River Corridor Planning on the Batten Kill, Vermont

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Executive Summary

Phase 1 and Phase 2 Geomorphic Assessment data of the Batten Kill watershed were used to develop a river corridor plan. Past human land use and river management practices in the watershed have created numerous channel instabilities that have degraded habitat and created flood and erosion hazards that place property and lives at risk. Several restoration activities have been prioritized to effectively manage the river towards equilibrium and ultimately mitigate flood and erosion hazards, reduce nutrient and sediment loading, and improve aquatic habitat throughout the watershed.

More than 40 percent of the Batten Kill mainstem was straightened more than 80 years ago. The increased channel gradient created by these actions has resulted in channel incision with excess stream power transferred downstream. Consequently, bridge constrictions and other areas where transport capacity is rapidly reduced are particularly sensitive to aggradation and bank erosion. The straightened reaches are prone to avulsions, whereby the position of the channel can rapidly shift and new meanders created across the floodplain. The timing, scale, and magnitude of these flood processes are unpredictable and potentially dangerous if occurring near human developments. Exacerbating instabilities on the mainstem is the presence of berms built along several Green Mountain tributaries following a large flood in 1973. The berms block access to alluvial fan surfaces at the lower ends of the tributaries and, therefore, excess flow energy and sediment are transferred to the mainstem. The bermed and confined tributary channels have been unable to regain equilibrium or reestablish aquatic habitat complexity since the 1973 flood, because flow energy is focused on the channel bed rather than dissipated across the fan surface. While the berms have been breached in a couple of localities, the potential for future breaches near developed areas presents a potential safety hazard during a future large flood.

Several restoration activities could be employed in the Batten Kill watershed to more evenly distribute sediment and flow energy and reestablish equilibrium conditions. Localized efforts to stabilize banks or create cover habitat are unlikely to be sustainable if the sediment and hydrologic stressors created by channel straightening, berming, and bank armoring are not addressed at the greater reach and watershed levels. River corridor protection efforts can be used to prevent future activities such as channelization and armoring that would prevent the natural evolution of the channel back to an equilibrium condition. Particularly high priority areas for protection are attenuation assets where meanders along straightened channels have already reformed or ample space exists to encourage additional meanders to form in the future. The increased flow path along the meander leads to deposition, reconnection of incised channels to the floodplain, and improved habitat as a greater complexity of flow velocities and flow depths are encountered.

More active restoration activities can be employed to accelerate the reestablishment of equilibrium conditions. The highest priority activity in the watershed from a technical standpoint is the removal of berms. Providing access to the alluvial fan surfaces on the lower tributaries would reduce the risk of unpredictable breaches of the berms in developed areas, while simultaneously improving habitat and reducing sediment loading downstream. Consequently, berm removal would not only improve conditions on the tributaries but will also be important for creating equilibrium conditions on the mainstem. However, before these and other active restoration activities are implemented, numerous stakeholders with varied, and sometimes conflicting interests, must be educated to the multiple and sustainable benefits that can be accrued when adopting strategies that manage towards equilibrium.

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1.0 INTRODUCTION

Between 2000-2005, a Phase 1 Assessment was conducted on all 71 reaches of the Batten Kill Watershed with a Phase 2 Assessment completed on the 13 mainstem reaches and on a total of 17 reaches covering the lower portions of nine major tributaries (Figure 1). These earlier assessment efforts identified extensive berming on several tributaries and channel straightening on the mainstem as the primary causes for channel instability and degraded physical habitat in the watershed. The continuing channel adjustments related to these past management activities are complicating efforts to restore depleted brown trout (*Salmo trutta*) populations.

To identify the best management strategies for restoring channel equilibrium and realizing sustainable habitat improvements, a river corridor planning effort, reported on here, was undertaken. Restoration projects that are completed in isolation and merely resolve an immediate conflict (e.g., an eroding bank, improve cover habitat) have the potential to generate further instabilities in adjacent reaches and often need long term maintenance. By completing the corridor planning process, projects can be identified that have a greater likelihood of success, because they recognize and address channel instabilities and constraints present within the entire watershed. River corridor planning consists of four parts: 1) identify the human stressors at the watershed and reach scale that are potentially altering the hydrologic and sediment inputs to the river channel; 2) determine the natural and human constraints within the river corridor that prevent sediment transport or attenuation; 3) prioritize restoration or conservation projects that are consistent with the development of equilibrium conditions; and 4) assess the technical and social feasibility of project implementation. The outcome of the planning process is a prioritized list of restoration projects for the watershed that will return the river to an equilibrium condition and, by so doing, will achieve the following three objectives: 1) mitigate erosion and flood hazards; 2) reduce sediment and nutrient loading; and 3) improve aquatic and riparian habitat. After a brief summary of geomorphic conditions in the Batten Kill watershed, the following report describes the corridor planning process and concludes with a discussion of the highest priority projects and the feasibility of their implementation.

2.0 GEOMORPHIC CONDITIONS

The Batten Kill watershed within Vermont has a drainage area of 200 mi^2 (Figure 1), although the river continues into New York where it ultimately flows into the Hudson River. Within Vermont, the focus of the current and earlier geomorphic studies, the Batten Kill flows for most of its length in a broad valley between the Green Mountains to the east and Taconic Mountains to the west. Sediment production is high from most Green Mountain tributaries (e.g., Mad Tom Brook, Bourne Brook, Lye Brook, Roaring Branch) with large alluvial fans developed where the streams flow onto the valley bottom. Tributaries draining the Taconic Mountains have lower rates of sediment production as bedrock controls are more prevalent (e.g., West River, Munson Brook). The Green River is an exception, since the large alluvial fan at its terminus is more similar to the Green Mountain tributaries.

Severe flooding and deposition in 1973 led to extensive berming on the Green Mountain tributaries (Figure 2). Earlier episodes of berming are evident on some of the tributaries, perhaps in response to severe flooding in the 1930's (Figure 2). After passage of the flood and subsequent berming in 1973, the channels were overwidened with respect to the natural reference condition, so deposition has ensued over the past 30 years as the channel returns closer to the expected equilibrium dimensions (Figure 3). However, stream power in the channel remains higher than under reference conditions during larger flows, because floodwaters remain confined by the berms. Consequently, the emerging gravel bars cannot become revegetated, channel evolution cannot be fully completed, and sediment delivery to the mainstem remains high.

The Batten Kill mainstem was extensively straightened over 80 years ago. In response to the straightening and resulting increased gradient, the river channel has become wide, shallow, and slightly to moderately incised with a plane bed morphology. While largely unchanging during low to moderate flows, the straightened channels are regaining sinuosity during large floods when debris blocks the channel and flow “breaks out” onto the floodplain with sufficient force to scour a new meander bend into the floodplain surface (Figure 4). Habitat conditions are improved in these areas of flow, sediment, and energy attenuation as evidenced by better particle size segregation, multiple velocity patterns, and deeper pools.

3.0 HUMAN STRESSORS

Stream channel adjustments that result in a departure from equilibrium conditions are caused by significant watershed-scale changes in water, sediment, and debris (i.e., wood) inputs into the channel or by changes at the reach-scale that alter the river’s ability to transfer water, sediment, or debris delivered to the channel. A stream channel in equilibrium is capable of transporting water, sediment, and debris through the river system with minimal changes in the channel’s dimension (i.e., width and depth), pattern (i.e., sinuosity), and profile (i.e., gradient). When watershed inputs change, a new equilibrium condition is achieved through mutual adjustments in the channel’s dimension, pattern, and profile until the most efficient morphology is developed for transporting the water, sediment, and debris inputs. Significant watershed or reach-scale alterations are generally associated with more dramatic channel adjustments, although certain channels are more sensitive to change than others depending on boundary conditions (i.e., bank resistance) and other factors.

The first step of the corridor planning process is to identify human stressors present in the watershed that might be causing channel adjustments and departure from the equilibrium, or reference, conditions. While natural alterations to the watershed might result in stream channel adjustments over longer time scales (e.g., climate change), human-caused stressors are of primary concern from a river management perspective, because they are generally the cause of active or recent channel adjustments that are responsible for increased flood and erosion hazards, higher sediment and nutrient delivery, and severe habitat degradation. Several human land uses and activities, at both the watershed and reach scale, are capable of inducing stream channel adjustments due to changes in hydrologic and sediment regimes. The identification and mapping of these conditions are necessary to accurately determine what might be causing ongoing or future channel adjustments. The watershed and reach scale human stressors in the Batten Kill that are most likely leading to changes in the hydrologic and sediment regimes are discussed below.

3.1 Hydrologic Regime Stressors

The hydrologic regime is characterized by not only the input of water from the watershed (i.e., rainfall runoff) but also manipulations of the runoff (e.g., dams) that alter the amount of water entering the channel. While quantitative measurements of hydrologic changes are difficult to make, a number of human activities are known to modify the timing, volume, and duration of flows such as urbanization, storm water discharge, dams, and road networks. Compared to other areas of Vermont, the hydrologic regime in the Batten Kill watershed is not significantly altered with only a few reaches or subwatersheds showing any significant change to the hydrologic regime (Table 1). (A subwatershed is the drainage area upstream of a given geomorphic reach break that is not part of other subwatersheds further upstream). Urban land use is locally significant in and around Manchester and Arlington such that the total percentage of urbanized land use in 6 subwatersheds exceeds 5 percent (Figure 5a). The Vermont River Management Program considers urbanized land use between 5 and 10 percent to have a significant impact on the hydrologic regime within the subwatershed in which the development occurs. Given that only 6 relatively small and widely separated subwatersheds have a significant impact rating, the cumulative impact on the Batten Kill as a whole should be considered minimal, although localized impacts could be present in areas of the densest urban development. Furthermore, a channel response could be initiated if continued development within these subwatersheds reaches a threshold level (of 10 percent urbanized area) and leads to a greater impact on the hydrologic regime. No storm water inputs have been mapped along the Batten Kill or its tributaries, but localized concentrations of runoff might be present near roadways and other paved surfaces that approach stream channels within the urbanized areas.

Dams have the potential to impound water upstream and release water downstream at a rate slower than is entering the impoundment. Dam operations such as this result in decreases in peak flows downstream. While one dam does exist on the Batten Kill mainstem in Manchester (i.e., Dufresne Pond), it is a “run of the river” dam, meaning that the discharge entering the impoundment equals the discharge flowing downstream. A dam on Mill Brook in Arlington (the only other dam identified during the Phase 2 Assessment) is also a “run of the river” structure. While several other dams were previously present in the watershed, including the mainstem, these have washed out during floods or otherwise been dismantled. The existing as well as past structures were primarily built for powering mills and were never used for controlling floods. Consequently, impacts to the hydrological regime resulting from the presence of dams in the Batten Kill watershed are insignificant.

Discharge from wetlands generally occurs at a rate slower than the inflow of runoff, so wetlands tend to decrease the rate of hydrologic inputs downstream. The loss of wetlands to urban development and agricultural cropland can, therefore, cause an increase in peak discharges. Significant wetland loss has been experienced in the Batten Kill watershed on the valley bottom between Manchester and Arlington (Reaches M5-M8) along the floodplain (Figure 5a) where agricultural land is now present on wetland soils. Wetlands are still largely intact in Reach M12, while elsewhere in the watershed wetlands were probably never a very significant component of the landscape. Although increased peak flows have probably resulted downstream of Reaches M5-M8, the conversion of the wetlands probably occurred over 100 years ago and channel adjustments resulting from this change in the hydrologic regime are likely already complete.

Dense road networks, drainage ditches, and skid trails can concentrate runoff and increase peak discharges in river channels. While difficult to characterize many of these features with existing data, a very low density of mapped roads is present in the Batten Kill watershed (Figure 5b). Therefore, roads and ditches are not considered to significantly alter hydrologic conditions in the Batten Kill watershed.

Although difficult to quantify, the greatest impact on the hydrologic regime in the Batten Kill watershed is related to the extensive deforestation that occurred over 100 years ago (Figure 6). The loss of interception and evapotranspiration afforded by the tree cover likely resulted in significant increases in runoff to the river channel. With subsequent reforestation over most of the watershed during the past several decades, runoff has declined and returned closer to the natural condition. This watershed wide decline in runoff probably offsets localized reach-scale increases in flow related to urbanization, wetland loss, and road networks (Table 1).

3.2 Sediment Regime Stressors

Changes in the amount of sediment delivered to a stream reach or in the capacity to transport sediment through that reach can lead to either channel aggradation or degradation depending on the changes encountered. For example, increases in sediment delivery will lead to aggradation or a build up of sediment on the channel bed. The resulting increase in channel slope leads to greater transport capacity that brings the channel into equilibrium with the higher sediment loads. Identifying potential sediment sources (or lack of sources) in the watershed and activities that might alter the stream's transport capacity are critical for anticipating the type and location of active and future channel adjustments in the watershed. Erosion occurs naturally along streams in equilibrium, but increased sediment loads can engender significant channel adjustments, sometimes, paradoxically, in response to efforts designed to stop natural levels of erosion.

3.2a Watershed-Scale Erosion

Erosion anywhere in the watershed represents a potential source of sediment to the river channel. A concentration of erosion areas is observed in the highly sinuous section of the Batten Kill (Reaches M5-M8), whereas relatively little bank erosion is recorded elsewhere (Figure 7). Two mass wasting sites on the mainstem, although relatively short in length, may, at times, introduce great quantities of sediment into the river given their height (Figures 7 and 8). The relatively few identified erosion and mass wasting sites shown on Figure 7 is misleading in regards to the actual sediment stressors that are likely present in the watershed. The upper reaches of the assessed tributaries as well as several smaller tributaries (e.g., Benedict Hollow, Little Mad Tom Brook) were not assessed, although numerous sediment sources must be present in these steeper mountainous portions of the watershed. Furthermore, many erosion sites are exposed during large floods and then slowly heal during the intervening years with only small to moderate discharge events. Consequently, many potential erosion sites are currently masked by vegetation, but could become reactivated during a severe storm when they might supply large volumes of sediment to the river channel.

Deforestation in the watershed over a century ago exposed much of the watershed to erosion and dramatically increased sediment delivery to the valley bottom. At least 3.0 feet of post-European settlement deposits are exposed along the banks of Mad Tom Brook (Figure 9; Reach T7.01) with similar light brown sediments above a dark organic-rich A-horizon likely present elsewhere on the valley bottom. While more recent reforestation of the watershed has reduced sediment delivery considerably, sediment supply likely remains higher than prior to land clearance. Many areas of the valley bottom remain cleared for agriculture. Since much of this land is used for pasture and hay, sediment supply is lower than would be expected if more croplands, with bare soils exposed for portions of the year, were present. Only 3 subwatersheds have croplands occupying between 3 and 5 percent of the total area and 7 others have between 1 and 3 percent (Figure 7).

Sediment supplied from croplands is considered insignificant compared to what is supplied from the upper watershed via the tributaries, although the croplands may increase the supply of fine silts and clay. While quantifying tributary inputs is difficult, the delivery of that sediment to the mainstem is evident from the numerous gravel bars found at the lower ends of tributaries (Figure 3), delta bars at the confluence with the mainstem (Figure 8), and mid-channel bars just downstream. As a result, the frequency of gravel bars in each reach is higher near tributary confluences (Figure 7).

Some sediment storage has occurred behind dams, but given the relatively small size and number of these dams the total volume of sediment storage is insignificant compared to total sediment delivery. The impounded areas behind existing dams are nearly filled with sediment, so minimal storage potential remains behind these dams. Therefore, changes to the sediment regime in the Batten Kill watershed due to the presence of dams is considered insignificant.

Overall, sediment supply in the watershed is currently greater than prior to European settlement. Reforestation has likely reduced sediment supply compared to conditions at the height of land clearance activities approximately 150 years ago. This overall reduction is periodically punctuated by large surges in sediment supply during extreme flood events when areas not yet fully stabilized from earlier land clearance are reactivated. Additional sediment is also likely generated during large floods as channel adjustments related to previous channel straightening and berming are rejuvenated. Table 1 details, by reach, the types of sediment load stressors present in the watershed, but does not include the numerous unassessed reaches in the upper watershed.

3.2b Reach-Scale Sediment Regime Stressors

Perhaps a more significant alteration to the sediment regime than changes in sediment supply is the change in sediment transport capacity that has occurred along the river channel and its tributaries. Past river management practices have largely increased the stream power and transport capacity of the stream in order to more efficiently transfer sediment and floodwaters through the watershed. These activities have included extensive berming along the tributaries (Figure 2) and channelization on the mainstem with more than 40 percent of the Batten Kill having been straightened (Figures 4 and 10; Table 1). Gravel mining was also regularly conducted until the 1980’s on the Batten Kill between the Roaring Branch confluence and the Route 313 Bridge (Figure 10; Reach M3). While the purpose of these management practices was to reduce or remove accumulating gravels to accommodate private investments and public infrastructure, a series of unintended channel adjustments have ensued that have caused stream channel departures from the preexisting equilibrium conditions (i.e., changing alluvial fans from depositional reaches to transport reaches). Increasing the efficiency of sediment transport by berming and straightening of the channel leads to excess sediment accumulation in downstream areas where transport capacity is reduced; sediment is more evenly distributed when a stream is in equilibrium. Upsetting the equilibrium condition through channelization often leads to a sequence of channel adjustments that impact downstream reaches due to increased sediment supply (Brookes, 1985). Ultimately, the resulting incision and widening render the benefits accrued by channelization unsustainable at the site while transferring the erosion and flooding problems trying to be addressed to downstream reaches.

