natural delivery and movement of sediment in the watershed has been altered by a history of deforestation, channel straightening, and other human activities. Deforestation destabilized hillslopes and increased sediment delivery to the channel. Channel straightening, undertaken in part to more efficiently move the excess sediment down the river, and reforestation in the past century has led to channel incision and subsequent widening that continue to dominate stream channel processes on the mainstem . The majority of the reaches studied in the Phase 2 Assessment are currently in Stage III of Schumm's (1977) Channel Evolution Model (i.e., widening) with only a few reaching Stage IV and reestablishing a floodplain and a new channel planform through aggradation.

River management practices in the last few decades such as bank armoring, gravel mining, removal of large woody debris and installation of undersized culverts have increased stream instabilities while continuing channel incision and widening. Narrow riparian buffer widths and poor bank vegetative protection, partly due to the widespread occurrence of Japanese knotweed in the watershed, have worsened bank erosion. One consequence of the channel adjustments resulting from historic and recent land uses and river management practices is poor instream habitat, characterized by high water temperatures, poor epifaunal substrate, lack of available cover, moderate sedimentation of pools, and isolation of fish populations.

Within this context, the Mad River Watershed provides many opportunities for stream restoration. Restoration should be prioritized based on the potential for a project to not only improve channel stability within the project reach but also move adjacent reaches towards stream equilibrium. Restoration strategies should address channel and bank stability, instream and riparian habitat, and impacts to infrastructure. Those techniques that maximize the potential for channel and floodplain storage of sediment are likely to be the most successful in achieving these goals. Although river corridor protection may be difficult in developed areas, protecting the river corridor immediately upstream can provide a location for sediment storage that will improve aquatic habitat while reducing sediment loading and related erosive pressures downstream near human investments. For example, river corridor protection in Reach M13 upstream of the Route 100 Bridge will allow for unconstrained planform adjustments of the channel. The resulting sediment storage will lead to improved pool-riffle bedforms, a greater variety of flow depths and velocities, and better sorting of substrate particle sizes while reducing the potential for large gravel bars to form near developments in Irasville. The planform adjustments that would be part of the natural evolution of the channel in the reach could be accelerated by increasing the area available for floodplain storage by lowering portions of the historic floodplain abandoned by earlier channel incision. The restoration strategies outlined in this report (Sections 6.0 and 7.0) will only be useful if applied in appropriate locations along the stream. Where landowner approval is possible, site selection should take into account the morphology and stage of channel evolution, so appropriate restoration strategies can be chosen that return the channel to an equilibrium condition, mitigate erosion hazards, reduce sediment loading, and improve aquatic habitat.

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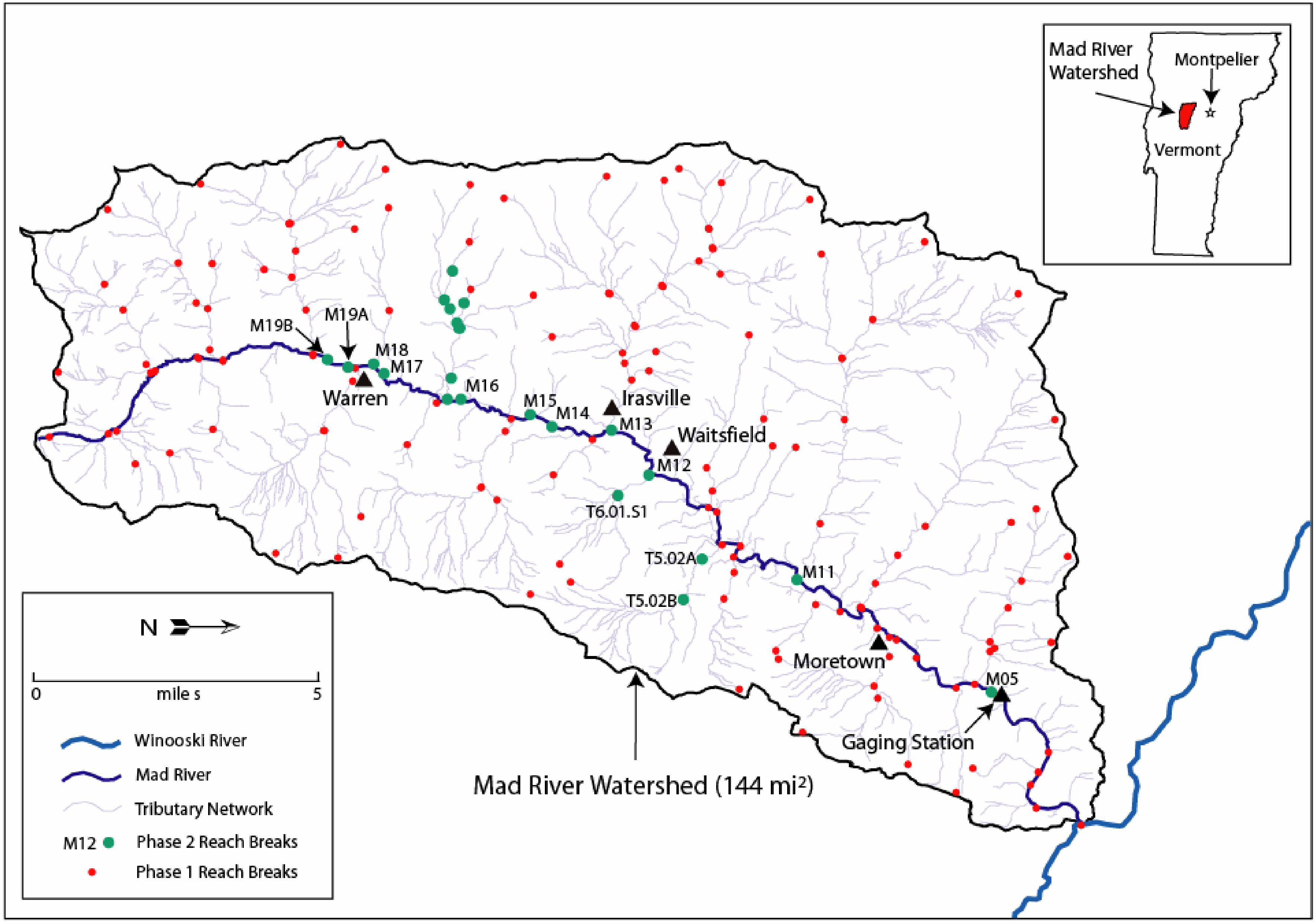

Figure 1: Map of the Mad River Watershed showing Phase 1 and Phase 2 reach breaks. Phase 2 reach breaks are labeled except for those in the Clay Brook Watershed, which are shown in Figure 15.

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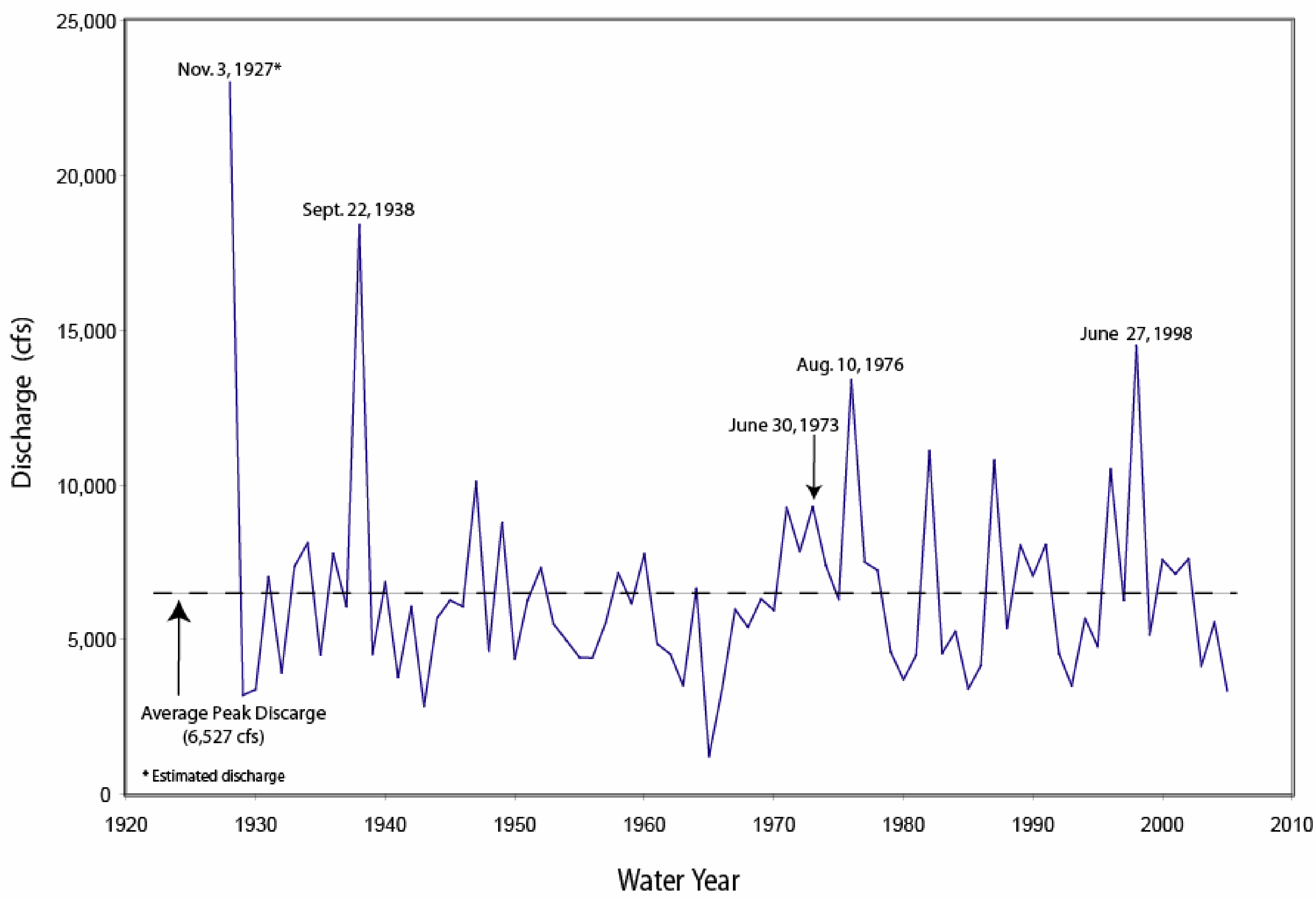

Figure 2: Annual peak discharges at Moretown, Vermont between 1927 and 2005

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Mad River Geomorphic Assessment - Figure 2

SOUTH PART OF THE VILLAGE FROM THE HILLS, WARREN, VT.

