Fluvial Geomorphic Assessment and River Corridor Planning in the Wood-Pawcatuck Watershed, RI and CT

Prepared for

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EXECUTIVE SUMMARY

A geomorphic assessment of the Wood-Pawcatuck Watershed was undertaken in the summer and fall of 2015 as part of a multi-phase assessment and planning effort to develop a watershed management plan designed to improve flood resiliency in the watershed. The geomorphic study was completed using a two-phase assessment method developed by the Vermont River Management Program. Remote sensing data was used for a Phase 1 assessment over most of the watershed to tabulate information on drainage area, valley width, valley gradient, changes in land use, and other watershed characteristics for 145 distinct riverine reaches of uneven length. A more detailed field-based Phase 2 assessment was completed on 44 of these reaches covering 38 stream miles to identify human manipulations of the channel and determine how the channel is responding to those human alterations. The assessment results were used to develop River Corridor Protection area maps for the Pawcatuck River, Wood River, Shunock River, Green Fall/Ashaway River, Queen/Usquepaug River, Beaver River, Chipuxet River, and Meadow Brook. The maps show river channel sensitivity to change and the zone within which channel migration is needed in order for the river to achieve an equilibrium condition. A River Corridor Planning guide that will prioritize restoration sites and methods for achieving channel equilibrium and increased channel stability is under development as a stand-alone document based on the geomorphic assessment results.

Flood and erosion hazards in the Wood-Pawcatuck Watershed have been exacerbated by human manipulations of the channel. Numerous dams on the mainstem and its tributaries reduce flow velocities and stream power in riverine reaches upstream of impoundments, leading to deposition, channel migration, and planform change. Downstream, sediment deposition is limited, channel evolution slowed, and channel incision sometimes significant due to the loss of sediment throughput past the dams. Undersized stream crossings have similar effects as the dams but are more localized. The impacts, however, can cause damage to the structures themselves as the rivers and streams in the watershed adjust to the sudden narrowing of the channel and/or blockage of the floodplain at the crossings. The detailed Phase 2 fieldwork revealed that more than 45 percent of the 52 bridges and 83 percent of the 12 culverts assessed were undersized and exhibited deposition upstream and/or scour downstream in response. Historic artificial channel straightening occurred along most of the watershed’s water courses and greatly reduced flow complexity and the quality of aquatic habitat throughout the watershed. In areas more sensitive to change (i.e., upstream of dams and undersized crossings), meanders are reforming as the straightened channels widen, sediment is deposited, and flow is deflected into the banks or onto the adjacent floodplain. A straightened configuration persists to this day in areas less sensitive to change such as downstream of dams. While the continued reformation of meanders, with the associated risks of bank erosion and channel avulsion, are potentially hazardous if occurring where infrastructure is present in the river corridor, the planform changes improve aquatic habitat while attenuating the downstream movement of floodwaters and sediment. Given the potential for reducing hazards downstream, protecting undeveloped areas from future development through land conservation and encouraging meander reformation on straightened reaches represent management strategies that could reduce flood risks to downstream infrastructure in the river corridor.

1.0 INTRODUCTION

A geomorphic assessment of the Wood-Pawcatuck Watershed in Rhode Island and Connecticut was conducted to identify flood hazards, areas of channel instability, and the underlying causes for channel adjustments threatening human infrastructure and aquatic habitat. The Wood-Pawcatuck Watershed at its outlet in Little Narragansett Bay drains more than 300 mi^2 and contains the towns of Westerly, Charlestown, Richmond, Hopkinton, South Kingstown, Exeter, and West Greenwich in Rhode Island. The watershed extends westward into the towns of North Stonington, Voluntown, Stonington, and Sterling in Connecticut. This study focused on the mainstem of the Pawcatuck River, and several of its larger tributaries including the Wood, Shunock, Green Fall/Ashaway, Chipuxet, Queen/Usquepaug, and Beaver Rivers as well as Meadow Brook (Figure 1).

Funding for the project came from a National Fish and Wildlife Foundation grant awarded to the Wood-Pawcatuck Watershed Association to develop a flood and storm resiliency management plan for the Pawcatuck Watershed that was severely impacted by a flood in 2010. The geomorphic assessment was conducted to assist in the development of the management plan and was completed using Vermont's Phase 1 and Phase 2 geomorphic assessment protocols (Web citation 1). The major outcomes of the geomorphic assessment include completion of: 1) a Phase 1 watershed assessment using remote sensing and existing GIS data for the Wood-Pawcatuck Watershed to characterize natural conditions influencing river conditions; 2) a Phase 2 geomorphic assessment utilizing field-generated GIS data to identify human impacts to river morphology and processes; 3) River Corridor Protection (RCP) area maps to highlight zones within which river migration might occur in the future; and 4) a geomorphology-based river corridor planning guide to prioritize sustainable restoration strategies for reducing flood hazards and improve aquatic habitat. Following a brief description of the Wood-Pawcatuck Watershed and discussion of the assessment methods, the findings of each project outcome are presented below. Implementation of the assessment findings will strengthen the watershed's resiliency to changing hydrologic regimes, restore habitat along degraded channels, and protect local communities from future floods.

2.0 WOOD-PAWCATUCK WATERSHED DESCRIPTION

The Pawcatuck River drains 300 mi^2 as it flows nearly 40 mi from its source at the Great Swamp 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 include 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 northern part of the watershed drains the New England uplands, and the southern divide is created by the Charlestown Moraine (WPWA, 2005). The highest point in the watershed is Bald Hill at 630 ft above sea level.

Geologically, the watershed drains Neoproterozoic and Paleozoic igneous and metamorphic rocks typical of the New England Upland physiographic province (Web Citation

2). Overlaying this bedrock are glacial deposits consisting of coarse ablation and lodgment till thinly draping hillslopes and more thickly filling valley bottoms. Finer, stratified glaciofluvial outwash sediments are found underneath flat terrace surfaces (Kaye, 1965). The glacial history of the watershed has played a large role in shaping modern drainage patterns. The deposition of the Charlestown Moraine blocked and filled in southerly flowing paleovalleys (Kaye, 1965). As the glaciers retreated behind this terminal moraine, Glacial Lake Worden filled in the blocked valley where the Great Swamp and Worden Pond exist today. Sediment-laden glacial meltwater streams flowing from the north deposited wide, level outwash plains and deltas that built out into this glacial lake. The Pawcatuck River eventually overtopped and breached the Charlestown Moraine in Westerly, resulting in the draining of the glacial lake. Subsequent river incision progressed eastward and captured the southward draining valleys represented today by the Pawcatuck tributaries assessed as part of this study. Several of the ledge waterfalls present on the Pawcatuck River are at points where the river breached paleo-drainage divides between these tributaries.

The modern streams draining the Wood-Pawcatuck Watershed typically have utilized paleo-valleys, ice collapse features, and erodible outwash deposits to establish their post-glacial courses. In the northern part of the watershed, streams typically flow over outwash deposited in the paleo-valleys with the valley's width defined by the location of low bedrock and till covered hillslopes. Further downstream, streams have incised into outwash deposits and high glacial outwash terraces define the valley edge. Where the streams abut these high banks of outwash sediments, a large amount of sediment can be delivered to the channel and cause downstream aggradation, bank erosion, and flooding.

Data on historic discharges in the watershed are available at several locations in the watershed. The longest operational gage is on the Pawcatuck River in Westerly with peak discharges recorded annually since 1941 (Figure 2 and Web citation 3). All nine USGS gages in the watershed record the flood of record on or near March 30, 2010. The flood resulted from a record breaking two-day rainfall in many parts of Rhode Island and was caused by several consecutive slow moving low pressure systems (NOAA, 2013). This flooding inundated parts of the Amtrak railroad line in Westerly and caused the Blue Hill Pond Dam to fail at the headwaters of Canonchet Brook. The Pawcatuck River stayed above flood stage for over 10 days. The Kenyon Industries and Bradford Mill complex were both completely inundated, and portions of several roads were under water for several days after the flood (Figure 3). Other major recorded floods include the June 6th flood of 1982, the Great Flood of 1936, the November 1927 flood, and a flood in 1968 (Web citation 4). Knowledge of these past geological events and historic flood events is important for interpreting the geomorphic assessment data and understanding how the river will respond to future extreme discharge events.

Much of the Pawcatuck River watershed is forested and the lower floodplain surfaces in most areas are free of human development. This is an important asset in the watershed as a key to watershed resiliency is to provide rivers and streams a sufficient corridor within which to migrate and maintain an equilibrium condition. A wooded, rather than developed, floodplain is important for attenuating flood discharges and erosive forces and preventing them from being concentrated near infrastructure. A river in equilibrium continues to shift and migrate and without the room to do so the river will often respond in a manner that exacerbates flooding, erosion, and habitat degradation. Wooded banks and floodplains reduces the rate of channel migration, thereby limiting downstream sediment loading while creating high-quality habitat as wood is recruited into the channel. Land conservation efforts targeting these forested floodplains may represent the best approach for ensuring long-term flood resiliency in the watershed.

Many reaches in the watershed were most likely artificially straightened historically. As a result of higher flow velocities due to the shortening of the channel, straightened reaches transport more sediment downstream that then accumulates in lower gradient reaches where flooding and erosion are exacerbated. Although flood stage may be temporarily reduced within the straightened sections themselves, higher peak discharges result downstream in addition to the greater sediment loading.

Encroachment into the river corridor by roads, railroads, and other structures are a human-induced alteration that constrains natural river processes in the watershed. Numerous dams and mills are found along the mainstem and tributaries alike, impacting both the channel and floodplain. For example, the Pawcatuck River descends vertically 90 ft from Worden Pond to the estuary in Westerly with approximately 54 ft of this drop occurring at dams and nearly 6 mi of river impounded upstream as a result. Dams disrupt the sediment supply to downstream reaches, potentially causing incision of the bed and the abandonment of the river floodplain. Upstream of impoundments, the backwater effects can cause excess sedimentation, promote the creation of meanders, and encourage channel avulsions (i.e., rapid shifts in channel position) (Figure 4). Several undersized stream crossings in the watershed also act as de facto dams during high flows and similarly cause backwatering, deposition, bifurcating flow, and channel avulsions upstream of the crossing and scour downstream (Figures 5 and 6). These undersized crossings increase the risk of floods inundating the associated road or railroad and could potentially cause floods to breach through a section of road fill adjacent to the existing channel. Beavers can also take advantage of undersized crossings, exacerbating the backwater effect (Figure 7).

[Undersized crossings for the purposes of the geomorphic assessment are defined as those crossings where the opening width is less than the bankfull width of the channel as determined from physical bankfull features in the field (e.g., slope break between bank and floodplain, edge of perennial vegetation). Although the bankfull width based on such physical indicators are likely consistent with the width of flow determined from hydraulic modeling of the 1-2 year recurrence interval flow, bankfull determinations in the geomorphic assessment are not based on hydraulic modeling results. Although a crossing that is undersized from a geomorphic perspective may still have the hydraulic capacity to convey a flow much greater than the bankfull discharge (because of its height and limited hydraulic roughness), channel adjustments are still likely to occur as the channel responds to the rapid change in flow width encountered between the natural channel and narrower opening at the crossing. Even if the crossing width matches the bankfull width, channel adjustments are still possible during large floods greater than the bankfull discharge if the road approaches block floodplain flow, because flow would still be squeezed through a crossing narrower than the width of flow spread across the floodplain. Consequently, floodplain relief culverts passing under elevated road approaches may need to be considered along with resizing the undersized crossings themselves in order to adequately address flooding and habitat concerns associated with undersized crossings.]

The floodplain alluvium and outwash terraces adjacent to the river and its tributaries are locally important sand and gravel resources. Gravel mining in some locations has lowered sections of elevated outwash terraces to the elevation of the river and, therefore, has increased the likelihood that the river could erode a new channel through an outwash terrace during a single flood event (Figure 8). A large scale avulsion occurred on the Suncook River in Epsom, NH in 2006 as the result of similar gravel mining that lowered a terrace surface sufficiently to enable floodwaters to overtop a low drainage divide (Web citation 5). Geomorphic assessments are useful for unravelling the relative influence of historic and modern land uses on current channel conditions and for identifying potential flooding and erosion problems such as the potential impacts of gravel mining, channel straightening, dams, and undersized stream crossings.

3.0 ASSESSMENT METHODS

Recognizing the value of fluvial geomorphology to reduce erosion hazards and improve aquatic habitat, Vermont's River Management Program developed a Stream Geomorphic Assessment methodology to reveal the underlying causes for channel instabilities resulting in erosion and other riverine hazards (Web citation 1). The Vermont protocols are gaining wider acceptance nationally as a method for delineating key areas needed to protect river processes and establish channel equilibrium, a channel condition that sustains flood resiliency and high quality aquatic habitat. The assessment methods detailed in Vermont's Stream Geomorphic Assessment protocols were used in the Wood-Pawcatuck Watershed assessment.

Fluvial geomorphology-based assessment approaches, such as that developed by the State of Vermont, are devoted to understanding how the natural setting and human land use in a watershed effect river channel processes (i.e., sediment transport) and form (i.e., channel dimensions and shape). River channels are in constant adjustment to alterations in watershed conditions, but can eventually establish an equilibrium channel form if no significant perturbations occur for extended periods. However, some river channel adjustments may continue for thousands of years when responding to climatic influences (e.g., deglaciation in New England), so river channel changes may be ongoing throughout the design life of flood control, bank protection, and river restoration projects. 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, rivers can experience bank erosion and changes in channel position even while maintaining an equilibrium condition where the channel dimensions and planform shape remain the same. Consequently, geomorphology assessments are essential before significant efforts are made to develop river management plans. Corridor protection and restoration projects are more likely to succeed with an understanding of how the channel is responding to natural conditions and human activities in the basin and how the channel may respond to the proposed management efforts. Therefore, geomorphic assessments, such as the Vermont protocol methodologies described below, must focus on both the natural and watershed conditions that engender channel adjustments and describe the current channel conditions that reflect the ongoing evolution of the river system.

3.1 Phase 1 assessment

Phase 1 of Vermont's Stream Geomorphic Assessment protocols utilizes topographic maps, aerial photographs, available LiDAR elevation data, soils maps, and archival records to characterize the natural conditions and human land uses in the watershed that may be controlling morphological conditions in the channel (Web citation 1). Since different portions of a river can respond differently to the same natural and human factors, one of the most important tasks of the Phase 1 assessment is to subdivide the river into distinct reaches. Within a given reach, the river is assumed to respond similarly to changing watershed conditions while adjacent reaches may respond differently. Reaches that share similar traits are referred to as "like-reaches" and an understanding of channel response or effective management techniques gained in one reach may apply to other "like-reaches". The break points between different reaches are made based on the presence of abrupt changes in valley slope or channel planform, grade controls (i.e., waterfalls and dams), constrictions of valley width, expansions of valley width, and the confluence of a major tributary. 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 9 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). Of all the reaches identified, 24 of the reach breaks occur at natural valley constrictions, 5 at artificial valley constrictions (i.e., road/rail grades blocking the floodplain), 20 at expansions in valley width, 25 at the confluence of major tributaries, 8 at significant natural changes in valley slope, 36 at dams, 27 at the upstream end of impoundments, and 4 at changes in planform (i.e., straightening, multithreaded channel).

Reaches downstream of constrictions occupy more confined valleys where the river channel has a greater likelihood of flowing against glacial sediments exposed along the high valley walls. The potential for high rates of sediment production in these locations can affect channel morphology differently than reaches occupying wide valleys where the channel is more likely to encounter only floodplain sediments. Reaches downstream of tributary confluences will generally have a morphology different than reaches immediately upstream because of the introduction of sediment from the confluence. The morphological impacts of tributary confluences, as well as valley constrictions and expansions, are generally most noticeable at or near the reach break. Consequently, the locations of the reach breaks themselves are likely points of channel instability with active bar formation, bank erosion, and channel migration possible.

After identifying the reaches, data on drainage area, valley width, valley slope, and other characteristics measurable from remote sensing data are gathered and recorded for each reach. Identifying the conditions adjacent to the channel (e.g., soil type, valley confinement) and in the larger watershed (e.g., drainage area, forest cover) can help determine the channel morphology that would be expected to develop in the absence of human impacts. Morphological parameters such as sinuosity, channel slope, and meander migration rates can be ascertained from current and historic topographic maps and aerial photographs and provide clues to past channel straightening and areas of rapid channel adjustment. Once the Phase 1 assessment was completed, 38 river miles encompassing 44 reaches were chosen for the Phase 2 assessment.

3.2 Phase 2 assessment

In the absence of human settlement, a channel's morphology (i.e., cross sectional dimensions and planform) responds to natural conditions present in the watershed. Differences between the morphology expected under natural conditions (as established in the Phase 1 assessment) and what morphology actually exists are generally an indication that human impacts are altering channel morphology. Determining and comparing these existing and expected morphological conditions within selected Wood-Pawcatuck Watershed reaches are accomplished through the Phase 2 assessment by surveying the existing channel dimensions and mapping channel conditions in the field. Large bar deposits can also be identified and may indicate areas of high sediment supply or rapid loss in sediment carrying capacity. Some of the bed and bank features mapped along the length of the river include bank stability (i.e., location of erosion), bank material (i.e., soil type), substrate particle size, depositional features (i.e., point bars, mid-channel bars), grade controls (i.e., waterfalls, dams), encroachments (i.e., roads, railroads, berms adjacent to the channel), and riparian buffer width. The mapping was completed with a Trimble Yuma tablet computer loaded with ArcPad 10 GIS software and a built-in GPS unit. GIS shapefiles were created for all bed and bank features such that the exact location of certain channel conditions is known for the assessed Phase 2 reaches.

The channel's dimensions were surveyed using a tape, level, and stadia rod. The morphological parameters recorded within each reach were the bankfull width, bankfull depth, and the height of the adjacent floodplain relative to the bankfull level. These parameters, explained in detail in the Vermont protocol handbooks (Web citation 1), enable a determination of the width:depth ratio, incision ratio, and entrenchment ratio, critical dimensionless values that can be compared from reach to reach and with reference values (i.e., the expected conditions in the absence of human influence) to determine the relative impacts of human activities on flooding, erosion, and aquatic habitat degradation. These measurements also determine the stream type of each reach using the nationally recognized Rosgen channel classification system (Rosgen, 1996).

The Phase 2 assessment protocols also consist of a Rapid Geomorphic Assessment (RGA) and Rapid Habitat Assessment (RHA), standardized forms that provide information on different aspects of the geomorphic and habitat conditions, respectively, of each reach. The forms provide a means by which the level of habitat degradation (e.g., lack of pools) and geomorphic instability (e.g., high width:depth ratios) can be compared between reaches, thus helping to select the most appropriate watershed management efforts throughout the watershed. The RGA protocol documents the past and current channel adjustments influencing the river's processes. The RGA draws on a set of specific observations to determine if degradation, aggradation, widening, and planform adjustment are occurring in a reach. Observations on bank stability, the presence of headcuts and flood chutes, and the abundance and relative height of channel bars factor into scores ranging from 0 to 20 (poor to reference conditions) for these 4 river processes.

The RHA protocol contains specific parameters designed to evaluate the physical components of the river, including the channel bed, banks, and riparian zone. The RHA is designed to provide an understanding of the physical conditions present that affect aquatic habitat. The results of the RHA can be used to compare physical habitat conditions between reaches and watersheds and serve as a management tool for watershed and land use planning. As with the RGA, each parameter is scored on a scale of 0 to 20 (poor to reference conditions), and the results are totaled to provide an overall score that reflects the habitat condition of the reach.

The existing stream type and stream condition (based on the RGA score) combine, through a rating table provided in the protocol, to yield a stream sensitivity rating for the reach. Stream sensitivity reflects the likelihood that a reach will respond rapidly to a disturbance or change in watershed conditions such as a large flood or change in land use within the river corridor. A reach's sensitivity to a change in condition is dependent upon its setting, channel form, and substrate particle size. For example, a steep confined bedrock channel will be much less sensitive to human activities in the channel or watershed than a steep confined channel with sandy banks.

Given that stream crossings are structures that can potentially impact channel stability, a bridge and culvert assessment form was completed for every bridge and culvert crossing the Phase 2 reaches assessed (Web citation 1). Changes in channel width as well as depositional and erosional features found immediately upstream or downstream of the crossing structure are recorded to identify potential impacts of the structure on channel stability. The results of the bridge and culvert assessment highlight crossing structures that may be: 1) acting as barriers to fish and aquatic organism passage, 2) impacting sediment transport, 3) creating erosion or inundation hazards, or 4) at risk of failure due to scour or overtopping. The bridge and culvert assessment results are not based on the current structural integrity of the crossings but rather incorporate field observations and measurements of channel conditions that can help state and local agencies red flag structures where the structural integrity might be threatened in the future by channel adjustments.

As human impacts on the channel are identified during the Phase 2 assessment, the reaches are sometimes further subdivided into segments. Through this segmentation process, a single reach that would be expected to have the same morphology throughout its length under natural conditions may be broken into two or more segments of potentially different morphology due, for example, to a road built right along the edge of the river for only a portion of the reach's full length. Most Phase 2 reaches in the Wood-Pawcatuck Watershed were not segmented, because no human influence was present along the reach or the entire reach was similarly affected by human impacts. However, five reaches were further segmented due to variations along their lengths (Table 1). Each segment is assigned a lowercase letter beginning with "a" at the downstream end of the segmented reach such that Segment PAR-21a is the downstream most segment in Reach PAR-21. Each segment identified is assessed separately with new Phase 2 forms completed for each segment in the reach rather than using a single form for the reach as a whole.

The description of the Phase 1 and Phase 2 results in Section 4.0 and Section 5.0, respectively, below refers to many geomorphic characteristics and methods that are described fully in Vermont's Stream Geomorphic Assessment Protocols (Web citation 1). The RGA, RHA, bridge and culvert assessment, and Phase 2 field forms used in this study are all available with the protocols. The data collected on the field forms were compiled in a Microsoft Access database (Appendix 1) from which much of the information presented in Section 4.0 and Section 5.0 has been extracted.

4.0 PHASE 1 GEOMORPHIC ASSESSMENT RESULTS

After establishing the reach breaks (Table 1 and Appendix 1), the Phase 1 assessment uses remote sensing data (e.g., topographic maps, aerial photographs, LiDAR, soils maps) to tabulate information on each reach such as subwatershed drainage area, gradient, valley width, expected bankfull channel width under natural conditions, valley length, and channel length (Table 2 and Appendix 2). The tabulated data is used to establish several dimensionless ratios that provide information on the channel type/morphology that would be expected to form under natural conditions and also provides hints as to how the expected morphology has been altered by humans. The channel type that emerges under natural conditions is in large part based on the gradient (as measured on topographic maps), bank composition (based on soils maps), and valley confinement (i.e., ratio of valley width to channel width). The expected natural channel width is derived from the Massachusetts regional hydraulic geometry curve (Bent and Wait, 2013) that compares the channel width (and other dimensions) of several relatively undisturbed rivers in a region with the drainage area of each site. The drainage area at the downstream end of each reach is the sum of the drainage area feeding the upstream end of the reach plus the additional area that drains directly into that reach (i.e., subwatershed area). Possible human alterations of the channel can be identified by calculating the channel's sinuosity (a measure of how much the channel meanders and based on the ratio of the channel gradient to valley gradient). A sinuosity of 1.0 represents a straight channel and is usually an indication of artificial channel straightening in unconfined valleys where meandering channels (with a high sinuosity) naturally form.

The Phase 1 assessment data is also used to develop GIS shapefiles of the valley wall, meander belt, and meander centerline – all important parameters in establishing the River Corridor Protection areas discussed in Section 6.0 below. The valley wall represents the outer edge of the floodplain where it contacts the base of the side slopes leading to an elevated hillside or terrace surface. The valley wall represents the outer limits of long-term channel migration across the floodplain and, depending on composition, can also be a source of large volumes of sediment to the channel when the river impinges along its edges. This contact between the flat floodplain and steeper valley side slopes is generally visible on topographic maps and for the Pawcatuck Watershed the valley wall was hand digitized in GIS with topographic maps as a base layer with aerial photographs and LiDAR consulted to clarify more complex areas (Appendix 1). Defining the valley wall was difficult in many parts of the Pawcatuck Watershed because of extensive wetlands that have little topographic relief but are at times located on drainage divides between multiple watersheds. In these instances, the valley wall was somewhat arbitrarily drawn across the wetland in order to complete unbroken valley wall shapefiles for the Pawcatuck River and its tributaries. The meander belt is generally inset within the valley wall and represents the zone within which meanders or former meanders have migrated along the river. The meander belt is assumed to encompass the zone within which future channel migration and meander growth is expected to occur. For the Wood-Pawcatuck Watershed, the outer edges of the meander belt were hand-digitized in GIS using aerial photographs as a base layer. The meander centerline is created by connecting the inflection points between successive meanders along the river to create a straighter line that largely follows the down-valley path of the river without expressing the full cross-valley amplitude of the meandering planform.

For brevity, the detailed findings for each Phase 1 reach assessed is summarized in Table 2 and more completely presented in Appendix 2 with a brief discussion provided below of the most significant natural conditions and human land uses/constraints that could be impacting channel processes and dimensions. The Phase 2 assessment results in Section 5.0 below are used to verify these findings and further define the impacts human alterations in the watershed and channel have had on river processes (and associated flood and erosion hazards).

4.1 Natural conditions

An analysis of valley confinement, valley slope, and other natural conditions help establish the reference channel condition that would be expected to develop in each reach in the absence of human influence. (Departures from this reference condition are later identified during the Phase 2 assessment to determine how the stream is responding to human land use and land management practices). The majority of reaches in the Wood-Pawcatuck Watershed are classified as having a reference channel type equating to a Rosgen (1996) C- or E-type stream, because valley gradients are less than 0.02 ft/ft, floods have access to a wide floodplain, and some meandering is expected. The narrowest floodplain assessed is four channel widths wide in Reach WOR-21, indicating that flood flows throughout the watershed have ample space to spread out and reduce erosive forces under natural conditions. Only six of the 145 reaches delineated have a valley slope greater than 0.02 ft/ft, but with floodplain access available on these reaches, a C-type stream is still the reference channel condition, although a less sinuous planform would be expected compared to the lower gradient reaches. Given the low-gradient valley bottoms and sandy soils that characterize the watershed, the channel bottom bedform expected to develop naturally is either riffle-pool or dune-ripple (see Montgomery and Buffington [1997] for description of bedform types).

4.2 Human land use and constraints

Superimposed on the natural watershed characteristics that control channel morphology are numerous human land uses that can potentially alter the expected natural reference stream type. The National Land Cover Data Set provides 30 meter pixel georeferenced raster maps of 1991 (Vogelmann et al., 2001) and 2011 (Homer et al., 2015) land use. The maps were used to identify subwatersheds where significant changes in land use have potentially altered watershed hydrology and sediment delivery to the watershed's rivers and streams. Comparing land use between 1991 and 2011 documents recent changes in land cover in the watershed. Percentage of forest in the river corridors was also extracted from the land use database to identify reaches where significant portions of the river corridor were deforested and therefore prone to rapid channel migration. Impacts to the river channel can result from human land uses and alterations in the watershed or directly in the river channel or adjacent river corridor.

Extensive land clearing in a watershed can increase runoff and sediment delivery to the river channel. By the 19th century most of Rhode Island and the Wood-Pawcatuck Watershed were deforested (USFS, 2002). Likely accompanying 19th century and earlier land clearing in the watershed was the loss of wood from the river channel. Prior to European settlement of the region, thick forests were probably present throughout the Wood-Pawcatuck Watershed with large trees falling into the stream channel and creating large log jams across smaller tributaries and at least along the margins of the mainstem and larger tributaries. Much of this wood may have been purposefully removed from the channel to facilitate log drives and to reduce flooding. The recruitment of new wood to the channel was greatly reduced by the clearing of forests on the floodplain for agricultural purposes. While much of this activity originally occurred over 100 years ago, wood removal from the channel likely occurred after the 1982 and 2010 floods and likely continues periodically to prevent snags from injuring recreational paddlers. However, wood is a critical element for creating and sustaining high quality aquatic habitat in stream channels and in undeveloped areas can be critical for slowing the downstream progress of floodwaters and sediment that can damage infrastructure in more populated areas. Streams with wood in the channel generally have higher fish populations (Flebbe, 1999), a greater abundance and richness of macroinvertebrates (Bond et al., 2006), and more complex physical habitat (Benke and Wallace, 2003). Wood is also a key pool-forming element in streams (Montgomery et al., 1995).

In order to estimate current impacts on watershed inputs of flow and sediment, several parameters were extracted for each reach subwatershed such as the percentage of developed land, agricultural land, and land use changes between 1992 and 2011 (Vogelmann et al., 2001; Homer et al., 2015). The entire watershed is only 11 percent developed land use (including infrastructure, parking lots, and lawns) and 8 percent agricultural. However urban/suburban development and agricultural land use has increased 6 percent between 1992 and 2011 with some subwatersheds (e.g., BER-4, MEB-1, PAR-3) developing much more rapidly than others during that time period (Table 3). Subwatersheds with significant development, especially recent development, could cause abrupt changes to the morphology of adjacent reaches from localized runoff and sediment inputs.

Land use in the river corridor can have a more direct impact on channel morphology than land use in the larger watershed. (The river corridor is the area that the river may occupy over time through channel migration in order to maintain an equilibrium condition.) An unforested corridor exposes non-cohesive floodplain soils, thus increasing the potential for bank erosion and channel avulsions (i.e., a rapid shift in channel position caused when a new channel is carved through the floodplain during a large flood). The highest impacts within the corridor are seen in reaches that have less than 10 percent forest cover.

5.0 PHASE 2 GEOMORPHIC ASSESSMENT RESULTS

The Phase 1 assessment identifies human land uses and constraints that might cause morphological adjustments along the channel. The Phase 2 assessment is designed to identify if and how the channel is responding (or has responded) to these human activities. Budget constraints prohibited all 145 delineated Phase 1 reaches from being assessed as part of the more time-consuming Phase 2 study. The Phase 2 assessment encompassed only 44 reaches with a total channel length of approximately 38 mi (Figure 9). An effort was made to select contiguous reaches for the Phase 2 assessment because information on adjacent reaches is often useful for establishing the causal factors for why specific channel conditions have developed in a given reach. However, several factors resulted in many of the 44 assessed reaches being separated from others. Stakeholders were interested in sites of known and repeated flooding problems that were in some cases isolated from other reaches. In general, though, the numerous dams and associated impoundments partition the river into separate sections making an assessment of one long continuous length of river impossible. Given those limitations, reaches were also selected to: 1) include areas where development on the floodplain is potentially at risk to flooding and erosion, 2) investigate the potential downstream impacts of possible watershed stressors (i.e., dams), and 3) provide additional information on reaches where in-stream management work is proposed (i.e., dam removals).

After summarizing the findings of the Phase 2 assessment, a more thorough discussion of each Phase 2 reach is provided for those interested in particular areas. Two or more contiguous reaches are in many cases grouped together to designate that those reaches are within the same zone of influence whereby channel adjustments in one reach could impact conditions in another. Reaches separated by grade controls (i.e., dams and waterfalls) are less likely to influence each other and as a consequence are not grouped together in the discussion below. Many of the characteristics mentioned in the summary and more thorough reach descriptions are detailed in the Phase 2 database (Appendix 2) and GIS shapefiles of the mapped Phase 2 features are included in Appendix 1. While some ground photographs taken during the assessment are used as figures to highlight certain features discussed in the ensuing discussion, all of the photographs taken during the Phase 2 assessment are presented by reach in Appendix 3.

5.1 Summary of Phase 2 assessment findings

Dams, stream crossings, and artificial channel straightening are the three primary types of channel alteration in the watershed that have engendered channel responses and exacerbated flooding, erosion, and channel migration along the Pawcatuck River and its tributaries. Twenty-five dams are located in the 44 Phase 2 reaches assessed. Five of these dams are partially breached and one, White Rock Dam, was removed in fall 2015 after fieldwork for the Phase 2 assessment was completed. This does not include 138 old dams that were once active in the watershed but no longer cross the given watercourse on which they were originally constructed, including the Lower Shannock Falls Dam removed from the mainstem in 2011. Although no longer extant, the river morphology of adjacent reaches may still reflect adjustments resulting from these old dams or remnants of these dams that remain along the margins of the channel.

The Wood-Pawcatuck Watershed has minimal total relief (630 ft at Bald Hill to sea level) with much of the elevation change on the mainstem and tributaries accommodated at the remaining dams. As a result, channel gradient is naturally low for most of the watershed's watercourses and reduced further by the dams. The average gradient of all reaches identified in the Phase 1 assessment is 0.0047 ft/ft while the average gradient of reaches immediately upstream of dams is 0.0037 ft/ft. Immediately upstream of many dams a pond is present and the entire riverine character of the channel is altered to the point where conducting a Phase 2 assessment, designed for rivers, is not possible. As a consequence, these impounded water bodies were not selected for assessment, but the dams' effects on stream gradient also effect the riverine reaches upstream of the impoundments that were, in some cases, assessed. Many of the reaches upstream of dams and impoundments show evidence of channel migration in the form of sinuous meandering planforms (e.g., WOR-3, PAR-28) and numerous abandoned channels and flood chutes (e.g., WOR-3, GAS-4, WOR-14). These migration features are embodied in low scores for the planform adjustment portion of the RGA (although these processes can create excellent flow complexity and habitat so should not be considered in a negative light when infrastructure is not threatened). The artificially reduced gradient of the reaches upstream of dams lowers flow velocities and bank heights because of backwater effects associated with the downstream dams, and, as a consequence, leads to increased flow deflection (giving rise to high channel sinuosity) and overbank flow (allowing new channels to be carved on the floodplain). Low flow velocities reduce the channel's erosive power, so severely eroding banks are not prevalent in reaches upstream of dams. Although the hazard of bank erosion is minimal, the potential for flood inundation and avulsions (i.e., rapid formation of new channels potentially hundreds of feet from the existing channel) upstream of dams is increased by the presence of the downstream dams.

Incision is a typical response downstream of dams worldwide because of sediment-deficient flows that are created when sediment is trapped in the upstream impoundment (Brandt, 2000; Williams and Wolman, 1984). In the Wood-Pawcatuck Watershed, some incision (as reflected in the incision ratios recorded in Appendix 2) is observed downstream of dams but is generally not severe, as the channel maintains access to the adjacent floodplain in almost all cases. Run-of-river dams like many on the Pawcatuck are sometimes able to pass sediment during floods such that the severity of incision downstream would be greatly reduced (Csiki and Rhoads, 2010). Furthermore, the incision observed may also be related to the artificial channel straightening observed downstream of dams in the watershed (see below). Although incision may not be significant, the dams in the Wood-Pawcatuck Watershed may still be limiting sediment throughput as the reaches downstream of dams exhibit limited deposition of sand/gravel bars (e.g., PAR-12, PAR-24) and channel evolution, often driven by sediment deposition, appears slowed as straightened channels have remained unchanged for decades (e.g., PAR-12, PAR-15) whereas meanders have reformed elsewhere where the influence of dams is limited (e.g., PAR-17).

Undersized stream crossings are somewhat similar to dams in their effect on channel processes and form with deposition typically occurring upstream in backwater areas during floods and scour of the bed and banks downstream as higher velocity sediment-deficient flow exits the structures. More than 45 percent of the 52 bridges and 83 percent of the 12 culverts assessed as part of the Phase 2 fieldwork in the Pawcatuck Watershed exhibited these impacts (Appendix 2). The deposition of sediment upstream of undersized crossings can lead to flow deflection into the banks leading to bank erosion, channel migration, and the formation of bifurcated or multi-threaded channels (e.g., QUS-11, GAS-8). Typically, the impact of undersized crossings is more localized than dams with a single large scour pool immediately downstream of the crossing (e.g., GAS-8, QUS-11, MEB-8b) rather than the continuous channel incision sometimes seen for hundreds of feet downstream of dams (e.g., MEB-8a). However, where road beds are elevated high above the crossing and a wide floodplain is blocked by the road approaches, the backwater effects of undersized bridges and culverts can extend upstream hundreds of feet along the low-gradient reaches typical of the Pawcatuck Watershed. Backwatering effects extend 150 ft upstream of the culvert in Reach QUS-11. A deep pool extends approximately 200 ft upstream of the Old Shannock Road stream crossing on PAR-23. The pool was scoured out partially by ledge upstream, but riprap added to the bed of the channel in 2013 (Figure 10) in response to scour at the bridge during the 2010 flood now backwaters flow upstream of the bridge.

Although largely localized, the channel responses to undersized crossings give rise to potential hazards at the crossings themselves and the roads or railroads passing over them. The scour downstream can potentially undermine bridge abutments or culverts (and also cause aquatic organism passage issues) (e.g.,QUS-11, GAS-8, MEB-8b, PAR-23). For example, approximately 2 ft of bed incision occurred underneath the undersized Old Shannock Road Bridge on PAR-23 (RIDOT, 2013). Upstream backwatering can overtop structures or inundate low spots along the road approaching the crossing. Several roads adjacent to crossings were submerged during the 2010 flood and impacts associated with undersized crossings are a likely cause of, or at the very least, exacerbated the flooding (e.g., BER-7, QUS-11, see also Figure 3). In severe circumstances, flow overtopping the road can erode through and breach the fill on which the road is built, creating a new channel that poses a potentially life-threatening risk to drivers unaware of the fresh gully that has cut through the road. Such an event occurred at the Beaver River Road crossing and all undersized culverts must be considered potential sites of such a hazard, particularly if pronounced low spots along the road are present near the structure and could preferentially concentrate flow during a flood.

Artificial channel straightening has been a common practice worldwide (Brookes, 1985; Zawiejska and Wyżga, 2010) and is nearly ubiquitous on rivers and streams throughout New England (Field, 2007; Yearke, 1971), the Pawcatuck River and its tributaries included. The increase in slope accompanying the shortening of the channel results in increases of flood flow velocities and stream power. These increases lead to channel incision and bank erosion that are further exacerbated by other common channelization practices often accompanying straightening such as the removal of wood and boulders from the channel. In the Wood-Pawcatuck Watershed, at least 50 percent of the channel was artificially straightened in the past with some reaches completely straightened along their length (Table 4). The actual percentage of total length straightened is likely much higher given that meanders have reformed on many previously straightened sections. Many of the straightened channels show evidence of some channel incision and few depositional features – both typical of historically straightened channels. The fact that many of the straightened channels occur downstream of dams, that also cause incision and limited deposition, complicates a definitive determination of which human alteration is causing the observed channel response. The two may operate together as a straightened condition persists downstream of many dams (e.g., PAR-3, PAR-12, PAR-15, GAS-2, GAS-1, WOD-6) because of limitations in the sediment supply needed to effect change. Upstream of dams and elsewhere many previously straightened reaches are reforming meanders as flow is deflected around sediment, wood, and perhaps occasionally ice accumulating in the channel (PAR-17, PAR-28). Recognizing the processes by which meanders reform and identifying where straightened channels persist provides a means for anticipating future, potentially hazardous, channel changes.