Past river management on Roaring Branch and downstream of its confluence on the Batten Kill exemplifies many of the issues that arise when the sediment regime is altered by increases in slope (i.e., straightening) and flow depth (i.e., berming)(Figure 11). Berming on Roaring Branch has transferred flow energy and sediment downstream where the excess energy impinges on a high bank across from the confluence and has led to the creation of a large mass failure (Figure 8). The channel straightening downstream of the confluence effectively moves sediment from the mass failure and Roaring Branch except in areas where the sediment transport capacity is rapidly reduced. Sediment accumulation is observed behind nearly every bridge constriction downstream of Roaring Branch, because of the backwatering of floodwaters that occurs (Figures 10-11). The most dramatic example is behind the West Mountain Bridge on River Road just west of Arlington where deposition has led to the creation of a meander as the river flows around the emerging gravel bar; the breaching of a dam immediately upstream during the 1973 flood has likely supplied additional sediment to enhance the channel adjustments at this location (Figure 12). Gravel deposition, channel avulsions, and the recreation of meanders have also occurred at temporary natural constrictions resulting from the inputs of sediment at tributaries or the formation of woody debris jams (Figures 4, 10, and 11). Gravel bars have not formed along the straightened reaches unless accompanied by a loss of transport capacity, demonstrating the effectiveness of channel straightening at transporting excess sediment loads. The result is an uneven distribution of sediment with greater accumulations at constrictions and less in the unimpeded straightened segments. The straightened sections, however, remain sensitive to change and rapid accumulations of gravel and debris can lead to unpredictable gravel deposition, channel avulsions, and meander creation.

A relatively intact riparian buffer in much of the Batten Kill watershed provides sufficient bank resistance that prevents the widespread bank erosion seen in other Vermont watersheds. Significant reductions in boundary resistance resulting from a narrow buffer are largely restricted to Reaches M1-M4 downstream of Arlington (Figure 13; Table 1). The bank resistance provided by bank armoring in these downstream reaches reduces the rate of erosion that might otherwise be expected (Figures 7 and 13). The effectiveness of sediment transport through straightened reaches is aided, in places, by the bank armoring. The increased bank resistance afforded by riprap impedes the natural evolutionary tendency of a straightened channel to undergo bank widening, thus maintaining greater flow depths and higher transport capacity. Decreased roughness along the banks due to the absence of vegetation further enhances sediment transport along sections of the channel with armored banks. Consequently, gravel bars are generally absent on the Batten Kill in areas where bank armoring is found. The effectiveness of channel straightening and bank armoring to transport sediment leads to increased sediment supply downstream, has degraded aquatic habitat through the loss of pools and other cover, and leaves the altered reaches prone to rapid and unpredictable channel avulsions and meander formation.

Variations in bank resistance along the channel resulting from the distribution of bank armor and changes in riparian buffer width are perhaps partially responsible for the location and frequency of avulsions. Where no bank armor or riparian buffer is present, the banks are less resistant and are more prone to bank erosion, meander creation, and gravel deposition as accommodation space is provided by bank recession. Bank recession and the recreation of meanders is essential to the redevelopment of equilibrium conditions along the straightened reaches as sediment deposition and bank erosion can be more evenly distributed along the channel rather than transferred to and focused in downstream reaches. The greatest frequency of meander recreation (i.e., avulsions) is observed downstream of Roaring Branch (Figure 7) along straightened areas with their location generally coinciding with areas of lowest bank resistance (i.e., no buffer or armor present along the banks). However, the location of channel constrictions along the channel, as discussed above, is probably the underlying cause initiating the avulsion process and formation of meanders.

No natural grade controls are present on the Batten Kill mainstem or the lower reaches of the Green Mountain tributaries. Bedrock falls and ledges are present on the Taconic Mountain tributaries, particularly the lowest reaches of West Branch and Munson Brook. The presence of these grade controls may partially explain the relatively low sediment inputs to the main stem from these tributaries. The grade controls prevent widespread incision of the bed and subsequent bank instability as well as promoting sediment storage within the tributary watersheds.

4.0 CONSTRAINTS TO SEDIMENT TRANSPORT AND ATTENUATION

4.1 Sediment Regimes

Significant human alterations to the hydrologic and sediment regime will generally lead to channel adjustments that result in departures from the equilibrium condition. Channel adjustments are often the result of multiple and overlapping stressors varying both in time and space. In the Batten Kill watershed, for example, deforestation (the initial human stressor) led to higher sediment loads and channel aggradation (the initial channel response). This response, in part, led to channel straightening (a later human stressor) to enhance transport of the higher sediment loads, but resulted in channel incision (a later channel response) due to the increases in channel gradient. Likely enhancing the incision was the overlapping change to the hydrologic and sediment regime resulting from reforestation after the initial land clearance. Rather than attempting to establish the timing, location, and predominance of various stressors and channel adjustments that have occurred along a particular channel reach, the Vermont River Management Program has established a process for comparing the existing channel morphology with the presumed reference state to provide a less complicated approach for understanding the natural and human conditions governing the evolution of the channel back to equilibrium conditions.

Since alterations in the river's ability to transport or store sediment is a primary control on channel condition and adjustments, maps that depict changes in sediment regime are particularly useful in identifying river reaches with the greatest departure from reference conditions and, therefore, most likely to experience future adjustments. Alterations to the sediment regime must be considered at the watershed scale, because largely unaltered reaches may be subject to future change due to excess (or decreasing) sediment delivery caused by upstream channel adjustments.

In the procedures created by the Vermont River Management Program (VTRMP, 2007), the sediment regimes at the watershed scale are simplified into five basic categories: 1) transport reaches; 2) confined source and transport reaches; 3) unconfined source and transport reaches, 4) fine source and transport reaches with coarse deposition; and 5) reaches in equilibrium with coarse sediment but experiencing fine deposition on floodplains. Deltaic areas where all sediment is deposited are not considered. The five sediment regime categories attempt to characterize the source and fate of both fine and coarse sediment. Transport reaches are typically steep mountainous reaches but do not supply appreciable quantities of sediment to downstream reaches on an annual basis because of bed and bank resistance afforded by bedrock, well compacted till, coarse glacial erratics, or well forested slopes. Confined source and transport reaches have a high transport capacity like the transport reaches, but are found lower in the watershed where more erodible bank materials are likely to be encountered. Therefore, considerable sediment can be supplied to downstream reaches, especially where land use and channel management activities have triggered incision, rejuvenation, and mass wasting processes. Reaches categorized as unconfined source and transport reaches are generally located in broad valleys where straightening, incision, or berming has converted a previously depositional reach into an area that is supplying and delivering sediment downstream. Fine source and transport reaches with coarse deposition are also in broad valleys disturbed by incision, but are undergoing a widening phase. Bank erosion supplies fine sediment while the widening results in a loss of transport capacity and provides the accommodation space for coarse deposition. Equilibrium reaches are relatively undisturbed meandering channels with floodplain access where coarse deposits are transported through the channel but fine sediments are deposited on the floodplain. These reaches, although in equilibrium and unaltered by direct human activities, are sensitive to changes resulting from excess or decreased sediment delivery from upstream.

The five sediment regime categories can be defined for both the existing condition and the reference condition with comparisons of the two proving useful for identifying stream departures and ongoing channel adjustments. The reference condition is based on valley confinement and gradient and represents the sediment regime that would be present in the absence of human alterations to the channel and larger watershed. Reference conditions along the Batten Kill mainstem were likely dominated by equilibrium conditions with a meandering channel transporting gravel and fine sediment deposited on the broad floodplain to which the channel would have had access (Figure 14). Coarse deposition on the lower Green Mountain tributaries and Green River where alluvial fans are present would have buffered the mainstem from excess sediment delivery, helping to maintain equilibrium conditions on the valley bottom despite serving as a source of fine sediment. The upper portions of the tributaries were likely transport and confined source and transport areas but these reaches were not part of the Phase 2 Assessment, so the nature of bed and bank materials is largely unknown. Bedrock grade controls on the Taconic Mountain tributaries would have reduced sediment supply and helped to maintain equilibrium conditions on the lower reaches.

Much of the Batten Kill mainstem has experienced a departure from the reference sediment regime due to the extensive channel straightening, increased sediment delivery from the Green Mountain tributaries, and resulting channel adjustments. Most of the channel downstream of Roaring Branch is now an unconfined source and transport reach, because incision along the straightened reaches has resulted in greater transport capacity (Figure 15). At constrictions behind debris jams, tributary delta bars, and bridges, meanders have redeveloped downstream of “break out” points (Figure 4). “Break outs” have also occurred at points of rapid flow expansion such as at the downstream end of a levee 1.4 miles upstream of the state border (Segment M1B). At least 5 mappable “break outs” or avulsions are found in Reaches M1-M4 downstream of Roaring Branch (Figures 7 and 11), but shorter ones may also exist. Flow attenuation in these zones leads to gravel deposition and development of fine source and transport reaches with coarse deposition (Figure 15). Similar conditions are observed in Reach M9 downstream of Bourne Brook where at least 3 avulsions are present (Figures 7 and 15). Elsewhere, particularly Reaches M5-M8, straightening is less continuous, so undisturbed equilibrium reaches alternate with straightened sections where the sediment regime has been converted to unconfined source and transport reach (Figure 15). In these areas, the equilibrium reaches may have a greater than normal occurrence of bars and could experience future adjustments due to the high sediment loads delivered from the straightened segments.

Changes to the sediment regime along the mainstem are partially in response to channel adjustments occurring on the lower tributaries. The reference condition on the alluvial fans at the downstream ends of the Green Mountain tributaries and Green River is considered to be fine source and transport with coarse deposition, because the expansion of flow on the unconfined surfaces leads to multiple distributary flow paths and gravel deposition. The existing berms on several of the Green Mountain tributaries has blocked off access to the fan surfaces and confine flow to a single channel (Figure 2), therefore increasing flow depths (Table 1) and sediment delivery to the mainstem. Although some gravel deposition still occurs within the berms (Figures 3 and 7), the increased sediment delivery downstream suggests the sediment regime on the lower tributaries has been altered to an unconfined source and transport condition. The Taconic Mountain tributaries with bedrock controls are considered equilibrium reaches both currently and in reference condition (Figures 14 and 15), because the more limited coarse sediment supply is readily accommodated by the available stream power.

Overall, the sediment regime changes on the mainstem and the tributaries have resulted in the loss of sediment storage as alluvial fan surfaces and floodplains have been cutoff from the main channel by berming and the channel incision induced by straightening. In general, watersheds which have lost attenuation or sediment storage areas, due to human-related constraints, are generally more sensitive to erosion hazards, transport greater quantities of sediment and nutrient to receiving waters, and lack the sediment storage and distribution processes that create and maintain habitat. "Break out" areas where meanders have been recreated on the mainstem (Figure 4) are closer to the reference condition than the straightened reaches and, consequently, have greater habitat value and store greater volumes of sediment.

4.2 Vertical and Lateral Constraints

Vertical and lateral constraints to channel evolution dictate how readily a reach that has undergone a sediment regime departure can progress through the channel evolutionary stages and return to the reference condition. In other cases, lateral constraints can be the cause of sediment regime changes along the river such as the significant increase in sediment storage that occurs just upstream of bedrock gorges or other constrictions. Along the Batten Kill and the lower tributaries very few natural constraints to vertical and lateral adjustment exist (Figure 14; Table 2). Despite the heavier urban land use and denser road network in the Munson Brook and West Branch watersheds, sediment regime is largely unchanged, in part, due to the presence of bedrock waterfalls. While a bedrock constriction also occurs on Bourne Brook just upstream of the Super-7 highway crossing, the 1.5 miles of stream downstream to the confluence flow across a largely unconfined alluvial fan surface. Many human constraints have been placed on all of the Green Mountain tributaries over the years, most notably the berms, to protect investments from the unconfined high velocity flows typical of alluvial fans (Figure 2). Developments and roads beyond the berms are in conflict with the natural evolution of the channel and serve as further constraints to future restoration. Lye Brook provides a more detailed example of how these constraints may prevent future adjustments and a return to reference conditions (Figure 16), but the other tributaries and mainstem can be analyzed in similar detail with the use of the GIS shapefiles provided in Appendix 1.

Multiple bridge and culvert crossings are found along the mainstem that not only constrict the channel, but the road approaches, if elevated, also bisect the floodplain (Figure 15; Table 2). These conditions inhibit the free development of meanders along straightened reaches and, in certain instances, can even control the location of meander development as gravel accumulates upstream of the constriction (Figure 12). Channel straightening has created higher than normal sediment transport rates. The bridge and culvert crossings are spaced far enough apart that many opportunities may still exist to encourage meander development and more evenly distribute the sediment load that currently passes through the straightened reaches.

Berms are the most significant constraint present on the Green Mountain tributaries preventing lateral channel migration across the otherwise unconfined alluvial fan surfaces. Under natural conditions, the alluvial fans are sites of sediment and flow attenuation. Attenuation zones on valley bottom floodplains will eventually reach an equilibrium condition whereby coarse sediment entering the reach is transported through the reach without additional sediment storage. Broad unconfined alluvial fans, however, can remain sites of sediment and flow attenuation for thousands of years as the slope is built up over time to establish a smoother grade between the steep mountainous channels and the flatter valley bottom that the fan surfaces connect. The removal of the berms and other constraints on the lower tributaries, therefore, could lead to long term sediment storage that can reduce hazards and improve habitat on the lower tributaries and mainstem reaches downstream.

Human development in the watershed has not created permanent constraints to channel evolution and reestablishment of reference sediment regimes (Appendix 1). The capacity for sediment storage behind dams has largely been exceeded such that sediment now passes over dams or the downstream effects of sediment storage behind dams are very localized. Urbanization in the watershed has not reached a threshold level to precipitate system wide adjustments in channel morphology. Therefore, if constraints at the reach level can be addressed, most of the mainstem and lower tributaries have the potential to evolve back to the reference sediment regime. Sediment and flow energy is typically focused at the downstream ends of straightened reaches, leading to elevated erosion and flood hazards. Straightened reaches are also characterized by plane bed features with a uniform depth across the channel. The creation of meanders leads to a greater complexity of habitat types, because of the resulting cross sectional variations in flow depths, velocity, and substrate particle size. The reestablishment of reference conditions, therefore, will maximize sediment storage, reduce flood hazards by more evenly distributing flow energy, and create higher quality habitat.

4.3 Sensitivity Analysis

In the absence of constraints to lateral and vertical adjustments, a reach that has departed from the reference sediment regime would be expected to progress through several channel evolutionary stages (Schumm, 2005) that culminate with a return to the equilibrium regime. The rate at which these transformations occur, referred to as stream sensitivity, is dependent upon boundary resistance, sediment load, and the degree to which the channel has been altered. Streams with unconsolidated bed and bank materials, such as sand, will undergo rapid adjustments and are considered to have an extreme or very high sensitivity to change. Typically, a stream that is responding to an increase in sediment transport capacity (resulting from straightening, for example) or a decrease in sediment load (as occurs downstream of a dam) will initially undergo incision or erosion of the bed. As the bank heights become higher and over-steepened, they will begin to fail and the channel then begins a widening phase. The loss of transport capacity that occurs as the flow widens results in aggradation. Flow deflected around the emerging gravel bars recreates sinuosity in the channel, returns the channel to near its original condition, and completes the channel evolutionary process. The rate of channel change, or stream sensitivity, is generally higher in the initial phases of channel evolution (i.e., incision) and become slower as a channel approaches the new equilibrium condition (i.e., aggradation).

The Vermont River Management Program rates sensitivity on a six-part scale: very low, low, moderate, high, very high, and extreme (VTRMP, 2007). In general, very low to low ratings are assigned to streams in equilibrium or good condition that flow through bedrock, boulders, or cobbles and are unlikely to experience rapid widening or downcutting. Moderate to high ratings are found on streams with cobble to sand-sized bank material and that are undergoing major channel adjustments. Very high to extreme ratings are reserved for streams with gravel and sand banks that are in poor condition, because of channel adjustments so significant that a stream-type departure has occurred (see Rosgen, 1996 for definition of stream-type departure). Braided rivers with cobble, gravel, or sandy banks are considered extremely sensitive even under reference conditions as they are characterized by frequent shifts in channel position.

The most sensitive reaches on the Batten Kill are the lower Green Mountain tributaries with sensitivity ratings ranging from high to extreme (Figure 17). With the berms in place, the lower tributaries are essentially incised channels created by the artificial build up of the banks rather than an actual downcutting of the channel bed (Figure 2). If the berms were to be uncontrollably breached during a flood or purposefully removed as part of a restoration project, flow energy and sediment would be rapidly attenuated. Rapid transformations in channel morphology would result with the artificially incised condition replaced by one that is in-regime for an alluvial fan (i.e., a fine sediment source and transport reach with coarse deposition).

Along the mainstem, reaches downstream of Bourne Brook (M9) and Roaring Branch (M1-M4) are more sensitive than others (M5-M8) due to the high sediment loads emanating from these tributaries (Figure 17). Where sediment transport capacity is reduced by constrictions, the accumulating gravels divert flows into the banks, causing channel widening and further aggradation. In areas with lower sediment loads, these processes progress much slower, because channel response is less dramatic at constrictions.

