River Corridor Plan for the Wood-Pawcatuck Watershed, RI and CT

Prepared for

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EXECUTIVE SUMMARY

Based on the results of a geomorphic assessment, corridor planning guidance for the Wood-Pawcatuck Watershed in Rhode Island and Connecticut is provided that identifies potential causes of flood and erosion hazards, increased sediment loading, and degraded aquatic habitat. Past land management activities and encroachments in the river corridor and channel have upset the balance of sediment transport including dams, channel straightening, undersized stream crossings, and elevated (rail)road grades. Undersized culverts and bridges create a backwater effect upstream during floods that induces sediment deposition, development of a braided planform, and formation of flood chutes and side channels. Downstream, scour and bank erosion occur that can potentially threaten the structure itself. Many of the dams in the watershed are no longer in use and could be removed to lower flood elevations upstream, eliminate flow impoundments, restore the continuity of sediment transport downstream, and improve aquatic organism passage. A number of other restoration methods can improve habitat complexity and help attenuate downstream flood peaks and sediment loading. For example, protecting river corridors along historically straightened and incised channels provides an opportunity to encourage the reformation of meanders and reconnection to floodplains through the construction of log jams and other wood addition techniques. The most appropriate restoration techniques for each Phase 2 reach in the Wood-Pawcatuck Watershed have been identified from a technical standpoint, although social and political factors might, in many areas, complicate implementation of the potential projects. Over 45 potential projects have been prioritized along the river's length that address channel instabilities resulting from numerous human impacts and, if implemented, should provide improvements to aquatic habitat while reducing flood hazards and downstream sediment loading.

1.0 INTRODUCTION

The geomorphology-based river corridor planning guide for the Wood-Pawcatuck Watershed in Rhode Island and Connecticut presented herein is the product of a geomorphic assessment completed by Field (2016). The geomorphic assessment was carried out using the Phase 1 and Phase 2 assessment protocols established 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 over time 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 watershed (e.g., 18^{th} – 19^{th} century land clearance), river corridor (e.g., homes and businesses beside the river), and in the river channel itself (e.g., dams, undersized stream crossings, and past channel straightening) have engendered river channel adjustments that have exacerbated flooding and erosion hazards, increased sediment loads, and degraded aquatic habitat. Highlighting the location, cause, and source of those problems is a critical component of the corridor planning process and can be used by watershed communities to select sustainable restoration strategies to improve channel stability.

The Wood-Pawcatuck Watershed drains 297 mi^2 of southwestern Rhode Island and eastern Connecticut with the mainstem Pawcatuck River flowing approximately 40 mi from its source at Worden Pond to the Pawcatuck River Estuary that begins in downtown Westerly, RI. The Pawcatuck River's largest tributary is the Wood River with a watershed area of 89.4 mi^2. Other major tributaries included in the river corridor planning process are the Chipuxet River (15.6 mi^2), Queen/Usquepaug (43.8 mi^2), Beaver (11.7 mi^2), Green Fall/Ashaway (29.0 mi^2) Shunock (16.6 mi^2), and Meadow Brook (7.0 mi^2). The Wood-Pawcatuck Watershed drains the towns of Richmond, Westerly, Charlestown, Hopkinton, Exeter, and South Kingston in Rhode Island, as well as Voluntown, North Stonington, and Stonington in Connecticut (Figure 1).

The mainstem and major tributaries were separated into reaches based on natural differences in gradient, valley confinement, and tributary inputs using procedures detailed in the Phase 1 assessment protocols (Web citation 1). Delineating reaches is critical in the corridor planning process because channel morphology and adjustments are likely to be consistent within a given reach but could vary dramatically from an adjacent reach despite similarities in human land use. Consequently, the delineation of reaches aids in the identification of appropriate restoration options for different portions of the watershed. Reach characterization also allows for the identification of "like" reaches (e.g., unconfined reaches) such that detailed studies in one reach can provide valuable information on the restoration potential and expected channel response in similar less studied reaches. On the Pawcatuck River mainstem, 29 such reaches of uneven length were identified using topographic maps and other sources with the reaches numbered consecutively from the downstream end of the river and designated PAR-1, PAR-2, etc. to indicate that the reaches are located on the Pawcatuck mainstem (Figure 2 and Table 1). The other tributaries were broken up into reaches and assigned reach codes in a similar manner with an additional 116 reaches identified along the assessed tributaries (Table 1). The Phase 2 assessment was completed by Field (2016) for 52 reaches and segments (i.e., subdivisions of reaches where varying human impacts are observed) with the corridor planning recommendations presented below restricted to these reaches and segments. The Phase 2 assessment data provides critical information on where different types of channel adjustments are occurring, which reaches are most sensitive to future changes, and how responsive each reach will be 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 in the Wood-Pawcatuck Watershed 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, or have their sediment supply cut off by a high dam or impoundment will 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 straightening, for example, 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. With the reformation of meanders, the channel closely approximates its former planform and equilibrium condition. In response to channel straightening and dam building in the 18th and 19th centuries, the Pawcatuck River and its tributaries have already undergone a period of incision and widening with some areas having progressed to the stage of deposition and the 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 Wood-Pawcatuck Watershed have initiated numerous channel adjustments that have degraded habitat, increased sediment loads, and placed property and lives at risk to flooding and erosion. River 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 transport the water, sediment, or wood delivered to the channel. A river 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., the bank and substrate material’s resistance to bank and bed 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 are 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., dams) 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 Wood-Pawcatuck 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 corridor planning process, 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 hydric soils, a proxy for 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 Wood-Pawcatuck Watershed reveal several subwatersheds with relatively high impacts, particularly reaches flowing through heavily developed urban areas such as Pawcatuck, CT/Westerly, RI (PAR 1-5), Ashaway, RI (GAS 1-2), and Hope Valley, RI (WOR 6-9) where numerous stormwater inputs and subwatersheds with high road densities are found (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. For example, the high road density and associated development in the Pawcatuck/Westerly area may be increasing runoff and potentially impacting small tributaries within the subwatershed. However, increases in runoff from the combined subwatersheds of PAR 1-5, representing only 1.6 percent of the watershed's total drainage area, are unlikely to be significantly increasing the total discharge of the Pawcatuck River and, thus, unlikely to be the cause of channel adjustments (e.g., bank erosion) on the large mainstem river channel. In general, impervious surfaces must cover 10 percent or more of a watershed before the net increase in runoff is 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 and towns that lie along the streams in the Wood-Pawcatuck Watershed, but the associated impervious surfaces represent only a small percentage of the entire watershed area that also includes large wetlands and 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. The significant wetlands found within much of the identified river corridors can attenuate floods and reduce downstream peak discharges, so should also be protected from development and encroachment in order to maintain their important ecosystem and flood storage functions.

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, although the resulting impacts on channel morphology can be significant (Williams and Wolman, 1984). While potential flood reductions accrue downstream, dams also slow down flow in the impounded reaches upstream, resulting in higher flood stages, sediment deposition in the channel, and more rapid channel migration. Four large extant dams are present on the Pawcatuck River mainstem and numerous other dams are found on the tributaries with several miles of impounded flow occurring upstream of these structures. Of the more than 100 mi of rivers and streams investigated as part of the Phase 1 assessment of the Wood-Pawcatuck Watershed, more than 22 mi are impounded behind dams. Only two impounded reaches were investigated as part of the Phase 2 assessment; both were associated with planned dam removals (i.e., upstream of Bradford Dam and the now removed White Rock Dam).

While urban development and dams typically affect higher flows, the withdrawal of water directly from the channel (or extraction of groundwater from floodplain aquifers) for gravel mining operations and irrigation in the Wood-Pawcatuck Watershed can drastically reduce low flows during the typically dryer late summer months. This in turn can effect the health and make up of riparian vegetation, reduce low flow refugia, increase water temperatures, and disconnect aquatic habitats (Poff et al., 1997). Riparian landowners can draw as much water as they want from streams in Rhode Island. Many farms and gravel pits in the watershed withdraw significant quantities of water when the river is already experiencing low flows and temperature stress. Parts of Meadow Brook go completely dry in the late summer and early fall due, in part, to water withdrawals and groundwater pumping.

3.2 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 (e.g., coarseness of 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 3), or the river's capacity to transport sediment is decreased, such as upstream of dams (Figure 4) or undersized stream crossings (Figure 5). 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 can harm aquatic habitat as is seen in the form of shallow braided channels where aggradation is occurring (Figure 5) or wide plane-bed channels where degradation removes sand/gravel bars and simplifies flow complexity (Figure 6).

Sediment regime stressor maps depict both potential sources of sediment and locations where sediment transport capacity is likely to decline and thus promote deposition (Appendix 1). A comparison of the mapped features is sometimes helpful in establishing the causal links between features but caution must be exercised in establishing such linkages. In GAS-1, mass wasting (i.e., landslides along high banks) observed at the upstream end of the reach is the likely source of sediment leading to the high density of bars and channel migration features lower in the reach. While few bars and channel migration features are recorded in PAR-18 such features are far more numerous in PAR-17 with the sediment likely derived from mass wasting at the upstream end of the reach and from tributary inputs at the Meadow Brook confluence (which forms the reach break between PAR-17 and PAR-18). Land use/land cover data are potentially useful for identifying sediment sources that might lead to aggradation and channel planform change. Although the majority of subwatersheds in the Wood-Pawcatuck Watershed have low percentages of agriculture, several subwatersheds have a high density of farms (e.g., PAR 5-6, BER 2-4). While these reaches may in fact be affected by increased runoff and sediment from the local farms, given the higher density of bars and migration features within these reaches, a causal relationship should not immediately be assumed without an obvious means by which upland soils are delivered to the river. 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, although bank erosion, while an issue locally at some sites, is generally not a severe problem throughout the watershed.

4.0 DELINEATING REACHES UNDERGOING OR SENSITIVE TO ADJUSTMENTS

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 factors controlling channel adjustment 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 Wood-Pawcatuck Watershed, for example, land clearance (and subsequent reforestation), dams, channel straightening, bank armoring, and stream crossings, among other human activities, are stressors that have, to varying degrees, not only altered water, sediment, and wood inputs into the channel but have also altered the river’s capacity to transport sediment through the channel. While dams and undersized stream crossings dramatically decrease transport capacity, channel straightening and bank armoring increase transport capacity such that sediment becomes concentrated in some areas (e.g., upstream of stream crossings), is absent in others (e.g., straightened reaches), and is not evenly distributed along the channel as expected under natural equilibrium conditions. 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, a less complicated approach for understanding ongoing adjustments is to compare the existing channel conditions with the presumed natural reference (i.e., equilibrium) state of the channel.

4.1a Alterations in sediment regime

Sediment regime maps depict how the sediment regime has been altered from the reference condition (Appendix 1) and, with an understanding of channel evolution (Schumm et al., 1984), can be used to identify those reaches most likely to experience future channel adjustments. Alterations to the sediment regime must be considered at the watershed scale, because reaches not directly altered by humans may be subject to excess (or decreasing) sediment loading caused by upstream human impacts. In the geomorphology-based river corridor planning process created by the Vermont River Management Program (Web citation 2), 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 transport reaches due to the low gradient and unconfined valleys of the Wood-Pawcatuck Watershed (Appendix 1).

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 a slowly accreting floodplain surface.

The numerous Equilibrium reaches in the Wood-Pawcatuck Watershed are not necessarily unaltered by human activity but rather indicate that the geomorphic imprint of incision is less than is typical of most New England settings. Along the mainstem of the Pawcatuck and the lower Wood River, dams are spaced closely enough, and consequently take up much of the total vertical drop, that reaches only incise a small amount due to backwatering from a downstream dam. The overall low gradient of the valleys, along with availability of coarser sediment, may further limit bed degradation.

Much of the Wood-Pawcatuck Watershed 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 fall with the Coarse equilibrium and fine deposition category, but many reaches upstream of impoundments are in the Deposition category. Straightened and incised reaches are typically in the Unconfined source and transport category. Fine source and transport reaches occur where sediment inputs are locally higher.

4.1b Slope modifiers and boundary conditions

There are abundant dams and small weirs in the Wood-Pawcatuck Watershed, as well as undersized stream crossings creating temporary flow impoundments upstream during floods. These structures have altered the slope of the rivers draining the watershed. Conversely, significant artificial channel straightening has increased slope elsewhere and bank armoring has fixed the channel boundaries in place such that channel adjustments are severely constrained. The Slope Modifiers and Boundary conditions maps (Appendix 1) show natural and artificial controls on channel morphology in order to elucidate potential locations for rapid channel change. Straightened channels efficiently transport sediment and floodwaters downstream to artificial constrictions (e.g., dams and undersized stream crossings), creating reaches prone to rapid deposition, flooding, and planform change (Figure 7). GAS-4 contains one such example of a recent channel avulsion downstream of a straightened reach and upstream of an artificial constriction (Figure 7). Knowledge of these artificial channel controls can help pinpoint where the river may rapidly adjust in response to the combined impact of multiple encroachments. Cross referencing such areas with the location of important infrastructure can prioritize restoration efforts in areas of greatest flood risk.

Lateral adjustments along artificially straightened channels in the Wood-Pawcatuck Watershed will be critical for the reestablishment of a meandering planform and the enhancement of aquatic habitat. Where no bank armor or riparian vegetation is present, channel migration can occur and meanders can reform. The recreation of meanders is essential to the redevelopment of equilibrium conditions along 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 near critical infrastructure such as stream crossings. However, many areas of the river are armored along the banks (Appendix 1) and the lateral migration of the river thus inhibited. The ongoing bank erosion observed in the watershed may reflect the lateral channel adjustments that must continue before an equilibrium condition is achieved. While future bank stabilization may be needed to protect critical infrastructure, bank erosion in areas where infrastructure is not at risk may represent priority areas for corridor protection (see Section 5.1 below), so future human activities do not compel the use of further bank protection that will deter the attainment of equilibrium conditions. 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 will be increasingly focused on shorter lengths of the river, exacerbating the erosion hazards and habitat degradation already present.

Human development in the watershed has created, in some locations, permanent constraints to channel evolution and is preventing the reestablishment of equilibrium conditions, particularly on the floodplain in Westerly, RI and Stonington, CT (Figure 8). However, overall levels of urbanization in the largely forested watershed have not reached a threshold level to precipitate system-wide channel adjustments in the Wood-Pawcatuck Watershed. Therefore, if further constraints in the watershed can be avoided in the remaining undeveloped areas of the floodplain, the river can undergo the necessary lateral adjustments to evolve back to an equilibrium condition in most locations. Sediment deposition is typically concentrated at undersized crossings, dams, or other grade controls located downstream of straightened reaches (Figure 5). Plane-bed features of poor habitat quality characterize straightened reaches with a uniform depth across the channel as the result of limited sediment deposition. 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 watershed.

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 Wood-Pawcatuck Watershed show that most of the reaches are sensitive to change (see River Corridor Protection Area maps in Field, 2016). 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 gravel to sand-sized bank material that are undergoing or subject to future channel adjustments. Most of the reaches assessed in the Wood-Pawcatuck Watershed are in unconfined valleys, have banks composed of fine sediment, and are, thus, sensitive to change. If meanders reform along straightened reaches either naturally (Figure 9) 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 as part of future restoration efforts has the potential to reduce channel sensitivity, habitat degradation, and flood hazards in downstream areas.

5.0 RESTORATION TECHNIQUES FOR ADDRESSING 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, or at least account for, upstream stressors. Flow energy expenditure and sediment deposition is ideally distributed along the length of a river and should not be focused at single points as this concentration of energy and sediment deposition inevitably leads to severe bank erosion and rapid channel migration in sensitive reaches. 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 2). The procedure identifies all of the restoration actions that are consistent with achieving equilibrium in the reach with those higher on the list above (e.g., protecting river corridors, planting stream buffers) prioritized over 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 in the Wood-Pawcatuck Watershed are discussed further below. Head cuts and nick points are not a significant problem in the watershed so restoration of these conditions is not addressed here but may become an issue in the future if dam removals occur where significant sediment storage is present. 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 in the Wood-Pawcatuck Watershed caused past incision that continues to result in excess sediment conveyance downstream. Restoration must occur in these reaches to accelerate the return of equilibrium conditions and improvements to aquatic habitat in the straightened reaches themselves and impacted downstream areas.

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 9). 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 associated with meander formation 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 colonize the bars 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 river corridor protection areas established by the Phase 2 assessment (Field, 2016).

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 channel migration 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 time is required for the trees to mature. Consequently, other restoration actions are often needed where a more immediate need for habitat improvements exists. Furthermore, in areas where rapid erosion is occurring, other bank stabilization techniques would be required to provide sufficient time for the planted buffer to grow to maturity. Despite these shortcomings, planting buffers along riverbanks and their adjacent floodplains should be considered a high priority in the Wood-Pawcatuck Watershed given the potential long-term advantages and the minimal effort, finances, and expertise required to do so.

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 restoring conditions in upstream reaches that are the ultimate cause for the destabilizing 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) human infrastructure is imminently threatened; 2) a reduced rate of lateral erosion on a reach is necessary to give riparian buffer plantings ample time to mature; 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 through flow deflection (Figure 10). 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 10d).

Large mass failures occur in a few places in the Wood-Pawcatuck Watershed and supply large amounts of sediment to the river (Figure 3). 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 log jam or boulder deflectors (Figure 10a-b), are likely to be the most effective 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 nearby 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 some assessed reaches are preventing the attenuation of flow and sediment across the floodplain. Likewise, raised road and railroad grades crossing the floodplain create artificial valley constrictions even when stream crossings are adequately sized with respect to channel width (Figure 11). Floodplain constraints include berms and railroad and highway grades paralleling the river that are built higher than the surrounding floodplain and cut off access to a portion of the floodplain (Figure 9). 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, 3) promote sediment deposition, 4) reduce the risk of a severe flood breaching the constraints and damaging property on the backside of the floodplain, 5) allow the stream to expend additional energy and attenuate its sediment load before reaching more sensitive reaches downstream, and 6) create a more natural flow and sediment regime through the reach. 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 stream power. From a technical standpoint, therefore, removing floodplain constraints and artificial constrictions is rated as one of the highest restoration priorities in the Wood-Pawcatuck Watershed, 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 floodplain relief culverts installed under an elevated 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. This approach may be most effective on the several major road and railroad grades that run perpendicular to the channel and bisect the floodplain.

5.5 Removing/replacing structures

Many bridges and culverts in the assessed reaches are significantly undersized (i.e., narrower than the bankfull channel width), resulting in flood hazards (Figure 12) and causing channel adjustments upstream and downstream of the structure (Figure 5). These localized adjustments have caused considerable damage to several structures in the Wood-Pawcatuck Watershed (Figure 13). Replacing undersized structures with larger spans will reduce hazards and effects on channel morphology that potentially damage the structures themselves while creating better hydraulic conditions for aquatic organism passage. Since stream crossings represent the majority of encroachments in the river corridor, their replacement and retrofitting should be a high priority.

Dams take up much of the actual vertical drop along the mainstem Pawcatuck River and turn a considerable amount of the river length into impoundment. While some impoundments and their dams are considered cultural, historic, and recreational resources, many dams serve little purpose and could be removed to improve the continuity of sediment transport, reduce backwater effects upstream, and restore anadromous fish passage. The three dams along the Ashaway River in Ashaway, RI are good candidates as they are no longer in use, are partially breached, are in poor structural condition, could reduce flood risk to several buildings and homes along the impoundment, and could provide access to many miles of high quality habitat. Special care will be needed post removal to make sure armored river banks that are protecting infrastructure remain stable if the river bed will be lower after dam removal.

5.6 Restoring incised reaches

Incised channels focus more flow energy on the channel bed as a greater percentage of flow is 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 downstream, further degrading aquatic habitat and compromising channel equilibrium. With greater transport efficiency through the incised reaches, greater rates of deposition occur downstream where channel transport capacity declines at bends in the channel or at channel constrictions.

Straightened reaches, a common feature in the Wood-Pawcatuck Watershed (Figure 6 and Appendix 1), tend to be slightly incised. 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 wood to the channel (Figure 14) such that sediment accumulation will raise the channel bed sufficiently such that smaller floods can once again access the floodplain. From a geomorphic equilibrium perspective, without consideration of the social constraints, the placement of engineered log jams in the river can also form new meanders by encouraging flows to "break out" of the channel and carve a new meander on the floodplain, as occurs naturally on straightened reaches elsewhere in New England (Field, 2007). The current dearth of attenuation assets along straightened reaches where meanders can reform in the Wood-Pawcatuck Watershed is preventing equilibrium conditions from becoming reestablished. This increases the potential that hazardous erosion and meander reformation will occur naturally, potentially in areas where human developments are present. Reducing these hazards will require protecting the corridor adjacent to straightened reaches, so meander creation can be encouraged to form 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 in the Wood-Pawcatuck Watershed 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 upstream of Westerly and Ashaway RI, 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 channel constrictions (Figure 5), upstream of dams (Field, 2016), and downstream of valley expansions can lead to rapid erosion as flow is deflected into the adjacent banks. 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 in the Wood-Pawcatuck Watershed 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 upstream of undersized crossings. 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. The benefits of watershed scale restoration will accrue only slowly over several decades and only by recognizing and taking advantage of corridor protection opportunities as they arise over time.

5.9 Technical and social feasibility of project implementation

The above restoration approaches have been deemed appropriate for the Wood-Pawcatuck Watershed based only on the likelihood from a technical perspective to 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 in the Wood-Pawcatuck Watershed can play an important role in implementing high priority projects. The adoption of river corridor protection areas (see Field, 2016) into zoning regulations can help limit future development within the river corridor. Over time, more landowners will become interested in state and federal programs that compensate landowners for protecting river corridors (e.g., NRCS). 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 that can reduce hazards downstream. A number of floodplain constraints in the Wood-Pawcatuck Watershed 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 channel constrictions (e.g., dams, undersized stream crossings). 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 context 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 IN THE PAWCATUCK WATERSHED

Over 45 priority restoration projects have been identified (Figure 15 and Table 3) using the Phase 2 geomorphic assessment data and the resulting River Corridor Protection Area maps (Field, 2016) and stressor and departure maps (Appendix 1). The selected sites are subdivided into a range of restoration activities consistent with Section 6.0 above. 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, floodplain constraints, dams, and undersized crossings. Successful restoration at a subset of these sites will provide examples of how to proceed with similar sites elsewhere in the watershed. The Phase 2 assessment results (Field, 2016) and stressor and departure maps (Appendix 1) can be used to select and prioritize additional sites or evaluate the potential benefits of restoration activities at various sites as opportunities and funding arise for land conservation, dam removal, culvert replacement, or other activities.

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 45 specific projects identified (Table 3) that will promote equilibrium conditions within the Wood-Pawcatuck Watershed. 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.

8.0 REFERENCES

Booth, D.B., Hartley, D., and Jackson, R., 2002, Forest cover, impervious-surface area, and the mitigation of stormwater impacts: Journal of the American Water Resources Association, v. 38, p. 835-845.

Field, J., 2016, Fluvial geomorphic assessment and river corridor planning in the Wood-Pawcatuck Watershed, RI and CT: Unpublished report prepared for the Wood-Pawcatuck Watershed Association, 127 p.

Field, J.J., 2007, The recreation of meanders along artificially straightened stream channels: Geological Society of America Abstracts with Programs, v. 39, p. 243.

Poff, N.L., Allan, J.D., Bain, M. B., Karr, J.R., Prestegaard, K.L., Richter, B., Sparks, R., and Stromberg, J., 1997, The natural flow regime: a new paradigm for riverine conservation and restoration: BioScience, v. 47, p. 769-784.

Schumm, S.A., Harvey, M.D., and Watson, C.C., 1984, Incised Channels: Morphology, Dynamics, and Control: Water Resources Publications: Littleton, CO.

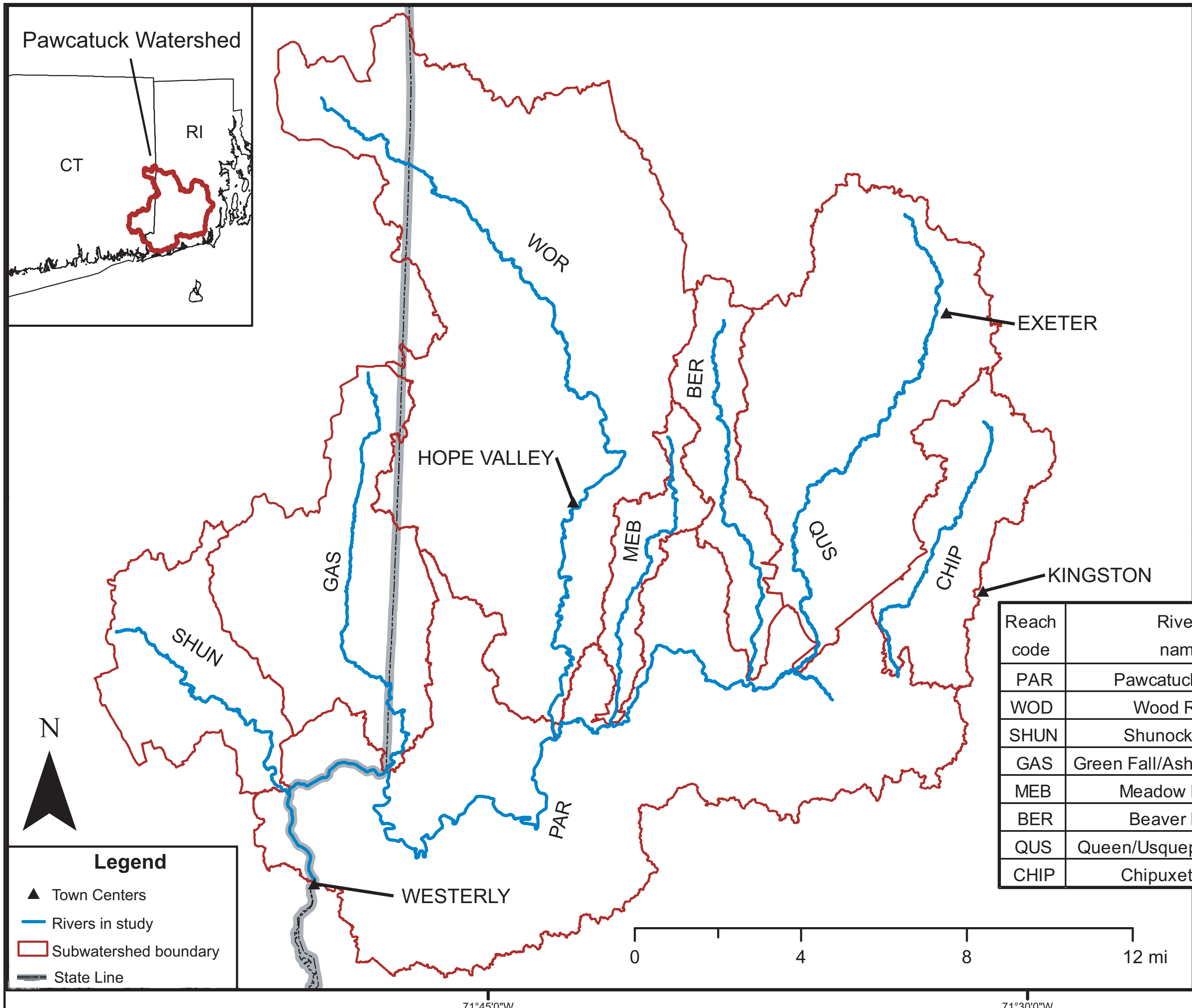
Williams, G.P., and Wolman, M.G., 1984, Downstream effects of dams on alluvial rivers: U.S. Geological Survey Professional Paper 1286, 83 p.

Web citations

Web citation 1: http://dec.vermont.gov/watershed/rivers/river-corridor-and-floodplain-protection/geomorphic-assessment

Web citation 2: http://dec.vermont.gov/sites/dec/files/wsm/rivers/docs/rv_rivercorridorguide.pdf

FIGURES



Reach code	River name	Watershed area mi^2	River length (mi)
PAR	Pawcatuck River	297	29.4
WOD	Wood River	89.4	25.5
SHUN	Shunock River	16.6	8.8
GAS	Green Fall/Ashaway River	28.9	12.8
MEB	Meadow Brook	7	9
BER	Beaver River	11.7	11.3
QUS	Queen/Usquepaug River	43.8	17.5
CHIP	Chipuxet River	15.6	8.7

Figure 1. Overview map of Pawcatuck Watershed. Table contains basic watershed information.

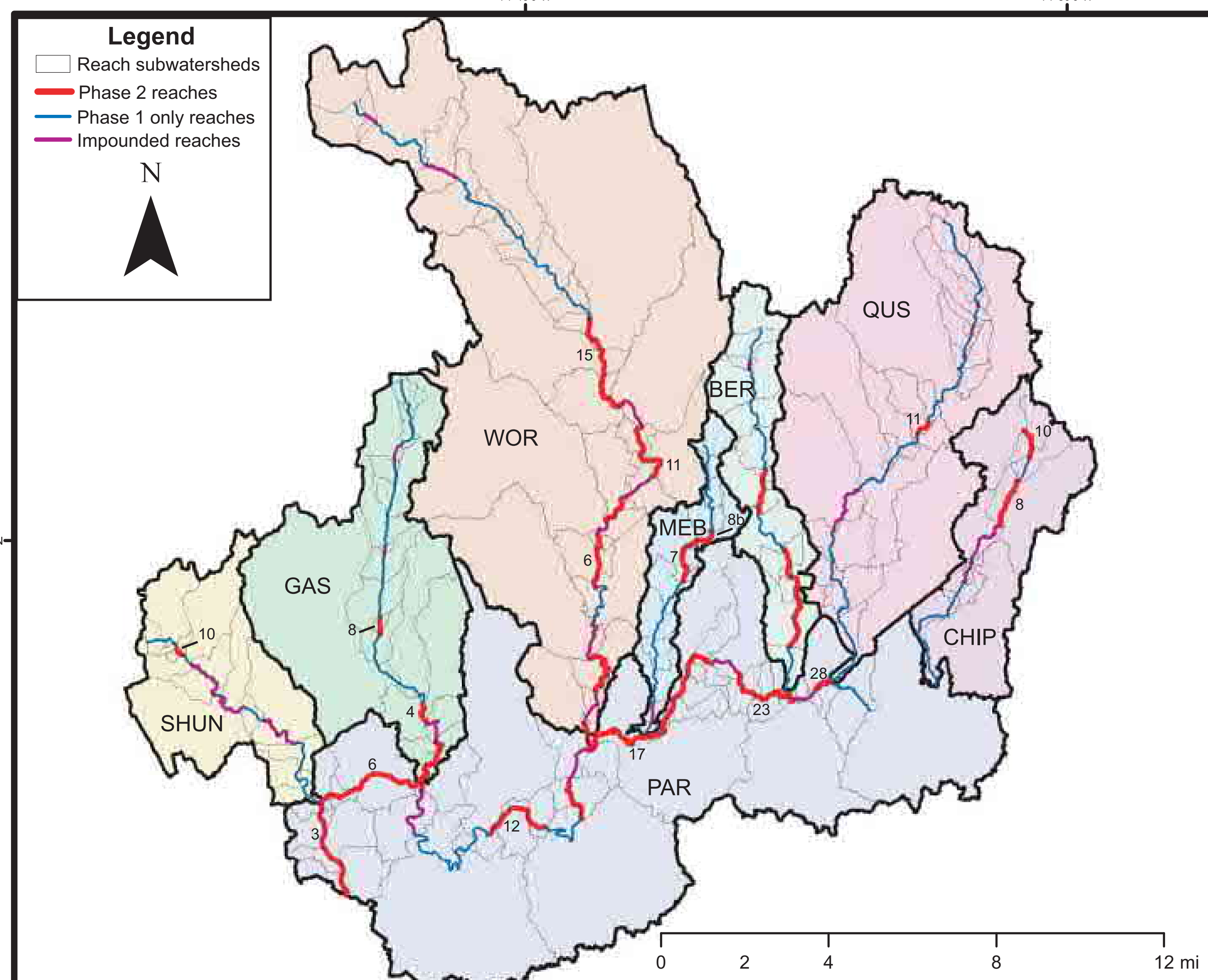


Figure 2. Watershed map showing reach subwatersheds, Phase 2 reaches assessed, and impounded reaches.


Figure 3. Mass wasting in GAS-1.

Figure 4. Deposition upstream of White Rock Dam (before its removal) at the mouth of the Shunock River confluence in PAR-5.

Figure 5. Deposition upstream of an undersized culvert in Reach QUS-11.

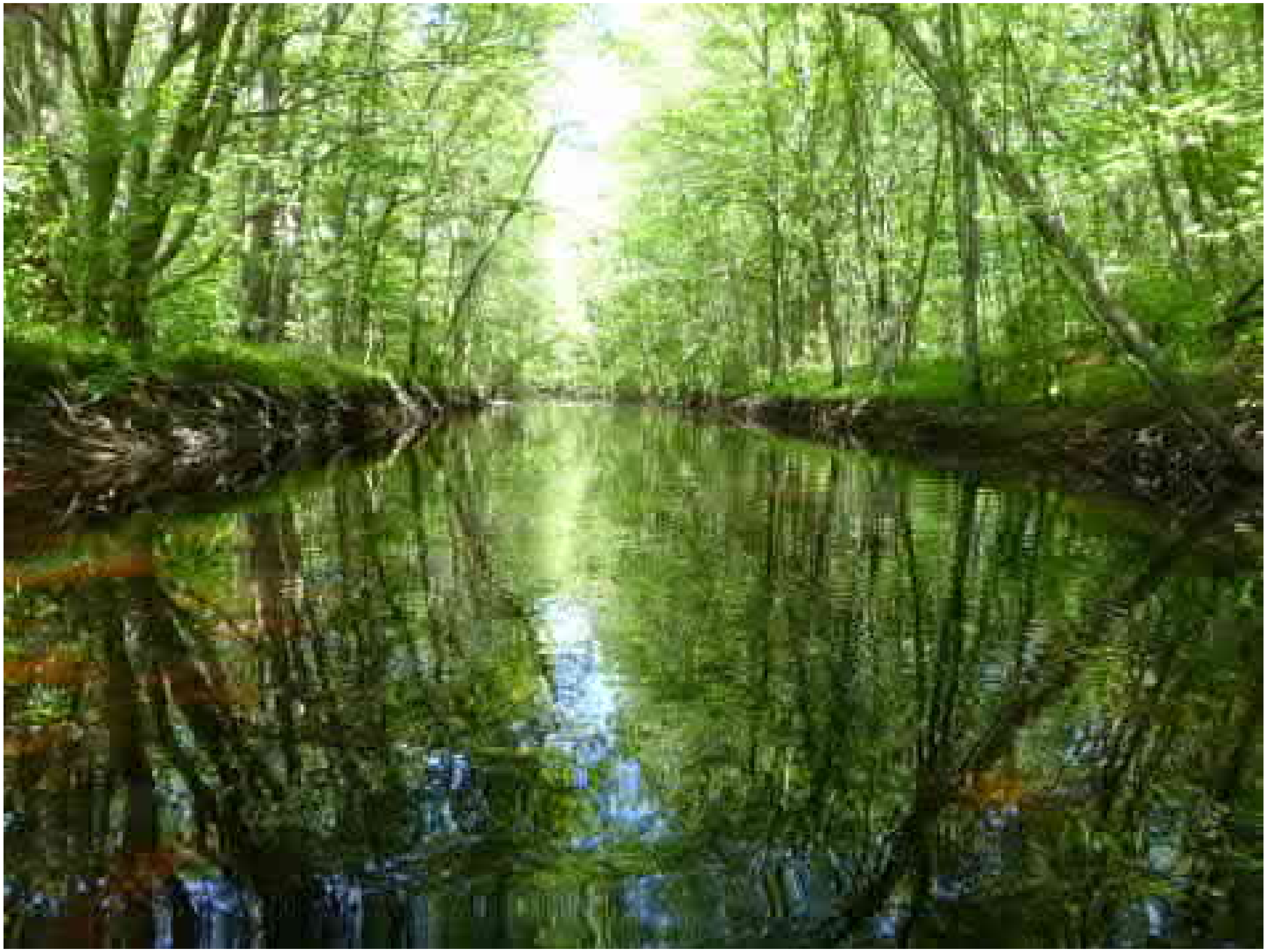


Figure 6. Upstream view of artificially straightened channel in GAS-4.

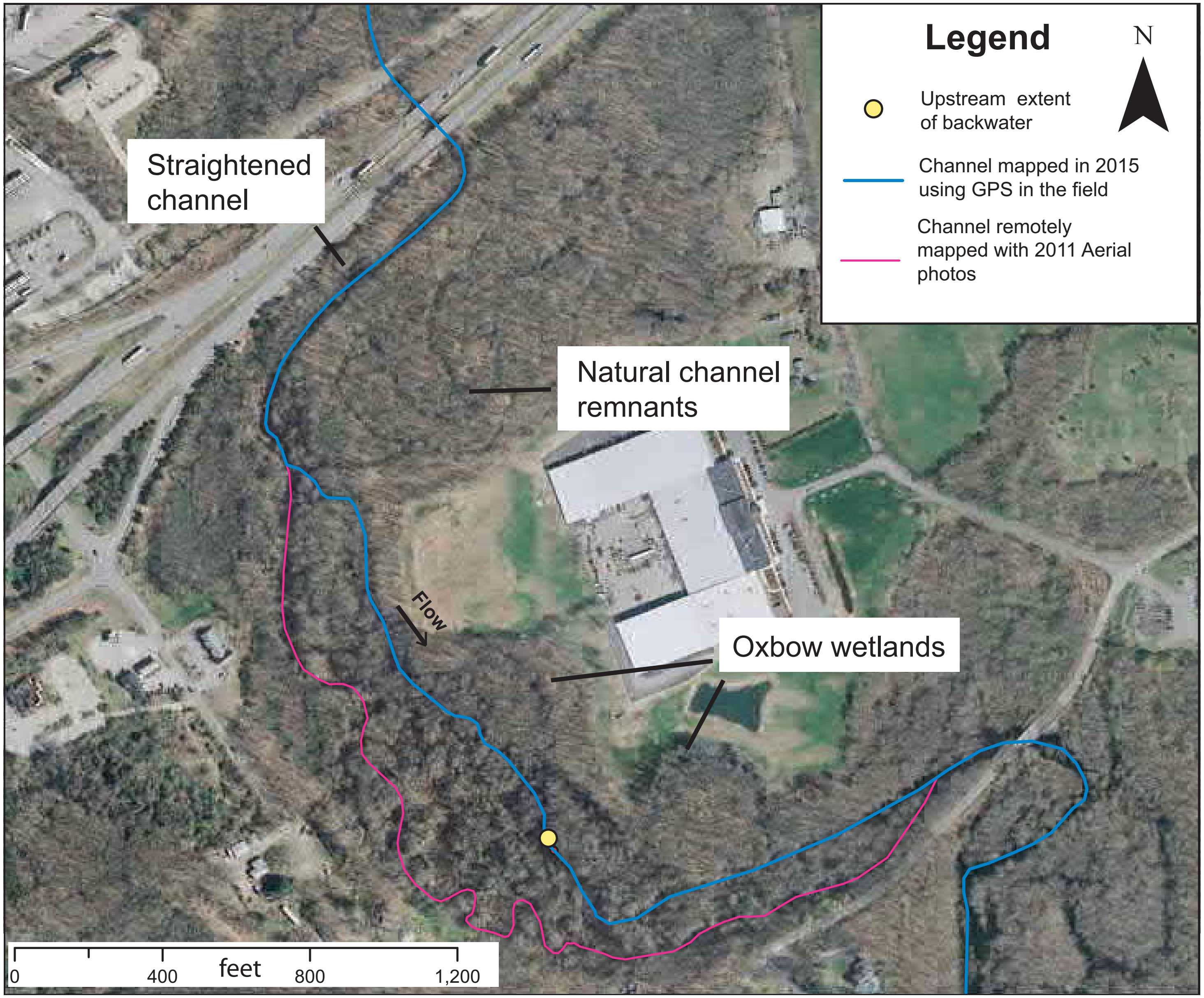


Figure 7. Aerial photograph showing channel planform changes upstream of undersized stream crossing in GAS-4.

Figure 8. Human development constrains channel adjustment on the lower Pawcatuck River.