Riverine hazards are not only dependent on the types and magnitude of fluvial processes operating along the watershed's watercourses, but also on the presence of infrastructure that can be potentially damaged by those processes. Most of the reaches selected for the Phase 2 assessment flow in relatively wide unconfined valleys. In the Wood-Pawcatuck Watershed, roads, buildings, and other infrastructure are somewhat limited within the riverine corridor (i.e., that portion of the floodplain which the river must be free to migrate in order to achieve and sustain an equilibrium condition over time). Development within the corridor is considered as an encroachment given its potential to not only be damaged by the river but its potential to alter the natural evolution of the river channel and thereby exacerbate potentially hazardous fluvial processes. Only 28 percent of the total assessed length of channel has some sort of encroachment on at least one bank of the river (Table 4). Where the encroachments consist merely of isolated widely spaced residences, the impact on riverine processes are likely minimal (e.g., CHIP-10, PAR-6). In other instances, where elevated road or railroad grades block the entire floodplain approaching a bridge or culvert crossing, the impact could be significant by increasing flood stage upstream due to backwatering or increasing downstream scour by disrupting the continuity of sediment transport (e.g., PAR-18, PAR-2). These potential impact areas will be highlighted in the River Corridor Plan to be developed from the Phase 2 assessment data and accompanied with potential restoration options (see Section 7.0 below). Many of the encroachments identified as part of the Phase 2 assessment are old buildings and other structures that were once part of old mill complexes or other former industries (e.g., PAR-7, PAR-23, PAR-21). The presence of wide floodplains with no or only relict developments may provide numerous land conservation opportunities that will enhance flood attenuation and enhance sediment storage in order to reduce downstream flooding and erosion in areas where considerable extant and at-risk infrastructure is within the river corridor.

5.2 Pawcatuck River reach descriptions

5.2.1 Great Swamp Reach (PAR-28)

The upstream-most reach assessed on the Pawcatuck River begins at the confluence with Usquepaug River and occupies a portion of the Great Swamp Wildlife Reservation. The highly sinuous stream channel is bounded on both sides by wetlands and a low elevation floodplain forest. This low gradient reach is considered as a reference reach (i.e., expected natural condition) based on the RGA score and is the only assessed reach in the watershed rated in reference condition. The pristine character of the sand bed ripple-dune channel has developed because the power of large floods is attenuated in the Great Swamp and flow complexity results from the plentiful wood within the channel. The Acela train tracks run along the stream corridor on a raised berm and represent the most significant encroachment into the stream corridor, but never approaches closer to the channel than 100 ft and is within 150 feet for only 400 ft of the reach's 4,075-foot length. One bridge, at the downstream end of the reach is a channel and floodplain constriction. Scour is occurring downstream of the bridge related to this constriction with some abutment damage noted. The corridor around this reach should be protected from future development to maintain the reference condition but no other management actions are necessary.

5.2.2 Kenyon Mill to Old Shannock Mill (PAR-26, PAR-24, and PAR-23)

PAR-26 begins at the Kenyon Mill Dam that is no longer in use but has been restructured as a series of steps to allow for aquatic organism passage (AOP). Immediately downstream, the river flows through the Kenyon Industries mill complex before entering Shannock Pond near the confluence of the Beaver River. The Kenyon Industries complex encroaches on most of the river corridor, the reach is 100 percent straightened, and lacks sufficient riparian vegetation along half of the reach length on both banks (Table 4). (Note: sufficient riparian vegetation refers to banks with riparian vegetation more than 25 ft wide along the reach's banks.) These human alterations significantly hinder the amount of aquatic habitat and results in a poor RHA score for the reach. However, little active erosion is recorded, and floods are probably attenuated upstream by the run-of-river impoundment behind Kenyon Mill Dam as well as Great Swamp further upstream. The dam upstream and the lack of recorded erosion in the reach may explain why few depositional features were observed in the reach. PAR-26 passes under two bridges, the Amtrak Bridge is far above the river and out of reasonable flood danger, but the Sherman Avenue Bridge, while appearing to be in good structural condition, may be at risk of overtopping during a very large flood. However, few geomorphic adjustments have resulted from the undersized bridge, perhaps due to the extensive bank armoring upstream and downstream (Table 4).

PAR-24 begins at the Horseshoe Falls Dam, flows down through an old impoundment to the ledge falls at the site of the Lower Shannock Falls Dam. The Lower Shannock Falls dam was removed in 2010 (Web citation 6). Part of the river's flow is routed through a side channel on the right bank corridor (looking downstream) for the first 500 ft of the reach. The remaining upstream dam and the removal of the dam downstream, with the associated drop in base level (i.e., lowering of the river), resulted in a period of channel incision. However, the incision was limited by bedrock encountered on the bed of the channel. The lack of depositional features and the presence of coarse material on the channel bed result from a limited supply of sediment to the reach. Significant residential development is present on the right bank at the upper and lower parts of this reach, but most of the river corridor is forested with forested river banks. River bank erosion is limited in this reach, and the primary infrastructure at risk is the old remnants of the Lower Shannock Falls Dam and the park and historic structures associated with the adjacent old mill.

PAR-23 starts in an overwidened plunge pool downstream of the breached Lower Shannock Falls Dam before flowing under Old Shannock Road. A bed of riprap was laid down in all three cells of the undersized bridge in 2013, in response to 2 ft of bed scour during the 2010 flood (RIDOT, 2013) (Figure 10). Downstream of the bridge, most of the bank and river corridor is floodplain forest, and log and boulder habitat structures appear to have been installed in the past (Figure 11). The reach has undergone limited incision with a measured incision ratio of 1.3 (Appendix 2). Large wood is abundant and is helping the channel establish a new equilibrium condition. The main threats to infrastructure are the undersized bridge and residential development located against a cut bank at the downstream end of the reach. Old abandoned meanders are present on the valley bottom, some of which may become reoccupied in the future. Such avulsions into the old meanders could be encouraged in future restoration efforts as no development is at risk and habitat could be improved.

Portions of both PAR-23 and PAR-24 could use more large wood in the channel to provide habitat cover. Buffers need to be reestablished where possible on the banks of PAR-26. Future management efforts could also focus on moving portions of the Kenyon Mill complex out of the river corridor in order to protect other infrastructure and reduce encroachments along the river channel.

5.2.3 Carolina Mill to Alton Carolina Road (PAR-21-19)

PAR-21 begins at the partially breached Carolina Pond Dam, a relict 7.3-foot high mill dam that was breached at the left bank bridge cell just upstream of Route 112. This partially breached dam still maintains a pond upstream. The steeper upper portion of the reach was designated as Segment PAR-21b due to changes in stream slope and bed substrate. Two straight armored mill races flow steeply downstream from the dam; the left mill race conveys the majority of flow today and is considered the active channel. The flow does enter the right mill race by way of a headcut through the granite wall which lines the length of the channel between the mill races. Buildings from the Carolina Mills complex still occupy a portion of the stream corridor, part of the industrial legacy of the site that has otherwise largely been replaced by floodplain forest and extensive wetlands. More recent development is limited to some residential neighborhoods in Charlestown built up on a terrace adjacent to the left edge of the river corridor.

Flow from White Brook enters the Pawcatuck River in PAR-21a where the valley expands into a wide wetland. This is the upstream extent of the impoundment formed upstream of a 4-foot high USGS stream gage weir damming the river at the downstream end of PAR-19. This concrete structure installed by the USGS as part of a stream gage that is currently operated at the site has a significant impact on stream morphology and sediment transport along this section of the Pawcatuck River. The impoundment extends upstream for more than 8,000 ft. This low dam in PAR-19 is also very likely a barrier to AOP including fish species targeted for restoration in the watershed. The river has been extensively straightened in these reaches and is currently undergoing significant channel widening as evidenced by the extensive bank erosion mapped in the field assessment (Table 4 and Appendix 2). As a result of the bank erosion, many trees are falling into the channel, restoring some of the flow complexity that was lost with construction of the weir and straightening of the channel. Stream sensitivity is ranked as Very High (Table 5), but no significant erosion hazards exist given the limited development in the river corridor.

Removal of the Carolina Pond Dam upstream to restore sediment continuity and accelerate meander formation could improve habitat and reduce flooding. Dam removal could also lower the flood stage along upstream reaches. Removal of the USGS gage dam would improve AOP and provide sediment to drive meander reformation along downstream reaches. However, as a site of an active USGS gage, retrofitting the site may allow gaging to continue while allowing AOP at one of the only impassable structures on the Pawcatuck River.

5.2.4 Alton Carolina Road to Wood River confluence (PAR-18 and PAR-17)

The upstream end of PAR-18 is straightened immediately downstream of the USGS gage before entering a portion of the river 2,350 ft downstream that has begun to reform meanders. A straightened planform again dominates for 630 ft at the downstream end of the reach. Wood is abundant in the channel, although few complete log jams are present. Depositional features are largely absent in the reach despite the wood and reforming meanders, likely due to limited sediment moving past the valley constriction and weir at the upstream end of the reach. The lack of coarse sediment transport from upstream sources likely explains the presence of a sand substrate. This reach has a Fair geomorphic condition and a Very High sensitivity rating due to significant erosion recorded along the newly reforming meanders (Table 5). However, the limited development in the river corridor means few significant erosion hazards exist. Adjacent to the valley, however, a gravel pit has been dug out of the glacial terrace on the left bank. This reach with its redeveloping meanders has the potential to reduce downstream sediment loading and flooding where more infrastructure is at risk. The railroad bridge crossing in the reach is in good condition and is tall enough to pass most floods. However, the elevated railroad grade is a significant valley constriction (Figure 12), so impacts during large floods are possible.

PAR-17 starts at the confluence of Meadow Brook and the Pawcatuck River and passes downstream under the Kings Factory Road before entering a sparsely populated section with little infrastructure. The Kings Factory Road Bridge is significantly undersized and poorly aligned with the stream such that an oversteepened riffle has formed due to deposition at the entrance to the bridge. Downstream of the bridge the reach is similar to PAR-18 except more new meanders have reformed and significantly more bar deposition is occurring to help sustain this ongoing planform change (Figure 13a). The bar formation is most likely due to sediment input from Meadow Brook, but several reforming meanders are also generating sediment through mass failures after migrating into higher floodplains and terraces. Remnants of the straightened channel are still visible among the reforming meanders (Figure 13a) as is an old low berm along the left bank along which the straightened channel previously flowed (Figure 13b). Another Amtrak Bridge spans this reach, but does not alter the channel's width, although the elevated fill across the valley creates an artificial valley constriction. PAR-17 is one of the few reaches on the Pawcatuck River that has a Good habitat rating (Table 6), because the reach has created new meanders, recruited abundant wood, and scoured deep pools.

The best management options for this reach would be to replace the undersized Kings Factory Road stream crossing with a larger span and to prevent future development out of the floodplain where possible. Adding wood structures to PAR-18 and PAR-17, removal of the berm in PAR-17, and removal of the upstream USGS dam will, respectively, encourage further meander formation, eliminate floodplain encroachments constraining meander migration, and increase sediment supply to the reaches to accelerate planform change. While these restoration strategies would be inappropriate for a heavily developed corridor because of the associated flood risks, they will, given the limited corridor development in PAR-18 and PAR-17, improve aquatic habitat in the reach and reduce flood peaks and sediment loading downstream without placing nearby infrastructure to increased risk.

5.2.5 Bradford area reaches (PAR-15-12)

PAR-15 begins at the mostly broken down Burdickville Dam in Hopkinton, RI. The upstream end of the reach is armored on both sides of the channel. An old rock wall continues to armor the right bank against Burdickville Road until the reach crosses under the Burdickville Road Bridge. Residential development occurs on both banks for the upper 480 ft of the reach so no riparian buffer is present. Downstream of the bridge, several homes in the valley are located upstream of the railroad crossing on the left bank. The elevated railroad grade creates a valley constriction, so these homes may be subject to flooding despite not being directly along the river bank. Aside from a single riffle downstream of the upstream most bridge, the reach as a whole is characterized by significant straightening of a deep and very low-gradient channel. The downstream end of the reach is most likely backwatered during high flows by the Bradford impoundment. Erosion and deposition are minimal throughout the reach. The RGA assessment score is Fair with a Very High sensitivity rating due to historical incision (Table 5), but little significant channel change has occurred on the straightened channel due to the lack of sediment and wood to drive the reformation of meanders. The RHA score is Fair due to a lack of wood and habitat complexity (Table 6).

PAR-13 is one of several impounded reaches assessed because of plans for dam removal. This reach extends for 4,050 ft upstream of the Bradford dam and old mill complex. The most significant development is the mill complex on the left bank that has flooded in large storm events (Figure 3). The right bank corridor is mostly wetlands and riparian forest with little development. The reach scored as Good using the RGA, but the Vermont protocols are not well suited for impounded reaches. A vegetated buffer is present along the banks for much of the reach with little bank erosion, but riprap has been placed on the bank at residential frontages, Route 216, the boat ramp, and at the downstream end of the reach to protect the mill buildings portage access around the dam. Crossings are present where the Amtrak Railroad and Route 216 pass over the river. Approaches to both crossings block floodplain flow with the Route 216 bridge also constricting the channel; the crossing at Route 216 was overtopped during the 2010 flood.

PAR-12 flows downstream of the Bradford Dam and is separated from the mill complex on the left bank by an old elevated berm and walking trail that ends upstream of an old abandoned channel at the confluence with Tomaquog Brook. This reach is similar to PAR-15 in that it has one riffle just downstream of the dam and then continues as one long very deep run/pool for the rest of the reach. The channel has been straightened and has very little flow complexity given the absence of wood or meander development; as a result, the RHA rating is only Fair. The mill complex on the left bank consists of buildings and several settling ponds for the factory. The river could potentially breach the berm in a large flood and cause the channel to avulse into the ponds. Several piping features caused by subsurface flow between the ponds and river were mapped in the field and might be weakening the berm and increasing the potential for an avulsion. The 2010 flood overtopped this berm and flooded the mill complex (Figure 3). The mill complex and ponds prevent the river from accessing any of its floodplain as a higher terrace occupies most of the right bank corridor.

If the Bradford Dam upstream is removed, the addition of sediment to the system will cause bars to form, encourage meander reformation along the straightened reach, and potentially cause erosion that will further threaten the berm's stability. If possible, the ponds should be moved further from the river if not completely removed from the floodplain as part of the dam removal project giving Reach PAR-12 the necessary space to achieve an equilibrium condition and preventing the additional sediment from causing downstream impacts in more densely developed areas.

5.2.6 Ashaway River confluence/Upper Westerly reaches (PAR-7-4)

PAR-7 starts at Potter Hill Dam and ends downstream at the confluence of the Ashaway River on river right. PAR-7 is a steeper reach that's essentially one long riffle. Development is found on both banks of the river for most of the reach's length (Table 4) with abandoned mill buildings on the left bank and residences on the right. Potter Hill Road and Laurel Lane in Hopkinton, RI lie within the river corridor along the right bank. This reach has a Very High RGA sensitivity rating, mostly the result of historic channel incision and straightening (Table 5). Although the banks are armored for nearly 40 percent of the reach's length, significant amounts of erosion and failed armor occur along the reach (Table 4). This reach has only a Fair habitat rating due to the corridor development and the incision and widening that has occurred (Table 6).

PAR-6 starts at the Ashaway River confluence and flows downstream along the border of Rhode Island and Connecticut. The low gradient reach is straightened for nearly 70 percent of its length (Table 4). Two bridges are present in the reach. The old Post Office Lane bridge connecting a house and its field is a significant channel constriction, but the bridge approaches do not block floodplain flow. Boom Bridge is in the lower part of the reach and has been closed due to severe erosion of the bridge piers (Figure 14). The farm bridge also has significant damage to its center pier and seems to no longer be in use either. The RGA score is Fair mostly due to historic incision (Table 5) but the impact is fairly minimal given the low incision ratio and low width to depth ratio (Appendix 2). Currently, aggradation and widening are occurring in the reach as the channel continues to respond to the historic incision. Some development is present in the river corridor at the upstream end of the reach at the old Post Office Lane bridge and downstream near Boom Bridge. Most of the banks are forested, although short stretches of insufficient buffer occur where pastures and farm fields are present. Significant bank erosion is mapped upstream of Boom Bridge on the right bank.

A high hillslope with exposed glacial till and bedrock ledge encroaches on the left bank at the upstream end of PAR-5. This reach is 100 percent straightened with a berm on the right bank associated with some historic gravel mining. The berm blocks the floodplain such that flow is contained within the channel even during larger floods. Although channel incision might be expected due to the straightening and berm, sediment inputs from an unnamed tributary just upstream of the reach is limiting such incision. Further downstream, the reach is confined by bedrock/till hillslopes with no natural floodplain present. Bank erosion is occurring along more than 20 percent of the reach's length (Table 4). In the lower reach, several sections of bedrock protrude into the river and create channel constrictions. Ledge may extend all the way across the channel beneath the water surface in this section and should limit upstream incision resulting from removal of the White Rock Dam. The confined valley characterizing much of the reach results in a Moderate sensitivity rating (Table 5). Despite the historic channel encroachments (e.g., gravel mining) very little development is present in the river corridor and the banks are completely forested. Riffles are better developed in this reach compared to PAR-6.

PAR-4 is another impounded reach – the impoundment upstream of White Rock Dam. This reach was chosen for assessment because the White Rock Dam was removed in Fall 2015 after the assessment of the reach was completed. Bars are abundant, including a large delta at the confluence with the Shunock River. A large gravel pit is present in the left bank river corridor. This gravel pit is on the inside of a meander bend and could potentially be an avulsion pathway, although bedrock outcroppings may be high enough to prevent a new channel from forming through the gravel pit.

Despite the removal of the White Rock Dam, incision will most likely be minimal in PAR-4 and PAR-5 (USFWS, 2015). AOP and sediment continuity is expected to improve between the two reaches due to dam removal. Other restoration options suggested for this part of the watershed would be to remove the old Post Office Lane bridge and remove Boom Bridge or replace it with a larger span. Currently, Boom Bridge acts as a channel and floodplain constriction that contributes to scour and flooding. Removing Potter Hill Dam would greatly increase AOP to large portions of the upper watershed.

5.2.7 Downtown Westerly reaches (PAR-3-1)

The Pawcatuck enters the more urbanized part of the watershed in Westerly, RI and Pawcatuck, CT downstream of the now removed White Rock Dam. PAR-3 begins at White Rock Dam with several mid-channel bars creating multiple flow paths in the channel downstream of the former dam as most of the flow was going through the old mill canal on the left bank. (With dam removal and a return of flow to the main channel the bars may rearrange over time.) This section is also confined by fill and armor on the right bank and an old masonry wall on the left bank. The river has a straightened single-thread planform downstream of where flow in the old canal returns to the main channel. Both banks in the upper portion of the reach have little vegetated buffer and the corridor is heavily developed with the Griswold Textile Mill on the left bank and a large aggregate company on the right bank. The reach is heavily armored with masonry walls on the left bank and riprap on the right bank. Downstream of the Bridge Road Bridge, the corridor and banks become more heavily forested though rock armor is still present on the right bank. Although the Bridge Road Bridge does not constrict the channel the bridge approaches do constrict the floodplain. The bridge is relatively new and in good repair with a separate pedestrian bridge attached to the road. One potential restoration idea would be to promote the reformation of meanders and overbank deposition into the wooded floodplain downstream of Bridge Road as a means of reducing downstream sediment loading and flooding. The Bridge Road crossing, while in good shape, is not high above the river, so keeping the canal open as part of the dam removal in order to convey portions of higher flows will help protect the bridge and other infrastructure downstream.

PAR-2 is 100 percent straightened with significant bank armoring (Table 4). The upstream end of the reach begins at the boat access just upstream of the Route 78 Bridge and downstream of where the White Rock Canal joins the mainstem. The Route 78 Bridge is high above the river, but the road approaches create a significant valley constriction. Portions of the reach have insufficient buffer on both banks and residential frontage is present. Active erosion is occurring where woody vegetation is absent. The upstream end of PAR-2 consists of riffles and runs until reaching the backwater created by an old broken down dam and ledge. Little sediment is observed in the reach perhaps due to the increased transport efficiency of the straightened channel. Most of the left bank corridor is developed and the right bank abuts against a high glacial terrace for most of the reach. The Stillman Avenue Bridge crosses the river near the downstream end of the reach. This bridge is older and not very high above the river, resulting in a channel constriction but not a valley constriction.

PAR-1 starts at the top of the broken down dam in downtown Westerly and flows downstream into the navigable bay at Broad Street in downtown Pawcatuck and Westerly. This reach is transitional into an estuary and may get backwatered by high storm surges. In many ways, the reach appears similar to other low gradient reaches in the watershed downstream of dams, beginning as a long series of riffles and runs and then transitioning into a low-gradient overdeepened backwater channel. The reach is 100 percent straightened and has development in the majority of the river corridor. Little vegetated buffer is present and the banks are nearly completely armored, so, not surprisingly, little bank erosion was observed. The Broad Street stream crossing is wide and the river passes under overhanging buildings just upstream of the bridge. The Amtrak Bridge is high above the river and is unlikely to be overtopped even during a large flood.

Management of the Pawcatuck River in Downtown Westerly should mainly focus on protecting undeveloped floodplain to maintain existing flood storage capacity, particularly the forested floodplain on the right bank at the upstream end of the reach. Replanting riparian vegetation where limited buffer is present will minimize erosion and maximize shading (Figure 15). Finally, access to floodplain wetlands currently blocked off by Canal Street at the downstream end of PAR-2 could be restored to provide additional flood storage.

5.3 Wood River reach descriptions

5.3.1 Arcadia reaches (WOR-16-14)

Reach WOR-16 starts at the junction of the Flat River and flows downstream into the Arcadia State Management Area in East Greenwich, RI. This is a very dynamic reach with abundant large wood in the channel creating diverse flow patterns, bar deposition, and high quality aquatic habitat. A couple of buildings, some gravel roads, and the Ten Rod Road stream crossing are the only developments in the river corridor. Multiple avulsions could potentially occur throughout the reach, resulting in a Fair RGA score (Table 5), but should not be considered in a negative light given the limited infrastructure. The channel planform changes associated with avulsions are an ongoing natural response to artificial straightening in the 20th century or earlier in many cases. The multi-thread morphology present in the reach probably closely represents what existed prior to European settlement of the region, so, not surprisingly, scores high in the RHA scores (Table 6). An old stone set of bridge abutments constricting the channel could be removed to prevent continuing scour upstream into the adjacent hunter check station (Figure 16). The excellent morphological conditions provide great habitat and should be protected from corridor development if possible. Wood addition projects may help to further restore geomorphic function and habitat as well as reduce downstream flooding. Ten Rod Road Bridge has some small scars from scour damage and is constricting the channel, causing some localized channel adjustments. The bridge is not an obstruction to aquatic organism passage.

WOR-15 begins where a glacial terrace protrudes into the valley from the right bank, giving rise to a much narrower valley downstream. This reach is similar to WOR-16 in terms of its habitat rating (Table 6), but is less dynamic, because of the lower gradient and narrower valley. Channel straightening likely occurred along most of the reach (Table 4) but the channel is reforming a more natural equilibrium condition. Limited development is found in the corridor (river access points and trails), so provides another opportunity for corridor protection and wood additions.

WOR-14 is not unlike the two upstream reaches as it flows through a largely undeveloped valley, though gravel mining may have occurred in the past. The upper part of the reach was historically straightened but meanders are reforming naturally. A past avulsion created an old oxbow along the right bank. This reach eventually grades into the wetland at the top of Frying Pan Pond in Arcadia, so is dynamic with lots of sediment deposition, some bank erosion, and abundant islands and flood chutes. This evidence of channel planform change and large amounts of deposition yield a Fair RGA rating with Very High sensitivity rating (Table 5). For many of the same reasons, this reach has a Good RHA rating (Table 6), but habitat could be further enhanced and downstream flooding reduced through corridor protection and wood additions.

These three reaches, though geomorphically dynamic, do not pose a risk to development. Ten Rod Road could be replaced with a larger span and the old abutments downstream of the Ten Rod Road removed. The valley bottoms along this section of the Wood River should be protected from further development. These reaches are good candidates for wood additions that will promote sediment deposition, flood attenuation, and habitat creation.

5.3.2 Barboursville to Wyoming Pond (WOR-12-11)

WOR-12 begins at the Barboursville Dam downstream of the Wood-Pawcatuck Watershed Association office. The first part of the reach has an old canal conveying a portion of the flow. The reach is actively widening and eroding on the outside of meander bends giving rise to the Fair RGA score (Table 5). Arcadia Road is the only stream crossing at the upstream end of the reach. The bridge, overtopped during the 2010 flood, has two spans to accommodate both the river channel and the canal. Most of the banks through the reach are forested (Table 4) with some old armor on the banks. Corridor developments consist mostly of residential homes and roads. The development at the downstream end of the dam is 10 ft above the river level but should still be considered subject to flooding. On the right bank of both WOR-12 and WOR-11, two large gravel pits have created potential avulsion pathways through the glacial terrace on the inside of the meander bend (Figure 8).

WOR-11 begins at a partial valley constriction where artificial fill has elevated the left bank. This reach is one of the few to score a Good RGA rating as incision is limited due to an impoundment downstream, only minor amounts of bank erosion are observed, and some deposition is present (Tables 4 and 5). The reach has significant development in the left corridor and some development along the bank that is at risk of flooding. As mentioned above, an avulsion could pass through the gravel pit.

Instream wood could be added to both reaches to attenuate downstream flooding, enhance sediment storage, and further improve habitat.

5.3.3 Hope Valley reaches (WOR-9, WOR-7, and WOR-6)

Downstream of the Wyoming Dam, WOR-9 immediately flows under Bridge Street in downtown Hope Valley. This bridge is in relatively good condition but is a constriction, partially due to multiple cells and canal crossings. The beginning of the reach is high gradient and flows around a ledge controlled island. At the crossing at Nooseneck Road, another significant channel constriction, an anastomosing planform (i.e., multiple relatively stable flow paths) has developed upstream as a result of backwatering. Downstream, the Chariho Little League Park occupies much of the lower floodplain with insufficient buffer for a great length (Figure 17). Active widening associated with significant bank erosion does not threaten the development in the right bank corridor but significant deposition has occurred. This widening and deposition yields a Fair RGA score. The downstream part of the reach grades into the backwater for the pond upstream of the Old Stone Dam.

WOR-7 starts at the Old Stone Dam in Hope Valley, RI and flows downstream under the Maple Street Bridge, past the mill, to a USGS gaging weir (different from the one on the Pawcatuck River). The bridge is a significant channel constriction and an island has formed upstream of the middle pier as sediment is deposited in the backwater area. WOR-7 has significant corridor development at the upstream end with residential homes, the Coastal Plastics facility on the right bank, and Switch Road on the left bank. Backwatering behind the weir has accelerated the reformation of meanders along a previously straightened section of channel. Fragments of glass from broken bottles and bricks have been transported through a portion of the reach downstream of an historic mill and deposited on point bars largely composed of gravel-sized pieces of brick and glass. The historic incision and planform changes associated with the reformation of meanders give this reach a Fair RGA score. Most of the reach has a forested buffer but is lacking at the upstream end. Some development may be at risk of flooding and erosion but the weir's presence has limited the effect of channel incision.

WOR-6 starts at the USGS weir and ends downstream at the Switch Road Bridge. This low-gradient reach remains in a straightened condition along its entire length and is characterized by long runs with an occasional riffle. The valley is encroached upon by Mechanic Street on the right bank for most of the reach. The I-95 bridge is well above the river, but does constrict the valley, putting Mechanic Street at risk of inundation upstream of the bridge during large floods. Despite Switch Road Bridge being a channel and valley constriction, the local channel morphology does not appear impacted. This reach has suffered more incision than WOR-7 as no grade control is present to check the downcutting. This is reflected in the lower width:depth ratio and slightly higher incision ratio in WOR-6 (Appendix 2).

Restoration projects that encourage the reformation of meanders through wood additions along the straightened channel will reduce downstream sediment loading and flooding while improving habitat. Log jams in WOR-9 can help reduce bank erosion and river widening while scouring deeper pools and improving aquatic habitat. Woody riparian buffers could be planted at several locations along these three reaches.

5.3.4 Lower Wood River (WOR-3 and WOR-1)

WOR-3 starts at the dam downstream of Woodville Pond in Richmond, RI and, like many other reaches assessed in the watershed, continues downstream to an impounded reach. Like these other reaches, the morphology is characterized by an oversteepened riffle/run sequence immediately downstream of the dam that transitions to a deeper low gradient channel before grading into backwater wetlands and the impoundment at the reach's downstream end. Numerous features indicating ongoing channel adjustments are found in the form of avulsions, flood chutes, and historic channel incision, yielding a Fair RGA rating (Table 5). The channel is one of the few Rosgen (1996) E-type channels (low gradient, low width:depth ratio) assessed in the watershed and, therefore, has an Extreme sensitivity rating. Development along the corridor is limited and mostly in the upper part of the reach, including residences and Woodville Road. Insufficient buffer is present for approximately 25 percent of the reach (Table 4) and is generally associated with private river access areas. Bank erosion is minimal, but the low gradient and downstream backwater make this reach prone to flooding. Depositional features are minimal despite the low gradient, likely due to low sediment input. The Woodville Road stream crossing consists of two bridges, one for the main channel and one for the old mill race. The bridge is a channel constriction that was overtopped in the 2010 flood and significant deposition is observed upstream. However, limited scour is observed at the bridge and most of the channel upstream and downstream of the bridge has intact armor on the banks.

WOR-1 begins at the top of Alton Dam in Wood River Junction, RI and ends downstream at the confluence with the Pawcatuck River. The reach immediately passes under Route 91 at the dam. This bridge has significant structural damage to the piers and the bridge deck (Figure 18) and was overtopped in the March 2010 flood. Widening of the reach is ongoing as the channel evolves in response to historic incision potentially associated with the dam. These adjustments yield a Fair RGA score and a Very High sensitivity rating (Table 5). Little development is present on the banks, but a mill complex that was flooded during the 2010 flood is located in the left bank corridor at the upstream end of the reach.

The most pertinent management action would be to replace the Route 91 bridge given the damage to the structure. The two dams cut off a large portion of the watershed from anadromous fish and should be considered for removal or fish passage retrofitting.

5.4 Reach descriptions of other tributaries

5.4.1 Shunock River downstream of Gallup Pond (SHUN-10)

SHUN-10 was split into two segments. The upstream segment, SHUN-10b, begins at the dam impounding Gallup Pond in North Stonington, CT and is a higher gradient, step-pool channel that is confined by an abandoned floodplain surface on the right bank and Route 2 (Norwich-Westerly Road) on the left bank. The banks are armored for 38.4 percent of the segment's length (Table 4). The individual steps in the step-pool morphology are largely comprised of stones mobilized from the armored banks. The Route 2 crossing is not a channel constriction but the floodplain fill to build the bridge approaches constricts the valley. The bridge is relatively wide and probably not at risk of inundation during floods. Downstream of the bridge, the valley is constricted by an old berm on the right bank and a high till hillslope on the left bank. This river has been artificially confined such that the channel is adjusting to the excess stream power now contained within the channel during floods and the bed of the channel, as a result, has become armored with coarse cobbles and boulders.

Downstream of the berm, the valley widens and transitions to a riffle-run, gravel-bedded stream. The berm's presence along only a portion of the reach necessitated the segment break. SHUN-10a has minimal development in the lower floodplain, but a large hay field on the right bank may be occasionally flooded. The reach slowly grades into a multi-threaded wetland pond at the downstream end of the segment. This reach was historically straightened and runs along the side of the valley, but is currently undergoing minor channel planform adjustments with some flood chutes and side channels forming. Despite those adjustments, the absence of major obstructions and the presence of a wooded floodplain yield a Good RGA score (Table 5). The gravel substrate, readily transported during floods, results in a High stream sensitivity rating.

Protecting the forested floodplain from development is essential for maintaining downstream flood attenuation. Removal of artificial fill and the berm from the upper segment to restore floodplain access would be important for increasing flood storage.

5.4.2 Green Fall River in Laurel Glen, CT (GAS-8)

GAS-8 starts upstream of Puttker Road in North Stonington, CT where the valley begins to widen. The upstream portion of the reach has many side channels, flood chutes, and islands. The reach contains the remnants of an old dam that was once over 18 ft tall (Figure 19). An old buried mill race that is now dry on the left bank continues under Puttker Road to mill ruins against the left bank valley wall. Upstream of the old dam structure, impoundment sediments 1 to 2 ft thick are present. The Puttker Road culvert is significantly undersized and contributes to island formation and bank scour upstream; a deep and overwidened scour pool downstream is eroding through armor and into a backyard on the right bank. Downstream of this property, the valley bottom is relatively undeveloped except for some ATV trails. The reach is completely straightened with old armor that is failing along much of the banks leading to significant bank erosion (Table 4). The straightening of the reach limits the quality of habitat and increases the channel's susceptibility to avulsing into old channels on the floodplain, yielding a Fair RGA score and a High sensitivity rating (Table 5). Downstream, an ATV bridge is a significant channel constriction, causing upstream scour, deposition, and erosion.

The river corridor should be managed to attenuate floods and downstream sediment loading with land conservation and restoration projects that encourage the straightened channel to reform meanders. The undersized crossings could also be replaced and the ATV crossing may simply be replaced with a stream ford.

5.4.3 Ashaway River in Clarks Falls, CT and Ashaway, RI (GAS-4, GAS-2, and GAS-1)

The Green Fall River is renamed the Ashaway River when reaching the confluence of Parmenter Brook near the Rhode Island state line. GAS-4 begins just downstream of the confluence with Parmenter Brook and ends downstream when reaching the influence of an impoundment downstream. This reach crosses under three bridges. Extension 184 in Hopkinton, RI crosses the reach at an older undersized bridge that has significant scour damage to the deck and both cells with bank scour and deposition upstream. The two I-95 bridges are newer and significantly higher, but act as valley constrictions. The reach upstream of the bridges is wide and has lots of instream wood and abundant high quality habitat. Downstream of the I-95 bridge, the reach is forced into a sharp right turn and enters a channelized section adjacent to the I-95 road fill (Figure 20). Abundant scour is observed along this portion of the reach due to the realignment of the channel to accommodate I-95 and absence of roughness features in the channel to reduce flow velocities. Remnants of the original channel configuration are still visible on the left bank (Figure 4). Downstream of the straightened section, the channel recently avulsed to river left. The river has many side channels and flood chutes as it grades into distributary wetlands in the next downstream impoundment. The RGA score is Fair because of recent and historic avulsions as well as active widening (Table 5). The habitat potential for this reach is high and has a Good RHA score (Table 6).

GAS-2 flows through the village of Ashaway and is similar to other reaches with an oversteepened section downstream of a dam grading into impoundment backwaters at the downstream end. Significant development is along the banks and river corridor at the upstream and downstream ends of the reach, mostly on the right bank and consisting of industrial complexes and residences. The reach is in a confined valley with a low gradient. The RGA score is Fair because of the abundant evidence of incision and backwater impacts. Two bridges cross this reach. High Street Bridge is built over the dam that used to feed the upper Ashaway twine mill and creates both a significant valley and channel constriction. This bridge should be rebuilt as part of any dam removal projects. The Laurel Street Bridge is a valley constriction but not a severe channel constriction.

GAS-1 begins at the lower dam in the Ashaway twine mill complex. This reach is channelized up against the valley wall at the upstream end and significant development is present in the left bank river corridor. The channel’s contact with the right valley wall has caused a large mass failure, supplying sediment that drives meander development downstream. The downstream end of the reach has created new meanders and has abundant large wood to support diverse habitat. The reach is still actively changing its planform so scores a Fair RGA ranking with a Very High sensitivity rating (Table 5). The reach scores Good on the RHA form due to the dynamic meandering and abundant wood (Table 6).

The straightened portion of GAS-4 along I-95 could potentially erode into the highway fill, so one possible management action would be to put the channel back in its natural meandering channel on the left bank side of the valley, moving it away from the highway. The Extension 184 bridge should be replaced with a wider span. Other restoration recommendations for GAS-2 would be to remove the dams in order to lower flood stages, but bank stabilization will need to take place as the river adjusts to the lowered grade. The corridor in GAS-1 should be protected from development and woody vegetation could be planted wherever presently absent to allow this reach to remain dynamic and act as important refugia habitat directly linked to the mainstem.

5.4.4 Meadow Brook in Richmond, RI (MEB-8 and MEB-7)

MEB-8 starts upstream of State Route 138 in Richmond, RI. The reach was segmented because the channel downstream of a large pond near the golf course is incised, has a coarser bed, and has less encroachment on the floodplain compared to upstream. MEB-8b is the segment with the lowest RHA score in the entire watershed but still achieves a Fair rating (Table 6). Development is prevalent on both sides of the brook. Upstream of Route 138, the segment is straightened and incised with abundant bank erosion. Remnants of the natural channel are on the left bank floodplain. In the left bank river corridor, developments include the Richmond School and its tennis courts and nature trail. The one excavated pond in the segment is dug below the river grade, so represents a potential avulsion risk given the lack of a grade control around the pond to prevent incision and stream capture. Two similar ponds lie downstream of the bridge on the Meadow Brook Golf Course and are also avulsion risks in MEB-8a. The section directly above the Route 138 culvert is straightened and armored, speeding up the flow before encountering a significantly undersized structure. A large scour hole approximately 2 ft below the outlet of the culvert has formed downstream. At the golf course the segment has no vegetated buffer (Figure 21) and flows through 3 culverts under a cart path and two golf cart bridges. The culverts are all channel constrictions. The segment flows through an open forested area at the edge of the golf course and into the pond at the downstream end of the segment. The segment had no flow when walked in October of 2015 after a long dry period.

MEB-8a starts at a small earthen dam and culvert at the downstream end of the pond adjacent to the Meadow Brook golf course. A steep coarse-bed channel is found downstream of the dam/culvert outlet and becomes incised downstream. This segment has minimal development with only one residential property on the right bank side of the valley. Downstream, the floodplain is forested but the channel has abundant erosion and deposition. This reach is still reacting to the grade control upstream and has a Fair RGA rating. The low RHA score is mostly due to the ephemeral nature of the stream on the day the assessment was completed. As long as development remains minimal in the segment, natural adjustments in response to the incision will continue as the channel evolves toward a stable configuration.