Even those reaches on the mainstem that are still in an equilibrium condition (Figure 15; e.g., Reach M10) are rated as moderately sensitive (Figure 17). The non-cohesive bank material in these reaches means they may respond readily to increases or decreases in sediment delivery from upstream. Consequently, segments that are essentially unaltered meanders in Reach M5 (Segments B and D) may be particularly susceptible to future change as straightened segments (Segments C and E) upstream may be transferring excess sediment into these undisturbed areas.

5.0 PRIORITIZATION OF RESTORATION OR CONSERVATION PROJECTS

An understanding of human stressors and their distribution throughout the watershed is critical for identifying and prioritizing restoration projects. Restoration must be geared to address the stressors present in order to return the stream channel to an equilibrium condition. Only by achieving equilibrium can the three primary objectives of restoration be met simultaneously: flood and erosion hazard mitigation, reduction in sediment and nutrient loading, and aquatic habitat improvements. Restoration projects implemented without consideration to the underlying causes for channel instability are subject to a higher rate of failure, so project designs should address upstream stressors prior to implementation. Flow energy and sediment must be evenly distributed over long distances and not focused at a single restoration site where they cannot be adequately accommodated. Consideration must also be given to how the channel will respond to a proposed restoration project and whether such a project will transfer instabilities elsewhere or successfully attenuate sediment and flow energy within the restored reach.

To assist in identifying high priority projects that are consistent with restoration at the watershed scale and attainment of channel equilibrium, a step-wise procedure has been developed by the Vermont River Management Program that considers the feasibility of implementing eight restoration actions: 1) protecting river corridors; 2) planting stream buffers; 3) stabilizing stream banks; 4) armoring head cuts and nick points; 5) removing berms and other constraints to flood and sediment load attenuation; 6) removing or replacing structures such as undersized culverts; 7) restoring incised reaches; and 8) restoring aggraded reaches. The most appropriate actions for each reach or segment along the river is identified by progressing through a menu of options that considers the stressors within the reach and further upstream (Appendix 2). The procedure will identify all restoration actions that are consistent with achieving equilibrium in the reach with those first on the list above (e.g., protecting river corridors, planting stream buffers) prioritized higher than those at the end (e.g., restoring incised and aggraded reaches) given the technical expertise required and risk of failure inherent in each action. This procedure identifies and prioritizes projects from a technical feasibility standpoint only; the social feasibility of such projects will also be discussed (see Section 6.0 below).

Each of the above restoration actions that are practicable for the Batten Kill watershed is discussed further below and its priority of use discussed. A listing and prioritization of restoration actions considered viable for each river reach and segment assessed during the Phase 2 Assessment is provided in Table 3. Arresting head cuts and nick points and restoring aggraded reaches are not discussed further as these are not widespread problems that presently exist in the watershed. Straightening on the mainstem probably did cause incision and headcut migration historically, but these processes are no longer active. However, the incised and straightened channels are still conveying excess sediment downstream, so restoration must occur, as discussed below, before equilibrium conditions will return to the watershed.

5.1 Protecting River Corridors

At several places where the Batten Kill mainstem has been straightened, the river has recreated meanders at “break out” points or avulsion sites (Figures 4 and 7). These areas are referred to as attenuation assets, because the loss of flow confinement and increase in channel length results in the loss of flow energy and deposition of coarse sediment that would otherwise be transferred downstream if flow remained in the straightened and incised channel. Sediment stored within the attenuation area reduces loading downstream. The variation in flow velocities within the meander segregates sediment into different particle sizes and leads to higher quality habitat as more closely spaced pool-riffle sequences develop. While more recently activated attenuation zones are characterized by large unvegetated gravel bars (Figure 18a), the expansion of flow and reductions in flow velocities will promote the vertical accretion of fine sediments on top of the bars and the eventual development of a well vegetated floodplain as observed at older “break out” sites (Figure 18b). Floodplain development ensures a long-term site for sediment and flow energy attenuation, leading to reductions in flood and erosion hazards at the site and further downstream.

Given that ongoing processes within these attenuation assets are consistent with restoration objectives (see Section1.0), efforts should be made to prevent activities such as bank armoring, gravel mining, or channelization that would alter the existing and evolving conditions. Protecting the river corridors within these areas should be considered a high priority, so flow and sediment attenuation can continue unconstrained. In addition, areas where future “break outs” can develop along straightened segments without threatening human investments should also be considered valuable attenuation assets with areas upstream of valuable infrastructure given a high priority for river corridor protection.

5.2 Planting Stream Buffers

A healthy riparian buffer is essential to long-term sustainability of equilibrium conditions and healthy aquatic habitat. Trees with their roots planted 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 sediment produced by the erosion concentrated in one area. Some erosion of river banks is critical to maintain 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, help 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, since 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, 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 Batten Kill watershed. Priority areas for buffer restoration are listed in Table 3.

5.3 Stabilizing Stream Banks

Erosion is a perfectly natural condition along streams in equilibrium. The position of a channel in equilibrium is not static and maintains the same dimension, pattern, and profile while migrating across its floodplain by balancing erosion on the outside of a meander bend with an equivalent amount of deposition on the inside of the bend. An attempt to stop all erosion in a watershed would not only be difficult and costly but would be inconsistent with maintaining channel equilibrium. Greater levels of bank erosion are expected in areas that are out of equilibrium due to natural or human perturbations that have initiated widespread incision or aggradation. Downcutting of the channel bed leads to bank failure on both sides of the river channel as bank heights become unstable; the critical height at which the bank collapses is less for loosely consolidated sandy banks compared to more competent silt and clay banks. Aggradation, in contrast, generally results in bank erosion on the outside of bends as flow is diverted around the gravel bars forming in the river channel. Given that incisional processes can lead to aggradation downstream due to the generation of excess sediment, the types of erosion can vary along the length of the river system. Long term remedies of bank erosion, therefore, depend on addressing stressors within the reach and upstream that are the ultimate cause for incision or aggradation. Channel evolutionary processes that will bring the channel back into equilibrium often result in bank erosion and require a supply of sediment from upstream to sustain the required channel adjustments. However, short-term bank stabilization may be required where: 1) a reduced rate of lateral erosion on a reach with good floodplain access is necessary to give riparian buffer plantings ample time to mature; 2) human infrastructure is imminently threatened; or 3) a valuable resource might be permanently lost, such as fertile floodplain soils, that will enable the establishment of a riparian buffer. Bank stabilization should avoid permanently armoring the banks, especially on incised reaches, because an even distribution of erosion cannot be achieved and the erosive forces acting on the bank will merely be transferred downstream. Ideally, bank stabilization should consist of bioengineering methods, such as log deflectors and root wad revetments, that permit a more even expenditure of the flow energy and provide short term stability while riparian buffer plantings have a chance to mature.

Several bridges crossing the Batten Kill mainstem have been the site of bank stabilization. This is most notable downstream of Roaring Branch where the high sediment loads make the river particularly responsive to the reductions in transport capacity occurring at the bridge constrictions. The resulting bar deposition upstream of these bridges (Figure 12), particularly the West Mountain Bridge and Hawley Bridge at the upstream and downstream ends of the River Road, respectively, has led to bank erosion that threatens the bridge abutments as flow is diverted around the bars. River Road, itself, approaches close to the river banks in several localities and periodic armoring has been needed to protect the road. Continued bank stabilization in these areas is likely to be necessary until the ultimate cause of these erosive forces can be addressed. Larger bridge openings and floodplain culverts will help maintain transport capacity through bridges (see Section 5.5 below) and increased sediment and flow attenuation along straightened reaches (see Section 5.6 below) will decrease erosive pressures currently focused at sharp bends where the river and road come close together. Where ample space is available between the river and threatened infrastructure, riparian buffer plantings should be established and bioengineering techniques used to stabilize the banks while the planted trees mature. Where the use of hard armoring techniques (i.e., riprap) is unavoidable, efforts should be made downstream to mitigate the impact of these destabilizing techniques.

The eroding banks that produce an excess of sediment to downstream reaches are often widely scattered. While only 2.0 percent of the banks on the Batten Kill and lower tributaries are eroding, many more eroding banks may be supplying sediment from the unassessed upper tributaries. Since the sources of sediments in the Batten Kill watershed are very diffuse, reducing sediment loads through bank stabilization may be impracticable; isolating and treating enough eroding banks to effect a significant change would be difficult. Furthermore, some sediment supply is essential to the creation of meanders along straightened segments and the reestablishment of equilibrium conditions. Consequently, a better approach for dealing with high sediment loads that accompany large floods is to promote the attenuation of flow energy, so sediment generated from eroding banks is stored along the river (see Section 5.6 below). This approach can focus restoration to a few isolated localities and will permit the sediment derived from upstream to contribute beneficially to floodplain redevelopment processes in formerly straightened and incised reaches on the Batten Kill mainstem. Bank stabilization efforts are best confined to areas already at or near equilibrium where added boundary resistance is needed to slow down erosion and allow for the reestablishment of a riparian buffer critical for maintaining equilibrium conditions. See Table 3 for areas rated as having the highest priority for bank stabilization.

Two large mass failures along the mainstem, at the Manchester wastewater treatment facility and at the confluence of Roaring Branch, may be supplying large amounts of sediment to the river during large flood events. Stabilizing these banks could reduce downstream sediment supply, but preventing continued failure of these banks could be extremely costly, technically difficult, and could lead to new mass failures adjacent to the stabilized areas. In lieu of stabilization efforts, a more advisable approach may be to monitor the sites and manage downstream areas in such a way that rapid and large increases of sediment supply from these mass failures can be adequately accommodated. Without establishing attenuation areas for storing sediment, the chances are greater that an unpredicted and damaging avulsion will occur.

5.4 Removing Berms

Berms on the lower Green Mountain tributaries of the Batten Kill are preventing the attenuation of flow and sediment across the alluvial fan surfaces on which they are built. The tributary channels are unable to achieve an equilibrium condition, because excess stream power during large floods is focused on the channel bed due to the flow confinement by the berms. Sediment that would accumulate on the tributaries is transferred downstream, complicating the stabilization of mainstem reaches as well. Consequently, removing berms, where socially feasible, would have several benefits: 1) create side channel habitat on the reactivated alluvial fan surfaces; 2) reduce peak flow velocities within the formerly confined tributary channel, thereby permitting revegetation of gravel bars and deposition of fine sediments; 3) reduce the risk of berms catastrophically failing in other areas where property might be damaged; 4) allow the stream to expend additional energy and attenuate its sediment load before entering the mainstem; and 5) return the stream to a more natural flow and sediment regime. Berm removal will permit achievement of restoration goals on the tributary reach involved as well as downstream reaches of the mainstem. Consequently, from a technical standpoint, berm removal is rated as one of the highest restoration priorities within the Batten Kill watershed (Table 3).

5.5 Removing/Replacing Structures

Bridges and culverts with openings for the free passage of water and sediment that are smaller than the bankfull dimensions will cause a localized channel response that typically involves deposition upstream in the backwater area behind the constriction and scour downstream by the sediment starved water that passes through the bridge. The response is even more pronounced with larger floods if floodplain conveyance is also blocked by the road grading approaching the bridge. Bank erosion generated by either the scour downstream or the diversion of water around gravel bars deposited upstream can threaten bridge safety and other infrastructure. Long-term reductions in the erosive forces generated by the bridge and floodplain constrictions require resizing the bridge openings to at least the bankfull width. Floodplain conveyance can be retained to a large degree with the placement of floodplain culverts underneath the road grade. HEC-RAS or other hydraulic modeling may be needed in certain instances to determine the number and size of floodplain culverts and bridge openings needed to ensure continuity of sediment transport past the bridge in at least small to moderate flood events. Where resizing bridge openings and use of floodplain culverts is not practicable, bank stabilization techniques may be needed (see Section 5.3 above).

While narrow bridge openings are causing local channel responses on the Batten Kill, the creation of gravel bars and channel sinuosity upstream of narrow bridge openings is actually consistent with the development of equilibrium in previously straightened segments by promoting sediment storage and flow attenuation. Consequently, from a technical standpoint, replacement of these bridges is a lower restoration priority than conservation of existing attenuation areas, berm removal, and restoration of incised reaches (see Section 5.6 below). However, a higher priority is placed on bridge replacement where bank erosion and the recreation of meanders threaten road safety or other infrastructure (Table 3). Resizing the bridge crossings would be a higher priority than bank stabilization in these instances, because of the habitat improvements associated with addressing aquatic organism passage problems that sometimes develop at undersized bridge openings.

5.6 Restoring Incised Reaches

Incised channels focus more flow energy on the channel bed, because a greater percentage of flow is confined to the channel and a greater discharge is needed to access the floodplain. Degraded habitat results within the reach as bed complexity is destroyed (i.e., pool-riffle features replaced by plane bed morphology) and the bed becomes armored with coarser particles able to resist the greater stream power. Channel equilibrium is also compromised as the greater transport efficiency in the incised reach leads to excess sediment delivery to downstream reaches. Although sediment passes through the incised reaches, greater rates of deposition occur where channel transport capacity declines at bends in the channel, channel constrictions, or areas where flow becomes unconfined. Restoration of incised reaches by allowing channel evolution to proceed unconstrained or by reconnecting the channel to its floodplain is, therefore, necessary to achieve equilibrium conditions.

Most of the straightened segments on the Batten Kill are slightly to moderately incised and encouraging the channel to occupy former meanders or create “break outs” where new meanders can form will assist the channel’s evolution back to an equilibrium regime. Floodplain reconnection and meander formation can be accomplished in several ways. One approach is to lower the existing floodplain to a level at which a new floodplain surface will naturally form over time as channel widening and aggradation progress. This would provide the incised channel access to a lower floodplain surface and result in more immediate sediment and flow attenuation. Another approach to restoring incised reaches involves the addition of woody debris in the channel. From a geomorphic equilibrium perspective, without concerns of social feasibility, the creation of debris jams in the river at points where the bank height is particularly low will force the channel to “break out” onto the floodplain and carve out a new meander on the floodplain as has previously happened naturally on the Batten Kill (Figure 4).

The current dearth of attenuation areas along straightened reaches of the Batten Kill prevents an even expenditure of energy along the channel’s length. This increases the potential that hazardous avulsions of the channel will occur in areas where human developments are present. Reducing these hazards will require the creation of attenuation zones where stream power can be expended across the floodplain rather than transferred downstream towards human infrastructure. Given the reductions in flood hazards and other benefits that would accrue from several attenuation zones along a long straightened segment, restoring incised reaches on the Batten Kill, through either passive or active restoration projects, is a high watershed priority (Table 3). Greater priority should be given to those reaches just upstream of human developments or other important assets as this will provide the greatest reduction in fluvial erosion hazards while providing the same sediment storage and aquatic habitat improvements.

5.7 Coordinating Restoration at the Watershed Scale

Reestablishing equilibrium conditions on the Batten Kill will require the coordination of restoration efforts throughout the watershed. Stabilizing eroding banks in one locality, for example, will meet with greater success if greater systemic attenuation is achieved and the upstream stressors leading to the erosive forces are simultaneously addressed. While some restoration activities can occur immediately without concern for upstream conditions, a higher priority is given to those restoration activities that can effect the greatest change beyond the project reach (Table 3). For example, removal of berms on the tributaries will reduce sediment loading to the mainstem. These reductions in sediment load from tributaries will decrease the propensity of straightened channel segments to “break out” in an unpredictable manner. With less uncertainty in channel behavior, more controlled efforts can be undertaken to restore incised reaches by creating new meanders or reoccupying old ones.

6.0 TECHNICAL AND SOCIAL FEASIBILITY OF PROJECT IMPLEMENTATION

The above restoration activities have been prioritized for the Batten Kill solely based on their ability to establish equilibrium conditions and achieve the three main restoration objectives of reducing flood and erosion hazards, decrease sediment and nutrient loading, and improve aquatic habitat (Table 3). Considering the highest priority reaches first, the social feasibility of each project should be determined and, if feasible, the greatest positive impact for the watershed can be realized more quickly by implementing the highest priority projects first. Where social issues prevent implementation of the highest priority activities, the feasibility of the next highest priorities can be determined and so forth down the list. This process will ensure the highest priority activities are considered for implementation, but will not prevent lower priority activities from occurring prior to building the consensus necessary to implement higher priority projects that more often involve multiple stakeholders and encompass a greater area.

In many cases, the priority restoration activities (e.g., corridor protection, berm removal) are in conflict with traditional management activities and considerable stakeholder education will be necessary to demonstrate how achieving equilibrium conditions along the river will lead to sustainable river management and reduce the number of repeated costly "fixes" needed along the river over time. Engaging landowners, town officials, and others that deal with riverine issues can help further prioritize restoration activities on those locations that experience frequent and repeated flood damages or where preserving healthy and productive soils is essential. Addressing the aquatic habitat improvements that can be realized by managing towards equilibrium is another important way of achieving consensus as most stakeholders, regardless of their own special interests, often see the value in creating and maintaining a healthy fishery in the watershed. Extensive data has been collected on fish and fish habitat throughout the Batten Kill and this data may help further prioritize restoration projects by identifying those activities that have the greatest likelihood of improving habitat and habitat forming processes.

