Ammonoosuc River Geomorphology Based River Corridor Planning Guide

Prepared for

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EXECUTIVE SUMMARY

Based on the results of a geomorphic assessment, corridor planning guidance for the Ammonoosuc River in New Hampshire is provided that identifies the potential causes of flooding and erosion hazards, increased sediment loading, and degraded aquatic habitat. Past land management activities within the river corridor and channel have upset the balance of sediment transport along the river with straightened channels and constrained floodplain areas now more efficiently transporting sediment downstream. The increased efficiency in sediment transport has caused aquatic habitat to be degraded through channel incision, bank erosion, substrate armoring, and loss of flow complexity. The excess sediment is now deposited and concentrated upstream of dams or natural valley constrictions where the sediment transport capacity declines. Where sediment accumulates the channel experiences rapid bank erosion and channel migration as the flow is deflected around the growing gravel bars. A number of restoration techniques can be used to address these and other erosion hazard and habitat concerns such as corridor protection, riparian buffer plantings, removal of floodplain constraints, bank stabilization with bioengineering methods, and using log jams to encourage meander formation along straightened reaches. Hard armoring techniques may be unavoidable in some instances where bank stabilization is needed to protect infrastructure immediately adjacent to the river. However, those restoration efforts that address the underlying causes for channel instability will more sustainably reduce erosion hazards and improve aquatic habitat. The most appropriate restoration techniques for each reach along the Ammonoosuc River has been identified from a technical standpoint, although social and political factors might complicate implementation of some of the proposed projects. In addition, 23 potential projects have been prioritized along the river's length that address the severest hazards and, if implemented, should provide improvements to aquatic habitat while reducing downstream sediment transport.

1.0 INTRODUCTION

The geomorphology based river corridor planning guide for the Ammonoosuc River in New Hampshire presented herein is the product of a Phase 2 geomorphic assessment completed by Field (2011). The Phase 2 geomorphic assessment was carried out using procedures developed and outlined by the Vermont River Management Program (Web citation 1). The river corridor from a geomorphic perspective is defined as that portion of the floodplain across which the river may shift due to avulsions (i.e., rapid formation of a new channel) or, more slowly, through persistent bank erosion and channel migration. Past and current human activities in the Ammonoosuc River watershed (e.g., 19th century land clearance), river corridor (e.g., homes and businesses by the river), and in the river itself (e.g., dams and past channel straightening) has engendered river channel adjustments (i.e., deposition and erosion) that have exacerbated flooding and erosion hazards, increased sediment loads, and degraded aquatic habitat. Identifying the location, cause, and source of those problems is a critical component of the corridor planning process and can help communities select appropriate and sustainable techniques to restore unstable areas along the river.

The Ammonoosuc River has a watershed area of 395 mi^2 and flows for nearly 60 mi from the western slope of Mount Washington through the towns of Carroll, Bethlehem, Littleton, Lisbon, Landaff, Bath, and Haverhill before reaching its confluence with the Connecticut River (Figure 1). The New Hampshire Department of Environmental Services has included the river in the New Hampshire River Management and Protection Program in recognition of the river's outstanding natural and cultural resources (Web citation 2). For the purposes of the Phase 2 geomorphic assessment, the Ammonoosuc River was subdivided into 50 reaches of uneven length with the natural setting within a given reach largely similar throughout its length but distinct from the conditions of adjacent reaches (Figure 2 and Table 1). Each reach is numbered sequentially from the downstream end and assigned the prefix "M" to indicate the reach is on the mainstem of the Ammonoosuc River. The breakpoints between reaches are often the location of rapid natural changes in the valley conditions whether due to an expansion or contraction of valley width, input of sediment at a large tributary confluence, or presence of a bedrock waterfall. Consequently, since the river adjusts to the changing settings, reach breakpoints tend to be the location of ongoing channel adjustments and are typically the most sensitive to watershed perturbations caused by human activities. Six of the 50 reaches are further subdivided into two segments each, because human activities have significantly altered the character of the channel within the reach such as results when a portion of the reach has been artificially straightened. The Phase 2 assessment was completed for each reach and segment (Field, 2011) and the corridor planning recommendations presented below are similarly made for each reach and segment, because these subdivisions of the river accurately reflect: 1) where different types of channel adjustments are occurring, 2) differences in the channel's sensitivity to future changes, and 3) potential responsiveness to proposed restoration activities.

The geomorphology based river corridor planning guide is comprised of four major components with the purpose of: 1) locating those features in the watershed and along the river that may be a causal factor of channel instabilities; 2) delineating those reaches actively undergoing adjustments or most sensitive to future adjustments; 3) describing restoration techniques that can be used to address both channel instabilities and the causal factors for those instabilities; and 4) identifying high priority restoration sites on the Ammonoosuc River and selecting the most appropriate restoration strategies for those sites. After a brief primer in fluvial geomorphology and its value in corridor planning, each component of the corridor planning guide is described in detail below.

2.0 FLUVIAL GEOMORPHOLOGY AND ITS VALUE IN CORRIDOR PLANNING

The science of fluvial geomorphology is devoted to understanding how the natural setting and human land use in a watershed effect river channel processes and form (i.e., channel dimensions and shape). A river adjusts its slope, channel dimensions, and planform geometry in order to reach an equilibrium condition where both the water discharge and sediment are conveyed through the channel without causing significant changes in the channel's morphology. A channel adjusts its morphology through erosion or deposition in response to alterations in the amount of water and sediment supplied from the watershed. Through these adjustments, the channel eventually achieves a state of equilibrium where the channel dimensions remain relatively constant as long as no significant watershed perturbations occur. River channels may not reach an equilibrium condition for thousands of years when responding to climatic influences (e.g., deglaciation in New England), so channel changes may be ongoing throughout the design life of a river restoration project. However, channels can also respond quickly to a single large flood or to direct human activities in the stream channel such as the construction of a dam across the river. Furthermore, geomorphic equilibrium does not mean the river channel is static; sensitive river reaches can experience rapid bank erosion and changes in channel position while still maintaining the same dimensions, slope, and shape, as long as the erosion is balanced with an equal amount of deposition. Consequently, river corridor protection and restoration projects are more likely to succeed if a geomorphic assessment is completed to better understand how the channel is responding to human activities in the watershed and how the channel might respond to proposed management efforts.

Channels that have been artificially straightened, a common practice on the Ammonoosuc River in the 19th century, pass through a series of predictable evolutionary changes in order to reestablish an equilibrium meandering planform (Schumm et al., 1984). First, the increased slope and sediment transport capacity resulting from the straightening initially causes incision (i.e., lowering) of the channel bed. Second, as increasing amounts of flow are confined to the deepening channel, a period of channel widening results from the greater shear stress exerted on the banks. Third, the channel eventually widens to the point that smaller flood flows spread out across the widened channel and are unable to transport sediment through the reach. The resulting deposition builds up the channel bed and reverses the earlier incision. Finally, flow deflected around the growing sand and gravel bars encourages the carving of new meanders that are inset within the widened channel or spread out over the preexisting floodplain. With the reformation of meanders, the channel closely approximates its former planform and equilibrium condition. In response to channel straightening in the 19th century, the Ammonoosuc River has already undergone a period of incision and widening with some areas experiencing deposition and reformation of meanders. Understanding which stage of channel evolution a given reach is experiencing can help predict how the channel will respond in the future and what restoration strategies may be most appropriate for reducing flooding and erosion hazards, decreasing sediment loads, and improving aquatic habitat.

3.0 CAUSAL FACTORS OF CHANNEL INSTABILITIES

Past human land use and river management practices in the Ammonoosuc River watershed have initiated numerous channel adjustments that have degraded habitat, increased sediment loads, and placed property and lives at risk to flooding and erosion. Stream channel adjustments result from significant watershed-scale changes in water, sediment, and wood inputs into the channel or by changes within a river reach that alter the river's ability to transfer the water, sediment, or wood delivered to the channel. A stream channel in equilibrium is capable of transporting water, sediment, and wood 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, mutual adjustments in the channel's dimension, pattern, and profile ensue until a new equilibrium condition is achieved whereby the channel is once again capable of transporting the water, sediment, and wood delivered to the river. 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 the boundary conditions (i.e., resistance to bed and bank erosion).

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 that were believed to be present prior to human impacts. Human stressors in the watershed or along the river are human imposed conditions that increase the likelihood of a channel response. The cumulative impact of several stressors or a single stressor impacting a large watershed area or long length of the river is more likely to induce channel changes. 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 channel adjustments responsible for increased flood and erosion hazards, higher sediment and nutrient delivery, and significant habitat degradation. Several human land uses and activities in the watershed (e.g., land clearance), along the river corridor (e.g., gravel extraction on the floodplain), and in the river (e.g., hard armoring of the river banks with riprap) are capable of inducing stream channel adjustments, because these actions change the amount of sediment, water, and wood delivered to and passing through the channel. The identification and mapping of these conditions are necessary to accurately determine the potential causes of ongoing and future channel adjustments. The watershed-scale and reach-scale human stressors in the Ammonoosuc River watershed that are most likely leading to changes in the hydrologic, sediment, and wood 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 potentially alter the discharge reaching a certain point on the river. While quantitative measurements of hydrologic changes are beyond the scope of this report, a number of human activities are known to modify the timing, volume, and duration of flows such as urbanization, stormwater discharge, dams, and road networks. Maps of road density serve as a proxy for total development in a watershed and the potential for increased and concentrated runoff to the river (Appendix 1). In contrast, mapping the location and extent of wetlands and hydric soils, a proxy for unmapped wetland areas, can reflect the potential of a watershed to slow the passage of runoff to the river. Mapping the location of water withdrawals, stormwater inputs, dams, and beaver dams show areas where sudden decreases or increases in runoff downstream might be more directly impacting adjacent areas of the river channel. Hydrologic alterations maps showing the extent and distribution of all of these factors in the Ammonoosuc Watershed reveal several subwatersheds with relatively high impacts, particularly Reach M20 in Littleton with numerous stormwater inputs and a subwatershed with a high road density (Appendix 1). (A subwatershed of a given reach is the drainage area that feeds directly into that reach and not from further upstream). Significant hydrologic alterations should not be construed, however, as the cause of bank erosion or other channel adjustments. The high road density and associated development in the Littleton area may be increasing runoff and potentially impacting small tributaries within the subwatershed. However, increases in runoff from this subwatershed, representing only 1.3 percent of the total watershed area to this point, are unlikely to be

significantly increasing the total discharge of the Ammonoosuc River. In general, impervious surfaces must cover 10 percent or more of a watershed before increases in runoff are significant enough to initiate a channel response or impact biotic diversity (Booth et al., 2002). Urban land use is locally significant in and around most of the villages in the Ammonoosuc River watershed, but represents only a small percentage of the entire watershed area, which includes vast forested uplands. Maintenance of these forested upland areas is therefore critical for buffering the river channel against the potential impacts of increasing development in the lower watershed.

Dams have the potential to impound water upstream and release water downstream at a rate slower than the discharge entering the impoundment. Dam operations such as this result in decreases in peak flows downstream with potentially significant impacts on channel morphology (Williams and Wolman, 1984). Five large extant dams are present on the Ammonoosuc River mainstem, but they all function as "run of the river" facilities, meaning that the discharge entering the impoundment equals the discharge flowing downstream. Several other dams were previously present on the river but no longer impact flows. Consequently, impacts to the hydrologic regime resulting from past and present dams on the Ammonoosuc River are not believed to be significant, although their impact on the sediment regime is much greater (see Section 3.2 below).

3.2 Watershed-scale sediment regime stressors

A river in geomorphic equilibrium matches the sediment delivered to a stream reach with the river's capacity to transport sediment through that reach. This is achieved through mutual adjustments in the channel's width, depth, slope, and boundary conditions (i.e., coarseness of wood and sediment substrate). This equilibrium balance in sediment movement through a reach can be disrupted by changes in the amount of sediment delivered to the channel (i.e., sediment load) and/or changes in the channel's capacity to move sediment through the reach relative to upstream conditions. Aggradation, or sediment accumulation, occurs when the sediment load is increased, as at mass wasting sites (Figure 3a) or tributary confluences (Figure 3b), or the river's capacity to transport sediment is decreased, such as in the impoundments upstream of dams (Figure 4a) or natural valley constrictions (Figure 4b). Degradation, or loss of sediment through erosion, occurs when the sediment load is decreased (e.g., downstream of impoundments) or capacity to transport sediment increased (e.g., along straightened reaches). Identifying potential sediment sources (or lack of sources) and disruptions in transport capacity is, therefore, critical for anticipating the type and location of channel adjustments along the river. Erosion and deposition occurs naturally along rivers in equilibrium, but rapid changes engender significant channel adjustments that harm aquatic habitat as is seen in the form of large unvegetated gravel bars in the case of aggradation (Figure 5a) and wide plane-bed channels in the case of degradation (Figure 5b).

Land Use/Land Cover maps can provide insights into potential sources of sediment in the watershed that might lead to aggradation and the formation of large unvegetated gravel bars. The relatively low percentage of agriculture in the subwatersheds of the Ammonoosuc River suggests direct runoff from fields may not greatly alter the total sediment budget of the river (Appendix 1). However, land use may, in part, contribute to the increases in sediment load observed at tributary confluences, particularly in those subwatersheds with more than four percent agriculture. The impact of agriculture is probably more keenly felt where riverside agriculture has resulted in the loss of a wide forested riparian zone. The associated loss in resistance to bank erosion may increase sediment loads directly to the river through the collapse of the river banks.

Deforestation in the watershed over a century ago exposed much of the watershed to erosion and dramatically increased sediment delivery to the valley bottom (Figure 6). Post European settlement deposits are common on floodplains throughout New England as a result of this land clearance (Brackenridge et al., 1988). While such deposits are likely present along the Ammonoosuc River, a detailed sedimentological study was not undertaken as part of this corridor planning process. Recent reforestation of the watershed has reduced sediment delivery considerably, but sediment supply likely remains higher than prior to land clearance. Consequently, reaches already naturally susceptible to aggradation (i.e., upstream of valley constrictions) are likely even more sensitive to reach-scale changes in sediment load or transport capacity due to these increased sediment loads at the watershed level.

The presence of dams may partially offset the higher watershed-levels of sediment resulting from earlier land clearance. Considerable sediment storage has occurred behind dams with the morphology of the river in the impounded areas greatly altered as a result. The impounded areas behind existing dams are nearly filled with sediment, so minimal storage potential remains behind these dams. The dams have been in place for many decades and the river channel has adjusted to their presence. The effect of high transport capacity along straightened channels can be enhanced by lower sediment loads downstream of the dams, but only if no tributaries or mass failures are supplementing the sediment deficit downstream of the dams. Future large-scale adjustments near dams are unlikely, but the poor habitat associated with the upstream impoundments and wide plane-bed channels downstream will persist without significant changes in the operation of the dams.

3.3 Reach-scale sediment regime stressors

Perhaps a more significant alteration to the sediment regime than changes in watershed sediment supply is the change in sediment transport capacity that has occurred along different reaches of the Ammonoosuc River. Land Use/Land Cover maps show considerable development within the corridor of several reaches on the Ammonoosuc River (Appendix 1). These maps provide an indication of those reaches where floodplain access might be blocked or where flood stage might be elevated as a result of developments filling in portions of the floodplain. Flow velocities and, therefore, sediment transport capacity are increased when floodplain storage area is lost by development. Large portions of the floodplain can be blocked by berms and railroad and highway grades that are built along the river and are higher than the surrounding floodplain (Figure 7). Channel Slope and Depth Modifiers maps of the Ammonoosuc River show where these features may be blocking access to the floodplain (Appendix 1). These maps indicate where human alterations of the river corridor might be increasing transport capacity and may elucidate the potential causes for known problem areas along the river. However, further study such as hydraulic modeling within particular reaches will be needed to determine how much the sediment transport capacity is actually changed by the berms, elevated road grades, and other human developments. The percentage of the floodplain blocked or storage area lost is an important factor in determining the potential impacts to the river channel.

Human activities occurring directly in the river channel can also alter the stream's power to transport sediment. The artificial straightening of stream channels, accompanied with the removal of large boulders and wood, was a common practice throughout the 19th and early 20th centuries in the United States (Rhoads, 1990; Hupp, 1992) and New England (Field, 2007). This channelization was completed for flood control, drainage of agricultural areas, railroad and highway construction, and log drives. Channel Slope and Depth Modifiers maps reveal that much of the Ammonoosuc River was straightened in the past (Appendix 1) with the now abandoned meanders still sometimes visible on the adjacent floodplain

(Figure 8). By reducing the length of the river channel, straightening increases the gradient and, therefore, the river's capacity to transport sediment. Consequently, straightened portions of the Ammonoosuc River are often slightly incised by bed erosion, significantly widened by bank erosion, and devoid of sand and gravel bars (Figure 5b). As a result of these changes, straightened channels are often associated with poor habitat quality as high flood flow velocities in incised reaches provide little refuge, high summer water temperatures result from the shallow flows spread out over a wide channel, and little flow complexity is generated without gravel bars or wood, both of which are removed in high-energy straightened channels.

The wide shallow configuration of the straightened channels makes these locations susceptible to the formation of ice jams in the winter and spring. Large blocks of ice can spread out and become grounded on the shallow channel bottom. Smaller blocks of ice can then also be blocked. Once initiated, a large ice jam can clog the entire channel, force the river's flow out onto the floodplain, and carve a new channel that returns some sinuosity to the straightened channel. While ice jams can, therefore, be seen as an agent of change that returns the channel to an equilibrium condition, the unpredictability of when and where these events will occur can result in rapid bank erosion near human infrastructure and other investments. The Bretton Woods area experienced erosion on a portion of the floodplain golf course during a damaging ice jam in March 2011 (Mount Washington, 2011). By mapping the sites of past channel straightening, the Phase 2 assessment results (Field, 2011) can be used by watershed planners to identify the most likely locations of ice jams and delineate areas where future developments might be restricted.

The sediment and wood transported through the straightened sections tends to be deposited downstream once the channel encounters an area of decreased sediment transport capacity such as at human constructed dams (Figure 4a) and natural valley constrictions (Figure 4b). The locations of dams and ledge outcrops along the river, generally associated with valley constrictions, provide a clue as to where excess sediment accumulations may be occurring (Appendix 1). Excess sediment deposition will be most enhanced when occurring immediately downstream of a straightened channel, where reach-scale increases of sediment transport capacity are present, or tributary confluences, where watershed-scale increases in sediment load are concentrated. In addition to large unvegetated gravel bars, sites of excess sediment accumulation are also characterized by severe bank erosion and rapid channel migration as the channel fills in with sediment and flow is deflected around the growing bars (Figure 4b and Figure 9). Sediment Load Indicators maps reveal that many reaches of the river have considerable deposition along their length (Appendix 1). The exact location of specific indicators of deposition, such as steep riffles, channel avulsions, braiding, and neck cutoffs, can focus attention on specific areas within the reach where deposition and rapid channel migration may be occurring. However, the maps do not clearly show the distribution of sediment through the reach. Sediment is generally more evenly distributed along the channel when a river is in equilibrium. The lack of deposition in straightened reaches (Figure 5b) and excess sedimentation at nearby valley constrictions (Figure 5a) reflect instabilities along the Ammonoosuc River that result in increased erosion hazards and degraded habitat. Furthermore, straightened channels throughout New England continue to have greater stream power to transport sediment than under natural conditions and, therefore, remain sensitive to change with rapid accumulations of gravel or wood having the potential to rapidly form new meanders or cause significant bank erosion (Field, 2007).

Large landslides on the mainstem (Figure 3a), although uncommon, may, at times, introduce great quantities of sediment into the river at the reach scale and result in bar formation and bank erosion as flow is diverted around the accumulating sediment downstream (Figure 10). Large bars form at the confluences of many tributaries joining the Ammonoosuc River, focusing sediment derived at the watershed scale into a single reach with the resulting deposition enhanced where downstream valley

constrictions impound floodwaters and decrease the river's transport capacity (Figure 11). Many additional watershed-scale and reach-scale sediment sources may be present that are not recognized until a large flood occurs. Previous erosion sites exposed during past floods may heal slowly and be masked by vegetation during the intervening years. The excess sediment generated by these events is most likely to pass through areas that were straightened in the past or currently confined by corridor development. The sediment will tend to concentrate in areas of decreased transport capacity such as upstream of valley constrictions, dams, and narrow bridges.

Thirty-five bridges cross the Ammonoosuc River, but, in general, have only a localized, if any, effect on sediment transport and channel morphology. Steep riffles are present upstream of 23 bridges, indicating some influence on local deposition. All but eight of the bridges entirely span the bankfull channel width, so significant impacts to the channel would not be expected. However, eight of the road approaches entirely block floodplain flow while another eight partially block the floodplain, potentially enhancing upstream sediment deposition during large floods. Other factors, such as channel straightening, are considered to exert a much greater influence on reach-scale sediment transport processes.

4.0 DELINEATING REACHES UNDERGOING OR SENSITIVE TO ADJUSTMENT

Changes in the river's sediment load or capacity to transport sediment are the primary causal mechanisms leading to adjustments in channel morphology. Determining how each reach is responding to human activities in the watershed also requires an understanding of the constraints controlling adjustment processes and the sensitivity of each reach to change.

4.1 Constraints to sediment transport and attenuation

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 through time and space. In the Ammonoosuc River watershed, for example, land clearance in the 19th century (the initial human stressor) led to higher sediment loads and channel aggradation (the initial channel response). This response, in part, created the need for channel straightening (a later human stressor) to enhance transport of the higher sediment loads, but, in turn, resulted in channel incision (a later channel response) due to the increased channel gradient. Likely enhancing the incision was the overlapping decrease in sediment loads associated with reforestation of the previously cleared land. Rather than attempting to establish the complex timing, location, and predominance of various stressors and channel adjustments that have occurred along a particular channel reach, the geomorphology-based corridor planning process compares the existing channel conditions with the presumed natural reference state to provide a less complicated approach for understanding the ongoing adjustments and evolution of the channel back to equilibrium conditions.

4.1a Sediment regimes

Sediment Regime maps depict how the sediment regime has been altered from the reference condition (Appendix 1) and, with an appreciation for channel evolutionary tendencies, can be used to identify the reaches most likely to experience future aggradation or degradation. Alterations to the sediment regime must be considered at the watershed scale, because unaltered reaches may be subject to

future change due to excess (or decreasing) sediment delivery caused by upstream channel adjustments. In the geomorphology based river corridor planning process created by the Vermont River Management Program (Web citation 3), each river reach is categorized into one of six sediment regimes: 1) transport reaches; 2) confined source and transport reaches; 3) unconfined source and transport reaches; 4) fine source and transport reaches with coarse deposition; 5) reaches in equilibrium with coarse sediment but experiencing fine deposition on floodplains; and 6) deposition. No reaches on the Sediment Regime maps were categorized as being in equilibrium, indicating a significant departure from reference conditions when most reaches would have been in equilibrium. (Even under natural conditions, bedrock gorges would be classified as transport reaches).

The six sediment regime categories attempt to characterize the source and fate of both fine and coarse sediment. Transport reaches are typically steep mountainous gorges, but do not supply appreciable quantities of sediment to downstream reaches on an annual basis because of the bed and bank resistance afforded by bedrock, well compacted till, or well forested slopes. Confined source and transport reaches have a high transport capacity like the transport reaches, but are typically 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 mass-wasting processes. Reaches categorized as unconfined source and transport reaches are generally located in broad valleys where straightening, incision, or floodplain confinement by berms or road grades have converted a reach previously in equilibrium into an area that is delivering excess sediment downstream. Fine source and transport reaches with coarse deposition are also in broad valleys earlier disturbed by incision, but are now further along in the channel evolutionary process and are beginning to experience aggradation. Equilibrium reaches are relatively undisturbed meandering channels where coarse deposits are transported through the channel, but fine sediments are deposited on the floodplain.

The absence of equilibrium reaches does not necessarily indicate that all reaches have been directly altered by human activity as some reaches may have been indirectly altered by changes in sediment delivery or transport capacity occurring in adjacent reaches. Whether directly or indirectly, much of the Ammonoosuc River has experienced a departure from the reference sediment regime due to the channel straightening, damming, floodplain development, and other activities (e.g., floodplain gravel removal) that have occurred and continue to occur. Most of the reaches downstream of Littleton are now fine source and transport reaches with coarse deposition. While incision and encroachment by roads, railroads, and buildings along the straightened reaches has resulted in greater transport capacity, much of the sediment is deposited at the downstream ends of the reaches where valley constrictions cause a loss in transport capacity (Figure 5 and Figure 11).

Changes to the sediment regime on lower gradient unconfined valleys such as in the Bretton Woods area are partially in response to channel adjustments occurring on the steeper confined reaches upstream. The removal of wood, channel straightening, and loss of flow complexity in the upper reaches has increased sediment delivery to the unconfined reaches. The natural loss of stream power associated with the decreasing gradient and valley width expansion are enhancing deposition caused by the upstream increases in sediment load, leading to extensive gravel bar formation and channel migration (Figure 12). Meanders have reformed in this previously straightened reach due to the high rates of sediment deposition (Figure 13) and recent attempts at bank protection are also proving to be short-lived remedies as the channel migrates around the stabilization efforts (Figure 14). With in-filling of the channel, the risk of avulsions (i.e., rapid large-scale shift in channel position) cutting across the golf course has increased, as occurred for a brief period in March 2011 when an ice jam clogged the river (Mount Washington, 2011).

Remedies to this and similar problems elsewhere on the river depend on decreasing upstream sediment delivery or having enough available space to accommodate the sediment deposition and channel migration without impacting human developments. At Bretton Woods, the need to stop the channel from migrating into and eroding portions of the golf course likely precludes the creation of the necessary accommodation space for sediment deposition and channel migration. The problems could be partially ameliorated by increasing wood loads in the upstream mountainous reaches, because the added roughness will spread flows out over a larger area in these forested reaches, encourage sediment deposition, and, thereby, reduce downstream sediment loading.

Overall, the sediment regime changes on the Ammonoosuc River have resulted in the concentration of sediment into areas where sediment transport capacity rapidly declines. Great lengths of the river that were once likely sites of meandering and gravel bar deposition have been converted through human activities to straightened channels with little sediment deposition. In general, watersheds which have lost their capacity to store sediment due to human-related constraints are generally more sensitive to erosion hazards, transport greater quantities of sediment and nutrients to receiving waters, and lack the ability to form and maintain habitat associated with sediment and wood accumulation. While sediment deposition provides greater flow complexity, the concentration of sediment deposition into short lengths of the river inhibits the reforestation of gravel bars and prevents the formation of habitat features that would develop if channel migration and sediment deposition were more evenly distributed along the length of the river.

4.1b Vertical and lateral constraints

Reaches that have undergone a sediment regime departure can progress through the channel evolutionary stages over time and return to an equilibrium condition. The Boundary Conditions and Riparian Modifiers maps provide an indication of how rapidly a particular channel may undergo these adjustments (Appendix 1). Along the Ammonoosuc River, several constraints exist that will slow the vertical (i.e., bed elevation) and lateral (i.e., bank) adjustments needed before the channel reachieves an equilibrium condition. Considerable vertical adjustments are unlikely to be needed on the Ammonoosuc River to achieve equilibrium conditions and the presence of dams constructed on top of natural bedrock waterfalls already inhibit adjustments in bed elevation on several reaches. Other activities on the floodplain have, however, caused vertical adjustments in the river channel. Gravel mining on the inside of a meander bend at Salmon Hole in Lisbon caused the river to cut across the meander when the channel shifted into the gravel pit whose bottom elevation was likely lower than the channel bed (Figure 15). Similar shifts in channel position are possible at other locations. If the bottom elevations of floodplain snow-making ponds at Bretton Woods are lower than the river bottom, then the river might move into the ponds during a large flood (Figure 16). Future activities within the river corridor that could lead to vertical adjustments in the river's bed elevation should be avoided, because of the instabilities that result and the potential impacts they promulgate upstream and downstream.

Lateral adjustments along the river will be critical for the reestablishment of a meandering planform and the creation and maintenance of aquatic habitat. Many areas of the river are armored along the banks (Appendix 1) and the lateral migration of the river thus prevented. Many other areas are experiencing bank erosion and, where infrastructure is at risk, additional bank protection may be required. However, ongoing bank erosion may reflect the lateral adjustments that must continue before an equilibrium condition is achieved. Consequently, areas of bank erosion where infrastructure is not at risk may represent priority areas for corridor protection (see Section 5.1), so future human activities do not

compel the use of further bank protection. If the amount of armoring along the river continues to increase, the remaining areas available for lateral adjustments will necessarily be reduced and the erosive power of the river focused on shorter lengths of the river, exacerbating the erosion hazards and habitat degradation already present.

Where no bank armor or riparian vegetation is present, the banks are less resistant to bank erosion, channel migration, and gravel deposition. Channel migration and the recreation of meanders is essential to the redevelopment of equilibrium conditions along the straightened segments of the river, eventually allowing sediment deposition and bank erosion to be distributed more evenly along the channel rather than transferred to and focused in downstream areas. Evidence for meander reformation on straightened reaches of the Ammonoosuc River is seen at many locations, including at Bretton Woods just upstream of the snow-making ponds (Figure 17). The long lengths of river without any, or with a very narrow, riparian forest (Appendix 1) limit wood inputs into the river. With low wood loadings, the recreation of meanders and a return to equilibrium conditions has been slowed, but may accelerate with future management efforts that encourage the growth of riparian forests.

Human development in the watershed has created, in some locations, permanent constraints to channel evolution and is preventing the reestablishment of reference sediment regimes, particularly on the floodplain in Littleton (Figure 18). However, overall levels of urbanization in the largely forested watershed have not reached a threshold level to precipitate system-wide channel adjustments along the Ammonoosuc River. Therefore, if constraints at the reach level can be avoided in the remaining areas of undeveloped floodplain, most of the Ammonoosuc River has the potential to undergo the necessary lateral adjustments to evolve back to an equilibrium condition. Sediment deposition (Figure 5a) is typically concentrated at the downstream ends of straightened reaches (Figure 5b) with elevated erosion and flood hazards located just upstream of valley constrictions, dams, or other grade controls where deposition is enhanced. Plane-bed features of poor habitat quality characterize straightened reaches with a uniform depth across the channel. Therefore, the recreation of meanders can lead to a greater complexity of habitat types and increased sediment storage while reducing flood and erosion hazards downstream, because sediment and flow energy expenditure will be more evenly distributed throughout the reach.

4.2 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 that would culminate in a return to equilibrium conditions (Schumm et al., 1984). The rate at which these transformations occur, referred to as stream sensitivity, is dependent upon bank 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 a very high or high sensitivity to change. 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.

Stream Sensitivity maps of the Ammonoosuc River show that most of the reaches are sensitive to change. In general, low sensitivity ratings are assigned to reaches in equilibrium or good condition that flow through bedrock, boulders, or cobbles and are unlikely to experience rapid widening or downcutting. Higher sensitivity ratings are assigned to reaches with cobble to sand-sized bank material that are undergoing or subject to future channel adjustments. The most sensitive reaches on the Ammonoosuc

River are in the unconfined reaches downstream of Littleton, because channel adjustments related to channel straightening and floodplain constraints are likely and limited bank resistance is present along the sandy banks with limited riparian vegetation. If meanders reform along straightened reaches either naturally (Figure 17) or as part of a restoration project, flow energy and sediment would be attenuated and a main driving force of rapid bank erosion and channel migration minimized. The recreation of meanders along straightened reaches would thus make other areas less sensitive to habitat degradation and hazardous flooding and erosion.

5.0 RESTORATION TECHNIQUES DESIGNED TO ADDRESS CHANNEL INSTABILITIES

An understanding of human stressors and their distribution throughout the watershed (Appendix 1) is critical for identifying and prioritizing restoration projects. Restoration must address the stressors in order to return the river channel to an equilibrium condition. Only by achieving equilibrium can the three primary objectives of restoration be met: 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 include components that address upstream stressors. Flow energy expenditure and sediment deposition ideally occurs over long distances and should not be focused at a single site where they cannot be accommodated without severe bank erosion and rapid channel migration. Consideration must also be given to how the channel will respond to a proposed restoration project and whether such a project will simply 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 utilizing eight different restoration techniques: 1) protecting river corridors; 2) planting stream buffers; 3) stabilizing stream banks; 4) armoring head cuts and nick points; 5) removing floodplain constraints to flood and sediment load attenuation; 6) removing or replacing structures such as narrow bridges; 7) restoring incised reaches; and 8) restoring aggrading 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 (Web citation 3). The procedure identifies all of the 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 depositional reaches) given the levels of technical expertise required, potential cost, and risk of failure inherent in each action. This procedure identifies projects from a technical feasibility standpoint only; the social feasibility of such projects will also be discussed (see Section 5.9 below). The above restoration actions that are potentially suitable for use on the Ammonoosuc River are discussed further below. Head cuts and nick points are not a significant problem on the Ammonoosuc River, so restoration of these conditions is not addressed here. A listing of restoration actions considered viable for each river reach and segment assessed during the Phase 2 Assessment is provided in Table 2. The straightening of reaches on the Ammonoosuc River was accompanied with some incision in the past, and the straightened channels are still conveying excess sediment downstream, so restoration must occur to accelerate the return of equilibrium conditions and improvements to aquatic habitat.