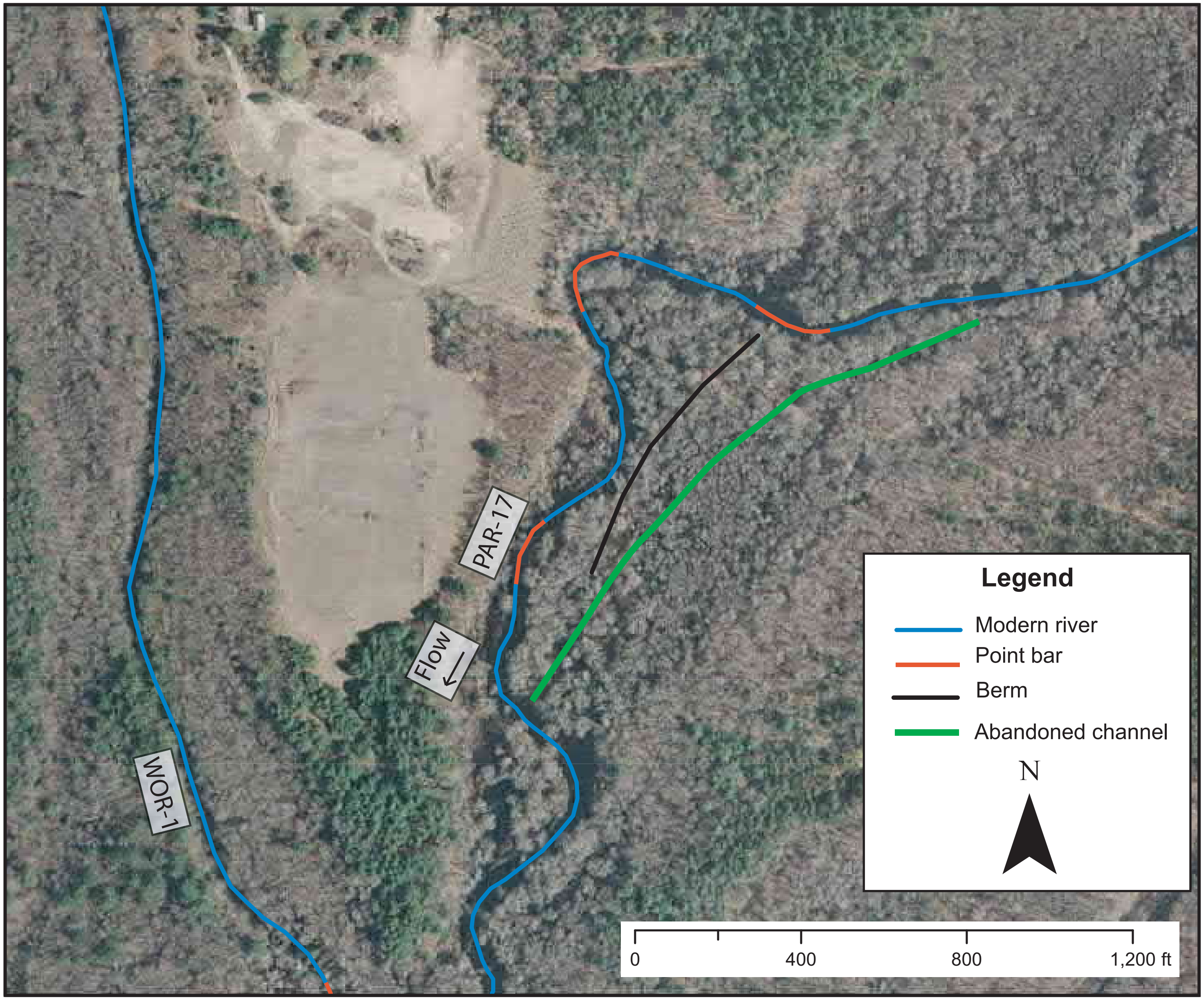


Figure 9. Meander reformed naturally on artificially straightened portion of PAR-17.

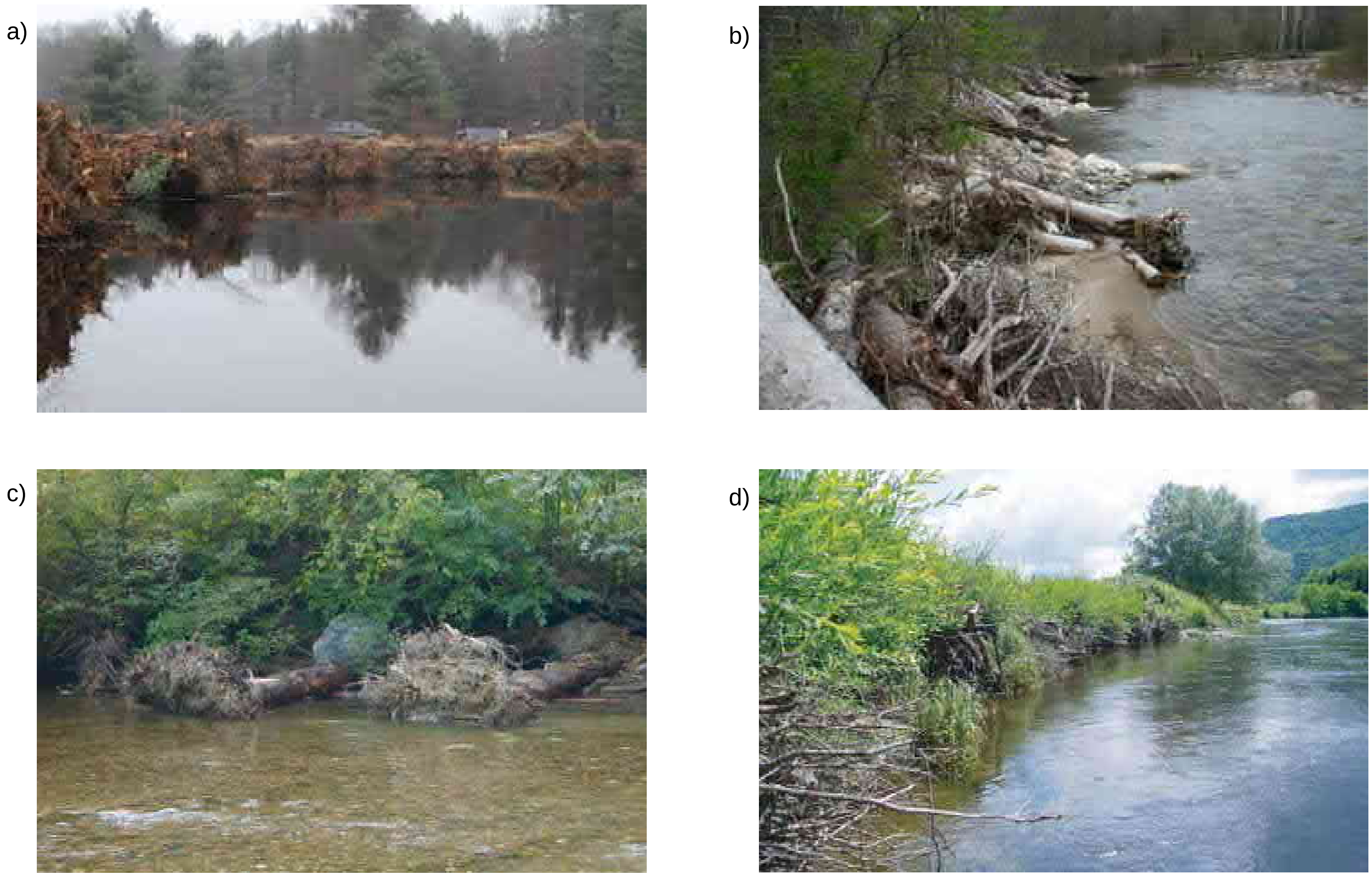


Figure 10. Examples of bioengineering techniques for bank stabilization include use of a) marginal log jams (Souhegan River in Merrimack, NH), b) boulder and log deflectors (Sunday River in Newry, ME), c) root wad revetments (Batten Kill in Arlington, VT), and d) willow stakes above root wad revetment (Connecticut River in Colebrook, NH).

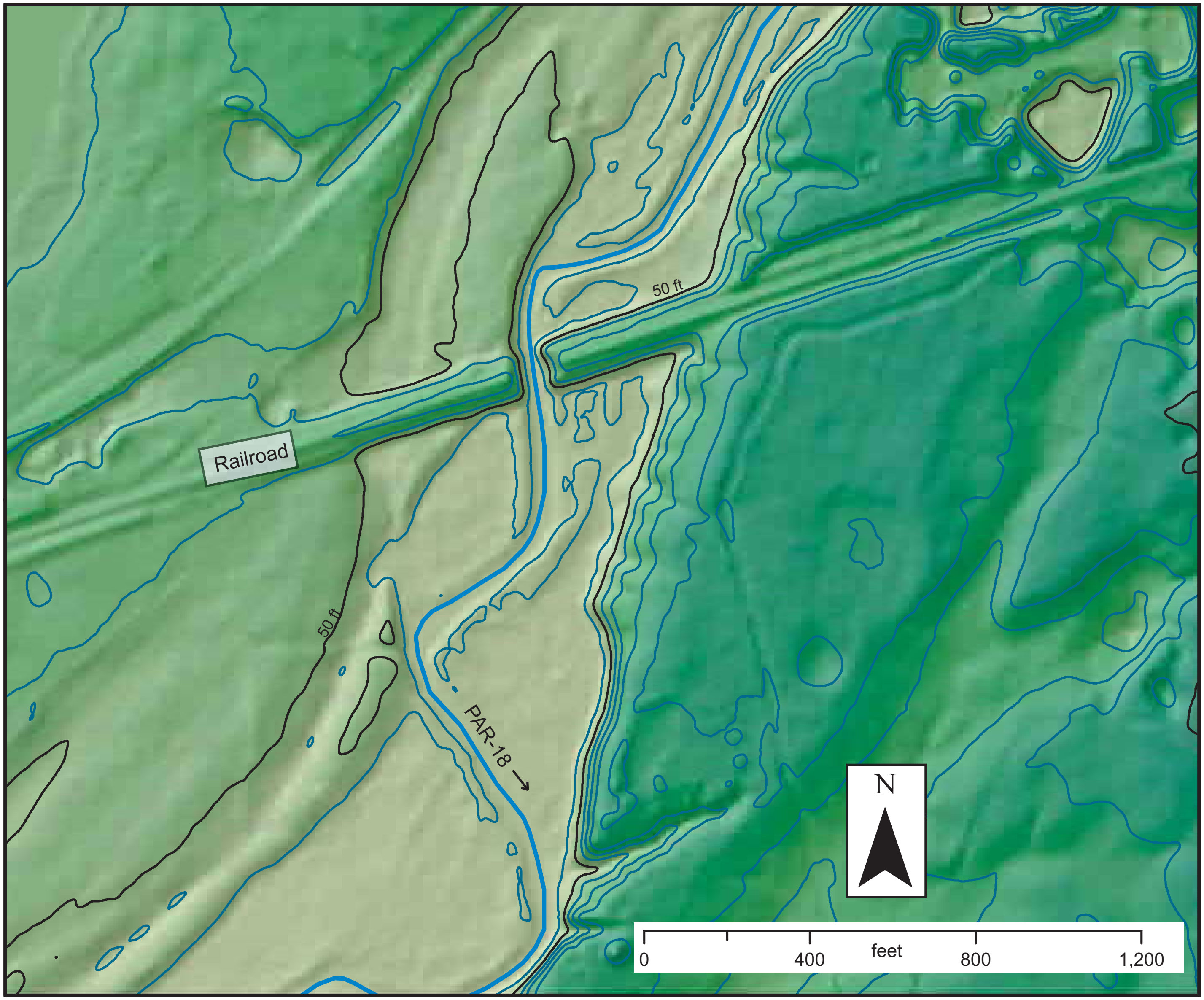


Figure 11. LiDAR shaded relief map of valley-constricting elevated railroad grade in PAR-18.

Figure 12. Hillsdale Road overtopped due to backwatering behind undersized culvert during 2010 flood on Beaver River in Richmond, RI.

a)

b)

Figure 13. Old Shannock Road Bridge in PAR-23 showing a) upstream overview and b) close up of scour damage and subsequent riprap protection.

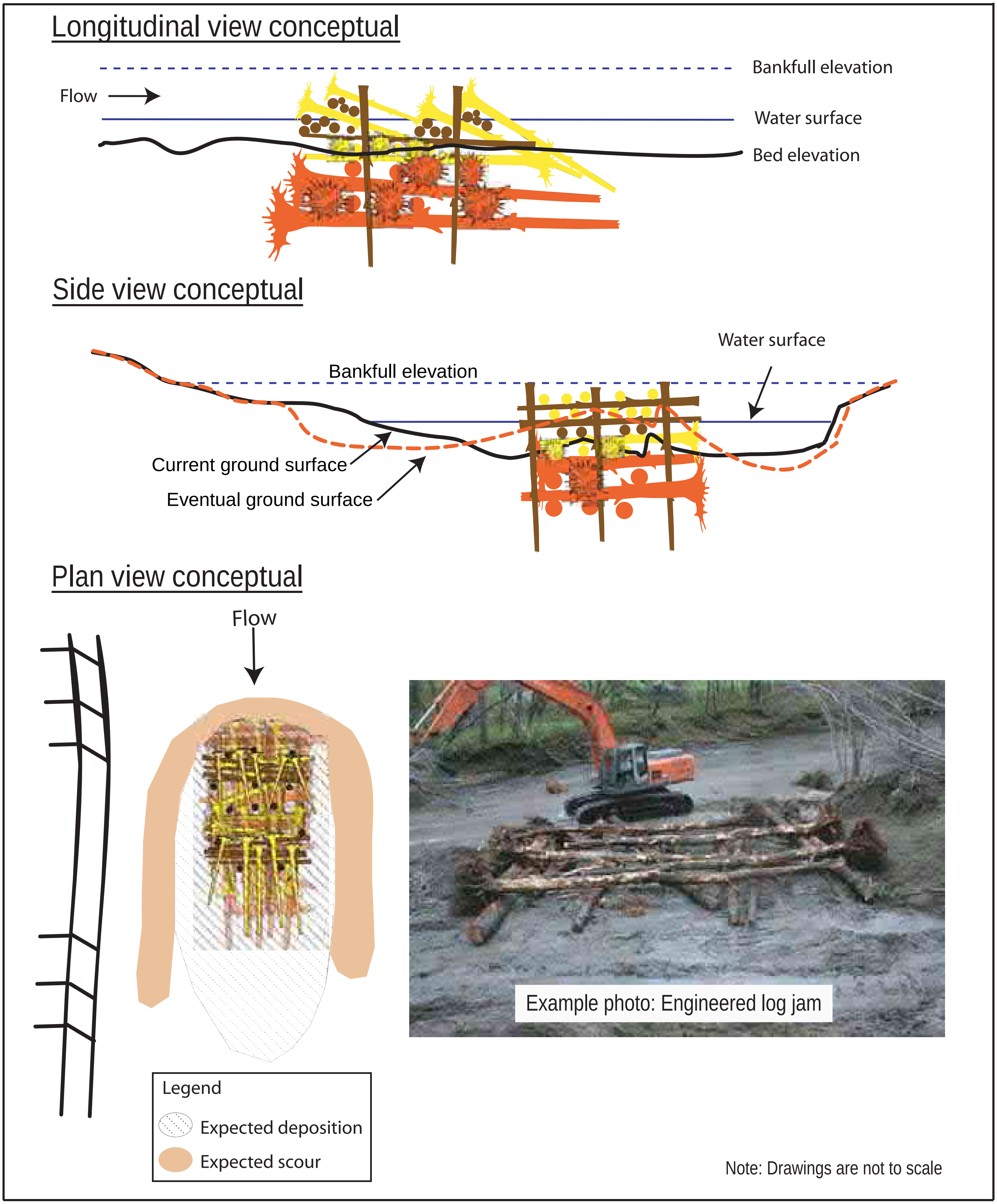


Figure 14. Design typical for an engineered log jam.

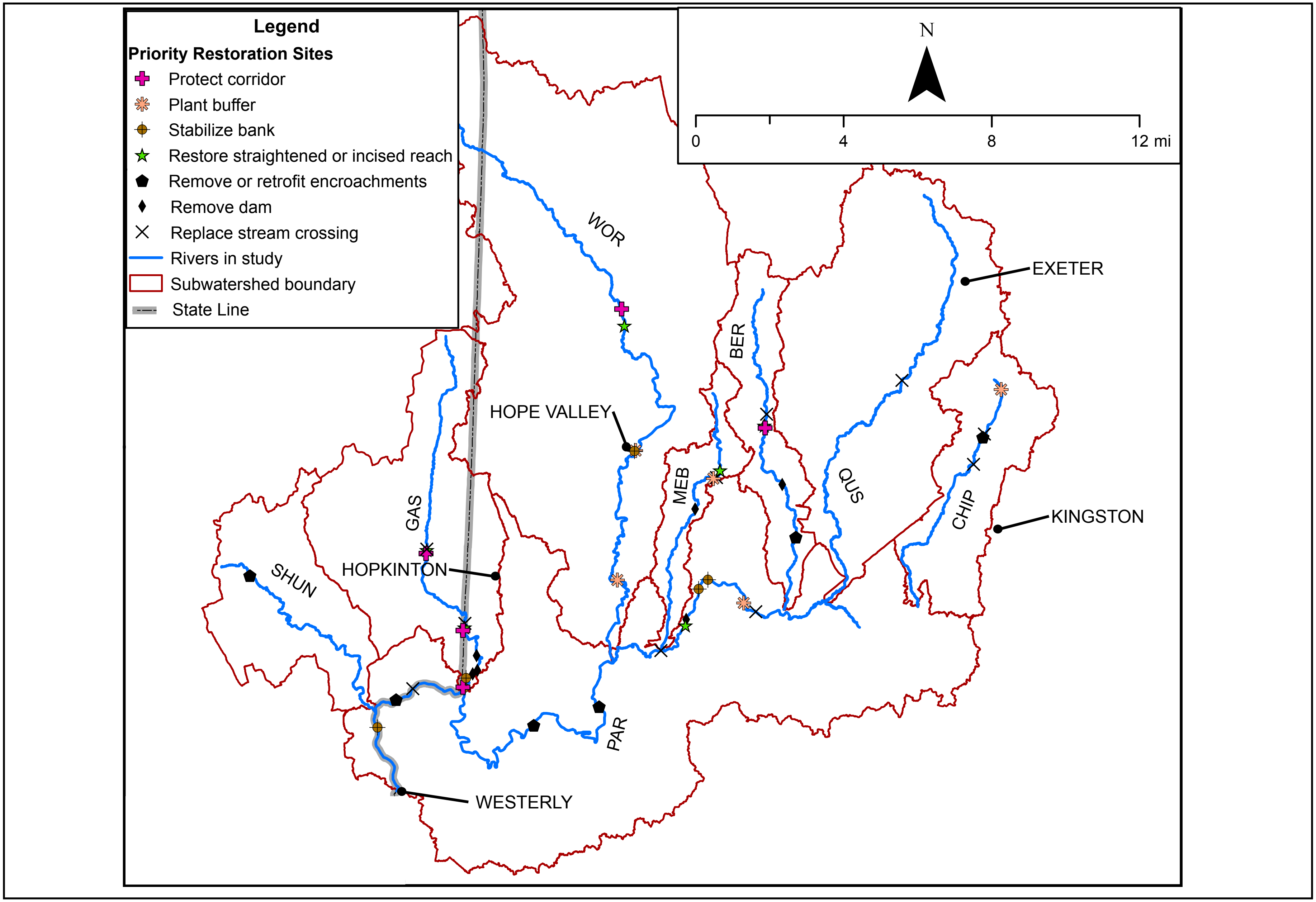


Figure 15. Map of priority restoration sites by project type.

TABLES

Table 1. Reach locations and details.

Water Body	Reach	Downstream Reach Break Location	Reason	Town	State
Pawcatuck	PAR-1	At Broad Street in downtown Westerly	Beginning of estuary	Stonington/Westerly	RI/CT
Pawcatuck	PAR-2	At old broken down dam in Westerly	Dam at reach break	Stonington/Westerly	RI/CT
Pawcatuck	PAR-3	At Route 78 Bridge in Westerly	Large diversion reenters channel	Stonington/Westerly	RI/CT
Pawcatuck	PAR-4	At (former) White Rock Dam	Dam at reach break	Stonington/Westerly	RI/CT
Pawcatuck	PAR-5	Upstream end of (former) White Rock Dam impoundment	Tributary junction	North Stonington/Westerly	RI/CT
Pawcatuck	PAR-6	Downstream of Boom Bridge	Valley constriction	North Stonington/Westerly	RI/CT
Pawcatuck	PAR-7	At Ashaway River confluence	Tributary junction	North Stonington/Westerly	RI/CT
Pawcatuck	PAR-12	Upstream of Kedinker Island and Tomaquag Brook confluence	Dam at reach break	Hopkinton/Westerly	RI
Pawcatuck	PAR-13	At Bradford Dam	Dam at reach break	Hopkinton/Westerly	RI
Pawcatuck	PAR-15	At Burlingame campsite in Phantom Bog	Dam at reach break	Hopkinton/Charlestown	RI
Pawcatuck	PAR-17	At confluence with Wood River	Tributary junction	Hopkinton/Charlestown	RI
Pawcatuck	PAR-18	At confluence with Meadow Brook	Tributary junction	Richmond/Charlestown	RI
Pawcatuck	PAR-19	At USGS gaging weir	Valley constriction	Richmond/Charlestown	RI
Pawcatuck	PAR-20	Near Riverview Drive neighborhood	Dam at reach break	Richmond/Charlestown	RI
Pawcatuck	PAR-21a	At confluence with White Brook	Tributary junction	Richmond/Charlestown	RI
Pawcatuck	PAR-21b	Downstream of historic Carolina Mill area	Slope decreases	Richmond/Charlestown	RI
Pawcatuck	PAR-23	At upstream extent of Carolina Pond	Upstream end of impoundment	Richmond/Charlestown	RI
Pawcatuck	PAR-24	At the Shannock Mill historic site	Dam at reach break	Richmond/Charlestown	RI
Pawcatuck	PAR-25	At Horseshoe Falls Dam	Dam at reach break	Richmond/Charlestown	RI
Pawcatuck	PAR-26	At the upstream extent of impoundment and Beaver River confluence	Upstream end of impoundment	Richmond/Charlestown	RI
Pawcatuck	PAR-28	At Biscuit City Road stream crossing	Upstream end of impoundment	Richmond/Charlestown	RI
Wood	WOR-1	At confluence with the Pawcatuck River	Tributary junction	Hopkinton/Richmond	RI
Wood	WOR-3	Upstream extent of Alton Pond	Upstream end of impoundment	Hopkinton/Richmond	RI
Wood	WOR-6	Downstream of Switch Road	Dam at reach break	Hopkinton/Richmond	RI
Wood	WOR-7	At USGS gaging weir	Change in planform	Hopkinton/Richmond	RI
Wood	WOR-9	At the beginning of the Old Stone Dam impoundment	Upstream end of impoundment	Hopkinton/Richmond	RI
Wood	WOR-11	Upstream extent of Wyoming Pond	Upstream end of impoundment	Hopkinton/Richmond	RI

Table 1 (continued). Reach break locations and details.

Water Body	Reach	Downstream Reach Break Location	Reason	Town	State
Wood	WOR-12	Near westernmost point of Wood River Drive	Valley constriction	Hopkinton/Richmond	RI
Wood	WOR-14	Upstream extent of Frying Pan Pond	Tributary junction	Hopkinton/Richmond/Exeter	RI
Wood	WOR-15	In Acadia Management Area	Dam at reach break	Exeter	RI
Wood	WOR-16	At the confluence with Parris Brook	Tributary junction	Exeter	RI
Shunock	SHUN-10a	Downstream of Route 2	Tributary junction	North Stonington	CT
Shunock	SHUN-10b	Downstream of Route 2	Change in planform	North Stonington	CT
Ashaway	GAS-1	At junction with Pawcatuck River	Tributary junction	Hopkinton	RI
Ashaway	GAS-2	Downstream of Laurel Street in downtown Ashaway, RI	Dam at reach break	Hopkinton	RI
Ashaway	GAS-4	At upstream end of Bethel Pond	Upstream end of impoundment	Hopkinton	RI
Green Fall	GAS-8	At confluence with Shingle Mill Pond Brook	Tributary junction	North Stonington	CT
Meadow	MEB-7	Downstream of Kenyon Hill Trail	Valley constriction	Richmond	RI
Meadow	MEB-8a	Near southern end of Meadowbrook Road	Dam at reach break	Richmond	RI
Meadow	MEB-8b	Downstream of Meadow Brook Golf Course	Dam at reach break	Richmond	RI
Beaver	BER-2	At Shannock Hill Road	Valley constriction	Richmond	RI
Beaver	BER-3a	Upstream of Beaver River School House Road	Valley constriction	Richmond	RI
Beaver	BER-3b	Near Beaver River playground	Slope decreases	Richmond	RI
Beaver	BER-4	At State Route 138	Valley constriction	Richmond	RI
Beaver	BER-6a	Downstream of Punchbowl Trail	Valley constriction	Richmond	RI
Beaver	BER-6b	Near Hillsdale Road	Slope decreases	Richmond	RI
Beaver	BER-7	At pond in Hillsdale	Dam at reach break	Richmond	RI
Queen	QUS-11	Downstream of Liberty Road	Valley constriction	Exeter	RI
Chipuxet	CHIP-8	Downstream of Wolfe Rocks Road	Upstream end of impoundment	Exeter	RI
Chipuxet	CHIP-10	Downstream of Railroad Road	Upstream end of impoundment	North Kingstown/Exeter	RI

Table 2. Potential for various types of restoration activities in each Phase 2 assessment reach.

Reach / Segment	Protect Corridor	Plant Buffer	Stabilize Stream Banks	Arrest Head Cut	Encroachment Removal	Encroachment Type	Replace Structure	Reoccupy Old Channel	Protect Downst. corridor	Protect Corridor (meander creation)	Remove/ Retrofit Structures	Restore Aggraded Reach	Protect Corridor (channel widening)
PAR-1	-	High	-	-	-	-	Low	-	-	-	-	-	-
PAR-2	High	High	-	-	Low	Road	Low	-	High	-	-	-	High
PAR-3	High	High	-	-	Low	Road	Low	-	High	-	-	-	High
PAR-4	High	Low	-	-	-	-	-	-	-	-	Completed	-	High
PAR-5	High	-	-	-	High	Berm	-	-	-	High	-	-	Low
PAR-6	High	Low	-	-	-	-	High	-	-	High	-	-	Low
PAR-7	-	High	-	-	-	-	Low	-	High	-	-	-	Low
PAR-12	-	Low	-	-	Low	Berm/Path	-	-	High	-	-	-	Low
PAR-13	High	Low	-	-	-	-	High	-	-	-	-	-	High
PAR-15	High	Low	-	-	-	-	Low	-	-	-	-	-	-
PAR-17	High	-	Low	-	Low	Berm	High	-	-	-	-	-	High
PAR-18	High	-	Low	-	-	-	Low	-	-	-	-	-	High
PAR-19	High	High	-	-	-	-	Low	-	-	-	-	-	High
PAR-20	High	High	-	-	-	-	-	-	-	High	-	-	High
PAR-21a	High	High	-	-	-	-	-	-	-	High	-	-	High
PAR-21b	High	High	-	-	-	-	High	-	High	-	-	-	High
PAR-23	High	-	-	-	-	-	High	-	-	-	-	-	High
PAR-24	High	-	-	-	-	-	Low	-	-	High	-	-	High
PAR-26	-	High	-	-	-	-	-	-	-	-	-	-	-
PAR-28	High	-	-	-	-	-	Low	-	-	-	-	-	High
WOD-1	High	-	-	-	-	-	High	-	-	-	-	Low	-
WOD-3	High	-	-	-	-	-	-	-	-	-	-	-	-
WOD-6	-	High	-	-	-	-	-	-	High	-	-	-	High
WOD-7	-	-	-	-	-	-	-	-	-	-	Low	-	-
WOD-9	-	High	-	-	Low	Berm	-	-	-	-	-	-	-

Table 2 (continued). Potential for various types of restoration activities in each Phase 2 assessment reach.

Reach / Segment	Protect Corridor	Plant Buffer	Stabilize Stream Banks	Arrest Head Cut	Encroachment Removal	Encroachment Type	Replace Structure	Reoccupy Old Channel	Protect Downst. corridor	Protect Corridor (meander creation)	Remove/ Retrofit Structures	Restore Aggraded Reach	Protect Corridor (channel widening)
WOD-11	-	-	High	-	-	-	-	-	-	-	Low	-	-
WOD-12	High	High	-	-	-	-	-	-	-	-	-	Low	-
WOD-14	High	-	-	-	-	-	-	-	-	-	-	-	High
WOD-15	High	-	-	-	-	-	-	-	-	Low	-	-	High
WOD-16	High	High	-	-	-	-	Low	-	-	-	-	High	-
BER-2	-	High	-	-	Low	Berm	-	-	-	-	High	-	-
BER-3a	High	High	-	-	-	-	High	-	-	-	High	-	-
BER-3b	High	-	-	-	-	-	High	-	-	-	High	-	-
BER-4	High	-	-	-	-	-	Low	Low	-	-	Low	-	-
BER-6a	High	High	-	Low	Low	Berm	Low	Low	-	-	-	-	High
BER-6b	High	High	-	Low	Low	Berm	High	-	-	High	-	-	High
BER-7	High	-	-	-	Low	Berm	Low	-	-	-	-	-	High
SHUN-10a	High	-	-	-	-	-	-	-	-	-	-	-	High
SHUN-10b	-	High	-	-	Low	Berm/Road	-	-	-	-	-	-	High
CHIP-8	High	-	-	-	-	-	High	-	-	-	High	-	-
CHIP-10	High	-	-	-	-	-	High	-	-	-	High	-	-
GAS-1	High	-	High	-	-	-	High	-	-	-	-	-	High
GAS-2	-	Low	-	-	-	-	-	-	-	-	High	-	-
GAS-4	High	High	-	-	-	-	High	High	-	-	High	-	-
GAS-8	High	High	-	-	-	-	-	-	-	-	-	-	-
MEB-7	High	High	-	Low	-	-	Low	-	-	High	Low	-	-
MEB-8a	High	High	-	Low	-	-	Low	-	-	High	-	-	High
MEB-8b	-	High	-	-	-	-	High	Low	-	-	Low	-	-
QUS-11	High	-	-	-	-	-	High	-	-	-	High	-	-

Table 3. Priority restoration sites by project type.

Reach	Town	Bridge/ Culvert Code	Location Lat.	Long.	Priority	Description	Photograph
Culvert Replacement							
MEB-8B	Richmond, RI	3016	41.501	-71.665	High	Severe erosion immediately downstream, head cut up to culvert outlet, undersized	
QUS-11	Exeter, RI	4768	41.539	-71.569	High	Severe deposition upstream, downstream scour, low bridge probably overtopped frequently	
CHIP-8	Exeter, RI	4509	41.506	-71.531	High	Beaver dam occupied, probably overtopped frequently	

Table 3 (continued). Priority restoration sites by project type.

Reach	Town	Bridge/ Culvert Code	Location Lat.	RCPA Long.	Priority	Description	Photograph
CHIP-8	Exeter, RI	4455	41.518	-71.526	High	Significantly undersized, beaver occupied	
BER-7	Richmond, RI	2967	41.526	-71.639	High	Undersized, perched at outlet, culvert was overtopped in 2010	
GAS-8	North Stonington, CT	347	41.472	-71.816	Low	Undersized, side channels and aggradation upstream, large scour pool downstream	

Table 3 (continued). Priority restoration sites by project type.

Reach	Town	Bridge/ Culvert Code	Location Lat.	RCPA Long.	Priority	Description	Photograph
Bridge Replacement							
PAR-23	Charlestown, RI	3869	41.448	-71.645	High	Scour issues in bed and downstream, undersized	
PAR-17	Charlestown, RI	3739	41.433	-71.694	High	Poor condition, oversized riffle upstream	
GAS-4	Hopkinton, RI	719	41.443	-71.796	High	Severely damaged	

Table 3 (continued). Priority restoration sites by project type.

Reach	Town	Bridge/ Culvert Code	Location Lat.	RCPA Long.	Priority	Description	Photograph
GAS-2	Hopkinton, RI	699	41.425	-71.790	High	Should be replaced with dam removal	
PAR-6	Westerly, RI	69	41.418	-71.823	High	Boom Bridge Road, heavily damaged and currently closed	
Dam Removal							
GAS-1	Hopkinton, RI		41.423	-71.792	High	Low head dam but prevents fish passage up the Ashaway River	

Table 3 (continued). Priority restoration sites by project type.

Reach	Town	Bridge/ Culvert Code	Location Lat.	RCPA Long.	Priority	Description	Photograph
GAS 2	Hopkinton, RI		41.425	-71.790	High	Causing vibration damage to adjacent house, raises water level around bridge potentially	
GAS-2	Hopkinton, RI		41.431	-71.790	High	Dam not in use, partially broken down, blocking fish passage to high quality habitat	
BER-6b	Richmond, RI		41.521	-71.640	High	Pond not in use but backs water up to road, potentially high quality habitat with connectivity	

Table 3 (continued). Priority restoration sites by project type.

Reach	Town	Bridge/ Culvert Code	Location Lat.	RCPA Long.	Priority	Description	Photograph
PAR-18	Charlestown, RI		41.443	-71.681	Low	Only dam/weir without some sort of fish ladder on mainstem, gage could function without weir	
BER-4	Richmond, RI		41.498	-71.631	Low	Splits up good habitat, not in use, contributed to trail washout	
MEB-7	Richmond, RI		41.488	-71.676	Low	Will turn wetlands back into a floodplain forest	

Table 3 (continued). Priority restoration sites by project type.

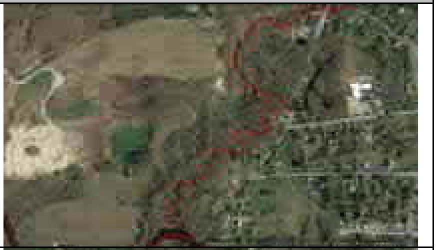
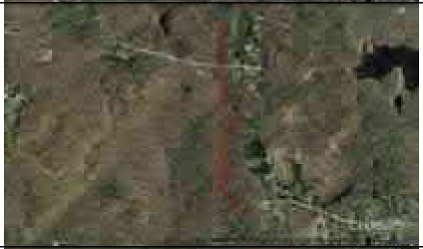
Reach	Town	Bridge/ Culvert Code	Location Lat.	RCPA Long.	Priority	Description	Photograph
Corridor protection							
GAS-1	Hopkinton, RI		41.418	-71.797	High	Entire reach should be protected, very dynamic, great habitat, poor location for development, luckily development has not encroached significantly	
GAS-4	Hopkinton, RI		41.441	-71.797	High	Dynamic channel, recent avulsion, good habitat	
GAS-8	North Stonington, CT		41.471	-71.817	High	Archaeological sites, good habitat potential, little modern encroachment	
BER-6-7	Richmond, RI		41.520	-71.640	Low	Archaeological sites, good cold water habitat potential, could use wood additions	

Table 3 (continued). Priority restoration sites by project type.

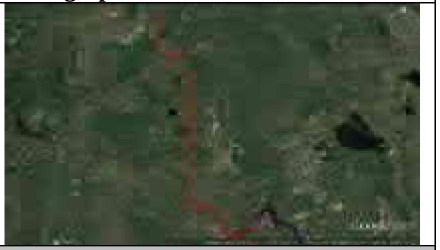
Reach	Town	Bridge/ Culvert Code	Location Lat.	RCPA Long.	Priority	Description	Photograph
WOR-14-16	Exeter, RI		41.567	-71.715	Low	Good habitat, in Acadia Management Area so may already be protected	
Bank stabilization							
GAS-1	Hopkinton, RI		41.422	-71.796	High	Logjams at the toe of mass failures represent potential stabilization option, house frontage is being eroded	
GAS-1	Hopkinton, RI		41.418	-71.796	High	House frontage is being eroded	

Table 3 (continued). Priority restoration sites by project type.

Reach	Town	Bridge/ Culvert Code	Location Lat.	RCPA Long.	Priority	Description	Photograph
WOD-9	Hopkinton, RI		41.511	-71.708	Low	Eroding bank with no riparian buffer	
PAR-20	Charlestown, RI		41.457	-71.674	Low	Erosion common in reach, could create log jams to protect banks and create habitat	
PAR-21	Charlestown, RI		41.461	-71.670	Low	Erosion common in reach, could create log jams to protect banks and create habitat	

Table 3 (continued). Priority restoration sites by project type.

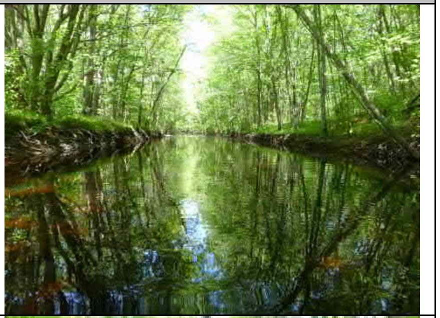
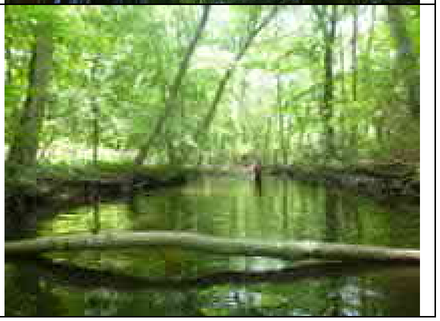
Reach	Town	Bridge/ Culvert Code	Location Lat.	RCPA Long.	Priority	Description	Photograph
PAR-3	Westerly, RI		41.402	-71.842	Low	Eroding and no riparian buffer but priority low	
Restoration of straightened and incised reaches							
GAS-4	North Stonington, CT		41.442	-71.797	High	Potential to reoccupy old meandering channel downstream of I -95	
GAS-8	North Stonington, CT		41.472	-71.816	High	Install marginal log jams to help channel aggrade and form meanders, downstream of Puttker Road	

Table 3 (continued). Priority restoration sites by project type.

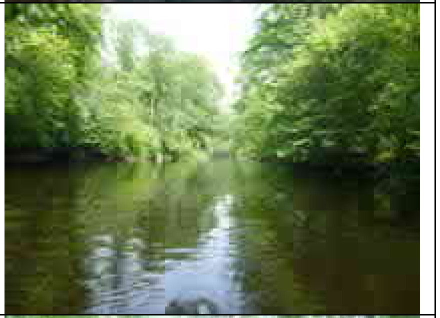
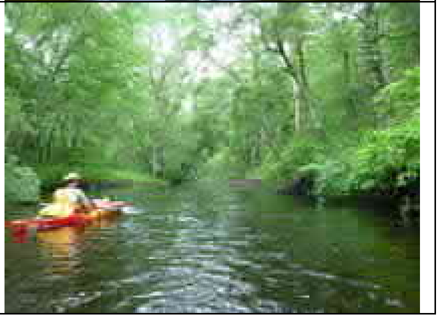
Reach	Town	Bridge/ Culvert Code	Location Lat.	RCPA Long.	Priority	Description	Photograph
BER-6-7	Richmond, RI		41.521	-71.640	High	Wood additions to create habitat complexity and increase use of side channels	
PAR-18	Charlestown, RI		41.443	-71.681	High	Log jams could be used to help reform meanders	
WOD-14-16	Exeter, RI		41.560	-71.714	Low	Improve already good habitat with additional wood to create log jams	

Table 3 (continued). Priority restoration sites by project type.

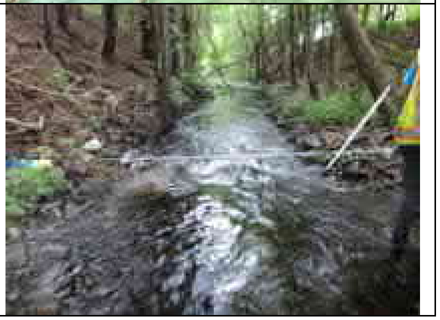
Reach	Town	Bridge/ Culvert Code	Location Lat.	RCPA Long.	Priority	Description	Photograph
MEB-8b	Richmond, RI		41.500	-71.667	Low	Reform meanders with wood additions along incised channel upstream of golf course running along the elementary school	
Removal or retrofitting of encroachment							
PAR-5	Westerly, RI		41.413	-71.832	High	Removal of right bank berm from past gravel mining to increase floodplain access at the upstream end of reach	
SHUN-10b	North Stonington, CT		41.462	-71.908	Low	Berm removal to lower flood stages downstream of the bridge and to keep flow off of steep hillslope on left bank that could become stabilized	

Table 3 (continued). Priority restoration sites by project type.