Municipalities within the Batten Kill watershed can play an important role in increasing the likelihood of implementing high priority projects. The adoption of fluvial erosion hazard zones, being mapped by the Vermont River Management Program, can assist in limiting and avoiding future development within the river corridor. Over time, this will increase the attractiveness of state and federal programs (e.g., Clean and Clear, WHIP, CREP) that assist or compensate landowners for protecting river corridors. Such programs will also create opportunities for more active restoration activities (e.g., removing berms, restoring incised reaches) that will lead to greater, and more quickly realized, sediment and flow energy attenuation. A number of bridges and culverts were identified as part of the Phase 2 Assessment as being too small to adequately convey the sediment and water delivered from upstream, leading to localized scour and deposition problems. Towns can address these problems through capital budgeting that will provide the funds over time to resize the bridges and culverts with the highest priority for replacement (Table 3). By creating a framework of policy and funding priorities, local municipalities can play a large role in creating the necessary social environment for implementing both reach-scale and watershed-scale restoration activities that will lead to reductions in flood and erosion hazards, decreased sediment and nutrient loading, and improved aquatic habitat.

7.0 CONCLUSIONS

Past human land use and channel management activities in the Batten Kill watershed have created channel instabilities that result in flooding and erosion problems, increased sediment and nutrient loading, and degraded habitat. Restoring channel equilibrium to the watershed could address these continuing problems in a sustainable manner without the need for frequent and costly interventions to protect infrastructure or ecosystem health. The restoration of channel equilibrium depends on the even distribution of flow energy throughout the system that is currently disrupted by extensive channel straightening and bank armoring on the mainstem and berming of several tributaries. These activities have led to increased transport efficiency through treated reaches, while focusing flow energy, sediment, and erosion problems on untreated downstream reaches. Even the treated reaches are susceptible to unpredictable channel adjustments if transport capacity is rapidly reduced during a flood due to the creation of a debris jam or mass failure of glacial sediment along a high bank.

A more even distribution of flow energy throughout the watershed will require the conservation or development of attenuation assets where sediment can be stored and flow energy dissipated, thereby reducing sediment loading and erosion hazards downstream. Given the relatively low concentration of developments within the river corridor, many opportunities still exist in the watershed for creating attenuation areas. If development is allowed to encroach into these areas, many of the highest priority restoration sites in the watershed could be permanently lost. Even if the current conditions are successfully preserved, the actual implementation of watershed-scale restoration activities (e.g., corridor protection, berm removal, restoration of incised reaches) will still require considerable stakeholder education, so all interested parties understand the potential value accrued in making short-term sacrifices in order to achieve sustainable erosion hazard mitigation, sediment load reductions, and aquatic habitat improvements.

8.0 REFERENCES

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Appendix 2

		Watershed-Scale Stressors		Reach-Scale Stressors	
River Segment		**Hydrologic**	**Sediment Load**	**Stream Power**	**Boundary Resistance**
Battenkill River	M01-A			Increase (straightening)	Increase (bank armoring)
Battenkill River	M01-B			Increase (straightening)	
Battenkill River	M01-C		Increase (depos. features)	Increase (berming and straightening)	
Battenkill River	M02		Increase (depos. features)	Increase (straightening)	Increase (bank armoring)
Battenkill River	M03-A			Increase (straightening)	Increase (bank armoring); Decrease (buffer impacts)
Battenkill River	M03-B		Increase (depos. features)		Increase (bank armoring); Decrease (buffer impacts)
Battenkill River	M03-C			Increase (straightening)	Increase (bank armoring); Decrease (buffer impacts)
Battenkill River	M04			Increase (straightening)	Increase (bank armoring)
Battenkill River	M05-A			Increase (straightening)	Increase (bank armoring)
Battenkill River	M05-B				
Battenkill River	M05-C			Increase (straightening)	Increase (bank armoring)
Battenkill River	M05-D			Increase (straightening)	
Battenkill River	M05-E			Increase (straightening)	Increase (bank armoring)
Battenkill River	M06				
Battenkill River	M07			Increase (straightening)	Increase (bank armoring)
Battenkill River	M08			Increase (straightening)	
Battenkill River	M09-A				
Battenkill River	M09-B		Increase (depos. features)	Increase (straightening)	
Battenkill River	M10				
Battenkill River	M11-A				
Battenkill River	M11-B				
Battenkill River	M11-C	not assessed	not assessed	not assessed	not assessed
Battenkill River	M11-D				

Table 1. River stressors identification.

		Watershed-Scale Stressors		Reach-Scale Stressors	
River Segment		**Hydrologic**	**Sediment Load**	**Stream Power**	**Boundary Resistance**
Battenkill River	M12-A				Decrease (buffer impacts)
Battenkill River	M12-B			Increase (straightening)	Increase (bank armoring); Decrease (buffer impacts)
Battenkill River	M13-A	reduction (plugged culvert)			Decrease (buffer impacts)
Battenkill River	M13-B	reduction (plugged culvert)			Increase (bank armoring); Decrease (buffer impacts)
Battenkill River	M13-C	not assessed	not assessed	not assessed	not assessed
Battenkill River	M13-D	not assessed	not assessed	not assessed	not assessed
Green River	T1.01		Increase (depos. features)	Increase (berming and straightening)	Decrease (buffer impacts)
Green River	T1.02			Increase (straightening)	
Green River	T1.03				
Roaring Branch	T2.01		Increase (depos. features)	Increase (berming and straightening)	Decrease (buffer impacts)
Roaring Branch	T2.02		Increase (depos. features)	Increase (berming)	
Warm Brook	T2S1.01-A		Increase (depos. features)	Increase (straightening)	
Warm Brook	T2S1.01-B			Increase (berming)	
Lye Brook	T3.01-A				
Lye Brook	T3.01-B			Increase (berming and straightening)	
Lye Brook	T3.02-A		Increase (depos. features)	Increase (berming)	Increase (bank armoring)
Lye Brook	T3.02-B				
Bourne Brook	T4.01		Increase (depos. features)	Increase (berming)	
Bourne Brook	T4.02-A			Increase (straightening)	
Bourne Brook	T4.02-B			Increase (straightening)	
Bourne Brook	T4.02-C			Increase (straightening)	
Bromley Brook	T4S1.01			Increase (berming)	
Munson Brook	T5.01-A		Increase (crop land use)		
Munson Brook	T5.01-B		Increase (crop land use)		
Munson Brook	T5.01-C	not assessed	Increase (crop land use)	not assessed	not assessed
Munson Brook	T5.01-D	not assessed	Increase (crop land use)	not assessed	not assessed
Munson Brook	T5.01-E	not assessed	Increase (crop land use)	not assessed	not assessed

Table 1 (con.). River stressors identification.

		Watershed-Scale Stressors		Reach-Scale Stressors	
River Segment		**Hydrologic**	**Sediment Load**	**Stream Power**	**Boundary Resistance**
West Branch	T6.01-A		Increase (crop land use)	Increase (straightening)	
West Branch	T6.01-B		Increase (crop land use)	Increase (straightening)	
West Branch	T6.02-A		Increase (crop land use)	Increase (straightening)	
West Branch	T6.02-B	not assessed	Increase (crop land use)	Increase (straightening)	not assessed
West Branch	T6.02-C	not assessed	Increase (crop land use)	Increase (straightening)	not assessed
West Branch	T6.03-A			Increase (berming and straightening)	
West Branch	T6.03-B	not assessed	not assessed	not assessed	not assessed
West Branch	T6.03-C	not assessed	not assessed	not assessed	not assessed
Mad Tom Brook	T7.01		Increase (depos. features)	Increase (berming and straightening)	Decrease (buffer impacts)
Mad Tom Brook	T7.02		Increase (depos. features)	Increase (berming)	

Note:
Straightening must be 20% or more
Bank armoring must be 10% or more
Buffer impacts based on Phase 1 data
Crop land use = 3 - 5% of subwatershed
Depos. features = 3 or more steep riffles, mid-channel bars, island bars, delta bars, and diagonal bars

Table 1 (con.). River stressors identification.

		Constraints		Transport		Attenuation (storage)		
River Segment		**Vertical**	**Lateral**	**Natural**	**Converted**	**Natural**	**Increased**	**Asset**
Battenkill River	M01-A							x
Battenkill River	M01-B						x	
Battenkill River	M01-C		human					x
Battenkill River	M02							x
Battenkill River	M03-A							x
Battenkill River	M03-B						x	
Battenkill River	M03-C							x
Battenkill River	M04							x
Battenkill River	M05-A						x	
Battenkill River	M05-B							x
Battenkill River	M05-C						x	
Battenkill River	M05-D							x
Battenkill River	M05-E						x	
Battenkill River	M06							x
Battenkill River	M07							x
Battenkill River	M08						x	
Battenkill River	M09-A							x
Battenkill River	M09-B							x
Battenkill River	M10							
Battenkill River	M11-A							
Battenkill River	M11-B	human						
Battenkill River	M11-C							
Battenkill River	M11-D							
Battenkill River	M12-A							
Battenkill River	M12-B							
Battenkill River	M13-A							
Battenkill River	M13-B							
Battenkill River	M13-C							
Battenkill River	M13-D							
Green River	T1.01		human					
Green River	T1.02	human						
Green River	T1.03							

Table 2. Departure analysis.

		Constraints		Transport		Attenuation (storage)		
River Segment		**Vertical**	**Lateral**	**Natural**	**Converted**	**Natural**	**Increased**	**Asset**
Roaring Branch	T2.01		human			x		
Roaring Branch	T2.02		human					
Warm Brook	T2S1.01-A							
Warm Brook	T2S1.01-B	human	human					
Lye Brook	T3.01-A					x		
Lye Brook	T3.01-B		human			x		
Lye Brook	T3.02-A		human					
Lye Brook	T3.02-B							
Bourne Brook	T4.01	natural	human					
Bourne Brook	T4.02-A		human					
Bourne Brook	T4.02-B							
Bourne Brook	T4.02-C							
Bromley Brook	T4S1.01							
Munson Brook	T5.01-A	natural						
Munson Brook	T5.01-B							
Munson Brook	T5.01-C	human						
Munson Brook	T5.01-D							
Munson Brook	T5.01-E							
West Branch	T6.01-A							
West Branch	T6.01-B	human / natural						
West Branch	T6.02-A							
West Branch	T6.02-B							
West Branch	T6.02-C							
West Branch	T6.03-A		human					
West Branch	T6.03-B							
West Branch	T6.03-C	human						
Mad Tom Brook	T7.01		human					
Mad Tom Brook	T7.02		human					

Table 2 (con.). Departure analysis.

River Segment		**Project Type**										
		protect river corridor	plant stream buffer	stabilize stream bank	arrest head cuts	remove berms	replace structure	remove structure	restore incised reach to abandoned channel	river corridor protection at downstream reach	restore incised reach with bed forms and floodplain features	potential restoration / protection project
Battenkill River	M01-A		x (1)							x (2)	x (3)	
Battenkill River	M01-B		x (1)							x (2)	x (3)	
Battenkill River	M01-C		x (2)			x (1)				x (3)	x (4)	
Battenkill River	M02		x (1)							x (2)	x (3)	
Battenkill River	M03-A		x (1)							x (2)	x (3)	
Battenkill River	M03-B		x (1)							x (2)	x (3)	
Battenkill River	M03-C		x (1)				x (2)			x (3)	x (4)	
Battenkill River	M04		x (2)						x (1)			
Battenkill River	M05-A		x (1)							x (2)	x (3)	
Battenkill River	M05-B	x (1)										
Battenkill River	M05-C	x (1)	x (2)						x (3)			
Battenkill River	M05-D	x (1)		x (2)								
Battenkill River	M05-E	x (1)	x (2)							x (3)	x (4)	
Battenkill River	M06		x (1)									
Battenkill River	M07	x (1)	x (2)									
Battenkill River	M08	x (2)	x (1)									
Battenkill River	M09-A	x (2)	x (1)							x (3)	x (4)	
Battenkill River	M09-B		x (1)							x (2)	x (3)	
Battenkill River	M10	x (1)										
Battenkill River	M11-A											
Battenkill River	M11-B		x (1)									
Battenkill River	M11-C	not assessed										
Battenkill River	M11-D	x (1)										
Battenkill River	M12-A	x (1)										
Battenkill River	M12-B		x (1)							x (2)	x (3)	

Table 3. Project identification.

River Segment		**Project Type**										
		protect river corridor	plant stream buffer	stabilize stream bank	arrest head cuts	remove berms	replace structure	remove structure	restore incised reach to abandoned channel	river corridor protection at downstream reach	restore incised reach with bed forms and floodplain features	potential restoration / protection project
Battenkill River	M13-A		x (1)							x (2)	x (3)	
Battenkill River	M13-B		x (1)				x (4)			x (2)	x (3)	
Battenkill River	M13-C	not assessed										
Battenkill River	M13-D	not assessed										
Green River	T1.01	x (3)	x (2)			x (1)						
Green River	T1.02	x (2)	x (1)									
Green River	T1.03	x (1)										
Roaring Branch	T2.01	x (2)	x (3)			x (1)						
Roaring Branch	T2.02	x (2)	x (3)			x (1)						
Warm Brook	T2S1.01-A	x (1)	x (2)									
Warm Brook	T2S1.01-B		x (1)							x (2)	x (3)	
Lye Brook	T3.01-A	x (1)	x (2)									
Lye Brook	T3.01-B	x (2)	x (3)			x (1)						
Lye Brook	T3.02-A	x (2)	x (3)			x (1)						
Lye Brook	T3.02-B		x (1)									
Bourne Brook	T4.01		x (2)			x (1)				x (3)	x (4)	
Bourne Brook	T4.02-A	x (2)	x (1)									
Bourne Brook	T4.02-B	x (1)										
Bourne Brook	T4.02-C	x (1)	x (2)									
Bromley Brook	T4S1.01	x (2)	x (3)			x (1)						
Munson Brook	T5.01-A	x (1)	x (2)									
Munson Brook	T5.01-B	x (1)	x (2)									
Munson Brook	T5.01-C	not assessed										
Munson Brook	T5.01-D	not assessed										
Munson Brook	T5.01-E	not assessed										
West Branch	T6.01-A									x (1)	x (2)	
West Branch	T6.01-B									x (1)	x (2)	

Table 3 (con.). Project identification.

River Segment		**Project Type**										
		protect river corridor	plant stream buffer	stabilize stream bank	arrest head cuts	remove berms	replace structure	remove structure	restore incised reach to abandoned channel	river corridor protection at downstream reach	restore incised reach with bed forms and floodplain features	potential restoration / protection project
West Branch	T6.02-A	x (2)	x (1)									
West Branch	T6.02-B	not assessed										
West Branch	T6.02-C	not assessed										
West Branch	T6.03-A	x (3)	x (2)			x (1)						
West Branch	T6.03-B	not assessed										
West Branch	T6.03-C	not assessed										
Mad Tom Brook	T7.01	x (2)	x (3)			x (1)						
Mad Tom Brook	T7.02	x (2)	x (3)			x (1)						

Table 3 (con.). Project identification.

River Segment		Project Type			Watershed Priority	Independent of Reach Restoration	Next Steps
		defer action on restoring incised reach	restore incised reach with new meanders and / or floodplain	restore aggraded reach			
Battenkill River	M01-A				35	plant buffer	
Battenkill River	M01-B				40	plant buffer	
Battenkill River	M01-C				17	plant buffer	survey and modeling of berm removal
Battenkill River	M02				34	plant buffer	
Battenkill River	M03-A				33	plant buffer	
Battenkill River	M03-B				45	plant buffer	
Battenkill River	M03-C				32	plant buffer	survey of structure and assess impact
Battenkill River	M04				18	plant buffer	floodplain survey and modeling
Battenkill River	M05-A				41	plant buffer	
Battenkill River	M05-B				10	protect corridor	assess landowner interest
Battenkill River	M05-C				21	protect corridor, plant buffer	floodplain survey and modeling
Battenkill River	M05-D				11	protect corridor	assess landowner interest
Battenkill River	M05-E				22	protect corridor, plant buffer	assess landowner interest
Battenkill River	M06				46	plant buffer	
Battenkill River	M07				12	protect corridor, plant buffer	assess landowner interest
Battenkill River	M08				38	plant buffer, protect corridor	assess landowner interest
Battenkill River	M09-A				37	plant buffer, protect corridor	assess landowner interest
Battenkill River	M09-B				44	plant buffer	
Battenkill River	M10				3	protect corridor	assess landowner interest
Battenkill River	M11-A						
Battenkill River	M11-B				42	plant buffer	
Battenkill River	M11-C	not assessed					
Battenkill River	M11-D				31	protect corridor	assess landowner interest
Battenkill River	M12-A				13	protect corridor	assess landowner interest
Battenkill River	M12-B				23	plant buffer	

Table 3 (con.). Project identification.