5.1 Protecting river corridors

Artificially straightened channels have a propensity to rapidly reform meanders along their length as the sinuosity that previously existed is reestablished (Figure 17). Encouraging meanders to reform where no human conflicts are present in the river corridor reduces the likelihood of meanders forming in other areas where homes, roads, or other infrastructure might be at risk. Identifying places where meanders can reform, known as attenuation assets or accommodation zones, are important for restoring the river as a whole, because the increase in channel length results in flow energy reductions and deposition of coarse sediment. Sediment stored and flow energy expended within the accommodation zones reduces downstream impacts. The variation in flow velocities within a sequence of meanders segregates sediment into different particle sizes and leads to higher quality habitat as more closely spaced pool-riffle sequences develop. If sediment can be more evenly distributed among several meanders on a straightened reach, the size of individual bars and their rate of growth will be reduced, allowing vegetation to encroach towards and eventually shade the channel.

Protecting the river corridor, without engaging in any active restoration activities, ensures sediment and flow energy attenuation will occur over the long term with habitat improvements occurring at the site and reductions in flood and erosion hazards realized further downstream. Within a protected river corridor, efforts should be made to prevent bank armoring that would prevent the lateral adjustments needed for meander formation. In fact, where bank armoring is already present, consideration could be given to removing these constraints once a protected corridor is established. Protecting river corridors along straightened reaches should be considered a high priority, so flow and sediment attenuation can occur in an unconstrained manner. The river corridors to be protected for conservation planning purposes should encompass, as much as possible, the fluvial erosion hazard zones established by the Phase 2 assessment (Field, 2011).

5.2 Planting stream buffers

A healthy riparian buffer is essential for sustaining equilibrium conditions and healthy aquatic habitat. Trees rooted in the riverbank help bind the soil together without hardening the bank like riprap, so erosion can continue at a reduced rate. Consequently, if a riparian buffer exists along the entire river, erosion can be evenly distributed along its length and excessive erosion and sediment production not focused at any one site. Some river bank erosion is critical for maintaining overhanging bank cover and for recruiting wood into the river as the banks are slowly undercut and trees fall into the channel. Wood in the river channel is not only critical for habitat diversity, but also adds hydraulic roughness that reduces flood-flow velocities and increases sediment retention. Reduced flow velocities also increase flood stage for the same discharge and help restore floodplain connectivity. 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 riverbanks and their adjacent floodplains should be considered a high priority along the Ammonoosuc River.

5.3 Stabilizing stream banks

Erosion naturally occurs along streams in equilibrium with the channel's dimension, pattern, and profile maintained while migrating across its floodplain. The erosion on the outside of a meander bend is balanced by an equivalent amount of deposition on the inside of the bend when the river is in equilibrium. Therefore, an attempt to stop all erosion in a watershed would not only be difficult and costly but would be inconsistent with maintaining channel equilibrium and creating excellent aquatic habitat. However, accelerated bank erosion does occur in areas that are out of equilibrium due to widespread incision or flow deflection around rapidly growing gravel bars. Downcutting of the channel bed leads to bank failure on both sides of the river as bank heights become unstable; the critical height at which the bank begins to collapse is less for loosely consolidated sandy banks compared to more competent silt and clay banks. Aggradation, in contrast, generally results in bank erosion along a single bank 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 and causes of erosion can vary along the length of even a single river reach.

Long-term remedies of bank erosion depend on reducing erosive forces within the reach and upstream that are the ultimate cause for the 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. Consequently, the need for bank stabilization must be closely examined in order to avoid slowing the process of channel evolution. 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. Bank stabilization efforts should avoid permanently armoring the banks, especially on incised reaches, because the necessary adjustments to achieve equilibrium will be hindered. Ideally, bank stabilization should consist of bioengineering methods that reduce the flow energy impinging on the banks (Figure 19a-c). Bioengineering treatments, such as willow staking, are less successful if not accompanied with the toe treatments required to reduce erosive forces along the bank (Figure 19d).

Bank armoring has occurred at many locations on the Ammonoosuc River, particularly where rapid deposition is occurring in the channel (Figure 20a). In some cases, bank armoring in these settings has been outflanked due to the rapidly shifting channel (Figure 20b). Continued bank stabilization in these areas is likely to be necessary and will be more successful if the ultimate cause of these erosive forces can be addressed. Where the erosion is related to deposition upstream of a valley constriction, limiting the sediment supply from upstream could reduce the rate of erosion. In general, the accelerated erosion in these settings is due to increased sediment supply from artificially straightened segments upstream. Where accommodation space is available upstream, steps can be taken to encourage the straightened reaches to reestablish meanders in order to improve aquatic habitat while attenuating the downstream transfer of sediment and energy.

Large mass failures occur in a few places along the Ammonoosuc River and supply large amounts of sediment to the river (Figure 3a). Stabilizing mass failures could reduce downstream sediment supply, but also could be costly, technically difficult, and could lead to new mass failures forming adjacent to the stabilized areas. Flow deflection techniques, such as boulder or log jam deflectors (Figure 19a-b), are likely to be the most efective in such settings. In lieu of stabilization efforts, another approach may be to monitor the mass wasting sites and manage downstream areas in such a way that rapid and large increases of sediment supply from the mass failures can be adequately accommodated. Without attenuation assets

for sediment storage, the chances are greater that rapid deposition and associated bank erosion could damage infrastructure elsewhere along the river.

5.4 Removing floodplain constraints

Floodplain constraints along portions of the Ammonoosuc River are preventing the attenuation of flow and sediment across the floodplain. Floodplain constraints include berms and railroad and highway grades paralleling the river, which are built higher than the surrounding floodplain, and cut off access to a portion of the floodplain (Figure 7 and Appendix 1). The river is unable to achieve an equilibrium condition in these locations, because excess stream power is concentrated in the channel during large floods. Sediment that would otherwise accumulate on the floodplain and flow that would enter side channels is instead transferred downstream, complicating the stabilization of sensitive areas downstream. Consequently, removing the floodplain constraints, where socially feasible, would have several benefits: 1) create habitat in side channels to which access is currently blocked; 2) reduce peak flow velocities within the formerly confined channel, promote sediment deposition, and improve habitat diversity; 3) reduce the risk of a severe flood breaching the constraints and damaging property on the backside of the floodplain; 4) allow the stream to expend additional energy and attenuate its sediment load before reaching more sensitive reaches downstream; and 5) return the stream to a more natural flow and sediment regime. Removing constraints on the floodplain will not only improve conditions within the reach involved, but will also improve downstream conditions by attenuating flow, sediment, and energy. From a technical standpoint, therefore, removing floodplain constraints is rated as one of the highest restoration priorities on the Ammonoosuc River, but societal needs may prevent the implementation of such projects in many areas. Complete removal of a highway or railroad grade is not necessarily required to achieve equilibrium conditions along a given reach. Allowing flow to pass through several bridged portions of a highway or railroad grade might be sufficient to allow flows to spread across the entire floodplain, access side channels, and reduce flow velocities in the main channel.

5.5 Removing/replacing structures

Bridges across the Ammonoosuc River alter channel morphology only locally and, thus, their removal, replacement, or resizing is not considered a high priority. The several dams on the Ammonoosuc River have created impounded areas upstream where sand and finer sediment has been deposited to form large bars and to split flow into multiple channels (Figure 4a). Given that most of the dams are actively being used to generate electricity or may be reactivated for that purpose in the future, their removal is not an option for restoring natural processes along the river. The dams currently operate as “run of the river” facilities, so their impact on the passage of flood flows is minimal. While the dams do alter the passage of sediment, their impact may not be too significant since the dams are largely built on natural bedrock waterfalls. Under natural conditions, therefore, sediment would also be impounded upstream to form a depositional zone, albeit likely smaller than those currently present behind the dams. Consequently, given the existing social constraints, addressing the morphological impacts of the dams is a low restoration priority.

5.6 Restoring incised reaches

Incised channels focus more flow energy on the channel bed with a greater percentage of flow confined to the channel and a greater discharge needed to access the floodplain. Degraded habitat results

within the incised channel, because bed complexity is destroyed (i.e., pool-riffle features replaced by plane bed morphology) and the bed becomes armored with coarser particles capable of resisting the greater stream power. The greater transport efficiency in the incised reach leads to excess sediment delivery to downstream reaches, further compromising channel equilibrium. Although sediment passes through the incised reaches, greater rates of deposition occur where channel transport capacity declines at bends in the channel or at channel constrictions. Straightened reaches, a common feature on the Ammonoosuc River (Figure 8 and Appendix 1), tend to be slightly incised and are considered as incised reaches for the purposes of corridor planning on the Ammonoosuc River.

Reconnecting the channel to its floodplain is the best way to restore incised reaches. Encouraging the channel to occupy former meanders or create new meanders on the floodplain will assist the channel's evolution towards 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 that the channel can access during even a small annual flood. This would allow flow to spread out over a wide area and result in more immediate sediment and flow attenuation. Another approach to restoring incised reaches involves the addition of woody material in the channel (Figure 21). From a geomorphic equilibrium perspective, without consideration of the social constraints, the placement of engineered log jams in the river at points where the bank height is particularly low will encourage the channel to either "break out" of the channel and carve out a new meander on the floodplain, as has occurred naturally on straightened reaches elsewhere in New England (Field, 2007), or divert flow into the banks, causing the bank to recede and eventually form a meander in a slightly different manner (Figure 17).

The current dearth of attenuation assets along straightened reaches where meanders can reform on the Ammonoosuc River is preventing equilibrium conditions from becoming reestablished. This increases the potential that hazardous erosion and meander reformation will occur on their own in areas where human developments are present. Reducing these hazards will require protecting the corridor adjacent to straightened reaches, so meander creation can occur across the floodplain without threatening human infrastructure or agricultural fields. Given the reductions in flood hazards and improvements in aquatic habitat that would accrue from several attenuation zones along a long straightened segment, restoring incised reaches on the Ammonoosuc River is a high watershed priority. The greatest priority should be given to those reaches just upstream of human developments in the river corridor, such as in Littleton, because this will provide the greatest reduction in fluvial erosion hazards while providing the same sediment storage and aquatic habitat improvements as elsewhere.

5.7 Restoring aggrading reaches

The excess sediment deposition that causes aggradation upstream of valley constrictions (Figure 4b) and downstream of valley expansions (Figure 12) also leads to rapid erosion as flow is deflected into the adjacent banks. Hard armoring of the banks to prevent erosion has not always led to long-term stabilization with some previous bank protection projects completely overrun as the channel shifts its position due to aggradation (Figure 14 and Figure 20b). Recognizing the difficulty in stabilizing banks in aggrading reaches, the best restoration approach is to protect the river corridor surrounding the channel, so the river has room to shift and migrate over time. This approach is especially important downstream of straightened reaches that cannot be restored because of social constraints and, therefore, will continue to transport excess sediment to the aggrading reaches downstream.

5.8 Coordinating restoration at the watershed scale

Reestablishing equilibrium conditions on the Ammonoosuc River will require the coordination of restoration efforts throughout the watershed. Stabilizing bank erosion caused by flow deflection around bars in one locality, for example, will meet with more success if greater systemic attenuation of sediment loads is achieved further upstream. While some restoration activities can occur immediately without concern for upstream conditions, a higher priority should be placed on those restoration activities that can effect the greatest change beyond the project reach. For example, removal of floodplain constraints along straightened reaches will reduce sediment accumulation near natural valley constrictions downstream. These reductions in sediment load from upstream will decrease the rate of bank erosion and channel migration occurring downstream. Bank stabilization in aggrading reaches, where necessary to protect infrastructure, will be more successful if sediment and flow energy is attenuated in adjacent reaches upstream.

5.9 Technical and social feasibility of project implementation

The above restoration activities have been deemed appropriate for the Ammonoosuc River based solely on their ability to establish equilibrium conditions and achieve the three main restoration objectives of reducing flood and erosion hazards, decreasing sediment and nutrient loading, and improving aquatic habitat (Table 2). In many cases, the priority restoration activities (e.g., corridor protection, removal of floodplain constraints) are in conflict with traditional river management practices 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 implement priority restoration activities at those locations experiencing frequent and repeated flood damages. Discussing the aquatic habitat improvements that can be realized by managing towards equilibrium is another important way of reaching consensus as most stakeholders, regardless of their own special interests, often see the value in creating and maintaining a healthy fishery in the watershed.

Municipalities along the Ammonoosuc River can play an important role in implementing high priority projects. The adoption of fluvial erosion hazard zones (see Field, 2011) can help limit future development within the river corridor. Over time, more landowners will become interested in state and federal programs (e.g., Clean and Clear, WHIP, CREP) that compensate landowners for protecting river corridors. More active restoration activities (e.g., removing floodplain constraints, restoring incised reaches) can occur within protected corridors, thus allowing for greater, and more quickly realized, sediment and flow energy attenuation. A number of floodplain constraints are blocking floodplain access and could be accelerating the delivery of sediment and flood waters downstream, leading to accelerated bank erosion and channel migration upstream of valley constrictions. Various governmental agencies could address these problems through capital budgeting, so funds will be available over time to alleviate the constraints and provide access to the blocked floodplains along high priority reaches. By creating a framework of policy and funding priorities, local, state, and federal agencies can play a large role in creating the necessary social environment for implementing both reach-scale and watershed-scale restoration activities that will reduce flood and erosion hazards, decrease sediment and nutrient loading, and improve aquatic habitat.

6.0 PRIORITY RESTORATION SITES ON THE AMMONOOSUC RIVER

Over 20 priority restoration projects have been identified by using the geomorphology-based corridor planning maps (Appendix 1) and the Phase 2 assessment data (Field, 2011) (Table 3). The selected sites represent the range of restoration activities presented in Section 6.0 above and include projects in each town through which the Ammonoosuc River flows. The projects are not numerically prioritized but rather given a priority ranking (i.e., highest, high, and moderate) reflecting the severity of the hazards present, the degree of habitat degradation, and the likelihood of improving equilibrium conditions not only at the site but in adjacent reaches as well. The proposed projects address instabilities caused by a range of conditions, including straightening, mass wasting, stormwater inputs, floodplain constraints, and aggradation. Successful restoration at many of these sites will provide examples of how to proceed with similar sites elsewhere along the river. Preliminary designs have been developed for the Salmon Hole site in Lisbon where a combination of corridor protection, riparian buffer planting, and in-stream structures incorporating the use of log jams to encourage meander development. The project has the potential to improve aquatic habitat while reducing sediment loads downstream where bank erosion threatens a soccer field (Field, 2011). The corridor planning maps (Appendix 1) and Phase 2 geomorphic assessment results can be used to select and prioritize additional sites or evaluate the potential benefits of restoration activities at various sites as opportunities arise.

7.0 CONCLUSIONS

The corridor planning guide presented here is intended to provide the necessary background information and procedures for identifying and prioritizing river restoration projects that will reduce flood and erosion hazards, decrease sediment and nutrient loading, and improve aquatic habitat. Restoration projects that are completed in isolation and merely resolve an immediate conflict (e.g., an eroding bank) have the potential to generate further instabilities in adjacent reaches and often require long-term maintenance. Through 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 identifying the river's departure from expected reference conditions and the human stressors at the watershed and reach scale that are potentially altering the hydrologic and sediment inputs to the river channel. At the reach scale, activities in the river corridor and within the channel itself can alter the river's capacity to transport sediment. Channel straightening and floodplain constraints increase sediment transport downstream and alleviating these conditions is critical for improving aquatic habitat within the reach and reducing flood and erosion hazards downstream. Several appropriate restoration activities have been identified for each river reach with more than 20 specific projects identified that will promote equilibrium conditions along the Ammonoosuc River. In addition to the proposed restoration projects, certain activities should be discouraged, so channel instabilities along the river are not exacerbated. These activities include gravel mining in the floodplain, development that fills or blocks access to large portions of the floodplain, and removal of wood and sediment from the channel.

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FIGURES

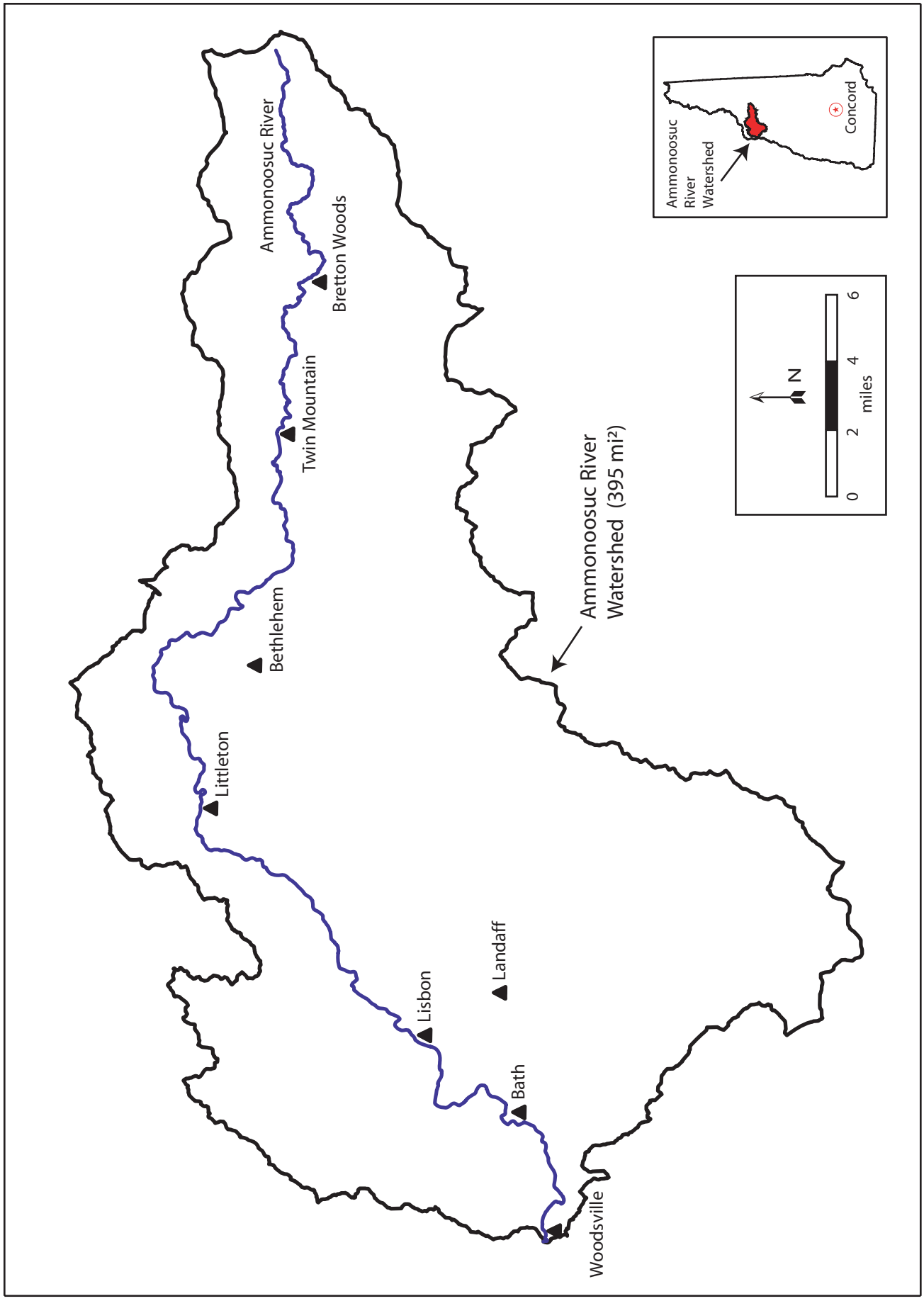


Figure 1. Ammonoosuc River watershed map.

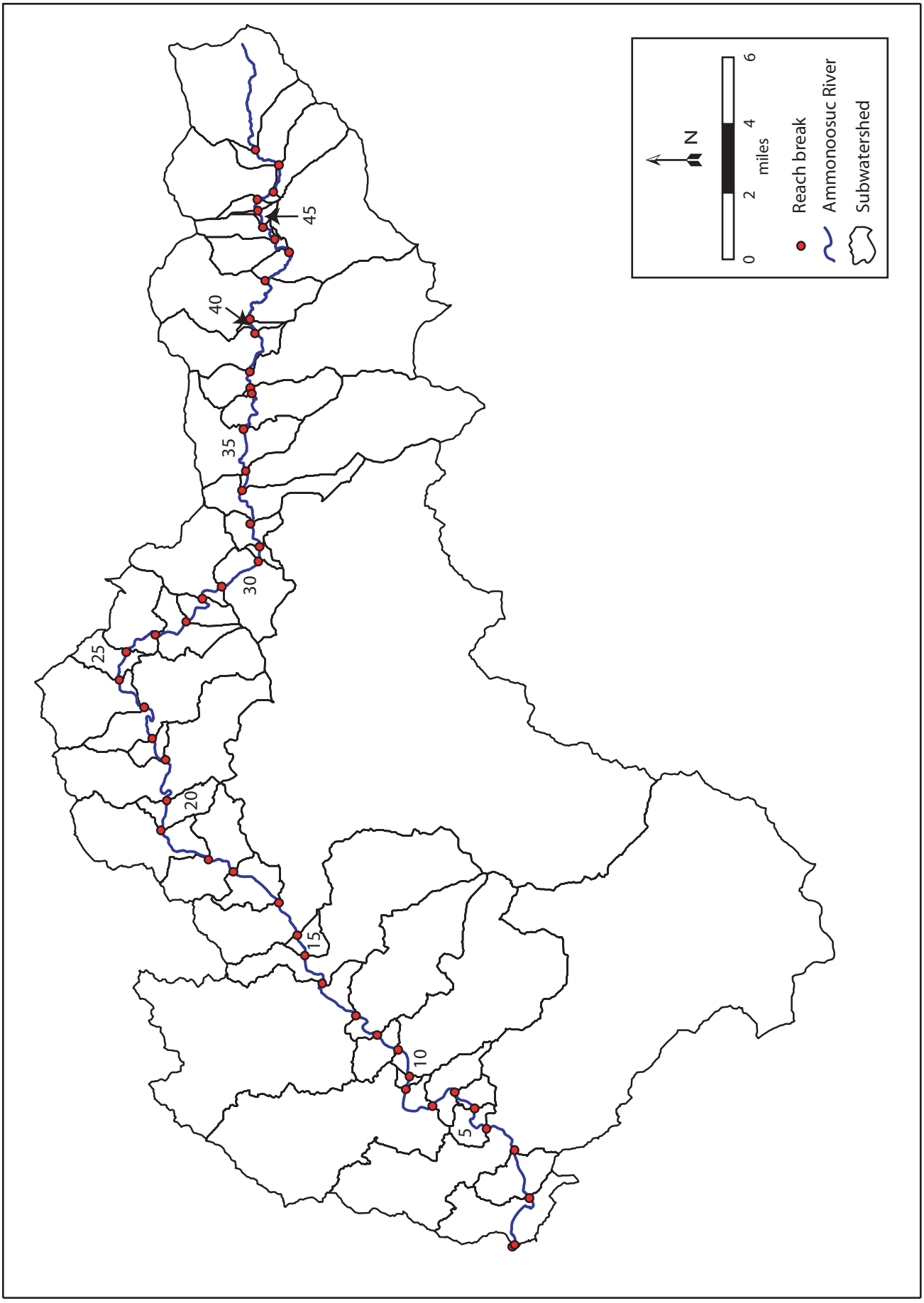


Figure 2. Ammonoosuc River reach map with every fifth reach labeled.

a)

b)

Figure 3. Sediment sources include a) mass failures such as this one in Reach 7 and b) tributary inputs (view of the Little River delta at the upstream end of Reach 34).

a)

b)

Figure 4. Sites of sediment deposition include a) upstream of dams (Reach 29 upstream of the Bethlehem dam) and b) upstream of natural valley constrictions (Reach 8 in Bath).

a)

b)

Figure 5. a) Large unvegetated gravel bars (Segment 35A) form downstream of b) straightened plane-bed channels (Segment 35B).

Figure 6. Historic panoramic image of Littleton from 1908 showing a lack of forest on the uplands.

Figure 7. Railroad grade now serving as a recreational path encroaches along much of the length of the Ammonoosuc River. In Lisbon (Reach 12), the path blocks the river's access to a large portion of its natural floodplain (arrow a), reducing the space that the river currently has to spread out at high flow stages (arrow b).

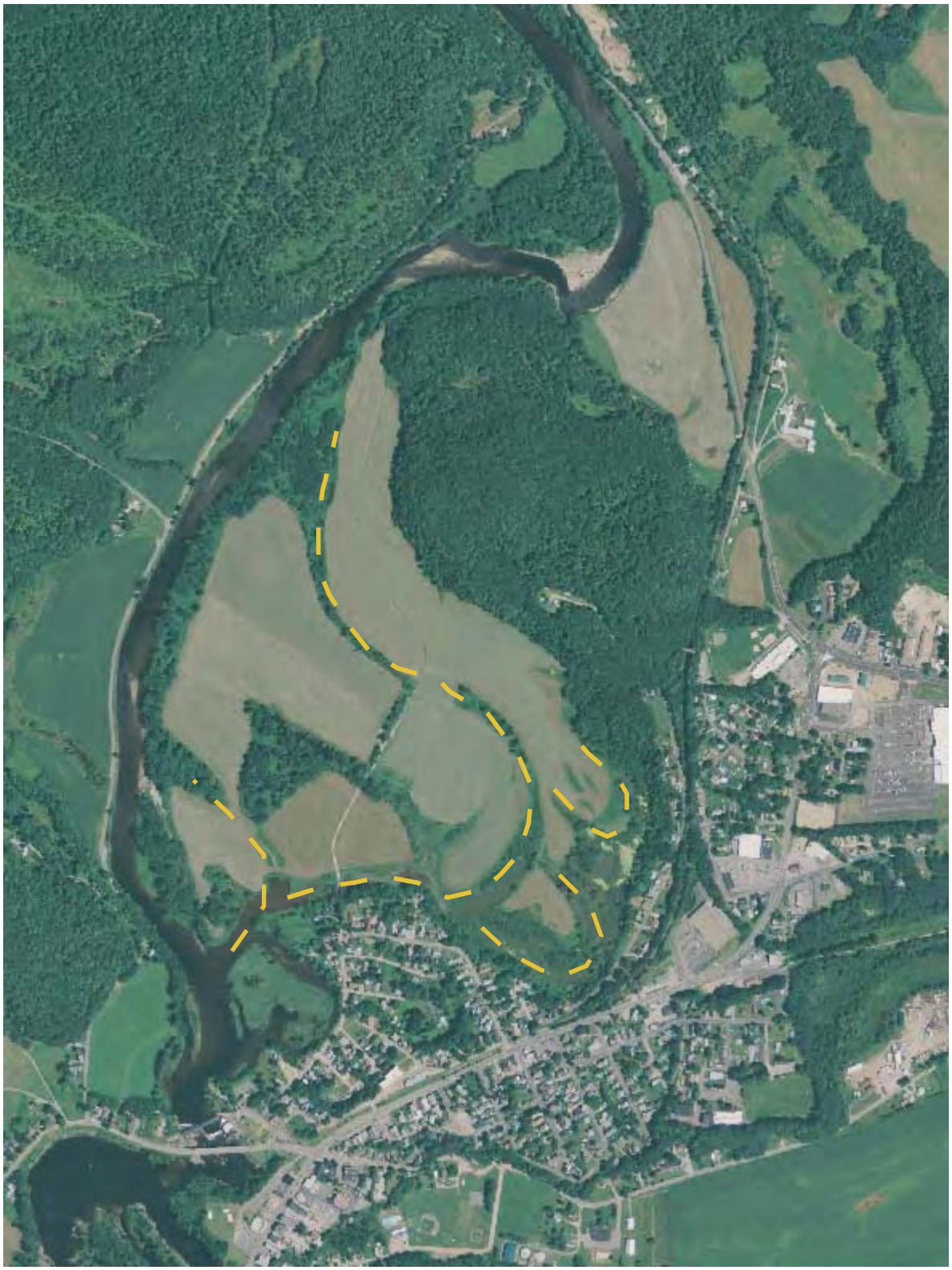


Figure 8. Artificially straightened channel upstream of Woodsville (Reach 2) and adjacent abandoned meanders (highlighted with yellow dashed lines).

a)

b)

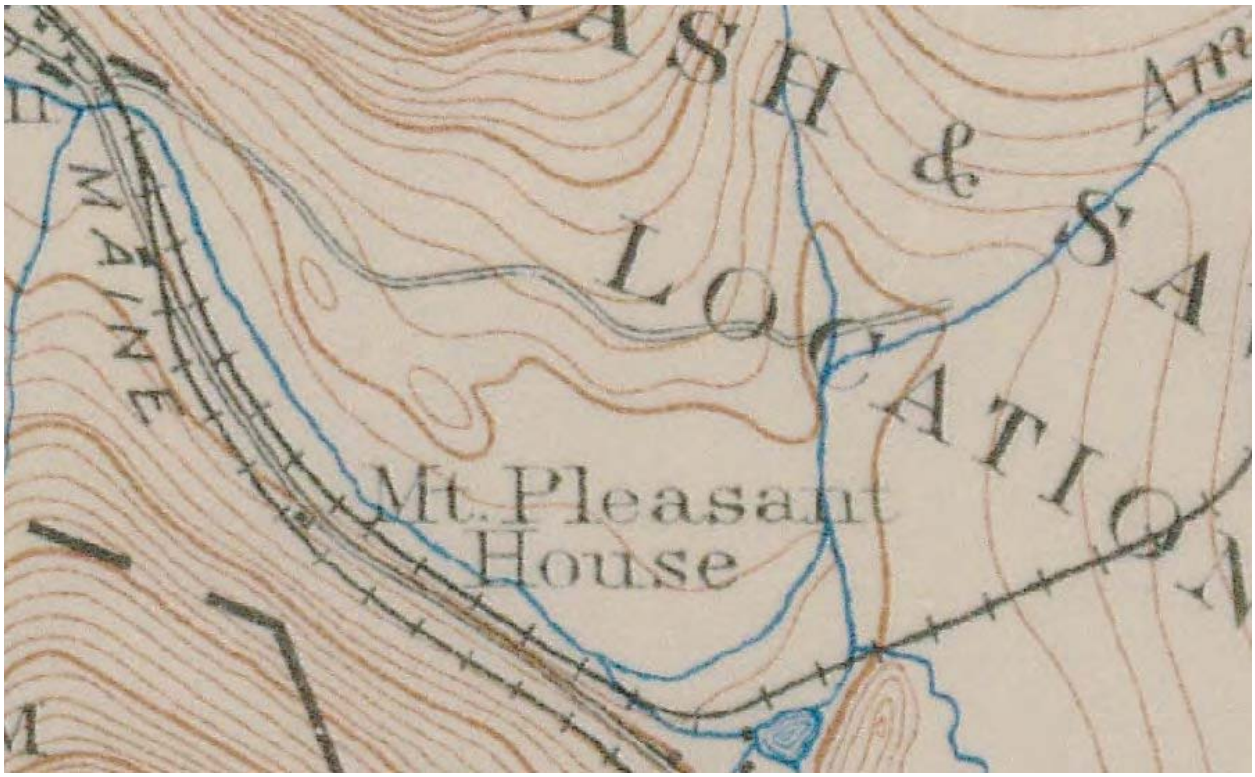
Figure 9. Aerial photos of the area upstream of the Bath valley constriction (Reach 8) from a)1999 and b) 2008 showing channel avulsion and active channel migration.

Figure 10. Bar deposition and accelerated bank erosion (Reach 7) downstream of large mass failure shown in Figure 3a.

Figure 11. Sediment inputs from Zealand River creating enlarged channel bars upstream of natural valley constriction (Segment 38B).