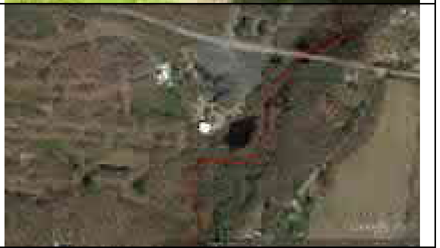
Reach	Town	Bridge/ Culvert Code	Location Lat.	RCPA Long.	Priority	Description	Photograph
PAR-12	Westerly, RI		41.403	-71.760	Low	Ponds downstream of Bradford mill complex should be moved further away from stream to remove avulsion hazard and increase floodplain width	
BER-2	Richmond, RI		41.478	-71.624	Low	Pond takes lots of water out of stream, potential avulsion risk	
CHIP-8	Exeter, RI		41.517	-71.526	Low	Pond/berm that could be breached to increase floodplain access	
PAR-15	Charlestown, RI		41.411	-71.726	Low	Artificial floodplain constriction that could be alleviated with flood relief culverts, development present upstream	

Table 3 (continued). Priority restoration sites by project type.

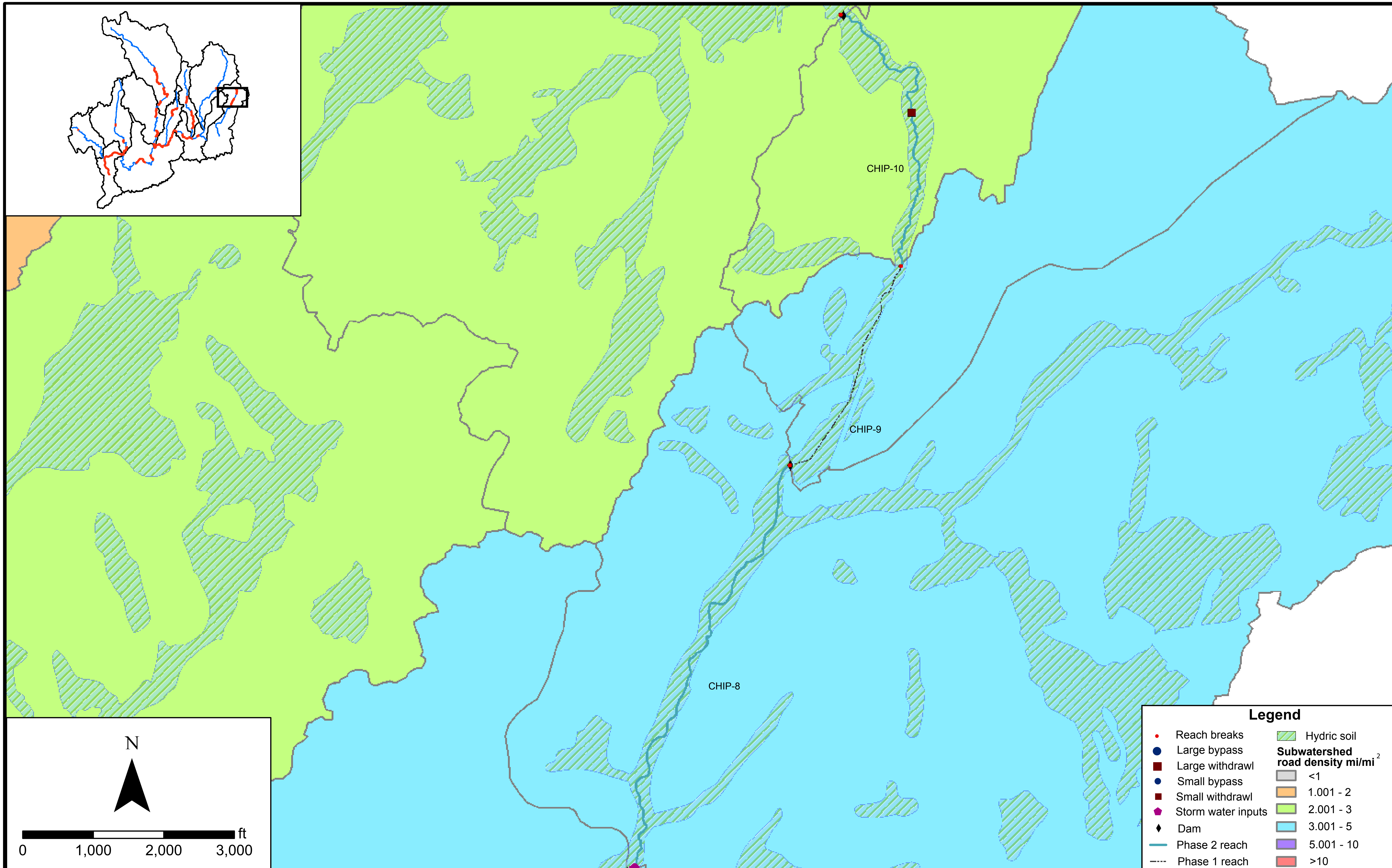
Reach	Town	Bridge/ Culvert Code	Location Lat.	RCPA Long.	Priority	Description	Photograph
Riparian buffer planting							
WOR-9	Hopkinton, RI		41.511	-71.708	High	Replant of buffer on right bank	
CHIP-10	North Kingstown, RI		41.536	-71.517	High	Encourage buffer planting along the left bank where residences abut the channel	
PAR-23	Charlestown, RI		41.452	-71.651	High	Encourage planting of woody vegetation at residential river frontages	

Table 3 (continued). Priority restoration sites by project type.

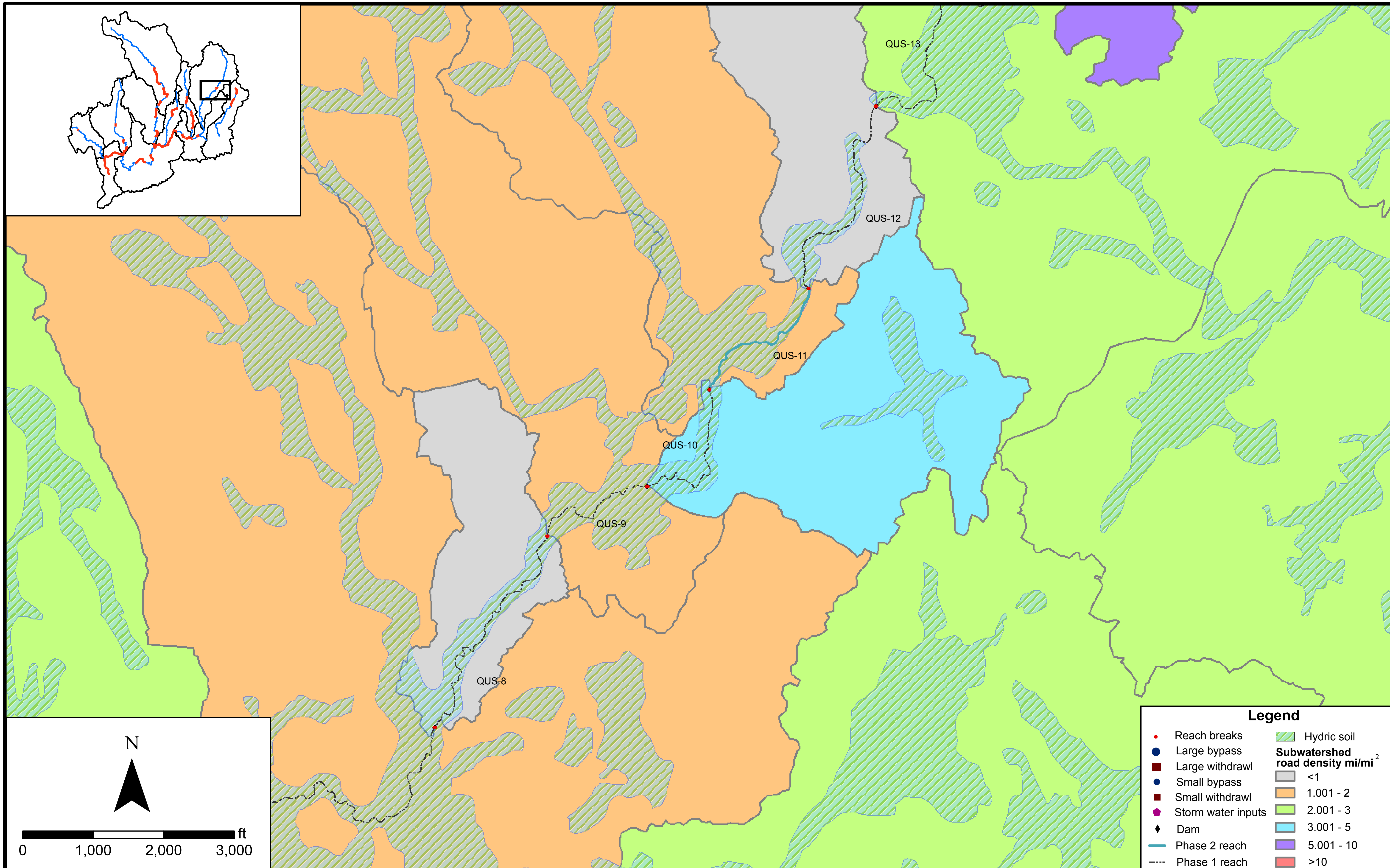
Reach	Town	Bridge/ Culvert Code	Location Lat.	RCPA Long.	Priority	Description	Photograph
MEB-8B	Richmond, RI		41.504	-71.664	High	Turn the series of ponds and garbage at Meadow Brook Golf Course into a more distinct stream channel	
PAR-3	Westerly, RI		41.402	-71.842	High	Gravel pit/ concrete business on the right bank, bank without buffer has suffered some erosion	

APPENDIX 1

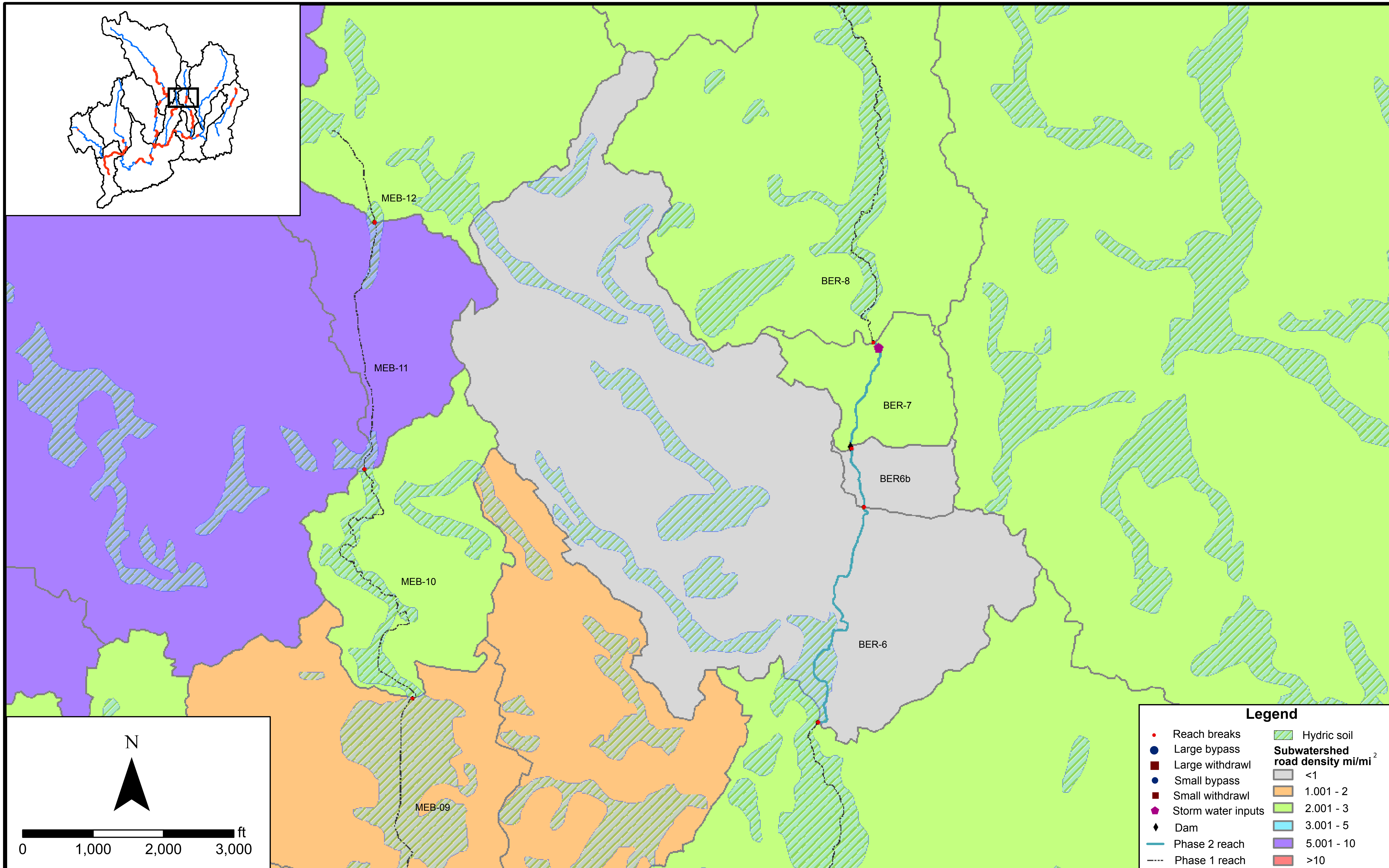
(Stressor and departure maps)



Appendix 1. Hydrologic alterations map.



Appendix 1. Hydrologic alterations map.



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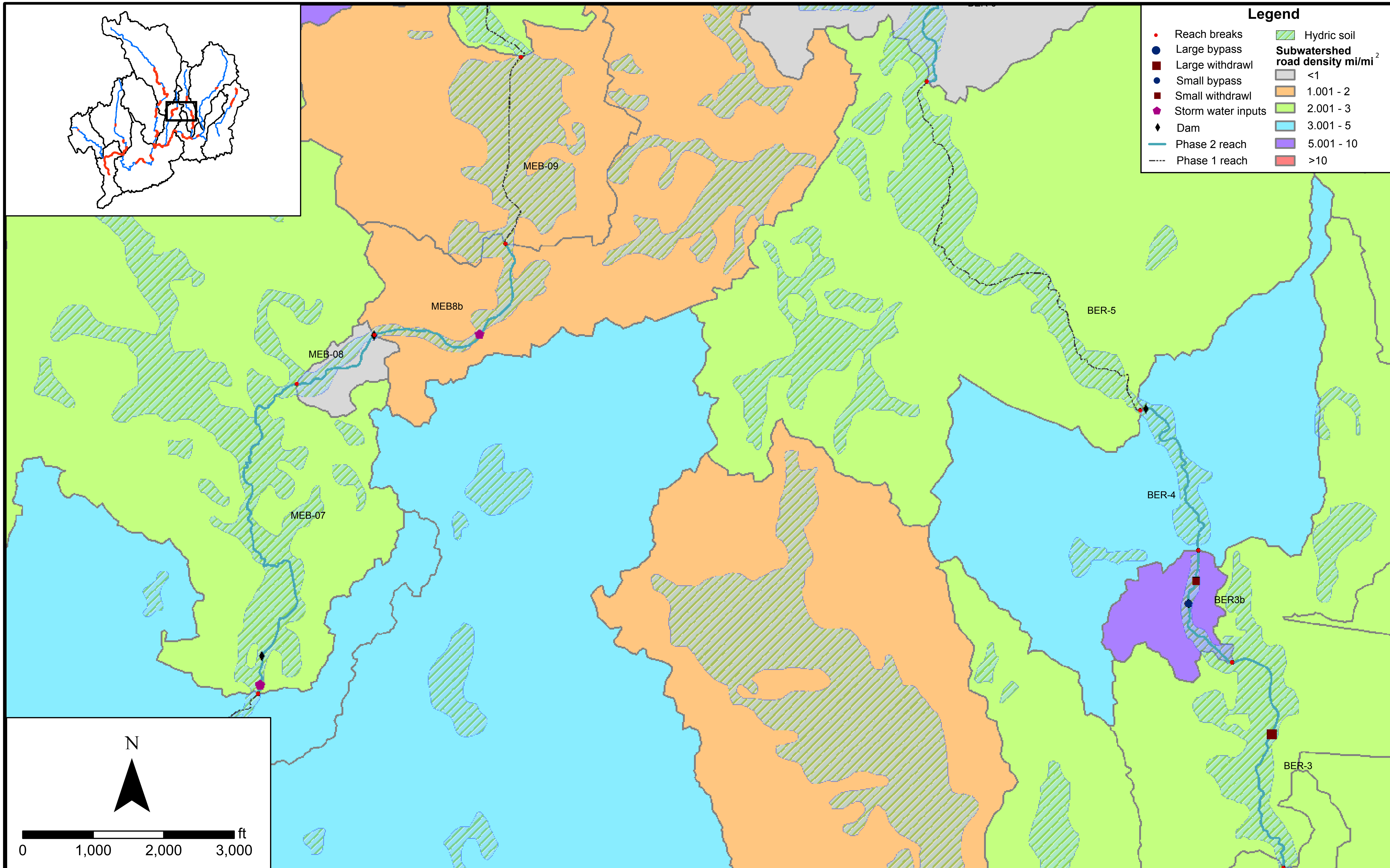

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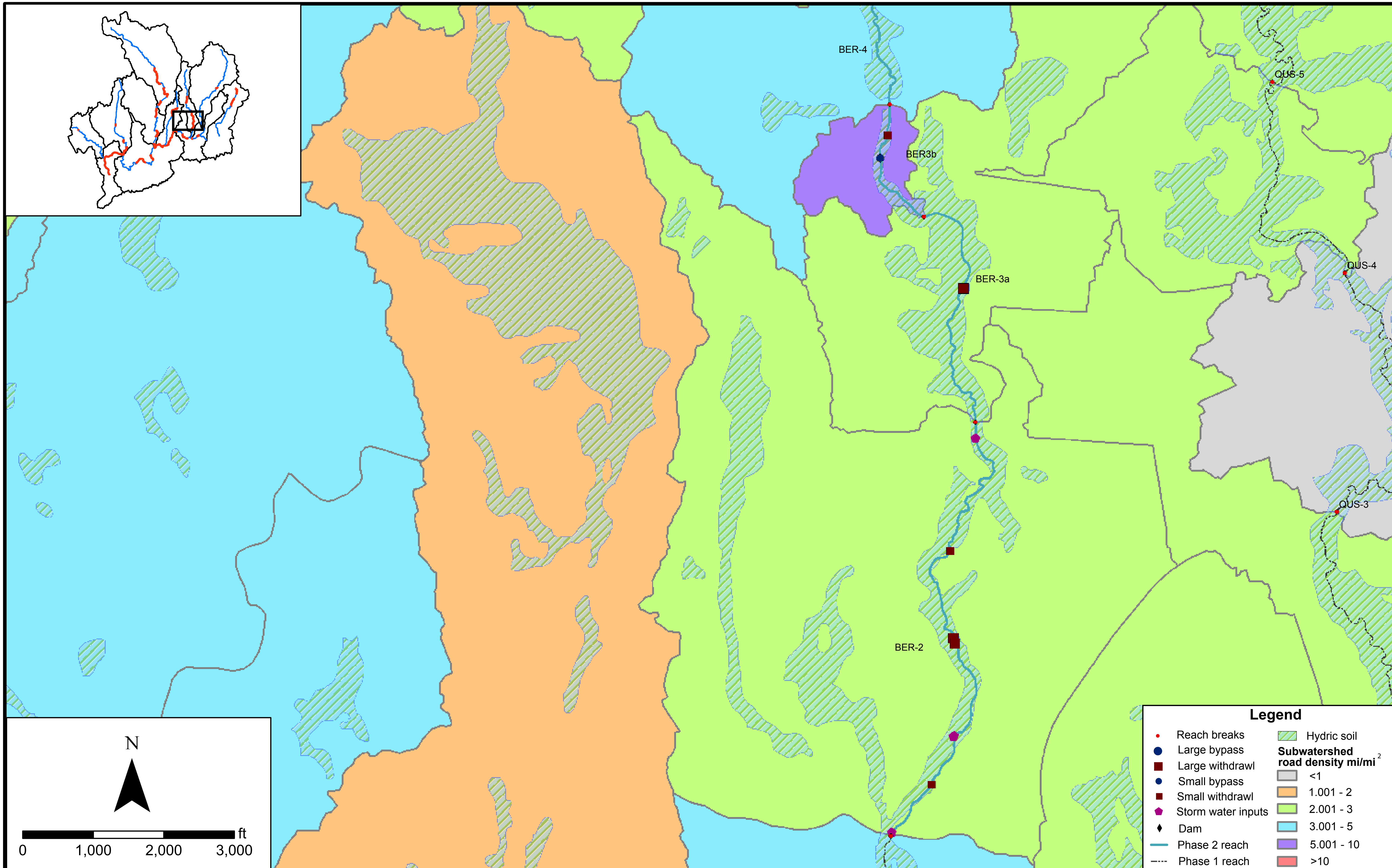

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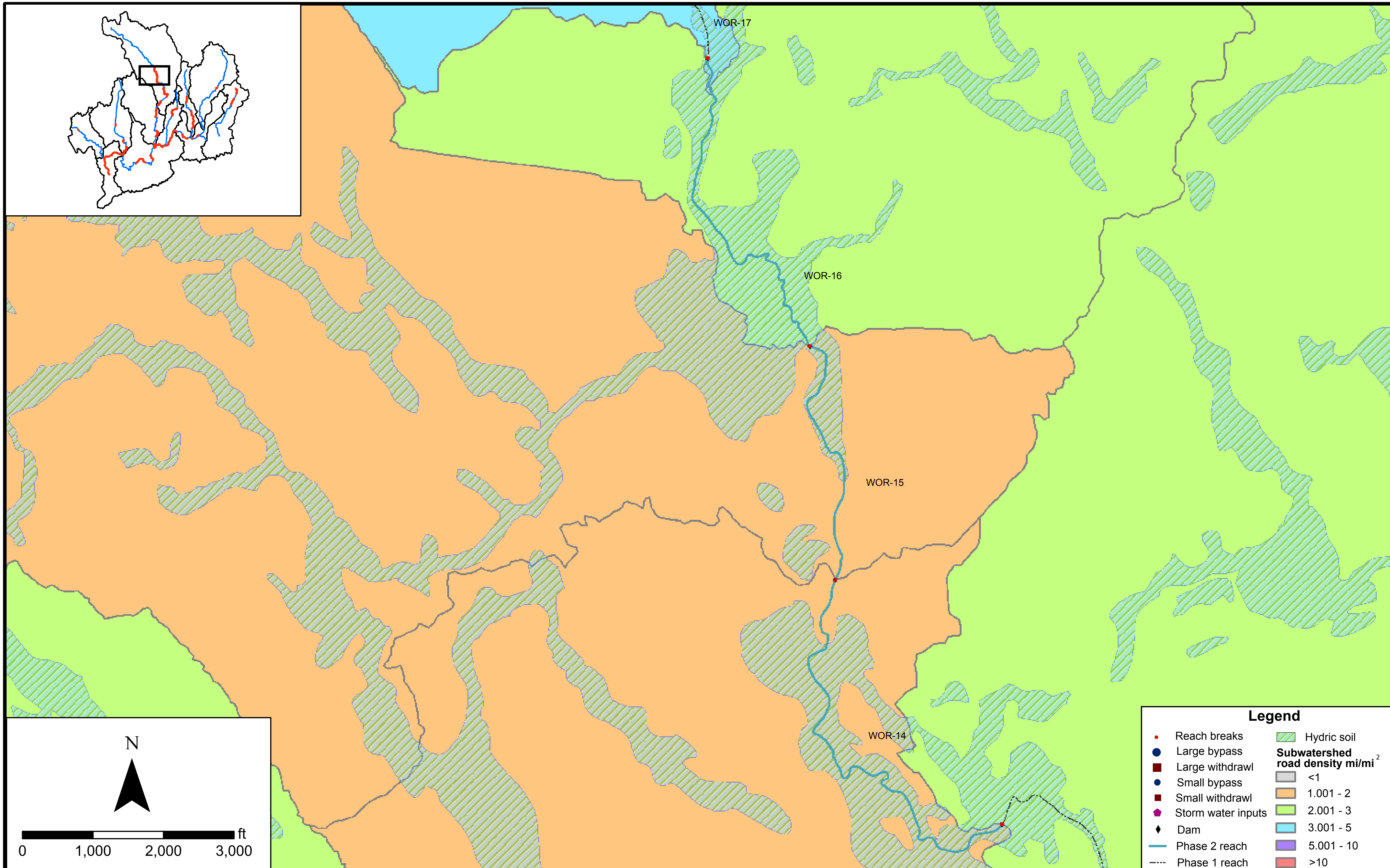

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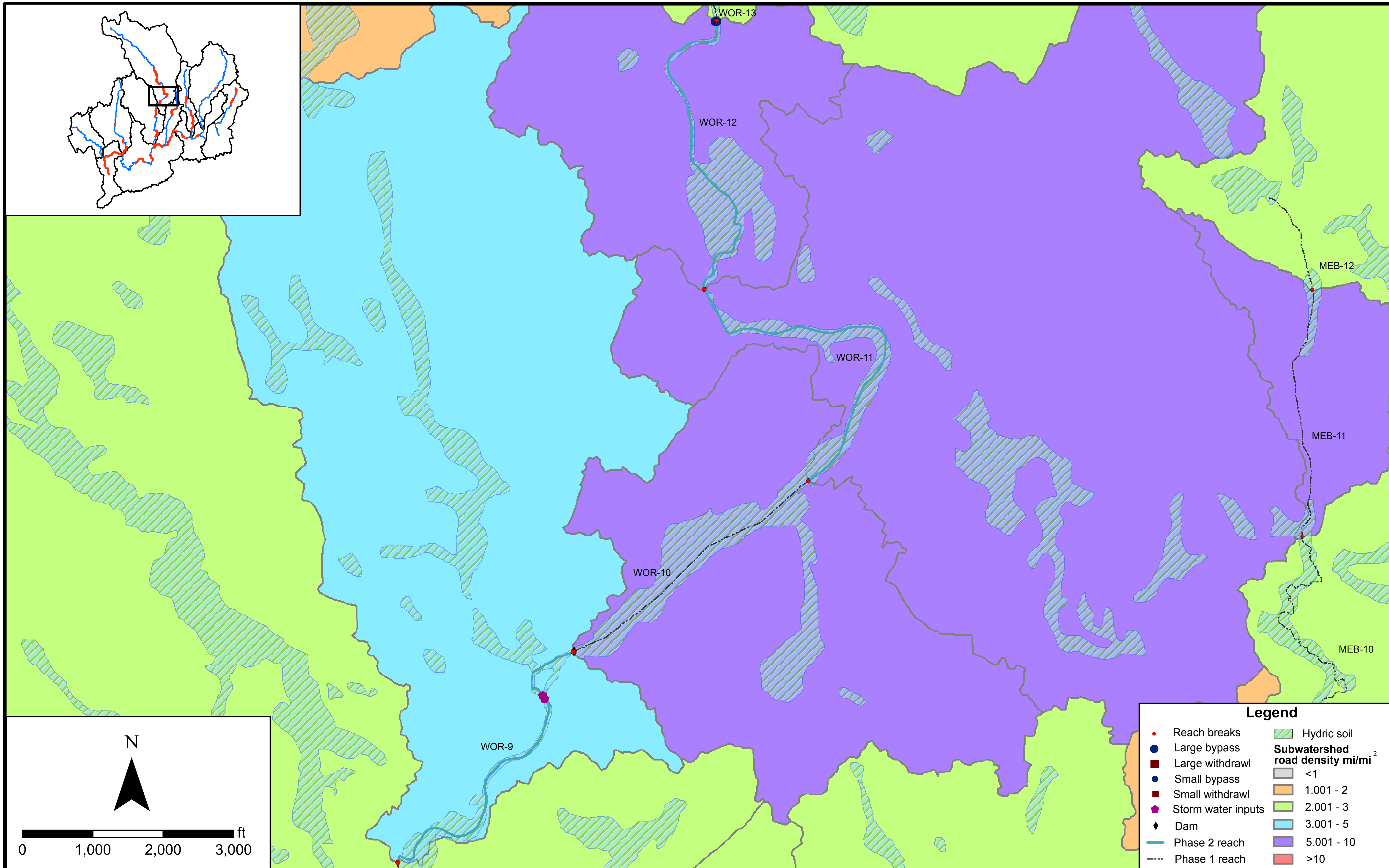

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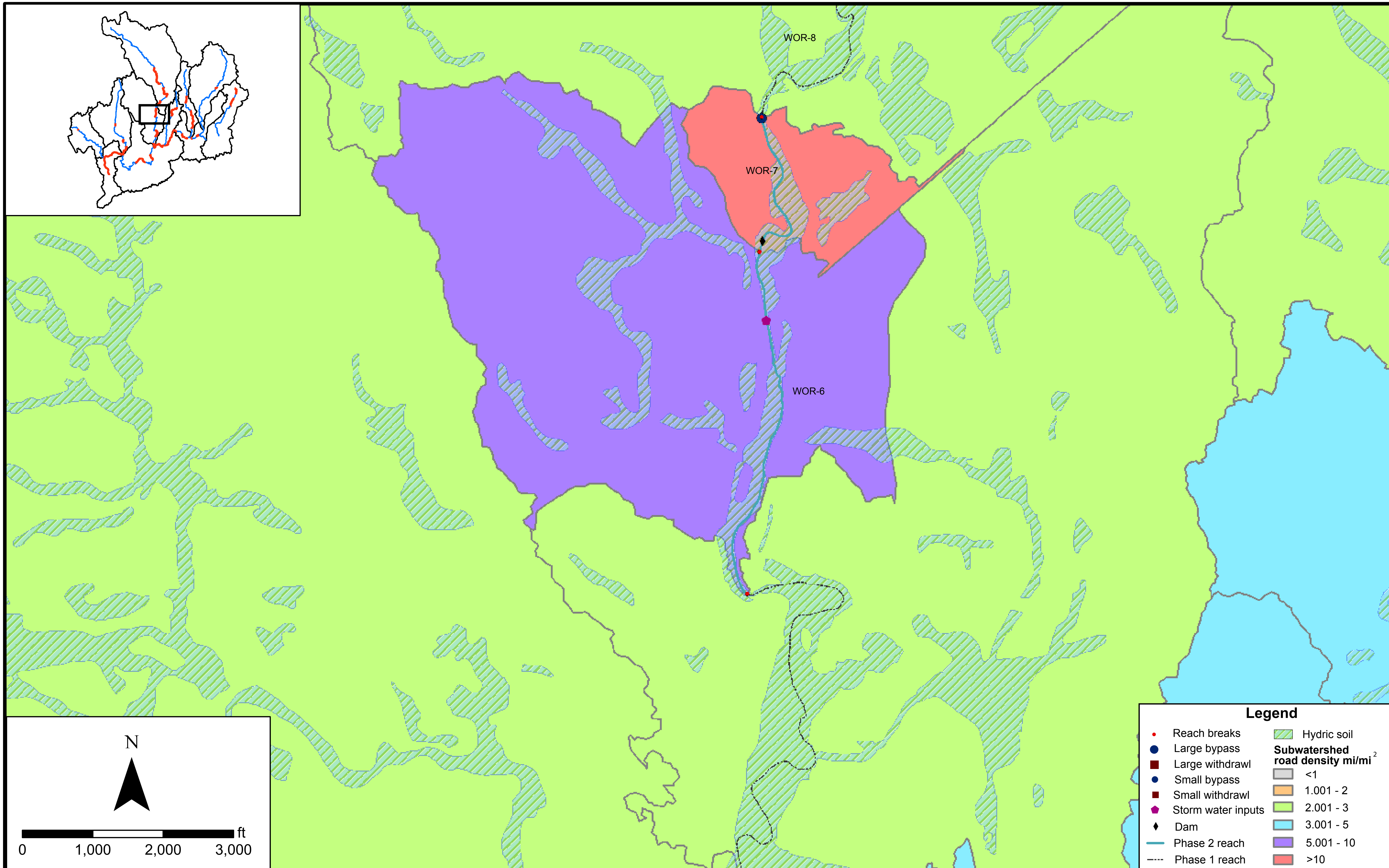

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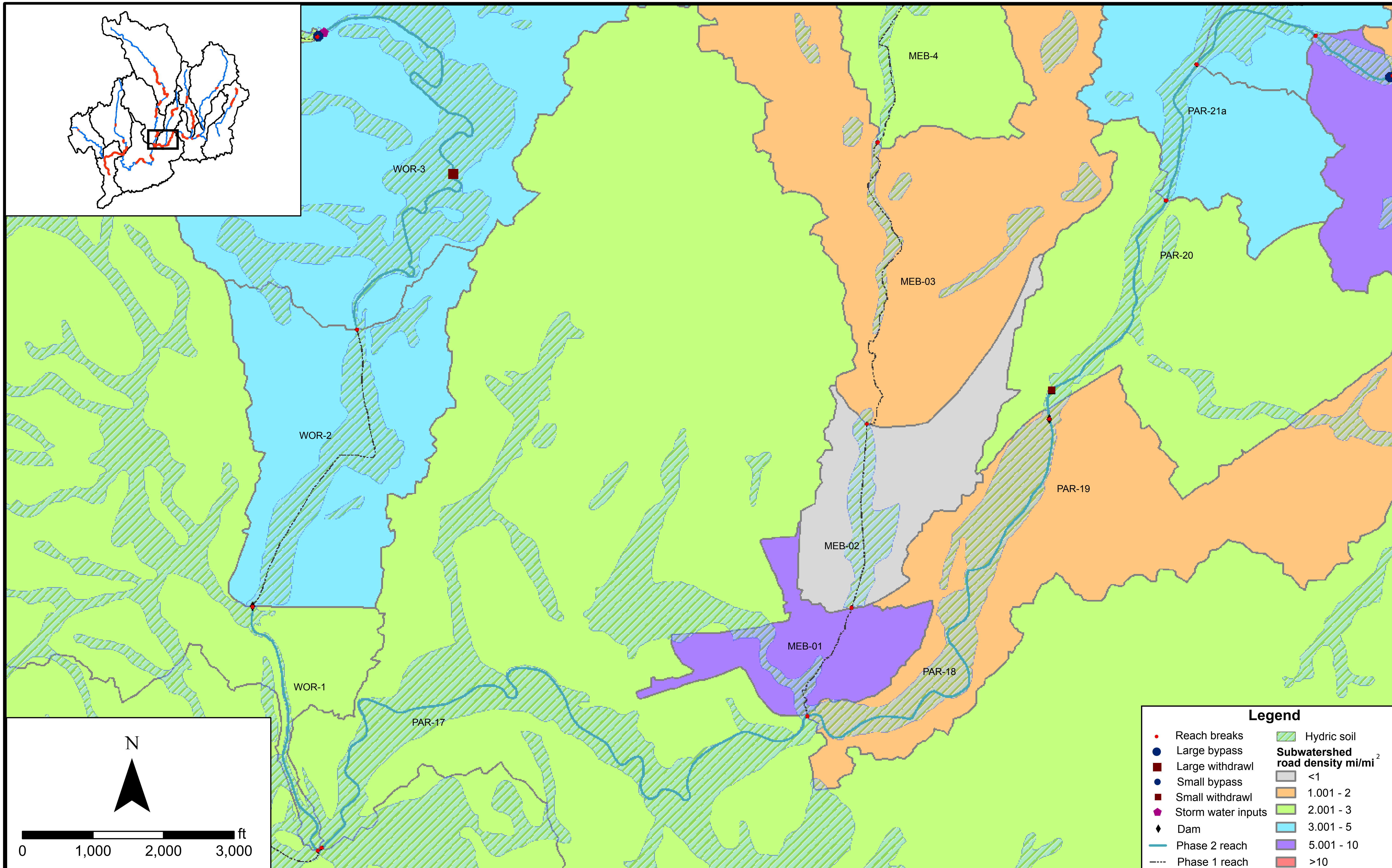

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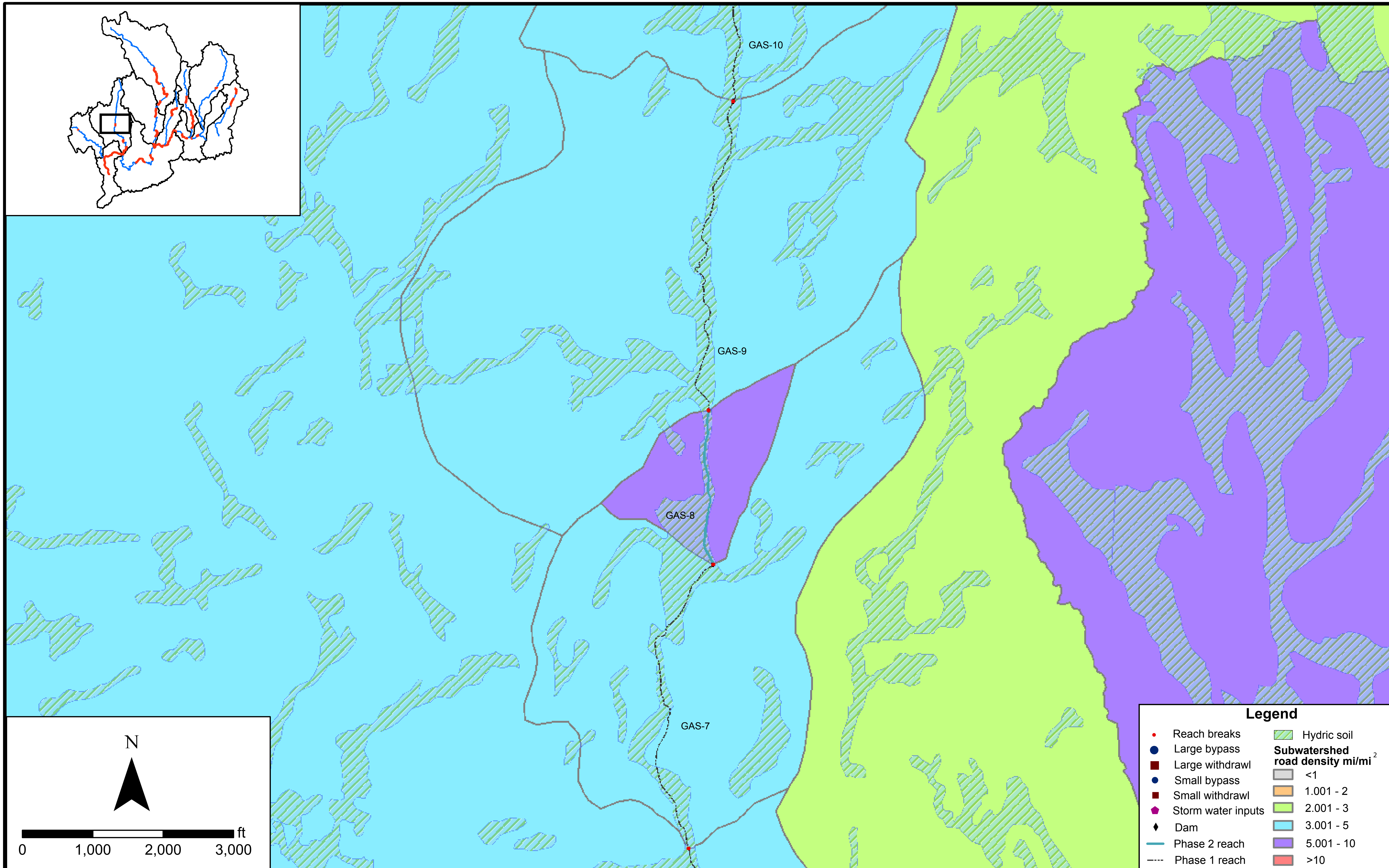