River Segment		Project Type			Watershed Priority	Independent of Reach Restoration	Next Steps
		defer action on restoring incised reach	restore incised reach with new meanders and / or floodplain	restore aggraded reach			
Battenkill River	M13-A				24	plant buffer	
Battenkill River	M13-B				36	plant buffer	
Battenkill River	M13-C	not assessed					
Battenkill River	M13-D	not assessed					
Green River	T1.01				15	plant buffer, protect corridor	survey and modeling of berm removal
Green River	T1.02				26	plant buffer, protect corridor	assess landowner interest
Green River	T1.03				20	protect corridor	assess landowner interest
Roaring Branch	T2.01				1	protect corridor, plant buffer	survey and modeling of berm removal
Roaring Branch	T2.02				2	protect corridor, plant buffer	survey and modeling of berm removal
Warm Brook	T2S1.01-A				19	protect corridor, plant buffer	assess landowner interest
Warm Brook	T2S1.01-B				39	plant buffer	
Lye Brook	T3.01-A				14	protect corridor, plant buffer	assess landowner interest
Lye Brook	T3.01-B				6	protect corridor, plant buffer	survey and modeling of berm removal
Lye Brook	T3.02-A				4	protect corridor, plant buffer	survey and modeling of berm removal
Lye Brook	T3.02-B		x (2)		47	plant buffer	
Bourne Brook	T4.01				5	plant buffer	survey and modeling of berm removal
Bourne Brook	T4.02-A				43	plant buffer, protect corridor	assess landowner interest
Bourne Brook	T4.02-B				29	protect corridor	assess landowner interest
Bourne Brook	T4.02-C				30	protect corridor, plant buffer	assess landowner interest
Bromley Brook	T4S1.01				7	protect corridor, plant buffer	survey and modeling of berm removal
Munson Brook	T5.01-A				27	protect corridor, plant buffer	assess landowner interest
Munson Brook	T5.01-B				28	protect corridor, plant buffer	assess landowner interest
Munson Brook	T5.01-C	not assessed					
Munson Brook	T5.01-D	not assessed					
Munson Brook	T5.01-E	not assessed					
West Branch	T6.01-A				48		
West Branch	T6.01-B				49		

Table 3 (con.). Project identification.

River Segment		**Project Type**			**Watershed Priority**	**Independent of Reach Restoration**	**Next Steps**
		defer action on restoring incised reach	restore incised reach with new meanders and / or floodplain	restore aggraded reach			
West Branch	T6.02-A				25	plant buffer, protect corridor	assess landowner interest
West Branch	T6.02-B	not assessed					
West Branch	T6.02-C	not assessed					
West Branch	T6.03-A		x (4)		16	plant buffer, protect corridor	survey and modeling of berm removal
West Branch	T6.03-B	not assessed					
West Branch	T6.03-C	not assessed					
Mad Tom Brook	T7.01				9	protect corridor, plant buffer	survey and modeling of berm removal
Mad Tom Brook	T7.02				8	protect corridor, plant buffer	survey and modeling of berm removal

Table 3 (con.). Project identification.

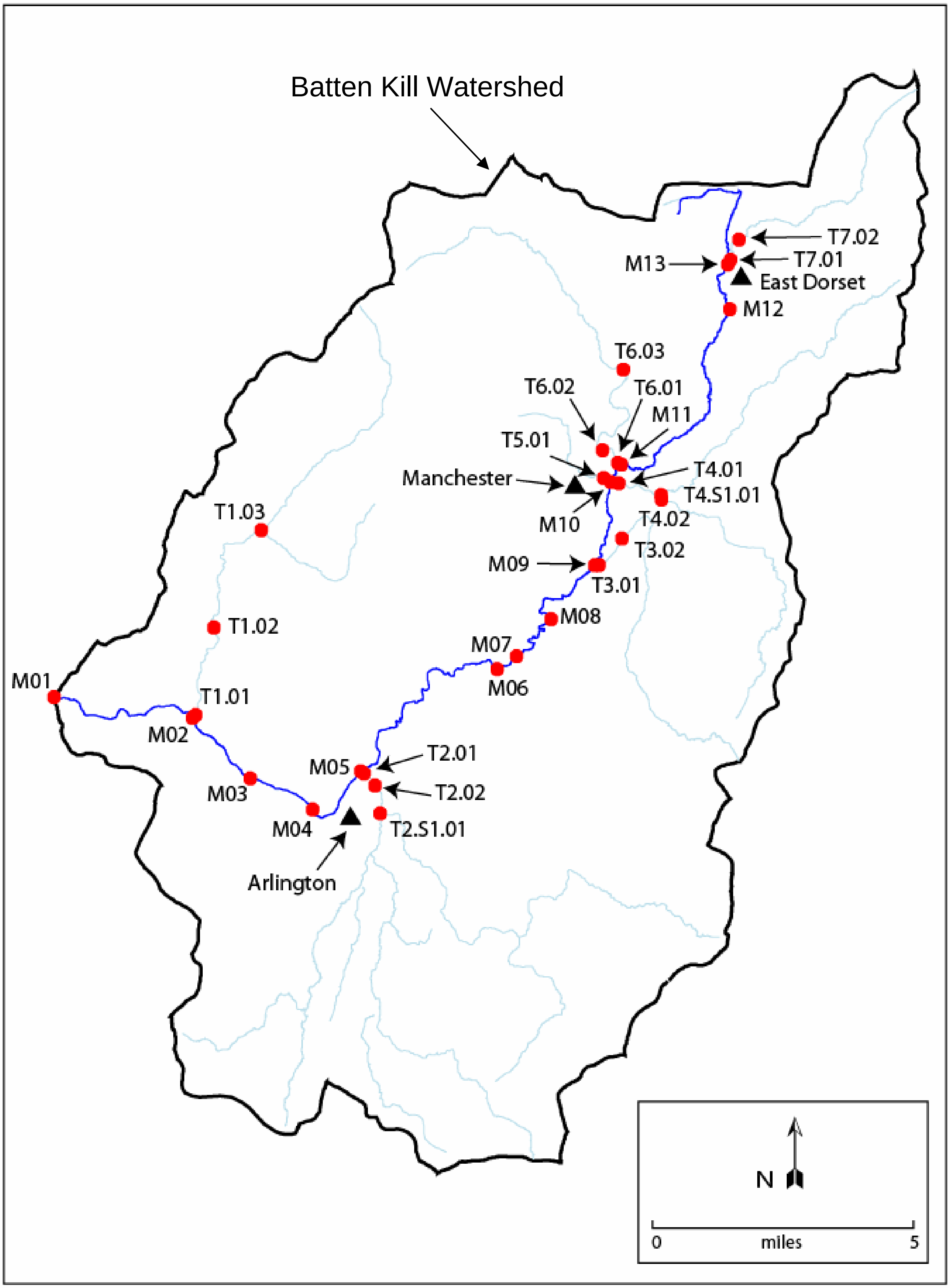
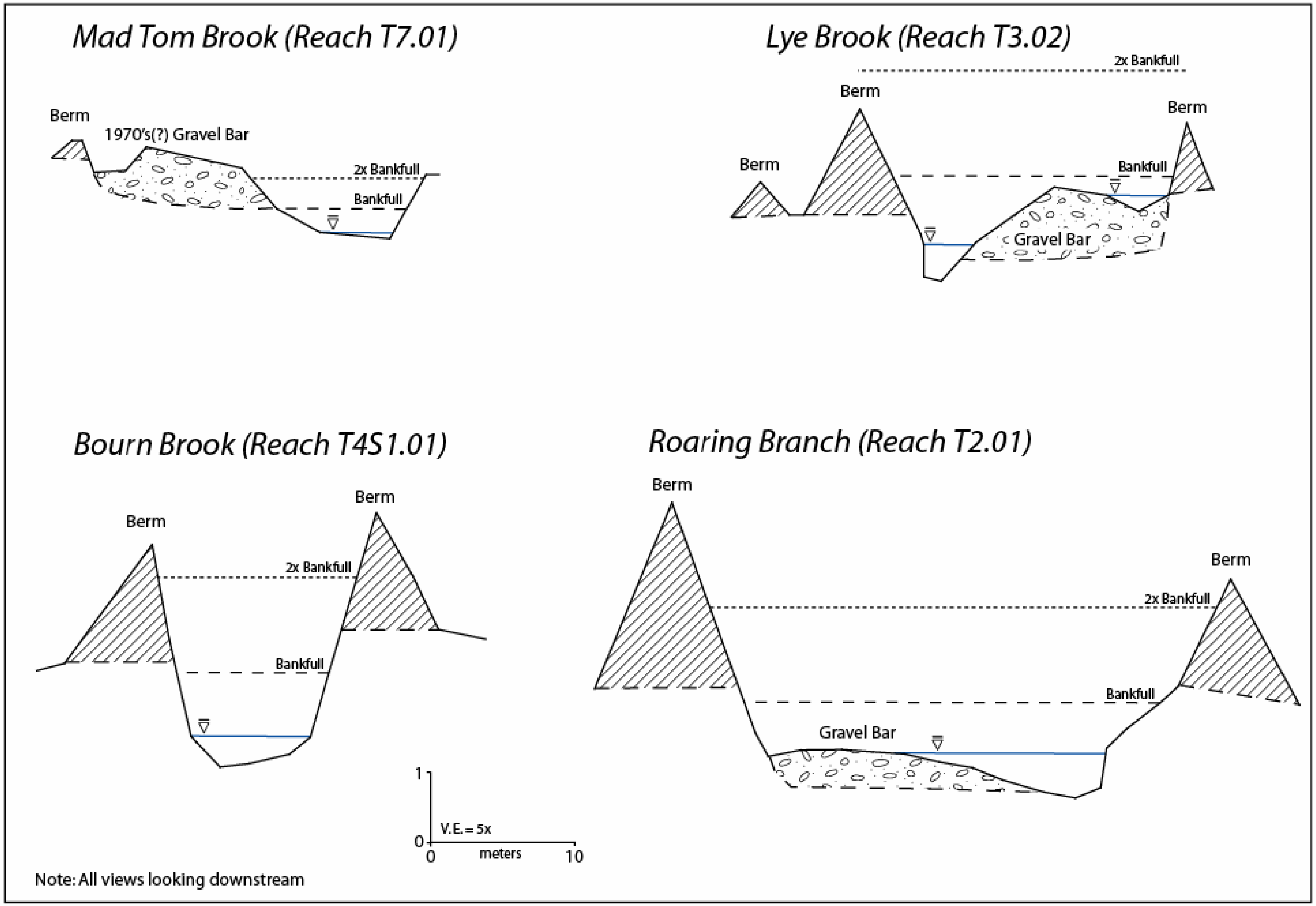


Figure 1. Batten Kill watershed with location of Phase 2 reaches shown.



Mad Tom Brook (Reach T7.01)

Lye Brook (Reach T3.02)

Bourn Brook (Reach T4S1.01)

Roaring Branch (Reach T2.01)

Note: All views looking downstream

Figure 2. Cross sections of Green Mountain tributaries showing placement of berms along channel margins.

Figure 3. Gravel bar deposition has narrowed Roaring Branch since berming was completed in 1973.

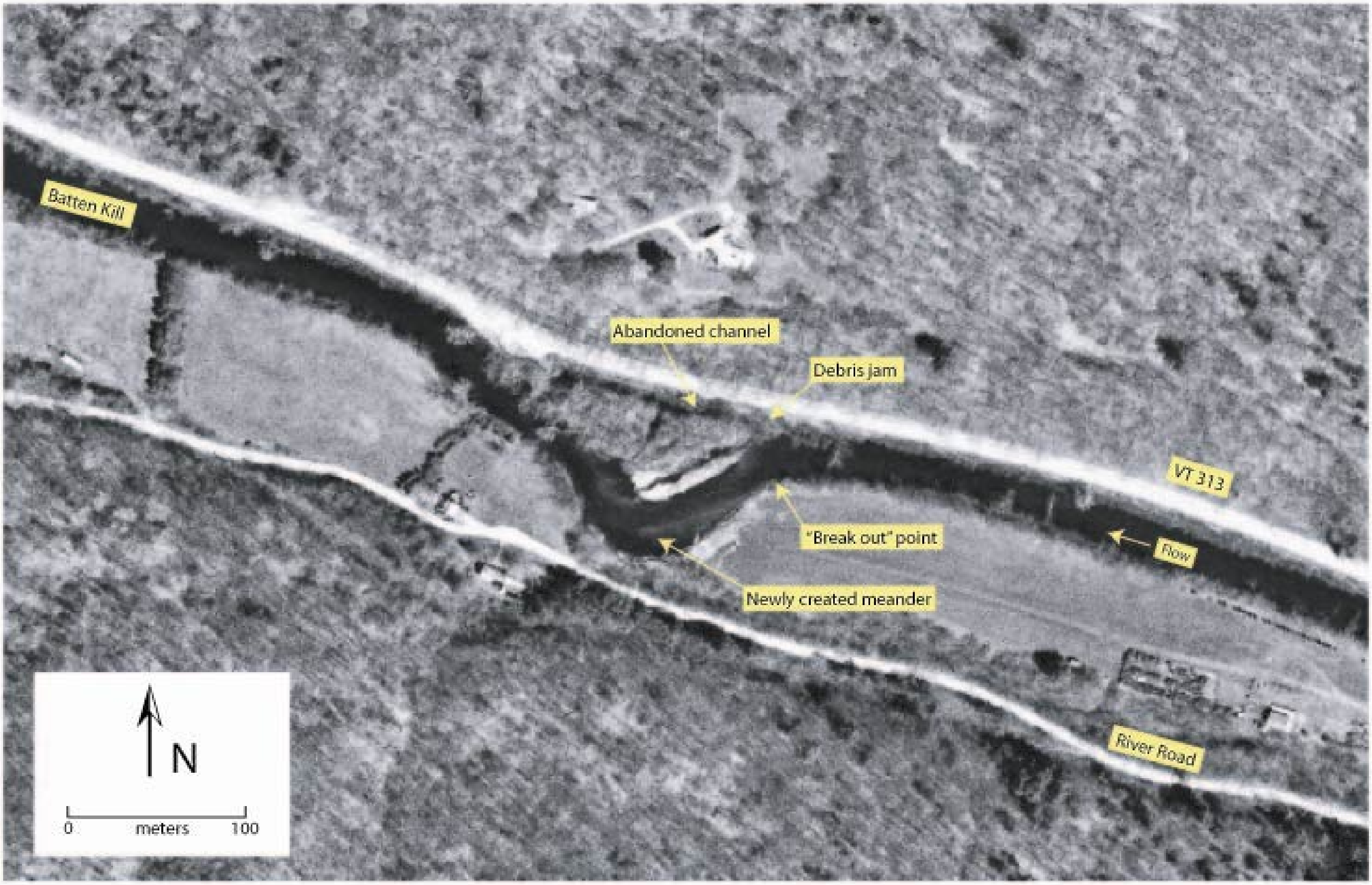


Figure 4. New meander created along straightened segment of the Batten Kill (Segment M3-B) where debris jam caused floodwaters to "break out" across the floodplain. Increase in channel length promotes sediment and flow attenuation.

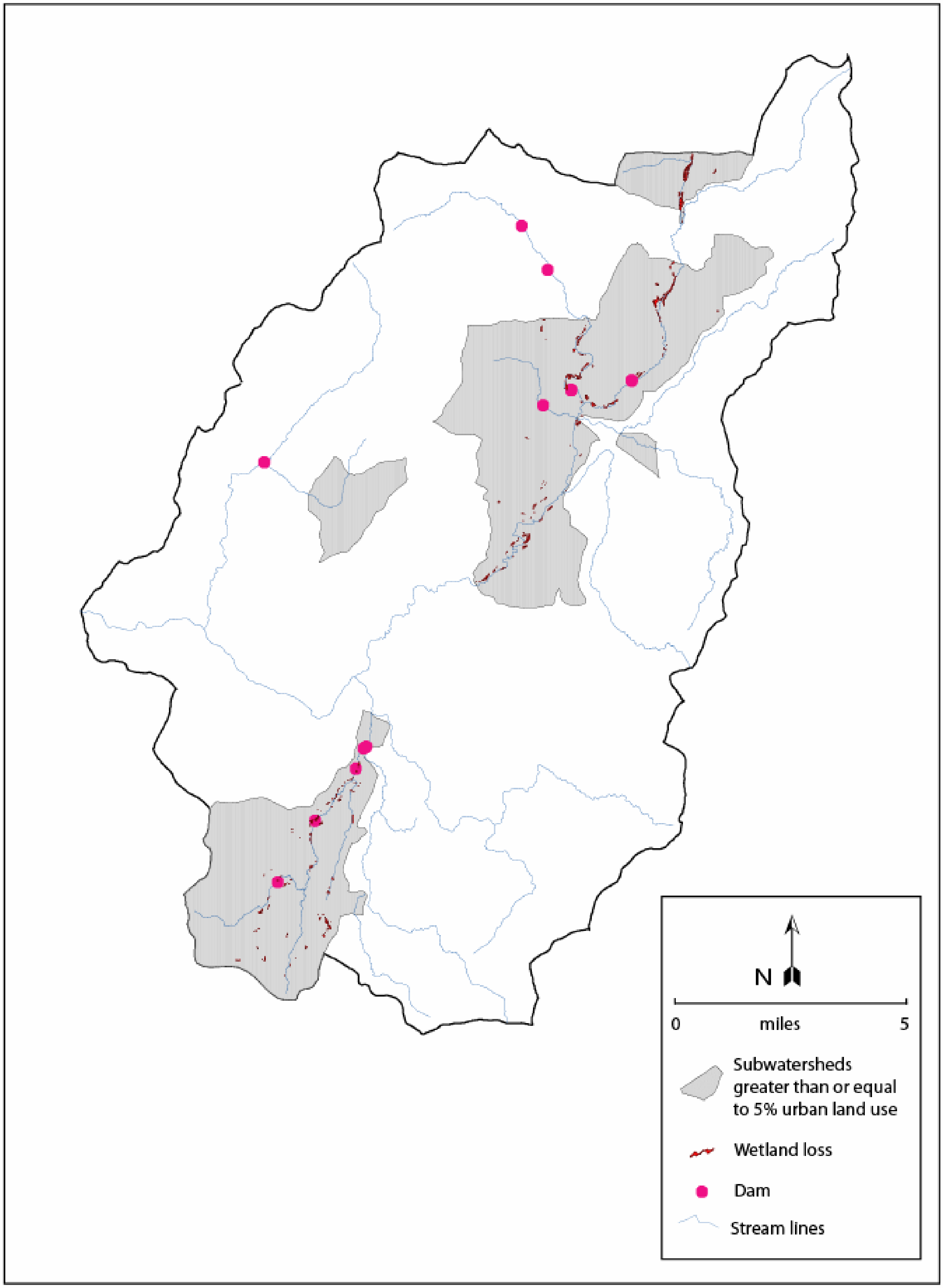


Figure 5a. Hydrologic alterations map showing human conditions that are potentially altering discharge in channel except road density (see Figure 5b).