Figure 12. Extensive deposition in Bretton Woods (Reach 42) leading to enlarged channel bars and bank erosion.

a)



b)

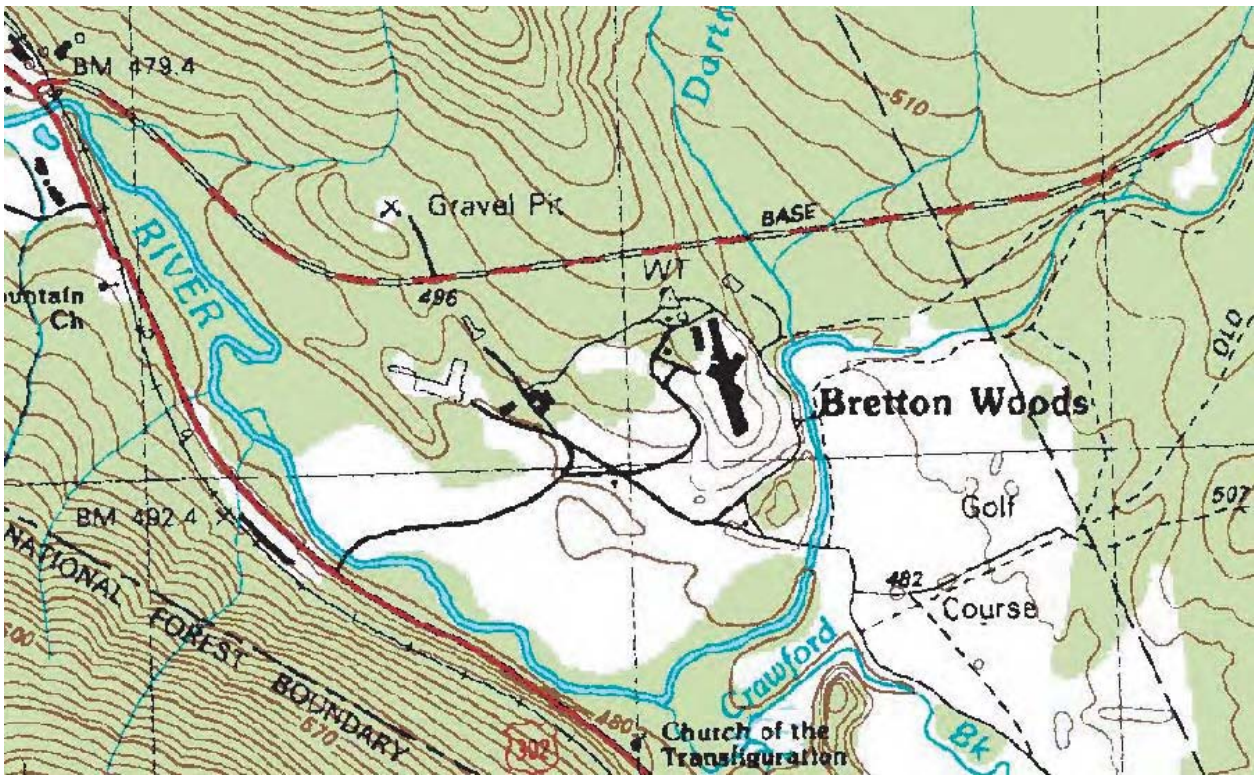
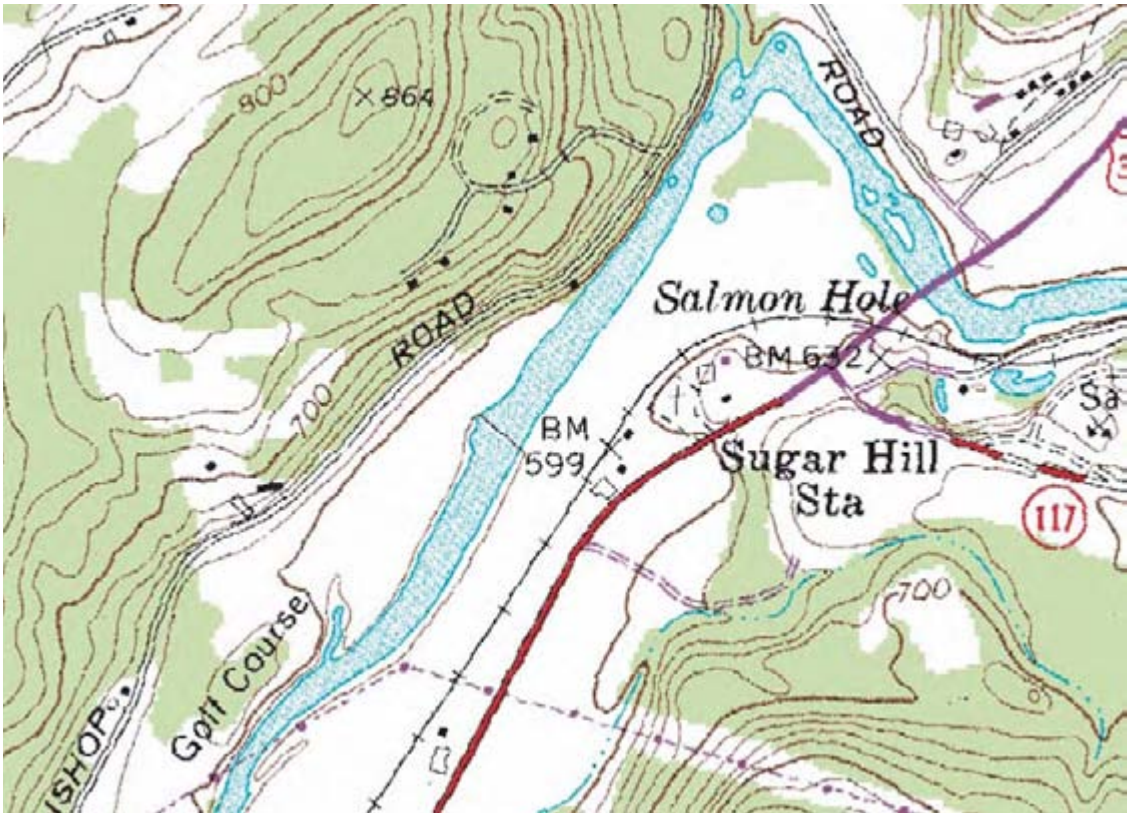


Figure 13. Topographic map from a) 1891 and b) 1980s showing the reformation of meanders along the course of the artificially straightened Ammonoosuc River in Reaches 43 and 42 (Bretton Woods).

Figure 14. Line of riprap has been outflanked and now crosses perpendicular to the current channel in Reach 42 (Bretton Woods).

a)



b)

Figure 15. a) Topographic map from 1980s showing Salmon Hole (Reach 13) prior to the avulsion and b) 2008 aerial photo showing Salmon Hole after the avulsion (yellow arrow highlights the avulsion site and current main channel).

a)

b)

Figure 16. Snow-making ponds adjacent to the Ammonoosuc River in a) aerial photo and b) ground photo represent a potential avulsion hazard (Reach 41).

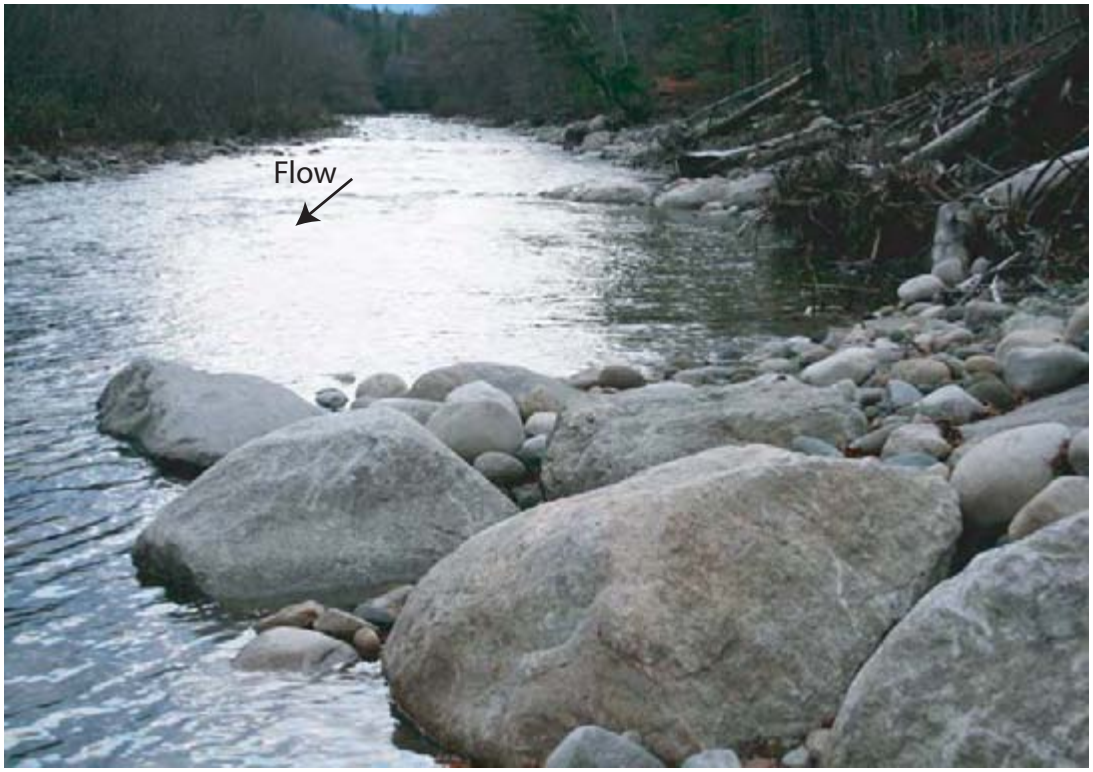
a)

b)

Figure 17. a) Aerial photo showing the location (see arrow) of b) a meander reformed along the straightened channel in Reach 41 (downstream view).

Figure 18. Significant development has occurred on Ammonoosuc River floodplain in Reach 19.

a)



b)

Figure 19. a) Boulder deflectors on the Sunday River, ME and b) root wad revetmenton the Batten Kill, VT.

a)

b)

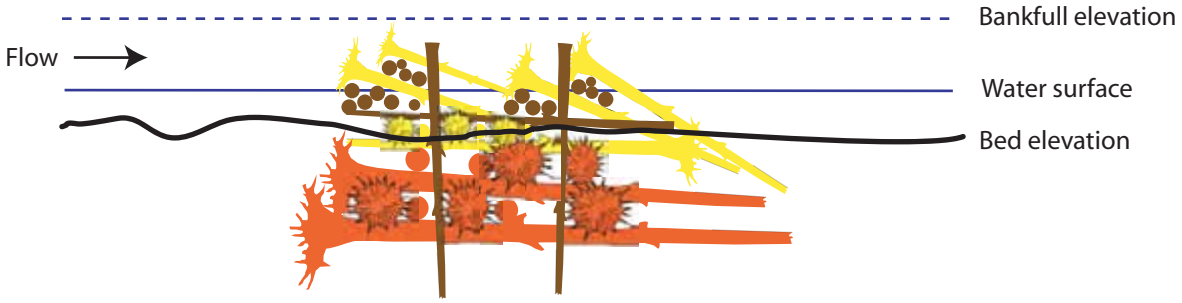
Figure 19 (continued). c) Log jam deflectors on Mohawk River, NH and d) willow stakes protected by root wads on the Connecticut River, NH.

a)

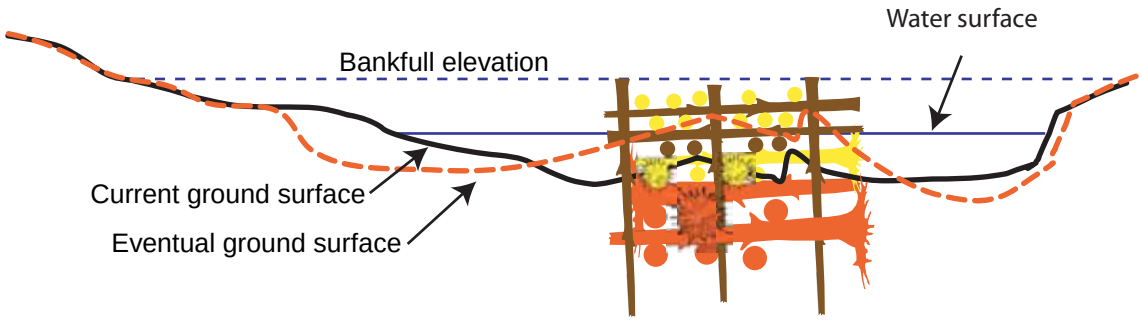
b)

Figure 20. a) Bank armoring has been used to prevent further erosion caused by flow deflection around gravel bars (Reach 8) but b) such efforts are sometimes outflanked in areas of rapid deposition such as upstream of natural valley constrictions (Reach 8).

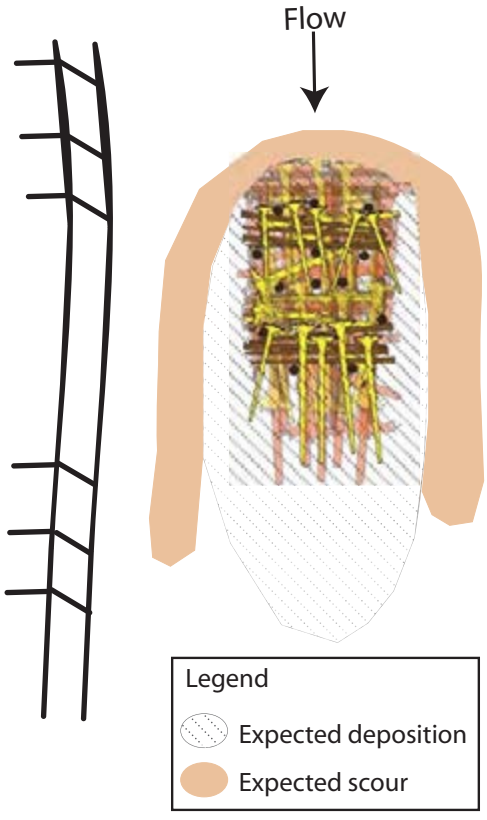
Longitudinal view conceptual



Side view conceptual



Plan view conceptual



Note: Drawings are not to scale

Figure 21. Engineered mid-channel log jam design typical.

TABLES

Table 1. Reach/segment locations and descriptions organized from upstream to downstream.

Reach / Segment	Town	Description / Location
49	Crawfords Purchase	Upstream most reach crosses Base Rd.
48	Crawfords Purchase	Alluvial fan downstream to Abenaki Brook
47B	Crawfords Purchase	Alluvial fan upstream of gorge
47A	Crawfords Purchase	Bedrock gorge upstream of Halfway Brook
46	Crawfords Purchase	Nice bedrock controlled reach upstream of Upper Falls gorge
45B	Crawfords Purchase	Upper Falls gorge
45A	Crawfords Purchase	Bedrock controlled unconfined reach
44	Crawfords Purchase	Bedrock grade controlled reach downstream of gorge
43	Carroll	Widening reach on alluvial fan entering Bretton Woods
42	Carroll	Bretton Woods to Fabyan
41	Carroll	Fabyan to Lower Falls gorge, very unstable with frequent enlarged bars
40B	Carroll	Lower Falls gorge
40A	Carroll	Bouldery confined reach downstream of Lower Falls gorge
39	Carroll	Bouldery reach with shallowing slope upstream of Zealand River
38B	Carroll	Downstream of Zealand River confluence
38A	Carroll	Stable bouldery reach with well-developed sand benches
37	Carroll	Very steep, extremely coarse channel with no visible bedrock controls
36	Carroll	Armored aggradational reach, entering Twin Mountain
35B	Carroll	Straightened plane bed channel through Twin Mountain
35A	Carroll	Aggradational segment upstream of Little River
34	Carroll / Bethlehem	Straightened, bouldery reach downstream of Little River
33	Bethlehem	Nice bouldery reach downstream of Haystack Brook
32	Bethlehem	Nice, stable, unconfined bouldery stream with abundant wetlands
31	Bethlehem	Stable confined bouldery reach in steep valley, railroad on right bank
30	Bethlehem	Stable bouldery reach at Pierce Bridge, ruined mill dam, upstream-most extent knotweed
29	Bethlehem	Impounded by abandoned dam, current channel incision, expansive gravel bars
28	Bethlehem	Bouldery, confined reach through Bethlehem Hollow
27	Bethlehem	Bouldery reach along Wing Rd.
26	Bethlehem	Bouldery reach with long-lived island at bottom of Wing Rd.
25	Bethlehem	Wide, shallow aggradational reach with good side channel access, mill pond seds exposed
24	Bethlehem	Relatively steep bouldery channel contains Alderbrook confluence and crib dam ruins
23	Bethlehem	Confined by terraces, RR bridge and associated upstream deposition pose possible avulsion risk
22	Littleton	Impoundment upstream of Littleton hydro dam, armored banks, pool morphology
21	Littleton	Downstream of Littleton Dam, confined by terraces, entering Littleton Village
20B	Littleton	Bedrock channel through upper portion Littleton village, banks 100% armored
20A	Littleton	Reach with several bridges through Littleton village
19	Littleton	Anastomosed reach with abundant wetlands through highly developed corridor
18	Littleton	Widening reach with many bedrock grade controls and wetlands, includes Willowdale dam site
17B	Lisbon	Incised bedrock-controlled reach with many grade controls
17A	Lisbon	Straight confined segment upstream of Gale River confluence, road and rail encroachments
16	Lisbon	Reach downstream of Gale River confluence
15	Lisbon	Short reach with many bedrock outcrops
14	Lisbon	Widening aggradational reach upstream of Salmon Hole
13	Lisbon	Widening aggradational reach below Salmon Hole
12	Lisbon	Soccer field reach above Lisbon Dam
11B	Lisbon	Bedrock gorge below Lisbon Dam
11A	Lisbon	Confined reach below Lisbon Dam, some bedrock control, good pools
10	Landaff / Lisbon	Landaff reach with large bedrock-controlled island and ruined mill dam at downstream end
9	Bath	Bedrock-controlled reach confined by terraces, downstream of mill dam ruins
8	Bath	Dynamic meandering channel upstream of bedrock valley constriction
7	Bath	Widening reach with huge mass failure and badly scoured railroad bridge
6	Bath	Aggradational widening reach, confining terraces, and network of side channels
5	Bath	Upstream of Bath Dam, agricultural landuse, bedrock outcrops, impounded reach
4	Bath	Downstream of Bath Dam and upstream of Wild Ammo confluence, bank erosion, many deep pools
3	Bath	Bedrock-confined reach downstream of Wild Ammo (gorge with some floodplain and terrace seds)
2	Bath / Haverhill	Upstream of Woodsville Dam, abundant side channels and oxbows, agricultural land use
1	Haverhill	Bedrock gorge graded to Connecticut River, downstream of Woodsville dam

Table 2. Appropriate restoration strategies for each reach organized from upstream to downstream

Reach Number	Segment	Protect River Corridor	Plant Stream Buffer	Stabilize Stream Banks	Remove Encroachments	Encroachment Type	Remove or Replace Structures	Restore Incised Reach	Protect River Corridor At Downstream Reach	Protect River Corridor To Accommodate Meander Redevelopment	Restore Aggraded Reach
49		Yes	No	No	Yes	No	Replace	No	No	Yes	No
48		Yes	No	No	Yes	Railroad	N/A	No	No	Yes	No
47	B	Yes	No	No	Yes	Railroad	N/A	No	No	Yes	No
47	A	Yes	No	No	Yes	Railroad	N/A	Yes	No	No	No
46		Yes	No	No	No	Railroad	N/A	No	No	No	No
45	B	Yes	No	No	No	No	Replace	No	No	No	No
45	A	Yes	No	No	Yes	No	N/A	Yes	No	No	No
44		Yes	LRB	No	Yes	Railroad	N/A	No	No	Yes	No
43		No	No	No	No	Railroad	Replace	No	No	Yes	No
42		No	LRB	No	No	Railroad	Replace	No	No	Yes	No
41		No	No	No	No	Railroad	Replace	Yes	Yes	No	No
40	B	Yes	No	No	No	No	N/A	No	No	No	No
40	A	Yes	No	No	No	No	N/A	No	No	Yes	No
39		No	No	No	Yes	Railroad	No	No	No	Yes	No
38	B	Yes	No	No	Yes	Railroad	N/A	Yes	No	No	No
38	A	No	No	No	Yes	No	N/A	No	No	Yes	No
37		No	LRB	No	No	No	N/A	No	No	No	No
36		No	RB	No	No	Railroad	N/A	No	No	Yes	No
35	B	No	LRB	No	No	Railroad	Replace	Yes	Yes	No	No
35	A	Yes	LRB	No	Yes	Berm and Railroad	N/A	Yes	No	No	No
34		Yes	RB	No	No	No	N/A	No	No	No	No
33		Yes	No	No	No	Railroad	N/A	No	No	No	No
32		Yes	No	No	No	Railroad	N/A	No	No	No	No
31		Yes	No	No	No	Railroad	N/A	No	No	Yes	No
30		No	No	Yes	No	Berm and Railroad	Replace	Yes	Yes	No	No
29		Yes	No	No	Yes	Railroad	N/A	No	No	Yes	No
28		Yes	No	No	No	Path	Replace	No	No	No	No
27		Yes	RB	No	No	Berm	N/A	Yes	Yes	No	No
26		Yes	RB	No	Yes	Railroad	N/A	No	No	Yes	No
25		Yes	No	No	Yes	Railroad	N/A	No	No	Yes	No
24		Yes	RB	No	No	Railroad	N/A	No	No	No	No
23		Yes	RB	No	No	Railroad	Replace	No	No	No	No

Table 2 (continued). Appropriate restoration strategies for each reach organized from upstream to downstream

Reach Number	Segment	Protect River Corridor	Plant Stream Buffer	Stabilize Stream Banks	Remove Encroachments	Encroachment Type	Remove or Replace Structures	Restore Incised Reach	Protect River Corridor At Downstream Reach	Protect River Corridor To Accommodate Meander Redevelopment	Restore Aggraded Reach
22		No	RB	No	No	Railroad	N/A	No	No	No	No
21		No	RB	No	No	Railroad	Replace	No	No	No	No
20	B	No	LRB	No	No	No	Replace	No	No	Yes	No
20	A	No	No	No	No	Path	Replace	Yes	Yes	No	No
19		No	No	No	No	Railroad	Replace	Yes	Yes	No	No
18		Yes	LRB	No	No	Railroad	N/A	Yes	Yes	No	No
17	B	No	RB	No	No	Railroad	N/A	No	No	Yes	No
17	A	No	No	No	No	Railroad	Replace	Yes	Yes	No	No
16		No	LB	No	No	Railroad	N/A	Yes	Yes	No	No
15		No	LB	No	No	Railroad	N/A	Yes	Yes	No	No
14		No	LB	No	No	Berm	Replace	Yes	Yes	No	No
13		Yes	LRB	No	No	Path	N/A	Yes	Yes	No	Yes
12		No	LB	No	No	Path	N/A	No	Yes	No	No
11	B	No	LRB	No	No	No	Replace	No	No	No	No
11	A	No	LRB	Yes	No	No	N/A	No	No	No	No
10		No	LB	No	No	Path	N/A	Yes	Yes	No	No
9		Yes	RB	Yes	No	Path	N/A	No	No	No	No
8		Yes	RB	No	No	Railroad and Path	N/A	Yes	Yes	No	No
7		No	LB	No	Yes	No	Replace	No	No	Yes	Yes
6		Yes	RB	No	Yes	Railroad and Path	N/A	No	No	Yes	No
5		Yes	RB	No	Yes	Railroad	No	No	No	Yes	No
4		Yes	LB	No	No	Railroad	N/A	No	No	No	No
3		Yes	LB	No	No	Railroad	Replace	No	No	No	No
2		Yes	LRB	No	No	Berm	Replace	No	Yes	No	No
1		No	LB	No	No	No	Replace	No	No	No	No

Table 3. Ammonoosuc River Corridor Planning Project Summary Table.

Project Number	Watershed Priority	Reach / Segment	Town	Site Description	Project Description	Technical Feasibility
1	Moderate	42-43	Carroll	Mt. Washington resort golf course, poor riparian buffer	Establish / enhance riparian buffer with riparian plantings and no-mow zones along streambanks	High
2	Highest	41	Carroll	Mt. Washington snowmaking ponds present avulsion risk	Mitigate hazard with upstream sediment/water attenuation and channel blocks/berms	Easy access, attenuation sites?
3	High	41	Carroll	Extremely dynamic reach upstream of Lower Falls prone to planform channel change	Corridor protection	High, land is highly valued for development
4	Moderate	35A-B	Carroll	Increased sediment transport capacity and flow velocity in straightened channel leading to degraded condition	Restore river to historic channel course, deflect flow, encourage meandering	Access points?, material source?
5	High	35A	Carroll	Extreme sediment aggradation leading to severe bank erosion	Corridor protection	Very high
6	Moderate	32	Bethlehem	Nice stable reach with abundant wetlands upstream of Pierce Bridge, good habitat	Corridor protection	Very high
7	High	31	Bethehem	Landfill drainage discharging into stream, destabilizing slope	Mitigate landfill drainage, stabilize slope	Unknown, difficult site access
8	High	28	Bethlehem	Mass failure behind Stoney's Auto Body contributing excess sediment to stream	Stabilize toe of mass failure, re-vegetate slope	Very high, easy access

Project Number	Watershed Priority	Reach / Segment	Town	Site Description	Project Description	Technical Feasibility
9	Moderate	27	Bethlehem	Gullying in road ditch along Wing Rd. destabilizing road and contributing sediment to channel	Stormwater retention ponds and / or improved road ditch drainage	High
10	High	26-30	Bethehem	Bethlehem is the upmost extent of japanese knotweed along the Ammo	Grassroots effort to eradicate invasive japanese knotweed using volunteers	Very high
11	High	25	Littleton	Undeveloped corridor ideally situated upstream of Littleton village, active bank erosion and bar aggradation, wetland habitat	Corridor protection	Very high
12	Moderate	23	Littleton	Railroad bridge constricts stream creating erosion and sediment transport issues	Replace / retrofit railroad bridge to pass flows / sediment	Access may be a problem
13	High	19	Littleton	Landfill drainage discharging into stream	Mitigate landfill drainage	Unknown
14	Highest	13	Lisbon	Salmon Hole avulsion area, sediment source and transport problems	River and riparian restoration, re-meandering, corridor easements, conservation	Easy access, material source?
15	High	13	Lisbon	Degraded riparian habitat along dynamic reach	Riparian buffer planting, restore upland forest habitat	Very high

Project Number	Watershed Priority	Reach / Segment	Town	Site Description	Project Description	Technical Feasibility
16	High	12	Lisbon	Increased sediment transport capacity and flow velocity in straightened channel leading to extreme erosion in village	Bank cutting / flow diversion and / or breach railroad grade to divert a portion of flow during high flow events	High
17	High	12	Lisbon	Bank erosion threatening town soccer field	Stabilize eroding bank with rock / wood deflectors	High
18	Moderate	11A	Lisbon	leftbank stormwater outfalls destabilizing slope causing gullying	Stormwater retention ponds and/or aprons at stormwater outfalls	High, steep slope
19	Low	10	Landaff / Lisbon	Forested island composed of impoundment sediments upstream of ruined mill dam	Corridor protection	Very high
20	High	8	Bath	Extremely dynamic reach downstream of Gilman Hill Rd. prone to planform channel change	Corridor protection, ideally located upstream of Bath village to provide sediment and water attenuation	Very high
21	High	7	Bath	Mass failure in upper Bath village contributing excess sediment	Stabilize toe of mass failure, deflect flow around slope and out of straightened channel	Unknown
22	Moderate	2	Bath / Haverhill	Dynamic reach prone to channel change upstream of village of Woodsville	Corridor protection	Very high
23	Moderate	2	Bath / Haverhill	Increased sediment transport capacity and flow velocity in straightened channel leading to erosion and flooding problems	Bank cutting / flow diversion	High

Project Number	Benefits	Stakeholders / Status	Costs	Next Steps	Photo
1	Stabilize banks, reduce erosion hazards, improve riparian and aquatic habitat	Mt. Washington resort, Town of Carroll	Low to moderate	Contact landowner	
2	Reduce risk of catastrophic river avulsion destabilizing adjacent reaches	Mt. Washington resort, Town of Carroll	Moderate to high	Survey area to establish relative elevations, locate attenuation sites	
3	Reduce potential losses through erosion hazards, provide sediment storage, moderate peak flows, reduce stress on downstream reaches	Mt. Washington resort, Town of Carroll	Depends on value of land	Contact landowner	
4	Increase sediment storage, improve riparian and aquatic habitat, reduce sediment transport to ds reaches, lower flow velocities	Town of Carroll, landowner	Unknown	Assess feasibility, look for habitat enhancement grant source	
5	Provide sediment storage, moderate peak flows, reduce stress on downstream reaches	Town of Carroll, landowner	Depends on value of land	Contact landowner	
6	Protect valuable habitat, provide sediment storage, moderate peak flows, reduce stress on downstream reaches	Town of Bethlehem, landowner	Low	Contact landowner	
7	Improved water quality, reduced health impacts	Town of Bethlehem, landfill owner	Unknown	Contact State agencies to determine next steps	
8	Reduce sediment loading to stream, stabilize slope, improve riparian habitat, aesthetic benefit	Town of Bethlehem, is landowner cooperative?	Low	Contact landowner, legal issues?	