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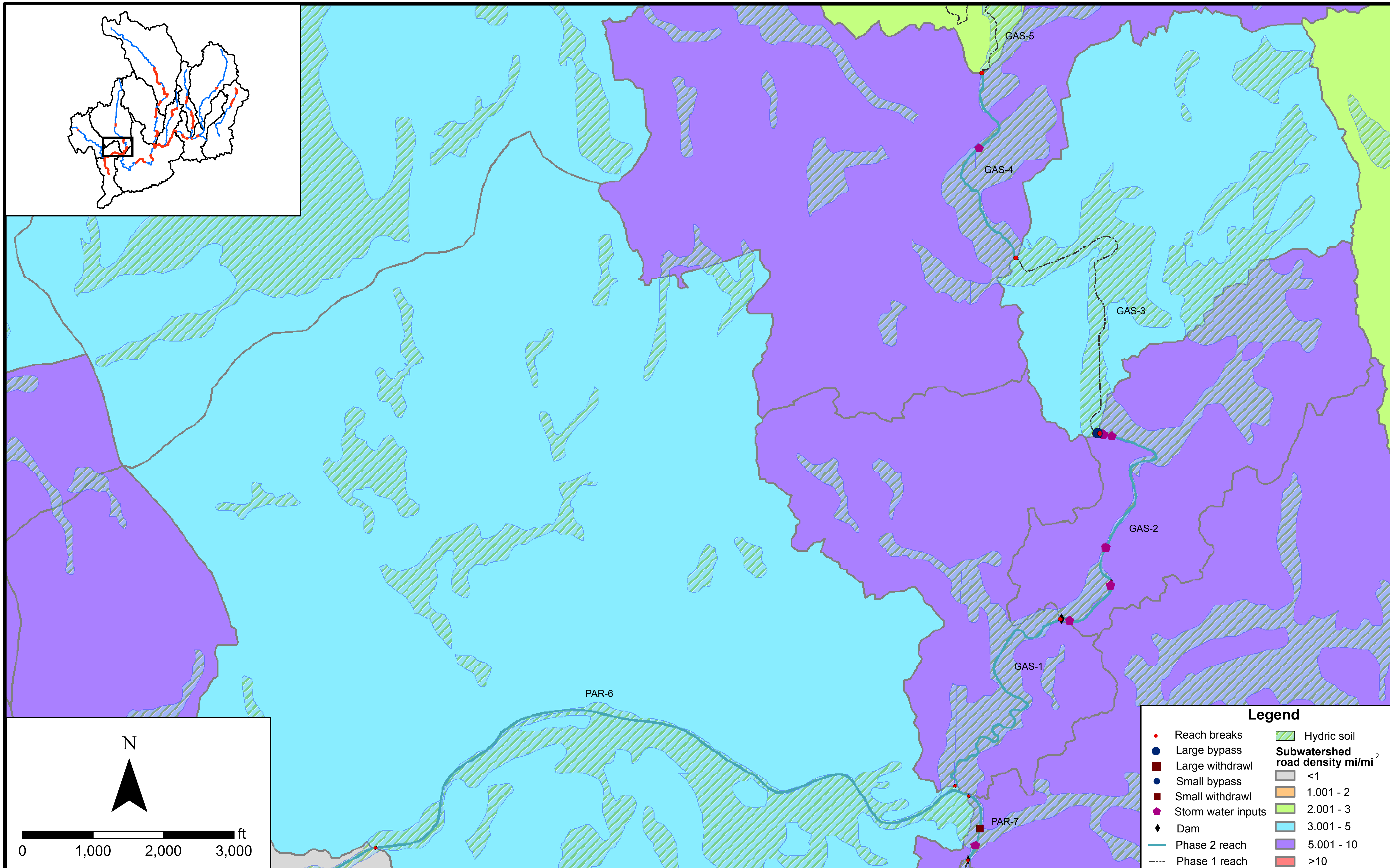

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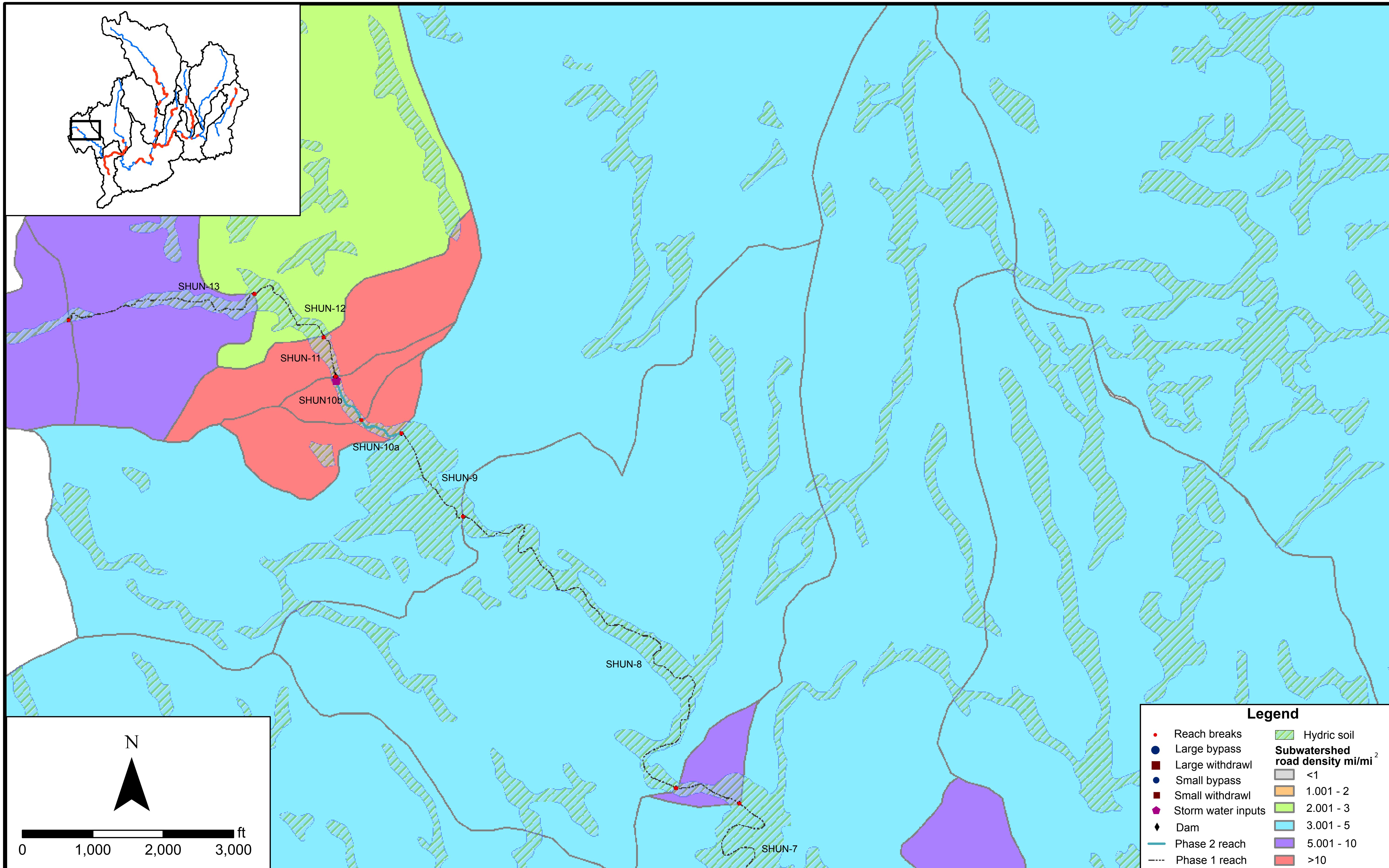

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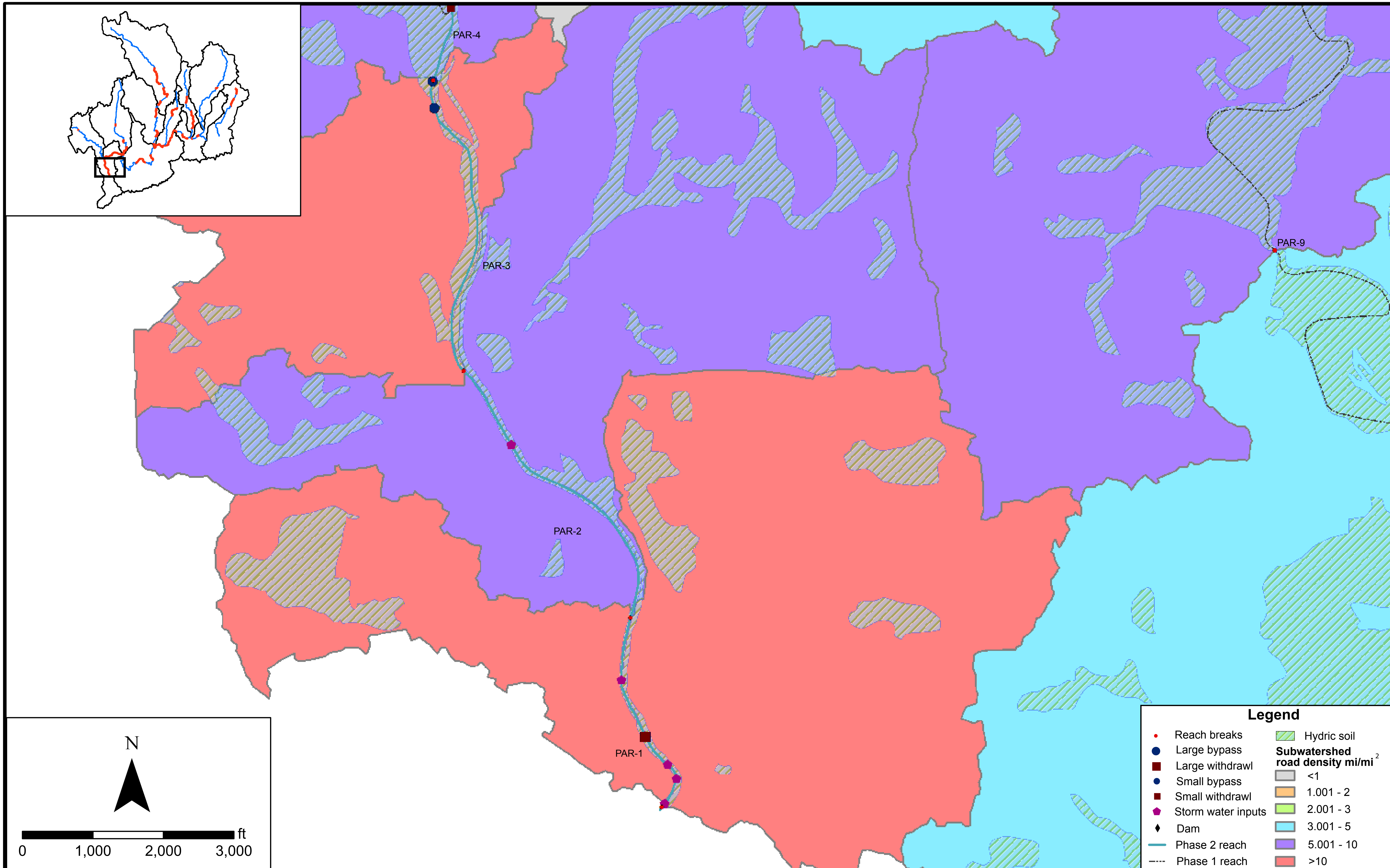

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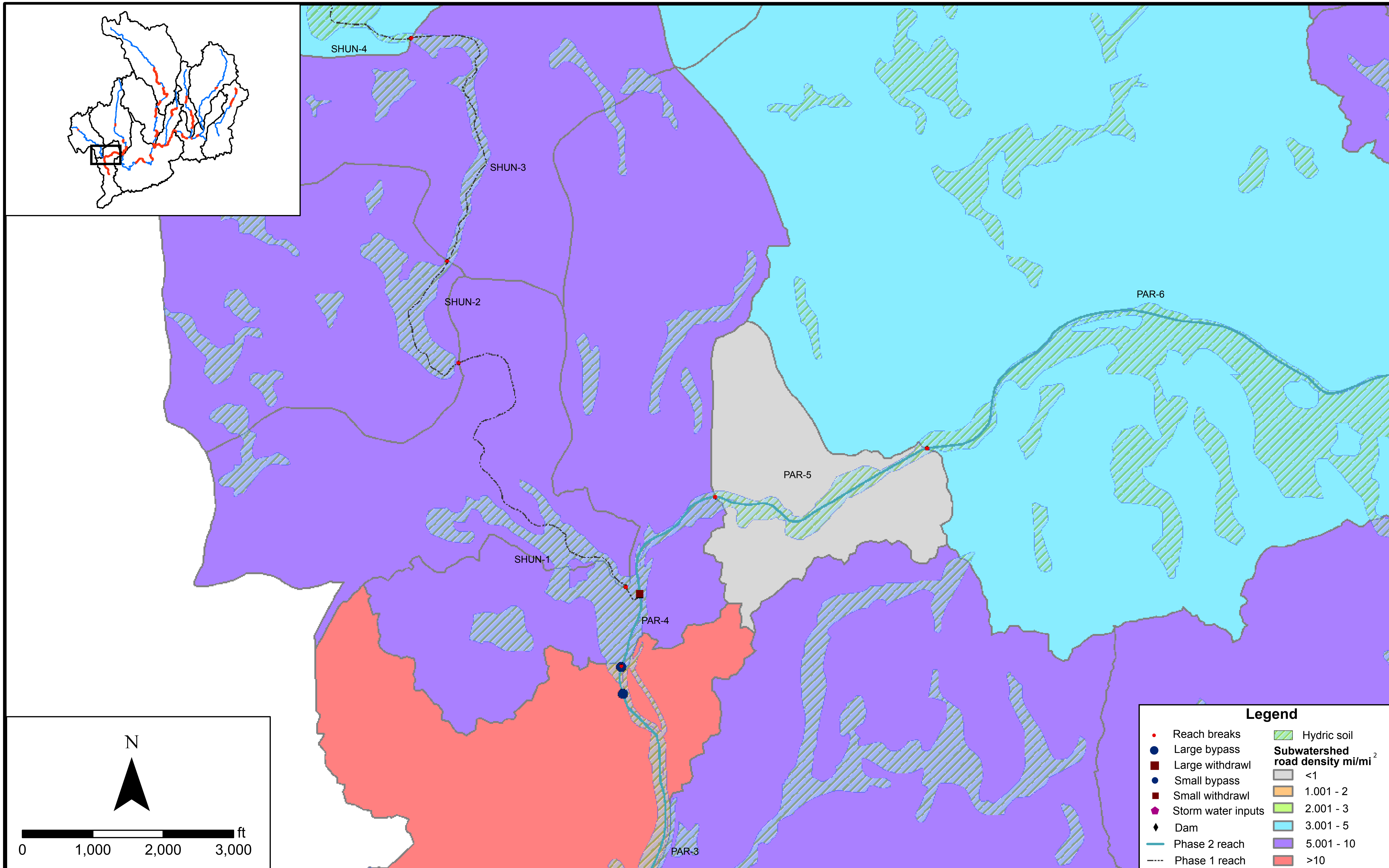

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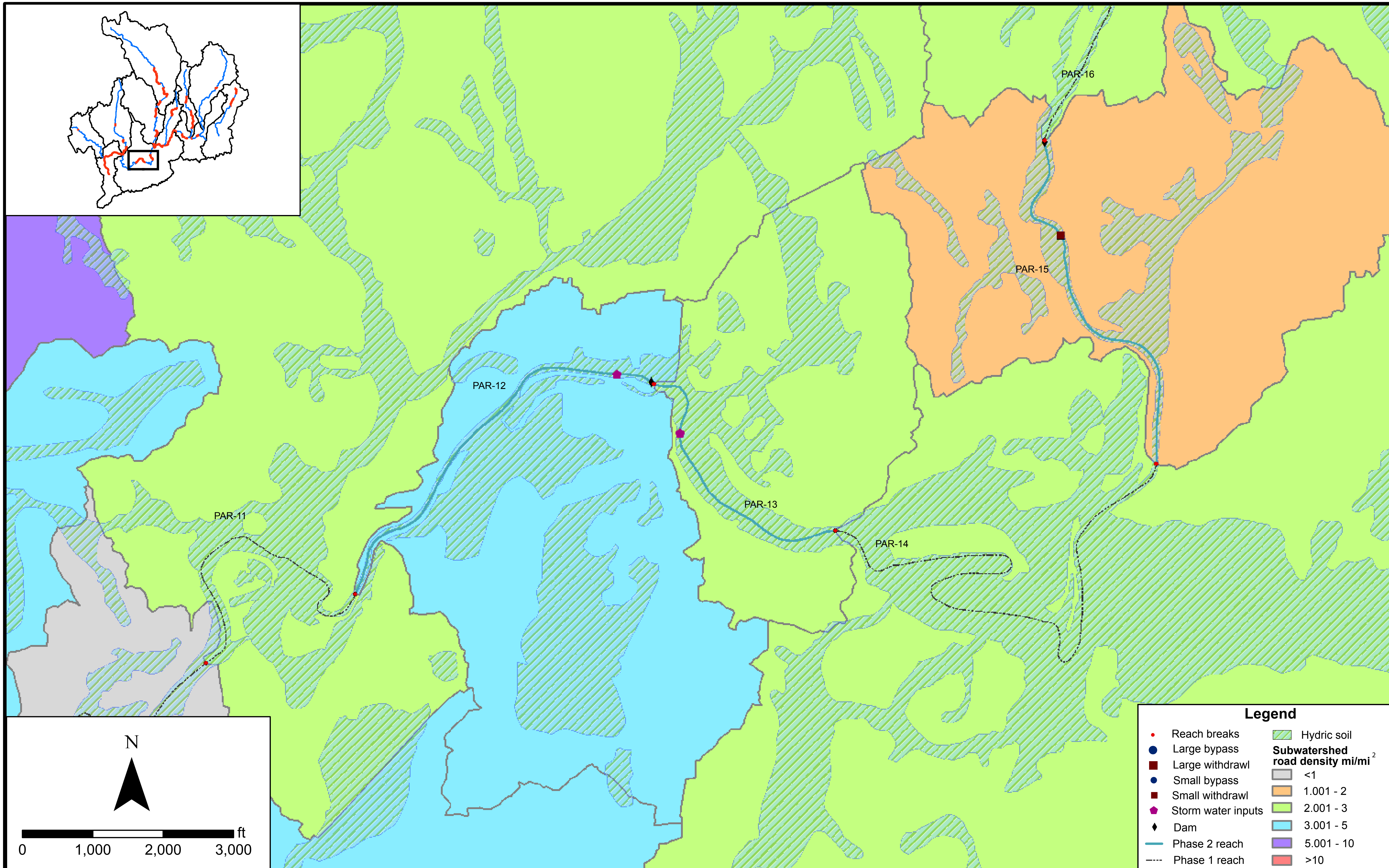

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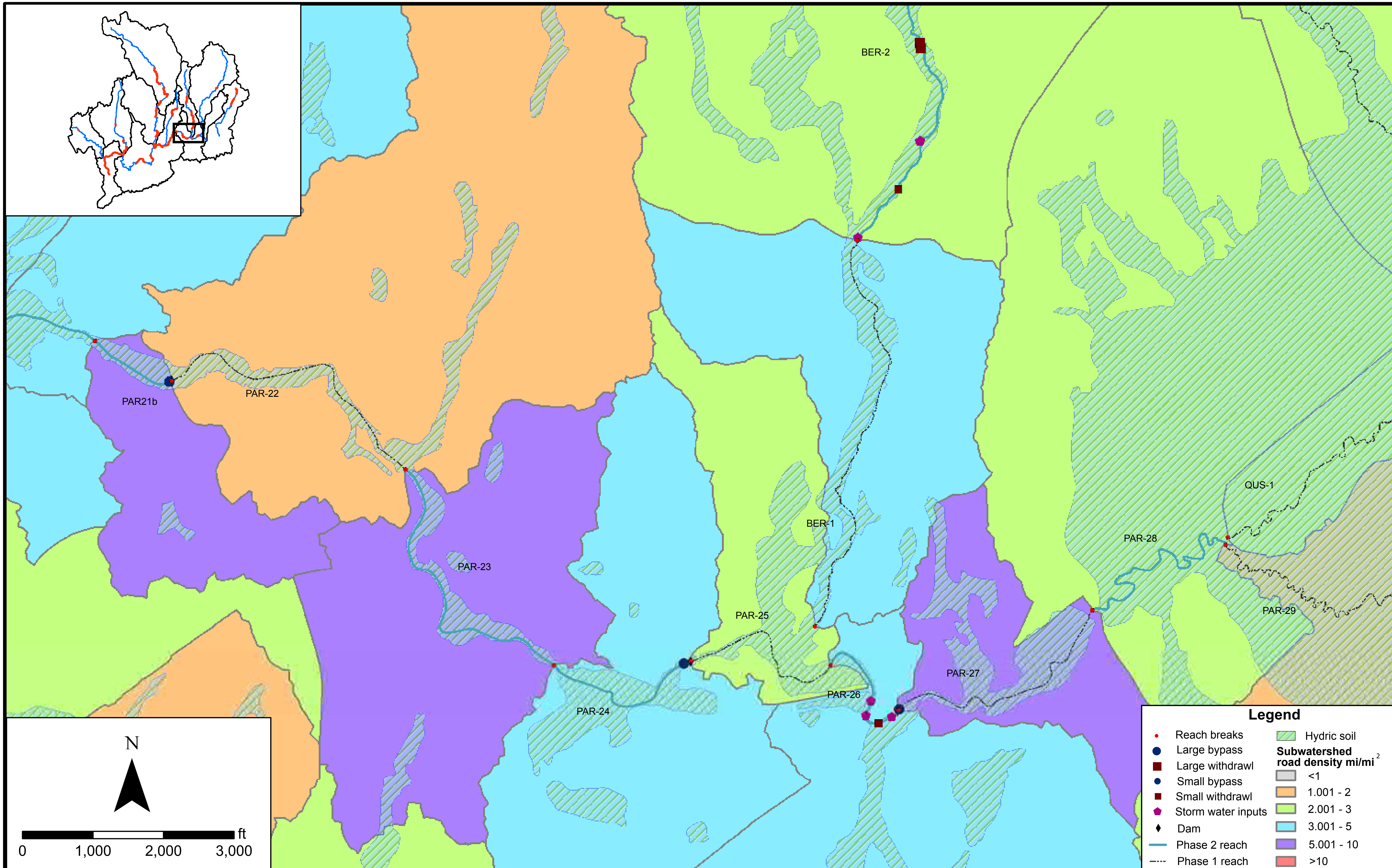

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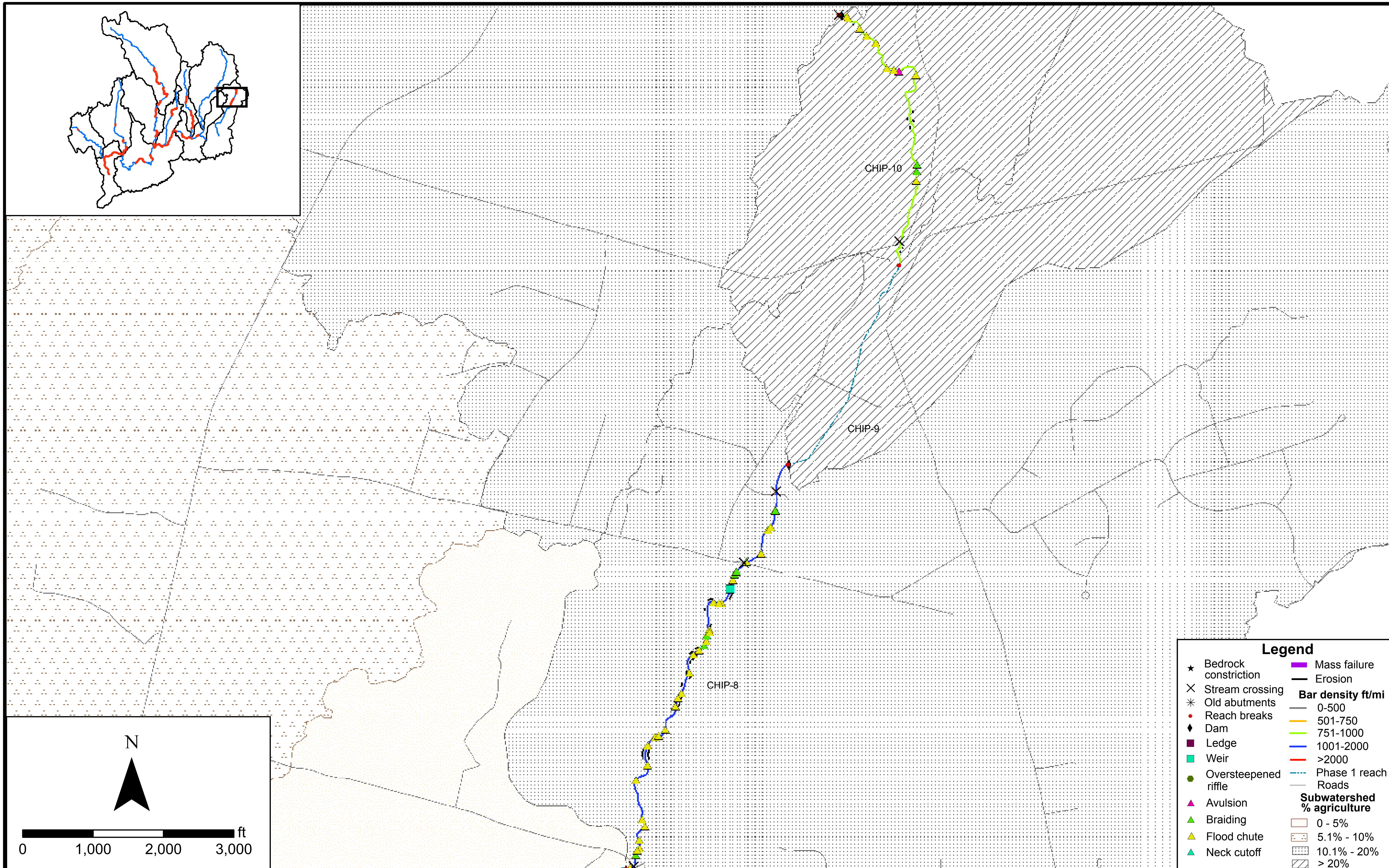
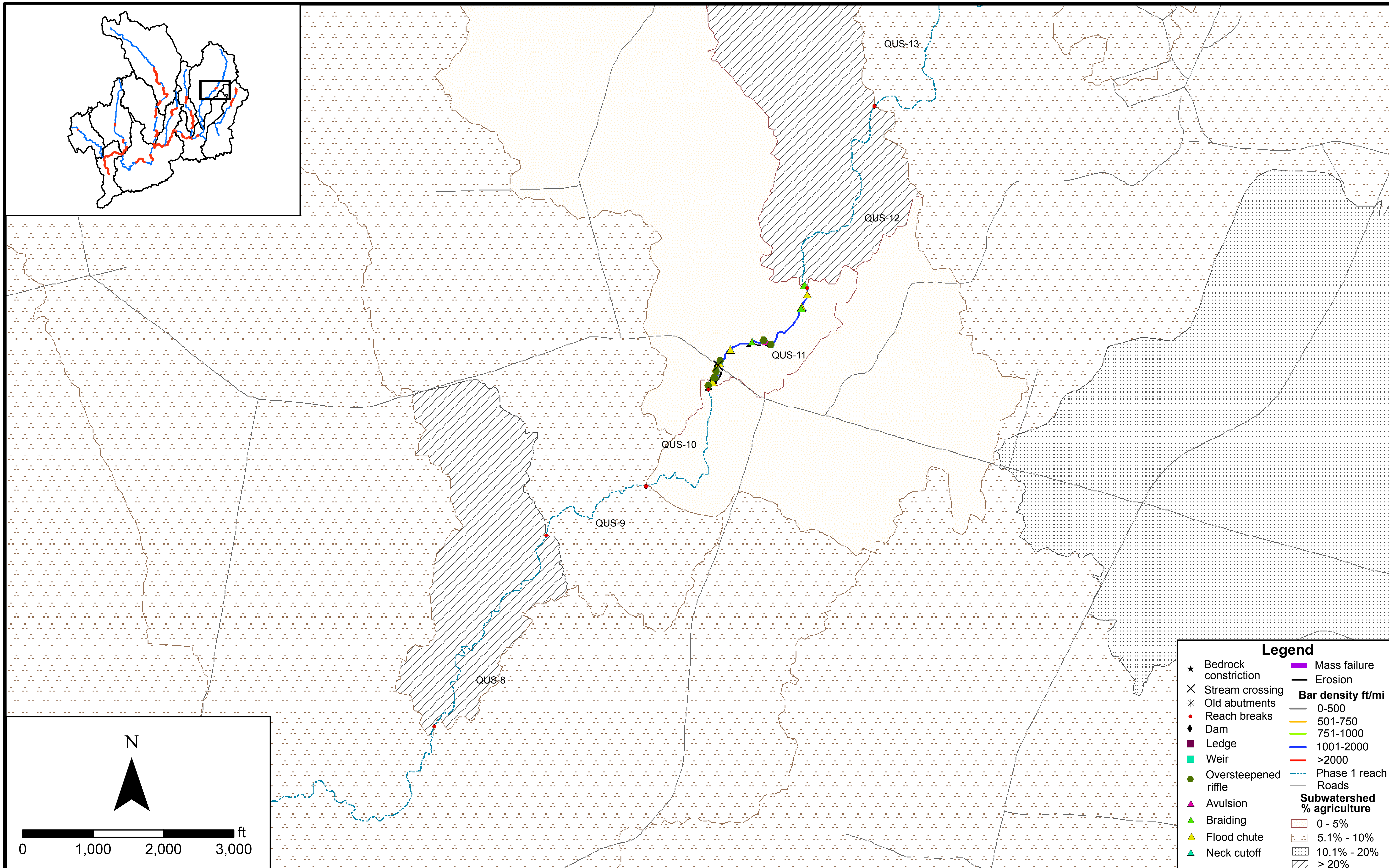


Appendix 1. Sediment stressor map.



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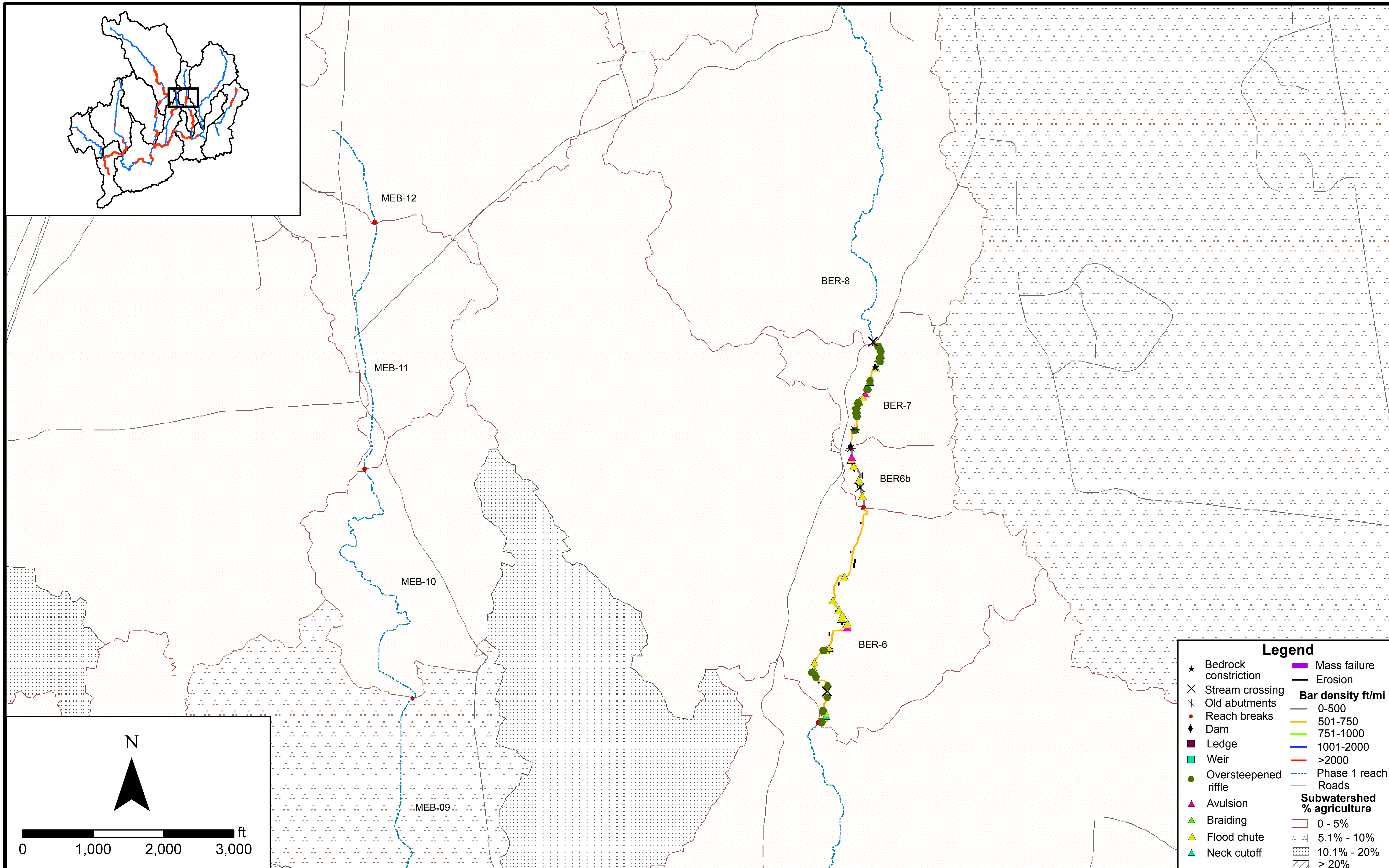

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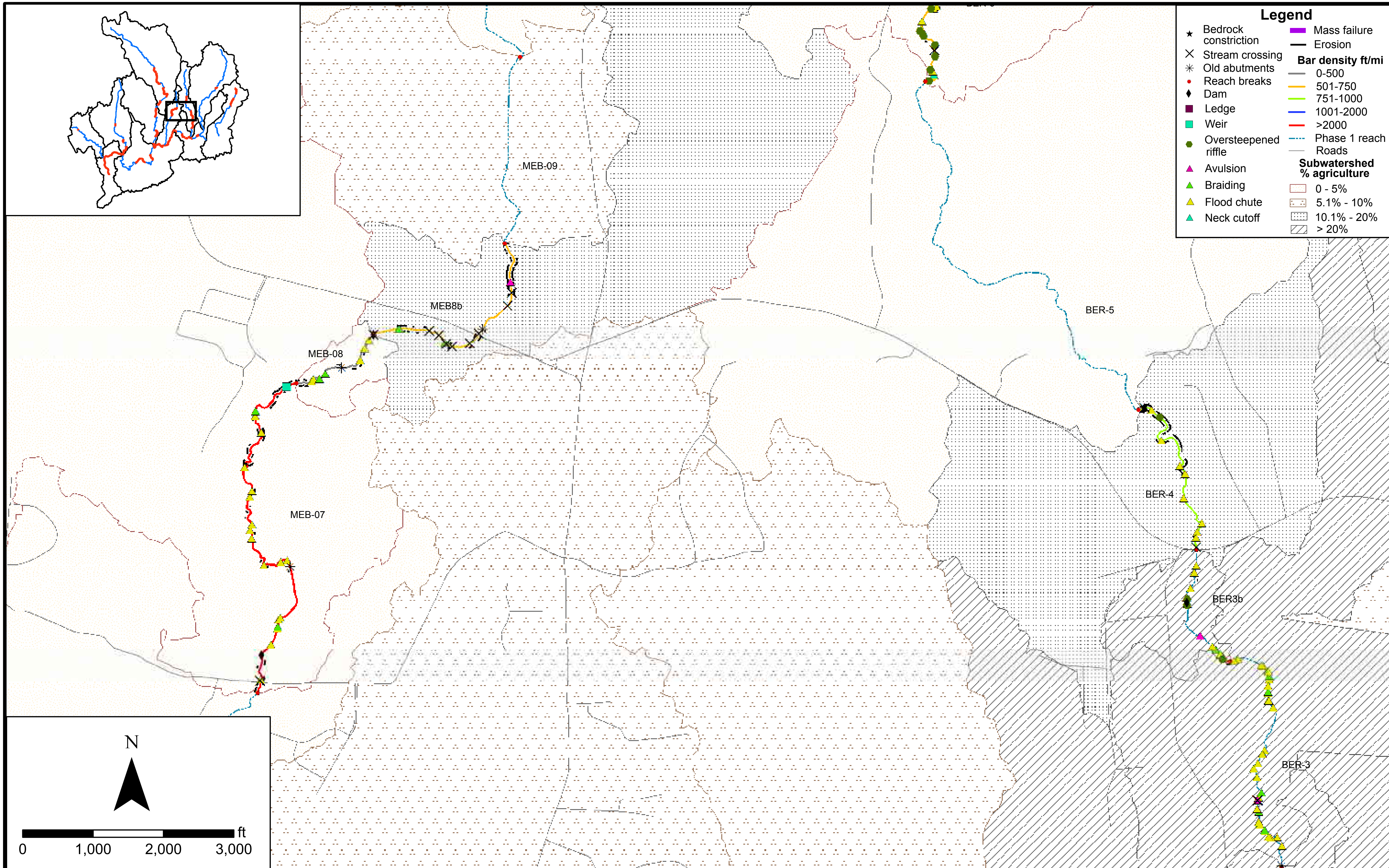

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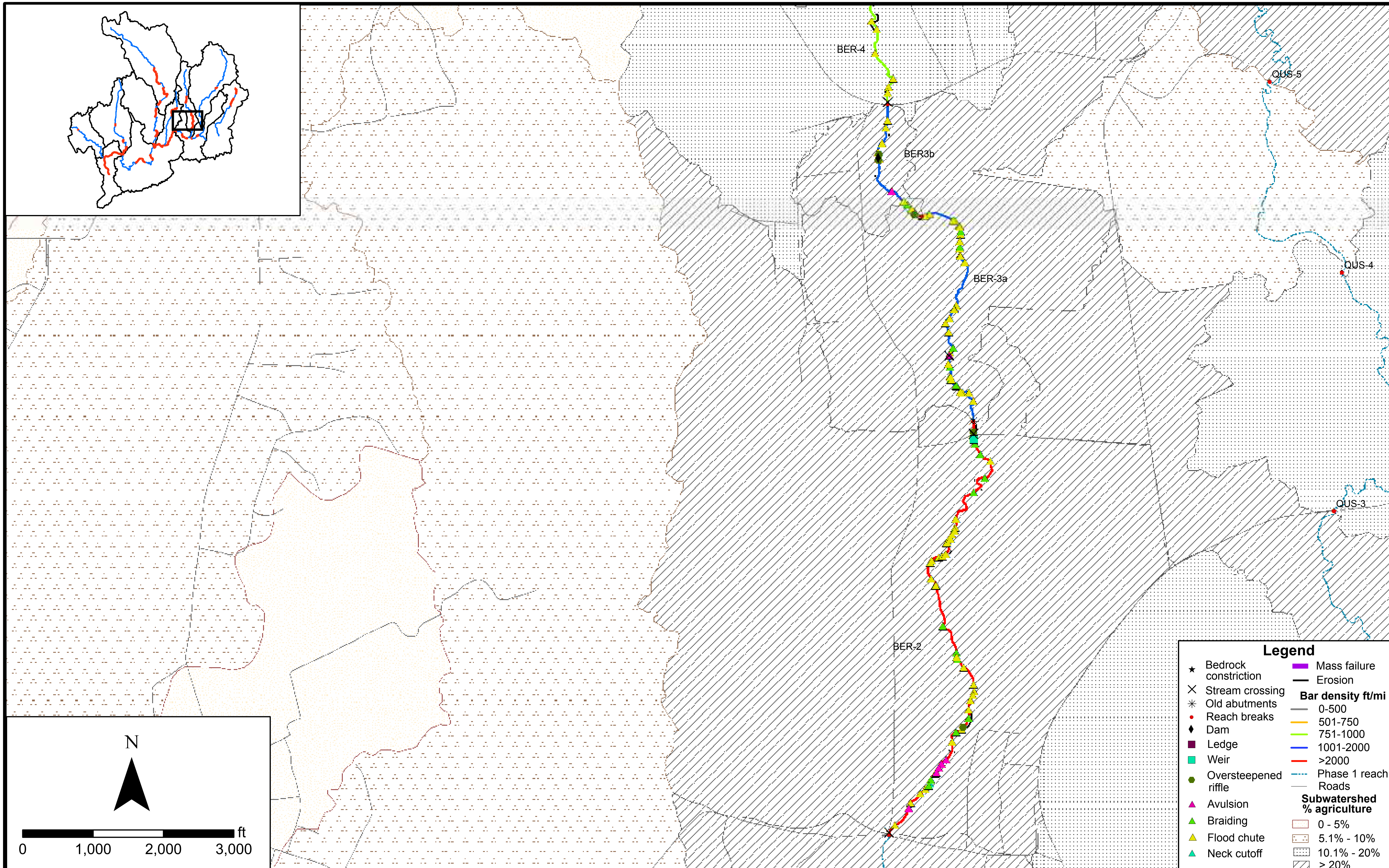