Figure 3: View of Warren Village prior to 1911 showing extensive land clearance. Impoundment behind the Warren Crib Dam can be seen at the bottom of the photo. Photo Courtesy of Vermont Landscape Change Program.

Figure 4: Erosion along the left bank of segment M19-B

Mad River Geomorphic Assessment – Figure 4

Figure 5: Warren crib dam looking upstream

Mad River Geomorphic Assessment – Figure 5

Figure 6: Large diagonal bar deposited upstream of bedrock constriction in Reach M16

Figure 7: Straightening and bank armoring in Reach M16

Mad River Geomorphic Assessment – Figure 7

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Figure 8: High eroding bank undermining building foundation in Reach M15

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Figure 9: Mossy bench of silt and sand representing an emergent floodplain along the margins of the channel in Reach M14

Figure 10: Eroding bank with narrow or absent riparian buffer located across actively growing point bar in Reach M13

Figure 11: Bank erosion and meander development upstream of constriction between bedrock bank and deposits at Mill Brook confluence

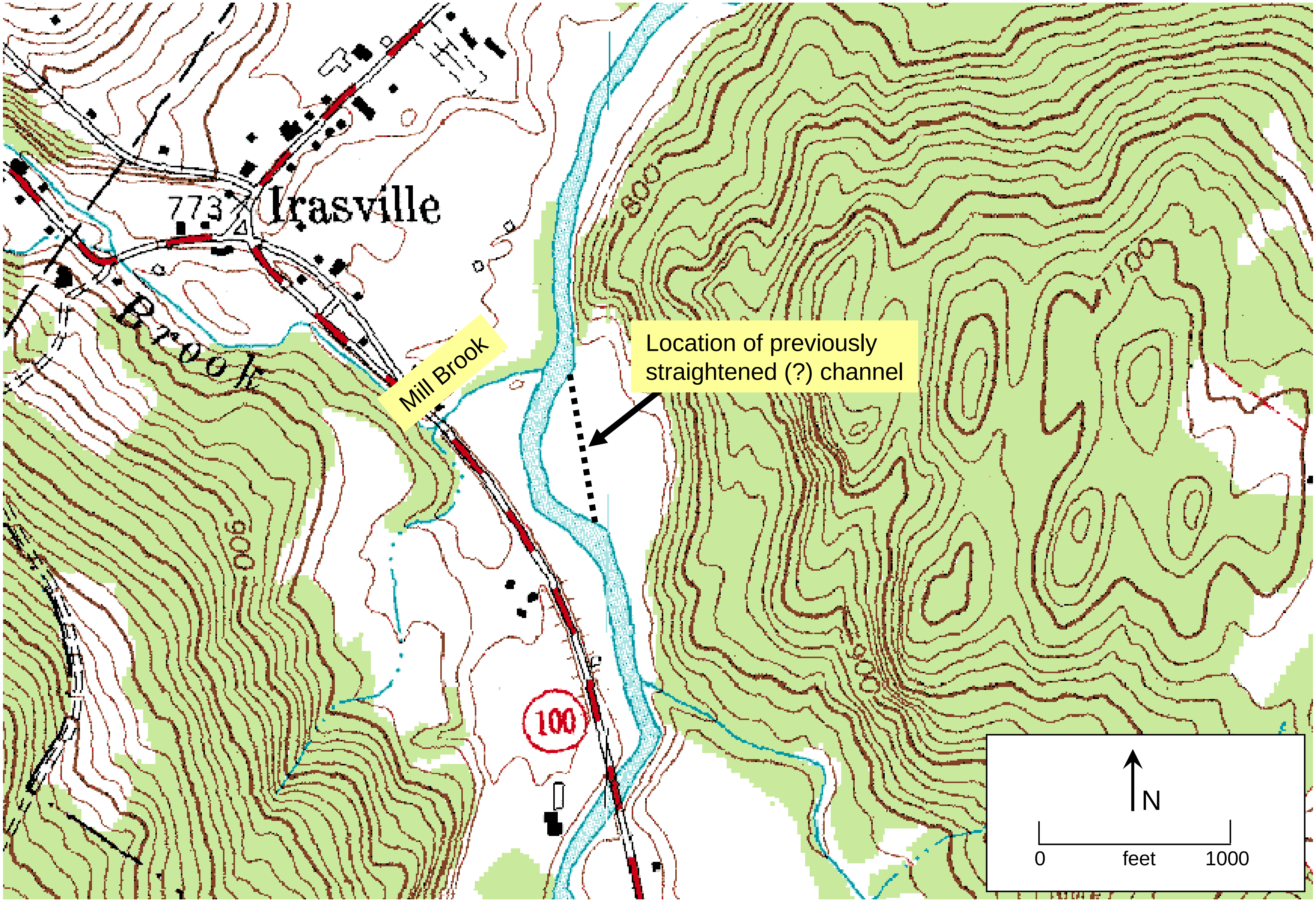

Figure 12: Large meander formed upstream of Mill Brook confluence where the river was likely previously straightened

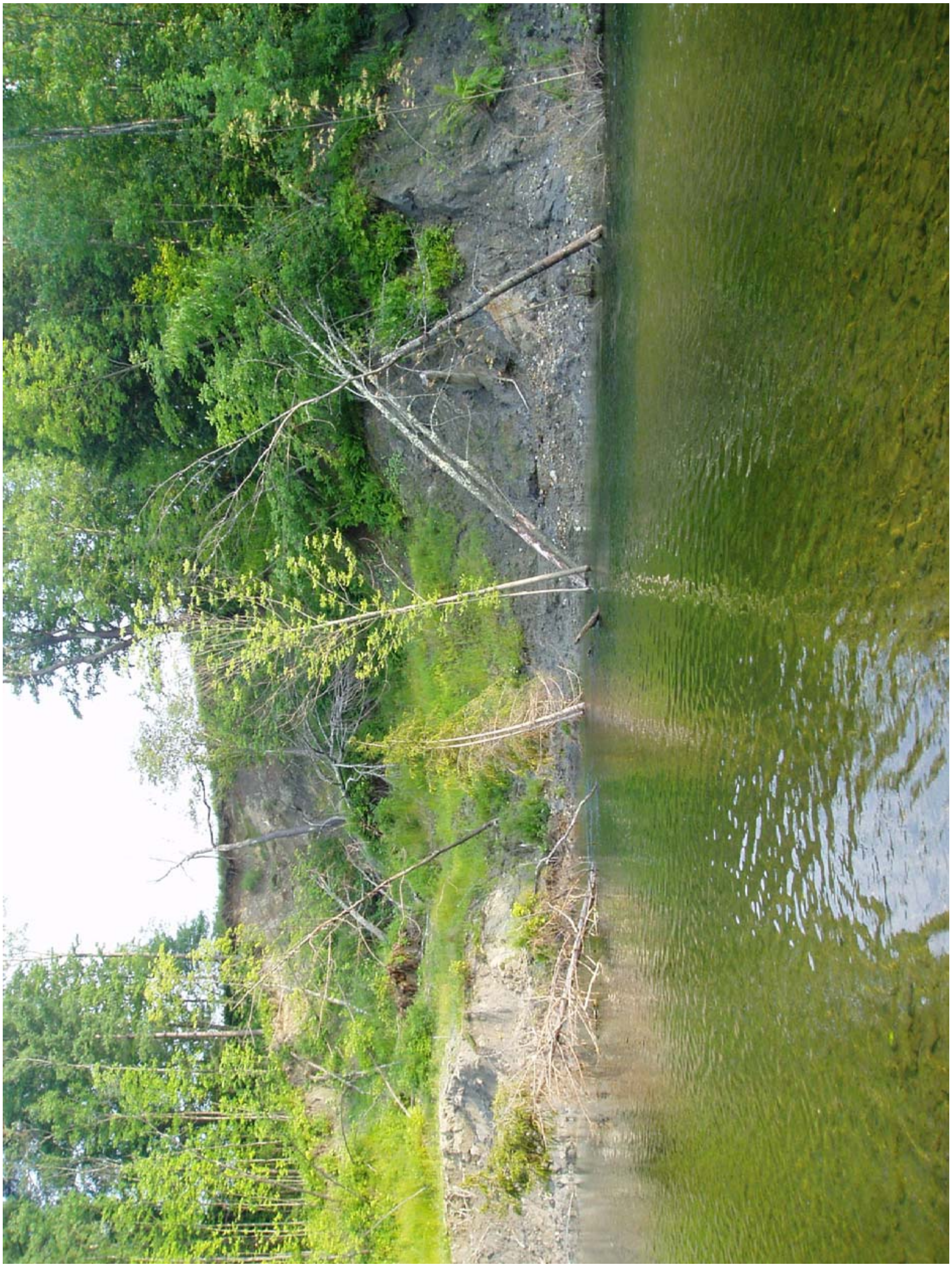

Figure 13: Large slump at downstream end of Reach M12

Figure 14: Deposition of gravel bar has led to continued erosion of the opposite bank near the 1824 House where earlier bioengineering efforts are barely visible today.