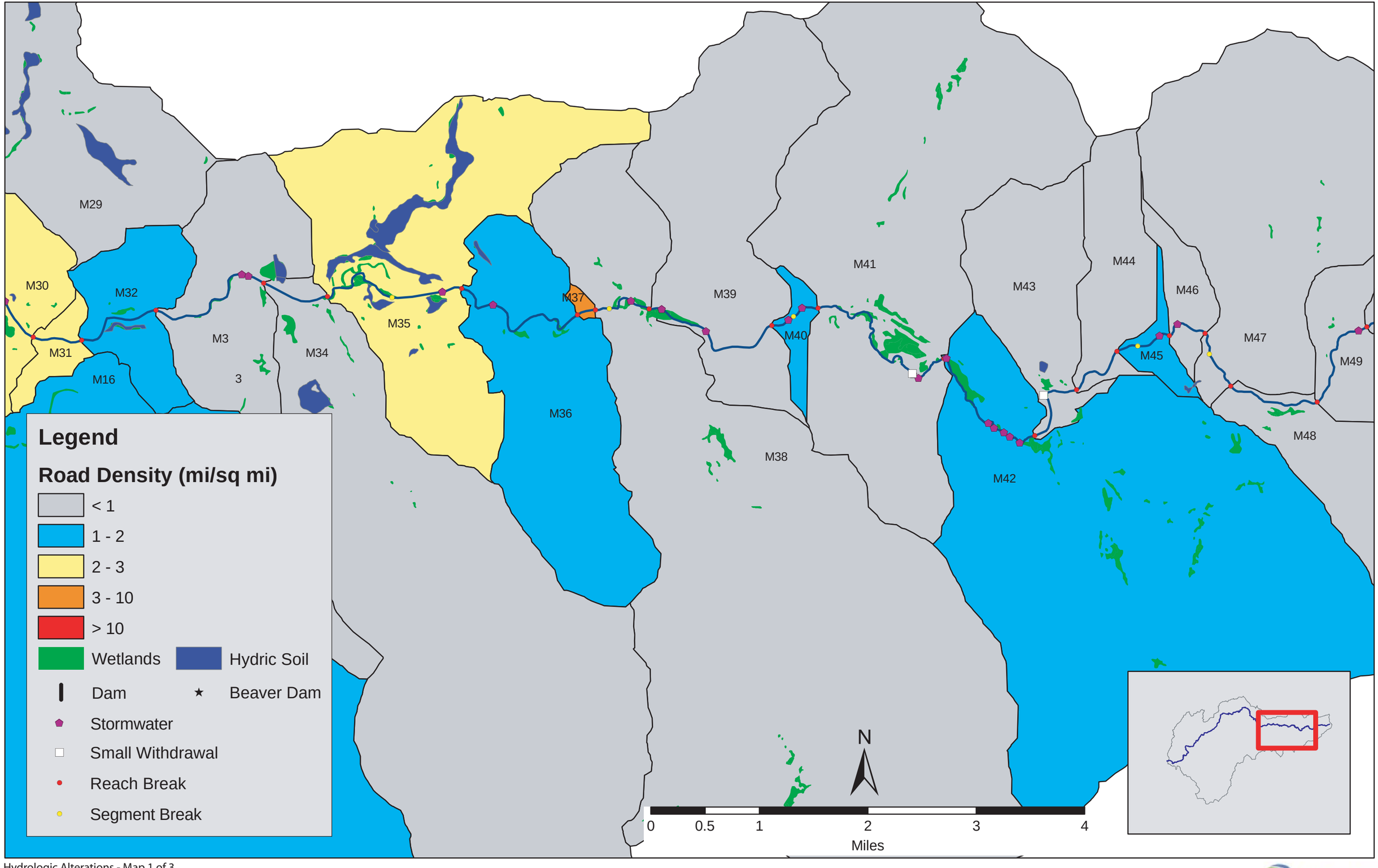
Project Number	Benefits	Stakeholders / Status	Costs	Next Steps	Photo
9	Stabilize road grade, reduce peak flows, improve water quality, reduce sediment loading	Town of Bethlehem road crew, gravel pit owner	Low to moderate	Talk to road crew, contact landowner	
10	Eradicating knotweed or llimiting its spread will improve and protect the integrity and quality of the riparian zone, increased bank stability, protect native plant species	Town of Bethlehem, Bethlehem LAC, landowners	Low to no cost	Public outreach, organize volunteer labor	
11	Provide sediment storage, moderate peak flows, reduce stress on downstream reaches, protect good aquatic and wetland habitat	Town of Littleton, landowner?	Low	Contact landowner	
12	Increased capacity to transport sediment and flow will move channel toward equilibrium and reduce bank instability	Town of Littleton, who owns right-of-way?	Relatively high for perceived benefits	Assess feasibility	
13	Improved water quality, reduced health impacts	Town of Littleton, landfill owner	Unknown	Contact State agencies to determine next steps	
14	Increased sediment storage, improved riparian and aquatic habitat, reduced sediment transport to ds reaches, lower flow velocities	ACT, Lisbon Golf Course, NE Wire / Survey and conceptual designs completed	$100K - $368K	ACT land acquistion, corridor easements, secure grant money	
15	Improve riparian and aquatic habitat, increase canopy and cover, trap sediment on floodplain	ACT, Lisbon Golf Course	Low to moderate	ACT land acquistion, corridor easements, secure grant money	

Project Number	Benefits	Stakeholders / Status	Costs	Next Steps	Photo
16	Reduce stress on eroding banks including soccer field, provide sediment storage, decrease flow velocities, improve side channel habitat, increase floodplain and wetland connection	ACT, NE Wire, Town of Lisbon	Low to moderate	Assess feasibility, determine impacts to town water supply well and recreational trail	
17	Arrest bank erosion and protect soccer field of high local importance, increase instream sediment storage, increase flow complexity, aquatic habitat benefits	ACT, NE Wire, Town of Lisbon / Survey and conceptual designs completed	Moderate to high	Assess feasibility and level of interest, search for funding sources	
18	Reduced peak flows, improved water quality, reduced sediment loading, stabilize slope	Town of Lisbon, property owner?	Low to moderate	Assess feasibility, contact landowner	
19	Provide sediment storage, moderate peak flows, reduce stress on downstream reaches	Towns of Landaff and Lisbon, landowner	Low	Contact landowner	
20	Provide sediment storage, moderate peak flows, reduce stress on downstream reaches	Town of Bath, is farmer interested in corridor plan or easements?	Low	Contact landowner, farmer	
21	Reduce sediment loading, lower flow velocities, reduce stress on adjacent downstream reaches	Town of Bath, landowner?, downstream landowners	Moderate to high	Contact landowner, assess feasilbility	
22	Provide sediment storage, moderate peak flows, reduce stress on Woodsville	Towns of Bath and Haverhill, landower, farmer	Low	Contact landowner	
23	Reduce stress on River Rd. area, provide sediment storage, increase floodplain and wetland connection, improve riparian and aquatic habitat	Towns of Bath and Haverhill, landower, farmer	Low to moderate	Assess feasibility, look for habitat enhancement grant source	

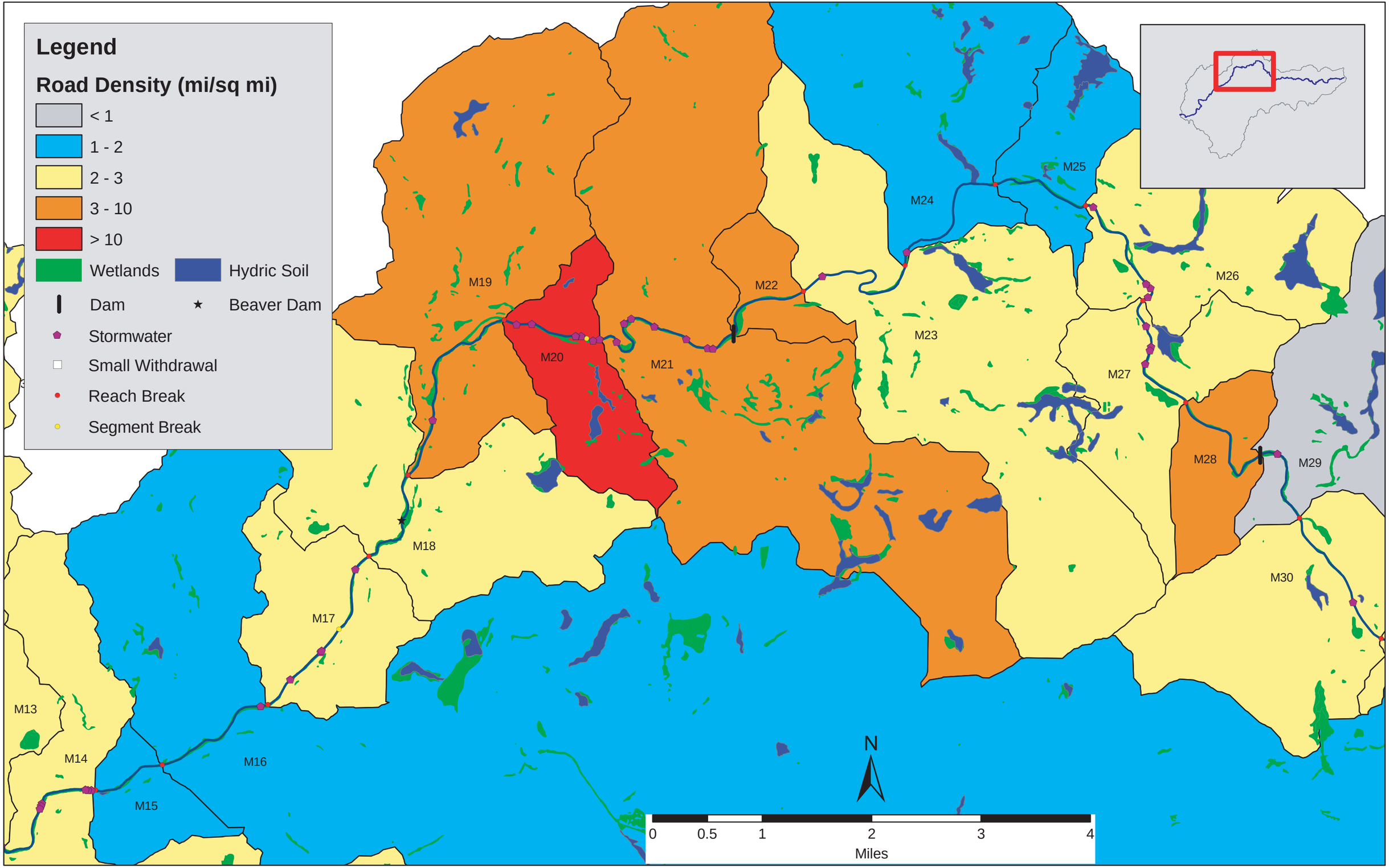
APPENDICES

Appendix 1

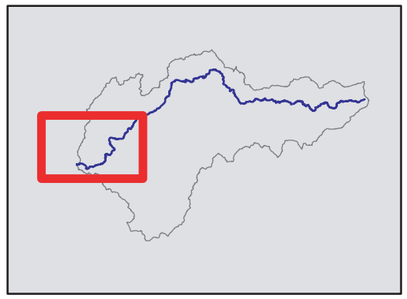
(Stressor and departure maps)



Hydrologic Alterations - Map 1 of 3.



Hydrologic Alterations - Map 2 of 3.



Legend

Road Density (mi/sq mi)

- < 1
- 1 - 2
- 2 - 3
- 3 - 10
- > 10
- Wetlands
- Hydric Soil
- Dam
- Beaver Dam
- Stormwater
- Small Withdrawal
- Reach Break
- Segment Break

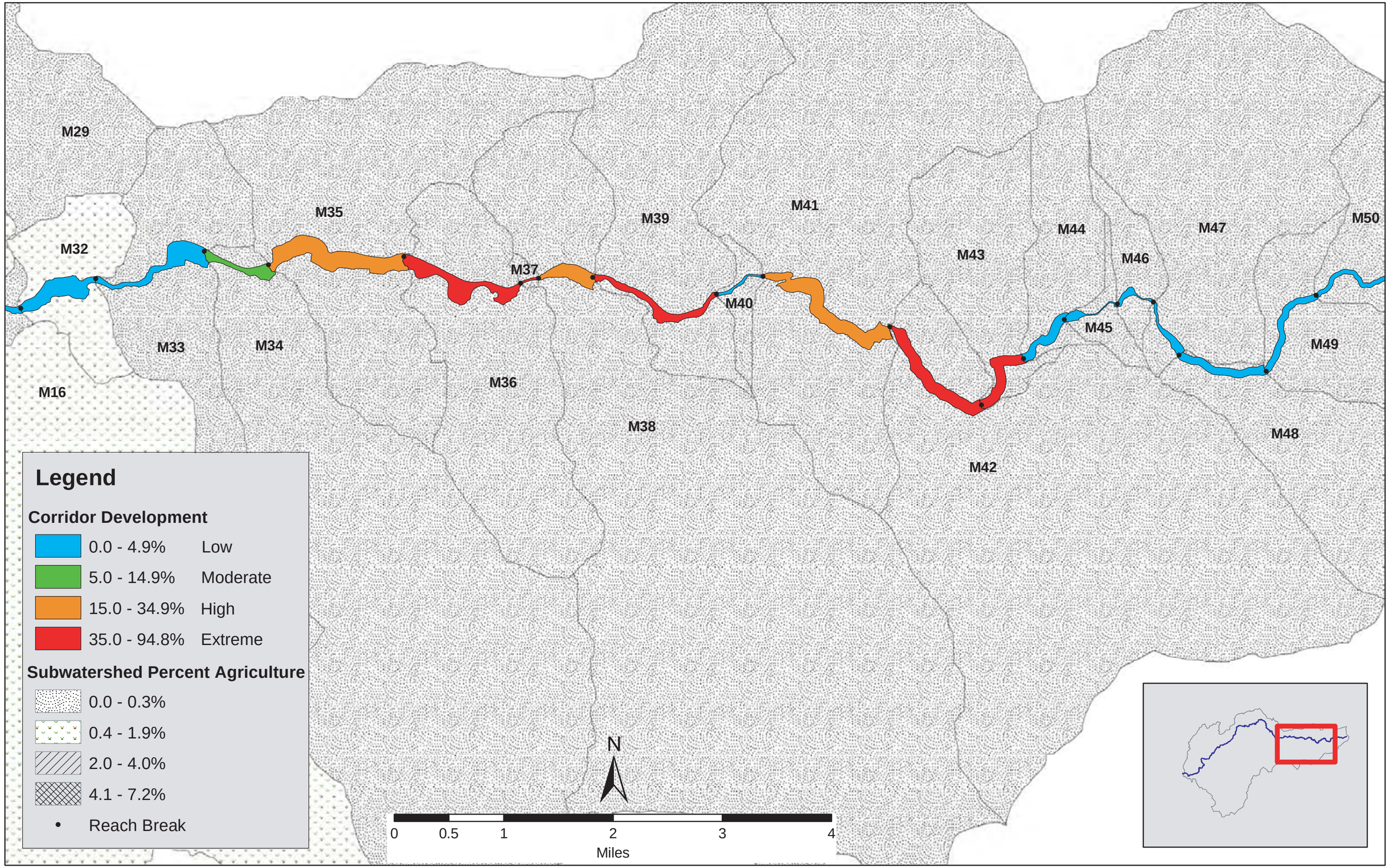
M01
M02
M03
M04
M05
M06
M07
M08
M09
M10
M11
M12
M13
M14

N

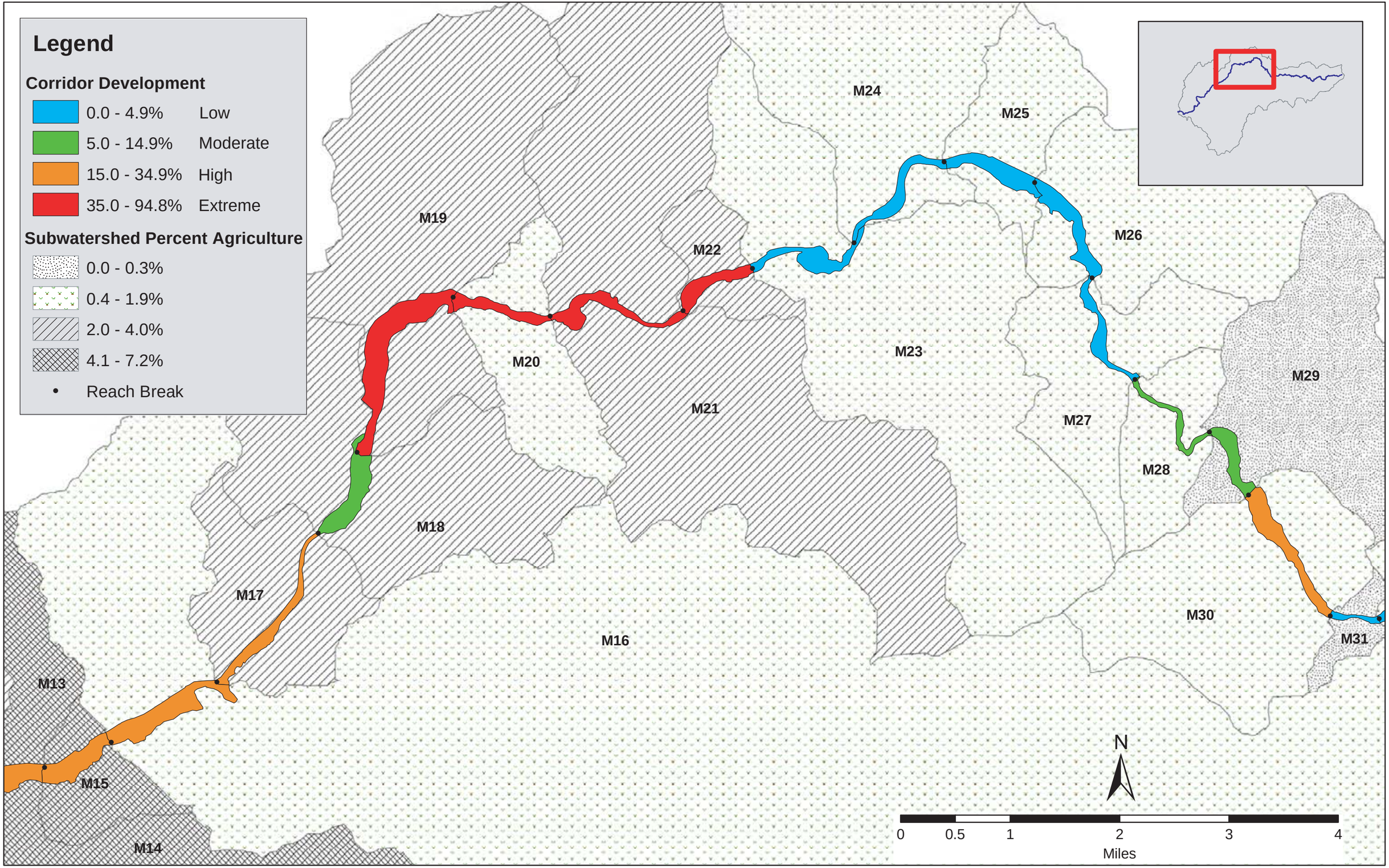
0 0.5 1 2 3 4
Miles

Hydrologic Alterations - Map 3 of 3.

Field Geology Services

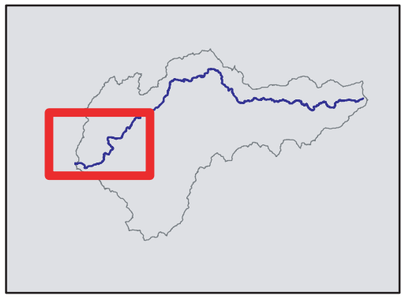


Land Use Land Cover - Map 1 of 3.



Land Use Land Cover - Map 2 of 3.

Field Geology Services



Legend

Corridor Development

	0.0 - 4.9%	Low
	5.0 - 14.9%	Moderate
	15.0 - 34.9%	High
	35.0 - 94.8%	Extreme

Subwatershed Percent Agriculture

	0.0 - 0.3%
	0.4 - 1.9%
	2.0 - 4.0%
	4.1 - 7.2%
•	Reach Break

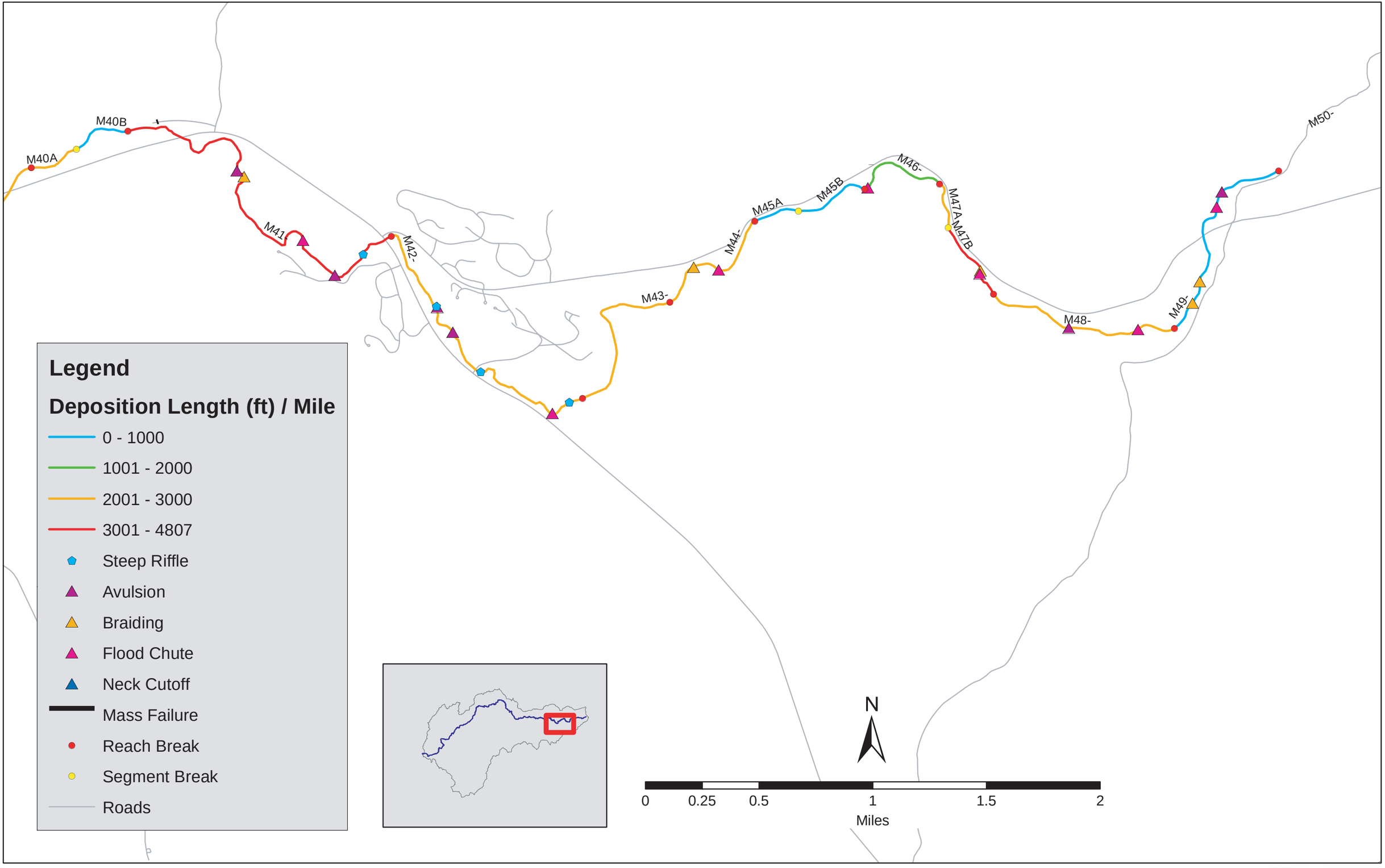
M15
M14
M13
M12
M11
M10
M09
M08
M07
M06
M05
M04
M03
M02
M01

N

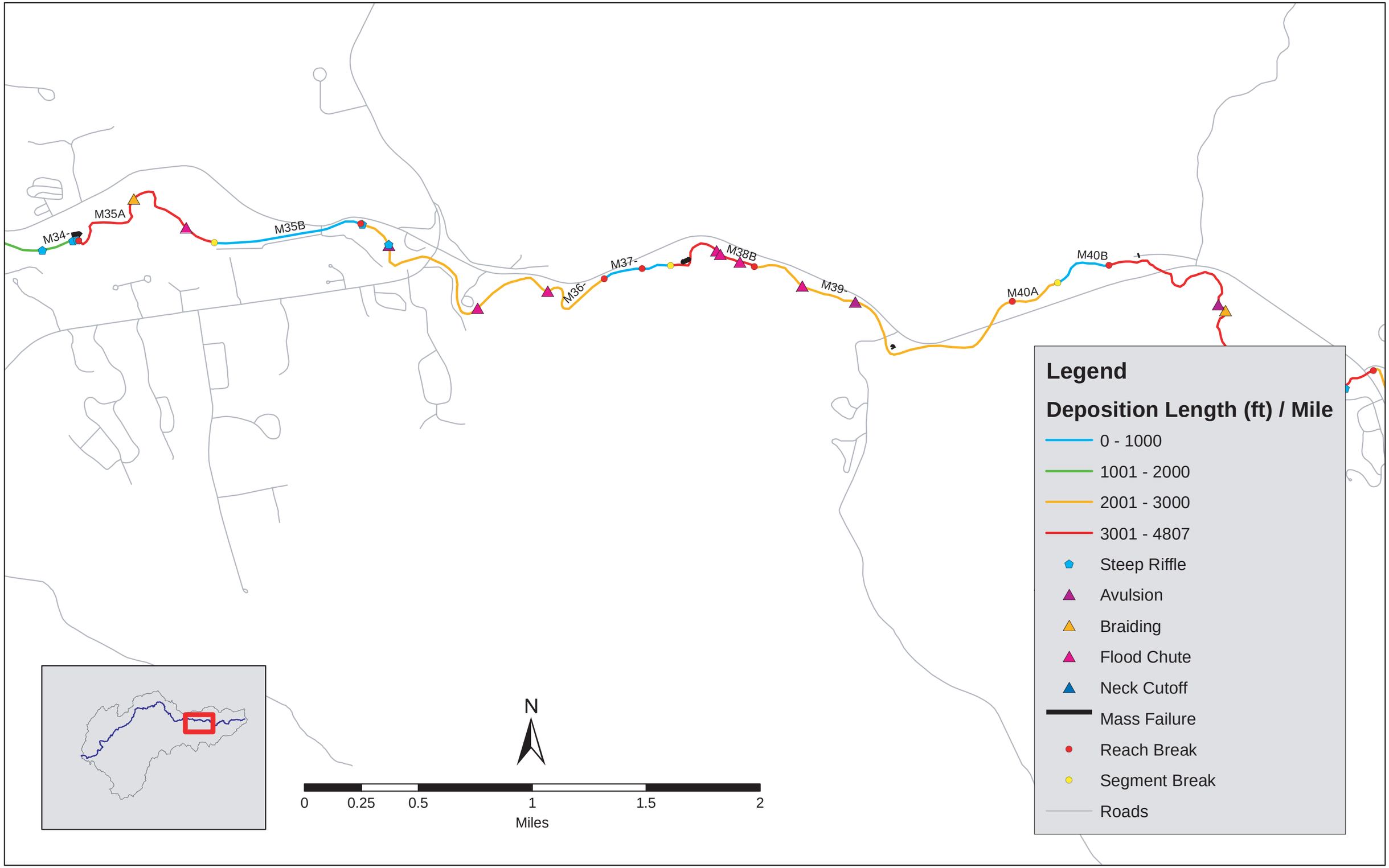
0 0.5 1 2 3 4
Miles

Land Use Land Cover - Map 3 of 3.

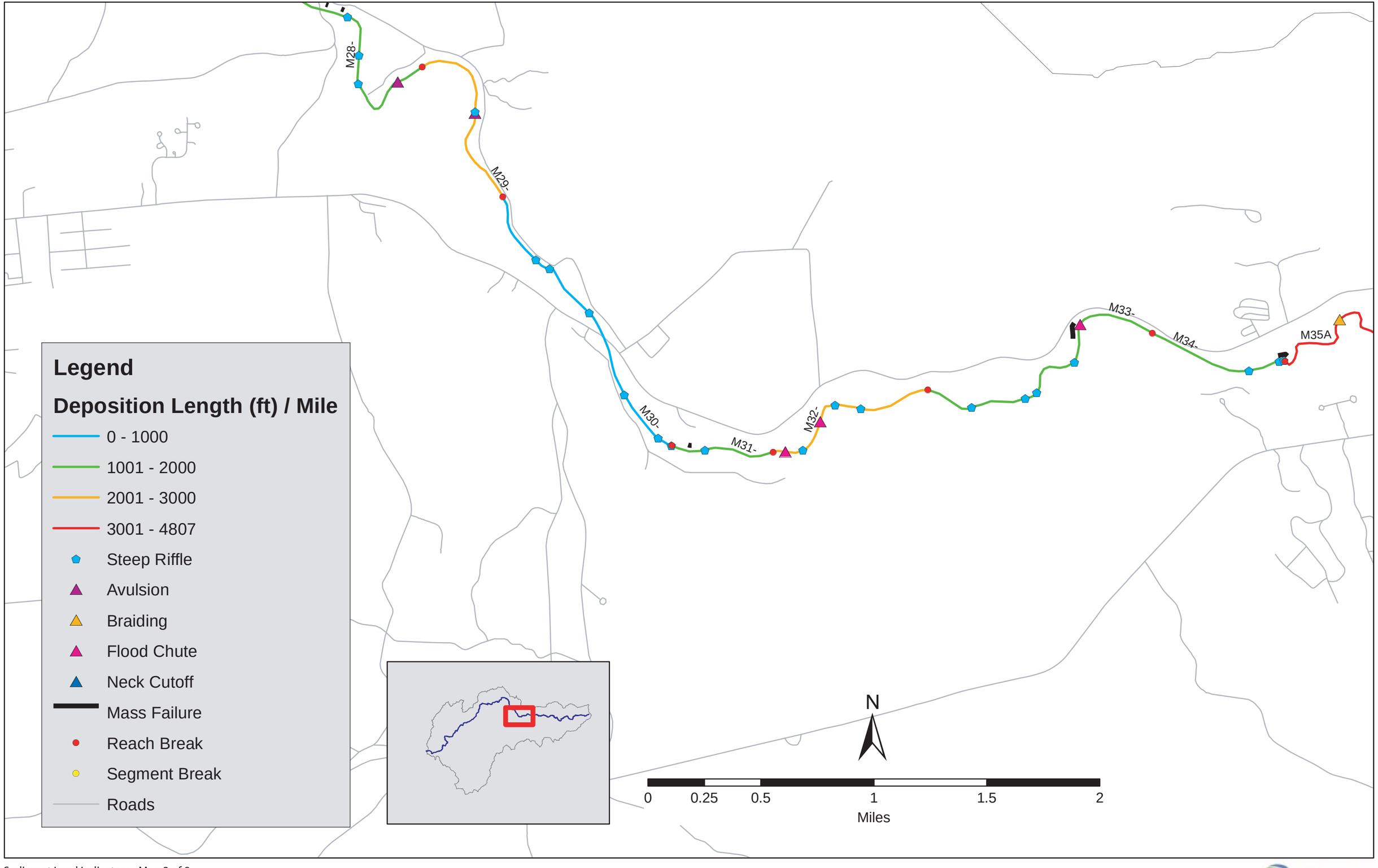
Field Geology Services
Fluvial Geomorphology



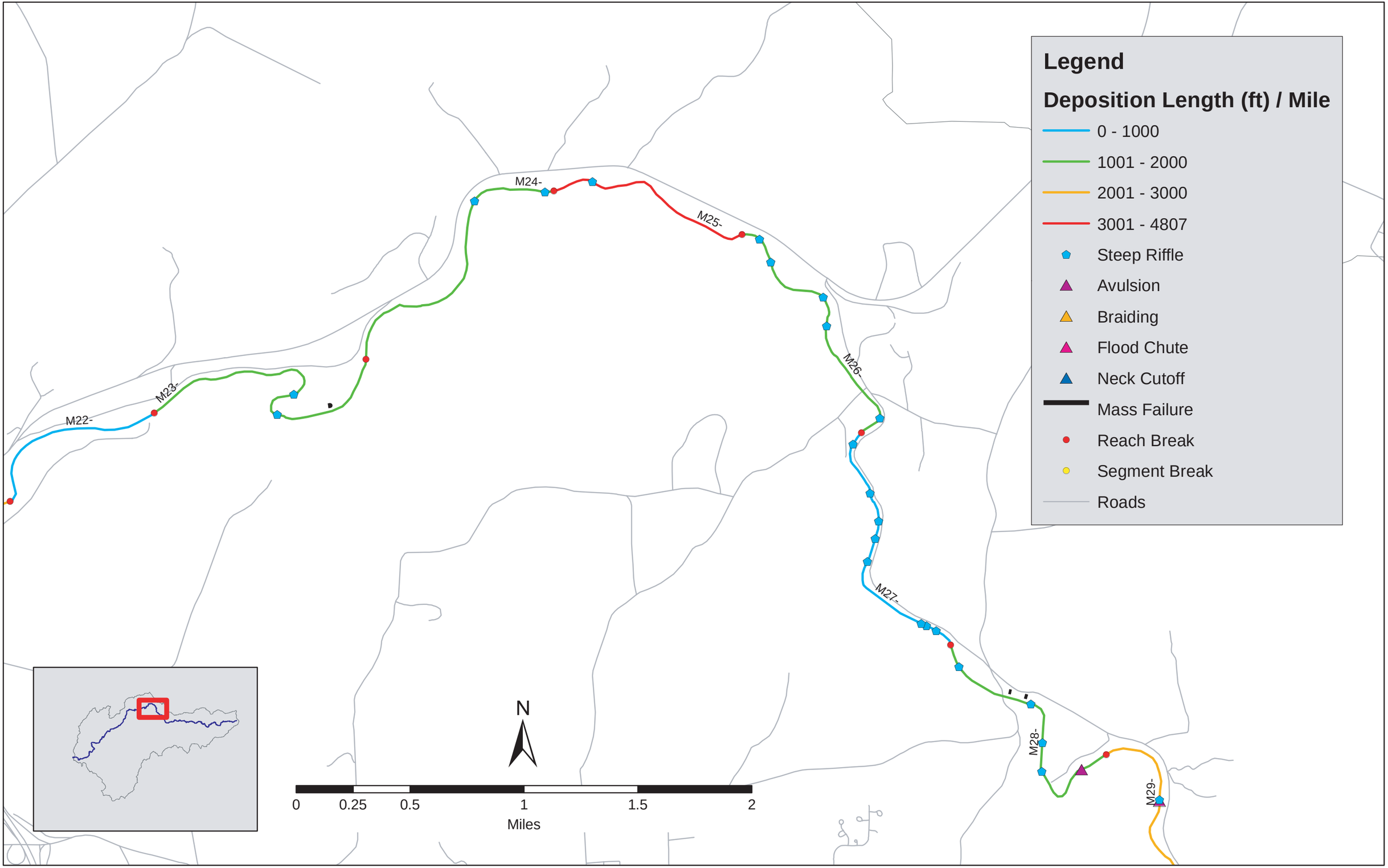
Sediment Load Indicators - Map 1 of 8.



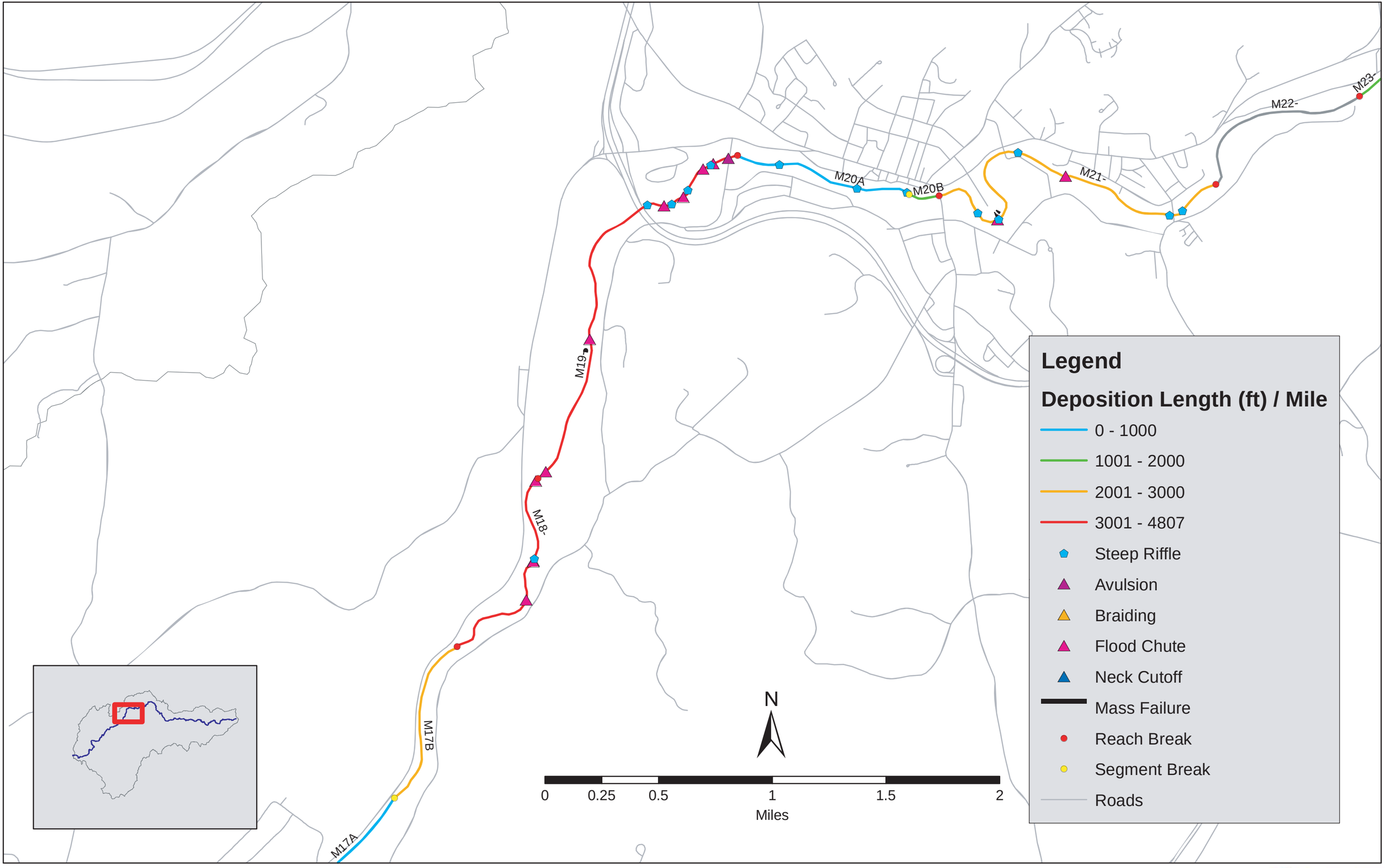
Sediment Load Indicators - Map 2 of 8.