MEB-7 starts where a small incised urban tributary meets Meadow Brook and higher terraces encroach from both sides, creating a valley constriction. This reach has several headcuts at the upstream end that have been arrested by the presence of large wood in the channel. However, the reach soon becomes significantly aggraded with fine sediment downstream. This aggradation causes significant erosion and frequent avulsions as flow is diverted around bars. These channel adjustments in turn recruit high amounts of large wood into the channel and create great habitat complexity when flow is in the channel (but was dry in October 2015). The aggradation results from a partially breached dam just upstream of Kenyon Hill Trail that backs up high flows for most of the reach, although the old impoundment is now only a wetland at low flow. An old pair of bridge abutments constrict the channel at the upstream end of the wetland, so, as is typical of undersized structures, deposition is occurring upstream and erosion downstream. Downstream of the partially breached dam, the reach is not incised but rather multi-threaded due to the effects of an undersized culvert downstream.

In-stream wood additions would speed the process of recovery of MEB-8a by arresting incision, aggrading the bed, and reconnecting the brook with its floodplain. In MEB-7, removing the old abutments and old dam will decrease the backwater in the old impoundment and potentially lower the water table so some of the wetlands can be converted into a floodplain forest over time.

5.4.5 Beaver River in Hillsdale (BER-7-6)

BER-7 is one of the highest gradient reaches assessed in the Wood-Pawcatuck Watershed. The reach begins at an extremely undersized culvert that has created a vertical drop at its outlet. The historically straightened reach has a step-pool morphology with a cobble bed. Most of the corridor is free of modern development, although several old mill foundations are in the right corridor; a breached dam is also present that acts as a channel constriction. Further downstream is another breached dam and old bridge abutments. Upstream of this second dam, an old side channel carries water during high flows. A short portion of the reach has an insufficient buffer on the right bank from Hillsdale Road to the downstream end of the reach. The reach is in Fair geomorphic condition due to incision from the breached dams, historic straightening, and a recent channel avulsion. The incision is limited by the coarseness of the bed. The RHA score is also Fair from lack of large wood and pools as well as obstructions to AOP at the culverts. The culvert at the upstream end of the reach needs to be replaced and the old dams could be removed to provide the river with better access to its floodplain and create a more natural anastomosing planform that would reduce downstream flooding and sediment loading.

BER-6 begins at the dam downstream of BER-7 and was split into two segments, because the upper section is a steep cobble-bed channel with a step-pool morphology. The lower section is less steep with a gravel bed and a riffle-pool bedform. BER-6b starts at a partial breach in the dam at the downstream end of BER-7. The upper segment is confined whereas the downstream segment is adjacent to a wide floodplain. Despite the floodplain, the channel is confined in BER-6a as a berm is present on the right bank and the channel flows against the left bank valley wall due to historic channel straightening. The reach is in Good geomorphic condition despite the historic channel changes, because the coarse substrate has prevented significant incision.

BER-6a begins where the valley widens significantly and flows down past the Punchbowl Trail ATV crossing. This reach is experiencing incision due to the dam upstream and the more easily eroded finer bed material. Further downstream, the channel has completed an incision phase and has begun widening and reforming meanders. Portions of this stream have been historically straightened with some evidence of berming (Figure 22). The only development in the river corridor are private camp sites and ATV trails. This reach has a Fair RGA score because it is actively responding to the upstream impoundment, but has a Good RHA score given its ability to migrate and create high quality habitat. As long as development does not encroach in the corridor, the reach will continue a natural evolution towards equilibrium. Removing the dam upstream will provide the segment with more sediment to create bars, develop a meandering planform, and achieve equilibrium more quickly.

Management actions could include removing the dam at the upstream end of BER-6b as the dam is no longer functioning. Replacing the Hillsdale Road culvert with a properly sized crossing, as well as removing old berms and dam remnants in both reaches, will give the reach greater floodplain access and allow for the maintenance of existing habitat. Wood additions could create pools and further promote floodplain connectivity. The valley bottom in both of these reaches should be protected from further development and the Punchbowl Trail crossing could be removed.

5.4.6 Lower Beaver River (BER-4-2)

BER-4 starts at an old low dam with a concrete farm bridge upstream of Route 138 in Richmond, RI. The bridge and dam at the top of the reach have been breached on the right bank through the elevated bridge approach. Further downstream, the reach has old armor on the left bank that is scouring due to an unnatural hard bend along an artificially straightened channel. This straight section is the steepest part of the reach and the old remnant meandering channel is now a side channel on the left bank. Downstream of this straightened section, the river has reformed meanders and flood chutes cross the inside of the bends. A small orchard and an old stone wall are found in the right bank river corridor. Some residential property is at the upstream end of the reach and some commercial property off of Route 138 is in the right bank river corridor. Otherwise, development in the reach is limited. The lower part of the reach has a finer substrate with greater deposition and evidence of planform change. The RGA score is Fair mostly due to historic incision, active aggradation, bank erosion, and planform changes.

BER-3 goes from the Route 138 culvert down to Beaver River School House Road and was split into two segments. BER-3b is steeper and flows through a narrower valley. The culvert at the upstream end constricts both the channel and valley. Development in the corridor is also limited to the upper reach and consists mainly of residential properties, river access areas, and one water withdrawal for a farm. The river avulsed around an old dam and mill race, creating an over-steepened riffle (Figure 23). The abundant flood chutes and islands in this segment reflect the ongoing aggradation and planform changes that result in a Fair RGA score and Very High sensitivity rating (Table 5). However, little development is at risk and the changes could be reducing downstream flooding and sediment loading.

Downstream of BER-3b, the valley widens and BER-3a is a lower gradient channel with a sand/silt bed, low banks, and abundant side channels and wetlands. Most of the reach is backwatered by a 4-foot high beaver dam built around an undersized culvert for a private driveway. This beaver dam creates abundant flood chutes upstream and blocks the culvert to create a risk to the private driveway and stream crossing. Downstream of the large beaver dam, depositional features abound as the river winds through a wetlands area that appears backwatered by an old bridge abutment downstream. The only other infrastructure in the corridor is a road crossing and a house beside the river at the downstream end of the reach that is at risk of flooding. The channel has Extreme sensitivity to planform change. The stream crossing with the beaver dam could be widened to discourage future beaver activity.

BER-2 begins downstream of the old abutments and immediately flows through a significantly undersized culvert at Beaver River Schoolhouse Road that is causing scour and widening upstream. Several human alterations of the channel are found in this reach including a failed weir perhaps intended to prevent the creation of a side channel. Several sites of water withdrawals that feed the adjacent turf farms are found along the reach with a large berm and pond created adjacent to the reach to store and release the majority of the in-channel flow. Not far downstream of this pond another low gradient section begins that is backwatered by a series of beaver dams much like BER-3 (Figure 24). The upper part of the beaver wetland is still a channel with abundant flood chutes and low banks. Downstream of the beaver dam the reach becomes a mostly anastomosing and aggrading channel with a pool-riffle morphology with some residential development on the left bank. Another significantly undersized culvert at Shannock Hill Road is at the downstream end of the reach. This reach nets a poor RGA score due to abundant aggradation and migration features, including some recent channel avulsions. The aggradation and migration are related to each other and enhanced by the undersized road crossings and beaver dams.

The culvert at the downstream end of BER-4 is a channel and floodplain constriction that causes backwater effects upstream. The reach has good habitat and should be allowed to adjust naturally by excluding further development in the corridor, a process that could be accelerated through large wood additions. The private driveway stream crossing in BER-3a could be replaced with a wider span and flood relief culverts also added to help prevent overtopping of the driveway. Both culverts in BER-2 should be replaced with wider spans. The corridors in all three reaches should be protected from further development to maintain the existing flood storage capacity.

5.4.7 Queens River at Liberty Road (QUS-11)

QUS-11 lies upstream of the Mail Road crossing in Exeter, RI. The reach begins where the valley expands downstream. This reach is very dynamic with primarily a multi-threaded channel, abundant side channels, and considerable in-stream wood. These features give the Queens River a Good RHA score. But the abundant bar deposition and migration features result in a Fair RGA rating and falls within the Very High sensitivity category. The only infrastructure in the reach is Mail Road and a USGS Gage. The Mail Road stream crossing is significantly undersized, creates multiple mid-channel bars and flood chutes upstream of the crossing, and a large over-widened scour pool downstream of the culvert. The culvert is slightly damaged as a result of these channel adjustments around, and because of, the structure. The only management suggestion for this reach is to replace the culvert with a wider span to eliminate the localized scour and deposition.

5.4.8 Upper Chipuxet River (CHIP-10 and CHIP-8)

CHIP-10 begins at the dam forming Slocum Reservoir. A pedestrian bridge on top of the dam does not influence the channel. The dam, however, has caused incision and subsequent widening downstream. In the upper portion of the reach, several major side channels, avulsions, and flood chutes are present. This anastomosing stream eventually abuts against residential properties for much of its length where armoring is on the left bank without woody vegetation on the bank (Figure 25). A large portion of the reach upstream of the Railroad Road stream crossing is a beaver pond. The beaver are not taking advantage of the culvert but using the elevated road fill and right bank valley wall to create the pond. The reach scores Fair in the RGA due to the channel's multi-threaded character. The reach grades into the top of the Yorker Mill Pond impoundment downstream.

CHIP-8 starts at the Yorker Mill Dam and ends downstream of Wolfe Rock Road in Exeter, RI. This reach at the upstream end is confined and encroached by the Dorset Mill development but enters into a beaver meadow downstream. A beaver dam was built immediately upstream of the Dorset Mill Road culvert. The culvert is undersized and constricts the channel and valley, but morphological adjustments are muted by other beaver dams both upstream and downstream. The section between Yawgoo Valley Road and Dorset Mill Road is entirely backwatered by a beaver dam at the Yawgoo Valley Road. The Yawgoo Valley Road stream crossing is likely the most undersized culvert assessed and the one with the greatest risk of failure in the watershed (Figure 26). The three 3-foot diameter culverts are almost completely blocked by a beaver dam. The road is only 4 ft above the water level, so is prone to overtopping during floods. Downstream of the culvert is a wide and deep scour pool along with a breached abandoned beaver dam. Along the right bank, the channel corridor contains the parking lot and portions of the Yawgoo Valley ski resort. A weir was built to raise the water level to feed a snowmaking pond intake. The channel was straightened along the berm by the pond and the old channel is still present on the left bank (Figure 27). The berm could potentially be breached and the channel avulse through the snowmaking pond. Downstream of the ski resort, the valley is free of development and the river contains many migration features associated with aggradation. Another beaver meadow is present at the downstream end of the reach and is created by a beaver dam blocking another undersized culvert and the several flood relief culverts on the floodplain. The channel constriction at the culvert has led to a deep scour pool downstream.

Management ideas for CHIP-10 include encouraging the planting of woody vegetation, encouraging migration of the channel away from the left valley wall using log jams and other wood additions, and installing a larger culvert at the stream crossing. The lower two stream crossings in CHIP-8 at Yawgoo Valley Road and Wolf Rock Road also need to be replaced to reduce risks to infrastructure associated with the Yawgoo Valley ski resort. Otherwise, the stream corridor should be protected from future development to allow the river to continue adjusting naturally.

6.0 RIVER CORRIDOR PROTECTION AREA MAPS

The Pawcatuck River and its tributaries are prone to changes in planform and channel position that can lead to bank erosion and flooding. The climate in the region is highly seasonal with deep winter snows, possible spring ice jams, and intense rainfalls possible at any time of year. These natural conditions paired with a legacy of human alteration in the watershed create channel instabilities that threaten human infrastructure. The continuing impacts of this human landscape manipulation periodically causes rapid channel adjustments during floods as channels reform meanders and redevelop more stable channel configurations along their length. While overbank flooding and the inundation of homes, agricultural fields, and other infrastructure causes significant damage in the watershed, the most dangerous and costly hazards are often caused by rapid bank erosion. The areas most sensitive to rapid adjustment and erosion tend to be where the sediment carrying capacity of the stream rapidly declines (i.e., natural valley constrictions or artificial constrictions at stream crossings) and the deposition of sediment in the channel diverts erosive flows into the adjacent banks or onto the floodplain. Accurately describing how and where the channel will adjust through time, therefore, depends on not only understanding how past and ongoing human land uses alter sediment and water discharge, but also identifying where rapid sediment deposition is possible.

Recognizing where channel adjustments may occur during future floods can be used by land managers and municipalities to: 1) avoid at-risk areas in future development, 2) warn riverside landowners of the potential threats to infrastructure and safety, 3) identify high priority areas for land conservation, and 4) establish the needed space for natural river processes to operate such that high quality habitat can develop and downstream flooding and sediment loading can be attenuated. River Corridor Protection (RCP) areas are corridors of a defined width along the river within which the river is considered to have the potential to migrate through time and reestablish equilibrium channel dimensions altered by past human disturbances. Homes, roads, and other infrastructure within such a corridor are potentially subject to damage as a result of this migration, but the timeframe of such changes can vary markedly depending on natural conditions (e.g., soil type, location of valley constrictions) and past human alterations (e.g., bank armoring). By providing the space for unconstrained channel evolution, the equilibrium conditions that ultimately result attenuate the downstream transfer of floodwaters, sediment, and erosive forces that can cause infrastructure damage in more heavily developed areas.

The RCP areas are created from the geomorphic assessment results. The meander belt width is used to define the outer limits of the corridor and envelops the maximum lateral extent of the river's position over time (i.e., the full cross valley extent [i.e., amplitude] of active and former meanders on the floodplain), including abandoned channels and oxbows (Web citation 1). The meander belt width is established by analyzing historical aerial photographs and topographic maps. The meander belt width varies from reach to reach with changes in soil type, valley slope, and proximity to valley constrictions or expansions. In valleys confined by high glacial deposits or bedrock, the belt width is necessarily narrow as the river's migration is laterally constrained. In confined valleys, the meander belt width and resulting RCP areas typically encompass the entire narrow floodplain. RCP areas do not extend up valley side slopes as channel migration and adjustment into valley side slopes is considered too slow to appreciably alter the valley's width on a time scale of interest to watershed managers (i.e., years and decades). However, the high sediment production from mass failures as a river impinges on the high steep side slopes of confined valleys can significantly alter the extent and rate of channel migration downstream, particularly in areas of valley width expansion.

RCP areas are typically wider immediately upstream of valley constrictions and downstream of valley expansions due to the associated rapid loss in sediment transport capacity that leads to bar formation, rapid channel migration, and growth of high amplitude meanders. The meander belt width, and as a consequence the RCP area, will also generally be wider in lower gradient settings and in finer-textured more-competent soils (i.e., silt and clay), because flow is more easily deflected away from a straight flow path and has a greater propensity to form high amplitude meanders. Sandy bank materials are less competent and highly sensitive to channel alterations, both natural and human, and are, therefore, most susceptible to rapid bank erosion and channel adjustment. Although channels flowing through sandy soils are generally straighter and have a narrower meander corridor width, the RCP areas are assigned a higher sensitivity rating (see further explanation below), because of the greater likelihood for more rapid and extensive changes in channel position over time or even during a single flood event.

The process for creating RCP areas is detailed in the Vermont protocols (Web citation 1). The first step is to digitize a meander centerline that crosses through channel inflection points as well as any dams or stream crossings. Previous studies show that a river's meander belt width varies with channel gradient, morphology, and bed and bank material. In the Vermont Protocol stream sensitivity (assigned to each reach in the Phase 2 assessment) is used as a proxy to account for this variation in meander belt width. The meander centerline for each Phase 2 assessed reach is buffered according to the reach's stream sensitivity, with higher sensitivity reaches requiring wider buffers. Following this methodology produces meander belt widths for reaches with sensitivities rated as low to moderate (4 channel widths), high (6 channel widths), and very high to extreme (8 channel widths) stream sensitivities. This produces a wider corridor of 8 channel widths along reaches considered more sensitive to channel migration including lower gradient reaches where sediment tends to accumulate, reaches with sandy soils, or those that were artificially straightened in the past.

The buffered meander centerline is clipped to the valley wall, such that in confined valleys where the floodplain is narrower than the prescribed meander belt width, the RCP area extends across the entire valley, but does not extend up the valley side slopes. In wider valleys where the channel runs close to one of the valley sides, the RCP area is clipped to the edge of the valley wall near the channel and the remaining width of the corridor is shifted towards the other side of the channel where channel migration is more likely to occur. In this way the meander belt width is conserved along the length of the reach, despite the encroachment of the valley wall or high glacial terrace on one side of the corridor.

For reaches without Phase 2 field data, RCP areas can be delineated based solely on remotely-sensed Phase 1 data in two ways. For headwater reaches with a contributing drainage area of less than two square miles (e.g., SHUN-13, GAS-17), the Vermont protocol defines the RCP area as 50 ft beyond the top of bank on each side of the stream. For the Wood-Pawcatuck Watershed, this corridor was delineated by buffering the stream centerline by 50 ft plus one half of the reference channel width. For example, a reach with a reference channel width of 10 ft will be buffered off the stream centerline by 55 ft to yield an RCP area 110 ft wide, which is expected to extend 50 ft beyond the top of each bank. For Phase 1 reaches with contributing drainage areas greater than two square miles, a meander belt width of 6 channel widths is delineated. This corridor is essentially equivalent to a Phase 2 reach with a "high" stream sensitivity. These RCP areas based on Phase 1 data are not rated by stream sensitivity (and are displayed in grey on the RCP area maps in Appendix 4 to indicate the lack of sensitivity data).

Visual inspections must be made of the GIS-generated RCP areas based on multiples of the channel width. The RCP areas are intended to encompass the entire zone within which the channel could migrate over time, so the limits of the RCP areas can be edited manually if the inspection of aerial photographs shows that current or past channel positions extend beyond the automatically generated RCP areas. This ensures all areas subject to future channel migration are incorporated into the RCP areas. The most common locations where manual adjustments to the RCP areas are needed are upstream of valley constrictions, downstream of valley expansions, or other areas where rapid sediment deposition and channel migration occur.

An RCP area of a given width and sensitivity rating was drawn for each reach assessed in the Wood-Pawcatuck Watershed based on the channel's bankfull width, reference channel condition (i.e., expected natural condition), soil type, and human modifications to the channel. In addition to establishing the width (as described above), the RCP area for each Phase 2 assessed reach is also assigned one of six sensitivity ratings: extreme, very high, high, moderate, low, and very low. Only four sensitivity ratings are used in the Wood-Pawcatuck Watershed as no reaches were assigned a low or very low sensitivity. RCP areas are also drawn for the Phase 1 reaches (except in impounded areas) but no sensitivity rating is assigned if Phase 2 assessment data is not available. The sensitivity rating provides an indication of how likely the reach is to experience rapid channel adjustments. The risk ratings are a relative scale enabling comparisons between reaches, but the ratings do not connote a timeframe within which (or a probability that) the channel will migrate across the entire width of an RCP area. In general, reaches unlikely to adjust through time (e.g., bedrock banks) will be designated with a lower sensitivity rating while reaches with soils more susceptible to erosion (e.g., sandy banks) or that have experienced destabilizing human alterations (e.g., artificially straightened channel) will be assigned higher sensitivity ratings.

The RCP areas are not the same as the 100-year flood zone on Federal Emergency Management Agency (FEMA) flood insurance rate maps (FIRMs), but the areas of both often overlap. The FIRMs show areas that are likely to be inundated by floodwaters that overtop the riverbanks during a flood with a one percent probability of occurring in any given year. In contrast, the RCP area maps identify areas, sometimes outside the 100-year flood zone, where the channel can potentially migrate over time through bank erosion or channel avulsions. Discrepancies between RCP area maps and FIRMs are possible especially along incised channels where a large flood may not spread across the floodplain, but may have sufficient force to cause bank erosion, channel widening, and meander formation – processes that would occur within the designated RCP area but outside the 100-year FEMA flood zone.

FIRMs and RCP area maps should be used in concert to identify appropriate management strategies for addressing flood hazards. For example, construction of structural measures, such as a berm, to prevent flood inundation should not be built within an RCP area as such structural measures impose constraints on natural channel processes (i.e., channel migration) that might exacerbate flooding and erosion downstream. In contrast, construction of a berm setback to the edge of an identified RCP area could prevent inundation of infrastructure within the reach yet allow natural channel processes to occur unabated with its intendent benefits to habitat and downstream hazard reduction. However, structural measures directly along the river are sometimes needed when preexisting infrastructure is already within the RCP area. In such instances the RCP area maps can be useful for identifying such conflicts and can provide a forewarning of potential channel adjustments that might result from the structural measures built within the RCP area.

Once established, the RCP areas can be of use to watershed managers wishing to reduce flooding and erosion. Avoiding conflicts with the river by limiting development, bank protection measures, and flood control structures within RCP areas is the most cost-effective strategy for mitigating hazards when compared to repairing, retrofitting, or replacing roadways, bridges, and other structures damaged or compromised by flooding or erosion. With this in mind, RCP areas can be an important municipal and regional planning tool for limiting encroachment along rivers. RCP area maps can be used to identify areas susceptible to channel migration and help prioritize river and floodplain restoration projects, bridge and culvert replacements, and river corridor protection opportunities.

Twenty-six RCP area maps, centered on the mainstem and assessed tributaries, have been created at a 1:24,000 scale to cover all of the assessed portions of the Wood-Pawcatuck Watershed (Appendix 4). Each map is displayed with a topographic map as a base layer. The GIS shapefiles used to create the maps are available in Appendix 1 and should be used in any detailed watershed planning. The maps are for general informational purposes only.

7.0 GEOMORPHOLOGY BASED RIVER CORRIDOR PLANNING

The results of the geomorphic assessment can be used in a river corridor planning process to identify the best management strategies for each reach to restore channel equilibrium, reduce flood hazards, and achieve sustainable habitat improvements. A stand-alone Wood-Pawcatuck Watershed Geomorphology Based River Corridor Planning Guide is currently under development utilizing the geomorphic assessment results described in Section 4.0 and 5.0 above. The Planning Guide will detail the process of prioritizing flood management and restoration efforts in the watershed and will include a prioritized list of potential restoration projects for the Wood-Pawcatuck Watershed. The Planning Guide, when completed, will be a stand-alone companion document to the geomorphic assessment results and RCP area maps presented here.

8.0 CONCLUSIONS

A Phase 1 and Phase 2 geomorphic assessment was completed of the Pawcatuck River and seven major tributaries using Vermont's geomorphic assessment protocols (Web citation 1). As part of the Phase 1 assessment, 145 geomorphic reaches of uneven length were identified largely based on rapid changes in valley confinement, channel gradient, and contributing watershed area. Remote sensing data on these watershed characteristics as well as channel dimensions, sinuosity, and other morphological parameters were tabulated to identify both natural conditions and human alterations impacting channel stability and, as a result, flood and erosion hazards in the watershed (Tables 1-3; Appendices 1 and 2). The Wood-Pawcatuck Watershed is a relatively low gradient system dominated by vast wetlands and wide floodplains, so is naturally prone to flood inundation but less likely to experience severe bank erosion associated with high velocity flows. However, extensive human alterations of the channel associated with dams, bridges and culverts, and artificial channel straightening have the potential to concentrate flows and erosive forces that destabilize the channel and give rise to hazards that may not have existed under natural conditions.

The Phase 2 assessment collected field data on 44 of the identified reaches covering 38 stream miles and provides details on how the river is responding to human alterations and how those responses continue to impact channel stability, aquatic habitat, flood and erosion hazards, and downstream sediment loading. The dominant stream type in the watershed has a meandering planform, access to a floodplain, and is characterized by a pool-riffle or sandy dune-ripple bed morphology. Past channel alterations such as dam construction and associated channel straightening and bank armoring has often led to channel incision that has, in severe cases, caused the channel to lose access to its floodplain even during large floods (e.g., MEB-8b). By confining larger floods within the channel, incised reaches are subject to greater erosion and increased downstream sediment transport. The resulting deposition of sediment downstream reduces channel capacity such that the risk of flooding, bank erosion, and rapid channel avulsions is increased (e.g., MEB-7). The widening that accompanies bank erosion within incised channels reduces the erosive power of flows until sediment ultimately begins to accumulate in the channel, allowing meanders to reform on the previously straightened channel as flow is deflected around the emerging bars. While several reaches have experienced meander reformation (e.g.,WOR-7, PAR-17), many reaches remain in an artificially straightened condition (e.g., PAR-20, PAR-19, WOD-6, PAR-3) because of bank armoring, limited sediment transport through the reach (possibly because of upstream dams), and limited wood loading (important for deflecting flow into the banks and initiating meander formation). As sediment throughput in the watershed continues to increase with planned dam removals or natural deterioration and as wood loadings increase with aging forests and changing management practices, many of these straightened reaches could begin reforming meanders in the future. This meander reformation with its intendent rapid channel migration and bank erosion should be perceived as a hazard where infrastructure is potentially at risk. However, where no infrastructure is nearby, the reformation of meanders, in addition to creating excellent habitat, can actually reduce flooding to at-risk areas downstream by attenuating floods and sediment loading. In certain instances, restoration projects could be designed to encourage this meander reformation by deflecting flow around engineered log jams (e.g., PAR-18).

Bridge and culverts crossing the Pawcatuck River and its tributaries represent another significant human alteration impacting channel morphology and processes. Forty-five percent of the bridges and more than 80 percent of the culverts assessed in the Phase 2 assessment are undersized with the crossing width narrower than the bankfull channel width. This rapid narrowing of the channel as the flow enters the crossing results in backwatering and deposition upstream. Flow deflection around the emerging bars can, in turn, cause bank erosion and form a multi-thread channel (e.g., Liberty Road in QUS-7). Downstream, water exiting the crossing is moving at a higher velocity (having been squeezed into the narrow opening) and is sediment starved (after sediment deposition upstream), so erosion of the bed and banks results with deep scour holes common at the crossing exits (e.g. Puttker Road in GAS-8); this scouring can sometimes be so severe as to cause undermining of bridge abutments or culverts (Shannock Hill Road in PAR-23 – see Figure 11) and create perched culverts with AOP issues (e.g., Hillsdale Road in BER-7). While the channel adjustments associated with undersized crossings generally remain localized around the structure, the upstream effects, even on small streams, can extend more than 100 ft upstream because of the low-gradient character of the watershed. If the backwatering is severe enough, as is possible during large floods and when the floodplain is blocked by the road approaches, the road or railroad grade above the crossing can be inundated (e.g., Hillsdale Road in BER-7 – see Figure 3) or be breached by flow eroding through the road to create a potentially life-threatening hazard. The hazards and habitat degradation associated with undersized crossings can be addressed by resizing the structure to at least match the bankfull width and to provide relief culverts where the floodplain is blocked by the road grade. Reducing or eliminating backwater issues at undersized stream crossings has the potential to increase the passage of flow and sediment, but is unlikely to significantly increase downstream hazards compared to the hazard reductions that would be achieved around the currently at-risk structures.

River Corridor Protection area maps were developed for the assessed portions of the watershed to identify the zones within which the river is most likely to migrate over time in order to achieve and maintain an equilibrium conditions (Appendix 4). Human developments that lie within the protection areas are potentially susceptible to erosion hazards over time, especially in areas of high sensitivity. The presence of significant developments in the corridor should be considered as constraining the river and, therefore, could be exacerbating hazards within the given reach and further downstream. To allow the river free access to its entire corridor such developments could be retrofitted (i.e., stream crossings enlarged or relief culverts added where road grades block the floodplain) or, where such developments are no longer being used, completely removed from the corridor (e.g., old bridge abutments, mill buildings, berms). By enabling natural river equilibrium to become established in undeveloped areas (and even accelerating channel evolution towards equilibrium through restoration projects), the resulting flood and sediment attenuation within the reach can decrease downstream inundation and erosion hazards where human developments may be present in the corridor. A River Corridor Planning guide to be completed in April 2016 will detail restoration opportunities for each Phase 2 reach that will provide specific actions that watershed managers can take to increase flood resiliency in the Wood-Pawcatuck Watershed while simultaneously improving aquatic habitat degraded by past human activities in the watershed.

9.0 REFERENCES

Benke, A. C., and Wallace, J. B., 2003, Influence of wood on invertebrate communities in streams and rivers: American Fisheries Society Symposium, v. 37, p. 149-177.

Bent, G., and Waite, A., 2013, Equations for estimating bankfull channel geometry and discharge for streams in Massachusetts: United States Geological Survey, Scientific Investigations Report 2013-5155.

Bond, N. R., Sabater, S., Glaister, A., Roberts S., and Vanderkruk, K., 2006, Colonisation of introduced timber by algae and invertebrates, and its potential role in aquatic ecosystem restoration: Hydrobiologia, v. 556, p. 303-316.

Brandt, S.A., 2000, Classification of geomorphological effects downstream of dams: Catena, v. 40, p. 375-401.

Brookes, A., 1985, River channelization: traditional engineering methods, physical consequences, and alternative practices: Progress in Physical Geography, v. 9, p. 44-73.

Csiki, S., and Rhoads, B., 2010. Hydraulic and geomorphological effects of run-of-river dams: Progress in Physical Geography, v. 34, p. 755-780.

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

Flebbe, P.A., 1999, Trout use of woody debris and habitat in Wine Spring Creek, North Carolina: Forest Ecology and Management, v. 114, p. 367-376.

Homer, C., Dewitz, J., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N., Wickham, J., and Megown, K., 2015, Completion of the 2011 National Land Cover Database for the conterminous United States - Representing a decade of land cover change information: Photogrammetric Engineering and Remote Sensing, v. 81, p. 345-354.

Kaye, C. A., 1965, Surficial Geology of the Kingston Quadrangle Rhode Island: Geological Survey Bulletin 1071-1.

Montgomery, D.R., and Buffington, J.M., 1997, Channel-reach morphology in mountain drainage basins: Geological Society of America Bulletin, v. 109, p. 596-611.

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M., and Pess, G., 1995, Pool spacing in forest channels: Water Resources Research, v. 31, p. 1097-1105.

NOAA/National Weather Service, 2013, The March, 2010 Floods in Southern New England: Weather Forecasting Office, Taunton, MA, Storm Series Report #2013-01.

RIDOT (Rhode Island Department of Transportation), 2013, State Wide Scour Remediation: Bridge #005801 permit submittal.

Rosgen, D.L., 1996, Applied River Morphology: Wildland Hydrology: Pagosa Springs, CO.

USFWS (United States Fish and Wildlife Service), 2015, Environmental assessment – White Rock Dam Removal Project, Westerly, Rhode Island, and Stonington, Connecticut.

USFS (United States Forest Service), 2002, The forests of Rhode Island: Northeastern Research Station, NE-INF-155-02.

Vogelmann, J., Howard, S., Yang, L., Larson, R., Wylie, B., and Van Driel, J., 2001. Completion of the 1990's National Land Cover Data Set for the conterminous United States: Photogrammetric Engineering and Remote Sensing, v. 67, p. 650-662.

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

WPWA (Wood Pawcatuck Watershed Association), 2005, Facts about the Pawcatuck River at Bradford.

Yearke, L. W., 1971, River erosion due to channel relocation: Civil Engineering - ASCE, v. 41, p. 39–40.

Zawiejska, J., and Wyżga, B., 2010, Twentieth-century channel change on the Dunajec River, southern Poland: Patterns, causes and controls: Geomorphology, v. 117, p. 234-246.

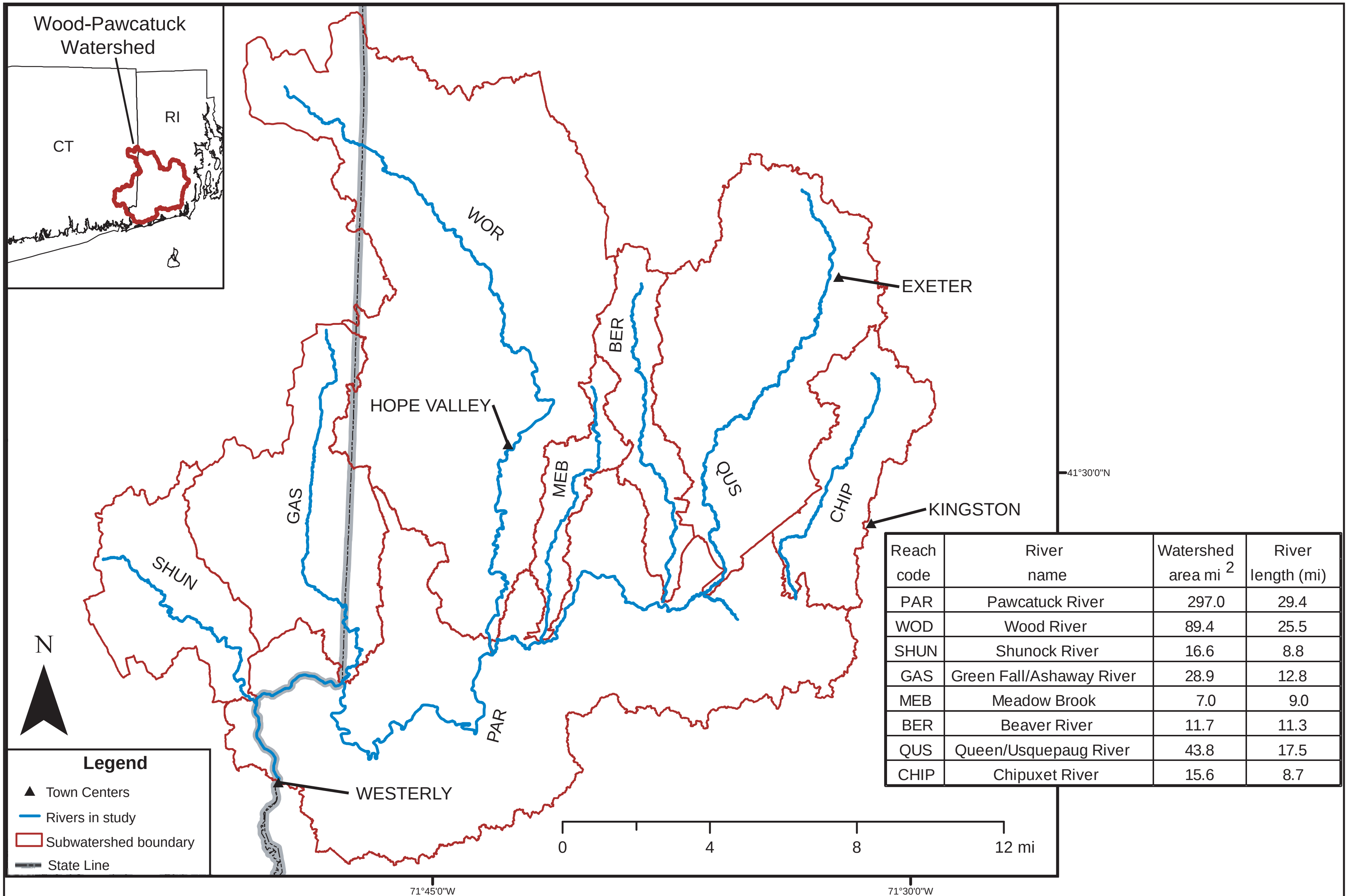
Web citations

Web citation 1: http://www.anr.state.vt.us/dec/waterq/rivers/htm/rv_geoassesspro.htm
Web citation 2: https://mrdata.usgs.gov/geology/state/state.php?state=RI
Web citation 3: http://waterdata.usgs.gov/ri/nwis/sw
Web citation 4: http://md.water.usgs.gov/publications/wsp-2375/ri/
Web citation 5: http://pubs.usgs.gov/sir/2010/5127/pdf/sir2010-5127.pdf
Web citation 6:
http://www.nbep.org/docs-restoration/RIRestorationWorkingGroup_HistoricalPresentation_20110413-1.pdf

GIS data sources

RI Statewide GIS data: http://www.edc.uri.edu/rigis/
Connecticut DEEP GIS data: http://www.ct.gov/deep/cwp/view.asp?a=2701&q=323444
National Land Cover Dataset: http://www.mrlc.gov/
USGS National Map Viewer: http://viewer.nationalmap.gov/viewer/
ArcGIS basemap layers: http://www.arcgis.com/home/item.html?id=483b230c56a44c33beb13f9b9ab9f88d

FIGURES



Reach code	River name	Watershed area mi ^{2}	River length (mi)
PAR	Pawcatuck River	297.0	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	7.0	9.0
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 Wood-Pawcatuck Watershed. Table contains basic watershed information.

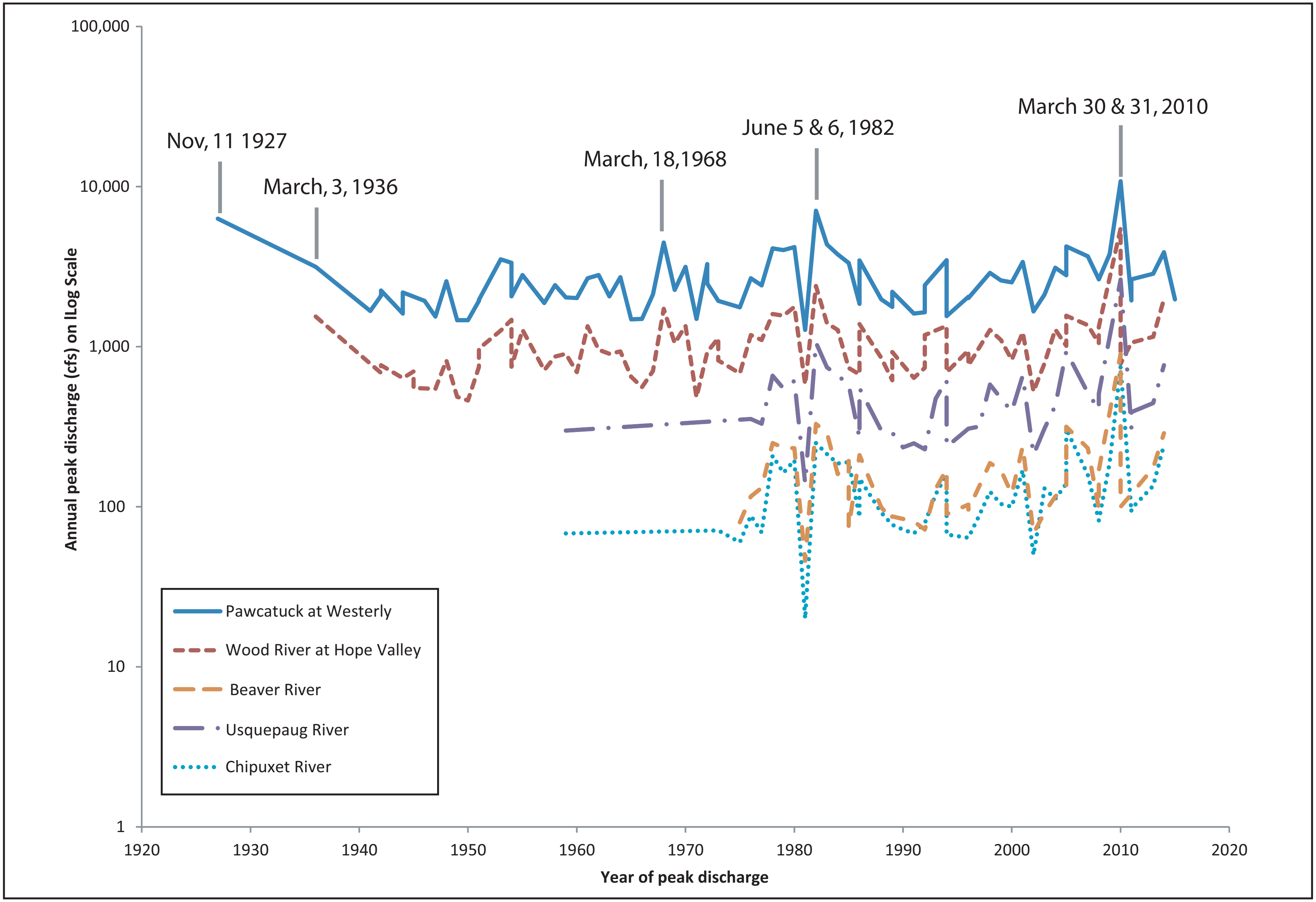


Figure 2. Plot of annual peak discharge vs. time at several USGS stream gages in watershed. Plotted on log scale to show tributary and mainstem discharges together.

a)

b)

Figure 3. a) Aerial view of flooding at Bradford Dye Association plant looking upstream on April 1, 2010 and b) photo of flooding at Kenyon Industries complex on March 31, 2010.