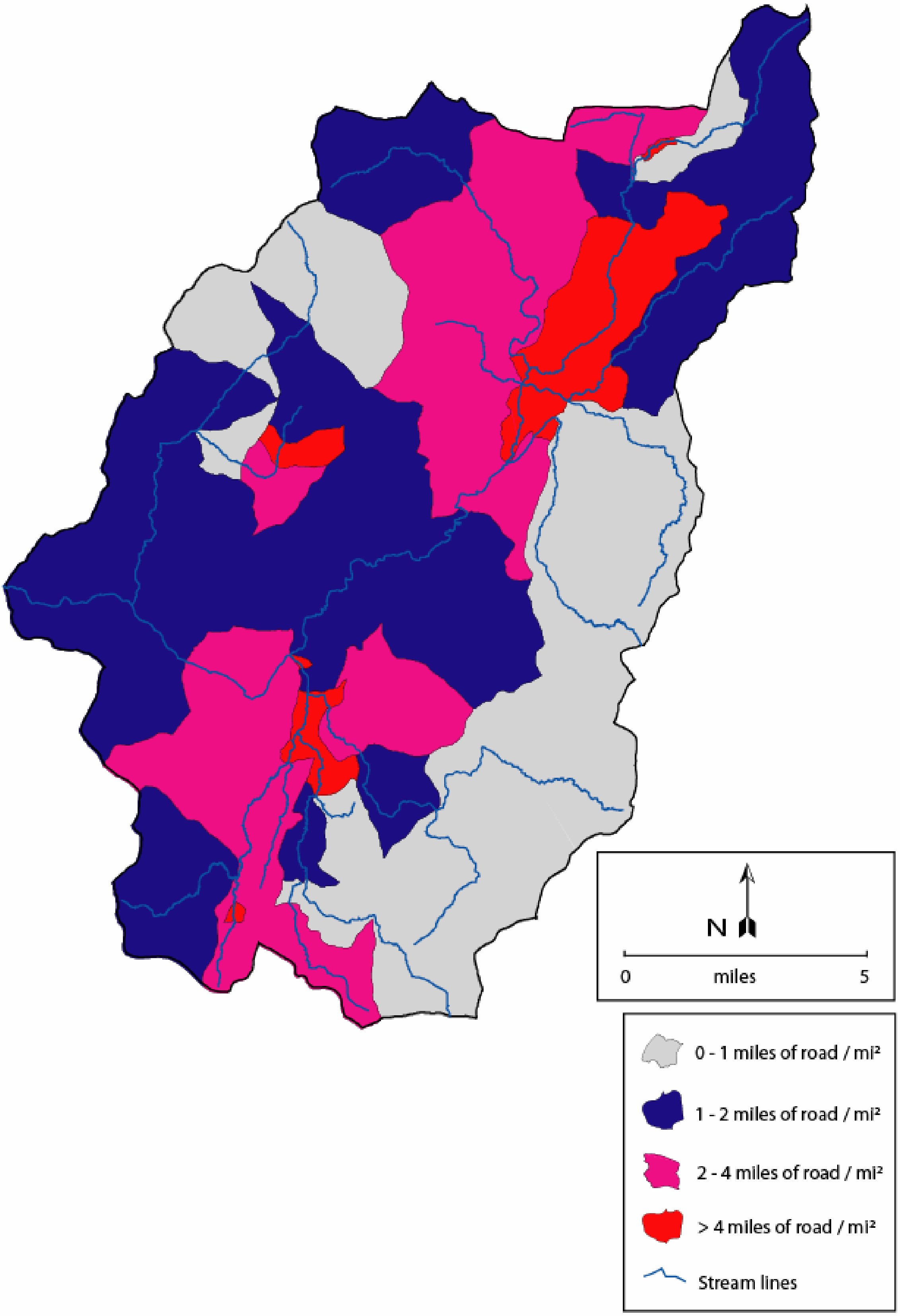


Figure 5b. Road density map showing greatest concentration of roadways that might be contributing to greater and faster runoff to stream channels.

Figure 6. 1913 ground photograph in Arlington, VT showing cleared hillslopes that contributed large quantities of sediment to the valley bottom.

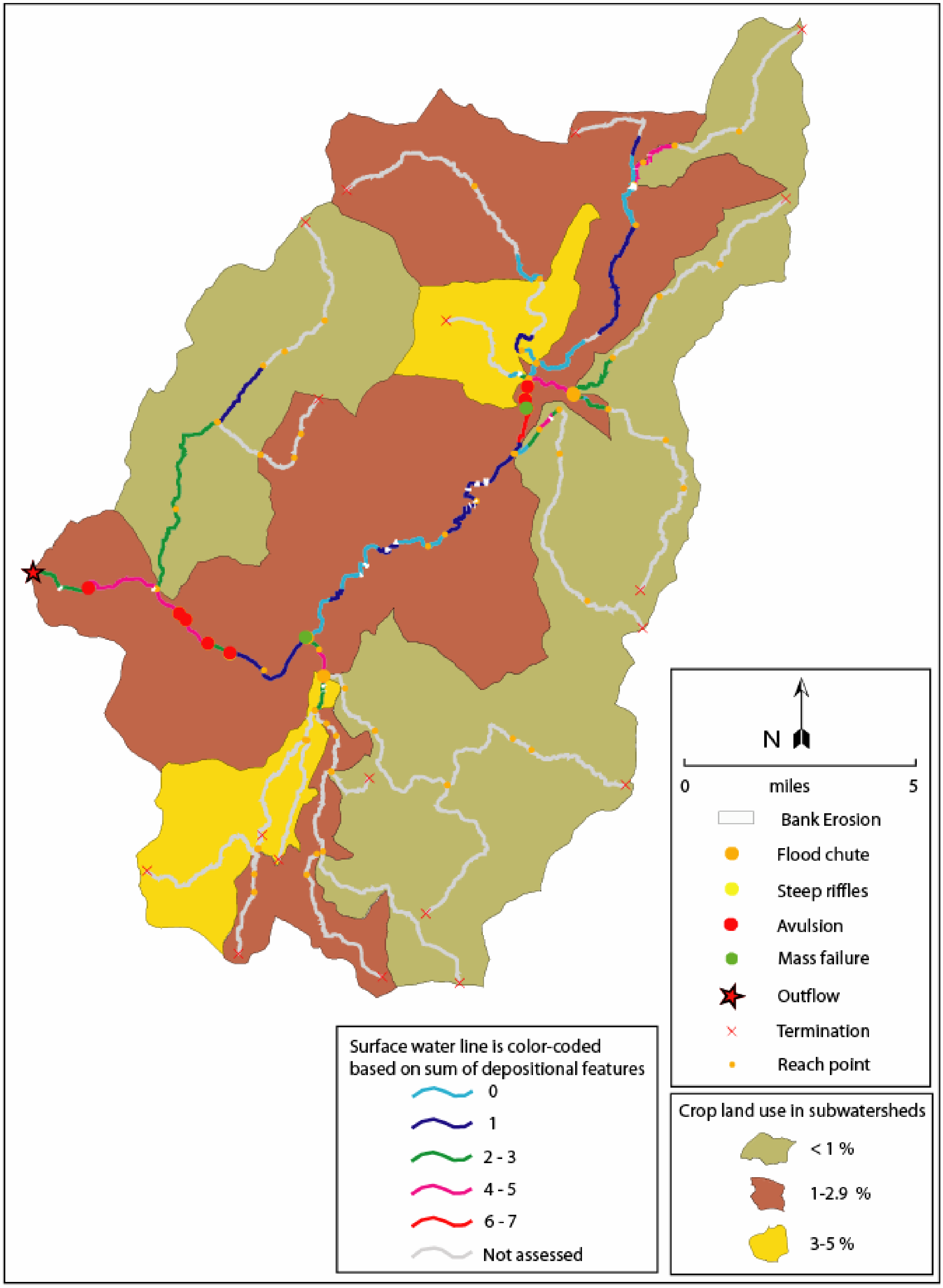


Figure 7. Sediment load indicators map highlighting both sources and sinks of sediment within the channel network.

Figure 8. Mass wasting at confluence of Roaring Branch. A portion of the gravel delta bar at the mouth of the bermed tributary bar is visible in the right foreground.

Figure 9. Historic sediments (light colored) deposited over older floodplain sediments (dark colored) in response to post-European settlement land clearance. Base of stadia rod is on contact between 2 deposits.

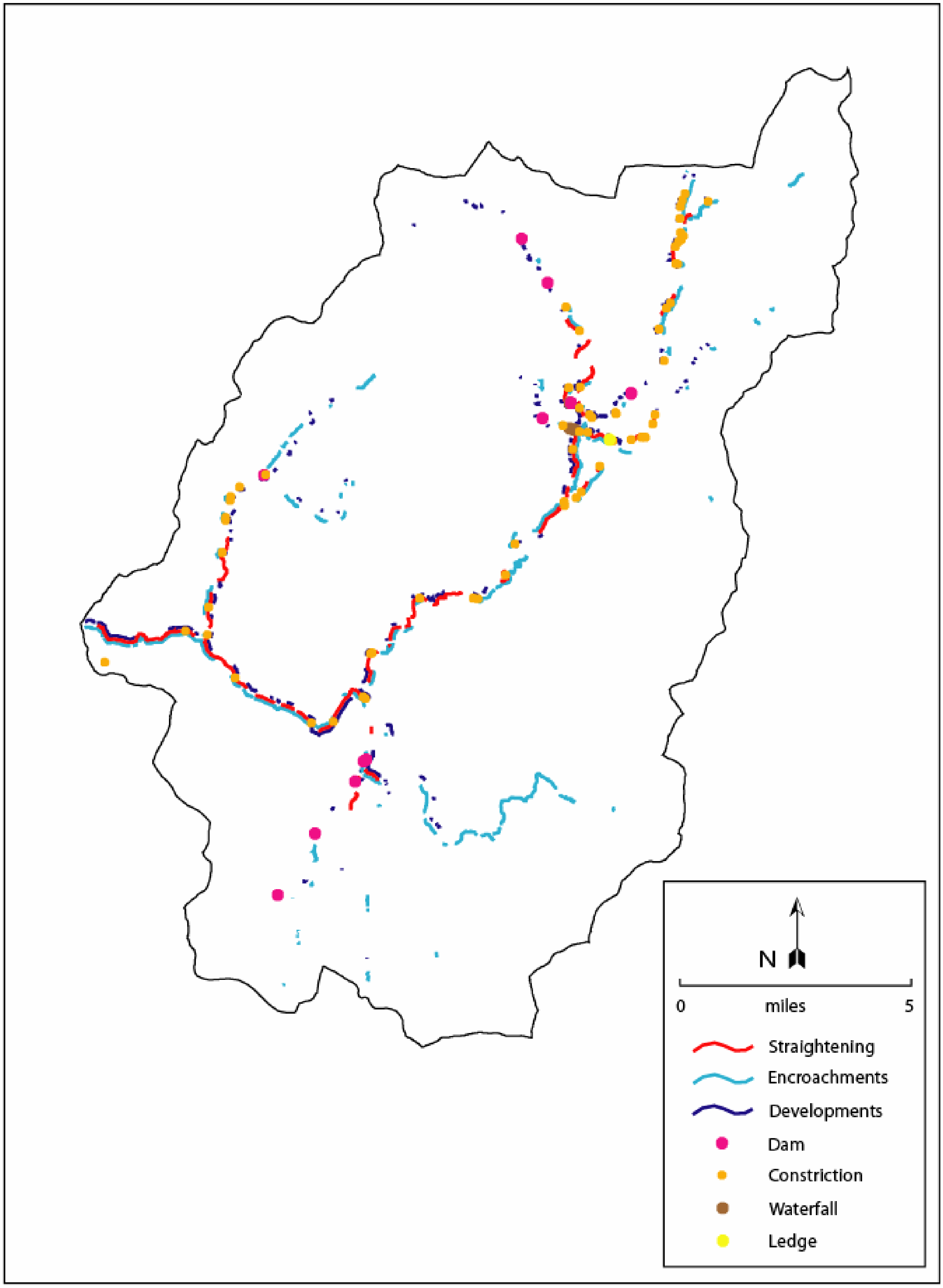


Figure 10a. Channel slope modifiers map. Reach breaks and stream channel not shown for clarity.

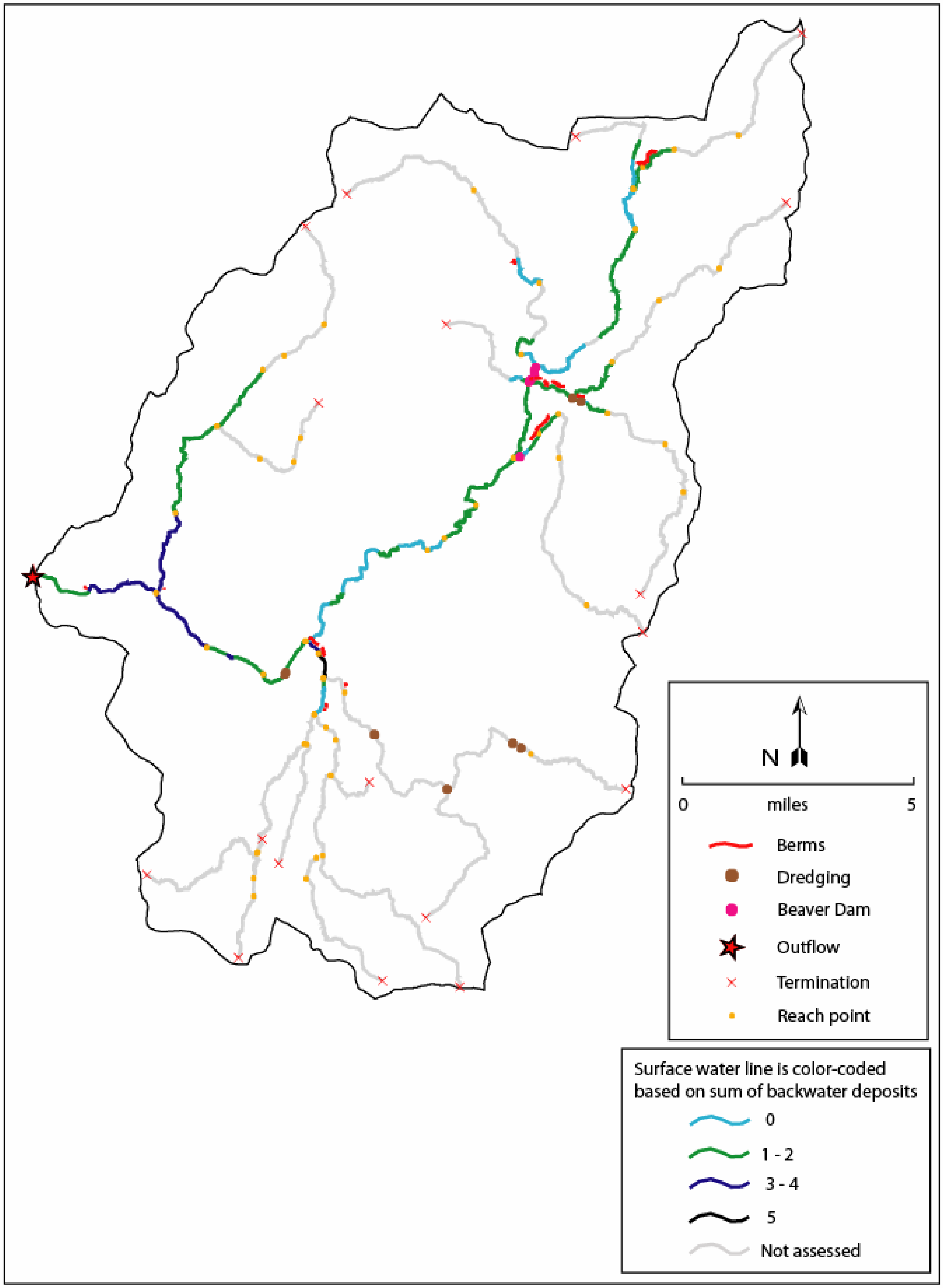


Figure 10b. Channel depth modifiers map.