Sediment Load Indicators - Map 3 of 8.

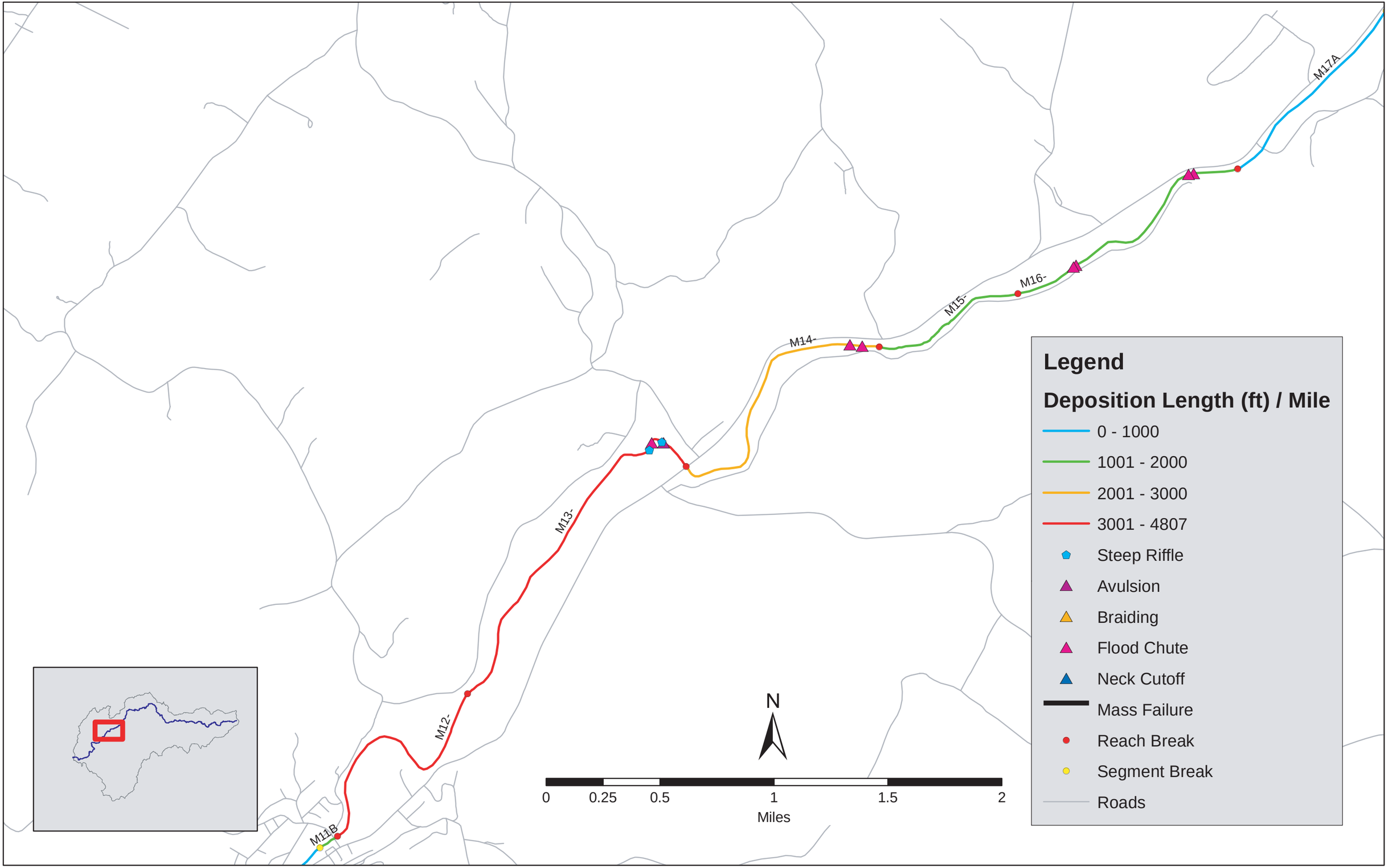


Sediment Load Indicators - Map 4 of 8.

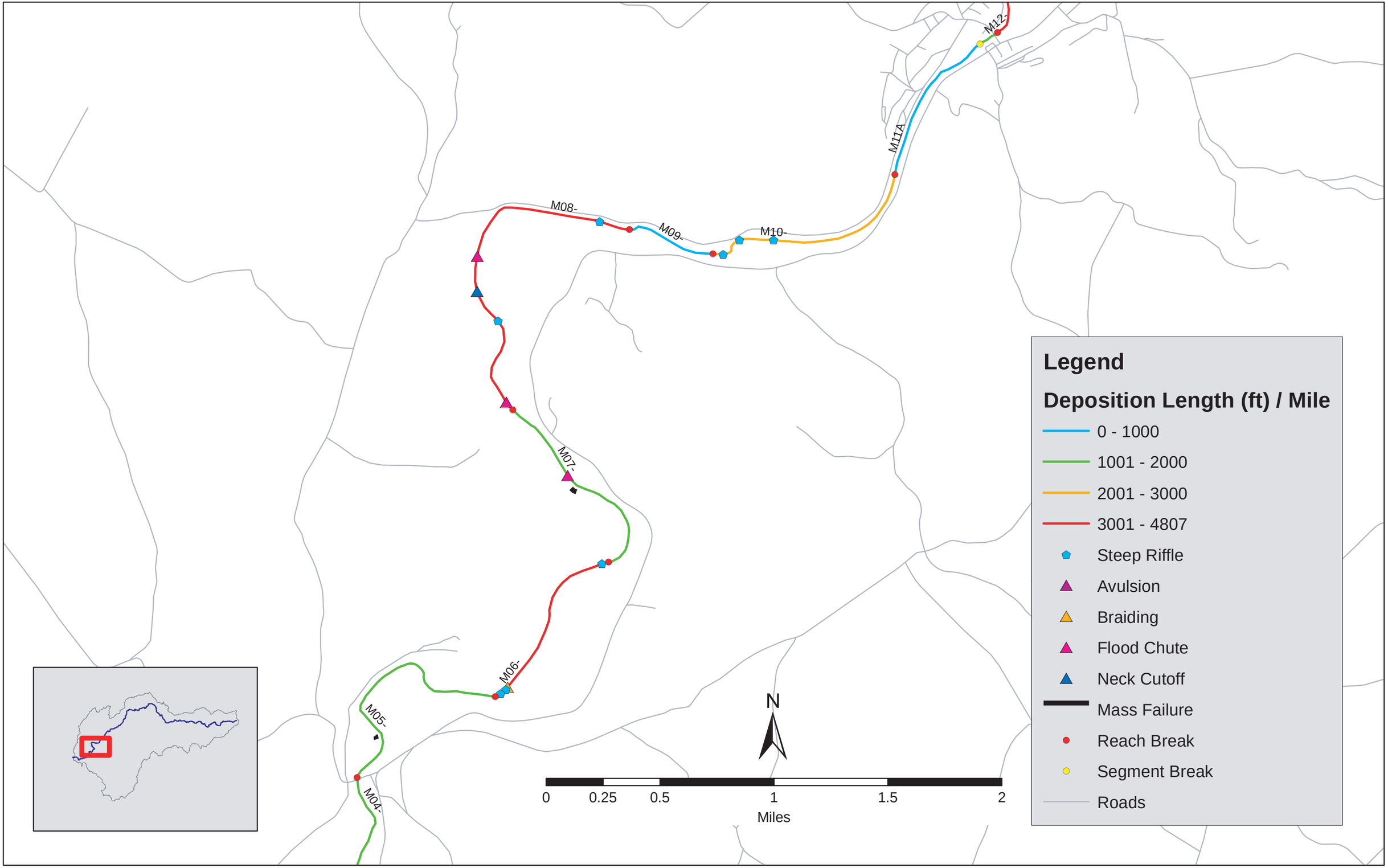


Sediment Load Indicators - Map 5 of 8.

Field Geology Services
Fluvial Geomorphology

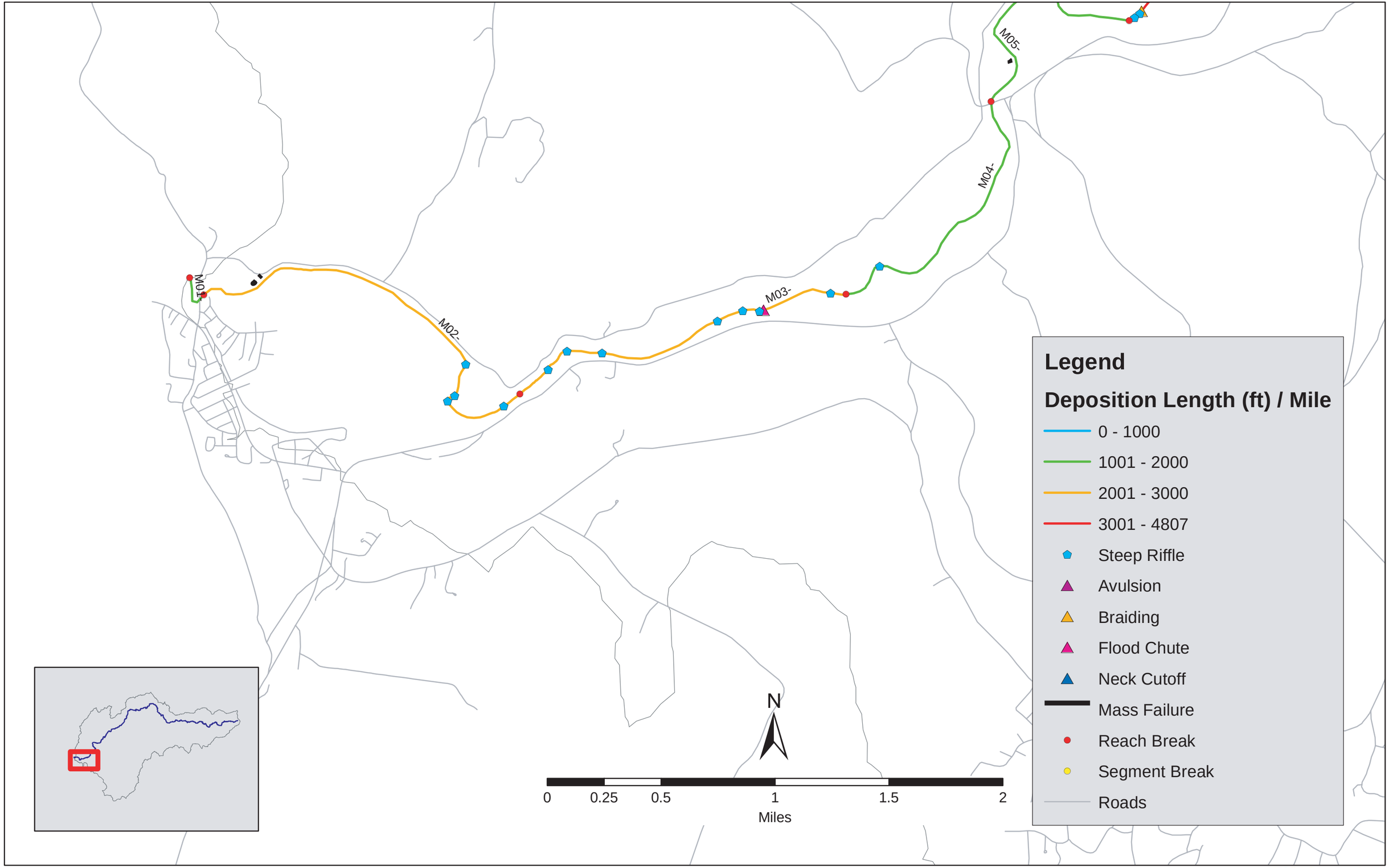


Sediment Load Indicators - Map 6 of 8.

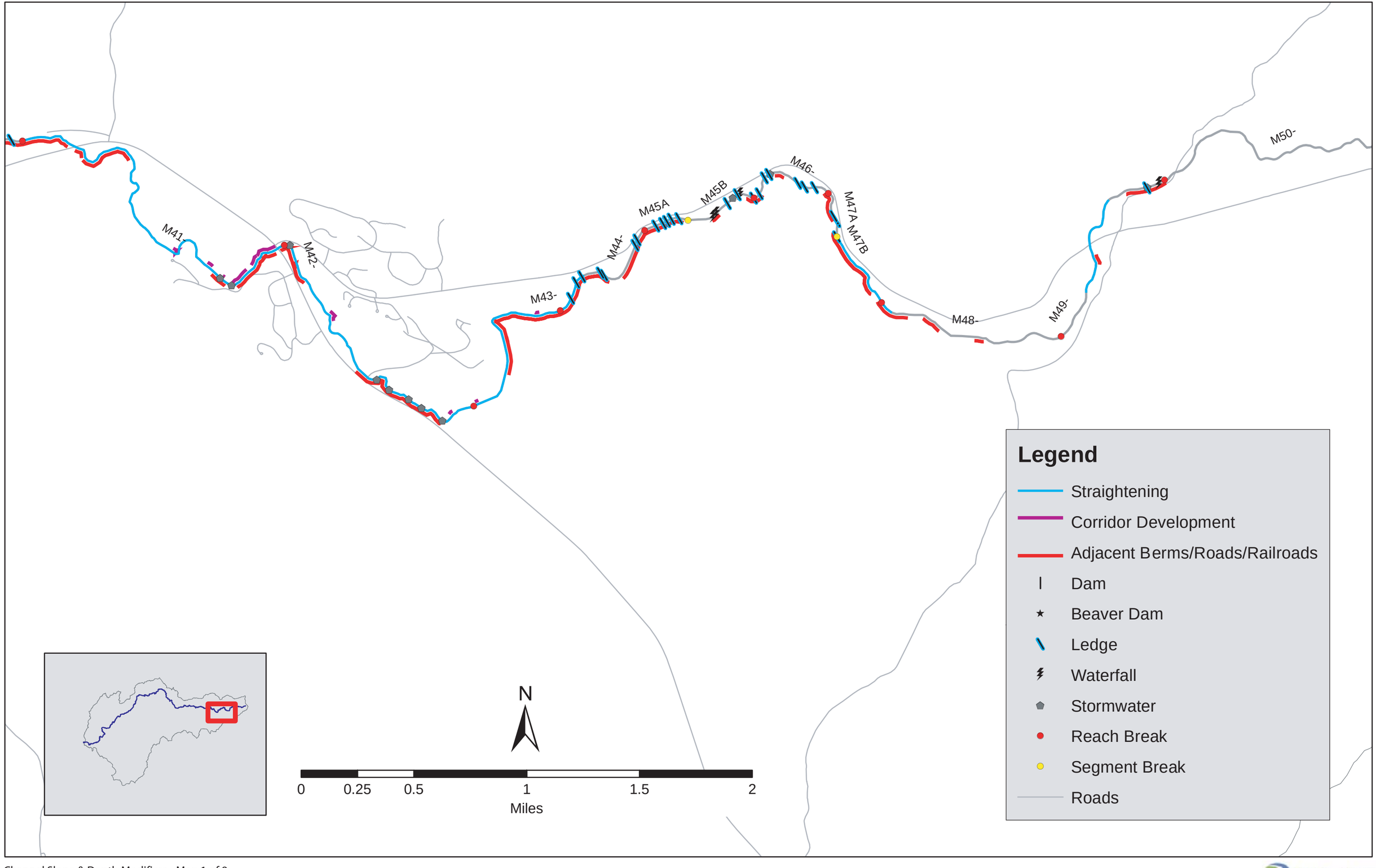


Sediment Load Indicators - Map 7 of 8.

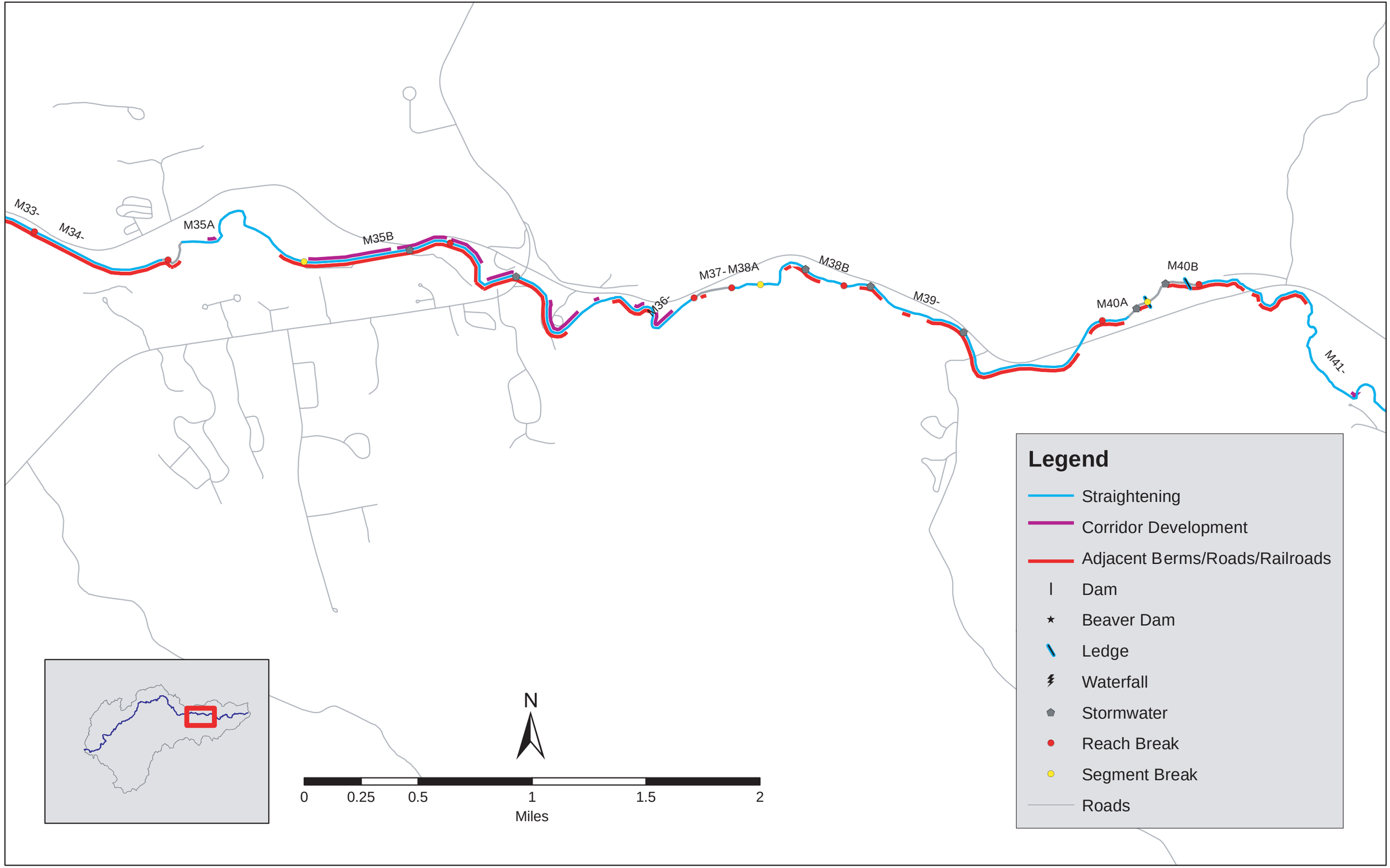
Field Geology Services



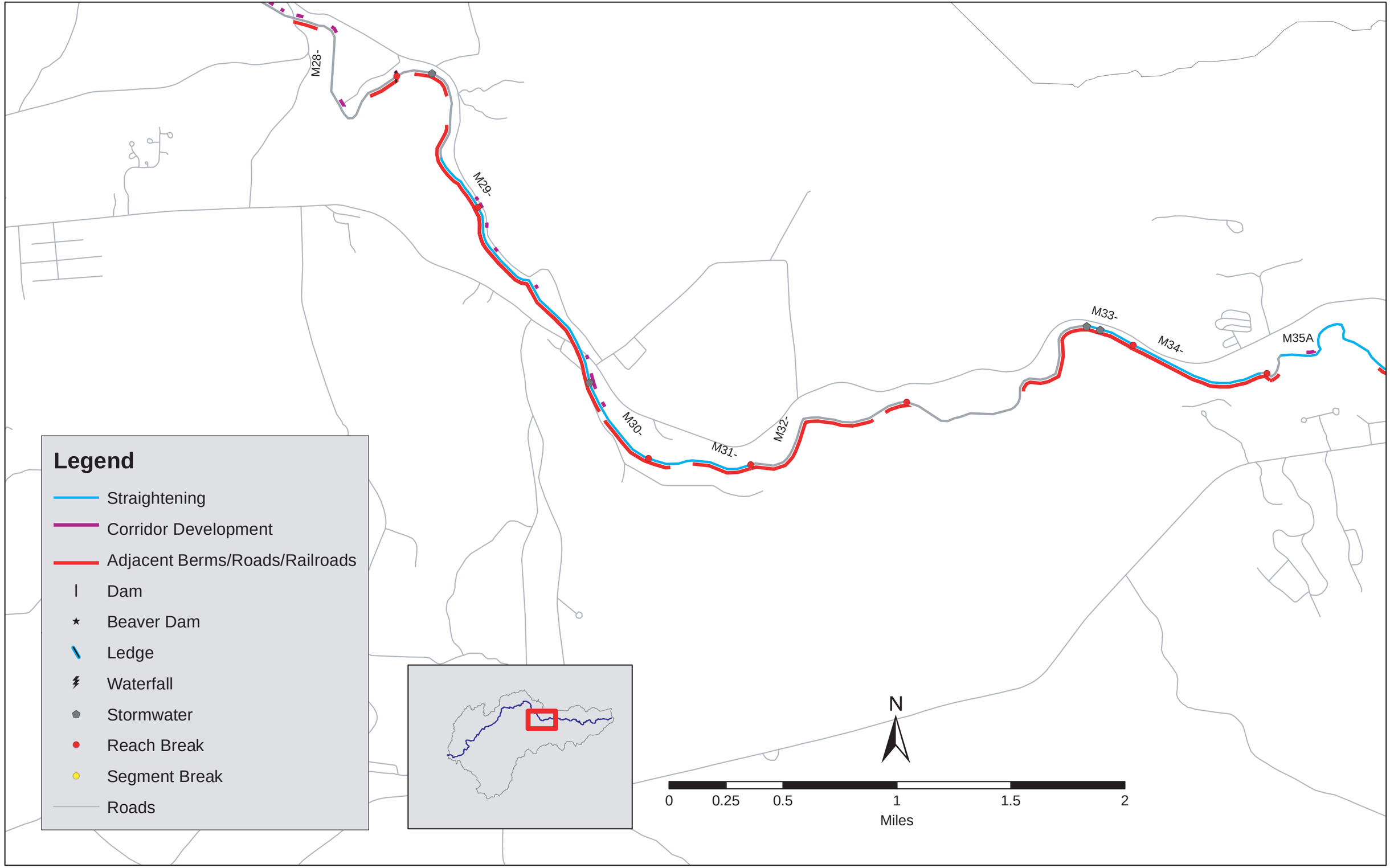
Sediment Load Indicators - Map 8 of 8.



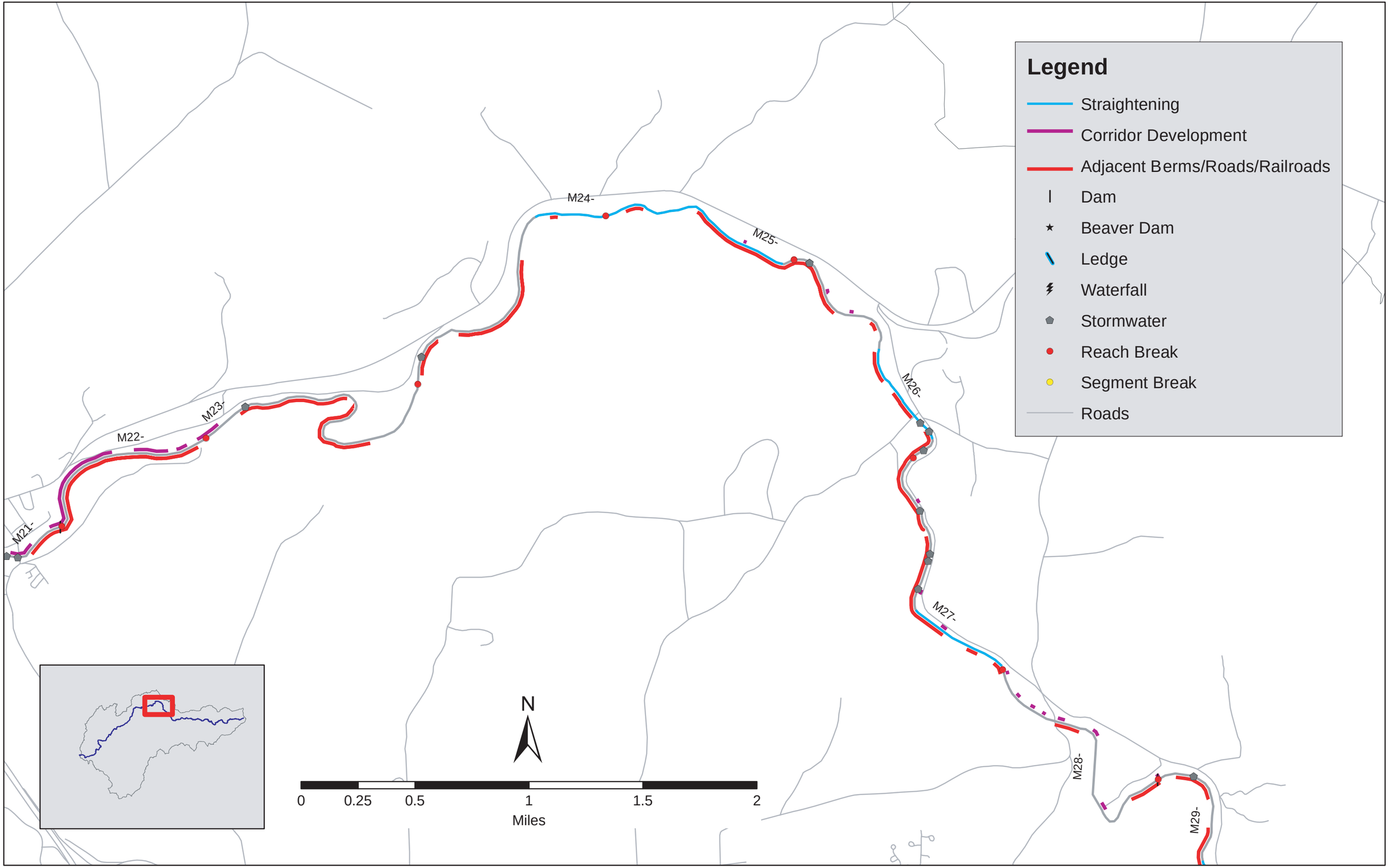
Channel Slope & Depth Modifiers - Map 1 of 8.



Channel Slope & Depth Modifiers - Map 2 of 8.

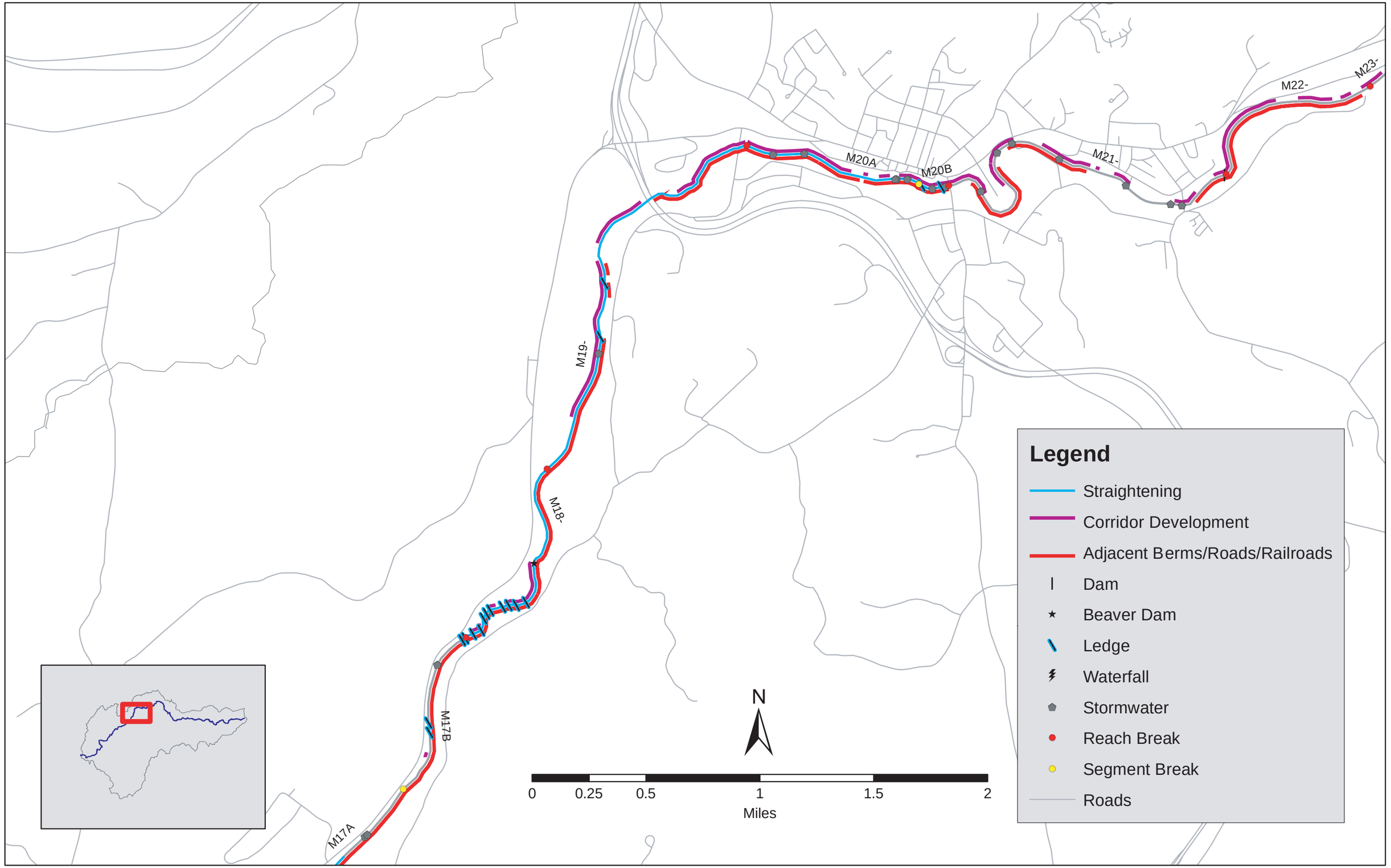


Channel Slope & Depth Modifiers - Map 3 of 8.