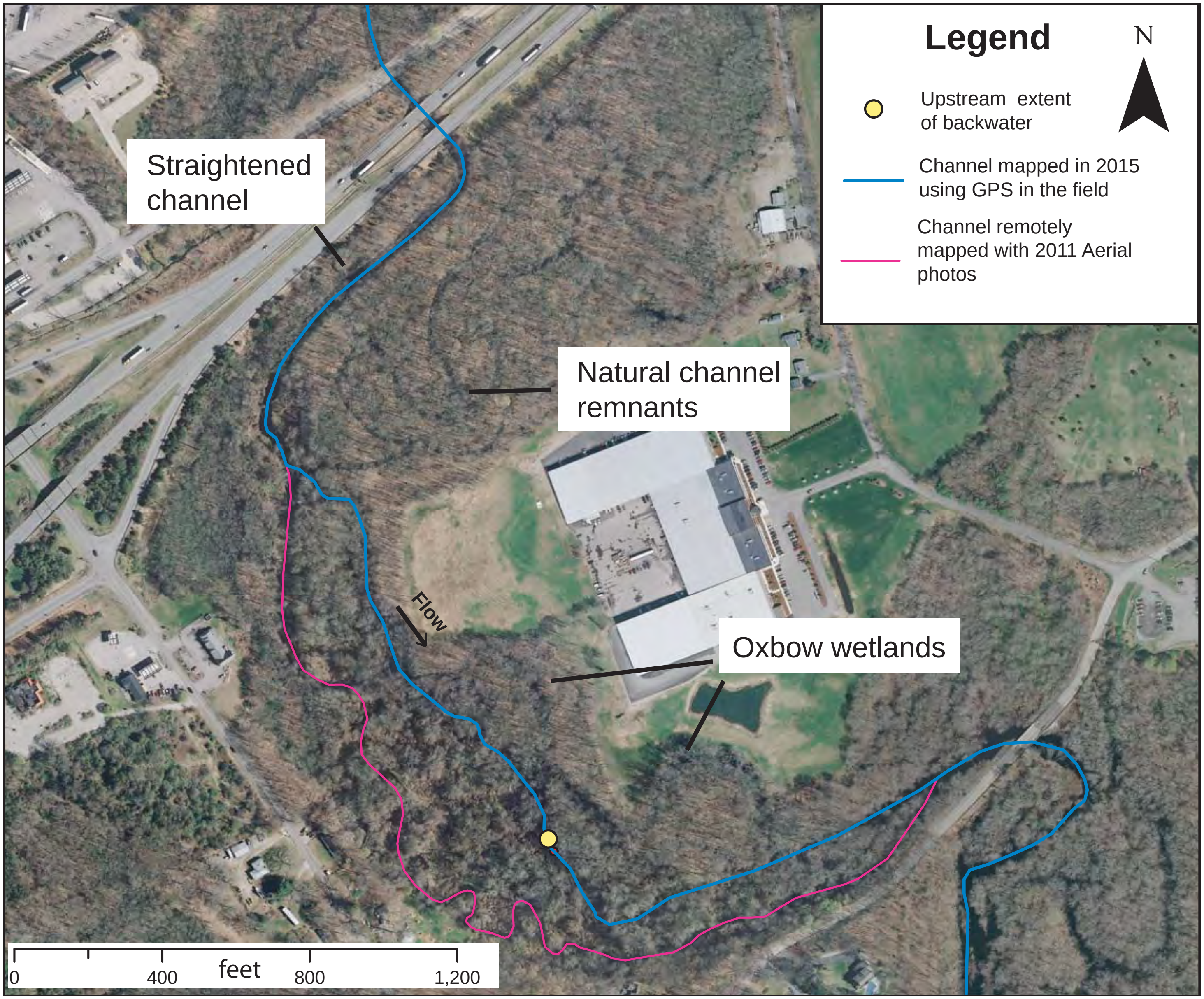


Figure 4. GAS-4 near Clarks Falls, CT overlaying 2011 6 inch orthoimagery. This reach is upstream of an impoundment, and a poorly aligned bridge. The backwater effects have caused a recent avulsion, and there is evidence of older avulsions. The recent avulsion shortened the stream, and began at the end of straightened channel.

a)

b)

Figure 5. a) Photo of culvert at Hillsdale Road and Beaver River in Richmond RI taken on March 31, 2010 and b) view upstream from Liberty Road on QUS-11 showing backwatering impacts on channel morphology.

a)

b)

Figure 6. Scour of bed and banks downstream of a) Puttker Road on GAS-8 and b) Mail Road on QUS-11.

a)

b)

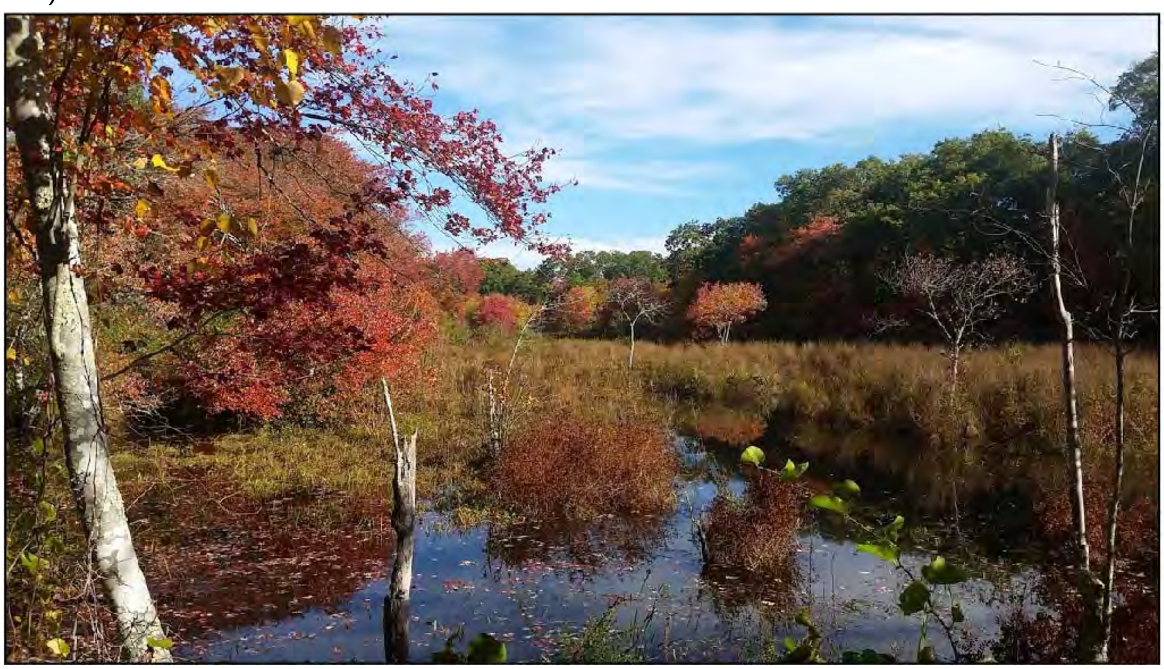


Figure 7. a) Upstream view of the beaver dam in the undersized culvert at Wolf Rock Road in Exeter, RI (CHIP-8) and b) upstream view from road of beaver meadow wetland.

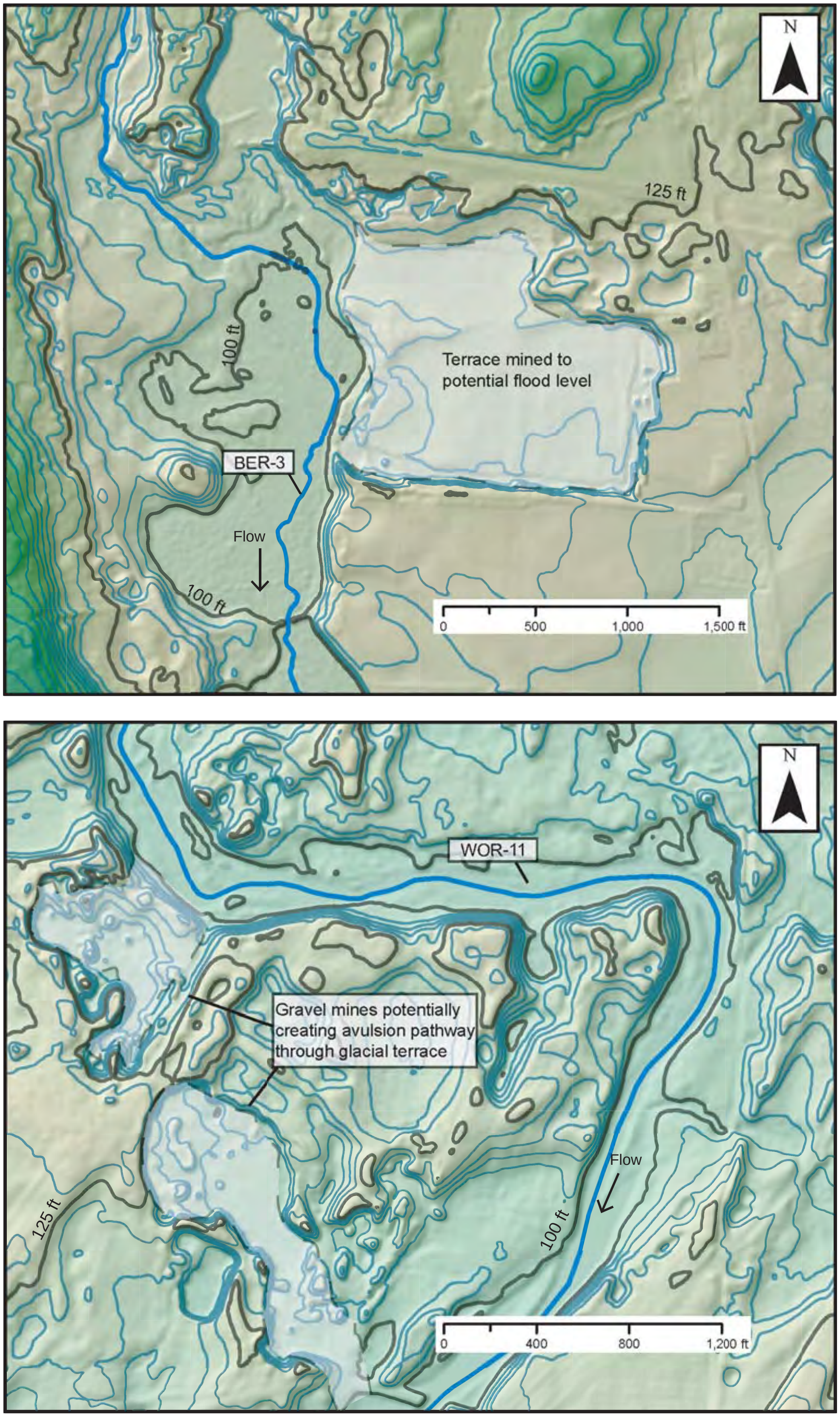


Figure 8. LiDAR shaded relief maps with 5-foot contours from 2011 RI 1-meter resolution dataset. Maps show two examples of gravel mining potentially effecting river corridor and geomorphic processes.

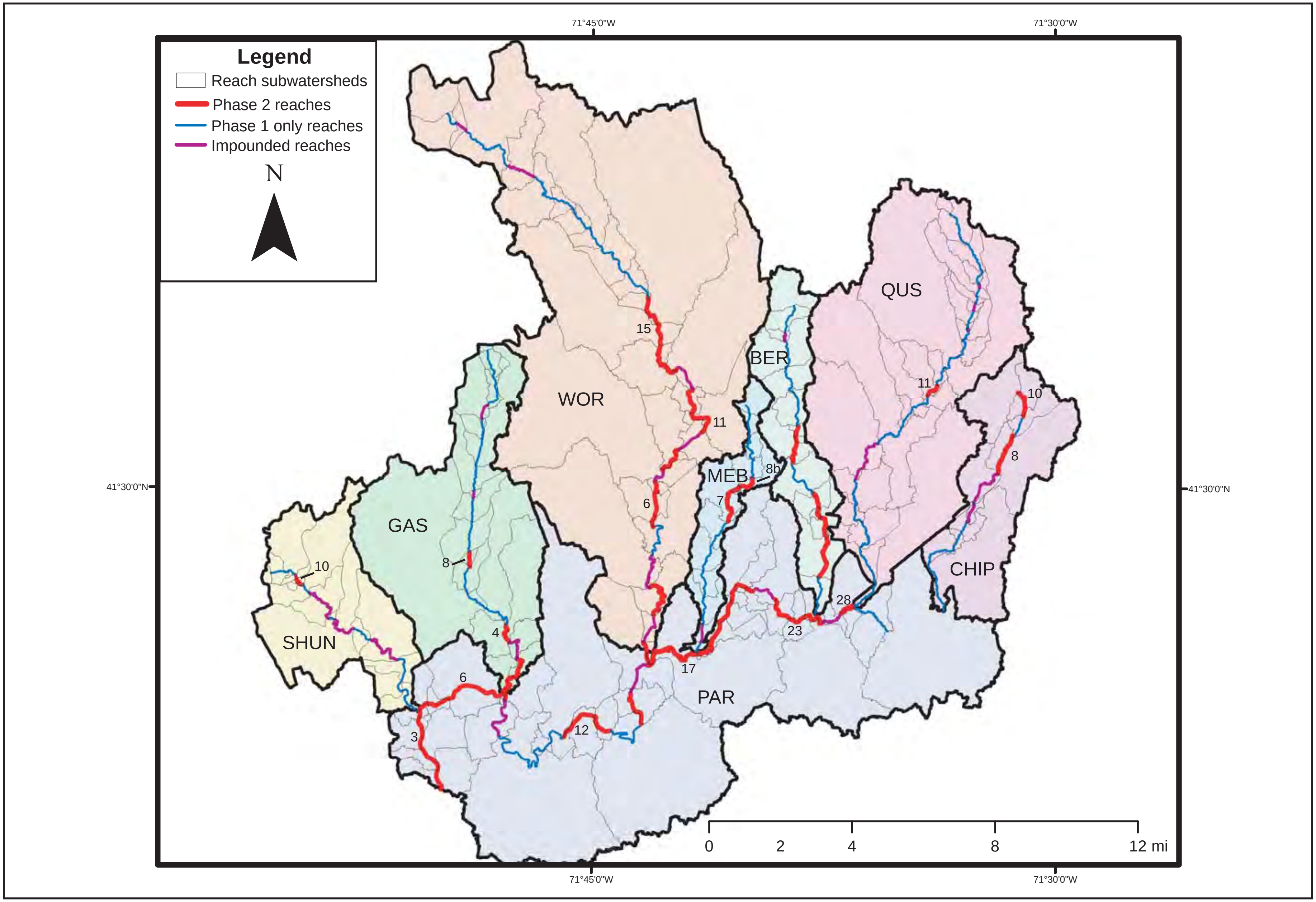


Figure 9. Watershed map showing reach subwatersheds, Phase 2 reaches assessed, and impounded reaches.

a)

b)

Figure 10. a) Downstream view of Old Shannock Road Bridge in PAR-23 and b) closeup of riprap placed on bed and scour of bridge pier in right bank cell.

a)

b)

Figure 11. Previous bank restoration efforts in PAR-23 include a) boulder supported marginal log jam structure and b) toe wood revetment. Views looking downstream.

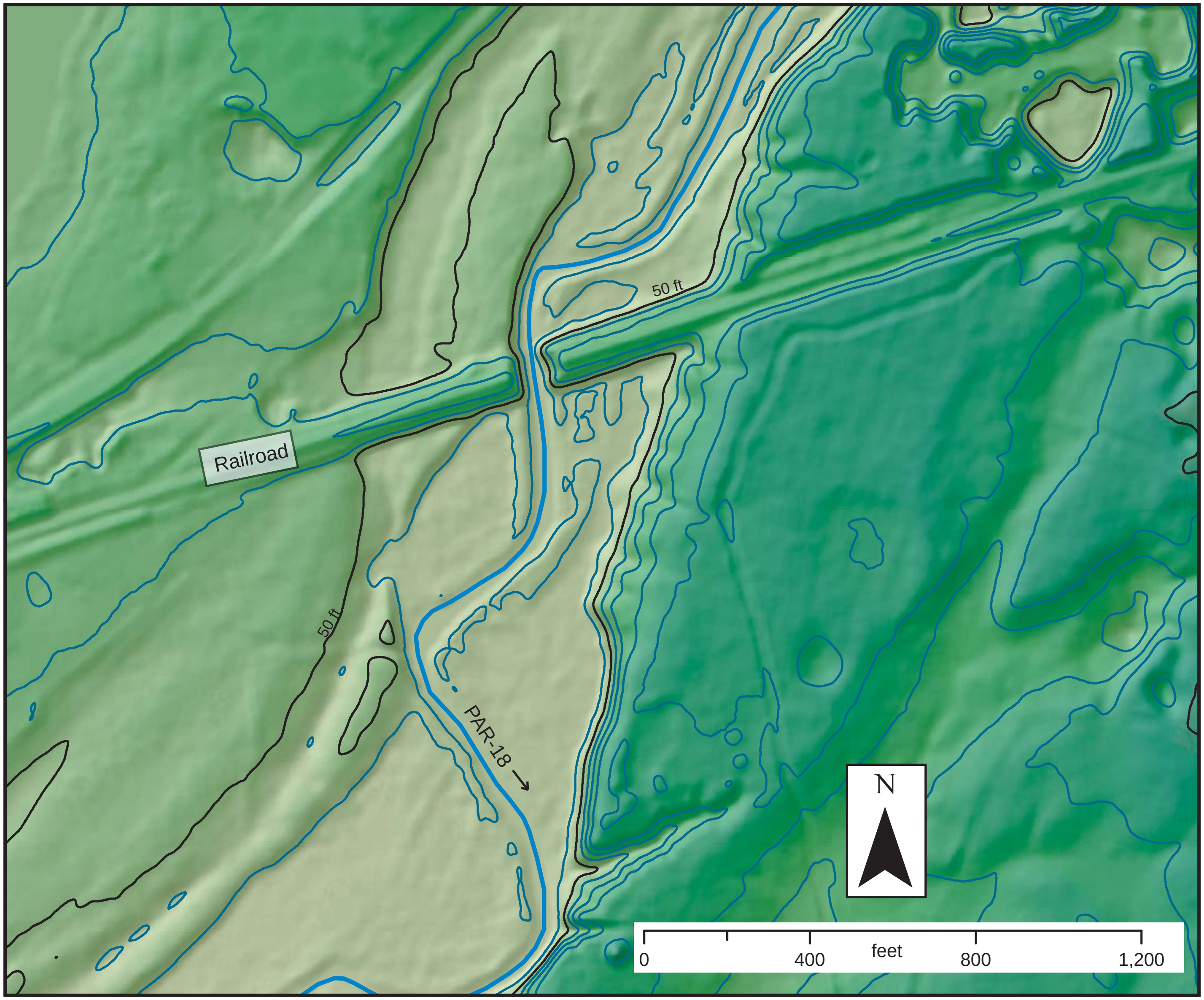


Figure 12. LiDAR shaded relief map of valley-constricting railroad fill in PAR-18. One-meter LiDAR is from 2011 RI statewide LiDAR dataset. Contours are in 5 ft intervals.

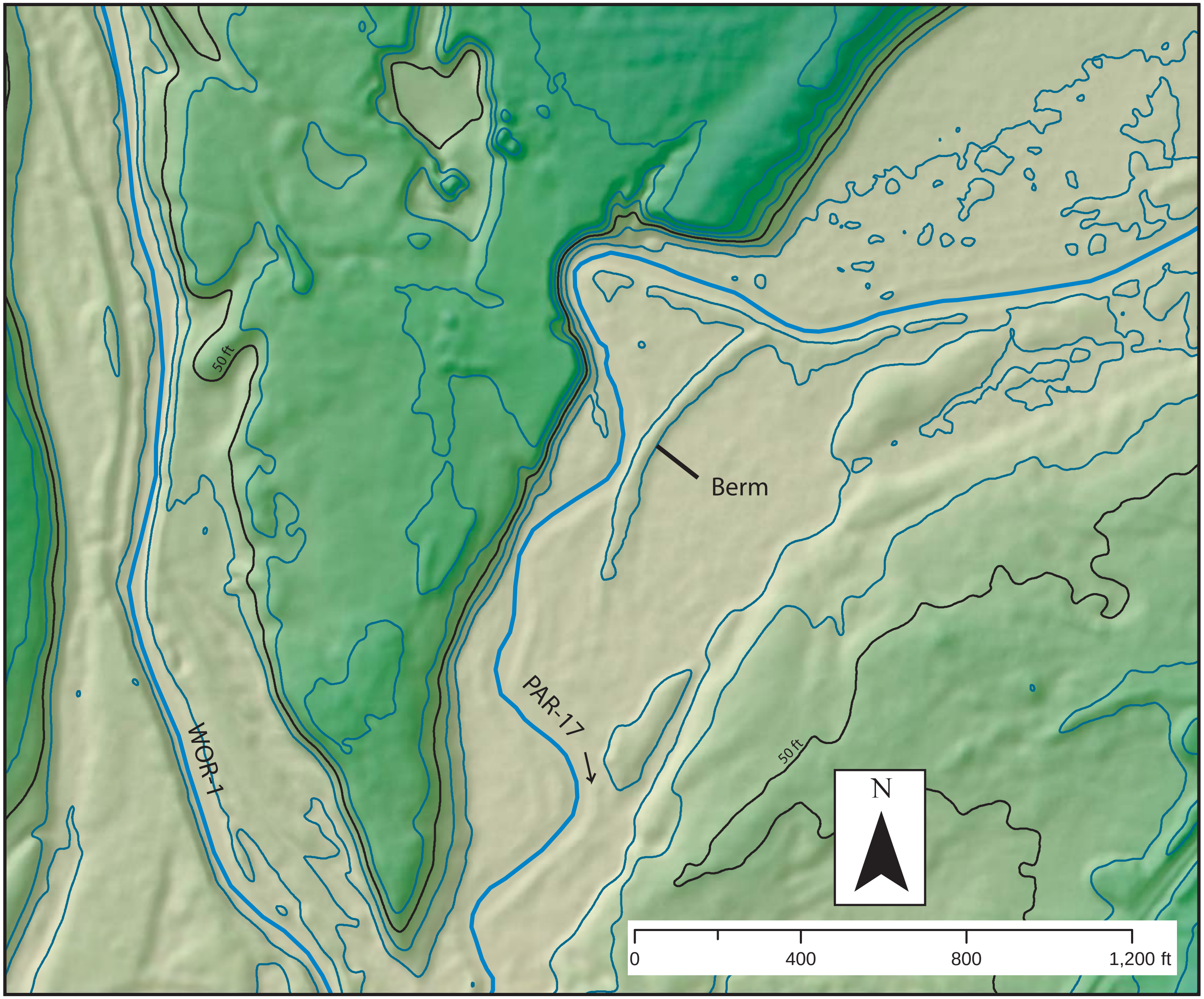


Figure 13a. LiDAR shaded relief map of of PAR-17 showing berm that runs along the left bank.

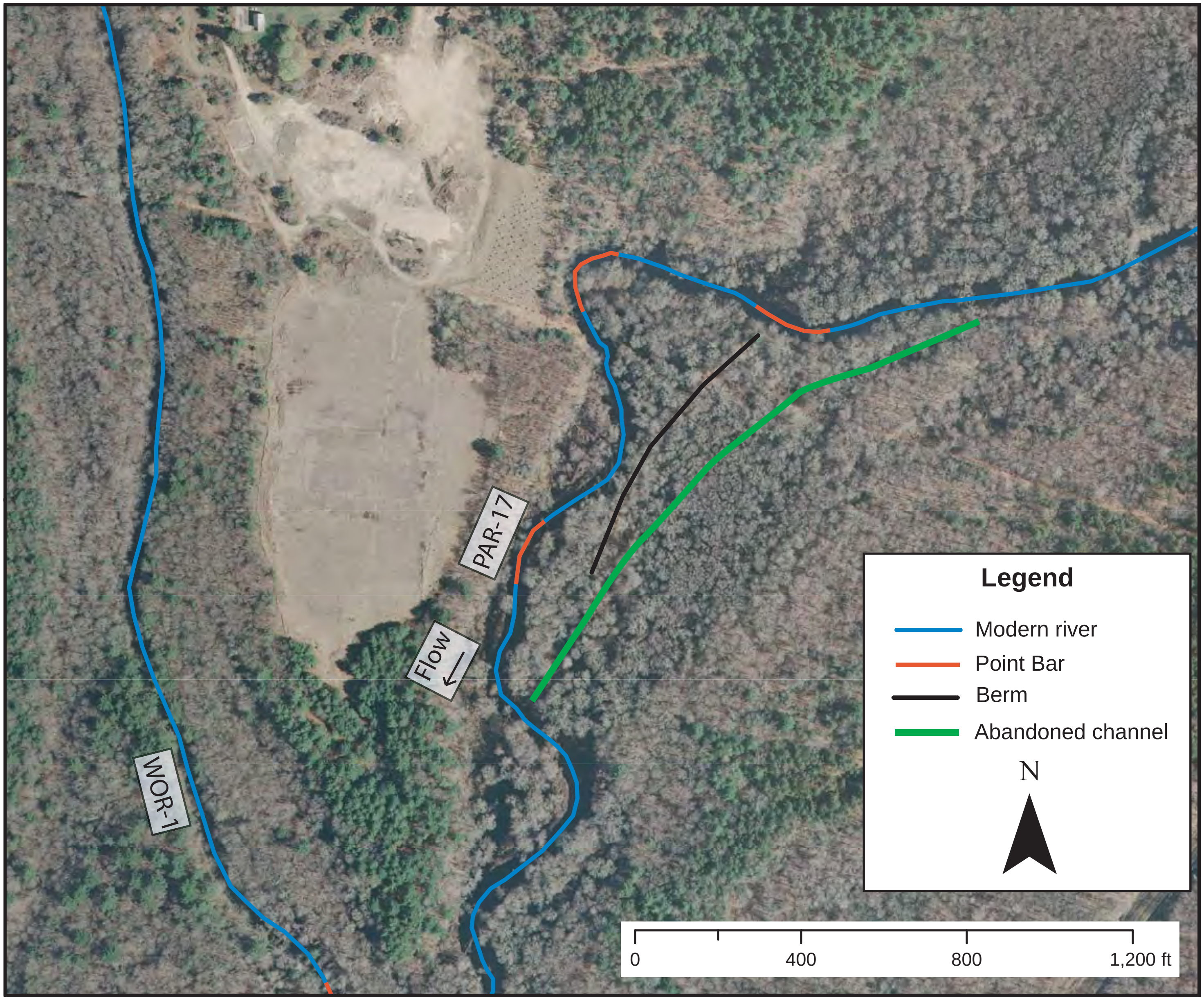


Figure 13b. Orthoimagery from 2012 showing PAR-17 with old berm, abandoned straightened channel, and point bars on modern river driving meander reformation.

a)

b)

Figure 14. a) Scour on the inside of a meander bend upstream of Boom Bridge in PAR-6 and b) severe damage to Boom Bridge pier.

a)

b)

Figure 15. a) Insufficient riparian vegetation in PAR-3 and b) downstream view of lower PAR-1 where downtown Westerly completely encroaches on the channel.

a)

b)

Figure 16. a): Downstream view of old abutments constricting channel in WOR-16 and b) right bank view of bank erosion due to abutments.

Figure 17. Right bank view of insufficient vegetation on bank in WOR-9.

a)

b)

Figure 18. Route 91 Bridge and Alton Dam in WOR-1 showing a) right bank view of pier scour and b) dam underneath bridge.

a)

b)

Figure 19. Old dam structure on left bank of GAS-8 showing a) downstream view of structure and b) close up of mill race intake.

Figure 20. Upstream view of artificially straightened channel in GAS-4.

Figure 21. Absence of riparian vegetation and poorly formed channel on golf course in MEB-8b.

Figure 22. Upstream view of straightened channel with an old berm on the right bank of BER-6a.

a)

b)

Figure 23. BER-3b showing a) old mill race channel that is now a flood chute and b) downstream view of modern stream flowing over old mill dam structure.

Figure 24. Active beaver dam in BER-2.

Figure 25. Bank armor on bank with insufficient riparian vegetation on the left bank of CHIP-10.

a)

b)

Figure 26. Undersized culvert at Yawgoo Valley Road in CHIP-8 showing a) upstream view of entire crossing and b) close up of beaver dam clogging culvert inlet.

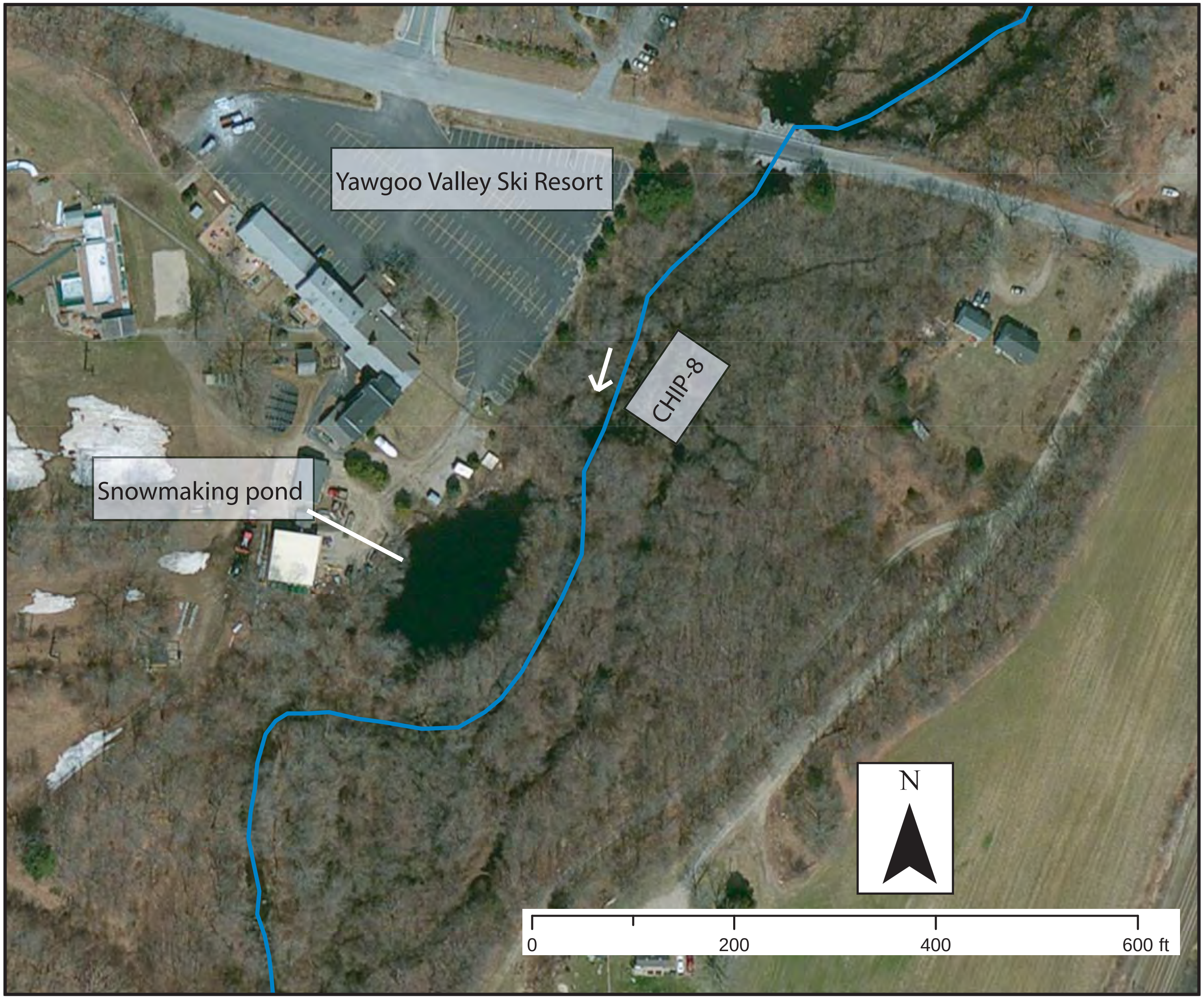


Figure 27. Aerial photograph showing a snowmaking pond that could potentially be an avulsion pathway in a dynamic section of CHIP-8.

TABLES

Table 1. List of Phase 1 reaches.

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 Rt 78 Bridge in Westerley	large diversion reenters channel	Stonington/Westerly	RI/CT
Pawcatuck	PAR-4	At White Rock Dam	dam at reach break	Stonington/Westerly	RI/CT
Pawcatuck	PAR-5	At top of 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-8	At Potter Hill dam	dam at reach break	Hopkinton/Westerly	RI
Pawcatuck	PAR-9	At Rt 3 Bridge	Valley Constriction	Hopkinton/Westerly	RI
Pawcatuck	PAR-10	Upstream of McGowan Brook confluence	dam at reach break	Hopkinton/Westerly	RI
Pawcatuck	PAR-11	Downstream of Kedinker Island and Tomaquag Brook confluence	Valley Constriction	Hopkinton/Westerly	RI
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-14	At upstream end of Bradford Dam impoundment	beginning of impoundment	Hopkinton/Westerly	RI
Pawcatuck	PAR-15	At Burlingame campsite in Phantom Bog	dam at reach break	Hopkinton/Charlestown	RI
Pawcatuck	PAR-16	At Burdickville dam	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 gage 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-22	At Carolina mill dam	dam at reach break	Richmond/Charlestown	RI
Pawcatuck	PAR-23	At upstream extent of Carolina Pond	beginning 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	beginning of impoundment	Richmond/Charlestown	RI

Table 1. (Continued) List of Phase 1 reaches.

Water body	Reach	Downstream reach break Location	Reason	Town	State
Pawcatuck	PAR-27	At Kenyon Mill dam	dam at reach break	Richmond/Charlestown	RI
Pawcatuck	PAR-28	At Biscuit City road stream crossing	beginning of impoundment	Richmond/Charlestown	RI
Pawcatuck	PAR-29	At confluence with the Usquepaug River	Tributary junction	Richmond/Charlestown	RI
Pawcatuck	PAR-0	Beginning of river at Worden Pond	Beginning of river	South Kingstown/Charlestown	RI
Wood	WOR-1	At confluence with the Pawcatuck River	Tributary junction	Hopkinton/Richmond	RI
Wood	WOR-2	At Alton Dam	dam at reach break	Hopkinton/Richmond	RI
Wood	WOR-3	Upstream extent of Alton Pond	beginning of impoundment	Hopkinton/Richmond	RI
Wood	WOR-4	At Woodville dam	dam at reach break	Hopkinton/Richmond	RI
Wood	WOR-5	Upstream extent of Woodville Pond	beginning of impoundment	Hopkinton/Richmond	RI
Wood	WOR-6	Downstream of Switch Road	dam at reach break	Hopkinton/Richmond	RI
Wood	WOR-7	At Gaging weir	Change in Planform	Hopkinton/Richmond	RI
Wood	WOR-8	At the Old Stone Dam	dam at reach break	Hopkinton/Richmond	RI
Wood	WOR-9	At the beginning of the Old Stone Dam impoundment	beginning of impoundment	Hopkinton/Richmond	RI
Wood	WOR-10	At Wyoming dam	dam at reach break	Hopkinton/Richmond	RI
Wood	WOR-11	Upstream extent of Wyoming Pond	beginning of impoundment	Hopkinton/Richmond	RI
Wood	WOR-12	Near western most point of Wood River drive	Valley Constriction	Hopkinton/Richmond	RI
Wood	WOR-13	Barberville Dam at WPWA	dam at reach break	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
Wood	WOR-17	At confluence with the Flat River	Tributary junction	Exeter	RI
Wood	WOR-18	Near river access along Brookie Trail	Valley Constriction	Exeter	RI
Wood	WOR-19	Upstream of Plain Road	Change in Planform	Exeter	RI
Wood	WOR-20	At the confluence with Kelley Brook	Tributary junction	West Greenwich	RI
Wood	WOR-21	Downstream extent of Stepstone Falls	dam at reach break	West Greenwich	RI
Wood	WOR-22	Beginning of Stepstone Falls	Valley Constriction	West Greenwich	RI
Wood	WOR-23	Upstrem extent of Upper Deep Hole	Change in Planform	West Greenwich	RI

Table 1. (Continued) List of Phase 1 reaches.