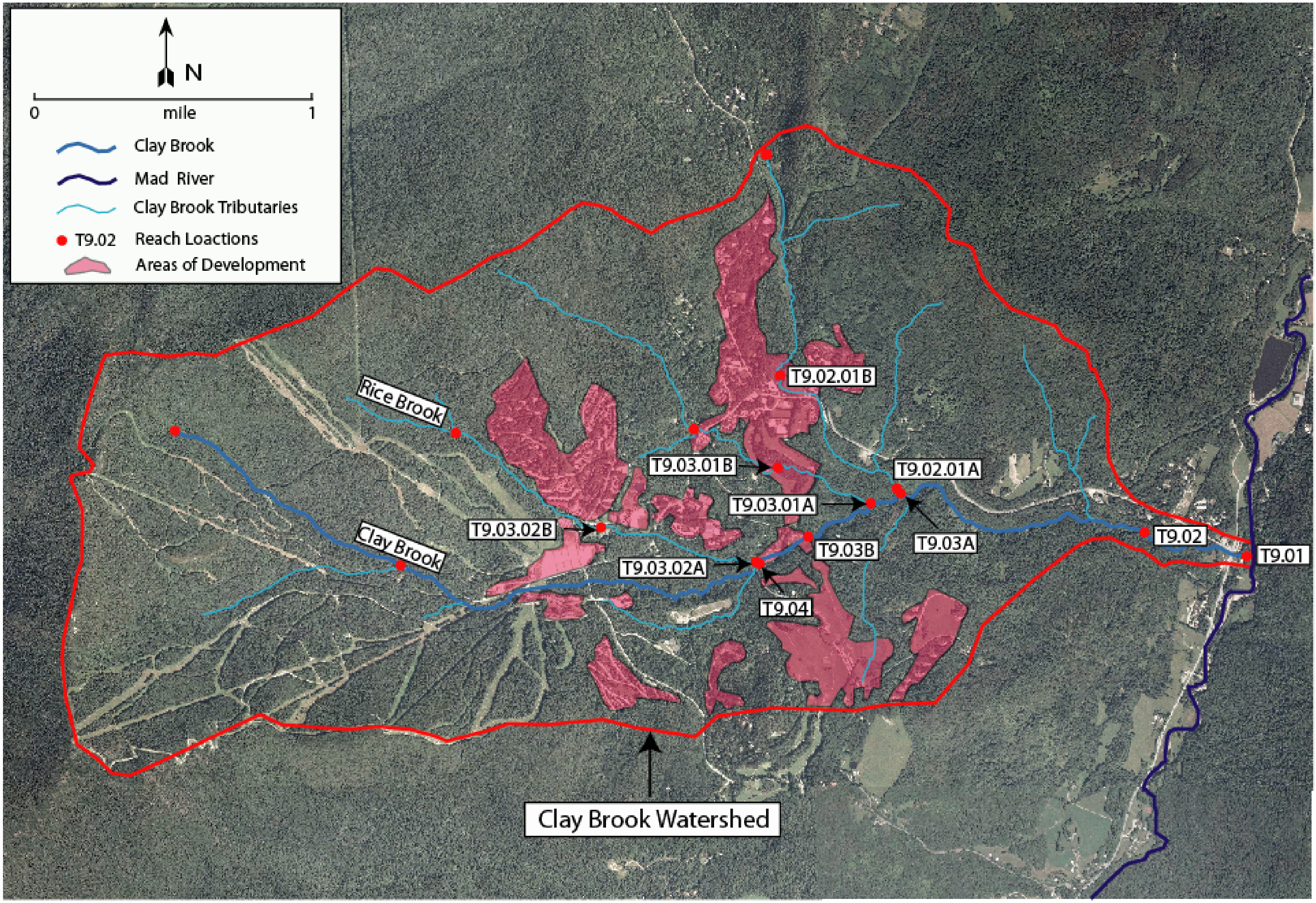

Figure 15: Aerial photograph of Clay Brook Watershed taken in 2003 showing areas of development. Development has continued in watershed since photo was taken.

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Figure 16: Lack of riparian buffer and cattle access are exacerbating bank erosion on Pine Brook (Segment T5.02-B)

Figure 17a: Aggradation of gravel bar upstream of undersized box culvert on High Bridge Brook tributary (Reach T6.1-S1.01)

Figure 17b: Culvert passing under North Fayston Road on unnamed tributary of Shepard Brook is perched 5 feet above water surface with footings being undermined by downstream scour

Figure 18: Mass failure on Clay Brook (Segment T9.03-A)

Figure 19: Debris jam associated with mass failure on Clay Brook (Reach T9.02)

Mad River Geomorphic Assessment – Figure 19

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Figure 20: Clay Brook (Reach T9.02). Note lack of debris and sediment accumulation in channel after large flood in 1998.

Figure 21: Headcut just upstream of North Fayston Road on unnamed tributary to Shepard Brook. Headcut is less than 50 feet from house damaged during a flood in 1986. Note flattened vegetation from recent high flows.

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Mad River Geomorphic Assessment – Figure 21

Figure 22: Area of runoff diversion from roadside ditch on Floodwoods Road on Pine Brook valley side slope.

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Figure 23: Gravel bar formed upstream of a natural woody debris jam on Esopus Creek in the Catskills, New York.

Figure 24: Small pool scoured locally around logs in channel (Reach M13)

Figure 25: Channel scoured over top of undersized culvert at the Sugarbush Golf Course in the Clay Brook Watershed

Figure 26: Outlet of culvert passing under Inferno Road on Clay Brook showing scour under culvert footings and boulders placed on channel bed to prevent further scour

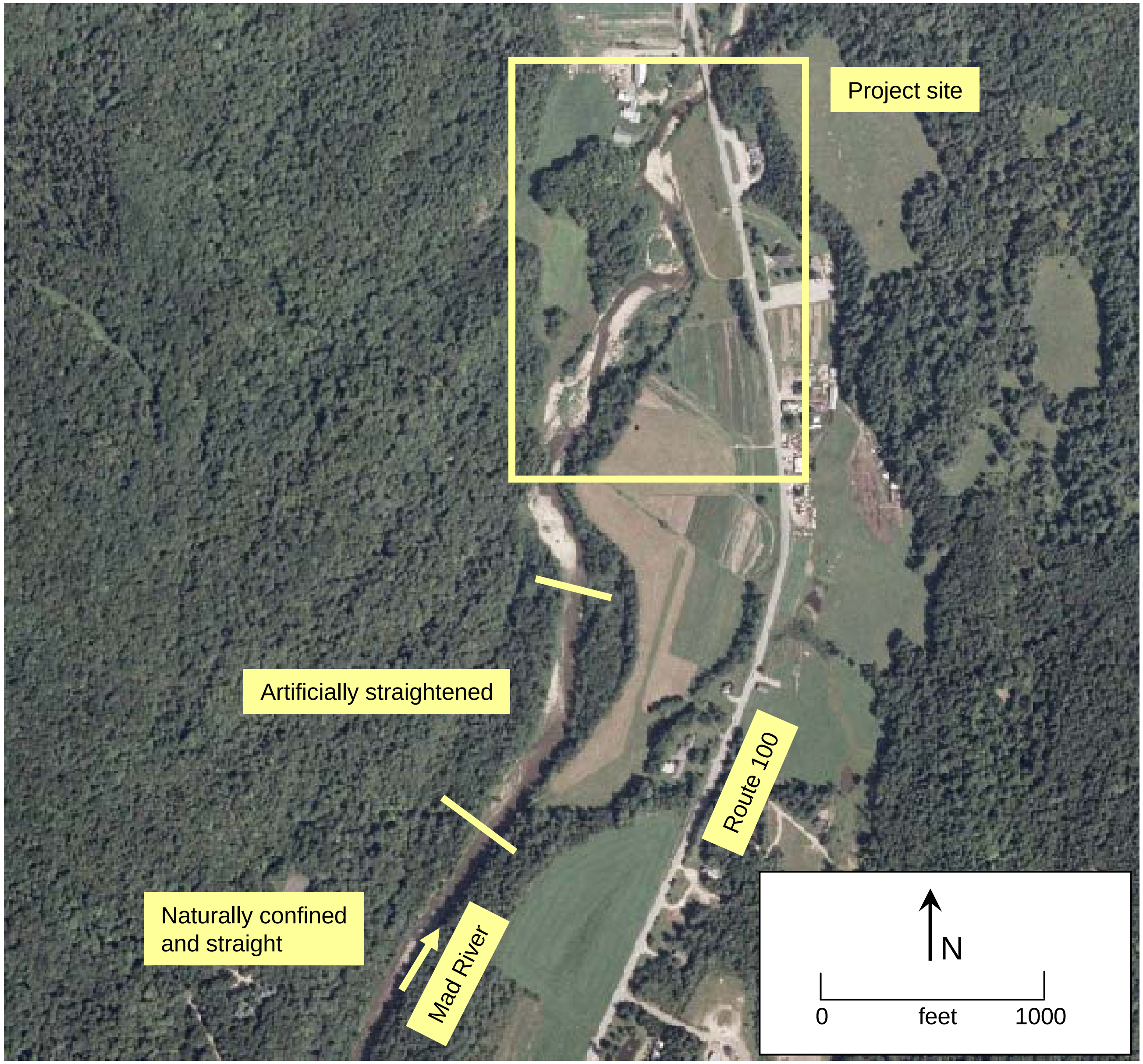

Figure 27. Aerial photograph of Mad River in Reach M13 showing location of project reach in relation to artificially straightened area upstream. Box around project site is roughly the area shown in Figure 28.