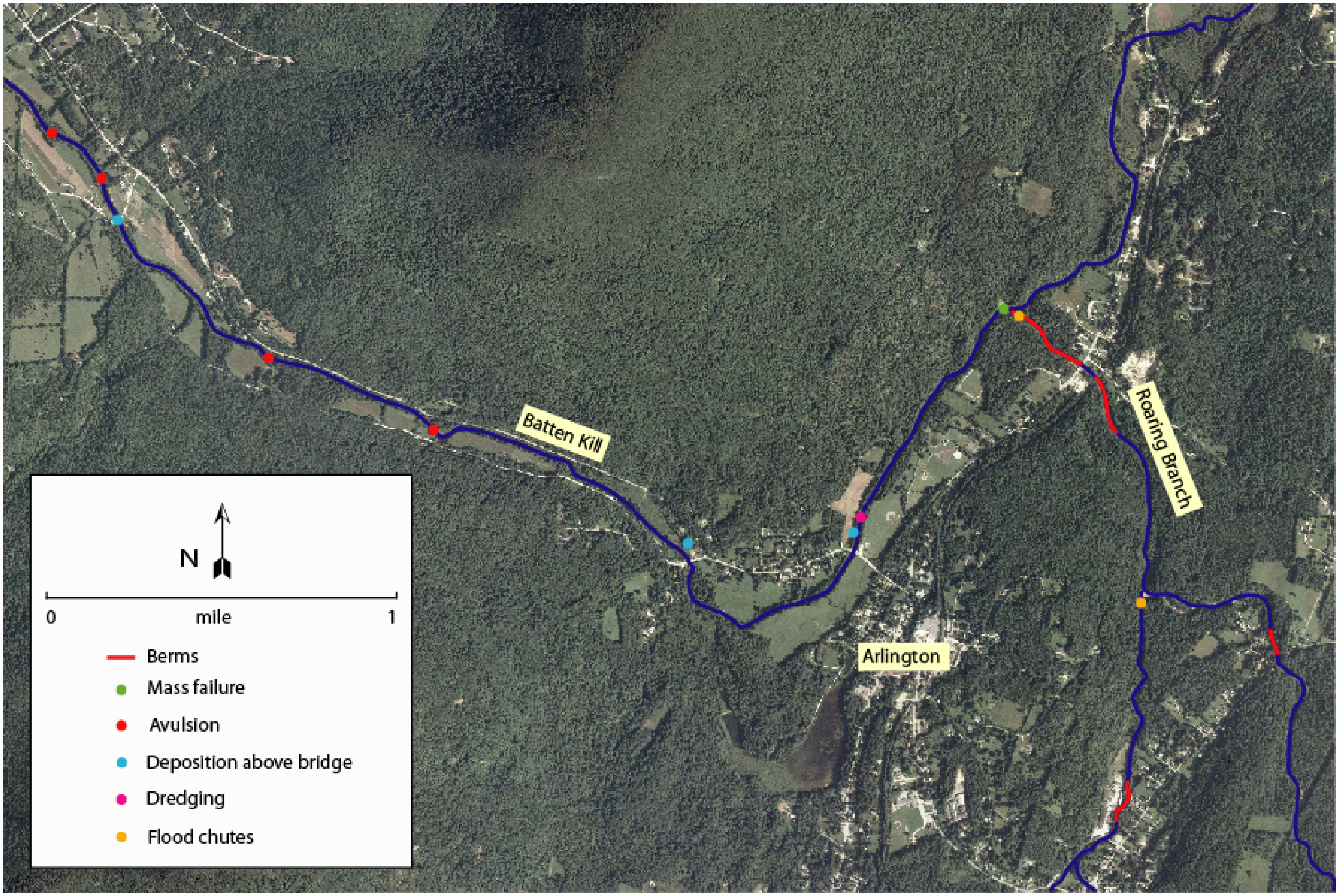


Figure 11. Close up of berming on Roaring Branch and resulting stressors created on the mainstem.

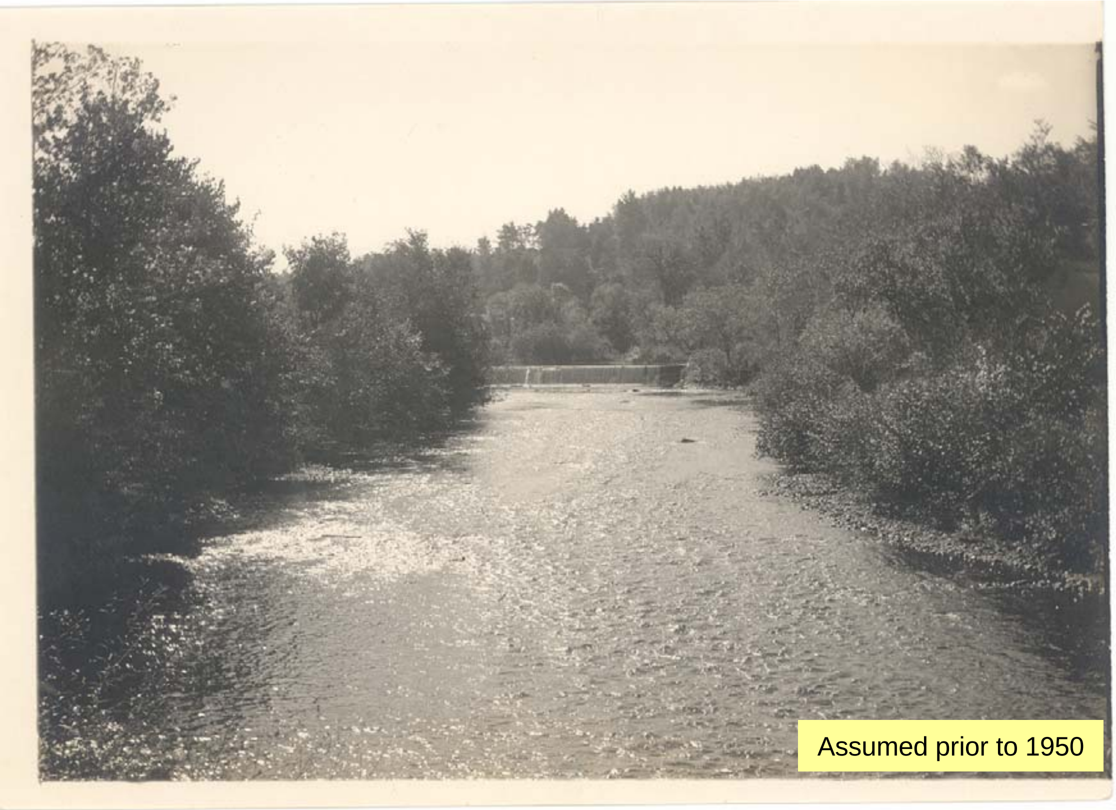


Figure 12. Photographs from the same position looking upstream from the West Mountain Bridge in Arlington (Reach M3) showing growth of gravel bar and meander in backwater of bridge due to excess sediment delivered from breached dam (visible in old photograph) and Roaring Branch after construction of berms in 1973.

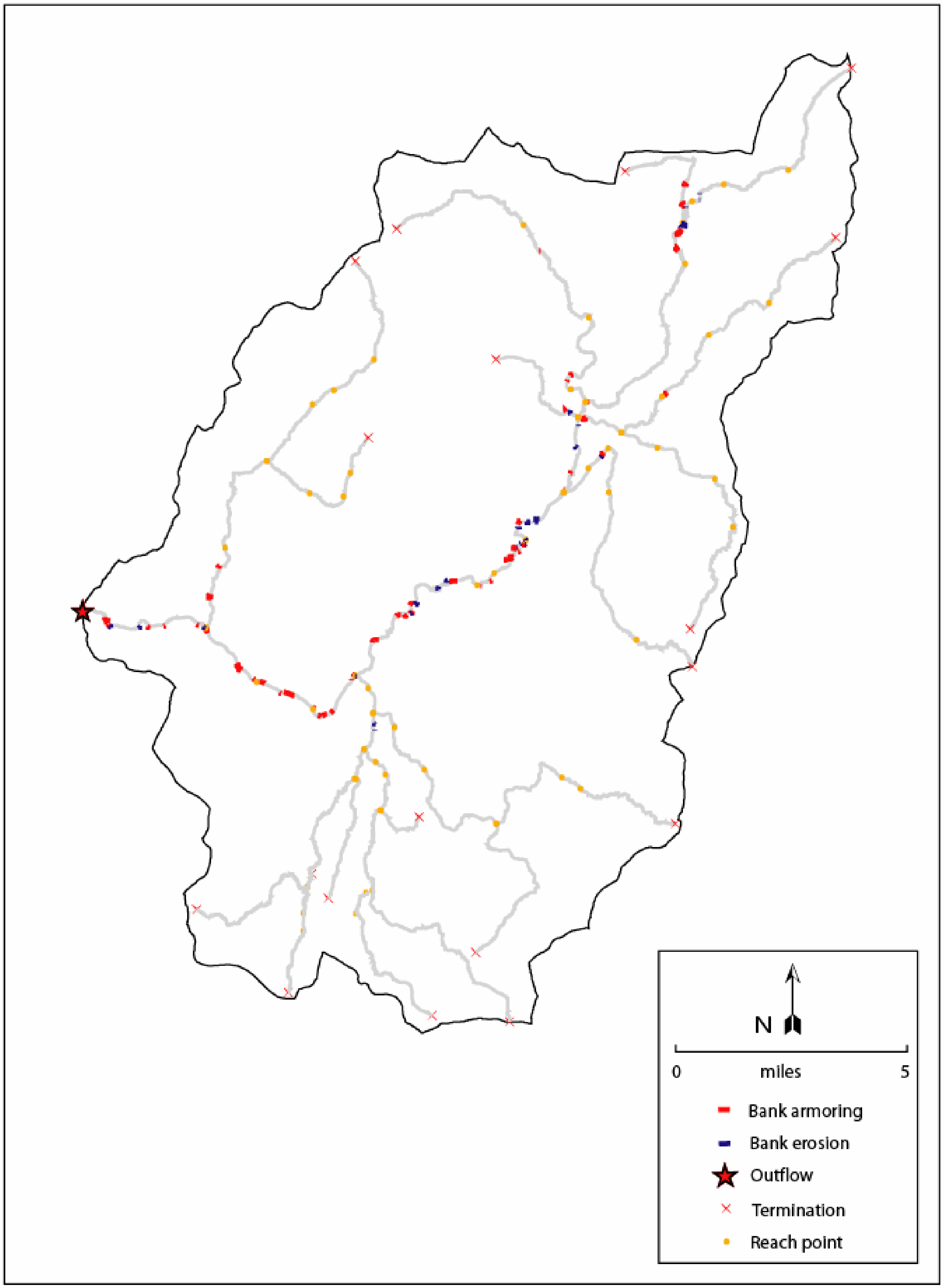


Figure 13a. Boundary conditions map. Note relative lack of erosion within assessed reaches.

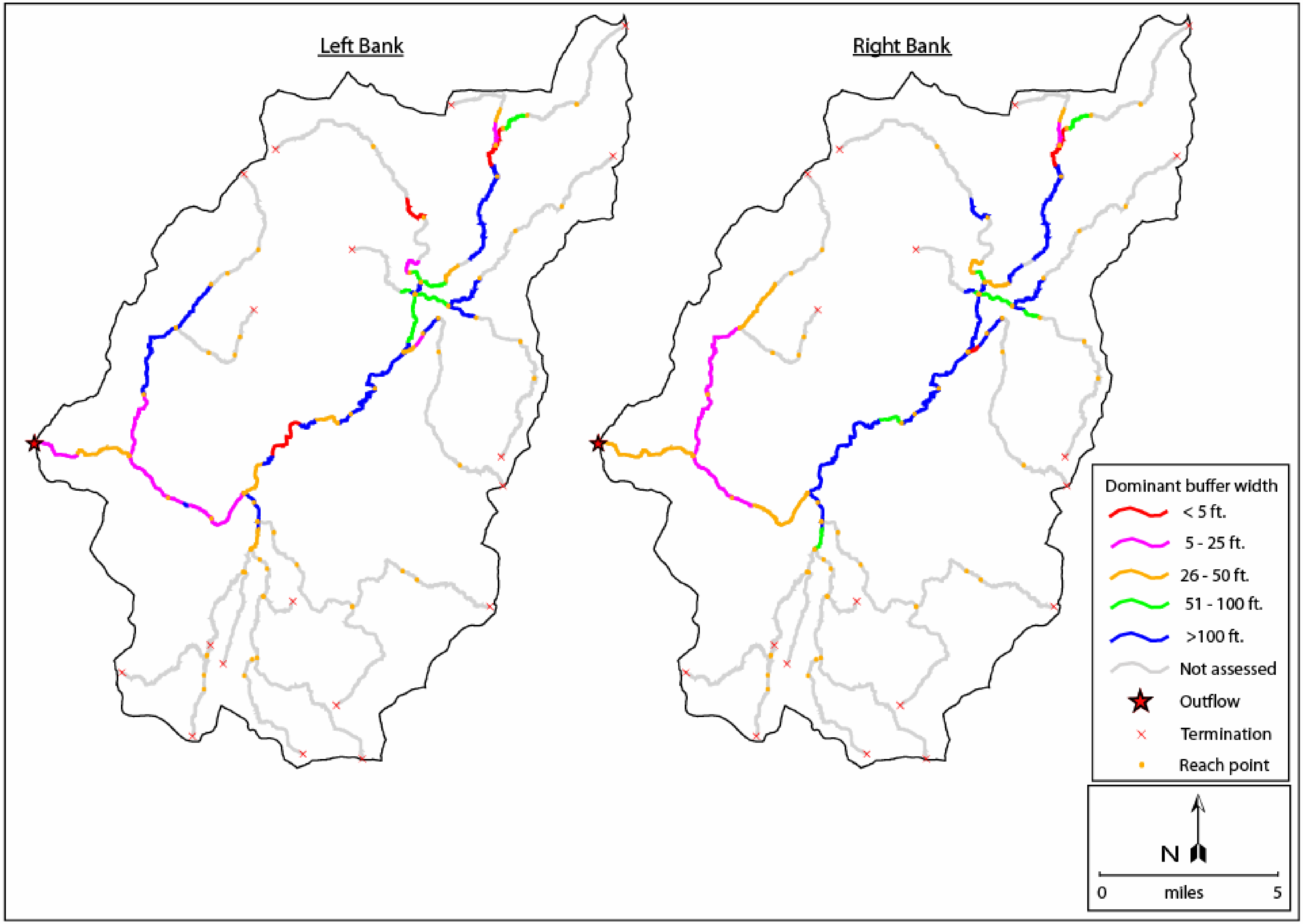


Figure 13b. Riparian modifiers map showing width of riparian buffer.

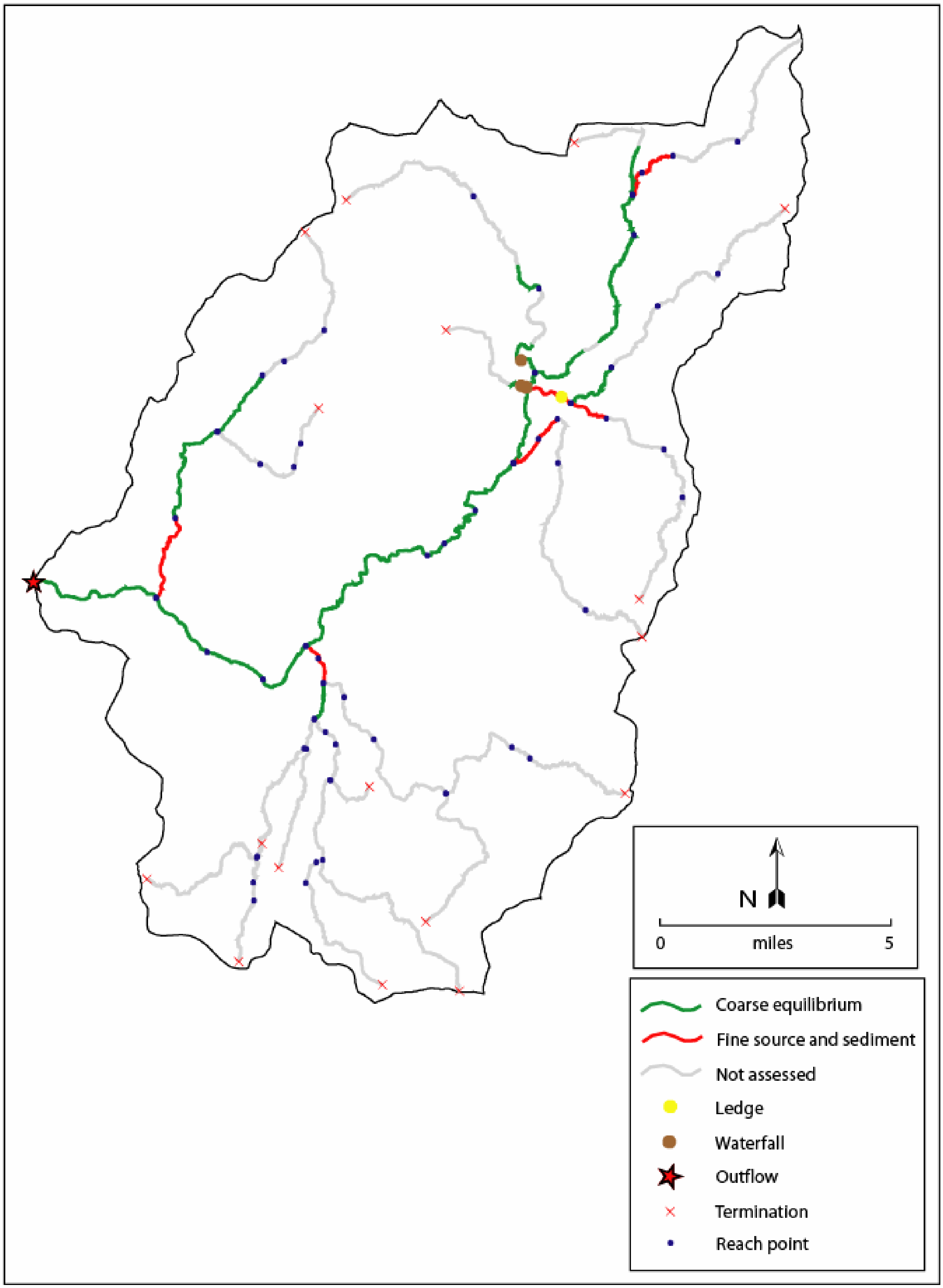


Figure 14. Reference sediment regime type that is thought to have existied prior to European settlement of the region.