Water body	Reach	Downstream reach break Location	Reason	Town	State
Wood	WOR-24	Dam at downstream end of Hazard Pond	dam at reach break	West Greenwich	RI
Wood	WOR-25	Upstream extent of Hazard Pond	beginning of impoundment	Voluntown/West Greenwich	RI/CT
Wood	WOR-26	Dam at downstream end of Porter Pond	dam at reach break	Voluntown	CT
Wood	WOR-27	Upstream extent of Porter Pond	beginning of impoundment	Voluntown	CT
Wood	WOR-	Stream begins at Cedar Swamp Road	Beginning of river	Voluntown	CT
Shunock	SHUN-1	At junction with Pawcatuck River	Tributary junction	North Stonington	CT
Shunock	SHUN-2	Upstream of I-95	Valley Constriction	North Stonington	CT
Shunock	SHUN-3	Between I-95 and State Route 184	dam at reach break	North Stonington	CT
Shunock	SHUN-4	Upstream of State Route 184	dam at reach break	North Stonington	CT
Shunock	SHUN-5	Upstream end of impoundment	Tributary junction	North Stonington	CT
Shunock	SHUN-6	At dam in North Stonington Village	dam at reach break	North Stonington	CT
Shunock	SHUN-7	Upstream end of Village impoundment	beginning of impoundment	North Stonington	CT
Shunock	SHUN-8	Downstream end of impoundment at Hewitt Road	dam at reach break	North Stonington	CT
Shunock	SHUN-9	Upstream extent of impoundment	beginning of impoundment	North Stonington	CT
Shunock	SHUN-10a	Downstream or Route 2	Tributary junction	North Stonington	CT
Shunock	SHUN-10b	Downstream of Route 2	Change in Planform	North Stonington	CT
Shunock	SHUN-11	At Gallup Pond dam	dam at reach break	North Stonington	CT
Shunock	SHUN-12	Upstream extent of Gallup Pond	beginning of impoundment	North Stonington	CT
Shunock	SHUN-13	At confluence with Phelps Brook	Tributary junction	North Stonington	CT
Shunock	SHUN-0	Beginning of mapped stream Along State Route 2	Beginning of stream	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-3	At dam at downstream end of Bethel Pond	dam at reach break	Hopkinton	RI
Ashaway	GAS-4	At upstream end of Bethel Pond	beginning of impoundment	Hopkinton	RI
Green Fall	GAS-5	Upstream of state line, at Parmenter Brook confluence	Tributary junction	Hopkinton/North Stonington	RI/CT
Green Fall	GAS-6	At Glade Brook confluence	Tributary junction	North Stonington	CT

Table 1. (Continued) List of Phase 1 reaches.

Water body	Reach	Downstream reach break Location	Reason	Town	State
Green Fall	GAS-7	Upstream of Clarks Falls road and tributary confluence	Tributary junction	North Stonington	CT
Green Fall	GAS-8	at confluence with Shingle Mill Pond Brook	Tributary junction	North Stonington	CT
Green Fall	GAS-9	Upstream of Puttker Road	Valley Constriction	North Stonington	CT
Green Fall	GAS-10	Near Dennison Hill Road	dam at reach break	North Stonington	CT
Green Fall	GAS-11	At downstream end of Pachaug state forest land	dam at reach break	North Stonington	CT
Green Fall	GAS-12	Upstream of pond at downstream end of Pachaug	beginning of impoundment	North Stonington/Voluntown	CT
Green Fall	GAS-13	In Pachaug State Forest	Tributary junction	Voluntown	CT
Green Fall	GAS-14	Downstream of Green Fall road at Mill Brook confluence	Tributary junction	Voluntown	CT
Green Fall	GAS-15	Upstream of Green Fall Road	slope decreases	Voluntown	CT
Green Fall	GAS-16	At downstream end of Green Fall Pond	dam at reach break	Voluntown	CT
Green Fall	GAS-17	At upstream end of Green Fall Pond	beginning of impoundment	Voluntown	CT
Green Fall	GAS-18	Upstream of Green Fall Pond Road	Valley Constriction	Voluntown	CT
Green Fall	GAS-0	Downstream of Rockville Road	Beginning of Stream	Voluntown	CT
Meadow	MEB-1	At junction with Pawcatuck River	Tributary junction	Richmond	RI
Meadow	MEB-2	Dam at downstream end of Meadow Brook pond	dam at reach break	Richmond	RI
Meadow	MEB-3	Upstream of meadow brook pond	beginning of impoundment	Richmond	RI
Meadow	MEB-4	Near Ellis Flats	dam at reach break	Richmond	RI
Meadow	MEB-5	Upstream of Pine Hill road crossing	valley widens	Richmond	RI
Meadow	MEB-6	Along Meadowbrook Trail	slope increases	Richmond	RI
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
Meadow	MEB-9	Upstream of Richmond Elementary School	Valley Constriction	Richmond	RI
Meadow	MEB-10	Along Carolina Nooseneck Road near Bailey Hill	dam at reach break	Richmond	RI
Meadow	MEB-11	Downstream of Buttonwood Corner	slope decreases	Richmond	RI
Meadow	MEB-12	Near junctin of Pines Road and Carolina Nooseneck Road	slope increases	Richmond	RI
Beaver	BER-1	at confluence with Horseshoe falls pond	beginning of impoundment	Richmond	RI

Table 1. (Continued) List of Phase 1 reaches.

Water body	Reach	Downstream reach break Location	Reason	Town	State
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-5	Near the northern end of Thorpe Lane	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
Beaver	BER-8	upstream of Hillsdale Road	Valley Constriction	Richmond	RI
Beaver	BER-9	Upstream of Old Mountain Trail	Valley Constriction	Richmond	RI
Beaver	BER-10	Near Wood Road in Richmond, RI	Valley Constriction	Richmond	RI
Beaver	BER-11	At dam upstream of New London Turnpike	dam at reach break	Richmond/Exeter	RI
Beaver	BER-12	Upstream of New London Turnpike	beginning of impoundment	Exeter	RI
Beaver	BER-0	At outlet of James Pond	Beginning of stream	Exeter	RI
Usquepaug	QUS-1	At junction with Pawcatuck River in the Great Swamp	Tributary junction	South Kingstown/Richmond	RI
Usquepaug	QUS-2	At the Confluence with Chickasheen Brook	Tributary junction	South Kingstown/Richmond	RI
Usquepaug	QUS-3	Upstream of South County Trail	valley widens	South Kingstown/Richmond	RI
Usquepaug	QUS-4	Near Laurel Lane Country Club	dam at reach break	South Kingstown/Richmond	RI
Usquepaug	QUS-5	Upstream of Laurel Lane Country Club	Valley Constriction	South Kingstown/Richmond	RI
Usquepaug	QUS-6	At Glen Rock Dam	dam at reach break	South Kingstown/Richmond	RI
Usquepaug	QUS-7	Upstream extent of Glen Rock Reservoir	beginning of impoundment	South Kingstown/Exeter	RI
Queen	QUS-8	Upstream extent of Locke Swamp	dam at reach break	Exeter	RI
Queen	QUS-9	In Between Liberty Road and Locke Swamp	Valley Constriction	Exeter	RI
Queen	QUS-10	Downstream of Liberty Road	dam at reach break	Exeter	RI
Queen	QUS-11	Downstream of Liberty Road	Valley Constriction	Exeter	RI
Queen	QUS-12	Between Liberty Road and Dawley Road	dam at reach break	Exeter	RI

Table 1. (Continued) List of Phase 1 reaches.

Water body	Reach	Downstream reach break Location	Reason	Town	State
Queen	QUS-13	Upstream of Dawley Road	Valley Constriction	Exeter	RI
Queen	QUS-14	At the confluence with Pendock Brook	Tributary junction	Exeter	RI
Queen	QUS-15	Downstream of Reynolds Road	dam at reach break	Exeter	RI
Queen	QUS-16	At dam upstream of Reynolds Road	dam at reach break	Exeter	RI
Queen	QUS-17	At top of pond	beginning of impoundment	Exeter	RI
Queen	QUS-18	At the bottom of the ponds along the Exeter Country Club Golf Course	dam at reach break	Exeter	RI
Queen	QUS-19	At the top of the ponds in the Exeter Country Club Golf Course	beginning of impoundment	Exeter	RI
Queen	QUS-20	Upstream of Ten Rod Road	Change in Planform	Exeter	RI
Queen	QUS-21	At downstream extent of Edward's Pond	dam at reach break	Exeter	RI
Queen	QUS-22	At Upstream extent of Edward's Pond	beginning of impoundment	Exeter	RI
Queen	QUS-23	Between Edward's Pond and Stony Lane	slope increases	Exeter	RI
Queen	QUS-24	Upstream of Stony Lane	Valley Constriction	Exeter/West Greenwich	RI
Queen	QUS-0	Near Hopkins Hill Road in Exeter, RI	Beginning of stream	West Greenwich	RI
Chipuxet	CHIP-1	at Worden Pond	Tributary junction	South Kingstown	RI
Chipuxet	CHIP-2	Near Camp Hoffman	dam at reach break	South Kingstown	RI
Chipuxet	CHIP-3	At William C. O'Neill bike path	dam at reach break	South Kingstown	RI
Chipuxet	CHIP-4	At state route 138	Valley Constriction	South Kingstown	RI
Chipuxet	CHIP-5	At downstream end of Thirty Acre Pond	dam at reach break	South Kingstown	RI
Chipuxet	CHIP-6	at Upstream end of Thirty Acre Pond	beginning of impoundment	South Kingstown	RI
Chipuxet	CHIP-7	At downstream end of One Hundred Acre Pond	dam at reach break	South Kingstown/Exeter	RI
Chipuxet	CHIP-8	Downstream of Wolfe Rocks Road	beginning of impoundment	Exeter	RI
Chipuxet	CHIP-9	at dam downstream of Yawgoo Mill Pond	dam at reach break	Exeter	RI
Chipuxet	CHIP-10	downstream of Railroad Road	beginning of impoundment	North Kingstown/Exeter	RI
Chipuxet	CHIP-0	At downstream end of Slocum Reservoir	Beginning of stream	Exeter	RI

Table 2. Phase 1 geomorphic data.

Reach name	Im--pounded	Phase 2 reach	Watershed area (mi^2)	Sub watershed area (mi^2)	Stream length (ft)	Valley width (ft)	Reference channel width (ft)	Valley width/ channel with (ft)	Stream slope	Valley slope	Sinuosity	Predicted stream type
PAR-1		yes	297.0	1.67	3051	949	149.9	6.3	0.14%	0.15%	1.07	C or E
PAR-2		yes	295.3	1.61	4574	1372	149.6	9.2	0.08%	0.08%	1.00	C or E
PAR-3		yes	293.7	0.75	4431	1416	149.2	9.5	0.17%	0.19%	1.09	C or E
PAR-4	yes	yes	292.9	0.83	3053	835	149.1	5.6	0.07%	0.07%	1.04	C or E
PAR-5		yes	275.6	0.27	3398	801	145.4	5.5	0.02%	0.02%	1.00	C or E
PAR-6		yes	275.3	3.21	10200	1039	145.4	7.1	0.02%	0.02%	1.20	C or E
PAR-7		yes	243.1	1.25	1024	645	138.3	4.7	0.23%	0.28%	1.21	C or E
PAR-8	yes		241.9	1.57	7951	1438	138.0	10.4	0.05%	0.08%	1.54	C or E
PAR-9			240.3	11.86	14415	1938	137.6	14.1	0.01%	0.01%	1.39	C or E
PAR-10			228.4	0.26	4115	1477	134.8	11.0	0.01%	0.02%	1.75	C or E
PAR-11			228.2	8.94	4879	3156	134.8	23.4	0.01%	0.02%	2.47	C or E
PAR-12		yes	219.2	0.95	5954	1788	132.6	13.5	0.05%	0.05%	1.00	C or E
PAR-13	yes	yes	218.3	0.60	4053	911	132.4	6.9	0.03%	0.04%	1.30	C or E
PAR-14			217.7	10.89	10136	3318	132.2	25.1	0.01%	0.02%	2.46	C or E
PAR-15		yes	206.8	1.02	5619	1162	129.5	9.0	0.02%	0.03%	1.28	C or E
PAR-16	yes		205.8	1.66	6077	418	129.3	3.2	0.03%	0.03%	1.07	C or E
PAR-17		yes	114.7	7.73	11816	1236	102.1	12.1	0.04%	0.05%	1.23	C or E
PAR-18		yes	100.0	0.82	7308	737	96.6	7.6	0.04%	0.05%	1.34	C or E
PAR-19		yes	99.2	0.62	3873	669	96.3	7.0	0.08%	0.08%	1.03	C or E
PAR-20		yes	98.5	2.58	2103	436	96.0	4.5	0.07%	0.07%	1.06	C or E
PAR-21a		yes	96.0	0.70	2215	997	95.0	10.5	0.03%	0.03%	1.07	C or E
PAR-21b		yes	95.3	0.24	1299	548	94.7	5.8	0.41%	0.46%	1.12	C or E
PAR-22	yes		95.0	2.36	4457	592	94.6	6.3	0.03%	0.04%	1.26	C or E
PAR-23		yes	92.7	0.63	4487	544	93.7	5.8	0.15%	0.16%	1.09	C or E
PAR-24		yes	92.0	0.63	2455	372	93.4	4.0	0.42%	0.45%	1.06	C or E

Table 2. (continued) Phase 1 geomorphic data.

Reach name	Im--pounded	Phase 2 reach	Watershed area (mi^2)	Sub watershed area (mi^2)	Stream length (ft)	Valley width (ft)	Reference channel width (ft)	Valley width/ chan-nel with (ft)	Stream slope	Valley slope	Sinuosity	Predicted stream type
PAR-25	yes	yes	91.4	0.30	2659	732	93.1	7.9	0.39%	0.45%	1.16	C or E
PAR-26		yes	79.4	6.31	1943	1196	88.0	13.6	0.09%	0.14%	1.56	C or E
PAR-27	yes		73.0	0.28	3765	566	85.1	6.6	0.02%	0.02%	1.00	C or E
PAR-28		yes	72.8	1.50	4075	739	84.9	8.7	0.01%	0.02%	2.33	C or E
PAR-29			27.4	1.55	9764	2796	57.3	48.8	0.03%	0.04%	1.46	C or E
WOR-1		yes	89.4	2.30	3905	589	92.3	6.4	0.17%	0.18%	1.09	C or E
WOR-2	yes		87.1	0.40	4841	854	91.3	9.4	0.09%	0.10%	1.14	C or E
WOR-3		yes	86.7	1.37	8998	1057	91.2	11.6	0.04%	0.07%	1.70	C or E
WOR-4	yes		85.3	7.97	6802	1253	90.6	13.8	0.07%	0.10%	1.39	C or E
WOR-5			77.4	2.64	7756	1108	87.1	12.7	0.04%	0.07%	1.67	C or E
WOR-6		yes	74.7	1.12	5181	850	85.9	9.9	0.07%	0.08%	1.13	C or E
WOR-7		yes	73.6	0.17	2478	697	85.3	8.2	0.15%	0.19%	1.26	C or E
WOR-8	yes		73.4	12.81	3036	1233	85.3	14.5	0.29%	0.44%	1.50	C or E
WOR-9			60.6	1.70	4989	1164	78.9	14.8	0.15%	0.19%	1.25	C or E
WOR-10	yes		58.9	0.83	4176	635	78.0	8.1	0.29%	0.30%	1.02	C or E
WOR-11		yes	58.1	2.51	5461	900	77.5	11.6	0.03%	0.03%	1.00	C or E
WOR-12		yes	55.6	0.54	5001	808	76.2	10.6	0.20%	0.25%	1.23	C or E
WOR-13	yes		55.0	7.59	4731	903	75.9	11.9	0.07%	0.07%	1.06	C or E
WOR-14		yes	47.4	1.94	6882	1560	71.5	21.8	0.06%	0.07%	1.20	C or E
WOR-15		yes	45.5	7.63	3831	483	70.3	6.9	0.06%	0.07%	1.19	C or E
WOR-16		yes	37.9	17.20	5565	2853	65.3	43.7	0.10%	0.12%	1.23	C or E
WOR-17			20.7	0.62	5516	780	51.1	15.3	0.16%	0.17%	1.05	C or E
WOR-18			18.5	1.42	7337	1191	48.9	24.4	0.36%	0.48%	1.32	C or E
WOR-19			17.1	5.06	2841	713	47.3	15.1	1.13%	1.23%	1.09	C or E

Table 2. (continued) Phase 1 geomorphic data.

Reach name	Im--pounded	Phase 2 reach	Watershed area (mi^2)	Sub watershed area (mi^2)	Stream length (ft)	Valley width (ft)	Reference channel width (ft)	Valley width/ channel with (ft)	Stream slope	Valley slope	Sinuosity	Predicted stream type
WOR-20			12.0	0.51	4184	876	41.1	21.3	1.40%	1.68%	1.20	C or E
WOR-21			11.5	0.02	758	254	40.4	6.3	3.97%	4.23%	1.06	B
WOR-22			11.5	0.37	3698	562	40.3	13.9	0.20%	0.23%	1.14	C or E
WOR-23			11.1	1.95	6323	833	39.8	20.9	0.57%	0.76%	1.34	C or E
WOR-24	yes		9.2	1.44	4545	1165	36.8	31.6	0.10%	0.11%	1.11	C or E
WOR-25			7.8	4.95	11402	1307	34.4	38.0	0.25%	0.29%	1.14	C or E
WOR-26	yes		2.8	0.29	1954	700	22.8	30.7	0.41%	0.41%	1.00	C or E
WOR-27			2.5	0.97	2464	589	21.8	27.0	1.06%	1.24%	1.17	C or E
SHUN-1			16.6	0.52	5913	796	46.7	17.0	0.61%	0.68%	1.11	C or E
SHUN-2			16.0	0.57	2311	861	46.1	18.7	0.39%	0.53%	1.35	C or E
SHUN-3			15.5	0.67	4451	833	45.5	18.3	0.45%	0.53%	1.18	C or E
SHUN-4	yes		14.8	2.67	7651	1127	44.7	25.2	0.03%	0.04%	1.32	C or E
SHUN-5			12.1	0.31	3457	414	41.2	10.1	0.72%	0.80%	1.11	C or E
SHUN-6	yes		11.8	5.25	6124	937	40.8	23.0	0.39%	0.57%	1.47	C or E
SHUN-7			6.6	0.04	981	1106	32.2	34.4	0.41%	0.43%	1.04	C or E
SHUN-8	yes		6.5	1.20	7336	526	32.1	16.4	0.10%	0.12%	1.18	C or E
SHUN-9			5.3	2.97	1592	1518	29.6	51.3	0.19%	0.19%	1.00	C or E
SHUN-10a		yes	2.4	0.08	691	860	21.3	40.5	1.30%	1.83%	1.41	C or E
SHUN-10b		yes	2.3	0.04	752	464	21.0	22.1	2.39%	2.33%	1.00	D
SHUN-11	yes		2.2	0.14	607	344	20.8	16.5	1.15%	1.22%	1.06	C or E
SHUN-12			2.1	1.68	1459	435	20.3	21.4	0.96%	1.19%	1.24	C or E
SHUN-13			0.4	0.32	3099	405	10.7	38.0	1.19%	1.37%	1.16	C or E
GAS-1		yes	29.0	0.59	4516	826	58.6	14.1	0.12%	0.20%	1.68	C or E
GAS-2	yes	yes	28.4	0.46	4184	421	58.1	7.2	0.33%	0.41%	1.23	C or E

Table 2. (continued) Phase 1 geomorphic data.

Reach name	Im--pounded	Phase 2 reach	Watershed area (mi^2)	Sub watershed area (mi^2)	Stream length (ft)	Valley width (ft)	Reference channel width (ft)	Valley width/ chan-nel with (ft)	Stream slope	Valley slope	Sinuosity	Predicted stream type
GAS-3	yes		27.9	0.66	4788	695	57.7	12.0	0.08%	0.09%	1.17	C or E
GAS-4		yes	27.3	3.76	3289	1194	57.1	20.9	0.12%	0.13%	1.08	C or E
GAS-5			23.5	2.94	5468	986	53.8	18.3	0.19%	0.26%	1.34	C or E
GAS-6			20.6	11.98	4167	751	51.0	14.7	0.39%	0.46%	1.17	C or E
GAS-7			8.6	0.71	4619	716	35.8	20.0	0.37%	0.41%	1.10	C or E
GAS-8		yes	7.9	0.13	2250	782	34.6	22.6	0.22%	0.22%	1.02	C or E
GAS-9			7.7	1.23	4909	557	34.4	16.2	1.06%	1.16%	1.09	C or E
GAS-10			6.5	0.86	3702	250	32.1	7.8	0.68%	0.71%	1.04	C or E
GAS-11	yes		5.6	0.05	1132	261	30.3	8.6	0.71%	0.75%	1.05	C or E
GAS-12			5.6	1.18	4558	374	30.2	12.4	0.39%	0.47%	1.21	C or E
GAS-13			4.4	2.13	4150	247	27.4	9.0	0.37%	0.37%	1.01	C or E
GAS-14			2.3	0.30	2141	373	21.0	17.8	1.56%	1.61%	1.03	C or E
GAS-15			2.0	0.02	986	146	19.8	7.4	3.46%	3.49%	1.01	D
GAS-16	yes		2.0	1.21	2349	1373	19.7	69.5	1.20%	1.25%	1.04	C or E
GAS-17			0.8	0.29	5496	517	13.4	38.5	1.68%	1.84%	1.10	C or E
GAS-18			0.5	0.40	4848	1611	11.0	146.2	0.93%	1.07%	1.15	C or E
MEB-1			7.0	0.15	1858	448	33.1	13.5	0.86%	0.95%	1.10	C or E
MEB-2	yes		6.9	0.21	2635	620	32.8	18.9	0.00%	0.00%	1.00	C or E
MEB-3			6.7	0.73	4720	429	32.4	13.2	0.17%	0.20%	1.18	C or E
MEB-4			5.9	0.44	4515	481	30.9	15.6	0.28%	0.30%	1.06	C or E
MEB-5			5.5	0.81	4546	461	29.9	15.4	0.25%	0.27%	1.07	C or E
MEB-6			4.7	0.78	4726	555	28.1	19.8	0.21%	0.23%	1.07	C or E
MEB-7		yes	3.9	1.49	6039	908	26.1	34.8	0.19%	0.25%	1.31	C or E
MEB-8a		yes	2.4	0.04	1501	356	21.5	16.6	0.90%	1.02%	1.13	C or E

Table 2. (continued) Phase 1 geomorphic data.

Reach name	Im-- pounded	Phase 2 reach	Watershed area (mi^2)	Sub watershed area (mi^2)	Stream length (ft)	Valley width (ft)	Reference channel width (ft)	Valley width/ chan-nel with (ft)	Stream slope	Valley slope	Sinuosity	Predicted stream type
MEB-8b		yes	2.4	0.72	3229	1242	21.4	58.1	0.57%	0.61%	1.06	C or E
MEB-9			1.7	0.48	2884	2153	18.5	116.5	0.10%	0.11%	1.07	C or E
MEB-10			1.2	0.29	5489	417	16.1	25.9	0.76%	0.93%	1.22	C or E
MEB-11			0.9	0.22	3659	206	14.4	14.4	2.98%	3.05%	1.02	D
MEB-12			0.7	0.67	1519	361	12.8	28.2	1.04%	1.03%	1.00	C or E
BER-1			11.7	0.55	6382	868	40.7	21.3	0.14%	0.15%	1.10	C or E
BER-2		yes	11.2	1.52	7403	1039	39.9	26.0	0.07%	0.08%	1.20	C or E
BER-3a		yes	9.7	0.67	3852	1437	37.6	38.2	0.09%	0.11%	1.18	C or E
BER-3b		yes	9.0	0.08	1991	679	36.5	18.6	0.87%	0.87%	1.00	C or E
BER-4		yes	8.9	0.61	2896	973	36.4	26.7	0.01%	0.01%	1.26	C or E
BER-5			8.3	1.47	7426	780	35.4	22.1	0.21%	0.25%	1.20	C or E
BER-6a		yes	6.8	1.20	3976	558	32.7	17.1	0.56%	0.71%	1.27	C or E
BER-6b		yes	5.6	0.05	897	313	30.2	10.4	3.33%	3.57%	1.07	D
BER-7		yes	5.6	0.12	1715	353	30.1	11.7	2.26%	2.45%	1.09	C or E
BER-8			5.5	0.75	6360	685	29.9	22.9	0.39%	0.48%	1.22	C or E
BER-9			4.7	0.94	5185	786	28.1	27.9	0.67%	0.83%	1.24	C or E
BER-10			3.8	1.89	5135	821	25.7	31.9	0.77%	0.92%	1.20	C or E
BER-11	yes		1.9	0.14	1391	877	19.4	45.2	0.09%	0.11%	1.21	C or E
BER-12			1.7	0.62	5306	844	18.8	44.8	0.40%	0.45%	1.12	C or E
QUS-1			43.8	6.39	6386	2200	69.2	31.8	0.04%	0.06%	1.38	C or E
QUS-2			37.4	0.83	7174	4773	64.9	73.5	0.09%	0.11%	1.24	C or E
QUS-3			36.6	1.06	6348	1401	64.4	21.8	0.01%	0.02%	1.52	C or E
QUS-4			35.5	0.42	4336	1530	63.6	24.1	0.04%	0.06%	1.38	C or E
QUS-5			35.1	1.50	6401	1023	63.3	16.2	0.11%	0.19%	1.72	C or E
QUS-6	yes		33.6	5.15	7754	651	62.2	10.5	0.06%	0.07%	1.13	C or E
QUS-7			28.5	7.19	6404	1104	58.2	19.0	0.05%	0.07%	1.37	C or E

Table 2. (continued) Phase 1 geomorphic data.

Reach name	Im-- pounded	Phase 2 reach	Watershed area (mi^2)	Sub watershed area (mi^2)	Stream length (ft)	Valley width (ft)	Reference channel width (ft)	Valley width/ chan-nel with (ft)	Stream slope	Valley slope	Sinuosity	Predicted stream type
QUS-8			21.3	0.24	4019	516	51.7	10.0	0.05%	0.06%	1.13	C or E
QUS-9			21.0	1.23	2065	1040	51.5	20.2	0.07%	0.08%	1.17	C or E
QUS-10			19.8	0.44	2498	443	50.2	8.8	0.06%	0.08%	1.32	C or E
QUS-11		yes	19.4	0.91	2370	1011	49.8	20.3	0.17%	0.20%	1.20	C or E
QUS-12			18.5	0.35	3487	347	48.8	7.1	0.13%	0.15%	1.13	C or E
QUS-13			18.1	13.31	3732	1203	48.4	24.8	0.05%	0.07%	1.30	C or E
QUS-14			4.8	0.42	4119	1243	28.3	43.9	0.17%	0.24%	1.39	C or E
QUS-15			4.4	0.56	2606	1127	27.3	41.3	0.53%	0.86%	1.63	C or E
QUS-16	yes		3.8	0.02	457	872	25.8	33.8	0.00%	0.00%	1.00	C or E
QUS-17			3.8	0.52	3673	604	25.8	23.4	0.63%	0.79%	1.25	C or E
QUS-18	yes		3.3	0.10	1161	503	24.3	20.7	0.18%	0.18%	1.00	C or E
QUS-19			3.2	0.23	1289	387	24.0	16.1	1.34%	1.46%	1.09	C or E
QUS-20			2.9	0.96	1271	725	23.3	31.2	2.23%	2.39%	1.07	C or E
QUS-21	yes		2.0	0.10	657	728	19.8	36.7	0.00%	0.00%	1.00	C or E
QUS-22			1.9	0.21	2499	679	19.4	34.9	1.67%	2.18%	1.31	C or E
QUS-23			1.7	0.65	5301	631	18.5	34.0	0.93%	1.06%	1.14	C or E
QUS-24			1.0	0.87	6441	453	15.2	29.8	0.87%	0.97%	1.12	C or E
CHIP-1			15.6	5.13	8595	7496	45.6	164.5	0.03%	0.04%	1.22	C or E
CHIP-2			10.4	0.58	6220	1237	38.8	31.9	0.03%	0.03%	1.06	C or E
CHIP-3			9.9	0.14	3328	955	37.9	25.2	0.13%	0.15%	1.12	C or E
CHIP-4			9.7	0.45	1781	688	37.7	18.3	0.00%	0.00%	1.00	C or E
CHIP-5	yes		9.3	0.16	3319	610	36.9	16.5	0.00%	0.00%	1.00	C or E
CHIP-6			9.1	0.08	357	494	36.7	13.5	4.66%	4.91%	1.05	C_b
CHIP-7	yes		9.0	1.19	6977	1941	36.6	53.1	0.00%	0.00%	1.00	C or E
CHIP-8		yes	7.8	3.92	7076	658	34.5	19.1	0.08%	0.09%	1.08	C or E
CHIP-9			3.9	0.75	3421	579	26.1	22.2	0.00%	0.00%	1.00	C or E
CHIP-10		yes	3.2	0.88	4743	338	24.0	14.1	0.25%	0.30%	1.18	C or E

Table 3. Phase 1 watershed land use statistics.

Reach Name	Sub watershed area (mi^2)	% Developed land 2011	% Agricultural land 2011	Development+ Agriculture 2011	Development+ Agriculture 1992	% Increase in Development +Agriculture from 1992 to 2011	Road density (mi/mi^2)
PAR-1	1.67	79.37%	0.83%	80.20%	64.80%	15.40%	14.7
PAR-2	1.61	56.15%	2.35%	58.50%	51.71%	6.80%	8.9
PAR-3	0.75	65.52%	0.97%	66.50%	42.11%	24.39%	10.4
PAR-4	0.83	30.24%	21.50%	51.74%	38.88%	12.86%	8.5
PAR-5	0.27	0.90%	26.71%	27.61%	23.33%	4.28%	0.6
PAR-6	3.21	9.81%	25.02%	34.83%	16.44%	18.40%	4.1
PAR-7	1.25	29.16%	9.69%	38.85%	35.26%	3.60%	6.5
PAR-8	1.57	39.53%	6.04%	45.58%	31.95%	13.62%	8.6
PAR-9	11.86	26.05%	7.47%	33.52%	23.88%	9.64%	4.4
PAR-10	0.26	0.13%	0.78%	0.92%	2.78%	-1.86%	0.0
PAR-11	8.94	9.01%	9.33%	18.34%	11.09%	7.25%	2.8
PAR-12	0.95	29.33%	4.79%	34.13%	38.35%	-4.22%	4.8
PAR-13	0.60	12.54%	5.52%	18.06%	18.54%	-0.48%	2.5
PAR-14	10.89	10.11%	1.98%	12.10%	5.08%	7.02%	2.9
PAR-15	1.02	8.11%	6.17%	14.28%	7.82%	6.46%	2.0
PAR-16	1.66	5.72%	5.97%	11.70%	5.71%	5.98%	2.4
PAR-17	7.73	8.12%	10.12%	18.24%	11.55%	6.69%	2.5
PAR-18	0.82	4.36%	3.56%	7.92%	5.23%	2.69%	1.1
PAR-19	0.62	12.08%	16.66%	28.74%	19.93%	8.81%	2.9
PAR-20	2.58	15.00%	7.42%	22.41%	12.68%	9.73%	3.4
PAR-21a	0.70	24.93%	3.50%	28.42%	19.91%	8.51%	4.5
PAR-21b	0.24	26.27%	6.39%	32.66%	17.71%	14.95%	7.5
PAR-22	2.36	6.54%	8.69%	15.23%	8.92%	6.31%	2.0
PAR-23	0.63	19.79%	11.25%	31.04%	18.45%	12.58%	5.6
PAR-24	0.63	18.34%	9.41%	27.75%	22.38%	5.37%	4.2
PAR-25	0.30	5.90%	18.87%	24.76%	13.40%	11.36%	2.2
PAR-26	6.31	10.61%	4.75%	15.36%	6.97%	8.39%	3.1
PAR-27	0.28	16.42%	11.90%	28.32%	16.10%	12.22%	5.5
PAR-28	1.50	10.90%	18.48%	29.38%	16.03%	13.35%	2.1
PAR-29	1.55	2.48%	6.04%	8.52%	3.58%	4.94%	1.1
PAR-0	10.33	5.38%	4.73%	10.11%	6.03%	4.08%	2.0
WOR-1	2.30	7.89%	10.24%	18.13%	10.97%	7.16%	2.4
WOR-2	0.40	16.43%	25.52%	41.96%	16.17%	25.79%	3.3
WOR-3	1.37	14.70%	16.10%	30.80%	18.66%	12.14%	3.3
WOR-4	7.97	10.10%	4.42%	14.52%	10.09%	4.43%	2.8
WOR-5	2.64	14.04%	2.89%	16.94%	6.86%	10.08%	2.8
WOR-6	1.12	22.92%	23.14%	46.07%	34.25%	11.81%	6.3
WOR-7	0.17	33.27%	13.75%	47.01%	36.49%	10.52%	11.7

Table 3. (continued) Phase 1 watershed land use statistics.

Reach Name	Sub watershed area (mi^2)	% Developed land 2011	% Agricultural land 2011	Development+ Agriculture 2011	Development+ Agriculture 1992	% Increase in Development +Agriculture from 1992 to 2011	Road density (mi/mi^2)
WOR-8	12.81	7.49%	4.19%	11.67%	7.50%	4.17%	2.6
WOR-9	1.70	18.43%	18.78%	37.21%	30.79%	6.41%	4.6
WOR-10	0.83	41.29%	10.25%	51.54%	41.27%	10.27%	9.4
WOR-11	2.51	28.32%	4.34%	32.67%	18.46%	14.20%	7.2
WOR-12	0.54	24.40%	9.30%	33.70%	24.85%	8.85%	5.0
WOR-13	7.59	9.87%	3.06%	12.93%	8.48%	4.45%	2.9
WOR-14	1.94	4.31%	2.20%	6.52%	3.10%	3.41%	1.7
WOR-15	7.63	5.10%	2.62%	7.72%	3.20%	4.52%	1.7
WOR-16	17.20	7.33%	2.27%	9.60%	3.52%	6.07%	2.2
WOR-17	0.62	10.34%	0.78%	11.12%	4.63%	6.49%	3.7
WOR-18	1.42	6.83%	0.91%	7.74%	1.28%	6.46%	3.2
WOR-19	5.06	4.82%	5.12%	9.94%	5.42%	4.52%	1.6
WOR-20	0.51	7.59%	3.08%	10.66%	5.01%	5.66%	3.8
WOR-21	0.02	13.95%	0.00%	13.95%	0.00%	13.95%	7.9
WOR-22	0.37	0.00%	0.00%	0.00%	2.80%	-2.80%	0.0
WOR-23	1.95	4.39%	0.00%	4.39%	1.86%	2.53%	2.1
WOR-24	1.44	6.66%	1.01%	7.68%	7.11%	0.56%	3.5
WOR-25	4.95	4.41%	4.99%	9.39%	5.16%	4.23%	3.9
WOR-26	0.29	4.65%	2.27%	6.92%	2.16%	4.77%	4.6
WOR-27	0.97	6.78%	19.06%	25.84%	21.34%	4.51%	3.7
WOR - 0	1.55	5.20%	21.15%	26.35%	18.18%	8.18%	4.1
SHUN-1	0.52	32.82%	10.45%	43.27%	23.67%	19.60%	9.3
SHUN-2	0.57	17.09%	9.31%	26.39%	11.26%	15.13%	6.9
SHUN-3	0.67	18.63%	20.90%	39.53%	21.56%	17.97%	8.1
SHUN-4	2.67	6.31%	18.15%	24.46%	17.39%	7.07%	3.6
SHUN-5	0.31	18.35%	3.67%	22.02%	12.47%	9.55%	7.7
SHUN-6	5.25	10.80%	17.81%	28.61%	22.07%	6.54%	3.9
SHUN-7	0.04	6.42%	58.72%	65.14%	36.45%	28.69%	6.5
SHUN-8	1.20	10.23%	15.49%	25.72%	21.03%	4.68%	4.2
SHUN-9	2.97	3.77%	9.49%	13.26%	9.44%	3.81%	3.2
SHUN-10a	0.08	8.81%	25.55%	34.36%	8.89%	25.47%	10.4
SHUN-10b	0.04	30.77%	20.19%	50.96%	23.58%	27.38%	20.4
SHUN-11	0.14	20.61%	6.87%	27.48%	4.79%	22.70%	11.8
SHUN-12	1.68	4.49%	3.91%	8.41%	3.30%	5.11%	2.8
SHUN-13	0.32	11.61%	0.22%	11.82%	2.72%	9.10%	5.5
SHUN-0	0.11	16.07%	15.08%	31.15%	17.22%	13.93%	6.3
GAS-1	0.59	20.99%	26.71%	47.70%	40.04%	7.67%	6.2

Table 3. (continued) Phase 1 watershed land use statistics.

Reach Name	Sub watershed area (mi^2)	% Develop-ed land 2011	% Agricul-tural land 2011	Development+ Agriculture 2011	Development+ Agriculture 1992	% Increase in Develop-ment +Agriculture from 1992 to 2011	Road density (mi/mi^2)
GAS-2	0.46	29.86%	12.99%	42.86%	31.59%	11.27%	5.3
GAS-3	0.66	18.97%	21.41%	40.38%	31.25%	9.14%	4.2
GAS-4	3.76	14.22%	13.05%	27.27%	17.45%	9.82%	5.0
GAS-5	2.94	3.47%	19.76%	23.23%	16.88%	6.35%	2.3
GAS-6	11.98	4.62%	8.78%	13.40%	9.55%	3.86%	3.5
GAS-7	0.71	3.09%	17.36%	20.45%	15.83%	4.62%	3.4
GAS-8	0.13	10.63%	0.00%	10.63%	1.64%	8.98%	9.6
GAS-9	1.23	4.68%	4.97%	9.65%	6.53%	3.12%	3.1
GAS-10	0.86	3.50%	2.17%	5.67%	2.46%	3.21%	3.5
GAS-11	0.05	0.00%	0.00%	0.00%	0.68%	-0.68%	0.0
GAS-12	1.18	3.50%	3.91%	7.42%	4.32%	3.09%	1.9
GAS-13	2.13	2.29%	0.33%	2.61%	1.14%	1.47%	2.1
GAS-14	0.30	1.62%	0.00%	1.62%	0.46%	1.16%	3.6
GAS-15	0.02	0.00%	0.00%	0.00%	0.00%	0.00%	4.7
GAS-16	1.21	2.96%	0.00%	2.96%	0.32%	2.65%	5.0
GAS-17	0.29	2.73%	0.00%	2.73%	0.00%	2.73%	4.6
GAS-18	0.40	3.18%	0.00%	3.18%	0.43%	2.75%	1.1
GAS-0	0.06	1.14%	0.00%	1.14%	8.62%	-7.48%	12.8
MEB-1	0.15	23.06%	36.00%	59.06%	24.34%	34.72%	7.3
MEB-2	0.21	11.39%	34.16%	45.54%	46.56%	-1.01%	0.7
MEB-3	0.73	6.90%	26.57%	33.48%	30.61%	2.87%	1.7
MEB-4	0.44	8.35%	1.64%	9.98%	3.29%	6.70%	2.2
MEB-5	0.81	6.90%	0.00%	6.90%	0.04%	6.86%	3.1
MEB-6	0.78	19.99%	4.61%	24.60%	13.58%	11.02%	3.6
MEB-7	1.49	18.66%	1.89%	20.56%	7.69%	12.87%	2.1
MEB-8a	0.04	0.00%	0.00%	0.00%	0.00%	0.00%	0.0
MEB-8b	0.72	12.27%	10.49%	22.76%	14.22%	8.55%	1.0
MEB-9	0.48	4.79%	6.53%	11.32%	6.19%	5.13%	1.3
MEB-10	0.29	7.83%	1.30%	9.13%	3.21%	5.93%	2.1
MEB-11	0.22	16.19%	2.67%	18.87%	5.32%	13.55%	6.1
MEB-12	0.67	9.30%	0.00%	9.30%	2.13%	7.17%	2.9
BER-1	0.55	7.79%	20.85%	28.64%	18.23%	10.41%	4.6
BER-2	1.52	6.15%	21.18%	27.32%	30.31%	-2.99%	2.4
BER-3a	0.67	7.03%	26.63%	33.66%	26.04%	7.62%	2.0
BER-3b	0.08	27.85%	34.25%	62.10%	48.86%	13.24%	8.4
BER-4	0.61	24.83%	12.75%	37.58%	9.53%	28.05%	4.6
BER-5	1.47	11.98%	3.49%	15.47%	6.49%	8.98%	2.4

Table 3. (continued) Phase 1 watershed land use statistics.