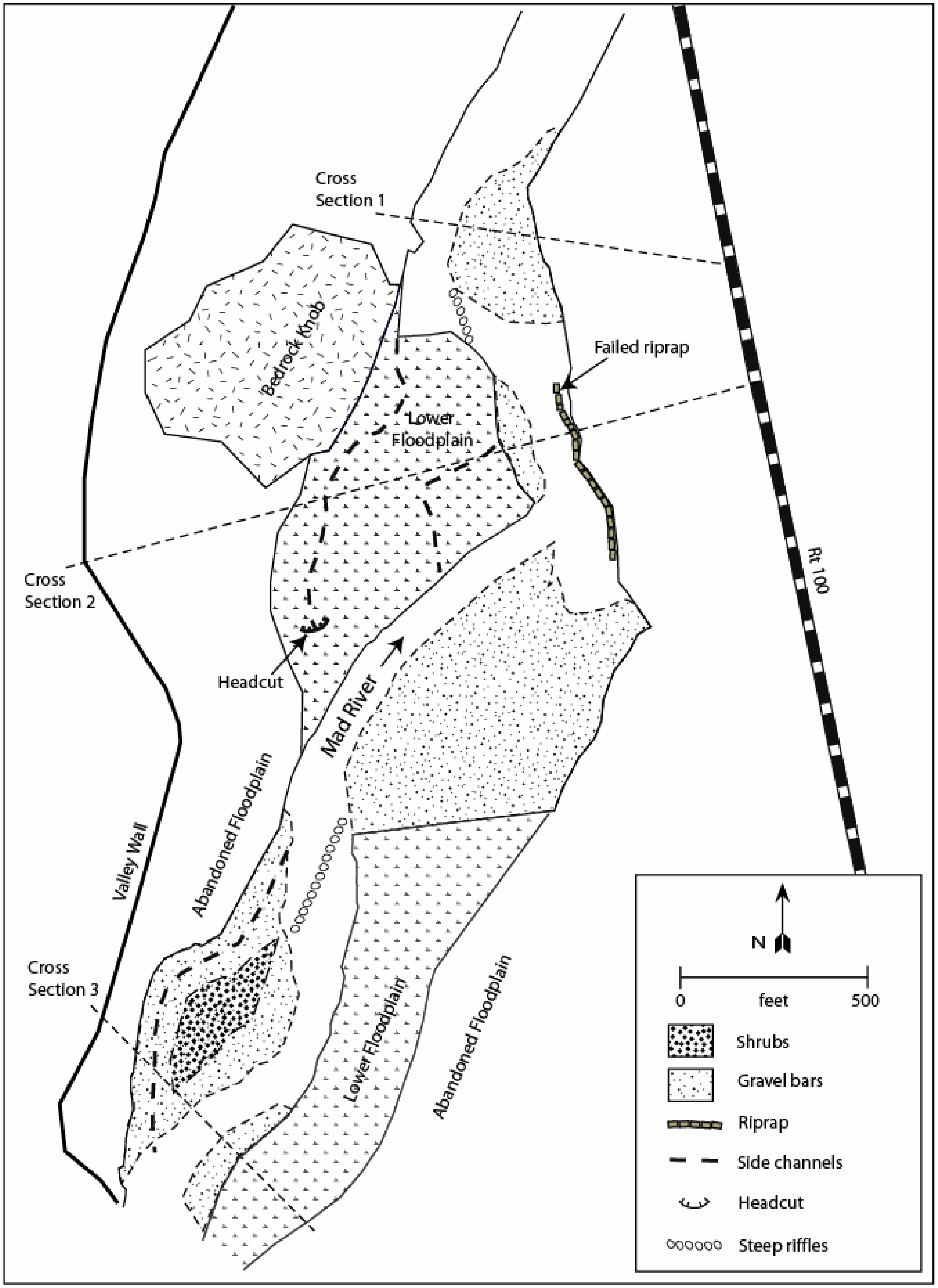

Figure 28. Plan view of project site. Failed riprap is shown in Figure 34.

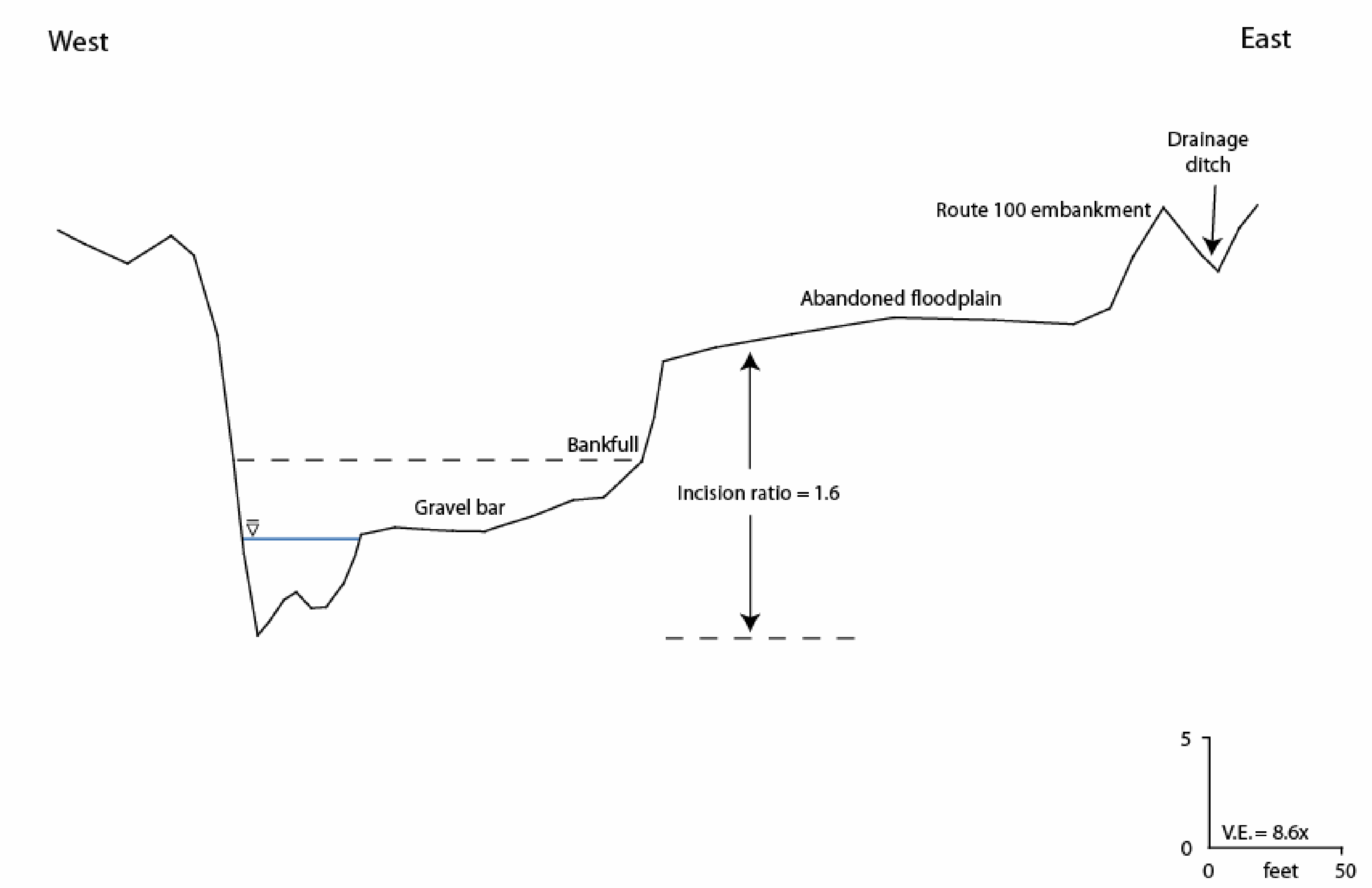

Figure 29. Cross Section 1 as shown on Figure 2 illustrating channel incision typical of Reach M13 and formation of gravel bars where widening has occurred.

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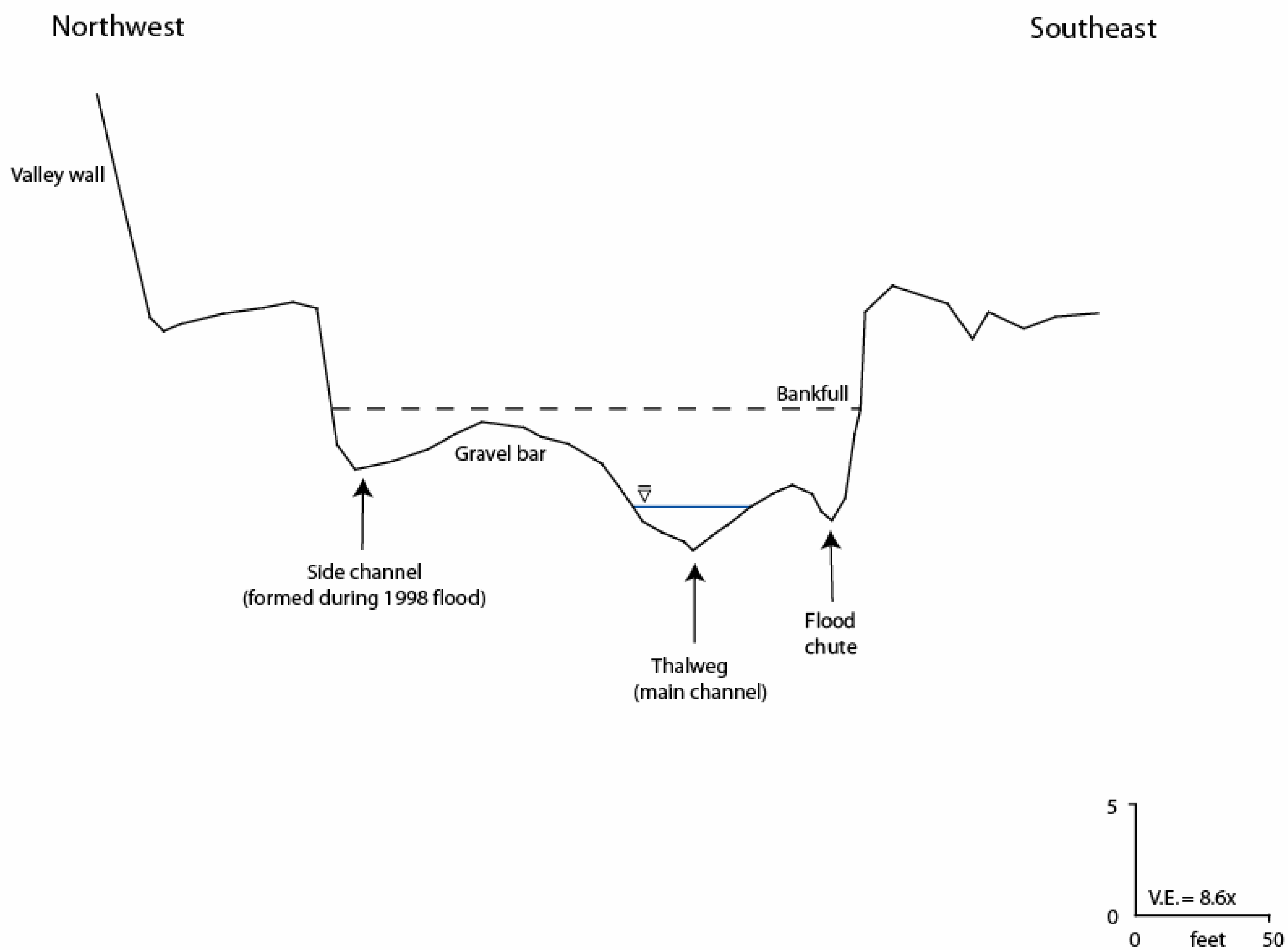

Figure 30. Cross Section 3 as shown on Figure 28 with side channel formed during 1998 flood.