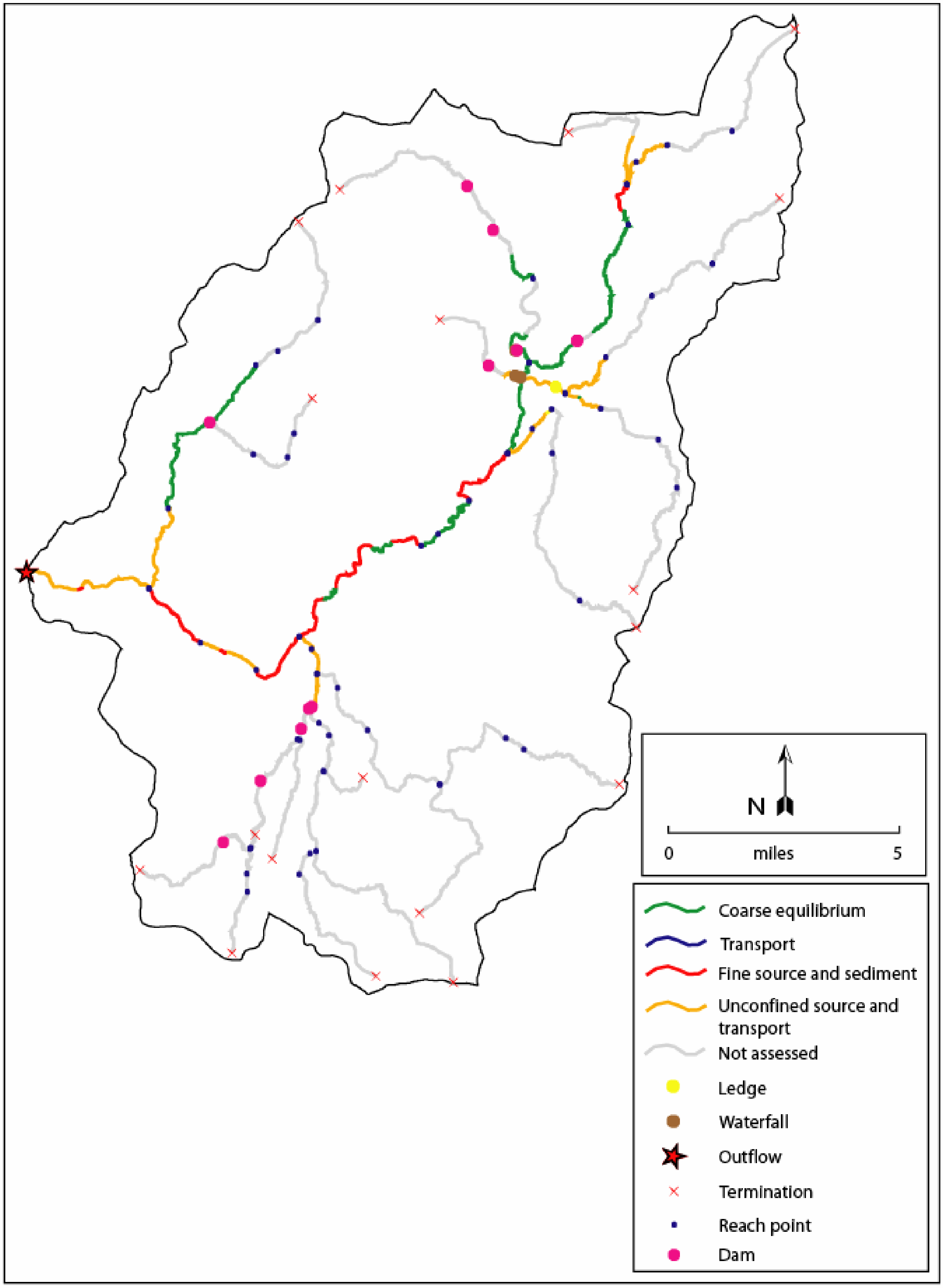


Figure 15. Existing sediment regime type. Compare with Figure 14.

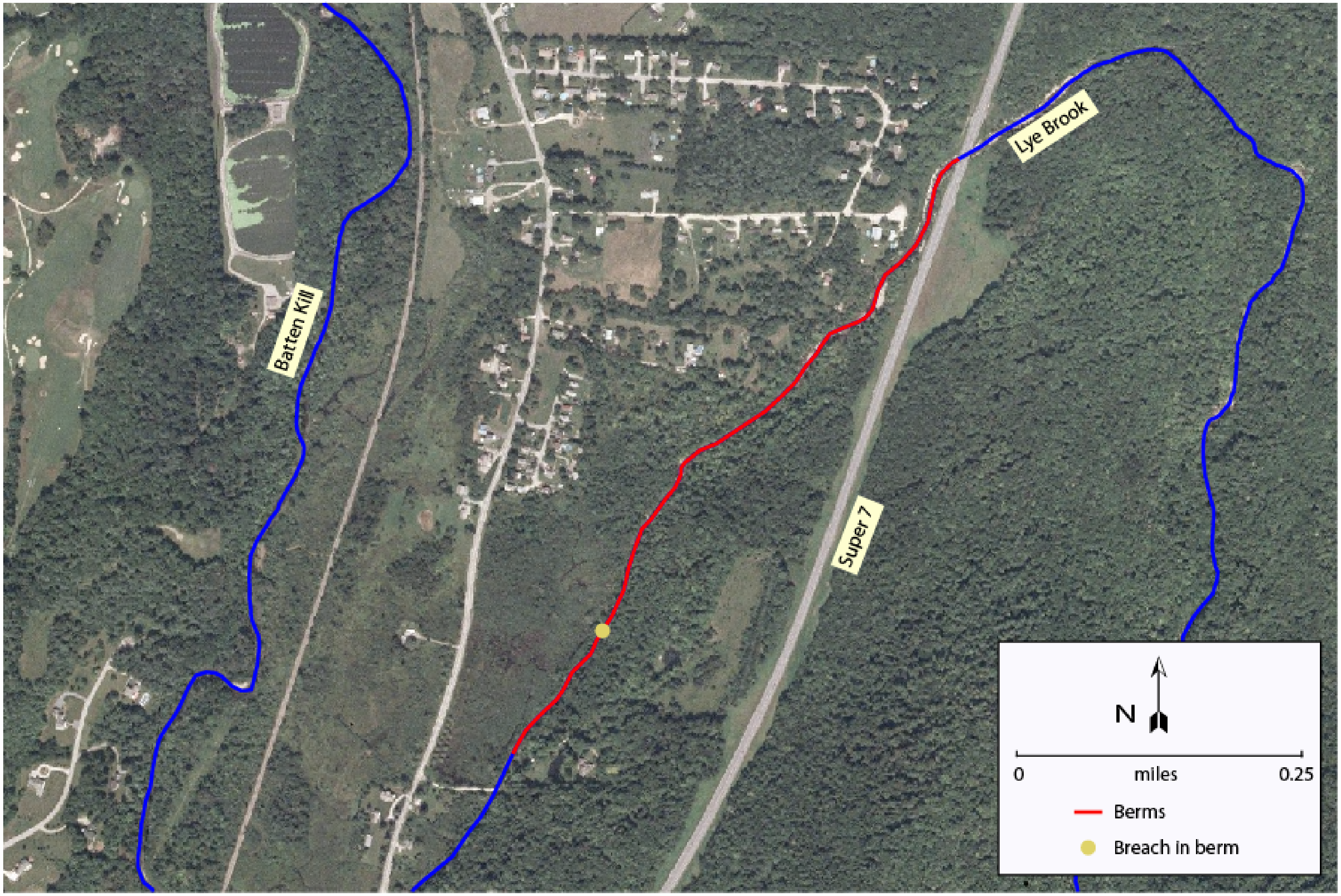


Figure 16. Close up of Lye Brook alluvial fan showing location of berms relative to human developments.

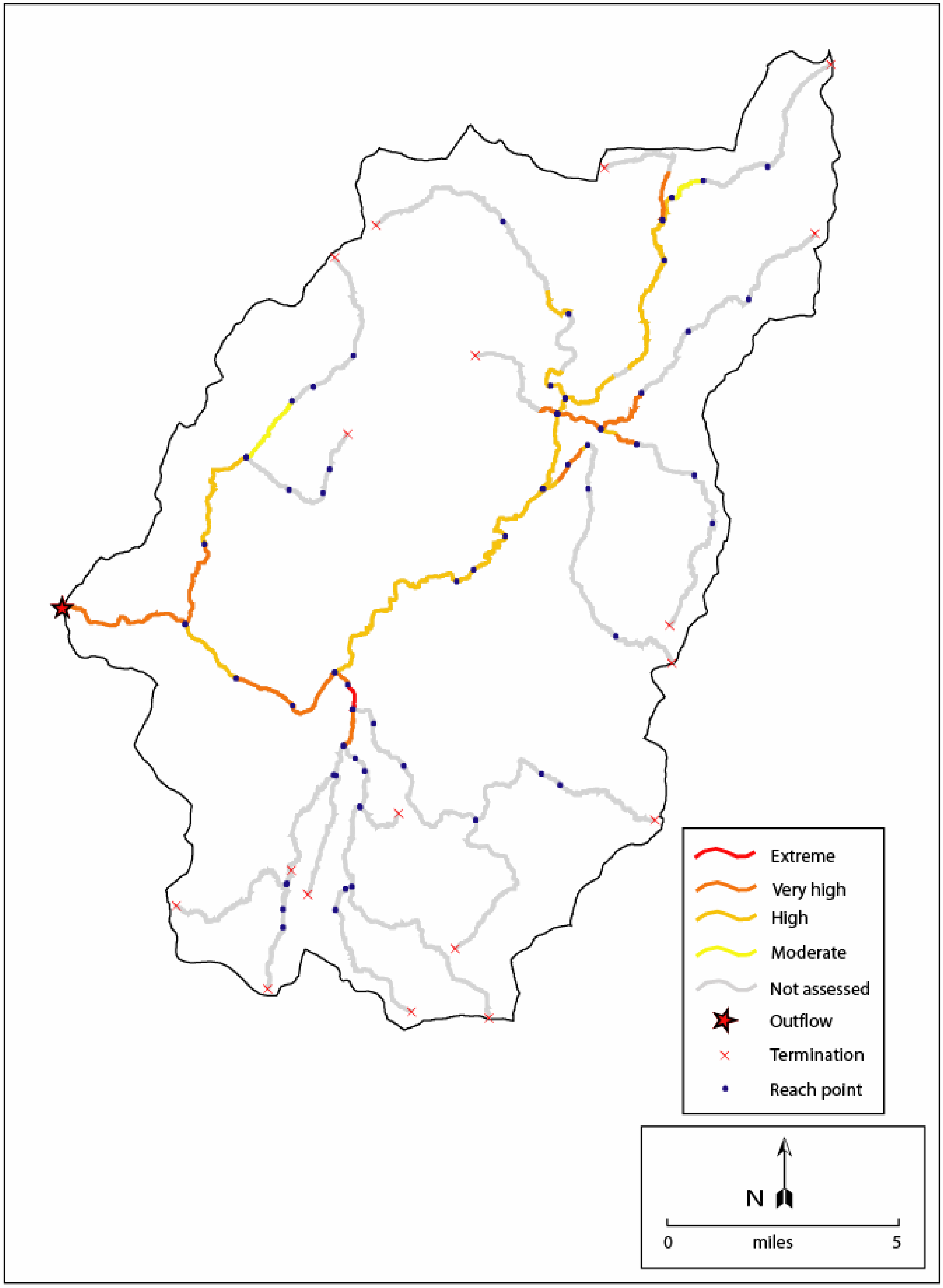


Figure 17. Sensitivity rating map showing areas most susceptible to future channel adjustments.

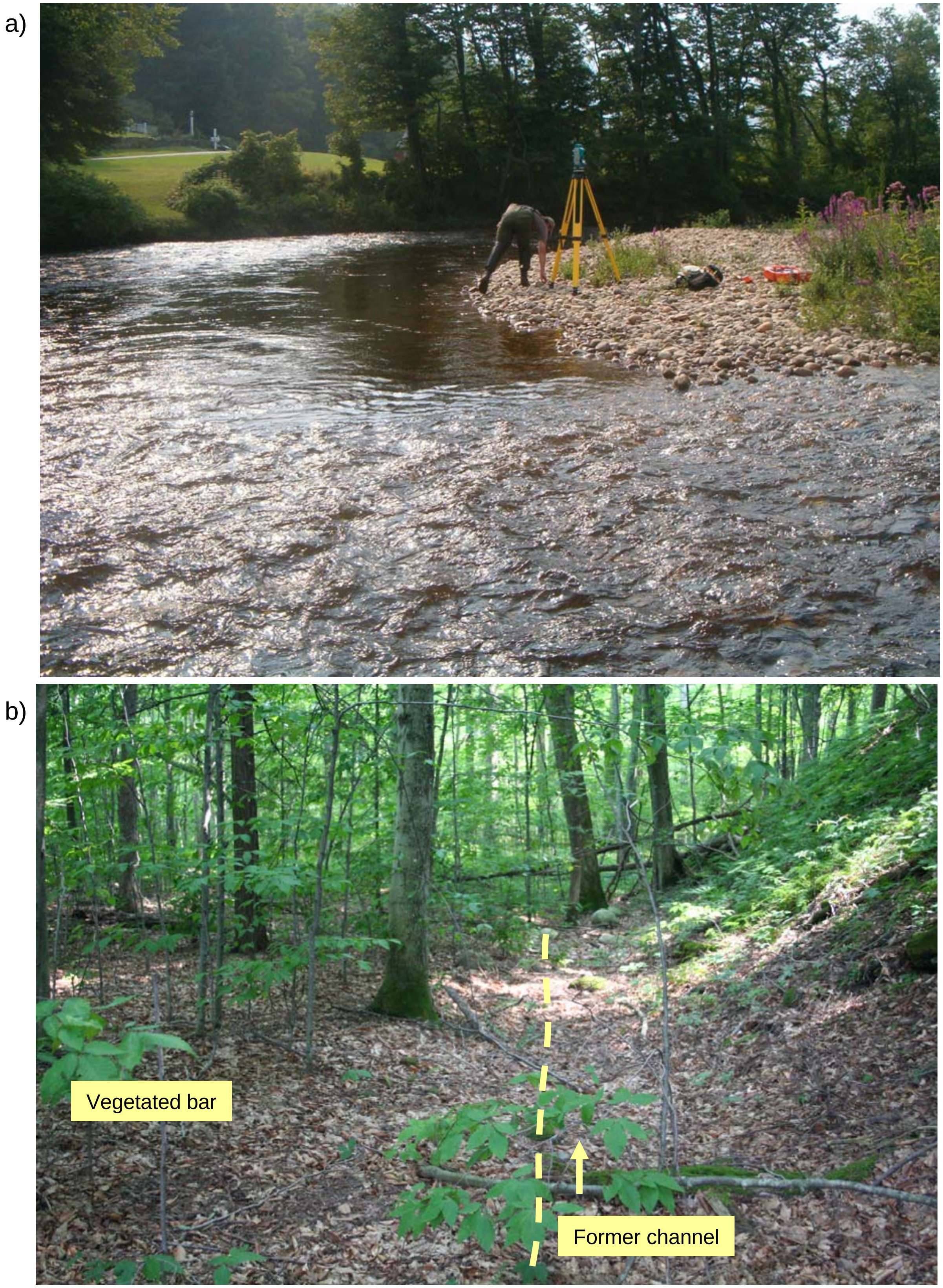


Figure 18. a) Unvegetated gravel bar on inside bend of recently formed meander at “break out” point in Segment M3-B. b) Vegetation covering older gravel bar formed when formerly straightened channel (shown) was formed to create a meander (not shown) in Reach M9.