Reach Name	Sub watershed area (mi^2)	% Developed land 2011	% Agricultural land 2011	Development+ Agriculture 2011	Development+ Agriculture 1992	% Increase in Development +Agriculture from 1992 to 2011	Road density (mi/mi^2)
BER-6a	1.20	3.46%	0.00%	3.46%	1.72%	1.74%	0.8
BER-6b	0.05	3.21%	0.00%	3.21%	0.00%	3.21%	0.4
BER-7	0.12	11.21%	0.00%	11.21%	1.78%	9.43%	2.8
BER-8	0.75	4.94%	0.00%	4.94%	1.30%	3.64%	2.5
BER-9	0.94	6.51%	0.37%	6.88%	5.10%	1.78%	2.5
BER-10	1.89	13.56%	2.53%	16.09%	5.44%	10.65%	3.8
BER-11	0.14	3.95%	11.60%	15.56%	15.85%	-0.30%	0.7
BER-12	0.62	8.91%	0.00%	8.91%	2.41%	6.50%	1.8
BER-0	1.12	10.84%	3.57%	14.41%	8.00%	6.41%	3.4
QUS-1	6.39	13.50%	8.92%	22.42%	13.09%	9.33%	2.7
QUS-2	0.83	10.35%	42.55%	52.90%	38.43%	14.47%	2.1
QUS-3	1.06	9.59%	18.29%	27.88%	22.62%	5.26%	0.4
QUS-4	0.42	15.41%	9.51%	24.92%	20.76%	4.16%	2.5
QUS-5	1.50	14.48%	25.53%	40.02%	34.44%	5.58%	2.8
QUS-6	5.15	5.28%	6.99%	12.28%	10.84%	1.44%	2.5
QUS-7	7.19	6.64%	7.48%	14.12%	8.28%	5.84%	2.0
QUS-8	0.24	0.00%	21.05%	21.05%	13.49%	7.56%	0.1
QUS-9	1.23	5.01%	6.00%	11.01%	5.29%	5.72%	1.5
QUS-10	0.44	8.89%	2.81%	11.70%	2.98%	8.72%	3.5
QUS-11	0.91	4.46%	3.66%	8.12%	5.37%	2.75%	1.8
QUS-12	0.35	0.00%	21.66%	21.66%	24.80%	-3.14%	0.0
QUS-13	13.31	9.41%	6.16%	15.57%	13.58%	1.99%	2.7
QUS-14	0.42	18.96%	5.76%	24.73%	23.75%	0.97%	5.6
QUS-15	0.56	18.01%	2.05%	20.06%	17.30%	2.76%	3.5
QUS-16	0.02	0.00%	25.76%	25.76%	27.14%	-1.39%	0.0
QUS-17	0.52	31.83%	1.66%	33.49%	24.21%	9.28%	2.6
QUS-18	0.10	75.87%	0.00%	75.87%	68.33%	7.55%	0.0
QUS-19	0.23	37.52%	0.15%	37.67%	19.42%	18.25%	3.3
QUS-20	0.96	9.04%	3.18%	12.22%	4.95%	7.27%	1.8
QUS-21	0.10	14.70%	24.01%	38.71%	14.86%	23.85%	6.9
QUS-22	0.21	0.00%	1.01%	1.01%	0.50%	0.50%	0.0
QUS-23	0.65	1.93%	0.00%	1.93%	0.43%	1.50%	0.9
QUS-24	0.87	0.40%	0.00%	0.40%	0.04%	0.36%	0.0
QUS-0	0.16	11.71%	0.00%	11.71%	6.37%	5.34%	3.4
CHIP-1	5.13	25.31%	10.07%	35.37%	29.13%	6.24%	4.9
CHIP-2	0.58	10.94%	10.70%	21.64%	22.36%	-0.72%	2.7
CHIP-3	0.14	40.93%	12.01%	52.94%	31.34%	21.60%	9.1
CHIP-4	0.45	35.24%	35.08%	70.32%	52.42%	17.90%	5.1

Table 3. (continued) Phase 1 watershed land use statistics.

Reach Name	Sub watershed area (mi^2)	% Develop-ed land 2011	% Agricul-tural land 2011	Development+ Agriculture 2011	Development+ Agriculture 1992	% Increase in Develop-ment +Agriculture from 1992 to 2011	Road density (mi/mi^2)
CHIP-5	0.16	8.80%	38.58%	47.38%	46.44%	0.94%	1.1
CHIP-6	0.08	19.94%	42.07%	62.01%	55.22%	6.79%	2.8
CHIP-7	1.19	7.24%	2.37%	9.62%	4.35%	5.27%	3.3
CHIP-8	3.92	12.67%	16.53%	29.19%	17.31%	11.89%	3.4
CHIP-9	0.75	19.24%	57.54%	76.79%	65.48%	11.30%	3.7
CHIP-10	0.88	11.96%	32.93%	44.89%	40.55%	4.34%	2.7
CHIP-0	2.29	16.61%	13.36%	29.97%	17.95%	12.02%	2.7
Whole Catchment	**297.0**	**11.25%**	**7.89%**	**19.15%**	**12.69%**	**6.46%**	**3.2**

Table 4. Summary of reach characteristics calculated using the Feature Indexing Tool.

Reach / Segment	Stream length (ft)	Channel straight-ening (%)	Bank erosion (%)	Bank armor (%)	Deposition length (ft/mile)	Buffer width <25 ft (%)	Corridor develop-ment (%)
PAR-1	3051	100.0%	1.3%	71.7%	302	59.1%	95.2%
PAR-2	4574	100.0%	5.0%	25.2%	404	28.9%	69.0%
PAR-3	4431	100.0%	17.5%	35.9%	1515	13.9%	72.8%
PAR-4	3053	100.0%	10.4%	14.0%	1357	4.2%	29.4%
PAR-5	3398	100.0%	21.1%	6.1%	516	0.0%	44.9%
PAR-6	10200	67.8%	19.7%	1.3%	1241	21.3%	24.7%
PAR-7	1024	100.0%	23.5%	39.5%	209	94.2%	83.4%
PAR-12	5954	100.0%	16.7%	14.3%	309	47.3%	46.9%
PAR-13	4053	100.0%	4.5%	4.5%	1266	8.0%	40.5%
PAR-15	5619	100.0%	9.5%	6.9%	548	9.3%	28.3%
PAR-17	11816	38.9%	22.1%	0.0%	3101	0.9%	20.5%
PAR-18	7308	34.0%	22.9%	1.3%	302	1.0%	15.1%
PAR-19	3873	100.0%	24.9%	0.0%	214	5.6%	25.7%
PAR-20	2103	100.0%	46.1%	0.0%	136	0.0%	11.1%
PAR-21a	2215	33.5%	40.4%	0.0%	261	0.0%	27.7%
PAR-21b	1299	100.0%	0.0%	75.6%	49	8.4%	45.5%
PAR-23	4487	38.4%	12.7%	21.6%	432	20.0%	41.8%
PAR-24	4545	35.6%	9.7%	5.0%	0	13.9%	18.3%
PAR-26	1943	100.0%	2.7%	38.6%	19	51.2%	79.1%
PAR-28	4075	0.0%	0.0%	1.4%	530	2.1%	16.0%
WOR-1	3905	100.0%	34.2%	4.2%	710	8.1%	12.0%
WOR-3	8998	19.6%	1.4%	3.4%	681	23.6%	9.7%
WOR-6	5181	100.0%	19.0%	4.8%	526	12.0%	36.2%
WOR-7	2478	38.7%	15.0%	18.5%	571	14.4%	54.6%
WOR-9	4989	20.0%	37.7%	4.6%	1271	27.9%	48.6%
WOR-11	5461	100.0%	18.4%	0.9%	1465	9.0%	36.9%
WOR-12	5001	59.0%	20.0%	9.2%	687	3.0%	38.8%
WOR-14	6882	0.0%	13.5%	0.6%	2812	0.6%	2.5%
WOR-15	3831	67.2%	7.2%	2.4%	1033	0.8%	0.3%
WOR-16	5565	20.6%	13.4%	3.0%	921	4.7%	7.0%
SHUN-10a	691	16.1%	0.0%	10.9%	151	4.1%	11.3%
SHUN-10b	752	100.0%	5.2%	38.4%	174	34.7%	55.5%
GAS-1	4516	45.4%	32.5%	2.5%	1305	9.6%	39.5%
GAS-2	4184	100.0%	6.8%	44.0%	647	27.4%	34.1%
GAS-4	3289	51.8%	38.7%	6.4%	1029	10.5%	21.0%
GAS-8	2250	100.0%	48.1%	9.0%	918	8.4%	28.7%
MEB-7	6039	47.2%	16.5%	0.9%	2483	1.1%	0.9%

Table 4. (Continued) Summary of reach characteristics calculated using the Feature Indexing Tool.

Reach / Segment	Stream length (ft)	Channel straight-ening (%)	Bank erosion (%)	Bank armor (%)	Deposition length (ft/mile)	Buffer width <25 ft (%)	Corridor develop-ment (%)
MEB-8a	1501	39.1%	17.5%	4.5%	483	0.0%	1.4%
MEB-8b	3229	93.9%	25.6%	7.3%	578	47.0%	53.8%
BER-2	7403	64.3%	2.7%	1.5%	2511	6.9%	22.2%
BER-3A	3852	0.0%	1.6%	1.4%	1222	3.2%	25.7%
BER-3B	1991	42.7%	2.4%	10.2%	1131	3.8%	41.5%
BER-4	2896	28.2%	27.9%	0.5%	858	0.0%	12.6%
BER-6a	3976	30.1%	5.5%	0.0%	711	0.5%	9.3%
BER-6b	897	100.0%	9.8%	3.8%	210	0.0%	39.6%
BER-7	1715	33.7%	0.7%	4.8%	658	6.0%	21.7%
QUS-11	2370	29.5%	14.3%	0.0%	1163	1.4%	1.5%
CHIP-8	7076	30.0%	9.7%	9.8%	1394	5.5%	14.7%
CHIP-10	4743	63.1%	3.4%	12.5%	956	12.0%	19.5%
Total	**204700**	**54.1%**	**15.5%**	**8.6%**	**1083**	**27.0%**	**28.2%**

Table 5. Summary of Phase 2 RGA scores and stream sensitivity rankings.

Reach / Segment	Channel degradation	Channel aggradation	Channel widening	Change in planform	Total score	Condition rating (%)	Stream condition	Stream sensitivity	Channel evolution stage
PAR-1	8	14	11	16	49	61	Fair	Very High	IV
PAR-2	10	12	11	14	47	59	Fair	Very High	IV
PAR-3	9	11	4	12	36	45	Fair	Very High	IV
PAR-4	15	10	14	15	54	68	Good	High	IV
PAR-5	5	14	5	14	38	48	Fair	Moderate	IV
PAR-6	7	10	12	12	41	51	Fair	Very High	IV
PAR-7	9	15	10	13	47	59	Fair	Very High	IV
PAR-12	9	9	10	9	37	46	Fair	Very High	IV
PAR-13	15	10	17	12	54	68	Good	High	IV
PAR-15	11	11	14	11	47	59	Fair	Very High	IV
PAR-17	11	8	12	9	40	50	Fair	Very High	III
PAR-18	10	12	9	8	39	49	Fair	Very High	III
PAR-19	10	11	11	11	43	54	Fair	Very High	III
PAR-20	7	13	8	9	37	46	Fair	Very High	III
PAR-21a	8	13	6	10	37	46	Fair	Very High	III
PAR-21b	7	16	13	8	44	55	Fair	Very High	II
PAR-23	11	12	15	11	49	61	Fair	Very High	V
PAR-24	10	14	13	14	51	64	Fair	Moderate	V
PAR-26	9	13	14	10	46	58	Fair	Very High	V
PAR-28	18	18	17	15	68	85	Reference	High	I
WOD-1	11	13	11	11	46	58	Fair	Very High	IV
WOD-3	11	11	13	12	47	59	Fair	Extreme	IV
WOD-6	11	13	13	14	51	64	Fair	Very High	IV
WOD-7	12	12	14	13	51	64	Fair	Very High	V
WOD-9	13	12	9	6	40	50	Fair	Very High	III
WOD-11	15	14	14	12	55	69	Good	High	IV
WOD-12	7	12	10	10	39	49	Fair	Very High	III
WOD-14	14	10	13	9	46	58	Fair	Very High	IV
WOD-15	12	14	11	9	46	58	Fair	Very High	IV
WOD-16	13	14	9	10	46	58	Fair	Very High	III
SHUN-10a	13	15	13	12	53	66	Good	High	IV

Table 5. (continued) Summary of Phase 2 RGA scores and stream sensitivity rankings.

Reach / Segment	Channel degradation	Channel aggradation	Channel widening	Change in planform	Total score	Condition rating (%)	Stream condition	Stream sensitivity	Channel evolution stage
SHUN-10b	7	13	12	12	44	55	Fair	High	II
GAS-1	14	14	11	5	44	55	Fair	Very High	III
GAS-2	10	11	12	9	42	53	Fair	Moderate	IV
GAS-4	13	12	10	5	40	50	Fair	Very High	IV
GAS-8	10	9	12	9	40	50	Fair	High	IV
MEB-7	11	5	9	9	34	43	Fair	Very High	III
MEB-8a	10	12	13	11	46	58	Fair	Very High	II
MEB-8b	11	9	13	12	45	56	Fair	Very High	IV
BER-2	11	5	12	5	33	41	Poor	Very High	III
BER-3a	14	8	13	5	40	50	Fair	Extreme	IV
BER-3b	11	10	13	12	46	58	Fair	Extreme	IV
BER-4	11	11	14	10	46	58	Fair	Very High	IV
BER-6a	10	13	14	5	42	53	Fair	Very High	III
BER-6b	10	14	15	13	52	65	Good	Moderate	II
BER-7	12	13	13	5	43	54	Fair	Very High	IV
QUS-11	15	10	10	5	40	50	Fair	Very High	III
CHIP-8	12	5	11	4	32	40	Fair	Very High	IV
CHIP-10	11	13	12	10	46	58	Fair	Very High	IV

Table 6. Summary of Phase 2 RHA scores and habitat ratings.

Reach / Segment	Woody debris cover	Bed substrate cover	Scour and deposition features	Channel morphology	Hydrologic characteristics	Connectivity	River banks		Riparian area		Total score	Percentage	Habitat condition
							LB	RB	LB	RB			
PAR-1	4	13	8	6	13	10	4	4	1	1	64	40.0%	Fair
PAR-2	7	16	6	6	13	12	7	7	2	4	80	50.0%	Fair
PAR-3	6	10	14	4	11	8	3	5	5	5	71	44.4%	Fair
PAR-4	9	8	4	11	12	9	5	5	7	9	79	49.0%	Fair
PAR-5	10	10	13	5	14	12	8	8	9	9	98	61.0%	Fair
PAR-6	12	11	7	8	13	13	8	8	7	7	94	59.0%	Fair
PAR-7	30	13	12	8	13	7	4	4	2	2	78	49.0%	Fair
PAR-12	10	3	5	11	15	13	4	6	1	8	76	47.5%	Fair
PAR-13	3	3	2	13	15	11	7	8	7	7	76	47.5%	Fair
PAR-15	11	8	4	13	13	10	8	8	9	9	93	58.0%	Fair
PAR-17	20	9	7	11	16	16	7	6	8	8	109	68.0%	Good
PAR-18	15	8	8	13	13	6	4	5	7	9	88	55.0%	Fair
PAR-19	16	13	5	8	14	10	7	7	7	9	96	60.0%	Fair
PAR-20	16	7	10	9	17	14	8	8	10	10	109	68.0%	Good
PAR-21a	15	8	9	10	16	16	7	7	8	8	104	65.0%	Good
PAR-21b	5	11	11	8	17	7	4	4	9	9	85	53.0%	Fair
PAR-23	12	13	10	12	13	10	5	6	6	7	94	59.0%	Fair
PAR-24	10	15	16	7	10	5	8	8	7	5	91	57.0%	Fair
PAR-26	7	8	1	10	10	6	2	2	2	1	49	30.6%	poor
PAR-28	13	20	20	15	20	17	8	8	8	8	141	88.00%	Reference
WOR-1	17	12	13	11	17	9	8	8	9	10	114	71.0%	Good
WOR-3	12	13	7	13	16	10	6	6	7	7	97	61.0%	Fair
WOR-6	15	9	10	9	13	10	7	7	7	7	94	59.0%	Fair
WOR-7	14	10	13	14	8	10	7	7	8	6	97	61.0%	Fair
WOR-9	16	13	13	13	16	10	8	8	9	5	111	69.0%	Good

Table 6. (continued) Summary of Phase 2 RHA scores and habitat ratings.

Reach / Segment	Woody debris cover	Bed substrate cover	Scour and deposition features	Channel morphology	Hydrologic characteristics	Connectivity	River banks		Riparian area		Total score	Percentage	Habitat condition
							LB	RB	LB	RB			
WOR-11	14	10	13	14	16	16	8	10	5	9	115	72.0%	Good
WOR-12	20	8	11	9	16	6	8	8	6	6	98	61.0%	Fair
WOR-14	17	11	6	12	13	14	7	7	10	9	108	67.5%	Good
WOR-15	16	14	17	13	18	16	9	9	10	10	132	82.5%	Good
WOR-16	18	15	18	12	16	16	9	9	10	10	132	82.5%	Good
SHUN-10a	10	14	11	8	11	7	8	6	7	3	85	53.0%	Fair
SHUN-10b	7	11	9	8	11	6	8	8	5	2	75	47.0%	Fair
GAS-1	20	14	17	14	15	11	8	8	6	8	121	76.0%	Good
GAS-2	16	5	9	11	10	10	7	6	6	5	85	53.0%	Fair
GAS-4	15	10	12	6	14	14	6	8	8	8	100	63.0%	Fair
GAS-8	17	14	9	10	11	12	8	8	8	8	105	65.0%	Good
MEB-7	17	3	8	13	7	8	7	7	8	8	86	53.0%	Fair
MEB-8a	18	10	5	13	2	4	7	7	8	7	81	50.0%	Fair
MEB-8b	8	8	5	10	1	5	3	3	1	1	45	28.0%	poor
BER-2	15	8	10	10	15	12	6	6	4	4	90	52.0%	Fair
BER-3A	7	4	8	19	15	13	6	6	7	7	92	57.5%	Fair
BER-3B	14	9	14	12	14	9	8	8	5	7	100	62.0%	Fair
BER-4	15	14	11	10	14	10	9	9	8	8	108	67.5%	Good
BER-6a	18	9	14	12	13	9	8	8	9	9	109	68.0%	Good
BER-6b	10	15	15	10	9	10	9	9	9	9	105	65.0%	Good
BER-7	9	13	11	10	12	7	9	9	8	7	95	59.0%	Fair
QUS-11	17	12	14	14	16	15	8	8	7	7	108	67.5%	Good
CHIP-8	15	10	7	13	13	9	6	8	5	8	94	59.0%	Fair
CHIP-10	17	9	10	7	12	10	5	7	5	7	89	56.0%	Fair

APPENDIX 1

(Phase 1 and Phase 2 assessment GIS shapefiles – see accompanying digital flash drive)

APPENDIX 2

(Phase 1 and Phase 2 assessment database – see accompanying digital flash drive)

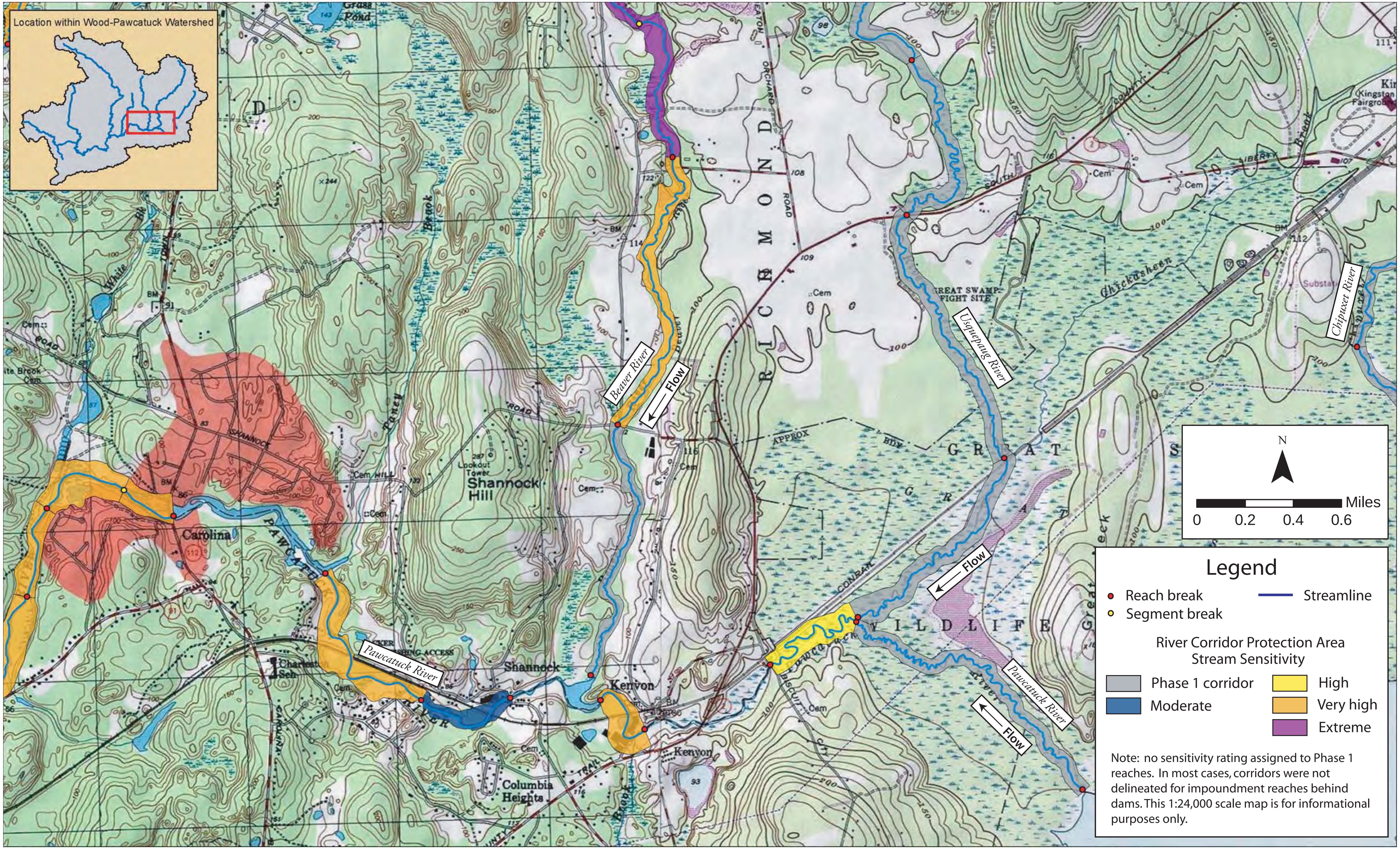
APPENDIX 3

(Phase 2 assessment photo log – see accompanying digital flash drive)

APPENDIX 4

(River Corridor Protection area maps)

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Pawcatuck River (Map 1 of 4)

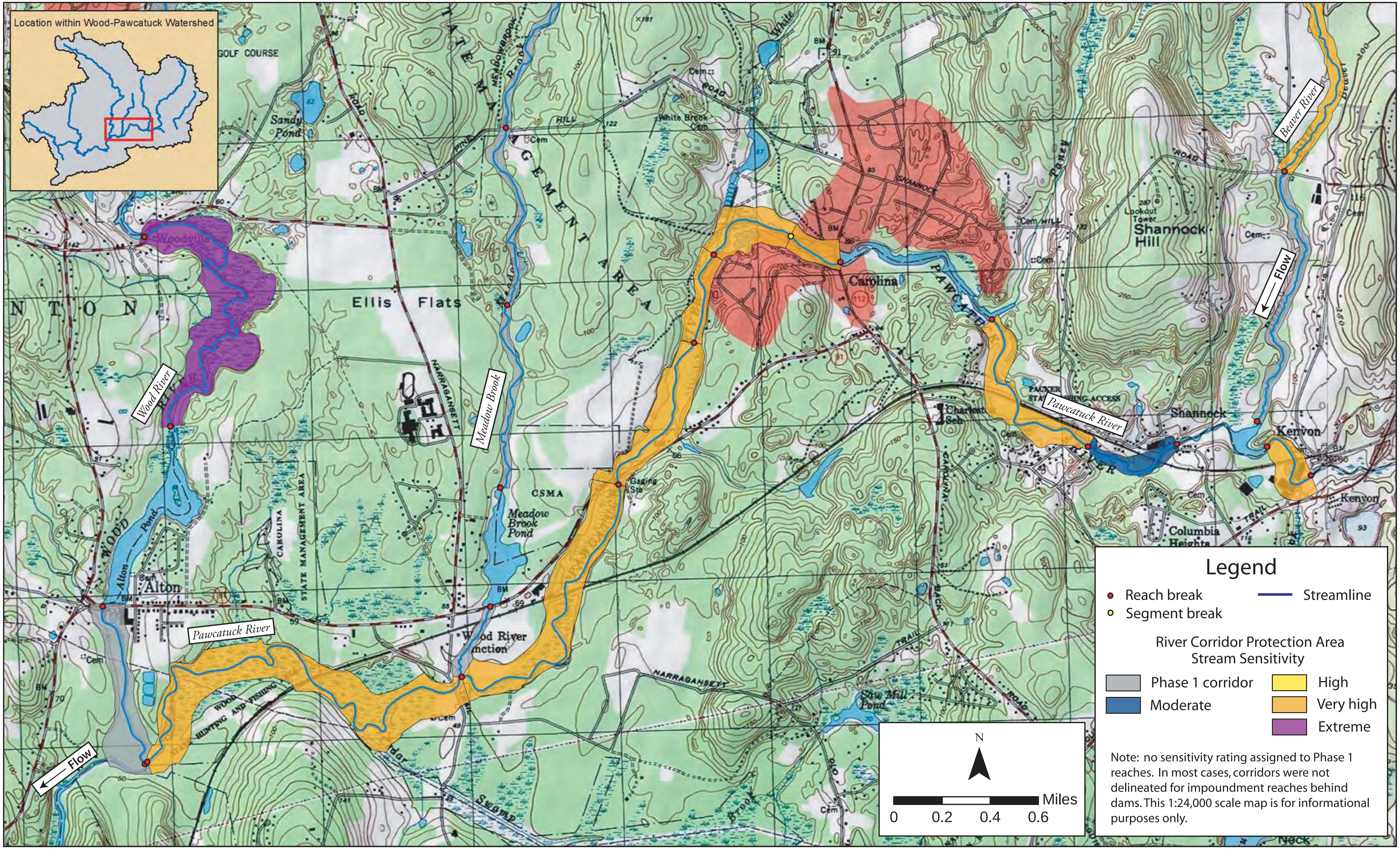


Basemap imagery: USA Topo Maps (http://services.arcgisonline.com/ArcGIS/rest/services/USA_Topo_Maps/MapServer)
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Pawcatuck River (Map 2 of 4)

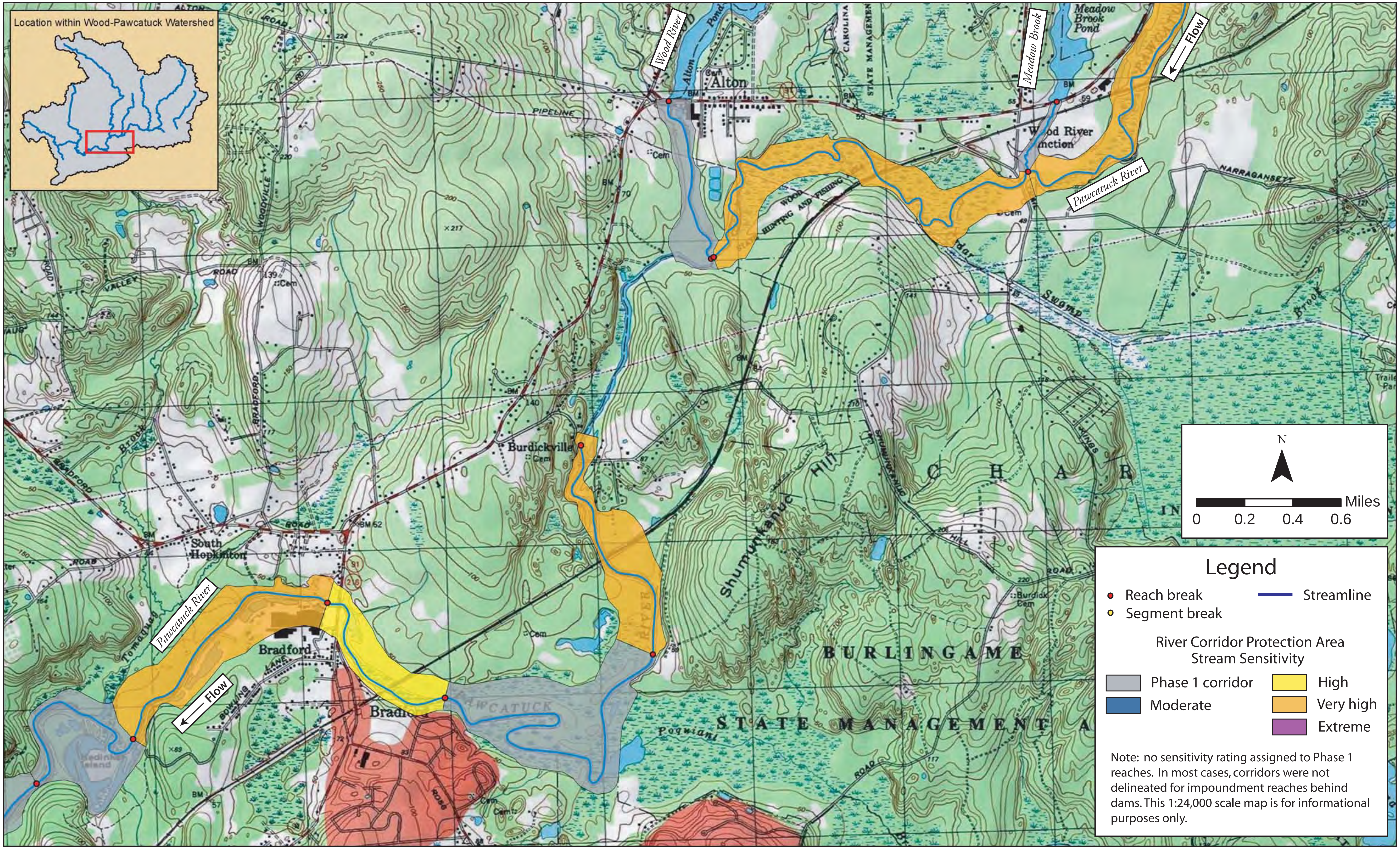


Basemap imagery: USA Topo Maps (http://services.arcgisonline.com/ArcGIS/rest/services/USA_Topo_Maps/MapServer)
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Pawcatuck River (Map 3 of 4)



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GIS data: Field Geology Services 2015-2016
Map prepared February 2016

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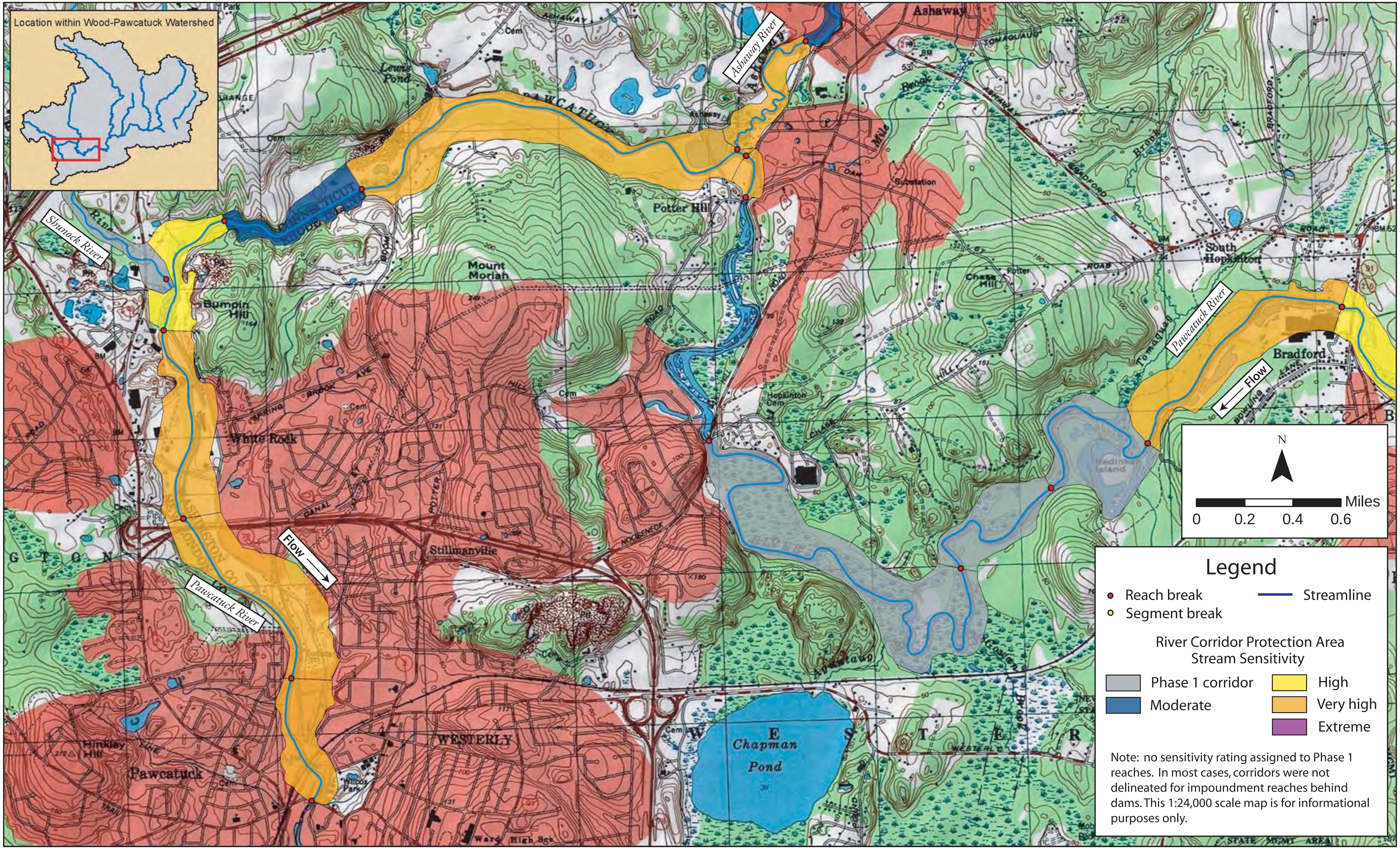
With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Pawcatuck River (Map 4 of 4)



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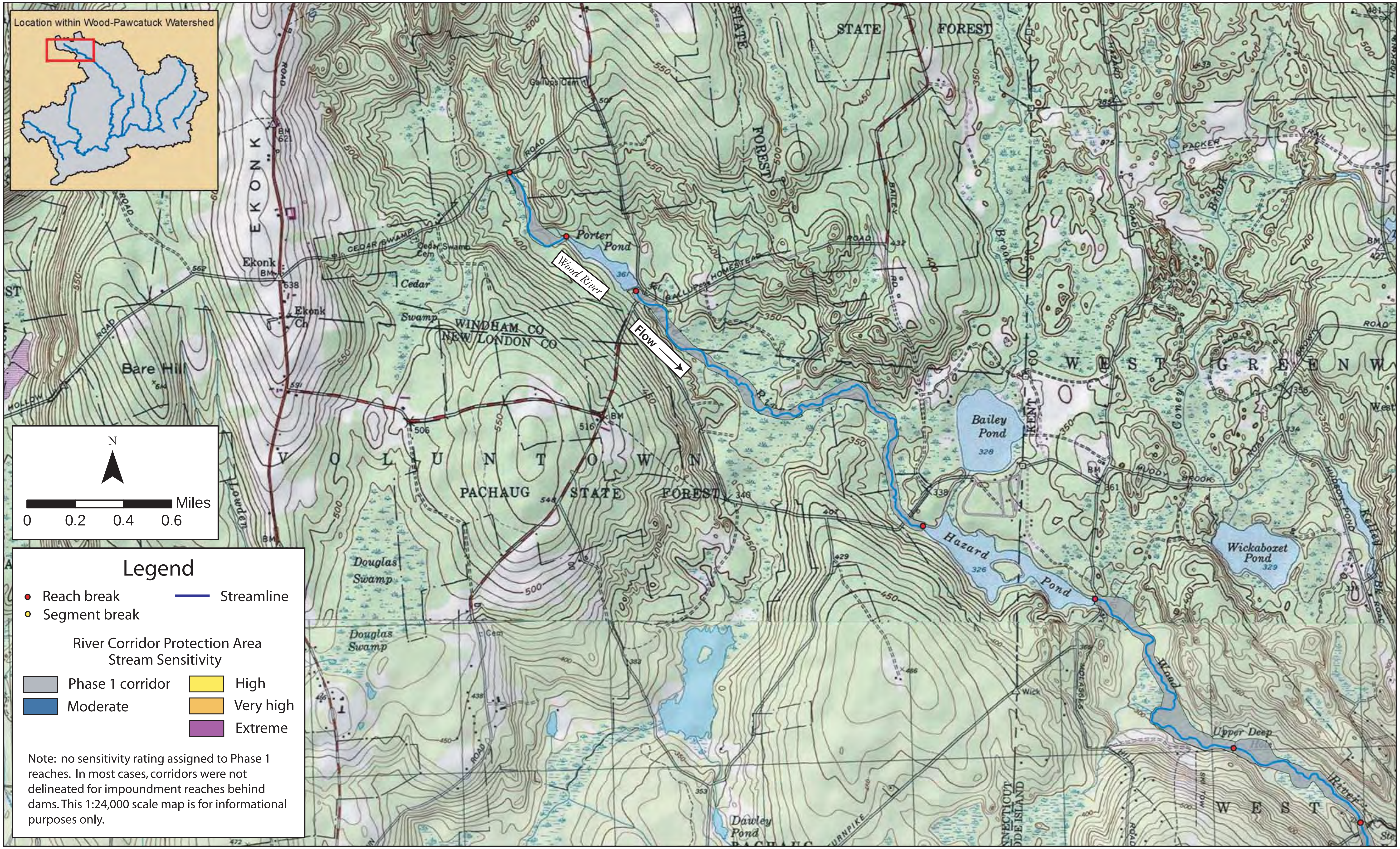
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Wood River (Map 1 of 5)