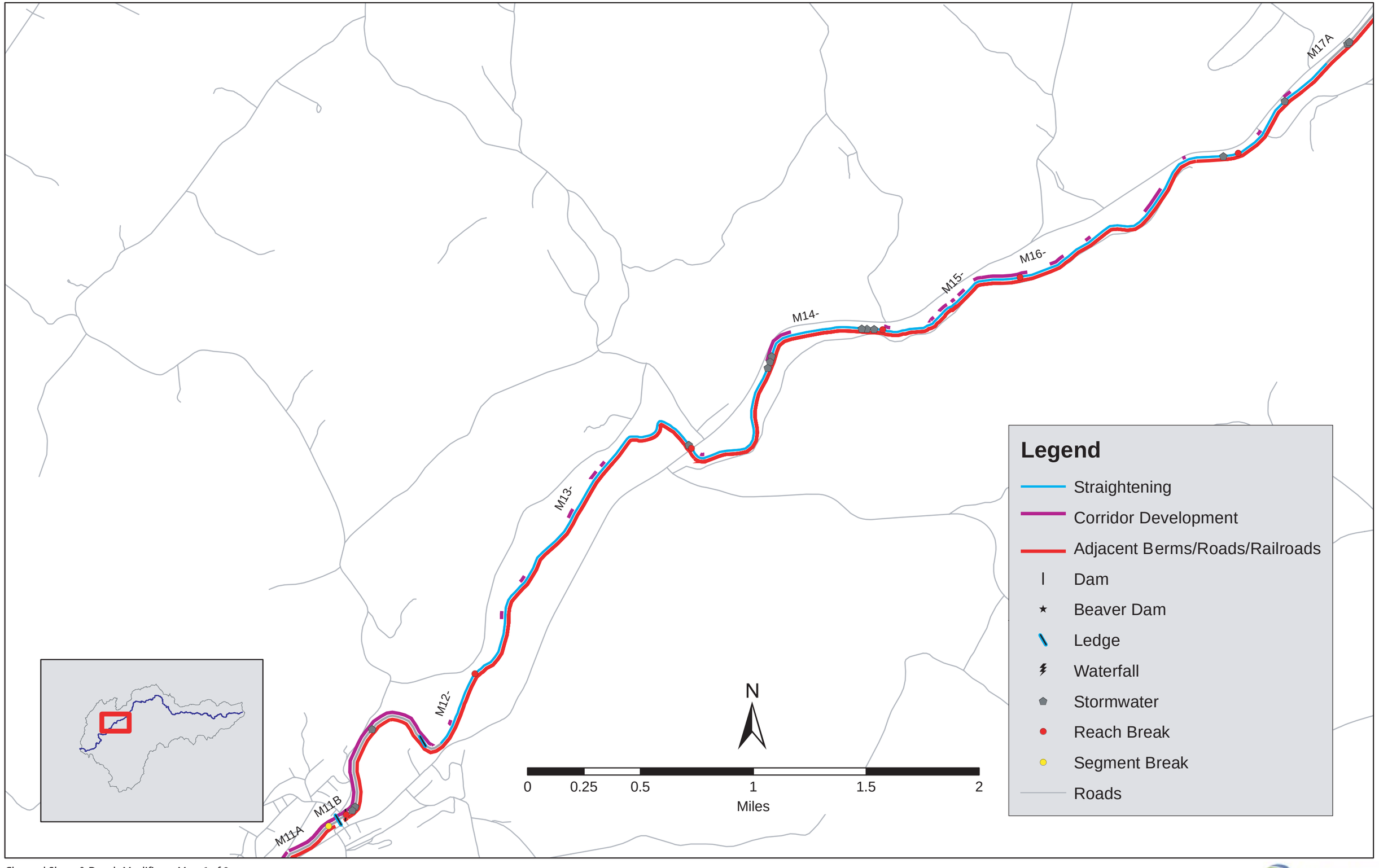
Channel Slope & Depth Modifiers - Map 4 of 8.

Field Geology Services
Fluvial Geomorphology

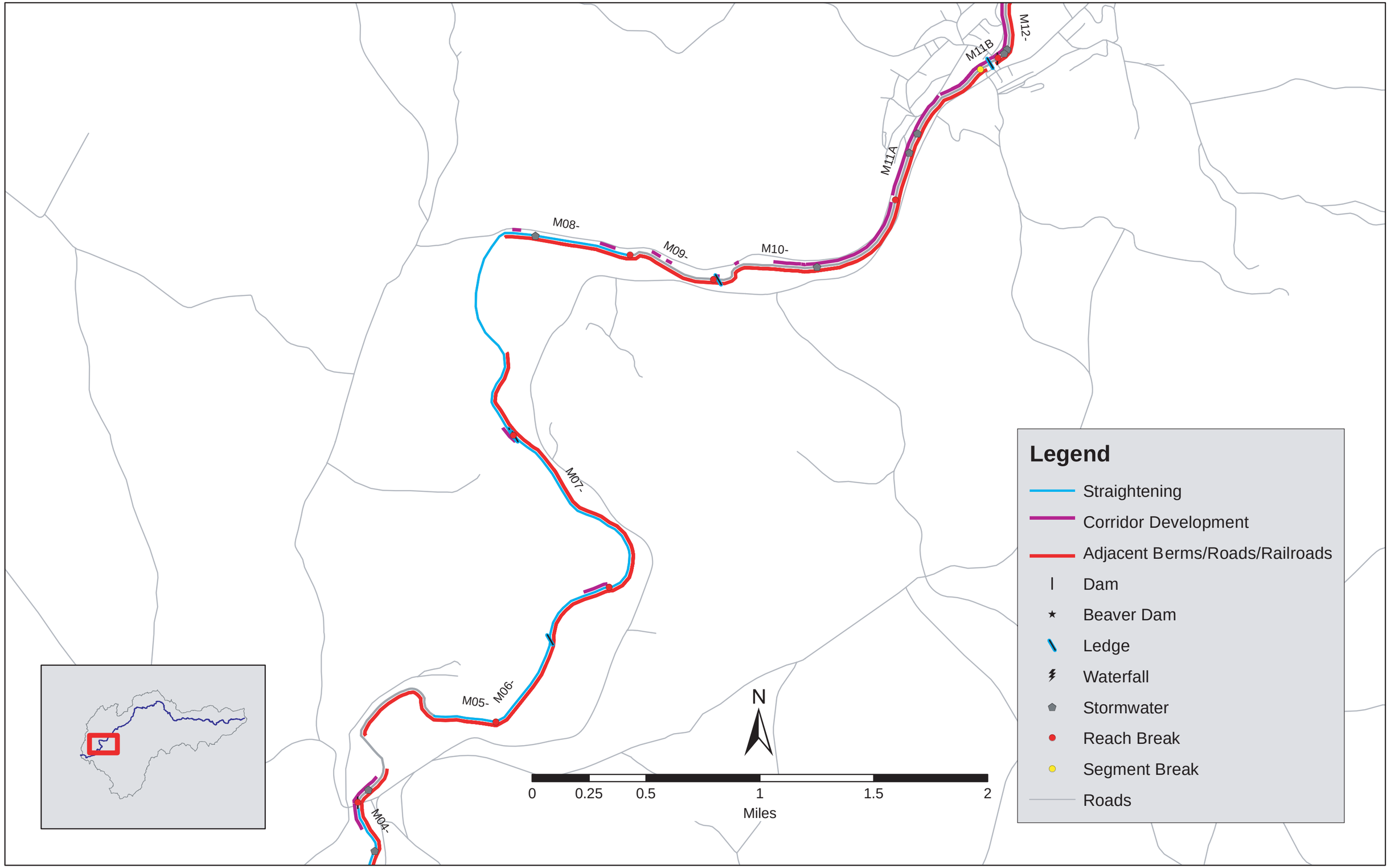


Channel Slope & Depth Modifiers - Map 5 of 8.

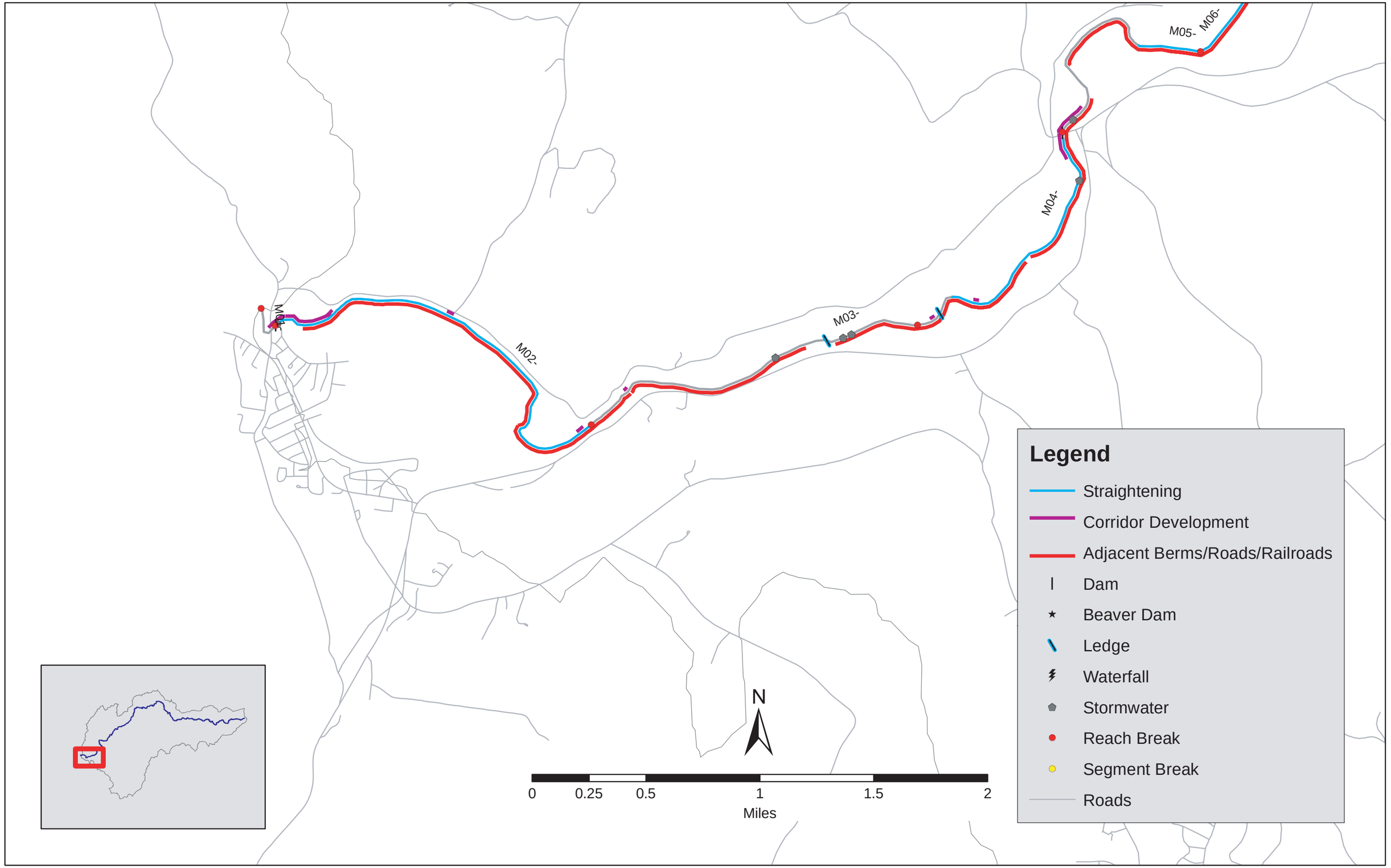
Field Geology Services



Channel Slope & Depth Modifiers - Map 6 of 8.

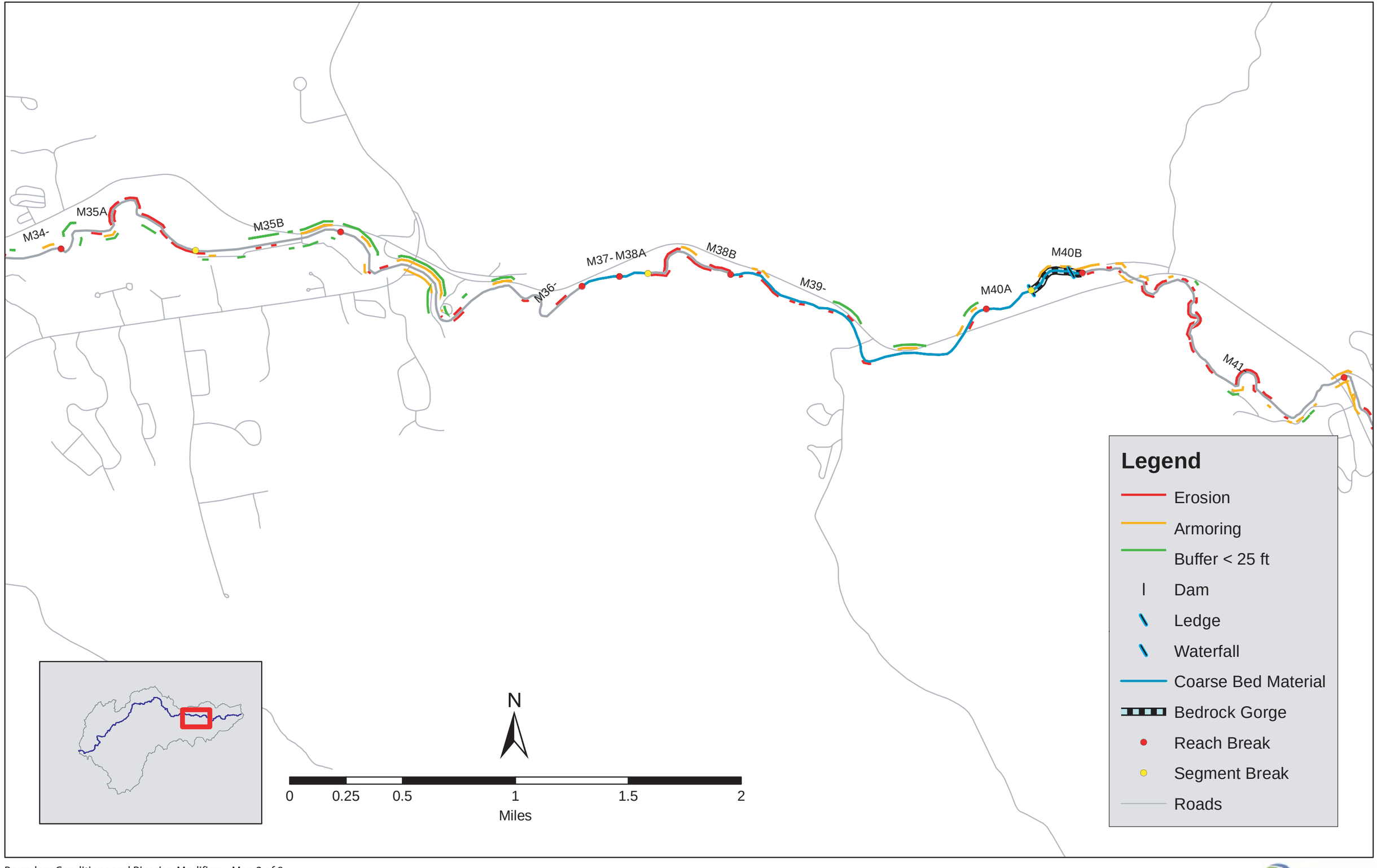


Channel Slope & Depth Modifiers - Map 7 of 8.



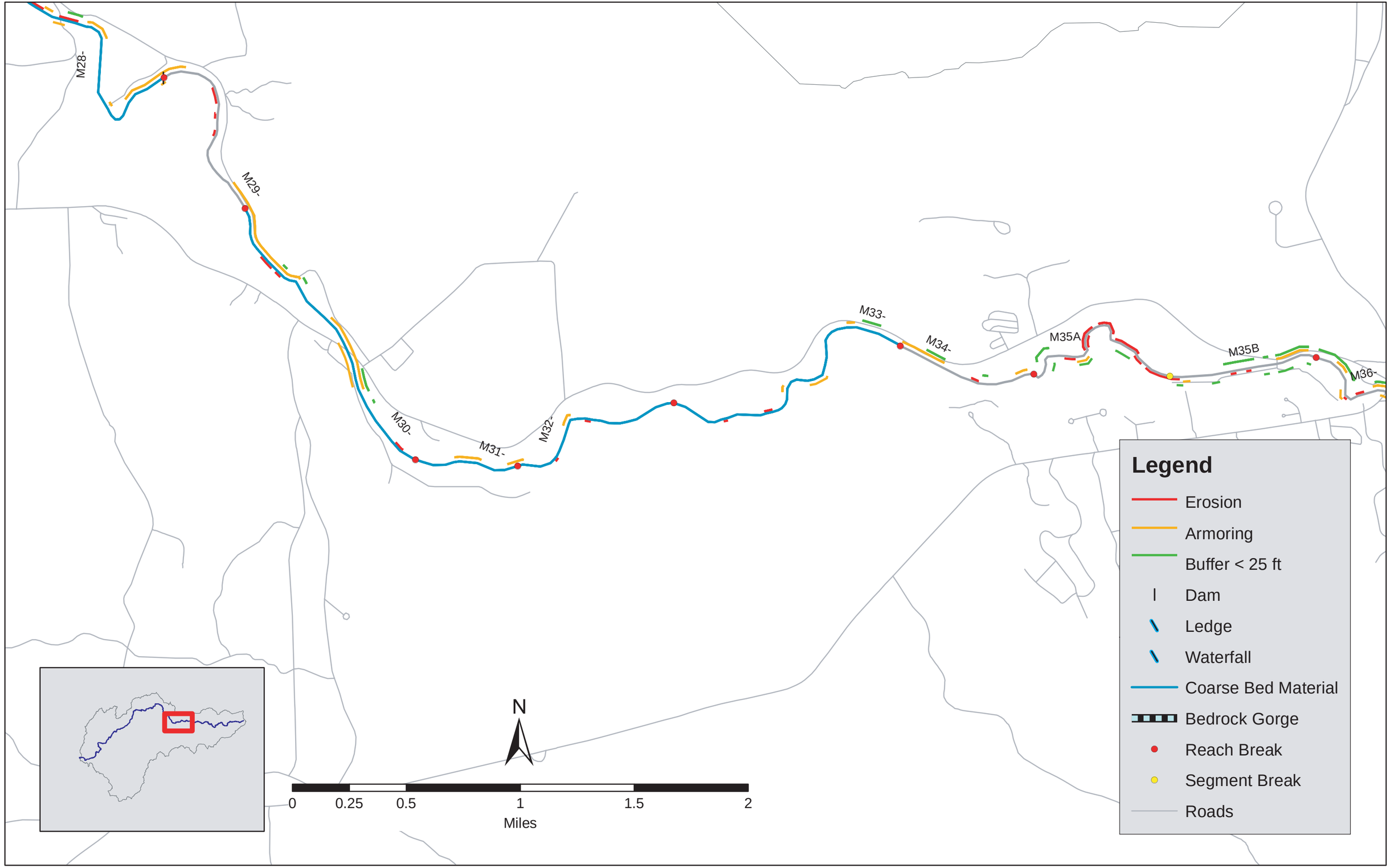
Channel Slope & Depth Modifiers - Map 8 of 8.

Boundary Conditions and Riparian Modifiers - Map 1 of 8.

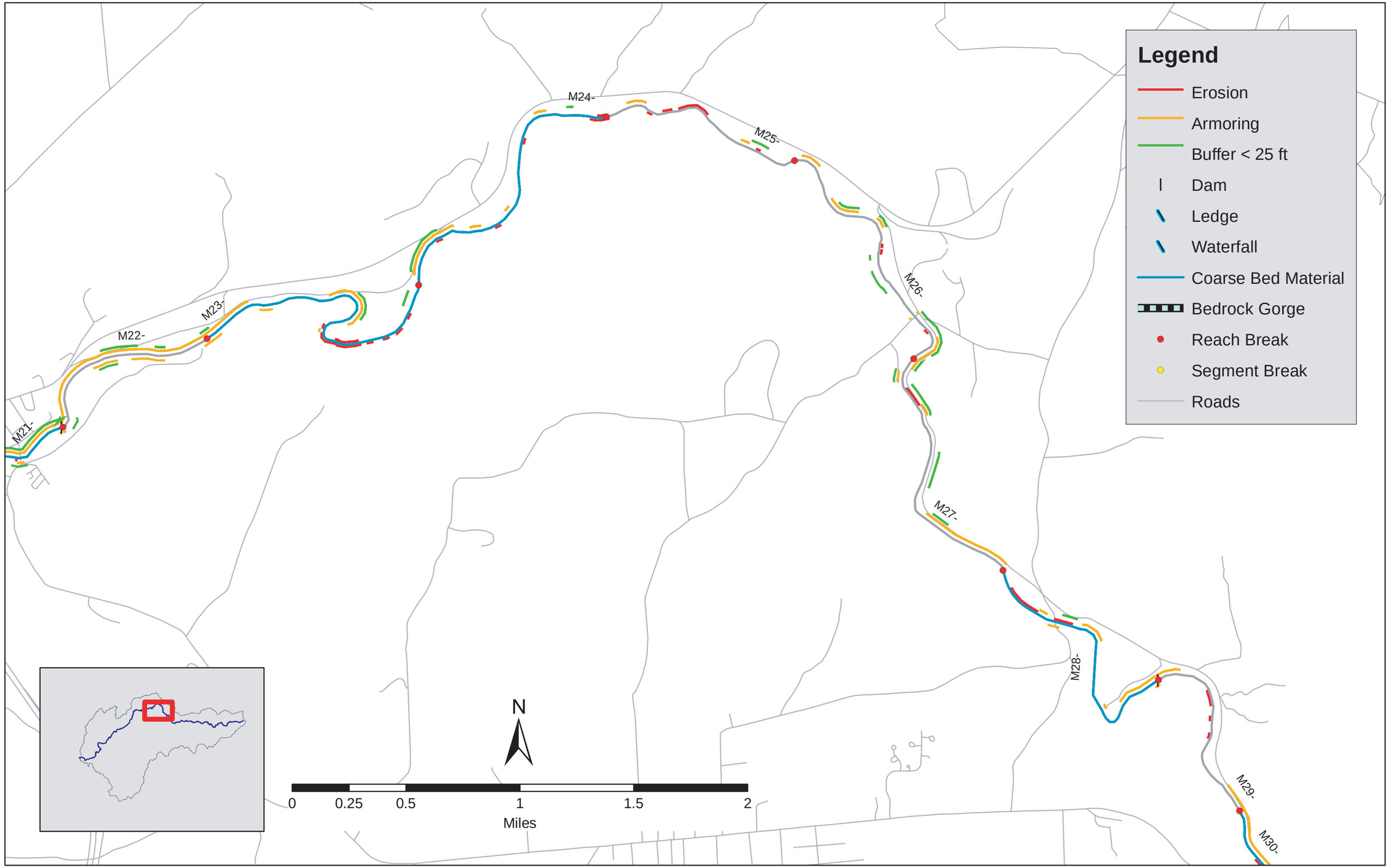


Boundary Conditions and Riparian Modifiers - Map 2 of 8.

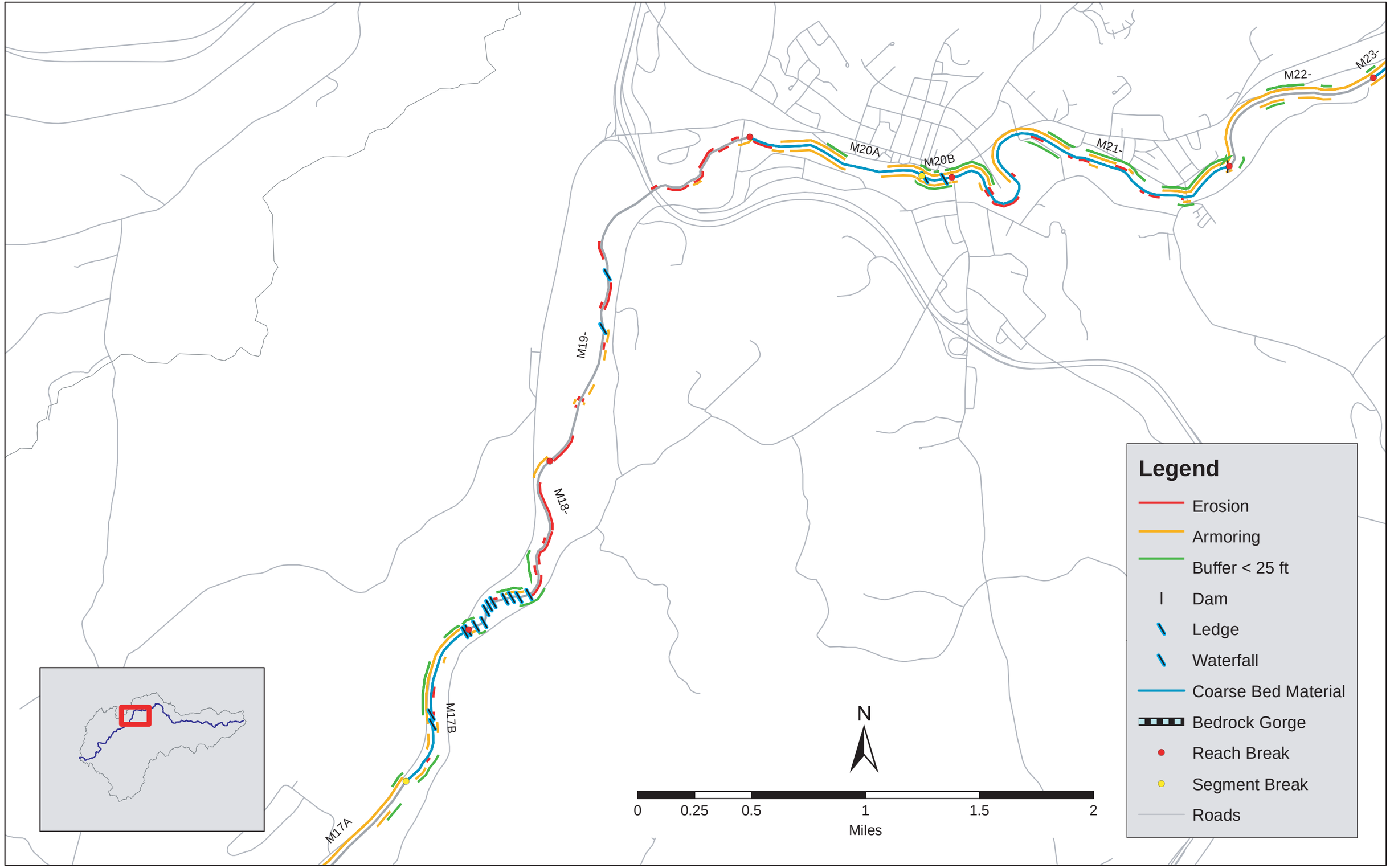
Field Geology Services
Fluvial Geomorphologists



Boundary Conditions and Riparian Modifiers - Map 3 of 8.

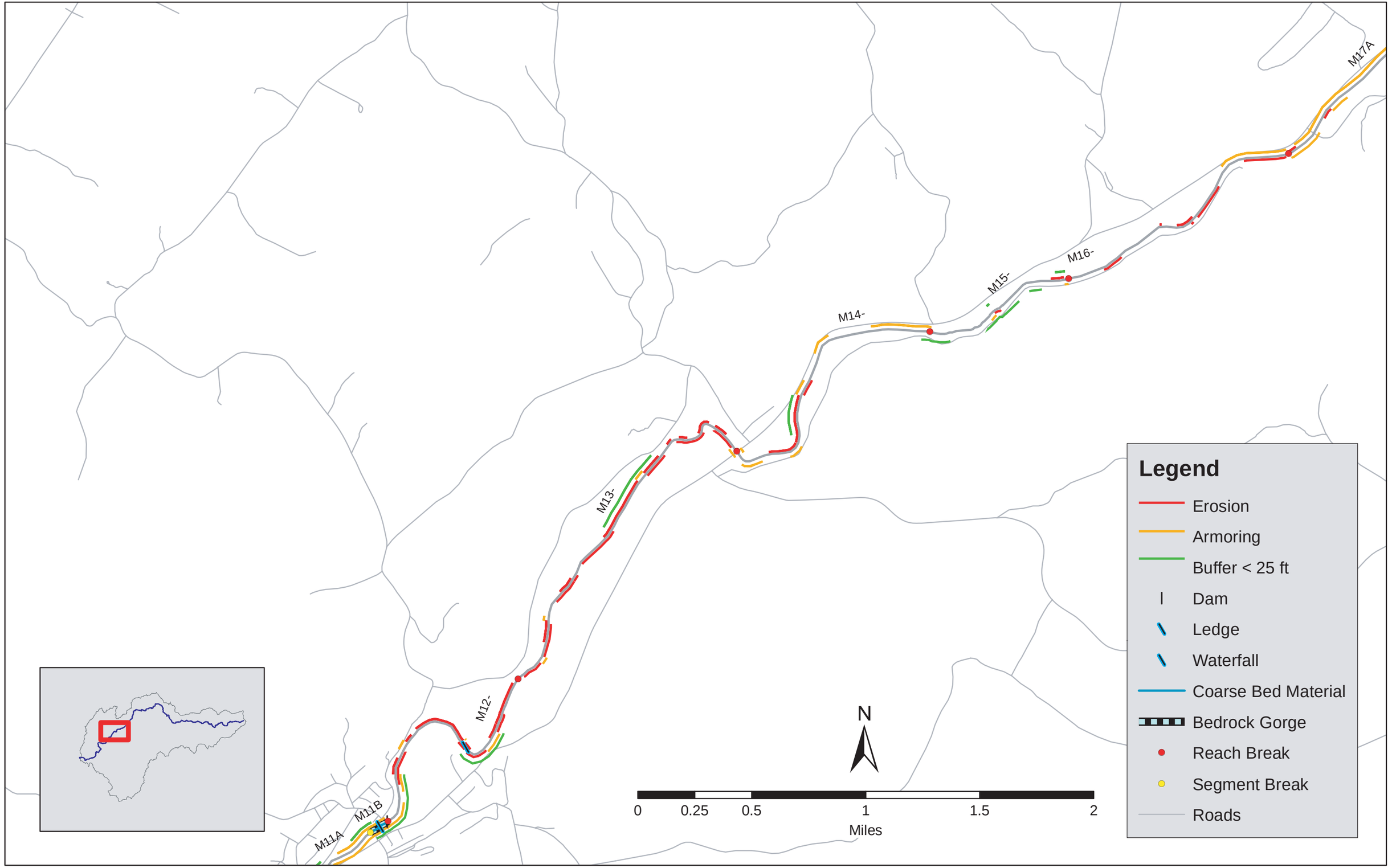


Boundary Conditions and Riparian Modifiers - Map 4 of 8.



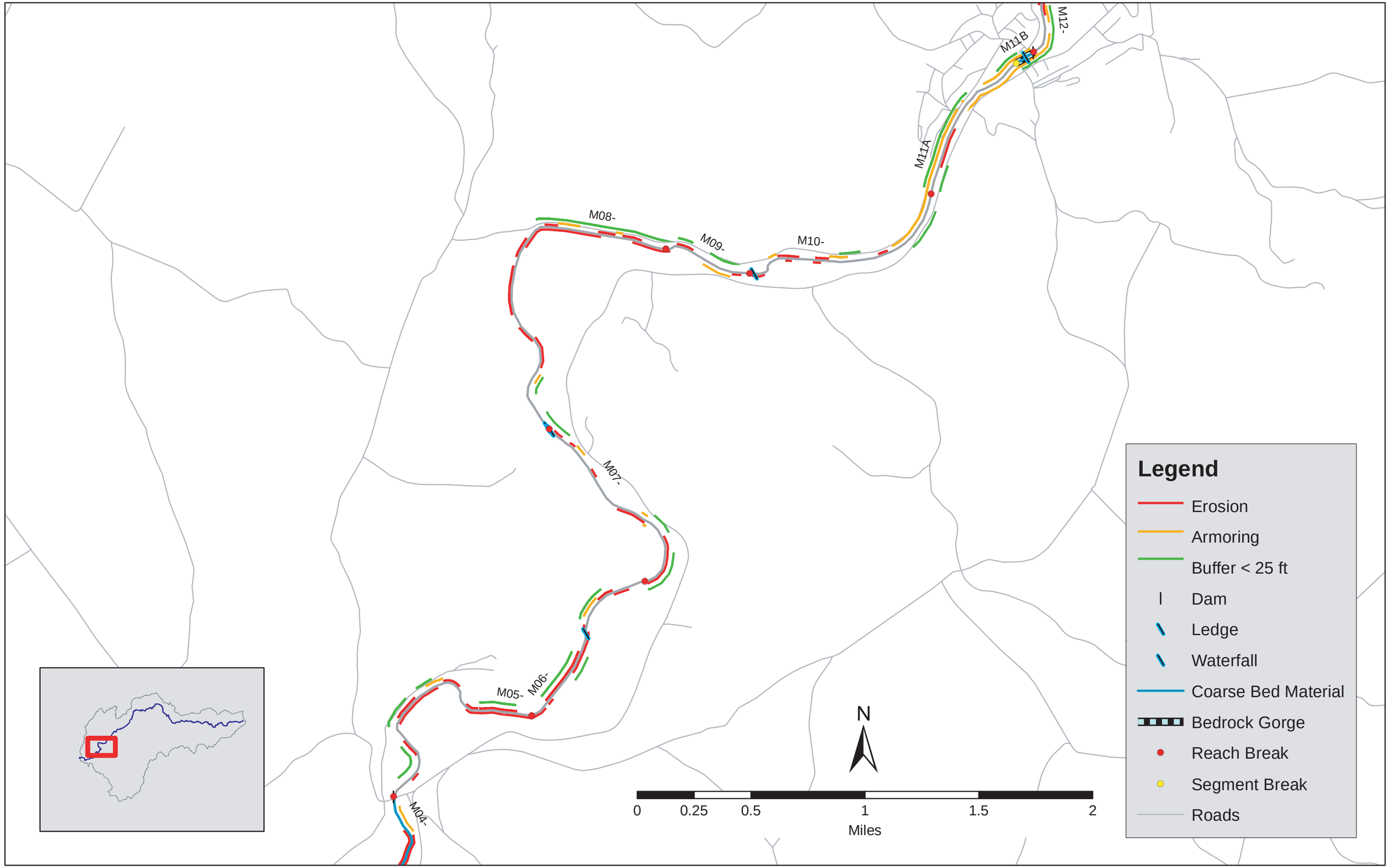
Boundary Conditions and Riparian Modifiers - Map 5 of 8.