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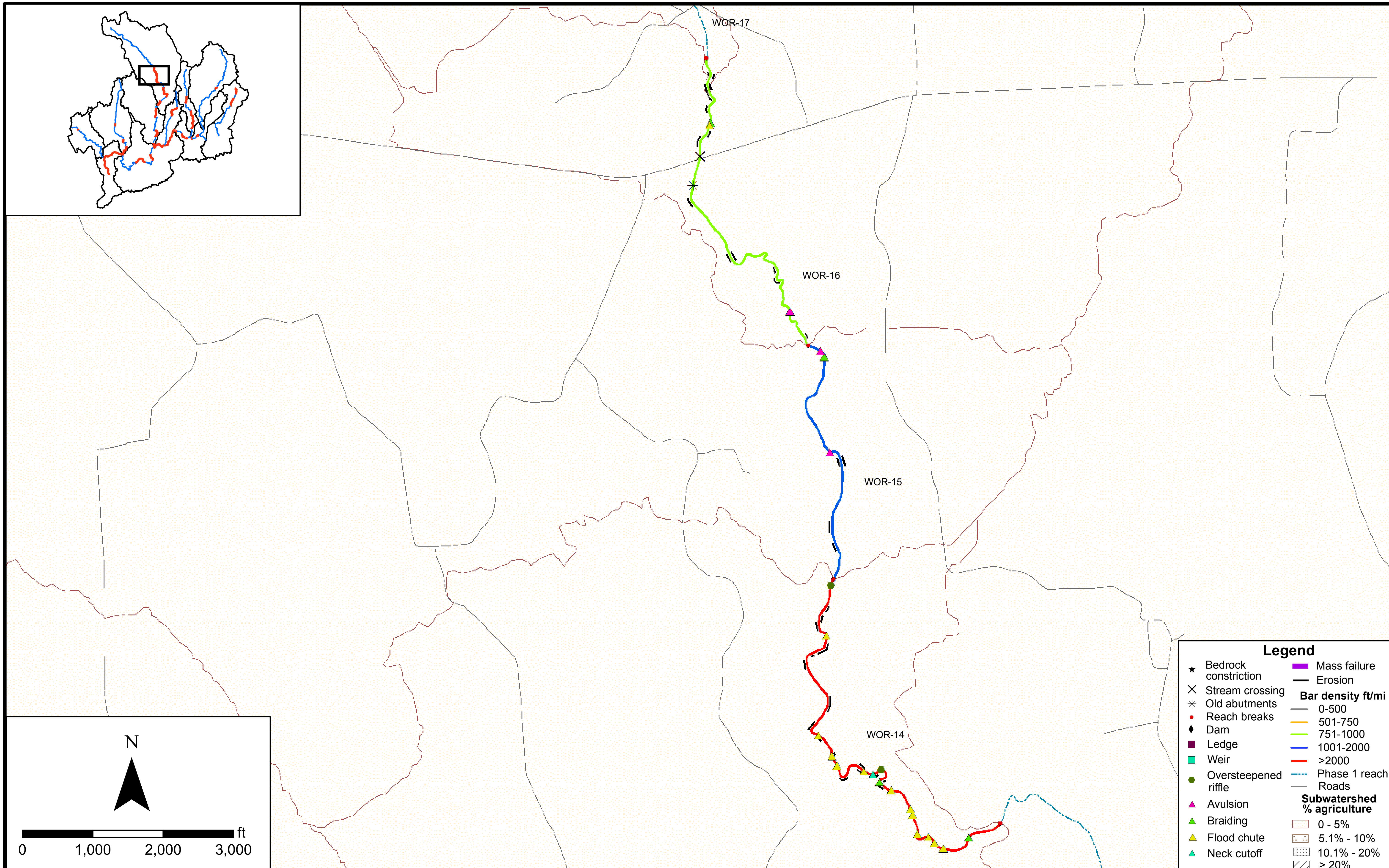

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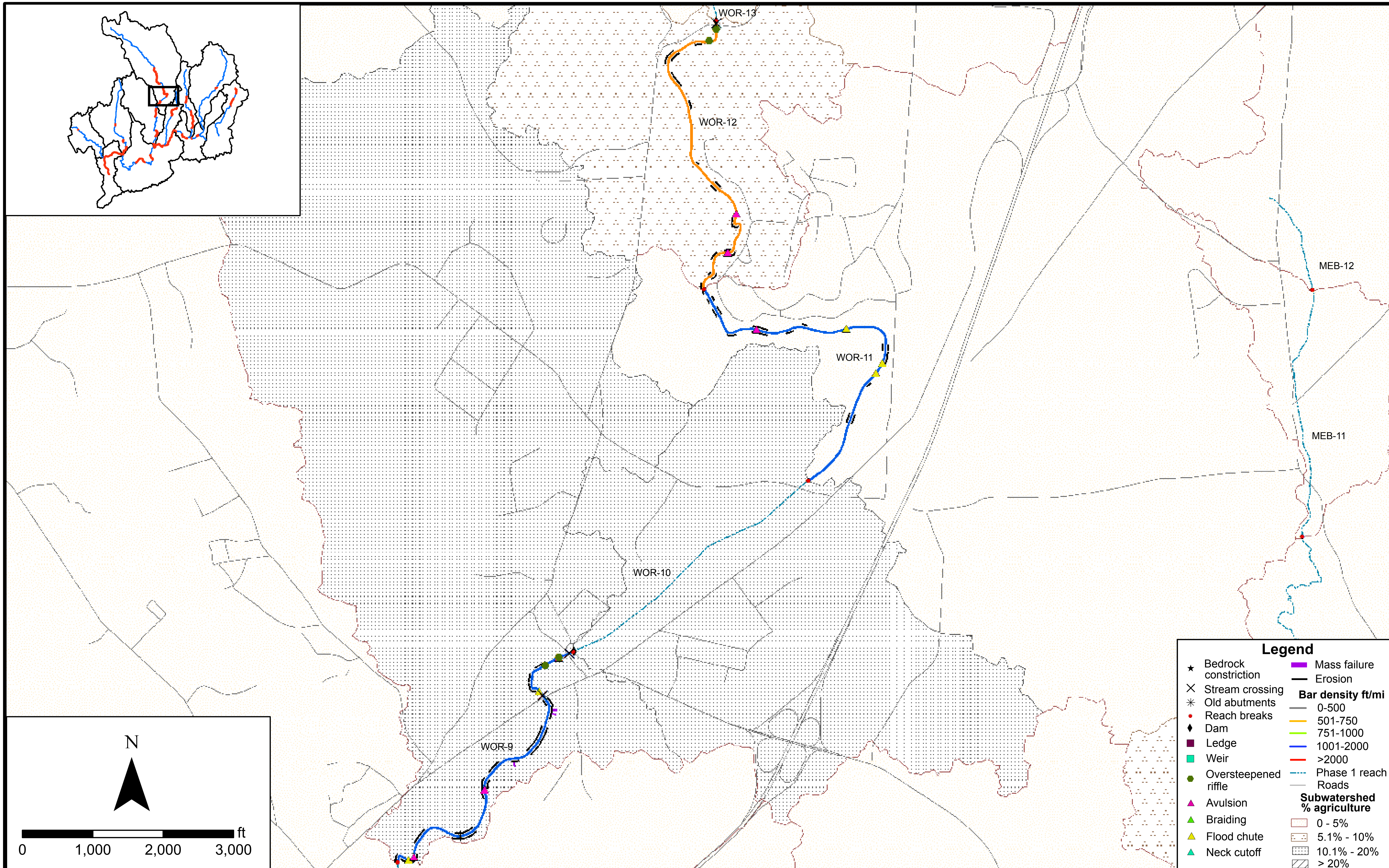

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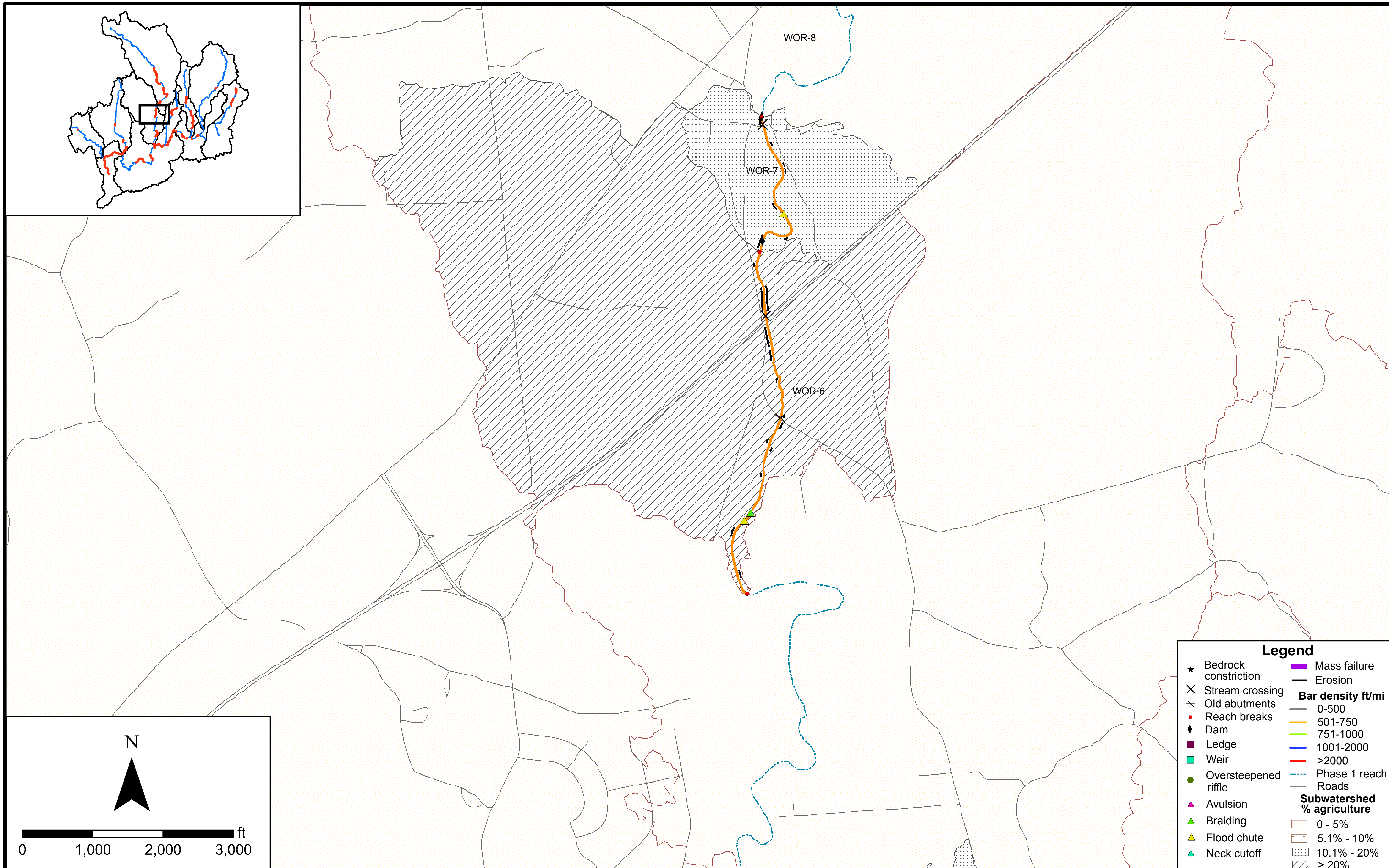

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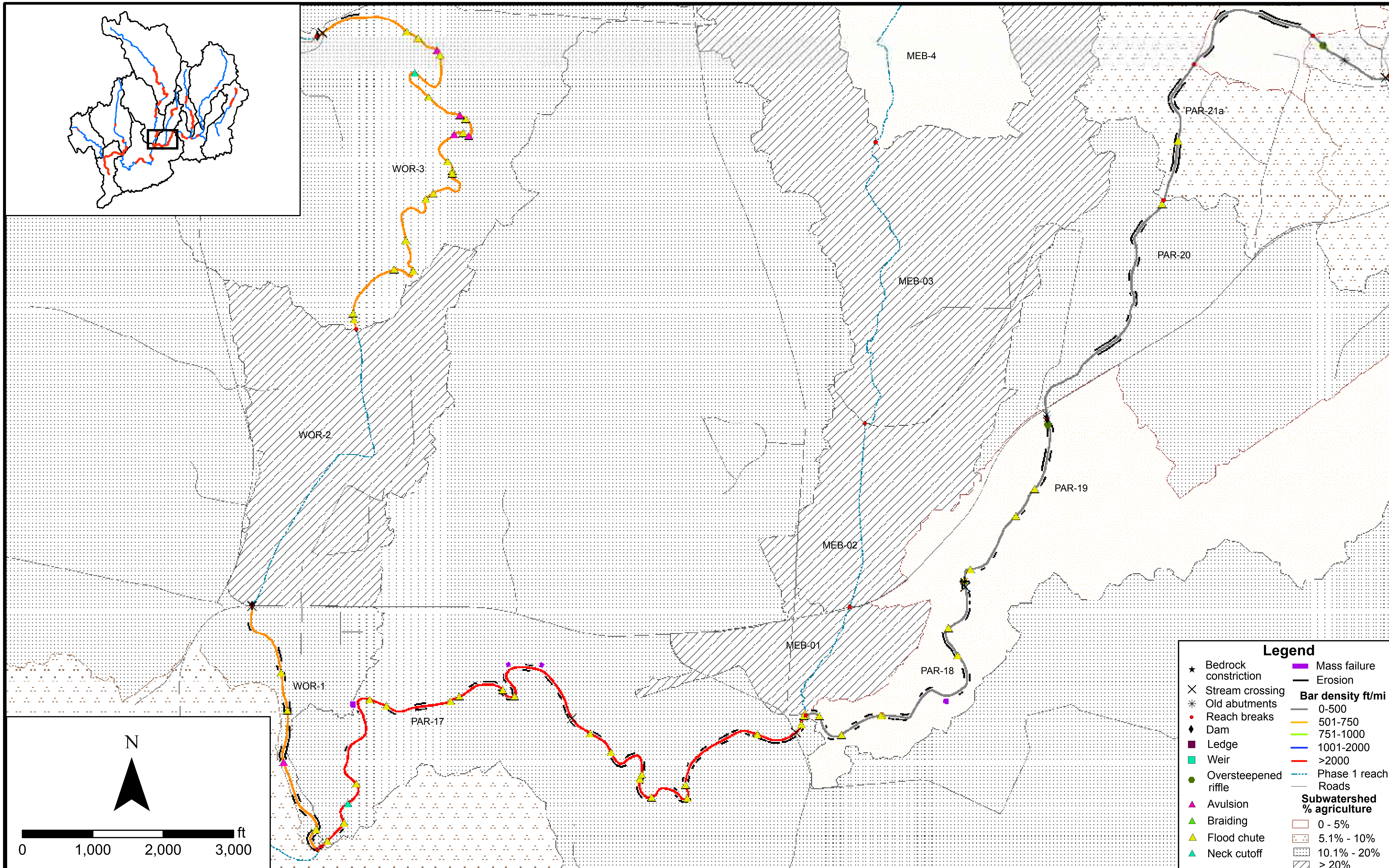

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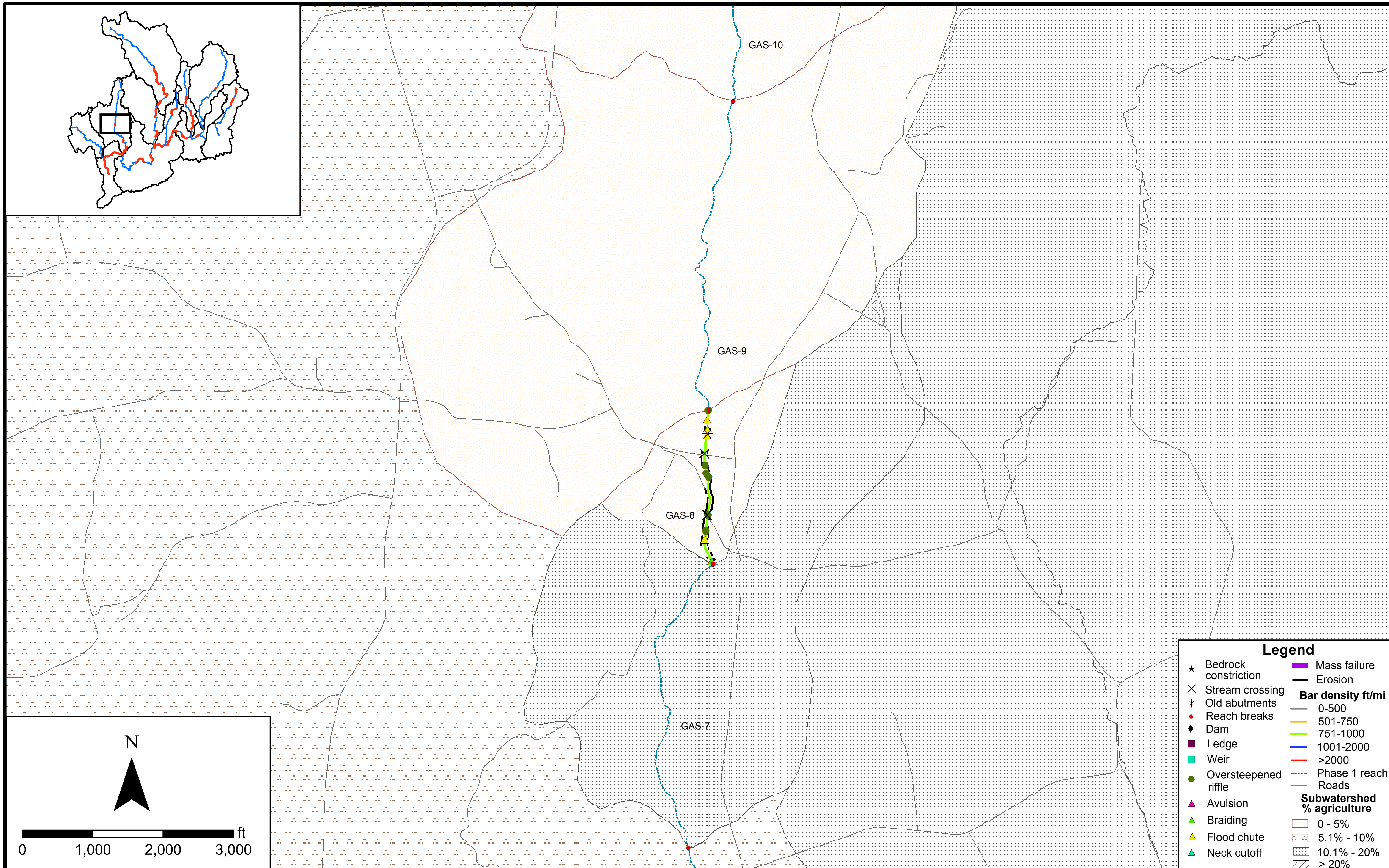

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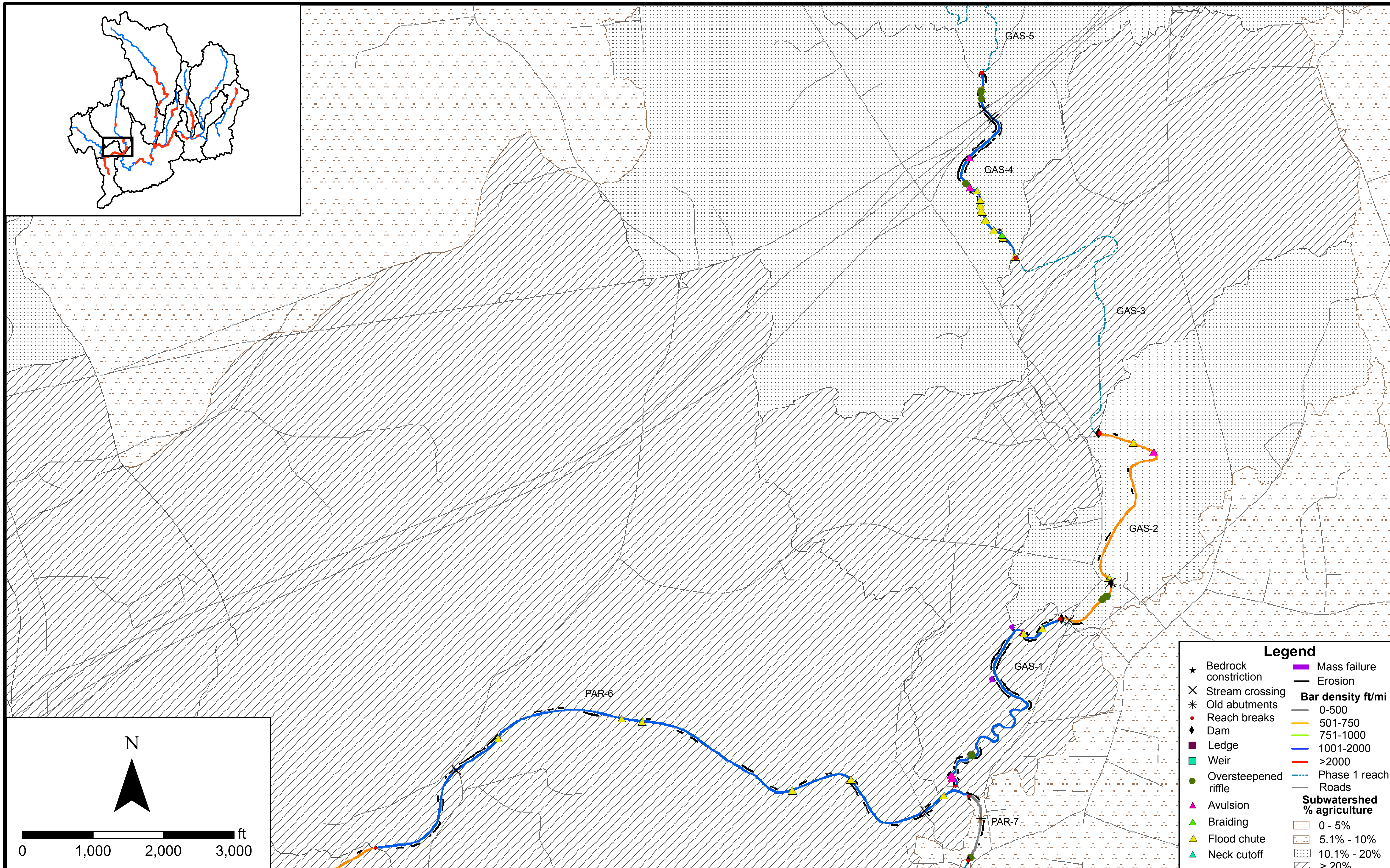

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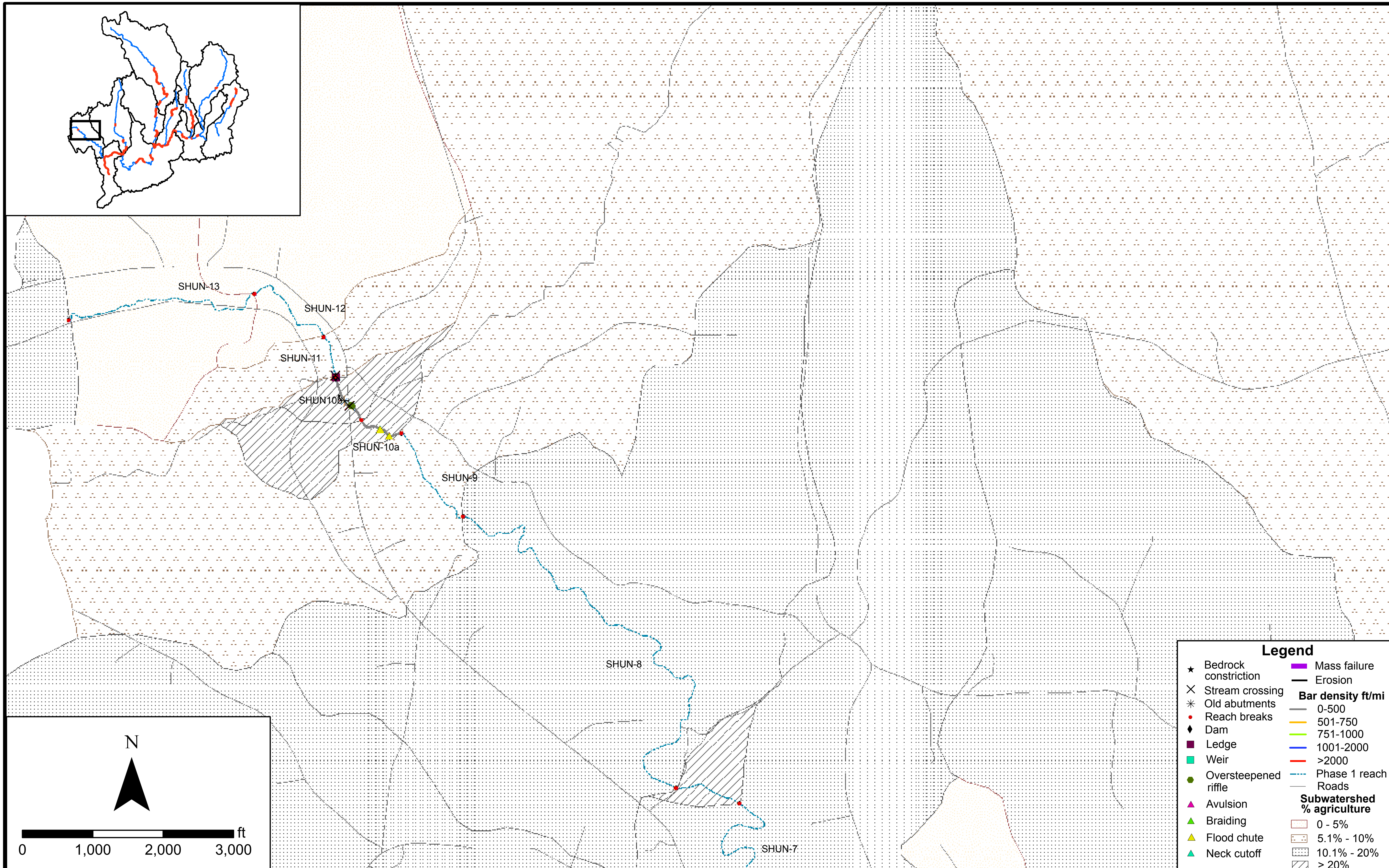

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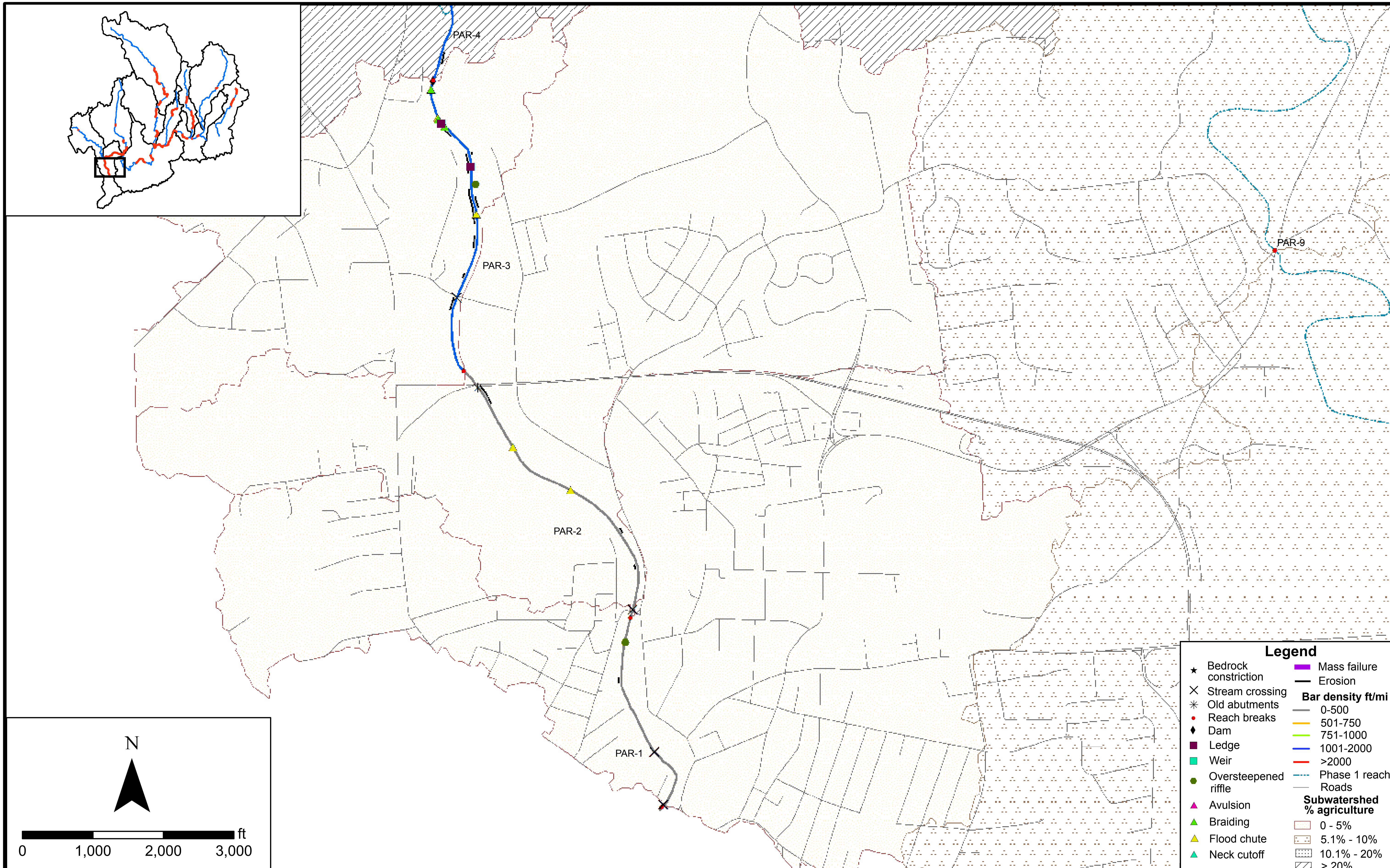
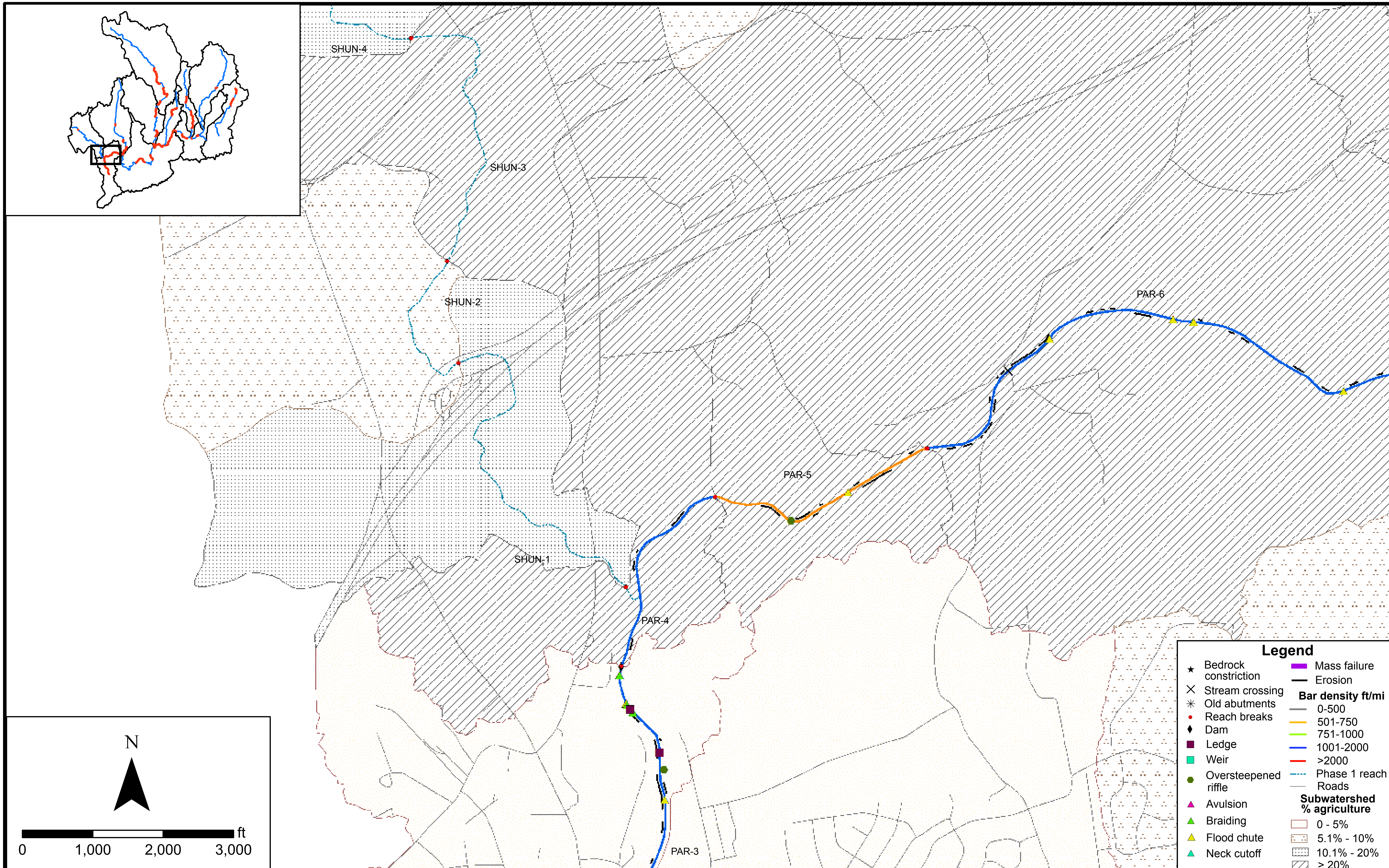


Appendix 1. Sediment stressor map.

Field Geology Services



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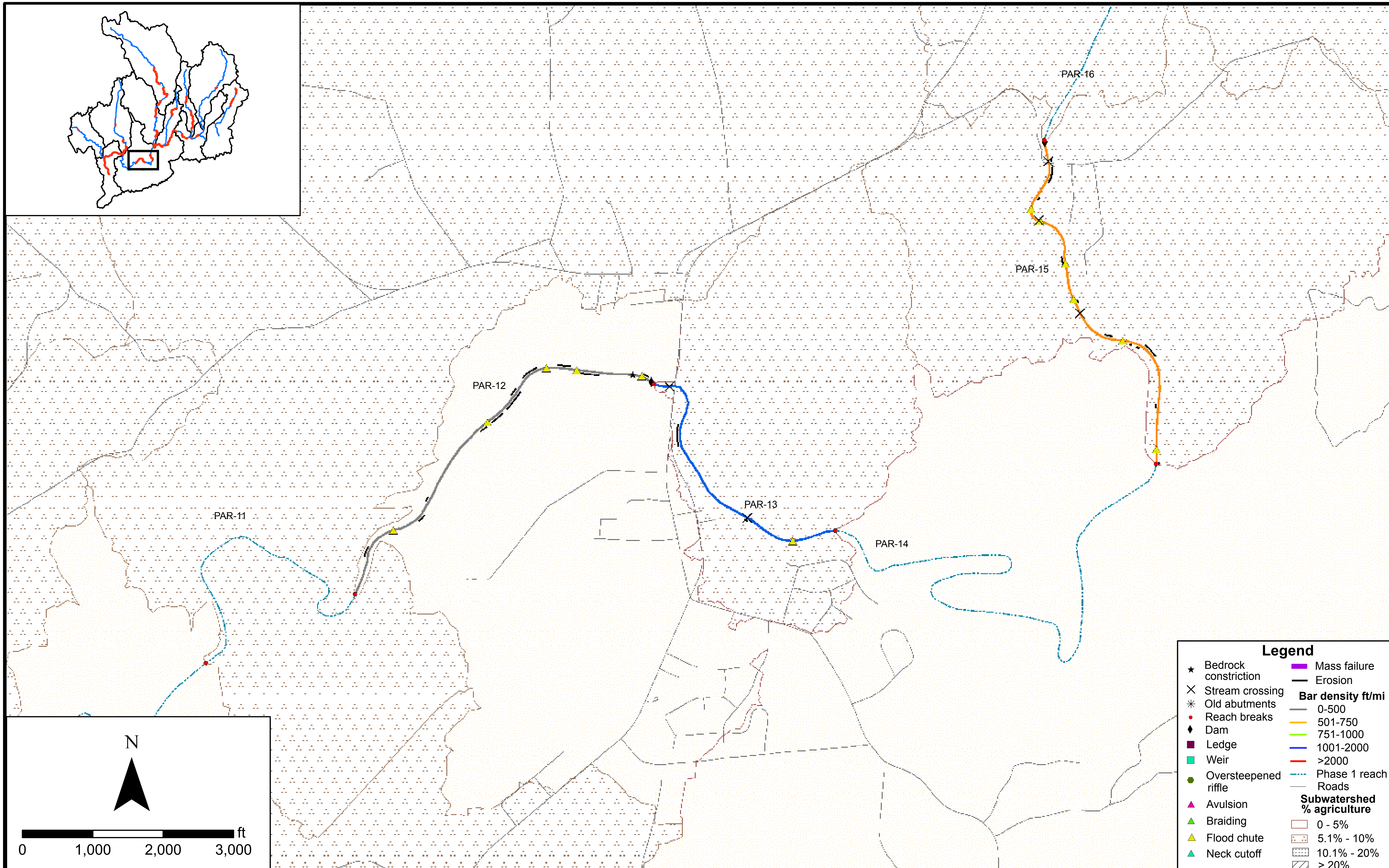
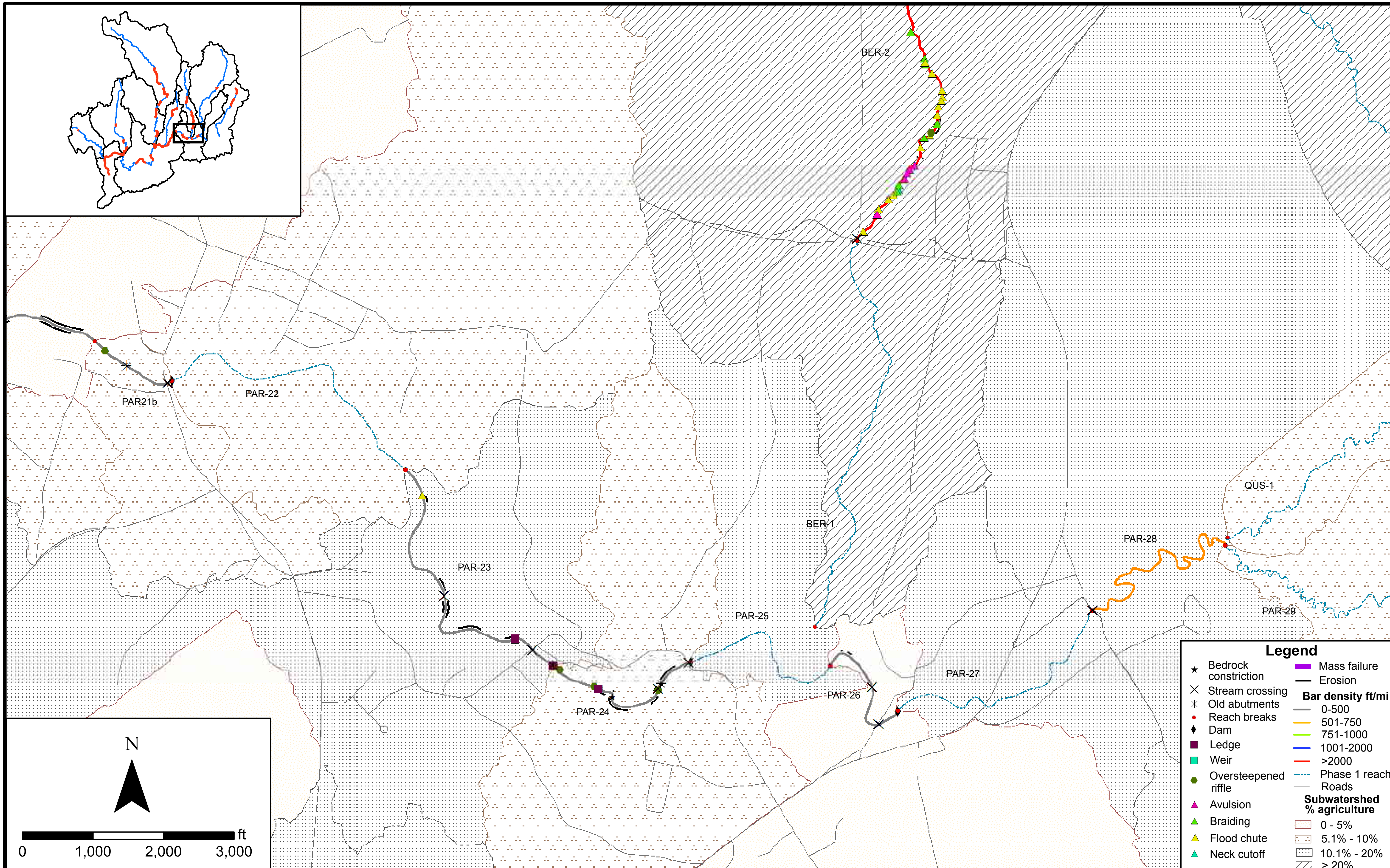
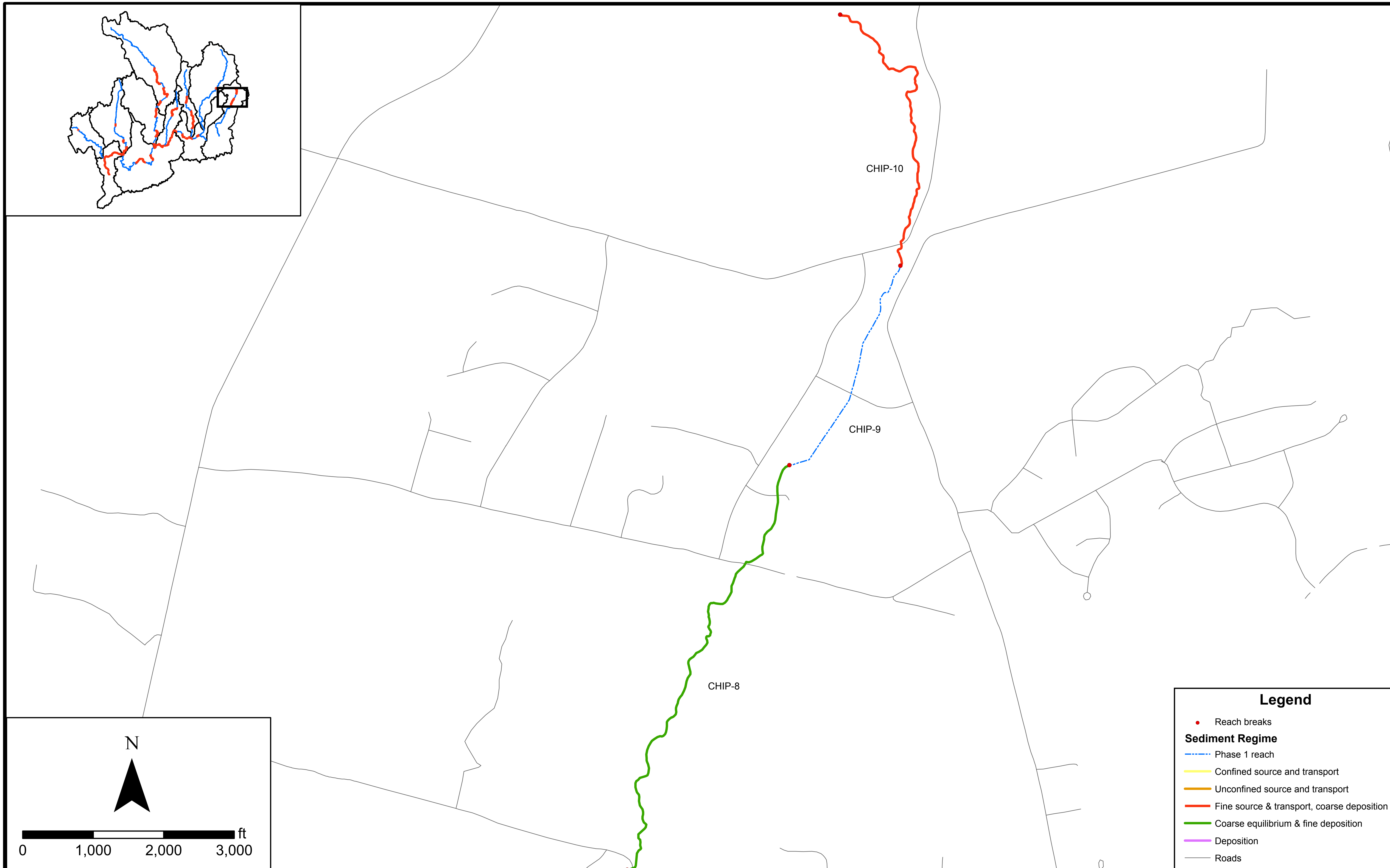