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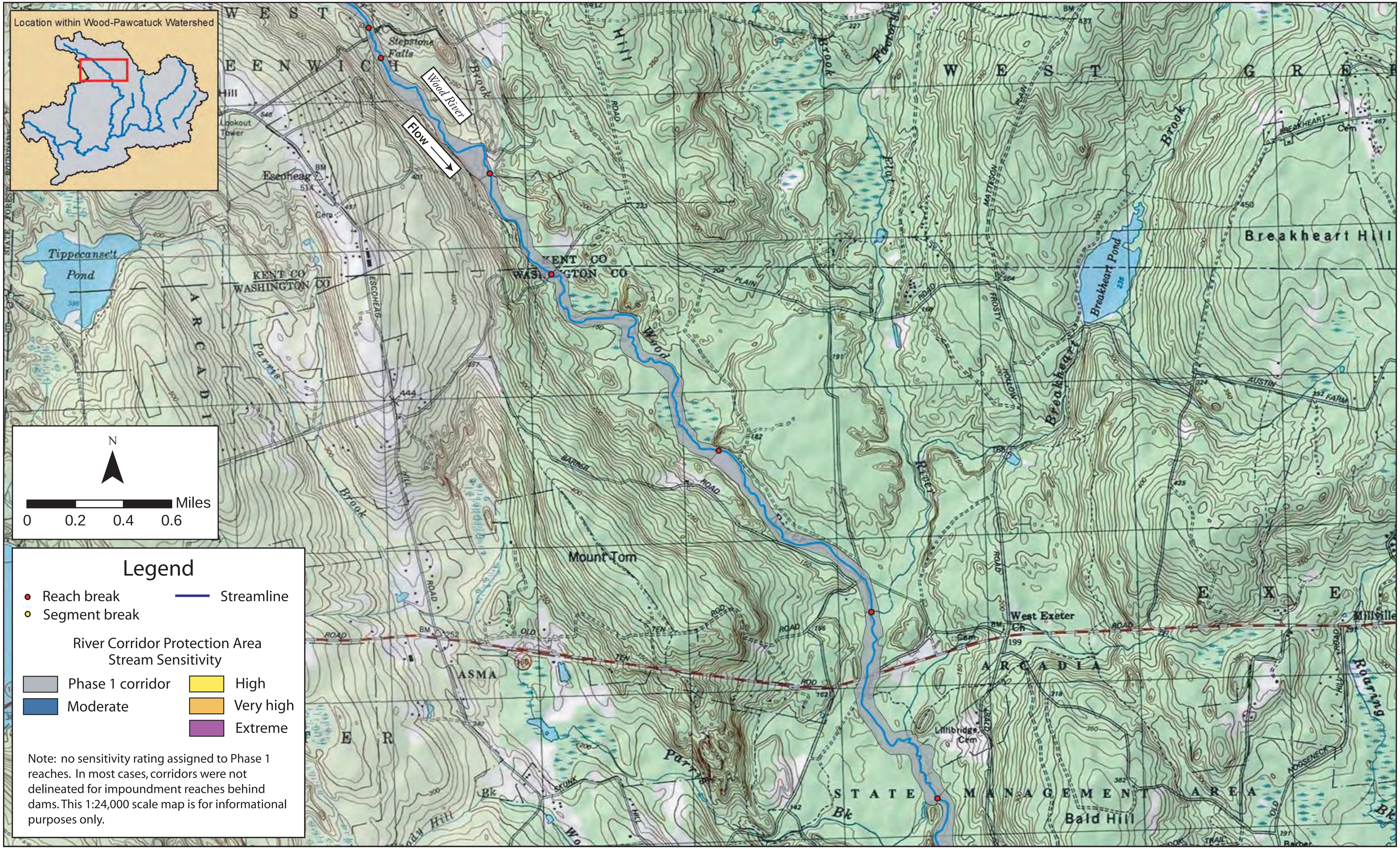
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Wood River (Map 2 of 5)



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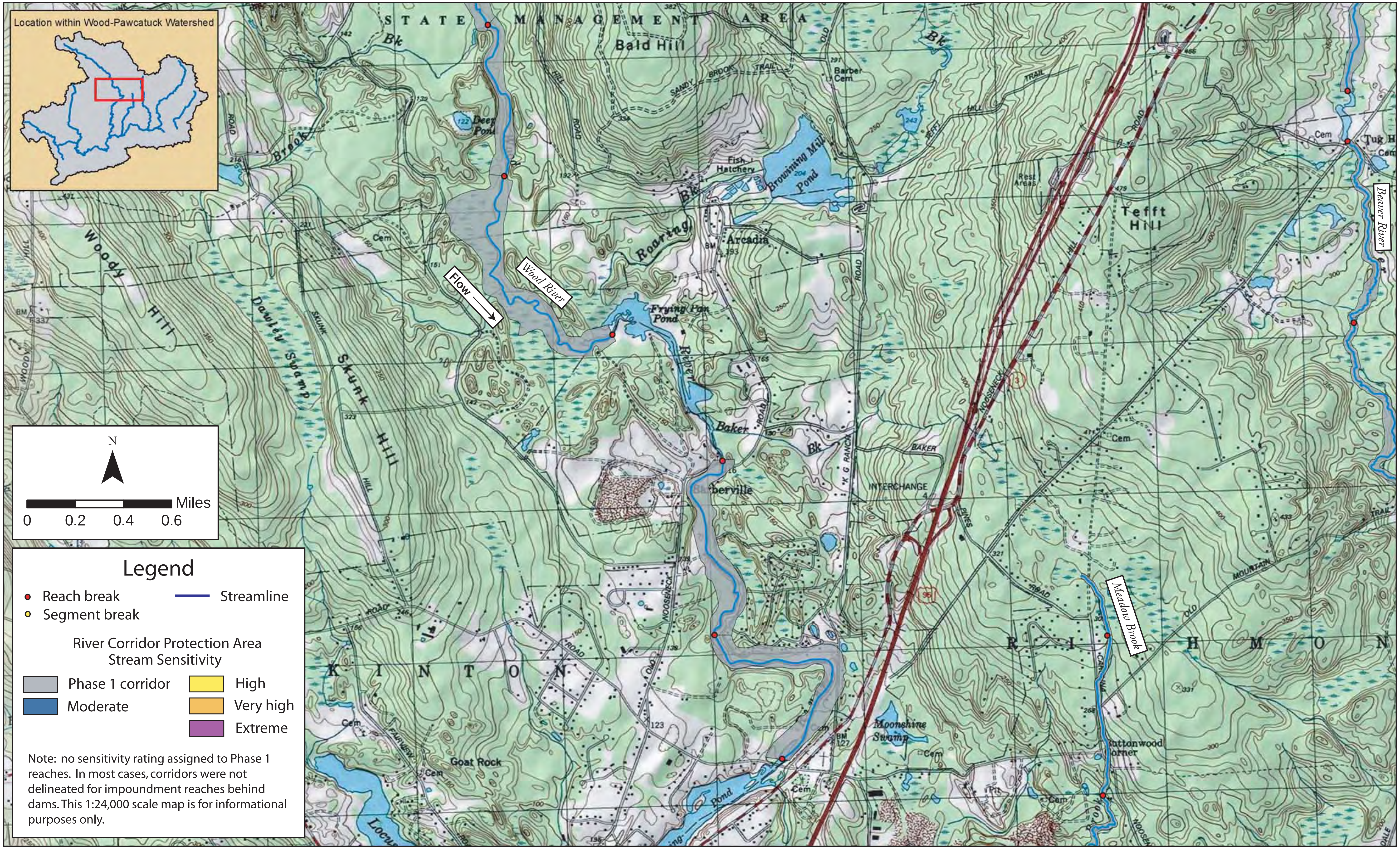
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Wood River (Map 3 of 5)



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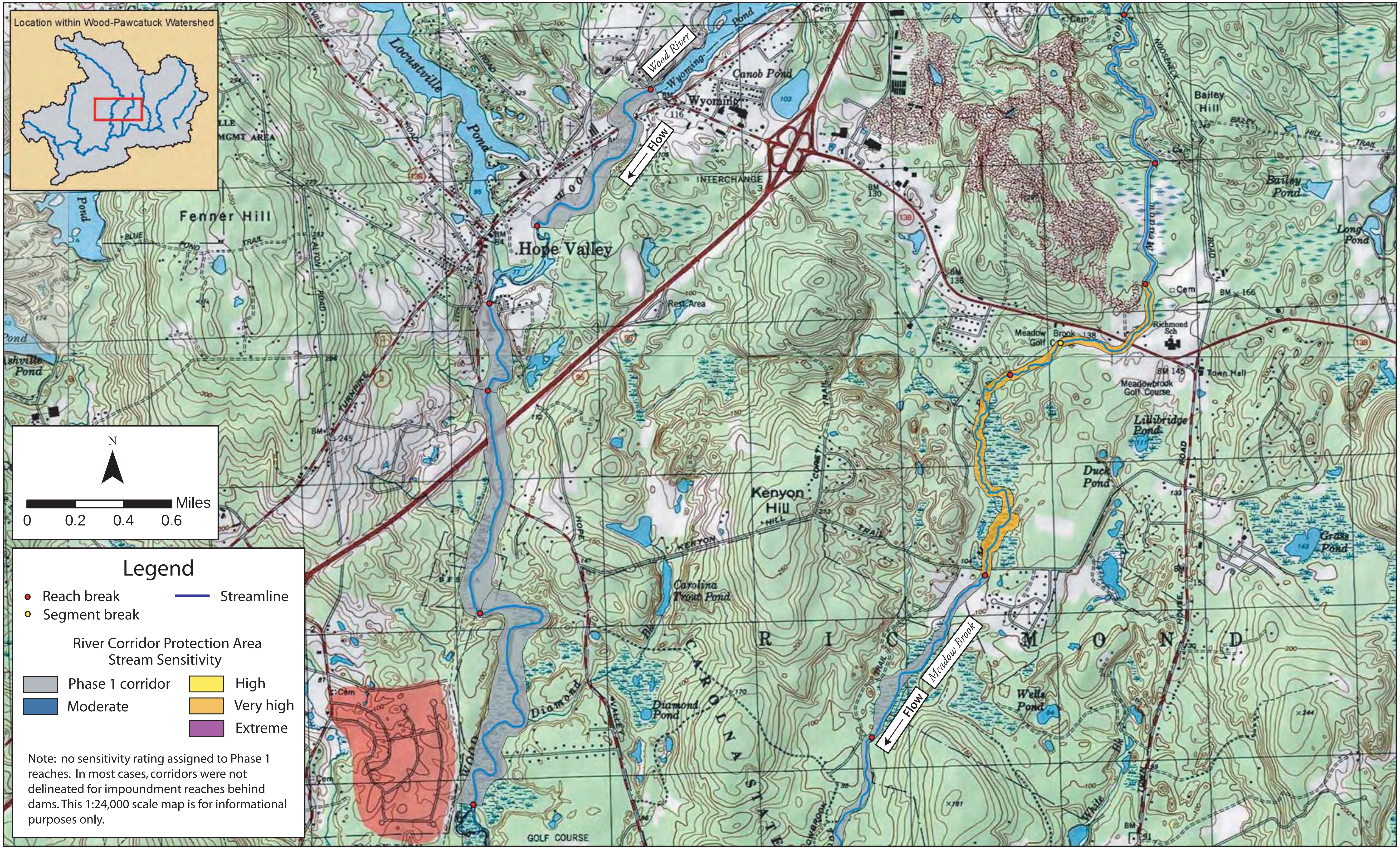
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services Fluvial Geomorphology

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Wood River (Map 4 of 5)



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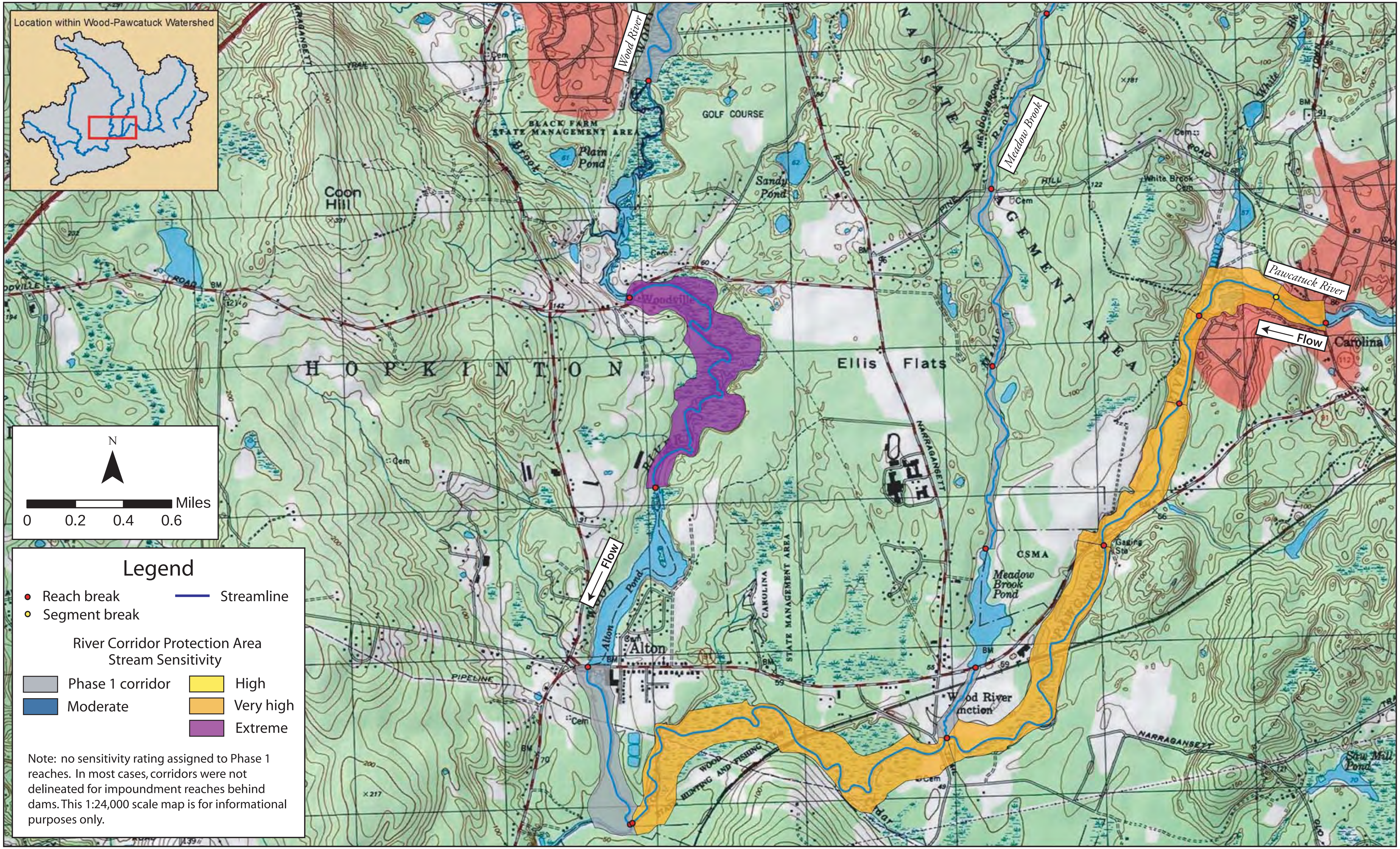
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Wood River (Map 5 of 5)



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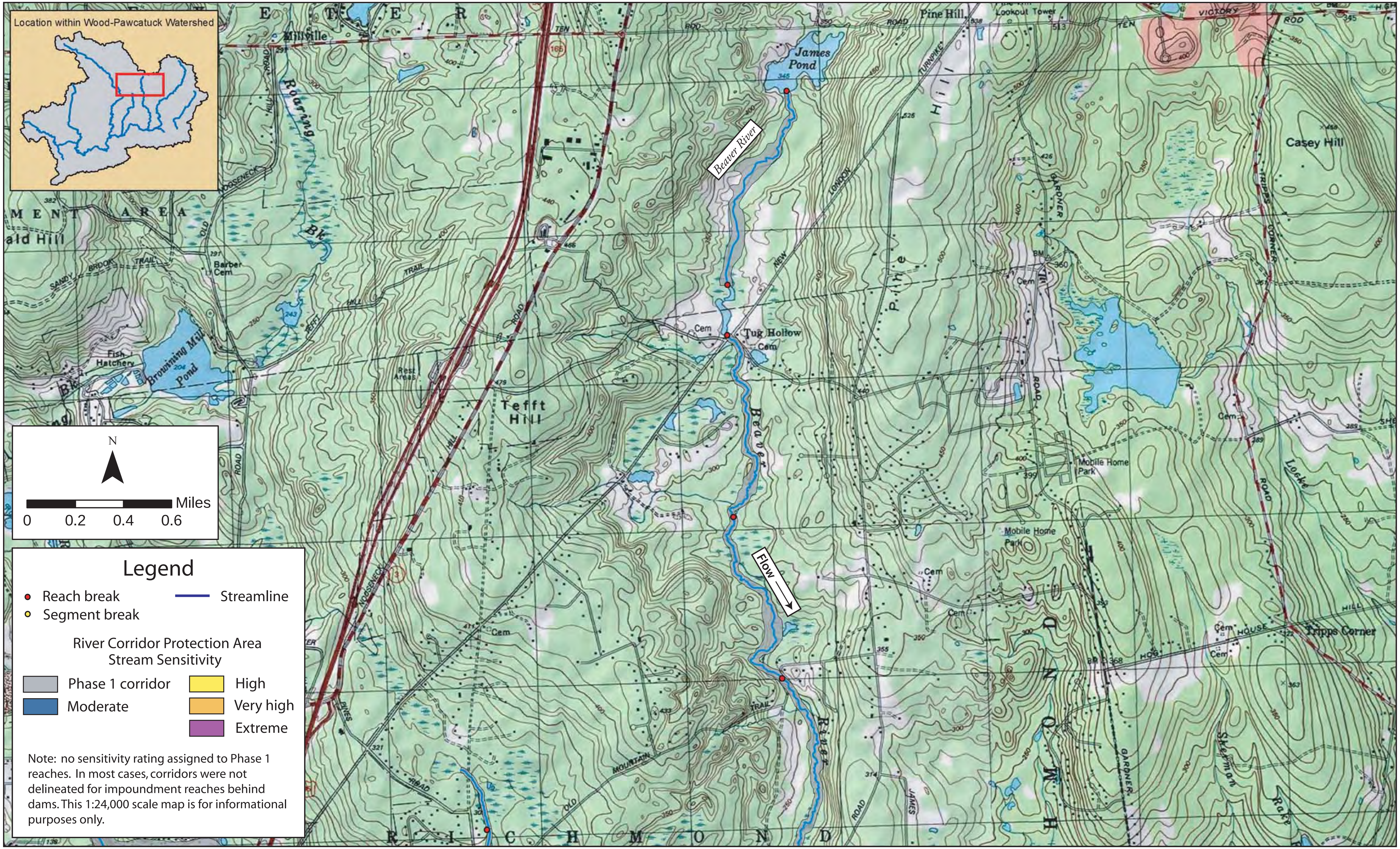
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by:
Field Geology Services
Fluvial Geomorphology

With support from:
FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Beaver River (Map 1 of 3)



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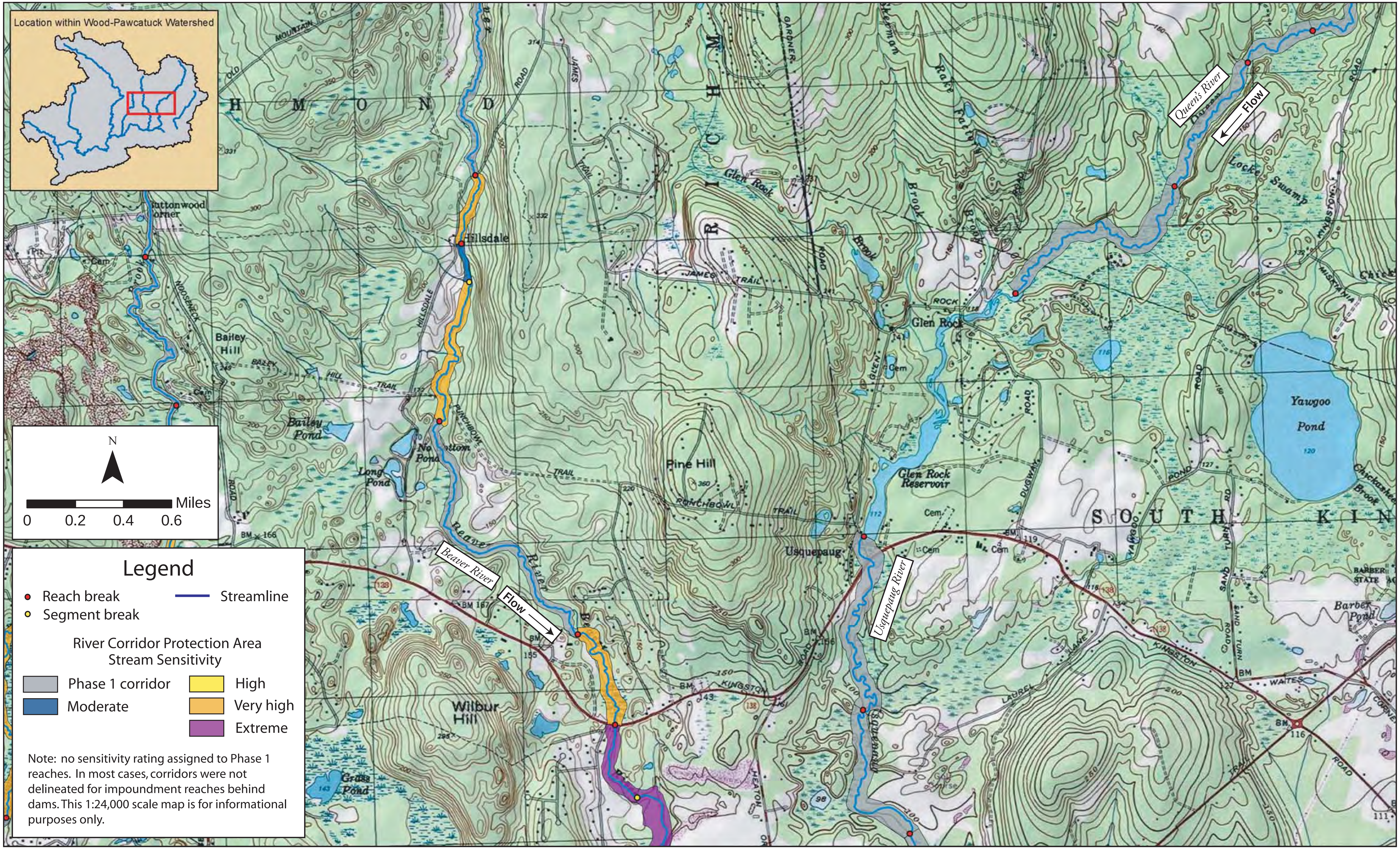
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Beaver River (Map 2 of 3)



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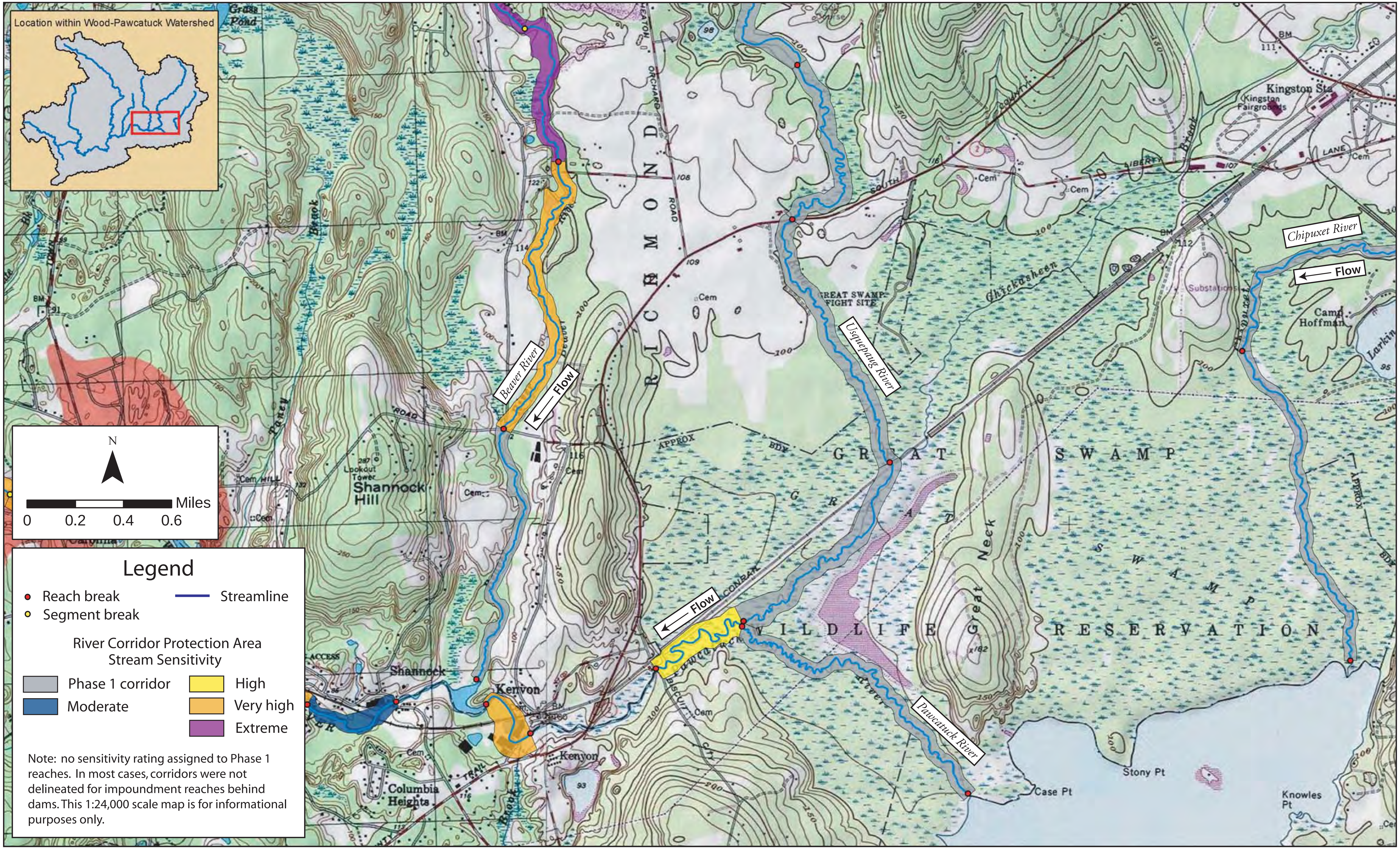
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Beaver River (Map 3 of 3)



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GIS data: Field Geology Services 2015-2016
Map prepared February 2016

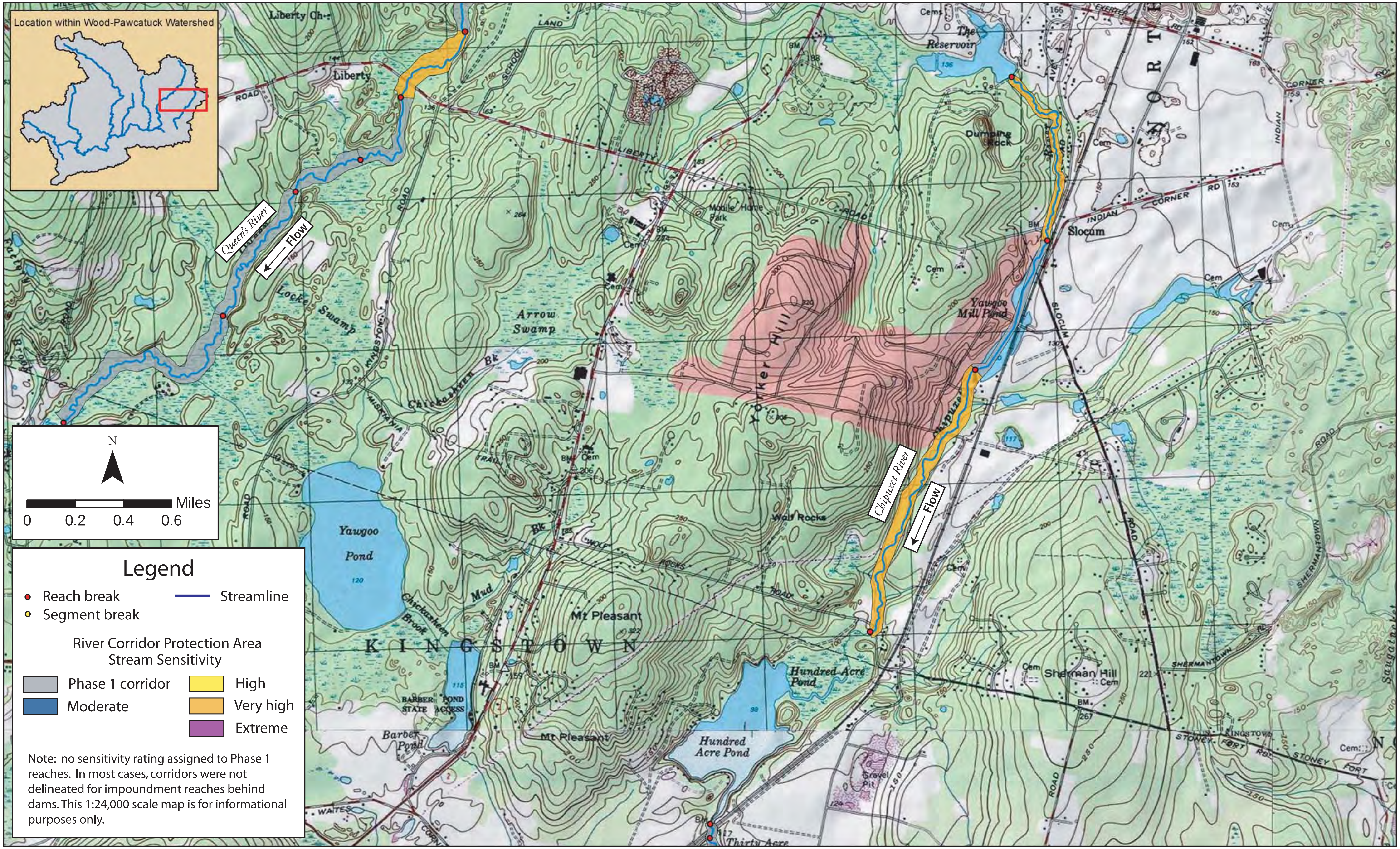
Map prepared by:

Field Geology Services

With support from:

FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Chipuxet River (Map 1 of 2)



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GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

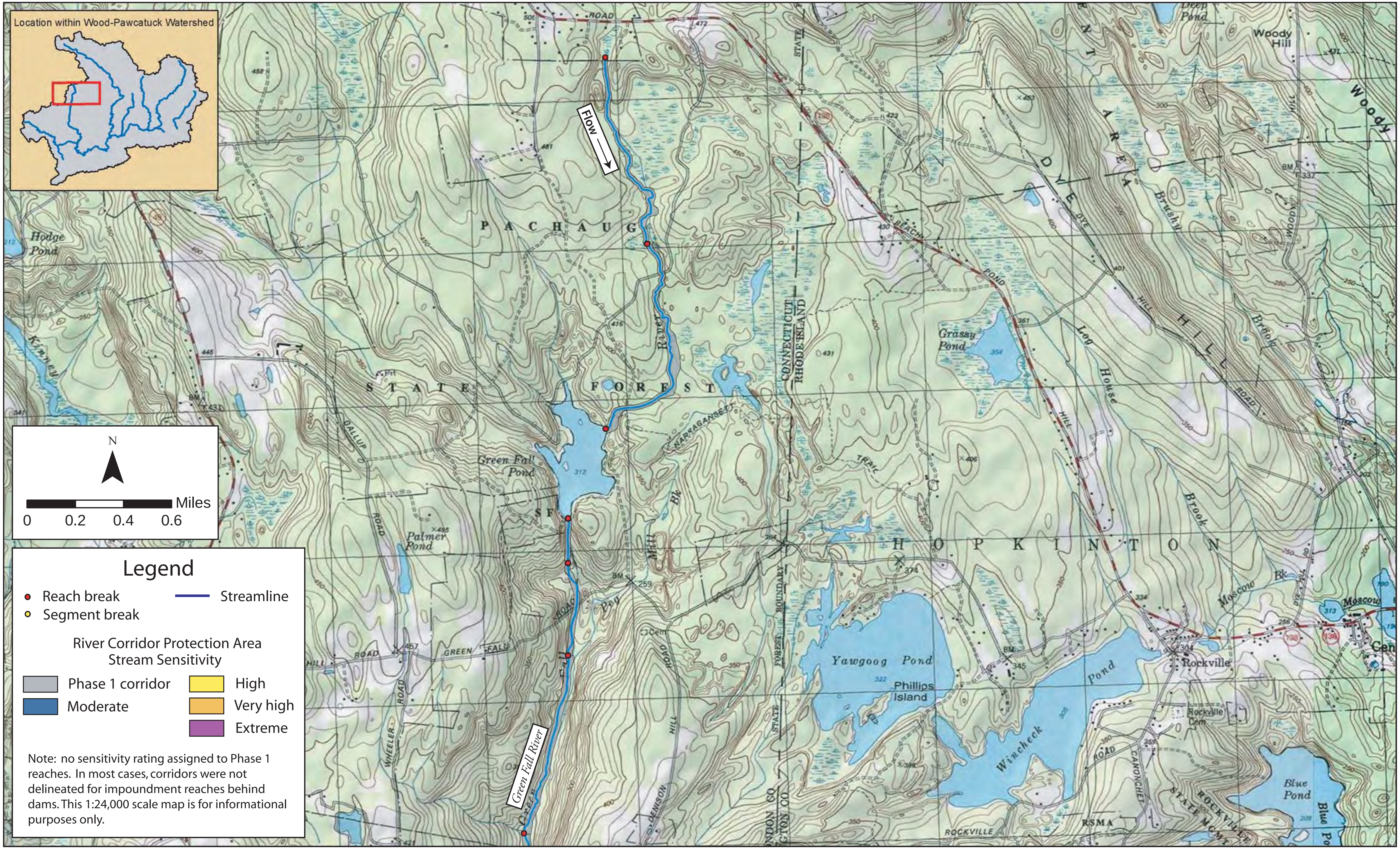
Wood-Pawcatuck Watershed River Corridor Protection Area Map - Chipuxet River (Map 2 of 2)

Basemap imagery: USA Topo Maps (http://services.arcgisonline.com/ArcGIS/rest/services/USA_Topo_Maps/MapServer)
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Green Fall / Ashaway River (Map 1 of 3)



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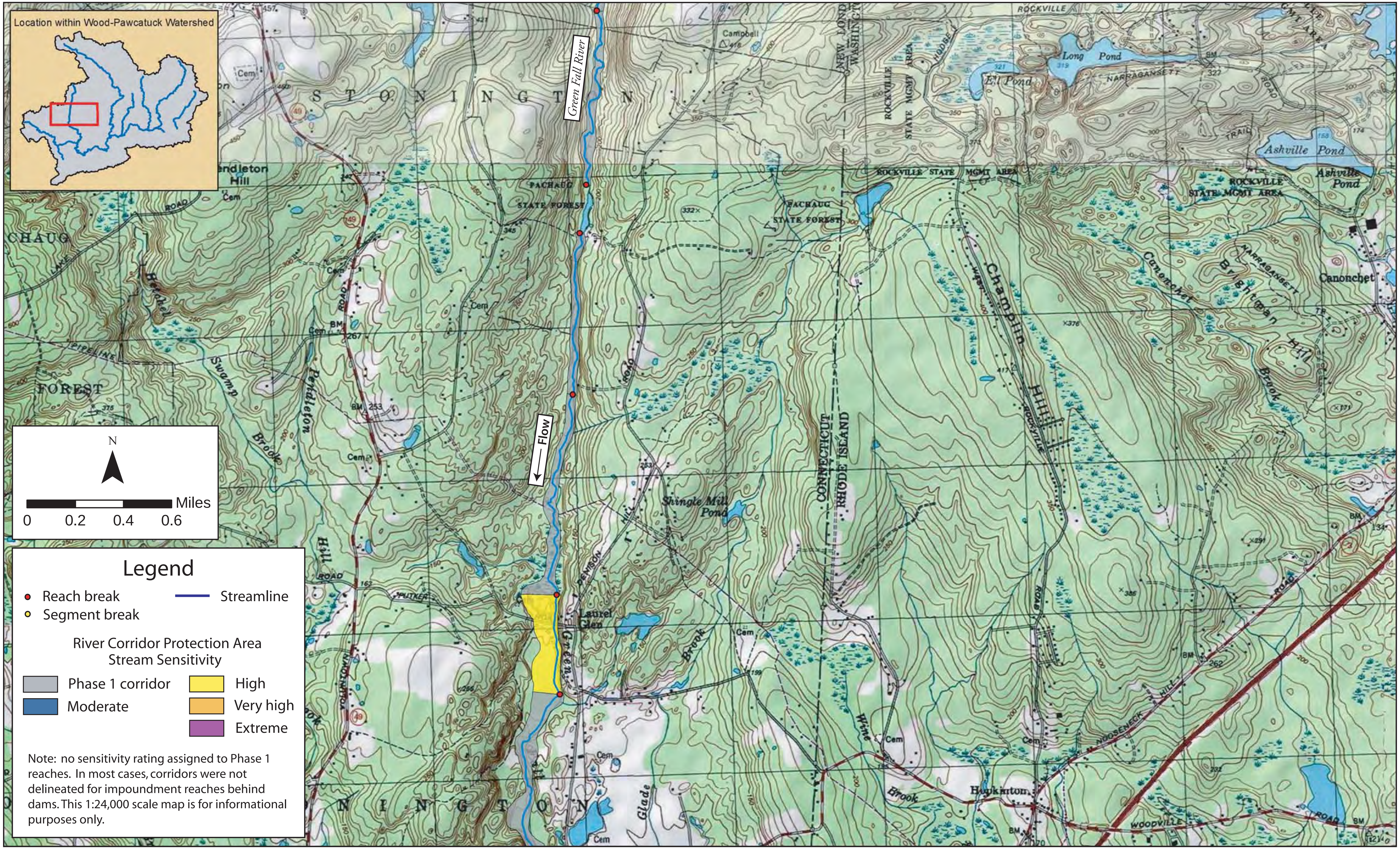
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Green Fall / Ashaway River (Map 2 of 3)