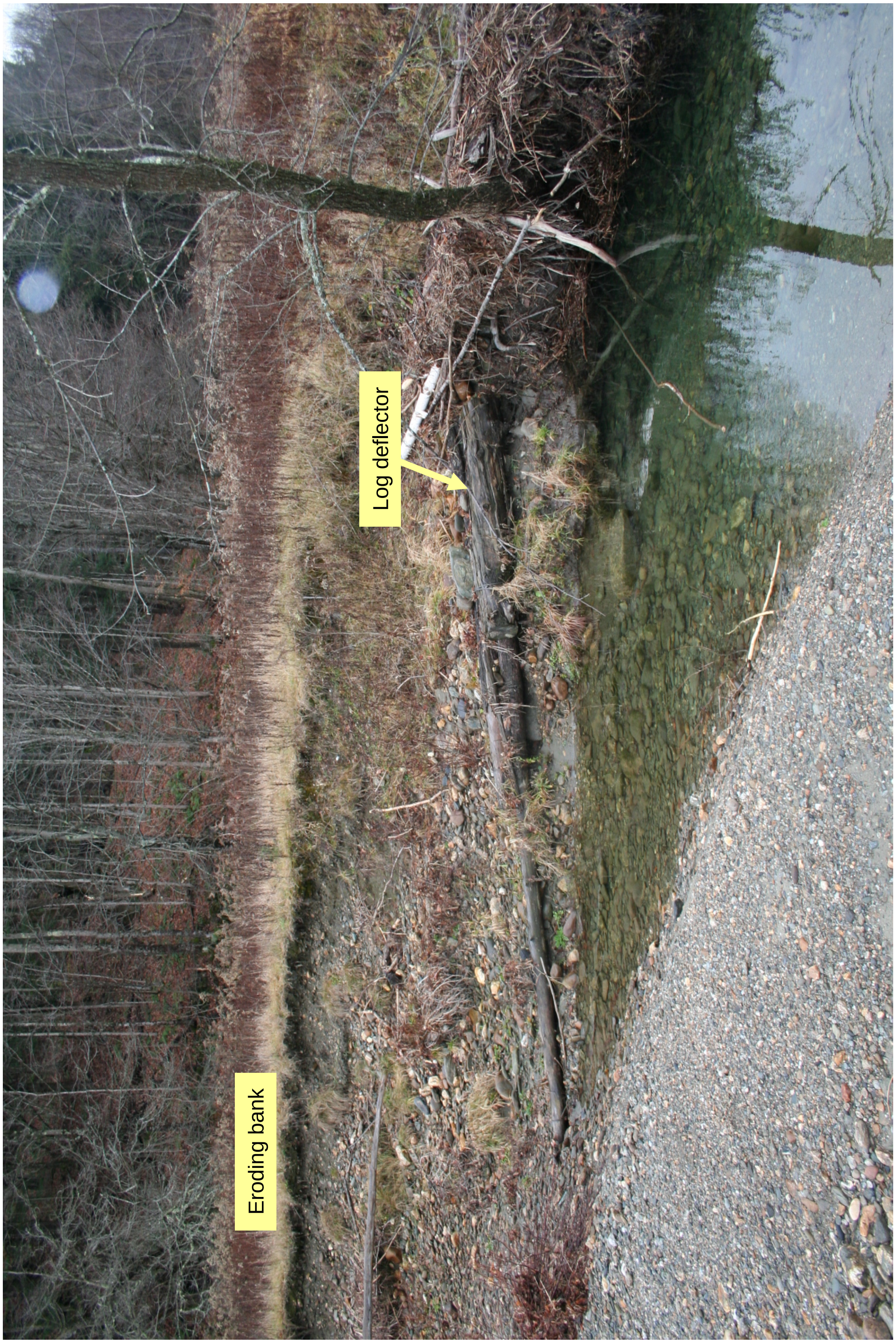

Figure 31. Remaining log deflector along eroding bank of meander and still active side channel created during 1998 flood.

Mad River Geomorphic Assessment – Figure 31

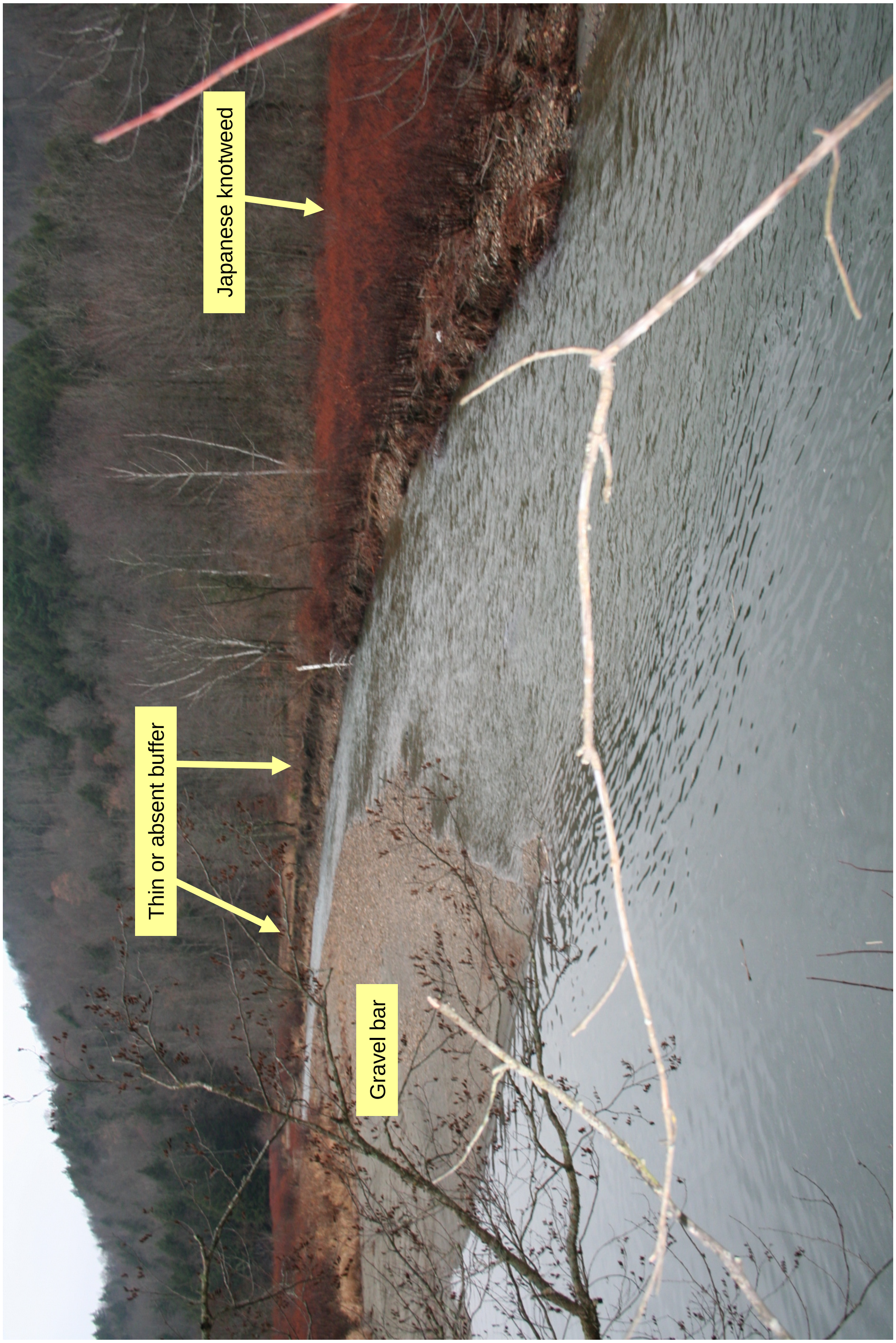

Figure 32. Large gravel bars forming where channel widens along area with thin or absent buffer. Japanese knotweed (red color) is predominate vegetation colonizing gravel bars. Looking upstream from area of riprap shown on Figure 28.