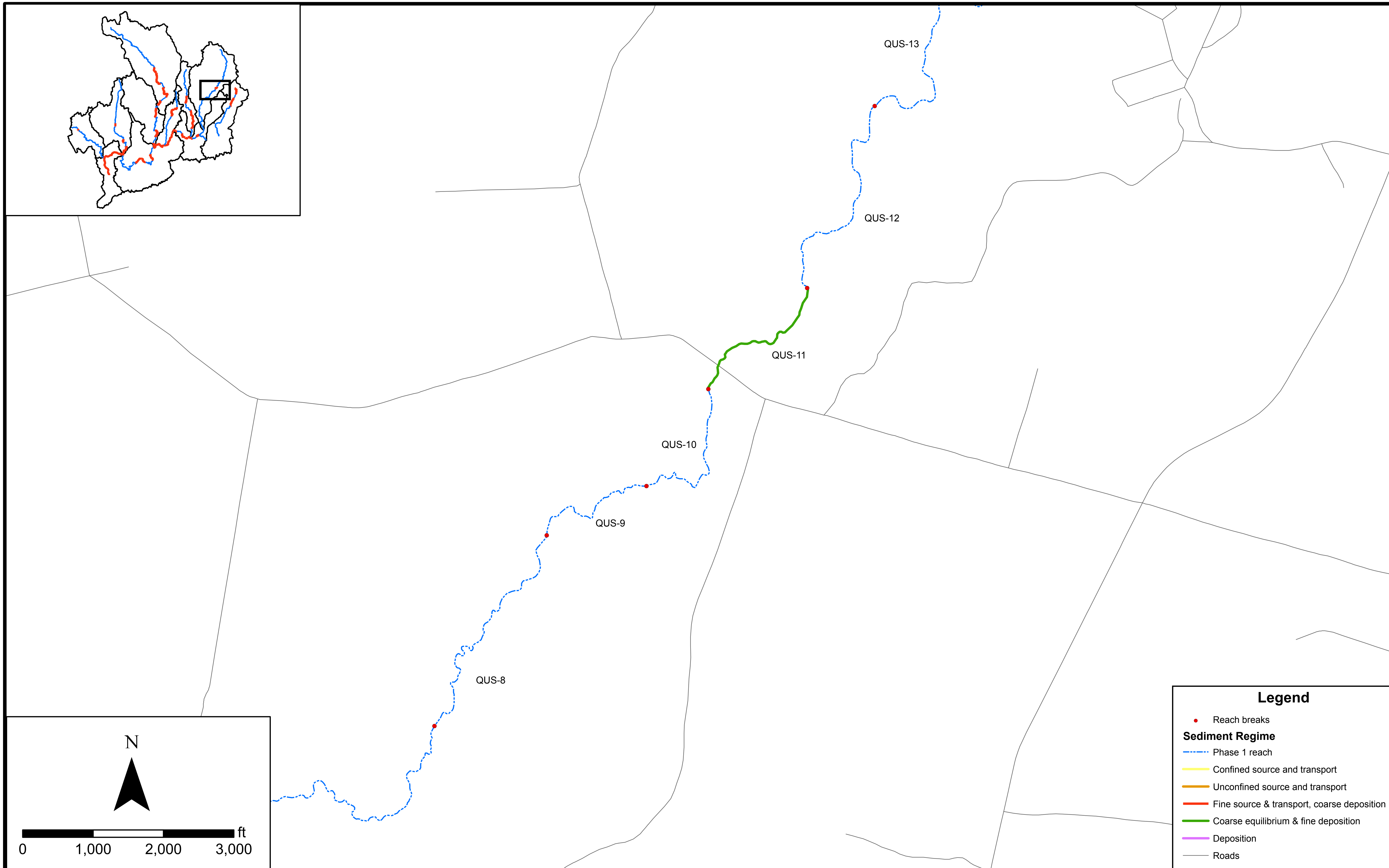
Appendix 1. Sediment stressor map.



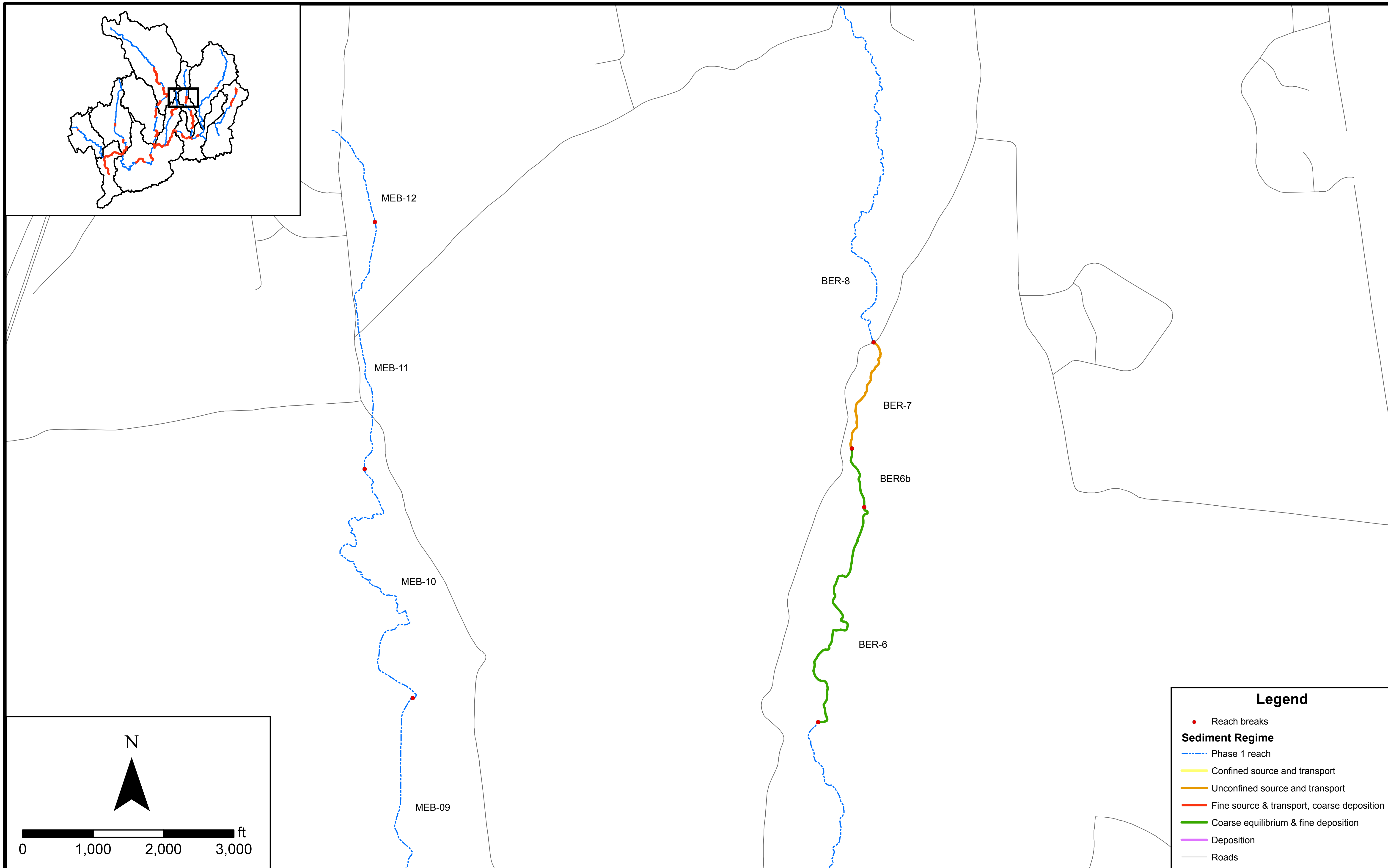
Appendix 1. Sediment stressor map.



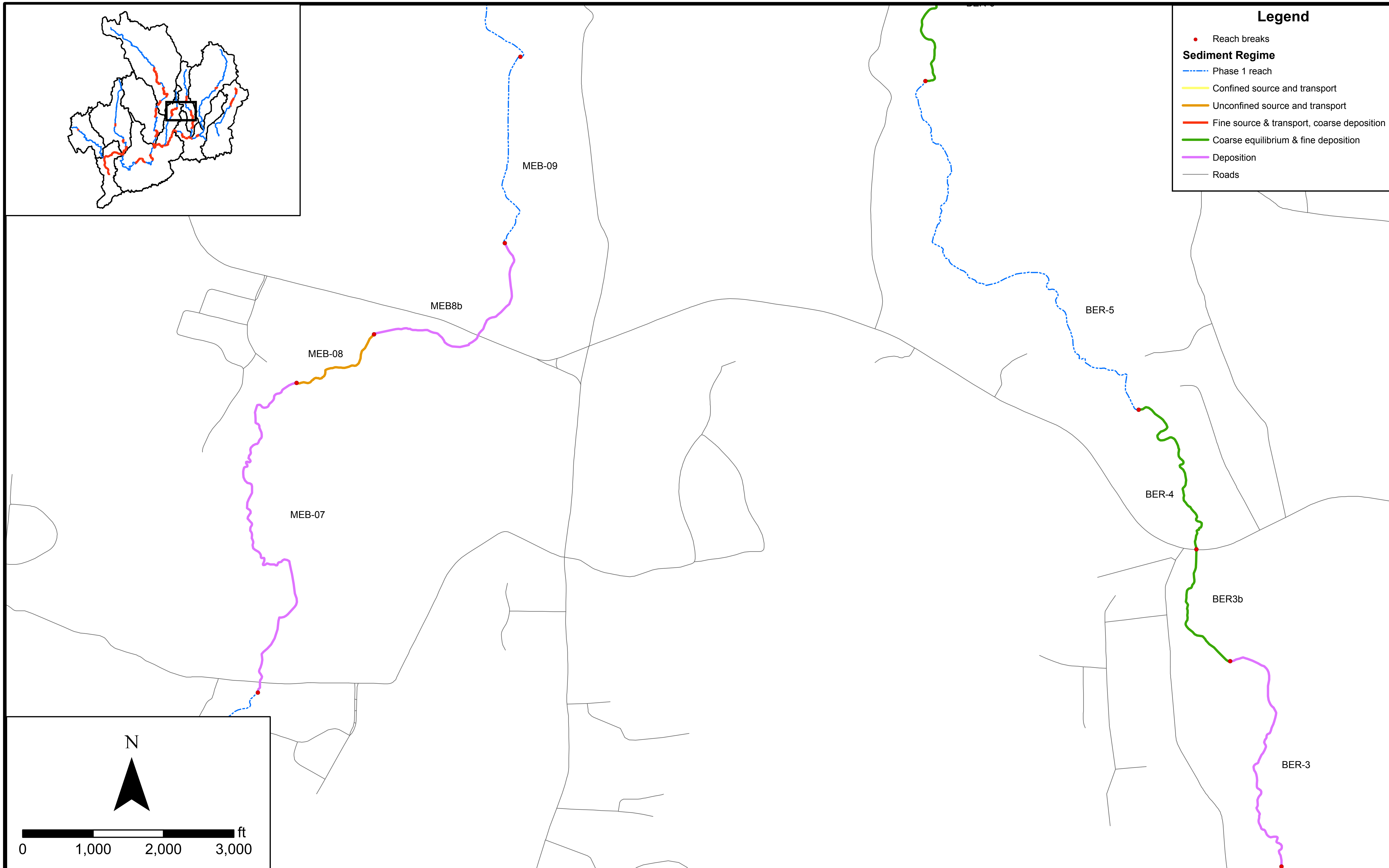
Appendix 1. Sediment regime map.



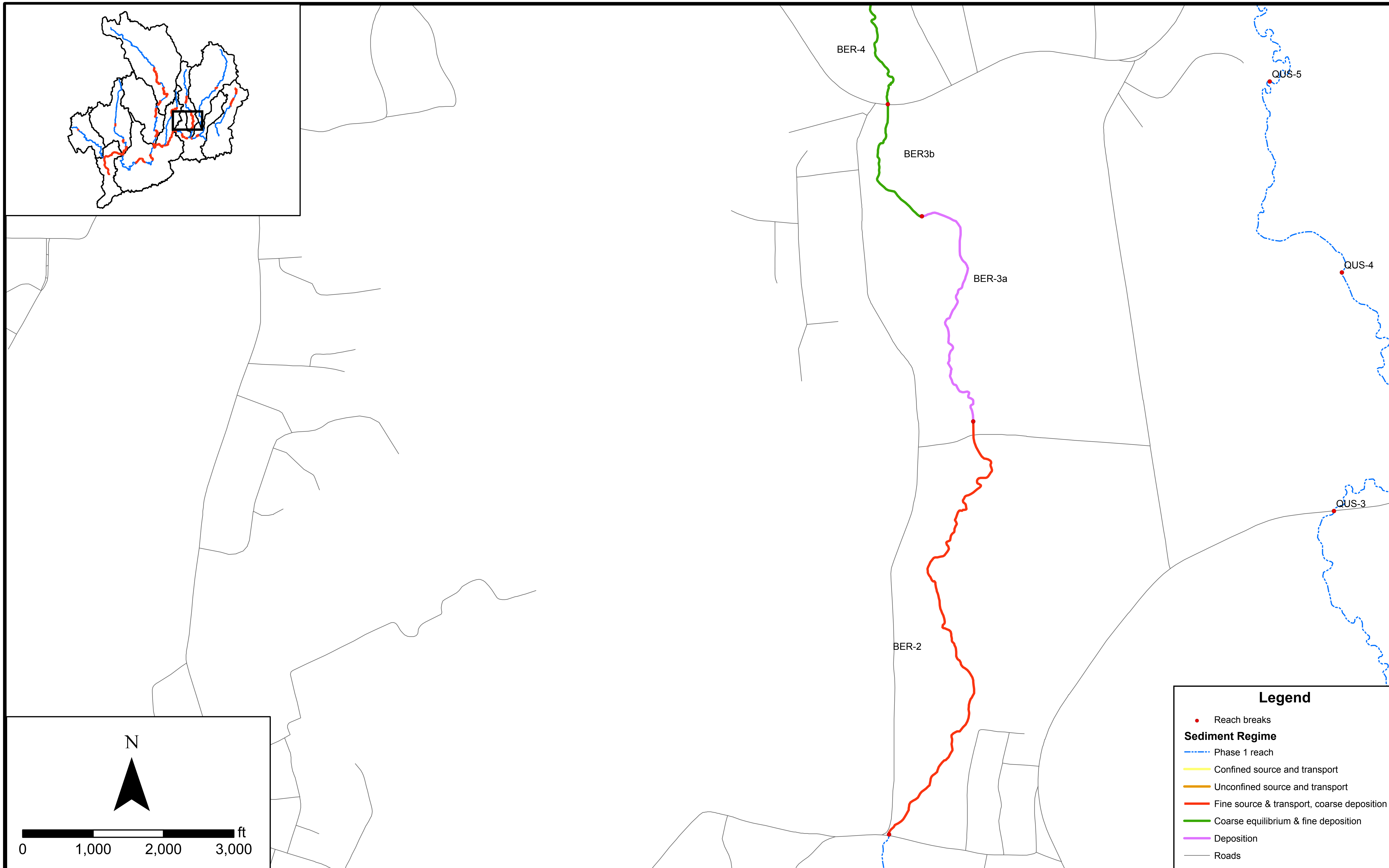
Appendix 1. Sediment regime map.



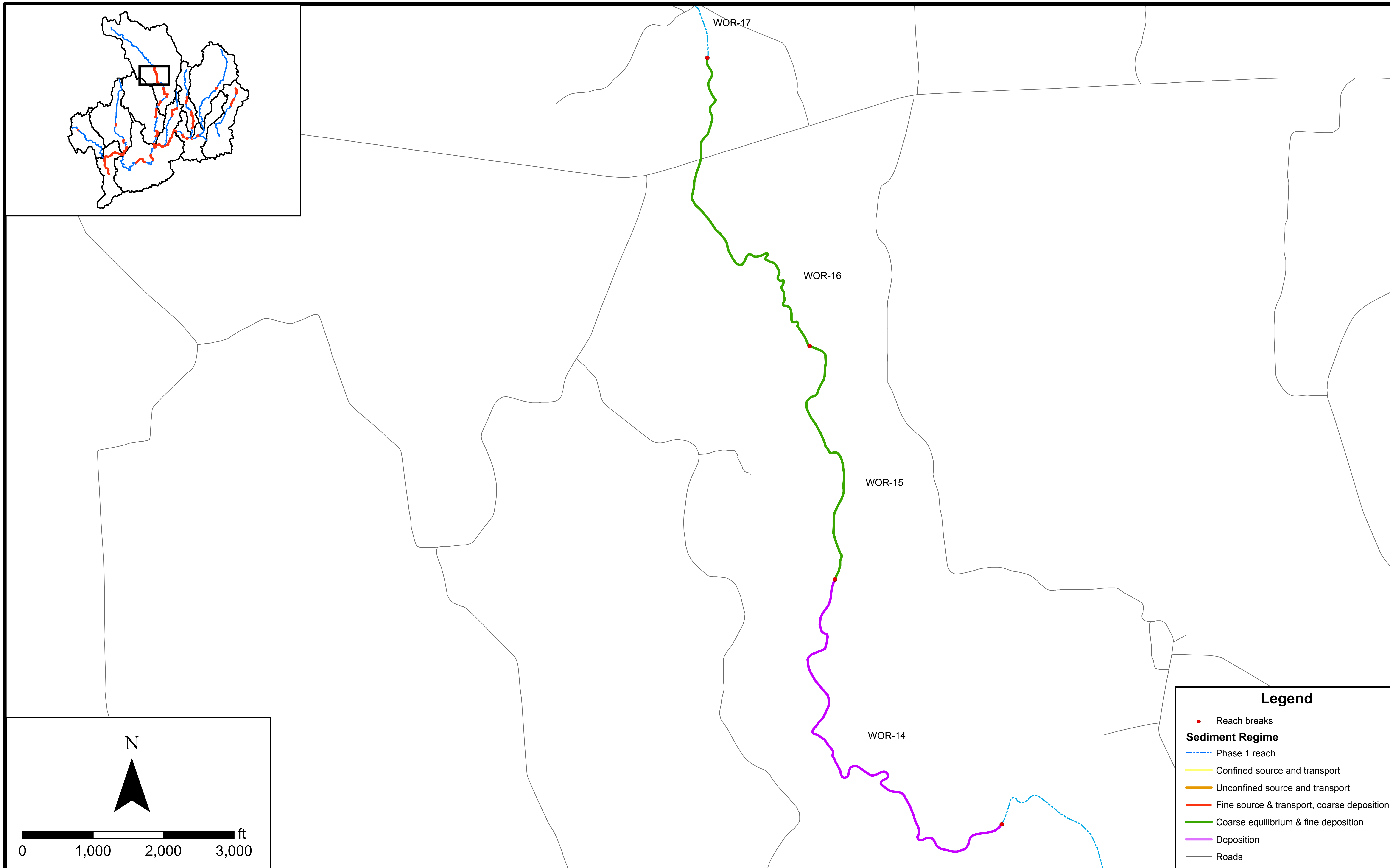
Appendix 1. Sediment regime map.



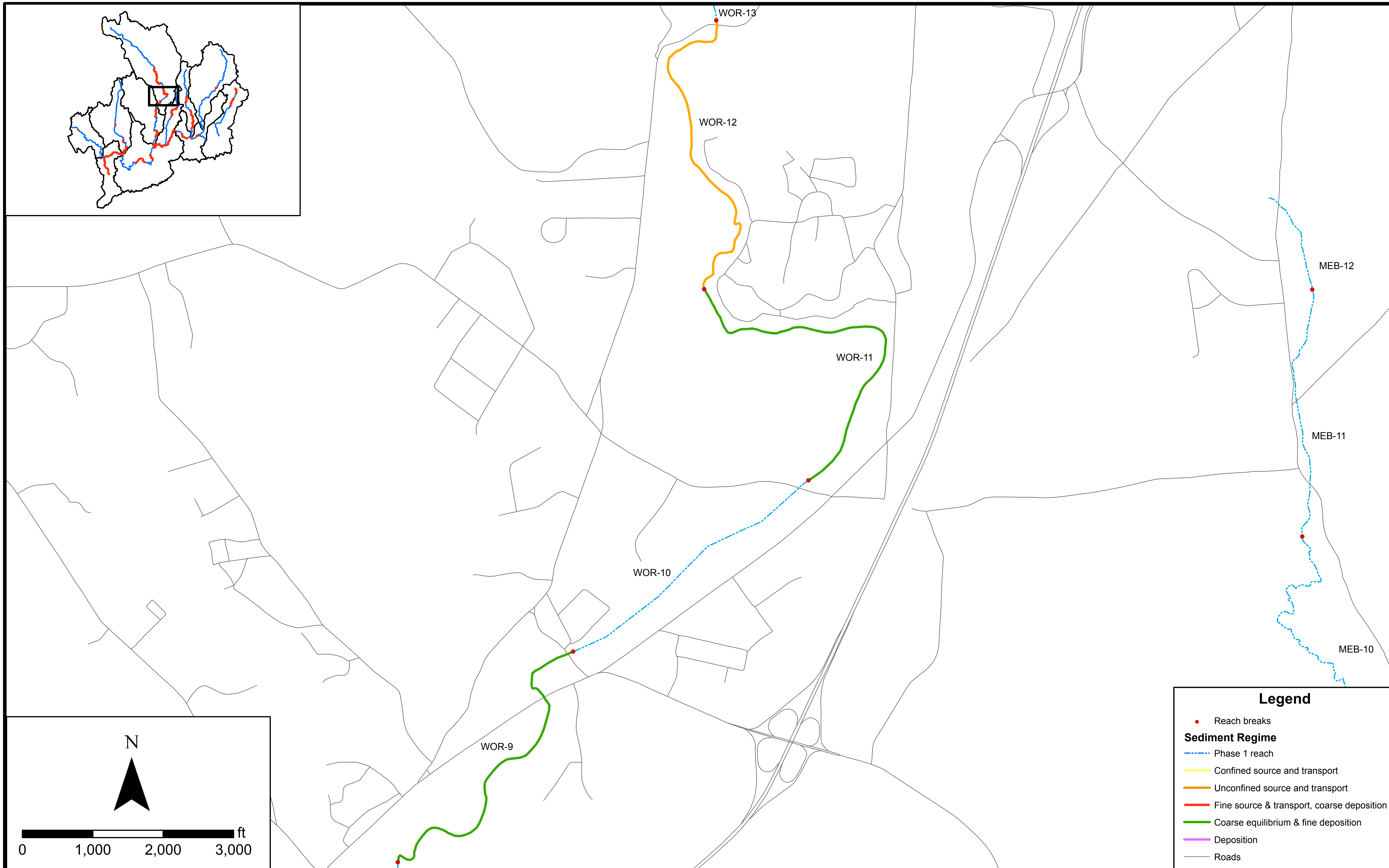
Appendix 1. Sediment regime map.



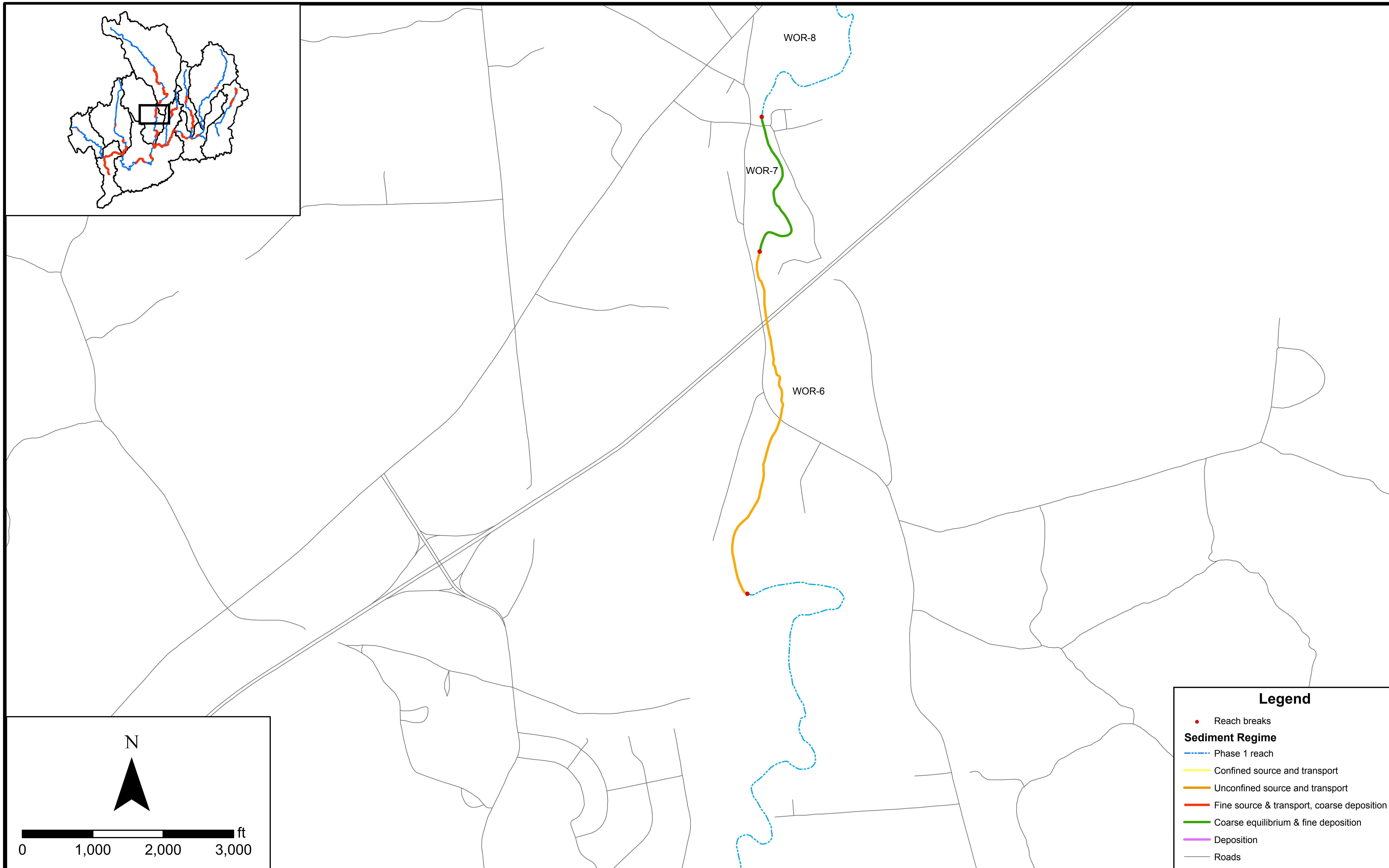
Appendix 1. Sediment regime map.



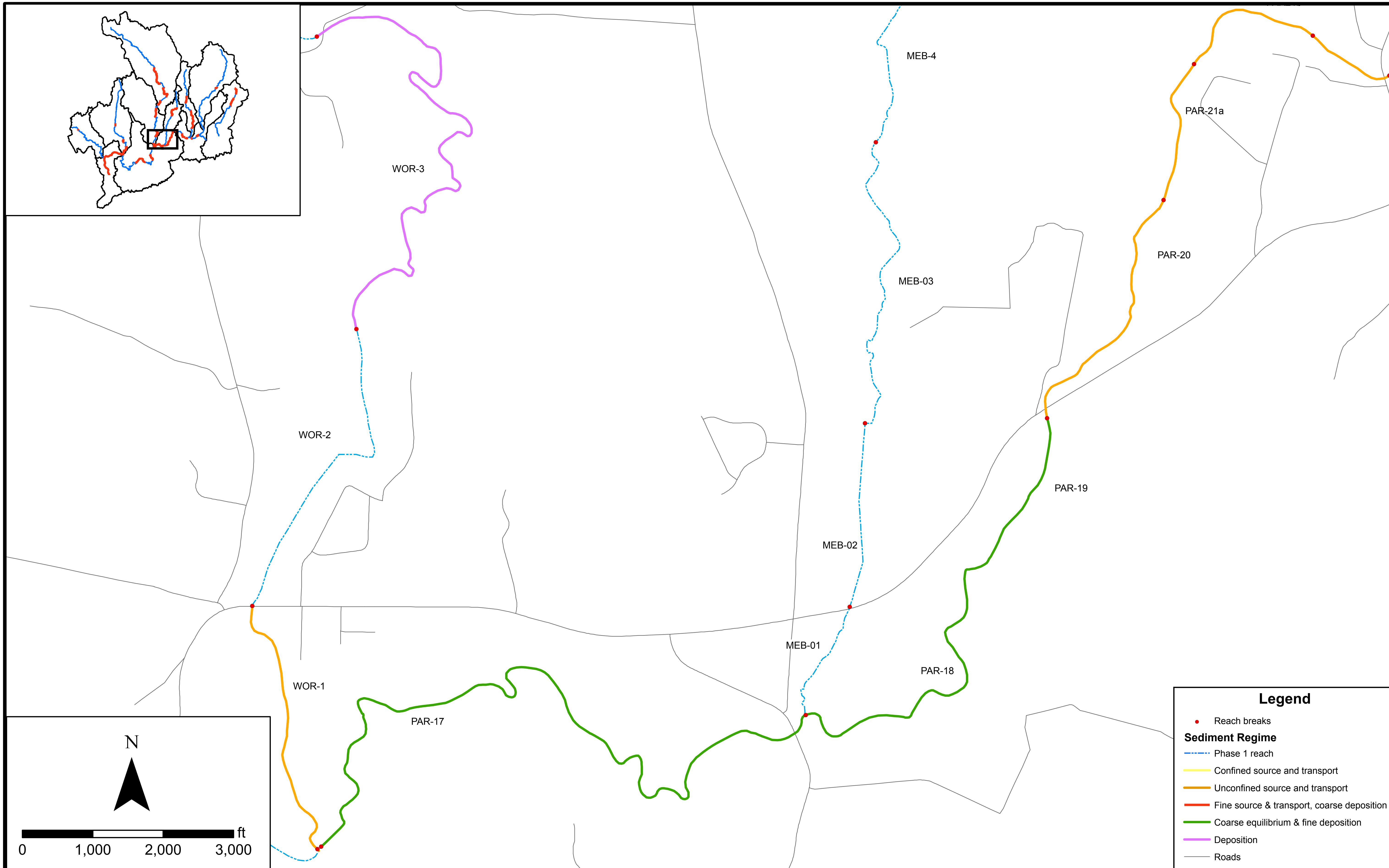
Appendix 1. Sediment regime map.



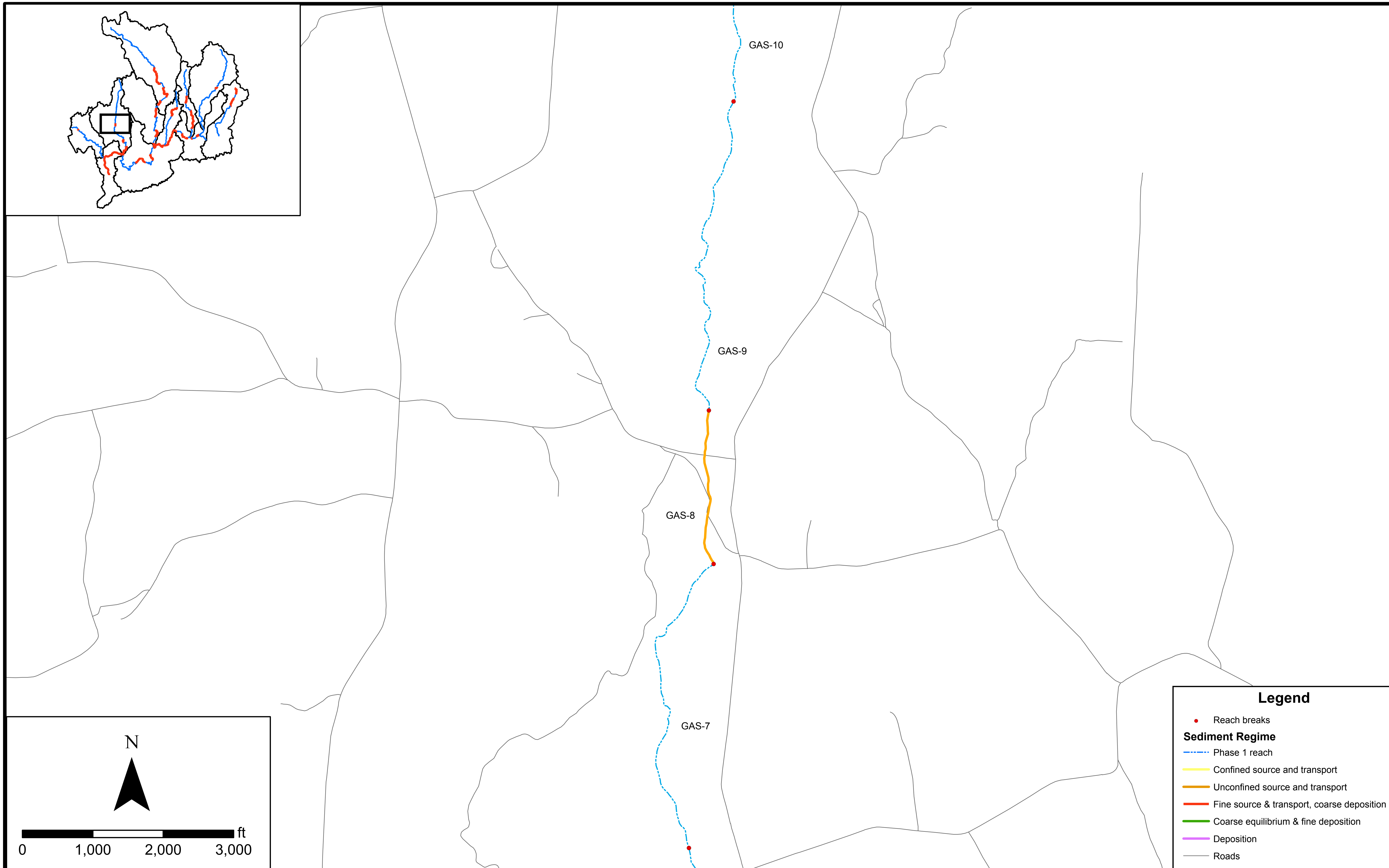
Appendix 1. Sediment regime map.



Appendix 1. Sediment regime map.



Appendix 1. Sediment regime map.