Field Geology Services

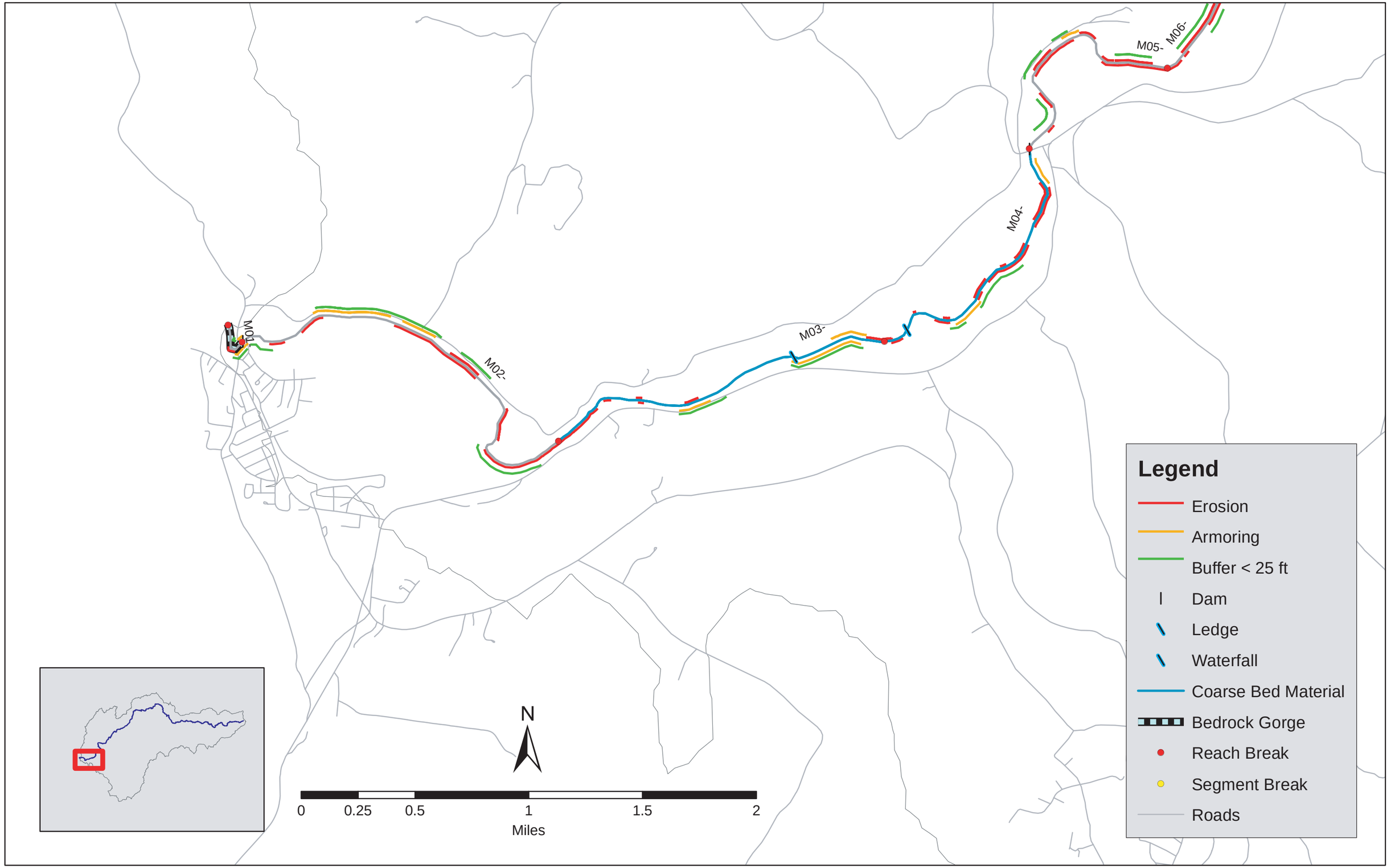


Boundary Conditions and Riparian Modifiers - Map 6 of 8.

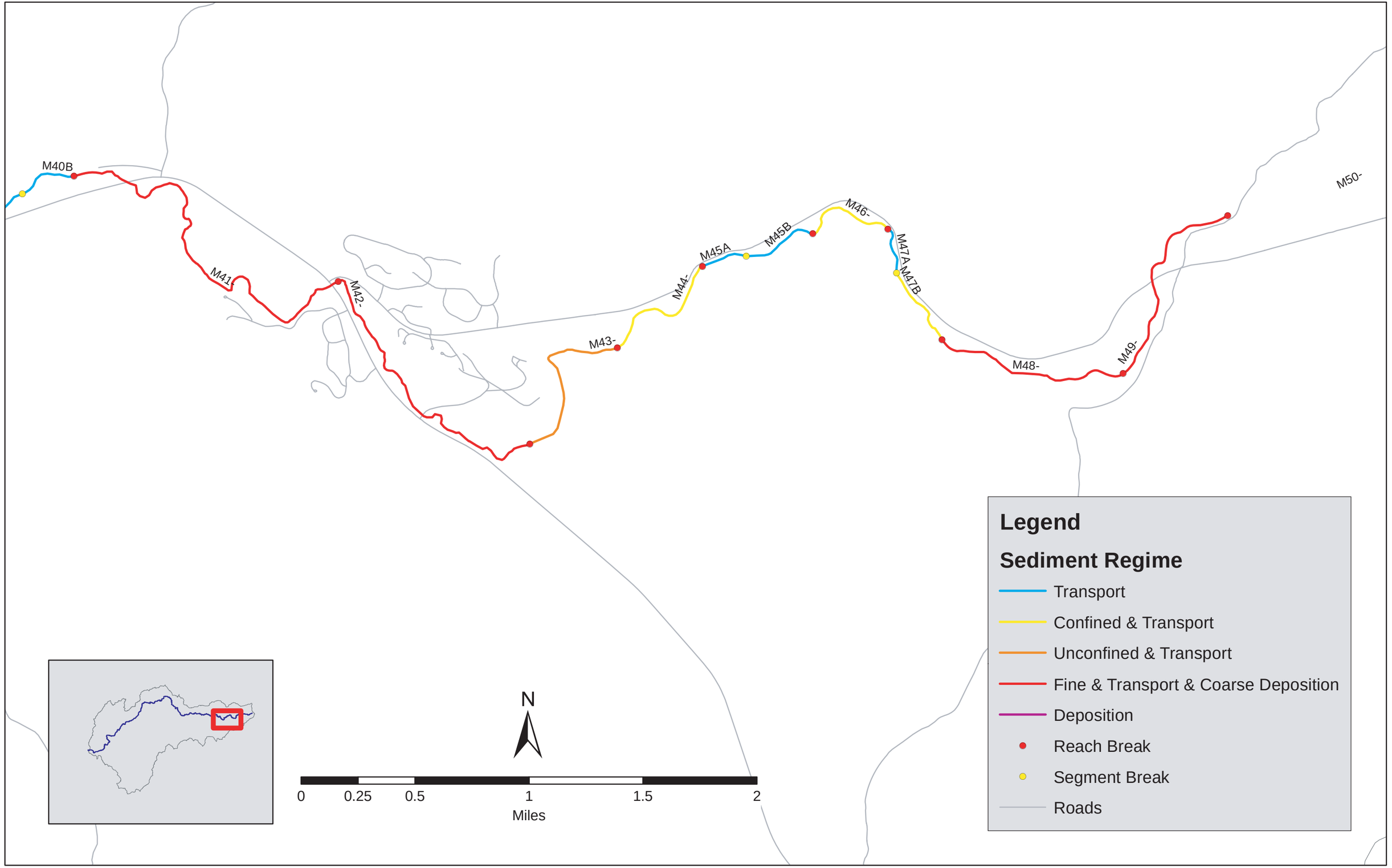
Field Geology Services



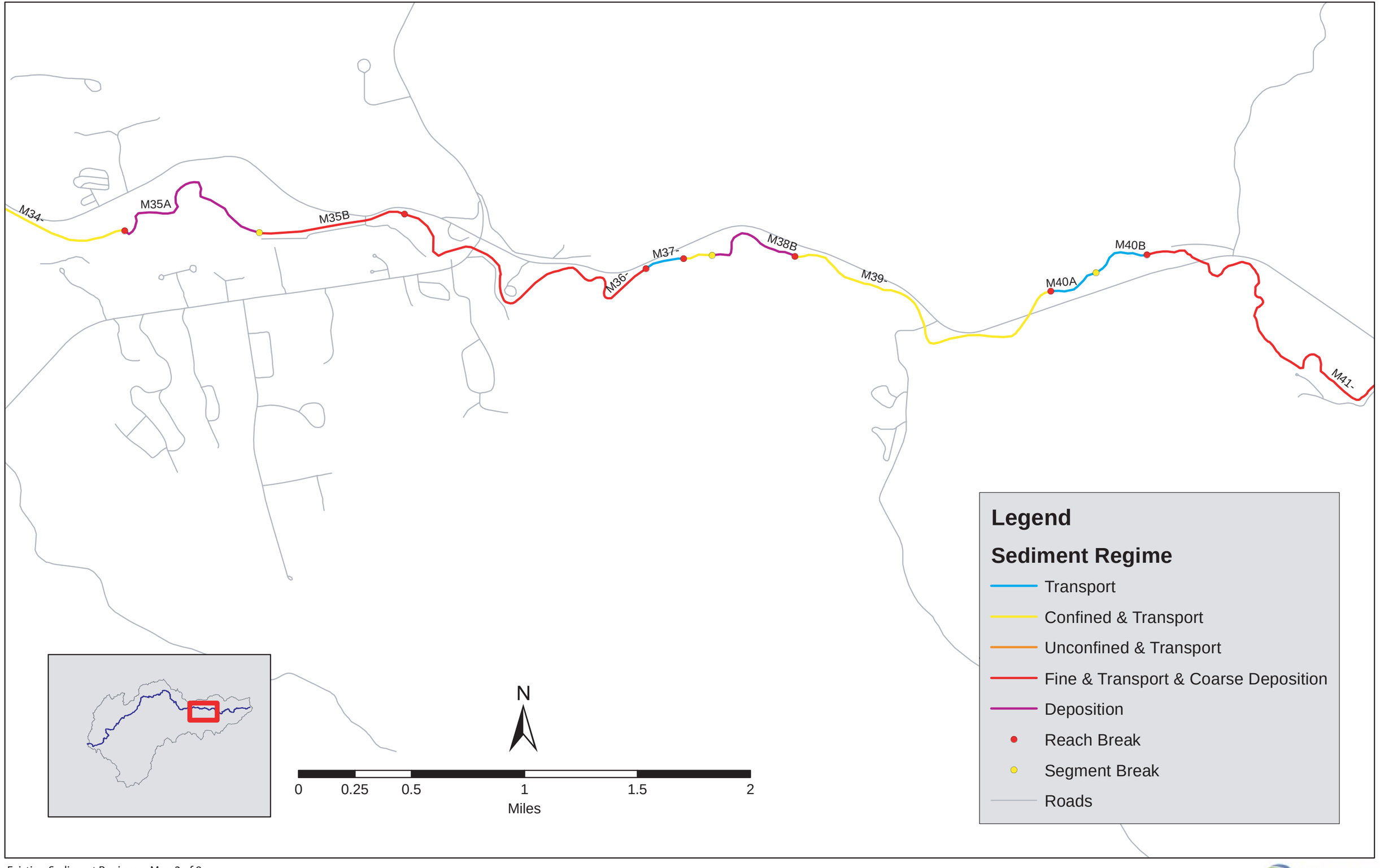
Boundary Conditions and Riparian Modifiers - Map 7 of 8.



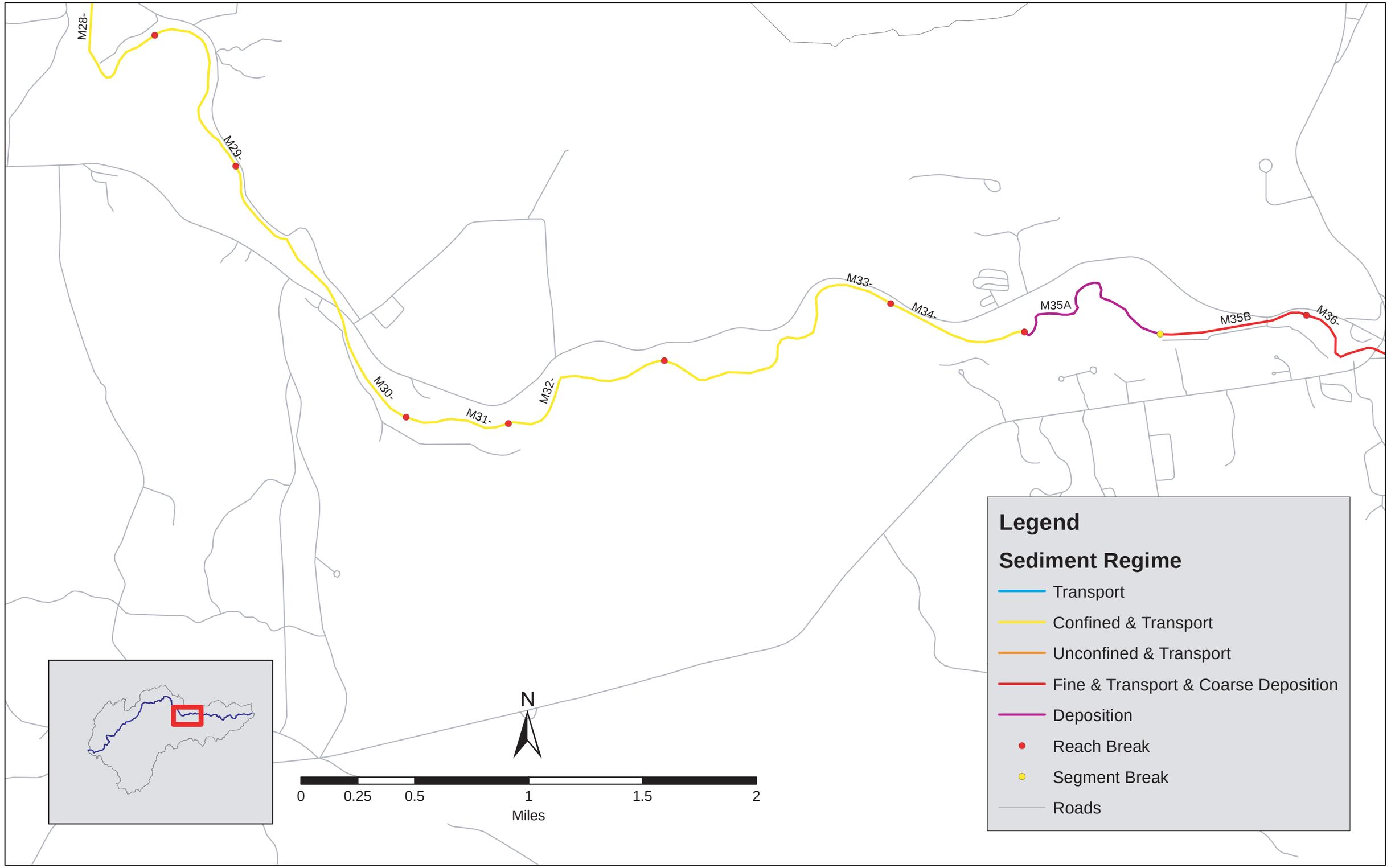
Boundary Conditions and Riparian Modifiers - Map 8 of 8.



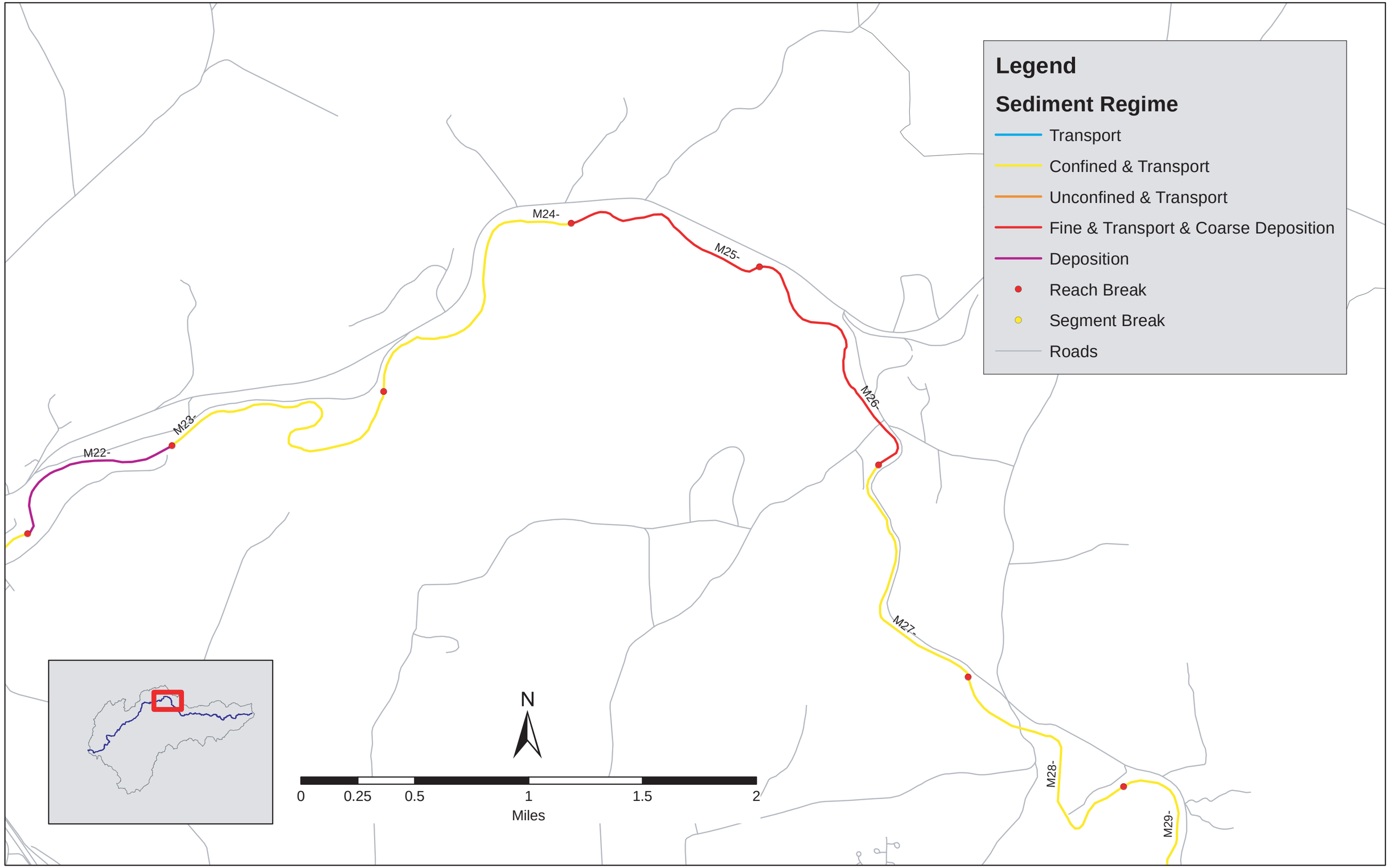
Existing Sediment Regimes - Map 1 of 8.



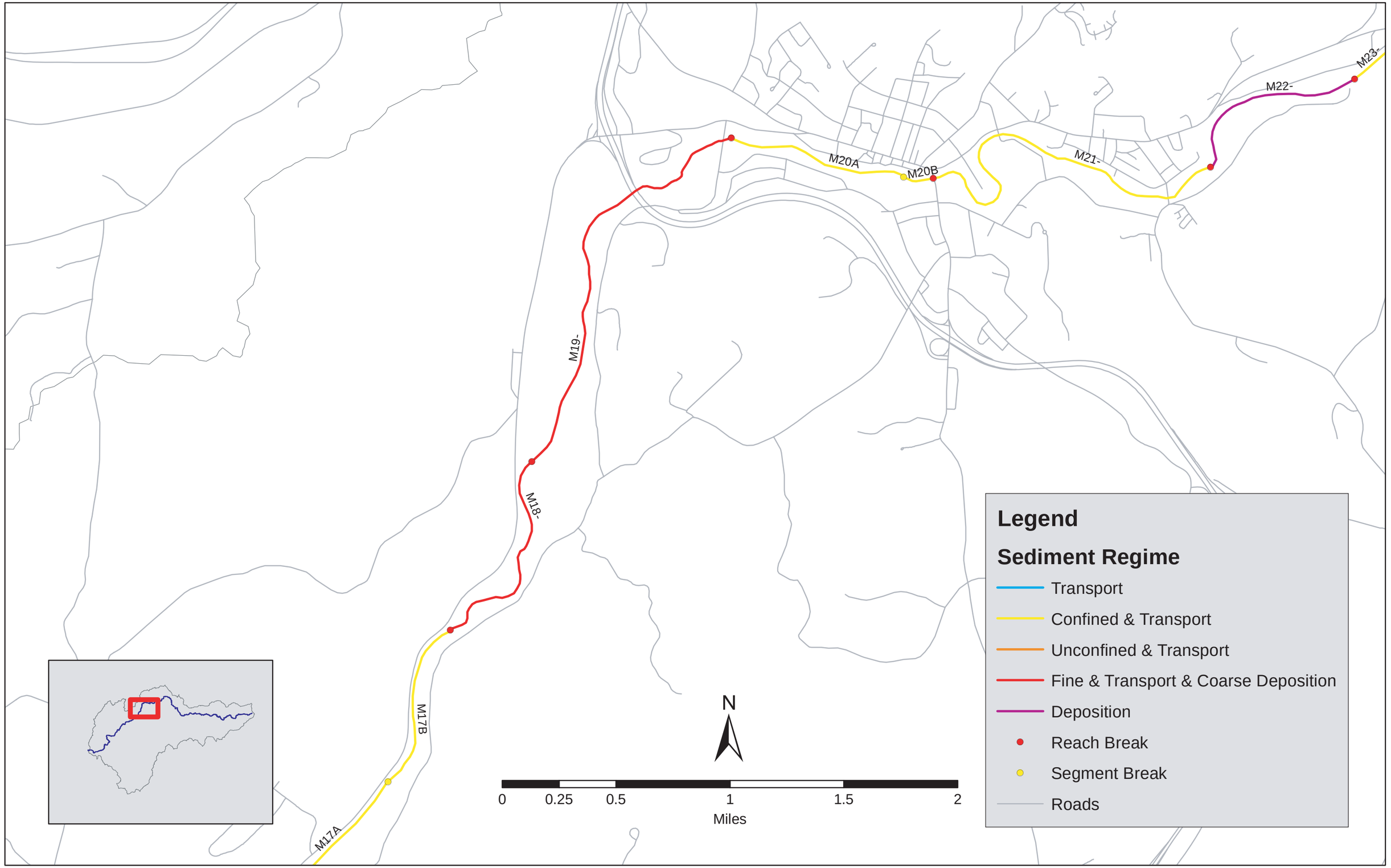
Existing Sediment Regimes - Map 2 of 8.



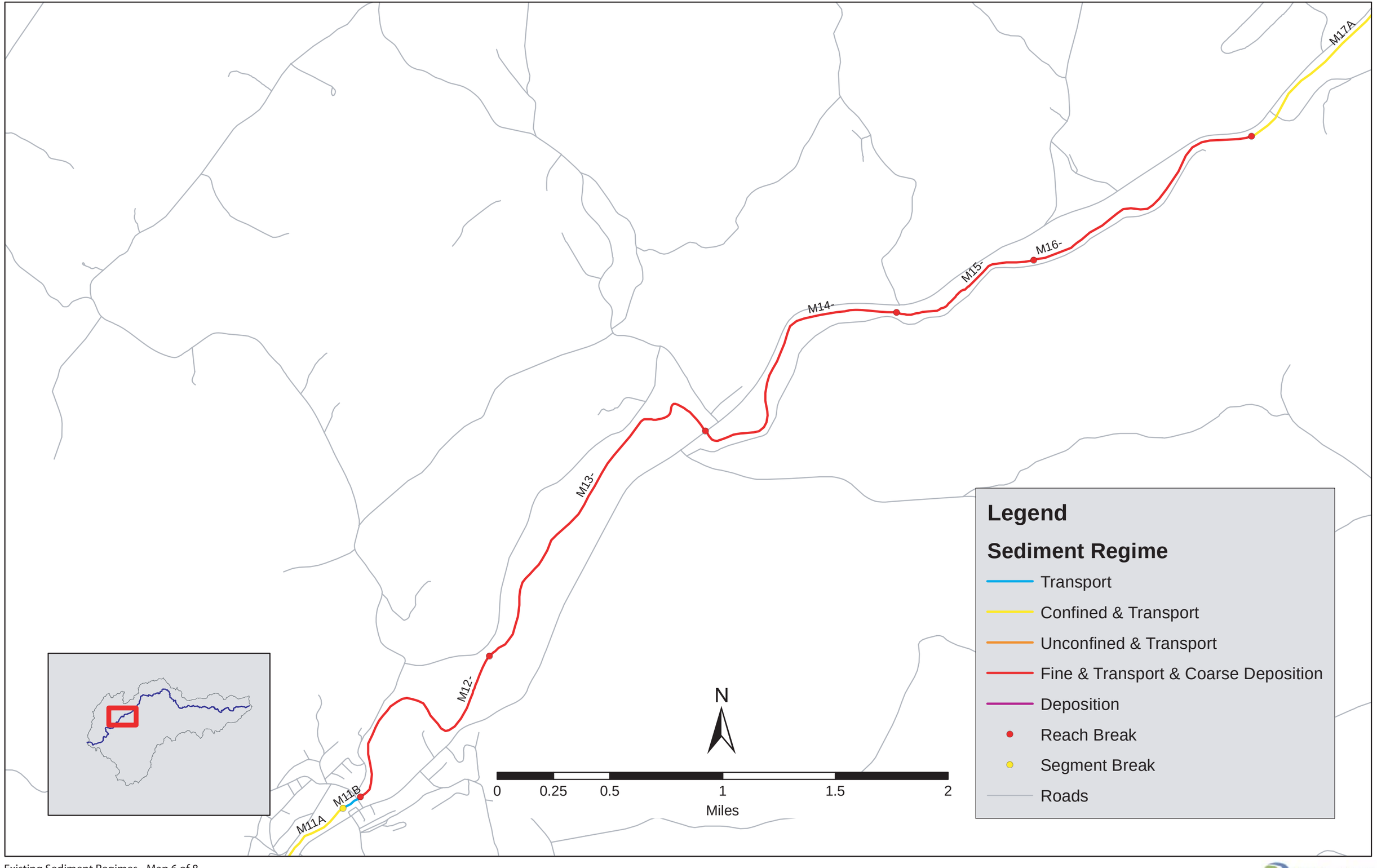
Existing Sediment Regimes - Map 3 of 8.



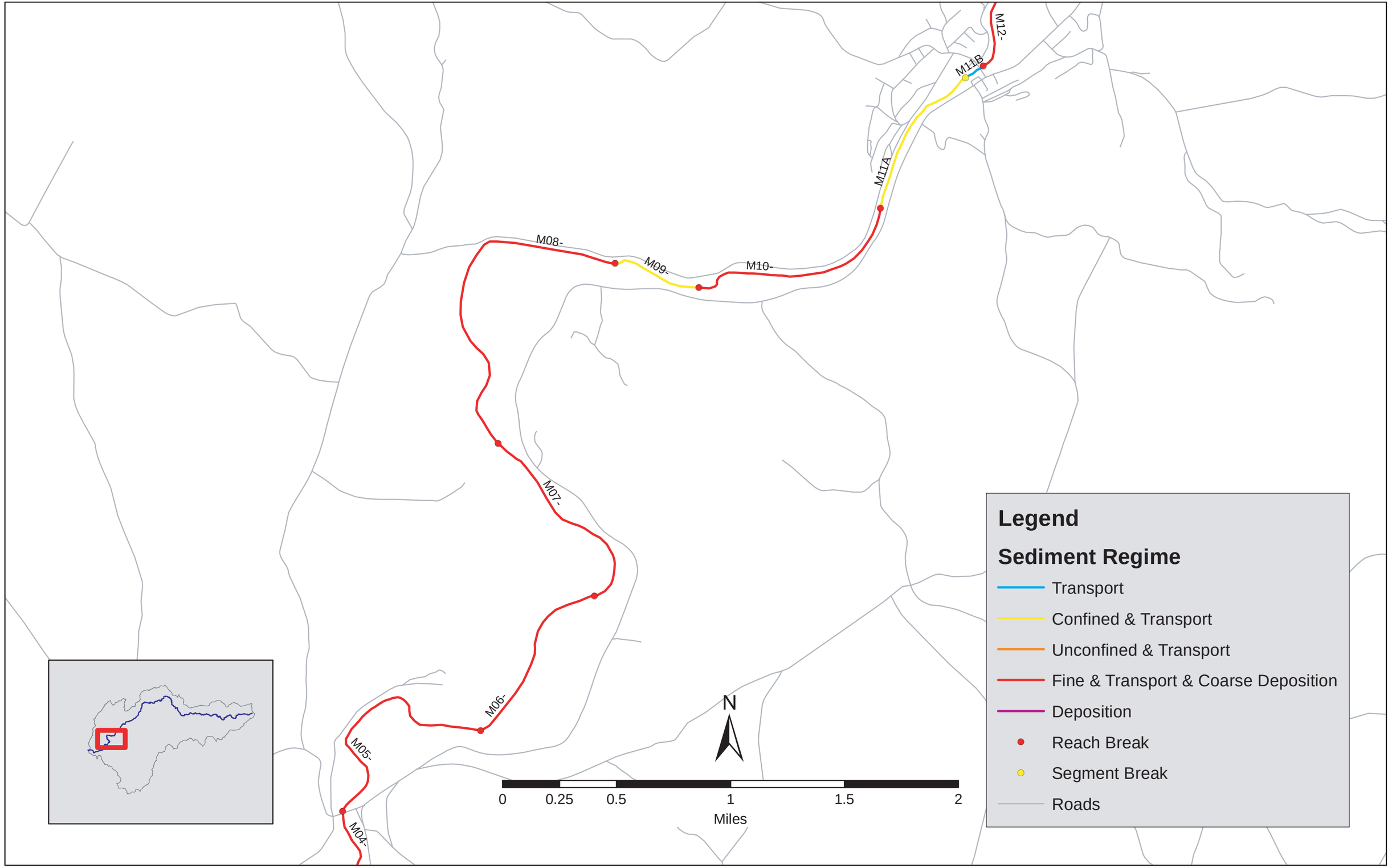
Existing Sediment Regimes - Map 4 of 8.