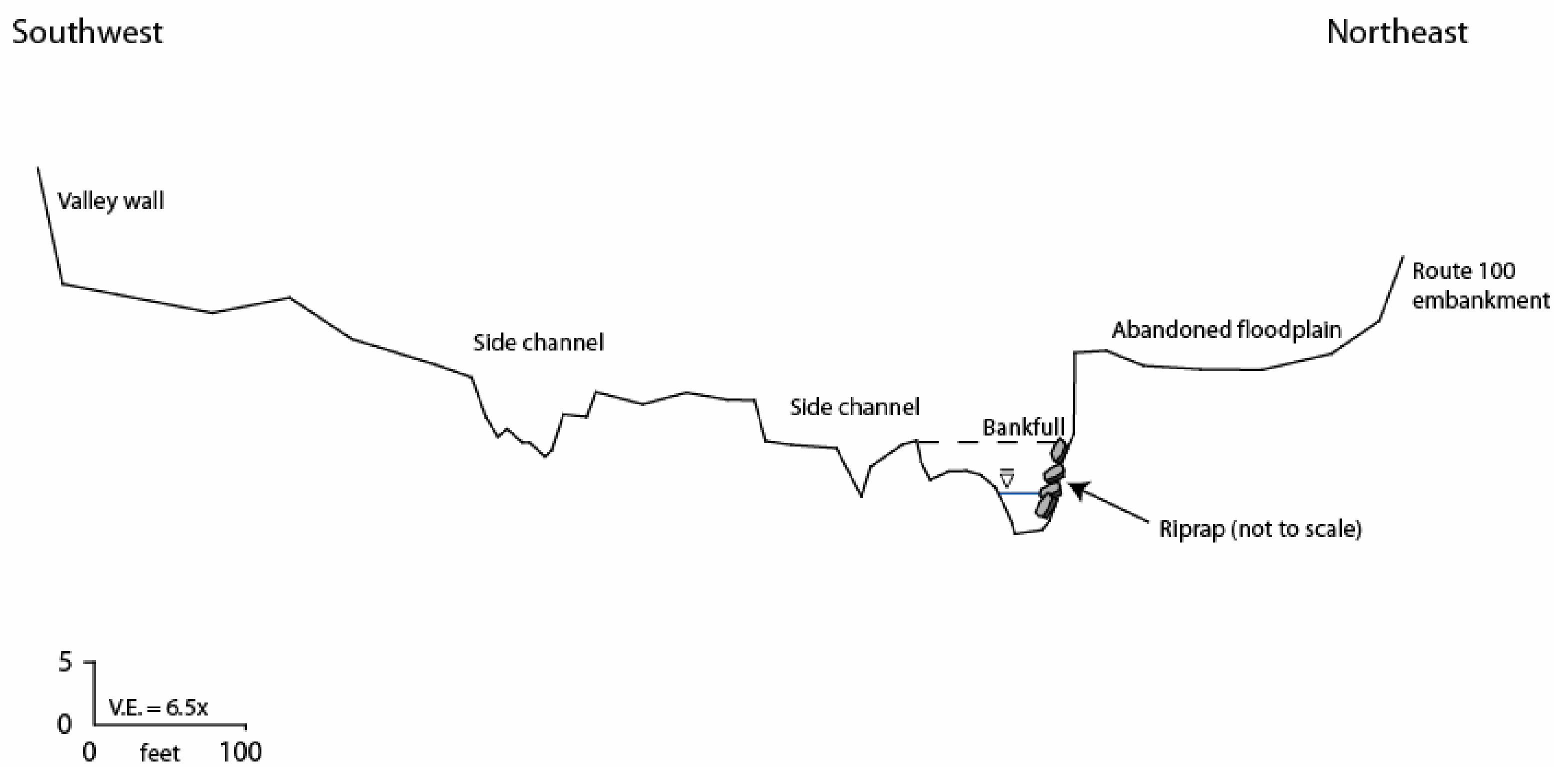

Figure 33. Cross Section 2 as shown on Figure 28 with multiple side channels at varying heights and occupied at different flow stages. The higher side channel further to the southwest is the one discussed under Option 3 in text.

Figure 34. Failed riprap that was previously lining the bank but is now in the river as the bank continued to recede behind it. Location of riprap shown in Figure 28.

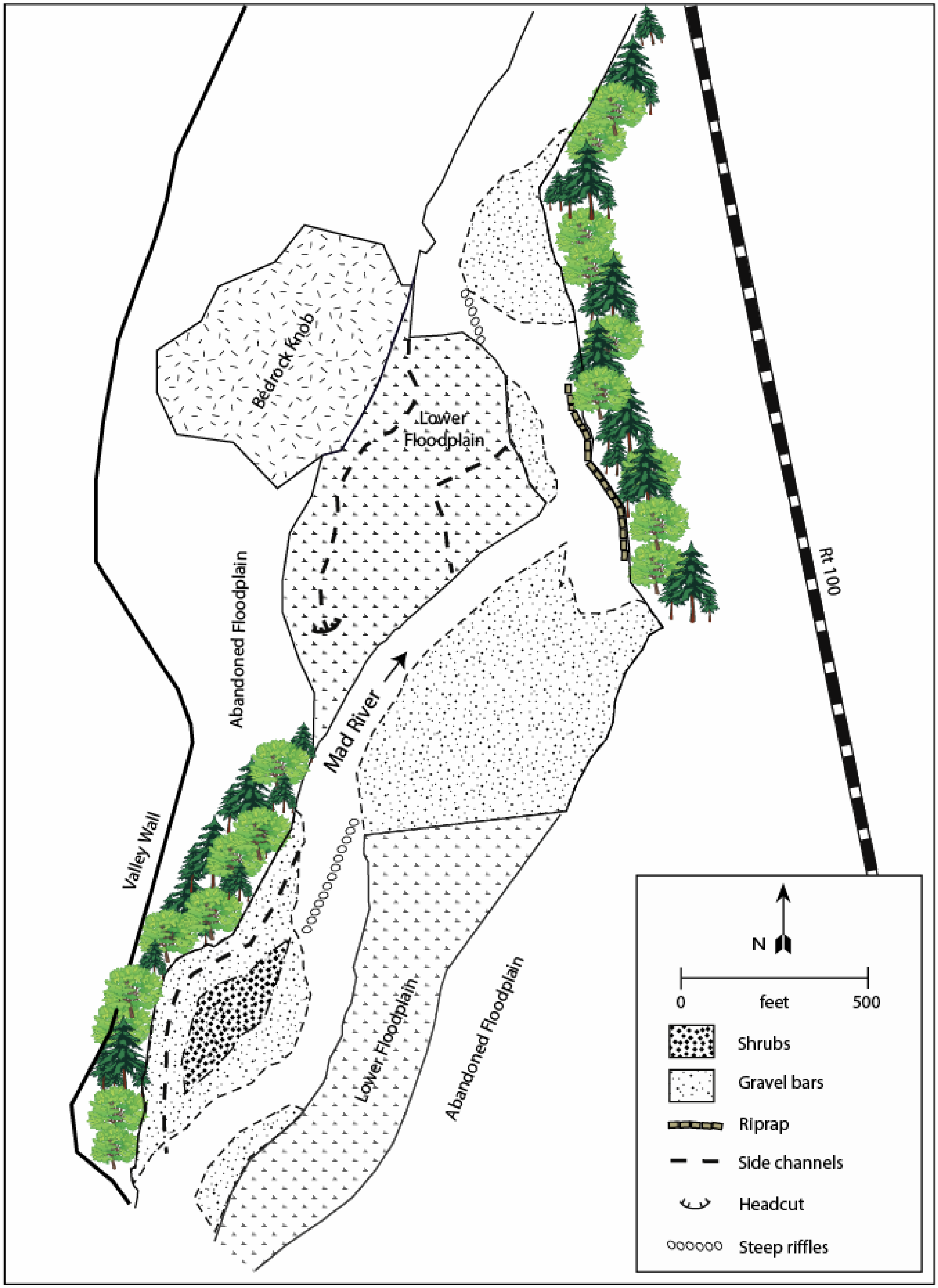

Figure 35. Plan view of riparian buffer planting option. Note that no action is taken within the channel. Trees not to scale.

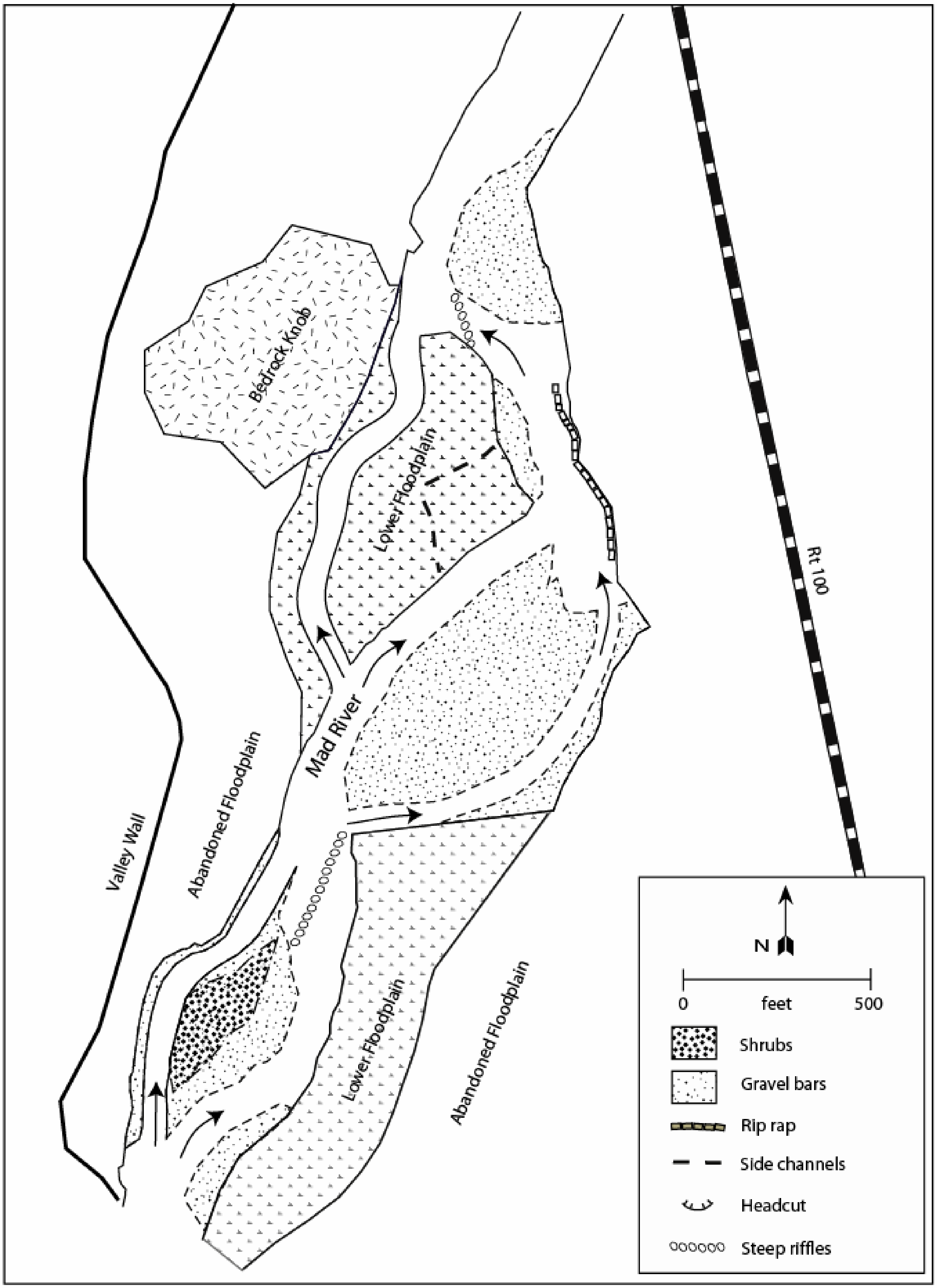

Figure 36. Plan view of increasing sediment attenuation option described in text. Arrows show direction of flow into connected side channels.