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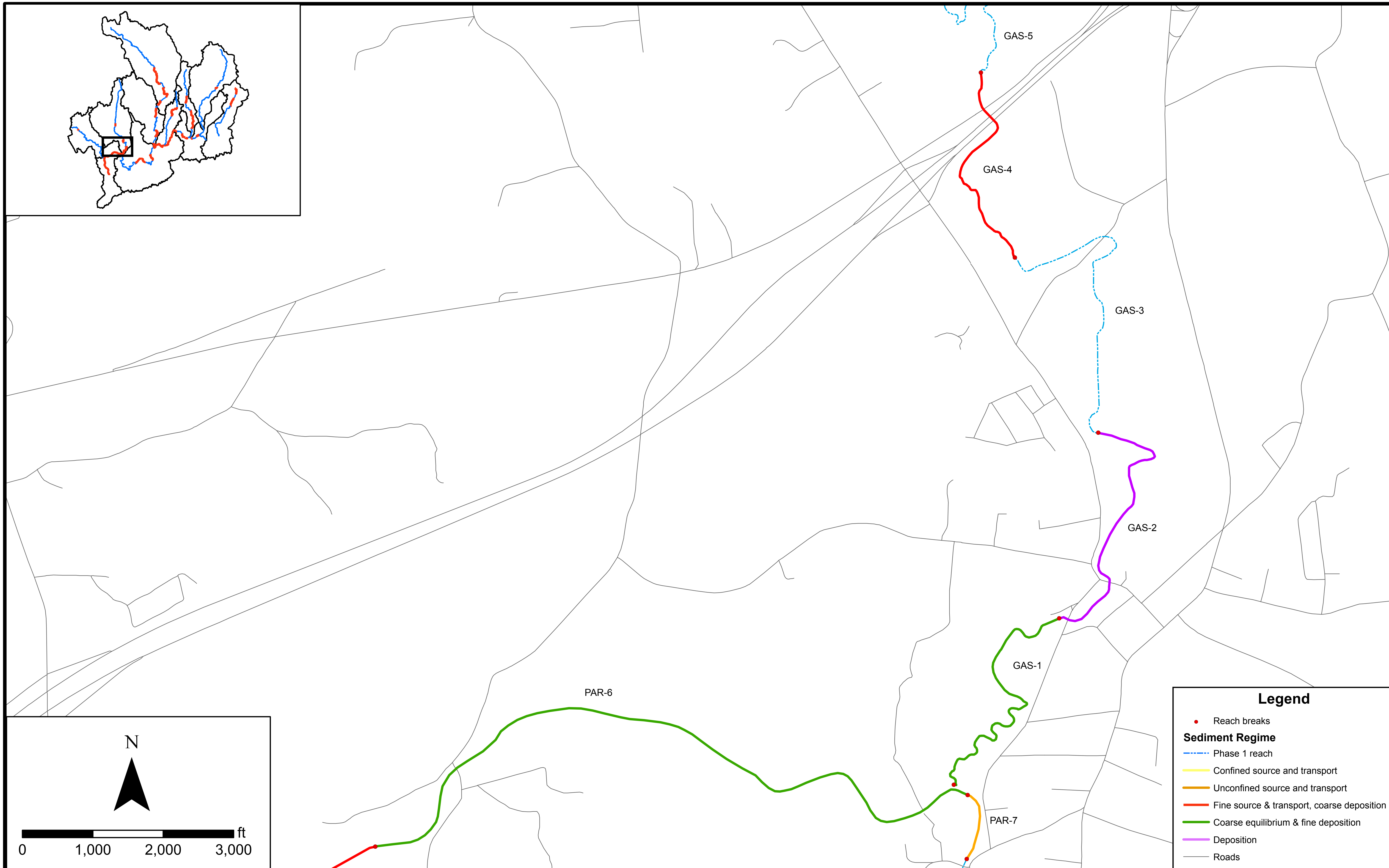

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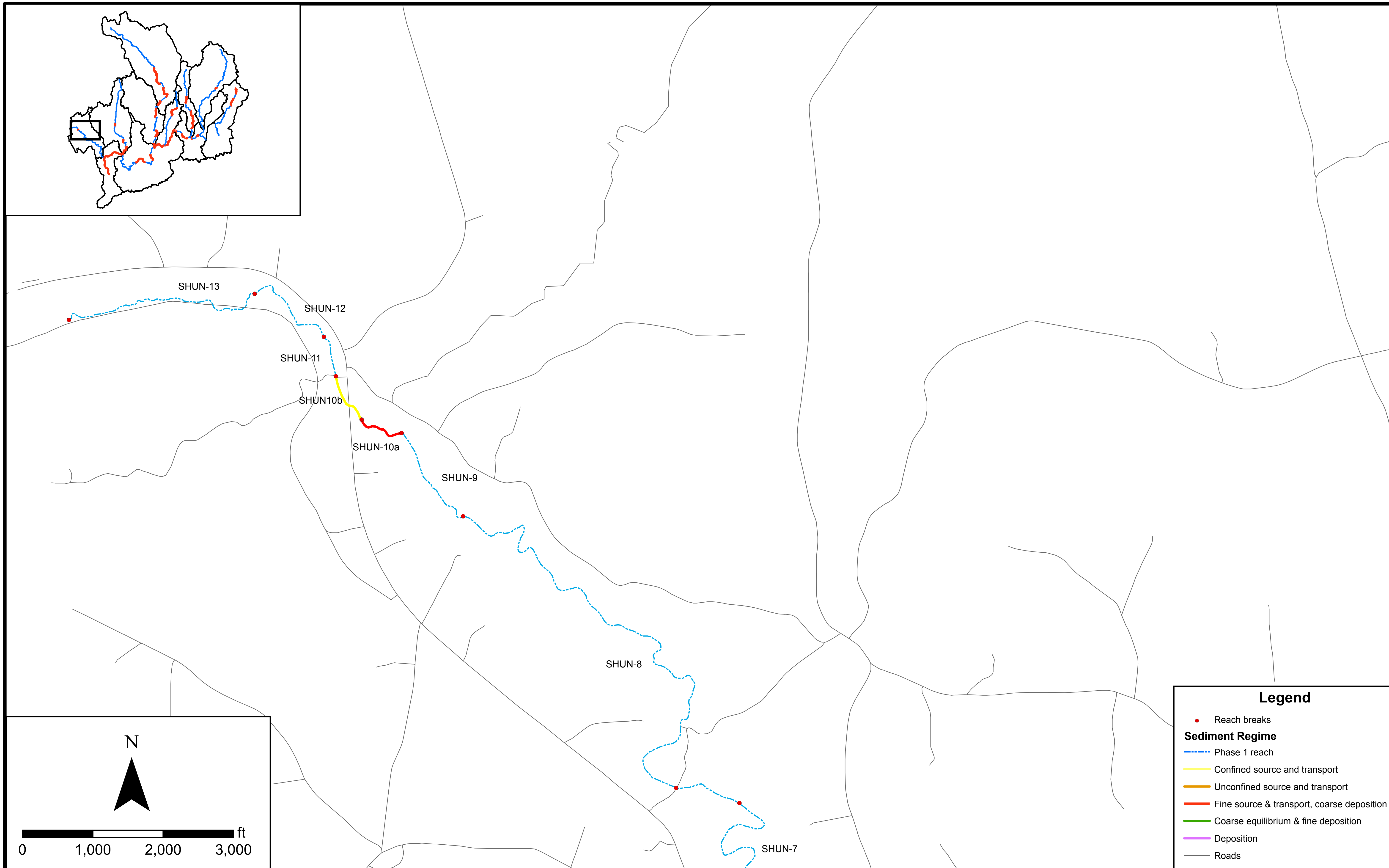
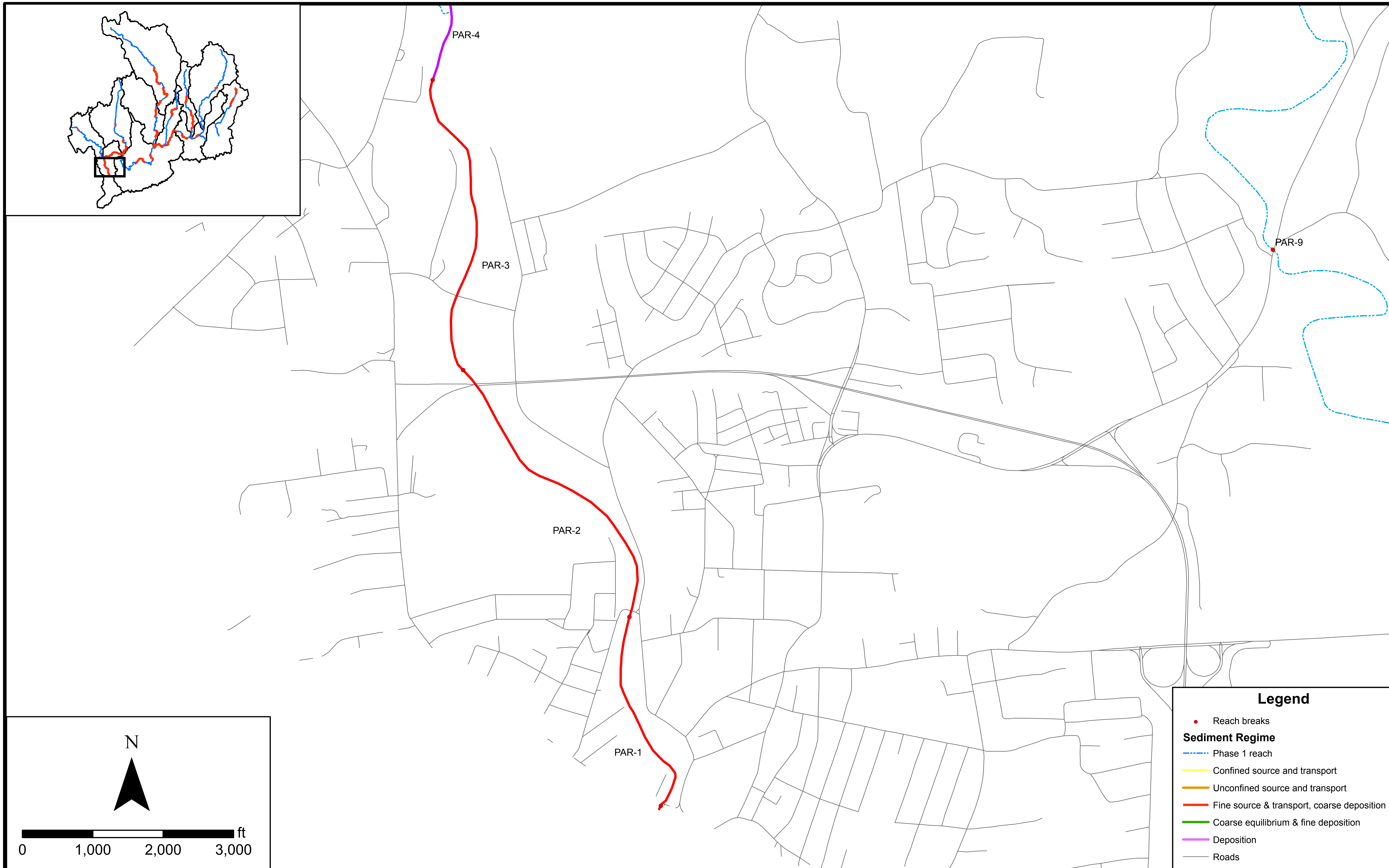
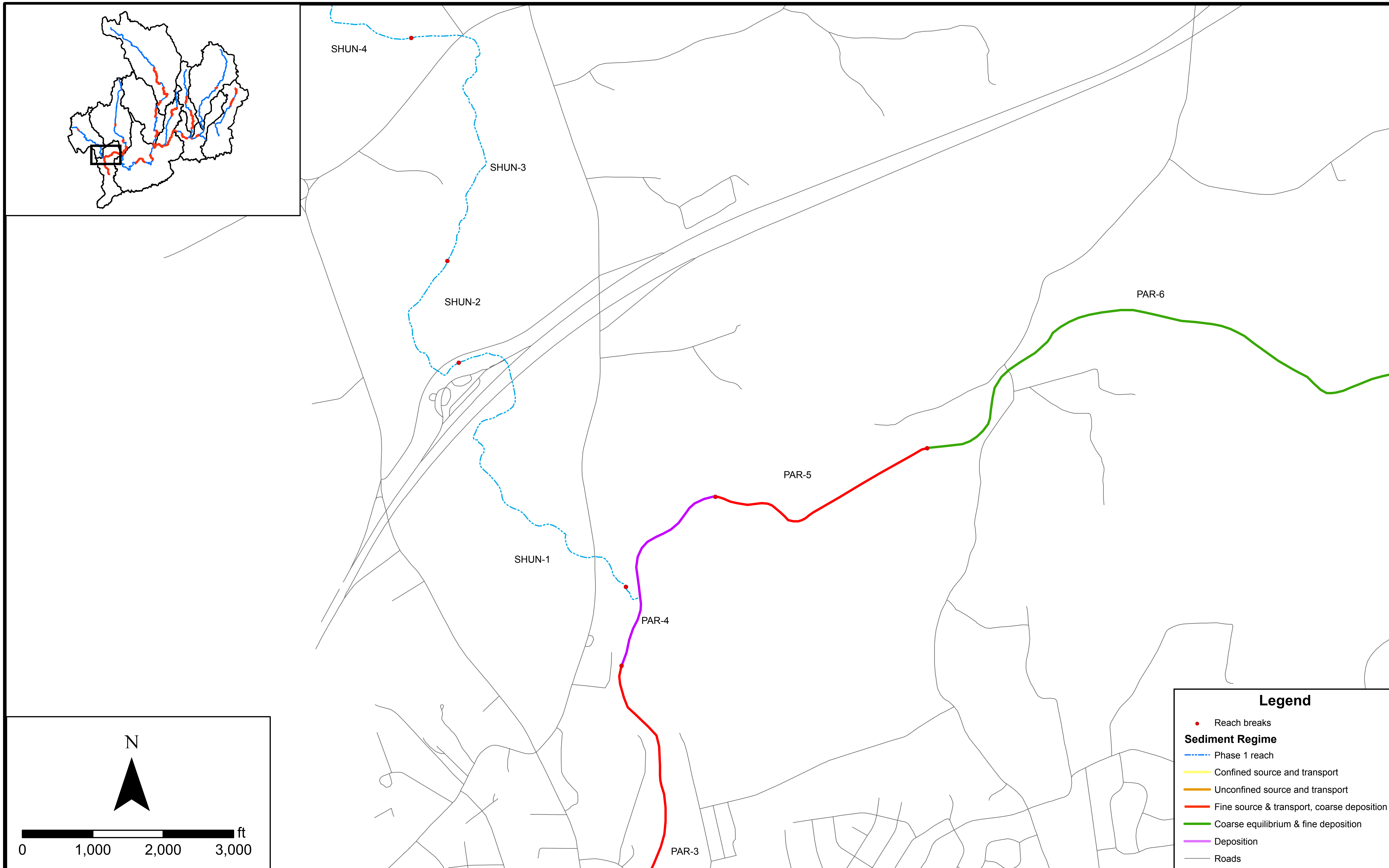


Appendix 1. Sediment regime map.



Appendix 1. Sediment regime map.



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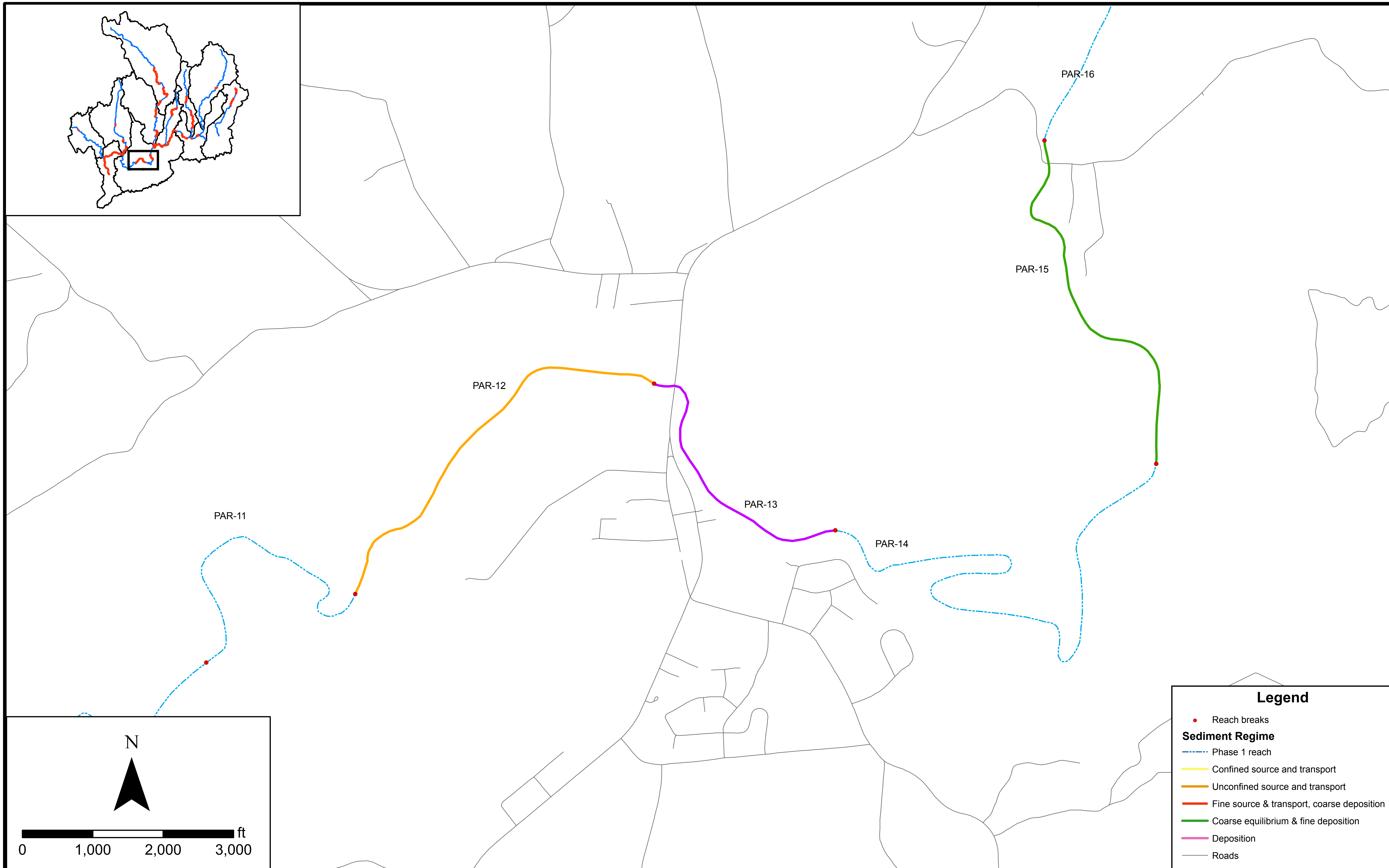
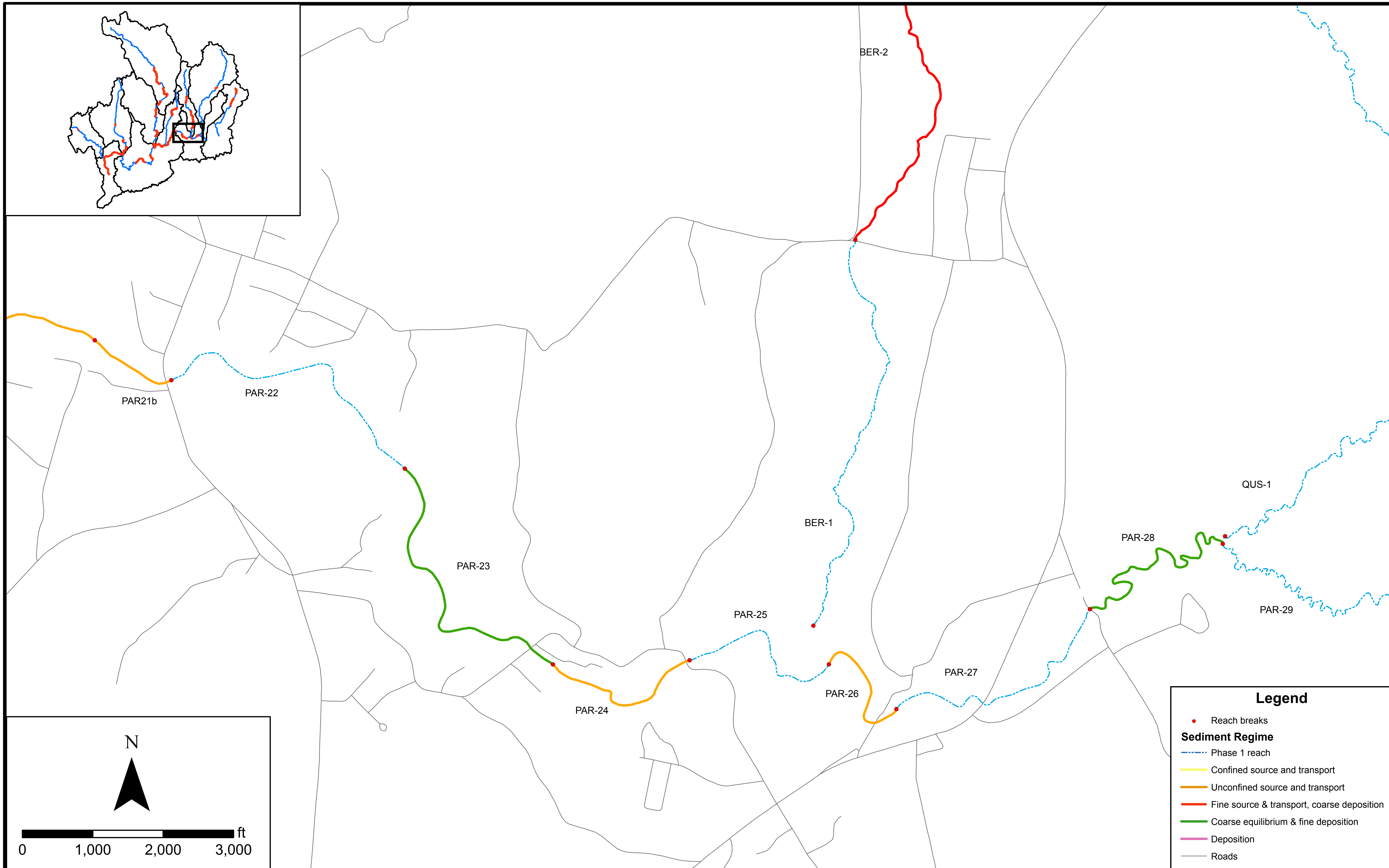
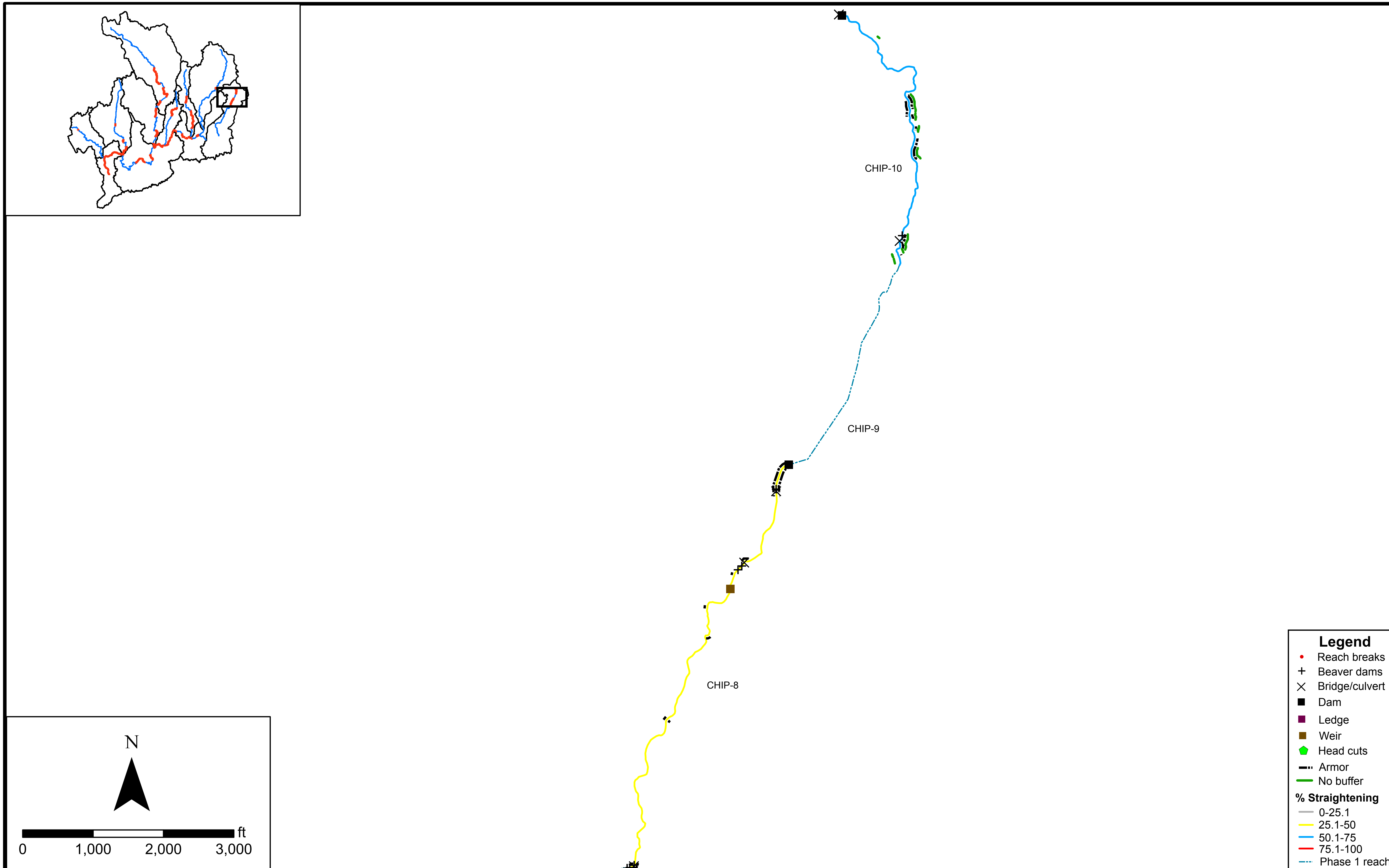


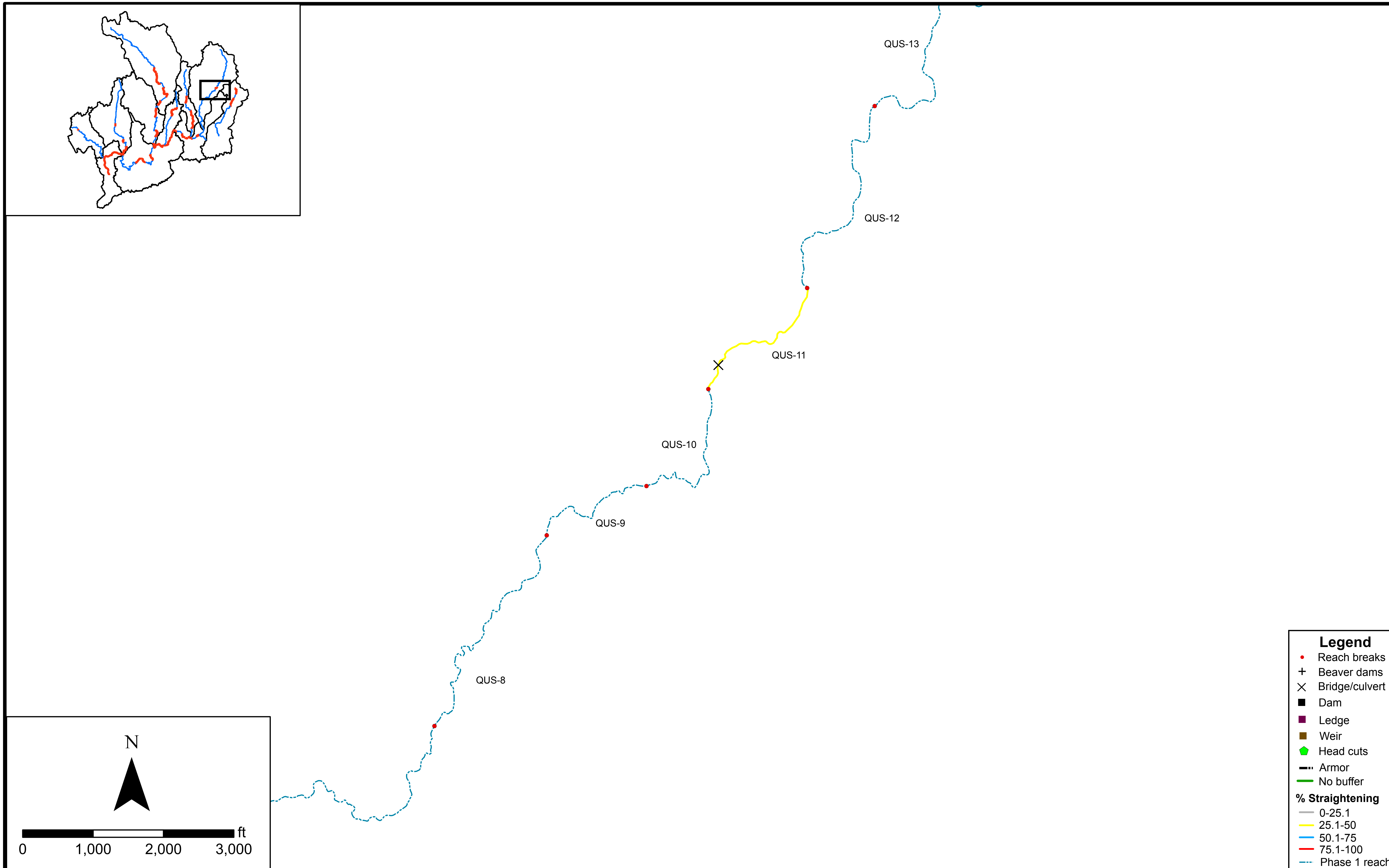
Appendix 1. Sediment regime map



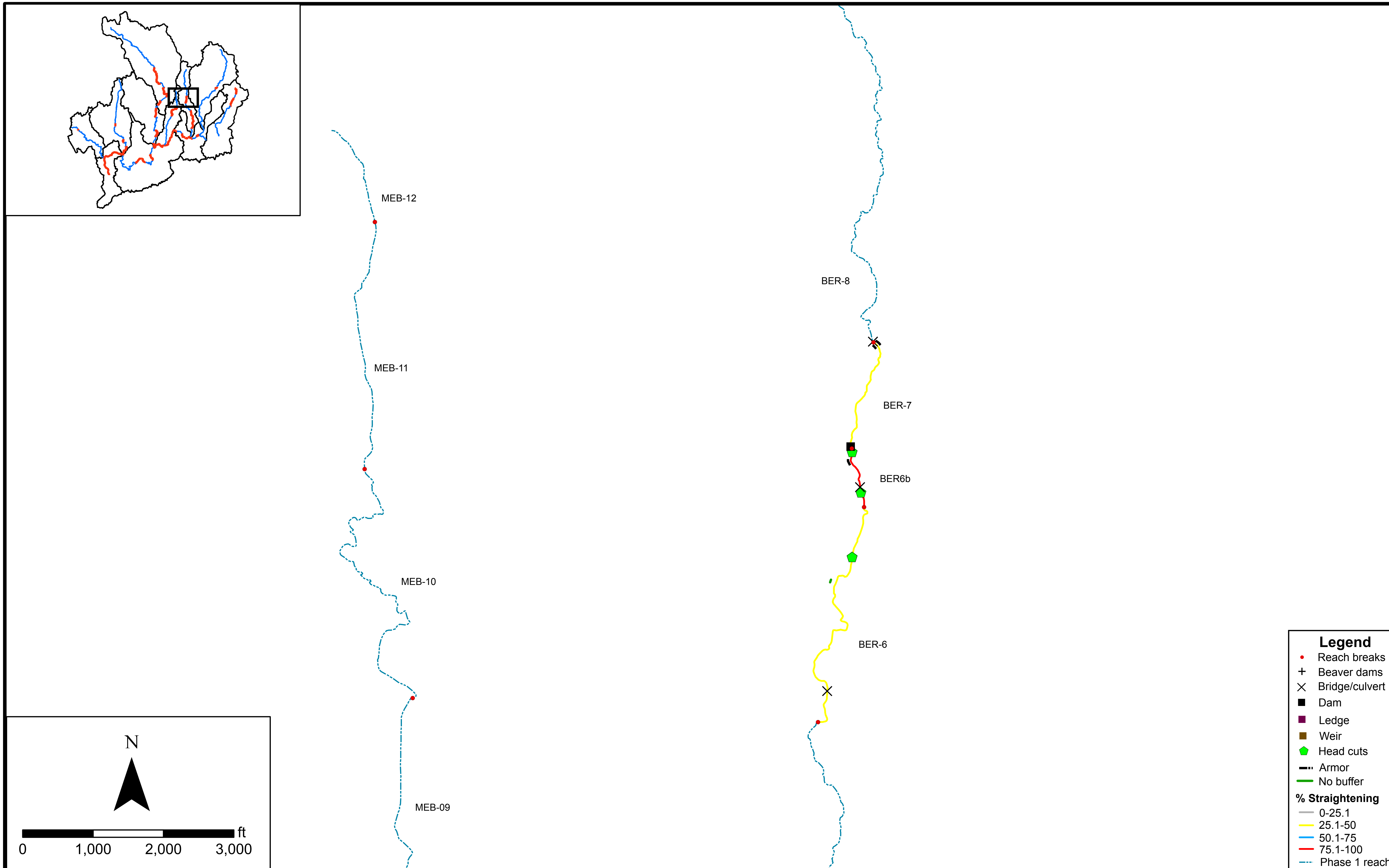
Appendix 1. Sediment regime map



Appendix 1. Channel boundary modifiers.

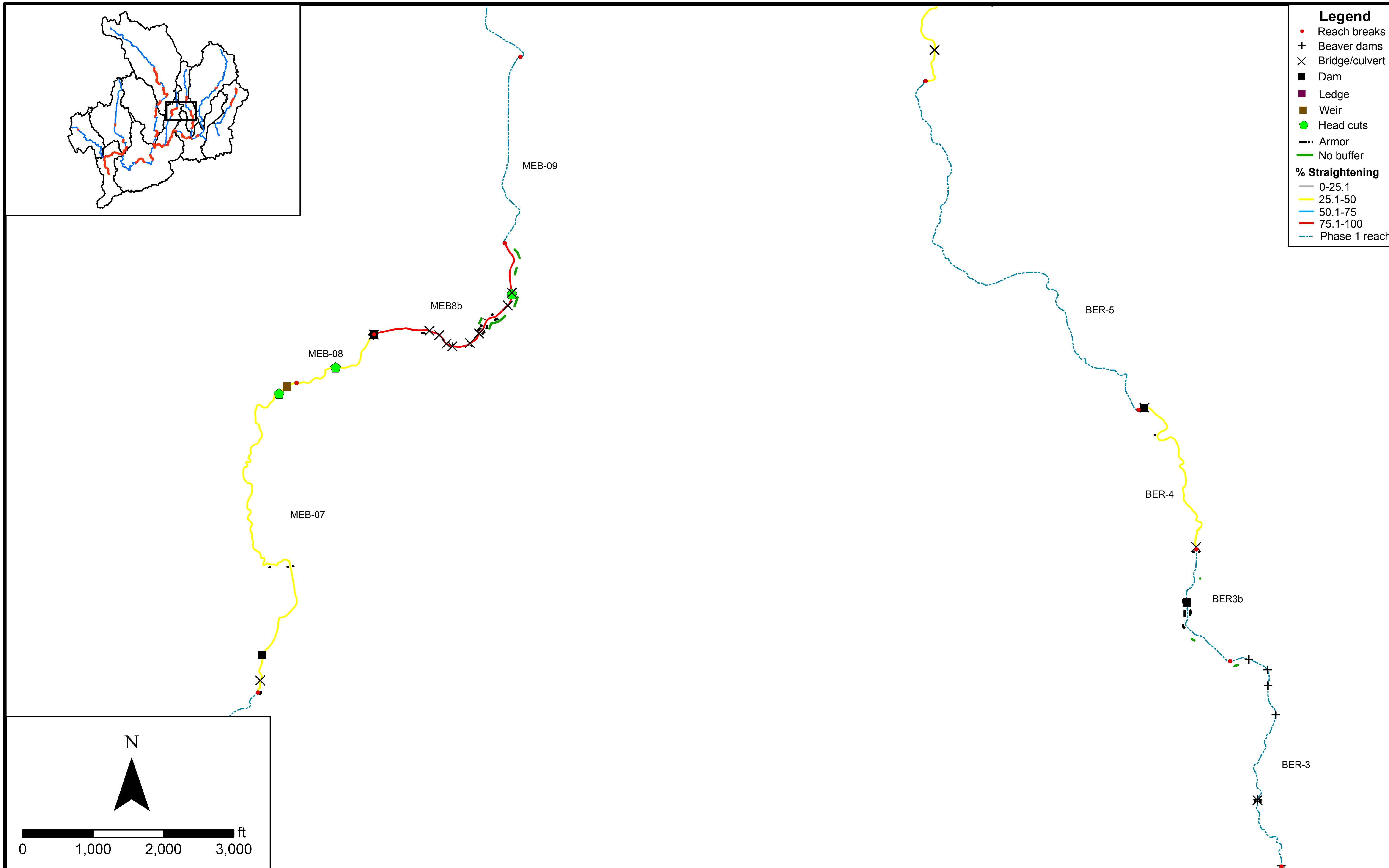


Appendix 1. Channel boundary modifiers.

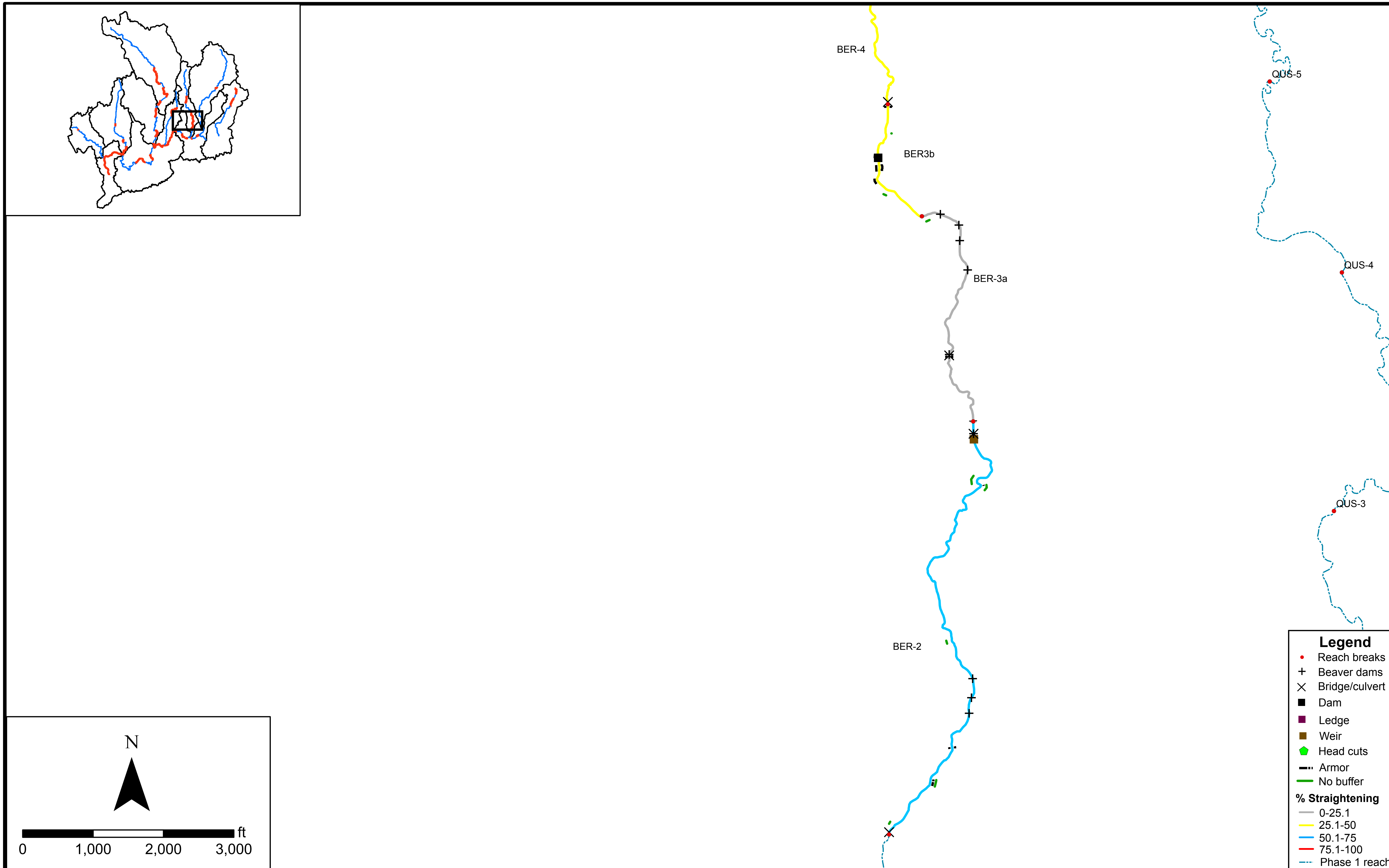


Appendix 1. Channel boundary modifiers.