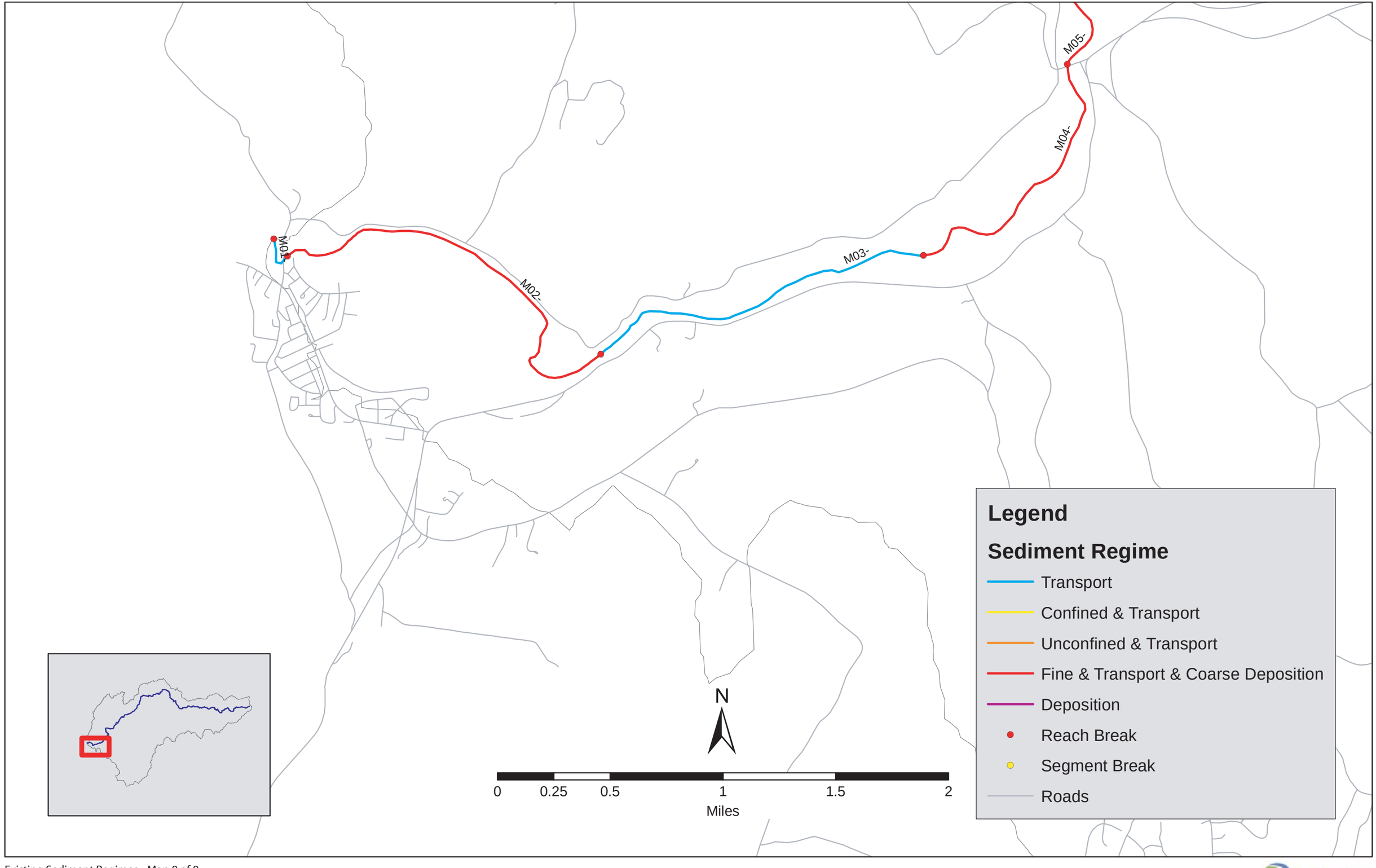
Existing Sediment Regimes - Map 5 of 8.



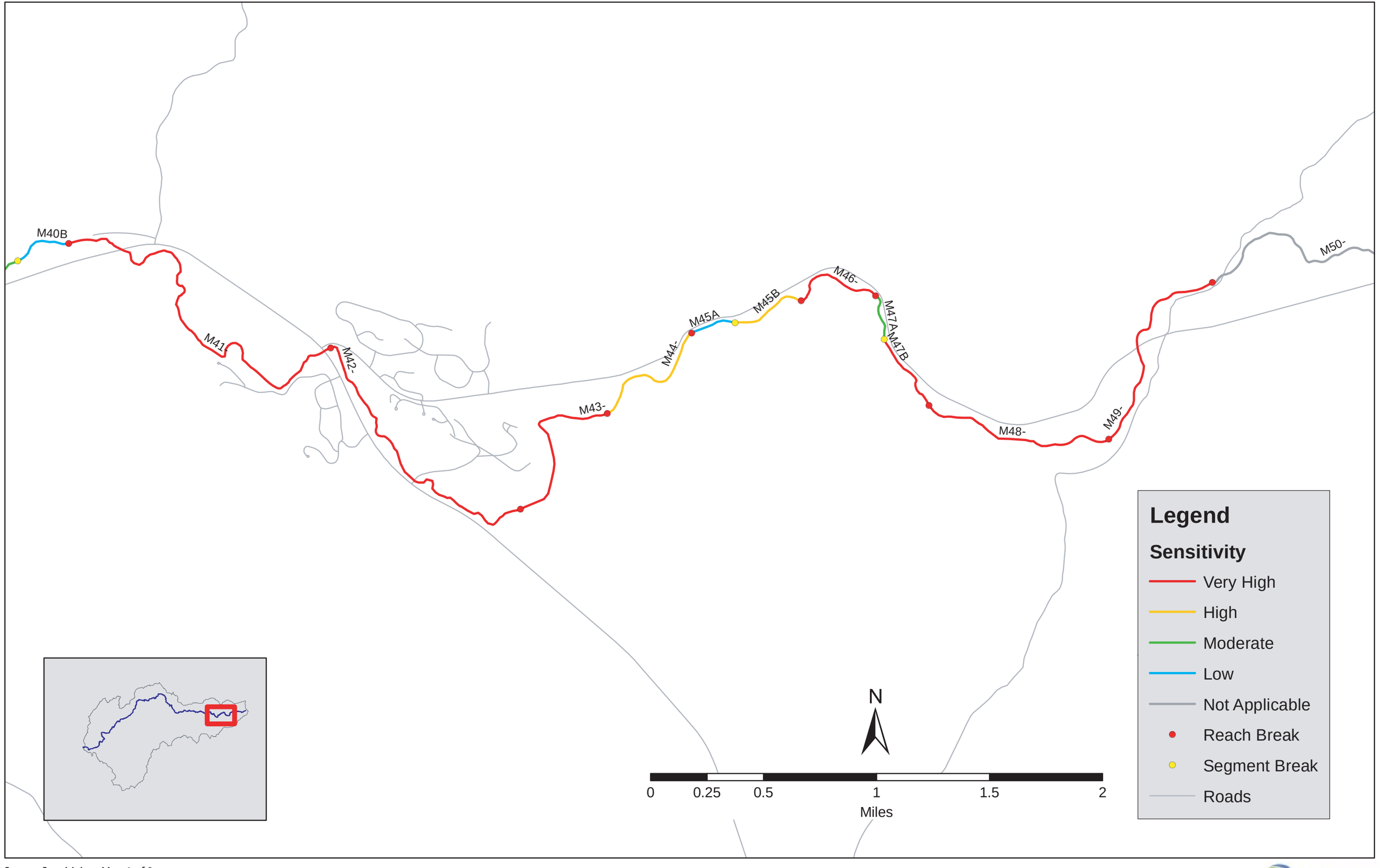
Existing Sediment Regimes - Map 6 of 8.



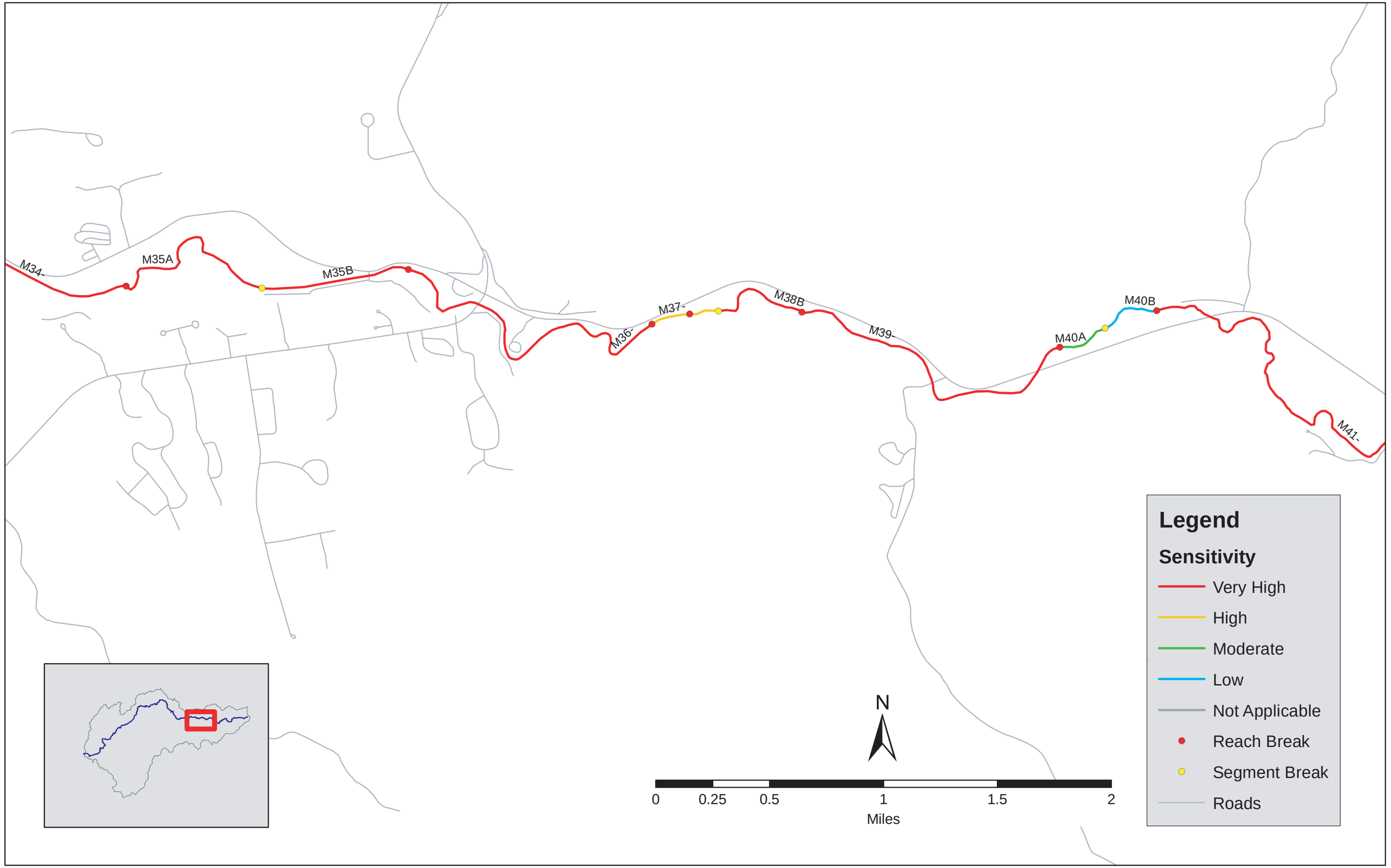
Existing Sediment Regimes - Map 7 of 8.



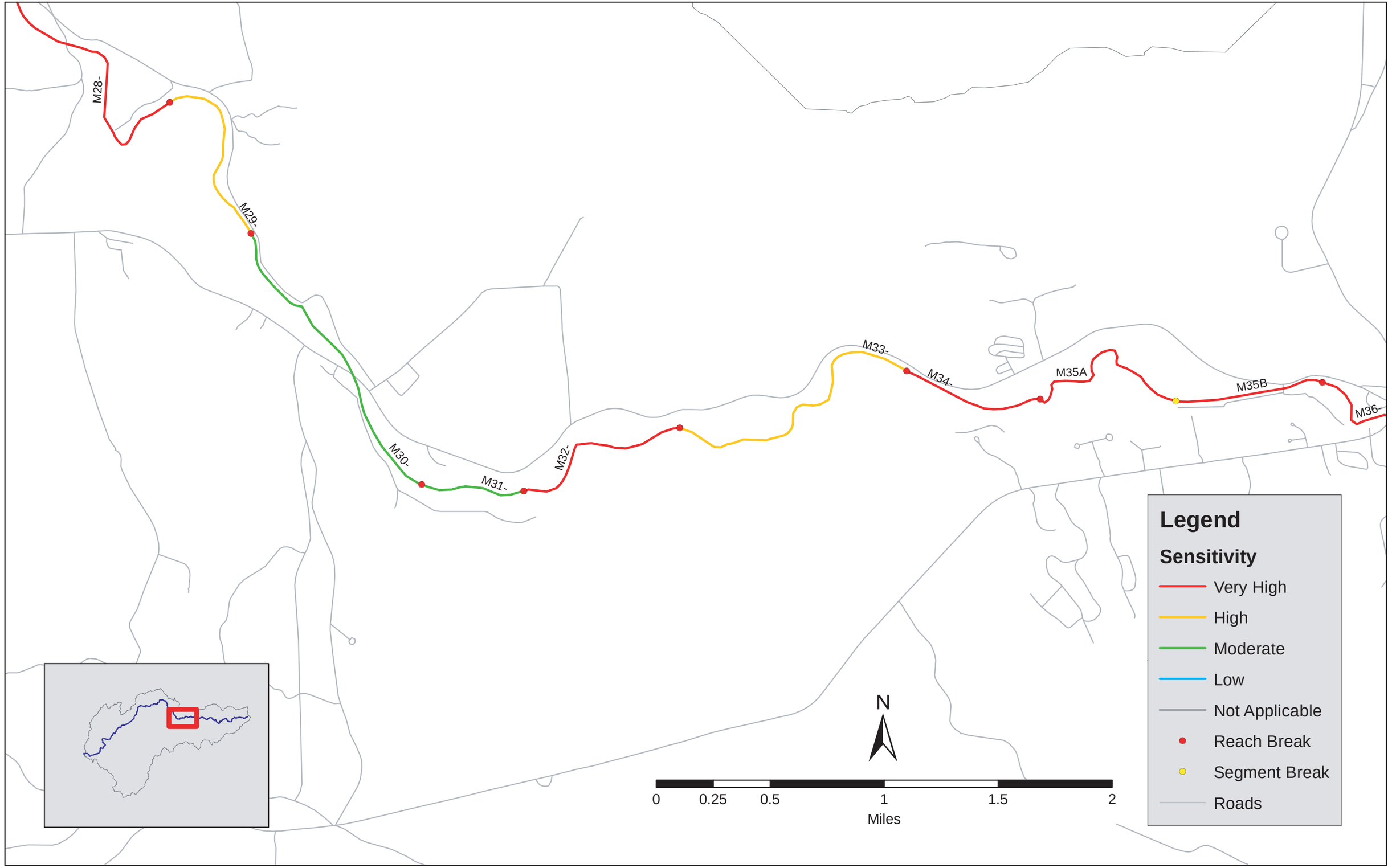
Existing Sediment Regimes - Map 8 of 8.



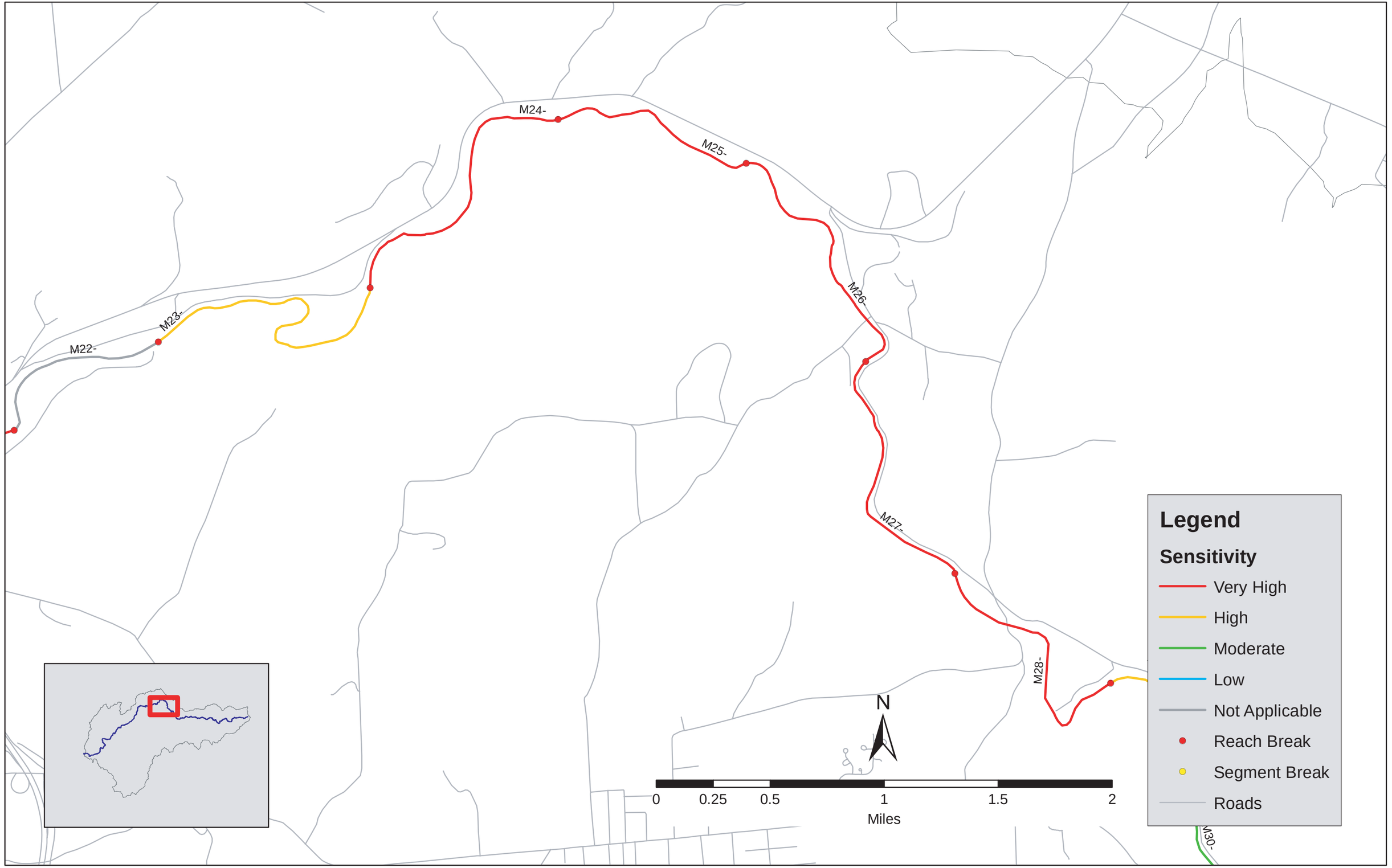
Stream Sensitivity - Map 1 of 8.



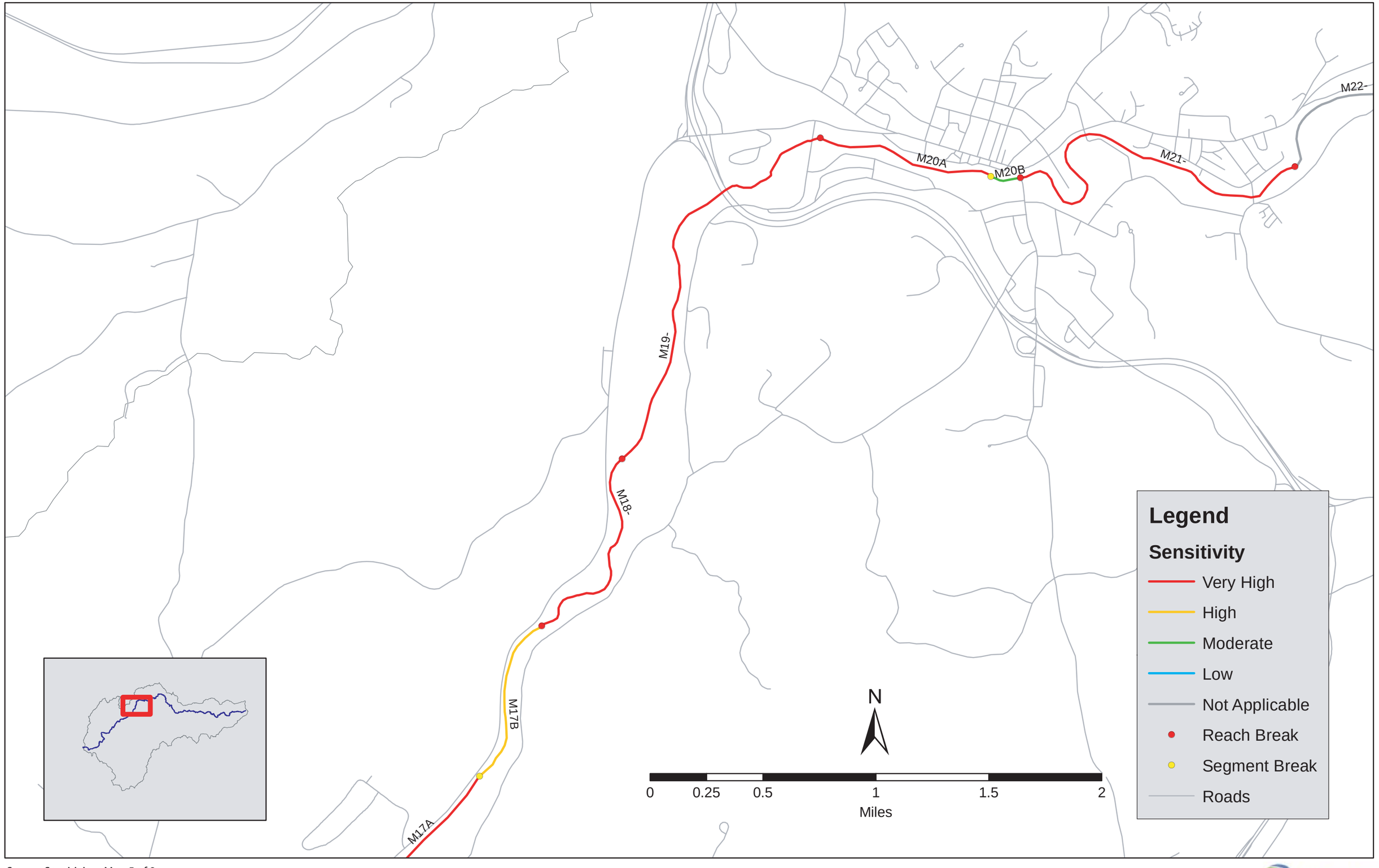
Stream Sensitivity - Map 2 of 8.



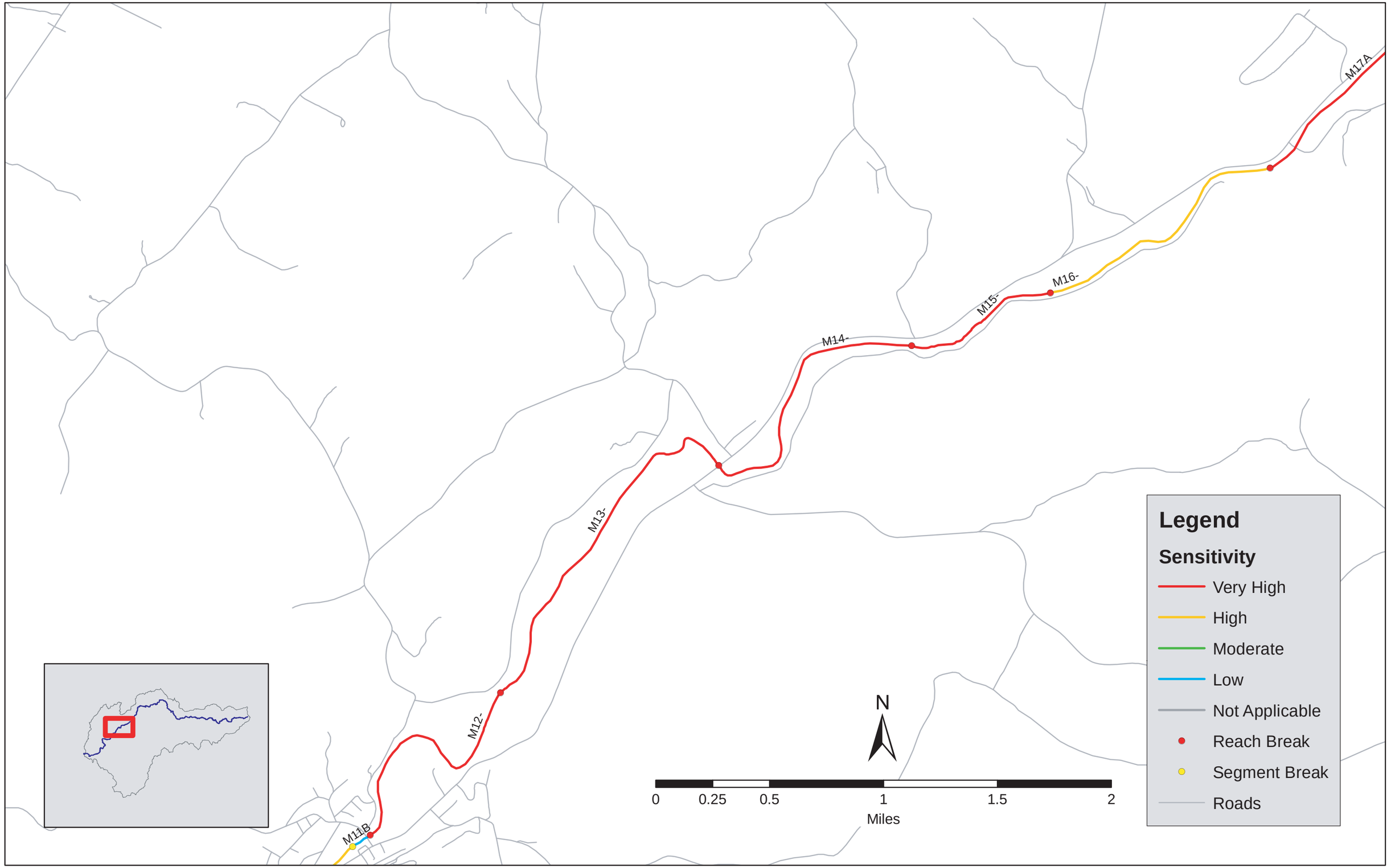
Stream Sensitivity - Map 3 of 8.



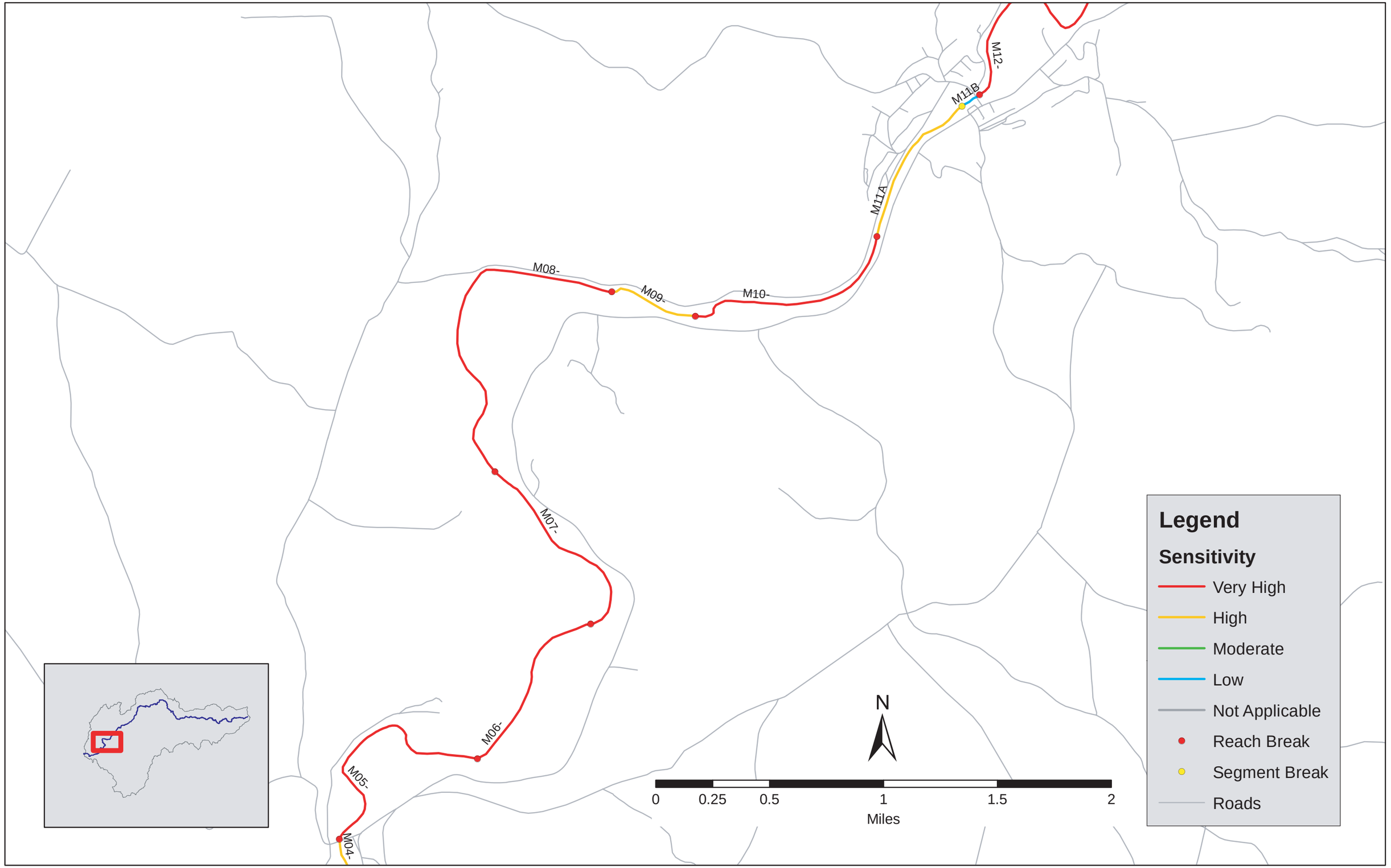
Stream Sensitivity - Map 4 of 8.



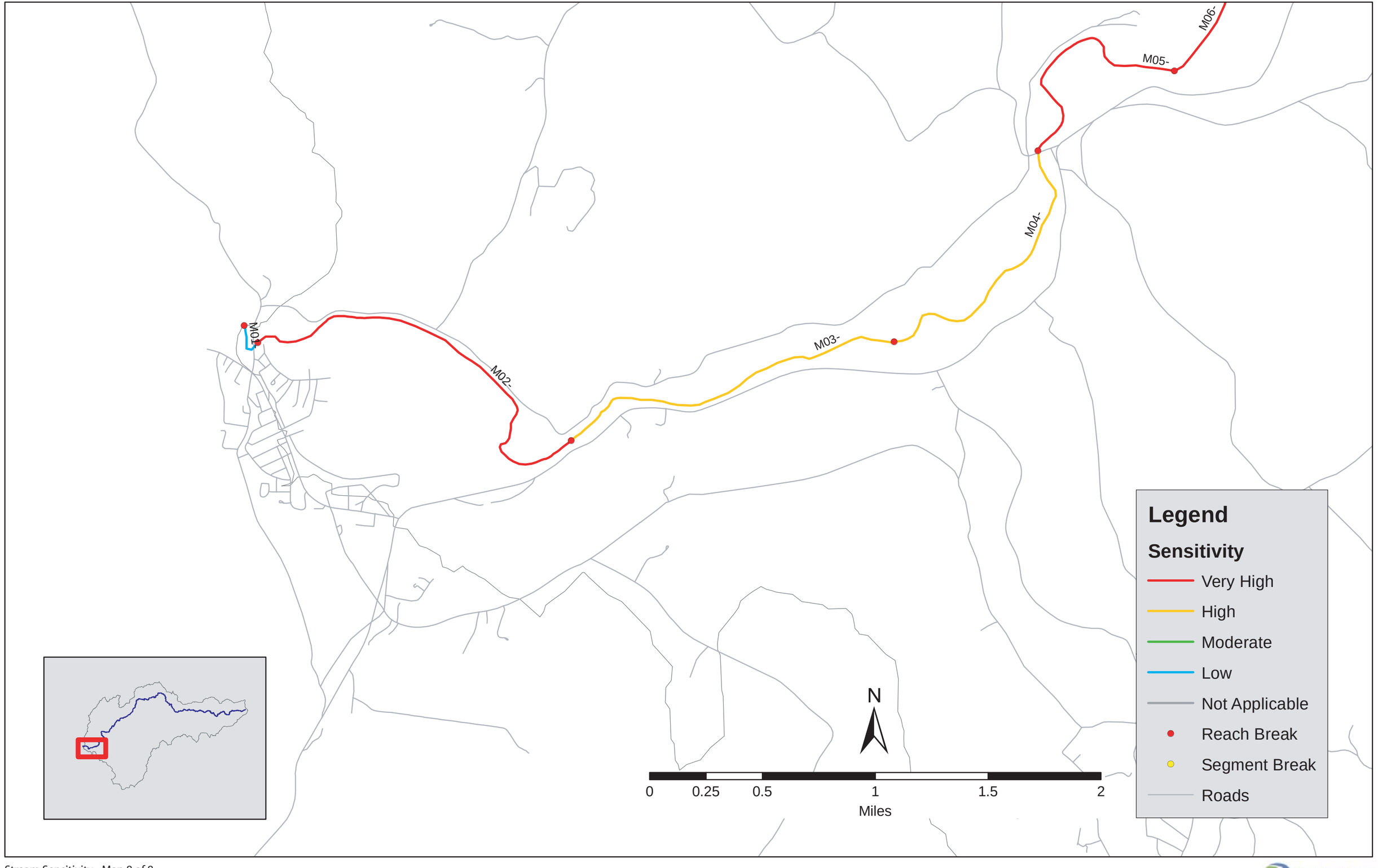
Stream Sensitivity - Map 5 of 8.



Stream Sensitivity - Map 6 of 8.



Stream Sensitivity - Map 7 of 8.



Stream Sensitivity - Map 8 of 8.