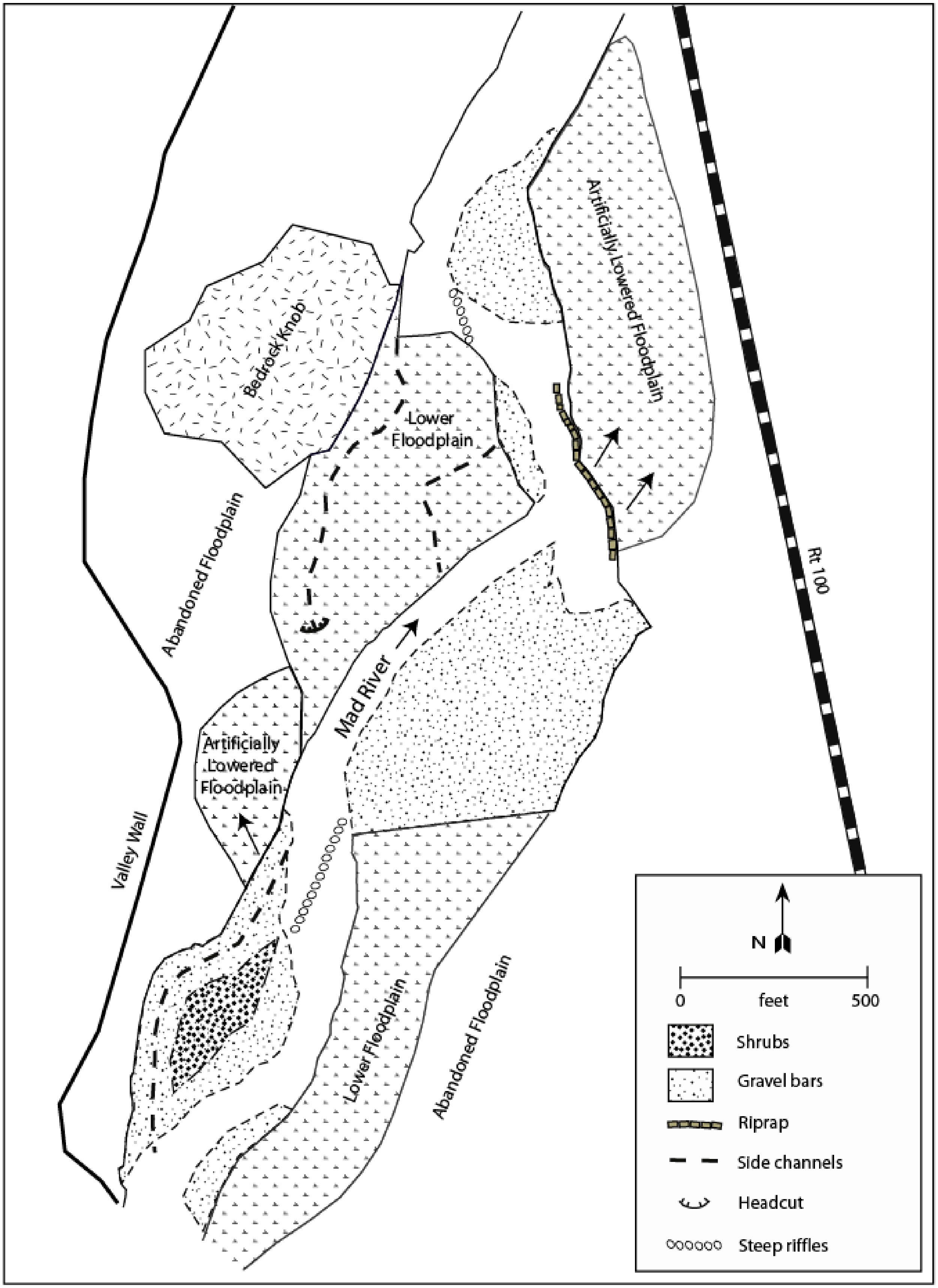

Figure 37. Plan view of increasing floodplain storage option described in text.

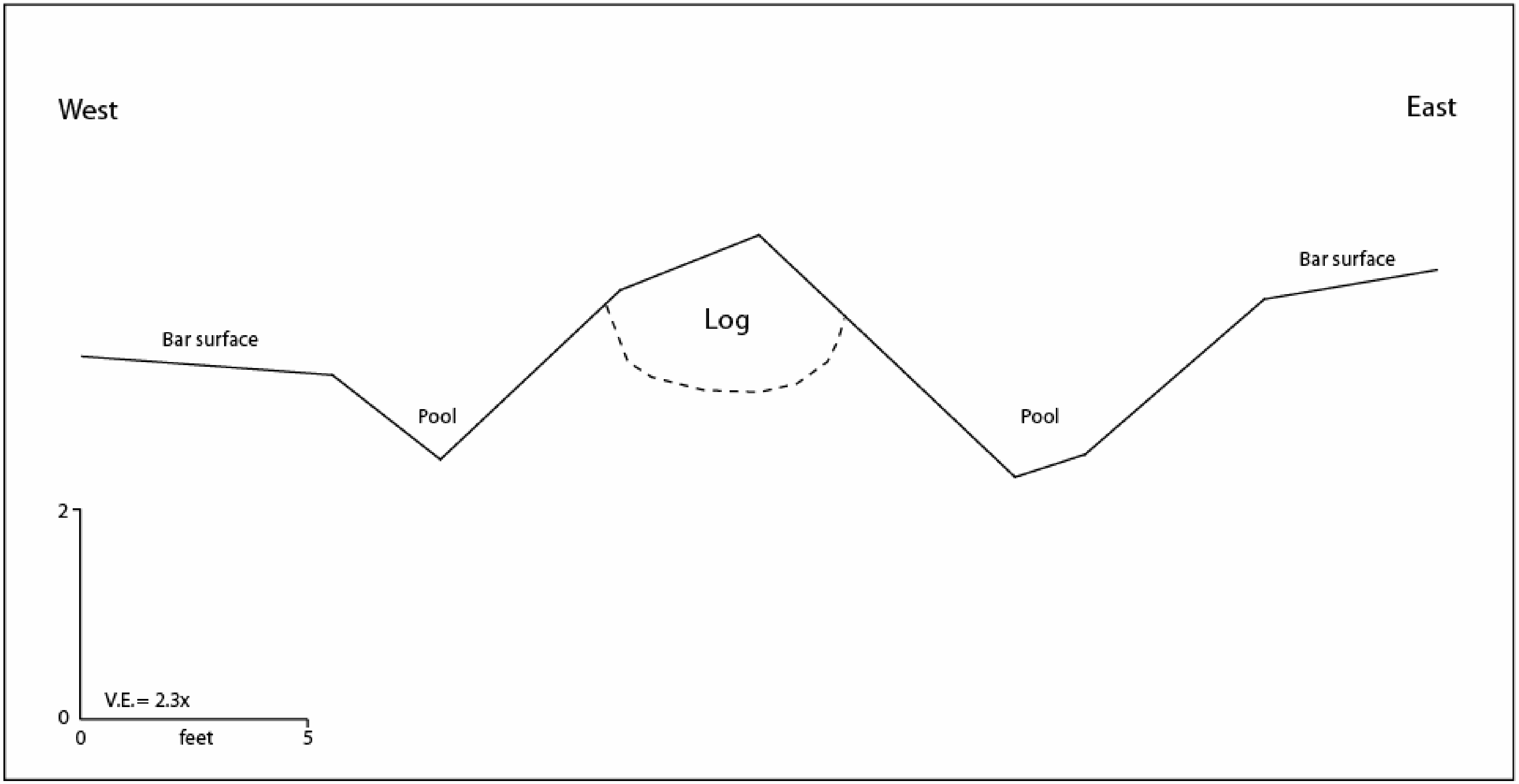

Figure 38. Cross section just downstream of root wad of log visible in Figure 24 showing pool formation resulting from scour around root wad.