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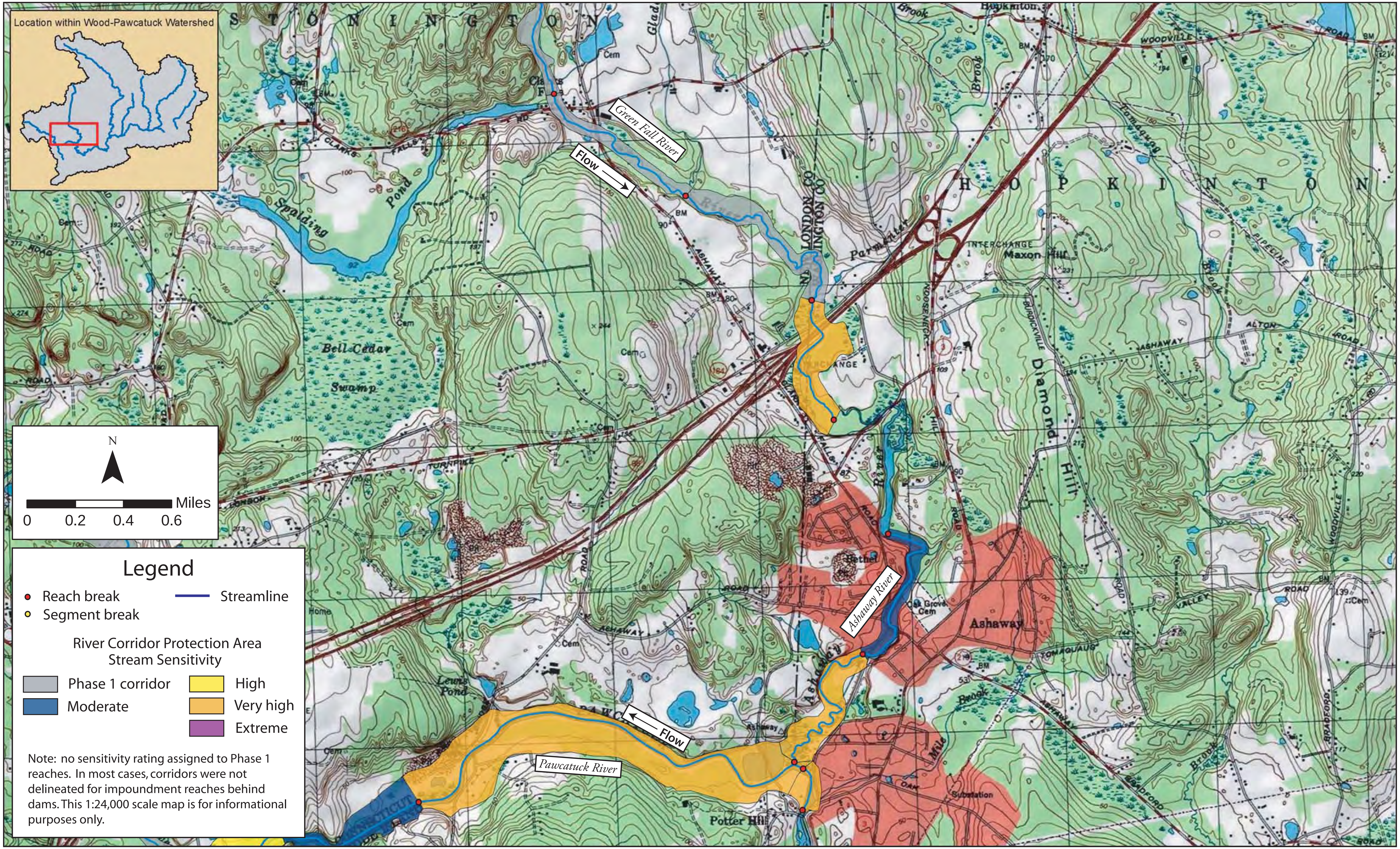
With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Green Fall / Ashaway River (Map 3 of 3)



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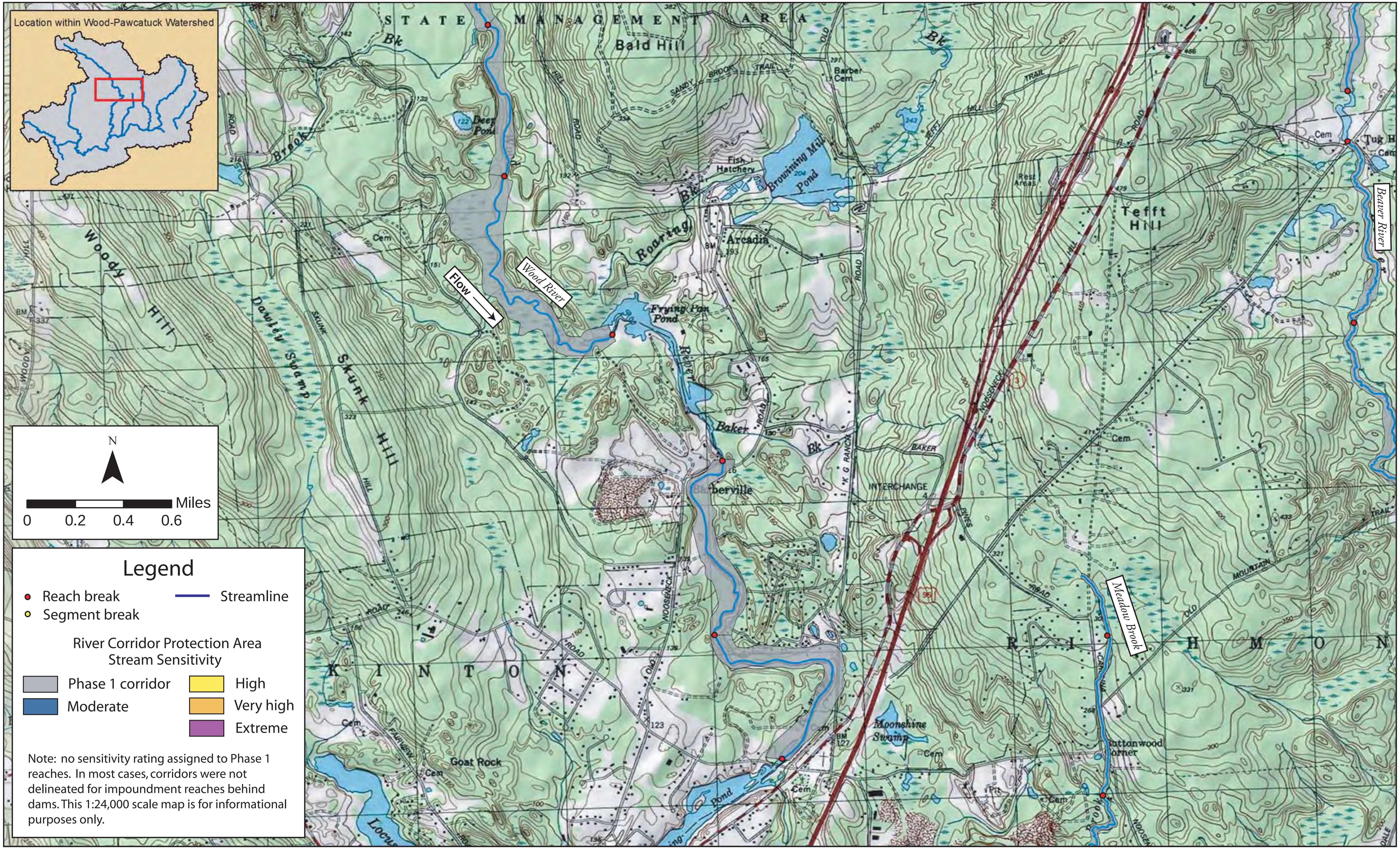
With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Meadow Brook (Map 1 of 3)



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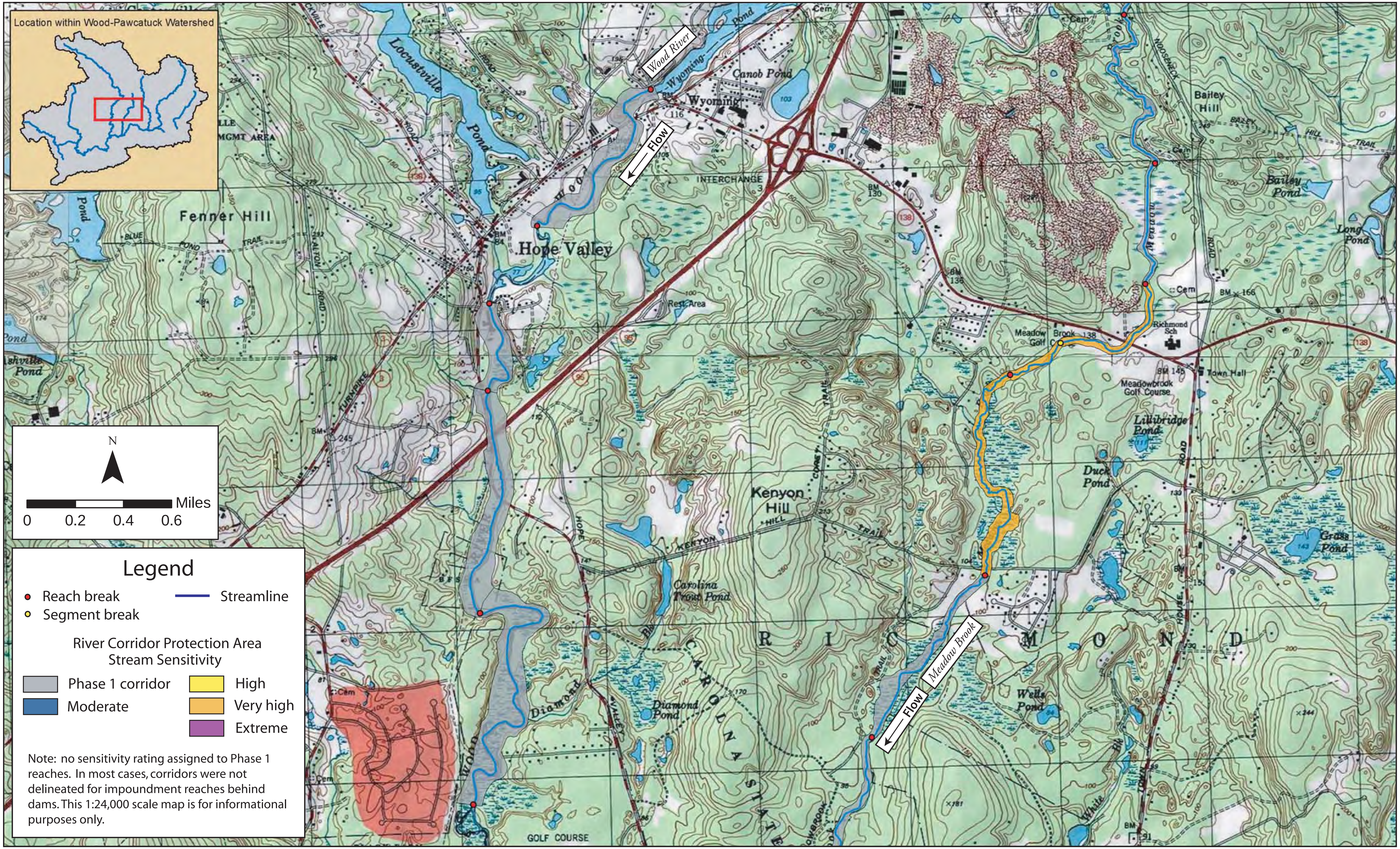
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Meadow Brook (Map 2 of 3)



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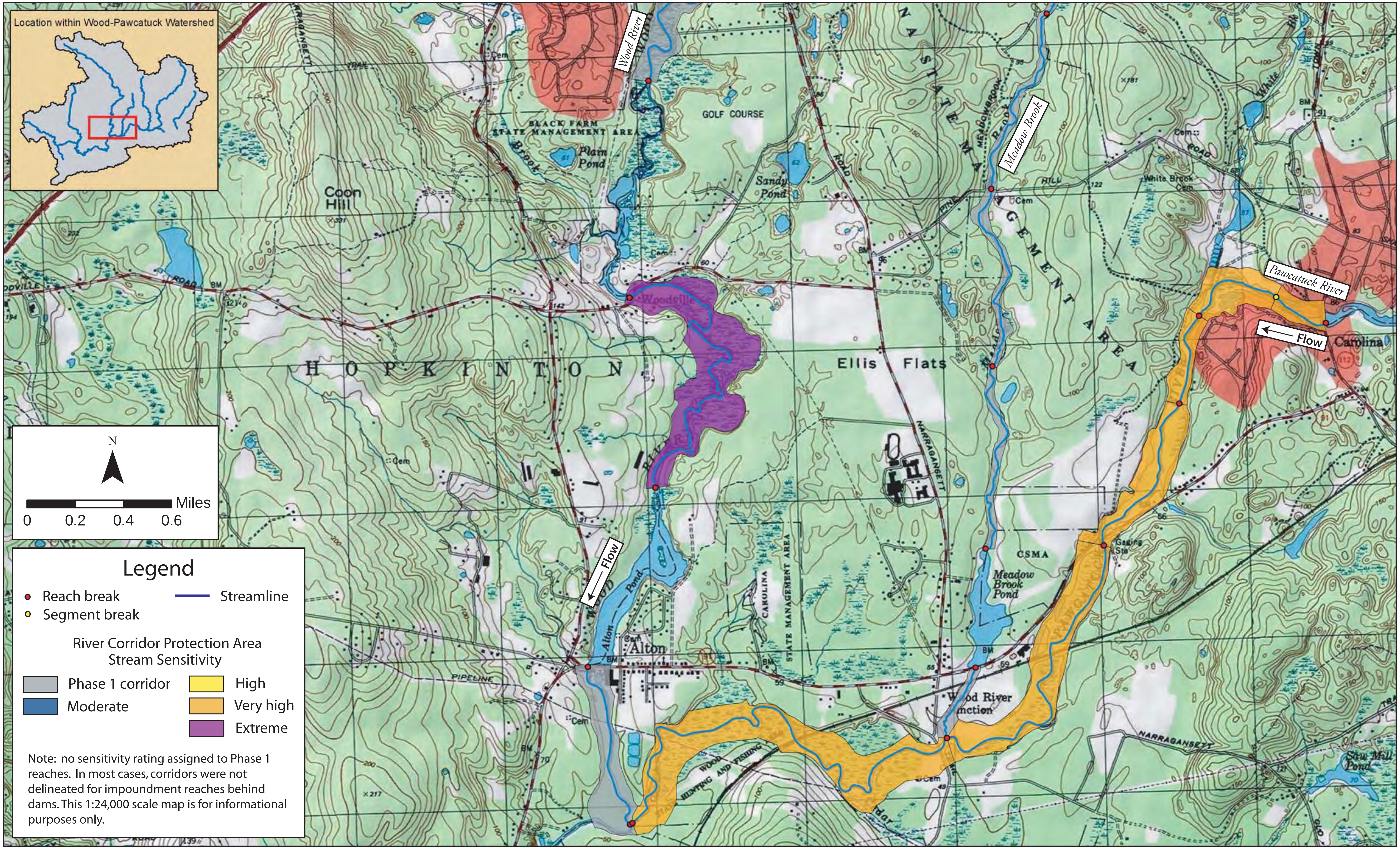
Wood-Pawcatuck Watershed River Corridor Protection Area Map - Meadow Brook (Map 3 of 3)



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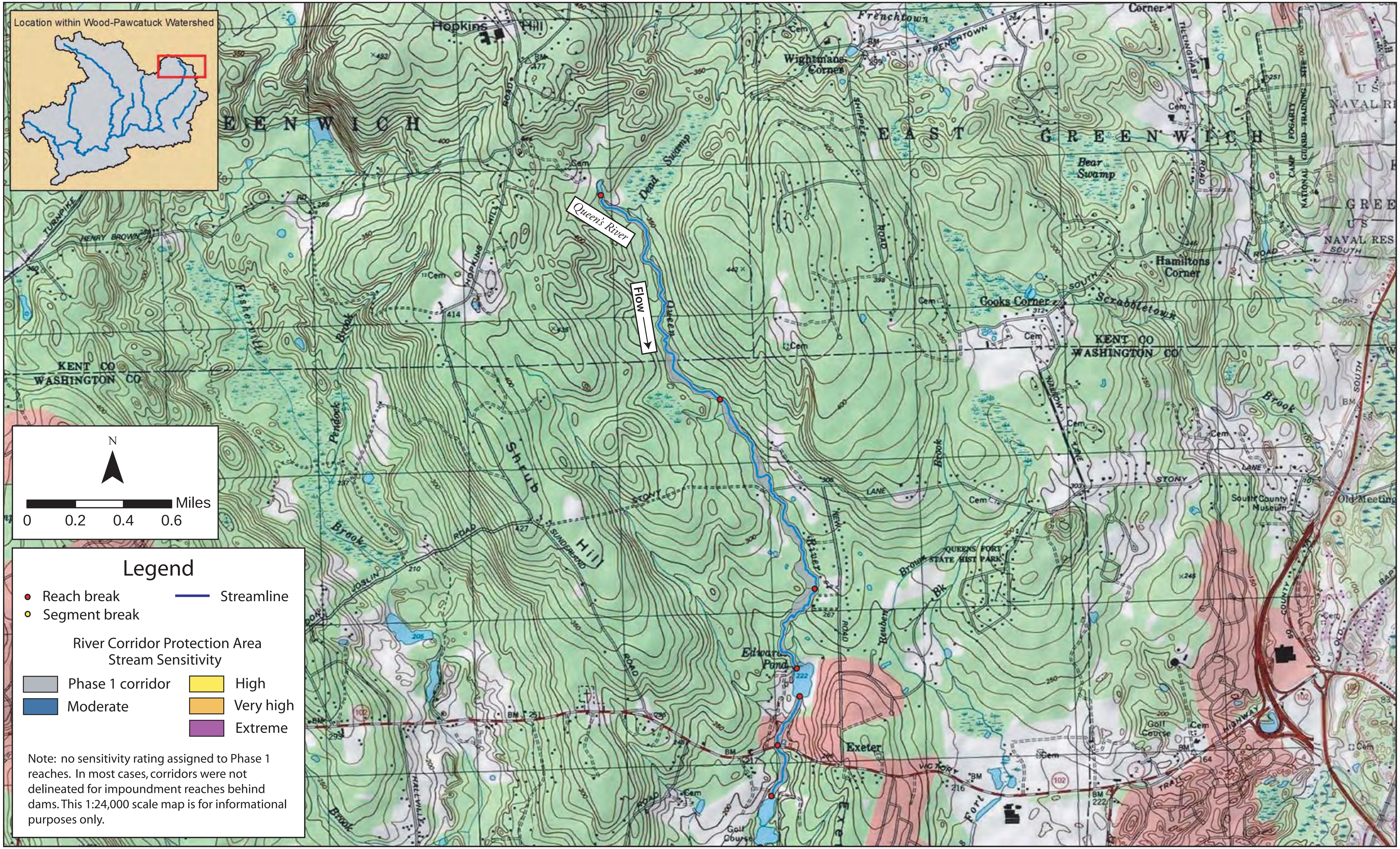
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Queen's / Usquepaug River (Map 1 of 4)



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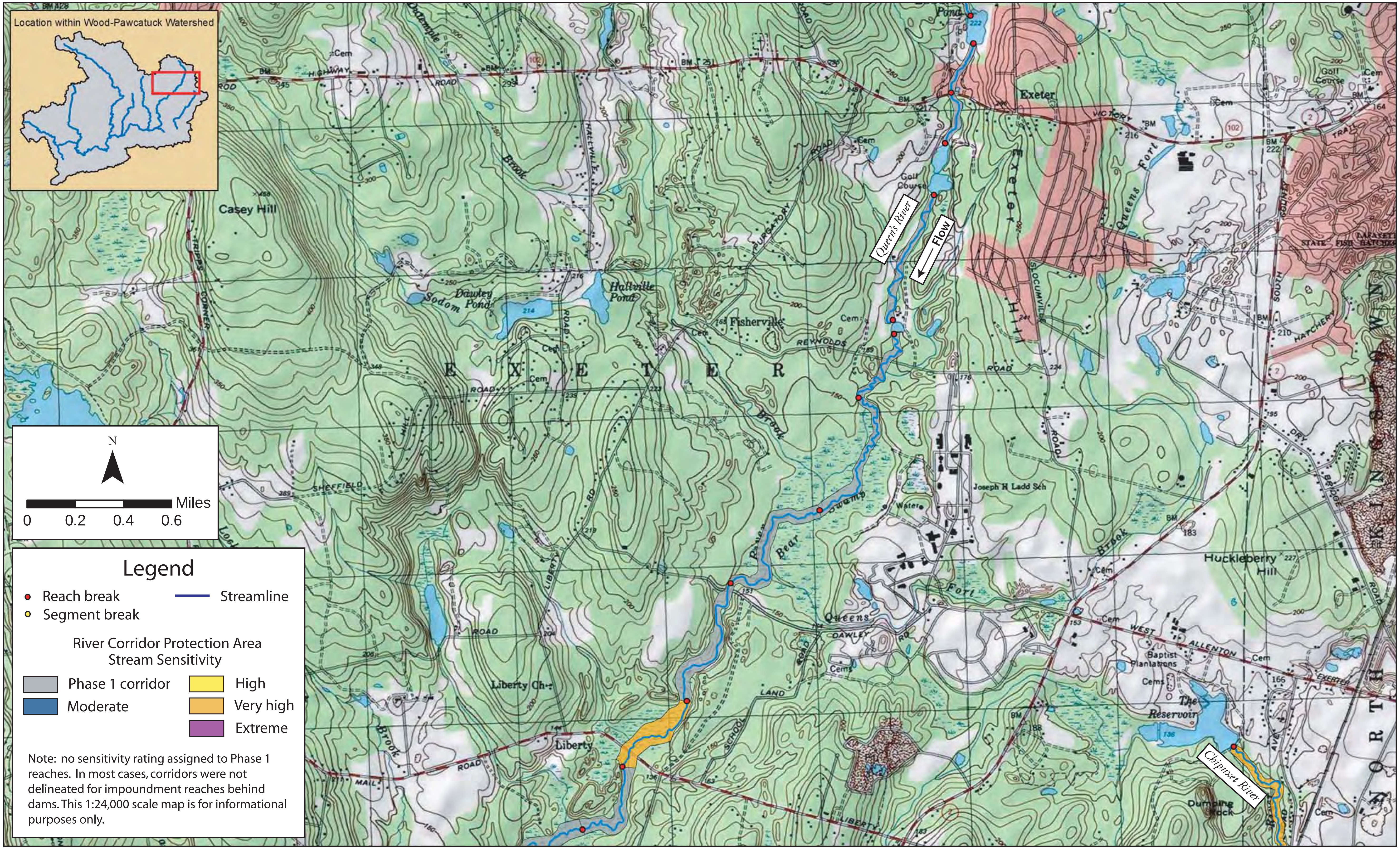
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Queen's / Usquepaug River (Map 2 of 4)



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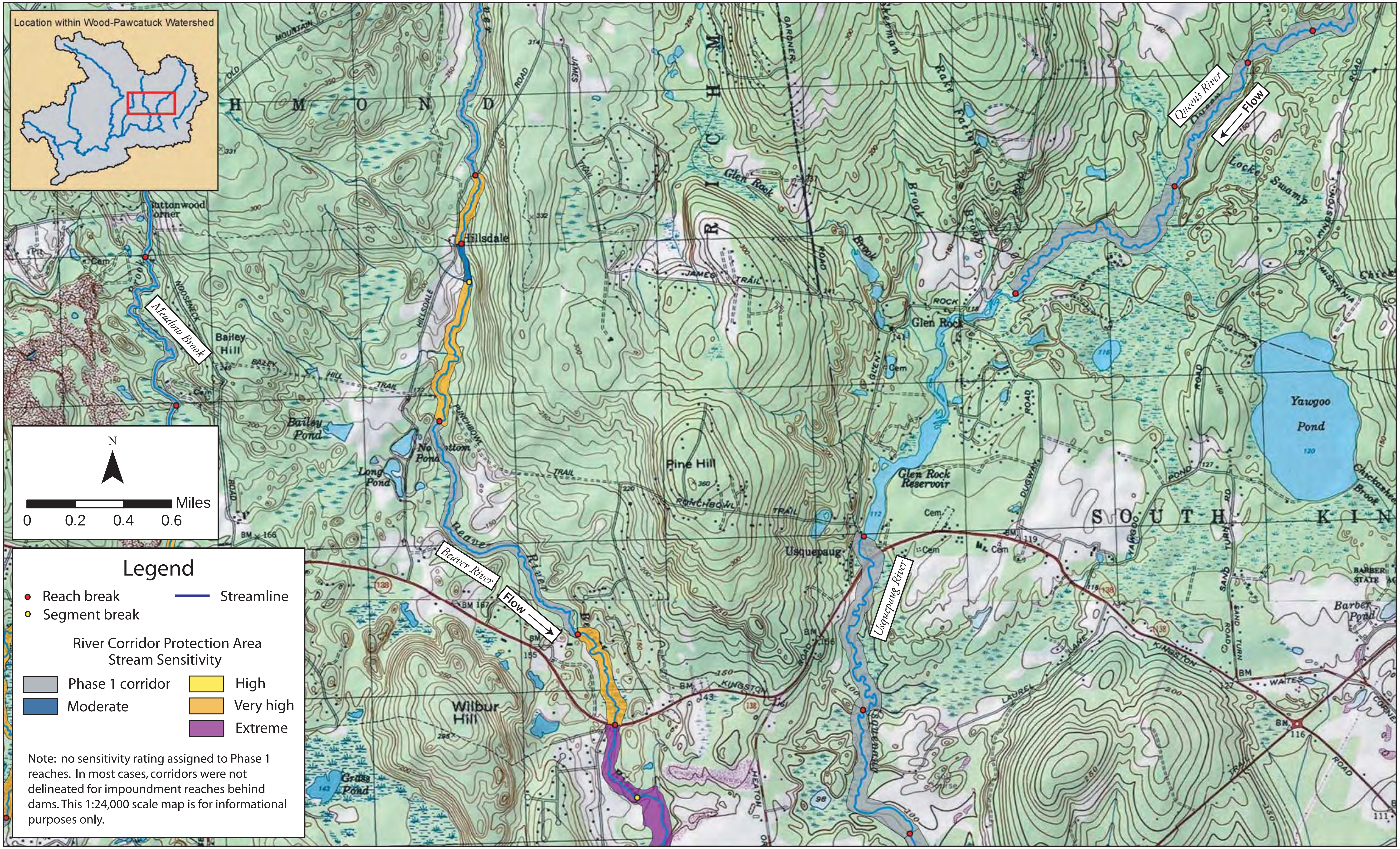
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by:
Field Geology Services
Fluvial Geomorphology

With support from:
FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Queen's / Usquepaug River (Map 3 of 4)



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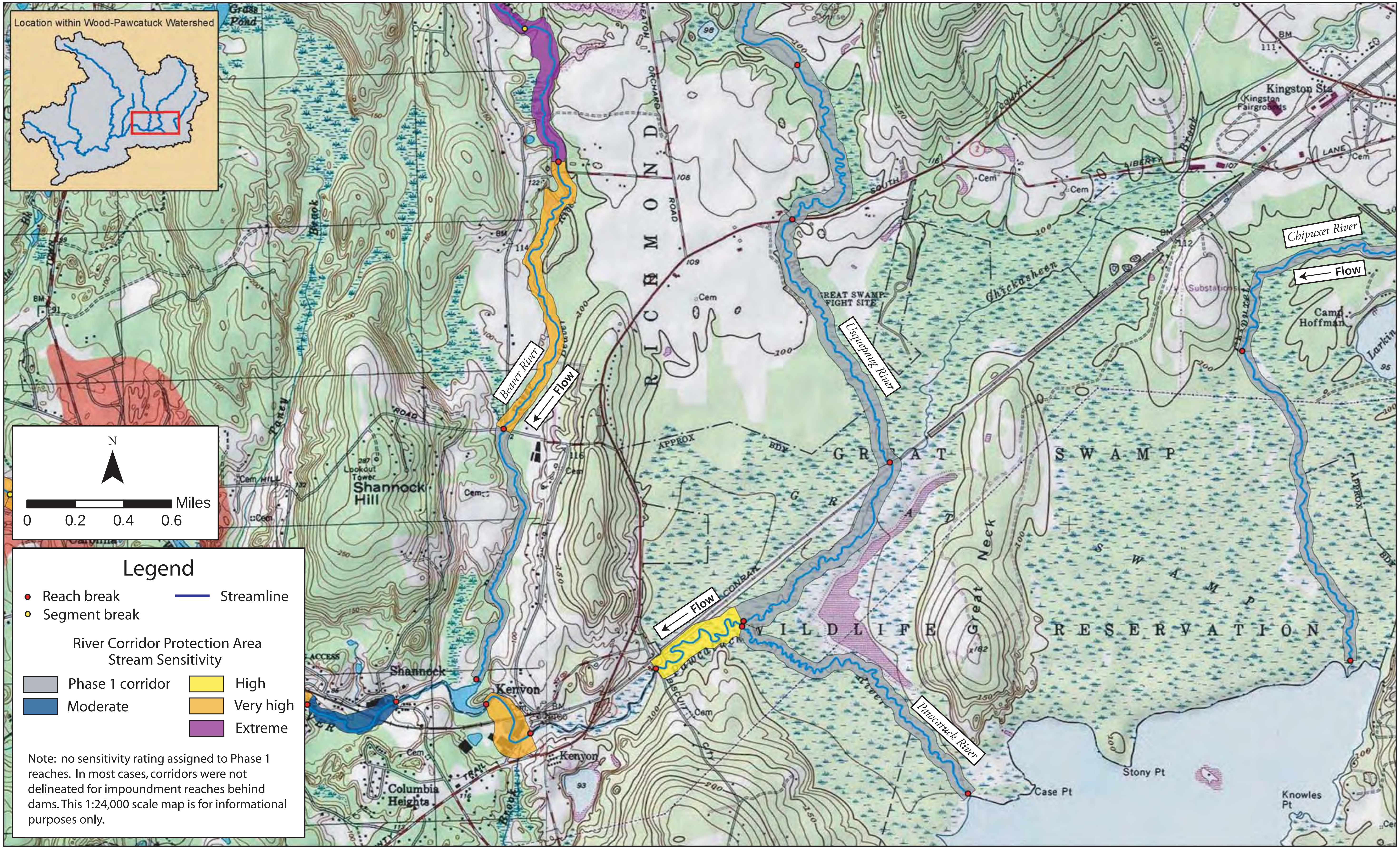
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Queen's / Usquepaug River (Map 4 of 4)



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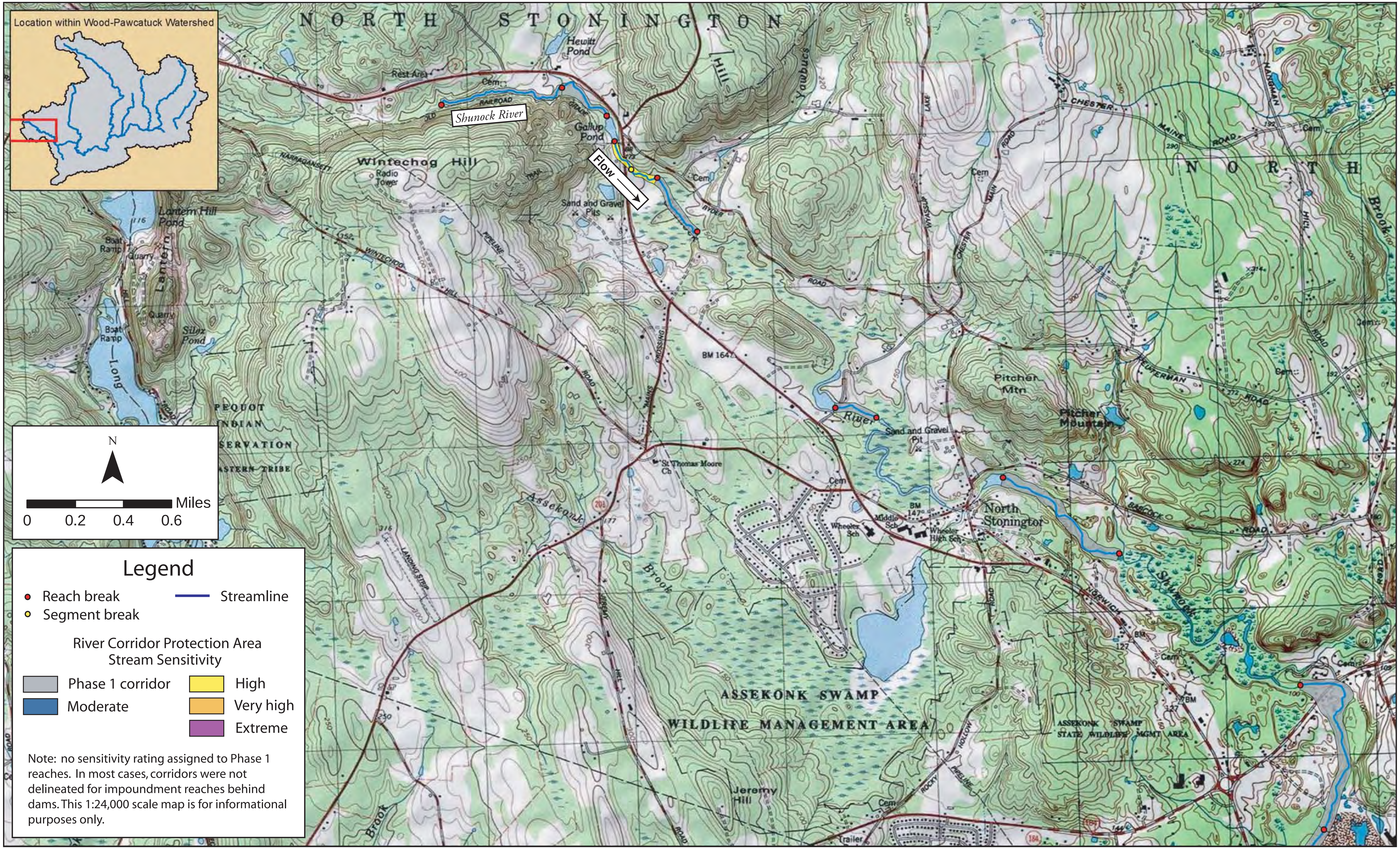
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services Fluvial Geomorphology

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Shunock River (Map 1 of 2)



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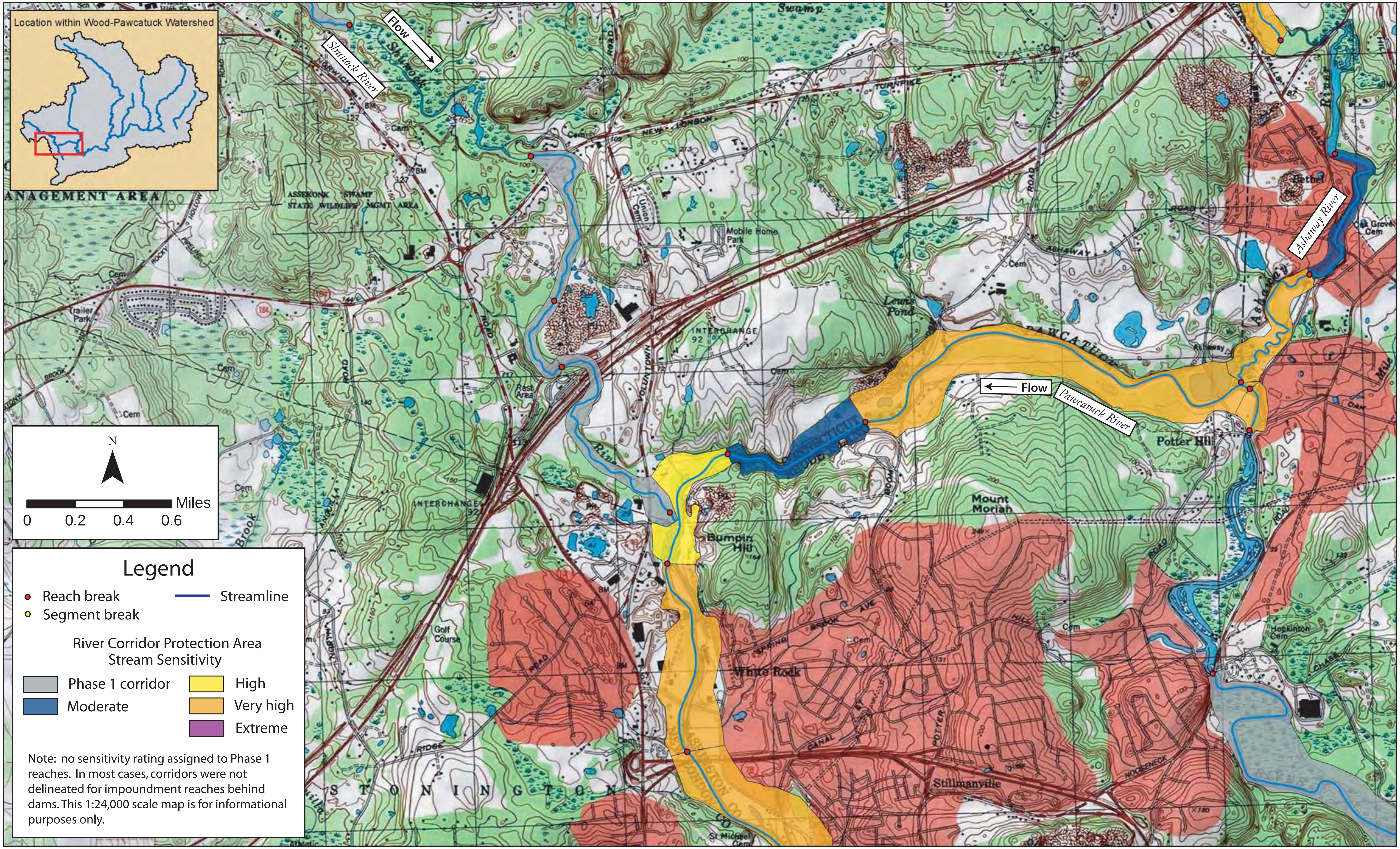
GIS data: Field Geology Services 2015-2016
Map prepared February 2016

Map prepared by: Field Geology Services

With support from: FUSS & O'NEILL

Wood-Pawcatuck Watershed River Corridor Protection Area Map - Shunock River (Map 2 of 2)



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GIS data: Field Geology Services 2015-2016
Map prepared February 2016

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