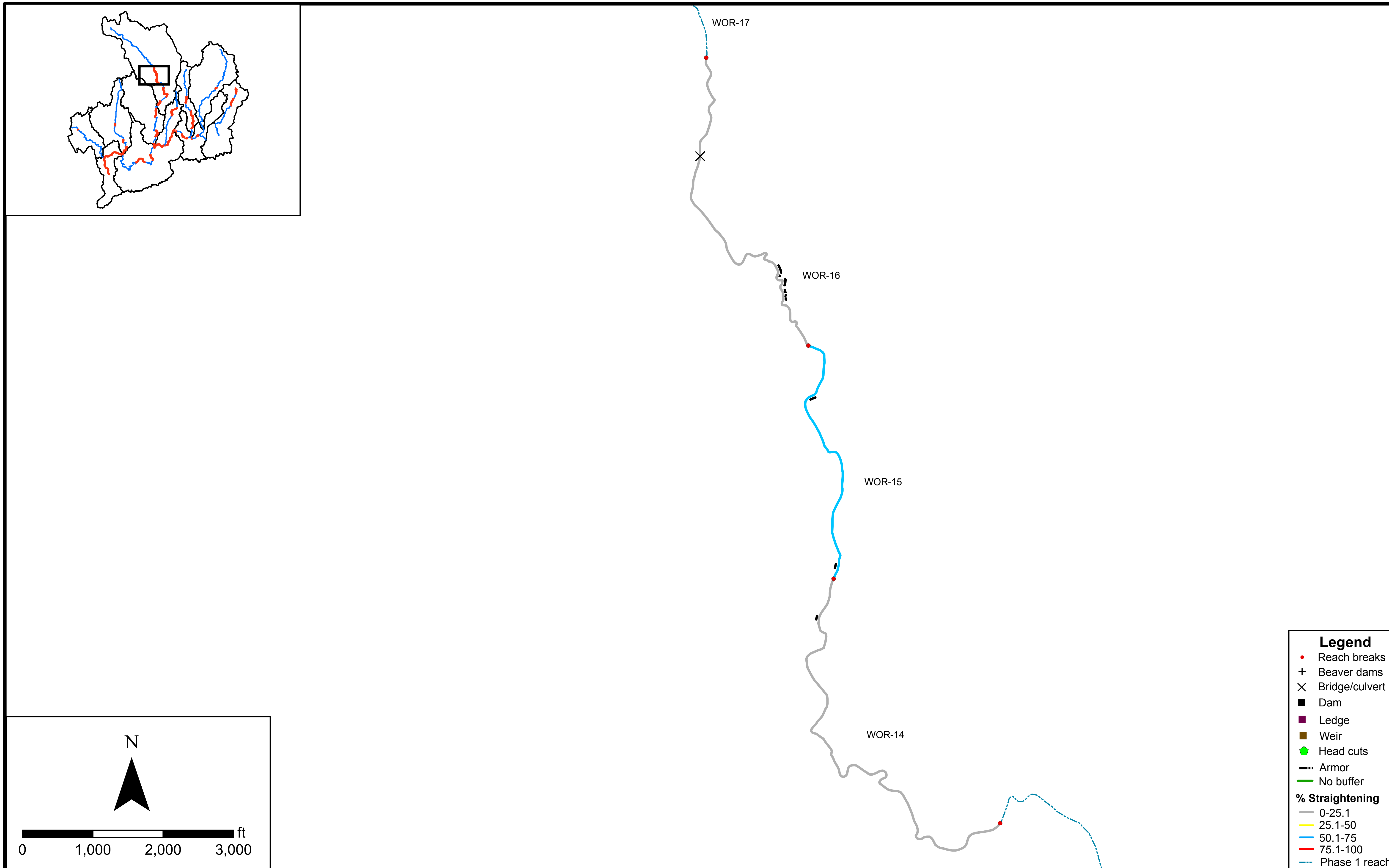
Field Geology Services



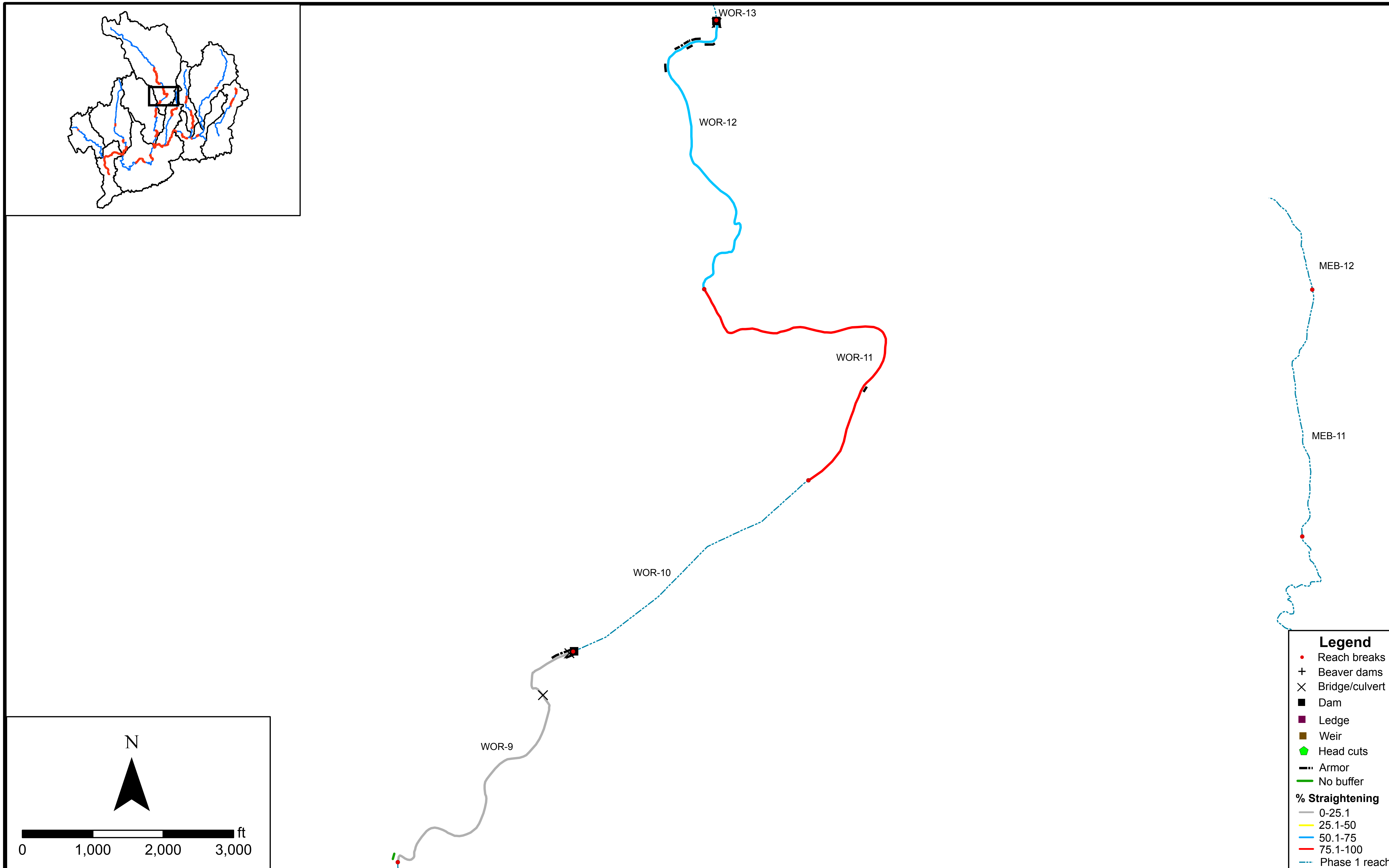
Appendix 1. Channel boundary modifiers.



Appendix 1. Channel boundary modifiers.



Appendix 1. Channel boundary modifiers.



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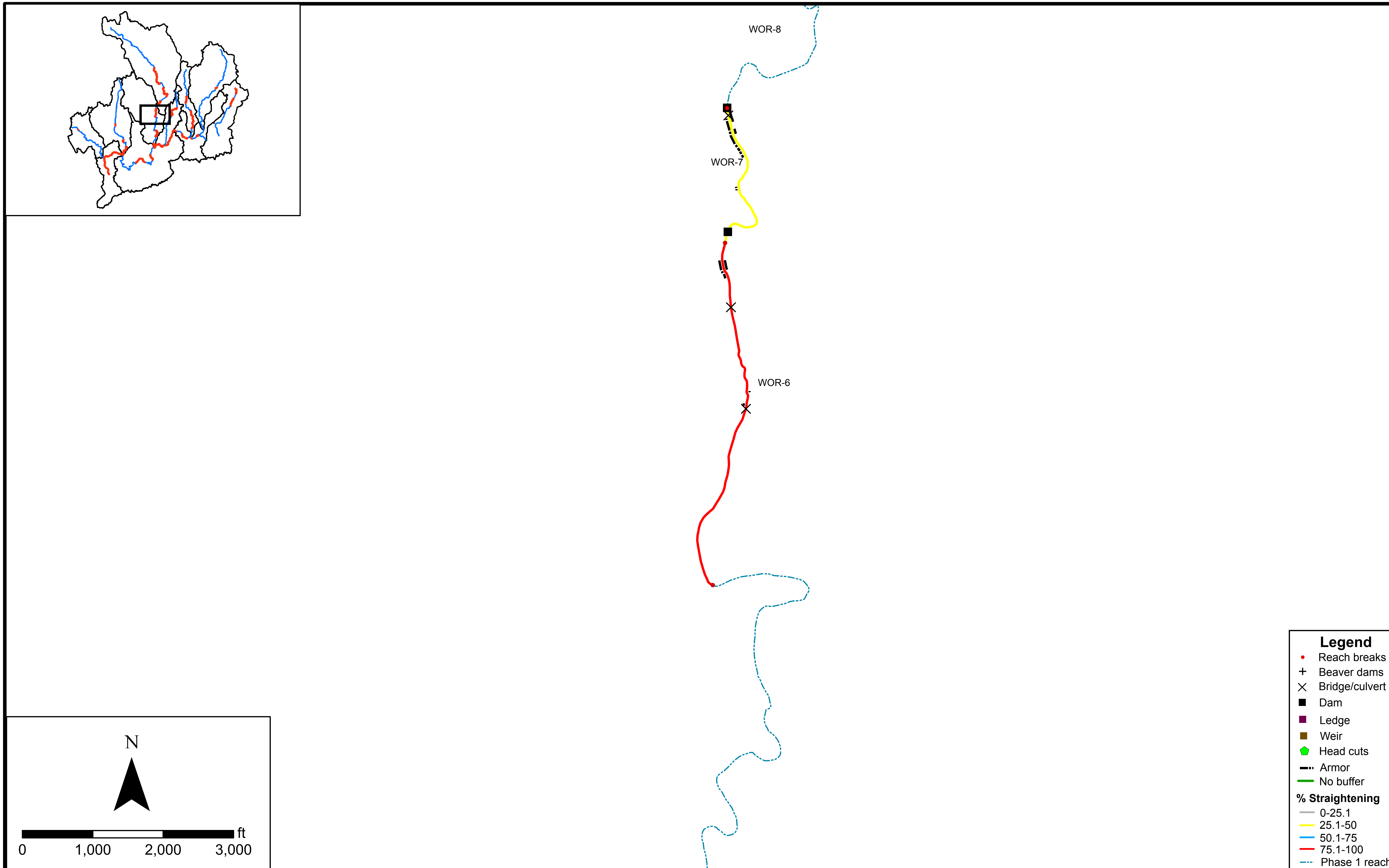

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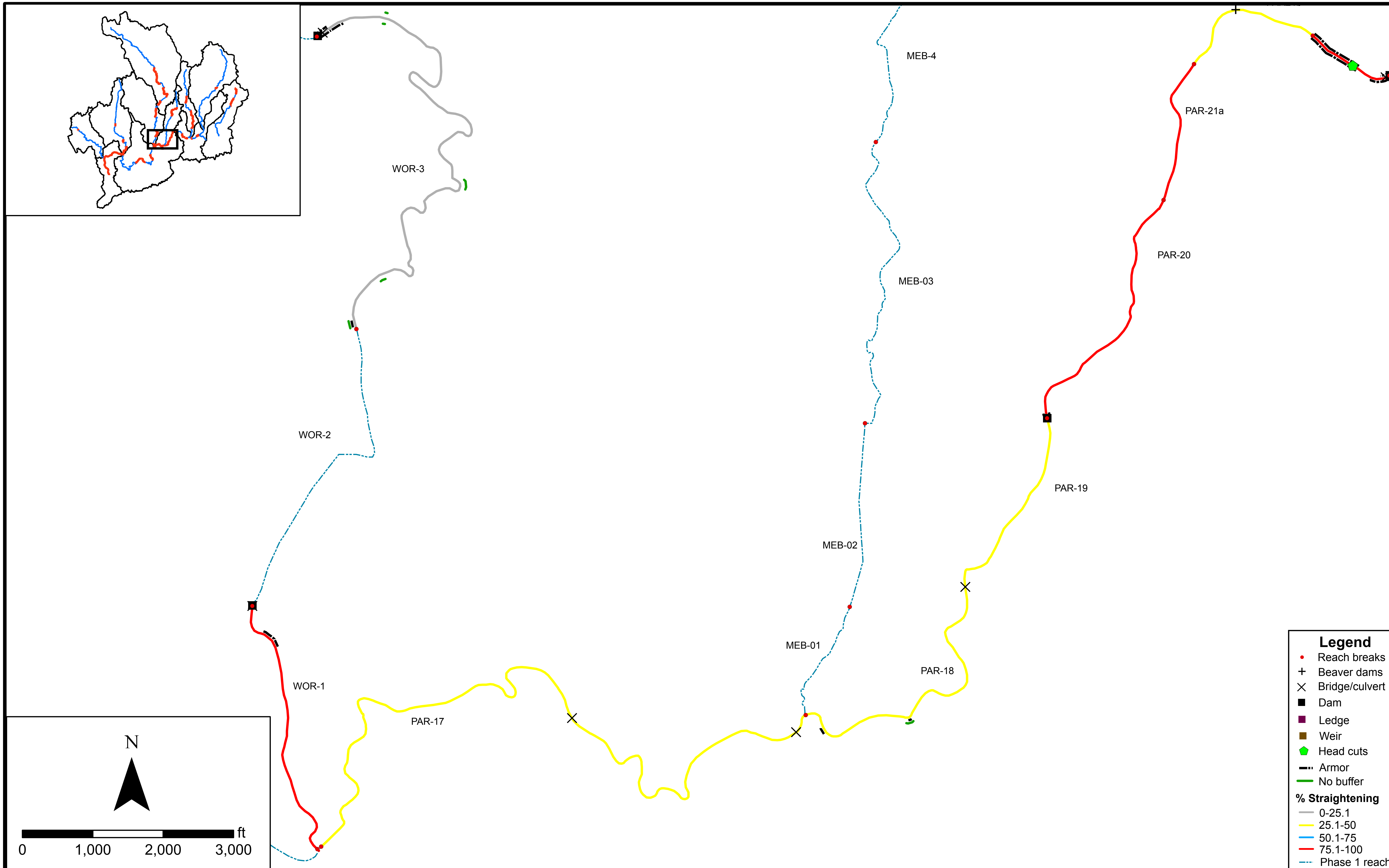

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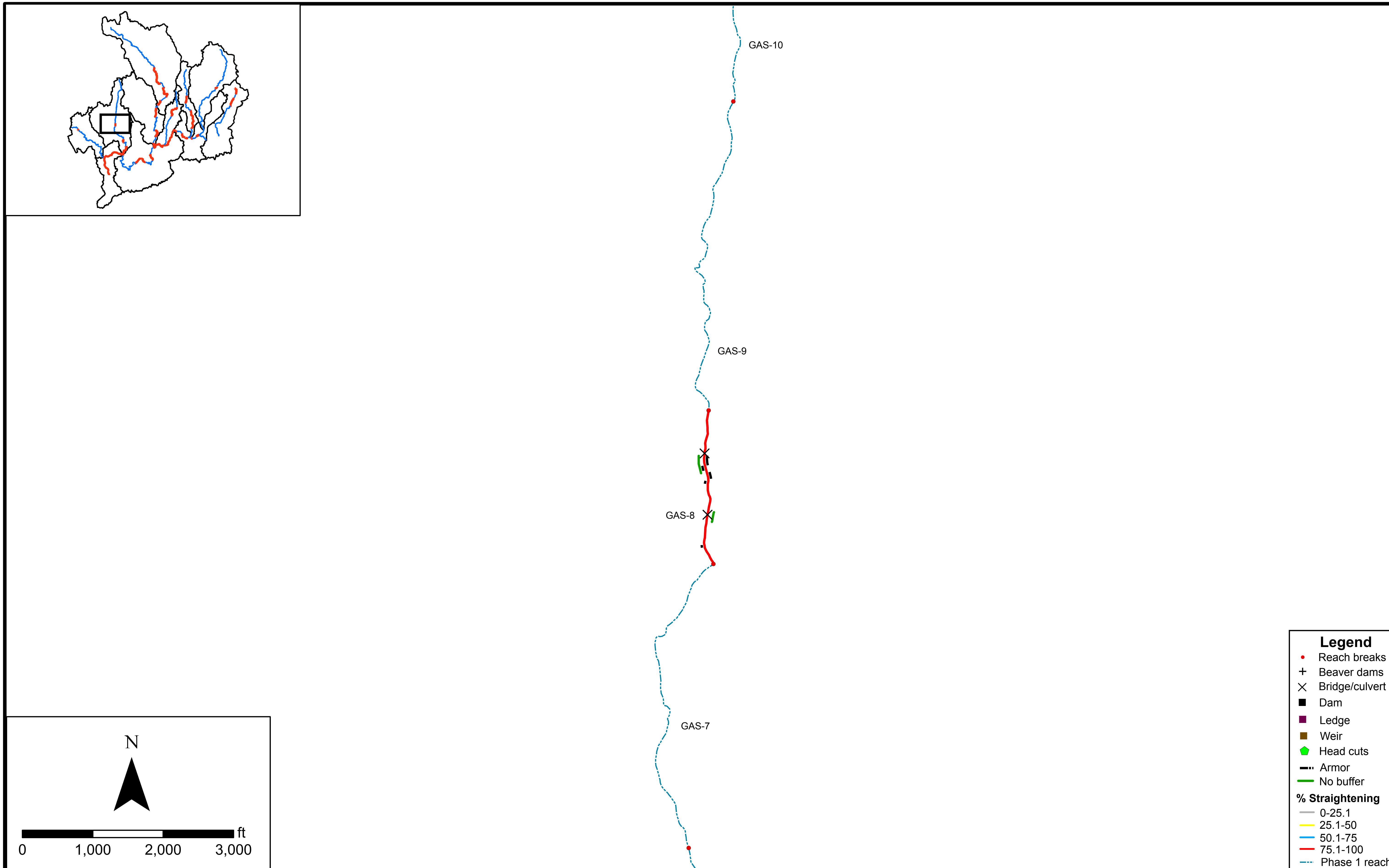

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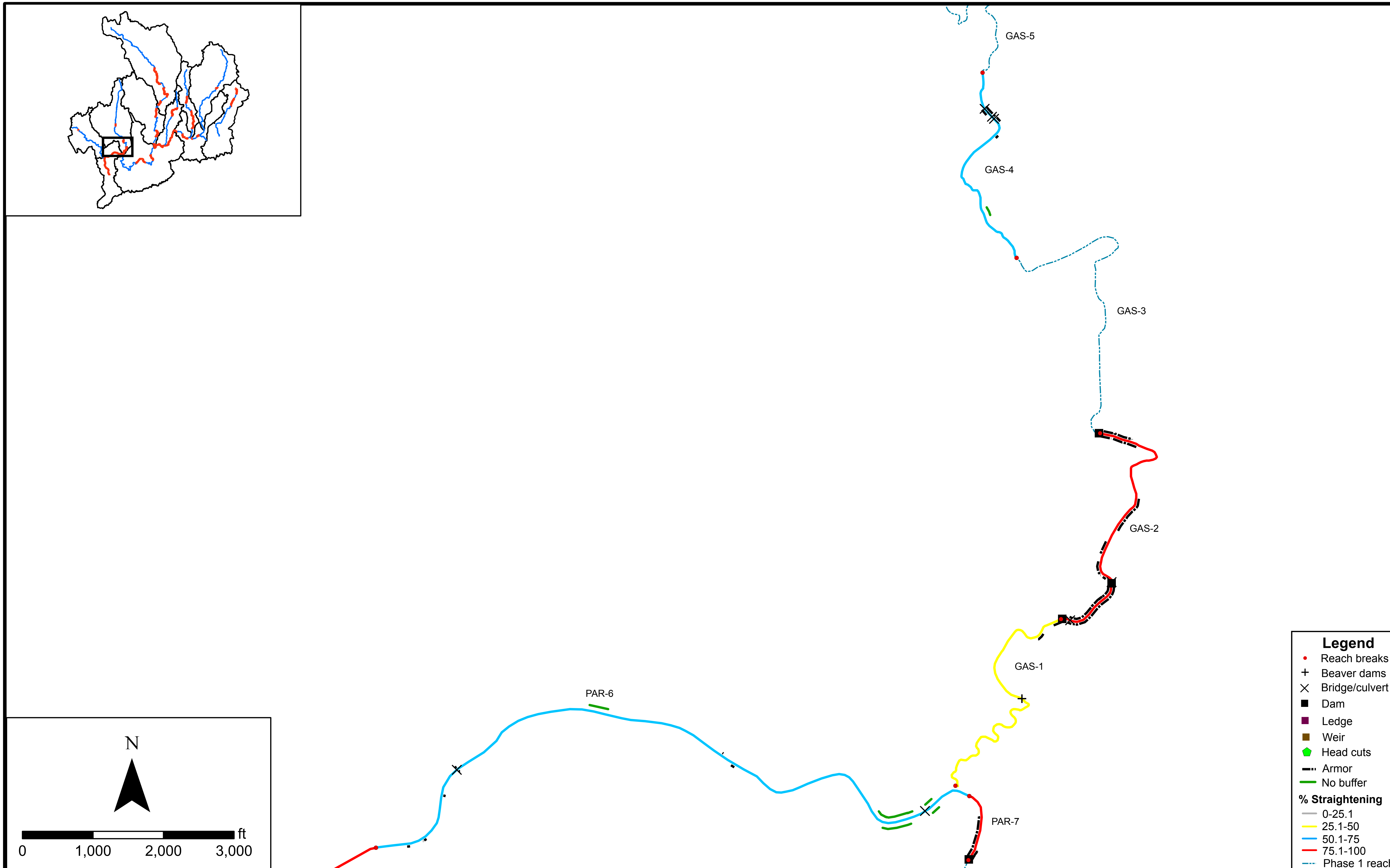

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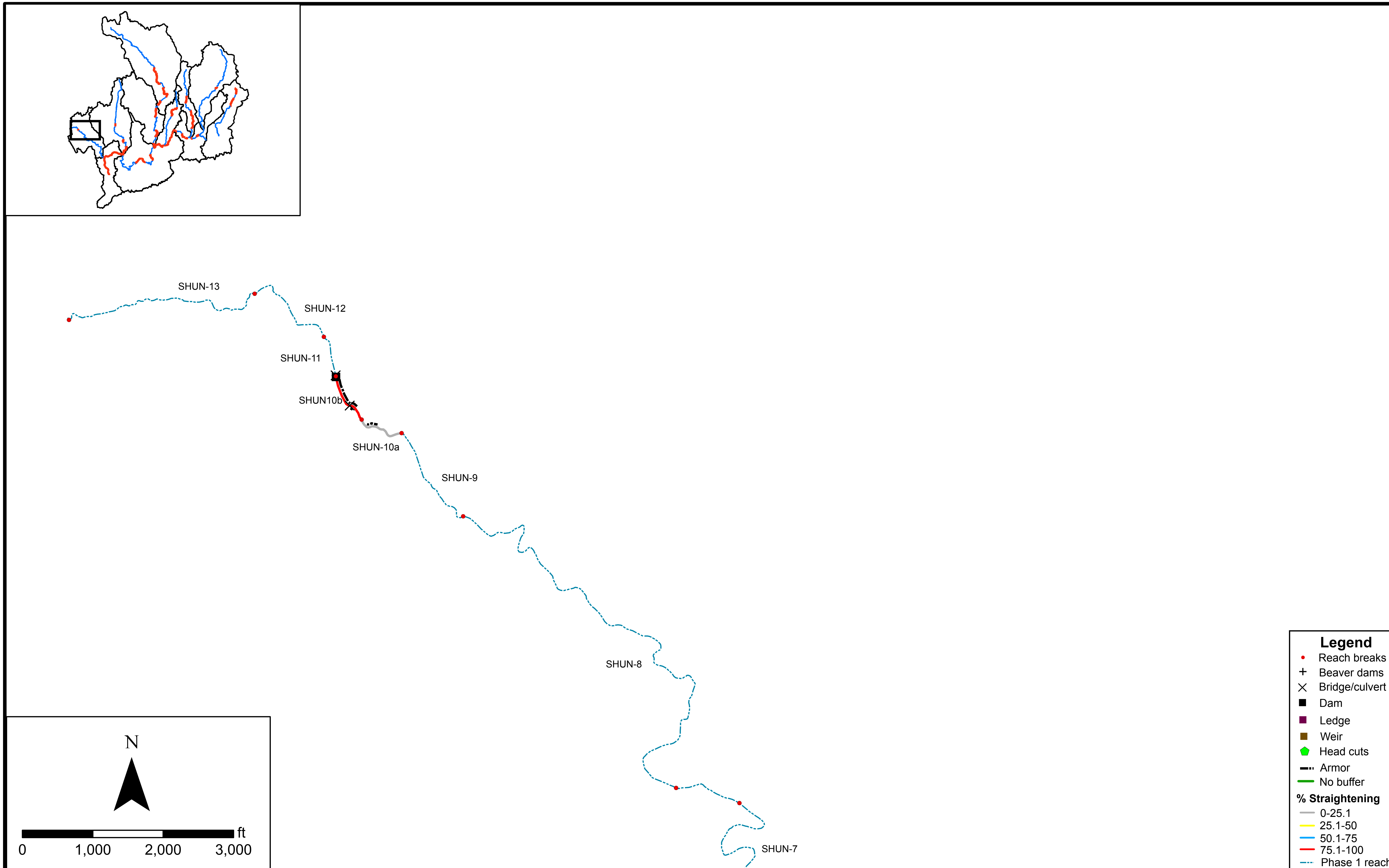

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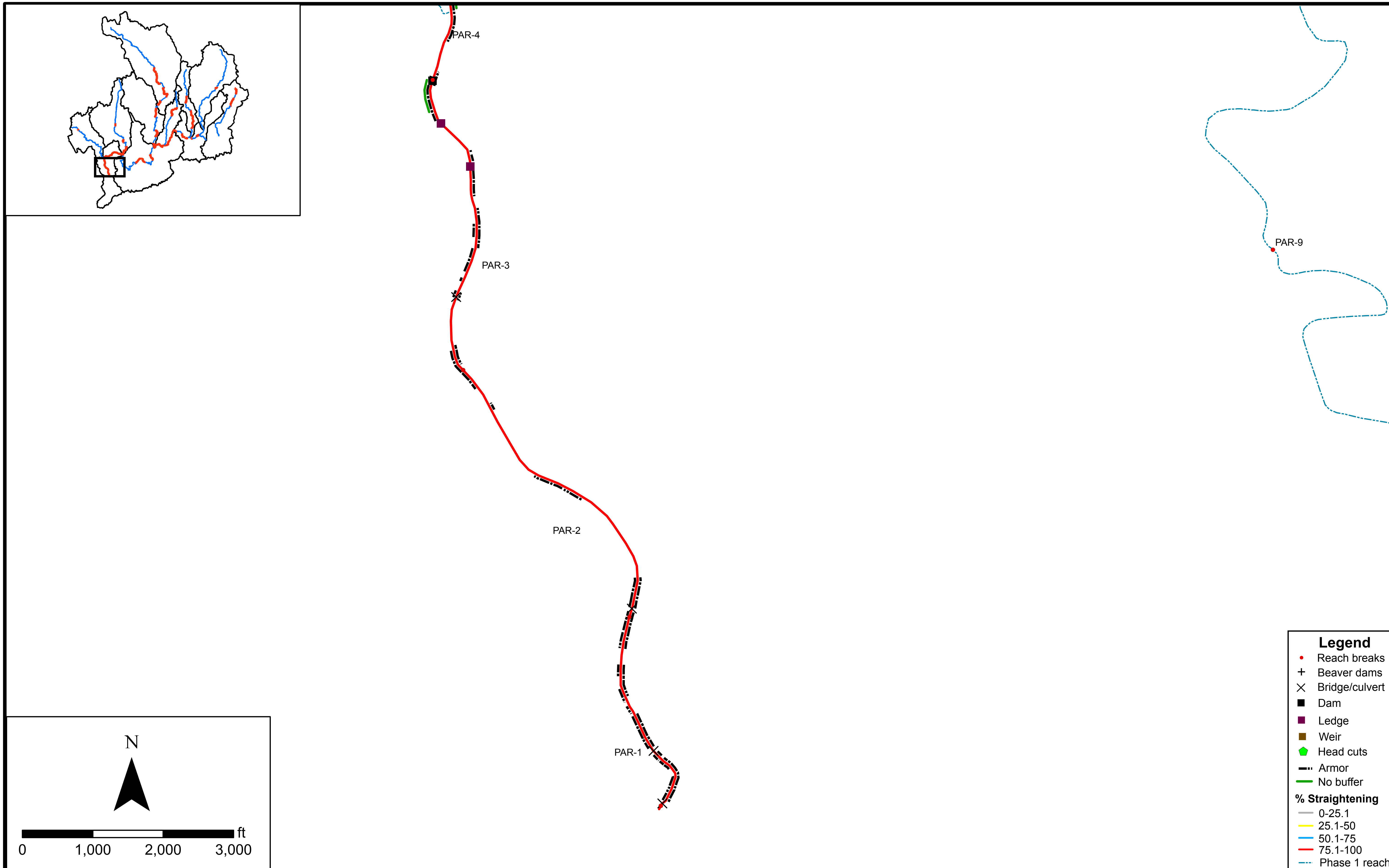

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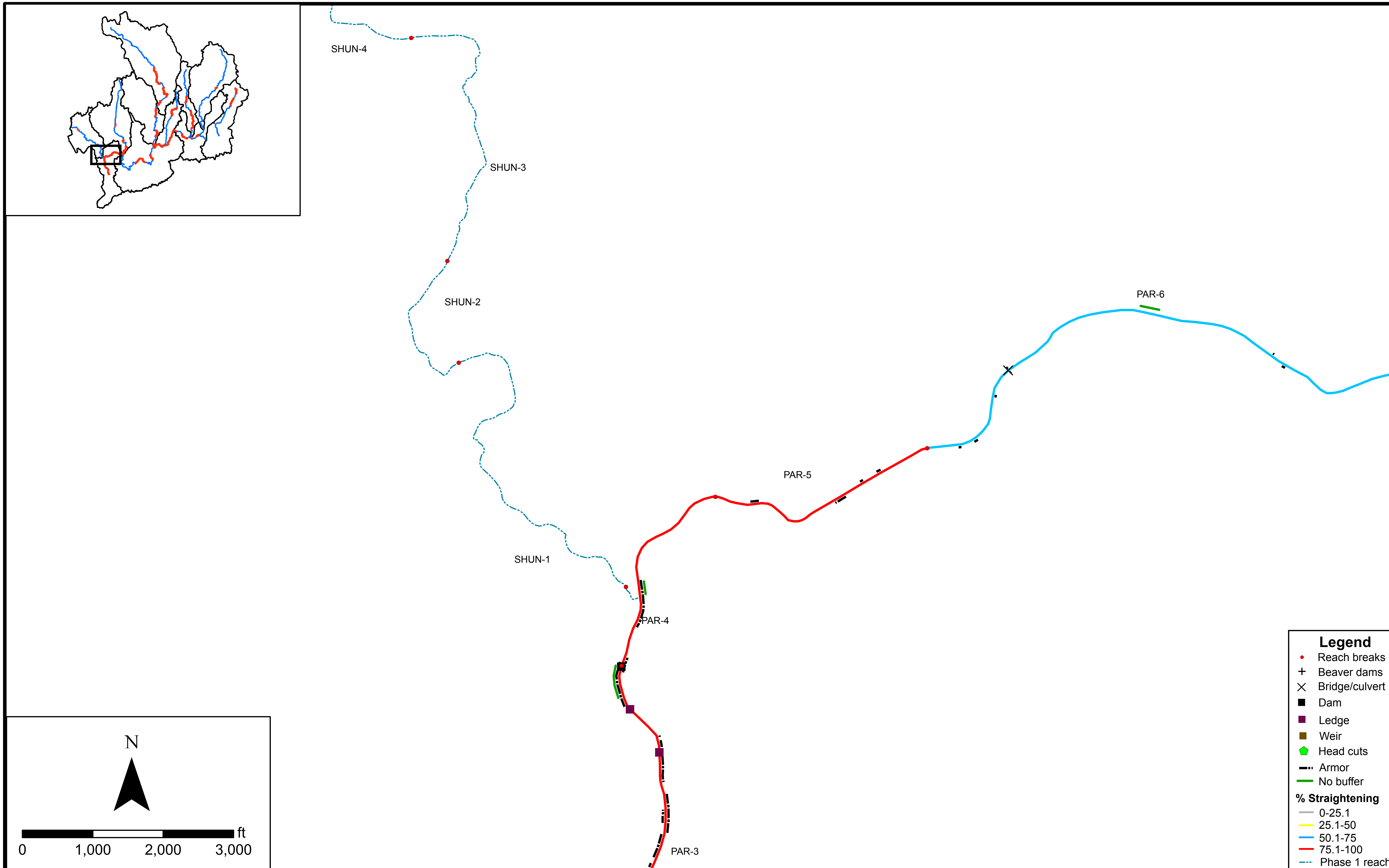

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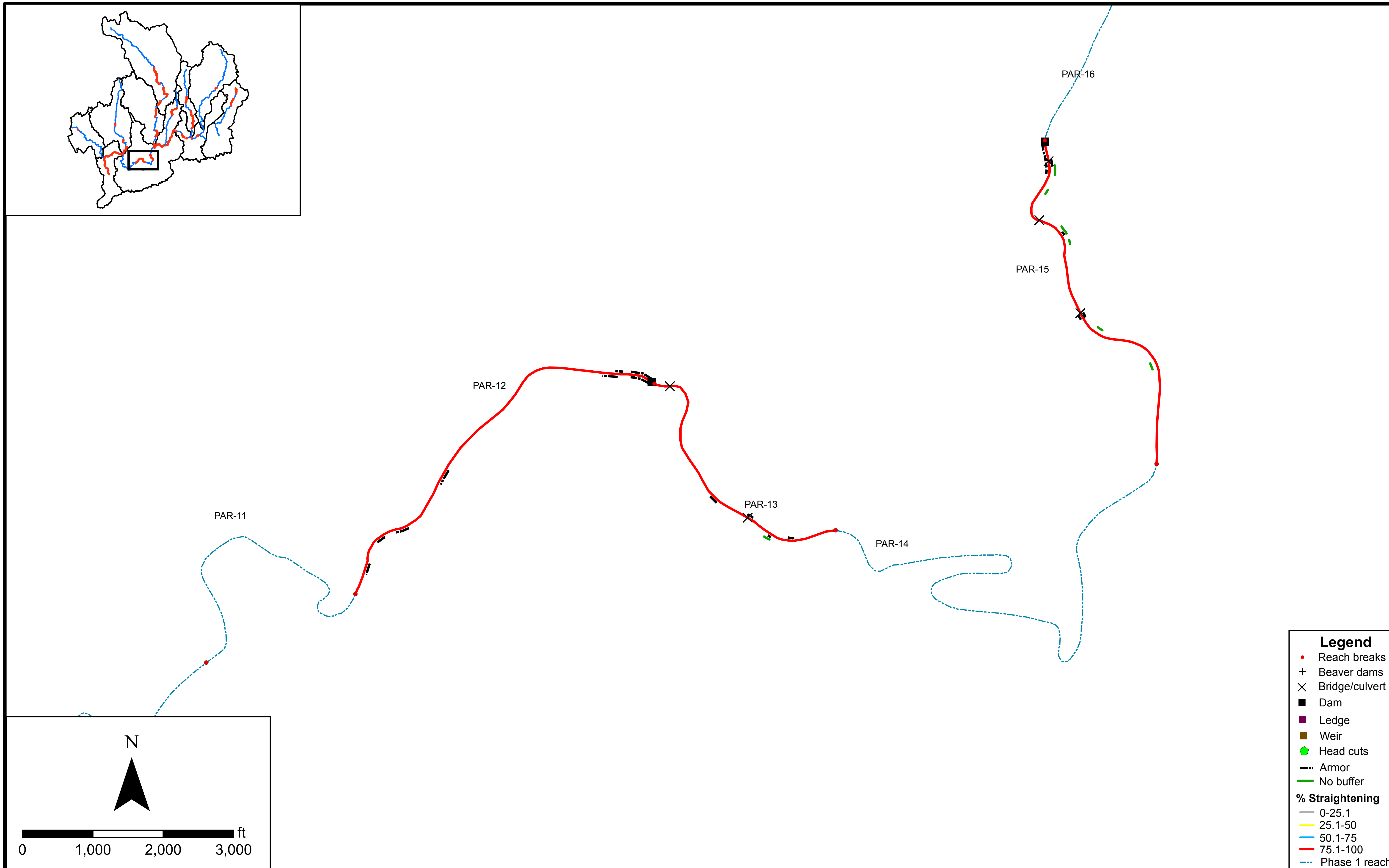

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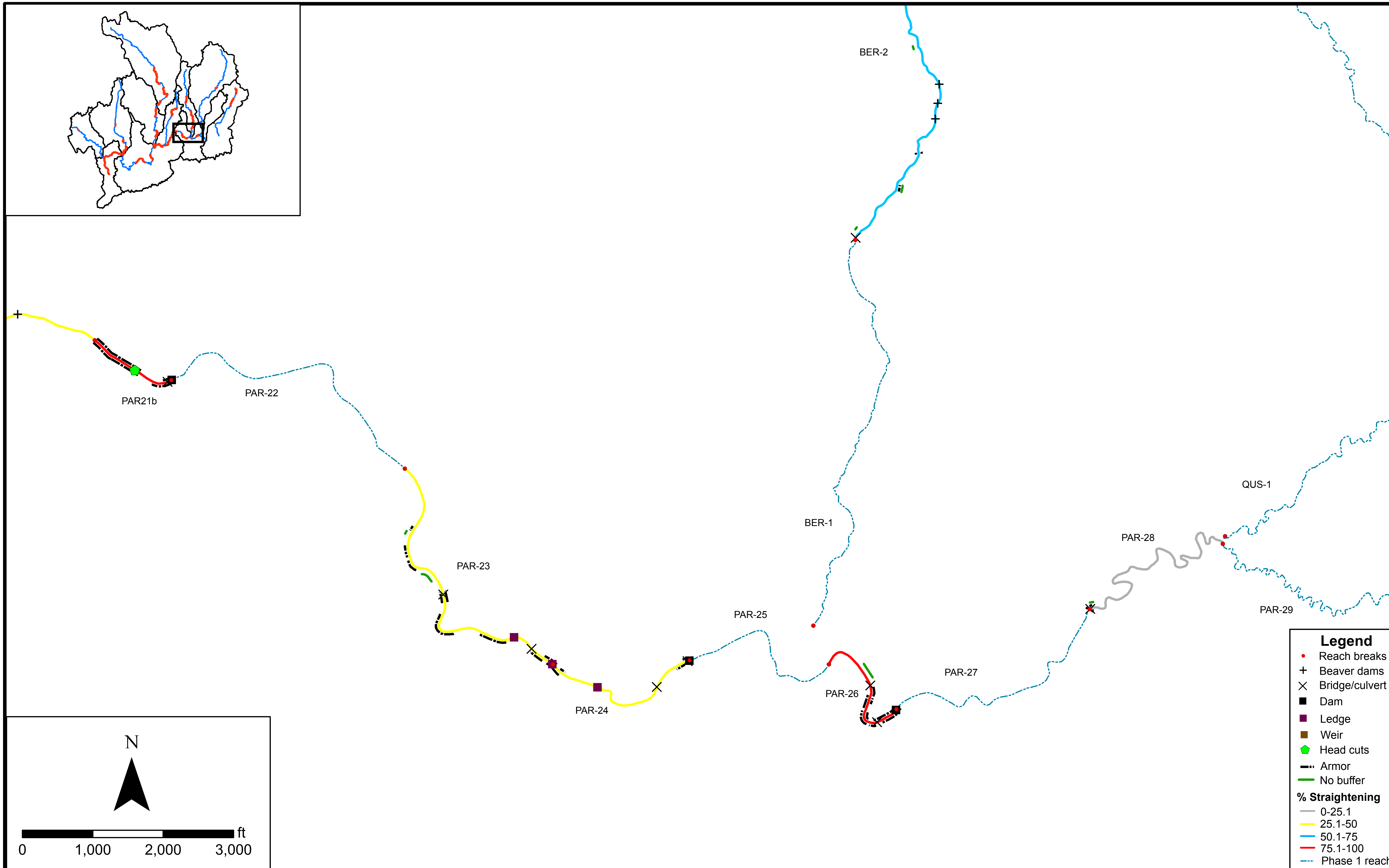

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