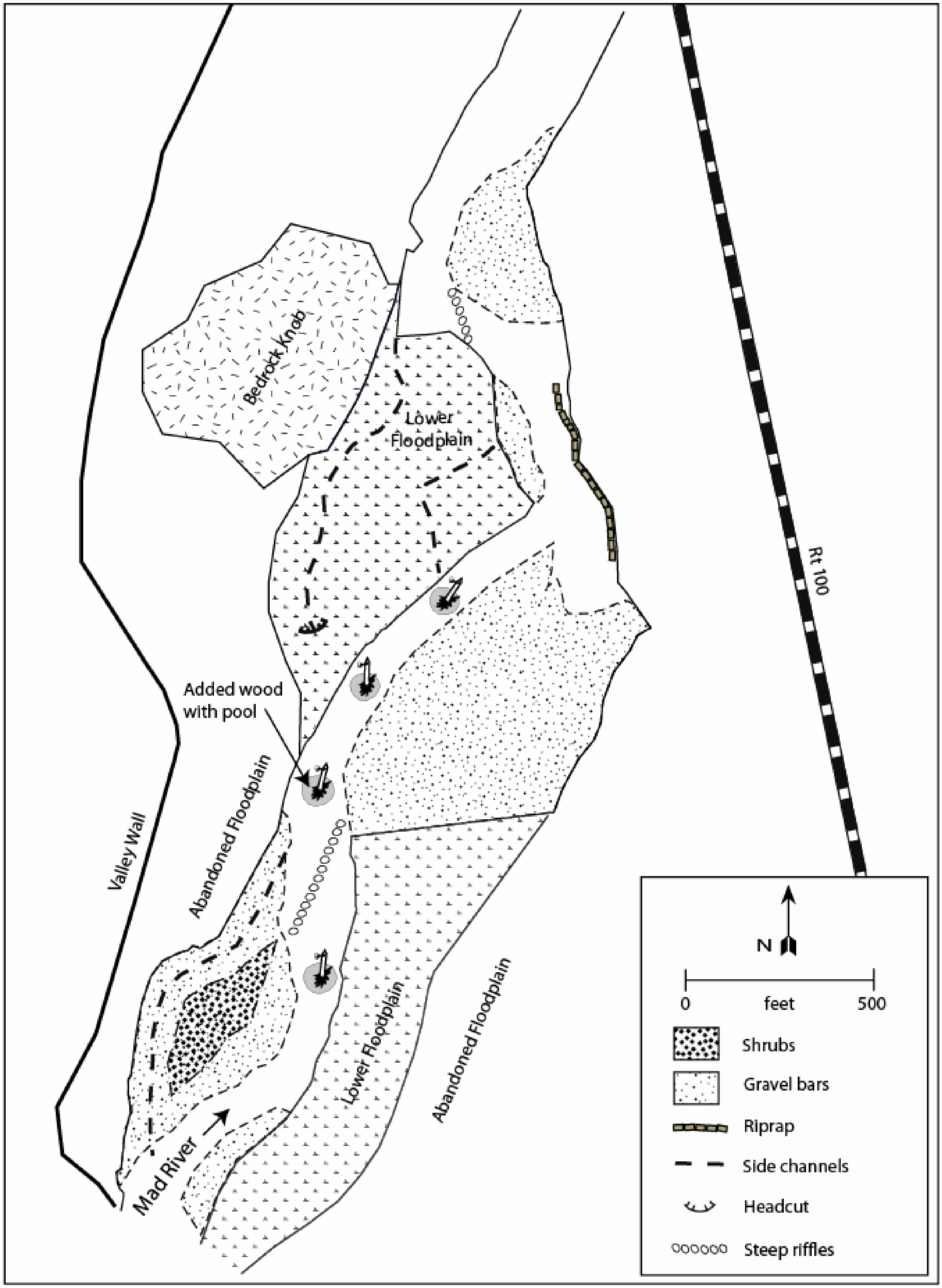

Figure 39. Plan view of addition of woody debris option described in text. Pools can be excavated with placement of wood or can be expected to form naturally with high flows. Logs and pools not shown to scale.

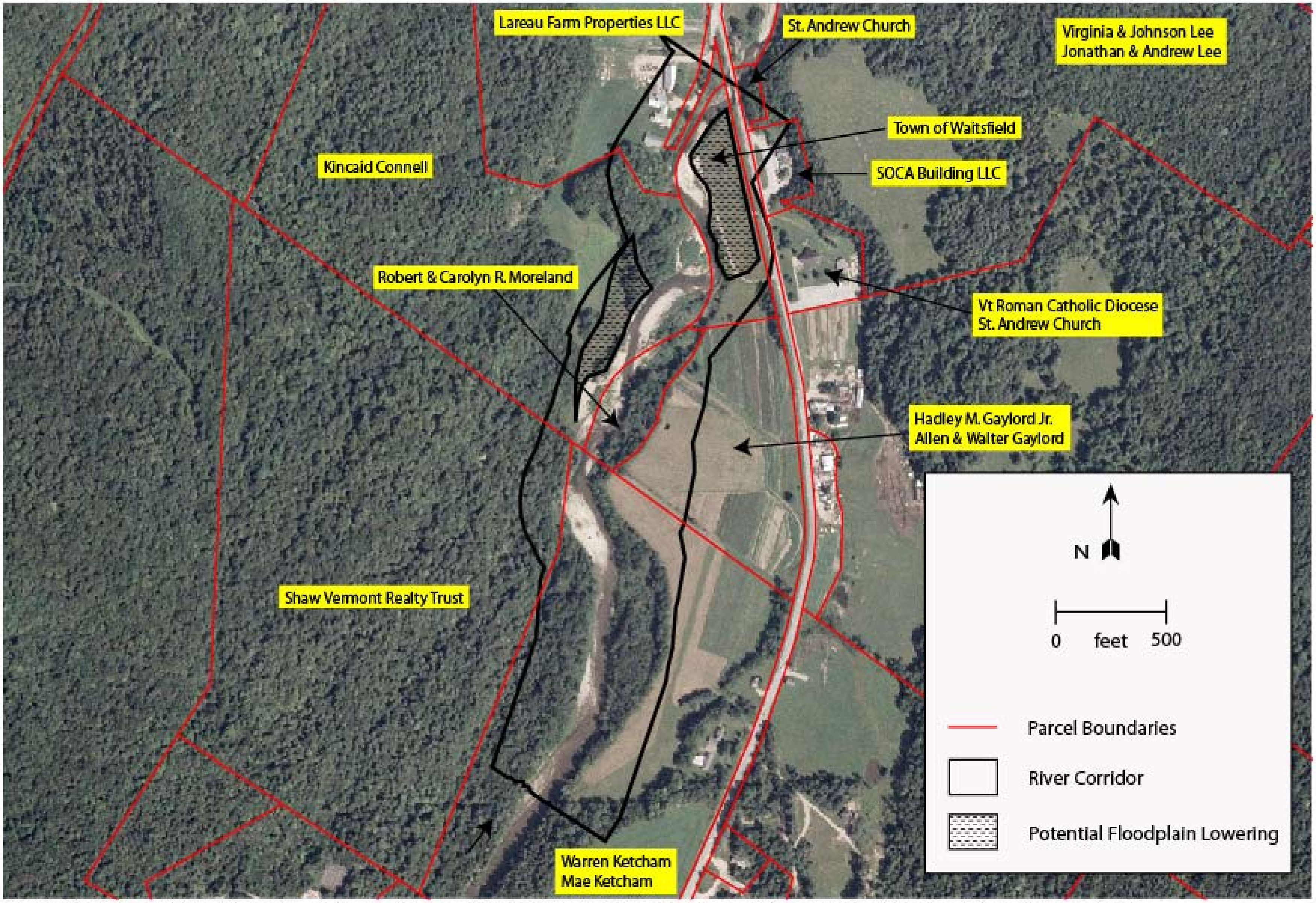

Figure 40. River corridor with land parcel boundaries and landownwers in Reach M13. Possible locations of floodplain lowering are shown.

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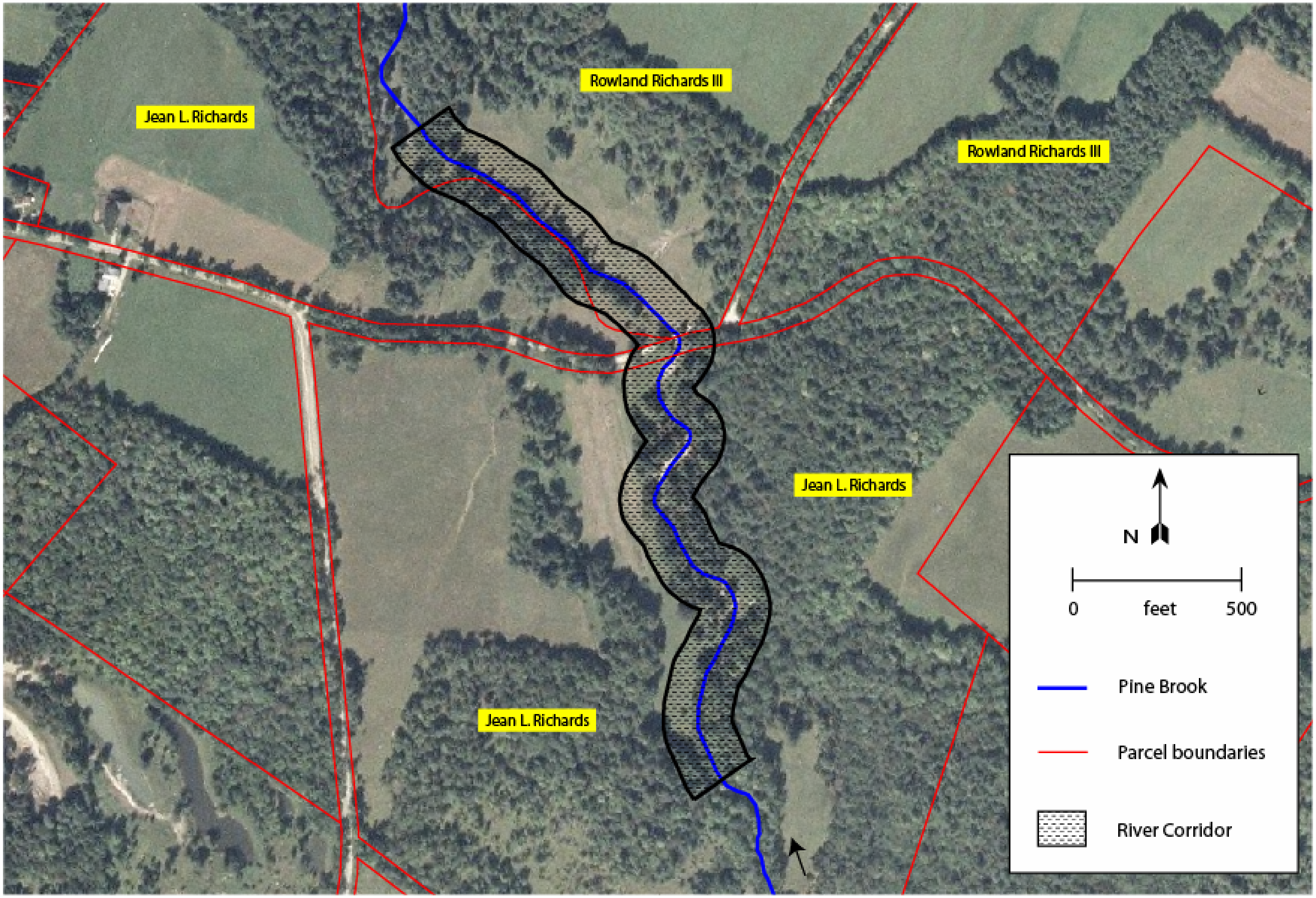

Figure 41: River corridor with land parcel boundaries and landowners in Segment T5.02-B on Pine Brook.

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Mad River Geomorphic Assessment - Figure 41